
Part 2 was introduced after Part 1 reached a length of almost 10000 pages. From now on Part 1 will remain essentially unchanged (except for the correction of errors and the inclusion of previously unrecognized book titles in one of the Part 1 sections entitled “Book Cover Gallery”). All additional citations will be included in Part 2. This includes citations dated 2019 or after; citations of previously published papers not included in Part 1; citations of some earlier papers on fluid-structure interaction; citations of some earlier papers on chaos and nonlinear dynamic response; citations of papers (published from 2014 on) from the journals, Nonlinear Dynamics, Smart Materials & Structures, Soft Matter, Earthquake Engineering & Structural Dynamics, Shock and Vibration, Mathematical Problems in Engineering and possibly from other journals not included in the list given at the beginning of Part 1. In March 2019 the citations of papers from 2014 - 2018 in International Journal of Structural Stability and Dynamics and the citations of papers from 2016 - 2018 in International Journal of Applied Mechanics were transferred from Part 1 to Part 2 in order to be able to include the list of references associated with each relevant citation without exceeding 10000 pages in Part 1.

With few exceptions, from now on all future effort on documenting the “shell buckling/vibration” field will generate additional entries only in Part 2 and in the image galleries of this website: “book cover gallery”, “shell buckling people” and “shell buckling images”.

Introduction:

MAY 2017: NEW STRATEGY USED FOR SEARCHING FOR “BUCKLING/VIBRATION” PAPERS:
I search the journals listed next for papers on buckling/vibration of thin-walled structures. From 2017 on I will search only the following journal issues published in the most recent year. This is not a complete list of journals in which “buckling/vibration” papers may appear, but it may be that most of such papers will probably continue to appear in the following journals:

Thin-Walled Structures
Journal of Constructional Steel Research
Computers & Structures
International Journal of Solids and Structures
Searches (from 2017 and on) for “buckling/vibration” papers includes the following recently added journals:
ASME Journal of Pressure Vessel Technology
Advances in Structural Engineering
Archive of Applied Mechanics
Meccanica
Latin American Journal of Solids and Structures
Computational Mechanics
Structural Engineering and Mechanics
Mechanics of Composite Materials
Mechanics of Advanced Materials and Structures
Advanced Composite Materials
Composites Science and Technology
International Journal of Steel Structures
ASME Journal of Mechanical Design
Steel and Composite Structures
Journal of Thermal Stresses
Applied Mathematical Modelling
Archive of Computational Methods in Engineering
International Journal of Mechanics and Materials in Design
International Journal of Advanced Structural Engineering
Journal of Applied Mechanical Engineering
International Journal of Applied Mechanics and Engineering
Thin Solid Films
Extreme Mechanics Letters
Proceedings of the Royal Society Series A
Applied Physics Letters

For each of the original set of above journals (the list above the heading, “from 2017 on”) I have searched for relevant papers published from 2012 – 2016, placing them under headings and over footings given in bold-faced-16-point font such as:

Many papers published in the journal, Thin-Walled Structures (2012-2016):

End of many papers published in the journal, Thin-Walled Structures (2012-2016).

For each of the above journals and for successive years I plan to search for relevant papers published from 2017 and on, placing them under headings and over footings in bold-faced 16-point font such as:

More papers published in the journal, Thin-Walled Structures (2017 and on):

End of more papers published in the journal, Thin-Walled Structures (2017 and on).

In December, 2018 I added the following journals for a search of buckling/vibration of thin-walled structures:

Nonlinear Dynamics
Google the string, “Nonlinear Dynamics” and click on the entry, “Nonlinear Dynamics – Springer”, then click on “Browse Volumes and Issues”.

Smart Materials and Structures
Google the string, “Smart Materials and Structures”, then click on “Smart Materials and Structures – IOPscience”, then look for “Journal Archive” and choose the volume and year.

Results of this December 2018 search are presented in Part 2 because Part 1 already has the maximum allowable number of pages.

I will, from time to time, GOOGLE the “Images for shell buckling” site. This large gallery contains images of and from papers on shell buckling that I may want to add to the “Bibliography” and images from links that I may want to add to the list of “Shell Buckling Links”. In this way I will be able to add citations and abstracts of papers in journals not included in the above list of journals, as well as citations and abstracts of papers published before 2012 that have not been not already included in the my very long “Bibliography”. The “Images for shell buckling” gallery will also continue to be a source of images that I may want to add to the “Shell Buckling Images” and “Book Cover Gallery” sections of this website. Of course, I will continue to add material that you send to me. Also, I include in my citations “References listed at the end of the paper” if such a list is available online. In this way, over the years, I hope to include citations of almost all “buckling/vibration” papers. However, please do not simply assume that this bibliography contains citations of ALL “buckling/vibration” papers. It is certain that I have missed and doubtless will continue to miss more than a few papers. Therefore, in your researches during specific projects please use other sources than this “shell buckling” website.

BEFORE MAY 2017: THE OLD STRATEGY USED FOR SEARCHING FOR “BUCKLING” PAPERS:
PRE-2017 OLD STRATEGY:
The following list of books and papers, etc. was constructed and continues to be constructed in a not entirely but somewhat helter-skelter manner. I make special attempts to find citations of work by my friends and colleagues in the “shell buckling” field, or citations of papers that referenced the work of my friends and colleagues who have spent much of their careers pushing back the frontiers in that field. I make some attempt to group papers by the same first or second author together, but not always. I make a minor attempt to group papers on the same subject together, but this was a very sporadic attempt and often at odds with the “same author” strategy. In the section containing early works on shell buckling I made an attempt to arrange papers more-or-less chronologically. There is some tendency for the most recent papers to be placed lower down in the file.

Some papers on fluid-structure interaction are placed at the beginning of Part 2 of this huge bibliography.

In some cases the citation of a paper is followed by a list of references (almost always in 10-point font) given at the end of that paper. This I do only when I have free access to a “pdf” file of the paper, and only when I can “cut-and-paste” the references listed at the end of that paper.

I use Google Scholar to do the searches, with many “sub-searches” with the use of search strings such as “Koiter shell buckling”, “Hutchinson shell buckling”, “Budiansky shell buckling”, “Stein shell buckling”, “Singer shell buckling”, “Almroth shell buckling”, “Simmonds shell buckling”, “Arbocz shell buckling”, “Riks shell buckling”, “Rankin shell buckling”, “Babcock shell buckling”, “Hoff shell buckling”, “Knight shell buckling”, “Noor shell buckling”, “Weller shell buckling”, “Hilburger shell buckling”, “Belytschko shell buckling”, “Chamis shell buckling”, “Stricklin shell buckling”, “Cohen shell buckling”, and so on. These GOOGLE searches bring up not only papers on shell buckling authored by these well-known researchers but
also papers in which works by these well-known researchers are cited by other authors, in other words, lots of papers. I also used search strings such as “shell buckling images”, “shell stability”, “shell wrinkling”, “shell nonlinear vibration”, “shell nonlinear dynamic response”, “thin shell nonlinear”, “phd dissertations shell buckling”, “Buckling of stiffened panels”, “nanotube buckling”, “buckling of tubes”, “thin-walled column buckling”, etc.

There are so many papers and even books in the shell buckling field that I apologize in advance for doubtless missing many of your contributions. At the time this file was initially created (March - August, 2011) there were about 500000 “hits” when the search string, “shell buckling” was entered into “GOOGLE Scholar/advanced GOOGLE search”. Here I have not much more than just scratched the surface. The vast universe of papers on the buckling and vibration of shells is like a fractal: no matter how much I narrow the search within that universe (for examples, “postbuckling composite shells” or “buckling sandwich shells” or “thermal buckling shells”, or Hutchinson buckling shells”), there still exists a vast sub-universe with essentially the same creators and characteristics as the entire “shell buckling” universe. I cannot possibly explore these universes and sub-universes completely. The shell buckling universe and its sub-universes are probably expanding faster than the cosmos itself.

The search strings, “shell buckling”, etc. also pull up papers about linear and nonlinear plate and shell vibration and dynamic response, buckling and vibration of columns and plates, stiffened plates, columns made of thin-walled segments, crushing of energy absorbing structures such as tubes and sandwich walls, wrinkling, crashworthiness papers, papers about nonlinear deformations of plates and shells with cracks, papers about new finite elements used for nonlinear analysis, and papers regarding buckling of carbon nanotubes, thin films, droplets and other “soft” structures. Therefore, many papers on these topics are cited here in addition to papers from the more traditional field of shell buckling.

END OF THE DESCRIPTION OF THE OLD STRATEGY SEARCHING FOR “BUCKLING” PAPERS

This file is a work in progress. From time to time I add more citations as I find additional old papers and new papers recently appearing in the literature.

FROM MAY 2017: THE NEW STRATEGY SEARCHING FOR BUCKLING/VIBRATION PAPERS:

In particular, there are many shell, column and beam buckling papers in the journal, Thin-Walled Structures. For example, see the website: http://www.sciencedirect.com/science/journal/02638231/109
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many papers on buckling of thin-walled columns and beams in the journal, Journal of Constructional Steel Research. For example, see the website: http://www.sciencedirect.com/science/journal/0143974X/46/1
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).
There are many “buckling” papers published in the journal, **Computers & Structures**. For example, see the website: [http://www.sciencedirect.com/science/journal/00457949](http://www.sciencedirect.com/science/journal/00457949)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Solids and Structures**. For example, see the website [http://www.sciencedirect.com/science/journal/00207683](http://www.sciencedirect.com/science/journal/00207683)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Mechanical Sciences**. For example, see the website [http://www.sciencedirect.com/science/journal/00207403](http://www.sciencedirect.com/science/journal/00207403)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Non-Linear Mechanics**. For example, see the website [http://www.sciencedirect.com/science/journal/00207462](http://www.sciencedirect.com/science/journal/00207462)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Pressure Vessels and Piping**. For example, see the website [http://www.sciencedirect.com/science/journal/03080296](http://www.sciencedirect.com/science/journal/03080296)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Impact Engineering**. For example, see the website [http://www.sciencedirect.com/science/journal/0734743X](http://www.sciencedirect.com/science/journal/0734743X)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Engineering Science**. For example, see the website [http://www.sciencedirect.com/science/journal/00207225](http://www.sciencedirect.com/science/journal/00207225)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Engineering Structures**. For example, see the website [http://www.sciencedirect.com/science/journal/01410296](http://www.sciencedirect.com/science/journal/01410296)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Composite Structures**. For example, see the website [http://www.sciencedirect.com/science/journal/02638223](http://www.sciencedirect.com/science/journal/02638223)
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).
There are many “buckling” papers published in the journal, **Composites Part B Engineering**. For example, see the website [http://www.sciencedirect.com/science/journal/13598368](http://www.sciencedirect.com/science/journal/13598368)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Finite Elements in Analysis and Design**. For example, see the website [http://www.sciencedirect.com/science/journal/0168874X](http://www.sciencedirect.com/science/journal/0168874X)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Computer Methods in Applied Mechanics and Engineering**. For example, see the website [http://www.sciencedirect.com/science/journal/00457825](http://www.sciencedirect.com/science/journal/00457825)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Structures**. For example, see the website: [http://www.sciencedirect.com/science/journal/23520124](http://www.sciencedirect.com/science/journal/23520124)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Journal of the Mechanics and Physics of Solids**. For example, see the website [http://www.sciencedirect.com/science/journal/00225096](http://www.sciencedirect.com/science/journal/00225096)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Journal of Sound and Vibration**. For example, see the website [http://www.sciencedirect.com/science/journal/0022460X](http://www.sciencedirect.com/science/journal/0022460X)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Procedia Engineering**. For example, see the website [http://www.sciencedirect.com/science/journal/18777058](http://www.sciencedirect.com/science/journal/18777058)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **European Journal of Mechanics – A/Solids**. For example, see the website [http://www.sciencedirect.com/science/journal/09977538](http://www.sciencedirect.com/science/journal/09977538)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Acta Mechanica Solida Sinica**. For example, see the website [http://www.sciencedirect.com/journal/acta-mechanica-solida-sinica/issues](http://www.sciencedirect.com/journal/acta-mechanica-solida-sinica/issues)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Structural Stability and Dynamics**. Google the string: “International Journal of Structural Stability and Dynamics”, then click on the first subheading under the entry: “International Journal of Structural Stability and Dynamics (World…”.

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **International Journal of Applied Mechanics**. Google the string: “International Journal of Applied Mechanics”, then click on the second entry, which is: “International Journal of Applied Mechanics (World Scientific)”. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **ASME Journal of Applied Mechanics**: For example, see the website [http://appliedmechanics.asmedigitalcollection.asme.org/issues.aspx](http://appliedmechanics.asmedigitalcollection.asme.org/issues.aspx)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many reviews of “buckling” papers published in the journal, **ASME Applied Mechanics Reviews**: For example, see the website [http://appliedmechanicsreviews.asmedigitalcollection.asme.org/issues.aspx](http://appliedmechanicsreviews.asmedigitalcollection.asme.org/issues.aspx)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Journal of Composite Materials**. Google the string: “Journal of Composite Materials”, then click on the third entry, which is: “Journal of Composite Materials – All Issues – SAGE Journals”

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Experimental Mechanics**. Google the string: “Experimental Mechanics”, then click on the first entry, “Experimental Mechanics – Springer”, then, on the resulting screen, click on “All Volumes & Issues” (located on the right-hand side of the screen near the top, in blue color)

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Acta Mechanica**.
Google the string: “Acta Mechanica”, then click on the first entry, “Acta Mechanica – Springer”, then, on the resulting screen, click on “Browse Volumes & Issues”.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Acta Mechanica Sinica. Google the string: “Acta Mechanica Sinica”, then click on the first entry, “Acta Mechanica Sinica – Springer”, then, on the resulting screen, click on “All Volumes & Issues” (located on the right-hand side of the screen near the top, in blue color). These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, AIAA Journal. For example, see the website: Google the string: “AIAA Journal”, then scroll down for a list of all issues, each of which you can click on to see authors, titles and abstract of papers. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, International Journal of Offshore and Polar Engineering. Google the string: “International Journal of Offshore and Polar Engineering”; click on one of the volumes/issues in the upper right-hand corner. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, International Journal of Crashworthiness. Google the string: “International Journal of Crashworthiness”, then click on the entry, “International Journal of Crashworthiness – Taylor & Francis Online”; you can then click on any Volume/Issue. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).


There are many “buckling” papers published in the journal, Marine Structures. For example, see the website: http://www.sciencedirect.com/science/journal/09518339 These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Ocean Engineering. For example, see the website: http://www.sciencedirect.com/science/journal/00298018
These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Aerospace Science and Technology. For example, see the website: http://www.sciencedirect.com/science/journal/12709638

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).


There are many “buckling” papers published in the journal, Curved and Layered Structures. For example, see the website: https://www.degruyter.com/view/j/clss

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, ASCE Journal of Structural Engineering. Google the string: “ASCE Journal of Structural Engineering”, then click on the entry, “ASCE Journal of Structural Engineering | ASCE Library”, then, on the resulting screen, click on “ALL ISSUES”. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Journal of Sandwich Structures and Materials. For example, see the website: http://journals.sagepub.com/loi/jsm

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, ASME Journal of Pressure Vessel Technology. For example, see the website: http://pressurevesseltech.asmedigitalcollection.asme.org/issues.aspx

These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Advances in Structural Engineering. Google the string: “Advances in Structural Engineering”, then click on the entry: “Advances in Structural Engineering – All Issues – SAGE Journals” These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, Archive of Applied Mechanics. Google the string: “Archive of Applied Mechanics”, then click on the entry: “Archive of Applied Mechanics – Springer – Springer Link”; then click on “Browse Volumes & Issues”. These papers are cited here primarily in sections under bold-faced headings that start with the words, “many papers published” (2012-2016) and “more papers published” (2017 and on).
There are many “buckling” papers published in the journal, **Meccanica**.
Google the string: “Meccanica”, then click on the entry: “Meccanica – Springer – Springer Link”; then click on “Browse Volumes & Issues”.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Latin American Journal of Solids and Structures**.
Google the string: “Latin American Journal of Solids and Structures”, then click on the item “Archives”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Computational Mechanics**.
Google the string: “Computational Mechanics”, then click on the entry: “Computational Mechanics – Springer – Springer Link”; then click on “Browse Volumes & Issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Structural Engineering and Mechanics**.
Google the string, “Structural Engineering and Mechanics”, then click on the entry, “Structural Engineering and Mechanics” | Korea Science” and see “Volume & Issues” on your screen
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on).

There are many “buckling” papers published in the journal, **Mechanics of Composite Materials**.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Mechanics of Advanced Materials and Structures**.
Google the string, “Mechanics of Advanced Materials and Structures”, then click on the entry, “Mechanics of Advanced Materials and Structures” and scroll down to “List of Issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Advanced Composite Materials**.
Google the string, “Advanced Composite Materials, then click on the entry, “Advanced Composite Materials – Taylor & Francis Online” and scroll down to “List of Issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Composites Science and Technology**.
Google the string, “Composites Science and Technology”, then click on the entry,
“Composites Science and Technology – ScienceDirect.com” and on that screen click on “All issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal. *International Journal of Steel Structures.*
Google the string: “International Journal of Steel Structures”, then click on the entry: “International Journal of Steel Structures – Springer – Springer Link”; then click on “Browse Volumes & Issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, *ASME Journal of Mechanical Design.*
Google the string: “Journal of Mechanical Design”, then click on the entry: “Journal of Mechanical Design – The American Society of Mechanical….”, then find “Browse All Issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal. *Steel and Composite Structures.*
Google the string, “Steel and Composite Structures”, then click on the entry, “Steel and Composite Structures” | Korea Science” and see “Volume & Issues” on your screen.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, *Journal of Thermal Stresses.*
Google the string, “Journal of Thermal Stresses, then click on the entry, “Journal of Thermal Stresses – Taylor & Francis Online”, and find the list of journal issues.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, *Applied Mathematical Modelling.*
Google the string, “Applied Mathematical Modelling”, then click on the entry, “Applied Mathematical Modelling | ScienceDirect.com” and scroll way down to “View all issues”
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, *Archive of Computational Methods in Engineering.*
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)


These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **International Journal of Advanced Structural Engineering**.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Journal of Applied Mechanical Engineering**.
Google the string: “Journal of Applied Mechanical Engineering”, then click on the entry: “Journal of Applied Mechanical Engineering – OMICS International”; then find “Archive” near the top of the screen, and click on it.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **International Journal of Applied Mechanics and Engineering**
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Thin Solid Films**
Google the string: “Thin Solid Films”, then click on the entry: “Thin Solid Films | ScienceDirect.com” and scroll way down to “View all issues”.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Extreme Mechanics Letters**
Google the string: “Extreme Mechanics Letters”, then click on the entry: “Extreme Mechanics Letters | ScienceDirect.com” and scroll way down to “View all issues”.
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Proceedings of the Royal Society Series A**
These papers are cited here primarily in sections under bold-faced headings that start with the words, “more papers published” (2017 and on)

There are many “buckling” papers published in the journal, **Applied Physics Letters**
Here is an idea which may help to compensate for my lack of completeness. Any of you may email to me, David Bushnell (email address: bush@sonic.net) your curriculum vitae (CV). Please include a close-up (head and shoulders) photograph of yourself and of course a list of your publications concerned with buckling/vibration. I will then include your CV on this website in the section called “Shell Buckling People”. A portrait photograph of yourself will be a very important part of the future assemblage of “Shell Buckling People” on this website. Therefore, make sure to include it with your buckling CV. We “buckling people” should get to know one another better, and I feel that a close-up photograph of yourself is a significant part of that. I also encourage you to include with your “buckling CV” one or more pictures of buckled shells, either actual shells that buckled unexpectedly in the “real world” or buckled shells from laboratory experiments or buckled shells from the application of theories described in one or more of your papers. When you send me such images please include a complete citation of the source so that credit can be properly given. Images of this type will continue to improve this website and keep it up-to-date. During my searches of the “shell buckling” field I encounter many such images that I obtain from the internet for inclusion on this website.

The citations listed in this file are somewhat unusual in that many of them include the affiliations of the authors and the authors’ abstracts. Recently (2018 on) I no longer include authors’ affiliations, mostly because recent papers have so many authors. In this regard, perhaps one should try to cut down on the number of authors, simply acknowledging in an “Acknowledgment” section the efforts of those who played a minor role. This will probably be more difficult for papers that involve experiments because so much effort can be expended with so little to show for it.

Some advice about abstracts:
1. Do not include what is essentially the title of your paper as the first sentence in its abstract. Anyone who sees the abstract also sees the title.
3. Be specific. Avoid vague words such as “capacity” and “reliability”. Do you mean “linear buckling” or “non-linear buckling” or “plastic collapse” or some combination? In your description stay close to the physical world by naming specific phenomena.
4. “The analysis was verified by test cases.” Be more specific.
5. Do not include math symbols or equations in your abstract.
6. Compose the abstract as a single paragraph.

Organization of this file:
This very long file lists “shell buckling” citations in the following sections:
Section 1. Especially useful papers in my opinion
Section 2. A list of mainly books on plates and shells compiled by Hans Obrecht in 2001
Section 3. Some of the review articles in Applied Mechanics Reviews or elsewhere
Section 4. Articles that are partly review articles and that partly contribute new material
Section 5. Special issues of journals with a given theme
Section 6. Books on shell buckling or on subjects related in some way to shell buckling
Section 7. Some early work on buckling of plates and shells
Section 8. There follow many, many citations on buckling and vibration of columns, plates and shells

Section 8 is by far the longest section in this file.

******************* IMPORTANT NOTE ABOUT “DOI” *******************

What is a doi?

A digital object identifier (or doi) is a standard for persistently identifying electronic documents on a digital network. A typical use of a DOI is to give a scientific paper or article a unique identifying number that can be used by anyone to locate details of the paper, and possibly an electronic copy. Unlike the URL system used on the Internet for web pages, the DOI does not change over time, even if the article is relocated. This means that you can always find a document you have referenced even if the original publisher changes its URL.

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To find a document using a DOI

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   The correct format for citing a DOI is as follows: doi:10.1016/j.physletb.2003.10.071
2. Open the following DOI site in your browser:
   http://dx.doi.org
3. Enter the entire DOI citation in the text box provided, and then click Go.

****************** END OF IMPORTANT NOTE ABOUT DOI******************

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Section 1: Some Especially Useful Papers in my opinion:


For an important review of NASA design recommendations relating to shell stability, see the file, 1998nasa.pdf, by Michael P. Nemeth and James H. Starnes, Jr.:

ABSTRACT: A summary of the existing NASA design criteria monographs for the design of buckling-resistant thin-shell structures is presented. Subsequent improvements in the analysis for nonlinear shell response are reviewed, and current issues in shell stability analysis are discussed. Examples of nonlinear shell responses that are not included in the existing shell design monographs are presented, and an approach for including reliability-based analysis procedures in the shell design process is discussed. Suggestions for conducting future shell experiments are presented, and proposed improvements to the NASA shell design criteria monographs are discussed.

References listed at the end of the report:

Arthur W. Leissa (The Ohio State University Research Foundation, 1314 Kinnear Road, Columbus, Ohio 43212), “Buckling of laminated composite plates and shell panels”, AFWAL-TR-85-3069, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio 45433, June, 1985, 392 references
http://handle.dtic.mil/100.2/ADA162723

ABSTRACT: This work summarizes the technical literature dealing with buckling and post-buckling behavior of laminated composite plates and shell panels. Emphasis is given to modern materials used in the aerospace industry having fiber-matrix constituents (e.g., glass-epoxy, boron-epoxy, graphite-epoxy, boron-aluminum), but other applications are also considered (e.g., plywood, paperboard). Geometric configurations taken up are either flat (plates) or cylindrically curved (shells), and have rectangular planform. All possible types of loading conditions and edge constraint conditions are considered. Both symmetrically and unsymmetrically laminated configurations are included, with symmetrical laminates represented by orthotropic or anisotropic plate or shell theory. Complicating effects dealt with include: internal holes, shear deformation, sandwich plates with soft cores, local instability, inelastic materials, hygrothermal effects and stiffeners. Approximately 400 references are used. Extension numerical results are presented in graphical and tabular form. Both theoretical and experimental results are summarized.

Jin Guang Teng (Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong) “Buckling of thin shells: Recent advances and trends”, Applied Mech. Reviews, Vol. 49, No. 4, pp. 263-274, April 1996, DOI: 10.1115/1.3101927

ABSTRACT: This paper provides a review of recent research advances and trends in the area of thin shell buckling. Only the more important and interesting aspects of recent research, judged from a personal view point, are discussed. In particular, the following topics are given emphasis: (a) imperfections in real structures
and their influence; (b) buckling of shells under local/non-uniform loads and localized compressive stresses; and (c) the use of computer buckling analysis in the stability design of complex thin shell structures.


ABSTRACT: The perturbation method and the continuation method are the two most popular techniques for the solution of finite element equations that describe instability phenomena. This paper presents a summary of the principles involved and describes some trends in the development of these techniques.

E. Riks (1), F.A. Brogan (2) and C.C. Rankin (2)
(1) National Aerospace Laboratory, Anthony Fokkerweg, Amsterdam, The Netherlands
(2) Applied Mechanics Lab., Lockheed Missiles & Space Co.Inc., 3251 Hanover Street, Palo Alto, California, 94304, USA


ABSTRACT: Many shell stability problems can be analyzed following the quasi static approach, i.e. with methods that solve the static equations of equilibrium. This paper focuses on some particular points of this approach. There are cases, however, mode jumping for example, where the methods of statics do not longer suffice and where it becomes necessary to combine the methods of statics with procedures for the integration of the equations of motion. The latter idea is illustrated with an example that was analyzed with the shell finite element code STAGS.

References listed at the end of the paper:
PARTIAL OUTLINE:

I. Introduction ...........................................272
II. Cylindrical Motion of Infinite Cylindrical Shells (Beamshells) .............. 274
   A. Geometry of the Undeformed Shell and Planar Motion .................. 274
   B. Integral Equations of Cylindrical Motion ..............................276
   C. Differential Equations of Cylindrical Motion ........................... 278
   D. Virtual Work (Weak Form of the Equations of Motion) ............... 279
   E. The Mechanical Work Identity ......................................... 280
   F. Strain Measures ................................................. 280
   G. Alternate Stresses and Strains ....................................... 282
   H. The Basic Assumption of Beamshell Theory ............................ 283
   I. The Mechanical Theory of Elastic Beamshells ........................... 283
   J. Constitutive Laws for Elastic Beamshells .............................. 284
   K. Elastostatics .................................................... 287
   L. Elastodynamics ............................................... 292
   M. Thermodynamics .............................................. 296
III. The Equations of General Nonlinear Shell Theory ....................... 302
ABSTRACT: This paper overviews the efforts that led to resolution of the 20th century conundrum in elastic stability of shells. In particular, the dramatic disagreement between theoretical and experimental results and the subsequent introduction of the empirical knockdown factor, is discussed in detail. The mismatch between theory and experiment was qualitatively explained by Warner Tjardus Koiter in his now famous thesis, as well as in the paper by Lloyd H. Donnell and C.C. Wan. However, these studies did not offer means for rigorous, theoretical derivation of the knockdown factor for the shells with generic imperfection patterns encountered in practice. Numerous attempts to resolve the conundrum via deterministic theoretical, experimental and probabilistic analyses remained unsuccessful. The conundrum consists in two facts. On one hand, it consists of the impossibility of using of hundreds and perhaps thousands of deterministic studies in predicting the rigorous knockdown factors. On the other hand, it lies in the fact that Wynstone Barrie Fraser and Bernard Budiansky (1969) [157] and numerous other investigators, although recognizing the need to utilize probabilistic approach to resolve the above conundrum, asserted that the buckling load of stochastic structures was a deterministic quantity. Some investigators suggested using that result as the design load. In 1979, this author lucked out on reliability-based theoretical means for derivation of the knockdown factor and its judicious allocation.

References listed at the end of the paper:


[151] Euler L. Methodus Inveniendi Lineas Curvas Maximive Porportiae Gaudentes (Appendix: De Curvis Elasticis), Marcum Michaelensem Bosquet, Lausanne, 1744 [in Latin].


ABSTRACT: Current procedures of buckling load estimation for thin-walled structures may provide very conservative estimates. Their refinement offers the potential to use structure and material properties more efficiently. Due to the large variety of design variables, for example laminate layup in composite structures, a prohibitively large number of tests would be required for experimental assessment, and thus reliable numerical techniques are of particular interest. The purpose of this paper is to analyze different methods of numerical buckling load estimation, formulate simulation procedures suitable for commercial software and give recommendations regarding their application. All investigations have been carried out for cylindrical composite shells; however similar approaches are feasible for other structures as well. A single perturbation load approach is reproduced and modified. Buckling behavior for negative values of the perturbation load is examined and a pattern similar to a positive perturbation load is observed. Simulations with three perturbation forces show a decreased (i.e. more critical) value of the buckling load compared to the single perturbation load approach. Global and local dynamic perturbation approaches exhibit a behavior suitable for lower bound estimation for structures with arbitrary geometries.

ABSTRACT: Spherical composite ribbed shell is made of thin reinforced concrete shell and composite ribs, which has many advantages such as large span, high rigidity, and large bearing capacity and low cost. It is one of the urgent issues to considering the mechanical performance under dynamic loading. Based on nonlinear finite element theory, a numerical calculation model is built, and then the dynamic response of composite ribbed shell under step load and seismic wave are respectively discussed. The results shows: under the vertical step load, a positive symmetric deformation appeared in unstable status; under horizontal step loads, an anti symmetric deformation emerged. While as the seismic wave was exerting, structural damage caused by thin concrete shell damage and plastic deformation development, namely it was the synthetic action result of structural stiffness weaken and P-△ effect from geometric nonlinear, so structure damage was the comprehensive effect of strength failure and dynamic instable.

References listed at the end of the paper:
Isaac Elishakoff (1), Julius Kaplunov (2) and Evgeniya Nolde (3)
(1) Dept. of Ocean and Mechanical Engineering, Florida Atlantic University, Boca Raton, Florida, USA
(2) School of Computing and Mathematics, Keele University, Keele, Staffordshire, UK
(3) Dept. of Mathematics, Brunel University, Uxbridge, Middlesex, UK

“Celebrating the centenary of Timoshenko’s study of effects of shear deformation and rotary inertia”, Applied Mechanics Reviews, Vol. 67, November 2015, 060802-1-11

ABSTRACT: This study revisits Timoshenko beam theory (TBT). It discusses at depth a more consistent and simpler governing differential equation. The so-called second spectrum is also addressed. Then, we provide the asymptotic justification of the aforementioned differential equation along with detailed discussion of the boundary and initial conditions. The paper also presents remarks of historical character, in the context of other pertinent studies. [DOI: 10.1115/1.4031965]

References listed at the end of the paper:
Incompressible Elastic Layer Near Cut

Isotropic Elasticity

the Scattering of an Obliquely Incident Plane Acoustic Wave by a Cylindrical Shell,” Acustica, 80, pp. 280


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Kaplunov, J. D., 1995, “Long

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Berdichevsky, V. L., 2009, Variational Principles in Continuum Mechanics, Spr

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300

AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Boston, MA, AIAA, Reston, VA, April

299

Dixit, A., 2013, “Mechanics

298


297


296


295


294


293


292


291


290


289


288


287


286


285


284


283


282


281


280


279


278


277


276


275


274


273


272


271


270


269


268

PARTIAL INTRODUCTION: In order to produce efficient, reliable designs & to avoid unexpected catastrophic failure of structures of which thin shells are important components, the engineer must understand the physics of shell buckling. The objective of this survey is to convey to the reader a “feel” for shell buckling, whether it be due to nonlinear collapse, bifurcation buckling, or a combination of these modes. …

(list of references is given below, at the end of the section, “Early works…”).

E. Ramm (1) and W.A. Wall (2)
(1) Institute of Structural Mechanics, University of Stuttgart, Germany
(2) Chair of Computational Mechanics, Technical University of Munich, Germany


ABSTRACT: It is apparent that physics and numerics are strongly linked in every serious undertaking in computational mechanics. This is in particular pronounced when the matter of study excels through a very sophisticated, even sometimes tricky physical behaviour. Such a delicate characteristic is the trademark of shell structures, which are the most often used structural components in nature and technology. This outstanding position in the hierarchy of all structures is due to their curvature allowing to carry transverse loading in an optimal way by in-plane membrane actions, despite an often extreme slenderness. As typical for optimized systems their performance might be on the one hand excellent, but can also be extremely sensitive to certain parameter changes on the other hand. This prima donna like mechanical behaviour with all its sensitivities is of course carried over to any numerical scheme. In other words it is a fundamental precondition to understand the principle features of the load carrying mechanisms of shells before designing and applying any numerical formulation. The present study addresses this peculiar interrelation between physics and numerics. At first typical characteristics of shell structures are described; this include their benefits but also their extreme sensitivities. In the second part these aspects are reflected on related computational models and numerical procedures. This discussion is carried through a number of selected problems and examples. It need to be said that the paper is the outcome of a general plenary lecture addressing fundamental aspects rather than concentrating on a specific formulation or numerical scheme.

References listed at the end of the paper:
34. Gee M, Wall WA, Ramm E. Preconditioning for Thin-Walled Structures and a Scaled Director Approach for a Three Dimensional Shell in preparation.
INTRODUCTION:

1.1 Historical Remarks

Thin-walled structures like plates and shells are the most common construction elements in nature and technology. This is independent of the specific scale; they might be small like cell membranes and tiny machine parts or very large like fuselages and cooling towers. This preference to apply walls as thin as possible is a natural optimization strategy to reduce dead load and to minimize construction material. In addition to the slenderness, the advantageous effect of curvature is utilized in shell structures allowing to carry transverse loading in an optimal way, a design principle already known to the ancient master builders. Their considerable heuristic knowledge allowed them to create remarkable buildings, like the Roman Pantheon (115–126) and the Haghia Sophia (532–537) in Constantinople, still existing today. It was not before the Renaissance that scientists began to mathematically idealize the structural response, a process that we denote nowadays as modeling and simulation.

Already, Leonardo da Vinci (1452–1519) stated (Codex Madrid I) a principle that later on emerged to a beam model. The subsequent process, associated with names like Galileo (1564–1642), Mariotte (1620–1684),
Leibniz (1646–1716), Jakob I Bernoulli (1654–1705), Euler (1707–1783), Coulomb (1736–1806), and Navier (1785–1836), led to what we call today Euler–Bernoulli beam theory (Timoshenko, 1953; Szabo, 1979). This development was driven by the ingenious ideas to condense the complex three-dimensional situation to the essential ingredients of structural response like stretching, bending, torsion, and so on, and to cast this into a manageable mathematical format. The inclusion of transverse shear deformation is attributed (1859) to Bresse (1822–1883) and extended (1921) to dynamics by Timoshenko (1878–1972), whose name has established itself as a common denomination for this model. Extensions to further effects like uniform and warping torsion, stability problems, cross-sectional distortion, and further refinements, for example, including higher-order kinematics, follows in the nineteenth and twentieth century.

The development of the theory of masonry arches and vaults had its own history, also starting with Leonardo da Vinci (for a detailed elaboration on this subject confer Benvenuto (1991)). The primary aspect in this context was the description of failure mechanisms, a problem investigated up to the present time (see e.g. the valuable work of Heyman). Also, Robert Hooke's (1635–1703) ‘Riddle of the Arch’ has to be referred to, phrased in a Latin anagram ‘Ut pendet continuum flexile, sic stabit contigum inversum rigidum’ (literally translated: As the flexible cable hangs, the inverted arch stands). It constitutes a form-finding principle for arches and shells (Mainstone, 1975), which became known as the inverted chain and membrane principle, often applied in the sequel. Christopher Wren's construction of St. Paul Cathedral in London, Poleni's experiment for the rehabilitation of the cupola of St. Peter in Rome, Rondelet's French Pantheon, Gaudi's work in Catalonia up to modern shell designs by Otto and Isler are based on this principle (Ramm and Reitinger, 1992).

The history of the development of two-dimensional plate theories has its own peculiarities (Timoshenko, 1953; Szabo, 1979). Inspired by Chladni's (1756–1827) experiments with vibrating plates, Jakob II Bernoulli (1759–1789) formulated a grid model of overlapping beams, neglecting the twisting mode. This was corrected by others later on. The related competition proposed by the French Academy and Sophie Germain's (1776–1831) various trials to win the prize and the involvement of Lagrange (1736–1813) became famous. They and others like Poisson (1781–1840) and Navier derived the proper differential equation; however, they still had some shortcomings in their result, in particular, with respect to the involved elastic constants. Kirchhoff (1824–1887) finally removed all doubts in 1850 (Kirchhoff, 1850) and is credited as the founder of modern plate theory. It took almost a century before E. Reissner (1913–1996) (Reissner, 1944; Reissner, 1945) and Mindlin (1906–1987) (Mindlin, 1951) extended the model including the role of transverse shear deformations. Innumerable modifications and extensions, like anisotropy, large deformation (v. Kármán plate theory), higher-order theories, and so on, have been derived over the years.

It is interesting that the initial derivation of a shell formulation was also motivated primarily by vibration problems. Euler developed in 1764 a model to simulate the tones of bells, cutting the axisymmetric structure into rings, applying curved beam models and leaving out the meridional effects. Also, here it took over a century before a consistent theory of thin shells had been derived by Love (1888) (August E. H. Love, 1863–1940). It is based on Kirchhoff's method and thus became known as the Kirchhoff–Love model. For a description of the subsequent emergence of this shell model and the related controversies among Love and his contemporaries on the role of the boundary conditions of both the membrane and the bending part (in particular Lord Rayleigh (1842–1919) and Lamb (1849–1934)), we refer to the article by Calladine (1988), which is worth reading. The need for detailed solutions has driven research in the first half of the twentieth century. Names like H. Reissner, Meissner, Geckeler, Flügge, Vlassov, Novozhilov have to be mentioned, to name just a few; later on further refinements have been introduced by E. Reissner, Gol'denveizer, Koiter, Naghdi, and many others. The inclusion of transverse shear deformations sometimes linked to the name of Naghdi today mostly is referred
to as a Reissner–Mindlin formulation, in recognition of their extended plate theories.

The series of names in connection with shell formulations could be continued forever; there are very few topics in structural mechanics where so many investigations have been published. Even for experts, it is hardly possible to have an overall view on the number of special finite element models developed so far. This is a strong indication for the complexity of the involved mechanics on the one hand and their practical relevance on the other hand.

It is obvious that the early developments of theories for thin-walled structures were governed primarily by the main applications in those times, namely, buildings in architecture. Since the industrial revolution, the picture changed completely: now other applications, for example, in mechanical engineering, in vehicle and aerospace industry, in biomechanics, and so on, became dominant and the driving force for further developments.

Large displacements, rotations and strains, buckling, composites, material nonlinearities, coupled problems, multiscale and multiphysics, solution methods, and higher-order formulations are a few keywords for problems that have been extensively investigated in the last few years. The finite element method as a discretization concept is absolutely predominant. An interesting example as to how the finite element developments have influenced the selection of specific structural models is the early shift from Kirchhoff–Love formulations to those with Reissner–Mindlin kinematics for plate and shell elements. It is motivated mainly by the reduced compatibility requirements, although from the practical point of application, the Kirchhoff–Love model is often sufficient.

In times where computer capacity has become so powerful and the simulation tools have reached such a high level of sophistication, we should not forget the main driving force of our ancestors: concentration on the essentials and reduction to the principal mechanical behavior of thin-walled structures (Ramm and Wall, 2004).

1.2. Overview

This paper concentrates on the mathematical modeling of nonlinear mechanics of thin-walled structures in view of associated finite element formulations. This means that we will primarily focus on formulations for structural models as prerequisite for derivation of finite elements, rather than specific ‘elementology’. The main emphasis is put on shells, including the special case of flat plates, turning into shells anyway in the nonlinear regime. The derivations are kept as general as possible, including thick and layered shells (laminated or sandwich structures), as well as anisotropic and inhomogeneous materials from the outset. Throughout Section 4.4, we will specify the corresponding restrictions and assumptions to obtain the classical 5-parameter shell formulation predominantly used for standard shell problems in the context of finite element analysis.

In most part of the text, we restrict ourselves to static problems within the framework of geometrically nonlinear elasticity, neglecting time dependence and inertia effects. The extension into the materially nonlinear area is a straightforward procedure. It is believed that this does not mean a too strong restriction in view of the underlying motivation.

It is a well cultivated tradition to let review articles start with the remark that a complete overview of existing methods and appropriate literature is utterly impossible. The multitude of existing concepts, methods, and implementations, as well as scientific papers, text books, and yet other review articles would effectively prohibit an exhaustive overview. J. E. Marsden and T. J. R. Hughes remark in what they call the ‘disclaimer’ of their
famous book on Mathematical Foundations of Elasticity (Marsden and Hughes, 1983) that

‘This book is neither complete nor unbiased. Furthermore, we have not mentioned many deep and highly erudite works, nor have we elucidated alternative approaches to the subject. Any historical comments we make on subjects prior to 1960 are probably wrong, and credits to some theorems may be incorrectly assigned.’

Although the present paper is neither a book nor covers such a broad field like the textbook by Marsden and Hughes (1983), it clearly shares the quoted property. We therefore directly head toward the ideas and inspirations driving the authors during the compilation of the paper at hand.

Motivations for concerning oneself with the present subject are many. They might be of purely scientific nature or driven by the need to find the necessary level for the mechanical content of a model or to have a reliable element as a tool for certain applications one might have in mind. Interest in the mathematical formulation and resulting numerical properties of finite elements for thin-walled structures may also arise when simply applying certain finite element formulations available in scientific or commercial codes. While trying to provide useful information for practitioners and users of commercial finite element codes, this treatise clearly addresses a readership with a scientific background, both things not being mutually exclusive anyway.

When developing and applying a finite element formulation for thin-walled structures, one comes across a couple of questions. Which mechanical effects should be included and which can be neglected? Is it better to start from a shell theory or develop continuum-based elements along the lines of the degenerated solid approach? And what about geometrically exact models? Which simplifications are useful – and admissible? Which consequences does the formulation have for the finite element model? Which parameterization of degrees of freedom are sensible for the applications one has in mind? Should drilling degrees of freedom be included in a shell formulation or not? There are many, many more questions.

It is in this spirit that we try to give an overview of the various decisions that one implicitly makes when choosing a specific theory or finite element formulation, respectively. Although such an overview is necessarily incomplete, it should not cover only a mere register of umpteen different plate and shell finite elements along with their alleged pros, cons, and limitations; to be even more specific, this aspect will be very limited in the present contribution.

By doing this, we carefully separate model decisions and the finite element formulation. The former addresses those approximations that are made while formulating the continuous theory. The latter is concerned with additional approximation errors, coming into play along with discretization and finite element formulation. While these numerical errors eventually vanish with mesh refinement, the model errors, inherent to the theory, persist. Distinguishing this is crucial for a sophisticated determination of feasible methods and a competent interpretation of numerical results.

References: The list of references is very long and would require a lot of editing to conform to the format of this bibliography.

-----end of the the Bischoff et al entry-----
ABSTRACT: Recent advances in shell buckling research are reviewed. Five separate subject areas are covered: elastic postbuckling behavior and imperfection sensitivity, plastic buckling, dynamic buckling, experiments and computations. Recent history of the research is presented emphasizing important advances in understanding. Areas of needed research and current trends are pointed out.

ABSTRACT: The present paper provides a unified, general presentation of the basic theory of the buckling and post-buckling behavior of elastic structures in a form suitable for application to a wide variety of special problems. The notation of functional analysis is used for this purpose. Before the general analysis, simple conceptual models are used to elucidate the basic concepts of bifurcation buckling, snap buckling, imperfection sensitivity, load-shortening relations, and stability. The energy approach, the virtual-work approach, and mode interaction are discussed. The derivations and results are applicable to continua and finite-dimensional systems. The virtual-work and energy approaches are given separate treatments, but their equivalence is made explicit. The basic concepts of stability occupy a secondary position in the present approach.

ABSTRACT: The weights of optimal compression structures of several types are estimated. Minimum weights of columns having solid square or circular cross-sections are compared with those of similar metal–foam-filled tubes, hollow tubes and tubes whose walls are foam-core sandwiches. Similarly, the minimum (of near-minimum) weights of wide sandwich compression panels are studied along with those of hat-stiffened, solid-skin panels and panels in which the skins and stiffeners are themselves metal–foam-core sandwiches. In these studies, weight comparisons are made on the basis of appropriate structural indices and compressive strength is the only failure criterion. These studies provide baseline comparisons that ignore other possible design constraints, such as longitudinal stiffness, minimum gage and cost.


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(2) Cambridge University Engineering Department, Trumpington Street, Cambridge, CB2 1PZ, U.K  
January 1993, pp. 183-211, doi:10.1016/0022-5096(93)90068-Q  
ABSTRACT: A review of experimental data and elementary theoretical formulas for compressive failure of polymer matrix fibre composites indicates that the dominant failure mode is by plastic kinking. Initial local fibre misalignment plays a central role in the plastic kinking process. Theoretical analyses and numerical results for compressive kinking are presented, encompassing effects of strain-hardening, kink inclination, and applied shear stress. The assumption of rigid fibres is assessed critically, and the legitimacy of its use for polymer matrix composites is established.

TABLE OF CONTENTS:  
I. Introduction ............................................. 43  
II. Competing Failure Mechanisms in Composites ............... 44  
   A. Elastic Microbuckling................................. 46  
   B. Plastic Microbuckling .................................. 48  
   C. Fiber Crushing .......................................... 53  
   D. Splitting .................................................. 54  
   E. Buckle Delamination ................................. 56  
   F. Shear-Band Formation ............................... 57  
   G. Failure Maps ............................................ 58  
III. Compressive Strength of Unidirectional Composites Due to Microbuckling ............................................. 62  
   A. Kinking Theory ........................................... 66  
   B. The Role of Fiber Bending: Infinite-Band Analysis ........ 77  
   C. Initiation Strength for a Finite Imperfection ............ 85  
IV. Propagation of a Microbuckle in a Unidirectional Composite .......... 94  
   A. Experimental Observations ............................. 94  
   B. Theoretical Predictions ................................ 97  
V. The Notched Strength of Multi-Axial Composites .............. 103  
   A. Large-Scale Crack-Bridging Model ..................... 105  
VI. Directions for Future Research ............................. 110  
Acknowledgments ........................................... 113  
References .................................................. 113
PARTIAL ABSTRACT: The overall performance of sandwich structures depends in general on the properties of the facesheets, the core, the adhesive bonding the core to the skins, as well as geometrical dimensions. Sandwich beams under general bending, shear and in-plane loading display various failure modes. Their initiation, propagation and interaction depend on the constituent material properties, geometry, and type of loading. Failure modes and their initiation can be predicted by conducting a thorough stress analysis and applying appropriate failure criteria in the critical regions of the beam. This analysis is difficult because of the nonlinear and inelastic behavior of the constituent materials and the complex interactions of failure modes. Possible failure modes include tensile or compressive failure of the facesheets, debonding at the core/facesheet interface, indentation failure under localized loading, core failure, wrinkling of the compression facesheet, and global buckling. In the present work failure modes of sandwich beams were studied. Facesheet materials were typically unidirectional and carbon fabric/epoxy and glass fab-ric/vinylester. Core materials discussed include four types of a closed-cell PVC foam (Divinycell H80, H100, H160 and H250, with densities of 80, 100, 160 and 250 kg/m$^3$, respectively) and balsa wood. The facesheet and core materials were fully characterized mechanically. The various failure modes were studied separately and both initiation and ultimate failure were determined. Following initiation of a particular failure mode, this mode may trigger and interact with other modes and final failure may follow a different failure path. The transition from one failure mode to another for varying loading or state of stress and beam dimensions was discussed. Experimental results were compared with analytical predictions.

References listed at the end of the paper:


TABLE OF CONTENTS:
1. Introduction
II. Initiation and Propagation of Bulges in Inflated Elastic Tubes
   A. The Problem
   B. Experiments: Initiation and Propagation of a Bulge
   C. Analyses
   D. Discussion and Conclusions

III. Initiation and Propagation of Buckles in Long Tubes and Pipes under External Pressure
   A. The Problem
   B. Propagating Buckle Experiments
   C. Analyses
   D. Effect of Tension on the Buckle Propagation Pressure
   E. Discussion and Conclusions

IV. Propagating Buckles in Long, Confined Cylindrical Shells
   A. The Problem
   B. Confined Propagating Buckle Experiments
   C. Analyses
   D. Discussion and Conclusions

V. Buckle Propagation in Long, Shallow Panels
   A. Buckling of Shallow Arches
   B. Propagating Buckles in Long, Shallow Panels
   C. Discussion and Conclusions

VI. Summary and Discussion
ABSTRACT: Koiter [1] was the first to formulate an asymptotic expansion to investigate postbuckling behavior and imperfection sensitivity of elastic structures. Since then, a large number of analyses of particular structures have appeared as well as some new expansions aimed at specific problems, such as interaction between buckling modes associated with simultaneous or nearly simultaneous buckling modes. In this contribution, various methods of this kind are discussed and compared as regards applicability and ease of use. Focus will be on Koiter's slowly varying local mode amplitude [2] and [3], on Byskov & Hutchinson's expansion [4] and on Peek & Kheyrkhahan's method [5], which enlarged the scope of the previous expansions in that it covers nonlinear prebuckling states, also. Other important contributions a number of which are based on these methods are also discussed. On the other hand, many important works, e.g. the comprehensive paper by Hunt [6] will not be mentioned in any detail. The accuracy of the methods as well as their mathematical complexity and ease of use are compared. Finally, in view of today's inexpensive and powerful computers, an obvious question is concerned with whether full analyses must always be preferred because asymptotic expansions are obsolete.

References listed at the end of the paper:


ABSTRACT: Carbon nanotubes subject to large deformations reversibly switch into different morphological patterns. Each shape change corresponds to an abrupt release of energy and a singularity in the stress-strain curve. These transformations, simulated using a realistic many-body potential, are explained by a continuum shell model. With properly chosen parameters, the model provides a remarkably accurate “roadmap” of nanotube behavior beyond Hooke's law.

References listed at the end of the paper:
Here is the citation of a survey article by Z.P. Bazant about stability in continuum mechanics in general. This survey references many of the original works:
ABSTRACT: The paper attempts a broad overview of the vast field of stability of structures, including elastic and anelastic structures, static and dynamic response, linear and non-linear behavior, energy approach, thermodynamic aspects, creep stability and fracture or damage-induced instability. The importance of stability theory to various fields of engineering and applied science is pointed out and the history of the discipline is briefly sketched. The principal accomplishments are succinctly reviewed, and fruitful recent trends, particularly the stability analysis of damage localization and fracture, are emphasized.
Reference listed at the end of the paper:
Hurlbrink, E., 1908. Schiffbau 9, 517.

Zeitschrift des Vereines Deutscher Ingenieure 52 (43), 1706-1713.
Young, T., 1807. A Course of Lectures on Natural Philosophy and the Mechanical Arts, London.


CONTENTS:
1. Introduction .................................................................5
   1.1 Buckling strength of shells.............................................5
   1.2 Working Stress Design .................................................5
   1.3 Design applying numerical methods...............................6
   1.4 Symbols and Definitions ..............................................6
   1.5 Buckling modes .............................................................8
2. Stresses in Closed Cylinders .............................................10
   2.1 General .................................................................10
   2.2 Stresses .................................................................10
3. Buckling Resistance of Cylindrical Shells ...............................13
   3.1 Stability requirement ...................................................13
   3.2 Characteristic buckling strength of shells .......................13
   3.3 Elastic buckling strength of unstiffened curved panels ........14
   3.4 Elastic buckling strength of unstiffened circular cylinders ..........14
   3.5 Ring stiffened shells ....................................................15
   3.6 Longitudinally stiffened shells ....................................19
   3.7 Orthogonally stiffened shells .....................................21
3.8 Column buckling .............................................................................................................. 21
3.9 Torsional buckling ......................................................................................................... 23
3.10 Local buckling of longitudinal stiffeners and ring stiffeners ...................................... 24

4. Unstiffened Conical Shells .............................................................................................. 26
4.1 Introduction .................................................................................................................... 26
4.2 Stresses in conical shells .............................................................................................. 26
4.3 Shell buckling ................................................................................................................ 27


Object and Scope of the Project:
The main objective of this study is to develop a set of numerical methods suitable for investigating the load-deflection and bifurcation characteristics of structures for which significant nonlinear behavior is possible. The methods are applicable to a wide variety of structures, but will be examined in detail only with reference to one of the simplest types of structures possessing the necessary complications in behavior - the planar arch under a concentrated load.

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(2) Department of Civil and Environmental Engineering, Tennessee Technological University
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ABSTRACT: A version of nonlocal elasticity theory is employed to develop a nonlocal Benoulli/Euler beam model. Some representative problems are solved to illustrate the magnitude of predicted nonlocal effects. Particular attention is paid to cantilever beams which are often used as actuators in small scale systems.

References listed at the end of the paper:

ABSTRACT: Most natural (or biological) materials are complex composites whose mechanical properties are often outstanding, considering the weak constituents from which they are assembled. These complex structures, which have risen from hundreds of million years of evolution, are inspiring Materials Scientists in the design of novel materials. Their defining characteristics, hierarchy, multifunctionality, and self-healing capability, are illustrated. Self-organization is also a fundamental feature of many biological materials and the manner by which the structures are assembled from the molecular level up. The basic building blocks are described, starting with the 20 amino acids and proceeding to polypeptides, polysaccharides, and polypeptides–saccharides. These, on their turn, compose the basic proteins, which are the primary constituents of ‘soft tissues’ and are also present in most biominerals. There are over 1000 proteins, and we describe only the principal ones, with emphasis on collagen, chitin, keratin, and elastin. The ‘hard’ phases are primarily strengthened by minerals, which nucleate and grow in a biomediated environment that determines the size, shape and distribution of individual crystals. The most important mineral phases are discussed: hydroxyapatite, silica, and aragonite. Using the classification of Wegst and Ashby, the principal mechanical characteristics and structures of biological ceramics, polymer composites, elastomers, and cellular materials are presented. Selected systems in each class are described with emphasis on the relationship between their structure and mechanical response. A fifth class is added to this: functional biological materials, which have a structure developed for a specific function: adhesion, optical properties, etc. An outgrowth of this effort is the search for bioinspired materials and structures. Traditional approaches focus on design methodologies of biological materials using conventional synthetic materials. The new frontiers reside in the synthesis of bioinspired materials through processes that are characteristic of biological systems; these involve nanoscale self-assembly of the components and the development of hierarchical structures. Although this approach is still in its infancy, it will eventually lead to a plethora of new materials systems as we elucidate the fundamental mechanisms of growth and the structure of biological systems.

References listed at the end of the paper:


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Section 2: List of mainly books on plates and shells compiled by Hans Obrecht in 2001:

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[34] Bushnell, D.: Computerized Buckling Analysis of Shells, Martinus Nijhoff Publishers, Dordrecht, The
Netherlands 1985
[40] Cosserat, E. and F.: Theorie de corps deformable, Hermann & Cie, Paris 1909
[60] Eckström: Studien über dünne Schalen von rotationssymmetrischer Form und Belastung mit konstanter oder veränderlicher Wandstärke, Stockholm 1933
[100] Hampe, E.: Kühltürme [Cooling Towers], VEB-Verlag für das Bauwesen, Berlin 1975
[114] Höhn: Über die Festigkeit der gewölbten Böden und der Zylinderschale, Berlin 1927
[121] Joedicke, J.: Raum und Form in der Architektur, Stuttgart 1985
[134] Kollar, L.: Statik und Stabilität der Schalenbögen und Schalenbalken [Static and Stability Analyses of Shell-Arches and Beams], Akadémiai Kiado, Budapest 1973; German Translation published by Verlag Wilhelm
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[148] Lewe: (Handbuch für Eisenbetonbau): Die statische Berechnung der Flüssigkeitsbehälter, Berlin 1928
[152] Lichnerowicz, A.: Einführung in die Tensoranalyse, Bibliographisches Institut, Mannheim 1966
[156] Love/Timpe: Lehrbuch der Elastizität, Leipzig 1907
[158] Lundgren, H.: Cylindrical Shells, 360pp., The Danish Technical Press, The Institution of Danish Civil Engineers, Copenhagen 1949
[185] Novozhilov, V.V.: The Theory of Thin Shells, P. Noordhoff Ltd., Groningen (Niederlande) 1959
[193] Pflüger: Einführung in die Schalenstatistik, Wolfenbüttel 1948
[207] Pöschl: Berechnung von Behältern nach neueren analytischen und graphischen Methoden, Berlin 1926
[222] Saudan, M.; Saudan-Skira, S: Coupoles, Rennes, Lausanne 1989
List of Citations found on the internet in a “pdf” file missing the text of the paper of which it is a part. The title of the paper might contain the string, “Buckling of Unstiffened Steel Cones Subjected to… and it might have been published in 2012 and it might have been written by Jan Blachut, et al. (That is just a guess!):


2008.
[75] C. Bisagni and P. Cordisco, “Post-buckling and collapse experiments of stiffened composite cylindrical
[95] L. Lanzi, “A numerical and experimental investigation on composite stiffened panels into post-buckling,”


M. K. Chryssanthopoulos and C. Poggi, “Collapse strength of unstiffened conical shells under axial


1996.


[180] L. Kollár, “Buckling of complete spherical shells and spherical caps,” in Buckling of Shells. A State-of-


List of citations from the paper by J. Blachut: Experimental perspective on the buckling of pressure vessel components”, Applied Mechanics Reviews, Vol. 66, January 2014, pp. 1-23, DOI: 10.1115/1.4026067 : 


University, Belgium, pp. 387–395.


List of Citations on the website: https://sites.google.com/site/thindomeshells/bibliography, “Thin Dome Shells” by Rob Duncan and Michael Hanning:


Carlson, R. L. (1), Sendelbeck, R. L. (2), Hoff, N. J. (2)
(1) School of Aerospace Engineering at the Georgia Institute of Technology, Atlanta, Georgia
(2) Department of Aeronautics and Astronautics of Stanford University, Stanford, California


ABSTRACT: Complete spherical shells with radius-to-thickness ratios of from 1570 to 2120 were produced by electroforming. For specimens of good quality and for optimum testing conditions, buckling pressures up to 86 percent of the classical value were obtained. The effect of loading-system characteristics was examined by pressurizing spherical shells in rigid and soft systems and no difference in buckling pressure was observed. It
was found that buckling behavior is strongly influenced by the nature and severity of flaws or imperfections; i.e., low buckling pressures can be correlated with the presence of severe flaws or nonuniformities.

References listed at the end of the paper:


ABSTRACT: Buckling of a series of thin-metal, shallow spherical shells under a uniform hydrostatic pressure has been investigated. Stress and deformation histories, as well as the critical buckling pressure and the post-buckling behavior, have been determined. Comparisons with theoretical analyses for buckling of spherical caps are given. Results are presented for an initial phase of a stability study of truncated conical sections which have been subjected to combinations of axial load and lateral pressure. A series of roll-formed and butt-welded, truncated aluminum conical shells with a 75-deg base angle have been tested. Buckle modes for axial-load condition alone, lateral-pressure load alone and combinations of these loading conditions are described. Interaction curves for the conditions investigated are given.

References listed at the end of the paper:


Photographic sequences show the transition from the unbuckled state to the fully buckled configuration for four types of loading: axial compression, torsion, external (hydrostatic) pressure and a suddenly applied external pressure.

ABSTRACT: In order to better understand the mechanism of elastic shell buckling, photographs of the buckling process were obtained for thin cylindrical shells subjected to four types of loading: axial compression, torsion, external (hydrostatic) pressure and a suddenly applied external pressure.

References listed at the end of the paper:


Chuen-Yuan Chia, 1967, Finite deflections of thin shallow spherical shells under axisymmetric line load and uniform pressure, ASME J. Appl. Mech., 34(4), 1022-1024,


ABSTRACT: The problem of the finite displacement and buckling, of a shallow spherical dome is investigated both theoretically and experimentally. Experimental results seem to indicate that the classical criterion of buckling is applicable to very shallow spherical domes for which the theoretical calculation was made. A transition to energy criterion for higher domes is also indicated.


ABSTRACT: Expressions for the physical tangential and bending strains of nonlinear thin elastic shell theory in nonorthogonal coordinates are derived in a new, relatively compact form. The geometric and physical significance of the results is interpreted, where possible. In addition, the quantities describing the differential geometry of a deformed surface are also given. All results obtained are exact in the sense that no restrictions are imposed on the magnitude of strains in the derivations. The expressions for the nonlinear case are compared with the corresponding formulas of the linear theory. The results obtained together with further results to be published on the strains of the parallel surface, the statics of shells, and constitutive relations find direct application in the analysis of the nonlinear behavior of thin shells.


ABSTRACT: Elastic stability of clamped shallow spherical shells subjected to a small finite-area load at the apex is studied experimentally. Upper and lower critical buckling loads and prebuckled and postbuckled deflections are found for λ between 10 and 17. Buckling modes have been observed and defined. Nonaxisymmetric deformations are noted. Shells for λ less than 8 1/2 exhibit plastic behavior and do not buckle.


ABSTRACT: The European Standard for Shell Strength and Stability has many provisions for the global analysis of shell structures using finite element analysis. Three alternative treatments are permitted: a simple linear analysis (LA) giving stress resultants to be compared with simple algebraic hand calculation strength assessment rules, a fully fledged nonlinear analysis, with material and geometric nonlinearities as well as properly characterised imperfections (GMNIA), and an intermediate treatment that requires only two strength assessments: linear bifurcation (LBA) and plastic limit (MNA). Because of the sensitivity of shell buckling to different forms and different amplitudes of imperfection, which depend strongly on the stress state, the GMNIA procedure is very onerous. This paper gives a brief outline of the design process and the relationship between algebraic and computational strength assessments. It then discusses the challenges facing the user of the LBA-MNA procedure and resolves some of the uncertainties surrounding it.

References listed at the end of the paper:


References from an unknown paper:


End of Section 2

Section 3: Some of the Review Articles in Applied Mechanics Reviews or Elsewhere


N. J. Hoff, “A survey of the theories of creep buckling”, AFOSR-TN-60-382; SUDAER-80, June 1, 1958 ABSTRACT: A survey is presented of the theories of buckling of structural elements whose material is subject to creep deformations. Two fundamentally different approaches to the solution of the buckling problem are discussed. In one, the structural element is assumed to be perfect and perfectly centered under the load and buckling is initiated by a disturbance in the configuration. In the second, the creep deformations begin in consequence of the deviation of the un loaded centerline or median plane of the structural eleme from the line of
load application. In both cases the element has a finite lifetime. A critical time of creep buckling is defined beyond which the element cannot be used to carry the prescribed loads.


ABSTRACT: The purpose of the present survey is to review the analysis of composite materials from the applied mechanics and engineering science point of view. The subjects under consideration will be analysis of the following properties of various kinds of composite materials: elasticity, thermal expansion, moisture swelling, viscoelasticity, conductivity (which includes, by mathematical analogy, dielectrics, magnetics, and diffusion), static strength, and fatigue failure.


ABSTRACT: A survey is presented which includes the buckling of shells under loads for which the shell is sensitive to initial imperfections. Results for such cases show that improvements in experiment and theory have produced previously unobtainable agreement. The necessity of the correct (and consistent) theoretical specification of boundary conditions is then demonstrated. Recent stiffened cylinder results are surveyed to expose the large effects on the buckling strength of internal or external stiffening, axial load applied eccentric to the wall neutral surface, and the addition of small meridional curvature.

ABSTRACT: A brief description of the essential nature of shell theory and the shell equations is followed by a survey, with examples, of the types of shell problems that are of important concern to the structural designer and, therefore, of interest to the shell analyst. The principal approaches to the shell problem solution are
outlined and some of the important effects that the computer has had on shell analysis and the analyst are
discussed. Deficiencies in shell technology, requiring additional research, are indicated.


ABSTRACT: The concept of finite elements for the analysis of shells is developed here with several important
advances. Firstly, the Kirchhoff theory of shells is refined to include a transverse shear deformation. The refined
theory admits simpler approximating functions while preserving continuity at the intersections of elements.
Secondly, the motion of the element is decomposed into a rigid body motion followed by a deformation. The
decomposition serves to extend existing formulations for linearly elastic elements to problems involving finite
rotations and buckling. Thirdly, the Lagrange equations are introduced to derive the equations of the discrete
system. The method yields the consistent inertial terms for any manner of motion, oscillatory or transient.
Finally, the simplest approximating polynomials are introduced in the context of the shear-deformation theory.
Further simplification is achieved by the introduction of constraints analogous to the Kirchhoff hypothesis of
the continuum theory. The constraints provide a rational basis for neglecting the contribution of transverse shear
in the strain energy. The resulting approximation converges rapidly to the Kirchhoff theory for examples cited.

Nurick GN, Martin JB, “Deformation of thin plates subjected to impulsive loading-a review”, Part-I:

Nurick GN, Martin JB, “Deformation of thin plates subjected to impulsive loading-a review”, Part-II:

shells”, Accession Number: ADA214764, September 1989

Wempner, Gerald. “Mechanics and Finite Elements of Shells”, Applied Mechanics Reviews, 42: No. 5,

Gerald A. Wempner (School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA),
“Shells: Mechanics and approximation – linear and nonlinear aspects”, in Computational mechanics in
structural engineering: recent developments and future trends, edited by Franklin Y. Cheng and Fu Zizhi, 1992,
ABSTRACT: The following paper focuses on the special attributes of shells, various mechanical peculiarities
and related problems. The presentation addresses theories and approximations which are applicable to thin and
thick shells, geometrical nonlinearities and inelastic deformations. Attention is given to the origins of particular
phenomena, to viewpoints and methods which appeal to basic concepts of mechanics.

1366 (215 references)

Carlos A. Felippa (1) and Ray W. Clough (2)
INTRODUCTION: The finite element method (FEM) is a numerical discretization procedure which permits the analysis of complex boundary value problems by an extension of the techniques originally used in the structural analysis of ordinary framed systems. The method has been extensively used in the field of structural mechanics, especially by the aircraft industry, but it has recently been applied to a wide range of nonstructural problems. The initial development of the FEM in the field of structural mechanics can be traced back to efforts, in the early 1950s, to formulate a satisfactory numerical procedure for the stress analysis of airplane wing panels [1]. The name of the method was introduced in [2], which was concerned with more general civil engineering applications. Two parallel developments were responsible for the widespread acceptance of the method: (a) The formulation of the matrix transformation theory of structures [3,4], which provided a very efficient and elegant means for simplifying the notation and organizing the computations. (b) The introduction of high-speed digital computers.

The purpose of this paper is to describe the mathematical foundations of the FEM and to present a brief summary of techniques for its practical application. In addition, results of a few specific FEM analyses are presented which demonstrate its versatility and accuracy, and also the basic steps in a FEM computer program are listed and discussed. A rather extensive list of references is included at the end of the paper in order to make available the wide and varied body of literature which already has been published on this rather new analytical technique.


ABSTRACT: This paper contains an assessment of current shell analysis capability. The assessment is based on work conducted at the Lockheed Palo Alto Research Laboratory under contract to the Air Force Flight Dynamics Laboratory. In addition to surveying the open literature, information for the study was gathered during a series of visits made to organisations throughout the United States at which there is an active shell analysis research effort. More than 40 industrial concerns, government agencies and universities have been visited to date. During each visit, technical personnel working in the area of shell analysis were interviewed to determine the scope of their present analysis capability, to learn of current research activities and to discuss computer methods of shell analysis in general.


ABSTRACT: A development of the finite element method for thin shell instability analysis is presented, covering three principal aspects:
1. representation of shell geometry
2. representation of element behavior
3. algorithmic tools for solution of the large-order systems of nonlinear algebraic equations which characterize various phases of shell instability.

Two shell elements are described, an arbitrary quadrilateral and a triangle, and numerical results are presented for two widely-employed comparison problems for linear (stable) analysis. Two shell problems which include instability effects are also solved.


ABSTRACT: Fifteen years of research, development, and application of the finite element concept, primarily to structural analysis, has yielded a host of techniques for computer implementation. The importance of using these techniques is shown by an estimated reduction in total computer costs by a factor of 20 over not using them. This paper describes the techniques which play an important role in currently available computer software. It indicates research work in the engineering literature which can be expected to stimulate development of new techniques in the next decade. It concludes that the thrust for better techniques will be provided by the expanding need for software in newer applications such as nuclear fusion, fracture mechanics, bioengineering simulations, and vehicle crashes. New techniques will yield computer software which more highly automates finite element use, will more efficiently solve large sets of equations, and which will be engineering discipline transportable.

David Bushnell (Lockheed Missiles and Space Company, Palo Alto, California USA), “Thin shells”. In Programs, Surveys, Assessments, and Availability, edited by Walter Pilkey and Nicholas Perrone, University of Virginia Press, 1974

ABSTRACT: A brief review of the available static buckling theory for both geometrically ‘perfect’ and ‘imperfect’ anisotropic composite circular cylinders is presented for various loading configurations. For comparison purposes, relevant experimental data are discussed, including recent combined loading test results and recommendations are made concerning the design of composite cylinders.


DTIC Accession No. ADA034186, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA034186
ABSTRACT: This report summarizes the first phase of a study of nonlinear structural analysis computer codes for rocket nozzle stress analysis. A brief summary of nonlinear structural mechanics is given, along with a discussion of features desired for rocket nozzle thermomechanical stress analysis. Several computer codes are evaluated, and four codes are selected for further study in a subsequent phase of this work. Two of the selected codes employed linear elastic material behavior, while the remaining codes employed fully nonlinear behavior. The codes selected for this study were SAAS III, TEXGAP, NONSAP, and NEPSAP. It should be noted that none of the codes selected for this study contained all of the features desired for structural analysis of modern rocket nozzles; however, it is anticipated that future versions of these codes will contain the desired features.

ABSTRACT: Advances in the limits of structural use in the aereospace and nuclear power industries over the past years have increased the requirements upon the applicable analytical computer programs to include accurate capabilities for inelastic and transient dynamic analyses. In many minds, however, this advanced capability is unequivocally linked with the large scale, general purpose, finite element programs. This idea is also combined with the view that such analyses are therefore prohibitively expensive and should be relegated to the “last resort” classification. While this, in the general sense, may indeed be the case, if the user needs only to analyze structures falling into limited categories, however, he may find that a variety of smaller special purpose programs are available which do not put an undue strain upon his resources. One such structural category is shells of revolution. This survey of programs will concentrate upon the analytical tools which have been developed predominantly for shells of revolution. The survey will be subdivided into three parts: (a) consideration of programs for transient dynamic analysis; (b) consideration of programs for inelastic analysis and finally; (c) consideration of programs capable of dynamic plasticity analysis. In each part, programs based upon finite difference, finite element, and numerical integration methods will be considered. The programs will be compared on the basis of analytical capabilities, and ease of idealization and use. In each part of the survey sample problems will be utilized to exemplify the state-of-the-art.

ABSTRACT: The safety analysis of nuclear reactors often involves the solution of non-linear, transient structure-continuum problems. Many general-purpose and special-purpose programs are available for this class
of problems. The methods of integration found in these programs are described, particularly from the viewpoint of computational efficiency for the various classes of problems that are found in reactor safety analysis. These methods are subdivided into two categories: explicit and implicit. The methods are summarized along with their advantages and disadvantages and some recent results on their stability and accuracy. Customary practice in the use of these methods is outlined. The programs used in reactor structural safety analysis are surveyed and their salient features tabulated.


ABSTRACT: This paper presents a survey of the formulations and solution procedures for nonlinear static and dynamic structural analysis. The formulations covered include the pseudo force method, the total Lagrangian method, the updated Lagrangian method, and the convected coordinate method. The relationship of each principle to the basic principle of virtual work is presented. For static analysis, the solution by direct minimization of the total potential, Newton-Raphson and modified Newton-Raphson, and the first and second order self correcting method are reviewed and put in proper perspective. It is concluded that the most efficient methods for static problems are the modified Newton-Raphson and the first order self correcting methods. For dynamic nonlinear analysis, a new method based on modal analysis using the pseudo force method is presented. Numerical results for the highly nonlinear dynamic response of a shallow cap (lambda = 6) under a step load at the apex shows the method to be 5 times faster than the Houbolt solution procedure. Other methods surveyed include the Newmark beta method, the Wilson method, central differences, and the stiffly stable solution procedure of Park.


ABSTRACT: The paper presents a classification of mathematical commonly encountered in connection with solution of non-linear finite element problems. The principal methods for numerical solution of the non-linear equations are surveyed and discussed. Special emphasis is placed upon the description of an automatic load incrementation procedure with equilibrium iterations. It is shown how this algorithm can be adapted for solving problems involving instabilities, snap-through and snap-back. A simple scalar quantity denoted the current stiffness parameter is suggested; this parameter is used to characterize the overall behaviour of non-linear problems. It can also be used as a steering parameter in the solution process. The use of the present technique is illustrated by several examples.


ABSTRACT: On the basis of a survey conducted in 1974 [1] on the availability and capability of general
purpose programs for plastic analysis, it is safe to assume that there are now a vast body of users of such programs. The objective of this paper is to familiarize these users with the assumptions and models generally employed in describing nonlinear material behavior. The treatment of plasticity within static and dynamic structural analysis is briefly reviewed with the discussion focused on some recent theoretical and computational advances. Some prophetic comments are given that are concerned with the future direction of existing capabilities and problem areas that will benefit from their extensions.


Leissa, A. W., “An Interpretive Study of Plate and Shell Buckling”, Ohio State University Research Foundation, Columbus, 10 June 1983, Accession Number: ADA140487, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA140487
ABSTRACT: The objective of the proposed research was to search the literature and locate all information relevant to plate and shell buckling; to collect the relevant journal articles, books, reports, theses, conference proceeding papers; to digest, summarize, organize and integrate the useful knowledge found and to make interpretative assessments; to determine problems where further research is needed; to produce a typed manuscript and ink drawings suitable for publishing a set of monographs; to clarify and unify the fields of plate and shell buckling.

ABSTRACT: A brief overview is presented of considerations involved in the buckling of composite plates made of laminae having continuous, parallel fibers. Such plates are governed by orthotropic or anisotropic plate buckling theory for laminates which are symmetrically stacked with respect to the plate midplane. Unsymmetric laminates require a more complicated theory with bending-stretching coupling. Additional complicating factors are considered, including: interior holes, shear deformation, sandwich construction involving other materials, local effects, nonlinear stress-strain relationships, hygrothermal effects, and external stiffeners. Postbuckling behavior and the effects of initial imperfections are also described. Some representative results from the extensive literature (352 references) are included to aid in describing the various effects.
PARTIAL INTRODUCTION: In order to produce efficient, reliable designs & to avoid unexpected catastrophic failure of structures of which thin shells are important components, the engineer must understand the physics of shell buckling. The objective of this survey is to convey to the reader a “feel” for shell buckling, whether it be due to nonlinear collapse, bifurcation buckling, or a combination of these modes. … (list of references is given below, at the end of the section, “Early works…”).

ABSTRACT: A brief survey of plastic buckling of axially compressed cylindrical shells is given. Results of nonlinear finite element analyses of several axially compressed, ring-stiffened, steel, cylindrical shells are presented, including comparisons with tests conducted at Chicago Bridge and Iron Co. and at the Los Alamos National Laboratory (LANL). Some of the LANL specimens with radius-to-thickness ratio of about 450 have reinforced circular openings that cut across various numbers of ring stiffeners. These cylindrical shells are loaded by enforced axial displacement applied to thick aluminum end plates halfway between the axis of
revolution and the shell wall. Measured imperfections are included in the analysis of one ring-stiffened specimen without any cutout. Inclusion of the imperfection field reduces the predicted collapse load by only eight percent. Reinforced openings that cut one or two or three rings reduce the collapse load by 14, 21 and 22 percent, respectively. Agreement between test and theory for the nonuniformly compressed LANL specimens is within 14 percent, even with initial imperfections neglected in the analysis.


ABSTRACT: The phenomenon of static collapse, henceforth called ‘buckling’, is first illustrated by the behavior of a fairly thick cylindrical shell, which under axial compression deforms at first axisymmetrically and later nonaxisymmetrically. Thus, static buckling encompasses two modes of behavior, nonlinear collapse at the maximum point in a load versus deflection curve and bifurcation buckling. Accurate prediction of critical loads corresponding to either mode in the plastic range of material behavior requires a simultaneous accounting for moderately large deflections and nonlinear, irreversible, path-dependent material. A survey is given of plastic buckling, which spans three areas: asymptotic analysis of postbifurcation behavior of perfect and imperfect simple structures, general nonlinear analysis of arbitrary structures, and nonlinear analysis for collapse at a maximum load and bifurcation buckling of shells of revolution. In the survey of general nonlinear structural analysis, some emphasis is given to strategies for solving the governing nonlinear equations incrementally. Numerous examples, generated primarily with the STAGS computer program, which was developed by Almroth and his colleagues, reveal many complex modes of buckling behavior.


ABSTRACT: (Abstract not given)


ABSTRACT: (Abstract not given)

References listed at the end of the paper:


ABSTRACT: A comprehensive survey is provided for the formulation and solution techniques of finite element applications in nonlinear continuum mechanics problems. The survey discusses the Lagrangian, the updated Lagrangian, and the Eulerian formulations. It is shown that many analysts describe relative or updated Lagrangian formulation under the name of Eulerian formulation. Hence, little effort has been devoted to the development of a consistent Eulerian formulation. The applications, limitations and suitability of each formulation to both material and geometrical nonlinear problems are discussed. In the solution methods, exact equilibrium, approximate equilibrium and self-correcting techniques are discussed. An emphasis is given to the applicability of these methods to particular nonlinear problems and to recent developments and modifications of each method to suit a particular nonlinear field.


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Knight, Norman F, Jr and Starnes, James H, Jr, “Developments in Cylindrical Shell Stability Analysis”, NASA no. 19980019015. Stability Analysis of Plates and Shells; UNITED STATES; 1998


ABSTRACT: The paper attempts a broad overview of the vast field of stability of structures, including elastic and anelastic structures, static and dynamic response, linear and non-linear behavior, energy approach, thermodynamic aspects, creep stability and fracture or damage-induced instability. The importance of stability theory to various fields of engineering and applied science is pointed out and the history of the discipline is briefly sketched. The principal accomplishments are succinctly reviewed, and fruitful recent trends, particularly the stability analysis of damage localization and fracture, are emphasized.
(Reference listed at the end of this paper are included in the “Bazant” citation near the end of Section 1)

ABSTRACT: This article attempts to review the main results in the vast field of stability of structures. The classical field of elastic stability is covered succinctly. The coverage emphasizes the modern problems of anelastic structures exhibiting plasticity and creep, and especially structures disintegrating due to localized fracture and distributed damage. The treatment encompasses thin or slender structures, i.e. the columns, frames, arches, thin-walled beams, plates, and shells, as well as massive but soft bodies buckling three-dimensionally, and includes the static as well as dynamic concepts of stability, dynamic instability of nonconservative systems, energy methods for discret and continuous structures, thermodynamics of structures, postcritical behavior, and imperfection sensitivity. The legacy of Ludwig Prandtl, who is commemorated by the present Special Issue, is briefly highlighted. The mathematics is kept to the bare minimum, and the derivations as well as the differential equations are omitted. Man attention is paid to the physical causes, mechanisms, and results. Only the main literature sources in this vast field are cited.
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ABSTRACT: As shown three decades ago, in situations where the initial stresses before buckling are not negligible compared to the elastic moduli, the geometrical dependence of the tangential moduli on the initial stresses must be taken into account in stability analysis, and the stability or bifurcation criteria have different forms for tangential moduli associated with different choices of the finite strain measure. So it has appeared paradoxical that, for sandwich columns, different but equally plausible assumptions yield different formulas,
Engesser’s and Haringx’ formulas, even though the axial stress in the skins is negligible compared to the axial elastic modulus of the skins and the axial stress in the core is negligible compared to the shear modulus of the core. This apparent paradox is explained by variational energy analysis. It is shown that the shear stiffness of a sandwich column, provided by the core, generally depends on the axial force carried by the skins if that force is not negligible compared to the shear stiffness of the column (if the column is short). The Engesser-type, Haringx-type, and other possible formulas associated with different finite strain measures are all, in principle, equivalent, although a different shear stiffness of the core, depending linearly on the applied axial load, must be used for each. The Haringx-type formula, however, is most convenient because it represents the only case in which the shear modulus of the core can be considered to be independent of the axial force in the skins and to be equal to the shear modulus measured in simple shear tests (e.g., torsional test). Extensions of the analysis further show that Haringx’s formula is preferable for a highly orthotropic composite because a constant shear modulus of the soft matrix can be used for calculating the shear stiffness of the column, and further confirm that Haringx’s buckling formula with a constant shear stiffness is appropriate for helical springs and built-up columns (laced or battened).

References listed at the end of the paper:

References listed at the end of the paper is a state of the art survey of the general area of buckling and postbuckling of thin-walled, geometrically imperfect, cylinders of various constructions, when subjected to destabilizing loads. The survey includes discussion of imperfection sensitivity and of the effect of various defects on the critical conditions.


ABSTRACT: Thin-walled cylinders of various constructions are widely used in simple or complex structural configurations. The round cylinder is commonly found in tubing and piping, and in offshore platforms. Depending on their use, these cylinders are subjected (in service) to individual and combined application of external loads. In resisting these loads the system is subject to buckling, a failure mode which is closely associated with the establishment of its load-carrying capacity. Therefore, the system buckling and postbuckling behavior have been the subject of many researchers and investigators both analytical and experimental. The paper is a state-of-the-art survey of the general area of buckling and postbuckling of thin-walled, geometrically imperfect, cylinders of various constructions, when subjected to destabilizing loads. The survey includes discussion of imperfection sensitivity and of the effect of various defects on the critical conditions.

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doi: 10.1007/BF00058512

ABSTRACT: On the occasion of the 100th anniversary of A.E.H. Love's fundamental paper on thin elastic shell theory, the present article summarizes a line of developments on shells of revolution related to the Love-Kirchhoff hypotheses which form the basis of Love's theory. The summary begins with the Günther-Reissner formulation of the linear theory which is shown to contain the classical first approximation shell theory as a special case. The static-geometric duality is deduced as a natural and immediate consequence of the more general theory. The repeated applications of this duality greatly simplify the solution process for boundary-value problems in shell theory, including the classical reduction of the axisymmetric bending problem and related recent reductions of shell equations for more general loadings to two simultaneous equations for a stress function and a displacement variable. In the nonlinear range, the article confines itself to Reissner's geometrically nonlinear theory of axisymmetric deformation of shells of revolution and Marguerre's shallow shell theory with special emphasis on recent results for elastic membranes, buckling of shells of revolution and applications of asymptotic methods. With fondness and appreciation, the authors dedicate this article to their teacher, collaborator and friend, Professor Eric Reissner, in the year of his seventy-fifth anniversary.

Z. Waszczyszyn (Institute of Structural Mechanics, Cracow Technological University, Poland), “Multiple subvolume models for the analysis of inelastic behaviour of metals”, Delft University of Technology, The Netherlands Memorandum M-594, June 1988

ABSTRACT: A review of papers devoted to formulation and applications of Multiple Subvolume (MS) models is given. Special attention is paid to the identification procedure of model parameters. The simplest MS model (MSPM), composed of elastic, perfect plastic components is considered in detail. Simple and refined identifications of model parameters are discussed with special attention turned out on the procedure used in the STAGS-A computer code. More complicated, strain-hardening and time-dependent MS mardels are shortly discussed.


A.K. Dhalla (Westinghouse Electric Corporation, PO Box 158, Madison, PA 15663, USA), “Nonlinear structural analysis methods and their application to elevated temperature design: A US perspective”, Nuclear Engineering and Design, Vol. 114, No. 3, June 1989, pp. 415-436, doi:10.1016/0029-5493(89)90119-2 ABSTRACT: Technological advances over the last two decades have been assimilated into the routine design of Liquid Metal Reactor (LMR) structural components operating at elevated temperatures. The mature elevated temperature design technology is based upon: (a) an extensive material data base, (b) recent advances in nonlinear computational methods, and (c) conservative design criteria based upon past successful and reliable operating experiences with petrochemical and nonnuclear power plants. This survey paper provides a US perspective on the role of nonlinear analysis methods used in the design of LMR plants. The simplified and detailed nonlinear analysis methods and the level of computational effort required to qualify structural components for safe and reliable long-term operation are discussed. The paper also illustrates how a detailed nonlinear analysis can be used to resolve technical licensing issues, to understand complex nonlinear structural behavior, to identify predominant failure modes, and to guide future experimental programs.

D. Moulin, A. Combescure and D. Acker (Commissariat á l'Energie Atomique, IRDI-DEMT, CEN Saclay – 91191 Gif sur Yvette, France), “A review of thermal buckling analysis methods”, Nuclear Engineering and Design, Vol. 116, No. 3, September 1989, pp. 255-263, doi:10.1016/0029-5493(89)90086-1 ABSTRACT: This paper highlights the main items emerging from a large bibliographical survey carried out on strain-induced buckling analysis methods applicable in the construction of fast neutron reactor structures, conducted within the framework of a study by the Codes and Standards Working Group of the EEC. The work is centred on the practical analysis methods used in construction codes to account for the strain-buckling of thin and slender structures. Methods proposed in the literature concerning past and present studies are summarized. Experimental, theoretical and numerical methods are considered. Methods applicable to design and their degree of validation are indicated.

J. Arbocz (Technical University of Delft), “Shell buckling research at the aerospace engineering faculty of Delft University of Technology”, Technical University of Delft Memorandum M-596, 1989


Ahmed K. Noor, “Recent advances in the sensitivity analysis for the thermomechanical postbuckling of
composite panels”, in Aerospace thermal structures and materials for a new era, edited by Earl Arthur Thornton, Volume 168 of the Progress in Astronautics and Aeronautics series, AIAA, 1995


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ABSTRACT: A first attempt is made to review the advances of the formulations for thin shell finite elements in the form of flat plates, axisymmetrical shells and curved shells. The Discrete Kirchhoff Theory shell elements and the degenerated shell elements are discussed. Experiences in shear and membrane lockings are elaborated. The survey is further illustrated with some extensions and applications to cases such as static and dynamic responses, static and dynamic bucklings, laminated composites, random loadings and random structural and material properties. In all cases, studies of the effects of geometric and material nonlinearities are discussed.


Tauchert, T. R., “Thermally Induced Flexure, Buckling and Vibration of Plates”, Applied Mechanics


ABSTRACT: This paper is an update of an earlier review on the mechanics of membrane structures. It provides more than 120 new references and includes topics not discussed earlier, such as under-constrained pneumatic envelopes. Thoughts on future research directions are given.


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ABSTRACT: This paper surveys about 350 publications related to the finite element models of moderately thick shells, concentrating on those related to consistent displacement and stress/mixed/hybrid models. A geographic-chronological criterion has been used in order to review the main ideas and their development in time. The survey is complete enough to show the trends. The ideas of such a list is to help those readers who are interested in special problems of the applications of the finite element method in the analysis of moderately thick shells.


ABSTRACT: The critical points of the generalized complementary energy variational principles are clarified. An open problem left by Hellinger and Reissner is solved completely. A pure complementary energy (involving the Kirchhoff type stress only) is constructed. We prove that the well-known generalized Hellinger-Reissner’s energy $L(u,s)$ is a saddle point functional if and only if the Gao-Strang gap function is positive. In this case, the system is stable and the minimum potential energy principle is equivalent to a unique maximum dual variational principle. However, if this gap function is
negative, then $L(u,s)$ is a so-called $\partial^*$-critical point functional. In this case, the system has two extremum complementary principles. An interesting triality theorem for nonconvex variational problem is discovered, which can be used to study nonlinear bifurcation problems, phase transitions, variational inequality, and other things. In order to study the shear effects in frictional post-buckling problems, a new second order 2-D nonlinear beam model is developed. Its total potential is a double-well energy. A stability criterion for post-buckling analysis is proposed, which shows that the minimax complementary principle controls a stable buckling state. The unilateral buckling state is controlled by a minimum complementary principle. However, the maximum complementary principle controls the phase transitions.

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[23] Rockafellar, RT (1974), Conjugate Duality and Optimization, SIAM.

ABSTRACT: Some properties of the tensor algebra on manifolds are discussed with respect to the classical tensor algebra of continuum mechanics. Basic definitions and relations of linear maps are briefly recalled and applied to tensor spaces, where special attention is focused to the definition of dual and transposed maps. As application to nonlinear continuum mechanics, algebraic pull-back and push-forward maps, and Lie-like time derivatives associated with linear maps are defined and used to build up commutative schemes for deformation measures, objective deformation rates, stresses, and frame-invariant forms of the stress power. The transition to the classical formulation of tensor algebra by identifying vector spaces and their duals is examined. It is shown how this concept enables a straight-forward derivation of the Doyle-Ericksen formula and its possible variants.

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ABSTRACT: The increasing complexity of engineering systems has sparked rising interest in multidisciplinary optimization (MDO). This paper surveys recent publications in the field of aerospace, in which the interest in MDO has been particularly intense. The primary challenges in MDO are computational expense and organizational complexity. Accordingly, this survey focuses on various methods used by different researchers to address these challenges. The survey is organized by a breakdown of MDO into its conceptual components, reflected in sections on mathematical modelling, approximation concepts, optimization procedures, system sensitivity, and human interface. Because the authors' primary area of expertise is in the structures discipline, the majority of the references focus on the interaction of this discipline with others. In particular, two sections at the end of this review focus on two interactions that have recently been pursued with vigour: the simultaneous optimization of structures and aerodynamics and the simultaneous optimization of structures with active control.

ABSTRACT: Considerable research interest has been directed towards the use of composite materials for crashworthiness applications, because they can be designed to provide impact energy absorption capabilities which are superior to those of metals when compared on a weight basis. This review draws together information from a variety of sources to compare the findings of researchers in this field. The anisotropy of composite materials means that there are a great number of variables controlling mechanical behaviour and much of the investigative experimental work conducted in this area has concentrated on composite tubular specimens. The material, geometrical and experimental factors which have been shown to affect the energy absorption capability of such samples are related and a comparison is made of some of the specific energy absorption values which have been quoted in the literature. A selection of methods for predicting composite material energy absorption capability is presented and consideration is given to some of the more practical aspects of employing composite materials for crashworthiness purposes.

ABSTRACT: This paper addresses the prediction of the behaviour of buried pipelines when they are considered to be shell structures and subjected to curvatures that exceed their limit points. It surveys work carried out at the University of Alberta over a period of approximately six years. The work considers the development of local buckling, and the softening, strain localization and wrinkling that characterize the behaviour of pipeline structures, and the relation between these phenomena. It offers a phenomenological explanation of the mechanism by which wrinkling develops in the post-buckling behaviour of structures. It then demonstrates that the experimental and analytical results of studies of pipe behaviour are consistent with this mechanism. The results of finite element analyses are compared with two series of tests on full-sized industrial pipe. The tests provide a database for the behaviour of the pipe against which the validity of the analyses can be established. Comparisons are made with respect to moment-curvature curves and postbuckling configurations. It is concluded that modern finite element analysis when properly done is capable of closely predicting the behaviour of the pipe when it is subjected to large deformations that carry it deeply into the postbuckling range.


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Ray W. Clough and Edward L. Wilson (Department of Structural Engineering, University of California, Berkeley, California, USA), “Early finite element research at Berkeley”, Fifth U.S. National Conference on Computational Mechanics, Aug. 4-6, 1999

ABSTRACT: Significant finite element research was conducted at the University of California at Berkeley during the period 1957 to 1970. The initial research was a direct extension of classical methods of structural analysis which previously had been restricted to one-dimensional elements. The majority of the research conducted was motivated by the need to solve practical problems in Aerospace, Mechanical and Civil Engineering. During this short period the finite element method was extended to the solution of linear and nonlinear problems associated with creep, incremental construction or excavation, crack closing, heat transfer, flow of water in porous media, soil consolidation, dynamic response analysis and computer assisted learning of structural analysis. During the last six years of this period the fields of structural analysis and continuum mechanics were unified. The computer programs developed during this early period at Berkeley were freely distributed worldwide allowing practicing engineers to solve many new problems in structural mechanics. Hence, the research was rapidly transferred to the engineering profession. In many cases the research was used professionally prior to the publication of a formal paper.

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ABSTRACT: This paper gives a survey of works on the theory of toroidal shells which were done by our two universities in recent years. (49 references)

ABSTRACT: There is an increasing usefulness of exact three-dimensional analyses of elastic cylinders and cylindrical shells in composite materials applications. Such analyses are considered as benchmarks for the range of applicability of corresponding studies based on two-dimensional and/or finite element modeling. Moreover, they provide valuable, accurate information in cases that corresponding predictions based on that later kind of approximate modeling is not satisfactory. Due to the complicated form of the governing equations of elasticity, such three-dimensional analyses are comparatively rare in the literature. There is therefore a need for further developments in that area. A survey of the literature dealing with three-dimensional dynamic analyses of cylinders and open cylindrical panels will serve towards such developments. This paper presents such a survey within the framework of linear elasticity.

ABSTRACT: This article presents a review of the research work related to the mechanical behavior of non-circular cylindrical shells and shell segments. To this end, after a brief reference to the basic nomenclature that is mainly used, it initially provides quite a general framework for most of the relevant governing equations employed in the relevant literature. It proceeds with a review of the corresponding dynamic analyses, which are primarily grouped according to the geometrical configuration of the noncircular shell considered and secondarily according to the type of the mathematical model employed. These deal with the dynamics of closed cylindrical shells and open cylindrical panels based on classical (CST) or transverse shear deformable shell theories (SDST). The static analyses reviewed next are divided according to the nature of the physical problem considered and deal with small as well as with large deflections of statically loaded non-circular cylindrical shells. These include both linearized and geometrically nonlinear elastic stability analyses as well as the very few relevant studies that assumed an elastic-plastic response of the shell material constitution. This review article contains 196 references.


ABSTRACT: A general overview of some recent developments related with the modeling and stability of sandwich structures is presented in this paper. The survey covers a number of issues related with the geometrically linear and non-linear formulations of curved and flat sandwich constructions featuring laminated anisotropic face sheets, and associated stability problems. Issues related with the enhancement of the load carrying capacity of sandwich panels resulting in the increase of the buckling strength, the reduction of the intensity of a snap-through buckling and even of its removal are also addressed. The provided list of references is not exhaustive, in the sense that it is mainly connected with topics of sandwich constructions in which the first author of this paper has been involved during a good part of his research activity. Moreover, the displayed
results illustrating some basic trends concern not only the ones previously obtained by the authors of this survey-paper, but also several others, presented here for the first time.


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ABSTRACT: The three-dimensional theory of laminated plates and shells has been developed by Chao et al.[10–13, 62, 63] with many applications to impact and shock modal analyses. In this research, a complete survey of the literature is made on the free vibration natural frequencies of simply supported rectangular plates. Various boundary conditions are composed of fixed pin, hinge-roller, and sliding pin supported edges. The lowest frequencies are obtained in the present study in comparison with those in earlier studies as a result of the close natural state reached in keeping with the three-dimensional boundary and interlaminar continuity conditions via a 3-D augmented energy variational approach.


ABSTRACT: The evolution of matrix structural analysis (MSA) from 1930 through 1970 is outlined. Highlighted are major contributions by Collar and Duncan, Argyris, and Turner, which shaped this evolution. To enliven the narrative the outline is configured as a three-act play. Act I describes the pre-WWII formative period. Act II spans a period of confusion during which matrix methods assumed bewildering complexity in response to conflicting demands and restrictions. Act III outlines the cleanup and consolidation driven by the appearance of the direct stiffness method, through which MSA completed morphing into the present implementation of the finite element method (FEM). No attempt is made at chronicling the more complex history of FEM itself.

ABSTRACT: The origination, stability, and postcritical behavior of delaminations under quasi-static, cyclic, and dynamic loads are analyzed. Some problems for further investigations are discussed.


[116] Ren W, Mingbao H, Zhuping H, Qingchun Y. An experimental study on the dynamic axial plastic buckling of cylindrical


ABSTRACT: Most natural (or biological) materials are complex composites whose mechanical properties are often outstanding, considering the weak constituents from which they are assembled. These complex structures, which have risen from hundreds of million years of evolution, are inspiring Materials Scientists in the design of novel materials. Their defining characteristics, hierarchy, multifunctionality, and self-healing capability, are illustrated. Self-organization is also a fundamental feature of many biological materials and the manner by which the structures are assembled from the molecular level up. The basic building blocks are described, starting with the 20 amino acids and proceeding to polypeptides, polysaccharides, and polypeptides–saccharides. These, on their turn, compose the basic proteins, which are the primary constituents of ‘soft tissues’ and are also present in most biominerals. There are over 1000 proteins, and we describe only the principal ones, with emphasis on collagen, chitin, keratin, and elastin. The ‘hard’ phases are primarily strengthened by minerals, which nucleate and grow in a biomediated environment that determines the size, shape and distribution of individual crystals. The most important mineral phases are discussed: hydroxyapatite, silica, and aragonite. Using the classification of Wegst and Ashby, the principal mechanical characteristics and structures of biological ceramics, polymer composites, elastomers, and cellular materials are presented. Selected systems in each class are described with emphasis on the relationship between their structure and mechanical response. A fifth class is added to this: functional biological materials, which have a structure developed for a specific function: adhesion, optical properties, etc. An outgrowth of this effort is the search for bioinspired materials and structures. Traditional approaches focus on design methodologies of biological materials using conventional synthetic materials. The new frontiers reside in the synthesis of bioinspired materials through processes that are characteristic of biological systems; these involve nanoscale self-assembly of the components and the
development of hierarchical structures. Although this approach is still in its infancy, it will eventually lead to a plethora of new materials systems as we elucidate the fundamental mechanisms of growth and the structure of biological systems.


Jayashree Sengupta and Dipankar Chakravorty (Jadavpur University, Kolkata, India), “Progressive failure analysis of laminated composite shells – a review”, (publisher and date not given; Most recent citation is 2012.)
http://www.academia.edu/7423161/Progressive_Failure_Analysis_of_Laminated_Composite_Shells_A_Review


ABSTRACT: Recent advances in structural analysis and design technology for buckling-critical shell structures are discussed. These advances include a hierarchical analysis strategy that includes analyses that range from classical analysis methods to high-fidelity nonlinear finite element analysis methods, reliability based design methods, the development of imperfection data bases, and the identification of traditional and nontraditional initial imperfections for composite shell structures. When used judiciously, these advances provide the basis for a viable alternative to the traditional and conservative lower-bound design philosophy of the 1960s. These advances also help answer the question of why, after so many years of concentrated research effort to understand the behavior of buckling-critical thin-walled shells, one has not been able to improve on this conservative lower-bound design philosophy in the past.


ABSTRACT: Laminated composite shells are increasingly being used in various engineering applications including aerospace, mechanical, marine, and automotive engineering. With the increasing awareness of and sensitivity to structural noise and vibration, research covering the dynamic behavior of composite shells has received considerable attention. The purpose of this article is to review most of the recent research done in this field. Review of the literature on the dynamic behavior of homogeneous shells is covered in Part 2 of this article to be published in the September 2002 issue of AMR. Research on shell dynamics is found to be mainly free vibration analyses. The review is conducted with emphasis given to the theory being applied (thin, thick, 3D, nonlinear, ...), the analysis method (exact, Ritz, finite elements, ...), complicating effects (initial stress, imperfection, added masses and springs, elastic supports, rotating shells, and others), and the various shell geometries that were subject to vibration research (cylindrical, conical, spherical, and others). There are 374 references cited in this review article.
ABSTRACT: Shell-like structures are used in various engineering applications including civil, aerospace, mechanical, marine, and automotive engineering. This article reviews most of the recent research done in the field of dynamic response of homogeneous shells with special attention to free vibrations. Literature on dynamics of laminated composite shells was reviewed in Part 1 published in the July 2002 issue of AMR. Emphasis is given to the theory being applied (thin, thick, 3D, nonlinear,...), the shell geometries that were subject to dynamics research (cylindrical, conical, spherical,...), the analysis method (exact, Ritz, finite elements,...), and the various complicating effects (initial stress, imperfection, added masses and springs, elastic supports, rotating shells, interaction with fluids, and others). This review article contains 606 references.


ABSTRACT: Laminated composite shells are frequently used in various engineering applications including aerospace, mechanical, marine, and automotive engineering. This article reviews the recent literature on the static analysis of composite shells. It follows up with the previous work published by the first author [1-4] and it is a continuation of another recent article that focused on the dynamics of composite shells [3]. This paper reviews most of the research done in recent years (2000-2010) on the static and buckling behavior (including postbuckling) of composite shells. This review is conducted with an emphasis on the analysis performed (static, buckling, postbuckling, and others), complicating effects in both material (e.g. piezoelectric) and structure (e.g. stiffened shells), and the various shell geometries (cylindrical, conical, spherical and others). Attention is also given to the theory being applied (thin, thick, 3D, nonlinear…). However, more details regarding the theories have been described in previous work [1,3]

References listed at the end of the paper:


References listed at the end of the paper:


ABSTRACT: Stiffened panels made out of isotropic or anisotropic materials are being extensively used as structural elements for aircraft, maritime, and other structures. In order to maintain stiffness and strength with light weight, new design techniques must be employed when utilising these materials. Their stability, ultimate strength and loading capacity are the key issues pertaining to these engineering structures which have attracted a number of investigators to undertake indepth research, either in an academic or actual engineering context. This paper provides an extensive review of the research which has been conducted in recent years (2000-2012) on the buckling and post-buckling response of isotropic and composite stiffened plate and shell structures related to analysis and experiment. The key objective of this review article is to collate the research performed in the area of buckling and post-buckling behaviour of stiffened structures, thereby giving a broad perspective of the state-of-the-art in this field.


ABSTRACT: Stiffened panels made out of isotropic or anisotropic materials are being extensively used as structural elements for aircraft, maritime, and other structures. In order to maintain stiffness and strength with light weight, new design techniques must be employed when utilising these materials. Their stability, ultimate strength and loading capacity are the key issues pertaining to these engineering structures which have attracted a number of investigators to undertake in-depth research, either in an academic or actual engineering context. This paper presents a review of the optimisation techniques applied to buckling and post-buckling of stiffened panels. Papers published in the period from 2000 to May 2015 have been taken into consideration. The topic is addressed by identifying the most significant objectives, targets and issues, as well as the optimisation formulations, optimisation algorithms and models available. Finally a critical discussion, giving some practical advice and pointing out the most common issues involved in optimisation of buckling and post-buckling of stiffened panels, is provided.

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93. Todoroki, A. And Sekishiro, M., ‘New iteration fractal branch and bound method for stacking sequence optimizations of multiple


ABSTRACT: The present paper is devoted to a state-of-the-art review on the computational treatment of laminated composite and sandwich panels. Over two hundred texts have been included in the survey with the focus put on theoretical models for multilayered plates and shells, and FEM implementation of various computational concepts. As a result of the review, one could notice a lack of a single numerical model capable for a universal representation of all layered composite and sandwich panels. Usually, with the increase of the range of rotations considered in the particular model, one can observe the decrease of the degree of complexity of the through-the-thickness representation of deformation profiles.

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ABSTRACT: In this review, I shall discuss some of the aspects of the Mechanics of Solid Deformable Media, which have been for more than half a century among my main research priorities. It is somewhat difficult to write about research to which one has devoted his life. First of all, because you have to write about yourself, describing personal feelings—successes and failures, triumphs and defeats. It is hardly going to be of major interest for the readers. Thus, I am just going to note down, with corresponding comments some results, obtained by my colleagues, followers and myself. I think this can be rather interesting for junior researchers, who have not tasted yet the joy of success and the bitterness of the failure. This might be interesting as well for the mature scholars with relatively high self-esteem, willing to present each and every obtained result as a discovery—classical theory to be followed. The weight of a scientific result is evaluated by time. Time and coming generations of researchers will show the place in science of all results, even those which are widely advertised.

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ABSTRACT: The aim of this paper is to provide a contemporarily relevant survey of studies on non-linear vibrations of shell-type structures. The effects of geometrical non-linearity, and specific difficulties encountered in non-linear dynamic analysis of shell-type structures are presented and discussed. Studies on non-linear vibrations of shells are categorized by different shell configurations (shapes) in a chronological order. Also, the most commonly used methods of modelling and solution are reviewed and commented. Published reviews on non-linear vibrations of shell-type structures including complicating effects of anisotropy, initial stress, added mass, elastic foundation, stiffeners, open geometry (singly and doubly curved), transverse shear deformations, torsion, and interaction with fluid are also surveyed. Comments on the previous non-linear works are presented and some orientations for future research are suggested. Another purpose of this paper is to provide engineers, scientists and researchers with a list of 175 references, which should be very useful for locating relevant existing literature quickly.


ABSTRACT: The present literature review focuses on geometrically non-linear free and forced vibrations of shells made of traditional and advanced materials. Flat and imperfect plates and membranes are excluded. Closed shells and curved panels made of isotropic, laminated composite, piezoelectric, functionally graded and hyperelastic materials are reviewed and great attention is given to non-linear vibrations of shells subjected to normal and in-plane excitations. Theoretical, numerical and experimental studies dealing with particular dynamical problems involving parametric vibrations, stability, dynamic buckling, non-stationary vibrations and chaotic vibrations are also addressed. Moreover, several original aspects of non-linear vibrations of shells and panels, including (i) fluid–structure interactions, (ii) geometric imperfections, (iii) effect of geometry and boundary conditions, (iv) thermal loads, (v) electrical loads and (vi) reduced-order models and their accuracy including perturbation techniques, proper orthogonal decomposition, non-linear normal modes and meshless methods are reviewed in depth.

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ABSTRACT: This review paper aims to present an updated review of papers, conference papers, books, dissertations dealing with nonlinear vibrations of circular cylindrical thin shells. This paper surveyed mathematically, experimentally, analytically, numerically analyzed vibrations of cylindrical shells. This includes shells of open type, closed type, with and without fluid interactions; shells subjected to free and forced vibrations, radial harmonic excitations, seismically excitations; perfect and imperfect shell structures of various materials with different boundary conditions. This paper presented 210 reference papers in alphabetical order. This paper is presented as Geometrically nonlinear shell theories, Free and forced vibrations under radial harmonic excitation, Imperfect shells, shells subjected to seismic excitations, References.

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ABSTRACT: principal achievements of science and engineering in the sphere of design, construction, and static, vibrational, and buckling analysis of thin-walled constructions and buildings in the shape of hyperbolic
surfaces of revolution are summarized in this review article. These shells are useful as hyperbolic cooling
towers, TV towers, reinforced concrete water tanks, and arch dams. They are also used as supports for electric
power transmission lines and as high chimneys. Several public and industrial buildings having the hyperbolic
form are described in the review. The basic results of theoretical and experimental investigations of stress-strain
state, buckling, and vibration are summarized. The influence of temperature and moisture on the stress-strain
state of the shells in question is also analyzed. This review article contains 261 references.

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No.1, January 2003, pp. 87-110, doi:10.1115/1.1521436
ABSTRACT: This survey is devoted to recent achievements in the field of asymptotic approaches. Here we
consider the asymptotics in relation to completely new and sometimes unexpected parameters. Some procedures
leading to improvement and isolation of the essential analytical structure of the perturbation series are
presented. It is also shown that many problems of perturbation theory, which seem to be relatively simple at a
first glance, are still far from completely solved. Different asymptotic techniques to solve the same problem and
their influence on the results are briefly illustrated and discussed. This review paper contains 310 references.

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“Review of studies on geometrically nonlinear vibrations and dynamics of circular cylindrical shells and
panels, with and without fluid-structure interaction”, Appl. Mech. Rev., Vol. 56, No. 4, July 2003, pp. 349-
381, doi:10.1115/1.1565084, 356 references.
ABSTRACT: This literature review focuses mainly on geometrically nonlinear (finite amplitude) free and
forced vibrations of circular cylindrical shells and panels, with and without fluid-structure interaction. Work on
shells and curved panels of different geometries is but briefly discussed. In addition, studies dealing with
particular dynamical problems involving finite deformations, eg, dynamic buckling, stability, and flutter of
shells coupled to flowing fluids, are also discussed. This review is structured as follows: after a short
introduction on some of the fundamentals of geometrically nonlinear theory of shells, vibrations of shells and
panels in vacuo are discussed. Free and forced vibrations under radial harmonic excitation (Section 2.2),
parametric excitation (axial tension or compression and pressure-induced excitations) (Section 2.3), and
response to radial transient loads (Section 2.4) are reviewed separately. Studies on shells and panels in contact
with dense fluids (liquids) follow; some of these studies present very interesting results using methods also
suitable for shells and panels in vacuo. Then, in Section 4, shells and panels in contact with light fluids (gases)
are treated, including the problem of stability (divergence and flutter) of circular cylindrical panels and shells
coupled to flowing fluid. For shells coupled to flowing fluid, only the case of axial flow is reviewed in this
paper. Finally, papers dealing with experiments are reviewed in Section 5. There are 356 references cited in this
article.


ABSTRACT: Thin-walled cylinders of various constructions are widely used in simple or complex structural configurations. The round cylinder is commonly found in tubing and piping, and in offshore platforms. Depending on their use, these cylinders are subjected (in service) to individual and combined application of external loads. In resisting these loads the system is subject to buckling, a failure mode which is closely associated with the establishment of its load-carrying capacity. Therefore, the system buckling and postbuckling
behavior have been the subject of many researchers and investigators both analytical and experimental. The paper is a state-of-the-art survey of the general area of buckling and postbuckling of thin-walled, geometrically imperfect, cylinders of various constructions, when subjected to destabilizing loads. The survey includes discussion of imperfection sensitivity and of the effect of various defects on the critical conditions.


ABSTRACT: Soon after the discovery of carbon nanotubes, it was realized that the theoretically predicted mechanical properties of these interesting structures—including high strength, high stiffness, low density and structural perfection—could make them ideal for a wealth of technological applications. The experimental verification, and in some cases refutation, of these predictions, along with a number of computer simulation methods applied to their modeling, has led over the past decade to an improved but by no means complete understanding of the mechanics of carbon nanotubes. We review the theoretical predictions and discuss the experimental techniques that are most often used for the challenging tasks of visualizing and manipulating these tiny structures. We also outline the computational approaches that have been taken, including ab initio quantum mechanical simulations, classical molecular dynamics, and continuum models. The development of multiscale and multiphysics models and simulation tools naturally arises as a result of the link between basic scientific research and engineering application; while this issue is still under intensive study, we present here some of the approaches to this topic. Our concentration throughout is on the exploration of mechanical properties such as Young’s modulus, bending stiffness, buckling criteria, and tensile and compressive strengths. Finally, we discuss several examples of exciting applications that take advantage of these properties, including nanoropes, filled nanotubes, nanoelectromechanical systems, nanosensors, and nanotube-reinforced polymers. This review article cites 349 references.

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ABSTRACT: Mechanical properties of carbon nanotubes are discussed based on recent advances in both modeling and experiment.

INTRODUCTION: Significant progress has been made in the area of nanoscale science and technology in the past decade. As one of the most interesting nanomaterials, carbon nanotubes (CNT) have received significant attention in terms of fundamental properties measurements and potential applications. This is largely due to the impressive physical properties as revealed from both theoretical and experimental studies. For example, the electrical properties of CNT may be tuned by mechanical deformation. Such properties are of great interest for applications such as sensors or smart materials. The study of these properties is multi-disciplinary and involves various branches of science and engineering. Steady progress has been made in exploring the mechanical properties and potential applications of two types of CNTs: single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT). The measured specific tensile strength of a single layer of a multi-walled carbon nanotube can be as high as 100 times that of steel, and the graphene sheet (in-plane) is as stiff as diamond at low strain. These mechanical properties motivate further study of possible applications for
ABSTRACT: Carbon nanotubes are unique tubular structures of nanometer diameter and large length/diameter ratio. The nanotubes may consist of one up to tens and hundreds of concentric shells of carbons with adjacent shells separation of ~0.34 nm. The carbon network of the shells is closely related to the honeycomb arrangement of the carbon atoms in the graphite sheets. The amazing mechanical and electronic properties of the nanotubes stem in their quasi-one-dimensional (1D) structure and the graphite-like arrangement of the carbon atoms in the shells. Thus, the nanotubes have high Young’s modulus and tensile strength, which makes them preferable for composite materials with improved mechanical properties. The nanotubes can be metallic or semiconducting depending on their structural parameters. This opens the ways for application of the nanotubes as central elements in electronic devices including field-effect transistors (FET), single-electron transistors and rectifying diodes. Possibilities for using of the nanotubes as high-capacity hydrogen storage media were also considered. This report is intended to summarize some of the major achievements in the field of the carbon nanotube research both experimental and theoretical in connection with the possible industrial applications of the nanotubes.

ABSTRACT: This survey paper comprises 5 sections. In Section 1, the reader is introduced to the world of carbon nanotubes where their structural form and properties are highlighted. Section 2 presents the various buckling behaviors exhibited by carbon nanotubes that are discovered by carbon nanotube researchers. The main factors, such as dimensions, boundary conditions, temperature, strain rate and chirality, influencing the buckling behaviors are discussed in Section 3. Section 4 presents the continuum models, atomistic simulations and experimental techniques in studying the buckling phenomena of carbon nanotubes. A summary as well as recommendations for future research are given in Section 5. Finally a large body of papers, over 200, is given in the reference section. It is hoped that this survey paper will provide the foundation knowledge on carbon nanotube buckling and inspire researchers to advance the modeling, simulation and design of carbon nanotubes for practical applications.

Hiroyuki Shima, Division of Applied Physics, Faculty of Engineering, Hokkaido University, Japan, “Buckling of Carbon Nanotubes: A State of the Art Review”, Materials 2012, 5, 47-84; doi:10.3390/ma5010047
ABSTRACT: The nonlinear mechanical response of carbon nanotubes, referred to as their “buckling” behavior, is a major topic in the nanotube research community. Buckling means a deformation process in which a large strain beyond a threshold causes an abrupt change in the strain energy vs. deformation profile. Thus far, much effort has been devoted to analysis of the buckling of nanotubes under various loading conditions: compression, bending, torsion, and their certain combinations. Such extensive studies have been motivated by (i) the structural resilience of nanotubes against buckling and (ii) the substantial influence of buckling on their physical
properties. In this contribution, I review the dramatic progress in nanotube buckling research during the past few years. 212 references cited:


4. See Appendix10.3 for the delicate issue about who should be credited as the first person to discover carbon nanotubes.


6. Together with the three famous nanocarbons, “nanodiamond” deserves attention as the fourth member of nanocarbon materials, being classic yet novel. Nanodiamond was initially synthesized by Volkov [7] in 1963, and recently, a wide variety of applications has been proposed; see References [8,9] for instance.


10. A forthcoming monograph [11], which covers broad topics of carbon nanotube deformation, including buckling, will be of great help to readers who are interested in the subject.


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Hasegawa, M.; Nishidate, K. Radial deformation and stability of single


122. Recently, shell buckling behavior of short nanotubes with aspect ratio ~1 or less was considered, showing the significant dependence of the buckling strain on the nanotube length [123].


124. The critical strain of shell buckling is inversely proportional to the tube diameter [125].


126. Similar sequential transitions can be observed when a SWNT is bent [68]. See Section 6.3 for details.


130. The actual direction of the applied force deviates from the exact axial one by approximately 15 degrees, as indicated in Figure 2(a).

131. The instability at (8) and the sharp rise at (9) during unloading stem from the tip pulled out of the contact, while the nanotube end remains in contact.


135. For larger radius SWNTs, the peanut-like deformed structure can be transformed to dumbbell-like configurations by van der Waals (vdW) attractions between the opposite walls of nanotubes. The latter structure is energetically stable even when the applied force is unloaded.


146. Yang, X.; Wu, G. The study of structural, electronic and optical properties of double-walled carbon nanotube bundles under hydrostatic pressure. EPL 2008, 81, 47003.


148. A radial pressure large enough to cause corrugation can be achieved by electron-beam irradiation [149]; the self-healing nature of eroded carbon walls gives rise to a spontaneous contraction that exerts a high pressure on the inner walls to yield their radial corrugation [60].


150. The authors in Reference [63] say that this conclusion was motivated by an experimental fact that cross sections of MWNTs synthesized in the presence of nitrogen are polygonal shapes rather than circular shapes [151,152]. It was argued that the polygonization may result from the interlayer thermal contraction upon cooling or interwall adhesion energy owing to the increased interwall commensuration [151].


153. Prior to structural optimization, the initial cross sections of all the MWNTs are of circular shape and the interwall spacing is 0.359 nm, which is 0.19 nm larger than the equilibrium spacing of two graphene sheets (=0.34 nm).


168. Interestingly, a buckled SWNT in the TBR is fully reversible. If bending is stopped before the second discontinuity occurs, unbending recovers the cross-sectional shapes at the buckling point.


085503.


181. The Yoshimura pattern is a special kind of surface deformation mode occurring in thin-walled cylindrical shells subjected to large lateral load. It is named after Prof. Yoshimura [182], a Japanese theoretician of fracture mechanics, and its profile is characterized by a periodic diamond-like corrugation.


183. Interestingly, the energetic cost of MWNT buckling under bending is altered by inserting cross-linking (i.e., sp³ covalent bonding) between adjacent walls, as presented in References [184,185].


195. Zhang, Y.F.; Liu, Z.F. Pressure induced reactivity change on the side-wall of a carbon nanotube: A case study on the addition of...
The relevant literature has been probed with great care by Boehm in 1997 [207] and Monthioux and Kuznetsov in 2006 [208]. The first half of this Appendix is based on the two excellent reviews.


211. Despite the omission of a scale bar, the magnification value indicated in the article allows one to estimate that the diameters of the carbon tubes imaged are in the range of 50 nm, i.e., definitely nanosized.

212. Abrahamson, J.; Wiles, P.G.; Rhoades, B.L. Structure of carbon fibers found on carbon arc anodes. Carbon 1999, 37, 1873–1874.


ABSTRACT: The first part of this paper describes some important underlying themes in the mathematical theory of continuum mechanics that are distinct from formulating and analyzing governing equations. The main part of this paper is devoted to a survey of some concrete, conceptually simple, pretty problems that help illuminate the underlying themes. The paper concludes with a discussion of the crucial role of invariant constitutive equations in computation.


ABSTRACT: The research and development in composite mechanics are reviewed from 1965 to 2006. The review covers micromechanics, macromechanics failure theories, impact resistance, structural analysis, plate and panel buckling, shell buckling, progressive fracture, containment, and probabilistic composite simulation. A few remarks are included about aerodynamic loads and a new all composite engine concept. Most of the sample cases are from the author's own research since this research covers all aspects of composites and since this avoids the permissions required by other authors when their results are included. References are cited as appropriate so that the reader can further look in any specific area.

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ABSTRACT: This paper reviews most of the recent research done in the field of dynamic stability/dynamic instability/parametric excitation/parametric resonance characteristics of structures with special attention to parametric excitation of plate and shell structures. The solution of dynamic stability problems involves derivation of the equation of motion, discretization, and determination of dynamic instability regions of the structures. The purpose of this study is to review most of the recent research on dynamic stability in terms of the geometry (plates, cylindrical, spherical, and conical shells), type of loading (uniaxial uniform, patch, point loading …), boundary conditions (SSSS, SCSC, CCCC …), method of analysis (exact, finite strip, finite
difference, finite element, differential quadrature, and experimental ...), method of determination of dynamic instability regions (Lyapunovian, perturbation, and Floquet’s methods), order of theory being applied (thin, thick, three-dimensional, nonlinear ...), shell theory used (Sanders’, Love’s and Donnell’s), materials of structures (homogeneous, bimodulus, composite, FGM ...), and the various complicating effects such as geometrical discontinuity, elastic support, added mass, fluid structure interactions, nonconservative loading and twisting, etc. The important effects on dynamic stability of structures under periodic loading have been identified and influences of various important parameters are discussed. A review of the subject for nonconservative systems in detail will be presented in Part 2. This review paper cites 156 references.

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S. N. Krivoshapko (Peoples’ Friendship University of Russia, 6 Miklukho-Maklaya Street, Moscow 117198, Russia), “Research on General and Axisymmetric Ellipsoidal Shells Used as Domes, Pressure Vessels, and Tanks”, Applied Mechanics Reviews, Vol. 60, No. 6, pp. 336-355, November 2007, DOI: 10.1115/1.2806278

ABSTRACT: The principal advances in the design and construction, as well as the static, vibrational, and buckling analysis of thin-walled structures and buildings in the shape of general and axisymmetric ellipsoidal shells are summarized in this review. These shells are particularly useful as internally pressurized vessels or as heads and bottoms of cylindrical tanks and vessels. Reinforced concrete and structural steel domes of buildings, air-supported rubber-fabric shells, and underwater pressure vessels are also made in the form of ellipsoidal shells. Knowing the geometry of ellipsoids, one can solve various problems in physics, optics, and so on. Basic results of theoretical and experimental investigations of the stress-strain state, buckling, and natural and forced vibrations contained in 209 references are presented in the review. The influence of temperature on the stress-strain state of the shells in question is also discussed. Some parts of the review are also devoted to an analysis of the literature on the stress-strain state of ellipsoidal and torispherical heads of pressure vessels with openings.

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“Modeling and analysis of functionally graded materials and structures”, Applied Mechanics Reviews,

ABSTRACT: This paper presents a review of the principal developments in functionally graded materials (FGMs) with an emphasis on the recent work published since 2000. Diverse areas relevant to various aspects of theory and applications of FGM are reflected in this paper. They include homogenization of particulate FGM, heat transfer issues, stress, stability and dynamic analyses, testing, manufacturing and design, applications, and fracture. The critical areas where further research is needed for a successful implementation of FGM in design are outlined in the conclusions.

References listed at the end of the paper:


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to a Piezoelectric Plate,” Int. J. Solids Struct., 37, pp. 4377–4401.


ABSTRACT: For better crashworthiness performance, vehicles must protect its occupants by maintaining structural integrity and converting the large amount of kinetic energy into other forms of energy in a controllable and predictable manner in a crash situation. In doing so, lower crushing force would provide better safety for the vehicle occupants. This paper reviews the axial response of “modified” tubular sections with imperfections and fillers subjected to axial impact loads relevant to the field of structural crashworthiness. The use of imperfections sets the mode and initiation of collapse of a tube at a specific location and reduces the maximum crush force, hence improving the energy-absorbing characteristics of tubular structures. The types of imperfections discussed include prebuckle, parallel and dished indentations, cutouts, stiffeners, fillers, and wrapping.

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ABSTRACT: Structural elements, which deform inelastically, are often used in energy-absorbing devices due to their simple design and the high efficiency achieved by several buckling deformation mechanisms. The application of light ductile materials in transportation systems and increased loading intensity requires studies on the influence of the rate of loading and material characteristics on dynamic buckling behavior. The present review article is focused on summarizing the state of the art related to the inelastic dynamic stability and postbuckling behavior of various basic structural members. In particular, studies on the dynamic response of axially loaded idealized elastic-plastic models, rods, shells with circular and square cross sections, and long tubes are discussed with consideration given to the influence of the geometric and material characteristics as
well as the loading conditions on the buckling phenomena observed in these structural elements. The findings from the theoretical and experimental investigations on the phenomenon of dynamic inelastic buckling reported in this review article are based on 118 references.

References listed at the end of the paper:

ABSTRACT: Recent research effort into some aspects of strength, static stability, and structural optimization of horizontal pressure vessels is reviewed in this paper. Stress concentrations at the junction of cylinder-ellipsoidal end closures are covered in detail. This in turn establishes efficient choices for wall thicknesses in the vessel. Detailed account of stresses for flexible supports of a horizontal cylindrical shell is provided. Dimensions of support components, which assure the minimum stress concentrations between a horizontal shell and its support, are calculated. In particular, the wall thickness is found for vessels being loaded by the weight of its content and placed on two supports. Stability issues are also reviewed in this paper. In particular, attention is paid to the stability of cylinder under external pressure and to the stability of end closures. The latter are loaded by internal or external pressure. Apart from buckling and plastic loads, the ultimate load carrying capacity, i.e., burst pressure, for internally pressurized heads is also examined. On a practical side, aboveground and underground cases are discussed. In the latter case of underground vessels the reinforcement by internal rings is assessed. The optimization part of this paper deals with the effective choice of the end closure depth and the shape of its meridian. The overriding aim here is to examine the stress concentrations and the ways in which they can be mitigated. The optimal shape of closures is also searched for, with respect to the maximum buckling pressure for a given mass of the head. In the case of internal pressure the maximum of plastic load is sought within a specified class of meridional profiles. Finally, optimal sizing of whole vessels is discussed for slender and compact geometries. Extensive references are made to relatively recent and ongoing work related to the above topics. This paper has 287 references and 50 figures.

ABSTRACT: This review aims to complement a milestone monograph by Singer et al. (2002, Buckling Experiments—Experimental Methods in Buckling of Thin-Walled Structures, Wiley, New York). Practical aspects of load bearing capacity are discussed under the general umbrella of “buckling.” Plastic loads and burst pressures are included in addition to bifurcation and snap-through/collapse. The review concentrates on single and combined static stability of conical shells, cylinders, and their bowed out counterpart (axial compression and/or external pressure). Closed toroidal shells and domed ends onto pressure vessels subjected to internal and/or external pressures are also discussed. Domed ends include: torispheres, toricones, spherical caps, hemispheres, and ellipsoids. Most experiments have been carried in metals (mild steel, stainless steel, aluminum); however, details about hybrids (copper-steel-copper) and shells manufactured from carbon/glass fibers are included in the review. The existing concerns about geometric imperfections, uneven wall thickness, and influence of boundary conditions feature in reviewed research. They are supplemented by topics like

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imperfections in axial length of cylinders, imperfect load application, or erosion of the wall thickness. The latter topic tends to be more and more relevant due to ageing of vessels. While most experimentation has taken place on laboratory models, a small number of tests on full-scale models are also referenced.

References listed at the end of the paper
(See above for the long list. Search for a paper with the same title as this paper. There are more than 200 citations.)

Osama Bedair (AMEC Americas Ltd., 116 Mount Aberdeen Manor SE, Calgary, AB, T2Z 3N8, Canada),

ABSTRACT: Stiffened plates and shells are encountered in many engineering applications. Several analytical and numerical procedures were developed over the past decades for analysis of these structures. Empirical and simplified analytical models were also developed to estimate their ultimate strength for various limit states. The paper reviews and pieces together engineering work developed for all the applications. The first part reviews the analytical, numerical, and orthotropic plate procedures that were developed for analysis of stiffened plates and shells. The structural idealization, the theoretical basis, and the merits of each method are also discussed. The second part of the paper reviews the design philosophies that were developed to predict the ultimate strength of these structures. The influence of various parameters affecting the structural performance, such as geometric and material imperfections, stiffener profile, etc., is discussed. The optimization procedures to minimize the weight of the structure are also reviewed. The paper offers a comprehensive and unique “reference-manual” for all types of stiffened plate applications. (409 references)

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Introduction of the two most used methods for analyzing carbon nanotubes, i.e., continuum mode.
atomistic simulations. Summary and recommendations for future research are also given. Finally, a large body of papers is given in the reference section. It is hoped that this paper provides current knowledge on the buckling of carbon nanotubes, reviews the computational methods for determining the buckling loads, and inspires researchers to further investigate the buckling properties of carbon nanotubes for practical applications.

References listed at the end of the paper:


The Role of Vacancy Defec


Model Accounting for Van


and Multi


X. M. Qiu (1) and T. X. Yu (2)
(1) Department of Engineering Mechanics, Tsinghua University, Beijing 100084, P. R. C.; State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, P. R. C.
(2) Department of Mechanical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, P. R. C.; School of Engineering, Ningbo University, Ningbo 315000, P. R. C., “Some Topics in Recent Advances and Applications of Structural Impact Dynamics”, Applied Mechanics Reviews, Vol. 64, No. 3, 034001 (12 pages), April 2012, DOI: 10.1115/1.4005571

ABSTRACT: This paper reviews some topics related to the advances and applications of structural impact dynamics in recent years. Dynamic behavior of structural members including tubes, beams and plates under axial or transverse loading, and cellular materials and sandwich structures under impact or blast loading are summarized here. The research methodology involves experimental studies, theoretical modeling, as well as numerical simulations. However, as we mainly focus on the longer time dynamic responses of structures and cellular materials, studies of stress wave propagation and the material’s strain-rate sensitivity are not included.

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“Review: Constrained finite strip method developments and applications in cold-formed steel design”, Thin-Walled Structures, Vol. 81, pp 2-18, August 2014

ABSTRACT: The stability of thin-walled members is decidedly complex. The recently developed constrained Finite Strip Method (cFSM) provides a means to simplify thin-walled member stability solutions through its ability to identify and decompose mechanically meaningful stability behavior, notably the formal separation of local, distortional, and global deformation modes. The objective of this paper is to provide a review of the most recent developments in cFSM. This review includes: fundamental advances in the development of cFSM; applications of cFSM in design and optimization; identifying buckling modes and collapse mechanisms in shell finite element models; and, additional stability research initiated by the cFSM methodology. A brief summary of the cFSM method, in its entirety, is provided to explain the method and highlight areas where research remains active in the fundamental development. The application of cFSM to cold-formed steel member design and optimization is highlighted as the method has the potential to automate generalized strength prediction of thin-walled cold-formed steel members. Extensions of cFSM to shell finite element models is also highlighted, as this provides one path to bring the useful identification features of cFSM to general purpose finite element models. A number of alternative methods, including initial works on a constrained finite element method, initiated by cFSM methods, are also detailed as they provide insights on potential future work in this area. Research continues on fundamentals such as methods for generalizing cFSM to arbitrary cross-sections, improved design and optimization methods, and new ideas in the context of shell finite element method applications.
ABSTRACT: The fracture mechanics of plates and shells under membrane, bending, twisting, and shearing loads are reviewed, starting with the crack tip fields for plane stress, Kirchhoff, and Reissner theories. The energy release rate for each of these theories is calculated and is used to determine the relation between the Kirchhoff and Reissner theories for thin plates. For thicker plates, this relationship is explored using three-dimensional finite element analysis. The validity of two-dimensional (plate theory) solutions to actual three-dimensional objects is analyzed and discussed. Crack tip fields in plates undergoing large deflection are analyzed using von Kármán theory. Solutions for cracked shells are discussed as well. A number of computational methods for determining stress intensity factors in plates and shells are discussed. Applications of these computational approaches to aircraft structures are examined. The relatively few experimental studies of fracture in plates under bending and twisting loads are also reviewed. There are 101 references cited in this article.

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ABSTRACT: It is 100 years since the well-known Mohr-Coulomb strength theory was established in 1900. A considerable amount of theoretical and experimental research on strength theory of materials under complex stress state was done in the 20th Century. This review article presents a survey of the advances in strength theory (yield criteria, failure criterion, etc) of materials (including metallic materials, rock, soil, concrete, ice,
iron, polymers, energetic material, etc) under complex stress, discusses the relationship among various criteria, and gives a method of choosing a reasonable failure criterion for applications in research and engineering. Three series of strength theories, the unified yield criterion, the unified strength theory, and others are summarized. This review article contains 1163 references regarding the strength theories. This review also includes a brief discussion of the computational implementation of the strength theories and multi-axial fatigue.


ABSTRACT: Due to advancements made in 3D weaving process, 3D woven composites have evolved as an attractive structural material for multi-directional load bearing and impact applications, due to their unique transverse properties such as stiffness, strength, fracture toughness and damage resistance. Substantial progress has been made in recent years for the development of new modeling techniques in design and analysis to understand the unique mechanical behavior of 3D woven composites. This paper systemically reviews the modeling techniques along with their capabilities and limitations for characterization of the micro-geometry, mechanical/thermo-mechanical behavior and impact behavior of 3D woven composites. Advantages, disadvantages and applications of 3D woven composites have also been delineated. In addition, this reference list provides a good database for future research on 3D woven composites.


ABSTRACT and OBJECTIVES: The purpose of this study is to review many of the available design guidelines for unidirectional tape, laminated aerospace composite panels. Guidelines for bonded and bolted joints, cutouts, and durability and damage tolerance are also presented, as they strongly influence designs for production aircraft. These guidelines are accompanied by explanations of why each one was generated and the influence each one has on the structural performance of various aircraft components. Most of these guidelines were developed during actual construction of relatively simple aircraft components in the late 1960s and early 1970s. Unfortunately, generally available literature detailing the derivation of these guidelines is scarce; hence, it was made necessary to obtain information directly from various aerospace engineering organizations and notes presented in lectures. The scarcity of formal documentation may also be due, in part, to the fact that many lessons were learned when unpredicted failures occurred during early development programs that are only now being declassified.

The present review is focused on composite laminates made of graphite fibers embedded in a polymer matrix since use of such laminates is increasing in highly loaded aerospace primary structures. Simple analyses and data are presented to illustrate the basis for many of the guidelines.

The objective of this review is to (1) gather the design guidelines currently used for structural design and analysis of unidirectional tape laminates, (2) review their derivation, and (3) explain their ranges of application. Many of these guidelines have served the aerospace industry for close to three decades as they were developed for fighter/attack aircraft structural components being designed in the late 1960s. Attention was directed towards production aircraft that were to be certified for operating lives on the order of 6,000 flight hours. By gathering together these guidelines and critically evaluating their derivation, it is feasible to assess situations under which they can be safely relaxed or even ignored. Such an assessment is performed for a spar cap
composed entirely of unidirectional plies proposed for unmanned air vehicles under development for NASA’s ERAST program.

References at the end of the report:

http://dx.doi.org/10.2514/6.2000-1322
ABSTRACT (not available)

ABSTRACT: Aviation safety can be greatly enhanced through application of computer simulations of crash impact. Unlike automotive impact testing, which is now a routine part of the development process, crash testing of even small aircraft is infrequently performed due to the high cost of the aircraft and the myriad of impact conditions that must be considered. Crash simulations are currently used as an aid in designing, testing, and certifying aircraft components such as seats to dynamic impact criteria. Ultimately, the goal is to utilize full-scale crash simulations of the entire aircraft for design evaluation and certification. The objective of this publication is to describe “best practices” for modeling aircraft impact using explicit nonlinear dynamic finite element codes such as LS-DYNA, DYNA3D, and MSC.Dytran. Although “best practices” is somewhat relative,
the authors’ intent is to help others to avoid some of the common pitfalls in impact modeling that are not generally documented. In addition, a discussion of experimental data analysis, digital filtering, and test-analysis correlation is provided. Finally, some examples of aircraft crash simulations are described in four appendices following the main report.

References listed at the end of the report:


S. D. Daxini (1) and J. M. Prajapati (2)
(1) Department of Mechanical Engineering, Babaria Institute of Technology, Vadodara, Gujarat 391240, India
(2) Department of Mechanical Engineering, M. S. University, Vadodara, Gujarat 390020, India

“A Review on Recent Contribution of Meshfree Methods to Structure and Fracture Mechanics Applications”,
DOI: 10.1155/2014/247172

ABSTRACT: Meshfree methods are viewed as next generation computational techniques. With evident limitations of conventional grid based methods, like FEM, in dealing with problems of fracture mechanics, large deformation, and simulation of manufacturing processes, meshfree methods have gained much attention by researchers. A number of meshfree methods have been proposed till now for analyzing complex problems in various fields of engineering. Present work attempts to review recent developments and some earlier applications of well-known meshfree methods like EFG and MLPG to various types of structure mechanics and fracture mechanics applications like bending, buckling, free vibration analysis, sensitivity analysis and topology optimization, single and mixed mode crack problems, fatigue crack growth, and dynamic crack analysis and some typical applications like vibration of cracked structures, thermoelastic crack problems, and failure transition in impact problems. Due to complex nature of meshfree shape functions and evaluation of integrals in domain, meshless methods are computationally expensive as compared to conventional mesh based methods. Some improved versions of original meshfree methods and other techniques suggested by researchers to improve computational efficiency of meshfree methods are also reviewed here.

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P. Hein, Diffuse element method applied to Kirchhoff plates, _ Technical Report, Department of Civil Engineering, Northwestern University, Evanston, Ill, USA, 1993.


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ABSTRACT: The paper reviews literature on buckling of conical shells subjected to three loading conditions: (i) axial compression only, (ii) external pressure only and (iii) combined loading. The review is from the theoretical as well as experimental points of view. This review covers known experiments on cones from (1958 – 2012). The literature review is split thematically into the following categories: theoretical prediction of axially compressed cones, theoretical prediction of externally pressurized cones, theoretical prediction of cones under combined loading, buckling experiments on axially compressed cones, buckling experiments on externally pressurized cones, buckling experiments on cones subjected to combined loading, buckling experiments on composite conical shells, equivalent cylinder approach, effect of initial geometric imperfection on the buckling behaviour of cones and effect of imperfect boundary conditions on the buckling behaviour of cones.

References listed at the end of the paper:


why buckling responses have certain advantages and are especially suitable for these particular applications.

this topical review is to showcase the recent advances in buckling-induced smart applications and to explain why buckling responses have certain advantages and are especially suitable for these particular applications.


ABSTRACT: A paradigm shift has emerged over the last decade pointing to an exciting research area dealing with the harnessing of elastic structural instabilities for 'smart' purposes in a variety of venues. Among the different types of unstable responses, buckling is a phenomenon that has been known for centuries, and yet it is generally avoided through special design modifications. Increasing interest in the design of smart devices and mechanical systems has identified buckling and postbuckling response as a favorable behavior. The objective of this topical review is to showcase the recent advances in buckling-induced smart applications and to explain why buckling responses have certain advantages and are especially suitable for these particular applications.
Interesting prototypes in terms of structural forms and material uses associated with these applications are summarized. Finally, this review identifies potential research avenues and emerging trends for using buckling and other elastic instabilities for future innovations.

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Some Surveys by Jaroslav Mackerle:


ABSTRACT: This paper is offered as a practical guide to sources of information on the finite element (FE) and boundary element (BE) techniques and software. It is intended for use by practical engineers, researchers and potential buyers of software as a help to find their way through the varying forms of literature. Reviewed are books, periodicals, bibliographies, abstracting journals, and databases.


ABSTRACT: The paper gives a bibliographical review of the finite element methods (FEMs) applied for the analysis of pressure vessel structures/components and piping from the theoretical as well as practical points of view. The range of applications of FEMs in this area is wide and cannot be presented in a single paper; therefore the aim of this review is to give the reader an encyclopaedic view of the different possibilities that exist today for the finite element analysis in the fields of pressure vessels and piping. The bibliography at the end of the paper contains approximately 1900 references to papers, conference proceedings and theses/dissertations on the subject that were published in 1976–1996. These are classified in the following categories: linear and non-linear, static and dynamic, stress and deflection analysis; stability problems; thermal problems; fracture mechanics problems; contact problems; fluid-structure interaction problems; manufacturing of pipes and tubes; welded pipes and pressure vessel components; development of special finite elements for pressure vessels and pipes; finite element software; and other topics. Also finite element software, general purpose and special purpose codes, used for the analysis of pressure vessels and pipes are briefly discussed and presented.


ABSTRACT: This paper gives a bibliographical review of the finite-element methods applied to the analysis and simulation of polymers. The bibliography at the end of the paper contains references to papers, conference proceedings and theses/dissertations on the subject that were published between 1976 - 1996. The following topics are included: polymer flow and mixing simulation; polymer processing; thermal analysis of polymers; fracture mechanics of polymers; modelling polymer behaviours and their mechanical properties; practical polymer applications in engineering; other topics.


ABSTRACT: This bibliography contains references to papers, conference proceedings and theses/dissertations dealing with stability problems and finite element and boundary element analyses that were published in 1994–1996.


ABSTRACT: This bibliography contains references to papers, conference proceedings and theses/dissertations dealing with finite element and boundary element analyses of fluid–structure interaction problems that were published in 1995–1998.


ABSTRACT: A bibliographical review of the finite element methods (FEMs) applied for the linear and nonlinear, static and dynamic analyses of basic structural elements from the theoretical as well as practical points of view is given. The bibliography at the end of the paper contains 1,726 references to papers, conference proceedings and theses/dissertations dealing with the analysis of beams, columns, rods, bars, cables, discs, blades, shafts, membranes, plates and shells that were published in 1996-1999.

Jaroslav Mackerle, (Linköping Institute of Technology, Department of Mechanical Engineering, Linköping, Sweden), “Finite element linear and nonlinear, static and dynamic analysis of structural elements, an

ABSTRACT: This paper gives a bibliographical review of the finite element methods (FEMs) applied for the linear and nonlinear, static and dynamic analyses of basic structural elements from the theoretical as well as practical points of view. The bibliography at the end of the paper contains more than 1330 references to papers, conference proceedings and theses/dissertations dealing with the analysis of beams, columns, rods, bars, cables, discs, blades, shafts, membranes, plates and shells that were published in 1999–2002.


ABSTRACT: This bibliography contains references to papers, conference proceedings and theses/dissertations dealing with the linear and nonlinear finite element and boundary element analyses of shells that were published in 1999–2001.


ABSTRACT: Gives a bibliographical review of the finite element analyses of sandwich structures from the theoretical as well as practical points of view. Both isotropic and composite materials are considered. Topics include: material and mechanical properties of sandwich structures; vibration, dynamic response and impact problems; heat transfer and thermomechanical responses; contact problems; fracture mechanics, fatigue and damage; stability problems; special finite elements developed for the analysis of sandwich structures; analysis of sandwich beams, plates, panels and shells; specific applications in various fields of engineering; other topics. The analysis of cellular solids is also included. The bibliography at the end of this paper contains 655 references to papers, conference proceedings and theses/dissertations dealing with presented subjects that were published between 1980 and 2001.

SECTION 8 of the paper:

8. Stability problems

An important factor for the sandwich structural integrity is the design against buckling. The interaction between the stiff faces and flexible core has a strong influence on the initial buckling load and the subsequent post-buckling which can be unstable on the contrary from isotropic materials.

This section deals with elastic instability and buckling. Another local buckling that can occur is the face wrinkling. Papers are listed that investigate the effect of coupling between faces and the core on the stability of sandwich structures.

The main topics include: linear and nonlinear stability analysis; static and dynamic buckling of sandwich structures; thermal buckling; pre-buckling analysis; post-buckling analysis; nonlinear post-buckling analysis; post-buckling analysis of debonded sandwich structures; strain-rate dependent buckling; local buckling behavior; effect of boundary conditions; parametric studies.

Type of structure: sandwich beams, plates, shells and panels; composite sandwich structures; soft-core and hard-core sandwich plates; stiffened sandwich panels; prestressed sandwich arches; curved sandwich panels; honeycombs.

References listed for the category, “6A.6 Stability problems”: 
6.6 Stability problems


ABSTRACT: This paper gives a bibliographical review of the finite element methods applied to the analysis and simulation of welding processes. The bibliography is an addendum to the finite element analysis and simulation of welding: a bibliography (1976-96) published in Modelling Simul. Mater. Sci. Eng. (1996) 4 501-33. The added bibliography at the end of this paper contains approximately 550 references to papers and conference proceedings on the subject that were published in 1996-2001. These are classified in the following categories: modelling of welding processes in general; modelling of specific welding processes; influence of geometrical parameters; heat transfer and fluid flow in welds; residual stresses and deformations in welds; fracture mechanics and welding; fatigue of welded structures; destructive and non-destructive evaluation of weldments and cracks; welded tubular joints, pipes and pressure vessels/components; welds in plates and other structures/components.

End of surveys by Jaroslav Mackerle

Encyclopedia entry that defines “functionally Graded Materials (FGM):


BEGINNING OF ARTICLE: A functionally graded material (FGM, or sometimes also ‘‘gradient material’’) is characterized by a gradual change of material properties with position. The property gradient in the material is caused by a position-dependent chemical composition, micro-structure, or atomic order. The spatial extension of the gradient may differ: in a bulk FGM the property variation extends over a large part of the material, whereas in a graded coating or joint it is restricted to the surface of the material or a small interfacial region. Although FGMs attracted scientific interest only towards the end of the twentieth century, these materials are not new. In fact, spatial variations in the microstructure of materials have been exploited for millions of years by living organisms. In many structures found in plants, microstructural gradients are formed in order to produce optimum structural and functional performance with minimum material use. An example is the culm of bamboo, which consists of high-strength natural fibers embedded in a matrix of ordinary cells (Fig. 1(a)). The fiber content is not homogeneous over the entire cross-section of the culm but decreases from outside to inside (Fig. 1(b)). This gradation in fiber content is a natural adaptation of the plant to flexural loads—the fiber content is high only in those sections where the highest stresses occur.

There are also some examples of early synthetic materials taking advantage of property gradients such as case-hardened steels in which a hard surface is combined with a tough interior. Nevertheless, it was only in 1987 that Japanese scientists conceived graded materials as a new concept and defined an FGM as an ‘‘inhomogeneous composite, in which the material’s mechanical, physical, and chemical properties change continuously, and which have no discontinuities within the material’’ (Hirai et al. 1987). Meanwhile it has become common
practice to use the term FGM not only for composites, but also for all materials with a macroscopic property gradient (see definition at the beginning of the article). Thus, materials containing only one phase such as graded glasses or graded single crystals are also FGMs. In such materials the spatial property variation is caused by a gradient in chemical composition. Nevertheless, the vast majority of FGMs are composite materials with a macroscopic micro-structural gradient. For example, the composite may contain a spatially varying volume fraction of one of the phases (Fig. 2(a)). In this case, the gradient material can be conveniently described by the use of a transition function \( f(x,y,z) \), where \( f \) is the volume fraction of one of the phases as a function of position. In many practical cases the compositional variation will be restricted to one coordinate, \( z \), and the different gradients can then be described by a so-called transition function of the type: \( f(z) = (z/d)^p \), where \( f \) denotes the volume fraction of one of the phases, \( d \) is the thickness of the graded region, and \( p \) is the so-called gradation exponent. However, a composition gradient is not inherent to all FGMs. Microstructural gradients may also be obtained in composites by changing the shape (Fig. 2(b)), orientation (Fig. 2(c)), or size (Fig. 2(d)) of the dispersed phase.

Properly designed property gradients in materials lead to a performance that cannot be achieved with a homogeneous material or by the joining of two different materials. The gradient can thus be regarded as an additional material design parameter which may be adapted and optimized to meet the requirements of a particular application. This leads to the unusual situation that the performance of the material is strongly influenced by geometric factors such as the shape of the material, and the extension and profile of the property gradient. Thus, a gradient material cannot be fully characterized by materials constants only, and already comprises certain aspects of the design of a component.

Most of the theoretical research on FGMs has been devoted to their macroscopic mechanical and thermal behavior and there has been considerable progress in understanding the effects of gradients on the stress distribution within such materials (reviewed by Suresh and Mortensen 1998). A gradation of the elastic modulus and/or of the thermal expansion coefficient...


ABSTRACT: Cylindrical steel storage tanks are shells designed to store different types of products such as liquids or grain. The thickness of the shell is calculated to withstand the circumferential stress resulting from the hydrostatic pressure due to the stored product. A unique situation when there is no stored product leads to the vulnerability of the shell to buckle when there is wind load due to external pressure. There are two major types of buckling modes: local and general. The local buckling mode is studied analytically in various studies and is easy to mitigate. The general buckling mode can be more damaging to the tank and more costly to mitigate. The prevention of general buckling due to wind load pressure is achieved through the addition of stiffener rings. However, the stiffener rings design procedure used by various design standards has little known background. This paper reviews the current design approach’s origin and explains a semi-analytical justification for it. The unfolding of the design expressions can lead to more freedom in design variables selection leading to more economical designs.

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End of some of the Review Articles in Applied Mechanics Reviews and Elsewhere
End of Section 3

Section 4: The following articles are partly review articles and partly contribute new material to the literature. Most of them are cited again in Section 8 with abstracts included and occasionally also references included.

ABSTRACT: The serious discrepancy between theoretical and experimental results for the buckling load of axially compressed cylindrical shells is well known. This paper presents results of a test program specifically designed to throw some light on the causes of the discrepancy. Ten nominally identical nickel cylinders were fabricated by electrodeposition and tested under both dead-weight and controlled end-shortening conditions. The test results indicate the following: the buckling load under usual laboratory conditions depends on the properties of the test specimen itself rather than on the testing environment, the buckling loads under dead-weight and controlled end-shortening conditions are the same, a sharp puff of air during loading can cause buckling at a considerably reduced load level, minimization of initial imperfections in the test specimens greatly increases the buckling load, and the magnitude of the minimum postbuckling equilibrium load is relatively insensitive to initial imperfections.

References listed at the end of the paper:


(References given later in this document)

Booton, M., Buckling of Imperfect Anisotropic Cylinders Under Combined Loading, Institute for Aerospace Studies, U. of Toronto, UTIAS Rept. No. 203, August 1976

S. Dharmarajan (1) and L.E. Penzes (2)
(1) Department of Aerospace Engineering, San Diego State University, San Diego, California, USA
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J. Spence (1) and S.L. Toh (2)
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(2) Babcock and Wilcox (Operations) Ltd., Research Station, High Street, Renfrew, Scotland
ABSTRACT: The elastic collapse of thin orthotropic elliptical cylindrical shells subject to pure bending alone or combined bending and uniform normal pressure loads has been studied. Nonlinear finite deflection thin shell theory is employed and this reduces the problem to a set of nonlinear ordinary differential equations. The resulting two-point nonlinear boundary-value problem is then linearized, using quasi-linearization, and solved numerically by the “shooting technique.” Some experimental work has been carried out and the results are compared with the theoretical predictions.


Noor, A. K. and Peters, J. M. (George Washington University, MS-269, NASA Langley Research Center,
ABSTRACT: The developments of an existing 48 degrees-of-freedom (d.o.f.), curved, quadrilateral, thin shell element, for materially and geometrically nonlinear static analysis of shell structures, are extended for the study of dynamic responses of nonlinear shells. The variable-order polynomial representations of the shell surface and the non-axisymmetric definition of the shell boundaries allow the study of the dynamic behaviour of a class of shell structures more general than those treated by using flat plate elements and elements with assumptions of axisymmetry. The equations of motion are based on a Lagrangian frame of reference. A combination of step-by-step and iterative procedures is used for the solution of nonlinear equations. The incremental equations of motion are linearized for computation purposes, and an algorithm for numerical integration based on Newmark's generalized operator for dynamic analysis, using optional iteration, is adopted. The flow theory of plasticity is used in the inelastic range, and perfectly plastic or isotropic strain hardening materials are considered. The spread of plastic zones in the thickness direction is treated by using a layered model. Numerical examples presented include the dynamic analyses of a square plate, a circular annulus, a cylindrical panel and a spherical cap. Comparisons with existing solutions demonstrate the validity and accuracy of the present developments.

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ABSTRACT: (cannot cut and paste)


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SUMMARY: Since the mid-1960s when the forms of curved shell finite elements were originated, including those pioneered by Professor Gallagher, the published literature on the subject has grown extensively. The first two present authors and Liaw presented a survey of such literature in 1990 in this journal. Professor Gallagher maintained an active interest in this subject during his entire academic career, publishing milestone research works and providing periodic reviews of the literature. In this paper, we endeavor to summarize the important literature on shell Finite elements over the past 15 years. It is hoped that this will be a be a fitting tribute to the pioneering achievements and sustained legacy of our beloved Professor Gallagher in the area of shell finite elements. This survey includes: the degenerated shell approach; stress-resultant-based formulations and Cosserat surface approach; reduced integration with stabilization; incompatible modes approach; enhanced strain formulations; 3-D elasticity elements; drilling d.o.f. elements; co-rotational approach; and higher-order theories for composites.

References listed at the end of the paper:
94. Destuynder P, Salaun M. A mixed finite element for shell model with free edge boundary conditions. Part 2. The numerical
122. Erickssen JL, Truesdell C. Exact theory of stress and strain in rods and shells. Archive for Rational Mechanics and Analysis


237. Betsch P, Gruttmann F, Stein E. A 4-node finite shell element for the implementation of general hyperelastic 3D-elasticity at
294. Gruttmann F, Stein E, Wriggers P. Theory and numerics of thin elastic shells with finite rotations. Ingenieur Archiv 1989; 59:54-


K. He, S. V. Hoa and R. Ganesan (Concordia Center for Composites, Department of Mechanical Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, PQ, Canada H3G 1M8), “The study of tapered laminated composite structures: a review”, Composites Science and Technology, Vol. 60, No. 14, November 2000, pp. 2643-2657, doi:10.1016/S0266-3538(00)00138-X


Luis A. Godoy and Genock Portela (University of Puerto Rico, Mayaguez Campus, Department of Civil Engineering), “A review of wind-tunnel results of pressures on tank models”, (publisher and date not given in the pdf file; latest reference is 2001)

J. C. Newman, Jr. (1), M. A. James (2) and U. Zerbst (3)
(1) Department of Aerospace Engineering, Mississippi State University, 314C Walker Engineering Laboratory, Hardy Street, Mississippi State, MS 39762, USA
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(3) GKSS Research Center, Geeshtacht, Germany


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(1) Fraunhofer Institut für Werkstoffmechanik, Freiburg, Germany
(2) Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Blacksburg, CA USA
ABSTRACT: A review of the progress in the stability analysis and design of concrete shells in the last two decades is presented. The decisive developments in the finite element analysis is stressed, but not examined in detail, since it is outside the scope of this review. Main attention is directed to the review of some approximate methods of buckling design of shells typically embodied in recommendations, guidelines or codes, primarily the IASS Recommendations of 1979 and the Kollár IASS Proposal of 1993. These two approaches are discussed in detail, and further modifications to the procedure are offered. The procedure is summarized in Section 5.


ABSTRACT: In this chapter dynamic stability loss of rectangular shells is addressed. A background containing types of dynamic buckling and prefect constructions, as well as the concept of finite-time stability, is given in Sects.4.1–4.3. Mathematical modeling of dynamical systems, problems of synchronization, chaos, and quasi-periodicity are also briefly revisited. Sections. 4.6–4.10 refer to both static and dynamic bifurcations and their numerical estimations. Stability loss of homogeneous shells subjected to an action of transversal loads is rigorously studied in Sect. 4.11.


B.W. Schafer (Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, 21218, United States), “Review: The Direct Strength Method of cold-formed steel member design”, Journal of Constructional Steel Research, Vol. 64, Nos. 7-8, July-August 2008, pp. 766-778, Special Issue: International Colloquium on Stability and Ductility of Steel Structures 2006, doi:10.1016/j.jcsr.2008.01.022

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“Stress-driven buckling patterns in spheroidal core/shell structures”, Proceedings of the National Academy of
ABSTRACT: Many natural fruits and vegetables adopt an approximately spheroidal shape and are characterized by their distinct undulating topologies. We demonstrate that various global pattern features can be reproduced by anisotropic stress-driven buckles on spheroidal core/shell systems, which implies that the relevant mechanical forces might provide a template underpinning the topological conformation in some fruits and plants. Three dimensionless parameters, the ratio of effective size/thickness, the ratio of equatorial/polar radii, and the ratio of core/shell moduli, primarily govern the initiation and formation of the patterns. A distinct morphological feature occurs only when these parameters fall within certain ranges: In a prolate spheroid, reticular buckles take over longitudinal ridged patterns when one or more parameters become large. Our results demonstrate that some universal features of fruit/vegetable patterns (e.g., those observed in Korean melons, silk gourds, ribbed pumpkins, striped cavern tomatoes, and cantaloupes, etc.) may be related to the spontaneous buckling from mechanical perspectives, although the more complex biological or biochemical processes are involved at deep levels.

References listed at the end of the paper:
ABSTRACT: Thin film buckling has become an interesting research topic with a focus on the underlying physics and its control. Here we highlight the prevention of buckling in nanomechanical films.
Binbin Pan and Weicheng Cui (China Ship Scientific Research Center, P.O. Box 116, No. 222 East Shanshui Road, Wuxi, Jiangsu 214082, China), “An overview of buckling and ultimate strength of spherical pressure hull under external pressure”, Marine Structures, Vol. 23, No. 3, July 2010, pp. 227-240,
doi:10.1016/j.marstruc.2010.07.005
ABSTRACT: The load-carrying capability of spherical shells under external pressure has been the subject of a long history and many theoretical and experimental studies have been carried out. However, from a comparative study on the design rules for the minimum thickness of the deep manned spherical shells from various classification societies, significant differences have been found. This indicates that these design rules need to be updated and unified like Common Structural Rules for tankers and bulk carriers. In order to lay a foundation for this target, a systematic study is carried out to develop a consistent calculation method for predicting the ultimate strength of spherical pressure hull under external pressure. This is the first paper of a series of three for reporting this study and in this paper, a critical review on the buckling and ultimate strength of spherical pressure hulls is carried out and further problems to be studied are identified. This could lay a solid foundation for the further study.


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ABSTRACT: A review of conventional testing methods for applying external hydrostatic pressure to buckling-
critical shells is presented. A new “volume-control” pressure testing method, aimed at preventing catastrophic specimen failures and improving control of specimen deformation near the critical load, is also introduced. The implementation of conventional and volume-control systems in an experimental program involving the destructive pressure testing of ring-stiffened cylinders is described. The volume control method was found to improve control of the specimen deformations, especially near the critical load, and catastrophic failures observed while using a conventional setup were avoided. The quasi-static tracking of post-collapse load-deformation relationships for snap-through buckling behaviour was possible while using a volume-control system, but precise control of dynamic shell deformations during buckling was not achieved for specimens failing with large buckling lobes. Expressions for estimating the available control over specimen deformations for pressure testing systems are presented.

References listed at the end of the paper:
1. BSI (1980) BS 5500 British standard specification for unfired fusion welded pressure vessels, Issue 5, United Kingdom: British Standards Institution (BSI)

DOI: 10.1016/j.finel.2012.10.009
ABSTRACT: A framework for the design of submarine pressure hulls using nonlinear finite element (FE) analysis is presented in order to improve upon the conventional analytical-empirical design procedure. A numerical methodology is established that allows the collapse pressure of a hull to be predicted with controlled accuracy. The methodology is characterized by quasi-static incremental analysis, including material and geometric nonlinearities, of FE models constructed from shell elements. The numerical methodology is used with ANSYS to predict the results of 47 collapse experiments on small-scale ring-stiffened cylinders representative of submarine hulls. A probabilistic analysis is applied to the experimental-numerical comparisons in order to estimate the accuracy of the FE methodology and derive a partial safety factor (PSF) for design. It is demonstrated that a high level of accuracy, within 10% with 95% confidence, can be achieved if the prescribed FE methodology is followed. Furthermore, it is shown that the PSF for design does not need to be very large, even if a high degree of statistical confidence is built in. The designer can be 99.5% confident that the FE error has been accounted for by dividing the predicted collapse pressure by a PSF=1.134.

ABSTRACT: This paper examines the application of structural reliability analysis to submarine pressure hulls...
to clarify the merits of probabilistic approach in respect thereof. Ultimate strength prediction methods which take the inelastic behavior of ring-stiffened cylindrical shells and hemi-spherical shells into account are reviewed. The modeling uncertainties in terms of bias and coefficient of variation for failure prediction methods in current design guidelines are defined by evaluating the compiled experimental data. A simple ultimate strength formulation for ring-stiffened cylinders taking into account the interaction between local and global failure modes and an ultimate strength formula for hemispherical shells which have better accuracy and reliability than current design codes are taken as basis for reliability analysis. The effects of randomness of geometrical and material properties on failure are assessed by a preliminary study on reference models. By evaluation of sensitivity factors important variables are determined and comparisons are made with conclusions of previous reliability studies.


ABSTRACT: The use of cylindrical shells in the aerospace industry is widespread as load carrying structures. This paper addresses the buckling capability of a cylindrical shell under a compressive axial load using finite element analysis and shows how variability in manufacturing processes, such as ovalization of a cylindrical duct, can affect the buckling capability of these parts. Results show that, as expected, buckling capability of a thin cylinder is significantly affected by out of roundness. Out of roundness of 1%, 10%, 50% and 100% of the shell thickness resulted in a reduction in buckling capability of 8.3%, 37.8% 65.9% and 75%, respectively. Finite element results were calibrated to and were in good agreement with the theoretical solution for a perfectly round cylinder under axial compression.

References listed at the end of the thesis:


ABSTRACT: This paper investigates experimentally the bending of inflatable cylindrical cantilevered beams made of modern fabric materials. A dimensionless form of load vs deflection has been developed to characterize and generalize the bending behavior of the inflatable cylindrical cantilevered beams of different sizes, materials, and inflation pressures in a unified way for easy application. The dimensionless form of experimental results demonstrates that the inflatable beams, highly or lightly inflated, can be modeled by the Euler beam theory accurately before wrinkle occurs. The initial wrinkle is hardly noticeable in the experiments and the transition from non-wrinkle to wrinkle is mainly defined by the slope change of load-deflection curve. Compared with the experimental data, the strain-based wrinkle moment provides a lower bound prediction while the stress-based wrinkle moment gives an upper bound prediction. In the post-wrinkle stage, the Euler beam theory using a nonlinear moment-curvature model gives an upper bound estimation of load-deflection
relationship while the finite element analysis based on membrane theory gives a lower bound estimation. The actual collapse moment is hard to measure in experiments due to the inflatable beam becomes unstable in the collapsed stage. However, the trends of experimental results show that the stress-based collapse moment gives the upper limit prediction and the strain-based collapse moment does not agree with the experimental data.

References listed at the end of the paper:

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(1) Department of Mechanical Engineering, Mississippi State University, Mississippi State, MS 39762, USA
(2) Department of Aerospace Engineering, Mississippi State University, Mississippi State, MS 39762, USA


ABSTRACT: Laminated composite shells are frequently used in various engineering applications in the aerospace, mechanical, marine, and automotive industries. This article follows a previous book and review articles published by the leading author (Qatu, 2004, 2002, 1989, 1992, 1999 1, 2, 3, 4 and 5). It reviews most of the research done in recent years (2000–2009) on the dynamic behavior (including vibration) of composite shells. This review is conducted with emphasis on the type of testing or analysis performed (free vibration, impact, transient, shock, etc.), complicating effects in material (damping, piezoelectric, etc.) and structure (stiffened shells, etc.), and the various shell geometries that are subjected to dynamic research (cylindrical, conical, spherical and others). A general discussion of the various theories (classical, shear deformation, 3D, non-linear etc.) is also given. The main aim of this review article is to collate the research performed in the area of dynamic analyses of composite shells during the last 10 years, thereby giving a broad perspective of the state of art in this field. This review article contains close to 200 references.


ABSTRACT: Budget and schedule restrictions sometimes require naval submarines to be operated with unrepaird corrosion damage to the pressure hull. It is important to understand the effects of corrosion wastage on the structural capacity of the hull, so that appropriate diving depth restrictions can be imposed if necessary. The current paper presents an experimental study of the interaction of material behavior with corrosion defects, especially with respect to their effect on overall elasto-plastic collapse of pressure hulls. Twenty ring-stiffened cylinders, representative of submarine pressure hulls failing by overall collapse, were machined from high- and low-grade aluminum alloy tubes. Artificial general corrosion damage was introduced in selected specimens by machining away material from the outside of the cylinder shell in rectangular patches of uniform depth. The cylinders were monotonically loaded to collapse under external hydrostatic pressure. One corroded cylinder was repeatedly loaded past the yield limit before the collapse test in order to study the effect of cyclic plastic loading on its ultimate collapse strength. Overall collapse pressures for corroded cylinders with a variety of patch sizes and depths and material strengths were reduced by, on average, 0.85 times the depth of thinning divided by the original shell thickness. The collapse strength of corroded cylinders was found to be more sensitive to the shape of the stress-strain curve than for intact specimens. Higher levels of strain hardening and ductility were found to improve the performance of damaged cylinders. Permanent deformations in the cyclically loaded cylinder, as measured with strain gauges, grew with each constant-amplitude load cycle; however, the additional deformations tended towards zero with increasing number of cycles, and a subsequent collapse test indicated that the cyclic loading did not affect the collapse pressure. The sensitivity of overall collapse to material strength is related to not only the yield stress, but also the plastic reserve of the material; higher levels of strain hardening and ductility increase overall collapse strength of hulls, especially those with general corrosion damage. The effect of a given level of corrosion thinning is less severe for cylinders with relatively greater levels of strain hardening. It is unlikely that cyclic plastic loading of corroded hulls will lead to premature collapse at a load level below the monotonic collapse pressure.

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(2) Faculty of Built Environment & Engineering, Queensland University of Technology (QUT), Brisbane, Australia
“A review of optimization techniques used in the design of fibre composite structures for civil engineering applications”, Materials & Design, Article in Press, Corrected Proof, July 2011,
End of survey articles and articles that have a significant survey component in them. 
End of Section 4

Section 5: Special Issues of Journals on a Given Theme

--------Special issue

--------Special issue on Recent research advances on thin-walled structures
Thin-Walled Structures, Vol. 61, pp 1-266, December 2012, edited by Dan Dubina and Viorel Ungureanu

--------Special issue on Advances in Stability of Structures
Thin-Walled Structures, Vol. 49, No. 5, May 2011, Special Issue: Recent Research Advances in Stability of Structures

--------Special issue on Stability of Structures
Thin-Walled Structures, Vol. 45, Nos. 10-11, October-November 2007, Special Issue: Stability of Structures

--------Special issue on Buckling and Postbuckling Behavior of Composite Laminated Shells
Composite Structures, Vol. 73, No. 2, May 2006, Special Issue: International Conference on Buckling and Postbuckling Behavior of Composite Laminated Shell Structures

--------Special issue
Computers & Structures, Vol. 84, Nos. 19-20, July 2006, Special Issue: Computational Models for Multilayered Structures and Composite Structures

--------Special issue
Computers & Structures, Vol. 44, No. 4, August 1992: Computational Structures Technology

--------Special issue on buckling strength of imperfection-sensitive shells:
Thin-Walled Structures, Vol. 23, Nos. 1-4, 1995, Special Issue: Buckling Strength of Imperfection-sensitive Shells

--------Special issue on stability and vibration of thin-walled structures:
International Journal of Non-Linear Mechanics, Vol. 37, Nos 4-5, June 2002, Special Issue: Stability & Vibration in Thin-Walled Structures

--------Special Issue
--- Special Issue
Honouring Jack Vinson on his 75th Birthday

--- Special issue on computational methods for shells:
Computer Methods in Applied Mechanics and Engineering, Vol. 194, Nos. 21-24, June 2005, Special Issue:
Computational Methods for Shells

--- Special issue on marine composites and sandwich structures:
Composites Part B: Engineering, Vol. 39, No. 1, January 2008, special issue:
Marine Composites and Sandwich Structures

--- Special issue on thick composites:
Composites Part B: Engineering, Vol. 27, No. 6, 1996, Special Issue on Thick Composites

--- Special issue on stability of composite structures

--- Special issue on Domain Decomposition Methods
Computer Methods in Applied Mechanics and Engineering, Vol. 196, No. 8, January 2007, Special Issue:
Domain Decomposition Methods: recent advances and new challenges in engineering

--- Special issue on steel structures
Journal of Constructional Steel Research, Vol. 64, Nos. 7-8, July-August 2008, Special Issue: International
Colloquium on Stability and Ductility of Steel Structures 2006

--- Special issue on coupled instabilities in metal structures
Thin-Walled Structures, Vol. 48, Nos. 10-11, October-November 2010, Special Issue: Coupled Instabilities in
Metal Structures CIMS 2008

--- Special issue on nonlinear dynamics
Computers & Structures, Vol. 82, Nos. 31-32, December 2004, Special Issue: Nonlinear Dynamics of
Continuous Systems

End of Special Issues of Journals on a Given Theme
End of Section 5

Section 6: Books on shell buckling or on subjects related in some way to shell buckling. These are listed in no particular order, just as I encountered them in my “shell buckling” GOOGLE search.

(See the “Book Cover Gallery” on the “Bibliography” page of the “shellbuckling.com” website for images of the book covers and for summaries of many of these and many other books related to the buckling of shells.)
---Book

---Book

---Book

ABSTRACT: The best available guide to the elastic stability of large structures, this volume was co-authored by world-renowned authorities on engineering mechanics. It ranges from theoretical explanations of 2- and 3-D stress and strain to practical applications such as torsion, bending, thermal stress, and wave propagation through solids. Equally valuable as text or reference. 1961 edition.

---Book
**On the stability of elastic equilibrium** by Warner Tjardus Koiter, National Aeronautics and Space Administration, 1967, 202 pages

---Book
**W.T. Koiter's elastic stability of solids & structures**, by Heijden Arnold van der, Hutchinson John, Achenbach Jan, October 2008, (publisher not given), Lavoisier Librarie, 216 pages

ABSTRACT: This book deals with the elastic stability of solids and structures, on which Warner Koiter was the world's leading expert. It begins with fundamental aspects of stability, relating the basic notions of dynamic stability to more traditional quasi-static approaches. The book is concerned not only with buckling, or linear instability, but most importantly with nonlinear post-buckling behavior and imperfection-sensitivity. After laying out the general theory, Koiter applies the theory to a number of applications, with a chapter devoted to each. These include a variety of beam, plate, and shell structural problems and some basic continuum elasticity problems. Koiter's classic results on the nonlinear buckling and imperfection-sensitivity of cylindrical and spherical shells are included. The treatments of both the fundamental aspects and the applications are completely self-contained. This book was recorded as a detailed set of notes by Arnold van der Heijden from W. T. Koiter's last set of lectures on stability theory, at TU Delft. Only book published based on Koiter's lectures. It deals with the elastic stability of solids and structures, the subject for which Koiter was the world's leading expert. He created much of field covered in this book. Includes coverage of nonlinear post-buckling behavior and imperfection-sensitivity, for which Koiter is most famous. Theory is applied to numerous applications.

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Book
Library of Congress Catalog Card Number: 67-17471, 1967

Selected references listed under some of the papers in the book:
Salmon, E.H., Columns, H. Frowde, London, 1921 (376 references)
Mönch, E., “Photoelastic Investigation of shells by means of a model in whose middle surface a semi-transparent mirror layer is embedded”, IX Congres International de Mécanique Appliquée, Bruxelles, Tome VIII, 1957, pp. 384-394
Card, M.F., “Preliminary results of compression tests on cylinders with eccentric longitudinal stiffeners”, NASA TM X-1004, 1964

-----Book
SUMMARY: This highly regarded hardcover engineering manual is mainly concerned with three important aspects of elasticity theory: finite elastic deformations, complex variable methods for two-dimensional problems for both isotropic and aeolotropic bodies, and shell theory. Also discussed are three-dimensional problems for isotropic and transversely isotropic bodies. Chapter 1, devoted to mathematical preliminaries, includes a summary of tensors for workers unfamiliar with those notations. Subsequent chapters deal with the general theory of elasticity for finite deformations, solutions of a number of special problems, mostly for incompressible isotropic bodies, a theory of small deformations superposed on finite deformations, classical infinitesimal theory of elasticity, the theory of plane strain, plate theory, plane problems for isotropic bodies, and for aeolotropic bodies. The last chapters, 10-16, are devoted to the theory of shells. For this second edition, the authors added material on thermodynamics, as well as a new chapter dealing with methods of deriving membrane theory, inextensional theory, and bending theory, by asymptotic expansions of the three-dimensional linear elastic equations. Unabridged Dover republication of the second edition published by Oxford University Press, 1968.

-----Book

-----Book
Buckling of bars, plates, and shells, by Don Orr Brush, Bo O. Almroth, McGraw-Hill, 1975, 379 pages

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Description:
We experience elasticity everywhere in daily life: in the straightening or curling of hairs, the irreversible deformations of car bodies after a crash, or the bouncing of elastic balls in ping-pong or soccer. The theory of elasticity is essential to the recent developments of applied and fundamental science, such as the bio-mechanics of DNA filaments and other macro-molecules, and the animation of virtual characters in computer graphics and materials science. In this book, the emphasis is on the elasticity of thin bodies (plates, shells, rods) in connection with geometry. It covers such topics as the mechanics of hairs (curled and straight), the buckling instabilities of stressed plates, including folds and conical points appearing at larger stresses, the geometric rigidity of elastic shells, and the delamination of thin compressed films. It applies general methods of classical analysis, including advanced nonlinear aspects (bifurcation theory, boundary layer analysis), to derive detailed, fully explicit solutions to specific problems. These theoretical concepts are discussed in connection with experiments. The book is self-contained. Mathematical prerequisites are vector analysis and differential equations. The book can serve as a concrete introduction to nonlinear methods in analysis.

--Book

--Book

--Book
The main properties that make carbon nanotubes (CNTs) a promising technology for many future applications are: extremely high strength, low mass density, linear elastic behavior, almost perfect geometrical structure, and nanometer scale structure. Also, CNTs can conduct electricity better than copper and transmit heat better than diamonds. Therefore, they are bound to find a wide, and possibly revolutionary use in all fields of engineering. The interest in CNTs and their potential use in a wide range of commercial applications; such as nanoelectronics, quantum wire interconnects, field emission devices, composites, chemical sensors, biosensors, detectors, etc.; have rapidly increased in the last two decades. However, the performance of any CNT-based nanostructure is dependent on the mechanical properties of constituent CNTs. Therefore, it is crucial to know the mechanical behavior of individual CNTs such as their vibration frequencies, buckling loads, and deformations under different loadings. This title is dedicated to the vibration, buckling and impact behavior of CNTs, along with theory for carbon nanosensors, like the Bubnov-Galerkin and the Petrov-Galerkin methods, the Bresse-Timoshenko and the Donnell shell theory.

Contents

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Selected works in applied mechanics and mathematics, by Eric Reissner, 1996, Jones and Bartlett Publishers, ISBN?

--------Book
The algebraic eigenvalue problem, J.H. Wilkinson, Oxford University Press, 1988

--------Book

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I. Senjanovic, Theory of shells of revolution, Brodarski Institut, Zagreb, Yugoslavia
Book

Book

Book

Book
*Sandwich construction: the bending and buckling of sandwich beams, plates, and shells*, Frederik Johan Plantema, Wiley, 1966

Book
*Analysis and design of structural sandwich panels*, Howard G. Allen, Pergamon Press, 1969

Book

Book

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This book provides an in-depth treatment of the study of the stability of engineering structures. Contributions from internationally recognized leaders in the field ensure a wide coverage of engineering disciplines in which structural stability is of importance, in particular the analytical and numerical modelling of structural stability applied to aeronautical, civil, marine and offshore structures. The results from a number of comprehensive experimental test programs are also presented, thus enhancing our understanding of stability phenomena as well as validating the analytical and computational solution schemes presented. A variety of structural materials are investigated with special emphasis on carbon-fibre composites, which are being increasingly utilized in weight-critical structures. Instabilities at the meso- and micro-scales are also discussed. This book will be particularly relevant to professional engineers, graduate students and researchers interested in structural stability.

CONTENTS: Experimental Studies of Stiffened Composite Panels under Axial Compression, Torsion and Combined Loading (H Abramovich); Buckling and Postbuckling Tests on Stiffened Composite Panels and Shells (C Bisagni); Mode-Jumping in Postbuckling Stiffened Composite Panels (B G Falzon); The Development of Shell Buckling Design Criteria Based on Initial Imperfection Signatures (M W Hilburger); Stability Design of Stiffened Composite Panels Simulation and Experimental Validation (A Kling); Anisotropic Elastic Tailoring in Laminated Composite Plates and Shells (P M Weaver); Optimization of Stiffened Panels using Finite Strip Models (R Butler & W Liu); Stability of Tubes and Pipelines (H A Rasheed & S A Karamanos); Imperfection-Sensitive Buckling and Postbuckling of Spherical Shell Caps (S Yamada & M Uchiyama); Nonlinear Buckling in Sandwich Struts: Mode Interaction and Localization (M A Wadee); The Boundary Element Method for Buckling and Postbuckling Analysis of Plates and Shells (M H Aliabadi & P M Baiz); Progressive Failure in Compressively Loaded Composite Laminated Panels: Analytical, Experimental and Numerical Studies (S Basu et al.); Micro- and Meso-Instabilities in Structured Materials and Sandwich Structures (T Daxner et al.).

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Honeycomb technology: materials, design, manufacturing, applications and testing, Tom Blitzer, Springer, 1997

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Sandwich panel construction: construction with factory engineered sandwich panels consisting of metallic facings and a foamed polyurethane core, Rolf Koschade, Institute fur sandwichtechnik, 2006

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Buckling strength of metal structures, by Friedrich Bleich, McGraw-Hill, 1952, 508 pages
Thin elastic shells: an introduction to the theoretical foundations and the analysis of their static and dynamic behavior, Harry Kraus, Wiley, 1967


Small elastic deformations of thin shells, Paul Seide, Noordhoff International Pub., 1975

Finite elements for thin shells and curved members, Derek George Ashwell and Richard H. Gallagher, Wiley, 1976


**Buckling and post-buckling**: four lectures in experimental, numerical, and theoretical solid mechanics based on talks given at the CISM-meeting, held in Udine, Italy, September 29-October 3, 1985 by Johann Arbocz, M. Potier-Ferry, J. Singer and V. Tvergaard, in Lecture Notes in Physics Series, Springer-Verlag, 1987 - Science - 246 pages

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**Mechanics of composite materials** by Robert Millard Jones, Taylor & Francis, 1999, 519 pages

ABSTRACT: This book balances introduction to the basic concepts of the mechanical behavior of composite materials and laminated composite structures. It covers topics from micromechanics and macromechanics to lamination theory and plate bending, buckling, and vibration, clarifying the physical significance of composite materials. In addition to the materials covered in the first edition, this book includes more theory-experiment comparisons and updated information on the design of composite materials.

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ABSTRACT: A greater use of composite materials in many areas of engineering has led to a greater demand for engineers versed in the design of structures made from such materials. This text offers students and engineers tools for designing practical composite structures. Among the topics of interest to the designer are stress-strain relationships for a wide range of anisotropic materials; bending, buckling, and vibration of plates; bending, torsion, buckling, and vibration of solid as well as thin-walled beams; shells; hygrothermal stresses and strains; finite element formulation; and failure criteria. More than 300 illustrations, 50 fully worked problems, and material properties data sets are included.

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ABSTRACT: This book compiles techniques used to analyze composite structural elements ranging from beams through plates to stiffened shells. The content is suitable for graduate-level students with a basic background in mechanics of composite materials. Moreover, this book will be placed in an active spot on the bookshelves of composite structures designers as well as researchers.

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PARTIAL PREFACE: As composite materials are used more extensively, a constant source of concern is the effect of foreign objects impacts. Such impacts can reasonably be expected during the life of the structure and can result in internal damage that is often difficult to detect and can cause severe reductions in the strength and stability of the structure. This concern provided the motivation for intense research resulting in hundreds of journal and conference articles. Important advances have been made, and many aspects of the problem have been investigated. One would need to study a voluminous literature in order to get an appreciation for this new research area. After writing three comprehensive literature reviews on the topic of impact on composite materials, I felt that there was a need to present this material in book form. The study of impact on composite
structures involves many different topics, including contact mechanics, structural dynamics strength, stability, fatigue, damage mechanics and micromechanics…. 

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DESCRIPTION: Buckling of structural elements has intrigued students for nearly three centuries. First, Euler studied bar buckling in the mid-18th century. Then, Bryan treated plate buckling in the late 19th century. Finally, shell buckling was a 20th-century pursuit of Timoshenko, Donnell, Flügge, and von Kármán, among many other notables. This graduate text and reference work is aimed at those involved in mechanical, civil, aerospace, and ocean engineering, as well as engineering mechanics. Fundamental buckling behavior is studied for three basic structural elements: one-dimensional bars, two-dimensional plates, and three-dimensional shells. The approach features a consistent energy-based formulation after Langhaar. The final topic in each of the chapters on bars, plates, and shells is an introduction to the essence of design for each structural element. Author Robert M. Jones, an ASME Fellow, is Professor Emeritus of Engineering Science and Mechanics
Similar books:
http://books.google.com/books?id=CXn7w0C8Te4C&dq=shell+buckling&source=gbs_similarbooks_s&cad=1

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Hui-Shen Shen, **Functionally Graded Materials: Nonlinear Analysis of Plates and Shells**, CRC Press, Jan 15, 2009, 280 pages
DESCRIPTION: Initially designed as thermal barrier materials for aerospace applications and fusion reactors, functionally graded materials (FGMs) are now widely employed as structural components in extremely high-temperature environments. However, little information is commonly available that would allow engineers to predict the response of FGM plates and shells subjected to thermal and mechanical loads. Functionally Graded Materials: Nonlinear Analysis of Plates and Shells is the first book devoted to the geometrically nonlinear response of inhomogeneous isotropic and functionally graded plates and shells. Concerned that the high loads common to many structures may result in nonlinear load–deflection relationships due to large deformations, author Hui-Shen Shen has been conducting investigations since 2001, paying particular attention to the nonlinear response of these plates and shells to nonlinear bending, postbuckling and nonlinear vibration. Nearly all the solutions presented are the results of investigations conducted by the author and his collaborators. The rigor of these investigative procedures allows the results presented within these pages to stand as a benchmark against which the validity and accuracy of other numerical solutions may be measured

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Description: As the theories and methods have evolved over the years, the mechanics of solid bodies has become unduly fragmented. Most books focus on specific aspects, such as the theories of elasticity or plasticity, the theories of shells, or the mechanics of materials. While a narrow focus serves immediate purposes, much is achieved by establishing the common foundations and providing a unified perspective of the discipline as a whole. Mechanics of Solids and Shells accomplishes these objectives. By emphasizing the underlying assumptions and the approximations that lead to the mathematical formulations, it offers a practical, unified presentation of the foundations of the mechanics of solids, the behavior of deformable bodies and thin shells, and the properties of finite elements. The initial chapters present the fundamental kinematics, dynamics, energetics, and behavior of materials that build the foundation for all of the subsequent developments. These are presented in full generality without the usual restrictions on the deformation. The general principles of work and energy form the basis for the consistent theories of shells and the approximations by finite elements. The final chapter views the latter as a means of approximation and builds a bridge between the mechanics of the continuum and the discrete assembly. Expressly written for engineers, Mechanics of Solids and Shells forms a reliable source for the tools of analysis and approximation. Its constructive presentation clearly reveals the origins, assumptions, and limitations of the methods described and provides a firm, practical basis for the use of those methods.


Partial Preface to the Second Edition:
During the nine years since the publication of the first edition of this book, there has been substantial progress on the treatment of well-set problems of nonlinear solid mechanics. The main purposes of this second edition are to update the first edition by giving a coherent account of some of the new developments, to correct errors, and to refine the exposition. Much of the text has been rewritten, reorganized, and extended. The philosophy underlying my approach is exactly that given in the following (slightly modified) Preface to the First Edition. In particular, I continue to adhere to my policy of eschewing discussions relying on technical aspects of theories of nonlinear partial differential equations (although I give extensive references to pertinent work employing such methods). Thus I intend that this edition, like the first, be accessible to a wide circle of readers having the traditional prerequisites given in Sec. 1.2.
I welcome corrections and comments. In due time, corrections will be placed on my web page: [http://www.ipst.umd.edu/Faculty/antman.htm](http://www.ipst.umd.edu/Faculty/antman.htm).

Partial Preface to the First Edition:
The scientists of the seventeenth and eighteenth centuries, led by Jas. Bernoulli and Euler, created a coherent theory of the mechanics of strings and rods undergoing planar deformations. They introduced the basic concepts of strain, both extensional and flexural, of contact force with its components of tension and shear force, and of contact couple. They extended Newton’s Law of Motion for a mass point to a law valid for any deformable
body. Euler formulated its independent and much subtler complement, the Angular Momentum Principle. (Euler also gave effective variational characterizations of the governing equations.) These scientists breathed life into the theory by proposing, formulating, and solving the problems of the suspension bridge, the catenary, the velaria, the elastica, and the small transverse vibrations of an elastic string. (The level of difficulty of some of these problems is such that even today their descriptions are seldom vouchsafed to undergraduates. The realization that such profound and beautiful results could be deduced by mathematical reasoning from fundamental physical principles furnished a significant contribution to the intellectual climate of the Age of Reason.) At first, those who solved these problems did not distinguish between linear and nonlinear equations, and so were not intimidated by the latter.

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*An introduction to the elastic stability of structures* by George J. Simitses, Prentice-Hall, 1976, 253 pages

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ABSTRACT: The ability of a structural assembly to carry loads and forces determines how stable it will be over time. Viewing structural assemblages as comprising columns, beams, arches, rings, and plates, this book will introduce the student to both a classical and advanced understanding of the mechanical behavior of such structural systems under load and how modeling the resulting strains can predict the overall future performance the stability of that structure. While covering traditional beam theory, the book is more focused on elastic theory in keeping with modern approaches. This text will be an expanded and updated version a similar, previously published book, but with pedagogical improvements and updated analytical methods. This engineering textbook will provide a focused treatment on the study of how structures behave and perform when under stress loading, including plastic deformation and buckling. All advanced engineering students studying engineering mechanics, structural analysis and design, fatigue and failure, and other related subjects need to have this knowledge, and this book will provide it in a thorough and coherent fashion. Written by two of the world's leading engineering professors in this subject area, the pedagogy has been classroom-tested over many years and should find a receptive readership among both students and instructors. An understandable introduction to the theory of structural stability, useful for a wide variety of engineering disciplines, including mechanical, civil and aerospace engineering Covers both static and dynamic loads, for both conservative and nonconservative systems. Emphasizes elastic behavior under loads, including vertical buckling, torsional buckling and nonlinear affects of structural system buckling and stability Case examples to illustrate real-world applications of Stability Theory.
Theory of elastic stability: analysis and sensitivity by Luis Augusto Godoy, Taylor & Francis, 2000, 434 pages
ABSTRACT: This book gives a unified presentation of the field of stability. Buckling and post-buckling states are studied on the basis of total potential energy of structural systems. Emphasis is placed throughout the text on post-buckling analysis and behaviour. The sensitivity of buckling and post-buckling states to changes in design parameters is also discussed as well as changes due to imperfections and damage.

Thin-walled structures with structural imperfections: analysis and behavior, by Luis Augusto Godoy, 1996, Pergamon (indicated on cover) or Elsevier Science Ltd (indicated inside), ISBN 0-08-042266-7


ABSTRACT: Rapid advances in analytical methods and computing enable engineers to apply stability/stiffness methods to increasingly complex real-life cases. This advanced and graduate-level text and self-tutorial teaches readers to understand and to apply analytical design principles across the breadth of the engineering sciences. Emphasizing fundamentals, the book addresses the stability of key engineering elements such as rigid-body assemblage, beam-columns, rigid frames, thin plates, arches, rings, or shells. Each chapter contains numerous worked-out problems that clarify practical application and aid comprehension of the basics of stability theory, plus end-of-chapter review exercises. Others key features are the citing and comparison of different national building standards, use of non-dimensional parameters, and many tables with much practical data and simplified formula, that enable readers to use them in the design of structural components.
---Book

**Stability of elastic structures** edited by Nikolai Anatolevich Alfutov, Springer, 2000, 337 pages

ABSTRACT: The subject discussed in this book is the stability of thin-walled elastic systems under static loads. The presentation of these problems is based on modern approaches to elastic-stability theory. Special attention is paid to the formulation of elastic-stability criteria, to the statement of column, plate and shell stability problems, to the derivation of basic relationships, and to a discussion of the boundaries of the application of analytic relationships. The author has tried to avoid arcane, nonstandard problems and elaborate and unexpected solutions, which bring real pleasure to connoisseurs, but confuse students and cause bewilderment to some practical engineers. The author has an apprehension that problems which, though interesting, are limited in application can divert the reader's attention from the more prosaic but no less sophisticated general problems of stability theory.

---Book


ABSTRACT: The up-to-date edition of the classic guide--from leading experts in structural stability theory and research. First published in 1960, the Guide to Stability Design Criteria for Metal Structures is the reference of choice for civil and structural engineers seeking reliable, in-depth coverage of stability problems and research. This extensively revised Fifth Edition bridges theory and practice to offer simplified and refined procedures both for design and for the assessment of design limitations, as well as detailed guidance on design specifications, codes, and standards concerning the stability of metal structures. Written by members of Structural Stability Research Council task groups and other specialists, all material has been updated to reflect recent developments in each subject area. The Fifth Edition features eight new chapters covering the latest procedures in horizontal curved steel I-girders, composite columns and structural systems, stability of angle members, bracing, frame stability, doubly curved shells and shell-like structures, stability under seismic loading, and stability analysis by the finite element method. Complete with over 100 new illustrations, plus references, technical memoranda, and name and subject indexes, the Guide to Stability Design Criteria for Metal Structures, Fifth Edition is ready to go to work for a new generation of structural and civil engineers in their daily practice.

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**Theory of stability of continuous elastic structures** by Mario Como and Antonio Grimaldi, CRC Press, 1995, 247 pages

---Book
**Structural stability in engineering practice** by Lajos Kollár, Taylor & Francis, 1999, 454 pages
ABSTRACT: Stability is an essential requisite in the design and manufacture of all structures, and engineers need a good understanding of critical loading factors in structure design. This book illustrates the various problems associated with attaining stability, and provides the results for practical use by the design engineer.

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---Book
Troisky MS. *Stiffened Plates, Bending, Stability and Vibrations*. Elsevier, 1976

---Book
**Background to buckling** by Howard G. Allen and P. S. Bulson, McGraw-Hill Book Co., 1980, 582 pages

---Book
**Elastic Stability of Circular Cylindrical Shells** by N. Yamaki, North-Holland, Amsterdam, 1984

---Book

---Book
**Thin plates and shells: theory, analysis, and applications** by Eduard Ventsel, Theodor Krauthammer, CRC Press, 2001, 666 pages
ABSTRACT: Presenting recent principles of thin plate and shell theories, this book emphasizes novel analytical and numerical methods for solving linear and nonlinear plate and shell dilemmas, new theories for the design and analysis of thin plate-shell structures, and real-world numerical solutions, mechanics, and plate and shell models for engineering applications. It includes computer processes for finite difference, finite element, boundary element, and boundary collocation methods as well as other variational and numerical methods. It also contains end-of-chapter examples and problem/solution sets, a catalog of solutions for cylindrical and spherical shells, and tables of the most commonly used plates and shells.

---Long Paper
**Buckling and postbuckling of composite structures** by Ahmed Khairy Noor, presented at 1994 International Mechanical Engineering Congress and Exposition, Chicago, Illinois, November 6-11, 1994, Pressure Vessels and Piping Division, American Society of Mechanical Engineers, 1994, 133 pages

---Book
**Shell Stability Handbook**
Author: Lars A. Samuelson, Sigge Eggwertz
SUMMARY: The Shell Stability Handbook is a handbook for calculation of the carrying capacity of shell structures with respect to buckling. The aim has been to develop a branch independent handbook which gives conservative estimates of the carrying capacity. The safety factors which should be used in a certain case must be taken from the applicable code for the considered structure, e.g. pressure vessel codes, steel structure codes etc. Initiator behind the handbook is Professor Lars A. Samuelson who already in the seventies during his time at the Aeronautical Research Institute of Sweden felt a strong need for such a handbook. The development of the handbook, which also included substantial research in the field of shell stability, started in 1982. The first Swedish edition was published in 1990.

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Book
ABSTRACT: Stop searching through the endless amount of literature to find the most recent information on plate buckling. The authors of Handbook of Thin Plate Buckling and Post Buckling have already done the work for you. Detailed and clearly written, the book contains a comprehensive, up-to-date treatment of the buckling and postbuckling behavior of perfect and imperfect thin plates. The authors study, in detail and with specific solved examples, the essential factors that influence critical buckling loads, initial mode shapes, and postbuckling behavior for thin plates. Through their analysis of rectangular, circular, and annular plates, they present valuable information, some of which has never before been published in book form. Such topics include hygrothermal buckling, viscoelastic and plastic buckling, and buckling of various thickness plates. With this important collection, the Handbook of Thin Plate Buckling and Post Buckling provides you with a one-stop source of current research findings.

Book
ABSTRACT: Contributed by leading authorities in the field from around the world, this text provides a comprehensive insight into buckling and postbuckling. Basic theory, methods of buckling analysis and their application, the effect of external variables such as temperature and humidity on the buckling response and buckling tests are all covered.

Book

Book
Introduction to composite materials, by Stephen W. Tsai and H. Thomas Hahn, CRC Press, 1980, 457 pages, COMMENTS: A widely used basic text by two recognized authorities. A unified and disciplined approach; advanced concepts reduced to easy-to-use charts, formulas and numerical examples.
Composites Design, by Stephen W. Tsai, Think Composites, 1987, 512 pages

Theory of composites design, by Stephen W. Tsai, Think Composites, 1992, 225 pages

Hull, D., An Introduction to Composite Materials, Cambridge University Press (year not given)

McCullough, R.L., Concept of Fiber-Resin Composites, Marcel Dekker, Inc., NY, 1971


ABSTRACT: A major basic text on the theory and structural applications of laminated anisotropic plates. Detailed coverage of problems of bending under transverse load, stability, and free-vibrations, as well as laminated beams, expansional strain effects, curved plates, and free-edge effects.

FOREWORD: …provides users with basic knowledge about the design and analysis of composite materials and structures. The six-volume indexed set is an ongoing series to which new volumes will be added as new needs arise and new knowledge is gained about this rapidly growing field of composites…
Volume 1 – Mechanical behavior and properties of composite materials
Volume 2 – Micromechanical materials modeling
Volume 3 – Processing and fabrication technology
Volume 4 – Failure analysis of composite materials
Volume 5 – Design studies
Volume 6 – Test methods
Index to Volumes 1-6

ABSTRACT: Composite materials are increasingly used in aerospace, underwater, and automotive structures. They provide unique advantages over their metallic counterparts, but also create complex challenges to analysts and designers. Practical Analysis of Composite Laminates presents a summary of the equations governing composite laminates and provides practical methods for analyzing most common types of composite structural elements. Experimental results for several types of structures are included, and theoretical and experimental correlations are discussed. The last chapter is devoted to practical analysis using Designing Advanced Composites (DAC), a PC-based software on the subject. This comprehensive text can be used for a graduate course in mechanical engineering, and as a valuable reference for professionals in the field.

SUMMARY: A systematic presentation of energy principles and variational methods. The increasing use of numerical and computational methods in engineering and applied sciences has shed new light on the importance of energy principles and variational methods. Energy Principles and Variational Methods in Applied Mechanics provides a systematic and practical introduction to the use of energy principles, traditional variational methods, and the finite element method to the solution of engineering problems involving bars, beams, torsion, plane elasticity, and plates. Beginning with a review of the basic equations of mechanics and the concepts of work, energy, and topics from variational calculus, this book presents the virtual work and energy principles, energy methods of solid and structural mechanics, Hamilton's principle for dynamical systems, and classical variational methods of approximation. A unified approach, more general than that found in most solid mechanics books, is used to introduce the finite element method. Also discussed are applications to beams and plates. Complete with more than 200 illustrations and tables, Energy Principles and Variational Methods in Applied Mechanics, Second Edition is a valuable book for students of aerospace, civil, mechanical, and applied mechanics; and engineers in design and analysis groups in the aircraft, automobile, and civil engineering structures, as well as shipbuilding industries.


**--------Book**


SUMMARY: Offering a thorough treatment of both contemporary design optimization techniques and the mechanics of composite laminates, Design and Optimization of Laminated Composite Materials broadens engineers' design horizons by providing them with the information they need to take full advantage of this important class of composite materials. Intended to serve as an undergraduate- to graduate-level course text or a professional reference for practicing engineers, it features a rational, integrated presentation, supplemented with case examples, practice exercises, and valuable programming tips. Important features include:
* An integrated approach to the analysis and design of laminated composites
* Selected optimization methods that are suited to the design of laminates with discrete thickness and orientation angles
* Guidelines on getting the most out of numerical and graphical software applications for laminate optimization problems
* A companion Web site containing valuable Mathematica(TM)-based programs and helpful tutorials: www.composite-design.vt.edu

**--------Book**


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SUMMARY: A compact presentation of the foundations, current state of the art, recent developments and research directions of all essential techniques related to the mechanics of composite materials and structures. Special emphasis is placed on classic and recently developed theories of composite laminated beams, plates and shells, micromechanics, impact and damage analysis, mechanics of textile structural composites, high strain rate testing and non-destructive testing of composite materials and structures. Topics of growing importance are addressed, such as: numerical methods and optimisation, identification and damage monitoring. The latest results are presented on the art of modelling smart composites, optimal design with advanced materials, and industrial applications. Each section of the book is written by internationally recognised experts who have dedicated most of their research work to a particular field. Readership: Postgraduate students, researchers and engineers in the field of composites. Undergraduate students will benefit from the treatment of the foundations of the mechanics of composite materials and structures.

**--------Book**

**Composite materials: design and applications**, by Daniel Gay, CRC Press, 2003, 531 pages

COMMENTS: Composite Materials: Design and Applications is an updated translation of the French book Materiaux Composites. It is a comprehensive, well-illustrated reference and text on composite materials and structures. The illustrations are uniquely clear and standardized throughout. This practical book addresses difficult design issues such as sandwich plates, bonded joints, and other details of design. It is a welcome

ABSTRACT: The use of composite materials in engineering structures continues to increase dramatically, and in the seven years since the first edition of this book appeared, advances in materials modeling in general and composite materials and structures in particular have been just as significant. To reflect these developments, renowned author, educator, and researcher J.N. Reddy has thoroughly revised, updated, and enhanced his standard-setting Mechanics of Laminated Composite Plates and Shells: Theory and Analysis. New in the Second Edition: A new chapter dedicated to the theory and analysis of laminated shells. New discussions addressing smart structures and functionally graded materials. Thorough updates to all chapters and a reorganization of chapters that improves the clarity of the presentation. Additional exercises and examples. No other book is as up to date. No other book approaches the subject primarily from the finite element method. And no other book provides such full, self-contained coverage of the theories, analytical solutions, and linear and nonlinear finite element models of plate and shell laminated composite structures.


Mechanics of laminated composite plates and shells, J.N. Reddy, 2004 (pdf from tamu.edu)


ABSTRACT: The calculation of buckling loads is key in designing structural elements and often hinges on numerical methods. However, analytical solutions can serve as critical cross-references that help assess the reliability and accuracy of numerical solutions. The quest for access to closed form analytical solutions that elucidate the intrinsic fundamental and unexpected features of numerical solutions drove the creation of Exact Solutions for Buckling of Structural Members. In researching this book, the authors gathered as many exact buckling solutions as possible, and have presented them in a concise treatment. This book condenses closed form buckling solutions of columns, beams, arches, rings, plates and shells from the vast literature into a single volume. It begins with an introduction to elastic buckling and the importance of elastic buckling load. The following chapters present coverage of flexural buckling solutions for columns under various loads, restraints, and boundary conditions; the exact flexural-torsional buckling solutions of beams; and the buckling solutions of circular arches and rings. Also included in these chapters are discussions of the effect of transverse shear
deformation on the buckling load of columns and the flexural-torsional buckling of columns for thin-walled members with open profiles. The final chapters discuss the elastic buckling of plates under inplane loads and buckling solutions for cylindrical and spherical shells. With coverage of a wide range of buckling load problems, this innovative reference provides engineers and researchers benchmarks for assessing the validity, convergence, and accuracy of solutions obtained by numerical methods.

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**Book**

**Flexural-torsional buckling of structures** by N. S. Trahair, CRC Press, 1993, 360 pages

ABSTRACT: Flexural-Torsional Buckling of Structures provides an up-to-date, comprehensive treatment of flexural-torsional buckling and demonstrates how to design against this mode of failure. The author first explains the fundamentals of this type of buckling behavior and then summarizes results that will be of use to designers and researchers in either equation or graphical form. This approach makes the book an ideal text/reference for students in structural engineering as well as for practicing civil engineers, structural engineers, and constructional steel researchers and designers. The book begins by introducing the modern development of the theory of flexural-torsional buckling through discussions on the general concepts of equilibrium, total potential, virtual work, and buckling. It then continues with in-depth coverage of hand methods for solving buckling problems, the analysis of flexural-torsional buckling using the finite element method, and the buckling of different types of structural elements and frames composed of various elastic materials. Other topics addressed include the design and inelastic buckling of steel members. The book's final chapter considers a collection of special topics.

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**Book**


ABSTRACT: This series provides survey articles on the present state and future direction of research in important branches of applied mechanics.

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**Book**

Ramm E. **Buckling of Shells**. Springer-Verlag, Berlin 1982

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ABSTRACT: Shell structures are found abundantly in engineering designs and are routinely analysed with finite element methods. The objective of this book is to present, in a unified manner, modern finite element
procedures for general shell analysis. The first chapters introduce the basic concepts for the analysis of shells, explain the mathematical preliminaries, and discuss the mathematical models of plates and shells including their asymptotic properties. The following chapters deal with finite element discretization methods for plates and shells. At the end of the book, applications of these methods in modern engineering practice are described and an overview of nonlinear shell analysis is given.

--------Book
Bathe, K., 1996, **Finite Element Procedures**, Prentice-Hall, Englewood, New Jersey

ABSTRACT: Elastic shells are pervasive in everyday life. Examples of these thin-walled structures range from automobile hoods to basketballs, veins and arteries, and soft drink cans. This book explains shell theory, with numerous examples and applications. This second edition not only brings all the material of the first edition entirely up to date; it also adds two entirely new chapters on general shell theory and general membrane theory. Aerospace, mechanical, and civil engineers, as well as applied mathematicians, will find this book a clearly written and thorough information source on shell theory.

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http://ebooks.cambridge.org/chapter.jsf?bid=CBO9780511624278&cid=CBO9780511624278A141
**Theory of Shell Structures**, By C. R. Calladine Print Publication Year: 1983 Online Publication Date: February 2010
Introduction: In most of the chapters of this book we have assumed that the material from which a shell is constructed behaves under stress in a linear-elastic manner. The materials which are used in structural engineering generally have a linear-elastic range, but behave inelastically when a certain level of stress is exceeded. Moreover at sufficiently high temperatures irreversible creep may be the most significant phenomenon. It is obvious that there are some circumstances in which it is necessary for the designer to understand the behaviour of shells in the inelastic range. This subject is a large one, and in this chapter we shall give an introduction to part of it. The aim of the present chapter is to give a glimpse, mainly through a few specific examples, of the ways in which the structural analyst may tackle problems connected with inelastic behaviour of shells. In general our plan will be to set up the simplest problems which illustrate various important points. But first it is necessary to discuss some general questions in connection with the scope of plastic theory, and the circumstances in which it is valid.
SUMMARY: Shells are basic structural elements of modern technology. Examples of shell structures include automobile bodies, domes, water and oil tanks, pipelines, silos, ship hulls, aircraft fuselages, turbine blades, loudspeaker cones, but also balloons, parachutes, biological membranes, a human skin, a bottle of wine or a beer can. This volume contains full texts of over 100 papers presented by specialists from over 20 countries at the 8th Conference "Shell Structures: Theory and Applications", 12-14 October, 2005 in Jurata (Poland). The aim of the meeting was to bring together scientists, designers, engineers and other specialists in shell structures in order to discuss important results and new ideas in this field. The goal is to pursue more accurate theoretical models, to develop more powerful and versatile methods of analysis, and to disseminate expertise in design and maintenance of shell structures. Among the authors there are many distinguished specialists of shell structures, including the authors of general lectures: I.V. Andrianov (Ukraine), V.A. Eremeyev (Russia), A. Ibrahimbegovic (France), P. Klosowski (Poland), B.H. Kröplin (Germany), E. Ramm (Germany), J.M. Rotter (UK) and D. Steigmann (USA). The subject area of the papers covers various theoretical models and numerical analyses of strength, dynamics, stability, optimization etc. of different types of shell structures, their design and maintenance, as well as modelling of some surface-related mechanical phenomena.


SUMMARY: Shells are basic structural elements of modern technology and everyday life. Examples of shell structures in technology include automobile bodies, domes, water and oil tanks, pipelines, silos, ship hulls, aircraft fuselages, turbine blades and nanotubes. Loudspeaker cones, balloons, parachutes, biological membranes, a human skin, a bottle of wine, and a beer can are examples of shells in everyday life. Shell Structures. Theory and Applications, Volume 2 contains 77 contributions from over 17 countries, reflecting a wide spectrum of scientific and engineering problems of shell structures. The papers are divided into six broad groups: 1. General lectures 2. Theoretical modeling 3. Stability 4. Dynamics 5. Numerical analysis 6. Engineering design. Shell Structures. Theory and Applications, Volume 2 will be of interest to academics, researchers,
designers and engineers dealing with theoretical modelling, computerized analyses and engineering design of thin-walled structures and shell structural elements.

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http://www.waterstones.com/waterstonesweb/products/william+a-+little/reliability+of+shell+buckling+predictions/4694235/
**Reliability of Shell Buckling Predictions** - Research Monograph, by William A. Little, 1964

------ Book
**Thin Plates and Shells, Theory: Analysis, and Applications**
Eduard Ventsel and Theodor Krauthammer

------ Book
**Advances in the Mechanics of Plates and Shells: The Avinoam Libai Volume**

------ Book
**Shell structures in civil and mechanical engineering: theory and closed-form analytical solutions**, by Alphose Zingoni, Thomas Telford, 1997 - Technology & Engineering - 349 pages

------ Book

------ Book
Petr E. Tovstik and Andrei L. Smirnov (Department of Theoretical and Applied Mechanics of the Faculty of Mathematics and Mechanics, St. Petersburg State University, Russia), “**Asymptotic Methods in the Buckling Theory of Elastic Shells**” (360 pages, 2011 ebook), in Series on Stability Vibration and Control of Systems, Series A - Vol. 4
ABSTRACT: This book contains solutions to the most typical problems of thin elastic shells buckling under conservative loads. The linear problems of bifurcation of shell equilibrium are considered using a two-dimensional theory of the Kirchhoff–Love type. The explicit approximate formulas obtained by means of the asymptotic method permit one to estimate the critical loads and find the buckling modes. The solutions to some of the buckling problems are obtained for the first time in the form of explicit formulas. Special attention is
devoted to the study of the shells of negative Gaussian curvature, the buckling of which has some specific features. The buckling modes localized near the weakest lines or points on the neutral surface are constructed, including the buckling modes localized near the weakly supported shell edge. The relations between the buckling modes and bending of the neutral surface are analyzed. Some of the applied asymptotic methods are standard; the others are new and are used for the first time in this book to study thin shell buckling. The solutions obtained in the form of simple approximate formulas complement the numerical results, and permit one to clarify the physics of buckling.

TABLE OF CONTENTS:
Equations of Thin Elastic Shell Theory
Basic Equations of Shell Buckling
Simple Buckling Problems
Buckling Modes Localized near Parallels
Non-homogeneous Axial Compression of Cylindrical Shells
Buckling Modes Localized at a Point
Semi-momentless Buckling Modes
Effect of Boundary Conditions on Semi-momentless Modes
Torsion and Bending of Cylindrical and Conic Shells
Nearly Cylindrical and Conic Shells
Shells of Revolution of Negative Gaussian Curvature
Surface Bending and Shell Buckling
Buckling Modes Localized at an Edge
Shells of Revolution under General Stress State

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Buckling of thin metal shells, Edited by J. G. Teng, J. Michael Rotter, Spon Press, 11 New Fetter Lane, London EC4P 4EE, 2004 (520 pages)
DESCRIPTION: Thin-walled metal shell structures are highly efficient in their use of material, but they are particularly sensitive to failure by buckling. Many different forms of buckling can occur for different geometries and different loading conditions. Because this field of knowledge is both complex and industrially important, it is of great interest and concern in a wide range of industries. This book presents a compilation and synthesis of a wealth of research, experience and knowledge of the subject. Information that was previously
widely scattered throughout the literature is assembled in a concise and convenient form that is easy to understand, and state-of-the-art research findings are thoroughly examined. This book is useful for those involved in the structural design of silos, tanks, pipelines, biodigestors, chimneys, towers, offshore platforms, aircraft and spacecraft.

-----Book
**Buckling of Thin Metal Shells** by JM Rotter Kindle Book, 5 Star Review, 2010-05-13

http://repository.tudelft.nl/file/889580/377794

-----Book

ABSTRACT: The increasing use of composite materials requires a better understanding of the behavior of laminated plates and shells. Large displacements and rotations, as well as shear deformations, must be included in the analysis. Since linear theories of shells and plates are no longer adequate for the analysis and design of composite structures, more refined theories are now used for such structures. This text develops, in a systematic manner, the overall concepts of the nonlinear analysis of shell structures. The authors start with a survey of theories for the analysis of plates and shells with small deflections and then lead to the theory of shells undergoing large deflections and rotations applicable to elastic laminated anisotropic materials. Subsequent chapters are devoted to the finite element solutions and include test case comparisons. The book is intended for graduate engineering students and stress analysts in aerospace, civil, or mechanical engineering.

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PARTIAL ABSTRACT: This book originally appeared as a text prepared for the Defense Nuclear Agency to summarize research on dynamic pulse buckling by the authors and their colleagues at SRI International during the period from 1960 to 1980. The objective of the book was to gather into a cohesive whole material that had been published in reports and the open literature during the two-decade period. In the process of knitting this material together, a substantial amount of new work was done. The book therefore contains many new results never published in the open literature….

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**Shell structures in civil and mechanical engineering: theory and closed-form analytical solutions**, by Alphose Zingoni, Thomas Telford, 1997

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**Finite element software for plates and shells**, by Ernest Hinton, D. R. J. Owen, Pineridge Press, 1984
ABSTRACT OF CHAPTER 7, “PLASTIC BUCKLING”, by Jagabandhu Chakrabarty (pp. 479-559)

In a typical boundary value problem involving prescribed nominal traction rates on a part $S_F$ of the boundary surface, and prescribed velocities on the remainder $S_v$, more than one mode of deformation may be possible when the applied load reaches a critical value. The lack of uniqueness of the deformation mode under given boundary conditions is commonly referred to as bifurcation, the current shape and mechanical state of the body being supposed to be given or previously determined. For a linear solid, in which the strain rate is a unique linear function of the stress rate during both loading and unloading, a bifurcation mode corresponds to an eigensolution of the field equations and represents a mode quasi-statically possible under constant loads on $S_F$ and rigid constraints on $S_v$. In dealing with the conventional elastic/plastic solid, which is bilinear in the sense that the strain rate is related to the stress rate by separate linear functions for loading and unloading, it is convenient to introduce a linear comparison solid with identical boundary conditions (Section 1.5). While bifurcation in the linearized solid can occur under any given traction rates on $S_F$ and velocities on $S_v$ when the load becomes critical, bifurcation in the actual elastic/plastic solid would occur only under those traction rates for which there is no instantaneous unloading of the material that is currently plastic. The incremental theory of plasticity will be almost exclusively used in this chapter for the estimation of the critical load.
Basic Dynamic Analysis of Plates, Solids of Revolution and Finite Prism Type Structures Appendices The Evaluation of Certain Strain Terms Evaluation of the Radius of Curvature

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Static and dynamic analyses of plates and shells: theory, software and applications, by Hou-Cheng Huang, Springer-Verlag, 1989
ABSTRACT: This book illustrates the element technology of plates and shells and compares and contrasts the behaviour of current plate and shell elements for thick and thin shell theories as well as for static and transient dynamic analyses. It also highlights the locking phenomenon experienced by most of the currently available elements and introduces a strategy for avoiding this phenomenon. In addition, the book provides the necessary benchmark tests for plate and shell elements. The book will be useful for undergraduates since all fundamental theories are included. It should also be useful for structural engineers in order to understand shell stress analyses. They would be particularly interested in the shear forces in plate and shell structures where most elements are seen to produce poor results. For postgraduates and researchers in this field, the book will be most helpful. Many research workers have been studying shell element technology for two decades. Consequently, plate and shell element design is still an active area. Two associated programmes are provided with the book. One is for static analysis and the other for dynamic analysis. The programmes can be compiled and run on either a mini or a mainframe computer via a terminal.

-------Book

Theory And Design Of Plate And Shell Structures by Maan H. Jawad
Book Summary of Theory And Design Of Plate And Shell Structures
This is the first book to integrate the theory, design, and stability analysis of plates and shells in one comprehensive volume. With authoritative accounts of diverse aspects of plates and shells, this volume facilitates the study and design of structures that incorporate both plate and shell components. Drawing on his extensive experience in plate and shell theory and design, the author: --introduces the principles and applications of bending of plates; membrane theory and bending of shells; and stability of plates and shells; --explains the crucial elements of roof structure analysis and finite element formulations; --explores topics of current interest, such as plastic design of plates and approximate solution of membrane stress in shells of revolution and in buckling of shells; --describes how to select design approaches according to the functional and safety requirements of specific structures. Each chapter demonstrates the principles, practical applications, and design of a plate or shell component using real-life examples, providing the reader with an in-depth, unified understanding of the theory and function of the component. Chapters are written to be as independent of each other as possible to allow for selective reading on either plates or shells. In addition, the text is conveniently supplemented by appendices of Fourier Series and Bessel Functions. Integrating the fundamental and applied aspects of plate and shell theory, this volume serves as an essential text for graduate students and as an easy-to-use reference for engineers in mechanical, civil, and aeronautical engineering. Mann H. Jawad is Chief Engineer at the Nooter Corporation in St. Louis, Missouri

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DESCRIPTION: This exciting text is written primarily for professional engineers interested in designing plate and shell structures. It covers basic aspects of theories and gives examples for the design of components due to internal and external loads as well as other loads such as wind and dead loads. Various derivations are kept relatively simple and the resultant equations are simplified to a level where the engineer may apply them directly to design problems. More elaborate derivations and more general equations may be found in the literature for those interested in a more in-depth knowledge of the theories of plates and shells. 

COMPLETE CONTENTS
* Bending of simply supported rectangular plates
* Bending of various rectangular plates
* Bending of circular plates
* Plates of various shapes and properties
* Approximate analysis of plates
* Buckling of plates
* Vibration of plates
* Membrane theory of shells of revolution
* Various applications of the membrane theory
* Bending of thin cylindrical shells due to axisymmetric loads, Various structures
* Buckling of cylindrical shells
* Buckling of shells of revolution
* Vibration of shells
* Basic finite element equations.

-----Book

-----Book
An Introduction to Modelling Buckling and Collapse by B. G. Falzon & M. H. Hitchings
First Published - September 2006, Softback, 136 Pages
DESCRIPTION:
The term ‘collapse’ is often used to refer to the sudden loss of structural integrity and does not distinguish between the two major categories leading to structural failure: (a) material failure or (b) structural instability due to loss of structural stiffness within the elastic limit of the material. The term ‘buckling’ is often reserved specifically for the latter category. At an elementary level, predicting material failure may be accomplished using linear finite element analysis. The strains and corresponding stresses obtained from this analysis may be compared to design stress (or strain) allowables anywhere within the structure. If the finite element solution indicates regions where these allowables are exceeded, it is assumed that material failure has occurred. Design allowables are based on experimentally-derived material strengths and usually include a safety margin. This type of analysis will give an adequate prediction for statically determinate metallic structures undergoing small deformations.

If the structure is statically indeterminate, as indeed the majority of practical structures are, the analyst may want to assess the evolution of material failure. The load at which material failure initiates may be significantly lower than that which leads to eventual collapse. The analyst may also want to know the nature of this failure progression, that is, is it gradual or does it occur rapidly? Material failure may be the result of plasticity in
metallic structures or fracture, which is a more prevalent form of failure in brittle materials such as ceramics or carbon-fibre reinforced plastics. The structure may also undergo large deformations before or during material failure and it is therefore apparent that the presence of geometric and material non-linearities requires more sophisticated finite element solution schemes.

Buckling refers to the loss of stability of a structure and in its simplest form, is independent of material strength where it is assumed that this loss of stability occurs within the elastic range of the material. It is primarily characterised by a loss of structural stiffness and cannot be modelled using basic linear finite element analysis. Slender or thin-walled structures under compressive loading are susceptible to buckling. Buckling may also be stable or unstable and different geometries lead to different forms of buckling stability. A distinction is also made between classical buckling and other forms of structural instability. Without resorting to formal definitions and distinctions at this stage, one physical manifestation of these differences is that classical buckling results in the structure deforming primarily in a direction orthogonal to that of the applied loading causing this instability.

Another form of structural instability, termed snap buckling, is where the deformation is primarily in the direction of the applied loading.

Material failure and buckling may both occur in sequence leading to structural collapse. A thin-walled or slender structure may initially buckle elastically but the resulting high deformations may cause localised material failure. A thicker-walled or less slender structure under high compressive loading may exhibit localised inelastic behaviour, such as plasticity, which lowers the stiffness leading to buckling.

Scope
This book provides an introduction to the various mechanisms which may lead to structural buckling or collapse and the strategies employed in modelling this behaviour using finite element analysis. While the use of some jargon is unavoidable, every effort has been made to ensure that definitions are given when required, either within the text or as an entry in the Glossary at the end of this book. It is also the authors’ view that the introduction of mathematical equations is central to giving the analyst further insight into the suitability of the various numerical strategies available in most finite element systems. If the reader is particularly averse to the mathematical treatment given herein, he or she may skip over these and still obtain useful and practical information on modelling buckling and collapsing structures.

The development of new finite element methodologies and formulations, to model highly non-linear behaviour such as buckling and collapse, continues to advance at a rapid pace. The majority of the methodologies and modelling strategies presented in this book may be found in current commercial finite element packages. To give this book relevance beyond the immediate time, recent developments which are still at the research stage are also discussed. While these may not be available commercially at the time of writing, there is enough information given for the interested reader to implement these schemes in non-commercial (research) codes or, if possible, as user subroutines in commercial finite element packages.

Contents
1. Introduction
   1.1. Scope
   1.2. Readership
   1.3. Layout
2. A Brief Overview of Elastic Stability
   2.1. Introduction
   2.2. Stiffening Behaviour
   2.3. ‘Snap-Through’ Behaviour
   2.4. Classical Buckling
2.5. Stable Symmetric Buckling  
2.6. Unstable Symmetric Buckling  
2.7. Asymmetric Buckling  
3. Linear Buckling Analysis  
3.1. Introduction  
3.2. Linear Buckling Analysis  
3.3. Steps for a Finite Element Eigenvalue Analysis  
3.4. Methods for Finding Eigenvalues and Eigenvectors  
3.5. Example 3A – Linearised Plate Buckling  
3.6. Buckling Analysis for Pre-Loaded Structures  
3.7. Symmetry  
3.8. Example 3B – Using Symmetry for Isotropic Plate Buckling  
4. Geometric Non-Linear Analysis  
4.1. Introduction  
4.2. Non-Linear Analysis Formulation  
4.3. Newton-Raphson Methods  
4.4. Limitation of Newton-Raphson Schemes  
4.5. Direct Load Incrementation Scheme  
4.6. Energy dissipation scheme  
4.7. Arc-Length Methods  
4.8. Follower Force Loading  
4.9. Example 4A – Clamped Curved Beam with Central Point Load  
4.10. Example 4B – Postbuckling Stiffened Carbon-Fibre Composite Panels  
5. Dynamic Analysis for Solving Non-Linear Problems  
5.1. Introduction  
5.2. Dynamic Solution Methods for Non-Linear Problems  
5.3. Implicit Solution  
5.4. Explicit Solution  
5.5. Other Forms of Explicit/Implicit Solution Methods  
5.6. Choice of Solution Method  
5.7. Mass-Scaling  
5.8. Load Rate  
5.9. Extended Explicit Solution Method  
5.10. Combined Quasi-Static/Pseudo-Transient Method  
5.11. Example 5A – Clamped Curved Beam with Central Point Load Using Explicit Dynamic Analysis  
5.12. Example 5B – Postbuckling Response of a Cantilever Beam Using Explicit Dynamic Analysis  
5.13. Example 5C – Clamped Curved Beam with Central Point Load Using a Combined Quasi-Static/Pseudo-Transient Method  
5.15. Example 5E – Postbuckling of an I-Stiffened Panel Using Combined Quasi-Static/Pseudo-Transient Method  
5.16. Remarks  
6. Modelling Collapse Through Material Plasticity  
6.1. Introduction  
6.2. Basic Plasticity  
6.3. Limit Load Analysis (Plastic Collapse)
6.4. Application to Structural Collapse – Limit Load Analysis
6.4.1. The First Theorem of Limit Analysis (Static Principle)
6.4.2. The Second Theorem of Limit Analysis (Kinematic Principle)
6.5. General Elastic-Plastic Analysis
6.6. Finite Element Modelling for a Plastic Collapse Analysis
6.7. Mesh and Element Considerations
6.8. Other Considerations
6.9. Example 6A - Finite Element Plastic Collapse Solution
7. Collapse due to Fracture
7.1. Introduction
7.2. Fracture Mechanics Basics
7.3. Example 7A - Stress Intensity Factor Calculation
7.4. Quarter-Point Isoparametric Elements
7.5. Virtual Crack Closure Technique
7.6. Interface Elements
7.7. Example 7B – VCCT Applied to Skin-Stiffener Debonding Problem
7.8. Example 7C – Mixed-Mode Multiple Delamination Using Interface Elements
8. Practical Guide to Selecting a Solution Scheme
9. Concluding Remarks


Thermal Stress Analysis of Beams, Plates and Shells presents classic and advanced thermal stress topics in a cutting edge review of this critical area. Tackling subjects with little coverage in existing resources, the book considers complex problems, such as multi-layered cases, using modern advanced computational and vibrational methods.

Authors Carrera and Fazzolari begin with a review of the fundamentals of thermoelasticity and thermal stress analysis relating to advanced structures and the basic mechanics of beams, plates and shells, making the book a self-contained reference. They move on to consider more challenging topics, including:

Multilayered, anisotropic thermal stress structures
Static and dynamic responses of coupled and uncoupled thermoelastic problems
Thermal buckling and post-buckling behavior of thermally loaded structures
Thermal effects on panel flutter phenomena
Static and dynamic thermal stress analysis of functionally graded material (FGM) structures

With practical advice on advanced computational methods, and sample problems throughout that cover both metallic and composite structures and account for mesh and meshless methods, Thermal Stress Analysis of Beams, Plates and Shells is a valuable resource for those working on thermal stress problems within mechanical, civil and aerospace engineering settings.

Contents:
1. Introduction
2. Solution of sample problems in classical thermoelasticity
3. Thermoelasticity, coupled and uncoupled variational formulations
4. Fundamental of mechanics of beams, plates and shells
5. Multilayered, anisotropic thermal stress structures
6. Advanced theories for multilayered beams, plates and shells
7. Through-the-thickness thermal fields in one-layer and multilayered structures
8. Computational methods for thermal stress analysis
9. Static response of uncoupled thermoelastic problems
10. Dynamic response of uncoupled thermoelastic problems
11. Static and dynamic responses of coupled thermoelastic problems
12. Thermal buckling
13. Post buckling behavior of thermally loaded structures
14. Thermal effect on flutter of panels
15. Thermal stresses in functionally graded materials

--------Book (found on the website: http://ebooks.cambridge.org (Cambridge Books Online):

--------Book

--------Books in English by Jan Awrejcewicz, et al (See the “book Cover Gallery” on the “Bibliography” page of the “shellbuckling.com” website for images of the book covers and for summaries of these books in English.)

--------Books (monographs) in Polish by Jan Awrejcewicz, et al
SUMMARY: In this monograph both theoretical and experimental approaches devoted to plates and shells analysis are described. A special emphasis is put on the theoretical-experimental method applied to analysis of multi-component non-homogeneity and the methods using laser technique. It has been shown, how to use
the regression technique during estimation of the function characterizing non-homogeneities. In addition, a hologram technique used to define the frequencies and corresponding modes is presented. The following non-homogeneity factors are used: holes and thickness variations, shells with various geometry (circular and rectangular) and the various boundary conditions. In the first case the Argyris element with 12 degrees-of-freedom is used to analyse plates with one and two non-homogeneity factors. In the second case different thickness plates and shells are analysed using sixth order approximations. Analysis of plates and shells vibrations with one-component non-homogeneity is carried out in Chapter 3. Among others, the first 6 frequencies and corresponding modes are estimated. The frequency spectra dependence on the non-homogeneity components is outlined. In Section 3.2 the experimental rigs are described, whereas in Section 3.3 the methods devoted to experimental investigations are outlined. Among others, the influence of non-homogeneous boundary conditions and various holes is investigated. Chapter 4 is devoted to analysis of the influence of holes (situated on the plates and shells edges) on the vibrations. Many experimental results are reported in tables and figures. Chapter 5 presents computational results of the plates with holes using FEM. The numerical results are compared with experimental ones. In Chapter 6 plates and shells with different thickness distribution are analysed using the Bubnov-Galerkin method with various approximations. Chapter 7 is devoted to experimental investigations of small diameters plates and shells used in electronic techniques. The eigenfrequencies and corresponding modes are found. The obtained results are compared using theoretical-experimental and experimental methods.


**SUMMARY:** This monograph is devoted to analysis of dynamical behaviour of shells with thermal excitations and consists of four parts. A state-of-art of the subject is reviewed in Introduction, where a special attention is paid to East European research. Many important results which are not widely known are outlined. It has been shown among others, that the problems of dynamical stability of shells subjected to thermal loads action and accounting nonlinear temperature distribution along their thickness are rarely discussed in the existing literature. In Chapter 1 the fundamental dependencies and computational algorithms are formulated. The general considerations yield further considered differential equations, initial and boundary conditions of the thermoelasticity. In the next step the finite difference method is applied to solve the obtained partial and nonlinear differential equations including thermal and mechanical loads. Then, using both analytical and numerical (Bubnov-Galerkin approach) methods, the applied finite difference approach is verified. The relaxation technique is further used and both static and dynamic loads are analyzed and many practically useful conclusions are given. In Chapter 2 stability of thin shells subjected to an action of transversal mechanical and thermal loads is analysed. First of all, the influence of heat stream magnitude on shells stability simultaneously thermally and transversally loaded is studied. Than, the analysis is extended into the case of sinusoidal transversal load action. Finally, the influence of thermal and mechanical material characteristics depending on the temperature on stability of thin shallow shells is reported. Chapter 3 is oriented on stability investigation of thin shells subjected to longitudinal mechanical and heat stream actions. First, the influence of boundary conditions and surrounding medium on the critical compressing load is investigated. Then the stability of a shell under an action of a constant compressing load and a heat stream is analysed. In Chapter 4 dynamical stability of thin shells under convectional heat transfer is studied. Firstly, the problem is mathematically formulated and then the influence of boundary conditions and thermal loading on the stress-strain shells states are investigated, among others.

SUMMARY: In this monograph dynamical problems of thermoelasticity of thin cylindrical shells thermally excited are analysed and the computational algorithms are proposed and illustrated. The book is oriented on students of mechanical and civil engineering, Ph.D. students, researchers and engineers working in the field of dynamics of plates and shells thermally excited. A state-of-the-art of the considered subject is reviewed in the Introduction, where a special emphasis is put on the Central and Eastern European Countries' achievements. The literature overview led to the following conclusions: (i) the influence of geometric parameters and the boundary conditions on the cylindrical shells with non-homogeneous thermoelastic load is not fully investigated; (ii) a buckling of thin cylindrical shell in conditions of both static and thermal loads is not satisfactorily analysed; (iii) there is a lack of satisfactory theoretical model within mechanical and thermal loads conditions. In Chapter 1 dynamical problem of thermoelasticity of thin cylindrical shells is addressed. First of all, fundamental relations, variational coupled thermoelastic equations and hybrid variational equations governing dynamics of composite orthotropic and thermosensitive shallow shells are derived. Then a rigorous mathematical discussion on existence of a solution to the formulated problem is carried out. The computational algorithms are reported in Chapter 2. First, the difference equations are formulated, and then a solution to the biharmonic equation with respect to the stress function F is given. Then, a discussion on the reliability of the obtained results follows. It includes a comparison of results with other researchers as well as with the experimental results. The application of the relaxation method in the statical and dynamical problems is addressed in Section 2.4. In Chapter 3 dynamical stability of thin shells with non-uniform excitation is discussed and illustrated. First, dynamical stability criterions are overviewed, and then a stability loss of shells under non-uniform load action is investigated. Many computational results with the associated figures are given. Dynamical stability loss and behaviour of thermosensitive shells in condition of non-uniform thermal load is studied in Chapter 4. In section 4.1 the singularities associated with thermal field computations are illustrated, whereas in section 4.2 an influence of geometrical parameters and loads duration on a thermosensitive shell dynamics is reported. The section 4.3 is devoted to analysis of dynamical stability loss of shells with imperfections under action of combined thermal and mechanical loads.

Asymptotical Methods and Their Applications in Theory of Shells, by Jan Awrejcewicz and Igor V. Andrianov, WNT, Warsaw, 2000, 184 pages (in Polish)
SUMMARY: This monograph is devoted to the new challenging applications of asymptotic approaches with a special emphasis on the shells theory. In many cases asymptotic analysis does not only give the qualitative and quantitative results but sometimes also yields the relations between various physical theories. For example, many new results in the fields of statics and dynamics of thin elastic cylindrical shells are obtained. In Chapter 1 a brief history and an overview of the existing asymptotical approaches are given. The updated state-of-the-art and the perspectives of the asymptotic approaches are outlined. The asymptotic series convergence, Padé approximations, advantages and disadvantages of the asymptotic techniques are illustrated and discussed. One of the most important problems occurring during the asymptotic analysis is related to the definition of "small" (perturbation) parameter. One would expect to have a possibly the largest value of the "small" parameter. An estimation of reliability of the obtained results does not belong to easy tasks, since the majorant inequalities should be used. Hence, very often the results obtained are verified numerically. Nowadays, the asymptotic methods possess large applications, also in mechanics of continuous systems like beams, plates, shells, etc. The analysis of thin-walled structures is carried out in Chapter 2. First, in Section 2.1 the introduction to the considered problem is given. Analysis of the boundary value problems in theory of smooth cylindrical shells is carried out in Section 2.2. The fundamental relations are formulated and asymptotic boundary value problems are outlined. Then the fundamental boundary value problems of the statics are formulated and the limiting relations of higher order approximations are derived. The Green function approach is introduced. A comparison of the obtained results with other methods is carried out. Finally, the dynamical boundary conditions are
analysed. Section 2.3 is devoted to the analysis of boundary value problems of theory of orthotropically designed cylindrical shells. This section is organized in a similar way of the previous one.

SUMMARY: This monograph can be treated as an attempt to original analysis of the plates and shells role in our nature, mechanics and biomechanics. In the Introduction the fundamental background of elasticity of deformable bodies, stress-strain states, Hooke's law, Young's modulus and Poisson's coefficients are given. In Chapter 2 the occurrence of shells and plates as the elements of our Earth surface, buildings or internal human organs are discussed and illustrated. A lot of interesting information not known to a reader so far is reported. In Chapter 3 a historical background of the plates and shells theory is given. Chapter 4 is devoted to the overview of the historical development of plates and shells with the emphasis on asymptotic and numerical methods development and their impact on the shell theory. After a brief introduction, a general description of an averaging approach in the shells theory is given. It is shown that sometimes what seems to be bad can be usefully applied. This sentence is supplemented by the appropriate examples. Then today's asymptotology and the computer-oriented methods are compared and discussed. In Chapter 5 the plates and shells theory precursors are described with their short biographies. It includes, among others, the biographies of Johann I Bernoulli, Jacob I Bernoulli, Daniel I Bernoulli, Enrico Betti, Augustin Louis Cauchy, Ernst Florens Chladni, Jean D'Alembert, Adhemar Jean de Saint-Venant, Leonard Euler, Marie-Sophie Germain, Robert Hooke, Edward Hu Law, Gustav Robert Kirchhoff, Werner Tjardus Koiter, Joseph Louise Lagrange, Gabriel LamÈ, Pierre Simon Laplace, Aurie Anatolij Isakowicz, Claude Navier, Witold Nowacki, Walentin Walentynowicz Nowo_li_Bow, Denis SimÈon Poisson, Lord Rayleigh, Eric Reissner, Stepan Prokofiewicz Timoszenko, W_Basow Wasilij Zacharowicz. Chapter 6 includes today's state-of-the-art and perspectives of theory and practice development in the field of plates and shells dynamics. In Chapter 7 some interesting examples of nonlinear dynamics of plates and shells are outlined. Among others, chaotic dynamics and solitons are discussed and reported. Chapter 8 consists of historical as well as new development directions of plates and shells theory, their physical behaviour and mathematical models and it includes the methods of analysis of plates and shells. The Chapter 9 written by Professor M. Kote_Bko and J. Rhodes is devoted to thin walled profile materials, plastic mechanisms of their damage and the numerical methods used for their analysis.

SUMMARY: A characteristic feature of this monograph is focused on the emphasis put on the achievements of Russian scientists in the field of plates and shells dynamics. The latter results are not widely distributed among the students and researchers interested in this branch of mechanics. In the Introduction a brief bibliographical review devoted to plates and shells with complicated shapes and non-homogeneous surfaces is given. It is pointed out, among others, that only a small amount of papers is focused on statical and dynamical analysis of sectorial shells within the geometrically nonlinear background. In Chapter 1 a theory of shallow sectorial shells is introduced. First of all, the fundamental relations, differential equations, initial and boundary conditions are outlined. Then in Section 1.2 the algorithm for solution of nonlinear problems of shallow sectorial shells in a thermal field is proposed. In fact, the modified version of the finite difference method is used, including Gauss and relaxation approaches. A verification of the proposed algorithms is carried out via comparison with available analytical or obtained by other authors numerical results. The comparison is carried out either via the data included in the tables or drawings of deflections, stresses or bending moments of the selected points of the investigated shells. In Chapter 2 a stability of sectorial shells with finite deflections is described. Firstly, the influence of the sectorial shell angle on the dynamical stability is given, which is illustrated via solution of five
different problems (Section 2.1). In Section 2.2 an application of the "set up" approach is applied to determine the critical loads. The approach is illustrated via five different examples. In Section 2.3 a shell stability subjected to heat impact action is analysed, whereas in Section 2.4 the influence on stability of a local surface load is investigated. Many useful conclusions are derived allowing for a direct application for engineers working in the field of shells dynamics. The monograph is oriented on students and Ph.D. students of mechanical and civil engineering faculties as well as the students of applied mathematics.


**SUMMARY:** This monograph belongs to the series yielded as a result of cooperation between the Technical University of Lodz (Poland) and The National University of Saratov (Russia) and devoted to the analysis of plates and shells. The majority of the books from this series has been published by Wydawnictwo Naukowo-Techniczne - Fundacja "Księga Naukowo-Techniczna". In Chapter 1 of this monograph, a general three-dimensional problem of thermoelasticity of a parallelepiped is formulated. Among others, a rigorous mathematical approach to an error estimation analysis and stability of the used difference schemes is addressed. Chapter 2 is devoted to description of various methods used to solve elliptic, parabolic and hyperbolic equations. In addition, a reliability of the obtained results is illustrated and discussed and also some numerical examples are given. Chapter 3 includes numerical analysis of some chosen linear problems of three-dimensional theory of plates. The following problems are considered: static and dynamic, non-stationary heat problems with sources situated inside a plate, solutions to the problems describing non-isotermic processes in statics of plates, influence of internal heat sources on a stress-strain state of a plate and influence of coupling between deformation and temperature on a plate behaviour. Chapter 4 is focused on temperature and deformation fields analysis including physical type nonlinearities. After derivation of differential equations and difference approximation within theory of small elastic-plastic deformations, influence of coupling between temperature and deformation on the stress-strain state is carried out. The monograph is meant for students, researchers within the fields of mechanics, physics and applied mathematics dealing both with theory of plates and analysis of partial differential and difference equations.

**Chaotic Dynamics of Beams, Plates and Shells**, by J. Awrejcewicz and V.A. Krysko, WNT, Warsaw (date not given), 342 pages, ISBN 83-204-3113-1 (in Polish)

**SUMMARY:** This monograph gives theoretical background, modeling and numerical techniques devoted to analysis of regular and chaotic dynamics of continuous mechanical systems represented by beams, plates and shells. The authors present novel approaches to analysis and control of the mentioned continuous objects from the field of nonlinear mechanics. The book is oriented on students, engineers and scientific staff in the area of dynamics and static's of continuous systems, bifurcations and chaos as well as modeling and various numerical methods.
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Section 6: Some Early Work on Buckling of Plates and Shells

End of the first section that lists books (Section 6)

End of Section 6

Section 7: Some Early Work on Buckling of Plates and Shells:


“The discovery of the shell as a loadbearing structure is a work of reinforced concrete and started around 1900 with the erection of water and gas tanks plus thin-wall domes. By the end of the accumulation phase of...
structural theory (1900–25) the Zeiss-Dywidag shell by Bauersfeld and Dischinger (see section 8.2.3) had appeared. This was also the period of the technicisation of shell theory, which had evolved in the tradition of the mathematical elastic theory. And by the middle of the invention phase of structural theory (1925–50) the new language of reinforced concrete had been completed by the shell constructions of Dischinger, Rüsch and Finsterwalder, which found their adequate engineering science expression in structural shell theory.

“In fact, Navier had investigated rotational shells in the membrane stress condition in his Résumé des Leçons [Navier, 1826], i.e. shells in which the element axial forces $N_\theta$ and $N_\phi$ plus the element thrust forces $T_\theta$ and $T_\phi$ act at their midsurface, i.e. where the element shear forces $Q_\theta$ and $Q_\phi$, the element bending moments $M_\theta$ and $M_\phi$ plus the element torsion moments $D_\theta$ and $D_\phi$ vanish (Fig. 9-31; see below).

“Lamé and Clapeyron calculated the stresses and deformations in a spherical shell subjected to internal or external pressure [Clapeyron & Lamé, 1833], and in 1854 the latter managed a complete solution to the deformation problem of spherical shells subjected to any distributed loads [Lamé, 1854]. Aron was the first person to consider all moments and formulated the bending theory of any curved elastic shell for the static and dynamic cases [Aron, 1874]. Unfortunately, Aron’s bending theory for shells was not adopted. It was not until 14 years later that Love, working independently of Aron, set up a bending theory for shells [Love, 1888], which he presented in his famous textbook A treatise on the mathematical theory of elasticity [Love, 1892/93]. Rayleigh, too, published separate contributions on shell theory in 1881, 1888 and 1889, and collected these together in a separate chapter in the second edition of the first volume of his The Theory of Sound [Rayleigh, 1894]. A generalisation of the bending theory for shells that did not use the Bernoulli hypothesis of plane sections remaining plane was provided by the Cosserat brothers [E. & F. Cosserat, 1909]. And that concluded the constitution phase of mathematical shell theory.

“Only by using the symbolic notation of H. Lamb in the second edition of his textbook [Love, 1906 & 1907] did Love manage to bring shell theory to the attention of engineering researchers. Nevertheless, a reviewer of the German edition of Love’s book writes [Love, 1907]: “This book is written by an expert for mathematicians and physicists ... A study of this book will not benefit the practising engineer because apart from a few cases the golden bridge leading from vague theory to practice is missing. However, the enthusiastic researcher who senses the familiar results of elastic theory on their theoretical foundations will derive much and new inspiration from this work” [Schönhöfer, 1907, p. 296].

“Practising engineers initially approached shell theory cautiously via the analysis of the simplest shell form, the single-curvature, fixed cylindrical shell; but the representatives of fundamental engineering science disciplines such as applied mechanics and theory of structures were no different. Using this structural model, engineers attempted to size vessels of steel and later reinforced concrete – the works of E. Winkler (1860), F. Grashof (1878), G. A. Wayss (1887), V. G. Shukhov (1888) (see [Ramm, 1990]), R. Maillart (1903) (see [Schöne, 1999]), C. Runge (1904), Panetti (1906), H. Müller-Breslau (1908), H. Reissner (1908), K. Federhofer (1909 & 1910), T. Pöschl and K. v. Terzaghi (1913), A. and L. Föppl (1920) to name just some. In 1923 V. Lewe summarised the methods for the structural calculation of tanks for fluids in a longer article for the Handbuch für Eisenbetonbau (reinforced concrete manual) [Lewe, 1923].”
References cited on pages 547 and 548 of the book, Karl-Eugen Kurrer, The History of the Theory of Structures from Arch Analysis to Computational Mechanics, Ernst & Sohn, 2008: 


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A list of the references relating to 1. Large Deflection Theory and 2 Theory of Elasticity with Finite Deformations:

1. **Large Deflection Theory:**
2.---------, Untersuchungen über Knickfestigkeit, Forschungsarbeiten, no. 81, 1910.
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14. -------, Die Durchschlagskraft eines schwach gekrümmten Balkens, Sitzungs- berichte der Berliner

2. Theory Of Elasticity With Finite Deformations:

Early Books relating to buckling of plates and shells:

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Albert G.H. Dietz, editor, Engineering Laminates, John Wiley & Sons, Inc., 1949

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Foundations of the Nonlinear Theory of Elasticity, by V. V. Novozhilov, Courier Dover Publications, 1999

COMMENT (by publisher?): This is an essential book for students and academicians alike. In addition to discussing theory, topics include the connection between stresses and strains in an isotropic elastic body, the geometry of strain and much more. Deductions are explained in the simplest, most intuitive manner for wide accessibility. 1953 edition.

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P. Kuhn, Stresses in aircraft and shell structures, McGraw-Hill, 1956

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W. Flügge, Stresses in Shells, Springer, 1960

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Large elastic deformations and non-linear continuum mechanics, by Albert Edward Green, J. E. Adkins, Clarendon Press, 1960
Y.C. Fung and E.E. Sechler, editors, **Instability of thin elastic shells**, Structural mechanics, 1960 (no publisher given, Symposium Publications Division)

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P.G. Hodge, **Limit analysis of rotationally symmetric plates and shells**, Prentice-Hall, Inc. 1963

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L.S.D. Morley, **Skew Plates and Structures**, Macmillan Co, 1963

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W. Hahn, **The theory and application of Liapunov’s direct method**, Prentice-Hall, New Jersey, 1963

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W.A. Litle, **Reliability of shell buckling predictions**, November, 1964, 188 pages (out of print, no publisher given)

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References listed at the end of the paper: “Postbuckling Theory” by J. W. Hutchinson and W. T. Koiter, Applied Mechanics Reviews, Vol. 23, No. 12, pp. 1353-1366, 1970 (For a copy of this paper, see the appropriate link under the list of “Classic Papers” on the “Bibliography” page of the shellbuckling.com website.):

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A.L. Cauchy, “Sur les équations qui expriment les conditions d’équilibre ou les lois de mouvement intérieur d’un corps solide”, Exercises de Mathématique, edited by Cauchy, Paris Academy, 1828


Rudolf Lorenz 1908 “Achsensymmetrische Verzerrungen in dünnwandigen Hohlzyllindern”, Zeitschrift des Vereines Deutscher Ingenieure, Vol. 52, 1907

A. Mallock, “Note on the instability of tubes subjected to end pressure, and on the folds in a flexible material”, Proceedings of the Royal Society A, 1908, Vol. 81, DOI: 10.1098/rspa.1908.0095, published December, 1908

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L.H. Donnell (Chance Vought Corp, Dallas Texas), “The Stability of Isotropic or Orthotropic Cylinders or Flat or Curved Panels, between and Across Stiffeners, with any Edge Conditions between Hinged and Fixed, under any Combination of Compression and Shear”, Report No. B353508, December 1943

Katsutada Sezawa and Kei Kubo, “The buckling of a cylindrical shell under torsion”, (The pdf file is provided by JAXA, no publisher given), Report No. 766, December 1931, pp. 251 - 314
ABSTRACT: The object of this investigation was to study, both mathematically and experimentally, the problem of the buckling of a cylindrical shell, that is clamped or supported at its two ends and subjected to a uniform shearing force.


Eugene E. Lundquist, “Strength tests on thin-walled duralumin cylinders in torsion”, NACA TN No. 427, 1932

Lundquist, Eugene E, “Strength Tests of Thin-Walled Duralumin Cylinders in compression”, NACA-TR-473, January 1934

Lundquist, E.E., “Strength tests of thin-walled duralumin cylinders in pure bending”, NACA TN 479, 1933


Lundquist, E.E., “Comparison of three methods for calculating the compressive strength of flat and slightly curved sheets and stiffener combination”, NACA TN 455 (no date given, probably about 1937)


Lundquist, E.E., and Stowell, E.Z., "Critical Compressive Stress for Flat Rectangular Plates Supported Along all Edges and Elastically Restrained Against Rotation Along the Unloaded Edges", NACA TR 733, 1942


Lundquist, E.E. and Stowell, E.Z., “Restraint provided a flat rectangular plate by sturdy stiffener along the edges of the plate”, NACA TN 735, 1942


ABSTRACT: This paper develops a new method for determining the buckling stresses of cylindrical shells under various loading conditions. In part I, the equation for the equilibrium of cylindrical shells introduced by Donnell in NACA report no. 479 to find the critical stresses of cylinders in torsion is applied to find critical stresses for cylinders with simply supported edges under other loading conditions. In part II, a modified form of Donnell's equation for the equilibrium of thin cylindrical shells is derived which is equivalent to Donnell's equation but has certain advantages in physical interpretation and in ease of solution, particularly in the case of shells having clamped edges. The question of implicit boundary conditions is also considered.


ABSTRACT: This paper discusses the collapse by instability of thin-walled cylindrical vessels subjected to external pressure. The most important of the theoretical and empirical formulas that apply to this subject are presented in a common notation. A new and simple instability formula is developed. Three classes of tubes are considered: Tubes of infinite length; tubes of finite length with uniform radial pressure only; and tubes of finite length with both uniform radial and axial pressure. Collapsing pressures calculated by the various formulas are presented in tabular form as a means of comparing the formulas. The formulas are discussed briefly and checked against the results of tests conducted at the U. S. Experimental Model Basin for the Bureau of Construction and Repair, Navy Department. This paper is a sequel to one previously published as a part of the work of the A.S.M.E. Special Research Committee on the Strength of Vessels Under External Pressure.

References listed at the end of the paper:
ABSTRACT: The first section of this paper describes a series of tests of the strength of thin-walled cylinders under a combination of torsion and axial compression or tension. Curves are obtained showing the strength of each of the several types of cylinders tested, under all possible combinations of these loads. All the curves obtained seem to have the same general form and the results suggest the possibility of finding a simple law by means of which a designer could determine the buckling strength of a structure under any combination of shear and normal stress, if he knows its strength under pure shear and under pure compressive stress. The second section describes tests made to investigate the independence of different possible types of buckling of a structure. A set of L-section struts, identical except for the widths of the sides, were tested in compression. With small widths the struts buckle as Euler columns but with the wider widths buckling of the sides, as plates hinged on three edges, occurs first. Great care was taken to eliminate the effect of initial eccentricities. The results check the well-known theories for these two types of buckling and indicate that, for practical purposes, the two types can be considered independently of each other. The results also illustrate how enormously the strength-weight ratio of thin wall construction may be affected by details of design.

H. Wagner, “Tension fields in originally curved, thin sheets during shearing stresses”, NACA, 1935


A.C. Kurzweil, “The bending and buckling of shells with special reference to truncated cones…”, Leland Stanford Junior University, 1939

Paul Kuhn, “Some elementary principles of shell stress analysis with notes on the use of the shear center”, NACA Technical Note No. 691, 45 pages, March 1939


ABSTRACT: In two previous papers (von Karman and Hsue-Shen, 1939; von Karman et al., 1940) the authors discussed in detail the inadequacy of the classical theory of thin shells in explaining the buckling phenomenon of cylindrical and spherical shells. It was shown that not only the calculated buckling load is 3 to 5 times higher than that found by experiments, but the observed wave pattern of the buckled shell is also different from that predicted. Furthermore, it was pointed out that the different explanations for this discrepancy advanced by Donnell (1934) and Fluegge (1932) are untenable when certain conclusions drawn from these explanations are compared with the experimental facts. By a theoretical investigation on spherical shells I the authors were led to the belief that in general the buckling phenomenon of curved shells can only be explained by means of a nonlinear large deflection theory. This point of view was substantiated by model experiments on slender columns with nonlinear elastic support (von Karman et al., 1940). The nonlinear characteristics of such structures cause the load necessary to keep the shell in equilibrium to drop very rapidly with increase in wave
amplitude once the structure started to buckle. Thus, first of all, a part of the elastic energy stored in the shell is released once the buckling has started; this explains the observed rapidity of the buckling process. Furthermore, as it was shown in one of the previous papers (von Karman et al., 1940) the buckling load itself can be materially reduced by slight imperfections in the test specimen and vibrations during the testing process. In this paper, the same ideas are applied to the case of a thin uniform cylindrical shell under axial compression. First it is shown by an approximate calculation that again the load sustained by the shell drops with increasing deflection. Then the results of this calculation are used for a more detailed discussion of the buckling process as observed in an actual testing machine.


ABSTRACT: Compressive tests were made of two series of stiffened circular cylindrical shells under axial load. All the shells were 16 inches in diameter by 24 inches in length and were made of aluminum-alloy sheet curved to the proper radius and welded with one longitudinal weld. The ratios of diameter to thickness of shell wall in the two series of specimens were 258 and 572. Strains were measured with Huggenberger tensometers at a number of gage lines on the stiffeners and shell. The results of these tests indicate that a spacing of circumferential stiffeners equal to 0.67 times the radius is too great to strengthen the shell wall appreciably. The results are not inclusive enough to show the optimum in stiffeners. Plain cylinders without stiffeners developed ultimate strengths approximately half as great as the buckling strengths computed by the equation resulting from the classical theory and slightly greater than those computed by Donnell's large deflection theory.


Wilson, W. M. and Olson, E. D., “Tests of cylindrical shells”, University of Illinois Engineering Experimental Station Bulletin Series, No. 331, 1941


D.M.A. Leggett, “The behavior of a cylindrical shell under axial compression when the buckling load has been exceeded”, HM Stationery Office, 1942

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N.J. Hoff, “General instability of monocoque cylinders”, J. of the Aeronautical Sciences, 1943

N.J. Hoff, “A strain energy derivation of the torsional-flexural buckling loads of straight columns of thin-walled open sections, Quarterly of Applied Mathematics, 1944


R.L. Moore and C. Wescoat, “Torsion tests of stiffened circular cylinders”, NACA ARR No. 4E31, 1944


Abstract: A general theory of elastic stability is presented. In contrast to previous works in the field, the present analysis is augmented by an investigation of the behavior of the buckled structure in the immediate neighborhood of the bifurcation point. This investigation explains why some structures, e.g., a flat plate supported along its edges and subjected to thrust in its plane, are capable of carrying loads considerably above the buckling load, while other structures, e.g., an axially loaded cylindrical shell, collapse at loads far below the theoretical critical load.


ABSTRACT: Until recently the famous principle of minimum complementary energy of the classical linear theory of elasticity has defied all attempts at an effective generalization to the nonlinear case where the strain-displacement relations are no longer linear. L. M. Zubov [4] has now taken a significant step towards the solution of this problem in the form of his principle of stationary complementary energy, expressed in terms of the Piola stress tensor. Zubov’s argument, however, is open to criticism at several points. The present paper aims at the removal of these weak points and at a simpler derivation of Zubov’s theorem. The theory is illustrated by some simple examples.


ABSTRACT: Mode interaction is an important and often dangerous phenomenon in the buckling of stiffened plate and shell structure with nearly equal critical loads for the long wave overall mode and the short wave local or panel mode. An approximate general theory is derived on the basis of amplitude modulation of the short wave mode due to its interaction with the long wave mode. The method of analysis is a generalization of previous work on mode interaction in stiffened flat plates and built-up columns. The interaction is shown to have always a detrimental effect on the load carrying capacity of the structure, in particular in the presence of unavoidable imperfections. A few numerical examples illustrate the theory, and some recommendations are formulated for a systematic numerical evaluation.
ABSTRACT: Elastic stability is perhaps the oldest topic in finite elasticity theory. Stability in the sense of Lyapunov is essentially a dynamic concept. Dynamics of continuous media find their proper place under the wings of thermodynamics. The thermodynamic foundation of the theory of elastic stability is now fairly secure, thanks to Duhem and Ericksen. Some subtle mathematical difficulties are still connected with questions of Fréchet differentiability of the elastic energy functional. Applications to specific problems of buckling of structures have preceded the complete development of the theory of elastic stability. This situation is indeed quite common in engineering science. The significance of post-buckling behaviour has been recognized much later. This essentially nonlinear aspect, so characteristic for finite elasticity theory, will be reviewed in some detail.

References listed at the end of the paper:


ABSTRACT: The energy approach to elastic stability is employed to describe characteristic differences in buckling behaviour between bars in compression, plates loaded in their plane, and shells, in particular in the absence of inextensional deformation. The initial stage of post-buckling behaviour of shells is discussed from the standpoint of shallow shell theory and it is applied to more or less localized buckling patterns.

References listed at the end of the paper:


ABSTRACT: Amplitude modulation of short-wave local buckling modes has proved to be a useful tool in the approximate analysis of a number of buckling problems for plates and shells. This concept seems to have been applied first in a modification of Hutchinson's analysis of a complete spherical shell under external pressure. More or less localized imperfections and the associated buckling analysis have improved the understanding of the effect of a local dent. Finally, the nonlinear interaction between local sheet buckling and overall bucking of stiffened plate and shell structures may be described effectively as a modulation of the amplitude of the local short-wave mode due to the long-wave overall mode.
SUMMARY: The theorem of stationary complementary energy is applied to buckling problems for structures of a semi-linear material in cases of an irrotational linear prebuckling state.

References listed at the end of the paper:

N.J. Hoff and S.E. Mautner, “The buckling of sandwich panels”, Journal Aeronaut Sci, 1945


ABSTRACT: Ten 24S-T alclad cylinders of 20-inch diameter, 45- or 58-inch length, and 0.012-inch wall thickness, reinforced with 24S-T aluminum alloy stringers and rings were tested in pure bending. In the middle of the compression side of the cylinders there was a cutout extending over 19 inches in the longitudinal direction, and over an angle of 45 degrees, 90 degrees, or 135 degrees in the circumferential direction. The strain in the stringers and in the sheet covering was measured with metal electric strain gages. The stress distribution in the cylinders deviate considerably from the linear law valid for cylinders without a cutout. The maximum strain measured was about four-thirds of the value calculated from the Mc/I formula when I was taken as the moment of inertia of the cross section of the portion of the cylinder where the cutout was situated. A diagram is presented containing the strain factors defined as the ratios of measured strain to strain calculated with the Mc/I formula. All the 10 cylinders tested failed in general instability. Two symmetric and one antisymmetric pattern of buckling were observed and the buckling load appeared to be independent of the method of manufacture and the length of the cylinder. The buckling load of the cylinders having cutouts extending over 45 degrees, 90 degrees, and 135 degrees was 66, 47, and 31 percent, respectively, of the buckling load of the cylinder without a cutout.


ABSTRACT: Determinations were made under comparison, particularly in that region of loading where the panels are in a buckled state. Cylinders were built and reinforced with a number of stringers and rings. Tests were made by measuring the twist angle of the cylinder caused by known amount of torque while the cylinder
was subject to uniform axial compression. Shearing rigidity of a panel decreases when increasing amounts of compressive loads are applied to the panel in the axial direction.


E. Reissner, “On stresses and deformations in toroidal shells of circular cross section which are acted upon by uniform normal pressure”, Quarterly of Applied Mathematics, Vol. 21, No. 3, 1963, pp. 177-188


Budiansky, B. and Seide, P., “Compressive buckling of simply supported plates with transverse stiffeners”, NACA TN 1557, 1948

Budiansky, Bernard; Stein, Manuel & Gilbert, Arthur C. “Buckling of a long square tube in torsion and compression, NACA Technical Note 1751, November 1948, UNT Digital Library.
http://digital.library.unt.edu/ark:/67531/metadc54891/.

ABSTRACT: The buckling of an infinitely long square tube under combined torsion and compression is investigated by means of an exact energy method utilizing Lagrangian multipliers. An interaction curve is obtained from which it is possible to determine the amount of one loading required to produce buckling when a given amount of the other loading is present.


Hickman, W.A. and Dow, N.F., “Compressive strength of 245-T aluminum-alloy flat compression panels with longitudinal formed hat-section stiffeners having a ratio of stiffener thickness to skin thickness equal to 1.00, NACA Technical Note 1439, 1947

Norris F. Dow and William A. Hickman (NACA Langley Aeronautical Laboratory, Langley Field, Virginia), “Effect of variation in diameter and pitch of rivets on compressive strength of panels with Z-section stiffeners, I – Panels with close stiffener spacing that fail by local buckling” NACA RB No. L5G03, August 1945


http://digital.library.unt.edu/ark:/67531/metadc60193/. Also see NACA Technical Note No. 1243, June 1947

ABSTRACT: Empirical design curves are presented for the critical stress of thin-wall cylinders loaded in axial compression. These curves are plotted in terms of the nondimensional parameters of small-deflection theory and are compared with theoretical curves derived for the buckling of cylinders with simply supported and clamped edges. An empirical equation is given for the buckling of cylinders having a length-radius ratio greater than about 0.75.


SUMMARY: Empirical design curves are presented for the critical stress of thin-walled cylinders loaded in axial compression. These curves are plotted in terms of the nondimensional parameters of small-deflection theory and are compared with theoretical curves derived for the buckling of cylinders with simply supported
and clamped edges. An empirical equation is given for the buckling of cylinders having a length-radius ratio greater than about 0.75. The test data obtained from various sources follow the general trend of the theoretical curve for cylinders with clamped edges, agreeing closely with the theory in the case of short cylinders, but failing considerably below the theoretical results for long cylinders. The discrepancy in the case of long cylinders increases with increasing values of the ratio of radius to wall thickness. Plotting curves for different values of this ratio reduces the scatter in the test data and a certain degree of correlation with theory is achieved. Advantage is taken of this correlation to obtain estimated design curves for cylinders with simply supported edges, for which little experimental information is available.

References listed at the end of the report:

13. Donnell, L. H.: The Stability of Isotropic or Orthotropic Cylinders or Flat or Curved Panels, between and across Stiffeners, with Any Edge Conditions between Hinged and Fixed, under Any Combination of Compression and Shear. NACA TN No. 918, 1943.


N.J. Hoff, Bruno A. Boley, and Bertram Klein (Polytechnic Institute of Brooklyn), “Stresses in and General Instability of Monocoque Cylinder with Cutouts. 3 - Calculation of the Buckling Load of Cylinders with Symmetric Cutout Subjected to Pure Bending”, NACA Technical Note, May 1947, Accession Number : ADA801227


H. W. March and C. B. Smith, “Buckling loads of flat sandwich panels in compression”, Forest Products Laboratory Report No. 1525, 1945, Madison, Wisconsin

H.W. March, “Buckling of flat plywood plates in compression, shear or combined compression and shear”, Forest Products Lab Report 1316, 1956


ABSTRACT: The results of torsion tests performed by the Forest Products Laboratory upon stiffened thin walled plywood cylinders showed that the buckling stress of the portion the shell between the stiffeners is about 85 percent of the buckling stress of an unstiffened cylinder of the same curvature and thickness The cylinders tested were about 0.04 inch thick and were curved with a 9-inch radius and had from 11 to 28 longitudinal stiffeners from 1/32 to 1/2 inch thick glued to the inner surface The theoretical buckling torque of an unstiffened cylinder of the same weight and curvature as a stiffened cylinder was found to be greater than that for the stiffened cylinder. At the time this work was begun in July 1943 it was thought that more information on the behavior of longitudinally stiffened shells was needed for the design of aircraft structures. Previous work of the Forest Products Laboratory on unstiffened shells showed that plywood is particularly useful for the experimental determination of the buckling stress of shell structures, ...


PARTIAL ABSTRACT: Eighteen 24S-T alclad cylinders of 20-inch diameter, with skin thickness varying between 0.012 inch and 0.025 inch and length varying between 40.5 inches and 64 inches, were tested in pure bending. They were reinforced with either 16 or 28 stringers and either 5 or 6 rings. One ...

N.J. Hoff, B.A. Boley, J.M Coan, “The development of a technique for testing stiff panels in edgewise compression”, proceedings of the Society for Experimental Stress Analysis, 1948

R. Peters, “Buckling tests of flat rectangular plates under combined shear and longitudinal compression”, NACA TN 1750, 1948


Stein, M. and Neff, J., “Buckling stresses of simply supported rectangular plates in shear”, NACA TN 1222, 1947


N.J. Hoff (Polytechnic Institute of Brooklyn), “Dynamic criteria of buckling”, 1949

N.J. Hoff, Bruno A. Boley, Merven W. Mandel, “Stresses in and general instability of monocoque cylinders with cutouts VIII : calculation of the buckling load of cylinders with long symmetric cutout subjected to pure bending”, NACA TN 1963, 1949

ABSTRACT: Differential equations and boundary conditions are derived for the bending and buckling of sandwich plates. The buckling load is calculated for a simply supported plate subjected to edgewise compression.

N.J. Hoff, S.V. Nardo, et al (Polytechnic Institute of Brooklyn), “The maximum load supported by an elastic column in a rapid compression test”, 1950


ABSTRACT: The present paper deals with the buckling of a circular cylindrical shell under axial compression from the viewpoint of energy and the characteristics of deformation. It is shown first, both theoretically and experimentally, that the reason why the buckling of a cylindrical shell is quite different from that of a flat plate is attributable to the existence of a nearly developable surface far apart from the original cylindrical surface. Based upon this result, the experimental fact that the buckling is really not general but local, that is, that the buckled region is limited axially to a range of 1.5 times the wave length of the lobe, is explained by the theoretical result that the minimum buckling load is smaller in the local buckling than in the general buckling case. The occurrence of local buckling is affirmed also from the viewpoint of the energy barrier to be jumped over during buckling, and from a comparison of the theoretical post-buckling state with the experimental results. Finally, the local buckling with the load applied by a spring is analyzed, and it is proved that the minimum buckling load increased with an increase of rigidity of the spring.

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ABSTRACT: The critical stress for torsional buckling of circular cylindrical shells obtained from the linear theory with small deformation is considerably greater than for the experimental stress. The present paper clarifies the cause of this discrepancy between theory and experiments on the assumption that the torsional buckling, as well as the compressive buckling, is a Durchschlag phenomenon. Based on the experimental fact that the buckled surface is approximately developable (the mean surface being drum-shaped), the equilibrium state after buckling was calculated by means of the minimum principle of potential energy, and, for the case of buckling under constant load, the lower buckling stress was obtained, which is considerably smaller than the upper buckling stress and which explains the experimental results approximately. In the case of buckling under constant angle of torsion there exists no lower stress.


G.N. White, Jr., “Application of the theory of perfectly plastic solids to stress analysis of strain hardening solids”, Graduate Division of Applied Mathematics, Brown University, Providence, RI, August 1950


W. Thielemann, “Contribution to the problem of buckling of orthotropic plates with special reference to plywood”, NACA TM 1263, 1950


V.L. Salerno and Bernard Levine, “Buckling of circular cylindrical shells with evenly spaced, equal strength circular ring frames, Part II, PIBAL Report No. ???, April 1950, DTIC Accession Number : AD0622902

ABSTRACT: A strain-energy solution of the buckling of a circular cylindrical shell reinforced by evenly spaced circular ring frames of equal strength under hydrostatic pressure was obtained in Part I. The buckled shape was assumed to be sinusoidal with inflection points at the location of the ring frames. For several geometrical configurations the critical pressure was found to be from two to three times that given by the von Mises solution. The assumed buckled shape used in Report I was modified to permit the inflection points of the deformed shape to occur between ring frames. For the geometrical configurations calculated in Report I, the
Critical pressure was found to be about one and one-third times that given by the von Mises solution. This represents a marked improvement over the solution obtained in Report I.


ABSTRACT: A solution is presented for the problem of the compressive buckling of simply supported, flat, rectangular, solid-core sandwich plates stressed either in the elastic range or in the plastic range. Charts for the analysis of long sandwich plates are presented for plates having face materials of 24S-TS aluminum alloy, 75S-T6 Alclad aluminum alloy, and stainless steel. A comparison of computed and experimental buckling stresses of square solid-core sandwich plates indicates fair agreement between theory and experiment.


1949

ABSTRACT: Charts are presented for the analysis of the stability under compression of simply supported rectangular plates with one, two, three and an infinite number of identical equally spaced longitudinal stiffeners that have zero torsional stiffness.


SUMMARY: A small-deflection theory that takes into account deformations due to transverse shear is presented for the elastic-behavior analysis of orthotropic plates of constant cylindrical curvature with considerations of buckling included. The theory is applicable primarily to sandwich construction.

References listed at the end of the paper:
5. Reissner, Eric, “Small bending and stretching of sandwich-type shells, NACA TN 1832, 1949


http://digital.library.unt.edu/ark:/67531/metadc56262/.

ABSTRACT: Theoretical solutions are presented for the buckling in uniform axial compression of two types of simply supported curved sandwich plates: the corrugated-core type and the isotropic-core type. The solutions are obtained from a theory for orthotropic curved plates in which deflections due to shear are taken into account. Results are given in the form of equations and curves.

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“Some extensions of elementary plasticity theory”, Journal of the Franklin Institute, Vol. 251, No. 6, June 1951,
pp. 581-605, doi:10.1016/0016-0032(51)90406-1

ABSTRACT: A detailed investigation is presented of yield or loading criteria, for work hardening materials,
which lead to constant strain ratios under increasing stress when stress ratios are maintained constant. The
experimenter is given a choice of incremental stress-strain theories with which results of simple or complicated
combined loading tests may be correlated. These theories are dealt with in order of increasing complexity and,
at the same time, increasing capacity to represent experimentally established phenomena. The objective is the
use of the mathematically simplest theory which will provide the desired flexibility in the analysis of
experimental data. Loading functions of isotropic as well as anisotropic types are examined, among them those
depending explicitly on stress alone and those depending on both stress and plastic strain. In the latter cases
only those functions are investigated in which plastic strain appears to the first order. The predicted results of
some basic tests are examined for several loading criteria.

Bruno A. Boley, Joseph Kempner and J. Mayers (Polytechnic Inst. of Brooklyn), “A numerical approach to the
instability problem of monocoque cylinders”, NACA Technical note, April 1951,
proxy Url: http://handle.dtic.mil/100.2/ADA382028

ABSTRACT: Two closely related numerical methods which employ operations tables have been developed and
used in the calculation of the buckling load of a monocoque cylinder subjected to pure bending. They are based
on the assumption of a simplified structure which includes only the most highly compressed portion of the
cylinder. The first method makes use of a 10-row determinant, whereas the second method requires the solution
of a single 10-row determinant. The buckling loads of three cylinders with widely different characteristics were
calculated by these methods. Reasonable agreement with experiment was obtained. A procedure similar to the
first method was developed for the calculation of the buckling load of a cylinder with a cutout. A limited
experimental check was obtained.

N.J. Hoff, “Buckling of thin cylindrical shell under hoop stresses varying in axial direction, 1951 (no publisher
given)

N.J. Hoff, “Dynamic analysis of the buckling of laterally loaded flat arches”, Polytechnic Institute of Brooklyn, 
…, 1951


Eric Reissner and Manuel Stein, “Torsion and transverse bending of cantilever plates”, NACA TN 2369, 1951

C. Libove and R. Hubka, “Elastic constants for corrugated core sandwich plates”, NACA TN 2289, 1951

A.E. Johnson and K.P. Buchert, “Critical combinations of bending, shear and transverse compressive stresses
for buckling of infinitely long flat plates”, NACA TN 2536, 1951

SUMMARY: In the first six paragraphs the energetic criterion of elastic stability is discussed and the differential equation for the critical vector of displacement in orthogonal curvilinear coordinates is derived. Together with this equation, the boundary condition on those parts of the boundary is given, where the displacements are free. In the last two paragraphs the corresponding basic expressions for thin shells are determined, under the assumption that plane sections remain plane and that surface forces behave as hydrostatic pressure, when the body is passing over from its critical position of equilibrium to a neighbouring one. References listed at the end of the paper:
2. Flügge, W., Statik und Dynamik der Schalen, Berlin 1934
4. Girkmann, K., Flächentragwerke, Vienna 1946

Y.C. Fung and A. Kaplan (California Institute of Technology), “Buckling of low arches or curved beams”, NACA Technical Note 2840, November 1952

PARTIAL SUMMARY: When a low arch (a thin curved beam of small curvature) is subjected to a lateral loading acting toward the center of curvature, the axial thrust induced by the bending of the arch may cause the arch to buckle so that the curvature becomes suddenly reversed. The critical lateral loading depends on the dimensions and rigidity of the arch, the elasticity of the end fixation, the type of load distribution, and the initial curvature of the arch. A general solution of the problem is given in this paper, using the classical buckling criterion which is based on theability with respect to infinitesimal displacements about the equilibrium positions….

References listed at the end of the paper:


ABSTRACT: A method is presented which permits the determination of the frequencies of vibrations of infinitely long thin cylindrical shells in an acoustic medium. Expressions are obtained for the displacements of the shell and for the pressures in the medium in the case of forced vibrations due to sinusoidally distributed radial forces. The results indicate that there is a low-frequency range, where no radiation takes place, and a high-frequency range where the external force provides energy which is radiated. Resonance occurs in the low-frequency range only; in the high-frequency range it is prevented by the damping due to radiation. Free and forced vibrations of steel shells submerged in water are discussed; with limitations, the theory may be applied approximately to stiffened shells. The method requires only a minor modification to account for the effect of static pressure in the surrounding medium. The treatment of transient problems is also considered. If high-frequency terms occur in the force, or shock effects are wanted within a short time after the application of the force, a treatment using solely modes of vibration of the submerged structure would be incomplete, as additional terms occur in the solution. As an alternative approach, the modes of free vibration of the structure may be used as generalized coordinates which fully describe the response of the structure but leave the medium to be treated, by means of the differential equations for the potential or in any other way desired.


Radok, J.R.M., “The theory of general instability of cylindrical shells”, Cranfield University, College of Aeronautics Report No. 61, June 1952

ABSTRACT: Using a new approach to the theoretical study of thin-walled cylinders with discrete reinforcing members developed in the paper, the problem of general instability of such structures is solved with more than usual generality. Continues …


F.I.N. Niordson, Vibration of a cylindrical tube containing flowing fluid”, Transactions of the Royal Institute of Technology, Stockholm, Vol 73, 1953


B. Altshuler, “Nonlinear buckling of a spherical shell”, Graduate School of Arts and Science…, 1953

D.M.A. Leggett (King’s College, London), “The buckling of thin cylindrical shells under axial compression”, Publications de L’Institut mathématique, 1953. Also see the paper with the same title presented at the Sixth International Congress of Applied Mechanics held in Paris in September 1946.

SUMMARY: The value of the compressive stress at which a thin circular cylindrical shell becomes unstable was worked out theoretically by Southwell. Subsequent experimental results, however, indicated that this result was appreciably too high, and von Karman and Tsien have shown that a thin cylindrical shell can be maintained in a buckled state by a compressive load considerably smaller than that previously predicted by theory. The present paper is an extension of the work of von Karman and Tsien, and shows that the smallest load which will keep a thin circular cylindrical shell in a buckled condition is about one third of that given by Southwell.


ABSTRACT: The various methods of structural analysis are reviewed, and the basic elastic buckling problem of the Euler strut is discussed. Simple models are used to show the important differences between buckling in the plastic range and classical elastic instability. Nonlinear behavior is shown often to be the key to a physically valid solution. The nonconservative nature of plastic deformation alone or in combination with nonlinearity requires concepts not to be found in classical approaches. However, the classical linearized condition of neutral equilibrium is not relevant in inelastic buckling. Analyses of the models suggest that the same information is
obtained from essentially static systems by assuming initial geometrical imperfections as by assuming dynamic disturbances. Both approaches are helpful in understanding the physical phenomena.


ABSTRACT: Descriptions are given of the test model, apparatus, and procedure. A study of the circularity plot at each station indicated (1) a fairly uniform inward radial displacement around the periphery of the model at each ring, and (2) radial displacements which were exaggerations of the initial no-load contours for those stations located midway between rings in the 4 equal bays of the model. The lobes in adjacent bays were staggered; virtually no rotation of the generator occurred at the 2 frames bounding a lobe. This mode of deformation differed from the von Mises assumption of no rotational restraint at the edge of a finite cylinder but was in agreement with 1 of the analyses of Salerno and Levine (PIBAL report 182, 1951). The von Mises theory yielded a minimum value of 123 psi for a buckled configuration of 16 lobes; the experimentally determined buckling pressure for model BR-5 was 80 psi with a buckled configuration of 14 lobes. Permanent set was evident in the regions of the first 3 lobes in the model after removal of the 80-psi pressure. The deviation of the experimental from the theoretical results was attributed to initial out-of-roundness and residual welding stresses.


ABSTRACT: During the past several years, investigation has been carried out at the Daniel Guggenheim School of Aeronautics, New York University, to study the buckling behavior of sandwich structures. The main effort has been directed towards the determination of the buckling loads of circular sandwich cylinders under different loading conditions. It was found that for cylinders with weak cores, linear theory predicts buckling loads which agree with experimental results. This is contrary to the case of homogeneous cylinders, where linear theory predicts buckling loads much higher than those observed in experiments. The reason for this has been explained in Reference 11. In this report, the theory of buckling of sandwich cylinders under axial compression, torsion, and bending, and combined loads is developed in a unified manner; and the principal experimental results are presented. The interrelationship obtained between the critical loads is plotted in the form of non-dimensional interaction curves.

References listed at the end of the paper:
12. Hoff, N.J., and Mautner, S.E., Bending and Buckling of Sandwich Beams (cannot read the rest of this citation)
15. Uerard, u., urixicai Shear Stress of Plates Above the Proportional Limit, J. of App. Mech., vol. 15 No. 1, pp. 7-12, Mar., 1948

M.L. Baron, „shell to a transverse shock wave”, Columbia University Technical Report No. 10, December 1953


ABSTRACT: We consider a thin homogeneous shell subjected to an arbitrary load causing loss of stability. We assume that the shell has some initial irregularities in its middle surface which can be described in terms of certain initial displacements. When the load is applied, these initial irregularities begin to develop due to creep and cause a redistribution of stresses over both the thickness and the entire area of the shell. This process of stress redistribution may be so considerable that at a certain moment the equilibrium state of the shell may become unstable in Euler's sense, i.e., at a certain moment several modes of equilibrium may be possible, transition to any one of these being instantaneous. We shall call this moment the “critical moment” of loss of stability of the shell. The deviation of the subcritical stress and strain state of an actual shell from the basic state corresponding to a perfectly smooth shell can be described by a system of equations in the stress and deflection functions, assuming that the quantities characterizing these deviations satisfy linearized creep relations analogous to the relations for viscoelastic bodies. This system of equations must be combined with a system of stability equations which takes into account the stresses and strains defined by the system of equations of the subcritical state.

References listed at the end of the paper:


ABSTRACT: Non-linear differential equations have been developed for the calculation of the deflections and buckling loads of Sandwich plates subjected to transverse loads and edgewise shears and compressions. The Sandwich plate consists of two thin metal face sheets bonded to a light slab-the core. The core is taken to have zero moduli as deformations in its own plane. This appears to give an adequate representation of behavior of
many core materials. Some previous theories are shown to be special cases of this more general theory. The essence of non-linearity are shown through the discussion of core properties and action of interface-and-core forces. The restriction of some special forms of displacements of practical interest has been studied and the existence of nonlinear element in the bending problem is clarified. The relative merit of using large bending deflection theory instead of the small bending deflection theory in the faces is given.


ABSTRACT: In the large deflexion of thin plates with free edges, boundary layers develop along those edges under certain conditions. The non-linear effects of membrane stress are confined to the boundary layers and elsewhere the equations are linear. Boundary layer equations are derived and integrated, and are then applied to some specific problems.


ABSTRACT: The magnitude of the uniformly distributed axial compressive load under which a thin-walled circular cylindrical shell buckles by developing bulges over its surface was calculated independently by Lorenz [1, 2], Timoshenko [3] and Southwell [4] over fifty years ago. Unfortunately, experimental results obtained both earlier, and particularly during the last thirty years, have fallen far short of the classical critical stress values. In a report presenting original test results and comparing them with data published by other investigators, Harris, Suer, Skene and Benjamin [5] showed in 1957 that the experimental buckling stress ranges between 20 and 60 percent of the classical value when the radius-to-thickness ratio $a/h$ of the shell is between 250 and 750. The maximal value given in the paper amounts to 82 percent, and the minimal value to 10 percent of the classical critical stress; the value of 10 percent was obtained with a specimen whose $a/h$ ratio was 2500.

References listed at the end of the paper:


A. Ralston, “On the problem of buckling of a hyperbolic paraboloidal shell loaded by its own weight”, Journal of Mathematics and Physics, 1956, Published for Massachusetts….


H.L. Langhaar and A.P. Boresi (Dept. of Theoretical and Applied Mechanics, Illinois University at Urbana), “Buckling and post-buckling behavior of a cylindrical shell subjected to external pressure”, April 1956, DTIC Accession Number : AD0094524, http://hdl.handle.net/2142/18754

ABSTRACT: In an earlier report (TAM Report No. 80), the authors considered the buckling and post-buckling behavior of an ideal elastic cylindrical shell loaded by uniform external pressure on its lateral surface, and by an axial compressive force. Assumptions were introduced which reduced the shell to a system with one degree of freedom. The present investigation is a generalization and a refinement of this theory. The shell is treated as a system with 21 degrees of freedom. By the imposition of constraints on the 21 generalized coordinates, various end conditions can be realized; for example, simply supported ends with flexible end plates (no axial constraint), simply supported ends with rigid end plates, and clamped ends. Also, effects of reinforcing rings have been incorporated in a more general way than in TAM Report No. 80. The restrictive assumption that the centroidal axis of a ring coincides with the middle surface of the shell has been eliminated. A pressure-deflection curve for an ideal cylindrical shell that is loaded by external pressure has the general form shown in Figure 1. The falling part of the curve (dotted in the figure) represents unstable equilibrium configurations. Also, the continuation of line OE (dotted) represents unstable unbuckled configurations. Actually, the shell snaps from some configuration A to another configuration B, as indicated by the dashed line in Figure 1. Theoretically, point A coincides with the maximum point E on the curve, but initial imperfections and accidental disturbances prevent the shell from reaching this point. Point E is the buckling pressure of the classical infinitesimal theory (called the "Euler critical pressure", since Euler applied the infinitesimal theory to columns). To some extent, point A is indeterminate, but it is presumably higher than the minimum point C unless the shell has excessive initial dents or lopsidedness. In TAM Report No. 80, a hypothesis of Tsien was used to locate point A. In the present investigation, point A is not considered. Rather, attention is focused on the development of a theory that will determine the entire load-deflection curve. For short thick shells, such as the inter-ring bays of a submarine hull, the Euler critical pressures, determined by TAM Report No. 80, are too high, presumably because the assumption that the shell buckles without incremental hoop strain is inadmissible in this range. The present report corrects this error. Numerical data on the Euler critical pressures of shells with simply supported ends and flexible end plates have been obtained with the aid of the Illiac, an electronic digital computer. The data are tabulated at the end of this report. For short shells without rings, the buckling pressures
are appreciably lower than those determined by von Mises' theory. The numerical data for the Euler buckling pressures of shells with uniformly spaced reinforcing rings are sufficiently extensive to permit interpolation to estimate effects of various ring sizes. Some exploratory numerical investigations of post-buckling behavior have been conducted with the Illiac. It is not feasible, at the present time, to handle nonlinear equilibrium problems for systems with 18 degrees of freedom. Consequently, for the numerical work, some higher harmonics were discarded so that the system was reduced to 7 degrees of freedom. Even then, the numerical problem is formidable. The calculations were confined principally to the determination of the minimum point C on the post-buckling curve (Figure 1). The pressure at point C is the minimum pressure at which a buckled form can exist. It is found that the ordinate of point C, determined by TAM report No. 80, is somewhat too high. The two theories are compared by a table and curves at the end of this report.

Henry L. Langhaar and Arthur P. Boresi, “Snap-through and post-buckling behavior of cylindrical shells under the action of external pressure”, University of Illinois Bulletin in cooperation with the Office of Naval Research, Engineering Experiment Station Bulletin No. 443, 1957

ABSTRACT: This report treats the buckling and post-buckling behavior of a cylindrical shell that is subjected to uniform external pressure p on its lateral surface, and an axial compressive force F. The force F varies with the pressure p in such a way that F = (lambda)a^2(p), in which a is the mean radius of the shell and lambda is a dimensionless constant. If the shell is immersed in a fluid at constant pressure p and if the force F results only from the pressure p on the ends, lambda = pi. The ends of the shell are assumed to provide simple support to the cylindrical wall. Accordingly, the radial and circumferential displacement components of the middle surface of the wall vanish at the ends. If the ends of the shell are free to warp, no other constraint is imposed on the deformation. If the ends of the shell are rigid, the axial displacement is constant at either end. Both of these cases were investigated. For generality, the shell was considered to be reinforced by several rings or hoops. Only geometrically perfect shells were studied; that is, initial dents and out-of-roundness were not taken into account. Only shells with a linear stress-strain relation were considered. If the axial force F is not too great, the shell assumes a fluted form when it buckles. This form is illustrated by Fig. B, which is a photograph of some of Sturm's test specimens (7). The number of flutes in the buckled form is influenced strongly by the ratio L/a, in which L is the length of the shell. Fig. C illustrates several forms of cross sections of cylindrical shells that have been buckled by external pressure. When the axial force F predominates, the buckled shell assumes a form in which diamond-shaped facets occur (1. Art. 85). This type of buckling was not considered in the present study; the axial force F was assumed to be so small that the fluted pattern occurs. The admissible range of F was not determined, but the fluted pattern usually occurs if lambda does not exceed pi.

References listed at the end of the report:


J.M. Massard (Civil Engineering Department, University of Illinois, Urbana, Illinois), “The effect of underwater explosions on ship and submarine hulls”, Experimental Program, Final Report to the Bureau of Ships, Department of the Navy, Contract Nobs 62250, Index No. 724017, December 1956


ABSTRACT: Equations for the large deflection of thin plate established by Th. von Karman has been well known for many years. But so far there have been only a few iproblems studied with numerical certainty. S. Way was the first to apply these equations to solve the problem of a clamped plate under uniform pressure by the method of power series. After this, S. Levy found the solution of the simply supported rectangular plate under uniform load by the method of double trigonometric series. Both methods are too labourious to be applicable to other more important cases. Lately, Chien Wei-zang treated Way's problem again by means of the perturbation method and obtained excellent results. By the method as given by Chien Wei-zang, Yeh Kai-yuan worked out the problem of circular plate with a central hole under central concentrated load. In this paper, more results are given for various circular plates under various edge conditions. These include uniformly loaded circular plate under various edge conditions (section 2) and central concentrated loaded circular plate under various edge conditions (section 3). Such edge conditions are: (1) simply supported, (2) simply hinged, (3) rigidly clamped, (4) clamped but free to slip, (5) edge clamped but with possible slipping in horizontal direction, (6) edge simply supported but elastically fastened, and (7) edge clamped in elastic wall. All these results are presented in such a form that direct application in design problem is possible. In particular cases,
under edge conditions (1) to (4), as \( \sqrt{=} = 0.3 \), design formulae and curves for central deflection, radial tensile stress and radial bending stress are presented.


ABSTRACT: This report is one of a series issued in cooperation with the Army-Navy-Civil Committee on aircraft design criteria under the supervision of the Aeronautical Board. Reviewed and reaffirmed March 1956. Original report issued March 1948.

N.J. Hoff, “Approximate analysis of the reduction in torsional rigidity and of the torsional buckling of solid wings under thermal stresses”, Journal of the Aeronautical Sciences, 1956

N.J. Hoff, “Buckling at high temperature”, Journal of the Royal Aeronautical Society, 1957


E. Sundstrom, “Creep buckling of cylindrical shells”, Tekniska högskolans handlingar: Transactions of the …, 1957


ABSTRACT: A problem of creep stability of columns and plates is considered. In an analysis use is made of two forms of the creep theory based on the strain hardening hypothesis. For a uniformly compressed plate a comparison is made between the results according to the flow theory and strain theory.

ABSTRACT: Available theories and test data on buckling of curved plates and shells are reviewed. The test data for torsion and external-pressure loadings are correlated in terms of linear buckling theories for both the elastic and inelastic ranges. The cases which exhibit a marked disagreement between linear theory and test data have been analyzed by a unified semi-empirical approach which is satisfactory for analysis and design purposes.

ABSTRACT: This report presents a theoretical analysis is presented for the behavior of long, circular, cylindrical shells of sandwich construction under axial compressive loads. The analysis is designed to evaluate the effects of the relatively low shearing moduli of sandwich cores on buckling stresses. Families of curves are presented for use in designing shells of sandwich construction having isotopic facings and orthotropic or isotropic cores. The results of the theoretical analysis were compared with those obtained from tests on a series of curved panels. It was found that the theory applied reasonable well to curved plates of sizes sufficient to include at least one ideal buckle. Application of the theory thus is not limited to long, complete cylinders.

ABSTRACT: The elastic stability of a thin-walled circular cylindrical shell is investigated by means of the small-deflection theory when the shell is subjected to such nonuniform heating as causes a uniform axial compressive stress to arise in a band of width 2b while the rest of the shell is free of stress. The critical value of the compressive axial stress is found to be equal to the critical stress of the same circular cylindrical shell when subjected to uniform axial compression provided the band is not extremely narrow. In the latter case the critical stress of the band is higher than that of the uniformly compressed shell.
ABSTRACT: By finite element elastic-plastic analysis it has been possible to obtain detailed information on the deformation process in the vicinity of a growing crack in sheet metal. It is found that the crack grows when the value of the crack tip opening angle exceeds some critical value. Particular attention is given to the closure behaviour if the loading forces are reduced. The results obtained are compared with experimental data. A flat triangular element with initial curvature can be looked upon as a doubly curved shell element. Thus a shell element is developed with nodal displacements in the three corner points and in the three midside points and with two parameters for rotations about each side. Element properties can be derived from quadratic displacement functions, linearly varying bending moments and linearly varying membrane deformations, the latter as an interpolation between the values in the corners. These corner values are determined by the appropriate nonlinear expressions in the displacements. On the basis of shell theory and the principle of minimum potential energy the merits of this particular finite element were thoroughly investigated. In view of its accuracy in linear problems, and since rigid body motions are fully represented, the element will also be very suitable for geometrically nonlinear problems. Though for the derivation of the features and properties of the finite elements the continuum theory will be used, in the analysis of a structure finite elements may be looked upon as models of mechanical behaviour in their own right. This approach proved to be particularly useful in the kinematic and dynamic analysis of mechanisms. Examples will be given of the kinematic description of some special elements, such as gears. Also for stability analysis the discrete approach was found to be fruitful of results. With properly chosen deformation parameters as generalized strains the buckling and postbuckling behaviour, as well as the nonlinear behaviour in general with small but finite rotations, can be analysed for struts, plates and shells, whilst the physical linearity on the level of the finite elements is retained. An effective elastic analysis of nonlinear problems is obtained in terms of perturbation equations for the participation factors of eigenvectors. These equations, limited in number, can be solved by a special method that was devised for the
computation of critical equilibrium states of nonlinear elastic systems. In this method difficulties due to matrix singularity in the incremental equations are overcome by the introduction of the path length as independent variable.


ABSTRACT: The stability of elastic-plastic sandwich shells of an arbitrary shape is investigated on the assumption that, at the moment of buckling, the load-carrying faces are in a fully plastic state and the core remains elastic. The equations are obtained on the basis of both the deformation theory and the plastic flow theory. The flexural stiffness of the faces is taken into account. The equations obtained permit the prediction of the critical loads of columns, plates, and shells of arbitrary form.


ABSTRACT: We consider in this report the determination of the upper limit of critical loads in the case of simultaneous action of a compressive force, uniformly distributed over plane cross sections, and of isotropic external normal pressure on cylindrical or conical shells of circular cross section. As a starting point we use the differential equations for neutral equilibrium of conical shells which have been used for the solution of the problem of stability of conical shells under torsion and under axial compression. Upon solution of the problem it is possible to satisfy all boundary conditions, in contrast to the report (ref. 3) where no attention is paid to the fulfillment of the boundary conditions and to the report (ref. 4) where only part of the boundary conditions are satisfied by solution of the problem according to Galerkins’s method. Approximate formulas are used for the determination of the critical external normal pressure with simultaneous action of longitudinal compression. Let us note that the formulas suggested in reference 5 are not well founded and may lead, in a number of cases, to a substantial mistake in the magnitude of the critical load.

References listed at the end of the paper:


ABSTRACT: A novel approximate theoretical solution is presented in this paper for the boundary disturbance of thin elastic shells of revolution with a nearly spherical middle surface and constant thickness. The indicated solution is a procedure of successive corrections, which was originally used by S. D. Poisson in handling non-linear differential equations and introduced into thin shell analysis by E. F. Burmistrov.


W.P. Vafakos, “Study of thermal stresses and buckling criteria of thin-walled circular conical shells”, Wright Air Development Center, 1958


ABSTRACT: A method is presented for obtaining nonlinear integro-differential equations equivalent to the differential equations of the nonlinear theory of depressed shells. It is shown that in a number of cases the integral equations obtained lead to the same results as the nonlinear differential equations.


ABSTRACT: This paper describes a practical, graphical and numerical procedure for the determination of the collapse time of pin-ended aluminum alloy columns subject to creep. A “critical deflection” is found at which the bending rigidity of the column is reduced to such an extent that the column becomes unstable under the constant load applied to it. To eliminate some of the unessential complexities of the problem, the analysis is carried out on the assumption that the actual column can be replaced by an idealized two-flange column which deflects sinusoidally up to failure. The flexural stiffness is taken as constant along the length of the column and equal to the mid-point stiffness, which is determined from the stress-strain curve of the material. The corresponding “critical time” is then calculated by using the creep-strain vs. time curves of the material. The method gives good agreement with experimental results obtained at the Polytechnic Institute of Brooklyn and at the Battelle Memorial Institute.

D.O. Brush, “Buckling of a cylindrical shell under a circumferential band load”, J. Aerospace Sci., 1959


ABSTRACT: The results of an extensive experimental program on the stability of cylindrical and conical shells under various loading conditions are presented and discussed. Loading conditions for both cylinders and cones include axial compression, axial compression with internal or external pressure, bending with and without internal pressure, axial compression combined with both bending and internal pressure, and a limited amount of data on torsion of conical shells. Where feasible, values suitable for design are recommended and areas needing additional theoretical and experimental study are indicated.


ABSTRACT: The results of an investigation to determine the influence of small deflections on the stability of internally pressurized conical shells under axial compression is presented. The critical axial load is found to depend on a geometry parameter for the small end of the cone, the internal pressure, and, unlike results for cylindrical shells, the end fixity of the shell. Experimentally obtained data are in qualitative agreement with theory but differ quantitatively, probably because of yielding of the low melting temperature alloy used to clamp the ends of the shells and yielding of the shell material.


J. Singer (Israel Inst. of Tech., Haifa) and N.J. Hoff (Stanford Unif., California), “Bucking Of Conical Shells Under External Pressure And Thermal Stresses”, AFOSR-TR-59-203, Dec 1 1959, OSTI ID: 4183539

ABSTRACT: Simplified differential equations governing the deformations of thin circular conical shells subjected to arbitrary loads and arbitrary temperature distributions are derived by the principle of the minimum total energy. The equations reduce to Donnell's expressions when the cone angle approaches zero. The same method of solution with slightly relaxed boundary conditions for the non-dimensional displacement along a generator, and the non-dimensional circumferential displacement, is then applied to the thermal buckling problem of truncated conical shells subjected to axisymmetrical temperature distributions. A typical example is analyzed. The equations are also extended to include problems of elastic stability
PARTIAL INTRODUCTION: During the next decades more and more shell-type structures in various areas of technology will be made out of composite materials. This refers also to toroidal shells encountered in spacecraft, in submarine structures, as well as in other areas of technology. In this connection it is important to investigate the stability of toroidal shells made out of composite materials having different elastic characteristics in various directions. To solve this problem we shall make use of the finite element method as the most suitable for computer implementation…


ABSTRACT: The structural design of a long range ballistic missile or a space rocket vehicle is an intriguing problem. It is hardly necessary to stress the importance of achieving as light a structure as possible, since any unnecessary increase of structural weight can severely affect its performance or result in a profound increase of its total weight. There is a dearth of published information on this subject, presumably because of security restrictions. Among the papers available, only Sechler dwells on the structural design consideration in any detail. We have therefore very few specific facts to guide us, and can only relate the problem to our aircraft design experience with commonsense.


ABSTRACT: The present article reviews some recent developments in nonlinear elastic membrane theory with special emphasis on axisymmetric deformation of flat circular and annular membranes subjected to a vertical surface load and with prescribed radial stresses or radial displacements at the edges. The nonlinear Föppl
membrane theory of small finite deflections as well as a simplified version of Reissner's finite-rotation theory is employed, assuming linear stress-strain relations. The main analytical techniques are reported which have been applied recently in order to determine the ranges of those boundary parameters for which solutions of the relevant nonlinear boundary value problems exist, and ranges of parameters for which the principal stresses are nonnegative everywhere. Concerning plane membranes, it is shown how the mathematical theory of existence and uniqueness was nearly completed in recent works in contrast to curved membranes where references can be given to rather few results.


W. Thielemann and M. Esslinger 1964 Einfluss der Randbedingungen auf die Beullast von Kreiszylinderschalen, Der Stahlbau, Vol. 33, December 1964

ABSTRACT: The objective of this investigation was to determine the polstbuckling strength of thin web plate girders. The design of transversely stiffened plate girders presently is limited to girders whose web depth to web thickness ratios do not exceed the value of 170. This limit was derived from the web buckling theory. But in discussing the application of the theoretical buckling formulae, Ref. 253, p. 415, Timoshenko suggests using a factor of safety of only 1.5…

Most of the references listed at the end of the report. (Most of these early papers are in German. I included the German titles only in the first few of the 272 references. In the many other references I give the titles in English only, even though the paper by Basler, et al. gives the titles first in German and then in English. I had to type all these references because I could not cut-and-paste. Therefore, please excuse typos. I skipped a few references either because they did not apply to buckling or because they were similar to a previous reference. I typed “etc.” on a line by itself indicating a skipped reference or skipped references.)

REFERENCES LISTED IN THE PAPER BY Basler, et al:
Corrugated Panels Due to Shear


34. Burchard, W., “Buckling of a square plate with a diagonal stiffener under compression or shear”, Ing. Archiv, Vol. 8, 1937, S. 332 etc.


43. Chwalla, E., “On the buckling problem of a longitudinally stiffened plate under bending moments and the problem of optimum stiffness”, Stahlbau, Nr. 18/20, 1944, S. 84 etc.


(Derives location of most efficient longitudinal stiffener.)


69. Gaber, E., “On the stiffening of plate girders”, Stahlbau, Heft 1 and 2, 1944 etc.


100. Klöppel, K. and Lie, K.H., “The sufficient criterion for the point of bifurcation of the elastic equilibrium”, Stahlbau, 1943, S. 17

101. Klöppel, K. and Scheer, J., “The derivation of buckling determinants of rectangular plates with stiffeners, the plate being simply supported and the stiffeners parallel to the edges”, Stahlbau, Vol. 25, 1956, S. 117 etc.


(The author used angles for his tests to simulate buckling of plates being simply supported along one edge and free along the other.)


116. Kollbrunner, C.F. and Meister, M., “Plate buckling” (Book), Springer-Verlag, Berlin (no date given)


130. Levin, L.R. and Sandlin, C.W., Jr., “Strength analysis of stiffened thick beam webs”, NACA TN 1820, 1949


136. Lundquist, E.E., “Comparison of three methods for calculating the compressive strength of flat and slightly curved sheets and stiffener combination”, NACA TN 455 (no date given, probably about 1937)


139. Lundquist, E.E. and Stowell, E.Z., “Restraint provided a flat rectangular plate by sturdy stiffener along the edges of the plate”, NACA TN 735, 1942


148. Mayers, J. and Budiansky, B., “Analysis of behavior of simply supported flat plates compressed beyond the buckling load into the plastic range”, NACA TN 3368, 1955
155. Massonnet, Ch., “The web stability of longitudinally stiffened plate3 girders subjected to pure bending”, A.I.P.C., Mém., Vol. 6, Zürich, 1940-41, pp. 234-246
172. Nádai, A., Theory of elastic plates (Book), Springer-Verlag, Berlin, 1925
176. Peters, R.G., “Buckling tests of flat rectangular plates under combined shear and longitudinal compression”, NACA TN 750,
1948


180. Pflüger, A., “Elastic Stability” (Book), Springer-Verlag, 1950


200. Scheer, J., “On the problem of the complete-stability* of simply symmetric girders with I-sections”, (*How does web buckling affect lateral buckling of the beam and vice versa? In a Doctor’s dissertation the author investigates the interaction of these two stability cases.)

201. Schleicher, F., “Buckling stresses of rectangular plates with clamped edges”, Mitteilungen der Forschungsanstalten Gutehoffnungshütte, Konzern 1, Heft 8, 1931


221. Seydel, E., “Contribution on the problem of buckling of stiffened plates due to shear”, Translation into English: NACA TM 602, 1931
236. Stowell, E.Z., “Critical shear stress of an infinitely long flat plate with equal elastic restraints against rotation along the parallel edges”, NACA WR L-476, 1943
244. Stüssi, F., Dubas, Ch. And Dubas, P., “Web buckling of plate girders with longitudinal stiffeners in the upper fifth point of the web: further study”, A.I.P.C. Mém, Vol. 8, Zürich, 1958
246. Stüssi, F., Kollbrunner, C.F. and Wanzenried, W., “The stability of rectangular plates under uniform compression, pure bending, and compression and bending”, Inst. f. Baust. a.d. E.T.H., Mitt. Nr. 26, Verlag Leemann, Zürich, 1953 (Contains calculations which check and improve various k-values obtained until 1953. They are considered to be the most accurate buckling values.) etc.
Tadao Kusuda, “Buckling of stiffened panels in elastic and strain-hardening range”, Fritz Laboratory Reports Paper No. 1668 (Fritz Laboratory Report No. 248.2), Interim Report No. 41, Civil and Environmental Engineering, Lehigh University, Bethlehem, Pennsylvania, USA, June 1958

ABSTRACT: (cannot cut and paste)

REFERENCES listed at the end of the paper:
9. Barbre, R., Beulspannungen In Rechteckplatten Mit Langssteifen Bel Gleichmassiger Druckbeanspruchung, Bauingenieur, Vol. 17, 1936

The theory of thin shells is examined and some simplified general expressions are presented. These reduce to Donnell's expressions in the case of circular cylindrical shells. An appropriate variational principle is formulated and the similarity to shallow-shell theory is shown. These results and those of the more exact Flugge shell theory are applied to the problem of free vibration of conical shells. Approximate solutions are obtained by variational methods using the various theories and various displacement and stress functions. Comparison of the results indicates that the method which utilizes a logarithmic transformation of the axial coordinate in conjunction with appropriate displacement expansion modes satisfying the geometrical boundary conditions yields results valid for both the membrane and bending cases and is capable of being used to obtain higher approximations. The results reveal that the influence of taper on membrane and bending frequencies of circular cylinders is opposite in nature, the former being increased, the latter-decreased by the taper. The general problem of panel and shell flutter is reviewed and a physical explanation of the phenomenon is offered. A general formulation is given, followed by a method of solution which is named here after Movchan and Houbolt, who apparently developed it independently. The Galerkin method is examined and its characteristics for this problem are discussed. This method is then applied in the solution of the flutter problem of cylindrical and conical shells. Extensive calculations indicate that by taking account of the previously neglected axial bending stiffness of the shell, the nature of the flutter mode is revealed and minimum flutter speeds are obtained, which are much lower than those obtained previously using 'medium shell' theory. The effect of large thermal stresses on the frequencies of plates under generalized support conditions is investigated. It is shown that whereas before buckling occurs the effect of a rising temperature is to decrease the frequencies, the opposite effect is true after buckling has taken place.
The role of the support conditions is stressed.

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63. Iguchi, S., "Die Eigenwerte Probleme fur die Elastische Rechteckige Platte", Memoirs of the Faculty of Engineering, Hokkaido Imperial University, Vol. 4, 1938, p. 305.


B.M. Broude, “Principles of the stability calculations of thin shells”, NASA Technical Translation, 1959

N.A. Alfutov, “On the dependence of the upper critical pressure of a cylindrical shell on the boundary conditions for the…”, NASA technical translation, 1959

C.E. Turner (Imperial College of Science and Technology, London S.W.7.), “Stress and deflection studies of flat-plate and toroidal expansion bellows, subjected to axial, eccentric or internal pressure loading”, ARCHIVE: Journal of Mechanical Engineering Science 1959-1982 (vols 1-23), Vol. 1, no. 1, 1959, pp. 130-143


ABSTRACT: The stability under axial compression and lateral pressure of a finite circular-cylindrical shell with an elastic core is treated by means of Donnell’s equations. For lateral pressure it is found that a previous solution treating the cylinder as a ring or a long cylinder is adequate for a wide range of combinations of length-radius ratio, radius-thickness ratio, and ratio of moduli of core and cylinder. Results for axial compression are included for completeness and to correct a previous analysis of the same problem.


D. O. Brush and B. O. Almroth (Lockheed Missiles and Space Co., Palo Alto, California, USA), “Buckling of core-stabilized cylinders under axially-symmetrical external loads”, (publisher or report number not given), January 1962, DTIC Accession Number: AD0610266
ABSTRACT: An equation is derived for the elastic stability of a circular cylindrical shell which is filled with a soft elastic core and is subjected to general axially-symmetrical lateral pressure combined with a central axial force. Numerical results are given for three lateral pressure distributions of interest in rocket motor case analysis: Uniform pressure, linearly varying pressure, and a circumferential band of pressure located at an arbitrary distance from one end of the cylinder. Comparison is made with results of previous theoretical and experimental investigations, where available.

ABSTRACT: A buckling analysis is presented for a circular cylindrical shell subjected to nonuniform external pressure. The general approach is not restricted with respect to the distribution of the lateral pressure. However, the final formulation is specialized for the case in which the pressure distribution is of the form \( p = p_0 + p_1 \cos(\phi) \) within a centrally located circumferential band. In the buckling analysis the stability criterion is based on the principle of minimum potential energy, and the Rayleigh-Ritz procedure is used to expand the displacement components in trigonometric series. Buckling pressures are computed in terms of nondimensional parameters and are presented in graphical form.


ABSTRACT: The postbuckling behavior of a circular cylindrical shell subjected to axial compression is considered. Because of numerical difficulties, previous analyses of this problem have been severely restricted and do not yield quantitatively satisfactory results. The most accurate such analysis gives a minimum postbuckling load that is approximately three times higher than corresponding test values. In the present analysis, the number of free constants in the displacement function has been considerably increased, and the computed minimum postbuckling load is in close agreement with available test results. Additional tests are suggested to support the establishment of a buckling criterion which, together with the presently computed postbuckling curve, could serve as a sound basis for the design of cylinders under axial compression.


W.F. Thielemann, “New developments in the nonlinear theories of the buckling of thin cylindrical shells”, Aeronautics and Astronautics, 1960


ABSTRACT: The correct solution of the problem of hazardous loads may be obtained only by means of statistical methods. The considerable discrepancy between the experimental values of the critical loads is explained by the fact that the value of the latter is very sensitive to initial deformations, defects in the
preparation and attachment, and to non-uniformities of loading, etc. In turn, the factors mentioned have an accidental character and are subject to some statistical laws. Knowing the laws of the distribution of these accidental factors, one can establish laws of the distribution of the parameters characteristic of the deformed state of the shell. The problem of the engineering calculation of the shell is then reduced to the determination of the load values at which the probability of 'buckling' (or of the hazardous state determined in any arbitrary sense) does not exceed some previously established value for a given construction. The statistical approach serves also as a basis for the correct interpretation of the experimental results and of the tabulation of the results of different authors.

H. Langhaar, “Buckling of a cylindrical shell subjected to external pressure”, Osterreichisches Ingenieur-Archiv, 1960

H. Langhaar (1), A. Boresi (1), L. Marcus (2) and G. Love (2)
(1) Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Ill.
(2) Allison Division of General Motors, Indianapolis, Ind.
ABSTRACT: The collapse of a cylindrical shell due to tight fiber windings is investigated theoretically and experimentally. Buckling in the infinitesimal sense of Euler appears to be possible, if the fibers are not bonded well to the shell. Perhaps more significant than the Euler critical load is a dangerous snap-through condition that may develop.

CONTENTS: Stresses Due To Impact; Impact By an Infinite Mabs: Initiation of instability, Critical length for inextensional buckling, Postbuckling behavior, Secondary buckling, Effect of internal pressure; Impact By a Finite Mass: Instability, Postbuckling behaviour, Secondary buckling; and Experimental buckling behavior: Buckling at the impacted end, Inextensional nature of buckling, and Change of buckle pattern during postbuckling.

ABSTRACT: Experimental and theoretical studies of the buckling and collapse of circular cylindrical and conical shells under longitudinal impact are described. Various conditions of loading were investigated such as impact with rigid, fluid, and granular media, and such effects as initial geometrical imperfections, edge support, and loading asymmetry were included. In addition, the effect of axial impact at velocities up to 391 ft/sec on the buckling of thin cylindrical shells was studied experimentally. Finally, three problems, relating to the experiments were studied theoretically: (1) the dynamic buckling of a circular cylindrical shell subject to an axial loading which varies linearly with time, using the nonlinear theory, (2) dynamic buckling of a circular cylindrical shell subject to a constant velocity end displacement, including the effects of plasticity and incorporating extremely large deflections, and (3) the inextensional shortening and collapse modes of conical shells for the complete range of end shortening.
A.P. Coppa, “Measurement of initial geometrical imperfections of cylindrical shells” (Imperfection maps of cylindrical shell surface measured with apparatus consisting of reference surface, rotating mounting plate, oscillograph, low pressure displacement transducer, etc), AIAA Journal, Vol. 4, January 1966, pp. 172-175

PARTIAL ABSTRACT: Experimentally observed effects of edge conditions on the buckling behavior of cylindrical shells under axial compression impact are presented. Three effects are discussed, namely, those due to (1) inward radial displacement restraint of the shell wall, (2) asymmetry of the applied loading resulting from obliquity between the impact plate and the end cross section plane of the shell, and (3) impact velocity…


ABSTRACT: (cannot cut and paste it)

Joseph Kempner, “Unified thin-shell theory”, Polytechnic Institute of Brooklyn, NY, March 1960, DTIC Accession Number : AD0689144
ABSTRACT: Structural components which have one dimension very much smaller than the other characteristic dimensions are widely used in many fields of engineering. Such plate and shell structures have received wide attention in the literature. Quite often a complex reinforced shell can be represented by an equivalent unreinforced anisotropic shell which under appropriate conditions can be considered to be of an orthotropic material. With very few exceptions, problems involving small deformations, large deformations, and buckling are treated separately with the interrelation of these three areas of theory not clearly revealed. It is the purpose of these notes to present in a concise manner a theory of thin-shells which, while revealing the essential unity of the whole of shell theory, still retains much of the simplicity afforded by the acceptance of the usual
assumptions. The general mathematical approach described by Novozhilov for problems of nonlinear elasticity is applied in the present development.


ABSTRACT: The studies briefly described stem from continuing investigations of plates and shells under external loading and elevated temperatures, and include problems of special interest to designers of missiles and aircraft. Chapter 1 presents the results of investigations of the effects of creep in structures, with particular emphasis on the bending of circular plates. Chapter 2 outlines the work performed on heat conduction problems using Biot's variational method. Chapter 3 discusses the problem of the buckling (small-deflection theory) and postbuckling (large-deflection theory) of noncircular (oval) cylindrical shells under axial compression. Chapter 4 describes work on the analysis of the effects of concentrated loads applied to reinforcing frames of finite and infinitely long circular cylindrical shells. Chapter 5 discusses the results obtained from the analysis of the dynamic response of plastic spherical shells.


J.P. Peterson, “Correlation of the buckling strength of pressurized cylinders in compression or bending with structural parameters, NASA, 1960

M.E. Lunchick, “Plasticity research on submarine pressure hulls conducted at the David Taylor Model Basin”, …, Rhode Island, April 5-7, 1960 (Symposium Publications Division)


ABSTRACT: The effects of initial imperfections and residual welding and rolling stresses on the yield strength of a stiffened cylinder were investigated by tests of a machined and stress-relieved model, Model BR-7M, identical in geometry and of the same material as a previously tested fabricated model, Model BR-7. The experimental collapse pressure of 1502 psi agreed well with collapse pressures computed from theories which account for the plastic reserve strength. The pressure at which yielding began agreed more closely with that calculated by the maximum-shear-stress or the Hencky-Von Mises criterion than with that calculated by the maximum principal-stress criterion. The data also indicated that the mathematical form of the deflection function of the shell did not change appreciably in the elastic-plastic range. Comparison of the collapse pressures of the machined and welded models indicated that, for the geometry tested, the residual welding and rolling stresses do not adversely affect the collapse pressure.

References listed at the end of the paper:


3. Von Sanden, K., and Gunther, K., “The Strength of Cylindrical Shells, Stiffened by Frames and Bulkheads, under Uniform Pressure on All Sides” (Über das Festigkeitsproblem querverstiefter Hohlzylinder unter allseitig gleichmässigem Aussendruck), Werft und Reederei, 1, Nos. 8, 9, 10 (1920), and 2, No. 17 (1921). See also David Taylor Model Basin Translation 38 (March 1952).


ABSTRACT: An approximate theory for the process is derived, leading to a solution of the type $P = Ct^{1.5} \sqrt{D}$, where $P$ is the collapse load, $t$ the shell thickness, $D$ the shell diameter, and $C$ a constant for any given material. Good agreement is exhibited between this relationship and experimental results.


ABSTRACT: The dynamic stability of a thin, perfectly conducting cylindrical shell in axial and azimuthal magnetic fields is investigated by means of the method of normal modes. It is found that in cases where a growth of a surface perturbation is indicated, the $e$-folding time corresponds to the time required for the shell to collapse radially. Where stability is predicted, an initial surface perturbation can be shown to execute an oscillatory and damped motion.


ABSTRACT: A historic review of the development of our ideas on buckling is presented. It continues with a report of work on the stability of thin shells now under way at Stanford University. The results obtained so far in this investigation can be presented under three headings: First, a new solution is found to the classical small-deflection equations of the stability of thin-walled circular cylindrical shells. The second part deals with the large displacements developing when the thin circular cylindrical shell suddenly snaps through into a polyhedral buckled shape often designated as the diamond shape. In the final part the transmission of the axial load through the fully buckled circular cylindrical shell is studied.

ABSTRACT: The bending by uniform lateral loading, buckling by two-dimensional hydrostatic pressure, and the flexural vibrations of simply supported polygonal plates are investigated. The method of meeting the boundary conditions at discrete points, together with the Marcus membrane analog [1], is found to be very advantageous. Numerical examples include the calculation of the deflections and moments, and buckling loads of triangular square, and hexagonal plates. A special technique is then given, whereby the boundary conditions are exactly satisfied along one edge, and an example of the buckling of an isosceles, right-angled triangle plate is analyzed. Finally, the frequency equation for the flexural vibrations of simply supported polygonal plates is shown to be the same as that for buckling under hydrostatic pressure, and numerical results can be written by analogy. All numerical results agree well with the exact solutions, where the latter are known.


Stachiw, J.D., “General instability of circumferentially stiffened sandwich shells subjected to uniform external pressure”, Master’s Thesis, Department of Engineering Mechanics, Pennsylvania State University, June 1961

ABSTRACT: (none given)

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77. Radkowski, P. P. "Elastic Stability of Thin Single- and Multi-Layer Conical and Cylindrical Shells Subjected to External
ABSTRACT: The stability of circular cylindrical shells under pure bending is investigated by means of Batdorf's modified Donnell's equation and the Galerkin method. The results have shown that contrary to the commonly accepted value, the maximum critical bending stress is for all practical purposes equal to the critical compressive stress.


Hiroichi Ohira 1965 Local Buckling of Circular Cylinders of Finite Length due to Axial Compression and the Effects of Edge Constraint, presented at the Fifteenth Japan National Congress for Applied Mechanics, Sept. 8, 1965, and to be published in the Proceedings. (Consise Japanese summary and a set of the figures sent to the author in October 1965.)


ABSTRACT: In this part, a method for measuring plate and shell buckling of fabrics is described. The same instrument can also be used to measure extension-compression in the plane of the fabric. The instrument consists of an attachment to the Instron Tensile Tester, and complete load-deformation curves are obtained.


ABSTRACT: Thermal stress distributions in uniform circular cylindrical shells due to axial temperature distributions are investigated. The discontinuity effect due to the presence of a cooler stiffening bulkhead is considered, and the possibility of thermal buckling of the shell due to the circumferential discontinuity stress is examined. The buckling analysis is based on Donnell's shell equation, and particular attention is given to shells having clamped edges. An experimental investigation of this buckling problem is discussed, and the results obtained are seen to agree reasonably well with theory.
ABSTRACT: Load-deformation curves obtained by the methods for shearing and buckling described in Part I and II are analyzed and discussed. Parameters obtained from these curves are given for 66 commercial fabrics covering an extreme range. Different fabrics show widely different values for the parameters obtained from both shearing and buckling curves. It is further shown that there exist close relationships between simple deformations like shearing and plane buckling and complex deformations like buckling of corrugated fabric shells. The formability of a fabric is defined as the maximum compression a fabric can take up before it buckles, given a certain geometric arrangement. The formability determines the tailorability and the crease pattern of fabrics. The formability is dependent on fabric direction, and it is shown that the integrated formability should be related to the product of buckling load and shear angle. A theoretical analysis of formability is given, and it is shown that it can be expressed as the product of an anisotropy ratio and the square of the fabric thickness. It is further shown that the shell buckling load depends on both the plane buckling load and the shear angle, in such a way that increasing shear angle leads to decreasing shell buckling load. It is shown that combination of high formability and low shell buckling load generally is attained by combining relatively high thickness with low bending modulus. It is also shown that wool fabrics generally have this combination of properties. A fabric map is given for all the commercial fabrics. Each fabric has a certain position on the map dependent on bending stiffness (which is closely related to buckling load) and shear angle. Attention is given to the relation between creasing behavior of fabrics and fabric properties. There is a certain relation between crease recovery angle and formability and a good relation between this angle and the noncyclical energy loss in shell buckling. The hypothesis that recovery properties depend mainly on the interaction within the fabric between frictional forces and elastic forces of the fibers is put forward. The energy loss following any fabric deformation depends mainly on friction. The permanent deformation is probably due to the fact that the elastic forces of the fibers cannot overcome the friction. By means of a rheological model it is shown how friction and fiber stiffness may interact in a fabric. It is shown that the stiffness value should be that obtained at infinitely slow loading of the fiber.

http://resolver.caltech.edu/CaltechETD:etd-02242004-151013
ABSTRACT: An experimental and theoretical investigation of the effect of a specific type of initial imperfection on the buckling load of a circular cylindrical shell under axial compression loading was carried out. The imperfection studied was axially symmetric in shape and had the form of a half sine wave in the length direction. Both inward and outward bowing imperfections were considered. The experiments were carried out with shells fabricated by a copper electroforming process. The shells had no longitudinal seams and had unintended imperfections of the order of the wall thickness. The buckling stress for the intended imperfection studied was only slightly influenced over a considerable range of imperfection amplitudes. The theoretical solution located the bifurcation points of the prebuckled axially symmetric state. The solution showed that outward bowing shells should have the same buckling stress as a perfect cylindrical shell and inward bowing shells should have a lower buckling stress than the perfect cylinder.


L.H.N. Lee, “Effects of modes of initial imperfections on stability of cylindrical shells under axial compression”, 1962, pp. 143-161 (publisher not given in the ProQuest-CSA file)


ABSTRACT: This paper presents a theoretical solution to the problem of determining the buckling characteristics of an axially compressed, long, cylindrical shell which contains a solid or elastic core with a modulus lower than that of the shell. The buckling mode is assumed to be sinusoidal in both the axial and circumferential directions, with the bellows mode taken as a special case. Numerical results are obtained for the buckling characteristics of cylinders with solid cores. These results are found similar to those of P. Seide, who considered the bellows buckling mode.


DOI: 10.1115/1.3640658

ABSTRACT: A theoretical study is made on the local ovaling of a relatively thick tube of low modulus caused by bending. Use is made of modified Donnell’s large-deflection theory [3] and the principle of minimum potential energy in the solution. It is found that tubes with small radius-thickness ratio tend to buckle by local ovaling rather than by the small wave pattern since the former yields lower buckling moment than the latter.


J. C. Yao, Buckling of a truncated hemispherical under axial tension. AIAA J. 1, 2316 (1963).


Yao J.C., Jenkins W.C., 1970, Buckling of elliptic cylinders under normal pressure, AIAA J., 8, 1, 22-27
ABSTRACT: The investigation of the behavior of a uniformly thick, thin spherical shell subjected to uniform external pressure in the buckling and post-buckling regions is undertaken both from a theoretical and from an experimental point of view. A perturbation scheme similar to one developed by Koiter is applied to the nonlinear buckling problem of a complete spherical shell. The nonhomogeneous linear differential equations which result are solved, with the aid of the high speed digital computer, in a finite series of Legendre polynomials. In the neighborhood of the linear buckling load, the shell is shown to be unstable both for the case of the linear buckling mode's being an odd function about the equator and for its being an even function. Four hemispherical shells made of materials with low Young's moduli (less than 1000 psi) were observed in the laboratory in several prebuckling and post-buckling states. Use of photographic methods for the measurement of the radial and tangential displacements of points marked along the meridians of the shells shows a region of small but very definite outward radial displacements adjacent to the main buckling dimple. Furthermore, the displacements observed were symmetric about the polar axis. The experimental buckling pressures observed for the four shells tend to indicate that the critical pressure calculated according to the linear theory may be the correct one, i.e., the buckling pressures varied from about half to over three quarters of the linear buckling load.


ABSTRACT: (none given)


ABSTRACT: (none given)


ABSTRACT: The most rigorous theory of the creep buckling of initially imperfect columns (due to Hoff and Fraeijs de Veubeke) is examined for possible simplifications. It is found that the influence of plasticity on the life of a column can be ignored under certain conditions characterized by the proportional limit stress, a creep parameter, the applied stress, and the initial curvature. These conditions are conveniently presented in the form of graphs for steady creep as represented by the power and the exponential laws. The simplification possible in the regions so defined permits the application of the early theories such as those due to Kemper, Libove, etc. For steady creep these lead to simple formulae which consist of the life determined according to Gerard’s suggestion multiplied by a correction factor. Some published data are examined in terms of the present ideas and give encouraging agreement with the theoretical results, for values of the correction factor ranging from 0.0074 to 1.25. Information is given on preliminary results of an experimental investigation now in progress at Stanford University.

References listed at the end of the paper:


ABSTRACT: Closed-form solutions are given of the linear Donnell equations defining the buckling of thin-walled circular cylindrical shells subjected to uniform axial compression. In addition to the classical simple support conditions requiring the vanishing of the radial displacement, the axial bending-moment resultant, the axial additional normal-stress resultant, and the circumferential displacement, three other, equally justifiable, simple support conditions are defined and studied in the case of the semi-infinite shell. Two of them yield buckling stresses amounting to about one half the classical critical stress.


DOI: 10.1115/1.3625041

ABSTRACT: Elastic stability of clamped shallow spherical shells subjected to a small finite-area load at the apex is studied experimentally. Upper and lower critical buckling loads and prebuckled and postbuckled deflections are found for lambda between 10 and 17. Buckling modes have been observed and defined. Nonaxisymmetric deformations are noted. Shells for lambda less than 8 1/2 exhibit plastic behavior and do not buckle.


ABSTRACT: The accurate calculation of stresses at boundaries and interfaces where FEM analysis may be unreliable is presently undertaken by an error analysis that derives a continuous approximation to discrete finite-element data, which can be differentiated to compute continuous stresses for component-failure predictions. An evaluation is conducted of this approximation in the context of the nonlinear PDEs. A novel interpolation formula which is a simple modification of the double Fourier sine series is used to reduce truncation errors near the rectangular plate boundary by means of an 'extended grid'. Results are presented from a FEM solution, a conventional double-Fourier series' continuous approximation, and a solution applying interpolation on the extended grid, which yields superior convergence properties near the plate boundaries.

ABSTRACT: The effect of axial elastic restraint on the instability of a circular cylindrical shell under uniform axial compression is analysed by a Rayleigh-Ritz approach within the bounds of linear theory. The effect is calculated for a wide range of parameters, and design curves are presented for the percentage increase in critical load.


## DTIC Accession Number: AD0630543

Handle / proxy Url: [http://handle.dtic.mil/100.2/AD630543](http://handle.dtic.mil/100.2/AD630543)

ABSTRACT: The analysis of the general instability of stiffened cylindrical shells under hydrostatic pressure carried out earlier is continued in order to study the inversion of the eccentricity effect. 250 typical shells of varying geometries are considered. The results show that the inversion of the eccentricity effect is practically independent of the geometry of the rings but depends very strongly on the shell geometry parameter Z. A range of inversion is found. A detailed physical explanation of the causes of the eccentricity effect and its inversion is proposed.

Selected references listed at the end of the report:


5. Geier, B. and Seggelke, P., Das Beulverhalten versteifter Zylinderschalen, Teil 2., Beullasten bei axial-symmetrischer Belastung (to be published in Zeitschrift fur Flugwissenschaften)


7. Card, M.F., “Preliminary results of compression tests on cylinders with eccentric longitudinal stiffeners” NASA TM X-1004, September 1964


Singer, J., “On the buckling of unstiffened, orthotropic and stiffened conical shells”, Presented at the 7th Congress International Aeronautique, Paris, June 1965


ABSTRACT: The effect of stiffener eccentricity on the critical load is studied for cylindrical shells under axial compression. Classical simple support and classical clamped end conditions are considered. A detailed physical explanation of the causes of the eccentricity effect is proposed and verified by computations for 350 typical shells. As in the case of buckling under hydrostatic pressure and torsion, the behavior of the eccentricity effect in the case of axial compression also depends very strongly on the geometry of the shell, represented by the Batdorf parameter. On the other hand the geometry of the stiffeners influences only its magnitude. At very low Z, inversion of the eccentricity effect occurs, but for practical dimensions outside stringers always stiffen the shell more than inside ones. The eccentricity effect has a pronounced maximum at practical values of Z. The behavior of the eccentricity effect is very similar for clamped and for simply supported shells. The effects of eccentricity of ring stiffeners are also considered.


ABSTRACT: Theoretical and experimental research on the buckling of stiffened and unstiffened conical and cylindrical shells, carried out over a period of 3 years, is summarized. The topics of earlier work are outlined and the more recent topics are summarized. These include: discreteness effect in stringer-stiffened shells and the effect of elastic restraint on panels and sub-shells; the influence of inplane boundary conditions for ring-stiffened cylindrical shells; extensive tests on stringer-stiffened cylindrical shells under axial compression and ring stiffened conical shells under torsion; and also thermal buckling of cylindrical shells.


ABSTRACT: The work is a further step towards optimization of stiffened cylindrical shells. Rings and stringers of non-uniform cross-section are analysed as a means of obtaining higher structural efficiencies. For lateral pressure loading, rings with non-uniform height or width are compared. The gain in general instability pressure
relative to the uniformly stiffened shell of the same weight amounts to 70-80%. For prescribed loading, 10-20% weight savings are obtained. For axially compressed cylinders, stringers with sinusoidal and linear height variation are studied and compared. Gains in load and weight savings of 30% and 10%, respectively, are obtained, and the sinusoidal variation is found to be superior to the linear variation. Finally, cylinders under hydrostatic pressure stiffened by a combination of uniform stringers and non-uniform rings are analysed. Different configurations are checked in order to obtain the highest possible efficiencies.


ABSTRACT: An experimental and theoretical study of the buckling of closely stiffened cylindrical and conical shells under axial compression has been undertaken to determine the influence of the stiffener geometry and spacing on the applicability of linear theory. Tests on integrally ring-stiffened cylinders, in which the spacing, cross-sectional area and eccentricity of the stiffeners are varied are described. The bounds of general instability are first determined by an elementary analysis of sub-shells and panels between stiffeners, in conjunction with “smeared” stiffener theory…

References listed at the end of the paper:
August 1957.
65. Horton, WH. and Cundari F.L., "On the Applicability of the Southwell Plot to the Interpretation of Test Data Obtained from Instability Studies of Shell Bodies", SUDAAR No. 290, Department of Aeronautics and Astronautics, Stanford University, August 1966.

ABSTRACT: An experimental program was conducted in order to determine the family of interaction curves for the buckling of unstiffened conical shells under combined axial compression, torsion, and external or internal pressure. Careful experimental technique permitted many repeated buckling tests on the same aluminum alloy shell without noticeable damage and yielded reliable interaction curves. Results of combined-loading tests are presented and compared with linear theory. Test results show that the interaction curve for compression-torsion-pressure loading is defined by superposition of compression-pressure, torsion-pressure and compression-torsion behavior.

References listed at the end of the paper:


Accession Number: AD0662358, Handle / proxy Url : http://handle.dtic.mil/100.2/AD662358
ABSTRACT: The buckling of ring-stiffened cylinders is studied by a 'discrete' approach, in which the rings are considered as linear discontinuities represented by the Dirac delta function. The analysis is a linear Donnell type theory that takes account of the eccentricity of stiffeners. Buckling loads under hydrostatic pressure, lateral pressure and axial compression are compared with those obtained by 'smeared-stiffener' theory for an extensive range of geometries. The discreteness effect depends very strongly on the geometry of the shell and the eccentricity of the rings. Significant discreteness effects are found for hydrostatic pressure loading.

References listed at the end of the report:
ABSTRACT: The stability of simply supported conical shells under axial compression is investigated for 4 different sets of in-plane boundary conditions with a linear Donnell-type theory. The first two stability equations are solved by the assumed displacement, while the third is solved by a Galerkin procedure. The boundary conditions are satisfied with 4 unknown coefficients in the expression for u and v. Both circumferential and axial restraints are found to be of primary importance. Buckling loads about half the “classical” ones are obtained for all but the stiffest simple supports SS4 (v = u = 0). Except for short shells, the effects do not depend on the length of the shell. The physical reason for the low buckling loads in the SS3 case is explained and the essential difference between cylinder and cone in this case is discussed. Buckling under combined axial compression and external or internal pressure is studied and interaction curves have been calculated for the 4 sets of in-plane boundary conditions.


Main purpose of test program is to make a close study of the influence of stiffener geometry and spacing on the applicability of the linear theory

ABSTRACT: The buckling of integrally external ringstiffened conical shells under axial compression was investigated experimentally. Experimental results were compared with theory to find the effect of the stiffener parameters (e/2h), (A2/a0h) and (I22/a0h^3) as well as of shell geometry. Agreement between classical linear theory and experiments was found to be governed primarily by the area parameter (A2/a0h), and correlation with theory was significantly affected in the range 0.1<(A2/a0h)<0.5 of that parameter. Beyond this region there is practically no improvement with increase in ring area, whereas the weight of the shell continues to increase linearly. An approximate formula is proposed for calculation of critical loads and found to yield results very close to the more exact critical values calculated by linear theory. A modified “Southwell plot” method was applied and both the intercept method and slope method were used. Critical loads computed from the strain records were found to be below the classical linear-theory predictions and closer to experimental ones.

References listed at the end of the paper:
Taylor's series is preferable. For assumptions of Koiter's theory. It is shown that a strain large reduction of the classical buckling load. The non-investigated. It seems that a slight non-
displacement relationship which in fact represents a slightly non-linear stress-strain constitutive relationship is investigated. It seems that a slight non-linearity in the stress-strain curve may lead in some cases to unexpected large reduction of the classical buckling load. The non-linear constitutive law is not consistent with the basic assumptions of Koiter's theory. It is shown that a strain-displacement relationship obtained by the use of Taylor's series is preferable. For complicated structures calculation errors are unavoidable. A straight forward
application of Koiter's theory for such structures would lead to incorrect interpretation. A method to avoid such a difficulty is proposed and both analytically and numerically described.

References listed at the end of the paper:


Abstract: Axial buckling tests on machined integrally stiffened cylindrical shells were carried out. Complete mappings of the shell imperfections and the prebuckling growth were obtained. The lightly ring-stiffened shells behaved in a manner similar to the isotropic shells that were previously tested. For these shells, the predominant prebuckling deformation consisted of a half-wave in the axial direction with several circumferential waves. The similarity of the lightly ring-stiffened shells and the isotropic ones suggests that the uniqueness of the buckling mode for stiffened shells may not greatly influence the prebuckling behavior. The heavily ring-stiffened shells showed a sizable amount of short wave length axisymmetric growth before buckling. Buckling in all cases resulted in an asymmetric pattern. The stringer-stiffened shells showed a prebuckling behavior also similar to the isotropic results. However, the buckling pattern consisted of longer axial wave lengths. Correlation of the experimentally obtained buckling loads with linear buckling theory showed good agreement in most cases.


ABSTRACT: A review of the existing knowledge of buckling of shells. Note is taken of the lack of information concerned with concrete shells as against that available for plastic and metal shells. Reported work in metal and plastic shells in the areas of elastic, inelastic, and large deflection theory of buckling is applied to concrete shells. Cylindrical shells are discussed under conditions of axial load, radial pressure load, torsional load, and bending. Spherical shells under radial pressure and curved plates under bending are also covered.


SUMMARY: The development of finite element calculational procedures for thin shell instability analysis has involved the definition of appropriate element representations (i.e. the geometric form of the element and the approximation of displacement and/or stress), constitutive expressions, and computational algorithms. Among these, the status of thin shell finite element representations remains unsettled. This paper therefore emphasizes recent developments in the basic aspects of thin shell finite element analysis and discusses one simplified approach in more detail. Formulative and computational procedures for elastic instability analysis are then summarized and numerical results are shown for the simplified shell element formulation.

References listed at the end of the paper:


ABSTRACT: Stiffness equations are formulated in representation of the elastic instability behavior of a doubly-curved thin shell element. The element is in the form of a shell of translation of constant thickness and constant principal radii of curvature. The derived relationships are expressed in curvilinear coordinates. An approximate method of eliminating unwanted degrees of freedom from the statement of the buckling eigenvalue problem is applied. Illustrative examples cover the utilization of the element in plate, cylinder, and doubly curved shell elastic instability problems with known solutions. Related comparisons assess the accuracy of the basic formulation, the approximate reduction procedure, and the ability of the present formulation to deal with special features of cylinder buckling.


R.C. Tennyson, (University of Toronto), “An experimental investigation of the buckling of circular cylindrical shells in axial compression using the photoelastic technique (Photoelastic analysis of circular cylinder shell buckling in axial compression)”, 1964 (no publisher given)


ABSTRACT: A novel method for fabricating “near-perfect” circular cylinders of photoelastic plastic is presented. The spin-casting technique was found to yield circular cylinders having thickness variations as low
as plus or minus 0.0006 in., and capable of maintaining this tolerance on shells with radius-to-thickness ratios in the range of 100 < R/t < 600. The cylinders generally were found to buckle within 10 per cent of the classical computed load, and within only a few per cent of the reduced value taking into account the clamped end constraints. This represents an increase over previous experimental data. Buckling was completely elastic, and, as a result, repeatability of the buckling load and buckling process was observed for as many as 20 tests on any one shell. Experimental evidence of the unstable states occupied by the shell during the buckling process was found by photographing the change in the 45-degree isoclinics with wave shape. Shell alignment, end constraints, and the method of applying a uniform compressive end load on the cylinder are also discussed. Although no new techniques were employed, the methods used were found reliable and accurate.

R.C. Tennyson and S.W. Welles (Institute for Aerospace Studies, University of Toronto, Ontario, Canada), “Analysis of the buckling process of circular cylindrical shells under axial compression”, February 1968, DTIC Accession Number: AD0665531

ABSTRACT: Geometrically 'near-perfect' circular cylindrical photoelastic shells having radius-to-thickness ratios of the order 100 - 440 were tested in pure axial compression. The critical buckling loads were found to agree within 10 - 14% of the classical value, or within a few percent of the reduced buckling load taking into account the clamped end constraint. High speed photographs of the buckling process were obtained using two cameras viewing the change in the 45 deg isoclinics over the entire cylinder's length and over 60% of the cylinder's perimeter. A theoretical analysis of the inception of buckling using Koiter's mode shapes demonstrated that the classical buckling mode was observed in the experiments for the first time. Further investigation of the nonlinear postbuckling mode shapes just after initial buckling predicted the wave forms observed. It was also determined that the shallow shell equations used to describe the large-deflection postbuckling behaviour do not predict isoclinic patterns which are observed in the later stages of buckling.


ABSTRACT: The effects of unreinforced circular cutouts on the buckling behavior of circular cylindrical shells subjected to axial compression have been investigated. In addition, the membrane stress distribution and isoclinic patterns were determined around the edge of the cutout, using photoelastic shells, and the results compared with recent theory. The membrane stress concentration factors were found to increase rapidly with increasing values in the curvature parameter β. Large reductions in the critical buckling loads occurred for relatively small cutouts (e.g., a 50 percent reduction in the collapse load was found for a/R = 0.10). As a result of the investigation, design information is provided for determining the effect of a/R on the critical buckling load of a circular cylindrical shell.


R.C. Tennyson, “Application of high speed photography to the photoelastic analysis of structural stability problems” (Circular cylindrical shell stability under axial compressive load, analyzing buckling process by high
speed photographic recording of photoelastic isoclinic pattern changes), SPIE JOURNAL. Vol. 8, pp. 167-174. 1970


ABSTRACT: A survey of recent work by the author on the interaction of highly controlled buckling experiments with various aspects of cylindrical shell theory for both homogeneous isotropic and laminated anisotropic structures is presented. Emphasis is placed on the necessity of utilizing accurately manufactured test models for validation of elastic buckling theory. The areas examined include: dynamic buckling under transient axial impulsive loading; static buckling of isotropic and laminated anisotropic (composite) cylinders due to combined axial compression, hydrostatic pressure and torsion loading; the effect of cylinder length on buckling behavior for both single and combined loading cases. Of particular interest is the buckling of cylinders under multiple loading where it was found that as L-squared/Rt was decreased, the interactive curve changed from 'concave' to 'convex'. The analytical models used in these studies include the effect of boundary conditions and associated nonlinear prebuckling deformations. In most instances, results are shown for both perfect and imperfect shells to demonstrate the comparative agreement one can achieve between theory and experiment.

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ABSTRACT: This report presents theoretical and experimental data on the buckling of short, homogeneous, isotropic circular cylinders subjected to simultaneous loading of axial compression and hydrostatic pressure. Of major significance is the drastic change from “concave” to “convex” interactive behavior as the Z parameter is decreased. This phenomenon is demonstrated for both clamped and simply supported boundary conditions.


ABSTRACT: Classical small deflection theory is used to derive buckling coefficients for cylinders of sandwich construction under axial compression. The core is assumed to be orthotropic, but the results do not differ much from isotropic core unless the core shear modulus is much smaller circumferentially than axially. The buckling coefficients for isotropic core and orthotropic core stiffened circumferentially are the same and are presented in a particularly simple formula…..

References listed at the end of the report:

PARTIAL INTRODUCTION: The difficulties inherent in the theory of the buckling of thin shells are most pronounced when a cylindrical shell under axial compression is considered. This problem was first attacked in the early 1900's by Lorentz, Southwell, Timoshenko, Flugge and Donnell. They neglected all terms higher than second order in the potential energy and solved the resulting linear equilibrium equations for the classical or linear buckling load (also called the Euler load). The theoretical results of the classical theory did not, however, agree well with the early experiments of Lundquist and Donnell. Significant disparities occur not only in the buckling load, which the theory predicts three to four times too high, but also in the wave form. In addition, the classical theory yields a wave pattern which envelops the entire surface of the shell and, is not in accord with the observed behavior of local instabilities. Lastly, the scatter of experimental points and the definite tendency for a shell to buckle radially inward, rather than, as predicted by the theory, both inward and outward, are two additional characteristics not described by the classical theory. Numerous attempts have been made to reconcile these discrepancies between the experiments and the classical theory. In one of the first, Flugge (16) adjusted the theoretical boundary conditions to coincide with those actually realized in the laboratory, but found only a negligible influence on the buckling loads of most cylinders. In contrast, a recent investigation by Stein (7) shows a significant drop in...

DTIC Accession Number: AD0410504, Handle / proxy Url: http://handle.dtic.mil/100.2/AD410504
ABSTRACT: Experimental verification has been made of the previously developed theoretical analysis, and corresponding design data sheet, which permits the prediction of critical shear buckling stresses for square panels of orthotropic material with clamped edges for any angle that the principal axis of elasticity makes with the reference edge. The theory correctly predicts low values of buckling stress for a 135-degree angle for materials in which the elastic constants in the two principal directions are widely different. Experiments with a woven roving laminate, in which the ratio of moduli in the principal directions is 2:1, show buckling stresses 15 percent lower than the predicted values. The differences are accounted for by the knowledge that theory predictions are about 5 percent high and by variations in properties and dimensions of actual materials which preclude the development of full buckling strength. A recommendation is made to utilize the data sheet with due consideration given to these differences.
(No references listed)

DTIC Accession Number: AD0407098, Handle / proxy Url: http://handle.dtic.mil/100.2/AD407098
ABSTRACT: The purpose of this program is to develop and prove out a theoretical method for accurately predicting the critical buckling strength of externally pressurized cylinders made from orthotropic materials and to find the optimum construction of filament reinforced plastic (FRP) cylinders under such loading. A description of the program and its significance to the overall BuShips Deep Submergence program and a summary of the work accomplished to date are given. Theoretical analytical expressions for predicting elastic buckling collapse and elastic constants of FRP cylinders are presented and discussed. Results of initial buckling and discontinuity stress analysis of proposed test cylinders are presented.

ABSTRACT: This paper shows that when very thin cylindrical shells are subjected to an external impulsive pressure, the interaction between the radial, purely extensional mode and the flexural modes is sufficient to precipitate permanent wrinkles. The theory predicts that these wrinkles occur at a wavelength which depends on the magnitude of the pressure pulse as well as on the cylinder parameters; experiments on cylindrical shells and thin strips confirm this prediction. Framing camera photographs showing the formation of wrinkles of this type are also presented.

ABSTRACT: Stiffening by means of an elastic core is demonstrated to increase significantly the resistance of a cylindrical shell to buckling from an external impulsive pressure. Both theory and experiments show that the elastic core constrains the shell to absorb more energy by membrane plastic flow. Inclusion in the theory of a continuously changing tangent modulus of the shell material leads to a critical core modulus which depends on the hoop strain and explains the increased wave numbers observed in the experiments with stiff cores.


ABSTRACT: Buckling of thin cylindrical shells from axial impact is studied under the assumption that initial imperfections can be approximated by “white noise.” Linear small-deflection theory is used to calculate the resulting growth of the normal modes, and a statistical analysis gives the expected values for the “preferred” axial and circumferential wave-lengths. Very high-speed photographs (240,000 frames/sec) of shells buckling under axial impact show excellent agreement with the theory and demonstrate that large-deflection buckling follows the pattern established by the early linear motion.


ABSTRACT: A theory of dynamic pulse buckling is developed for cylindrical shells subjected to symmetric lateral pressure pulses of duration ranging from an ideal impulse to durations so long that the pulse is a step load. To cover this range three theoretical models are used: a tangent modulus model for impulsive loads that produce plastic flow buckling, a strain reversal model for loads of intermediate duration which produce complicated elastic-plastic buckling, and an elastic model for long loads that produce elastic buckling. Peak pressure and impulse are identified as the most significan load parameters, and critical curves for buckling are generated in the pressure-impulse plane based on an amplification of shell imperfections. It is shown that these curves, from the symmetric load theory, can be used to give reasonable estimates for critical loads for smoothly varying asymmetric loads, such as from a lateral blast wave. Simple formulas are given for the critical curves in terms of the shell elastic and plastic material properties, radius-to-thickness ratio, and length-to-diameter ratio. The curves agree well with experimental results over the entire range of pressure and impulse.


ABSTRACT: The formation of small, flexural wrinkles in the walls of a sandwich shell under uniform radial impulse is examined. A buckling criterion based on the magnifications of initial wall imperfections is used to evaluate threshold impulses. Using a given weight of material, this criterion is used to determine the optimum ratios of the inner and outer wall thicknesses for various core thicknesses. It is shown that the optimum shell for a given weight of material and outer diameter is a single-wall shell. The loss in efficiency obtained by using typical sandwich shells is about 30 percent. These results are supported by experimental evidence.

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ABSTRACT: A great deal of work has been done on buckling of cylindrical shells under dynamic axial loads. The motivation for much of this work stems from the design of missiles to sustain the sudden application of thrust from rocket engine ignition. The thrust-time history is idealized as a step or a linear ramp increase to a constant operating thrust. The concern is that the dynamic buckling load may be smaller than the buckling load for a slowly applied thrust. Other applications occur in transportation accidents, where the loading is from impact and often exceeds the static buckling load.

References listed at the end of the paper:


ABSTRACT: A theory is postulated to explain the plastic buckling of cylindrical shells caused by uniform radially inward impulses. Experimental results are presented which show that the number of buckles increases with the shell length. A simple formula is derived which predicts preferred mode numbers in agreement with the experimental results for shells with lengths up to about 1 1/2 dia. For longer shells, mode numbers may be obtained by numerical integration of the equation of motion. The increase in mode number with shell length is attributed to the relative effects of the “directional” and hardening contributions to the reactive bending moment, the former stemming from yielding in a biaxial plastic state of stress. In short shells (length < dia), it is shown that the directional moment dominates, whereas in long shells (length > 3 dia) the hardening moment dominates. The mode prediction formula just mentioned applies whenever the directional moment dominates and the difficulty in treating cases where the hardening moment is significant is indicated. Again, for the former case, a simple threshold impulse formula is derived conforming to the experiments.
ABSTRACT: An experimental and theoretical investigation of dynamic buckling of thin cylindrical shells under oscillating stress waves following axial impact shows that hoop breathing response induced by the Poisson effect plays a strong role in initiating buckling, and that the stress oscillations allow buckling initially localized near the impacted end to propagate up the shell toward the free end. As a result of this energy spreading, the total compressive impulse of multipulse loading can be substantially larger than the critical impulse for a single pulse. The radial deformation of breathing provides a deterministic mechanism for initiation of symmetric buckling, which dominates early response for superclassical impact loads. For subclassical impact loads, the circumferential stress resultant from the Poisson effect excites hyperbolic growth of a large group of asymmetric modes; a continuous range of impact loads extending to values below the static classical buckling load therefore result in dynamic buckling within the scope of classical buckling theory with inertia terms added.


ABSTRACT: Comparisons between an unknown-but-bounded imperfection model and a random imperfection model show that for simple pointwise failure measures, at least, the two models give the same expressions for their measures of response, but each measure has a distinctly different interpretation. The former gives the maximum possible response for any imperfection within a specified bound. The latter gives the standard deviation of response, which, together with the statistical distribution, can be used to specify the maximum response at a specified confidence level. However, since the statistical distributions of imperfections, and hence of the response are often unknown, confidence levels are difficult to define, especially in the tail of the distribution at high confidence levels. The unknown-but-bounded model requires less information about the imperfections to come to a well-defined bound on response. It is further shown that, while the maximum possible response might seem to be a severe failure avoidance criterion, it can be less constricting than having to impose artificially high confidence levels with poorly known statistical distributions.


ABSTRACT: The theoretical basis of two related but distinctly different dynamic buckling criteria are summarized with the objective of demonstrating the range of applicability of each, so that together they cover the entire range of dynamic pulse loads from nearly impulsive loads to step loads of infinite duration. The example chosen is a cylindrical shell under elastic axial loads but the approach is applicable more generally. A critical amplification-of-imperfections criterion with a linear shell theory is shown to be applicable for short duration loads, for which a threshold nonlinear divergence criterion gives loads an order of magnitude too conservative. Conversely, the linear theory is inapplicable for long duration loads, for which critical loads are lower than the linear static buckling load because of imperfection sensitivity. In this range the threshold
nonlinear divergence criterion is used. For loads of intermediate duration, an extended critical amplification criterion is used with equations that conservatively assume zero static buckling load but give an unchanged formula for critical load amplitude-duration combinations.

References listed at the end of the paper:

ABSTRACT: Convex and probabilistic model solutions are obtained for multimode dynamic buckling of cylindrical shells with uncertain imperfections under symmetric radial impulse loads. It is found that the maximum possible buckling deformations for any imperfection within uniform bounds can be made comparable to the buckling deformations from the probabilistic models at a reliability of about 99.5 percent. Numerical evaluation and interpretation of the convex model is much simpler than for the probabilistic models, and the convex model solution provides means for quality control of each and every shell by simply recording the values of the bounds from appropriately filtered imperfection measurements.

Joshua E. Greenspon (Ballistic Research Laboratories, Aberdeen Proving Ground), “Post failure deflections of cylindrical shells under dynamic lateral loads”, AD 607746, August 1964
Joshua E. Greenspon, “Collapse, Buckling and post failure behavior of cylindrical shells under elevated temperature and dynamic loads”, AD630269, November 1965


Michael F. Card (NASA Langley Research Center, Hampton, Virginia, USA), “Bending tests of large-diameter stiffened cylinders susceptible to general instability”, NASA TN D-2200, 1964


ABSTRACT: Elastic moduli for filament wound cylinders having a wall configuration composed of several alternating helically and circumferentially wrapped layers are determined experimentally. The moduli were determined from measurements made on several glass epoxy cylinders and tubes loaded in pressure, torsion, or compression. Computations of elastic constants were made for the test specimens as well as for hypothetical boron epoxy cylinders to demonstrate the importance of the matrix in determining extensional stiffness. A comparison of calculations and experiment indicates that moduli measured in regions where the cylinder matrix behaves linearly are in reasonable agreement with computed values.


ABSTRACT: Results of compression tests conducted on 51 multilayered glass-epoxy cylinders are presented. Tests were conducted at both room temperature and elevated temperatures on cylinders having various helical wrap angles, matrix materials, and diameters. Experimental results indicate that, in some of the cylinders, failures were induced by buckling whereas, in others, failures were induced by thermal degradation and/or nonlinearity in the stiffness of the matrix material in the cylinder wall. The data obtained from the unheated cylinders are compared with buckling predictions based on linear anisotropic shell theory and with material strength predictions based on anisotropic yield criteria. The comparison indicated that agreement obtained between buckling tests and theoretical predictions was comparable to that obtained in previous experience with metal cylinders and that strength predictions were overly conservative. The results suggest that the compressive strength of a filament-wound cylinder can be limited by its material strength and that more refined material strength analyses are needed for multilayered fibrous composites loaded in axial compression.

L. K. Chang and Michael F. Card (NASA Langley Research Center, Hampton, Virginia, USA), “Thermal Buckling Analysis for Stiffened Orthotropic Cylindrical Shells” (Structural analysis of thermal buckling of orthotropic, multilayered, stiffened cylindrical shell using finite differences and determinant plotting or modal iteration), NASA Technical Note TN D-6332, April 1971

Accession Number: ADA309606, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA309606
ABSTRACT: A theory for thermal buckling of an orthotropic, multilayered, stiffened cylindrical shell is presented. The theory includes the effects of eccentricity of layers and stiffening, and deformations prior to buckling. It is sufficiently general to account for discrete rings and averaged properties of longitudinal stiffening, as well as arbitrary temperature distributions through the thickness of the shell and depth of the stiffeners. Two computer programs are described corresponding to solutions for buckling obtained by using finite differences and determinant plotting or modal iteration. Computed results for thermal buckling of unstiffened and ring-stiffened shells are presented and are in reasonable agreement with published results. The interaction of thermal loading and axial compression in two large-diameter stiffened shells representative of a launch vehicle interstage and a preliminary supersonic transport fuselage design is investigated. Results indicate that buckling can occur in both structures at a realistic temperature under thermal loading alone.

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Also see: Journal of Applied Mechanics, Vol. 31, No. 3, pp. 447-457, September 1964, DOI: 10.1115/1.3629662
ABSTRACT: A theoretical study of buckling of clamped shallow spherical shells under uniform external pressure is presented. For sufficiently large deflection, deformations of such shells are not proportional to the applied pressure. The shell deforms axisymmetrically under sufficiently low pressure. The problem of axisymmetrical snapping has been solved by different numerical methods and the results agree with each other. The buckling pressures obtained in such a manner are too high as compared with experimental results obtained in References. Initial imperfections of the shell and unsymmetrical buckling are presumed to be the sources of this discrepancy between axisymmetrical buckling theory and experiment.

ABSTRACT: For a viscoelastic clamped shallow spherical shell, the vertical deflection due to uniformly distributed external pressure is a function of time. When time reaches a critical value, the shell may snap through suddenly. This critical time depends on the magnitude of the applied pressure as well as the shell geometry. The governing equations for large deformations of viscoelastic shells can be derived by applying the correspondence principle to the equivalent equations in the elastic case. The critical times for various shells under different pressures are evaluated numerically. If the deflection volume of the shell is a constant throughout the deformation process, the external pressure decreases due to relaxation of stresses in the viscoelastic shell. This decreasing external pressure is also calculated in this paper.


ABSTRACT: The serious discrepancy between theoretical and experimental results for the buckling load of axially compressed cylindrical shells is well known. This paper presents results of a test program specifically designed to throw some light on the causes of the discrepancy. Ten nominally identical nickel cylinders were fabricated by electrodeposition and tested under both dead-weight and controlled end-shortening conditions. The test results indicate the following: the buckling load under usual laboratory conditions depends on the properties of the test specimen itself rather than on the testing environment, the buckling loads under dead-weight and controlled end-shortening conditions are the same, a sharp puff of air during loading can cause buckling at a considerably reduced load level, minimization of initial imperfections in the test specimens greatly increases the buckling load, and the magnitude of the minimum postbuckling equilibrium load is relatively insensitive to initial imperfections


OUTLINE: Contents: The elastic law; Equations of equilibrium; Shells of revolution under axially symmetric loads; Toroidal shell under external pressure-theoretical analysis; Toroidal shell under external pressure-numerical results; Free vibrations of prestressed shells of revolution.


BRIEF SUMMARY: Report tests "conducted on nominal 8.0-in.-OD by 0.25-in.-wall and 4.0-in.-OD by 0.12-in.-wall specimens made from commercial pipe and tubing" (p. 1).


ABSTRACT: An experimental investigation was carried out to determine the critical buckling loads of several shallow spherical sandwich shells. A cold-forming process simultaneously using pressure and vacuum was employed to manufacture the nearly perfect spherical facing layers from 5052 aluminum-alloy sheets of 0.006 and of 0.008-in. thicknesses. Eight shallow spherical-shell specimens of 20-in. base diameter and of 20 and 30-
in. radii with 1/8 and 1/4-in. thickness of “Flexcore” have been tested in a 300-psi autoclave specifically designed for these experiments. The pressure on shells was developed by the differential pressure between the inner and the outer chambers separated by the shell being tested. When the inner chamber was maintained at atmospheric pressure and gas pressure was applied in the outer chamber, the testing procedure was termed “soft.” Alternatively, the inner chamber would be filled with fluid with the outer chamber remaining filled with gas. By initially pressurizing both chambers equally, a load on the shell could be developed by the differential pressure due to controlled bleeding of the fluid inside the inner chamber, while the gas in the outer chamber was maintained at the initial pressure. This is an accurate volume-control experiment and this testing procedure was termed “hard.” In the latter case, it was possible to monitor the displacements of the shell for each load increment with a nest of clip gages of an unique design. It was found that there is no substantial difference in the buckling loads between the hard and “soft” systems. All shells buckled in the plastic range. A reasonably good correlation is obtained with a linear theory using the double modulus for the sandwich segments.

References listed at the end of the paper:


A.J. Sobey (Delft University of Technology, The Netherlands), “The buckling of an axially loaded circular cylinder with initial imperfections”, RAE Technical Report 64016, September 30, 1964, Royal Aircraft Establishment, uuid: 489c0c0e-ca73-44aa-8f22-dbc60d90c0e3
ABSTRACT: An extension of the Donnell and Wan analysis for the buckling of a shell with initial imperfections is presented for a mode of arbitrary profile. Results for a mode with 26 arbitrary parameters are given with charts of the stress strain characteristics for cylinders with initial displacements of between one eighth and five times the skin thickness of the cylinder. A direct optimisation of the energy function is used. Almroth's minimum post buckled stress for the ideal cylinder (0.0656 Et/R) is lowered to 0.0518 Et/R and a critical assessment of the value of such figures provided.


ABSTRACT: The theoretical estimation of the buckling strength of a cylinder loaded in axial compression is improved by the use of a more representative deflected form of the buckled cylinder than has previously been used. Kempner’s buckling strength for dead-weight loading is reduced by 18 per cent. The presentation of the magnitude and distribution of the constraint system required to maintain the mode is novel and instructive. References listed at the end of the paper:

D.M.A. Leggett and R.P.N. Jones, “The behavior of a cylindrical shell under axial compression when the buckling load has been exceeded”, A.R.C. R. & M. 2190, August 1942


ABSTRACT: Calculations are presented from an analytical investigation on the influence of ring stiffeners on the instability modes of orthotropic cylinders subject to compressive or bending loads. The analysis is performed by employing small-deflection theory and by modifying the equilibrium equations to include the effects of discrete ring stiffeners characterized by a bending stiffness that restrains radial deformation of the shell. These calculations indicate that the ring bending stiffness necessary to cause panel instability can be adequately determined by use of an analysis which does not include the discreteness of the rings. Comparison of the results of the calculations with an empirical ring design criterion in common use indicates that the empirical formula can be either very conservative or very nonconservative depending on the cylinder geometry.


ABSTRACT: A small-deflection theory for buckling of stiffened orthotropic cylinders which includes eccentricity (one-sided) effects in the stiffeners is derived from energy principles. Buckling solutions
corresponding to classical simple-support boundary conditions are obtained for both orthotropic and isotropic stiffened cylinders subjected to any combination of axial and circumferential loading. Comparable solutions for stiffened flat plates are also given. Sample calculations of predicted compressive buckling loads obtained from the solutions are compared with existing solutions for ring-stiffened corrugated cylinders, ring-and-stringer-stiffened cylinders, and longitudinally (stringer) stiffened cylinders. The calculations demonstrate that eccentricity effects are large even with very large diameter cylinders of practical proportions and should be accounted for in any buckling analysis.


ABSTRACT: The stability of stiffened orthotropic cylinders which include the effects of eccentric stiffeners and are loaded with pure bending or any combination of bending and compression is investigated analytically by means of a small deflection theory. Solutions to the buckling equations are obtained for simple support boundary conditions by use of the Galerkin method. The pure bending buckling loads are compared with existing pure compression buckling loads for three contemporary cylinder configurations. Also shown are predicted buckling modes and typical interaction curves between bending and compression. The results show that eccentricity effects are substantial and that the maximum pure bending load may be as much as 40 percent greater than the pure compression load.


ABSTRACT: Buckling experiments were performed on a series of model torispherical bulkheads loaded by internal fluid pressure. Models were rigid polyvinyl chloride with a base diameter of 10.52 in. Parameters examined included thickness, central angle and toroidal radius. Initial data obtained show the critical buckling pressure to vary as a power of the thickness and almost linearly with central angle. The buckling pressure was found also to be very sensitive to change in toroidal radius. The use of rigid polyvinyl chloride as a model material permitted economical fabrication of test bulkheads with very uniform thickness and uniform material properties throughout.


ABSTRACT: Measurements were made of the dynamic buckling displacements of the surfaces of spherical caps during buckling under uniform external pressure. Relationships between shell geometry and the magnitude of the surface displacements, velocities and accelerations during buckling were obtained. The use of a displacement transducer whose sensing element is a photovoltaic cell is described.

PARTIAL INTRODUCTION: The problems of determining theoretically the conditions under which a thin circular shell under axial compression becomes unstable, and of determining the postbuckling behavior of the shell have been of interest to engineers and scientists for nearly sixty years. The first theoretical work on this problem was done by such noted investigators as Lorentz (1), Timoshenko (2) Southwell (3), and Flugge(4). They found what might be called the classical or Euler buckling load. This is the load at which an equilibrium configuration differing from the initial configuration by an infinitesimal displacement can be found. In other words, it is the load at which a bifurcation in the load-axial deflection curve exists. When a cylindrical shell buckles, the change in the potential energy of the shell can be expressed as a sum of second, third, and fourth order terms in the radial displacement, wr. The equilibrium equation in the radial direction can be found by setting the first variation of this additional potential energy equal to zero. If only the second order terms are used, the resulting equilibrium equation is linear. The resulting system is homogeneous, and the lowest value of axial load for which a nontrivial solution exists is the Euler load… References listed at the end of the dissertation:


ABSTRACT: Energy expressions and related differential equations for non-circular cylindrical shells, analogous to the corresponding relations presented by Donnell for thin-walled circular cylindrical shells, are summarized. Appropriate energy expressions are then applied to the classical buckling and to the nonlinear postbuckling problems of an axially compressed oval cylinder whose cross section is characterized by a simplified form of an expression proposed by Marguerre. In the case of classical buckling, the results show, for a range of major-to-minor axis ratio of the cross section lying between 1 (the circular cylinder) and 2.06, that the out-of-roundness has a marked effect on the critical load, and that introduction of the maximum radius of curvature into the formula for the classical buckling stress of a circular cylinder leads to good results for thin-walled shells of moderate eccentricity of the cross section. The postbuckling behavior is investigated through the application of the principle of stationary potential energy together with an approximate deflection function. The latter represents a modification of the expression applied earlier by the authors. The new results show that, in addition to the previously observed relative minimum postbuckling load, a relative maximum postbuckling load can exist. Furthermore, for controlled end-displacement loading, the large-deflection load vs end-shortening curve can correspond to stable equilibrium configurations throughout the entire loading range, whereas for dead-weight loading the region of the curve between the maximum and the minimum loads represents unstable configurations.

References listed at the end of the paper:

ABSTRACT: Buckling and initial postbuckling of an oval cylindrical shell under pure bending and under combined uniform axial compression and bending is investigated. The first- and second-order stability equations are developed from the Donnell-type equations that are shown to be appropriate. The solution of these two sets of equations determines, respectively, the buckling characteristics and a “sensitivity parameter.” The buckling loads are found to be in good agreement with the engineering approximation based on the assumption that buckling occurs when the local axial stress equals that corresponding to the classical buckling stress of a locally equivalent circular cylindrical shell under uniform axial compression. Results also show that an oval cylinder can be stronger or weaker than the equivalent circular cylinder, depending on the orientation of the couples. However, in any case the oval shell is always found to be sensitive to imperfections; the greater the load-carrying capacity, the greater the sensitivity. Furthermore, in contrast to the behavior of the circular and weak oval cylinders, buckling of the strong oval cylinder need not initiate at the position of maximum compressive stress.


ABSTRACT: The serious discrepancy between theoretical and experimental results for the buckling load of axially compressed cylindrical shells is well known. This paper presents results of a test program specifically designed to throw some light on the causes of the discrepancy. Ten nominally identical nickel cylinders were fabricated by electrodeposition and tested under both dead-weight and controlled end-shortening conditions. The test results indicate the following: the buckling load under usual laboratory conditions depends on the properties of the test specimen itself rather than on the testing environment, the buckling loads under dead-weight and controlled end-shortening conditions are the same, a sharp puff of air during loading can cause buckling at a considerably reduced load level, minimization of initial imperfections in the test specimens greatly increases the buckling load, and the magnitude of the minimum postbuckling equilibrium load is relatively insensitive to initial imperfections.

References listed at the end of the paper:

ABSTRACT: Recent investigations by Stein and by Fischer on the influence of edge conditions on the critical load of cylindrical shells are here extended to cover six additional combinations of boundary conditions. The results show that drastic reductions of the critical load for cylinders with lateral support of the edges are obtained only if the edges are free in the tangential direction. For other boundary conditions, this reduction is never more than about 20 percent. Consequently, the results of this investigation alone cannot explain the well-known discrepancy between theory and test data. However, the importance of the choice of boundary conditions for practical analysis is clearly demonstrated.


ABSTRACT: Recent investigations on the influence of edge conditions on the critical axial load of cylindrical shells are extended here to include cylinders with elastic edge restraint. It is shown that weak edge conditions are unlikely to affect the critical load significantly in experiments or in practice. Also the effects of symmetric initial imperfections were investigated. The critical load for cylinders with initial imperfections in the form of a cosine function was found to be somewhat lower than was indicated in a previous analysis by Koiter. The analysis also disclosed that very short cylinders would not be sensitive to the types of imperfections which were considered. A few tests were performed and their results tend to support this conclusion.


ABSTRACT: Axial compression tests were performed on eleven thin-walled aluminum cylinders with rectangular cutouts. Various types of cutout reinforcement were installed on seven of the test specimens. The test results are compared with the cylinder buckling loads prior to installation of the cutouts, and correlated with computer-predicted failure loads. The latter were based on the use of the STAGS computer program. For thin cylinders such as these, the test and computer-based analysis shows that for small to moderate size cutouts, reinforcement of the cutout is of no benefit unless the cylinder is of extremely high (geometrical) quality. For cylinder quality and cutout size where reinforcement is beneficial, the relative merits of the various reinforcement configurations are discussed and an empirical basis for design is proposed.


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ABSTRACT: (shells, failure, structural properties, numerical analysis, buckling, plastic properties, tensor analysis, computer programming newton-raphson method, collapse, plates, finite difference theory, stags computer program, structural analysis. The report presents a theory for nonlinear collapse analysis of shells with general shape. The theory combines energy principals and finite difference methods to obtain a system of nonlinear equations; these are solved by a modified Newton-Raphson technique. For greater economy and flexibility in the analysis a capability is provided for use of variable spacing finite difference grids. Inelastic material behavior, as predicted by the White-Besseling Theory, is incorporated into the analysis. A computer code, STAGS, based on the theory has been written and used to solve a number of sample problems. Results for these problems are presented.


ABSTRACT: Some examples in which the high-speed computer has been used to improve the static stability analysis capability for general shells are examined. The fundamental concepts of static stability are reviewed with emphasis on the differences between linear bifurcation buckling and nonlinear collapse. The analysis is
limited to the stability of conservative systems. Three examples are considered. The problem of cylinders subjected to bending loads is used as an example to illustrate that a simple structure can have a sufficiently complicated nonlinear behavior to require a computer analysis for accurate results. An analysis of the problems involved in the modeling of stiffening elements in plate and shell structures illustrates the necessity that the analyst recognizes all important deformation modes. The stability analysis of the Skylab structure indicates the size of problems that can be solved with current state-of-the-art capability.

ABSTRACT: An efficient and general computer program for structural analysis allows the user to choose between a number of different procedures. New methods for computerized structural analysis are still being improved at a rapid pace. Consequently only a very few structural analysts can be expected to be well acquainted with all aspects of the technology, and will often find it difficult to use the sophisticated programs that presently are available. If dynamic loading or possible stability failure must be considered, the computer programs are becoming increasingly difficult to use. The trends in future computer programming for structural analysis must include efforts to facilitate the user's burden without significant loss of efficiency. This paper contains a discussion of the difficulties involved in modeling and in the choice of solution procedures. Special emphasis is placed on the possibility of designing computer programs so that sound selection of procedures can be made automatically if the user declines to state a preference.

ABSTRACT: An evaluation is undertaken of currently used discretization procedures in numerical analysis of structures. Emphasis is on the nonlinear behavior of thin shells and plates. It is found that the computer economy is extremely sensitive to the choice of element configuration. A proper balance between the order of the approximations of inplane and lateral displacements is important. The best finite element procedures are superior to finite differences for bifurcation buckling and for moderate nonlinearity. However, for shell collapse analysis the finite differences approach is quite superior to the finite elements. Suggestions are made for improvement of finite element technology for structures undergoing large rotations.

ABSTRACT: Composite materials have favorable stiffness/weight and strength/ weight ratios. Since the technology is relatively new and use of such materials introduces special problems, there has been some reluctance among designers to adopt composites in primary structures, particularly for buckling critical components. The purpose of the review of the literature presented in this report is to illustrate the special problems connected with use of composites. The body of the report summarizes the conclusions the author felt could be based on the available material. The Appendix contains an annotated bibliography, listing 95 references on the subject.  
The references listed in Section VII of the report, pp. 18 and 19:

**Also from the 1981 Almroth Report:**

**References listed in Section A of the Appendix, A. General Theory:**

The publications in Section A discuss the bifurcation buckling analysis based on a first order shell theory, i.e., the influence of transverse shear deformations is not included.


Almroth’s comments: This paper does not discuss the buckling. However, it appears to represent the first recognition of the importance of the membrane-bending coupling. It is indicated that the plate bending stiffness due to this effect can be considerably reduced.
Almroth’s comments: The paper derives the general theory of buckling of laminated plates. Many of the applications to practical cases presented subsequently were based on these equations.

Almroth’s comments: A completely general set of buckling equations for cylindrical shells is derived. An analytic solution for special boundary conditions is presented.

Almroth’s comments: The theory of Reference A-2 is applied in a study of the buckling of cylindrical shells. The results indicate a deleterious effect of the membrane bending coupling.

Almroth’s comments: The paper shows by use of theory as well as experiment that if both ends of an anisotropic cylinder are restrained from rotation, an applied axial extension results in the development of inplane shear in the shell wall and eventually in buckling.

Almroth’s comments: The stability equations, including "smeared stiffeners" are derived and applied to one example. The author warns that the coupling between membrane and bending effects should not be overlooked.

Almroth’s comments: The paper presents an approximate method to account for membrane bending coupling by reducing the bending stiffness in an orthotropic analysis.

Almroth’s comments: A Fourier series solution, including membrane bending coupling, is derived. It is shown that this coupling is important if the plies are few but that the deleterious effect can be practically eliminated in plates with many plies (six or more). For crossplies (theta = 0deg., 90deg.) the reduced stiffness method presented in Reference A-7 gives a good approximation.

Almroth’s comments: Nonlinear equations including the effect of coupling between membrane and bending action. Subsequently, the equations are linearized and used in a bifurcation buckling analysis of angle-ply plates. The number of plies and the fiber orientation are varied. With only two layers, theta = 45deg. and EI/E2 = 40, the coupling effect reduces the buckling load by a factor of about three.
Almroth’s comments: A Galerkin solution is presented to the buckling problem for anisotropic plates with simple support and under different types of loading. Effects of membrane bending coupling are included and the reduced stiffness method of Reference A-7 is found to be a good approximation.

Almroth’s comments: The theory neglects anisotropy as well as membrane bending coupling.

Almroth’s comments: The paper summarizes some of the work on buckling and vibrations of composite material plates. A warning is issued that the reduced bending stiffness approach (Reference A-7) may not always be accurate.

Almroth’s comments: The stress-strain curve for the material is assumed to be bilinear with the discontinuity at the origin. An interaction curve for axial load and lateral pressure buckling is computed for a material with the tension modulus twice as large as the compression modulus. Further results on this topic are presented in Reference A-26.

Almroth’s comments: Aluminum cylindrical shells with T-stiffeners are reinforced with strips of boron-epoxy. It is shown that 10% of the composite material by volume can increase the buckling load by as much as 80% for elliptical cylinders under external pressure. A couple of experiments verify the analytical results.

Almroth’s comments: Theoretical results are presented for the buckling of single-ply rectangular plates. Buckling loads are given as functions of the fiber orientation.

Almroth’s comments: Toroidal shell segments are analyzed. The effects of membrane bending coupling are demonstrated.

Almroth’s comments: Essentially the same as Reference A-14. A computer program listing is added.

Almroth’s comments: The author observes that the stress-strain curve for shear in single laminates may be highly nonlinear. This may reflect the time dependence of the deformation of the matrix. The results indicate
that inclusion of this effect might reduce the buckling load by some 5%. The effect may be of importance when composites are used at elevated temperatures.


Almroth’s comments: The paper considers two different stacking sequences for the wall of cylindrical, barrel shaped, "inversely barrel shaped", and spherical shells. The stacking sequence that gives the highest buckling loads for cylinders and spheres is found to be the least efficient for barrel shaped shells.


Almroth’s comments: The computer program BUCLISP 2 for buckling of panels and including composite material is described. The program applies to cases in which it can be assumed that the buckling mode in the direction of the stiffeners is sinusoidal. Some numerical results are presented. These include some comparisons to analytical solutions. Special problems considered are comparison between bonded and riveted structures and the effects of boron fiber reinforcement of titanium panels.


Almroth’s comments: This is an excerpt from Reference A-20.


Almroth’s comments: Circular plates, materially orthotropic with respect to the polar coordinates, are subjected to axisymmetric loading. Buckling loads are presented for a few cases demonstrating some sensitivity to the fiber orientation.


Almroth’s comments: This very brief note shows how natural frequencies for 45-degree angle-ply and cross-ply plates vary as the buckling load is approached.


Almroth’s comments: The effect of membrane bending coupling is illustrated by use of a few examples.


Almroth’s comments: Some numerical results from BUCLAP2 on the buckling of long laminated plates are presented. A warning is included that the "reduced bending stiffness method" (Reference A-7) does not always give good results.


Almroth’s comments: A buckling criterion is derived for shells with different moduli in tension and
compression. The effect of this difference is significant only if the ratio between the moduli is larger, say 2 or so, than it is for most composites. The effect is illustrated on interaction curves where discontinuities occur as the stress in one direction changes sign. Presumably the modulus in any given direction also depends on the stress in the other direction. If such an effect could be included, the interaction curves may be somewhat smoother.

Almroth’s comments: A discussion is presented on the critical buckling loads for typical tubular stress specimen for assessment of strength and stiffness.

Almroth’s comments: The paper elaborates on the applicability of bifurcation theory in view of the lateral displacements caused by membrane bending coupling effects. The bifurcation buckling load is a meaningful parameter only if prebuckling bending is insignificant. It is claimed that the "reduced bending stiffness method" (Reference A-7) is applicable only if the principal directions of the laminates are parallel to the plate edges.

Almroth’s comments: The need to include membrane bending coupling effects in buckling and vibration analyses is demonstrated.

Almroth’s comments: The paper considers optimum fiber orientation for angle plies with 20 layers. Plates with different aspect ratios are included.


Almroth’s comments: A large number of numerical results are presented for rectangular orthotropic panels in shear. The variation of shear and compression buckling loads with the fiber orientation is presented for plates of different aspect ratios.

Almroth’s comments: A buckling analysis based on a sinusoidal mode is presented. It is pointed out that constraint on transverse displacement can severely reduce the buckling load.

Almroth’s comments: The paper reviews the literature on the problem of buckling of cylindrical shells under different loading conditions. The special problems of nonlinear stress/strain behavior, different moduli in
tension and compression and the effects of shape imperfections are discussed. In addition to the review, a series of torsion tests are reported with the experimental results ranging from 0.79 to 1.17 times the analytical. The conclusion is that a moderate reduction factor is sufficient in the case of torsion. In the case of axial compression, a more severe reduction is needed. The authors suggest that many more tests are needed.

Almroth’s comments: A Galerkin solution based on beam functions is presented for bifurcation buckling and flutter. The emphasis in the paper is on the effects of anisotropy and fiber-orientation. Both for shear and axial compression, the optimum angle-ply corresponds to a fiber orientation of about 45 degrees.

Almroth’s comments: A two-term Galerkin solution is used for analysis of critical axial compression of orthotropic plates. Results are given for different degrees of rotational constraint along the edges.

Almroth’s comments: Local and general instability failures are considered for a compression member in a lightweight satellite structure of composite material. Results of two crippling tests show good agreement with analysis.

References listed in Section B of the Appendix of Almroth’s 1981 report, B. EFFECTS OF TRANSVERSE SHEAR:
The following publications are concerned with the deleterious effects of transverse shear deformation on the buckling load of shells and plates. While the first two are concerned with the theory in general, the remaining papers apply specifically to composite material.

Almroth’s comments: The effect of transverse shear is introduced in the plate bending theory. The shear stress distribution through the thickness is assumed to vary in a way that is consistent with a linear normal stress distribution.

Almroth’s comments: The influence of transverse shear deformation is introduced in a way that is similar to the procedure in Reference B-1.

Almroth’s comments: A laminated shell is modeled by representation of bond layers with a set of springs. The springs can deform in the lateral direction and also undergo slip to represent the shear deformation. A few numerical results are given.

Almroth’s comments: The paper considers the effect on the buckling of isotropic plates of the transverse shear deformation. Results are given for simply supported plates of different aspect ratios.

Almroth’s comments: Shear deformations in the bond layer between different laminates are included in an analysis of bending and buckling of laminated beams.

Almroth’s comments: Equations for vibration and buckling are derived for plates consisting of isotropic lamina. Some results are given for three-ply laminates. If the shear modulus is the same in all lamina and h/b = 0.1, the error due to neglect of transverse shear is about 7%. If the shear stiffness in the middle layer is reduced by a factor of 15, the error is 35%.

Almroth’s comments: The theory of Reference B-6 is extended to orthotropic laminates. It is shown by comparison to 3-dimensional analysis that the second order shell theories by Reissner and Mindlin (References B-1 and B-2) give good results for very thick plates.

Almroth’s comments: The effect of transverse shear on the buckling of composite material columns is studied. Results are shown in the range of 20 < EI/G < 50.

Almroth’s comments: A theory is derived for buckling of laminated shells in which the transverse shear deformation is included and the corresponding modulus can vary from layer to layer. Buckling loads are presented as functions of G/E in the range of 0.01 - 1.0.

Almroth’s comments: Mindlin's second order theory (Ref. B-2) is used in analysis of plates of width b loaded in the axial direction. The aspect ratio a/b and the parameter S is approximately equal to (EI/GT)x(h/b)^2 are varied in a parametric study.

Almroth’s comments: A second order theory (Reissner-Mindlin) is derived. Results from this theory are compared to results from three-dimensional theory. It is found that the plate theory can give good approximations for plates with b/h = 0.3. It is also found that the correction for shear deformation varies with the number of layers. With moduli typical for glass/epoxy composites (EI/E2 = 30 and the transverse shear moduli 0.5 and 0.6 times E2 ) it is found that the effect should be included if h/b > 0.05.
Almroth’s comments: For the purpose of examining the effects of transverse shear, it adds little to the results of Reference B-11.

Almroth’s comments: The paper is primarily concerned with computer economy. In regard to the effects of transverse shear deformation, it is noted that this effect in the postbuckling range is similar to its effect on the buckling load. That is, it should be included for a typical (simply supported plate) if h/b > 0.05.

References listed in Section C of the Appendix of Almroth’s 1981 report, C. IMPERFECTION SENSITIVITY AND POSTBUCKLING STRENGTH
The following publications discuss the imperfection sensitivity of the buckling load and possible postbuckling strength for plates and shells in compression. Except for the first three papers on the general theory, they consider the special problems connected with use of composite materials.


Almroth’s comments: An analysis is presented of buckling and postbuckling behavior of simply supported cylindrical shells of composite material. A Donnell type theory including the effects of anisotropy is used. The deformation pattern in the postbuckling range is represented by a four term series. Numerical results are obtained for a number of different three-layered shells. The maximum efficiency is obtained with the combinations theta = (0deg., 70deg., -70deg.) and (90deg., 20deg., -20deg.).

Almroth’s comments: A nonlinear analysis is formulated for anisotropic shells with imperfections under torsional loading. The numerical results indicate moderate imperfection sensitivity.

ABSTRACT: A perturbation technique is employed to determine the critical buckling stress of a simply supported rectangular plate of variable thickness. The differential equation is derived for a general thickness
variation. The problem of bending, vibration, buckling, and that of dynamic stability of a variable thickness plate can be deduced from this equation. The problem of buckling of a rectangular plate with simply supported edges and having general variation in thickness in one direction is considered in detail. The solution is presented in a form such as can be easily adopted for computing critical buckling stress, once the thickness variation is known. The numerical values obtained from the present analysis are in excellent agreement with the published results.


Almroth’s comments: The same deformation mode as in Reference C-3 is here applied in a nonlinear analysis of axially compressed cylinders with geometric imperfections. Shells with close to optimum fiber orientation appear to be the more sensitive, but within the range under investigation the optimum orientation remains unchanged.


Almroth’s comments: The paper contains a summary of the results presented in Reference C-3.


Almroth’s comments: The analysis of Reference C-3 is extended through the addition of an internal pressure. It is shown that the internal pressure has a beneficial effect on the imperfection sensitivity. For the cases investigated, the Donnell and Sanders equations give essentially the same results.

ABSTRACT: In recent years orthotopic cylindrical shells such as stiffened or fiber reinforced cylinders have been used extensively in aerospace structures. These structures are often subjected to axial compression and internal pressure. The thin cylindrical shells are known to be imperfection sensitive, and their buckling loads are substantially reduced by the presence of small initial deviations from the circular shape of the shell. The behavior of imperfect cylindrical shells has been studied by various investigators [1–5]. Both isotropic and anisotropic shells have been considered in these structures. In most of these investigations Karman-Donnell strain-displacement equations were used.

References listed at the end of the paper:


Almroth’s comments: The paper presents some of the results in Reference C-6 in a more readily available source.

Almroth’s comments: It is concluded in the paper that composite shells may be somewhat less sensitive to imperfections than the isotropic shells are. Consistently with this observation it is found that boron-epoxy shells are less sensitive than glass-epoxy shells.


Almroth’s comments: A method is presented to determine the “knockdown factor” for different types of cylinders based on their relative sensitivity to axisymmetric imperfections (Koiter's special theory). For composite material cylinders (filament wound), it appears that the method gives results that are only slightly less conservative than those obtained through application of the same knockdown factor as for an isotropic cylinder with the same "effective thickness."


Almroth’s comments: In this paper the authors base their analysis on Koiter's general theory. In comparison to Reference C-6, shells with larger imperfection amplitude are included in the study. With an imperfection of about the size of the shell thickness, the advantage of using a fiber orientation close to optimum is totally eliminated.


Almroth’s comments: The effect of axisymmetric imperfections is studied by use of Koiter's special theory. The numerical study is restricted to the three-layered combinations (theta, 0deg., -theta) and (theta, -theta, 0deg.), of which the latter appear to be the most efficient. As in Reference C-9, it is shown that shells with optimum fiber orientation are the most sensitive to imperfections and that a moderate imperfection amplitude is sufficient to wash out the advantages of an optimum design.


Almroth’s comments: A buckling and postbuckling analysis based on a double Fourier-series approach is presented for flat plates. Some plots are given that indicate outer surface stresses as functions of applied load.


Almroth’s comments: A number of cylinders were measured to determine initial deviations from true geometry. The axisymmetric part of the imperfections was isolated and Koiter's special theory applied. The same results are also presented in Reference D-2 with some additional detail.

C-17. Kulkarni, S. V., and Frederick, D., Buckling of Partially Debonded Layered Cylindrical Shells,
Almroth’s comments: A local buckling analysis is applied to the two separate branches corresponding to an axisymmetric delamination at midplane.

Almroth’s comments: This represents an extension of the investigation reported in Reference C-15.

Almroth’s comments: In contrast to References C-15 and C-18, this paper considers the case in which the applied shortening is uniform rather than the force intensity. The postbuckling analysis is based on the assumption that the lateral displacement varies sinusoidally in the axial direction (the direction of the load) and can be accurately defined by a 4-term power series in the transverse direction. A couple of test results were included showing good agreement between computed and measured lateral displacements. The agreement on the stress distribution deteriorates with increasing load.

Almroth’s comments: A one term solution is presented for the postbuckling behavior of unsymmetrically stacked cross-plies.

Almroth’s comments: Blade-stiffened composite material panels under axial compression are designed for minimum weight with buckling constraints. The bending stresses due to a bow-type imperfection are included. It is found that the weight efficiency is much better if the imperfection is allowed to affect the optimized design. Authors’ ABSTRACT: A structural synthesis computer code which accounts for first order effects of an initial bow and which can be used for sizing stiffened composite panels having an arbitrary cross section is used to study graphite blade-stiffened panels. The effect of a small initial bow on both the load carrying ability of panels and on the mass of panels designed to carry a specified load is examined. Large reductions in the buckling load caused by a small initial bow emphasize the need for considering a bow when a panel is designed.

Almroth’s comments: In comparison to the results of Reference C-19, an additional term is added to describe the displacement as a function of the axial coordinates. There is no indication of whether this improves correlation with test.

References listed in Section D of the Appendix of Almroth’s 1981 report, D. EXPERIMENTAL VERIFICATION
The papers in the following are mainly devoted to the verification of analytical results by use of experiments.

Almroth’s comments: Filament winding is not representative for modern manufacturing techniques of composite shells. The comparison between test and theory may not be quite the same for modern specimens. From the theoretical part of the paper it is concluded that the best efficiency is obtained if the balance between helical and hoop windings is such that 0.5 < Ex/Ey < 1.0. Four cylinders were tested and the reduction factor, phi, was found to be much the same as for metal cylinders. The results were:

- R/t = 152, 128, 123, 122
- Ex/Ey = 0.62, 0.83, 1.26, 1.93
- phi = 0.655, 0.630, 0.685, 0.688


Almroth’s comments: The cylinders were manufactured through winding. The inplane stiffnesses were determined experimentally through application of lateral pressure, torsion, and tension. The shells were essentially orthotropic. Presumably the number of layers was large enough so the shell wall material could be considered to be homogeneous and orthotropic. Four of the cylinders buckled between 40 and 48 percent of the classical buckling load. This severe reduction was assumed to have been caused by pretest damage at the ends. For the other ten cylinders, the knockdown factor varied from 0.66 (R/t = 238) to 0.85 (R/t = 85). These results are in line with the behavior of isotropic shells.


Almroth’s comments: The cylinders were manufactured through winding. All cylinders had a thickness of 0.035 in. with the three different layups:
- 0deg., 45deg., -45deg., 90deg. (labeled isotropic)
- 0deg., 22.5deg., -22.5deg., 90deg. (labeled orthotropic)
- 30deg., 90deg. (labeled anisotropic)

For each of the three layups and three different radii (3.6, and 12 in.) five cylinders were manufactured so that for all different geometrical configurations test could be performed in, axial compression, torsion, bending, combination of axial load and torsion, combination of axial load and bending. The results of torsion tests can only be explained by the assumption that the theory used underestimates the critical torque approximately by a factor of two. Possibly this is due to inaccuracy in applied boundary conditions. All the configurations give approximately the same theoretical buckling load. There is not a clear trend indicating a variation in the knockdown factor, not even with the radius/thickness ratio. Typical results are (given in a table in Almroth’s report.) With a larger number of specimens it seems that at least a more pronounced tendency would be found towards decreasing knockdown factor with increasing radius.


Almroth’s comments: Experimental buckling loads are determined for a large number of plates, of which the majority were of composite material with graphite, glass or boron fiber reinforcement. In almost all cases the load displacement curve indicates large lateral displacements and the test is interrupted before the theoretical buckling load is approached. This behavior is observed also for metal plates and composites with little or no membrane bending coupling. Therefore, the eccentricity seems to be due to initial curvature or offset in loading rather than to membrane bending coupling.

D-5. Leone, E. M., Oplinger, D. W., and Serpico, J. C., Experimental Studies of the Elastic Stability of Three-

Almroth’s comments: A total of seven cylinders were tested. The material featured graphite fibers in axial and radial directions and quartz filaments for radial reinforcements. The radius-thickness ratio was in the range of 35 to 40. The loading was lateral pressure, hydrostatic pressure, or hydrostatic pressure with the addition of a component of axial compression. With use of experimentally determined inplane shear modulus, predicted lateral pressures agree well with experimental results. The tests including an axial load component seem to fall somewhat below prediction although conservatively a linear interaction curve was used and the selected example indicates that strain reversal may have occurred well below final collapse.

D-6. Ashton, J. E., and Love, T. S., Shear Stability of Laminated Anisotropic Plates. (no publisher or date given)
Almroth’s comments: Shear buckling tests were performed on 14 boron epoxy laminated plates. The load was applied as a diagonal tension on a "rigid picture frame." The corners on the panel were notched so that local failure would be avoided. The critical load is determined by use of the Southwell plot. The load displacement curve is given for one example and indicates a gradual growth of the lateral displacement. As the specimens were symmetric with 16 layers, this is not the result of membrane-bending coupling but rather it must be assumed that the initial geometric deviations were relatively large. As must be expected, the agreement between the Southwell load and analytical (Rayleigh-Ritz) results is good. The failure load (35,800 lb) is given only for one panel (with a buckling load of 29,000 lb). For all panels b/t was about 100.

Almroth’s comments: Both these publications summarize the results of Reference D-4. The article in the AIAA Journal is somewhat more specific about the test setup.

Almroth’s comments: The tests on torsion tubes were intended as fracture tests. However, it is observed in many cases that fracture was preceded by strain reversal. Evaluation of the results seems difficult because the stress-strain curves show considerable nonlinearity at low stress.

Authors’ ABSTRACT: Results are presented from torsion tests conducted on 36 multilayered, filament-wound, glass-epoxy tubes. Configurations with helical windings and with alternating helical and circumferential windings were investigated for various winding angles. Under small loadings, shear moduli deduced from linear shear stress-strain curves were found to be in reasonable agreement with analytical predictions. Under larger loadings, various degrees of nonlinearity in shear stress-strain curves were encountered, depending on the helical winding angle. Experimental torsional strengths were defined by a 0.2-percent offset yield stress or by maximum stress when large nonlinearities did not exist. These strengths were compared with torsional buckling predictions for orthotropic cylinders, and with material strength predictions based on orthotropic yield criteria and elastic stress analysis. Computed elastic buckling stresses were considerably higher than the experimental strengths for most of the test specimens except for those with only 30 deg and 45 deg windings. Experimental torsional strengths were found to correlate with conventional yield predictions if predicted yielding in certain layers were ignored or if unrealistically large transverse tensile and shear strengths of unidirectional laminae were employed in the analysis.


Almroth’s comments: Some 70 flat plates, approximately square with a side of 6-114 in., were tested under axial compression. The plates were manufactured from cloth and very thin, b/t = 175 or so. The report gives the Southwell load for all panels. Excessive scatter probably indicates nonuniform material properties. It is stated that the agreement between the Southwell load and observed strain reversal is poor. The author's conclusion that the strain-reversal technique has no value is dubious. Strain reversal is a definite indication of the development of buckles and as such a physically meaningful parameter. On the other hand, any experimental method (whether in agreement with theory or not) that gives a different result is not applicable to the case in question. It may be noticed that at least some of the panels were tested up to 3 or 4 times the bifurcation buckling load.


Almroth’s comments: An experimental analysis is presented of the postbuckling behavior of shear panels. The panel dimensions were 6x18 in. and the thickness about 0.02 in., i.e., b/t = 300. The panels were tested to failure which occurred at 8 to 10 times the bifurcation buckling load. In a couple of cases, the panels were tested without failure 100 times to a load level corresponding to 5 times the bifurcation load. Subsequently, these panels were tested to failure with no obvious reduction in strength. Generally, failure occurred in one of the corners of the panel before the average shear strain in the panel had reached half of the shear strain corresponding to fracture.


Almroth’s comments: A number of glass-epoxy cylinders were manufactured with considerable care. The initial geometrical imperfections were measured. The axisymmetric part of these imperfections was isolated and expressed in terms of trigonometric series. By use of the classical bifurcation buckling analysis, critical loads were computed and the cylinders subsequently were tested. The agreement between computed and measured buckling loads is fair. For the 14 cylinders tested, predictions range from 0.50 to 0.85 times the critical load for perfect cylinders while the experimental results range from 0.41 to 0.75 times this load. In general, the predictions were 10 to 20% on the high side.

Authors’ ABSTRACT: An analytical solution for the buckling load was obtained by using cylindrical shells. An analytical solution for the buckling load was obtained by using Koiter's theory for axisymmetric and asymmetric imperfections. For axisymmetric imperfections, numerical evaluation were carried out for the case of three-ply composite shells of glass, boron and graphite-epoxy construction. It was found that drastic buckling load reductions occurred comparable to isotropic shells for small values of imperfection amplitudes. For each cylindrical shell, test model fabricated from three ply preimpregnated glass-epoxy, an equivalent imperfection amplitude was computed by using the root mean square imperfection measurements obtained from several generators. Fairly good agreement was found between the analytically predicted and experimental buckling loads.


Almroth’s comments: Four boron-epoxy and four titanium cylinders with boron-epoxy reinforcement were tested in axial compression, all with R/t about 25. Inside and outside strains are recorded as functions of the load for the four composite material cylinders and for one of the titanium cylinders. Only for the titanium cylinder is there some indication of buckling (strain reversal) before failure occurs.

Almroth’s comments: A number of cylindrical panels were tested under axial compression. Some of the test specimens suffered no damage and could be retested under different conditions. Therefore, 72 panels yielded 84 test results. All panels had a length of 13 in., a radius of 12 in., and a width of 9 in. (43 deg.). Panel thickness and layup were varied through the test series. Buckling loads were registered by use of the Moiré grid technique. For flat panels it appears that initial eccentricities or membrane bending coupling would render this technique useless; compare the results of Reference D-4. However, for the cylindrical panels, it appears that the development of the buckling pattern is rapidly accelerated as the critical load is reached and the Moiré technique seems to have been very useful. In some cases, the tests were continued after the Moiré pattern indicated buckling. In no case could the load be significantly increased before snap-through occurred. Typical examples are:

Moiré: 6300, 715, 1290, 5700, 3530
Snap-through: 6340, 725, 1315, 5810, 3685

In nine cases snap-through occurred without previous indication by the Moiré pattern. In five cases the indication by the Moiré pattern was essentially simultaneous with snap-through. In the remaining cases the test was interrupted when the Moiré pattern indicated buckling and the specimens could be used again. (cannot copy and paste more comments with regard to this reference.)


Almroth’s comments: Six cylinders were manufactured for the tests. The laminates were four-ply (±45)s and six-ply (0/±45)s. The outside diameter was 15 in. and the cylinder length 15 in. The ply thickness varied from 0.0053 to 0.0065. Strain reversal was used to indicate buckling and in most cases the test was nondestructive so that a complete or partial interaction curve could be obtained for one specimen. The knockdown factor for axial compression is about 0.65. The analytical solution for torsion buckling appears to be off approximately by a factor of two.


Almroth’s comments: Four graphite-epoxy and four boron-epoxy cylindrical panels were tested in shear. The panels covered each 45 degrees and four panels were mounted together. The shell wall consisted of 8 ply plus-minus 45 deg. laminate. Due to the fact that relatively few laminates were used, the critical torque is about 50% higher in the favorable direction. The panels were 9 in. long and the radius was 12 in. The average thickness was about 0.056 (R/t about 200). The specimens were first tested in the weaker direction. The buckling load was registered by use of a Southwell plot based on bending strain rather than displacement. The critical load so determined varied between 84 and 106 percent of the theoretical load corresponding to clamped edges. In a second test, the torque was applied in the opposite direction. The Southwell load varied between 85% and 95% of the theoretical value for clamped shells. Furthermore, the Southwell loads agreed very well with the load level at which the lateral displacements started to grow rapidly. The tests in this direction were continued to failure which occurred at about 20% above the buckling load. At this load level, the buckle depth was of the same order of size as the shell thickness.


Almroth’s comments: Of 39 cylinders tested, a few were pure metal cylinders, a few composite reinforced metal
cylinders, but the majority were pure composite cylinders. Since many of the cylinders were tested in both directions, a total of 51 test results were available for comparison to theory. Boron-epoxy and graphite-epoxy cylinders were tested with various layups and for two different R/t values (150 and 75) and three different values of L/R (3.2, 6.7, 13.3). Due to the great variety of specimens, duplication is minimal which makes it difficult to discover any clear trends. There is, for example, no indication that the parameters L/R or R/t should have any influence on the knockdown factor phi. It may be noticed, however, that two tests with R/t = 75 and with a favorable layup fractured without any previous indication of buckling at about 60% of the critical load. An optimum layup was determined analytically for shells subjected to torsion in one direction only. For these cylinders (-82.5, 30, 20, -82.5) s, the knockdown factors were relatively low (0.79, 0.88, 0.61, 0.54). For this layup the ratio between critical loads for loading in the two directions is as high as 3.5. For shells with 45deg. windings this ratio is only of the order 1.5 to 2.0. There is no indication among these that the more efficient layups should be more sensitive to imperfections. Generally the torque drops somewhat after buckling or it stays constant. In no case is there any indication of postbuckling strength above the bifurcation load. The strain at fracture is not observed but stress-strain curves are shown for all specimens. In many of these (including some with R/t = 75), strain levels were reached which considerably (5 times or so) exceed the critical strain. The knockdown factor for the 51 experiments varies from 0.54 to 0.95 with an average close to 0.80.

Almroth’s comments: The results of Reference D-16 are presented in a slightly more polished form.

Almroth’s comments: Composite flat plates were tested under different compression. The value of b/t was about 100 for all plates. Most plates have considerable membrane-bending coupling. Load displacement curves are not shown but it can be assumed that the bending of the plate sets in gradually and that the bifurcation buckling load is insignificant as a design parameter. The buckling load is determined by use of the Southwell plot as well as by the dynamic method (extrapolation to zero of natural frequency). The agreement between these two methods is good.

Almroth’s comments: Tests were carried out on three T- and blade-stiffened panels. Buckling and crippling predictions (elastic) based on "elementary methods" were in good agreement with test results. Some of the stress-strain curves for the material (transverse stress and shear) show considerable non-linearity.

Almroth’s comments: Tests were conducted on a number of hat-stiffened graphite-epoxy panels. The panel dimensions correspond to optimum weight configurations. A number of panels (23) of length 16 in. were critical in local buckling. In the experiments local buckling was observed by use of the Moire pattern and by the observation of strain reversal. These two methods agree with one another but the agreement with theory (BUCLASP) is not good. This is assumed to be due to large deviations from nominal thicknesses and to local initial stresses due to the curing process. The experiments were continued to ultimate failure which typically
occurred at about 25% above the experimental buckling load. The authors conclude that "buckled skin concepts" might be possible (but that), the brittle nature of graphite-epoxy composites makes their practicality highly speculative at this time. In addition, six longer panels (60 in.) were tested. These were critical in Euler buckling. The test results in these cases fall between 64 and 90 percent of the critical load. This disagreement appears to be the result of transverse shear effects. The disagreement between experiment and theory reduces a potential 50% weight saving (in comparison to aluminum) to a 32% saving. This estimate does not account for the use of buckled skin concepts for aluminum panels.

Almroth’s comments: A literature review is presented on the subject of buckling of cylindrical shells. Available closed form solutions are summarized. A computer program listing is presented for the buckling of anisotropic cylinders under torsion, external pressure and axial load. A number of numerical results indicate that the shapes of the interaction curves vary considerably with the layup. Two fiberglass cylinders were tested. An inside mandrel was used to arrest the buckles and allow repeated testing on the same specimen. The shape of the interaction curves agrees with theoretical results. For comparison with theory an analysis was carried out including axisymmetric imperfections. These were chosen equal to those on the "worse meridian". The test results in axial compression were some 10% below the bifurcation load for the imperfect cylinder. In both cases, the radius to thickness ratio was 234.

Almroth’s comments: Graphite-epoxy plates with the unloaded edges simply supported and channel sections were tested in axial compression. Results were compared to results of "classical, closed-form orthotropic elastic buckling theory for flat plates." In many cases, the registered buckling load was well below the theoretical values. For the plates with b/t varying from 19 to 45, the ratio between experimental and theoretical results varied between 0.61 and 0.88. For the channels the corresponding ratio varied from 0.77 to 1.10. Ultimate failure for the plates varied from 0.71 to 1.55 times the bifurcation buckling loads. For the channels this range was 1.18 to 3.83.

Almroth’s comments: Three panels, 845 x 115 mm, were tested in shear. The layups were 8-ply (±45)s (t = 1.04 mm), 10-ply (90, 2±45)s (t = 1.30 mm) and 8-ply (2 + 90, 2±45)s (t = 1.04 mm). Buckling at test was observed by use of the Moire pattern. The ratios between test and theory for the three specimens were 0.72, 1.27, and 0.75. The tests were continued to failure. The ultimate load values were 2.73, 1.9 and 2.87 times the bifurcation buckling loads (theoretical). The STAGS computer program and Tsai's fracture criterion were used to determine the ultimate load analytically. The agreement between test and theory on this point was surprisingly good, the ratios between experimental and theoretical results being 0.93, 1.16 and 1.07.

End of Almroth’s 1981 survey

ABSTRACT: In the following paragraphs possible future trends in the nonlinear analysis of structures are contemplated. If any predictions at all are to be made, they must be based on the assumption that research and development in the area will be responsive to the needs of the engineering community, perhaps primarily within the aerospace and nuclear industries. This need is definitely for more efficient general purpose programs derived in such a way that they are reasonably easy to use. Some new technology is presented in the recent literature, in the form of new ideas in discretization procedures and in automation of the methods for solution of nonlinear equation systems. The prediction is simply that these are going to be further developed, thoroughly evaluated and eventually included in commonly available software.

ABSTRACT: Equations are presented for the analysis of simply-supported orthotropic plates subjected to static and dynamic loading conditions. Transient loading conditions considered include sine, rectangular, and triangular pulses, and pulses representative of high explosive blast and nuclear blast. These pulses can be applied as a uniform load over the panel, a concentrated load, a uniform load applied over a small rectangular area, and a cosine loading applied over a small rectangular area. A method for the analysis of low velocity impact is also presented.

John L. Sewall, Robert R. Clary and Sumner A. Leadbetter, “An experimental and analytical vibration study of a ring-stiffened cylindrical shell structure with various support conditions”, NASA TN D-2398, 1964

M. Mikulas, Jr., et al, “Buckling of a cylindrical shell loaded by a pre-tensioned filament winding”, NASA, 1964

ABSTRACT: Exact solutions are derived of the classical differential equations defining the deformations of axially compressed thin-walled circular cylindrical shells. The end conditions along the circular edges are assumed as the vanishing of (1) the radial displacement; (2) of the longitudinal bending moment; (3) of the variation in the axial normal stress, and (4) of the circumferential membrane shear stress. Under these conditions of simple support the critical value of the uniformly distributed axial normal stress is one-half the classical critical value.

K. Forsberg, “A review of analytical methods used to determine the modal characteristics of cylindrical shells”, NASA CR 613, 1965

doi: 10.1007/BF02327148
ABSTRACT: The results of buckling tests on circular cylinders heated uniformly along axial strips are presented and discussed. Calculations of critical temperature based upon the small-deflection theory for thin circular cylindrical shells are included and a comparison is made between theoretical and experimental results. Cylinders heated along axial strips of given widths have a theoretically predicted behaivor which corresponds
reasonably well to the behavior obtained by experiment. Curves are included showing the variation of critical
temperature with respect to heated axial-strip width.

References listed at the end of the paper:


L. Katz, “Compression tests on integrally stiffened cylinders”, NASA TMX-55315, August 1965


ABSTRACT: The paper presents methods for the analysis of framed structures which behave primarily as shells. Questions of membrane forces, analogous elastic properties, and buckling criteria are treated. The collapse of a 307-ft span reticulated dome in Bucharest in 1963 is investigated, and it is shown that the analyses presented in the paper gives a buckling load which is only approximately one-fifth of the critical load expected by the original designers, but which indeed agrees within 10% with the actual load at failure. Analyses of other important reticulated domes are also given.


K. Buchert, “Buckling of doubly curved orthotropic shells”, Engineering Experiment Station, University of Missouri, Columbia, Missouri, November 1965


K.P. Buchert, “Effect of edge conditions on buckling of stiffened framed shells”, Engineering Experiment Station Bulletin Series No. 65, University of Missouri, Columbia, Missouri, October 1967


Weingarten, V. I. and Seide, P., “Buckling of thin-walled circular cylinders”, NASA SP-8007, September 1965


ABSTRACT: A state-of-the-art review of the stability of cylindrical shells is presented. The copious theoretical results available in the literature are discussed and compared with available experimental results. Reasons for the well-known discrepancies between theory and experiment are indicated and various design formulas which take these discrepancies into account are given. Most of the available experimental data are for linearly elastic metallic or plastic specimens. The behavior of these can differ markedly from the behavior of reinforced concrete structures which are subject to cracking and material nonlinearity. The applicability of linearly elastic shell data to the buckling analysis of concrete shells is discussed briefly on the basis of a comparison of the few test results for reinforced concrete shells with those for elastic shells.

DOI: 10.1115/1.3627252
ABSTRACT: It is shown in this paper that previous, independent analyses of the phenomena of dynamic elastic instability and dynamic plastic-flow buckling of circular cylindrical shells can be combined in a single approach leading to results consistent with those that follow from these analyses. The response of the shell in both cases is governed by the interaction between the fundamental radial, purely extensional mode of deformation and inextensional flexural modes always present in the response. An analytical procedure is given for the determination of dominant modes in the elastic and plastic phases of the response, and the results of this procedure are verified by comparison with numerical and experimental data.

ABSTRACT: The asymmetric buckling of truncated and complete conical shells under uniform hydrostatic pressure has been studied by many authors. In all of these investigations, membrane theory has been used to define the stress state prior to buckling. In the present paper this problem is studied by means of finite difference analysis, taking into account the large deformation in the prebuckling state. Numerical results are obtained and compared with the results of other investigations.

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“Buckling of thin cylindrical shells heated along an axial strip”, Experimental Mechanics, Vol. 5, No. 8, pp 247-256, August 1965
ABSTRACT: The results of buckling tests on circular cylinders heated uniformly along axial strips are presented and discussed. Calculations of critical temperature based upon the small-deflection theory for thin circular cylindrical shells are included and a comparison is made between theoretical and experimental results. Cylinders heated along axial strips of given widths have a theoretically predicted behavior which corresponds reasonably well to the behavior obtained by experiment. Curves are included showing the variation of critical temperature with respect to heated axial-strip width.

References listed at the end of the paper:
ABSTRACT: The plastic buckling of cylindrical shells under axial compression is studied analytically and experimentally. Attention is given to both the nonlinear and nonconservative aspects of the stress-strain relation. The effect of unloading is investigated in an exact manner for a hinge model which is proposed and in both an exact and an approximate manner for a geometrically perfect shell. Thirty tests are reported on cylindrical shells of 2024-T4 aluminum with radius to thickness ratios of 120 through 10 and length to radius ratios of 0.20 to 7. Specimens were prepared with three different types of end conditions and were tested either through a ball and socket arrangement or flat ended between smooth bearing blocks. A simple (j sub 2) incremental theory gives results very close to j sub 2 deformation theory and does predict both buckling strength and the geometry of buckling for thick and moderately thick shells.

ABSTRACT: Axisymmetric plastic buckling of axially compressed cylindrical shells is studied for semi-infinite shells and shells of finite length subject to free-edge boundary conditions. It is shown that the length of the cylinder has a negligible effect on the buckling load. Reductions in buckling stresses from the classical simple-support value are significant, with the amount of reduction dependent on the details of the variation of tangent modulus with stress. Numerical results are presented for cylinders composed of 2024-T4 aluminum and 3003-0 aluminum.


ABSTRACT: The Sanders’ equations for a circular cylindrical elastic shell of constant thickness are reduced to a single, simple, fourth order partial differential equation for the complex-valued function $W+i\sqrt{A/D}F$, where $W$ is the midsurface normal deflection, $F$ is a stress function, and $A/D$ is an elastic constant. Auxiliary equations expressing the tangential midsurface displacements, stress resultants, stress couples, and Kirchhoff edge forces in terms of $W$, $F$, and surface load integrals are also derived. Approximations are introduced only in the stress strain relations, but the resulting errors are shown to be negligible by Koiter’s arguments. Work of previous writers is reviewed and compared with results of the present paper.


ABSTRACT: The intrinsic equations of nonlinear thin shell theory are reduced to a relatively simple set of six equations in six unknowns. Boundary conditions to use in conjunction with the equations are obtained. The equations are compared with those of other authors for some special cases. For easy use, the equations and boundary conditions are given in lines-of-curvature coordinates.

ABSTRACT: Fung and Tong have recently explained the sphering of red blood cells in hypotonic solution by showing that a thin-walled elastic membrane with the right extensional stiffness and surface tension distribution will swell into a sphere under internal pressure. In this report we investigate the stability of the spherical state of Fung and Tong's model by applying the static energy criterion, which requires a determination of the sign of the quadratic terms in the potential energy functional. It turns out that a spherical cell model with radius less than that of the equatorial radius of the original undeformed cell is indeed stable, if and only if the supposedly arbitrary elastic parameters in the model are restricted in their possible range of values.


PARTIAL ABSTRACT: Experimental data on the mode of buckling of circular cylindrical shells under axial compression enables us to draw the conclusion that the number of dents in the peripheral direction, n, depends only on the ratios L/R and R/h, where L, R, and h are respectively the length, radius, and thickness of the shell...


ABSTRACT: A theoretical investigation is made of the axisymmetric snap-through buckling of a shallow conical shell subjected to an idealized impulse applied uniformly over the surface of the shell. The shell is assumed to behave as a single-degree-of-freedom system, and a study is made of the strain energy at maximum displacement: i.e., zero velocity. Under certain conditions this equilibrium position becomes unstable and the shell can snap through (or buckle). Nonlinear strain displacement equations are used and solutions are obtained for clamped and simply supported boundaries at the edge of the shell. Results for the cone are compared with similar results for a shallow spherical cap having the same rise as the cone. This comparison indicates that the spherical shell can resist a larger impulse than the conical shell before buckling.


ABSTRACT: This paper deals with the dynamics and stability of flexible pipes containing flowing fluid, where the flow velocity is either entirely constant, or with a small harmonic component superposed. An extensive historical review of the subject is given. In the case of constant flow velocity, the dynamics of the system is examined in a general way and it is shown that conservative systems are subject not only to buckling
(divergence) at sufficiently high flow velocities, but also to oscillatory instabilities (flutter) at higher flow velocities. Also presented are some new results for cases of systems subjected to internal dissipative forces. In the case of harmonically varying flow velocity, the equation, of motion derived here exposes an error in a previous derivation. Stability, maps are presented for parametric instabilities, computed by Bolotin's method, for pipes with pined or clamped ends, as well as for cantilevered pipes. It is found that the extent of the instability regions increases with flow velocity for clamped-clamped and pinned-pinned pipes, while a more complex behaviour obtains in the case of cantilevered pipes. In all cases, dissipation reduces the extent of, or entirely eliminates, parametric instability zones.


ABSTRACT: Design of efficient cylindrical shells for carrying moderate compressive loads leads to the requirement that they be stiffened. The buckling behavior of such stiffened cylinders differs considerably from that of thin monocoque cylinders in several noteworthy respects: 1) Stiffened cylinders are often effectively "thick," and exhibit large buckle wavelengths. Their strength is consequently influenced little by imperfections and can be predicted accurately by linear buckling analysis. Refined and sophisticated linear analysis thus becomes a powerful design tool. 2) One-sidedness of stringers and rings produces strong interaction between "membrane" and bending forces. Calculations and tests have revealed instances where change of reinforcement from one surface to the other changes buckling strength by a ratio of two or more. 3) Because of the larger, well defined wave form, the strength of stiffened cylinders always depends on the constraint (or lack of it) from adjoining cylinders and domes (or test fixtures), and the resistance to bending moment may appreciably exceed the resistance to uniform load. This paper describes several methods, having varying complexity and versatility, for treating buckling of stiffened cylinders. The determination of the required ring stiffness for preventing general instability is identified as being central to optimum design; commonly used methods of determination are shown to be unreliable. Theoretical and experimental results are compared, and future development is outlined.


G. A. Thurston, “Buckling of imperfect cylinders under axial compression”, NASA, 1966


ABSTRACT: An extension of the finite-element displacement method to the analysis of linear bifurcation buckling of general shells of revolution under static axisymmetric loading is presented. A systematic procedure for the formulation of the problem is based upon the criterion that the condition for neutral stability of a system is the vanishing of the second variation of the total potential energy from the stable equilibrium state to the perturbed bifurcation state; this results in an eigenvalue problem. For solution, the shell is discretized into either a series of conical frusta or of frusta with meridional curvature. The prebuckling equilibrium solution is axisymmetric, but the perturbation-displacement field within each element is represented by Fourier circumferential components of the generalized displacements which are defined at the nodal circles. The present formulation is applied to a number of shells of revolution with and without meridional curvature, and comparisons are made with other theoretical and available experimental results.


ABSTRACT: Dynamic equilibrium equations and boundary conditions are derived from energy principles for eccentrically stiffened cylinders and flat plates. In-plane inertias are neglected and frequency expressions are obtained for simple-support boundary conditions for both the cylinder and the plate. Results in the form of plots of frequencies as a function of mode shape illustrate the effects of eccentricities. It is found that these eccentricities can have a significant effect on natural frequencies and should be investigated in any dynamic analysis of stiffened structural members.


ABSTRACT:

T.C. Soong, “Buckling of circular cylindrical shells under external pressure”, SUDAER Report No. 228, Department of Aeronautics and Astronautics, Stanford University, April 1965

T.C. Soong, “Influence of boundary constraints on the buckling of eccentrically stiffened orthotropic cylinders”, presented at the 7th International Symposium on Space Technology and Science, Tokyo, May 1967


ABSTRACT: Closed-form solutions are given of the linear Donnell equations defining the buckling of thin-walled circular cylindrical shells subjected to uniform axial compression. In addition to the classical simple
support conditions requiring the vanishing of the radial displacement, the axial bending moment resultant, the axial additional stress and the circumferential displacement, three other, equally justifiable, simple support conditions are defined and studied in the case of the semi-infinite shell. Two of them yield buckling stresses amounting to about one-half the classical critical stress.


ABSTRACT: The results of buckling tests on uniformly heated, clamped, thin circular cylindrical shells are presented and discussed. Particular attention is paid to both the actual buckling process and the ensuing postbuckling behavior. Load vs. end-shortening curves are included. The possibility of “snap-through” buckling which occurs at a value of end shortening greater than that corresponding to the maximum supported load is experimentally verified. A comparison of the present experimental results with available theory is made. It is observed that the experimental values of the buckling temperature can be substantially greater than the temperatures calculated by linear theory from the experimental buckling loads; however, the buckling stresses are the same whether the loading is thermal or mechanical.

References listed at the end of the paper:


ABSTRACT: Considered are problems of free and forced vibrations, static and dynamic stability and aeroelasticity of orthotropic shells and plates placed in a variable temperature field. It is assumed that the physical-mechanical characteristics of the material of the shell (plate) depend on the temperature. It is shown that taking into account the dependence of the physical-mechanical properties of the material of the shell (plate) on temperature introduces essential qualitative and quantitative changes in the problem of vibration and stability.


N.C. Lind, “Stability analysis of symmetric dome frameworks”, Presented at the first joint meeting, Structural Engineering, Colegio de Ingenieros Civiles de Mexico, ASCE, Mexico City, February 1966


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ABSTRACT: The solution for buckling of a stiff elastic layer bonded to an elastic half-space under a transverse compressive plane strain is presented. The results are compared to an approximate solution that models the layer using beam theory. This comparison shows that the beam theory model is adequate until the buckling strain exceeds three percent, which occurs for modulus ratios less than 100. In these cases the beam theory predicts a larger buckling strain than the exact solution. In all cases the wavelength of the buckled shape is accurately predicted by the beam model. A buckling experiment is described and a discussion of buckling-induced delamination is given.

M.F. Card and R.M. Jones, “Experimental and theoretical results for buckling of eccentrically stiffened cylinders”, NASA TND-3639, October 1966


ABSTRACT: The nonlinear analysis of shell structures is studied by both the Eulerian and the Lagrangian approach. Current methods are discussed on the basis of both formulations. It is found that the widely used updated procedure is a combination of both approaches. From the current standpoint it makes use of a mixture of incremental stiffnesses derived by both approaches. The ‘bowing’ effect was found to be the main source of error in this updated procedure, and this effect was shown to be negligible when a large number of elements were used. Case studies investigate various aspects of the nonlinear behavior of arches, axisymmetric shells of revolution, flat plates, and arbitrary shells.


ABSTRACT: In this work a numerical model is developed for the welding and subsequent loading of a fabricated structure. The model treats the weld process as a thermo-mechanical problem. A finite element formulation derived from the uncoupled thermal and mechanical energy balances forms the basis of the model. During the development of the thermal model, two significant problems are discussed. One is the material nonlinearity, which manifests itself in the temperature dependence of the thermal properties, and in the fusion problem, where the material phase change is accompanied by a latent heat effect. This latter is modeled by use of a modified specific heat, since the materials of prime concern are alloys which melt over a finite range of temperature, while the former are introduced through periodic re-evaluation of the properties throughout the analysis. The second problem is that of boundary conditions: The deposition of molten bead on the base is modeled by using the intimate contact boundary condition, which is developed into a set of impulse type equations on the finite element model. Since radiation is a dominant cooldown mechanism, this boundary condition is also included. Thus the first part of work develops a non-linear finite element thermal analyzer capable of modeling all of the above effects. This program is then applied to several problems in order to assess its accuracy. During the second part of the work the mechanical model is described. This is an incremental finite element model in which the basic constitutive descriptions are time independent elastic-plastic behavior with temperature dependent properties, and a creep rate formulation for the time dependent behavior. The development is not based on thermodynamic theories but on direct extension of the classical (isothermal) theories. The model includes finite strain effects during isothermal loading, so that it may be used in the modeling of distortion sensitive structure. The integration of the rate equations is discussed with respect to the introduction of a residual load (total equilibrium) correction; it is shown that such a correction must be introduced very carefully in a completely incremental formulation such as is developed here. Finally the model is compared with simple bead-on-plate weld experiments, performed with high strength steels. It is found that in one case the experimental approximations are well justified by the finite element results, but there is no
agreement with the experimentally measured residual stresses. The suggested explanation for the unique stress patterns observed experimentally is shown to have little effect on the finite element stress predictions, so that it is concluded that the finite element model does not include a significant material behavior in this case. In the second example it is shown that the experimental assumptions were not justified by the results of the present model. In both cases the model predicts the usually expected residual stress patterns. Use of a simple creep formulation is shown to give the same order of residual stress reduction as a result of post weld heat treatment as is measured experimentally.


ABSTRACT: The first part of this paper is in the nature of a progress report on recent developments of analysis methods for filamentary composites. Theoretical predictions of the stiffness and strength properties of a unidirectional composite based on a knowledge of the constituent properties are correlated with experiments for both tensile and compressive loadings. The analysis of multilayer or laminated composites based upon the unidirectional composite properties then requires the rather straight forward use of classical anisotropic shell theory. Some structural aspects of filamentary composites designed for biaxial loads are considered in the second part. In particular, certain design restrictions inherent in the use of such composites become evident when compared to the more familiar isotropic sheet. Some of these restrictions can be overcome by a close matching of filament orientations and stress field. These factors serve to emphasize the overwhelming importance of creative structural concepts in the design of successful filamentary composites.


ABSTRACT: This paper presents an approximate finite deflection analysis of the buckling behaviour of long, slightly curved panels in uniform compression parallel to the generators; the sides, which may be clamped or simply-supported, are either free to move circumferentially or are completely restrained against circumferential movement.

References listed at the end of the paper:

W. H. Horton, S. C. Bailey and A. M. Edwards (Department of Aeronautics and Astronautics, Stanford University, Stanford, California, USA), “Nonsymmetric buckle patterns in progressive plastic buckling” (Experiments conducted by the authors were concerned not only with the method in which a buckle generates
and develops in a thick-walled shell, but also with the influence of geometric and mechanical parameters on this process), Experimental Mechanics, Vol. 6, No. 9, 1966, pp. 433-444, doi: 10.1007/BF02326556

ABSTRACT: This paper presents the results of a series of experiments on the progressive plastic buckling of cylindrical shells under axial compressive load. It shows that, for shell bodies with anR/t less than 100, the normal axisymmetric ring buckling will develop into nonsymmetric patterns. We demonstrate that there exists also a class of shells within this thickness-radius range for which nonsymmetric plastic buckling always occurs without the prior formation of a ring. It appears from the limited number of tests made that, for a particular R, R/t, material and rate of loading, there is a critical value of L, above which there is a high probability of the buckle pattern developing in a nonsymmetric fashion. It seems probable, too, that there are bands of R/t for a particular L/R, R, material and rate of loading for which the buckle number will be constant. The experiments tend to indicate that the postbuckling efficiency of the shell decreases with increasing buckle number.

The nonsymmetric patterns demonstrated appear to be inextensional deformations. They are very similar in character to the Yoshimura pattern which occurs as the limiting case for thin shells in axial compression and, under impact loading. Load-displacement histories are presented for some of the various modes of failure demonstrated.

References listed at the end of the paper:

**ABSTRACT:** The buckling of cylindrical shells with free longitudinal edges subjected to uniform axial compression is examined. The solutions are based on the simplified elastic equations of the small deflection theory known as the Donnell's equations. Results obtained were presented in a number of charts. It was found that in the practical range of thin shell structures, the critical buckling stress of a cylindrical shell may be 1/10, 1/100, or 1/1000 of the buckling value of a corresponding cylindrical tube with the same radius, $R$, thickness, $t$, and length $L$, as the ratio of $t/R$ decreases and the ratio of $L/R$ increases. Although the small deflection theory may give buckling stresses higher than the actual buckling values, it will serve the purpose of establishing the upper bounds of the buckling loads. The study of shells with free longitudinal edges and subjected to uniform axial compression may be regarded as an initial step for studying shell roofs with edge beams and subjected to longitudinal membrane stresses varying from compression to tension.


proxy Url : [http://handle.dtic.mil/100.2/AD660535](http://handle.dtic.mil/100.2/AD660535)

**ABSTRACT:** An exact solution is derived for the buckling of a circular cylindrical shell with multiple orthotropic layers and eccentric stiffeners under axial compression, lateral pressure, or any combination thereof. Classical stability theory (membrane prebuckled shape) is used for simply supported edge boundary conditions. The present theory enables the study of coupling between bending and extension due to the presence of different layers in the shell and to the presence of eccentric stiffeners. Previous approaches to stiffened multilayered shells are shown to be erratic in the prediction of buckling results due to neglect of coupling between bending and extension.


**ABSTRACT:** A solution for the plastic buckling of eccentrically stiffened cylinders is derived by use of the J2 deformation theory of plasticity for a set of simply supported edge boundary conditions. The uniaxial character of the stiffeners and the stiffener eccentricity (asymmetry about the cylinder middle surface) are explicitly accounted for as is a variable Poisson's ratio in the plastic region. A closed-form stability criterion is obtained for axial compression, lateral pressure, and hydrostatic pressure loadings. The present results are more realistic for most practical stiffened cylinders than an existing solution in which an orthotropic shell model is used. A numerical example is given to illustrate the effect of plastic action on the buckling load of a typical aerospace structure. The FORTRAN IV computer program is described and listed.


**ABSTRACT:** An exact buckling criterion, within the framework of classical buckling theory, is derived for eccentrically stiffened multilayered circular cylindrical shells made of materials that have different orthotropic
moduli in tension and compression. Such behavior is typical of many current composite materials. The buckling criterion is valid for arbitrary combinations of axial and circumferential loading, including axial compression and internal pressure as well as axial tension and lateral pressure. The material model (stress-strain relationship) involves a bilinear stress-strain curve with a discontinuity in slope (modulus) at the origin. A numerical example of buckling of a ring-stiffened two-layered circular cylindrical shell is given to illustrate application of the buckling criterion. A FORTRAN IV computer program, BOMS II, that implements the aforementioned analysis is described and listed.


ABSTRACT: Small geometrical imperfections in some structures can be responsible for large reductions in their static buckling strengths. As is well known, a thin shell is often very imperfection-sensitive in this sense, with a perfect specimen sometimes having a “classical” buckling strength several times higher than that of an imperfect one. Many analytical studies have sought to correlate reductions in buckling strength with assumed initial imperfections of various sizes and shapes. Such studies may eventually provide the quantitative information needed for the establishment of a statistical theory of buckling, which would relate the probability of buckling under a given static load to the spectrum of imperfections (see [1]). But at the present time, the design of shells leans heavily on experiment, and analysis has been mainly useful in identifying imperfection-sensitive structures and in establishing, in a qualitative way, the degree of this sensitivity.

References listed at the end of the paper:


ABSTRACT: The present paper continues an earlier study by the same authors with a view toward presenting a complete picture of the dynamic buckling of some imperfection-sensitive models. The initial study was concerned with buckling of the models, and real structures as well when subject to loads suddenly applied and subsequently held constant. Here, consideration is extended to buckling under loading histories characterized by a finite length of time of load application. The results are presented in a form such that the dynamic buckling load of the initially imperfect model is related to its static buckling load. Thus, explicit dependence on its initial imperfection has been bypassed. In this form the implication of the model results for real structures are most apparent. The application of these results to actual structures is discussed, and several observations on the general character of dynamic buckling are noted. Finally, attention is focused on the cylindrical shell under axial compression. The limited results obtained tend to substantiate the validity of the model results, and we are led to suggest what should be a conservative criterion for this structure for design against dynamic buckling.


ABSTRACT: The initial postbuckling behavior of a shallow section of a spherical shell subject to external pressure is studied within the context of Koiter’s general theory of postbuckling behavior. Imperfections in the shell geometry are shown to have the same severe effect on the buckling strengths of spherical shells as has been demonstrated for axially compressed cylindrical shells. Large reductions in the buckling pressure result from small deviations, relative to the shell thickness, of the shell middle surface from the perfect configuration.

ABSTRACT: The initial post-buckling behavior of double curvature shell segments subject to several loading conditions is determined on the basis of Koiter's general theory of initial post-buckling behavior. Previously, the classical buckling loads associated with these shells were shown to be strongly dependent on the two radii of curvature and their relative magnitudes. Here, the initial post-buckling behavior and associated imperfection sensitivity are also seen to be strongly dependent on the two curvatures.


ABSTRACT: A quantitative study of the imperfection-sensitivity of eccentrically stiffened cylindrical shells is presented. Results are given for both axial and ring stiffened cylinders under axial compression and hydrostatic pressure. In some instances, in particular in the case of axially stiffened cylinders under axial load, the sensitivity to imperfections, as well as the classical buckling load, appears to be strongly dependent on whether the stringers are attached to the outside or inside of the cylinder. Under certain conditions stiffening can significantly reduce or perhaps completely eliminate imperfection-sensitivity, whereas in other cases it may play a much smaller role in lowering the sensitivity.


ABSTRACT: Buckling and initial postbuckling behavior is determined for thin, elastic cylindrical shells of elliptical cross section. This study complements the buckling and advanced postbuckling calculations reported by Kempner and Chen on a similar class of shells. The initial postbuckling analysis indicates that like compressed circular cylinders, the oval cylinders will be highly sensitive to small geometrical imperfections and may buckle at loads well below the predictions for the perfect shell. On the other hand, buckling will not necessarily result in complete collapse. A series of simple tests has been performed which provide qualitative verification of the major features of the theory.


ABSTRACT: The initial postbuckling behavior of axially stiffened cylindrical shells is studied with a view to ascertaining the extent to which various effects such as [indecipherable] eccentricity, load eccentricity, and barreling influence the imperfection sensitivity of these structures to buckling. In most cases, when these effects result in an increase in the buckling load of the perfect structure, they increase its imperfection-sensitivity as well. In some instances, however, barreling can significantly raise the buckling load of the shell while reducing its imperfection-sensitivity. The analysis, which is based on Koiter's general theory of postbuckling behavior and is made within the context of Kármán-Donnell type theory, takes into account nonlinear prebuckling deformations and different boundary conditions.

Steven E. Forman and John W. Hutchinson (Harvard University, Cambridge, Massachusetts, USA), “Buckling
ABSTRACT: Buckling analyses of several reticulated shell structures are carried out using both an approximate equivalent shell analysis and a discrete analysis which is essentially exact. The structures considered are: an infinite reticulated beam under axial compression and resting at equally spaced intervals on elastic springs; a shallow section of a reticulated sphere with an equilateral triangle grid subject to normal loading; and an infinite reticulated cylindrical shell with an equilateral triangle grid subject to axial compression. The discrete analysis is used to evaluate the accuracy of the predictions of the equivalent shell analysis. The buckling load computed on the basis of the equivalent shell analysis is nonconservative when a characteristic wavelength of the buckling deformation is on the order of the member length or the axial load in a member at buckling is on the order of the Euler buckling load of a simply supported column. The effect on the buckling load of reducing the rigidity of the joints is investigated for both the beam-spring model and the reticulated spherical shell. Finally, the importance of the discrete analysis is illustrated by the determination of the optimum properties of a shallow section of a reticulated sphere subject to a prescribed normal loading and designed against buckling.

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ABSTRACT: A combined theoretical and experimental investigation has been carried out on the effects of certain types of local axisymmetric imperfections on the buckling of cylindrical shells under axial compression. Buckling loads have been calculated for a variety of "dimple" imperfections. Results have been obtained for constant thickness shells with middle surface variations from the geometry of a perfect cylinder as well as for shells with local axisymmetric thickness variations. Nonlinear prebuckling effects and edge conditions are taken into account. In the experimental program a series of seven photoelastic plastic circular cylindrical shells each containing a local axisymmetric dimple centered at mid-length were tested under pure axial compression. All cylinders were constructed by the spin-casting technique and the local imperfection was cut on both the inner and outer walls using a hydraulic tracer-tool apparatus in conjunction with a metal template. A broad range of imperfection amplitudes and wavelengths was investigated. The experimental results were in good agreement with the theoretical predictions.

References listed at the end of the paper:
ABSTRACT: Aspects of postbuckling behavior are investigated for structures undergoing plastic deformation. The structures singled out are characterized by a highly imperfection-sensitive behavior where buckling takes place in the elastic range. A simple model study is carried out and is followed by an analysis of the plastic buckling of a complete spherical shell under external pressure. In both instances, the bifurcation behavior and subsequent deformation of the perfect structure as well as the influence which geometric imperfections have on buckling are studied.

ABSTRACT: In the first part of the paper a simple model is used to introduce some of the analytical and physical features of post-bifurcation phenomena in continuous elastic-plastic systems. An analysis is presented for the initial post-bifurcation behavior of a class of elastic-plastic solids subject to loads characterized by a single load parameter. Bifurcations which occur at the lowest possible load are singled out for attention. The theory makes connection with Hill's general theory of bifurcation and uniqueness in elastic-plastic solids and Koiter's general approach to the initial post-buckling behavior of conservative elastic systems. Buckling of an axially compressed column in the plastic range is used to illustrate the theory.

ABSTRACT: The effect of small imperfections on the buckling of continuous structures loaded into the plastic range is studied. A simple model study is presented and several additional examples are discussed. The rôle of the load at which elastic unloading first occurs is emphasized, and a general asymptotic analysis is given for the behavior prior to the onset of elastic unloading for a class of elastic-plastic solids subject to loads characterized by a single load parameter. Asymptotic imperfection-sensitivity formulae are obtained whose features are similar to analogous formulae for elastic structures.

OUTLINE:
I. Introduction
II. Simple models
   A. Discrete Shanley-Type Model
   B. Continuous Model
III. Bifurcation Criterion
   A. Criterion for Three-Dimensional Solids
   B. General Bifurcation Criterion for the Donnell-Mushtari Vlasov Theory of Plates and Shells
   C. Discussion of Bifurcation Predictions Based on the Simplest Incremental and Deformation Theories of plasticity
IV. Initial Post-Bifurcation Behavior for Donnell-Mushtari Vlasov Theory
   A. General Theory
   B. Two Column Problems
   C. Circular Plate under Radial Compression
   D. Effect of Initial Imperfections
V. Numerical Examples
   A. Column under Axial Compression
   B. Circular Plate under Radial Compression
   C. Spherical and Cylindrical Shells

References


DTIC Accession Number: ADA447921, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA447921
ABSTRACT: A method is presented to determine the general instability load of a ring-stiffened corrugated
cylinder under axial compression. This method is developed using linear small deflection theory. The stiffness properties of the rings are uniformly distributed along the cylinder and the eccentricity of the rings with respect to the corrugation centerline is taken into account. Analytical and experimental results are compared. In this comparison good agreement is obtained for cylinders loaded in pure compression. For the cylinders subjected to bending or a combination of bending and compression the analytical calculations are conservative. A computer program for the application of this method has been developed. The program and an explanation of its notation are included in this report.

J.N. Dickson and S.B. Biggers (NASA Langley Research Center, Hampton, Virginia, USA), “POSTOP: Postbuckled open-stiffener optimum panels-theory and capability” (no publisher or date given by ProQuest-CSA)

ABSTRACT: The computer program POSTOP was developed to serve as an aid in the analysis and sizing of stiffened composite panels that are loaded in the postbuckling regime. A comprehensive set of analysis routines was coupled to a widely used optimization program to produce this sizing code. POSTOP is intended for the preliminary design of metal or composite panels with open-section stiffeners, subjected to multiple combined biaxial compression (or tension), shear and normal pressure load cases. Longitudinal compression, however, is assumed to be the dominant loading. Temperature, initial bow eccentricity and load eccentricity effects are included. The panel geometry is assumed to be repetitive over several bays in the longitudinal (stiffener) direction as well as in the transverse direction. Analytical routines are included to compute panel stiffnesses, strains, local and panel buckling loads, and skin/stiffener interface stresses. The resulting program is applicable to stiffened panels as commonly used in fuselage, wing, or empennage structures. The analysis procedures and rationale for the assumptions used therein are described in detail.


ABSTRACT: Stiffness and mass matrices have been developed for rings, which together with similar matrices for shell elements have been applied to ring-reinforced circular cylindrical and conical shells. The finite-element solution, for the general instability and vibration of circular cylinders and cones, has been compared successfully with existing theories and also with experimental results, where the latter have been available. An investigation has been made also of the effects of pressure on the vibration characteristics of a ring-reinforced circular cylinder.


ABSTRACT: Analysis of the simple model proposed yields equilibrium curves in agreement with those obtained by other investigators for axially compressed, thin-walled, circular cylindrical shells. A rigorous calculation of the stability of the equilibrium of the model indicates that the snap-through phenomenon can be entirely absent when an imperfect shell is heated in a perfectly rigid testing machine. When the testing machine is sufficiently elastic, snap through will occur. It may take place at a temperature smaller than, equal-to, or greater than $T = \epsilon_{cr}/\alpha$, where $\epsilon_{cr}$ is the theoretical critical strain of the perfect shell and $\alpha$ is the coefficient of expansion of the material of the shell, but the maximum stress produced in the imperfect shell will always be less than $\epsilon_{cr}E$, where $E$ is Young’s modulus of the material.


ABSTRACT: Earlier numerical solutions of the von Karman-Donnell large-displacement equations for thin circular cylindrical shells have been extended by considering larger numbers of terms in the double Fourier series representing the radial displacements after buckling. In the most comprehensive one of the calculations whose results are presented here a total potential energy expression consisting of about 1100 terms was minimized with respect to 16 unknowns. The results of the computations as well as theoretical considerations indicate that the solution for long shells of the von Karman-Donnell equations with the aid of the von Karman-Tsien Leggett procedure leads in the limit to the trivial solution in which the amplitude of the displacements tends to zero, the number of waves around the circumference tends to infinity and the average axial compressive stress capable of maintaining equilibrium in the post-buckling state tends to zero.


SUMMARY: The, development of our knowledge of the buckling of thin-walled circular cylindrical shells subjected to axial compression is outlined from the beginning of the century until the present, with particular emphasis on advances made in the last twenty-five years. It is shown that practical shells generally buckle under stresses much smaller than the classical critical value derived by Lorenz, Timoshenko, Southwell and Flügge. A first explanation of the reasons for the discrepancy was given by Donnell and the problem was explored in detail by von Kármán, Tsien and their collaborators. More recently, Yoshimura discovered the existence of an inextensional displacement pattern which the wall of the shell can suddenly assume, and Koiter found an explanation of the sensitivity of the buckling stress to small initial deviations from the exact circular cylindrical shape. In the last few years further interesting discoveries were made in Japan and in California regarding the effects of details of the boundary conditions, and many additional numerical results were obtained with the aid of high-speed electronic digital computers. Improvements in experimental techniques have also contributed significantly to a clarification of the problem and to an establishment of the unavoidable deviations from the
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J.M.T. Thompson 1964 Eigenvalue Branching Configurations and the Rayleigh-Ritz Procedure, Quarterly of Applied Mathematics, Vol. 22, 244, October 1964
S. Timoshenko 1914 Bulletin, Electrotechnical Institute, St. Petersburg, Vol. 11.
Wilbur M. Wilson and Nathan M. Newmark 1933 The Strength of Thin Cylindrical Shells as Columns, Engineering Experiment Station of the University of Illinois, Bulletin No. 255.

ABSTRACT: The creep deformations of a circular cylindrical shell are calculated under the action of uniform axial compression. The edges of the shell of finite length are simply supported and the deformations are assumed to be axially symmetric. Such axisymmetric deformations have been observed to occur when the shell is moderately thin-walled. The solution is obtained in the form of trigonometric series for the stresses and displacements.

References listed at the end of the paper:

ABSTRACT: This paper is not meant to be the definitive publication on the creep buckling of plates and shells; it is rather a progress report on work completed in the relatively near past, mostly by the present author and his collaborators. Results obtained by other researchmen will also be discussed, particularly if there has been some interaction between these men and the present author. Omission of reference to the work of any other investigator should not be interpreted to mean that it is considered to be of an inferior quality; lack of such mention may simply indicate that the present author is unfamiliar with the work, or that he had to leave it out for lack of space.

References listed at the end of the paper:
ABSTRACT: Curvilinearity of the generators forces the structure to behave in a qualitatively different way under the action of axial forces. Firstly, up to loss of stability the individual generators of the system are in a state of longitudinal-transverse bending. Secondly for a shell with negative Gaussian curvature there may be a sharp drop in the critical axial compressive loads even in structures that deviate only slightly from the cylindrical. All this means that shells of revolution with curvilinear generators in axial compression cannot be designed for stability using the formulas derived for cylindrical systems.

References listed at the end of the paper:


ABSTRACT: Complete spherical shells with radius-to-thickness ratios of from 1570 to 2120 were produced by electroforming. For specimens of good quality and for optimum testing conditions, buckling pressures up to 86 percent of the classical value were obtained. The effect of loading-system characteristics was examined by pressurizing spherical shells in rigid and soft systems and no difference in buckling pressure was observed. It was found that buckling behavior is strongly influenced by the nature and severity of flaws or imperfections; i.e., low buckling pressures can be correlated with the presence of severe flaws or nonuniformities.

(not permitted to see the abstract)
J.P. Peterson, “Influence of specimen design and test procedure on results of buckling tests of shell structures”, in Test Methods for Compression Members, ASTM STP 419, Am. Soc. Testing Mats., 1967, p. 97 (not permitted to see the abstract)


ABSTRACT: (none given)
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ABSTRACT: The stability of a long, thin, elastic circular cylindrical shell subjected to axial compression and an axisymmetric load moving with constant velocity along the shell axis is studied. With the aid of the direct method of Liapunov, and employing a nonlinear Donnell-type shell theory, sufficient conditions for local stability of the axisymmetric response are established in a functional space whose metric is defined in an average sense. Numerical results, which are presented for the case of a moving decayed step load, reveal that the sufficient conditions for stability developed here and the sufficient conditions for instability obtained in a previous paper lead to the actual stability transition boundary.


ABSTRACT: (none given)


ABSTRACT: The plastic collapse of thin shells of revolution under axisymmetric loads is considered. A rigid perfectly-plastic material is assumed. Methods of limit analysis are applied to find collapse loads. The Tresca-Mohr yield criterion, as closely approximated by Nakamura [1, 2] is used.

References listed at the end of the paper:


ABSTRACT: A study of the coupling effect of inertia terms and vibration modes on the dynamic stability of simply supported cylinders of finite or infinite length subjected to uniform radial impulsive pressure (as in space reentry or underwater explosion). In the prebuckling stage, the shells exhibit symmetrical motion; during buckling they oscillate, but if the oscillation is bounded rather than uncontrolled, the system is called dynamically stable. The well-known analogy between thermal stress and equivalent loading is used to derive an equivalent thermal stress problem. The coupling of radial and tangential inertia terms does not seem to be pronounced for radial pressure. The consideration of nonlinear terms in the stability equation is essential. Appendices give the derivation of the problem, the two inertia terms, and the nonlinear effect.
Engineering Mechanics Division, No. EM5, October 1967

C. A. Brebbia and J. M. Deb Nath (Civil Engineering Department, University of Southampton), “A comparison
of recent shallow shell finite-element analyses”, International Journal of Mechanical Sciences, Vol. 12, No. 10,
ABSTRACT: Recent advances in the analysis of shallow shells by finite-element technique are reviewed and
results obtained using different stiffness matrices compared. The question of including rigid body modes in the
prescribed displacement field is discussed. It is found that the constant strain condition, other than the trivial
one—i.e. rigid body modes—cannot be satisfied in the case of curved plates and shells.

C.A. Brebbia and J. Connor, “Geometrically nonlinear finite element analysis”, Proc. ASCE, Vol. 95, No. EM2,
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Yukio Ueda, “Elastic, elastic-plastic and plastic buckling of plates with residual stresses”, Ph.D. Dissertation,
Department of Civil Engineering, Lehigh University, 1962
ABSTRACT: Welded built-up members are being used more frequently in steel construction due to economy,
convenience and aesthetics. The residual stresses produced in the members as a result of the welding play an
important role in the buckling strength of the members. This dissertation presents the results of an investigation
into the elastic, elastic-plastic and plastic buckling of steel plates containing residual stresses. Particular
attention is given to the local buckling of built-up columns of box-shaped cross section. The material of the
members is steel with a stress-strain relationship assumed to be elastic perfectly plastic, and with a Poisson's
ratio of 0.3 in the elastic range and 0.5 in the plastic range. The analysis of the behavior of the plate material in
the plastic range was based on both the secant modulus deformation theory and the flow theory. The theorem of
minimum potential energy was applied to solve the buckling problem. A simplified residual stress distribution
was used in the analysis. Analytical solutions were obtained for the elastic, elastic-plastic and plastic buckling
of a plate simply supported at the loading edges with the other edges elastically restrained or simply supported
or fixed. Numerical examples of the analytical solution were presented for the study on the strength of local
buckling of square built-up columns, that is, case (a) above. This study showed that the first term of the series of
the assumed deflection function was sufficient to investigate the elastic, elastic-plastic and plastic buckling of
the plate with residual stresses. An experimental study was performed on two short columns to check the theory
for the square built-up column of the numerical examples. Good agreement was obtained with the results of the
numerical calculation for elastic buckling and for elastic-plastic buckling, based on the secant modulus
deformation theory. The experiments also showed that the ultimate load was very close to the critical buckling
load for the elastic-plastic buckling, but that the post buckling strength was large for the elastic buckling.

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Fumio Nishino (1), Yukio Ueda (2) and Lambert Tall (3)
(1) Structural Testing Laboratory, Engineering Research Institute, University of Tokyo, Tokyo, Japan
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(3) Structural Metals Division, Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh
University, Bethlehem, PA
“Experimental investigation of the buckling of plates with residual stresses”, in Test Methods for Compression
ABSTRACT: This is a summary of local buckling tests of plate elements in square columns built up by
welding. The experiments were conducted to verify theories for the elastic and elastic-plastic buckling of plates
with emphasis on the effect of residual stress. This was part of a general study on the strength of welded
columns and the influence of residual stress on plate buckling. Both ASTM A 7 and A 514 steels were used.
The square section simulated plates simply supported at the unloaded edges, and the length of the column was
chosen so that end conditions had no effect either on the residual stress distribution or on the local buckling
strength of the columns. Short columns were tested in the “as-placed” condition in a mechanical-type testing
machine. The transverse deflection (local buckling) of the plates was measured at a number of cross sections by
a 1/10000 in. dial gage fixed to a frame held manually. The “top of the knee” method was used to estimate the
bifurcation load. The experimental results showed good correlation with theoretical predictions including the
effect of residual stress for elastic buckling and for elastic-plastic buckling based on the total strain theory. The
results of experiments indicates that considerable post-buckling strength may be expected for elastic buckling of
plates, although not for elastic-plastic buckling.

Masao Yoshiki and Yuzuru Fujita (Department of Naval Architecture, University of Tokyo, Tokyo, Japan),
“Determination of plastic buckling load for axially compressed plates from experimental data”, in Test Methods
PARTIAL ABSTRACT: Many papers have been published on the instability of plates in the plastic range.
However, it has been a difficult problem for researchers to determine the buckling load of a plate from
experimental data. Several approaches have been used. The critical buckling load for applied average strain has
been assumed to be equal to the maximum load (or the corresponding strain) carried by the plate. Another
approach is to take the point of a rapid increase in deflection or a point of bifurcation of strains measured on
both surfaces at a certain point on the plate. In this paper a new method is proposed for determining the critical
load from experimental data. A theoretical justification is furnished by using the energy approach and the
deformation theory of plasticity. The method was verified by carrying out plate and angle compression tests….
E.A. Witmer, et.al. (Aeroelastic and Structures Research Laboratory, MIT, Cambridge, Massachusetts), SABOR 4: An improved discrete-element analysis and program for the linear-elastic static analysis of meridionally-curved, variable-thickness, branched, thin shells of revolution subjected to general external and thermal loads”, MIT Aerospace Report 146-4 (no date given)


ABSTRACT: Explosive-loading and structural-response measurement techniques are described for obtaining definitive large dynamic and permanent-deformation data on simple structures which undergo (a) two-dimensional deformations, or (b) general three-dimensional deformations. In the former category, explosively loaded structures discussed include freely suspended single-layer circular rings, freely suspended unbonded concentric rings, and flat circular plates with clamped edges. Representing category (b) is an explosively loaded cylindrical panel with clamped edges. To define the impulse which was imparted explosively to these structures, appropriate impulse-calibration tests were performed on high-explosive-loaded single-layer and unbonded double-layer specimens; these testing techniques and the results obtained are discussed. General numerical methods for predicting large elastic-plastic dynamic and permanent deformations of structures which undergo either two-dimensional or general three-dimensional deformations are described briefly. Dynamic responses and permanent deformations predicted with these methods are compared with data from the present experiments. Certain problems, both experimental and theoretical, requiring further investigation are indicated.


ABSTRACT: The behavior of a shallow arch and a thin ring under a dynamic pulse loading is studied for a wide range of geometric and load parameters. The nonlinear dynamic response and static load deflection characteristics of the systems are related and employed to define dynamic elastic snapping and dynamic elastic buckling. When such a relationship cannot be established, the mechanism of dynamic elastic-plastic buckling is introduced. Critical dynamic load criteria are specified, and critical dynamic load data are developed as a function of structural geometry and load duration. Finally, a classification scheme for dynamic load problems is suggested.

References listed at the end of the report:


7. Y. C. Fung and A. Kaplan, "Buckling of Low Arches or Curved Beams of Small Curvature," NACA TN 2840, California Institute of Technology (1952)


27. J. Taub and C. Koning, "Impact Buckling of Thin Bars in the Elastic Range Hinged at Both Ends, NACA TM 748 (1934)


INITIAL PART OF THE INTRODUCTION: The theory of large deformations is now applied in an extensive variety of problems, e.g. the calculations for the construction of modern flexible structures, matters pertinent to the study of blood flow in blood vessels, pressure fabrication of metal objects, geophysics, etc. Experimental observation of the loading of some systems suggests the existence of a critical buckling load, while the occurrence of creep gives indication of a critical time of application of a particular load. The task of determining a critical load for the case of momentless shells, i.e. membranes, is of some practical importance. The present paper deals only with the specific problem of tensile instability at large deformations. It is possible to observe such a phenomenon and to treat it theoretically in some special cases. The formation of a ‘neck’ in a tensile test piece during static loading or in subsequent creep is a classic example of a system that exhibits such a loss of stability. As another example, experimental study of the deformation of a right cylinder under the action of an internal pressure readily reveals the existence of a maximum confinable pressure and the localization of deformation. It is possible theoretically to demonstrate the existence of such a maximum confinable pressure for elasto-plastic cylinders at some finite deformation. It seems to us that a study of local bulging due possibly to a loss of stability in massive bodies such as plates, is of great interest to tectonophysics, but as a preliminary to this it is interesting to study the case of stability loss in membranes.

References listed at the end of the paper:


ABSTRACT: The collapse and recovery loads have been experimentally determined for glass-reinforced-plastic shells compressed along the axis. Compressive force-displacement diagrams have been recorded, and it is shown that the experimental and theoretical diagrams qualitatively coincide. The collapse and recovery times have been ascertained. It is shown that glass-reinforced plastics can be used as an elastic material for investigating shell stability at large deformations.

James A. Stricklin, Jose C. DeAndrade, Frederick J. Stebbins and Anthony J. Cwiertny (Department of Aerospace Engineering, Texas A and M University, College Station, Texas, USA), “Linear and Nonlinear Analysis of Shells of Revolution with Asymmetrical Stiffness Properties”, AFFDL-TR-68-150, October 1968, DTIC Accession Number: ADA446937, Handle / proxy URL: http://handle.dtic.mil/100.2/ADA446937

ABSTRACT: In this paper, the authors apply an extension of the direct stiffness method of structural analysis to the linear and nonlinear analysis of shells of revolution under arbitrary static loading with variable thickness properties in the circumferential direction and the meridional direction. The primary difference between this research and previously published research is that all the Fourier harmonics in the circumferential direction are now coupled. The thickness variation in the circumferential direction yields an 8N x 8N element stiffness matrix in which N is the number of harmonics. The resulting computer program is used to conduct a linear, nonlinear, and stability analysis of the Apollo aft heat shield.


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PARTIAL ABSTRACT: For shallow caps under an axisymmetric external pressure distribution which is inward in a neighborhood of the pole and outward away from the pole, it has been shown previously that a finite axisymmetric dimple state of deformation is possible if the inward pressure is at least of the order of the classical buckling pressure for a complete spherical shell and that, asymptotically, the corresponding dimple base is located by the condition of no resultant vertical force over the dimpled region. In the present paper we treat the more difficult load magnitude range...


ABSTRACT: The application of the direct stiffness method in the solution of doubly curved shell stability problems is demonstrated. Discussed first are the modifications necessary to the basic linear matrix displacement approach of structural analysis to solve large deflection and stability problems. The resulting nonlinear system of equations is solved using the piecewise linearization technique. Buckling loads are predicted for several shallow spherical shells of varying geometry and compared to known solutions. Finally, the method is applied to a radome shell with nonuniform surface loads and the critical buckling load is established.


ABSTRACT: (none given)

References listed at the end of the paper:


PARTIAL ABSTRACT: The carrying capacity of a shell subjected to an external pressure uniformly distributed over a portion of its length was investigated on an experimental facility…


PARTIAL ABSTRACT: Publications by Korbet and Saksonov [5], Varvak [2], Kan [4], and by investigators abroad [5-9] are devoted to the solutions of the problem of stability of a cylindrical shell under axial compression, when the shell is strengthened by an elastic core. A considerable complication of the solution takes place in the case of one-sided constraints of the shell and the core. A theoretical investigation of such a problem is presented only in [3], where two variants of the solution are given for different specification of an
axisymmetric mode of the buckled surface of the shell… In the present article this problem is solved for a shell of an arbitrary length for arbitrary boundary conditions. Here the form of the bent surface is not specified beforehand: it is calculated simultaneously with the critical load. The elastic Winkler foundation, with the known bearing coefficients alpha1 and alpha2 respectively inside and outside the shell, is not joined to the latter…


ABSTRACT: A theory is postulated to explain the dynamic plastic buckling of short cylindrical shells subjected to uniform radially inward impulses. Formulas are derived which predict wavelengths (or mode numbers) and threshold impulses in general agreement with the experimental results that are presented. According to the theory, the restoring moment primarily consists of a directional moment brought about by yielding in a biaxial plastic state of stress; for the practical strain hardening values used the hardening contribution to the restoring moment is secondary. This conclusion is based on the relative influences on the preferred modes and threshold impulses.


ABSTRACT: This paper explores the nonlinear problem of determining the local shape of all possible equilibrium paths through a point where a unique path is not assured. For the sake of rapid insight the treatment is confined to systems having a potential energy depending on any finite number of variables, one direct application being in the theory of structures. The relation with stability is described. The problem is reduced to a readily defined sequence of linear and nonlinear governing equations. These are all expressed explicitly in terms of the orthonormal eigenvectors of an algebraic eigenvalue problem, and the case of a multiple zero eigenvalue (related to the existence of multiple buckling modes) is thereby concisely treated. Branching points which do not permit changes of load are distinguished from those which do. A comparison with Koiter’s work is given.


ABSTRACT: The bifurcation stress is calculated for a simply-supported elastic-plastic plate in uniaxial compression, in the case when the stress is at a vertex of the yield surface which is locally similar to that of Tresca. The effect of coupled hardening between yield-surface facets which meet at the vertex is included. It is found that the bifurcation stress may be substantially lower than that associated with the von Mises yield surface. The latter is known to give results too high to be reconciled with experiment. Reductions of order 10–30 per cent are shown to be unexceptional, even with the retention of an elastic value for the shear modulus.


ABSTRACT: The effect of initial geometric imperfections on the buckling and postbuckling behavior of composite cylindrical shells subjected to uniform axial compression is studied in this report. The solution is obtained by employing von Kármán-Donnell nonlinear strain-displacement relations and the principle of stationary potential energy. Numerical results are given for various fiber orientations in the three-layer shell consisting of either glass-epoxy or boron-epoxy composites, with different initial imperfections. Results indicate that the boron-epoxy composite shells are less imperfection sensitive than the glass-epoxy composite shells. Isotropic shells are found to be more imperfection sensitive than composite shells. It is noticed that the increase or decrease in the classical buckling load with change in fiber orientation is generally accompanied by a decrease or increase in imperfection sensitivity of the shell.

References listed at the end of the report:
17. Khot, N. S., On the Effects of Fiber Orientation and Nonhomogeneity on Buckling and Postbuckling Equilibrium Behavior of


G.R. Monforton (1) and L.A. Schmit, Jr. (2)
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ABSTRACT: A linear finite element capability for predicting displacements, stresses, and natural frequencies of sandwich plates and cylindrical shells with unbalanced laminated faces is reported. The geometric admissibility conditions of the principle of minimum total potential energy are conveniently satisfied by representing the displacement variables in terms of assumed displacement patterns formed by the sum of products of one-dimensional Hermite interpolation polynomials. Stiffness and consistent mass matrices for small displacements are presented in terms of the element geometry, the stiffnesses of the faces (membrane, bending, and coupling) and the transverse shear stiffnesses of the orthotropic core. Specialization for the analysis of thin laminated plates and cylindrical shells is achieved by simply considering one face of the sandwich. Several numerical examples are presented and comparison is made with existing theoretical and experimental results.


ABSTRACT: A numerical graphic method, based on common assumptions of classical membrane theory, for determining the internal pressure that gives rise to plastic instability in membrane shells with a continuous meridional and simply connected surface is described.

References listed at the end of the paper:


References:


References:


C.C. Chamis, Design oriented analysis and structural synthesis of multilayered filamentary composites, Ph.D. thesis, Case Western Reserve University, Cleveland, Ohio, 1967


(Abstract not available)

ABSTRACT: A FORTRAN IV computer code for the micromechanics, macromechanics, and laminate analysis of multilayered fiber composite structural components is described. The code can be used either individually or as a subroutine within a complex structural analysis/synthesis program. The inputs to the code are constituent materials properties, composite geometry, and loading conditions. The outputs are various properties for ply and composite; composite structural response, including bending-stretching coupling; and composite stress analysis, including comparisons with failure criteria for combined stress. The code was used successfully in the analysis and structural synthesis of flat panels, in the buckling analysis of flat panels, in multilayered composite material failure studies, and lamination residual stresses analysis.

Handle / proxy Url: http://handle.dtic.mil/100.2/ADA309269
ABSTRACT: Theoretical results are presented for the buckling of anisotropic plates. The plates are subjected to simple and combined in-plane loading. The plates are made from fiber composite material of boron/aluminum or high-modulus graphite/resin. The results are presented in nondimensional form as buckling load against fiber orientation angle for various plate aspect ratios. The results indicate that buckling loads of boron/aluminum plates are independent of fiber direction if the plate aspect ratios are greater than about 1, and moderately dependent when this ratio is less than about 1. In addition, the results indicate that the buckling loads are independent of aspect ratio for plates with aspect ratios greater than about 2. Boron/aluminum composite plates can resist buckling loads more efficiently than graphite/resin composites on a specific buckling stress basis. The numerical algorithm and a listing of the computer code used to obtain the results are included.

ABSTRACT: NASA Lewis Research Center research in the field of composite laminate residual stresses is reviewed and summarized. The origin of lamination residual stresses, evidence of their presence, experimental methods for measuring them, and theoretical methods for predicting them are described. Typical results are presented which show the magnitudes of residual stresses in various laminates including hybrids and superhybrids, and in other complex composite components. Results are also presented which show the effects of
lamination residual stresses on laminate warpage and on laminate mechanical properties including fracture stresses. Finally, the major findings and conclusions derived therefrom are summarized.

Cristos C. Chamis (NASA Glenn Research Center, Cleveland, Ohio 44135, USA), “Dynamic probabilistic instability of composite structures”, publisher and date not given in the pdf file; most recent reference is 2001.

ABSTRACT: A computationally effective method is described to evaluate the non-deterministic dynamic instability (probabilistic dynamic buckling) of thin composite shells. The method is a judicious combination of available computer codes for finite element, composite mechanics and probabilistic structural analysis. The solution method is incrementally updated Lagrangian. It is illustrated by applying it to thin composite cylindrical shell subjected to dynamic loads. Both deterministic and probabilistic buckling loads are evaluated to demonstrate the effectiveness of the method. A universal plot is obtained for the specific shell that can be used to approximate buckling loads for different load rates and different probability levels. Results from this plot show that the faster the rate, the higher the buckling load and the shorter the time. The lower the probability, the lower is the buckling load for a specific time. Probabilistic sensitivity results show that the ply thickness, the fiber volume ratio and the fiber longitudinal modulus, dynamic load and loading rate are the dominant uncertainties in that order.

References listed at the end of the paper:


ABSTRACT: A computationally effective method for evaluating the dynamic buckling and postbuckling of thin composite shells is described. It is a judicious combination of available computer codes for finite element, composite mechanics and incremental structural analysis. The solution method is an incrementally updated Lagrangian. It is illustrated by applying it to a thin composite cylindrical shell subjected to dynamic loads. Buckling loads are evaluated to demonstrate the effectiveness of the method. A universal plot is obtained for the specific shell that can be used to approximate buckling loads for different dynamic loading rates. Results from this plot show that the faster the rate, the higher the buckling load and the shorter the time. They also show that the updated solution can be carried out in the postbuckling regime until the shell collapses completely. Comparisons with published literature indicate reasonable agreement.

ABSTRACT: Reentry vehicle shell analysis capabilities and problem areas are surveyed as of the spring and summer of 1970. Some of the major reentry vehicle contractors were consulted in this survey. (GE, AVCO, LMSC, MDAC, Kaman Nuclear, and TRW). Each was asked to state his capabilities and was given an opportunity to give his opinion as to important problem areas that require attention. The contractors' opinions are summarized in addition to comments on development, documentation, and dissemination of computer programs, which is a topic that has become increasingly important in the technical community.


ABSTRACT: A technique is presented for simulating simply supported boundary conditions in axial cylinder buckling experiments. An internal mandrel is employed. The geometric and material constants of the mandrel can be carefully selected allowing it to expand, through a Poisson effect, at the same rate as the shell. The mandrel provides an expansion mechanism for the edges of the shell which allows the shell's generators to remain straight until buckling occurs. In addition, the mandrel can also be used to limit buckle deformations to the elastic region

References listed at the end of the paper:

ABSTRACT: An approximate numerical analysis procedure is presented which is capable of solving thin shells of arbitrary shape, boundary conditions and loading. The shell is idealized as an assemblage of triangular finite elements representing both membrane and flexural stiffness properties, and the solution is carried out by digital computer. Five examples are presented which demonstrate the versatility of the procedure in treating different shell configurations, as well as the accuracy of the results which may be obtained.


DTIC Accession No: ADA447741, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA447741
ABSTRACT: The formulation of a fully compatible general quadrilateral plate bending element is described. The element is assembled from four partially constrained linear curvature compatible triangles, arranged so that no mid-side nodes occur on the external edges of the quadrilateral; thus, the resulting element has only 12 degrees of freedom. Also described is a simple shear distortion mechanism which may be incorporated into the element without changing its basic structure. Results are presented for static analyses with and without shear distortion, and for plate vibration and plate buckling studies, all performed with this quadrilateral element. It is concluded that this is the most efficient general bending element yet devised.


ABSTRACT: A brief review of the development of finite element procedures for the analysis of thin shells is presented, together with a discussion of the four types of approximations involved in the application of the method. Then two factors which influence the efficiency of the finite element solution are considered: the properties of the individual elements (including curvature, deformation refinement, etc.) and the nodal degree of freedom representing rotation about the shell surface normal. Comparative analyses are presented to illustrate the influence of these factors in practical cases. Finally, the formulation of the finite element system equations of motion is discussed and techniques of solution are outlined, taking account of both linear and non-linear classes of problems. A series of examples (both linear and non-linear) are presented which demonstrate the effectiveness and generality of this dynamic analysis technique.

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ABSTRACT: An experimental investigation on the seismic response of ground-supported, cylindrical metal tanks is described. Experimental and analytical research by other investigators over the past forty years has provided a firm basis for the computation of free- and forced-vibration behavior in ideal liquid-filled circular cylindrical shells with a variety of elementary support conditions. However, the actual seismic behavior of ground-supported tanks has not been known, and practical design methods necessarily have been based on simplifying assumptions. The present results provide the first opportunity for rational evaluation of seismic design assumptions, and suggest theoretical developments which would enhance the realism of refined seismic analyses. The aluminum scale model discussed here, 12 ft in diameter and 6 ft high, represents a 36-ft diameter steel prototype. It was tested, in anchored and unanchored base configurations, under action of a time-scaled El Centro, 1940, earthquake with peak acceleration of 0.5 g, using the Earthquake Simulator Facility of the University of California, Berkeley. Stresses and displacements of the model, in both anchored and unanchored conditions, were dominated by effects of “out-of-round” response in higher-order circumferential modes, a result which is not predicted by current seismic analysis theory, and which contradicts basic assumptions of current design practice. The experimental observations are discussed in relation to dynamic analysis theory, practical design methods, and the history of tank performance in past earthquakes.


ABSTRACT: Equations are presented to describe the large deflection behavior of doubly curved shallow thin shells under nonuniform thermal loading. Approximate solutions are obtained by means of the Galerkin method for temperature distributions which a) vary over the surface of the shell and b) vary over the surface and linearly through the thickness of the shell. Load-deflection curves are plotted for simply supported shell panels. The results are used to study buckling and post-buckling behavior of the panels. It is shown, that the buckling temperature is a function of the sum of the curvature parameters, dimensions of the shell and its material properties.

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“Experimental studies of the postbuckling behavior of complete spherical shells: The results of experiments on the postbuckling behavior of electroformed spherical shells under uniform external pressure are presented”, Experimental Mechanics, Vol. 8, No. 12, December 1968, pp. 548-553, doi: 10.1007/BF02327517

ABSTRACT: In experiments performed on elastic, complete spherical shells of large radius-to-thickness ratio, pressure and volume-displacement instrumentation and photography were used to study postbuckling behavior. Photographs of a number of the distinct modes observed are presented.

References listed at the end of the paper:

ABSTRACT: The buckling stability analysis of long cylindrical shells with random imperfections subjected to axial load is treated using two different approaches. The first study is based on a Lyapunov method which enables one to establish sufficient conditions for buckling stability of a long cylindrical shell with axisymmetric random imperfections. A perturbed system of equations in the neighborhood of the prebuckling solution is investigated. By reducing the problem to a system of integral equations, it is observed that the stability boundary value problem of a long shell is similar to that of a dynamical system with random parametric excitations. Initial imperfections were assumed to have Gaussian distribution and an exponential cosine correlation function. The critical load was obtained as a function of the root mean square of the imperfections. Results obtained are qualitatively similar to those of Koiter for a periodic imperfection (Ref. 1). The second part is based on the approximate method of truncated hierarchy. The prebuckling state of equilibrium for asymmetric imperfections is found by a successive substitution technique. A homogeneous variational system of equations is set up in order to examine the existence of bifurcation in the neighborhood of the equilibrium state. These last equations involve random parametric terms. The truncated hierarchy method is applied and characteristic equations are obtained. Various exponential cosine correlation functions associated with asymmetric imperfections are examined numerically. Qualitatively the results obtained are as anticipated.

References listed at the end of the Ph.D. dissertation:


ABSTRACT: An experimental investigation of the effect of the cone semivertex angle alpha on the buckling load of a conical shell under axial compression was carried out. The effect of a specific type of initial imperfection was also investigated. The imperfection studied was axially symmetric in shape. The experiments were carried out with shells fabricated by a copper electroforming process. The shells had no longitudinal seams. Final results showed that the dependence of the buckling load on the semivertex angle alpha is adequately represented by the linearized theory. Also the upper bound to the experimental results of the cones with known axisymmetric initial imperfections agreed well with previously published analytical values.


ABSTRACT: An experimental and theoretical investigation of the effect of general imperfections on the buckling load of a circular cylindrical shell under axial compression was carried out. A non-contact probe has been used to make complete imperfection surveys on electroformed copper shells before and during the loading process up to the buckling load. The data recording process has been fully automated and the data reduction was done on an IBM 7094. Three-dimensional plots were obtained of the measured initial imperfection surfaces and of the growth of these imperfections under increasing axial load. The modal components of the measured imperfection surfaces were also obtained. The theoretical solution located the limit points of the post-buckled states. A simplified imperfection model was used consisting of one axisymmetric and one asymmetric component. For global buckling the correlation between the theoretical buckling loads and the experimental values was found to be good.

References listed at the end of the dissertation:


ABSTRACT: An experimental and theoretical investigation of the effect of general imperfections on the buckling load of a circular cylindrical shell under axial compression was carried out. A noncontact probe has been used to make complete imperfection surveys on electro-formed copper shells before and during the loading process up to the buckling load. The data recording process has been fully automated and the data reduction was done on an IBM 7094. Three-dimensional plots were obtained of the measured initial imperfection surfaces and of the growth of these imperfections under increasing axial load. The modal components of the measured imperfection surfaces were also obtained. The theoretical solution located the limit points of the postbuckled states. A simplified imperfection model was used consisting of one axisymmetric and two asymmetric components. For global buckling the correlation between the theoretical buckling loads and the experimental values was found to be good.


ABSTRACT: The results of an extensive imperfection survey on a 10-ft-diameter integrally stiffened cylindrical shell are presented. The shape of the measured initial imperfections is clearly influenced by details of the shell construction. The modal components of the measured imperfection surface as a function of the circumferential and of the axial wave numbers are calculated. The discrete axial power spectral density functions and the corresponding root-mean-square values of the imperfections are also determined for given circumferential wave numbers. Using the Fourier coefficients of the measured initial imperfections, buckling loads are calculated by solving the nonlinear Donnell-type imperfect shell equations iteratively. The calculated lowest buckling load compares favorably with the values usually recommended for similar shell structures.
Persistent Identifier: urn:NBN:nl:ui:24-uuid:e51012e0-9c52-466d-8c3b-713c16dbb882


J. Arbocz and C.D. Babcock, Jr., “The Buckling Analysis of Imperfection Sensitive Shell Structures” (Pamphlet), National Aeronautics and Space Administration, 30 pp, 1980
ABSTRACT: Several types of analyses used to predict the buckling behavior of imperfect Al shell structures are described. These analyses are used to study one well characterized stringer-stiffened cylindrical shell. The ability of each analysis to predict the actual experimental buckling load is examined. In addition, the information obtained from each analysis is used when proceeding to a higher level of analysis complexity. Based upon this study, a procedure for calculating a "knockdown" factor is proposed to replace the traditional empirical knockdown factor.

ABSTRACT: (none given)

SUMMARY: Despite decades of intensive research work most shells continue to be designed by the so-called Lower Bound Design Philosophy which has been in use since the turn of the century. It is shown that by collecting the data of extensive initial imperfection surveys on full scale structures in Initial Imperfection Data Banks improved design criteria can be developed. Especially the use of the Monte Carlo Method to derive reliability functions (based on measured initial imperfection distributions that are characteristic of the different fabrication processes), may finally provide the practicing structural engineers with a design procedure that incorporates the concept of imperfection sensitivity in a rational manner.
References listed at the end of the paper:
M. El Raheb (1) and C. D. Babcock, Jr (2)
(1) Jet Propulsion Laboratory, USA
(2) Department of Aeronautics, California Institute of Technology, Pasadena, California 91103, U.S.A.
ABSTRACT: The effect of elastic end rings on the eigenfrequencies of thin cylindrical shells is studied by using an exact solution of the linear eigenvalue problem. The out-of-plane and torsional rigidities of the rings are responsible for the overall shell stiffness. Considerable mode interaction exists for modes with low circumferential wave numbers when the mass of the ring is comparable with that of the shell. The hypothetical simply supported and clamped boundary conditions are practically impossible to realize with a finite-mass ring for relatively short and thin shells.

ABSTRACT: A general form of perturbation analysis for discrete non-linear structural systems is presented. This generates a system of linear equations which can be solved sequentially for the path derivatives in the unloaded state. Each set of linear equations has the same basic non-singular matrix, and the method is thus ideally suitable for use with a digital computer. The general theory is illustrated firstly by an harmonic and secondly by a finite element analysis of a beam suffering large bending deflections, an exact beam formulation being employed and a continuum perturbation analysis being presented for comparison. The first seven path derivatives are evaluated and are observed to converge rapidly in each case to the continuum values which are then used to construct the load-deflection characteristic of the beam: the choice of independent variable in this final construction is seen to be highly significant. Good agreement is achieved with the known non-linear solution, and it is concluded that the perturbation analysis will be a useful tool in problems of moderate non-linearity.

ABSTRACT: A general perturbation theory for the branching analysis of perfect and imperfect discrete conservative structural systems is presented. Such systems are best analysed without resort to a scheme of diagonalization, and the absence of such a scheme distinguishes the present development from an earlier study by the author. The tensor notation and the system of sliding axes employed in that study are however of considerable analytical value and are therefore retained. The theory is presented for both a general and a specialized class of system and some general features of the perturbation scheme are established. For imperfect systems the concept of a spiralling eigenvector is introduced to yield the equations of imperfection-sensitivity explicitly in terms of the post-buckling derivatives of the perfect system and in a form that can be directly employed in numerical analysis.

ABSTRACT: The large deflection behaviour of a shallow circular arch subjected to a vertical point load is studied analytically using the Rayleigh-Ritz finite element method. The energy functional employed is a little more exact than that normally used for shallow arches and the functions used in the finite element method maintain continuity up to the second derivative of the normal displacement and up to the first derivative of the tangential displacement. The non-linear algebraic equations of equilibrium are solved to a high degree of accuracy using a Taylor's expansion technique together with the Newton-Raphson method. The stability of the symmetric deformation path is studied and a detailed analysis is carried out at the point of bifurcation to an asymmetric deformation path. The slope of this post-buckled path is computed and is shown to be accurate for deformations well beyond the point of bifurcation.


ABSTRACT: A general perturbation theory for the branching analysis of discrete conservative structural systems is presented. Such systems are best analysed without resort to a scheme of diagonalization, and the absence of such a scheme distinguishes the present development from earlier studies. The tensor notation and the system of sliding axes employed in earlier studies are however of considerable analytical value and are therefore retained. The theory is presented for both a general and a specialized class of system and some general features of the perturbation scheme are established. The application of the general theory to two branching problems is finally outlined and its merits discussed.


References listed at the end of the paper:

ABSTRACT: Bifurcation theories for the instability of slowly evolving systems have been developed in various disciplines, and a first step is here taken towards some desirable unification. A modern account of the authors' general branching theory for discrete systems is first presented, some new features being the introduction of principal imperfections and the delineation of the important semi-symmetric points of bifurcation. This theory, embedded in a perturbation approach ideal for quantitative analysis, is complementary to the far-reaching qualitative catastrophe theory of René Thom which offers a profound topological classification of instability phenomena. For this reason, we present here a detailed correlation of the two theories. Also presented in the paper is a survey of some fields of application ranging from classical fields such as hydrodynamics, through thermodynamics, crystallography and cosmology, to the newer domains of biology and psychology.

ABSTRACT: The classification of initial postbuckling behavior is known to be governed by the energy function of the critical equilibrium state, and this can be emphasized by viewing the load as a Lagrange multiplier in a constrained minimization. The energy of the critical branching point itself also uniquely determines the catastrophe theory classification of instability phenomena, and it is shown how a finer bifurcational classification arises when a load parameter, and hence an approach route in control space, is specified a priori. These ideas are illustrated for the compound, twofold, semisymmetric branching points with an examination of two pathological cases that have not been previously analyzed. The first of these is the degenerate situation typified by the rotationally-symmetric buckling of a complete spherical shell in which the load and engineering imperfections fail to fully unfold the topological singularity, and generate a trace of hill-top branching points. The second is the paracinal point of bifurcation (parabolic umbilic catastrophe) that forms the typical transition from a homeclinal to an anticlinal point of bifurcation, and represents an important practical problem in the interactive buckling of stiffened plates and shells.


ABSTRACT: The vibrations and stability of a thin cylindrical circular shell and a three-layered plate are studied. The structure is considered as a system with many degrees of freedom. This model permits investigations of the dynamic properties of the structure due to loads and temperature. An approximate solution of the wave problem is obtained.


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ABSTRACT: A theoretical analysis of the buckling of a multilayered thin orthotropic composite circular cylindrical shell of finite length, subjected to (a) uniform axial compression, and (b) axial compression combined with radial pressure, is presented. At each end of the shell, four boundary conditions are satisfied. Four combinations of boundary conditions for simply supported shells, and four combinations of boundary conditions for clamped shells, are treated. These boundary conditions are reduced to the vanishing of a fourth-order determinant. Buckling loads for boron-epoxy composite shells are determined and the results are shown in a series of diagrams. The effect of boundary conditions on the buckling load for various geometrical dimensions of composite cylinders is investigated. Details of the boundary conditions are shown to have strong influence on the buckling load of the shell. The minimum critical axial compression for a simply supported shell with
boundary conditions SS1 is as low as 79 percent of the minimum critical axial compression for a shell with classical boundary conditions SS3. As a special case of a composite shell, the minimum critical axial compressive stress for a homogeneous, isotropic, simply supported shell with end conditions SS1 is found to be 43.7 percent of the classical critical stress.

ABSTRACT: The buckling of imperfection-sensitive elastic structures is examined from a statistical point of view. Given the relation between the imperfection and the buckling load, an account is given of the dependence of the statistical parameters of the critical load distribution upon the parameters of the imperfection distribution. It is shown that the statistics of the critical load distribution are highly dependent on both the mean and the dispersion about the mean of the imperfections. The question of the probability of failure at a specified nominal load, and its dependence on the degree of uncertainty of both load and imperfection, is also analysed. Numerical results are obtained on the basis of a normal imperfection distribution for two classes of structures, namely symmetric and asymmetric structures.

ABSTRACT: The erratic buckling behavior of cylindrical shells in axial compression is analyzed using the concept of equivalent imperfections. It is postulated that the sum of all departures from perfection in a real shell can be replaced by a hypothetical axisymmetric imperfection in a corresponding shell of infinite length. The equivalent imperfect is treated as a random variable with a normal distribution whose mean and variance are assumed to be directly proportional to the shell radius to thickness ratio. This leads to a design formula which is compared with the results of some 360 cylinder buckling experiments published elsewhere. An appropriate choice of proportionality constants yields a curve which gives a good lower bound on the experimental buckling loads over the whole range of radius to thickness ratios. An analogy is drawn between the Perry-Robertson strut formula and the one proposed here for cylinders.

ABSTRACT: Accurate equations for the neutral equilibrium of arbitrary elastic shells are derived. These equations involve no displacement components and thus complement alternate sets of neutral equilibrium equations proposed by Koiter and Budiansky. The equations are specialized to a uniformly loaded circular cylindrical shell and reduced to a single partial differential equation. For a simply supported cylindrical shell, expressions for the buckling loads are obtained which are as simple as those predicted by the Donnell equations, yet as accurate as those predicted by the more elaborate Flügge equations.

ABSTRACT: A non-linear shell theory valid for large displacements and finite strains is presented for thin homogeneous and elastic shells whose material exhibits curvilinear orthotropy, though it is subject to the restriction of the Kirchhoff hypothesis. By introducing certain simplifying assumptions of “orders of smallness”, approximate field equations are obtained for thin circular cylindrical shells. The equilibrium configuration of postbuckled states of isotropic circular cylinders under external lateral pressure is investigated with the aid of the basic equations derived above, and the results are compared with the solution due to the conventional large deflection theory.


ABSTRACT: The post buckling behavior of an axially compressed corefilled circular cylindrical shell is presented. The soft elastic core is represented by the Pasternak foundation model which is a Winkler foundation model with shear interactions. The Ritz energy method is employed to obtain the load-deformation relationship. The stabilizing effect of soft core on the buckling strength of shell is illustrated.


Koryo Miura (Institute of Space and Aeronautical Science, University of Tokyo), “Proposition of pseudo-cylindrical concave polyhedral shells”, University of Tokyo Report No. 442, November 1969

ABSTRACT: A proposition of a new shell form, which is cylindrical in a macroscopic sense and is concave polyhedral in a microscopic sense, is the purpose of this paper. It is shown that the inextensional post-buckling configurations of general cylindrical shells subjected to axial loading have peculiar geometrical characteristics, and that these configurations compose a general group of surfaces which may be designated as the pseudo-
cylindrical concave polyhedral surface. Then the fixed idea that these surfaces are essentially failed forms is abandoned and is replaced by the idea that these are the basic forms of a new shell which could function superbly as the structure under some loading conditions. It is shown that the new shell, which may be called for convenience, the pseudo-cylindrical concave polyhedral shell and the PCCP shell for its abbreviation, has many useful characteristics as follows: inclusion of an arbitrary curvature distribution, developability of its midsurface, intrinsically high circumferential bending rigidity, and simplicity of elementary faces. The application of PCCP shells to large span shell structures, reservoirs, expansion joints, and others is suggested.


ABSTRACT: Unidirectional boron/aluminum stiffeners have been used to save weight in stiffened panels, where the cross-sections were of such shapes as hats, rs, Z’s, channels, etc. The buckling analysis of these structures is usually found to be unconservative when tests are performed. Even so, a weight saving of approximately 50% can be achieved in the stiffeners themselves by replacing their metal counterparts. A no-edge-free crippling test was performed on a unidirectional boron/aluminum laminated plate, where collapse occurred at a compressive load considerably below the theoretical bifurcation buckling point. This premature failure is explained by a numerical analysis of the test by the use of a nonlinear computer code, which revealed the presence of high transverse bending stresses beyond the capacity of the composite.


ABSTRACT: The primary objective of the present work is to assess the effect of curvature upon the vibration frequencies of shallow shells. For this purpose, the shell is chosen to have a rectangular boundary supported by shear diaphragms and yields exact, closed form solutions for convenient comparison in the linear, small deflection regime and, at the same time, represents a situation which can readily occur in practical application. The shell is taken to have two independent radii of curvature, Rx and Ry whose planes are parallel to the edges. The linear eigenvalue problem is solved, both when tangential inertia is included and when it is neglected.
Extensive tabular and graphical results are presented which show the effect of curvature ratio $R_x/R_y$ in the interval $-1.5 < R_x/R_y < +1.5$ and the “average curvature” upon the frequencies. The analysis is extended into the non-linear, large deflection régime by assuming mode shapes and satisfying the non-linear field equations of motion and compatibility approximately by means of the Galerkin procedure. The effect of large deflections upon frequencies and phase plane plots as the curvature ratio changes is shown.

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ABSTRACT: The differential equations which govern the vibrations with initial stresses of thin non-circular cylinders of arbitrary curvature are obtained by a variational approach. The initial stresses which are considered are stresses produced by axial loads, torsion, and normal pressure. The solution procedure is presented and numerical results are presented for the free vibrations of freely supported oval cylinders without initial stress. Frequency factors of oval cylinders are compared with those of circular cylinders as the length, thickness, and non-circularity are varied. The equivalence of the solutions for the free vibrations with and without initial axial stress is also established.

ABSTRACT: The paper describes external radial and hydrostatic pressure tests on 12 mild steel, thin-walled cylindrical shells. Radial deflections and surface strains on the inside and outside of the cylinders’ walls are related to the conventional small deflection theory. The elastic deformation patterns are found to be similar in shape to the lobar modes which can be predicted by elastic instability theory. The collapse pressures of the shells and their modes of failure are considered in relation to the rigid-plastic theory, the importance of initial imperfections is discussed and an attempt is made to relate the geometric and material properties of the cylinders to modes of failure and to appropriate collapse analyses.

ABSTRACT: Circular, thin-walled, steel tubes, with elongated, non-axisymmetric openings subjected to compressive, longitudinal load are examined. Thirteen laboratory tests are described in which careful measurements were made of displacements and strains. The tested specimens were in two geometrically dissimilar groups and their modes of failure were found to be different. In one group the free edges of the openings buckled before failure of the tube and in the other group large displacements at the free edges coincided with the reducing axial stiffness of the tubes. Two theories are proposed to explain these different kinds of behaviour and their predictions are compared with the experimental results.

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DTIC Accession Number: ADA308518, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA308518
ABSTRACT: A study was made to determine the mechanical behavior of boron-epoxy and S-glass-epoxy filament-wound cylinders under tensile, compressive, torsional, and pressure loads. These cylinders were fabricated in either an orthotropic winding pattern or an isotropic pattern. Conventional theory used to predict the elastic behavior of glass-epoxy filament-wound cylinders was discovered to be equally adequate for the boron-epoxy cylinders. Attempts to correlate cylinder failure strengths calculated from existing state-of-the-art theories with experimental failure strengths met with varying success.


ABSTRACT: This paper discusses a variety of experimental techniques used in the United States to characterize the static mechanical properties of filament-wound composites, such as used in vessels subjected to internal pressure. Also discussed are practical pitfalls to be avoided and the data reduction procedures necessary to reduce the test data. Properties covered include tension (flat, ring and tube specimens), in-plane shear (panel, off-axis tension, rail and torsion tube specimens) and multiaxial tension (plate and shell specimens).

ABSTRACT: A method of post-buckling analysis is described which is related to some work of W.T. KImage . Differences in starting data and objectives between this method and the author's recent general theory of equilibrium behaviour near critical points are pointed out. Some remarks are made about convergence difficulties which can arise when critical points are close together.


ABSTRACT: Previous work on mode interaction refers to a column model consisting of two equal flanges. This model is extremely sensitive to imperfection. Actual panel structures are unsymmetrical: the plate side has more cross section than the topside of the stiffeners; and the plate side is more affected by local buckling than the topside. This effect is exaggeratedly represented in a model where the stiffeners do not participate in local buckling. It appears that the sensitivity to imperfections of this model is very little and restricted to geometric parameters $R$ in the near vicinity of $R = 1$. These two models represent extreme cases. The position of actual tophat stiffened panels between these extremes is being explored. It appears that mode interaction is less severe than with the two flange model though still significant.

References listed at the end of the paper:

ABSTRACT: The implications of core shear deformations in the calculation of stresses, deflections and buckling loads are discussed in elementary terms. Simple criteria are given for the classification of panels according to the stiffness of the cores. Desirable attributes of good core materials are described.


ABSTRACT: The geometrically nonlinear analysis of elastic inplane oriented bodies, e.g. beams, frames and arches, is presented in a total Lagrangian co-ordinate system. By adopting a continuum approach, employing a paralinear isoparametric element, the formulation is applicable to structures consisting of straight or curved members. Displacements and rotations are unrestricted in magnitude. The nonlinear equilibrium equations are solved using the Newton-Raphson method for which a number of examples are given. The derivations are extended to include axisymmetric structures.


ABSTRACT: Using dimensions which are typical of current laboratory tubular specimens, critical buckling loads are determined for unidirectional and laminated cylinders subjected to torsion and to axial compression.
Buckling loads are obtained by using classical Fourier analysis in conjunction with Flugge's shell equations modified for anisotropic laminated materials. Comparison of buckling loads to composite strength, as estimated from maximum strain criterion, suggests that buckling is a potential problem in the use of tubular specimens. A relatively easy method for estimating buckling loads is also presented.


ABSTRACT: This report covers three topics in mechanics of advanced composites: effect of fiber cross-section on stiffness and strength of laminated composites; failure criteria for composites under combined loading; and stress analysis models for thick composites. In the area of fiber cross-sectional effect, micromechanics analysis addresses the effect of elliptical fibers on the stiffness and in-plane stress concentrations. Numerical results show that fiber cross-sectional geometry has only a modest influence on laminate elastic constants. The second topic addresses the interaction between longitudinal compression and transverse loading (tension and compression). Data obtained with a mini-sandwich beam are used to generate failure stresses. Classical lamination theory, including thermal residual stresses due to cure, is utilized for determining play stresses. Experimental results reveal little interaction between longitudinal compression and transverse stresses as long as the transverse load is below uniaxial transverse failure. Under the topic of thick composites, the effect of shear deformation and transverse normal stress on the cylindrical bending of laminated, anisotropic plates subjected to a uniform lateral load is investigated. closed form solutions indicate that the effect of transverse normal stress on maximum deflection is small, even for relatively thick plates.

References listed at the end of the report:

ABSTRACT: On the basis of a statistical analysis of the test data it is shown that there is a difference between the mechanical characteristics (in tension and compression) of laminated glass-reinforced plastics obtained under laboratory and industrial conditions by impregnation under pressure in a closed mold. The stability of the strength properties of the glass-reinforced plastic in various conical shells, produced in large batches, is considered. Certain experimental relations between the material properties and the total number of shells produced are also established.

References listed at the end of the paper:


References listed at the end of the paper:
17. R. Lorents, “Die nicht achsensymmetrische knickung dunnwandiger Hohlzylinder,” Physikalische Zeitschrift, 12, No. 7 (1911).


ABSTRACT: In the past, design of submarine pipelines has not taken full cognizance of the fact that such pipelines are structures and should be designed as structures. The submarine pipeline is, in fact, an extremely complex structure. It is much more complex than many larger and more impressive surface structures. Structural design considerations both during and after construction are discussed. The submarine pipeline is seen to function as a continuous beam, a beam on elastic foundation, a tension member, a compression member, a pressure pipe, an externally loaded conduit, and a suspension element. The system of loads on a submarine pipeline include gravitational, environmental, constructional and operational loads. These can be both static and dynamic. Additionally, when pipelines are buried, the loads from saturated and, in some cases, liquefied soils must be considered. This system of loading is very complex and involves environmental loadings that are extremely variable and location dependent. Recommendations are made for a systematic and rational approach to structural analyses which takes into account the individual nature of each submarine pipeline design problem. Areas where further research would be beneficial are also discussed.


PARTIAL INTRODUCTION: In a recent article [19], it was shown that the equations of the linear theory of elastic shells of revolution under arbitrary loads, after a harmonic analysis in the polar angle of the base plane of the shell, can be reduced to two simultaneous fourth order ordinary differential equations for a stress function and a displacement function. The exact reduction procedure of [19] was applied to a circular cylindrical shell. Also mentioned was the possibility of a simplified procedure based on the fact that there is an inherent error in shell theory of the order h/R, where h is the shell thickness and R is a representative magnitude of the two principal radii of curvature. In the present paper, the exact and the simplified procedure of [19] will be applied.
to a conical shell frustrum. The simplified procedure leads to two differential equations as well as to auxiliary equations for the calculation of stress resultants and couples which differ from those of the exact procedure only in terms which are O(h/R). . .

References listed at the end of the paper:

ABSTRACT: The character of the instability and the degradation of the moment-carrying capacity are found by Mylar model experiments for cylinders in bending when subjected to concentrated lateral loads. Lateral loads can seriously degrade the moment capability of cylinders. Critical combinations of moment and lateral load cause two distinct modes of failure—collapse and snapping. Collapse modes exhibit buckles which cover the compression half of the cylinder and are critical for large values of moment and small values of lateral load. Snapping modes of failure involve a single dimple and exist for smaller values of moment and larger values of lateral load.

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ABSTRACT: An infinitesimal theory of instability of an elastic orthotropic shell of revolution subjected to uniform external normal pressure is developed. The theory leads to a linear eigenvalue problem for determination of the buckling pressure. Illustrative numerical calculations based on piecewise-polynomial approximations and the partition method are given for the Fort Martin tower erected in West Virginia by the Marley Co. The tower is a reinforced concrete hyperboloidal shell of revolution, 370 ft. high and 5.5 in. thick for most of its height.


ABSTRACT: A compressive test specimen has been developed for unidirectional carbon fibre reinforced plastics which enables the ultimate compressive strength to be determined. Failure occurs remote from the specimen ends and tests show good repeatability. Results are compared with theory and reasons for the differences are discussed.

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ABSTRACT: Recent developments in the application of reticulated or shell-type construction are presented. Five general methods of analysis are given: (1) the stiffness approach; (2) continuum shell analogy; (3) concepts of discrete field mechanics; (4) split rigidity concepts; and (5) the use of models. Analysis, member loading, physical properties, edge effects, general buckling, and local buckling of domed structures are described. Equations and computer methods that have been used in the design of domed reticulated space structures are given. Suggestions are made for future research and development for these types of structures.


ABSTRACT: The problem of buckling of curved shear panels of corrugated sheets, which is encountered in the design of long shells is examined theoretically. Overall panel buckling, and not local buckling, is analyzed. Thus, the corrugated sheets are treated as orthotropic curved plates. Equilibrium conditions, as well as geometric and elastic relations of a deformed infinitesimal element, are governed by two linear simultaneous coupled differential equations in deflection w and stress function F. Series presentation for w and F yielded a set of homogeneous linear algebraic equations in the unknown deflection coefficients. A nontrivial solution of these equations is possible provided that the determinant of their matrix is equal to zero. The eigenvalues of the shear load are calculated and only the lower value is considered. The few experiments available show reasonable agreement with the theoretically obtained ones. For practical use, curves are given for the calculation of critical shear load.


ABSTRACT: The overall buckling of half-barrel shells made of corrugated steel sheets is studied in this paper. This type of buckling is recognized as a prime factor in defining ultimate load carrying capacity of such shells. The mathematical formulations are based on the linear theory or orthotropic cylindrical shells. The stability conditions are governed by two linear simultaneous differential equations in the deflection and a stress function. The series presentation of the deflection and the stress function yield a set of homogeneous linear simultaneous algebraic equations in the unknown deflection coefficients. The eigenvalues of this system are calculated with different load distributions representing the cases of snow and wind loads, as well as combined loading. Note that the magnitude of critical load as well as the mode of buckling are dependent on the ratio of length to radius of shell and the ratios between the rigidities in the longitudinal and circumferential directions.

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ABSTRACT: Cylindrical shells made of cold formed deep profiles or corrugated steel sheets are analyzed, using the theory of orthotropic shells. The governing equations and solution are modified to correct a deficiency of a previously reported solution, especially for shells supported along their four edges. Improved solutions are obtained by: (1)Accounting for the effect of the transverse shear forces on the condition of equilibrium in the
radial direction; and (2) applying a particular solution that satisfies the governing equations. The modified solution is valid for long shells and converges to that of simple arches with the increase of length of the shell. Also, an experimental program is undertaken and the comparison shows good agreement between the theoretical and experimental results.

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ABSTRACT: An incremental variational method is presented for the determination of the inelastic load-deformation relationship, as well as buckling or collapse load for a shell of revolution which is made of a work-hardening material and subjected to axisymmetric loadings. A variational principle involving Kirchhoff stress tensor, Green strain tensor, and their rates is employed. The isothermal stress-strain relationship based on a modified J2 incremental theory of plasticity is used. The finite difference method of variational calculus is utilized in a numerical procedure to determine discrete velocities and subsequent deformation process. A comparison of the buckling loads of a number of elastic conical shells and inelastic cylindrical shells obtained by the present approach with available experimental results is made. A reasonable agreement is found.

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ABSTRACT: Buckling of open cylindrical shells with free longitudinal edges and simply supported ends, subjected to an axial compression, with imperfections due to end eccentricity or initial deflections, is examined. Field equations based on large deflection theory are reduced to a set of nonlinear finite difference equations and a computer technique for solving this set by the Newton-Raphson method is presented. Equilibrium paths and deflection patterns for examples with three types of imperfections (constant end moment, constant end eccentricity and specified initial deflection) are presented. The equilibrium paths exhibit an asymmetric type of postbuckling behavior; that is, negative imperfections which initially cause the shell to deflect outward would cause a buckling load lower than the linear buckling load without imperfections; whereas, positive imperfections would cause the opposite if there is no external disturbance. The behavior of a shell with Poisson’s ratio $\nu$ not equal to 0 and circumferential displacement equal to zero at the ends, is similar to a shell with negative imperfections since the axial compression would induce an outward (negative) displacement.

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ABSTRACT: A technique for obtaining the buckling load of open cylindrical shells with simply supported ends and free longitudinal edges, subjected to lateral gravity loading, is presented. General equations based on
the large deflection theory are developed and a set of nonlinear finite difference equations is obtained and solved by the Newton-Raphson method. Using the linear terms only, deflections and stresses based on relatively coarse nets compared favorably with existing analytical solutions. The lowest nonlinear buckling load was found to be associated with a deflection pattern symmetric about the transverse centerline, but asymmetric about the longitudinal centerline. In an example, equilibrium paths and deflection patterns were obtained for a shell subjected to uniform load, and to uniform load with a small additional antisymmetric load. The lowest buckling under uniform load was obtained by reducing this additional load to zero. For the example examined, the buckling load was about 1/2 of the classical linear buckling pressure of a full cylinder.


ABSTRACT: Koiter's approach is used to formulate the influence of fiber orientation on the behavior of the cylindrical shell in the initial postbuckling region. Results are presented for three-layer composite cylindrical shells of either glass-epoxy or boron-epoxy subjected to uniform axial compressive load. The results show that the initial postbuckling coefficient that characterizes the extent of imperfection sensitivity of a structure is greater for the glass-epoxy shells than for the boron-epoxy shells. For the glass-epoxy cylinders the slope of the load vs. end-shortening curve in the initial postbuckling region is found to have high negative value, which is not significantly affected by the change in fiber orientation. This suggests that the buckling of a nearly perfect glass-epoxy cylinder under prescribed end-shortening will be catastrophic, regardless of fiber orientation. However, for the boron-epoxy cylinders the negative slope varies with the change in fiber orientation, and whether the failure will be catastrophic or not will depend on the fiber orientation.

References listed at the end of the report:


INTRODUCTION: The safe design of a circular cylindrical shell structure subject to hydrostatic pressure and axial compression necessitates the determination of the loads which will produce elastic instability of the structure. There are two important modes of elastic instability to consider--local and general instability. Local instability is characterized by inward-outward dents which form on the shell surface in contrast to an overall collapse of the entire shell when general instability occurs. Failure by general instability is usually catastrophic and hence it is of primary concern. Analyses of perfect shells for general instability loads based on the solution of the governing differential equations are well known [21,23]. However, experimental tests on circular cylinders subject to hydrostatic pressure or axial compression loads show that in many instances the failure strength is 15 to 60 percent less than that predicted by theoretical analysis. The difference in analytical and theoretical results is attributed to geometrical and material imperfections of the test cylinders. Several empirical and semi-empirical modifications of the theoretical analysis have been proposed in order to gain better
correlation between analytical and experimental results [7,11]. No general method, however, exists to account for the various types of imperfections when applied to a perfectly general problem. Accounting for geometric imperfections, especially out-of-roundness, complicates the analytical solution, because the cylinder no longer can be treated as circular, but takes some other form such as an ellipse. The finite element method of analysis has been used recently to predict the elastic instability load of perfect cylinders and can be used to account for geometrical imperfections as well. However, care must be taken in choosing the type of finite element used or complications will arise in defining the character of the out-of-roundness and a large set of simultaneous equations will be required for the solution.

References listed at the end of the dissertation:


ABSTRACT: Koiter's approach to the analysis of load-displacement behavior in the neighborhood of a bifurcation buckling point is adapted to permit the analysis of behavior in the neighborhood of the buckling point for a structure that exhibits snap-through buckling. The essential concept is the consideration of pre-buckling nonlinearities as generalized initial imperfections of a derived perfect structure called the modified structure. The asymptotic character of Koiter's approach is preserved in this modified structure method of analysis. The development is stated in a functional notation and is then discretized into a matrix procedure based upon finite element idealization. Numerical results are presented for the load-displacement behavior of a circular arch.


ABSTRACT: The movement of the elements of a shell during the instability, i.e. during the “snap”, is subject to the general principles of mechanics, in particular, to the principle of the least constraint (the Gauss principle).

Wei-wen Yu and Charles S. Davis, “Buckling behavior and post-buckling strength of perforated stiffened compression elements”, First International Specialty Conference on Cold-Formed Steel Structures, August 1971

ABSTRACT: (Cannot cut and paste)


ABSTRACT: Since Kármán and Tsien [1] treated the buckling of cylindrical shells under axial compression, introducing the nonlinear theory based on the finite deformation, this problem has been improved and enlarged by the cumulative efforts of subsequent investigators [2 to 6] and the large discrepancy between the experimental buckling values and the classical value has been gradually clarified. In almost all the previous analyses, cylindrical shells are assumed to buckle in a periodic pattern over the whole surface, but localized diamond-shaped buckling patterns have usually been found. Apart from some analyses on local buckling very close to the ends resulting from the end constraint, Yoshimura [4] and Hoff [7] treated the two-tier buckling,
taking into account only the two tiers of periodic undamped waves. The difficulty encountered in such a local buckling is that the deflected shape is not exactly polyhedral. In this paper, the author will attempt to clarify the mechanism of the above-mentioned local buckling. The method of solution employed is based on the stationary principle of energy.

References listed at the end of the paper:

doi: 10.1007/BF00532194

ABSTRACT: This paper deals with the buckling of a shallow spherical cap subjected to uniform edge moment and a clamped deep spherical shell under uniform pressure. The first problem is formulated in integral equations which are solved by an iterative procedure. The buckling moments are determined for a wide range of the shell geometrical parameter. The second problem is based on the concept that the highly deformed region around the apex is treated as a shallow spherical cap elastically supported by the rest of the shell. The stability of a thin sphere is treated as a special case. The results obtained in both problems are compared with existing solutions.

References listed at the end of the paper:

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ABSTRACT: The transfer matrix method is extended to the analysis of non-circular cylindrical panels. The exact solution for the transfer matrix of a panel with exponential curvature is obtained by solving exactly the variable coefficient differential equations of motion of the shell using a Laplace transform—difference equation technique. The results are compared with respect to accuracy and computer time with various approximate methods of computing the transfer matrix for the same panel. Natural frequencies and mode shapes for typical non-circular panels are computed and compared with a constant curvature panel to show the effects of variable curvature.

ABSTRACT: A method of calculating the creep deflections and predicting the creep collapse of a thin-walled circular cylindrical shell, subject to uniform external radial pressure and arbitrary temperature gradients, is shown. This method may also be applied to investigate the behavior of a shell subject to time-dependent temperature gradients and deformations due to other inelastic causes. The set of simultaneous differential equations of equilibrium in terms of creep, thermal, and other inelastic strains is presented. Applications of this method to long cylindrical shells are illustrated by two numerical examples.

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ABSTRACT: The snap-buckling instability of shallow shell-type structures that are subjected to a random transverse load is presented. The deformation of the structure is primarily under a symmetric and an antisymmetric mode and the investigation employs a method initially proposed by Kramers in the theory of kinetics of chemical reactions and later adapted by the present authors for the case of symmetric snap-through of shallow, two pinned arches. Analytical expressions are derived for the probability of snap-buckling in a time interval T in terms of the potential energy functions in the neighbourhood of the stable and unstable equilibrium states of the structure.

ABSTRACT: The relation of initial imperfections to the postbuckling behavior of thin-walled shells is explained, commencing with treatment of the cylindrical shell under external hydrostatic pressure. It is shown that from theoretical studies of the postbuckling behavior of perfect cylinders a lower bound for the scatter region of the buckling loads can be determined. Approximate buckling loads of imperfect cylinders are calculated, utilizing measured initial imperfections. In studying cylinders under axial load, theoretical and experimental postbuckling curves show good agreement, and a lower limit for the scatter region of the buckling loads can be determined from postbuckling investigations of perfect cylinders.


D. S. Kruger and P. G. Glockner, “Experiments on the stability of spherical and paraboloidal shells” (The experimental part of an investigation of the elastic stability of clamped and hinged spherical and paraboloidal thin shell caps subjected to external uniform pressure is discussed by the authors), Experimental Mechanics, Vol. 11, No. 6, 1971, pp. 254-262, doi: 10.1007/BF02329036

ABSTRACT: This paper presents the experimental part of a study of the elastic stability of clamped and hinged spherical and paraboloidal shell caps subjected to external uniform pressure loading. Ninety-six poly-vinyl-chloride (PVC) shells of 15-in. base diameter and formed by thermovacuum process, were tested and their critical loads recorded. The effects of geometry, clamped and hinged boundary conditions, height/span and radius of curvature/thickness ratios on the critical pressure were investigated. The results are compared, where possible, with experimental data obtained by previous investigators.


ABSTRACT: This paper describes experiments carried out in a 17 in air-driven shock tube on polyvinyl-chloride (PVC) plastic shells. This series represents the preliminary phase of an experimental programme designed to study the non-linear dynamic response of such shells to blast waves. In addition to testing eight clamped models of identical geometry, a resin/plywood dummy model of the same configuration was subjected to shock waves in order to determine the pressure time-map over the surface. However, this dummy was found
to be too flexible for pressure calibrations and was subsequently redesigned. Pressures, deflections, and strains were recorded by means of pressure transducers, capacitance displacement transducers and strain gauges. In addition, photographic and video recording were used to monitor the deformation of the shells. The data obtained are presented in graphical form. Emphasis in the paper is given to a detailed description of the experimental techniques and procedures used.


ABSTRACT: This paper describes a series of experiments carried out in the six-foot diameter explosive-driven shock tube of the Defence Research Establishment Suffield (D.R.E.S.) on polyvinylchloride (PVC) plastic shells. The object of the program was to acquire data on the dynamic large-deformation behaviour of shells subjected to simulated blast waves. Spherical and paraboloidal shells with hinged or clamped boundaries, representing a total of 32 different geometries, were tested. In addition, pressure calibration shots were carried out on dummy models designed to simulate the various geometries of the shells. Shock wave pressure and velocity, as well as the deformation of the models were monitored and recorded by means of high-speed and television cameras. Results are presented in tabular, graphical and photographic form.

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ABSTRACT: Non-linear snap-through behavior of a thin concrete shell roof characterized by free edges, or free edge members supported by several columns, is considerably influenced by the boundary conditions and the edge disturbances developed in the prebuckling state. This paper presents a method of realizing all four natural boundary conditions along a free edge of a roof shell model subjected to external pressure. The experimental method is shown to be useful for investigating non-linear behaviour of circular cylindrical roof shell models with free generator edge beams. The method has a wide applicability to a variety of roof shell models with free edge members lying on a horizontal plane.


ABSTRACT: The free vibration characteristics of a singly curved rectangular plate have been obtained by four theoretical methods and compared with experimental results. The variations of a non-dimensional frequency parameter with aspect ratio, a thickness parameter, curvature and fuselage pressurization are indicated.

ABSTRACT: The creep-buckling phenomenon of circular cylindrical shells subjected to axial compression is studied in the presence of initial imperfections when the creep strain rate is proportional to a power of the stress with the exponent greater than unity. A closed-form solution is obtained for the critical time; that is, for the finite time at which the analysis predicts the development of indefinitely large displacements.

C. L. Dym, N. J. Hoff (Department of Aeronautics and Astronautics, Stanford University, Stanford, Calif.), “Perturbation Solutions for the Buckling Problems of Axially Compressed Thin Cylindrical Shells of Infinite or Finite Length”, Journal of Applied Mechanics, Vol. 35, No. 4, pp. 754-762, December 1968, DOI: 10.1115/1.3601301

ABSTRACT: A study is presented of the effect of initial deviations on the load carrying capacity of thin circular cylindrical shells under uniform axial compression. A perturbation expansion is used to reduce the nonlinear equations of von Karman and Donnell to an infinite set of linear equations, of which only the first few need be solved to obtain a reasonably accurate solution. The results for both infinite shells and shells of finite length indicate that a small imperfection can sharply reduce the maximum load that a thin-walled cylinder will sustain. In addition, for a particular set of boundary conditions, it is shown that the effect of the length of a finite shell is small as far as the load carrying capacity is concerned, but significant when the number of waves around the circumference has to be determined. A further result of the study is that axisymmetric initial deviations reduce the load carrying capacity only slightly more than deviations characterized by a product of trigonometric functions of the axial and circumferential coordinates if the wave lengths are properly chosen.


ABSTRACT: The dynamic response of an initially imperfect circular cylinder to a load applied with constant velocity is considered. It is shown that the governing equation is essentially the same as the non-linear equation given by Hoff for the dynamic buckling of columns.


ABSTRACT: The report treats the buckling and postbuckling behavior of circular arches and rings under constant directional pressure. New exact and approximate solutions are given for the linearized eigenvalue problem. It is clearly demonstrated that the assumption of inextensibility is quite reasonable for the asymmetric buckling of steeper arches and of rings. Asymptotic analyses of early postbuckling behavior are given, based on the theory of Koiter and the formalism of Budiansky and Hutchinson. The postbuckling behavior is shown to be stable, and unaffected by the assumption of inextensibility.

References listed at the end of the report:
5. Singer, J., and Babcock, C.D., "On the Buckling of Rings under Constant Directional and Centrally Directed Pressure", Journal of
ABSTRACT: The bifurcation buckling and postbuckling behavior of steep, compressible, circular arches is examined. The arches are loaded with a uniform constant directional pressure and may be either pinned or clamped. The development is based on Koiter's theory. Two different arch theories are used so as to facilitate a study of bending in the prebuckling state. It is shown that clamped arches are always unstable after bifurcation, while pinned arches exhibit a transition from unstable to stable behavior as a semi-circular arch is approached. The results are also compared to results obtained using shallow arch theory and the comparison is reasonably good for moderately steep arches. The effect of middle surface extensibility (compressibility) and of the prebuckling bending is virtually undetectable.

ABSTRACT: The purpose of this study is the evaluation of the effects of curvature, material orthotropy and internal pressure upon the non-linear vibrations of shallow shells. The shells considered here are complete in the circumferential coordinate. A mode shape that leads to a continuous circumferential displacement is used as the basic solution in a Galerkin type procedure. Among the results of interest are the effects of the aforementioned physical parameters on the relative hardness of the shell response, as well as some interesting new perspectives on jump phenomena in non-linear shell vibrations.

Nicholas Mariani (1), John D. Mozer (2), Clive L. Dym (2) and Charles G. Culver (2)
(1) Charles T. Main, Inc., Boston, Massachusetts, USA
ABSTRACT: The buckling of integrally external ring-stiffened conical shells under axial compression was investigated experimentally. Experimental results were compared with theory to find the effect of the stiffener parameters (e 2 /h), (A 2 /a 0 h) and (I 22 /a 0 h^3 ) as well as of shell geometry. Agreement between classical linear theory and experiments was found to be governed primarily by the area parameter (A 2 /a 0 h), and correlation with theory was significantly affected in the range 0.1<(A 2 /a 0 h)<0.5 of that parameter. Beyond this region there is practically no improvement with increase in ring area, whereas the weight of the shell continues to increase linearly. An approximate formula is proposed for calculation of critical loads and found to yield results very close to the more exact critical values calculated by linear theory. A modified “Southwell plot” method was applied and both the intercept method and slope method were used. Critical loads computed from the strain records were found to be below the classical linear-theory predictions and closer to experimental ones.

References listed at the end of the paper:
SS1 critical loads are identical with the SS2 loads and the SS4 loads are almost the same as the 'classical' SS3 conditions SS1 and SS2 yield here critical loads about one half of the 'classical' loads. It was observed that the stiffened cylindrical shells is studied. As in the case of unstiffened shells, the 'weak' in

**ABSTRACT:** The effect of in-plane boundary conditions on the buckling of ring-stiffened cylindrical shells is studied. As in the case of unstiffened shells, the 'weak' in-plane boundary conditions SS1 and SS2 yield here critical loads about one half of the 'classical' loads. It was observed that the SS1 critical loads are identical with the SS2 loads and the SS4 loads are almost the same as the 'classical' SS3...
loads. The combined effect of stiffener parameters and in-plane boundary conditions is studied. For internally stiffened shells the influence of in-plane boundary conditions is found to diminish with increasing values of stiffener eccentricity and area. No such effect is observed for externally stiffened shells. The buckling modes are also studied and found that they are dependent upon shell length (or Z) and upon stiffener location and parameters.

References listed at the end of the report:
Josef Singer (Department of Aeronautical Engineering, Technion – Israel Institute of Technology), “The buckling of stiffened and unstiffened shell structures”, AFOSR-TR-72-0232, TAE Report no. 139, October 1971, Accession No. AD736044

ABSTRACT: Theoretical and experimental research on the buckling of stiffened and unstiffened cylindrical and conical shells, and arches and rings carried out over a period of 2 years in the Department of Aeronautical Engineering is summarized. The topics of earlier work are outlined and the more recent topics are summarized. These include: the influence of in-plane boundary conditions for stringer and ring-stiffened cylindrical shells; extensive tests on integrally stringer-stiffened and ring-stiffened cylindrical shells under axial compression; thermal buckling of cylindrical shells; a collocation method for buckling analysis of elastically restrained conical shells; buckling of cylindrical panels under non-uniform axial compression; and instability of closely ring-stiffened conical shells.

References listed at the end of the report:
ABSTRACT: An experimental study of the buckling of closely spaced integrally stringer-stiffened cylindrical shells under axial compression was carried out to determine the influence of shell and stiffener geometry on the applicability of linear shell theory. 38 specimens fabricated from 7075-T6 aluminum alloy with different geometries were tested. Most test specimens were designed to fail in general instability and under low critical stresses to assure elastic buckling. Agreement of experiments with linear theory was found to be governed primarily by the stringer area parameter, \((A_1/bh)\) and the shell geometry parameter, \(Z\). Values of linearity, \(\rho\), (ratio of experimental buckling load to the predicted one) higher than 80% were obtained in the ranges \(Z > 100\).
and \((A_{1}/bh) > 0.5\) and a clear trend towards \(\rho = 1\) was observed with increasing values of these parameters. Correlation with linear theory was also found to be influenced by panel unstable postbuckling behavior. 

References listed at the end or the report:

25. Horton, W.H., and Cundari, F.L., "On the Applicability of the Southwell Plot to the Interpretation of Test Data Obtained from
Instability Studies of Shell Bodies SUDAAR No. 290, Department of Aeronautics and Astronautics, Stanford University, August 1966.


T. Weller and J. Singer, “Further experimental studies on buckling of integrally ring-stiffened cylindrical shells under axial compression”, (Tests were carried out to verify the results of previous investigations and to establish a lower bound for applicability of linear theory), Experimental Mechanics, Vol. 14, No. 7, 1974, pp. 267-273, doi: 10.1007/BF02322830

ABSTRACT: An experimental study of the buckling of closely spaced integrally stiffened cylindrical shells under axial compression was carried out to determine the influence of shell and ring geometry on the applicability of linear theory. Twenty-nine specimens fabricated from 7075-T6 aluminum alloy with different geometries were tested. Test specimens were designed to fail in general instability and under low critical stresses to assure elastic buckling. Agreement of experimental results of the present study, and of those obtained in other studies with linear theory was found to be governed primarily by the ring area parameter, (A 2 /ah). Values of “linearity” rho (ratio of experimental buckling load to the predicted one), higher than 80 percent were obtained for (A 2 /ah)>0.3 and a clear trend towards rhov=1 was observed with increasing values of this parameter. Correlation with linear theory was also found to be influenced by ring spacing, (a/h), or rather the combination (a/h) [1+(A 2 /ah)] to the −1/2 power. No significant effect of shell and other ring parameters on the correlation with linear theory could be discerned for the shells tested. By a conservative structural-efficiency criterion it was observed that only for low values of the area parameter, (A 2 /ah)< approximately 0.5 ring-stiffened shells are more efficient than equivalent-weight isotropic ones. Highest efficiencies are obtained for (A 2 /ah) approximately equal to 0.2.

References listed at the end of the paper:


ABSTRACT: Theoretical and experimental studies on the influence of boundary conditions on the buckling of stiffened cylindrical shells and their vibrations are discussed. The effect of prebuckling deformation on the buckling loads and vibrations of stiffened shells is studied and compared with that in the case of unstiffened shells. The in-plane boundary conditions are found to be of particular importance for stiffened cylindrical shells and their effect differs significantly from that in unstiffened shells. Axial restraints are found to be of prime importance in stringer-stiffened shells, and therefore the effect of elastic axial restraints is also studied. By correlation with the vibration tests on the same shells a method is developed for definition of the actual boundary conditions of a stiffened shell non-destructively. The effect of eccentricity of loading on stringer-stiffened shells is studied experimentally and correlated with vibration tests on the same shells. Preliminary results of a non-destructive experimental method for prediction of buckling loads based on vibration testing of stiffened shells are also presented.


ABSTRACT: A theoretical and experimental investigation of the vibrations of axially loaded stiffened cylindrical shells is presented. In the theoretical study three sets of equilibrium equations and boundary conditions are derived from the Donnell and Flügge theories. These sets are solved in a manner usually referred, to as the “exact method”. In the experimental study seven different clamped cylindrical shells, stiffened by outside stringers or rings, were tested. The experimental investigation included frequencies and mode shapes. Good agreement was achieved between experiments and theory, and the predicted differences between the different types of shells were verified.

ABSTRACT: The influence of eccentricity of loading on the vibrations and buckling of stringer-stiffened shells is studied. An established nonlinear theory, which takes into account nonlinear prebuckling, is applied and the predictions are compared with experimental results. Two families of shells, one isquioheavilyrsquo stiffened and the other isquomoderatelyrsquo stiffened, were tested but detailed results are presented only for the isquioheavilyrsquo stiffened shells. In each family there are three identical shells, each with different eccentricity of loading. In all cases, different in-plane-boundary conditions are considered and correlated with experimental results.

References listed at the end of the paper:

ABSTRACT: A theory is derived for calculation of the influence of elastic edge restraints on the vibrations and buckling of stiffened cylindrical shells. The stiffeners are considered “smeared” and the edge restraints can be axial, radial, circumferential or rotational. Extensive computations are performed for special kinds of stringer-stiffened shells, and the theoretical predictions are compared with experimental results. A method of definition of equivalent elastically restrained boundary conditions by use of vibration tests is discussed. Application of this technique to tests on 10 shells significantly reduces the scatter in the ratio of experimental to predicted buckling loads.


ABSTRACT: An experimental study of the buckling of closely spaced integrally stringer-stiffened circular cylindrical shells under axial compression was carried out to determine the influence of stiffener and shell geometry, as well as mechanical properties of shell material, on the applicability of linear theory. Tests included 84 shells made of two different kinds of steel with completely different mechanical properties and 74 shells made of 7075-T6 Aluminum alloy. Agreement between linear theory and experiments was found to be governed primarily by shell geometry, Z, where for Z > 1000 values of “linearity” (ratio of experimental buckling load to the predicted one) of 70 percent and considerably above were obtained. Correlation with linear theory was also found to be affected by stringer area parameter (A1 /bh) where for (A1 /bh) > 0.45 the values of linearity obtained exceeded 65 percent and usually were much higher. No significant effect of other stiffener and shell parameters on the applicability of linear theory could be discerned for the specimens tested. The boundary conditions were found to be of importance and for some steel shells the inelastic behavior of the shell material was found to have a considerable effect on the linearity. Predictions of imperfection sensitivity studies could not be correlated with test results. By a conservative structural efficiency criterion all the tested stringer-stiffened shells were found to be more efficient than equivalent weight isotropic shells.


ABSTRACT: The influence of in-plane boundary conditions on the critical loads of axially compressed simply supported stiffened cylindrical shells, stiffened by stringers and by combinations of rings and stringers is studied. It is observed that the axial restraint, u = 0, at the edges and the dimensions of either the stringers or the rings characterize the type of influence experienced. In shells stiffened by medium and heavy stringers the axial restraint is a predominant factor and the weak in shear, Nxphi = 0, B.Cs. have only a slight secondary effect. For such shells a stiffening effect is observed for SS2 and SS4 B.Cs. As the stringers become weaker the influence of the axial restraint diminishes and the isotropic or ring-stiffened like type of behavior, sensitivity to the vanishing of the circumferential restraint, overtakes the stiffening effect due to u = 0. In shells stiffened by combinations of rings and stringers the influence of the in-plane boundary conditions is governed by the relative
magnitudes of the rings and stringers under consideration. Combinations of heavy stringers and weak rings behave like stringer-stiffened shells, exhibiting the stiffening effect due to $u = 0$ whereas shells stiffened by heavy rings and light stringers tend to behave like ring-stiffened shells, revealing their sensitivity to the weak in shear boundary conditions, $N_{\phi} = 0$.


Eduard Riks (Department of Aeronautics and Astronautics, Stanford University, California, USA), “The Influence of Periodic Axisymmetric Imperfections of Various Wavelengths on the Buckling Load of a Cylindrical Shell in Axial Compression”, March 1971, (un-numbered report in the DTIC citation), DTIC Accession Number: AD0747061

ABSTRACT: Koiter's well-known buckling analysis of cylindrical shells with periodic axisymmetric imperfections yields a solution which is valid for imperfection of different wavelengths and amplitudes. Numerical calculations were carried out to evaluate several of these cases. Of particular interest are imperfections of the wavelength which are larger than the one considered in Koiter's original analysis. In such cases, the validity of the solution may be extended to imperfection amplitudes of a much larger order of magnitude hitherto considered. The numerical results are plotted and tabulated. A rederivation of Koiter's analysis is added in an appendix together with a brief description of the computational method that was used.


ABSTRACT: A completely forgotten paper by C.T. Wang on the extension of the Southwell plot to inelastic buckling of columns is revived, rederived and amplified. A theoretical justification is presented for the application of the Southwell method to plastic buckling of columns made of a strain-hardening material, showing that it predicts the double (or reduced) modulus buckling load. Typical experimental verifications are recapitulated. This puts practical applications of the Southwell method in the plastic region on firmer ground.

References listed at the end of the paper:


ABSTRACT: An asymptotic integration technique is developed to describe the post-buckling behavior of thin elastic shells. The introduction of slow space and time scales directly into the shell differential equations permits a modeling of dynamic effects and a means of accounting for finite boundaries. In most cases, quadratic nonlinear interactions dominate the dynamics and lead to hexagonal shaped patterns in the buckled shell. The form of the initial imperfection is crucial in determining the critical buckling load, as, for a given plan form, there are two separated branches in the load-displacement curve. The critical points on each branch occur at different values of the load parameter. Finally, a minimal principle is derived which exhibits the consistency of the present approach with the variational procedures of Koiter and others.

ABSTRACT: The work of Ashwell and Sabir [1] assessing the power of curved finite elements by applying them to circular arches, is extended. An element I based on the cylindrical shell element of Bogner et al. [3] converges satisfactorily for deflexions, for all arch types, but is inferior to a new element II based on simple strain functions. A natural (“exact”) shape function is also presented. When stress resultants are calculated, both I and II converge rapidly if the stress resultants are calculated from an element stiffness matrix, but are sometimes unsatisfactory (except for mid-element stress resultants) if a normal type of stress matrix is used. Element I becomes unsatisfactory if nodal continuity of the gradient of circumferential displacement is imposed.


ABSTRACT: Gradient minimization methods have been successfully applied to the discrete element analysis of shells with geometric nonlinearities and to plates with material nonlinearities. More recently, the feasibility of using such methods for the lower buckling and vibration modes of large eigenproblems has been established. The present investigation extends this work by developing scaling criteria and rescaling strategies based on the second variation of the discretized Rayleigh quotient. The importance of scaling to the efficiency of the conjugate gradient algorithm is found to be similar to that reported for potential energy minimization. Several shell vibration and shell buckling problems are then analyzed using the 48 degree of freedom Bogner cylindrical panel element reformulated to include an incremental stiffness matrix. This element is based on bicubic Hermite polynomials for which discretization error bounds indicate rapid eigenvalue and eigenvector convergence in certain elliptic boundary value problems. These convergence rates are numerically tested in both shell buckling and vibration eigenproblems.


ABSTRACT: NASTRAN is a large digital computer program for static and dynamic structural analysis by the finite element approach. It is nearing completion after three years of development under NASA sponsorship. It will be made available to all interested users and it will be maintained by NASA. It is currently programmed for the IBM 360, the UNIVAC 1108, and the CDC 6600 computers. The major functional capabilities of NASTRAN are static analysis of structures with either linear or nonlinear material properties; buckling analysis; vibration modes analysis of either conservative or damped systems; frequency response analysis; and transient response analysis. Many convenience features are provided to the user including an extensive list of structural elements; the automatic generation of several types of loads including gravity loads and loads induced by thermal strains; plots of deformed and undeformed structures; and the choice of alternate methods of analysis, including, for example, either direct or modal formulations of dynamic problems. NASTRAN is intended primarily for large problems with hundreds or thousands of degrees of freedom. All mathematical subroutines have been designed to provide for the efficient solution of large problems by taking maximum advantage of matrix sparsity and bandedness. A flexible Executive System is provided that facilitates the addition of new functional capabilities to NASTRAN.

ABSTRACT: The paper describes a new four-noded quadrilateral shell element, called QUAD4, which is based on isoparametric principles with modifications which relax excessive constraints. The modifications include reduced order integration for shear terms, enforcement of curvature compatibility, and the augmentation of transverse shear flexibility to account for a deficiency in the bending strain energy. Practical features are discussed, including conversion to a nonplanar shape, coupling between bending and stretching, mass properties, and geometric stiffness. Experimental results are described which illustrate the accuracy and economy claimed for the element.


ABSTRACT: The subject is treated chronologically and in a manner which emphasizes the background for design decisions, including examination of the roles of element testing and failure analysis. The elements treated are the original nastran elements, the quad4, and the tria3, together with their modifications. The quad4 element, in particular, has become a much better element than its 1976 prototype through the process of evolutionary reform in response to weaknesses revealed by practical application.

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ABSTRACT: The powerful technique of parametric differentiation is illustrated, coupled with numerical integration schemes for solving highly nonlinear problems in shell stability. As an example, the axisymmetric buckling pressures of clamped spherical shells of constant thickness, under external pressure are obtained. The application of this technique to the study of postbuckling behavior is demonstrated. This technique is equally applicable to the solution of a wide class of nonlinear differential equations arising out of various physical problems.


ABSTRACT: A review is presented of the shear buckling of isotropic and orthotropic plates with a detailed consideration of the latter. An extensive bibliography is given and the details of the analyses in these papers are also discussed briefly in order to illustrate the development of theoretical and analytical technique. The relevant theoretical information for shear buckling and for the determination of buckling under combined stress systems including shear is presented graphically in the form of data sheets. (Cannot cut and paste references)


ABSTRACT: The buckling of a ring subjected to external pressure but supported by a rigid cavity wall is investigated using small deflection linear theory. It is assumed that the cavity wall moves in with the deflection of the ring prior to the onset of buckling. The ring buckles locally with an arc length no greater than pi
depending on the ratio of the radius of the ring to the radius of gyration of the cross section, \( R/\rho \). A curve is given for numerical evaluation of the critical pressure for all values of \( R/\rho \) in a ring or an infinitely long cylindrical shell.

ABSTRACT: Buckling and post buckling behavior of axially loaded cylindrical shells is studied. Linear and nonlinear equations are solved by finite difference techniques. Eight boundary conditions that differ from those assumed in the classical solution are considered. It is shown that changes in the boundary conditions have a significant effect on both the linear buckling load and on the shape of the post buckling curve. Critical loads and buckling mode shapes are obtained for a wide range of shell curvature.

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ABSTRACT: The effects of inelastic strains on the deflection and stability of thin spherical domes with roller-supported edges under point loads at the apex are studied analytically and experimentally. The governing nonlinear differential equations are derived by applying Reissner’s nonlinear shell theory and the total deformation theory of plasticity. These equations are solved by a finite difference scheme using Newton’s method. Four domes, hydroformed from 6061-O aluminum, are tested. It is concluded that the inelastic strains do account for most of the discrepancies existing between the analytically predicted (based on elastic analysis alone) and the experimentally observed shell responses. It is found that for certain geometric configurations (i.e., \( \lambda > 6 \)) the local existence of finite strains and significant strain reversal indicates that closer correlation between theory and experiment is possible using an incremental plasticity theory.

ABSTRACT: Elastic buckling under axial compression of finite, oval cylindrical shells with clamped boundaries was investigated experimentally. The determination of the buckling strength was made on a series of oval shells made of Mylar A. The test results indicated that the discrepancy between theoretical and experimental initial buckling loads for the ovals is similar to that of the circular cylindrical shells. However, in contrast to the circular case, a collapse load significantly exceeding the initial buckling load is observed in the case of ovals with moderate-to-large eccentricity.

References listed at the end of the paper:

Lee, Y. C. and Advani, S. H. (West Virginia University, Morgantown, West Virginia, USA), “Forced axisymmetric response of fluid filled spherical shells”,

NASA Technical Reports Server (NTRS)
ABSTRACT:
A general solution for the forced, linear axisymmetric response of a fluid filled spherical shell is derived with the effects of shell transverse shear and rotational inertia included. The fluid is assumed to be inviscid and compressible. Expressions for the shell radial displacement are computed for the problem of a uniform radial Heaviside load on a cap of the shell surface. In addition, the time history of the shell inner fiber stresses at the impact pole is obtained. Some comparisons with the in vacuo shell theory are also given.

ABSTRACT: When the designers of reinforced concrete shell structures consider buckling, they have to apply data derived from elastic analyses or elastic model tests to a nonelastic material. The research described was designed to reduce the uncertainties involved by investigating the effect of tension cracking and nonlinearity on the buckling of concrete shells. The information desired was obtained experimentally by comparing the buckling of reinforced mortar models to geometrically similar models fabricated from plastics. The program included tests on 4 long-span single-barrel cylindrical roof shells, on 5 shallow spherical caps, and on 11
cylindrical panels. The results from the cylindrical shells and spherical caps are summarized, while the cylindrical panel tests are described in some detail. The complete curve for interaction of axial and circumferential buckling was established for the cylindrical panels. Conclusions are made about the use of appropriate models in buckling studies, and on the effects of tension cracking and nonlinearity in concrete shells.

ABSTRACT: The special phenomena of reinforced concrete shell buckling is described on the basis of the latest results of research. The method presented takes into consideration the special properties of the reinforced concrete including, plasticity, creep, and quantity of reinforcement. Snap-through critical loads calculated by the described method are compared to the results of model tests and to the loads and critical loads of erected domes. The shell buckling stiffness was seen to be composed of two parts; the bending and the axial stiffness of the reinforced concrete cross section. The critical load is reduced by the plasticity and the imperfections. The critical load of the reinforced concrete shells decreases by the craks of concrete and increases by the reinforcement.

ABSTRACT: The paper presents a simple procedure to establish the buckling load of shell structures. It is essentially based on the assumption that the various factors influencing buckling can be assessed as multipliers of the ‘classical’ critical load. These factors are: imperfections, creep, plasticity, cracks and the steel reinforcement. The paper gives the values of these factors, thus establishing a method which can be used in practical design.

Koryo Miura and Masamori Sakamaki, “Discontinuity in buckle pattern tessellation of cylindrical shells of variable curvature”, Institute of Space and Aeronautical Science, University of Tokyo, Report No. 461, March 1971, pp. 77 – 82
ABSTRACT: This paper presents experimental evidence that the discontinuity of buckle pattern tessellation exists in the elastic postbuckling configuration of cylindrical shells of variable curvature. This raises the question on the validity of some assumptions generally prevailing in analytical studies about the problem. References listed at the end of the paper:


ABSTRACT: When the flow velocity in a finite, thin, circular cylindrical shell, either clamped at both ends or cantilevered, exceeds a certain critical value, the system is observed to lose stability by flutter in its second circumferential mode. This paper describes the phenomenon, and presents a theory for its analysis which is based on Flügge's equations for the description of shell motion and a classical potential-flow theory for the coupled hydrodynamic forces. Complex frequency calculations reveal the existence of flutter in the case of cantilevered shells; for clamped-clamped shells the theory predicts buckling instability followed by coupled-mode flutter. Theory and experiment are in adequately close agreement.


ABSTRACT: An analysis is presented of the interaction between longitudinal and transverse motions of a circular cylindrical shell under impact on the end surface. At infinite and finite velocities of perturbation propagation along the generatrix this analysis reveals the instability modes in the shell which build up fastest and are similar to those revealed if the buckling process at a finite velocity of perturbation propagation were described in the real time of compressive loading action. It is established that a cylindrical shell under intensive loading can be simulated by a rod under longitudinal impact (the similarity parameters are indicated). This conclusion is confirmed by a comparison with experimental results.

References listed at the end of the paper:

V.I. Etokov (Institute of Mechanics, Academy of Sciences of the Ukrainian SSR, Kiev, Ukraine), “Post-critical

ABSTRACT: Pogorelov used a geometric method to investigate the post-critical elastic states of cylindrical shells under axial compression in [4] under the assumption that the nature of the periodicity of the shell deflections is conserved throughout the whole time of strain. An investigation is made herein without the mentioned constraint. The domain of existence of the solution obtained is determined, and it is shown how this domain can be extended. An isometric surface is constructed by using the deflection function obtained from the strain compatibility equation.


ABSTRACT: An approximate method is presented for predicting elastic collapse of complete spherical shells subject to uniform external pressure. The shell contains an imperfection in the form of an isolated flat spot and the snap through behavior of the flat spot region is analyzed. The existence of higher modes is demonstrated and the effect of various choices for the stiffness coefficients at the edge of the flat spot is investigated.

References listed at the end of the paper:
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(2) Department of Engineering Science, State University of New York at Buffalo, Buffalo, N. Y.
ABSTRACT: The effect of random geometric imperfections on the maximum load-carrying capacity of an axially compressed thin cylindrical shell is studied. Following a perturbation approach, equations are derived which relate the first and second-order statistics of the maximum load to the statistics of the initial imperfections. Assuming that the imperfections are represented by Gaussian stationary and ergodic random processes, it is shown that the mean maximum load is expressible in quadrature forms involving the power spectral density of the initial imperfection. Furthermore, the maximum load is seen to be equal to its mean value with probability one. A simple asymptotic formula for the maximum load is derived assuming the variance of the initial imperfection is small. In this case the critical load depends only upon the imperfection variance and the power spectral density at a given wave number. For the types of imperfections considered, it is found that random axisymmetric imperfections reduce the load-carrying capacity of the cylindrical shell more than nonaxisymmetric imperfections.

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ABSTRACT: A study is presented concerning the buckling characteristics of spherical shells with small initial symmetric and asymmetric imperfections in the geometry. The governing nonlinear partial differential equations are formulated using general relations with no restriction on shallowness. The effect of initial geometric imperfections is included in the equations. The shell material is assumed to be linearly elastic. The solution of the differential equations is carried out numerically using the method of L.V. Kantorovich in combination with finite differences. Numerical results are obtained by means of a digital computer, for spherical shells clamped at the boundary and subjected to uniform external pressure. Buckling pressures are determined from the load deflection relationship. The cases of asymmetric imperfections, and symmetric imperfections are studied. A wide range of shell geometries and imperfections is covered. Comparison with earlier experimental results shows good agreement.

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ABSTRACT: A numerical method for determining the buckling loads and stresses for elastic-plastic spherical shells subjected to uniform external pressure is presented. No restriction is placed on shallowness in the
analysis. The incremental theory of plasticity and the von Mises yield criterion are used in formulating the problem. The governing differential equations are formulated in terms of displacements and are solved with the aid of finite differences, an incremental-iterative technique, and a high speed digital computer. Buckling loads are taken as the first maximum of a load-average deflection curve. Numerical results are presented for a clamped spherical shell. Buckling loads are compared to the elastic complete sphere value and the limit analysis load. The relationship of the radius-thickness ratio to buckling stress is presented.


ABSTRACT: Theoretical and experimental studies of the free vibrations and the loss of stability of thick-walled cylindrical and spherical shells subjected to external pressure are presented. General equations for the oscillations of the shell under pressure are formulated on the basis of a rigorous theory of finite elasticity. Loss of stability is determined when the fundamental natural frequency of the prestressed shell ceases to be real-valued. Numerical solutions are obtained by solving the specialized equations that are applicable to neo-Hookean materials. Experiments using specimens made of silicone rubber closely verify the theoretical results.

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ABSTRACT: Layered spherical shells of arbitrary wall thickness subjected to uniform external and/or internal pressure and undergoing large elastic deformations are investigated. Layers are assumed to be made of neo-Hookean materials and perfectly bonded to one another along the interfaces. The stability of the finitely deformed state is studied using the theory of small deformations superposed on large elastic deformations where the secondary displacement field is assumed to be vibratory. The governing equations are solved numerically by a finite difference scheme to yield the frequencies of the small, free, asymmetric vibrations about the prestressed state. The loss of stability occurs when the superposed motions cease to be periodic.


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Chandrakant S. Desai and John F. Abel, Introduction to the finite element method, Van Nostrand Reinhold Co., 1972

ABSTRACT: The finite element method is employed to study the nonlinear dynamic effect of a strong wind gust on a cooling tower. Geometric nonlinearities associated with finite deformations of the structure are considered but the material is assumed to remain elastic. Load is applied in small increments and the equation of motion is solved by a step-by-step integration technique. It has been found that the cooling tower will collapse under a wind gust of maximum pressure 1.2 psi (8.27 kN/m²). The collapse is caused by a local buckling phenomenon along the waist of the cooling tower. The response of the structure before collapse is presented and compared with a linear solution. These results have demonstrated the importance of considering nonlinear behavior in the analysis.

ABSTRACT: Extensive tests on inverted umbrella and saddle-shaped models indicate that the design of thin-steel hypar roofs is usually governed by stiffness, rather than by stress limitations. The rise-span ratio and the shear rigidity of cold-formed decks are the most important factors determining the stiffness of the structure. Deck buckling is caused by the uniform shear stresses in the shear-diaphragm type of action of the shell which dominates the response of hypar shells. This experimental investigation yielded empirical design information in thin-steel hypars and also provided checks on other analytical studies.

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“Analysis of Thin-Steel Hyperbolic Paraboloid Shells”, ASCE Journal of the Structural Division, Vol. 98, No. 11, November 1972, pp. 2605-2621
ABSTRACT: Finite element analyses of orthotropic hypar structures, using flat and curved elements, are compared with experimental results. The flat element approach tends to predict the deflections of flat corners better than the curved element formulation. The buckling of the deck is also studied for a range of edge member and deck properties.


ABSTRACT: A generalized eigenvalue algorithm is presented herein along with the complete listing of the associated computer program, which may be conveniently utilized for the efficient solution of certain broad classes of eigenvalue problems. Extensive applications of the procedure are envisaged in the analysis of many important engineering problems, such as stability and natural frequency analysis of practical discrete structural systems, idealized by the finite element technique. The procedure based on the Sturm sequence method is accurate and fast, possessing several significant advantages over other known methods of such analysis. Numerical results are also presented for two representative structural engineering problems.


ABSTRACT: This article presents an efficient and numerically stable algorithm, along with a complete listing of the associated computer program, developed for the accurate computation of specified roots and associated vectors of the eigenvalue problem \( Aq = \lambda Bq \) with band symmetric \( A \) and \( B \), \( B \) being also positive definite. The desired roots are first isolated by the Sturm sequence procedure; then a special variant of the inverse iteration technique is applied for the individual determination of each root along with its vector. The algorithm fully exploits the banded form of relevant matrices, and the associated program written in FORTRAN V for the JPL UNIVAC 1108 computer proves to be most significantly economical in comparison to similar existing procedures. The program may be conveniently utilized for the efficient solution of practical engineering problems including free vibration and buckling analysis of structures. Results of such analyses are presented for representative structures.

Stuart E. Swartz and Vernon H. Rosenbraugh (Department of Civil Engineering, Kansas State University, Manhattan, Kansas, USA),” Experiments with Elastic Folded Plate Models”, ASCE Journal of the Engineering Mechanics Division, Vol. 98, No. 3, May/June 1972, pp. 711-729

ABSTRACT: Three series of tests were conducted on small scale aluminum models of single cess, folded plate structures with symmetrical cross sections. In the first series of tests, the models were supported on plexiglass plates at the ends and were subjected to uniform, symmetrical loads. In the second series, the models were subjected to asymmetrical loads. A third series of tests was made on the models with the ends and center supported on plexiglass plates and subjected to symmetrically applied, uniform loads. In the first two series of tests, the models were loaded into the post-buckling range. The load which caused a plate element to exhibit local buckling was determined from deflection profiles taken along the longitudinal direction of the models.

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ABSTRACT: This paper investigates the effect of external lateral pressure on the free vibrations of hyperboloidal shells of revolution. A finite element computer program was developed based on Sander’s linear shell theory. This analysis was in good agreement with available experimental results and can be used in the future cooling tower structures. The most interesting result obtained from the investigation was the discovery that for certain hyperboloidal shell geometrics, the lowest frequency mode shapes contain more than one meridional half wave. This result was verified experimentally in the reference.

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ABSTRACT: A computer method is presented to obtain solutions for buckling of the open cylindrical shell, or panel, with the curved edges simply supported. The radius of curvature may vary. The boundary conditions along the straight edges of the panel are arbitrary. The solution is accomplished by the substitution of mixed trigonometric-power series into equations similar to Donnell’s stability equations, with the curvature expression written as a power series. The resulting infinite-terms recurrence relations are truncated to form an eigenvalue problem. Examples involving various combinations of loading, boundary conditions, and noncircularity are presented.

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ABSTRACT: Solutions are developed for non-axially symmetric shallow shells subjected to normal surface loading or thermal loading. The singular solutions which correspond to the concentrated normal load, the concentrated application of heat and the concentrated thermal gradient are identified by a consistent limiting process applied to the complete set of singular solutions. Numerical results are presented for the case of the normal concentrated load acting on shallow shells having negative, zero or positive Gaussian curvature. The behavior of the shallow shells in the neighborhood of the applied concentrated load is seen to be similar to that of a disc subjected to the same load. The influence of the concentrated load is felt over a wider region in shells of negative Gaussian curvature compared to shells of positive Gaussian curvature. However, for the case of the concentrated load, the stress and deflection parameters of the shell do not change dramatically as the Gaussian curvature of the shell is varied from positive to negative values.

ABSTRACT: An experimental and theoretical investigation of the effect of a circular hole on the buckling of thin cylindrical shells under axial compression was carried out. The experimental program consisted of tests performed on seamless electroformed copper shells and Mylar shells with a lap joint seam. The copper shells were tested in a controlled displacement testing machine equipped with a noncontacting surface displacement measuring device. Three-dimensional surface plots obtained in this manner showed the changes in the displacement field over the entire shell, including the hole region, as the applied load was increased. The Mylar shells were tested in a controlled load testing machine and demonstrated the effect of increasing the hole radius on the buckling loads of the cylinder. The theoretical solution was based on a Rayleigh-Ritz approximation. The solution provided an upper bound for the buckling stresses of the cylinders tested for hole radii less than ten per cent of the shell radii. The theoretical solution also identified the governing parameter of the problem as being related to the hole radius, the shell radius, and the shell thickness. The theoretical part of the investigation showed that even a small hole should significantly reduce the buckling stresses of circular cylinders. Experimentally, it was found that the effect of a small hole is masked by the effects of initial deformations but, at larger hole radii, the reduction in buckling stress took the form predicted by the theory. The experimental results also showed that the character of the shell buckling was dependent on the hole size. For very small holes the shell buckled into the general collapse configuration and there was no apparent effect of the hole on the buckling mode of the shell. For slightly larger holes the shell still buckled into the general collapse configuration, but the buckling stresses of the shell were sharply reduced as the hole size increased. For still larger holes the buckling stresses did not decrease as sharply as the hole size increased and the shell buckled into a stable local buckling configuration.


ABSTRACT: An experimental and analytical investigation of the effect of a circular hole on the buckling of thin cylindrical shells under axial compression was carried out. The experimental results were obtained from tests performed on seamless electroformed copper shells and Mylar shells with a lap joint seam. These results indicated that the character of the shell buckling was dependent on a parameter which is proportional to the hole radius divided by the square root of the product of the shell radius and thickness. For small values of this parameter, there was no apparent effect of the hole on the buckling load. For slightly larger values of the parameter, the shells still buckled into a general collapse configuration, but the buckling loads were sharply reduced as the parameter increased. For still larger values of the parameter, the buckling loads were further reduced, and the shells buckled into a stable local buckling configuration.


ABSTRACT: This paper provides the basis for a very general approach to the determination of initial buckling stresses of long stiffened panels in uniform longitudinal compression. The panels are assumed to consist of a series of long flat strips, rigidly connected together at their edges, as in panels with top-hat or Z-section stringers, or in sandwich panels with corrugated cores. Whatever the buckling mode, the individual flats are subjected, just after buckling, to sinusoidally varying systems of both out-of-plane and in-plane edge forces and moments, superimposed on the basic state of uniform compression. The stiffness matrices corresponding to these sinusoidal edge loads are derived, taking account of the destabilising effect of the basic longitudinal compressive stress, not only in the out-of-plane but also in the in-plane deformations. For the latter purpose a non-linear theory of elasticity is used. The application of these stiffness matrices to specific panels is briefly
described. All possible modes are incorporated within one determinantal equation. For panels with identical stiffeners spaced at equal intervals, the order of the determinant is independent of the number of stiffeners.


ABSTRACT: Prismatic plate assemblies include closed and open section struts, stiffened panels with open or closed section longitudinal stiffeners and longitudinally stiffened tubes. Recent theoretical advances have made possible the computation of critical buckling loads (or natural frequencies) for such assemblies. The answers obtained are “exact”, in the sense that only the usual thin plate assumptions are made, so long as the ends of each component plate are simply supported or the longitudinal half-wavelength of the buckling mode is short compared with the length of the assembly. Initially, the theory only applied to assemblies of uniformly compressed, flat, isotropic plates. However, results can now be computed for assemblies which include curved anisotropic plates which carry in-plane bending and uniform in-plane shear and transverse stresses. Existing computer programs enable one to investigate the critical buckling behaviour of a vast range of interesting plate assemblies. So far, results obtained cover only a relatively small part of this range. In this paper, a summary is given of the more interesting conclusions drawn from these results. The results include (a) comparisons with results from simpler, approximate analyses, (b) investigations of novel, advantageous structural forms, (c) examples of the effects of idealisations such as ignoring eccentricities between connected plates and finite radii of curvature at bends, (d) interaction between shear, bending and longitudinal compression for stiffened panels and (e) critical loads other than the lowest.

References listed at the end of the paper:

ABSTRACT: The non-linear post-buckling behaviour of a complete spherical shell is studied analytically in the vicinity of the buckling load. It is assumed that the shell buckles in a rotationally symmetric wave pattern and specific attention is given to deformation modes symmetric about the equator, in the longitudinal direction. The energy functional is reduced to approximate functions using the Rayleigh-Ritz method with which two types of assumed functions are considered, viz. Legendre polynomials and localized Rayleigh functions (finite elements). The algebraic equations of equilibrium are solved approximately using a series expansion technique, and it is shown that the use of Legendre polynomials gives exact values for the coefficients of the series, whilst use of the finite element method results in coefficients which converge monotonically to the exact values as the number of elements is increased.

L.J. Hart-Smith (Department of Mechanical Engineering, Monash University, Wellington Road, Clayton, Victoria, 3168, Australia), “Buckling analyses of ideal thin shells and new thin elastic shell theory formulations”, International Journal of Mechanical Sciences, Vol. 10, No. 8, August 1968, pp. 665-667, doi:10.1016/0020-7403(68)90071-4 (no abstract; this is a letter to the editor.)

ABSTRACT: The problem of the elastic buckling under uniform axial compression of an ideal thin cylindrical shell is examined using a new self-consistent theory of thin shells derived according to the Kirchhoff-Love hypotheses. The collapse stress deduced lies between half of the classical value and that value depending on the exact nature of the end-conditions. The onset of buckling, at which the diamond wrinkles first appear, is shown to be at a stress as low as one-sixth of the classical value. This is a close lower bound of the published experimental data. The solution agrees with the observed diamond wrinkling pattern and predicts nominally square diamonds. The analysis is linear and the actual buckling stress is obtained, not the post-buckling minimum. The present analysis is, in fact, directly comparable with the classical analysis. A classical-type bifurcation analysis of the equilibrium equations is carried out to determine the wavelengths under which buckling can occur for a prescribed axial load. This is complemented with a strain-energy analysis to identify the particular wavelength coinciding with the lowest collapse load.

ABSTRACT: The results are presented of an experimental investigation of creep buckling of circular cylindrical shells. The test specimens, manufactured from an aluminum alloy similar to 24S, had radius to thickness ratios between 30 and 150 and length to radius ratios greater than 2. They were subjected to axial compression or bending at a temperature of 225 deg C (430 deg F) and at various stress levels. The critical time under a constant load was determined as a function of the stress level, the shell geometry, and the type of loading. It was found that the shells subjected to pure compression had a substantially shorter lifetime than those subjected to pure bending with the same maximum applied stress. The thickest test specimens failed through collapse into a “wrinkling” mode which for the pure compression case is axisymmetric, whereas the
thinner cylinders buckled into a typical diamond pattern. In all cases, buckling occurred at one of the edges. The postbuckling configuration was found to depend not only on the geometry of the shell but also on the load level. For very low stress levels, even the thinner cylinders buckled in the short wave pattern (symmetric for compression). A comparison between the present experimental results and theoretical values of the critical time presented in earlier works showed that a fairly good estimate may be obtained for the case of axial compression, whereas the approximate theory for creep buckling under pure bending gives an unduly conservative result.

ABSTRACT: A method of analysis is presented for circular cylindrical shells under non-uniform external loads. The equations are valid for moderately large displacements and take secondary creep into account. Thermal effects and initial imperfections are included. As the general equations are non-linear, an iterative method is used in the numerical analysis. The nonlinear terms are at a certain iteration considered as known, generally determined by the previous iteration. They may thus be regarded as pseudo loads which are added to the actual external load terms. The variables of the thus linearized differential equations are expanded in Fourier series with respect to the circumferential coordinate. As a result, a series of sets of ordinary differential equations is obtained, one set for each Fourier index. These sets of equations are solved by use of a finite difference method. For each load or time step the equations are repeatedly solved until convergence is obtained. A computer program was developed and was verified by comparison with known solutions for elastic buckling of shells. The theoretical behavior of a cylinder under creep is demonstrated for a number of different loading conditions, in particular the response is studied of an imperfect shell under uniform loads. In the case of external pressure, the critical time was found to be extremely sensitive to the imperfection shape. For a short cylinder under axial compression the presence of initial imperfections was shown to shorten the creep life substantially in comparison with the critical time corresponding to axisymmetrical collapse of the perfect shell.

ABSTRACT: The possibilities to analyze complicated shell stability problems have improved enormously during recent years through the development of powerful computer programs. Still there is a need for simple design rules for shell geometries commonly used in practice. The present investigation forms part of the work by task group TWG 8/4 “Shell Stability” of the European Convention for constructional steelworks, ECCS. The purpose is to provide simplified methods of analysis for the design of circular cylindrical shells with longitudinal stiffeners and subjected to axial compression. Various methods of analysis are discussed and comparisons with tests are carried out. The design procedures proposed for the ECCS recommendations are presented. In view of the complexity of the problem it is necessary for the simplified rules to be fairly conservative in order to guarantee a safe design over the range of geometries considered. However, the designer should always have the option to use improved design methods whenever required.

References listed at the end of the paper:


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ABSTRACT: Shell structures are often designed to carry compressive loads which may cause buckling. Openings and cutouts in the shell are known to reduce the carrying capacity, sometimes to a substantial degree. Although extensive research has been devoted to the problem, very few attempts have been made to incorporate the results into existing design codes. One reason for this may be the fact that even the design of simple shell elements under uniform loading conditions is complex, and the emphasis has been to develop design methods for these standard cases. The present paper discusses a number of problems associated with cutouts in shells subjected to buckling. Simple design rules are proposed based on theoretical (finite element analysis or equivalent) and experimental results.


PARTIAL ABSTRACT: Rules for design of structures with respect to buckling have existed for a long time. The stability behavior of columns and plates is fairly well known among engineers and design methods are available for many of the problems arising in practical applications. Shell buckling has been studied intensively during the last decades and the behavior is now fairly well known. The tendency of shells to be imperfection sensitive has caused problems in defining a safe design procedure and the code cases developed up till the present time are fairly limited in scope. This fact has also resulted in a reluctance to address other practical problems such as the effect of local disturbances because “we do not even have sufficient knowledge on how to design shells subjected to uniform loads”. Such special problems have so far been left to the designer to solve through, for instance, testing, rigorous nonlinear analysis or alternative design avoiding the problems….

N. Yamaki, “Influence of prebuckling deformations on the buckling of circular cylindrical shells under external pressure (Prebuckling deformations influence on circular cylindrical shell buckling under external pressure, applying Galerkin method to Donnell equations)”, Tohoku University, Institute Of High Speed Mechanics, Reports. Vol. 21, pp. 81-104. 1970


ABSTRACT: Applying the Galerkin procedure to the Donnell basic equations, solutions of exact nature are obtained for the postbuckling behavior of circular cylindrical shells under hydrostatic pressure. Through detailed calculations, connections of the edge shortening, deflection and volume change with applied pressure are clarified for a wide range of shell geometries. The results here obtained are ascertained to be in good agreement with experimental results.

ABSTRACT: On the basis of the Donnell-type shell equations with the effect of nonlinear prebuckling deformations taken into consideration, a theoretical analysis is performed on the buckling of clamped truncated conical shells under two loads combined out of uniform pressure, axial load, and uniform heating. The problem is solved by a finite difference method. It is found that the interaction curves of buckling loads are changed remarkably by the difference in the shape of conical shells. This is due to the large nonlinear prebuckling deformation and the difference in the buckling mode between two cases of single load.


ABSTRACT: From Von Karman’s large deflection equation of the plate and by assuming that a plate has an initial deflection in the form of a spherical cap, the equilibrium equation of a spherical cap subjected to hydrostatic pressure is obtained, simplified and solved in the same way as an equilibrium equation of a beam on an elastic foundation subjected to axial and lateral loads. The influence of pre-buckling deformations and stresses on the buckling of the spherical shell may be evaluated, and the relation between the buckling strength of the spherical shell and the column is obtained by analyzing the buckling problem of the beam on an elastic foundation. The formula presented for calculating the stability of the spherical shell gives a lower limit of buckling pressure and is in good agreement with test data recorded in the literature.


ABSTRACT: The buckling mode of a structure is defined to be symmetric if its sign is indefinite; this happens when the potential energy expansion near the buckling point does not contain terms which are cubic in the buckling mode. If, in addition, the cubic terms vanish identically for all possible modes then the structure is defined to be “completely symmetric”. Many structures of technical significance are included in this definition, such as columns, plates, frameworks, etc. If certain technically realistic order-of-magnitude assumptions are made, the analysis of the buckling and post-buckling behavior of completely symmetric structures can be carried out in great generality. For example, it is shown in the present paper that structures of this type buckle under increasing loads and are therefore insensitive to initial imperfections. The post-buckling state is characterized by the satisfaction of a minimum complementary energy principle, which represents an extension of the corresponding classical principle into the nonlinear domain. Moreover, the energy can be bracketed between upper and lower bounds and an error estimate is thus established at least in an averaging sense. Under certain circumstances the load approaches a finite value as the structure approaches collapse. This collapse load can also be bracketed between classes of “statically admissible” load parameters (representing lower bounds) and “kinematically admissible” load parameters (representing upper bounds). The gap between these bounds can be reduced arbitrarily. The example of a slender statically indeterminate beam subjected to lateral and torsional buckling is introduced to demonstrate the general principles developed in the paper.

ABSTRACT: A general discussion of the behavior of the shallow circular arch is presented. It is shown that, irrespective of specific loading or boundary conditions, it is possible to arrive at general conclusions regarding buckling, postbuckling, and imperfection sensitivity. General methods of analysis are established which lead to the determination of points of bifurcation and of postbuckling paths under symmetric loads. Modifications accounting for antisymmetric load components are introduced, with special emphasis on their asymptotic and limit load effect.

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ABSTRACT: A systematic derivation of the expression for the complementary energy in elastic buckling problems is presented. Compatibility is identified with variation with respect to the stress components, and the resulting eigenvalue problem is shown to be equivalent to, and sometimes more convenient than, the corresponding formulation in terms of the potential energy. Similarly, approximate techniques may lead to better as well as simpler estimates, whose upper bound property can, however, be assured only through appropriate safeguards. The method is applied in some detail to buckling of columns of arbitrary boundary conditions and axial force distribution. Another example is the problem of lateral beam buckling, with the effect of warping restraint included. In both cases (and presumably in many others) the complementary energy formulation is of lower order than the conventional potential energy formulation, and it is clear that the same simplification should also apply to finite elements or other discrete formats. The method is restricted to the (technically significant) case of a linear prebuckling state.

David Bushnell, “Axisymmetric deformation of a shallow spherical cap clamped at the edge and submitted to uniform external pressure”, Chapter 1 in Some Problems in the Theory of Thin Shells, Ph.D dissertation, Aeronautics and Astronautics, Stanford University, Stanford, California, February 1965

ABSTRACT: In Chapter 1 a shallow spherical cap clamped at the edge and subjected to uniform external pressure is studied. This non-linear problem is approached from the equilibrium and the potential energy points of view. In both approaches the dependent variables, which are the displacement components of points on the middle surface, are expanded in trigonometric series each of whose terms satisfies the boundary and symmetry conditions. Undetermined coefficients of the terms in the series are evaluated by solving the set of non-linear algebraic equations which is generated in the equilibrium approach by direct substitution and in the potential energy approach by minimization of the total potential. Load-deflection curves are established for various cap geometries, and the stability curve is obtained by plotting the values of the pressure for which the load-deflection curves have maxima versus a parameter LAMBDA-squared which describes the geometry of the cap. The early post-buckled behavior is explored and the effect of deviations from sphericity on the critical pressure determined. A limited investigation is made of the effect of small non-linear terms in the meridional strain-displacement expression on the stability and early post-buckling characteristics of shallow clamped caps.
ABSTRACT: The finite-difference method is used for the nonlinear analysis of shells of revolution consisting of elastic shell segments of various geometries and wall constructions joined by elastic rings. The analysis and associated digital computer program were developed in response to the need for a better design tool for practical shell structures. Numerical results are presented for displacement and stress distributions in various pressure vessels. Particular emphasis is given to systems in which nonlinear effects are important and may influence the design. Values calculated with linear theory are compared with those from nonlinear theory.


ABSTRACT: Two computer programs, BOSOR3 and STAGS, have been developed for the general analysis of shells. These programs are based on a finite-difference energy method. BOSOR3 performs stress, stability and vibration analyses of ring-stiffened, segmented shells of revolution with various wall constructions. STAGS performs similar analyses for shells of general shape. The analysis on which both programs are based is similar to the finite-element method in that extensive use is made of matrix algebra in the development of the governing equations. These equations are derived by the digital computer in terms of mesh point displacement variables. Several example cases from BOSOR3 and STAGS are given. Effects are shown of various finite-difference schemes, comparison with finite-element results, and complex nonlinear behavior involving large deflections and redistribution of stress during loading.

ABSTRACT: An energy formulation is used in conjunction with the method of finite differences to develop equations leading to buckling loads and vibration frequencies of segmented elastic shells of revolution supported by rings which are treated as discrete elastic structures. A quadratic form for the total potential and kinetic energy is derived through extensive use of matrix methods. The development is similar to that used in the finite element method, and is ideally suited for programming on the digital computer. Numerical results are presented in which two types of finite difference approximations are compared, and convergence properties of eigenvalues and eigenvectors are explored.

ABSTRACT: A comprehensive computer program BOSOR4 for the stress, stability, and vibration analysis of segmented, ring-stiffened, branched shells of revolution is presented. The program includes nonlinear prestress effects and is very general with respect to geometry of meridian, shell wall design, edge conditions, and loading. Despite its generality the program is easy to use. Branches are provided such that for commonly cases the input data involve only basic information such as geometrical and material properties. The computer program has been verified by comparisons with other known solutions and test results. This manual consists of several sections in which the program scope is described, the analysis on which it is based is given, the flow of calculations is outlined, the input data are defined with sample cases, various possible pitfalls are emphasized, and sample list and plot output are given and described.

ABSTRACT: Two computer programs, BOSOR3 and STAGS, have been developed for the general analysis of shells. These programs are based on a finite-difference energy method. BOSOR3 performs stress, stability and vibration analyses of ring-stiffened, segmented shells of revolution with various wall constructions. STAGS performs similar analyses for shells of general shape. The analysis on which both programs are based is similar to the finite-element method in that extensive use is made of matrix algebra in the development of the governing equations. These equations are derived by the digital computer in terms of mesh point displacement variables. Several example cases from BOSOR3 and STAGS are given. Effects are shown of various finite-difference schemes, comparison with finite-element results, and complex nonlinear behavior involving large deflections and redistribution of stress during loading.

David Bushnell (Lockheed Missiles and Space Company, Palo Alto, California USA), “Local and general buckling of axially compressed semi-sandwich, corrugated, ring-stiffened cylinders (Axially compressed semi-sandwich corrugated ring-stiffened cylindrical shell crippling local buckling and general instability prediction by finite difference energy method)”, AIAA Aerospace Sciences Mereting, San Diego, California, 17-19 January, 1972
ABSTRACT: A finite-difference energy method is used for prediction of crippling, local buckling, and general instability. Reasonably good agreement is obtained between test and theory for shells that cripple due to pure axial compression, shells that cripple due to axial compression combined with hoop compression induced by local radial restraint at rings and boundaries, shells that buckle locally due to axial load path eccentricity, and shells that buckle between ring stiffeners. Crippling loads are calculated by treatment of a portion of the corrugation-sheet combination as a shell of revolution with radius very large compared with a typical dimension of the corrugation. Critical loads for buckling between rings are rather strongly dependent on boundary conditions, load eccentricity, and length of cylinder, even for cylinders with many bays.

ABSTRACT: An iterative procedure for solving axisymmetric shell problems involving large deflections and
nonlinear material behavior is described. Deformation theory and incremental flow theory with isotropic strain hardening and secondary creep are both included as analysis branches in a computer program called BOSOR5 for the treatment of axisymmetric shells. Numerical examples show that the deformation theory is surprisingly accurate, even if the material is loaded nonproportionally. The iteration method seems to be reliable and generally permits accurate determination of deformations even if very large load increments are used in the analysis. Axisymmetric stresses and displacements are calculated for centrally loaded circular plates and creep buckling analyses performed for axially compressed elastic-plastic cylinders and columns.

ABSTRACT: A comprehensive computer program, designated BOSOR4, for analysis of the stress, stability and vibration of segmented, ring-stiffened, branched shells of revolution and prismatic shells and panels is described. The program performs large-deflection axisymmetric stress analysis, small-deflection nonsymmetric stress analysis, modal vibration analysis with axisymmetric nonlinear prestress included, and buckling analysis with axisymmetric or nonsymmetric prestress. One of the main advantages of the code is the provision for realistic engineering details such as eccentric load paths, internal supports, arbitrary branching conditions, and a ‘library’ of wall constructions. The program is based on the finite-difference energy method which is very rapidly convergent with increasing numbers of mesh points. The organization of the program is briefly described with flow of calculations charted for each of the types of analysis. Overlay charts and core storage requirements are given for the CDC 6600, IBM 370/165, and UNTVAC 1108 versions of BOSOR4. A large number of cases is included to demonstrate the scope and practicality of the program period.

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ABSTRACT: Experimental buckling pressures are given in the paper for six cylinder-cone combinations which were carefully machined and stress-relieved and then tested under uniform external pressure. Failure in all cases occurred by asymmetric buckling (i.e. with circumferential waves); although some failures were elastic, others were elastic-plastic. Theoretical buckling pressures for the models (assumed perfect) were obtained from a variational finite-difference formulation of the problem which has been incorporated into a comprehensive digital computer program. The agreement between theory and experiment was very satisfactory and may be summarized as: (i) for elastic buckling, it was within 5% and (ii) for elastic-plastic buckling, it was within 2%. This latter figure is surprisingly good. With regard to the repeatability of experimental results, the tests conducted so far have agreed to within 3%.
References listed at the end of the paper:
4. Aylward, R. W., Galletly, G. D., Moffat, D. G.: Buckling Under External Pressure of Cylinders with Toriconical or Pierced Torispherical Ends — A Comparison of Experiment and Theory. To be published
13. Bushnell, D.: Bifurcation Buckling of Shells of Revolution Including Large Deflections, Plasticity and Creep. To be published


ABSTRACT: A summary is first presented of the conceptual difficulties and paradoxes surrounding plastic bifurcation buckling analysis. Briefly discussed are nonconservativeness, loading rate during buckling, and the discrepancy of buckling predictions with use of J2 flow theory vs J2 deformation theory. The axisymmetric prebuckling analysis, including large deflections, elastic-plastic material behavior and creep is summarized. Details are given on the analysis of nonsymmetric bifurcation from the deformed axisymmetric state. Both J2 flow theory and J2 deformation theory are described. The treatment, based on the finite-difference energy method, applies to layered segmented and branched shells of arbitrary meridional shape composed of a number of different elastic-plastic materials. Numerical results generated with a computer program based on the analysis are presented for an externally pressurized cylinder with conical heads.

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ABSTRACT: Experimental and analytical buckling pressures are presented for very carefully fabricated thin cylindrical shells with 45, 60 and 75° conical heads and for cylindrical shells with torispherical heads pierced by axisymmetric cylindrical nozzles of various thicknesses and diameters. Nonsymmetric buckling occurs at pressures for which some of the material is loading plastically in the neighborhoods of stress concentrations caused by meridional slope discontinuities. The buckling pressures for the cone-cylinder vessels are predicted within 2.6 per cent and for the pierced torispherical vessels within 4.4 per cent with use of BOSOR5, a computer program based on the finite difference energy method in which axisymmetric large deflections, nonlinear material properties and nonsymmetric bifurcation buckling are accounted for. The predicted buckling pressures of the pierced torispherical specimens are rather sensitive to details of the analytical model in the neighborhood of the juncture between the nozzle and the head. The buckling pressures of the cone-cylinder vessels can be accurately predicted by treatment of the wall material as elastic, enforcement of the full compatibility conditions at the juncture in the prebuckling analysis, and release of the rotation compatibility condition in the bifurcation (eigenvalue) analysis.


ABSTRACT: The theory is summarized for axisymmetric prebuckling and nonsymmetric bifurcation buckling of ring-stiffened shells of revolution. The analysis is based on finite difference energy minimization in which moderately large meridional rotations, elastic-plastic effects, and primary or secondary creep are included. This theory is implemented in a computer program called BOSOR5, for the analysis of segmented and branched ring-stiffened shells of revolution of multi-material construction. Comparisons between test and theory are given for axisymmetric collapse and nonsymmetric bifurcation buckling of 69 machined ring-stiffened aluminum cylinders submitted to external hydrostatic pressure. Because most of the cylinders fail at an average stress which corresponds to the knee of the stress-strain curve, the analytical predictions are not very sensitive to modeling particulars such as nodal point density or boundary conditions. Agreement between test and theory is improved if the analytical model reflects the fact that the shell and rings intersect over finite axial lengths.


ABSTRACT: B0S0R5 can handle segmented and branched shells with discrete ring stiffeners, meridional discontinuities, and multi-material construction. The shell wall can be made up of as many as six layers, each of which is a different nonlinear material. In the prebuckling analysis large-deflection axisymmetric behavior is presumed. Bifurcation buckling loads are computed corresponding to axisymmetric or nonaxisymmetric buckling modes. The strategy for solving the nonlinear prebuckling problem is such that the user obtains reasonably accurate answers even if he uses very large load or time steps. B0S0R5 has been checked by means of numerous runs in which the results have been compared to other analyses and to tests. The prebuckling and plastic bifurcation (eigenvalue) analyses are described, with the most important equations given. These equations are derived from a finite difference energy method. The strategy for solving problems simultaneously
involving large deflections, elastic-plastic material behavior, and primary and secondary creep permits the use of rather large time and load steps without undue sacrifice in accuracy. This strategy is based on a subincremental iteration method in which the size of the subincrement is automatically determined such that the change in stress is less than a certain prescribed percentage of the effective stress. The theoretical treatment of discrete ring stiffeners, the material of which is elastic-plastic and can creep according to a primary or secondary creep law, is also given. Discrete rings of arbitrary cross-section are considered to be assemblages of thin rectangular elements. The structure of the BOSOR5 computer program, which runs on the CDC 6600 and on the UNIVAC 1108 and 1110, is described. The paper gives comparisons between test and theory for many configurations, including axially compressed cylinders and internally and externally pressurized shells of various shapes with and without ring stiffeners. The results of sensitivity studies are given in which the effect on predicted critical load of various analytical models of the ring-shell wall intersection area are explored. A method of predicting the effect of welding on buckling load is described, and an example involving a ring-stiffened doubly-curved shell is given. Welding the ring stiffeners to a shell introduces residual stresses and geometrical imperfections, both of which reduce the load-carrying capability.


ABSTRACT: The analysis is applicable to bodies of revolution composed of thin shell segments, thick segments and discrete rings. The thin shell segments are discretized by the finite difference energy method and the thick or solid segments are treated as assemblages of 8-node isoparametric quadrilateral finite elements of revolution. Suitable compatibility conditions are formulated through which these dissimilar segments are joined without introduction of large spurious discontinuity stresses. Plasticity and primary or secondary creep are included. Axisymmetric prebuckling displacements may be moderately large. The nonlinear axisymmetric problem is solved in two nested iteration loops at each load level or time step. In the inner loop the simultaneous nonlinear equations corresponding to a given tangent stiffness are solved by the Newton-Raphson method. In the outer loop the plastic and creep strains and tangent stiffness are calculated by a subincremental procedure. The linear response to nonaxisymmetric loading is obtained by superposition of Fourier harmonics. Many examples are given to demonstrate the scope of the computer program, BOSOR6, derived from the analysis and to illustrate certain stress concentration effects in shell-type structures which cannot adequately be treated with use of thin shell theory.

ABSTRACT: A strategy for solving problems involving simultaneously occurring large deflections, elastic-plastic material behaviour, and primary creep is described. The incremental procedure involves a double iteration loop at each load level or time. In the inner loop the material properties are held constant and the non-
linear equilibrium equations are solved by the Newton-Raphson method. These equations are formulated in terms of the tangent stiffness. In the outer loop the plastic and creep strains are determined and the tangent stiffness properties are updated with use of a subincremental algorithm. The magnitude of each time subincrement is determined such that the change in effective stress is less than a preset percentage of the effective stress. The strategy is implemented in a computer program, BOSOR5, for the analysis of shells of revolution. Examples are given of elastic-plastic deformations of a centrally loaded flat plate and elastic-plastic-creep deformations of a beam in bending. The major benefits of the subincremental technique are the increased reliability with which problems involving non-linear plastic and time-dependent material behaviour can be solved and the greatly relaxed requirement on the number of load or time increments needed for satisfactory results.

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ABSTRACT: Comparisons of test and theory are presented for the nonaxisymmetric bifurcation buckling of ten aluminium vessel heads fabricated and tested by Patel and Gill at the University of Manchester in 1976. In the test specimens, the sphere radius was equal to the cylinder diameter and only the torus radius was varied. All specimens were of constant internal cylinder diameter to nominal thickness ratio of 531.5. Meridional variation of thickness was accounted for in the analysis, which was carried out with the BOSOR5 computer program. The analysis includes both material and geometrical nonlinear prebuckling behavior. The results indicate that incipient nonsymmetric buckling can be predicted with reasonable accuracy by means of an eigenvalue formulation.

ABSTRACT: Task I Hygrothermal, viscoelastic plane stress and generalized plane strain analysis codes were developed and employed to determine the influence of hygrothermal history on laminate in-plane and free edge stresses and dimensional stability. Task II Monographs were written on plastic buckling, stability and optimization of panels, and buckling of shells. The surveys include many examples of nonlinear collapse and bifurcation buckling in which moderately large deflections, nonlinear material effects, and imperfections are accounted for. Their purpose is to give the reader a physical 'feel for thin shell behavior that will help him to design appropriate tests and perform efficient numerical analyses with existing computer programs for the treatment of structures composed of thin sections.

ABSTRACT: Techniques for the branching analysis of structural systems possessing a potential function are classified according to the order in which the conditions of stationarity, perturbation and discretization are imposed. It is shown that the recently developed algorithm for branching analysis of discrete systems, in which contraction of the algebraic perturbation equations plays a significant role, has an even closer analogy with the
related continuum analysis than hitherto supposed. The proposed algorithm for the continuum branching analysis is outlined in general terms, and its use is illustrated by reference to the “elastica”. More important than the analytical treatment of the resulting differential perturbation equations, however, is that the method proposed offers a viable alternative means of deriving practical numerical solution analogues. Broadly, numerical analogues derived on the present basis possess all the advantages and disadvantages of the generalized finite difference technique over the generalized finite element technique.

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ABSTRACT: Previously postulated, lower bound estimates of the buckling loads for axially loaded unstiffened cylinders are simplified by means of a Donnell-type approximation to provide compact, explicit, analytical expressions which could prove particularly suited to design. For a wide range of practical geometric parameters these simplified expressions are shown to provide close approximations of the exact lower bound loads and associated modes. In addition they allow the independent and significant influence of length to radius, radius to thickness, and Poisson's ratio to be isolated, and suggest a convenient means of summarising buckling loads in terms of a single composite geometric parameter.


doi:10.1115/1.3408738 (or the title is: “Snapping of Imperfect Thin-Walled Circular Cylindrical Shells of Finite Length”)
ABSTRACT: The nonlinear partial differential equations of von Karman and Donnell governing the deformations of initially imperfect cylindrical shells are reduced to a consistent set of ordinary differential equations. A numerical procedure is then used to solve the equations together with the associated boundary conditions and to determine the number of waves at buckling as well as the load-carrying capacity of imperfect cylindrical shells of finite length subjected to uniform axial compression in the presence of a reduced restraint along the simply supported boundaries. It is found that details of the boundary conditions have little effect on the number of waves into which the shell buckles around the circumference. This number is determined essentially by the length-to-radius and radius-to-thickness ratios. The absence of an edge restraint to circumferential displacement reduces the classical value of the buckling load by a factor of about two. On the other hand, shells with these boundary conditions appear to be less sensitive to initial imperfections in the shape, and thus the maximal load supported in the presence of unavoidable initial deviations can be the same for shells with and without a restraint to circumferential displacements along the edges.

ABSTRACT: This paper describes an analysis and its application in design for compressive buckling of flat stiffened plates considered as an assemblage of linked orthotropic flat plate and beam elements. Plates can be multilayered, with possible coupling between bending and stretching. Structural lips and beads are idealized as beams. The plate and the beam elements are matched along their common junctions for displacement continuity and force equilibrium in an exact manner. Buckling loads are found as the lowest of all possible general and local failure modes. The mode shape is used to determine whether buckling is a local or general instability and is particularly useful to the designer in identifying the weak elements for redesign purposes. Typical design curves are presented for the initial buckling of a hat stiffened plate locally reinforced with boron fiber composite.


ABSTRACT: This paper summarizes the major computer programs in existence for the analysis of shells of revolution by numerical integration and finite difference procedures. The report describes programs for (1) linear and nonlinear analysis of shells subjected to axisymmetric and asymmetric static loads, (2) buckling and vibration behavior including effects of axisymmetric nonlinear prestress, and (3) transient response. Extensions of these programs which are currently underway and some of the primary assets of both the numerical integration and finite difference procedures are discussed. In addition, a summary of the shell theory formulation, the numerical approximation, and the solution techniques of a set of programs denoted SALORS (Structural Analysis of Layered Orthotropic Ring-Stiffened Shells), developed at the NASA Langley Research Center, are described. Stress, vibration, and buckling results from the SALORS program are given for several shell configurations having a variety of structural complexities that illustrate the current capability of shell of revolution programs.


ABSTRACT: Solutions are developed herein for the evaluation of frequency and stability eigenvalues of macro-scopically fully anisotropic circular cylindrical shells subjected to nonuniform lateral prestress. Included in the analysis is the presence of torsional prestress. The results obtained are applicable to any type of prestress which satisfy Dirichlet's conditions for Fourier series. Furthermore, in the manner of Kalnins [3], using the procedure outlined herein, similar results could be obtained for general anisotropic shells of revolution.

ABSTRACT: Applying Vlasov-Ambartsumyan shell theory to anisotropic and laminated cylinders, equations are developed for calculating the stresses in a composite tube under combined axial load, torsion, and internal pressure. Comparison to results obtained from exact elasticity theory shows that the shell equations are capable of predicting, with a reasonable degree of accuracy, the large stress gradients found in highly anisotropic tubes. Thus the shell theory provides the experimentalist with a set of closed form expressions for readily defining the proper specimen dimensions for precise characterization of unidirectional and laminated composite tubes. A modification to the shell theory, in which the effects of transverse normal strain are included is also discussed. Numerical results show that such a modification is necessary for determining stresses induced by free thermal expansion. It is also shown that certain classical thin shell kinematic relations are incapable of predicting stresses in composite tubes.


ABSTRACT: The results of testing the stability of glass-reinforced plastic cylindrical shells under hydrostatic pressure are examined. The initial imperfections and deflections of the shells were directly measured. It is found that during loading or in the course of time (under load) the shape of the initial imperfections is transformed. An algorithm (see [11]) based on the approximation of the experimental deflection function by a Fourier series is used to establish the characteristic coefficients of the series important in connection with the elastic loss of stability and progressive buckling of the shell.

References listed at the end of the paper:


ABSTRACT: The creep buckling of polyethylene cylindrical shells in axial compression has been investigated. The changes in the shape of the shell surface up to loss of stability were measured with a special radial
deflection gauge. The experimentally determined shape of the buckled surface at discrete moments of time is approximated by a double Fourier series. The characteristic coefficients of the series of importance in creep buckling are established. From an analysis of the coefficients of the series it follows that the amplitudes of the axisymmetric coefficients diminish with time, while those of the coefficients giving a nonaxisymmetric buckled shape grow.

References listed at the end of the paper:


ABSTRACT: Recent research on the stability of plastic plates and shells, mostly by workers in the Soviet Union, is briefly reviewed.

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ABSTRACT: The synthesis of anisotropic cylindrical shells of minimum weight is considered; the initial data relate to the characteristics of the reinforcing filaments and binder. The optimum case satisfying the requirements of stability, strength, and geometrical limitations is found by the method of projective gradients.

ABSTRACT: (none given)

References listed at the end of the paper:


Arturs Kalnins, “Static, Free Vibration, And Stability Analysis Of Thin, Elastic Shells Of Revolution”, Lehigh University, Bethlehem PA, Technical rept. Apr 66-Jul 68, October 1968, DTIC Accession Number : AD0686446,

ABSTRACT: This project was undertaken to present workable methods of analyses for thin, elastic shells of revolution, and to provide computer programs for performing such analyses. By means of these methods, the following problems for a thin, elastic shell of revolution can be solved: (1) stresses and deflections can be determined when the shell is subjected to arbitrary mechanical and/or thermal loads; (2) natural frequencies and mode shapes can be found for free vibration when the shell is subjected to or is free of prestress; (3) buckling loads, according to the classical stability theory, can be found when the shell is subjected to axisymmetric or sinusoidal nonsymmetric prestress.


ABSTRACT: This paper presents the first phase in the analysis of the deformation of a shell of revolution when it is being crushed by a rigid wall. In this paper, the analysis accounts for finite deflections and rotations but assumes that the material remains linearly elastic. The load-deflection behavior is obtained for a hemispherical shell, and it shows that the shell cannot collapse with a flat contact region. The conditions for the buckling of the contact region are determined.

ABSTRACT: Starting from the equations of a 3-dimensional medium, governing equations for infinitesimal, elastic deformations, superimposed upon a prestressed state, are derived for a thin shell. No further approximations are made except those of the Kirchhoff hypothesis of shell theory. The equations are referred to the prestressed state for which geometry, initial stress, and material properties are assumed known. The final equations are listed in terms of physical components of all variables and are referred to the lines of curvature of the reference surface of the shell in the prestressed state. They can be used directly for such problems as the stability or free vibration of initially stressed shells.


ABSTRACT: The authors have previously shown that a thin, complete spherical shell compressed between two parallel rigid plates deforms initially with the polar portion of the shell flattened against the plates and that at a critical deformation the flat region may buckle into an axisymmetric inward dimple. The present paper presents an analysis of the stresses and deflections produced during axisymmetric postbuckling and determines the deformation states at which the shell may buckle into a nonsymmetric shape. The analysis accounts for finite deflections and rotations, but assumes that the material remains linearly elastic throughout the deformation. An experiment shows that both the primary axisymmetric bifurcation point and the secondary nonsymmetric bifurcation point are stable for a shell with R/h \(\approx 40\).


ABSTRACT: Thin shells are widely used structural elements and are sometimes subjected to time-dependent loads after they have already acquired some prestress. The response of such a shell can be very different from that when the prestress is absent. The general methods of calculation of the response of the shell are discussed. The stability limit of the shell is viewed as a special result obtained in the free vibration analysis. An example of a typical containment shell of a nuclear power plant, housing the reactor, is worked out in detail.


ABSTRACT: A procedure for the analysis of dynamic buckling of axisymmetric shells subjected to axisymmetric, periodic loads of long duration is proposed that is based on the calculation of the nonsymmetric modes of free vibration and associated mode integrals over the reference surface of the shell. Numerical results are presented for the evaluation of dynamic stability of an actual shell that is designed for the cooling system of a nuclear power plant.

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ABSTRACT: The problem of dynamic stability is substantially more complex than the buckling analysis of a shell subjected to static loads. Even at this date suitable criteria for dynamic buckling of shells, which are both logically sound and practically applicable, are not easily available. Thus, a variety of analyses are available to the user, encompassing various degrees of complexity, and involving a range of simplifying assumptions. The purpose of this paper is to compare and evaluate some of these solutions by applying them to a specific problem. A shallow spherical cap, subjected to an axisymmetric, uniform-pressure, step loading, is used as the structural example. The predictions, by various methods, of the dynamic buckling of this shell into unsymmetric modes, are then investigated and compared. The approximate methods used by Akkas are compared to the more rigorous and general solutions of the KSHEL, STARS, DYNASOR, and SATANS computer programs, and the various simplifying assumptions utilized are evaluated. Also included in the comparisons, are the predictions of the relatively simple “dynamic buckling model” approach of Budiansky and Hutchinson. The approaches utilized by the more complex programs [KSHEL (spatial integration, modal superposition, perturbation approach), DYNASOR (finite elements, time integration of non-linear dynamic equilibrium equations), SATANS (finite differences, pseudo load method, time integration), STARS (spatial and time integration, non-linear equilibrium or perturbation approaches)] will in turn be compared in terms of accuracy, idealization complexity, ease of use, and user expertise and experience required for analysis. The comparisons show that the more approximate methods underpredict the dynamic buckling loads for this problem. In addition, some basic assumptions of the simpler solutions are found to be invalid.

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ABSTRACT: The use of numerical integration for the analysis of practical shell-of-revolution structures was documented almost simultaneously in the United States by three independent groups of researchers (Cohen, Kalnins, Mason et al.). These early efforts have been refined, reformulated, and increased in scope and applicability to become major program systems (SRA, Kalnins, STARS). While all three programs utilize basically the same mathematical formulation for integrating the shell differential equations, the matrix solution procedures from this point are basically different. The purpose of this paper is twofold, as follows: (1) to present the differences in solution procedures of the largest system (the Grumman — NASA STARS) from the other two, and point out the inherent advantages of this approach; and (2) compare the numerical integration procedure, as utilized in the STARS, with finite difference and finite element procedures, noting the relative advantages of each in the analysis of shells of revolution for static, buckling, and dynamic loadings. To fulfill the above purpose, a brief review of the numerical integration procedure for the analysis of shells of revolution is presented, and the matrix solution procedures of the SRA, Kalnins, and STARS programs are contrasted. The limitations imposed by the relative procedures are discussed. The unique formulation utilized by STARS for the solution of stability and vibration problems, and its advantages, are discussed in detail. The STARS program's analytical capabilities, capacity, and user options are compared with those of other major systems utilizing either finite differences or finite elements for the analysis of shells of revolution. Comparisons are made in terms of program size, program accuracy, number of degrees of freedom required for analysis, ease of idealization and user inputs, limitations imposed on analysis capability or output, running time, and so forth. All advantages and differences are demonstrated by use of solutions for realistic shell problems in the areas of statics, stability (including dead and live load distributions), vibrations, and dynamic response of shells subjected to time-dependent loadings.
D.B. Simmons, “NASA automatic system for computer program documentation, volume 2 (Computer program for dynamic analysis of shells of revolution)” [Final Report], no publisher or date given, ProQuest-CSA

ABSTRACT: The DYNASOR 2 program is used for the dynamic nonlinear analysis of shells of revolution. The equations of motion of the shell are solved using Houbolt's numerical procedure. The displacements and stress resultants are determined for both symmetrical and asymmetrical loading conditions. Asymmetrical dynamic buckling can be investigated. Solutions can be obtained for highly nonlinear problems utilizing as many as five of the harmonics generated by SAMMSOR program. A restart capability allows the user to restart the program at a specified time. For Vol. 1, see N73-22129.


ABSTRACT: The approximate load-deflection behavior of a simply supported cylindrical shell subjected to external pressure is determined for the case where the shell has a dimple shaped initial deflection. This is accomplished by the use of a “two-timing” perturbation expansion applied to the Kármán-Donnell shell equations. We show that if the shell is imperfection-sensitive to an initial deflection in the shape of the linear buckling mode, then it is also imperfection-sensitive to a dimple imperfection. The degradation in buckling load for the dimple imperfection depends linearly upon the initial deflection amplitude epsilon whereas for the modal imperfection it is proportional to the two-thirds power of epsilon.

R. S. Sendelbeck and N. J. Hoff (Stanford University), “Loading rig in which axially compressed thin cylindrical shells buckle near theoretical values”, (A holding and alignment test rig for use when buckling thin circular cylindrical shells is described. The consistency of high buckling values is demonstrated along with results concerning different holding restrictions), Experimental Mechanics, Vol. 12, No. 8, 1972, pp. 372-376, doi: 10.1007/BF02321695

ABSTRACT: Fifteen near-perfect electroformed nickel cylindrical shells of highR/t ratios have been buckled by axial compression using a special loading-rig system. Buckling-stress values averaged 85 percent, and ranged from 80 to 96 percent, of the classical theoretical bucklingstress value. The loading rig described in this report makes use of a simple procedure for accurately aligning the thin shell with the load axis and, also, for maintaining the circularity of the shell at its end by accommodating for slightly different diameters, with the use of tapered circular end caps which provide exact fits in each case. The rig also provides a setup in which shells may be free to twist, tip and translate, or be restrained from these motions. Comparison between restrained and unrestrained tests revealed no noticeable change in the buckling load. However, with the restraining mechanism, slightly higher postbuckling loads, repeated buckling loads and an increased number of circumferential waves resulted.

References listed at the end of the paper:

ABSTRACT: Thin shells of revolution, closed in the circumferential direction, and with an arbitrary meridian shape, are considered. The density of the vibration frequencies is determined by using an asymptotic method of integration [1 – 3]. The density of the frequencies in the neighborhoods of condensation points is investigated. The question of the density of vibration frequencies of thin shells has been examined in [4 – 7]. Shallow shells of rectangular planform were examined in [4, 5].


ABSTRACT: The nonlinear membrane problem is presented in terms of the curvatures and stresses (or strains) as field variables. As a part of the formulation, appropriate boundary conditions are studied. The significant features of the equations are discussed. Among the topics are included: dependence on initial shape, types of equations, ability to clarify anomalies of the linear membrane problem, stability and the membrane edge effect problem. A perturbation series scheme for the solution of the equations is also presented. The usefulness of the theory in solving practical problems is demonstrated by presenting a solution to the problem of the noncircular cylindrical membrane shell under lateral pressure.

ABSTRACT: A procedure is presented which relates the solution of the stability problem for an elastic structure subjected to a complex prebuckling stress distribution, to that of a solved stability problem for the same structure but with a “simple” stress distribution. The procedure reduces to obtaining the characteristic roots of a symmetric matrix. It is then applied to the buckling problem of a circular cylindrical shell subjected to a circumferentially varying compressive stress field and boundary conditions of the SS1-2 types. The main result is that for the boundary conditions and number of harmonic terms in the edge load taken, the buckling parameter approaches, as h/R \rightarrow 0, that of a cylinder uniformly subjected to the maximum circumferential stress.
ABSTRACT: The buckling analysis of a circular cylindrical shell under non-uniform axial compression is considered, using Donnell's equations with a Galerkin procedure and with boundary conditions of the SS3-SS4 types. Three problems are studied: (1) It is proven analytically that in the limiting case (h/R tending to zero) the eigenvalue for any load distribution approaches that of uniform loading. (2) A numerical parametric study of the effects of finite thickness, length and load distributions on the buckling load is presented. (3) The interactions among several load distributions are investigated numerically. The numerical results confirm the limiting behavior and indicate that a linear interaction formula is justified.

ABSTRACT: The linear buckling problem of a cylindrical shell subjected to circumferentially varying axial edge loads or thermal loads is considered. The case of an oscillatory loading having a cosinusoidal form with a single arbitrary harmonic index is treated first. Closed-form expressions for the critical eigenvalues are obtained, spanning the entire range of the harmonic index. Buckling modes are also presented. An interaction law among harmonic loadings based on existing numerical evidence is then postulated. This leads to the capability of calculating the buckling load for any given distribution. The method is compared, and good agreement is obtained, with published results on the heating of an axial strip. It is then used to calculate the buckling of a cylindrical shell subjected to a concentrated axial force.

ABSTRACT: The results of a numerical study of the buckling and initial post-buckling behavior of clamped shallow spherical shells under axisymmetric band type loads are presented. This behavior is studied, first, for a cap with fixed geometry when the radial location of a band load of constant width is allowed to vary; second, for a cap with fixed geometry under a uniform pressure distributed over the outer region of the cap; and third, for a band load of constant width and radial location when the shell geometry is allowed to vary. It is found in each of these studies that, for a significant range of the geometric shell parameter, lambda, the spherical cap under axisymmetric band load is imperfection-sensitive.

ABSTRACT: This paper presents the results of a numerical study of the buckling and initial post-buckling behavior of clamped shallow spherical shells under axisymmetric ring loads. This behavior is studied for a cap with fixed geometry when the location of the ring load is allowed to vary from the equivalent of a concentrated load at the apex to a location near the midpoint of the shell base radius, and for a fixed ring load location when the shell geometry is allowed to vary. It is found in both studies that a significant range of the geometric shell...
parameter, lambda, exists such that buckling is accompanied by a loss in load-carrying capacity.

ABSTRACT: The boundary-value problems associated with the axisymmetrical, asymmetrical, and initial postbuckling behavior of the clamped shallow conical sandwich shell under a uniform pressure are developed for face sheets of the same material and equal thicknesses. The numerical results presented show that the buckling and initial postbuckling behavior of the sandwich cap is similar to that of the conical homogeneous cap. The effects of the thickness and material parameters on the axisymmetric snap-through buckling behavior of the clamped shallow spherical and conical sandwich shells are also studied. For one material parameter considered the axisymmetric buckling behavior of the sandwich shells is similar to that of the corresponding homogeneous shells; so it is suggested that, without any further analysis, the asymmetric buckling and the initial postbuckling behavior of the sandwich cap can be obtained by conjecture. For the other material parameters considered, the axisymmetric buckling behavior of the sandwich caps is different from the axisymmetric buckling behavior of the corresponding homogeneous caps.

ABSTRACT: The buckling and initial postbuckling behavior of clamped shallow spherical sandwich shells with dissimilar face sheets under a uniform pressure is studied. The numerical results show that the buckling and initial post-buckling behavior of clamped shallow spherical sandwich shells with dissimilar face sheets is similar to that of the corresponding homogeneous shell. The classical buckling analysis for spherical sandwich shells under a uniform pressure is also presented. The results indicate that it is possible to obtain the buckling curves of spherical sandwich caps from those of the homogeneous cap using a magnification factor which is obtained via the classical buckling analysis, for large values of the sandwich shell parameter.

ABSTRACT: The asymmetric dynamic behavior of clamped shallow spherical shells under a uniform step pressure of infinite duration is investigated. The solution of a linear eigenvalue problem yields the bifurcation paths and also the lower bound for the asymmetric dynamic snap-through buckling pressure. The asymmetric dynamic response of shells with a shape imperfection is studied. The asymmetric dynamic snap-through buckling load is defined to be the threshold value of the step pressure at which the asymmetric response shows significant growth rate. The snap-through buckling loads are obtained for a few shell parameters. The numerical results are compared with the available experimental results and they are in good agreement. Finally, a preliminary study of the phase planes is presented.

ABSTRACT: This paper investigates the dynamic behaviour of a shallow, viscoelastic, spherical shell under a harmonic excitation. The time evolutions of the response of the corresponding nonlinear dynamical system are described by the phase portraits and the bifurcation of the parameter dependent system is studied numerically so as to identify qualitative changes in the phase portrait. The viscoelastic shell, having more than one equilibrium configuration for some problem parameters, shows periodic and/or randomlike chaotic oscillations under the given excitation according to the dimensions of the attracting set. The occurrence and nature of the chaotic attractors are verified by evaluating Lyapunov exponents.

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ABSTRACT: The purpose of this work is to present some numerical results on nonlinear, snap-through buckling of shallow spherical shells made of laminated composite materials under general static loading. Isotropic shells are covered as a special case of the general problem. A special-purpose finite-difference computer program has been developed. Moreover, the general-purpose computer program ANSYS has also been used. Effects of various material properties on the nonlinear behavior of the shells are investigated. One of the conclusions of the study is that ANSYS may yield erroneous results in some cases. Another conclusion is that the buckling curves of composite shallow spherical shells have a shape similar to that of the corresponding isotropic shell. This finding implies that the geometry of a shell may be an important factor in giving a characteristic shape to the buckling curve, at least for the shell parameters considered here.

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ABSTRACT: In this study, the snap-through buckling behaviour of axisymmetric shells, subjected to axisymmetric horizontal peripheral load or displacement for various shell parameters and various boundary conditions, is investigated. Results obtained seem not to have been reported previously. An application of peripheral displacement type of loading is seen in metal-ceramic composite transducers developed by sandwiching a piezoelectric (PZT) ceramic between two metal end caps which serve as mechanical transformers for converting and amplifying the lateral displacement of the ceramic into an axial motion normal to the metal cap. In our numerical search, we have observed that snap-through and snap-back buckling is possible for shallow spherical caps for a very narrow range of the shell parameter used. When a hole is opened around the apex of the cap, buckling is possible for a larger range of the shell parameter. Obtaining the displacement amplification and the blocking or generative force for various material and geometric properties is necessary for the possible application of the findings in transducer design. The numerical results are presented in graphical forms.
References listed at the end of the paper:


Gassan Odeh (Dept. of Civil Engineering, Eastern Mediterranean University, Gazimagusa, North Cyprus), “Nonlinear dynamic response of shells of revolution”, ECAS2002 International Symposium on Structural and Earthquake Engineering, Middle East Technical University, Ankara, Turkey, October 14, 2002

ABSTRACT: The nonlinear dynamic buckling behavior of axisymmetric spherical shells subjected to radial dynamic edge loading has been investigated. The peripheral dynamic loading is in the form of step loading of infinite duration in the time domain. This kind of loading is seen in actuators known as displacement transducers, where the radial motion of the edges is converted into a flex-tensional motion in the spherical caps. As a result a large displacement is obtained in the perpendicular direction, which may result in snap-through buckling. It is theoretically possible to develop magnification mechanisms that produce sizeable displacements necessary for actuating functions. For the numerical solution of the problem a computer program, using a linearized finite element incremental-iterative approach based on updated Lagrangian formulation is developed, and the whole process is accomplished using the Newmark β method as the time integration scheme.

References listed at the end of the paper:
ABSTRACT: In using the finite element method to compute a transient response, two choices must be made. First, some form of mass matrix must be decided upon. Either the consistent mass matrix prescribed by the finite element method can be employed or some form of diagonal mass matrix may be introduced. Secondly, some particular time integration procedure must be adopted. The procedures available divide themselves into two classes: the conditionally stable explicit schemes and the unconditionally or conditionally stable implicit schemes. The choices should be guided by both economy and accuracy. Using exact discrete solutions compared to the exact solutions of the differential equations, the results of these choices are displayed. Concrete examples of well-matched methods, as well as ill-matched methods, are identified and demonstrated. In particular, the diagonal mass matrix and the explicit central difference time integration method are shown to be a good combination in terms of accuracy and economy.


ABSTRACT: The instability of thin elastic shells still remains the most challenging of all the classical problems of the theory of elasticity. It is the aim of this investigation to verify a rational experimental technique for predicting the buckling loads of cylindrical tubes under axial load as well as under external radial pressure, by measuring their natural frequencies under different loadings. Cylindrical tubes made of Hostaphan (thickness 0.254 mm and radius 100 mm) were tested under axial load and under external radial pressure in the German Air and Space Research Laboratory (Deutsche Forschungsanstalt für Luft und Raumfahrt) at Braunschweig, West Germany, and the results compared with an actual buckling test. The tests revealed that the buckling load can be predicted satisfactorily by the proposed non-destructive vibration method of testing.

R.E. Ball and H.G. Schaeffer, “Nonlinear deflections of asymmetrically loaded shells of revolution” (Asymmetrically loaded shells of revolution nonlinear deflections analyzed by algorithm, determining snap buckling load of shallow spherical shell), 1968 (no publisher given; csa.com)

Charles C. Cromer (1) and Robert E. Ball (2)
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ABSTRACT: The nonlinear, damped dynamic response of a simply supported, nearly circular cylindrical shell due to an exponentially decaying, uniform radial pressure is computed for peak pressures and total impulses between the static and dynamic buckling limits. The analysis employs Fourier series expansions of the dependent variables in the circumferential coordinate, finite difference approximations of the axial derivatives, and Newmark’s beta-method for the time integration. All nonlinear coupling between the retained modes is included. The inclusion of damping reduces the maximum amplitudes of the dominant modes by approximately 30%, but stresses larger than the yield stress can occur at peak pressures and total impulses well below the dynamic buckling limit. The amplitudes of the static buckling modes are found to be linearly proportional to the magnitude of the initial imperfections, but the parametrically excited modes are unaffected by the initial imperfections.

W.C. Stilwell and R.E. Ball, “A digital computer study of the buckling of shallow spherical caps and truncated hemispheres” (Digital computer program used for thin shell buckling analysis of spherical caps under pressure loading and truncated hemispheres under axial tension), (no publisher given; csa.com), 1972
ABSTRACT: A study of the buckling of thin shells was conducted using a digital computer program for the geometrically nonlinear analysis of arbitrarily loaded shells of revolution. The objective was an evaluation of the program's applicability to bifurcation buckling and imperfection sensitivity analysis. Clamped spherical caps under pressure loading and clamped truncated hemispheres under axial tension were investigated. Buckling loads were determined for axisymmetric and nearly axisymmetric loads and are compared with previously published analytical results based on geometric imperfections.

ABSTRACT: As a part of the Air Force Flight Dynamics Laboratory's program to assess the current U. S. capability for computer analysis of shell structures, the Lockheed Palo Alto Research Laboratory prepared and distributed to the structures community a series of three sample problems. These problems are intended to be representative of current engineering situations. The analyses requested consisted of linear stress, free vibration, bifurcation buckling, elastic and inelastic collapse, and linear and nonlinear transient response. Solutions to these problems were solicited with the objective of obtaining information that could be used to compare and assess contemporary computer-oriented analysis methods. The solutions that were submitted are presented in this report. Comparison of the several solutions for each analysis reveals that in general there is good agreement for the linear and eigenvalue analyses. For the nonlinear analyses, multiple solutions were received only for the transient response problem. Comparison of these solutions shows limited agreement between any of the results.

ABSTRACT: A digital computer program for the geometrically nonlinear static and dynamic response of arbitrarily loaded shells of revolution is described. The governing partial differential equations are based upon
Sanders' nonlinear thin shell theory for the conditions of small strains and moderately small rotations. The governing equations are reduced to uncoupled sets of four linear, second order, partial differential equations in the meridional and time coordinates by expanding the dependent variables in a Fourier sine or cosine series in the circumferential coordinate and treating the nonlinear modal coupling terms as pseudo loads. The derivatives with respect to the meridional coordinate are approximated by central finite differences, and the displacement accelerations are approximated by the implicit Houbolt backward difference scheme with a constant time interval. At every load step or time step each set of difference equations is repeatedly solved, using an elimination method, until all solutions have converged. Results from the program are compared to previously published data for several problems, and the versatility, efficiency, and limitations of the program are candidly evaluated.

R.E. Ball, “A computer program for the geometrically nonlinear static and dynamic analysis of arbitrarily loaded shells of revolution, theory and user’s manual”, NASA CR 1987, April 1972

R.L. Citerley (1) and R.E. Ball (2)
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ABSTRACT: A comparison between the linear and nonlinear seismic analysis of a thin unreinforced steel reactor containment vessel is presented. The effects of the nonlinear coupling between the low Fourier harmonic excitations and the higher Fourier harmonics producing an ovalling response are examined. Imperfection shapes of the containment vessel are employed to provide the mechanism for this response.

ABSTRACT: The dynamic behavior of clamped shallow spherical shells subjected to axisymmetric and nearly axisymmetric step-pressure loads is examined using a digital computer program for the geometrically nonlinear static and dynamic analysis of arbitrarily loaded shells of revolution. A criterion for dynamic buckling under the nearly axisymmetric load is proposed and critical buckling pressures are determined for a large range of shell sizes.

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ABSTRACT: Solutions from five computer codes for both the linear and the geometrically nonlinear response of an impulsively loaded, truncated elastic cone are presented. The codes used are DYNAPLAS (Von Riesemann), REPSIL (Huffington), SATANS (Ball), SHORE (Underwood), and SMERSH (Hubka). Displacements and strains at two locations on the shell are plotted for the period 0 - 1500 micro sec. The
solutions are presented to illustrate the state of the art of linear and nonlinear dynamic response computations of shell structures and to provide users of other codes an opportunity to compare results. The five codes provide essentially identical linear results for all quantities except the meridional strain at the outer surface. There is fair agreement between the nonlinear results for the first 750 micro sec; for later times the solutions, except for DYNAPLAS and SATANS, progressively diverge. Thus, the linear analysis appears to be well in hand, but the nonlinear problem cannot be considered solved. Additional studies are required to determine the cause(s) of the differences between the nonlinear results.

ABSTRACT: Computer programs are considered for the dynamic buckling of beam, plate, and shell type structures due to deterministic forces. The material presented is intended to assist the analyst in selection of the proper software and in the development of a meaningful numerical model for dynamic buckling. Several examples of dynamic buckling are described to illustrate the various aspects that must be considered such as snap buckling, asymmetric buckling, and parametric resonance. The most common methods of solution are briefly discussed and some modeling guidelines are given. Most of the public and commercially available programs for the geometrically nonlinear, dynamic analysis of thin beam, plate, and shell structures are described in detail. User evaluations are also listed.


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ABSTRACT: This paper presents the equations for thin shell-of-revolution tanks containing an arbitrary level of fluid. The mass matrix can be used with any finite element or finite difference digital computer program that computes either the dynamic response or the natural frequencies and modes of a thin shell of revolution and that has provision for a nondiagonal mass matrix. The method does not require a numerical finite difference or finite element discretization of the fluid, but instead provides, in series form, a mass matrix that exactly satisfies the governing field equations for the fluid and satisfies the fluid-shell interface condition with a least-squares fit.

ABSTRACT: The frequency versus wave number characteristics of four O(deltaS2) finite difference formulations for one-dimensional linear shell (ring and axisymmetric) equations are investigated and compared with the exact continuum characteristics. It is found that three of the formulations give virtually identical results. These are half-spacing techniques with equilibrium in terms of displacements or resultants and whole-spacing with equilibrium in terms of displacements. The formulation based on whole-spacing with equilibrium in terms of resultants produces some dramatically different results. These discrepancies partially explain some
late time instability problems and critical time step behaviour that have been reported by other investigators.


ABSTRACT: A large deflection elastic-plastic analysis is presented applicable to orthotropic axisymmetric plates and shells of revolution subjected to monotonic and cyclic loading conditions. The analysis is based on the finite-element method. It employs a new higher order, fully compatible, doubly curved orthotropic shell-of-revolution element using cubic Hermitian expansions for both meridional and normal displacements. Both perfectly plastic and strain hardening behavior are considered. Strain hardening is incorporated through use of the Prager-Ziegler kinematic hardening theory, which predicts an ideal Bauschinger effect. Numerous sample problems involving monotonic and cyclic loading conditions are analyzed. The monotonic results are compared with other theoretical solutions. Experimental verification of the accuracy of the analysis is also provided by comparison with results obtained from a series of tests for centrally monotonically-loaded circular plates that are simply supported at their edges.


ABSTRACT: Tests were performed on three simply supported circular plates of aluminum alloy 2024-0, under a central concentrated load, with large deflection. The load was provided by a small diameter hard steel rod. Measurements were made of load, deflections, and strains, and membrane and bending strains were calculated from the test data. Twenty electrically bonded strain gauges were used to measure the distribution of radial and circumferential strain components along a radial line on both faces of each plate. The test data are presented in comparison with theoretical predictions generated by the Grumman-developed finite element computer code PLANS.

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ABSTRACT: As an exploratory effort toward improving the crashworthiness of light aircraft cabins, a theoretical analysis was made to predict the dynamic buckling load and buckling time of a stiffened, thin-walled circular cylindrical shell. To provide for the large stiffener spacing in light aircraft, the stiffeners were considered as discrete elements by means of a Dirac delta procedure. The nonlinear governing equations were derived using Hamilton’s principle and the final equations were obtained by means of Galerkin’s method. Solution was carried out by using a Gauss-Jordan technique on the algebraic equations and a Runge-Kutta technique on the nonlinear differential equations. Numerical results are presented for an idealized model of a typical light aircraft cabin.

ABSTRACT: An alternative to the currently used Perzyna's theory of viscoplasticity for small strains is presented. The plastic strain rate vector is normal to the quasistatic yield surface which in turn may not include the origin. Consequently, new loading/unloading criteria are introduced.

ABSTRACT: The concepts of yield surface and loading surface at room temperature and elevated temperature are discussed and experimental results on pure aluminum in support of these concepts are presented. Recommendations for future experimental research are presented.

ABSTRACT: The current version of the computer program SAP for the static and dynamic analysis of linear structural systems is described. The analysis capabilities of the program, the finite element library, the numerical techniques used, the logical construction of the program and storage allocations are discussed. The main advantages of the program as a general purpose code become apparent. Results of analyses as comparisons with other existing solutions are given, and running times which demonstrate the efficiency of the program are included.

ABSTRACT: The computer is frequently used in the solution of structural problems involving composite materials. The algebraic manipulations required to cast the problem into a form suitable for direct computer
solutions have become the most tedious and error-prone parts of the solution process. This step may now be markedly simplified by using a symbolic algebra manipulation language. The use of PL/I FORMAC for this purpose is described.

ABSTRACT: The behavior of natural draft cooling tower wind pressure is investigated. Buckling loads of the towers of different meridional curvatures and shell thicknesses are computed and compared. The results show that: (1) an increase in stiffness of the structure with an increase in meridional curvature; and (2) changes of buckling load caused by changes in shell thickness is approximately proportional. A dynamic analysis of the tower is also presented. The response of the structure is increased by the dynamic effect. The amount of increase depends upon the wind time history.


ABSTRACT: A new design approach is presented to provide a conservative estimate of the buckling strength of laminated anisotropic circular cylinders under axial compression. The analysis is based on Koiter’s “special theory” for uniform axisymmetric shape imperfections which is valid for imperfections of the order of the shell wall thickness. Fourteen three-ply, glass-epoxy cylinders containing random imperfections of small mean square amplitude were characterized in terms of an equivalent axial imperfection component. Good agreement was found between theory and experiment for the range of imperfection amplitudes encountered.

ABSTRACT: Both ring and stringer stiffened circular cylinders with and without shape imperfections have been studied under axial compression, external hydrostatic pressure and combined loading of compression-hydrostatic pressure. To provide reference data for the stiffened shell results, compressive buckling tests were performed on unreinforced cylinders containing asymmetric imperfection distributions. In addition, hydrostatic buckling of unstiffened cylinders was also investigated to assess the effects of different boundary conditions on the critical pressure for varying values of cylinder lengths.

P. G. Bergan and T. Søreide (Institutt for statik, The Norwegian Institute of Technology, The University of Trondheim, Norway), “A comparative study of different numerical solution techniques as applied to a nonlinear

ABSTRACT: This paper describes and compares a number of different numerical methods frequently used in solution of nonlinear problems in structural mechanics. A simple mechanical system is chosen. By varying the geometry and the stiffness of the members, different types of nonlinear structural behavior may be simulated. A comparative study of various solution techniques applied to the sample problem is given. The solution paths followed by these methods are illustrated by use of map plots of the strain energy and the total energy of the system. Also, a new method for automatic computation of steps for incremental techniques is suggested.


ABSTRACT: The paper describes a general formulation for geometrically nonlinear analysis of shells using very simple flat finite elements. The approach is based on the “updated Langrangian” description of motion (co-rotational coordinates), in which the geometry of the shell structure is continuously updated during deformation to establish new reference configurations. The numerical solution technique adopted in the paper allows tracing of the entire nonlinear load-deflection path including unstable branches in the solution space. Numerical studies are presented in order to demonstrate the accuracy and efficiency of the proposed method.


ABSTRACT: The paper describes briefly a class of shell elements based on the free formulation by Bergan and Nygård. The elements include the “drilling” freedom that gives a significantly improved membrane action as compared to traditional elements. The elements may undertake arbitrarily large displacements and rotations and account for material nonlinearities. The “hyperplane displacement control” method is applied for solution of the static instability problems including singularities. The presented examples cover snap-through analysis of shells and buckling of plates. The examples verify that the shell elements and the solution algorithms are accurate, reliable and efficient.

References listed at the end of the paper:


ABSTRACT: The present paper describes a hybrid stress finite element formulation for geometrically nonlinear analysis of thin shell structures. The element properties are derived from an incremental form of Hellinger-Reissner's variational principle in which all quantities are referred to the current configuration of the shell. From this multi-field variational principle, a hybrid stress finite element model is derived using standard matrix notation. Very simple flat triangular and quadrilateral elements are employed in the present study. The resulting non-linear equations are solved by applying the load in finite increments and restoring equilibrium by Newton-Raphson iteration. Numerical examples presented in the paper include complete snap-through buckling of cylindrical and spherical shells. It turns out that the present procedure is computationally efficient and accurate for non-linear shell problems of high complexity.


ABSTRACT: A buckling theory valid for finite prebuckling deformations is presented for thin homogeneous, isotropic and elastic shells. It is subject to the restriction of the Kirchhoff hypothesis. A set of stability equations is derived by decomposing strain and stress components into four classes according to their characteristics. The influence of the prebuckling deformations on the buckling of thin circular cylindrical shells under lateral pressure is investigated with the aid of the basic equations derived above and the results are compared with the solutions of the Flügge equations and those obtained by Yamaki.

James C. Frauenthal (Anderson Hall, Tufts University, Medford, Massachusetts 02155 U.S.A), “Initial postbuckling behavior of optimally designed columns and plates”, International Journal of Solids and

ABSTRACT: The initial postbuckling behavior of optimally designed structures of two generic types is investigated. The structures are straight, simply-supported, inextensional columns, loaded by axial thrust and flat, simply-supported, axisymmetric circular plates, loaded by radial thrust. The structures are optimal in the sense that they withstand the largest possible loads prior to buckling, while satisfying fixed volume and minimum allowable gage constraints. The stability analysis is based upon Koiter's general theory of the postbuckling behavior of structures.


ABSTRACT: The static, vibration, and buckling analysis of axisymmetric circular plates using the finite element method is discussed. For the static analysis, the stiffness matrix of a typical annular plate element is derived from the given displacement function and the appropriate constitutive relations. By assuming that the static displacement function, which is an exact solution of the circular plate equation down triangle, open2down triangle, open2W = 0, closely represents the vibration and buckling modes, the mass and stability coefficient matrices for an annular element are also constructed. In addition to the annular element, the stiffness, mass, and stability coefficient matrices for a closure element are also included for the analysis of complete circular plates (no center hole). As an extension of the analysis, the exact displacement function for the symmetrical bending of circular plates having polar orthotropy is also given.


ABSTRACT: A computer program for the linear and nonlinear analysis of shell structures (STAGS) is applied to the instability analysis of a complex stiffened structure subjected to complicated sets of distributed and concentrated loads. Results obtained from two-dimensional bifurcation and nonlinear collapse analyses are presented. The nonlinear analysis includes the effects of an imperfection in a shell stiffened by heavy longerons. Several problems associated with the analysis of very large eigenvalue problems are discussed (one case involved a model with 20,910 degrees-of-freedom). These include the use of the appropriate finite-difference formulation to ensure convergence in a desired direction (approaching the asymptotic value either from above or from below) and the use of variable grid spacing to induce buckling in one part of the structure or the other. A technique of finding higher eigenvalues by removing the prestress at the point of bifurcation is described.


ABSTRACT: The dynamic buckling of thin viscoplastic cylindrical shells is considered in the formulation developed by Abrahamson and Goodier [1]. The constitutive equations employed describe the rate sensitive plastic material and a biaxial state of stress is considered. The influence of the viscosity parameter on the buckling process is discussed in detail and in the limiting case the solution for a perfectly plastic material is obtained. From the analysis of the final deflections as a function of the applied impulse the “stability effect” of the viscous properties of the material on the buckling process is determined.

ABSTRACT: This thesis has the objective of establishing the stability behaviour of a thin clamped-ended pipe with internal flow. The unsteady fluid forces on the pipe wall is determined by using classical potential flow theory for an incompressible, inviscid fluid and the motion of the pipe is represented by Flügge-Kempner shell equation. The solution is obtained using Fourier integral theory and the method of Galerkin. It is found that the pipe becomes unstable statically in a mode being comprised of one axial half-wave and a number of circumferential waves depending on the length and thickness ratios. For the limiting case of a relatively long thin pipe the mode of instability is the first beam mode and a particularly simple expression is found for the critical flow velocity. Furthermore, the mode shape at instability always corresponds to that of the lowest natural frequency of the pipe. The theoretical results are compared with experiments and previous work developed by different methods and the agreement found is good.

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ABSTRACT: In this paper the stability behaviour of a thin, clamped ended pipe with a high velocity internal flow is considered. The dynamic fluid loading is developed by using potential theory for an incompressible, inviscid fluid and the motion of the pipe is represented by the Flügge-Kempner shell equation. The solution is obtained by using Fourier integral theory and the method of Galerkin. For the limiting case of a relatively long thin pipe a particularly simple expression is found for the critical velocity. When both ends of a pipe are fixed, static divergence always precedes the onset of flutter and, hence, a relatively simple approach is sufficient for predicting the critical velocity. Furthermore, the mode shape at divergence instability always corresponds to that of the lowest natural frequency of the pipe, being comprised of one axial half-wave and a number of circumferential waves depending on the length and thickness ratios.

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ABSTRACT: The stability behaviour of thin-walled tubes conveying fluid is examined with an emphasis on the effects of tube flattening. Two simplified theoretical models are developed which represent a flattened tube as two parallel flat plates. The first model is in terms of standing waves on finite length plates whereas the second model is in terms of travelling waves on infinitely long, finite width plates. The fluid forces are determined by using potential flow theory. Experiments were conducted with three different tubes, one of which was initially flat. The experimental observations agree with the predictions of the first theoretical model, at least qualitatively.


ABSTRACT: Bifurcation stresses and initial postbuckling behavior of both unstiffened and outside ring stiffened circular cylindrical shells under axial compression are analyzed. The shells are assumed to have axisymmetric sinusoidal imperfections with arbitrary wavelengths and amplitudes. It is found that for large imperfection amplitudes and wavelengths both the unstiffened and the stiffened shells have extremely small bifurcation loads. The postbuckling analysis shows that for small imperfection amplitudes the bifurcations from the axisymmetric state are initially unstable and collapse is associated with the bifurcation points. However, for larger values of the imperfection amplitudes the bifurcations are stable. For unstiffened shells the transition from unstable to stable bifurcations can take place at very small values of the load. On the other hand, for stiffened shells it is found that bifurcations at load levels less than about 40 per cent of the classical buckling load have stable initial postbuckling behavior.


ABSTRACT: A generalized beam theory, earlier developed by the author, is applied to a rotationally symmetrical shell structure consisting of cylindrical and conical sections. It is shown that this theory, in which the flexibility of the beam is specified by four functions, is adequate for treating the shell structure as a beam in bending in cases where the Bernoulli-Euler and Timoshenko beam theories prove to be deficient. Flexibility functions are derived from the membrane equations of the shell structure, and modifications at the boundaries are obtained from the complete shell equations.


ABSTRACT: The initial post-buckling behaviour is determined for an integrally stiffened wide panel under compression. Overall buckling of the panel as a wide Euler column and local buckling of the plates between the
stiffeners are considered. Designing the panel so that the critical bifurcation load is the highest possible for a given amount of material per unit width tends to lead to a structure in which Euler-type buckling and local buckling occur simultaneously. It is shown that such a panel is very sensitive to geometrical imperfections. Thus, the critical bifurcation load cannot be reached in a practical structure and the two-mode design may not be optimal.

ABSTRACT: For an eccentrically stiffened wide panel under compression the optimality of a design with simultaneous occurrence of buckling as a wide Euler column and local buckling of the plate between the stiffeners is investigated. The total amount of material per unit width of the panel is prescribed. As a function of the distribution of this material in the plate and the stiffeners the maximum carrying capacities are calculated approximately by application of Galerkin's method. The design with the highest carrying capacity and the design with the best ability to retain axial stiffness, corresponding to given imperfections, are determined. It is shown that imperfections move the optimum away from the coincident buckling mode design.


ABSTRACT: For an axially compressed elastic-plastic cylindrical shell with elliptical cross-section the buckling behaviour is investigated. The initial post-bifurcation behaviour of a perfect shell compressed into the plastic range is determined in terms of an asymptotic expansion. The behaviour of shells with initial stress free imperfections is computed numerically using an incremental procedure. For shells with sufficiently eccentric cross-sections elastic analyses predict final collapse loads considerably above the bifurcation load, but the present numerical results show that elastic-plastic material behaviour reduces these collapse loads to such an extent that the elastic-plastic shells are moderately imperfection-sensitive.

ABSTRACT: The behaviour of elastic-plastic spherical shells under internal pressure is investigated numerically for thickness-to-radius ratios ranging from cases of thin shells to very thick shells. The shells under consideration are made of strain-hardening elastic-plastic material with a smooth yield-surface. Attention is restricted to axisymmetric deformations, and results are presented for initial thickness inhomogeneities in various axisymmetric shapes. For smooth thickness-variations in the shape of the critical bifurcation mode, the reduction in maximum pressure is studied together with the distribution of deformations in the final collapse mode. Also, the possibility of flow localization due to more localized, initially thin regions on a spherical shell is investigated.


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ABSTRACT: For an elastic-plastic, wide panel with eccentric stiffeners plastic buckling due to axial compression is investigated. Special attention is directed to panels designed so that overall buckling as a wide column and local buckling of the plate between the stiffeners occur simultaneously or nearly simultaneously. The bifurcation behaviour for a perfect panel compressed into the plastic range is determined analytically, and the asymptotic initial post-bifurcation analysis is mentioned briefly. Mode interaction and imperfection-sensitivity is investigated numerically by application of an incremental method. Computations for panels that bifurcate in the plastic range show a considerable imperfection-sensitivity, in some cases due to mode interaction and in some cases due to a single mode.

References listed at the end of the paper:


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ABSTRACT: For a simply supported elastic-plastic square plate under axial compression the post-bifurcation behaviour and the sensitivity to initial imperfections are investigated. An exact asymptotic expansion is given for the initial post-bifurcation behaviour of a perfect plate compressed into the plastic range. The imperfection sensitivity is studied through an asymptotic analysis of the behaviour of the hypoelastic plate that results from neglecting the effect of elastic unloading. The results of the asymptotic analyses are compared with results of a numerical incremental solution by means of a combined finite element—Rayleigh Ritz method. The paper considers the effect of different in-plane boundary conditions and the effect of various degrees of strain hardening.

ABSTRACT: Through the use of an integral transform, the present paper extends the applicability of the multisegment numerical integration technique to include the solution of general macroscopically anisotropic multilayered shells of revolution. It is found that compared with orthotropic shells, material anisotropy induces a doubling in the number of transformed fundamental equations characterizing the static response. Employing the transform together with the multisegment integration technique and several concepts from the direct stiffness method of structural analysis, procedures are developed which can handle branched anisotropic multilayered shells of revolution in a more effective manner than was previously possible. Based on the procedures outlined in the paper, numerical studies are presented which show the effect of segment size on the solution accuracy and the effects of material anisotropy on selected shell configurations.

ABSTRACT: Through the use of a complex series representation, a complex multi-segment numerical integration procedure is developed which can handle the static analysis of mechanically and thermally loaded branched laminated anisotropic shells of revolution with arbitrary meridional variations in thickness and material properties. In contrast to the real numerical integration treatment of anisotropic shells, the present procedure develops local and global stiffness matrices which require only half the computer storage and which requires significantly less overall computer time. Furthermore, since the overall procedure requires fewer computational steps, an improvement in numerical resolution is also obtained for a given word size machine. To illustrate the procedure several numerical examples are included.


ABSTRACT: The vibration of stiffened cylindrical panels with simply supported boundary conditions in the presence of initial axial and pressure loads is investigated by using a direct method. The effects of in-plane, transverse and rotary inertias are included in the formulation. The results are obtained for the stability and free
vibration of cylinders and panels as special cases and compared with other solutions. The behavior of a cylinder and the behavior of a panel (a segment of the cylinder) in stability and vibration are similar if the panel is wide enough to contain at least half a wave of the circumferential wave pattern of the cylinder.


ABSTRACT: A computer program, STAGS, for analysis of the behavior of shells of general shape has been extended by the addition of a capability for transient response analysis. A brief discussion of the numerical integration procedures included as options in STAGS is presented here, together with some numerical results obtained by use of the program. The results are included to demonstrate how rapid development of computers and numerical analysis methods has enhanced our capability to solve complex shell stability problems. In addition, they illustrate some facets of shell behavior under transient and static loading. The applications are concerned with an axially loaded cylindrical shell with unstiffened rectangular cutouts. The effect of the loading rate on the shell response is studied. The definition of a dynamic buckling criterion is discussed in view of the results obtained. Also considered is the possibility of determining a static collapse load (limit point) by use of a transient response analysis with the load applied slowly.

References listed at the end of the paper:


ABSTRACT: The equations of a symmetrically loaded elastic thin shell of revolution are set up in such a way that the effects of small deviations of the meridian from a “perfect” form may be analyzed with ease. Solutions are found for several kinds of imperfection and the results plotted in a specially compact form. The structural effects depend strongly on the meridional length of the imperfection. Some shell junction problems can be
analyzed in terms of imperfections. The method can be extended to find classical buckling loads for axially symmetric modes.


ABSTRACT: Rayleigh successfully analysed inextensional deformation of thin elastic shells by using a simple energy method. Subsequent workers seem to have been put off from using similar methods for shells which suffer extensional as well as bending deformations by the fact that the calculations get messy. In this paper we develop the kinematic relation between surface strains and changes in Gaussian curvature, and show that this is a very convenient tool for use in energy calculations. We give two examples of energy calculations for shells loaded by point forces. We find that once the energy expressions have been set up, certain analogies with simpler and already-solved problems become obvious. This leads to simple solutions. A feature of the method is that physically important quantities are not obscured, and distinct regimes of structural action are clearly delineated.

ABSTRACT: It is proved that cylindrical shells and two dimensional flat panels constrained to zero displacement at their leading and trailing edges, and exposed to subsonic flow, can lose their stability by divergence (buckling) while in supersonic flow two-dimensional panels can only flutter. Moreover, it is proved that in incompressible flow flutter can only occur—if at all—above the critical divergence velocity. The proofs are based on a qualitative analysis of the expressions for generalized aerodynamic forces derived in references [1]–[3], and on the assumptions that linearization of the stability problem is admissible and that Galerkin's method is convergent.

ABSTRACT: An exact solution and numerical results are presented for simply supported circular cylindrical shells that are laminated unsymmetrically about their middle surface. The coupling between bending and extension induced by the lamination asymmetry substantially decreases buckling loads and vibration frequencies for common composite materials such as boron/epoxy and graphite/epoxy. For antisymmetric laminates, the effect of the coupling dies out rapidly as the number of layers is increased. However, for generally unsymmetric laminates, the effect of coupling dies out very slowly as the number of layers is increased. That is, having a large number of layers is no guarantee that coupling will not seriously degrade the shell buckling resistance and vibration frequencies. Thus, designers must include coupling between bending and extension in all analyses of unsymmetrically laminated shells.

ABSTRACT: A description is given in this paper of part of a larger study directed toward the investigation of the buckling characteristics of thin, open cylindrical shells. The load-deflection response of transversely loaded shells is treated in this study. A subsequent paper will deal with the behavior of end-loaded open shells. Measured values of buckling loads are compared with analytical predictions based on the presumption that prior to the onset of buckling the shell material behaves elastically but large deflections of the shell surface may occur.

References listed at the end of the paper:


ABSTRACT: Applying the strain energy principle, the stiffness matrix Cij is derived for a triple-layered fibre-reinforced laminate having fibre orientations (beta, alpha, -beta). Next, the stiffness coefficients, CBARij, are determined for laminated composites consisting of such triple layers. The present formulation is more general in nature, since it permits analysis for arbitrary stacking sequences. A few numerical results are presented for commonly used fibre-reinforced composites, employing the effective micromechanics properties as summarised by Tsai [1] for unidirectional composites.


ABSTRACT: This paper presents some numerical results of the effects of several nondimensional parameters
on the buckling and initial post buckling behaviors of shallow sandwich panels under axial compression. Results are presented that show these effects due to transverse shearing resistance of the core material, different face-sheet thicknesses, and different core thicknesses. Further effects on the buckling and initial postbuckling behaviors of sandwich panels are presented due to the torsional resistance of longitudinal edge stiffeners. The results show that the range of flatness parameter, _¥/d, for which sandwich panels remain imperfection-insensitive increases with increases in transverse shearing resistance of the core material and with larger core thicknesses. These results also indicate that this range of _¥/d is smallest when the face-sheet thicknesses are equal. Finally, as in the case of homogeneous panels, torsional resistance of the longitudinal edge stiffeners has the effect of making the sandwich panel less imperfection-sensitive.


ABSTRACT: Design study methods and results are presented of a composite reinforced base ring for the conical aeroshell structure of the planetary lander vehicle for Project Viking, an unmanned mission to Mars. The aeroshell is a ring and stringer-stiffened conical shell structure having a half angle of 70° with a large base ring mounted at the outer edge of the cone and a large pay-load ring in the interior with many smaller rings spaced along the inside shell surface. The purpose of the structure is to develop the aerodynamic drag required to decelerate the lander in the Mars atmosphere to facilitate a soft landing. The shell, therefore, must be designed to resist external pressure loads during Martian entry. Unlike conventional shell structures, the Viking aeroshell has no connecting supports at its large diameter edge and, therefore, it must resist the external pressure as an unsupported inertia-loaded shell. Very little design information is available on large shell structures under these loading conditions. The structural weight of the aeroshell must be reduced to the minimum possible level while still retaining structural integrity. A currently proposed design for this structure is all metal, and the base ring accounts for 41 per cent of the total aeroshell structural weight. One possible method of reducing the weight of the proposed design is to selectively apply filamentary composites to reinforce a redesigned base ring. The filamentary reinforced base ring must be designed to take into account all possible modes of failure under the maximum design load conditions. The possible modes of failure are local or general buckling of the shell, ring buckling, and exceedence of the maximum permissible stress levels. The design of a shell structure of this complexity requires the use of the latest technology available in a large general purpose shell buckling program. A large general purpose non-linear shell buckling program developed by Lockheed (BOSOR 2) was used. Since the amount of computational effort is considerable for such a study, the turnaround time for using such a program as an aid in the design process was reduced by adapting the program to an interactive real time graphical system using the facilities of the Langley Research Center CDC computer complex. This paper describes the shell structure model and the stability results of a large Langley Research Center Viking aeroshell model, the BOSOR 2 computer program and its adaptation to an interactive system, and the design strategy used to re-design the base ring and the weight savings achievable by composite reinforcements.

Paul A. Cooper and Cornelia B. Dexter (Langley Research Center, Hampton, CA 23665), “Buckling of a conical shell with local imperfections”, NASA Technical Memorandum NASA TM X-2991, July 1, 1974

ABSTRACT: Small geometric imperfections in thin-walled shell structures can cause large reductions in buckling strength. Most imperfections found in structures are neither axisymmetric nor have the shape of buckling modes but rather occur locally. This report presents the results of a study of the effect of local imperfections on the critical buckling load of a specific axially compressed thin-walled conical shell. The
buckling calculations were performed by using a two-dimensional shell analysis program referred to as the STAGS (Structural Analysis of General Shells) computer code, which has no axisymmetry restrictions. Results show that the buckling load found from a bifurcation buckling analysis is highly dependent on the circumferential arc length of the imperfection type studied. As the circumferential arc length of the imperfection is increased, a reduction of up to 50 percent of the critical load of the perfect shell can occur. The buckling load of the cone with an axisymmetric imperfection is nearly equal to the buckling load of imperfections which extended 60 deg or more around the circumference, but would give a highly conservative estimate of the buckling load of a shell with an imperfection of a more local nature.

ABSTRACT: An incremental finite element procedure is presented for nonlinear buckling (collapse) analysis of composite shells undergoing large elastic deformations. The type of element employed is a modified version of Clough-Felippa's quadrilateral shell element. The element is made of any number of rigidly bonded orthotropic layers of different thicknesses and material properties. Transverse shear deformations are neglected but the coupling between the inplane and bending, as well as between shear and normal deformations, is retained. A number of buckling problems of composite panels and shells are worked out and the results are presented.

ABSTRACT: This paper analyze the nonlinear buckling and post buckling of thin composite cylindrical shells under axial load. In order to analyze and validate the results of analytical and numerical methods are used. In this paper the effects of orthotropic materials, boundary conditions, geometry, geometric imperfections and buckling modes of thin-walled composite cylindrical shells are studied. Static buckling of shells under axial load obtained for two type of lay up. This calculation was applied to finding the critical buckling load with some methods that included the linear static analysis of to modes shape of buckling, nonlinear static analysis (Analysis Riks) and dynamic analysis (explicit). The results, showed less difference in response to dynamic analysis to analytical solution method compared with other methods. It also became clear that the nonlinear static analysis, the smallest difference with the experimental test response is compared to other methods. In the first cylindrical shell without of geometric imperfections and then the effects of imperfections modeled and studied. Type text or a website address or translate a document. [Did you mean:The results showed that the static buckling load decreases with increasing structural geometric imperfections?]. Sensitivity to geometric imperfections depends on the type of lay up.

ABSTRACT: In structures subjected to high temperatures and large thermal gradients, the total strain consisting of the sum of thermal, elastic, plastic, and viscous (creep) parts must be considered. Elastic and thermal strains are reversible and depend on the instantaneous stress and temperature levels; plastic and viscoelastic (creep) strains are irreversible, and their complete determination requires that loading and temperature histories be
known. For many practical applications high mechanical or thermal loadings are of short duration; hence, viscoelastic (creep) strains are not significant. In such cases, the elastic and plastic strains represent the significant response of a structure to the applied loadings. An adequate description of the behavior of such structures can be obtained by the use of the theory of non-isothermal plastic deformation of elastic strain-hardening solids. For structures exposed to high temperature, long duration loadings, such as liquid metal fast breeder reactor components, the above theories do not provide adequate design evaluation and the knowledge of creep strain as a design allowable is necessary. Further, since the loading is transient with multiple complex cycles, creep and plasticity strain portions must be considered simultaneously. This paper presents a method for solving the problem of non-isothermal elastic-plastic creep structures. Finite element discretization is utilized, based on a number of flat and curved, thick and thin shell elements of triangular and quadrilateral form. Material nonlinearities are treated by the tangent stiffness method; geometric nonlinearities are considered by updating the geometry after each loading increment. Non-isothermal loading is considered by making a transition to the new temperature at the beginning of the load step and allowing the solution to settle at the position of overall equilibrium by iterative steps.


References listed at the end of this paper:

ABSTRACT: Most early discharges of nuclear reactor fuel elements have been associated with exposure of the fuel to the coolant. Such failures have dominated the design and developments of gas and water-cooled thermal reactor fuel. It is less well known that a number of fuel discharges and reactor output limitations have taken place in thermal reactors because of fuel element deformations which have occurred without loss of clad integrity. The paper reviews recent developments in the physical understanding of fuel element deformations during life. The important features of these deformations are established in this paper using approximations leading to simple theoretical analyses of fuel elements deforming in the presence of creep. This theoretical treatment is applied illustratively to the following problem areas: (1) the change of thermal bow as the bending moments induced by lateral restraints relax due to creep; (2) the restraint of fast reactor sub-assembly bowing; (3) the estimation of lateral deflections in lengthening fuel pins which are restrained axially; and (4) the causes of waving of the heat transfer surfaces of certain uranium-magnox fuel elements. It is concluded from these examples that many of the characteristics of fuel element deformations during life can be obtained from quite simple ideas and mathematical analyses. The methods thus provide a useful tool for design and research.

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ABSTRACT: A numerical procedure is presented for determining the unsymmetrical buckling pressure for clamped, elastic-plastic spherical shells. The general deep-shell equilibrium equations are used along with an incremental plasticity theory based on the Prandtl-Reuss equations. The material is assumed to obey a Ramberg-Osgood type uniaxial stress-strain law. A linear eigenvalue problem is formulated where the buckling pressure is obtained by plotting the pressure versus the determinant of the stability matrix. Coefficients in the governing system of homogeneous equations are evaluated by solving the nonlinear problem for the axisymmetric deformation prior to unsymmetrical buckling. Buckling pressures are computed for a wide range of geometries and compared with existing theoretical results.

H. Dean Bartel (Air Force Weapons Lab, Kirtland AFB, New Mexico, USA), “A Study of Load-Deformation and Buckling Relationships for Reticulated Shells”, AFWL-TR-74-87, April 1974
DTIC Accession Number: AD0778756, Handle / proxy Url: http://handle.dtic.mil/100.2/AD778756
ABSTRACT: The objectives of this research were to determine the theoretical and experimental load-deformation response and buckling loads of reticulated shells and to study the growth of imperfections in reticulated shell models. Two types of theoretical analyses (elastic material behavior was assumed) of reticulated shells were conducted to predict load-deformation relationships. A 'split rigidity' concept was used in which equivalent membrane and bending thicknesses were calculated. The second technique was a space frame analyses using the NASTRAN computer code. Three spherical reticulated shell models (two brass and one plastic) were fabricated and tested experimentally. Results of the study indicated that the NASTRAN code predicted the deflection patterns well and identified the final buckle locations.

ABSTRACT: It is the purpose of this dissertation to investigate the dynamic stability of elastic shells of revolution. Two specific areas of this broad field are treated in detail. First, this analytical study generates previously unavailable interaction relations for combined dynamic loadings as they interact to cause passage from a dynamically stable state to other states. Secondly, the concept of linearized dynamic stability is extended to include geometrically nonlinear effects. One role of these effects is to allow the possibility of autoparametric excitation of preferred flexural modes by the driven modes. The question of whether such excitation can occur during the primary dynamic instability motion sufficiently to affect the magnitude of critical dynamic loads is studied. A modified version of the subdomain method in combination with circumferential modal analysis is developed for the solution method. A computer program is constructed to obtain numerical results and the dynamic stability characteristics of a conical frustum are studied under a variety of combined dynamic loadings. Interaction curves for static stability, linearized dynamic stability, and nonlinear dynamic stability are generated. For the particular loading conditions studied, the results indicate that dynamic instability will occur at loads below critical static loads. This reduction in critical dynamic loads was shown to be the result of both the dynamic load factor effect and of autoparametric excitation. The interaction curves which are generated illustrate these effects quantitatively under conditions of combined dynamic loading. A criterion for dynamic buckling is established based on meridional mode shape changes. This ability to detect sudden jumps in the meridional profile helps to verify instability detected by divergence on displacement time history curves and provides additional information about the poststable state.

References listed at the end of the dissertation:
ABSTRACT: Plexiglass cylindrical shell models with nearly perfect geometry and constant thickness were tested under various combinations of membrane stresses. In cylinders under axial compression alone and axial compression with internal pressure, the buckling procedure was initiated by means of a small dynamic disturbance which reduced the dispersion of the test results. The normal forces and bending moments in the middle of the model were measured. The number of buckling waves observed in the tests agreed quite well with the result of the classical theory for the laterally loaded cylindrical shell. Only the shape, the length, and the depth of the buckling waves changed with the stress state. A buckling criterion and an interaction curve realistic for civil engineering purposes are proposed for checking the stability of cylindrical shells with fixed ends under combined membrane stress states.

ABSTRACT: Araldite hyperboloidal shell models with nearly perfect geometry and constant thickness were tested under various axisymmetric combinations of membrane stresses. During the tests the normal forces and bending moments in the middle of the model were measured and the initiation of the buckling process was studied. The experimental results are compared with calculated values using the classical linear buckling theory. The experimental values fitted an empirical law. A new approach, based on the theoretical results and the tests carried out, is proposed to determine the buckling safety of hyperboloidal shells.

Ihsan Mungan (Wissenschaftlicher Angestellter, Ruhr-Universität Bochum Institut fur Konstruktiven Ingenieurbau, Bochum, West Germany), “Buckling Stresses of Stiffened Hyperboloidal Shells”, ASCE Journal of the Structural Division, Vol. 105, No. 8, August 1979, pp. 1589-1604
ABSTRACT: Three hyperboloidal shell models made of epoxy resin (araldite) having nearly perfect geometry and constant wall thickness were tested first without stiffeners, afterwards with five, nine and 19 rings and 19 rings plus 36 meridional ribs. The axisymmetric loading resulting in various combinations of membrane stresses in ring and meridional directions was increased in steps until the first buckling wave could be observed. The initiation of the buckling process and the shifting of the region where the first buckling wave was observed were studied. The experimental results are compared with calculated values using a classical linear buckling theory. The experimental values fitted a nondimensional empirical law in terms of the uniaxial buckling stresses for each type of stiffening. An approach, based on the theoretical results and the tests carried out, is proposed to describe the buckling behavior of hyperbolic shells of revolution with and without stiffeners.

Ihsan Mungan (1) and Otto Lehmkamper (2)
ABSTRACT: With increasing dimensions of the cooling towers built of reinforced concrete, the buckling behavior becomes crucial in the proportioning of the shell. Ring stiffeners prove to be most effective in this respect with up to four stiffening rings the so called optimal position provides the highest efficiency. After five rings the equidistant positioning becomes effective as well. However, after a value of approx 6 this ratio doesn’t influence the buckling load because the local buckling between the stiffening rings becomes decisive. The quality of the numerical analysis is checked by calculating the buckling loads obtained in tests on stiffened hyperboloidal models. The deviation between the theoretical results and experimental values is approximately the same and about 0.83 both for unstiffened models and stiffened models with five or nine rings. Also the high efficiency of the rings with ring depth to shell thickness ratio of about 6 could be verified.


ABSTRACT: In addition to geometric parameters buckling of shells of negative Gaussian curvature depends mainly on the membrane stress state present. According to buckling tests the effect of boundary conditions is relatively low whereas the numerical results are highly dependent on the boundary conditions. Again according to tests the hyperboloidal shell has a higher buckling resistance than a cylindrical shell having the same throat radius. The buckling resistance of hyperboloidal shells against circumferential compression can be increased by arranging stiffening rings of adequate size and number. Due to nonlinear behavior of reinforced concrete the buckling load factor drops to the half or less of the value obtained assuming a linear elastic behavior. This high reduction is mainly due to orthotropy and descending tangent modulus at the near of ultimate load of reinforced concrete cooling tower shells.

References listed at the end of the paper:

ABSTRACT: A two-degree of freedom structural system with both buckling loads equal or nearly so is examined, allowing for the presence of small imperfections specified by the values of two general imperfection parameters. A discrete generalized coordinates energy method is used, and the system considered is non-symmetric in the two modes of deflection. Conclusions regarding the types of behaviour possible are obtained by examination of all possible equilibrium path shapes. Comparison is made to behaviour of idealized systems. Change in buckling load value with imperfection size, or imperfection sensitivity, is established and imperfection sensitivity surface forms are sketched.

ABSTRACT: An energy principle is employed to derive the equations governing the stability of a simply-supported, eccentrically ring-stiffened, oval, orthotropic cylindrical shell. The kinematic relations used are those of Love-type shell theory and the effect of reinforcing rings is accounted for by a distributed stiffness approach. The cylinder is subjected to a combination of uniform axial and lateral pressures. It is determined that the domain of stability of such a stiffened cylinder is bounded by two distinct solutions, herein denoted as corresponding to ‘long’ and ‘short’ axial wavelengths, with the extent of the short wavelength solution being dependent upon the degree of stiffening afforded by the rings. The analysis of the effects of ring eccentricity
shows that ovals are affected in a similar manner to circular cylinders in that outside rings provide the greatest capacity for sustaining axial compression, while inside rings are capable of supporting the greatest lateral pressure. Finally, it is found that the buckling load of an oval cylinder under uniform lateral pressure slightly exceeds the corresponding value for an equivalent circular cylinder. As a further verification of this phenomenon, a Rayleigh-Ritz procedure is employed to determine the buckling load of an oval ring under uniform radial load. The results of this analysis corroborate those obtained for the cylinder.

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ABSTRACT: The concept of almost sure sample stability and sample stability in probability are formulated for elastic systems. Using a Koiter type approach these concepts are used in the analysis of imperfection sensitive structures. The applied load and the initial geometric imperfections are introduced into the analysis as random quantities. A compressed beam of finite length on a nonlinear elastic foundation is used in an example calculation.


ABSTRACT: The current version of the computer program NONSAP for linear and nonlinear, static and dynamic finite element analysis is presented. The solution capabilities, the numerical techniques used, the finite element library, the logical construction of the program and storage allocations are discussed. The solutions of some sample problems considered during the development of the program are presented.


ABSTRACT: (none given)

References listed at the end of the paper:


ABSTRACT: An analytical method is developed to solve approximately the bifurcation buckling load of a circular cylindrical shell under nonaxisymmetrical lateral pressure. The assumption of semi-inextensible deformation is made, which sets the circumferential strain to zero and simplifies the system of equations as well as the boundary conditions. In order to investigate the accuracy of the new method, solutions are first obtained for a cylindrical shell under uniform lateral pressure with either simple-simple or clamped-free boundary conditions. Comparisons are made in the former case to Flugge’s theory and, in the latter case, to a finite element analysis. Agreement in both cases is very good. The theory is then applied to find the buckling load of a clamped-free cylindrical shell under nonaxisymmetrical lateral pressure created by wind. Disagreement with a
previous theory by Langhaar and Miller is examined. Comparisons with results of some experiments are also made and possible reasons of the discrepancies are considered.

Herbert Anton Mang (Texas Tech University, USA), “Analysis of doubly corrugated shell structures by the finite element method”, Ph.D. Dissertation, August, 1974

PARTIAL INTRODUCTION: The specific purpose of this investigation is to develop a new and more accurate technique for the static and dynamic analyses of cylindrical, doubly corrugated shell structures used, for example, as protective shelters for aircraft …, and to verify the suitability of this technique by comparing some of the results of the analyses with analytically and experimentally obtained data due to Smith (1) and with experimentally obtained data due to Stokley (89). As a by-product of the investigation a general concept developed by Bogner et al. (2), which utilizes products of Hermitian interpolation polynomials of the same order as shape functions, is extended to encompass products of Hermitian polynomials of different order.…

List of references at the end of the dissertation:
4. Nilson, A.H., "Analysis of Light Gage Steel Shear Diaphragms", Proceedings of the Second Specialty Conference on Cold-Formed Steel Structures, Department of Civil Engineering, University of Missouri, Rolla, Missouri, pp. 325-363, 1973.
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“Buckling of Cooling-Tower Shells: Bifurcation Results”, ASCE Journal of the Structural Division, Vol. 101, No. 6, June 1975, pp. 1205-1222

ABSTRACT: This paper describes studies of bifurcation buckling of hyperboloids used for large-scale cooling towers. Those studies include the effects of flexible supports, combined loadings from wind, dead weight, and temperature, shell cracking, different variations in the wind pressure distribution, and changes in the shell thickening. Comparisons are made between numerical and wind-tunnel results. The finite element formulation used is examined and results are presented for the tower at the Trojan Nuclear Power Plant on the Columbia River, Oregon.

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ABSTRACT: In the light of recent contributions by Batoz’ and Hibbitt, two aspects of finite element formulations for shell stability analysis are examined. The first is the consistency of the shell strain-displacement equations employed; the second is the proper representation of ‘follower forces’—pressures that are always normal to the deforming surface. Numerical studies of an arch indicate that improper representation of either of these factors can have a significant effect on predicted buckling loads. Numerical studies of an arch indicate that improper representation of either of these factors can have a significant effect on predicted buckling loads.

ABSTRACT: The paper presents an initial post buckling analysis for the rotationally symmetric branching of a cylindrical shell with a free edge following the linear eigenvalue analysis of Ashwell. The shell is supposed to be infinitely long and a closed form solution is obtained for the initial curvature of the post buckling path. This curvature is seen to be negative and more severe than that of the corresponding classical solution. The solution is shown to be relevant to the buckling of a cracked concrete shell such as a cooling tower.

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ABSTRACT: Large amplitude flexural vibration of some moderately thick, straight and curved elements have been analysed in a unified way. Transverse shear and rotatory inertia effects have been included. The final approximate governing equation comes out as a second order total differential equation, which on integration gives a relationship between amplitude and period. Phenomena like dynamic buckling, transition from a slightly curved element to a shallow element, etc., have been studied.


ABSTRACT: A finite element is developed to analyse the vibration characteristics of initially stressed shells of revolution. The meridional, circumferential and normal displacements over the element are assumed to be cubic polynomials of the meridional co-ordinate. Numerical integration is used to generate the elastic stiffness, geometric stiffness and mass matrices. The element is used to analyse three typical problems pertaining to the vibrations of initially stressed thin shells of revolution.


ABSTRACT: A theoretical investigation of an efficient numerical solution scheme to solve approximately the nonlinear Donnell equations for imperfect isotropic cylindrical shells with edge restraints and under axial compression was carried out. The nonlinear partial differential equations have been reduced to an equivalent set of nonlinear ordinary differential equations. The resulting two-point boundary value problem was solved, first, by using "Newton's Method of Quasilinearization" to obtain a set of linearized differential equations for the correction terms and, secondly, these differentials were approximated as finite differences to cast the linearized system of equations into the form of a block tridiagonal matrix equation. The Potters' Method solution scheme was used to solve efficiently the block tridiagonal matrix equation. By successive iterations a solution to the set
of nonlinear ordinary differential equations was obtained. The use of this method makes it possible to investigate how the axial load level at the limit point is affected by the following factors: the choice of inplane boundary conditions, the prebuckling growth caused by the radial edge constraint, the orientation and shape of the axisymmetric and asymmetric imperfection components, and the finite length of the shell.

References listed at the end of the thesis:

Bathe, K.-J. (1), Ramm, E. (2) and Wilson, E. L. (1)
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ABSTRACT: Starting from continuum mechanics principles, finite element incremental formulations for nonlinear static and dynamic analysis are reviewed and derived. The aim in this paper is a consistent summary, comparison, and evaluation of the formulations which have been implemented in the search for the most effective procedure. The general formulations include large displacements, large strains and material nonlinearities. For specific static and dynamic analyses in this paper, elastic, hyperelastic (rubber-like) and hypoelastic elastic-plastic materials are considered. The numerical solution of the continuum mechanics equations is achieved using isoparametric finite element discretization. The specific matrices which need be calculated in the formulations are presented and discussed. To demonstrate the applicability and the important differences in the formulations, the solution of static and dynamic problems involving large displacements and large strains are presented.

ABSTRACT: A computer code, based on finite difference techniques, has been developed to analyze finite length soft-bonded multilayered shells of revolution for dynamic loadings. The paper reviews the capabilities of the basic shell dynamics code used to analyze the individual shell layers and then discusses the development of the code for soft bonded shells. The implementation of the computer code with emphasis on the bond modeling is also presented. Several numerical examples are included that provide a comparison with an analytical solution, illustrate various design parameter studies performed with the code, and show experimental-numerical data correlation studies. These examples serve to illustrate the validity and usefulness of the code plus the necessity of including bond deformation effects to properly analyze bonded shell structures.


PARTIAL INTRODUCTION: The theoretical aspects of the stability of smooth longitudinally compressed cylindrical shells of a cross section different from circular have been most extensively investigated in the case of oval and elliptical shells and shells whose cross sections deviate from the circular shape in accordance with certain definite periodic laws [1-6]…. This article describes the results of an experimental investigation of the stability of smooth thin-walled longitudinally compressed cylinders having either slightly elliptical cross sections or cross sections whose deviation from the circular shape is describe by \( w = A \cos(4\theta) \), where \( w \) and \( A \) denote the deviation and the amplitude of the deviation of the cross section from the circle, and \( \theta \) is the circular coordinate….


ABSTRACT (none given)

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2. V. V. Bolotin, Dynamical Instability of Elastic Systems [in Russian], Gostekhizdat, Moscow (1956).


ABSTRACT: In some technically important structures, finite prebuckling displacements have a profound effect on the bifurcation load. To ignore these displacements, as is done in most instability analyses, is to invite major errors, usually on the unsafe side. A method is presented which approximates this effect without the necessity of
solving nonlinear equations. The general theory is developed for any elastic body under conservative loads. The governing equations are subsequently discretized by a finite element approach and it is shown that for planar framed structures, the second order approximation to the buckling load can be found in terms of the standard linear and geometric stiffness matrices of structural analysis; the solution procedure does not require iterations. For illustrative purposes, a computer program was developed for planar structures and the results are compared to the exact solution for the buckling of shallow circular arches.

ABSTRACT: Computational algorithms for the analysis of fluid and structural dynamics are reviewed, with particular emphasis on methods that are employed or of potential benefit in reactor safety analysis, where coupled fluid-structure analyses are of interest. The fluid dynamics algorithms are classified according to time integration methods, mesh descriptions, and compressible/incompressible flow, while the structural dynamics algorithms are summarized from the view-points of time integration and the types of nonlinearities which can be treated. Alternative means of coupling these various fluid and structures algorithms are examined. Finally the principal features of some existing programs are summarized.

ABSTRACT: The nonlinear collapse behavior of long cylindrical shell structures subject to a bending load only or combined bending and uniform normal pressure loads is studied using the STAGS computer code. Two modes of nonlinear collapse are investigated to determine maximum strength. One mode of collapse is described by circumferential flattening of the cylinder cross section and the other mode is represented by axial wrinkling of the region of maximum compression. Results compare favorably with available published data for cylinders loaded by pure bending and results are presented for combined loads which have not been previously reported. The collapse loads obtained in this study show that current design criteria are conservative except for a narrow range of length-to-radius ratios and pressures.


Daniel R. Veronda (1) and Victor I. Weingarten (2) (1) Hughes Aircraft Co., Fullerton, California, USA (2) Department of Civil Engineering, University of Southern California, Los Angeles, California, USA “Stability of Pressurized Hyperboloidal Shells”, ASCE Journal of the Engineering Mechanics Division, Vol. 101, No. 5, September/October 1975, pp. 663-678
ABSTRACT: The data obtained are compared with predicted results using a linear finite element stability analysis and a corresponding nonlinear analysis wherein the effects of geometric nonlinearities are included. Experimental buckling loads were in good agreement with linear theory predictions, and the geometric nonlinearities were found to have little effect on the calculated critical loads of the hyperboloids tested. The experimental results were also compared to analytical data for cylindrical shells. The ratio of experimental
results to analytical predictions were far lower for cylindrical shells than hyperboloidal shells. These results indicate that hyperboloidal shells have a lower sensitivity to geometric imperfections than cylindrical shells. The experimental data for internally pressurized hyperboloidal shells under axial load indicate that the axial buckling value asymptotically approaches a constant value when the additional load carried by the internal pressure is subtracted. Sanders thin shell (strain-displacement) equations were used to develop finite element models for both the linear and nonlinear analyses.


ABSTRACT: Static stability analysis of clamped-free cylindrical shells subjected to wind pressure is presented, using the energy theory of buckling. The criterion used is the vanishing of the second variation of potential energy, i.e., expressed in terms of prebuckling membrane strains and the assumed virtual displacement components. The prebuckling analysis has been carried out using Donnell’s linear shell theory. Numerical results are presented for various shell geometries. Supporting experimental evidence is also provided. The effect of relaxing the axial displacement and rotation at the “clamped” base has also been theoretically studied. Current engineering practice of determining buckling load for maximum uniform pressure condition is shown to be conservative.

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(2) Department of Civil Engineering, University of Southern California, Los Angeles, California, USA

ABSTRACT: An analytical and experimental investigation was carried out to determine the buckling loads of hyperboloidal shells with different geometries subjected to the axisymmetric loadings of external pressure and axial compression. Sander’s thin shell equations were used in conjunction with the finite element method to determine the bifurcation buckling load of the shell. The experimental program yielded data on the instability behavior of hyperboloidal shells subjected to combined loadings. Molded PVC specimens were used in the experiments. Shell specimens were: (1) Clamped on both ends; and (20 clamped on one end and free on the other end. The experimental data were found to be in good agreement with the analysis for all types of loading conditions.

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ABSTRACT: The effect upon the buckling strength of a soft elastic core attached to a shell of revolution subjected to axisymmetric loads is investigated. The axisymmetric stress problem is solved by using the finite element method to solve the body of revolution problem with an axis of material symmetry subjected to Fourier expandable thermal, body force, and surface traction loading. The governing equations are derived for a
triangular toroidal continuum element attached to shell elements. The elastic core influence coefficient matrix of the core is derived by applying the unit line load at the interface nodal point of the core. The inversion of the influence coefficient matrix yields an equivalent stiffness matrix of the core which is then combined with the shell stiffness matrix. Results from this investigation are in good agreement with available analytical and experimental results for cylindrical shells. New results are obtained for conical and spherical shells.

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ABSTRACT: The buckling characteristics of hyperbolic paraboloid shells loaded by uniform pressure were first analyzed by Reissner. Governing equations of elastic stability have been derived by Wilson and are based on the existence of an adjacent equilibrium position.

ABSTRACT: Several aspects of the axisymmetric buckling of elastic-plastic circular plates are investigated. For plates that bifurcate in the plastic range, a comparison is made between the results of a numerical calculation of the postbuckling behavior and the predictions of an asymptotic analysis. Also, the imperfection sensitivity of elastic-plastic circular plates is investigated numerically when bifurcation of the perfect plate occurs in the elastic range and when bifurcation of the perfect plate occurs in the plastic range.

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ABSTRACT: Results have been collected on studies relating the stability load of a structure to stiffness and natural frequency. Additional experimentation has been done to include effects of residual stresses and the major portion of this paper is devoted to a discussion of these studies. Finally, further examinations have been made of recent theories to relate stability load, stiffness, frequency and residual stress. The results have been reported here in order to reveal the range of relationships that can be found among these four structural features, and to demonstrate a reasonably sound basis for non-destructive testing procedures to determine residual stresses and structural stability. Hopefully, it also will stimulate further research in this hitherto neglected area.


Accession Number: ADA304616, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA304616
ABSTRACT: Several finite-element models are applied to the linear static, stability, and vibration analysis of laminated composite plates and shells. The study is based on linear shallow-shell theory, with the effects of shear deformation, anisotropic material behavior, and bending-extensional coupling included. Both stiffness (displacement) and mixed finite-element models are considered. Discussion is focused on the effects of shear deformation and anisotropic material behavior on the accuracy and convergence of different finite-element models. Numerical studies are presented which show the effects of (a) increasing the order of the approximating polynomials, (b) adding internal degrees of freedom, and (c) using derivatives of generalized displacements as nodal parameters.

ABSTRACT: Mixed isoparametric elements are presented for the geometrically nonlinear analysis of laminated composite shells. The analytical formulation is based on a form of the nonlinear shallow shell theory with the effects of shear deformation, material anisotropy and bending-extensional coupling included. The fundamental unknowns consist of the 13 stress resultants and generalized displacements of the shell. The generalized stiffness matrix is obtained by using a modified form of the Hellinger-Reissner mixed variational principle. Both triangular and quadrilateral elements are considered. The accuracy of the mixed isoparametric elements developed is demonstrated by means of numerical examples and their advantages over commonly-used displacement elements are discussed. Also, computational procedures are presented for the efficient evaluation of the elemental matrices and for overcoming the difficulties associated with the large, sparse system of equations of the mixed models thus making them competitive with displacement models.

ABSTRACT: A computational procedure is presented for predicting the dynamic response of curved beams with geometric nonlinearities. A mixed formulation is used with the fundamental unknowns consisting of stress resultants, generalized displacements and velocity components. The governing semidiscrete finite element equations consist of a mixed system of algebraic and differential equations. The temporal integration of the differential equations is performed by using an explicit half-station central difference method. A procedure is outlined for lumping both the flexibilities and masses of the mixed model, thereby uncoupling all the equations of the system. The advantages of the proposed computational procedure over explicit methods used with the displacement formulation are discussed. The effectiveness and versatility of the proposed approach are demonstrated by means of numerical examples.

J.G.A. Croll, “Towards simple estimates of shell buckling loads”, Der Stahlbau, 1975


ABSTRACT: A series of experiments has been carried out on electroformed cylindrical shells under axial compression to determine the effect of the stiffness of the testing machine on the buckling load. The effect of the testing machine has also been calculated using Tsien's criteria. It is shown that the calculated energy loads have a strong dependence on the testing machine while the experimental data are virtually independent of the testing machine stiffness.

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ABSTRACT: The effect of prismatic imperfections on the buckling load of circular cylindrical shells under axial compression is examined by considering the problem as one of interaction between panels forming the shell. The imperfections are in the form of flat spots. Numerical results are presented to show the effect of shell geometric parameters and the number, size, and the type of flat spots on the buckling load.


ABSTRACT: This review is specifically directed toward experimental shell buckling. The time period is primarily over the past 20 years. The subjects covered are specimen fabrication, initial imperfections, mounting and loading, and special techniques. The main purpose is a discussion and evaluation (with appropriate author bias) of experimental methods and techniques used in shell buckling research. The message that is clear from past work is that carefully conducted and reported work is infinitely more useful than tests carried out without much pretest thought. The emphasis is on model structures.


ABSTRACT: Correlation studies between experimental buckling loads and analytical predictions based on experimentally measured initial imperfections were carried out for axially compressed isotropic and stiffened cylindrical shells. By expanding the response of a cylindrical shell in truncated Fourier series, the nonlinear Donnell type shell equations for imperfect stiffened shells were reduced to a set of linear equations in the
correction terms by Newton's method of quasi-linearization. Solutions were obtained for isotropic and for ring and stringer stiffened shells. The amplitudes of the initial imperfections used in the analysis were calculated from the corresponding Imbert-Donnell imperfection models. The free parameters in this imperfection model were obtained by least square fitting the harmonics of the experimentally measured initial imperfections. It was possible in all cases to achieve satisfactory correlation using only a few suitably chosen deflection and imperfection modes.

References listed at the end of the paper:
ABSTRACT: A study has been made to determine the dynamic stability of an imperfect circular cylindrical shell subject to a step loading in the axial direction. In the analysis, the radial displacement of the shell is approximated by a finite degree-of-freedom system. The dynamic analysis includes not only the effect of the radial inertia, but also, in an approximate manner, that due to the axial inertia. The critical loads are determined by numerical integration of the equation of motion. Compared with the static case, there is a significant reduction of the dynamic buckling load for the high wave number range of the radial modes. It is concluded that due to frequency coupling between axial and radial motions, the axial inertia plays an essential role in characterizing the dynamic instability of a finite length shell.

Gerald A. Cohen, “Evaluation of configuration changes on optimum structural designs for a Mars entry capsule”, NASA CR-1414, August 1969

Gerald A. Cohen, “Structural optimization of sandwich and ring-stiffened 120 degree conical shells subjected to external pressure”, NASA CR-1424, August 1969


ABSTRACT: The field method, presented previously for the solution of linear boundary-value problems defined on one-dimensional open branch domains, is extended to one-dimensional domains which contain
circuits. This method converts the boundary-value problem into two successive numerically stable initial-value problems, which may be solved by standard forward integration techniques. Also presented is a new treatment of singular boundary conditions (kinematic constraints) — this is problem independent with respect to both accuracy and efficiency. The method has been implemented in a computer program which calculates the asymmetric response of ring-stiffened orthotropic multicircuit shells of revolution.


ABSTRACT: The additional constitutive equations required by transverse shear deformation theory of anisotropic heterogeneous shells are derived without the usual assumption of thickness distribution for either transverse shear stresses or strains. The derivation is based on Taylor series expansions about a generic point for stress resultants and couples which identically satisfy plate equilibrium equations. These equations give the in-surface stress resultants and couples in terms of the transverse shear stress resultants at the point and arbitrary constants, which may be interpreted as redundant “forces”. Starting from these expressions, we derive statically correct expressions (in terms of the transverse shear stress resultants and redundants) of the following variables: (1) in-surface stresses, using the stretching-bending constitutive equations and the Kirchhoff distributions of in-surface strains, (2) transverse shear stresses, by integration in the normal direction of the three-dimensional equilibrium equations, and (3) the area density of transverse shear strain energy, by integration in the normal direction of the corresponding volumetric density. Finally, by applying Castigliano's theorem of least work, the shear strain energy is minimized with respect to the redundants, thereby leading to the desired constitutive equations. Corresponding transverse shear stiffnesses are presented for several laminated walls, and reasonable agreement is obtained between transverse shear deformation plate theory using these stiffnesses and exact three-dimensional elasticity solutions for the problem of cylindrical bending of a plate.


ABSTRACT: FASOR (Field Analysis of Shells of Revolution) is a user-oriented code for the analysis of stiffened, laminated axisymmetric shells. Very general shell geometries are allowed in that the reference surface meridian may form a branched, multi-circuit figure. Modes of response treated are linear asymmetric and geometrically nonlinear axisymmetric prebuckling, and asymmetric buckling and vibration under static axisymmetric loads. Bifurcation buckling under asymmetric loads is also treated by using a symmetrized prebuckling state based on the linear response of a user-specified meridian. For each mode of response, the user may specify any combination of orthotropic or anisotropic material properties with classical or transverse shear deformation shell theories. FASOR employs a numerical integration method (called the field method) whereby a numerically unstable linear boundary-value problem (all modes of response reduce to a sequence of such problems) is converted into two successive numerically stable initial-value problems. In this context, numerical stability means that round-off errors introduced at each step of the integration process tend to decay out. As a consequence, solution accuracy is controlled essentially by a single number, the truncation error tolerance, which is satisfied by automatically adjusting the size of each integration step. The field method thus eliminates the need for mesh generation required by finite element and finite difference methods, and the associated problem of numerical convergence. It also provides for automatic determination of response storage points so as to obtain a uniformly valid discrete approximation of the continuous response. In this paper the field method is
briefly described, basic aspects of the mathematical model are discussed, the organization of input data is presented, and input and plot output are given for specific examples.


ABSTRACT: An integrated computer program entitled Field Analysis of Shells of Revolution (FASOR) currently under development for NASA is described. When completed, this code will treat prebuckling, buckling, initial postbuckling and vibrations under axisymmetric static loads as well as linear response and bifurcation under asymmetric static loads. Although these modes of response are treated by existing programs, FASOR extends the class of problems treated to include general anisotropy and transverse shear deformations of stiffened laminated shells. At the same time, a primary goal is to develop a program which is free of the usual problems of modeling, numerical convergence and ill-conditioning, laborious problem setup, limitations on problem size and interpretation of output. The field method is briefly described, the shell differential equations are cast in a suitable form for solution by this method and essential aspects of the input format are presented. Numerical results are given for both unstiffened and stiffened anisotropic cylindrical shells and compared with previously published analytical solutions.


ABSTRACT: The subspace iteration method used in the buckling options of the shell code FASOR is discussed. Buckling modes of a laminated anisotropic cylindrical shell and a sandwich spherical cap are presented and compared with previously published results.


ABSTRACT: The present theoretical investigation studies the effect of small multilobed initial deviations from the exact shape upon the deformations and the critical time of a thin-walled circular cylindrical shell which was manufactured with initial axisymmetric deformations. To facilitate the analytical work, the actual solid wall of the shell is imagined to be replaced by an equivalent sandwich wall. The general equilibrium equations derived for shallow shells are expressed in terms of stresses and deviations corresponding to the equivalent sandwich model. The radial displacement as well as the meridional, circumferential and membrane shear stresses are expressed by finite Fourier series for each face of the sandwich model. The compatibility conditions used in conjunction with the equilibrium equations lead to a system of linear and nonlinear equations. It is assumed that all deformations are due to nonlinear steady creep governed by Odqvist's power law. The solution of this system of equations is carried out by introducing the solution obtained from the axisymmetric creep buckling theory.
developed by N.J. Hoff. Furthermore, in order to simplify the equations, it is assumed that the deformations remain small compared to the shell thickness. A closed form solution is found for the multilobed deformation rates and for the critical time as well. However, the latter is too complicated to be evaluated by hand. A numerical integration of the deformation rates shows, for a given cylinder, that the multilobed creep buckling deformations grow much faster than the axisymmetric. Indeed, we find that Koiter's theory of bifurcation buckling for perfectly elastic axially compared circular cylindrical shells has its counterpart in creep buckling.

ABSTRACT: This paper examines the thesis that a process of structural optimization leads inevitably to designs which exhibit the notorious failure characteristics often associated with the buckling of thin elastic shells. This means that an idealized perfect structure exhibits an unstable and often compound branching point and would fail by an explosive instability while nominally perfect real structures containing inevitable small imperfections fail at scattered loads which can be quite considerably lower than that of the idealization. It is shown via a fairly wide spectrum of examples that an increasing degree of optimization is likely to lead in turn to an unstable bifurcation, a very unstable bifurcation, and finally a very unstable compound bifurcation with the possible added danger of an unsuspected nonlinear coupling action.

ABSTRACT: A theoretical investigation is undertaken into the dynamic instability of complete spherical shells which are loaded impulsively and made from a rigid-plastic material. The threshold velocities for the rigid-plastic spherical shells are larger than those for cylindrical shells having the same R/h ratios and material parameters, while the critical mode numbers are similar.

ABSTRACT: A theoretical investigation is undertaken into the dynamic instability of complete spherical shells which are loaded impulsively and made from either linear elastic or elastic-plastic materials. It is shown that certain harmonics grow quickly and cause a shell to exhibit a wrinkled shape which is characterized by a critical mode number. The critical mode numbers are similar for spherical and cylindrical elastic shells having the same R/h ratios and material parameters, but may be larger or smaller in an elastic-plastic spherical shell depending on the values of the various parameters. Threshold velocities are also determined in order to obtain the smallest velocity that a shell can tolerate without excessive deformation. The threshold velocities for the elastic and elastic-plastic spherical shells are larger than those which have been published previously for cylindrical shells having the same R/h ratios and material parameters.

ABSTRACT: An experimental investigation was undertaken into the dynamic plastic buckling of circular rings subjected to uniformly distributed external impulsive velocities. The experimental values of the average final radial deflections, critical mode numbers and dimensions of the permanent wrinkles in the mild steel and aluminum specimens are compared with various theoretical predictions and other experimental results.


ABSTRACT: The advantages and limitations of a perturbation method of analysis for the creep buckling of shells is explored in this note by examining the particular case of a long cylindrical shell subjected to a uniform external pressure. It turns out that the oval deformation mode is the most critical as assumed in previous theoretical investigations. However, other modes can make important contributions to the deformation of a cylindrical shell and can, in fact, dominate the response if important imperfections are present in these harmonics.


ABSTRACT: The creep buckling behavior of a complete spherical shell which is subjected to a uniform external pressure is investigated using a perturbation method of analysis. The spherical shell has an arbitrary initial imperfect shape and is made from a material which creeps according to the generalized Norton's law. It turns out that the critical mode number of the deformed profile is identical to that obtained previously by various authors for the linear elastic instability of complete spherical shells. It also appears that the resistance to creep buckling of complete spherical shells is greater than the resistance of a long cylindrical shell having the same R/h ratio and material properties.

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ABSTRACT: This article contains a brief survey of the literature on the creep buckling of shells published since the second IUTAM Symposium on Creep in Structures held at Gothenburg in 1970. The authors provide further details of their recent numerical study into the creep buckling of spherical shells subjected to external pressures together with some additional results. These numerical results and those of OBRECHT on axially loaded cylindrical shells are used to assess the accuracy of the simple methods of analysis proposed recently by HAYMAN, CHERN, GERDEEN and co-workers.

References listed at the end of the paper:

ABSTRACT: A theoretical analysis of the local buckling of corrugated-core sandwich panels with truss-type (i.e. triangular) corrugations in compression is developed. It has the unusual feature that the nodal lines of the buckling mode are not assumed to be straight and perpendicular to the direction of compression. Such modes are found to correspond to slightly lower buckling stresses than the usual type, for panels with a wide range of geometries. The existence of modes of this type has been observed experimentally.


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ABSTRACT: The postbuckling behavior of simply supported columns with thin-walled open cross section is investigated by means of the general nonlinear theory of elastic stability. Fourth-order terms in the series expansion of the total potential energy are disregarded. It is shown that interaction between linearly independent simultaneous buckling modes is responsible for neutral equilibrium at bifurcation if the column cross section has two axes of symmetry, and unstable if it has only one. If the buckling modes are not simultaneous, the equilibrium is neutral in both cases. Finally, the equilibrium at bifurcation is usually unstable if the cross section has no axis of symmetry.


ABSTRACT: The buckling of an axially loaded cylindrical shell is considered when imperfection components corresponding to all of the classical buckling modes are taken into consideration. The analysis represents an extension of Koiter's axisymmetric solution and in the asymptotic sense due to Koiter the imperfections
considered are as general as possible. The results obtained reveal many interesting aspects of shell buckling which arise for various imperfection forms. The buckling behaviour which results is associated with both bifurcation and limit point critical states.

ABSTRACT: A recent test has provided significant results important for laminate composite shell design. The buckling load of composite shells may be increased substantially through the careful choice of laminate configurations. An increased buckling load capability may be combined without paying a severe penalty with regard to imperfection sensitivity, and the presence of imperfections can cause a change in failure mode from global to local. This characteristic has been observed experimentally and is consistent with analytical predictions.

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“The Dynamic Behaviour of Stiffened Composite Fuselage Shell Structures”, December 1988
ABSTRACT: This report presents an overview of the development of a computer model for analysing the crash response of stiffened composite fuselage structures together with the experimental validation program. Using a finite element formulation based on Reissner/Mindlin plate theories, the numerical model can treat stiffened laminated shell buckling, large deflections, nonlinear material behaviour and element failure. Numerical results are presented for several 'test cases', although experimental comparisons are not yet available. Details on the design and construction of our first prototype composite fuselage model are also provided together with a description of the crash test facility.

ABSTRACT: This paper proposes a technique to optimize structural components for buckling when the applied loads are partially unknown or unpredictable. As opposed to the traditional buckling optimization situation where the loading configuration is specified, the load ratios are assumed uncertain and are incorporated as variables in the optimization problem formulation. As a result, the optimal designs obtained are insensitive to load variations within an admissible convex set. Additionally, in order to generalize the results and therefore provide a systematic solution procedure, a theorem concerning the shape of the stability boundary of structures whose buckling loads are the solution of linear eigenproblems is stated and proven.

ABSTRACT: Optimal elastic buckling loads of composite axisymmetric circular cylinders under uncertain loading conditions are investigated. The mechanical loads applied to the cylinder are a combination of axial compression, lateral pressure, and torsion. Additionally, these loads are allowed to vary within a certain class of admissible loads during the optimization search, as opposed to the restriction of fixed loads in the traditional optimization. The consideration of a degree of uncertainty in the mechanical loads leads to optimal designs which are inherently insensitive to perturbations and/or randomness in the applied loads.

References listed at the end of the paper:
5 Booton, M., 1976, “Buckling of Imperfect Anisotropic Cylinders under Combined Loadings”, UTIAS Report No. 203, University of Toronto, Institute for Aerospace Studies, Downsview, Ontario, Canada.

Alfredo R. de Faria (Instituto Tecnologico de Aeronautica – ITA, Sao Jose dos Campos, SP, Brazil),

ABSTRACT: Crooked beams and plates with arbitrary initial geometric imperfections are optimized in order to improve their prebuckling response in the presence of uncertain loadings. A novel optimization approach is presented to simultaneously handle the two types of uncertainties: arbitrary initial imperfection patterns and arbitrary loadings. A remarkable improvement in the prebuckling response of optimal designs is achieved by reducing the level of prebuckling displacements measured in some appropriate norm, irrespective of the uncertain imperfection pattern or loading. Two different norms are proposed, each one applicable to the beam or to the plate problem. The definitions of appropriate norms allow for the use of a minimax optimization approach that can consider the arbitrariness of both geometric imperfections and loadings. It is shown that the minimax procedure leads to optimum structural designs, in terms of optimal stiffness distribution, that are at the same time insensitive to perturbations in the loading space and to the pattern of initial imperfections in structure.
ABSTRACT: Under operational conditions, some loads acting on a beam are known (deterministic loads), but there usually exist other loads the magnitude and distribution of which are unpredictable (uncertain loads). If the uncertainty in the loading is not taken into account in the design, the likelihood of failure increases. In the present study beams are designed for minimum weight subject to maximum stress and buckling loads, which are unpredictable (uncertain loads). The uncertain load, which is subject to a constraint on its magnitude and uncertainty levels. Results are given for a number of problem parameters including the axial load, elastic foundation modulus and uncertainty levels.

References listed at the end of the paper:

5. de Faria, A.R., 2005, "Solution of buckling eigenproblems through a new variant of the Lanczos algorithm", COBEM 2005 18th International Congress of Mechanical Engineering, 6-11 Nov., Ouro Preto, MG, Brazil
ABSTRACT: The buckling of ring and stringer stiffened cylinders under axial compression, external hydrostatic pressure and combined loading of axial compression with internal or external hydrostatic pressure
was studied. The effect of initial sinusoidal axisymmetric and asymmetric shape imperfections on the reduction of the buckling strength of stiffened cylinders was investigated for varying reinforcement parameters. Calculations were performed by extending Koiter's special theory taking into account nonlinear prebuckling deformations in the form of the shape imperfection, the eccentricity and the bending stiffness of the ring stiffeners. The Donnell-von Kármán shell equations were solved using the Galerkin method. The quantitative effect of asymmetric shape imperfections (in the form of the buckling mode) on reducing the buckling strength of stringer stiffened shells was determined with Hutchinson's Model and experimentally investigated on four stringer stiffened cylinders.


ABSTRACT: In the following paper new variational methods for the solution of problems of postbuckling of elastic plates are formulated, and approximate solutions for various cases are obtained using finite element methods. Initially, the postbuckling problem is phrased as a nonlinear eigenvalue problem. Variational principles for the nonlinear eigenvalue problem of the postbuckling of structures are developed. These variational principles have a form which can be characterized as a nonlinear Rayleigh principle, finite-element models are introduced and are used to implement the postbuckling variational principle. Incremental amplitude solution schemes are developed to solve the corresponding finite-element equations. Sample results are presented for the postbuckling behavior of circular plates.

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ABSTRACT: This paper investigates the effects of boundary conditions and panel width on the axially compressive buckling behavior of unstiffened, isotropic, circular cylindrical panels. Numerical results are presented for eight different sets of boundary conditions along the straight edges of the panels. For all sets of boundary conditions except one (SSI), the results show that the panel buckling loads monotonically approach the complete cylinder buckling load from above as the panel width is increased. Low buckling loads, sometimes less than half the complete cylinder buckling load, are found for simply supported panels with free in-plane edge displacements (SSI). The SSI buckling loads are below the complete cylinder load even for '360° panels'. It is also observed that the prevention of circumferential edge displacement is the most important in-plane boundary condition from the point of view of increasing the buckling load, and that the prevention of edge rotation (i.e. clamping) in the circumferential direction also significantly increases the buckling load. Parametric studies are also performed to determine the effects of variations in panel length and thickness on the buckling loads.

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Buckling of eccentrically stringer-stiffened cylindrical panels under axial compression

ABSTRACT: This paper investigates the effects of boundary conditions and panel width on the axially compressive buckling behavior of eccentrically stringer-stiffened circular cylindrical panels. Numerical results are presented for eight different sets of boundary conditions along the straight edges of the panels. As the panel width is increased, the results show that the complete cylinder buckling load is reached only for one set of boundary conditions (SS3, classical simple support conditions). However, for 180∞ and wider panels, the panel buckling loads are within ± 10% of the complete cylinder load for all cases except SS1 panels (free in-plane edge displacements) with outside stringers. Low buckling loads, as low as half the complete cylinder load, are found for some SS 1 panels. It is also observed that the prevention of circumferential edge displacement is the most important in-plane boundary condition from the point of view of increasing the buckling load, and that the prevention of edge rotation (i.e. clamping) in the circumferential direction is more effective in increasing the buckling loads of panels with free circumferential edge displacement _≈ that it is for panels with _≈ = 0. From stringer-eccentricity studies, it is shown that buckling loads are generally at least 40 _50% higher for the case of outside stringers, and that eccentricity effects are generally similar for clamped and simply supported panels with the same in-plane boundary conditions.


ABSTRACT: This work presents optimum designs for unstiffened, hat stringer-stiffened and honeycomb sandwich cylinders under axial compression. Optimization results for graphite-epoxy cylinders show about a 50 percent weight savings over corresponding optimized aluminum cylinders for a wide loading range. The inclusion of minimum gage considerations results in a significant weight penalty, especially for a lightly loaded cylinder. Effects of employing a smeared stiffener buckling theory in the optimization program are investigated through comparison of results obtained from a more accurate branched shell buckling computer code. It was found that the stiffener cross-sectional deformations, which are usually ignored in smeared stiffener theory, result in about a 30 percent lower buckling load for the graphite-epoxy hat stiffened cylinder.

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ABSTRACT: This paper presents a finite element analysis of the in-plane bending behavior of elastic elbows. Rules and guidelines are presented for the systematic selection of the dimensions of the finite element meshes and for the interpretation of the numerical results. A simple asymptotic formula is presented that gives the dimensions of a so-called “optimum” (or “upper bound”) mesh as a function of the geometry of the elbow. This mesh, along with a companion one, the “lower bound” mesh, serve to establish the basis for the selection of the range of mesh dimensions that are used in the convergence studies of the MARC finite element computations for stresses, displacements and stress intensification and flexibility factors appropriate to a typical FFTF elbow. Reasonable good agreement is found in a comparison of the MARC results with those obtained from the ELBOW computer program, as well as with results predicted by Clark and Reissner's asymptotic formulas.

ABSTRACT: Analytical and experimental results are presented for the axisymmetric plastic buckling of axially compressed cylinders made from strain hardening materials. Buckling loads predicted by two simple bifurcation buckling formulas (simplified analysis) and by the STAGS finite difference computer program (detailed analysis) are compared with buckling loads measured in room temperature tests on Type 304 stainless steel cylinders. The comparison shows that the loads predicted by Gerard’s bifurcation buckling formula agree well with the test results and the STAGS solution. Thus, the present results provide further confirmation that Gerard’s simple formula furnishes a reasonably good approximation to the load carrying capacity of strain hardening cylinders that buckle axisymmetrically at nominal axial stresses equal to or greater than the yield stress.


ABSTRACT: Large amplitude asymmetric vibrations of shells of revolution are analysed in this paper by using a finite element method. Sanders’ non-linear strain displacement relations are used to derive the element stiffness matrix. In the derivation of the mass matrix, the effect of in-plane inertia is included. Three numerical examples are presented to show the reliability and effectiveness of the present finite element formulation.


ABSTRACT: This study was intended to contribute to the development of more rational practical methods for predicting the transient responses of structures which are subjected to transient and impact loads. Attention is restricted to the global structural response; local (or stress-wave-induced) response is not included. The use of higher-order assumed-displacement finite elements (FE) is investigated to seek more efficient and accurate strain predictions; these studies were carried out for 2-d structural deformations typical of beams and curved rings to minimize cost and labor. These studies were done in conjunction with the use of various approximations to the nonlinear strain-displacement relations since large deflections and rotations need to be taken into account. Transient large-deflection elastic-plastic structural response predictions are made for these various FE models for impulsively-loaded beams and a free initially-circular ring, for which high quality experimental measurements of strains and deflections are available. From comparisons of (a) predictions with each other for the various FE models investigated and (b) predictions vs. experimental data, it appears to be more efficient for the same number of degree-of-freedom (DOF) unknowns to use the simple 4 DOF/node elements rather than fewer of the more sophisticated 8 DOF/node elements although the latter provide a physically superior and more realistic distribution of strain along the structural span at any given time instant compared with the use of the 4 DOF/N elements. Comparisons of measured with predicted transient strain and final deformation of a thin aluminum beam with both ends clamped and impacted at midspan by a 1-inch
diameter steel sphere show very good agreement. Extensions to the present analysis to accommodate more general types of fragments and fragment-impacted structures are discussed briefly.


ABSTRACT: This paper discusses computer-aided design procedures for antenna reflector structures and related components. The primary design aid is a computer program that establishes cross sectional sizes of the structural members by an optimality criterion. Alternative types of deflection-dependent objectives can be selected for designs subject to constraints on structure weight. The computer program has a special-purpose formulation to design structures of the type frequently used for antenna construction. These structures, in common with many in other areas of application, are represented by analytical models that employ only the three translational degrees of freedom at each node; The special-purpose construction of the program, however, permits coding and data management simplifications that provide advantages in problem size and execution speed. Size and speed are essentially governed by the requirements of structural analysis and are relatively unaffected by the added requirements of design. Computation times to execute several design/analysis cycles are comparable to the times required by general-purpose programs for a single analysis cycle. Examples in the paper illustrate effective design improvement for structures with several thousand degrees of freedom and within reasonable computing times.


ABSTRACT: This paper describes the combined use of symbolic formula manipulations and numerical computations in the study of the interaction, within the elastic range, of local (plate) and overall (column) buckling of rectangular thin-walled tubular columns. The study is made using the Rayleigh-Ritz procedure. The selection of the analytical expression for the assumed deflected shape has been based on existing solutions for column and plate action considered individually. The minimization of the total energy of the column is performed by the computer using a symbol manipulation package (Macsyma). This minimization yields a set of nonlinear simultaneous algebraic equations which are then solved numerically. The problems encountered in implementing the formal and numerical parts of the computations (as well as their interaction) are discussed in the paper. The results of the computer analysis are presented in the form of diagrams showing the variation of the important generalized coordinates with the applied load.


ABSTRACT: This paper presents a procedure and computer program for the minimum weight design of circular, cylindrical, ‘T’ frame (ring) reinforced, submersible shells where all metal thicknesses may be confined to specified gage thickness values. Using the designer specified parameters defining shell radius shell length, eccentricity, operating depth, design factors of safety, construction materials properties and when used, the specified gage thickness values, the program will generate those values of skin thickness stiffener web and
flange thicknesses, stiffener web depth and flange width, and if desired, stiffener spacing that will produce the smallest shell weight to liquid weight displaced ratio. Experience with the program has demonstrated that there is usually little weight penalty associated with the use of discrete metal thickness values when the stiffener spacing can be optimized. This weight penalty can, however, be significant where the number of stiffeners is held fixed.


ABSTRACT: The new “Direct Search-Feasible Direction” (DSFD) nonlinear mathematical programming optimization algorithm is applied to the design of stiffened submersible shells. An automated design capability for this problem (SBSHL6) is described wherein the program will generate the least weight design by locating the optimal, or near optimal, values of skin thickness, web thickness and height, flange thickness and width, and stiffener spacing given the design parameters such as shell size, immersion pressure, shell eccentricity, materials properties, and minimum natural frequency. Constraint equations control, general, panel (between stiffener), web, and flange instability, skin and stiffener yielding, and minimum natural frequency. The DSFD procedure appears capable of reliably locating optimal designs whereas earlier attempts in investigations using other optimization methods, including the popular SUMT procedure, failed to provide optimal solutions to the same problem. This and an earlier detailed comparison study strongly suggest that SUMT is not a reliable procedure for structural optimization while DSFD seems to provide reasonably reliable performance. Designs generated by SBSHL6 are presented and compared with those of the earlier studies. The results of a series of synthesis runs from widely separated starting points are also presented. The designs developed by SBSHL6 are substantially lighter than those reported earlier. The multipath runs for each set of parameters studied all converged to similar designs of essentially identical weights demonstrating program reliability.

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ABSTRACT: This paper describes an experimental investigation of the buckling behavior of axially-loaded thin open cylindrical shells. The results of experiments with 36 aluminum shell specimens are compared with predictions of buckling made by means of two separate theoretical approaches. Discrepancies between measured and predicted values of buckling load are treated in detail. Generally speaking, the experiments revealed a satisfactory agreement between measured buckling loads and predicted values especially in instances where the slenderness ratio exceeds 1.5.


ABSTRACT: This paper describes a new finite element scheme for the analysis of instability phenomena of arbitrary thin shells. A computationally efficient procedure is proposed for calculating the non-linear stiffness
and tangential stiffness matrices for a doubly-curved quadrilateral element defined by co-ordinate lines. The essential feature is the explicit addition of the non-linear terms into the rigid-body motion of the element. Thus the non-linear and tangential element stiffness matrices can easily be generated by transforming the generalized element stiffness matrix for linear analysis, and the non-linear terms of these matrices are separated into a number of component terms multiplied by the rigid-body rotations. These component terms can be stored permanently and used to calculate efficiently the non-linear and tangential stiffness matrices at each iteration. Illustrative examples are presented which confirm the validity of the present approach in the analysis of instability phenomena of thin plates and shells.


ABSTRACT: A finite element formulation is presented to study the non-linear buckling of arbitrary shallow elastic thin shells with general boundary conditions and subjected to conservative pressure loading. Pre and post buckling behaviour of a large number of shallow and semi deep doubly curved shells is studied in detail. Unsymmetrical bifurcation paths of a shallow spherical shell subjected to uniform inward pressure are also investigated.


ABSTRACT: The choice of strain-displacement relations to formulate curved finite elements for the geometrically nonlinear analysis of deep thin shells of general shape is discussed. It is clearly demonstrated on a simple arch problem how the strain-displacement relations can affect the buckling pressure and it is concluded that inconsistent expressions should be avoided.


ABSTRACT: Detailed experimental studies are performed on the postbuckling behavior of circular cylindrical shells under hydrostatic pressure, by using lap-jointed polyester test cylinders with radius 100 mm, thickness 0.25 mm and lengths ranging from 23 to 165 mm. Connections of the edge shortening and radial displacement with applied pressures as well as wave forms for typical postbuckling configurations are determined for various values of the shell curvature parameter $Z$ ranging from 20 to 1000. It is found that the buckling pressure and the corresponding wave number for each cylinder compare favorably with those theoretically predicted, and that the minimum pressure after buckling decreases with the increase in $Z$, until it becomes about 70 percent of the theoretical buckling pressure for long shells with $Z$ greater than 200.

References listed at the end of the paper:

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“Experiments on the postbuckling behavior of circular cylindrical shells under compression” (Precise experimental results are presented clarifying the whole aspect of the postbuckling behavior of circular cylindrical shells under compression for a wide range of shell geometries), Experimental Mechanics, Vol. 15, No. 1, 1975, pp. 23-28, doi: 10.1007/BF02318521

ABSTRACT: Detailed experimental studies are performed on the postbuckling behavior of circular cylindrical shells under compression, by using polyester test cylinders with the geometric parameter Z ranging from 20 to 1000. In each case, variations of the equilibrium load, circumferential wave number and maximum inward and outward deflections, with applied edge shortenings, are clarified. Contour lines for typical postbuckling configurations are also shown. It is found that, as the cylinder is compressed beyond the primary buckling, secondary bucklings take place successively with diminishing wave numbers, and that postbuckling equilibrium loads become significantly lower than those at buckling as Z increases. Further, for short shells with Z less than or equal to 100, the buckled waveforms are always symmetric with one-tier diamond buckles, while for longer shells, asymmetric postbuckling patterns with two tiers of buckles dominate.

ABSTRACT: Applying the Galerkin procedure to the Donnell basic equations, reasonably accurate solutions are obtained for the postbuckling behavior of clamped circular cylindrical shells under axial compression. To make a distinct comparison with the previous experimental results, calculations are carried out for shells with the same elastic and geometric parameters and the relations between the waveform, axial shortening and maximum deflections with applied loads are clarified. The results here obtained are found to be in reasonable agreement with experimental ones throughout the regions with fairly large deformations.


ABSTRACT: The dynamic von Karman field equations are used to analyse the influence of large amplitude on the free vibrations of shallow cylindrical shells made of orthotropic material and resting on an elastic Winkler foundation. The “snap-through” phenomenon for such shells subjected to a dynamically applied uniform pressure that increases linearly with time is also investigated.


CONCLUSIONS: 1. The number of natural vibration frequencies in any frequency interval for an empty cylindrical shell increases in direct proportion to the second power of the interval size, and for a shell with filler — in direct proportion to the third power of it. 2. The widest (and also located at the smallest frequencies) dynamical instability region of a cylindrical shell with elastic filler corresponds to nonaxisymmetrical modes of wave formation. 3. The limiting transition in the equations of this paper in the case of the frequency of the driving force tending to zero results in an expression for the critical static force for a shell with an incompressible filler. Numerical calculations in this case show, in particular, an increase of the critical force upon an increase in the modulus of elasticity of the filler, which has been noted in a number of the papers of other authors.

References listed at the end of the paper:


ABSTRACT: This paper has two main objectives. First to describe a very simple facet triangular plate and shell finite element called TRUMP which includes, if required, transverse shear deformation and is based on physical lumping ideas with a simple mechanical interpretation [ 1,2,4,5 ]. Second to give an account of some non-trivial numerical examples of large deflection and post-buckling of shells. There are two types of non-linear structural problems which give rise to particularly delicate numerical experimentation. They are those involving deflections of the order of the structural dimensions, such as three-dimensional elastica, and the instability phenomena of the type leading to dynamic snapthrough, e.g. in cylindrical panels. To tackle such problems using a highly sophisticated shell element such as SHEBA is neither easy nor inexpensive. It is shown that the TRUMP element with only 18 displacement and rotation degrees of freedom is relatively economical to use and yet capable of engineering accuracy. The paper makes use of the theory of simplified geometrical stiffness based on the natural mode method which has been described fully in previous publications [1,2].

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ABSTRACT: A review of the most important publications and computer programmes dealing with shell structures is presented. Most of the information is available through open technical publications; however, some of the listings of these programmes may be of a proprietary nature. A brief development of composite shell theory is presented, and an outline of the major methods of solution to the governing equations of motion is included.


ABSTRACT: A perturbation method is presented for the analysis of postbuckling behavior and imperfection sensitivity of elastic structures which have more than one buckling mode. The method is exemplified by analyzing a complete spherical shell under external hydrostatic pressure. For this analysis, use is made of two- and three-mode models of the shell derived earlier from the shallow shell equations.


ABSTRACT: The problem examined in this paper concerns the use of the procedure encountered in the literature that, in investigating instability phenomena of systems with nontrivial prebuckled equilibrium branches, a linearized prebuckling analysis may be employed provided that “buckling” takes place in the small deflection range. In clarifying this problem it will be shown that, although this procedure has been used with reasonable success on symmetrical systems, such an approach may in fact yield totally misleading results when applied to nonsymmetrical systems. The principal tool that will be employed in the investigation of this problem will be the systematic application and analysis of the techniques associated with regular perturbation expansions. Using this approach it will also be shown that there are two possible characteristic equations that one can use to determine critical points of neutral equilibrium; and that by using these two equations, one can immediately determine whether a point of neutral equilibrium is a bifurcation point (generally characterized by sidesway or adjacent path buckling) or a limit point (generally characterized by snap-thru or discontinuous buckling).

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ABSTRACT: An exact analytic expression for the unsteady fluid pressure acting on the internal walls of a simply-supported circular cylindrical tube of finite length, carrying flow, is presented. The generalized force coefficients corresponding to specific modes of deformation are given explicitly. The results are applied to two problems: (1) the interaction of flow and buckling of thin-walled cylindrical shells subjected to lateral pressure and/or end thrust; (2) the aeroelastic stability of the shells. The second problem is aimed at resolving some
controversy about post-divergence flutter oscillation of cylindrical shells or plates exposed to a subsonic flow. The shell equation, of the Morley type, is solved by Galerkin's method and an analytic approach is used to examine the stability of the system. It is important that damping be taken into account in the analysis. The undeformed configuration is always unstable when the flow speed exceeds the minimum divergence boundary.


ABSTRACT: Because of intractable ventricular arrhythmias after a near-fatal episode of ventricular fibrillation, a patient with idiopathic mitral valve prolapse was subjected to mitral valve replacement. Vector analysis and intraoperative epicardial mapping localized the ectopic focus to the region of the posterior papillary muscle. The patient is alive and well two years after surgery; chronically inverted T waves have become upright. But propranolol and diphenylhydantoin are needed to prevent arrhythmias and T wave abnormalities during standing and exercise. Preoperatively, with the onset of mitral regurgitation and a second rapid phase of prolapse, the ventriculogram was deformed by abnormal midsystolic hyperkinesis at both sites of papillary muscle insertion. Postoperatively, focal hypokinesis appeared in the same areas, implying that they had been retracted by the prolapsing valve. Preoperatively, a papillary tip could be seen entering the mitral ring while coronary arteriography showed late systolic elongation of a small vessel feeding the anterior papillary muscle, suggesting that the papillary apparatus was indeed subject to damaging stress during the abnormal basal movement. Three other persons with severe mitral prolapse (but intact chordae) have had valve replacement and developed qualitatively similar changes in the ventriculogram. Papillary specimens in two showed significant fibrosis. Indication for operation in one of these was episodic ventricular fibrillation, which has not recurred. A spectrum of ventriculographic abnormality associated with mitral prolapse could be partly explained by hypokinesis of the papillary loops, variably disguised by retraction stress transmitted from the billowing leaflets, translocation of blood into the expanding valve sail, and various degrees of unloading into the left atrium. Abnormal intraventricular flow may probably result from associated prolapse of the anterior leaflet and from buckling of the papillary sites toward the mitral annulus. Unusual physical findings in the operated cases and in eight other patients define a clinically recognizable syndrome in which severe prolapse abbreviates left ventricular ejection. Liability to symptoms and to progression of disease seems high in this group.


ABSTRACT: A study of the non-linear pre-buckling state and the bifurcation and initial post-buckling behaviour of infinitely long, cylindrical, elastic tubes subjected to bending, pressure and axial loads is presented. The collapse behaviour is analysed by determining both the limit load and the possibility and significance of axial wrinkling of the compressed region of the shell prior to the limit load.


ABSTRACT: The analysis is applicable to bodies of revolution composed of thin shell segments, thick segments and discrete rings. The thin shell segments are discretized by the finite difference energy method and
the thick or solid segments are treated as assemblages of 8-node isoparametric quadrilateral finite elements of revolution. Suitable compatibility conditions are formulated through which these dissimilar segments are joined without introduction of large spurious discontinuity stresses. Plasticity and primary or secondary creep are included. Axisymmetric prebuckling displacements may be moderately large. The nonlinear axisymmetric problem is solved in two nested iteration loops at each load level or time step. In the inner loop the simultaneous nonlinear equations corresponding to a given tangent stiffness are solved by the Newton-Raphson method. In the outer loop the plastic and creep strains and tangent stiffness are calculated by a subincremental procedure. The linear response to nonaxisymmetric loading is obtained by superposition of Fourier harmonics. Many examples are given to demonstrate the scope of the computer program, BOSOR6, derived from the analysis and to illustrate certain stress concentration effects in shell-type structures which cannot adequately be treated with use of thin shell theory.

Y. Frum and M. Baruch (Aeronautical Department, Technion, Haifa, Israel), “Buckling of cylindrical shells heated along two opposite generators combined with axial compression” (Experimental technique developed during a study of buckling under a combination of axial load and heated generators is described, and test results are compared with theory), Experimental Mechanics, Vol. 16, No. 4, 1977, pp. 133-139, doi: 10.1007/BF02321107

ABSTRACT: A series of tests was carried out on clamped cylindrical shells under a combination of thermal and mechanical loads. The shells were linearly heated along two opposite generators in addition to a uniform axial pressure applied before the heating. The paper describes the test setup, equipment and techniques used. Systems for rapid measurement, data analysis and storage designed for the experimental work are presented. As an outcome of this study, a linear-interaction line is proposed in order to express the interaction between thermal and mechanical-buckling loads.

References listed at the end of the paper:
ABSTRACT: Postbuckling behavior and imperfection sensitivity associated with mode interaction in axially stiffened cylindrical shells are studied. The two modes considered are an overall mode compared to stiffener spacing and a short-wavelength panel mode involving buckling between the stiffeners. A restricted optimization study is made where the number of stringers is treated as a design parameter, and the range of designs considered includes the optimum design for the perfect shell, where the two modes are simultaneous. The influence of a given level of imperfections on the optimum is explored. A general method for analyzing initial postbuckling behavior is proposed for structures with simultaneous or nearly simultaneous modes. Asymptotic expansions of all fields in the amplitudes of the competing modes provide a set of uniformly valid results.

ABSTRACT: Tests were performed on two simply supported plates of aluminum alloy 2024-0, under a central concentrated load, with peak deflections up to 2.6 times the thickness. The load was provided by a small-diameter hard-steel rod. The plates had diameter-to-thickness ratios (D/h) of 20 and 41. Measurements were made of load, deflections and strains; membrane and bending strains were calculated from the test data. The test data are presented in comparison with theoretical predictions generated by the Grumman-developed finite-element-computer code PLANS, which includes material and geometric nonlinearities. The theoretical prediction was excellent for deflections, and generally good for strains, when the central force was represented by a line load around the loading rod's contact circle. Using a uniform pressure as the central force caused the theory to slightly overpredict the peak deflections and greatly overpredict the peak strains at the plate center. The plates exhibited initial loss of stiffness under the plastic-bending behavior, followed by a restiffening when the large deflections caused a rapidly increasing membrane action that provided much additional resistance to the applied load.

References listed at the end of the paper:


ABSTRACT: The vibration of cylindrical panels with simply supported boundary conditions in the presence of an initial bending moment is investigated. The analysis is based on the theory of Herrmann and Armenàkas. The results for the stability and free vibration of the panels are obtained as special cases.


SUMMARY: The free vibrations of cylindrical panels with elliptical cross section subjected to an initial stress state are investigated. The buckling problem of the panel under the stress state considered is studied as special case of the free vibration problem.

References listed at the end of the paper:

SUMMARY: The geometry of the middle surface lines of curvature of a thin conical shell, whose cross-section is bounded by a certain closed convex plane curve, is studied. Then, for such a shell, several sets of linear and nonlinear equations of motion are derived in terms of its middle surface orthogonal line-of-curvature coordinate system. As an application of the presented analysis, the free vibration problem of thin circular and elliptical frustums is investigated by means of linear Donnell-type equations of motion. These equations are expressed in terms of the shell middle surface displacement components and they are solved approximately by means of Galerkin's method. Numerical results are presented for frustums with clamped both edges.

References listed at the end of the paper:
ABSTRACT: By employing the finite element displacement method using the tangent stiffness approach, the paper presents results of post-buckling analysis of plates and three-dimensional thin-walled members subjected to uniaxial compressive loads. A simple rectangular element with six degrees of freedom at each node, suitable for the analysis of nonplanar prismatic members with slope discontinuities (folded plates), is employed. Both geometric and material nonlinearities have been considered based on a Lagrangian coordinate system and the flow theory of plasticity. The nonlinear equations are solved using the Newton–Raphson method in the elastic range and the step-by-step method with equilibrium corrections in the plastic range. A modified Cholesky decomposition technique is employed to solve the basic stiffness equations.

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ABSTRACT: A nonlinear finite element computer program has been developed to analyse thin-walled metal structural members. The program has the ability to handle both geometrical and material nonlinearities so that the post-buckling behaviour and ultimate strength of members can be predicted. A bending-membrane rectangular element with six degrees of freedom at each node forms the basic type of element used in the program. Marguerre's shallow shell theory is adopted for the strain-displacement relationships and hence the bifurcation point at buckling can be bypassed by providing an initial imperfection. The finite element formulation is based on the total Lagrange coordinate system and the flow theory of plasticity. Explicitly shown in the paper is the formation of the tangent stiffness matrix and the tridiagonal block form of solution procedure. Two problems of a square tube and a channel section beam subjected to pure bending were tested and found to be in close agreement with previous theoretical work.


ABSTRACT: This technical note indicates alternative applications of the nonlinear programming techniques and the finite element discretization to the limit analysis of shells of revolution. The numerical results are good even though the numbers of degrees-of-freedom used are limited. Both statically and kinematically finite element formulations are general, so extension to more complicated structures is possible. The flexibility and the efficiency of the finite element technique are preserved and combined with the algorithms of nonlinear programming.


ABSTRACT: Over the past few years, fibre-reinforced laminates have been found to be highly desirable for aerospace structural applications. This paper is concerned with one of the problem areas connected with these
applications; namely, the stability of midplane symmetric, laminated composite plates. The results of plate buckling analyses performed by means of the BENST module of the PLANS system of finite element structural analysis programs are presented. These analyses involve a wide variation in laminate orthotropic and material axis orientation and a number of plate aspect ratios and support conditions. The efficacy of the BENST finite element program is demonstrated by comparison with published results. Peak buckling loads for simply supported plates at material axes orientation other than the plate principal axes are predicted for laminate material properties ranging from mildly orthotropic to severely orthotropic. This indicates that the common design practice of calculating simply supported plate buckling levels by applying a ‘knock down’ factor to existing clamped plate data may often be unnecessarily conservative. Also included in this paper are details on the finite element method implemented in BENST and the development of the expressions that permit the calculation of laminate effective material properties from the properties of the individual layers.

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doi: 10.1002/nme.1620120116
ABSTRACT: The visco-plastic model is used in the context of large displacement (geometrically non-linear) analysis. As the process now involves in numerical computation an updating of relevant stiffness matrices, formulation which is stable and computationally more efficient. The applications shown demonstrate the applicability of the process to large displacement elasto-plastic shell analysis as well as to problems of creep buckling.

ABSTRACT: A method is presented for determining the linear critical force of thick-faced sandwich cylinders compressed along the generatrix. Contrary to deductions neglecting transversal shear deformations, critical buckling form of sandwich cylinders under uniform compression along the generatrix is always so-called annular buckling, hence by no means an indeterminate buckling form. Critical forces deduced according to flexural theory assumptions for thin- and thick-faced sandwiches significantly differ: upper bound of the critical force of thin-faced sandwich plates is the effective shear rigidity value of the sandwich, while for thick-faced sandwich structures (with non-negligible flexural rigidity of facings) the critical force may exceed the shear stiffness. An illustrative analogy, useful for practical computations, may be found between the buckling of sandwich cylinders and elastically bedded sandwich beams. In either case, the exact solution of the used mathematical model yields a formula, the same as given by the Bijlaard’s principle which is a known method of stability analysis for estimating the critical force.

References listed at the end of the paper:
4. Hegedüs, I., “Buckling of Sandwich Cylinders with Ring Stiffeners” (in Hungarian), Manuscript. Lecture at the Conference II on Sandwich Construction of the Scientific Society for Machines
ABSTRACT: This paper extends the use of the Semiloof shell element to geometrically and materially nonlinear situations. For the geometrically nonlinear analysis a moving coordinate process is used. Local coordinate systems are considered, one at each integrating point, which move with the structure and allow deformation and rotation within the element to be taken into account. For elasto-plastic analysis the initial stress method is used and the yield conditions are expressed in terms of nondimensional stress resultants. The element formulation is briefly considered and in particular the definition of the global and local displacements and their first and second derivatives in the non-constrained and constrained form of the element are discussed. Numerical results are presented and comparisons made with other sources where available.

DOI: 10.1108/eb023586
ABSTRACT: A generalized displacement method has been previously presented for the analysis of thin plate-shell structures with the use of bilinear 4-node isoparametric shell elements. Following this approach, a procedure for the geometrically non-linear analysis of thin plates and shells based on both updated and total Lagrangian formulations is developed. The results of some numerical examples are presented to show the versatility and effectiveness of the method.

ABSTRACT: The Structural Analysis Program, SAP, has been widely accepted and modified to perform a wide variety of structural analyses at many universities, government and industrial organizations. This paper will document the development of SAP into a user-oriented program for linear dynamic and static analysis of large complex structures which is referred to as FESAP (Finite Element Structural Analysis Program). The paper will also describe companion computer programs which constitute a total design system for thermo-structural analysis. The total system includes mesh generation programs, a heat transfer program, the structural analysis program, batch and interactive graphic computer programs, and post-processors for the results of the heat transfer and structural analysis programs.

ABSTRACT: The purpose of this paper is to look at the analysis of a nuclear reactor system as a total analysis task and to examine the assumptions which are made in the separation of the analysis task into its component disciplines. The structural analysis discipline is then examined in more detail to try to define a workable approach to an integrated structural analysis of the reactor system. We will start with a general discussion of the
total analysis task, starting from the initial concept of the reactor plant. The total task will then be subdivided into the respective disciplines and an attempt will be made to rationalize or criticize the division into separate disciplines. The discipline of structural mechanics will then be examined in view of its interactions with other disciplines such as fluid flow and nuclear analysis to determine the degree of coupling which exists among these disciplines. This will be done by examining the interactions of the state variables which apply at each point of the system. The state variables considered will include fluence, temperature, displacement and pressure. The state variables defined will then be used as the basis for the definition of an overall structural model of the reactor system. Such an overall model can be conceived in terms of the present status of analytical techniques, by the use of such concepts as substructuring, constraint equations, coupled solutions for heat transfer, stress and dynamic analysis, along with fourth generation computer capabilities. A block design for an overall structural model will be discussed and also the areas which require new analysis techniques. The last section will present an outline of a mode of operation of a structural design/analysis activity which is established to implement a comprehensive integrated structural analysis of an entire reactor system. The concept of an evolving model of the system will be presented and the coordination required to successfully manage such a design/analysis approach will be discussed. A brief discussion of the effects of non-linear effects such as creep, plasticity, gaps on the overall approach will be included.


ABSTRACT: This paper is intended to review the present state-of-the-art in computerized structural analysis, to look at the present trends in analysis, and to project these trends over the next 3–5 yr and try to predict the forms which computerized structural analysis will take over the next few years. The various components making up the structural analysis system are examined in some detail followed by an assembly of the present components into the present state-of-the-art system and an attempted assembly of the projected components into a future state-of-the-art system. This projection is the basis for the present hardware and software developments being done at Swanson Analysis Systems, Inc., in conjunction with the ANSYS Computer Program.


PARTIAL INTRODUCTION: The known solutions [3,5,7,10] of the problem of the stability of a toroidal shell have been based on the conversion to a Sturm-Liouville problem. Since the linearization was performed in the neighborhood of the initial zero-moment stressed state, which can be calculated relatively simply, the authors of the papers were able to obtain an analytic solution…


PARTIAL INTRODUCTION: By methods of the theory of perturbations [1-4], upper critical loads have been obtained for nonideal cylindrical shells under transverse and hydrostatic loading. Problems of approximation are studied in particular. When determining the total and ordinal numbers of degrees of freedom, the information about the density of the spectrum of the corresponding linear stability problems is used [5-7]. The band of scatter of the upper critical load is obtained. A numerical experiment allowed the probability
characteristics of the process of stability loss to be calculated. We consider a nonlinear system of equations of the theory of shells which relative to the stress function $F$ and the normal deflection $w$ describes the buckling of ideal thin-walled cylindrical shells under transverse or hydrostatic loading.


PARTIAL INTRODUCTION: The inevitable initial irregularities arising in the construction of structures or the perturbations in loading cause a premature loss of stability (compared with Euler loading) of elastic constructions and are the main reason for the scatter in experimental data. In the present paper a combined (numerical-analytical) approach to the solution of nonlinear boundary problems is expounded, as applied, by way of example, to the study of the buckling of closed ideal cylindrical shells under transverse or hydrostatic loading with perturbations taken into account. Numerical analysis of the buckling process under transverse and hydrostatic loading shows that the process of successive loading of a shell is accompanied by the distortion of the initial section of the critical load spectrum and by the reconstruction of buckling modes.


ABSTRACT: The objectives of the program reported here are to advance lightweight composite shell design technology and evaluate appropriate design and analysis procedures for lightweight composite shells that must satisfy buckling requirements. To accomplish those objectives the primary effort was to design and fabricate a graphite-epoxy cylindrical shell 3.05m (10 ft) in diameter by 3.05m (10 ft) long for evaluation in shell bending tests to be conducted by the Structures and Dynamics Division of the NASA Langley Research Center. Through such tests, the use of advanced composite materials will be evaluated for structural applications in future space missions such as those that involve spacecraft and structural assemblies to be used in geosynchronous missions. Spacecraft for such missions will require ultralightweight structures to achieve maximum payloads. Of equal importance is the requirement to provide designs that are cost-competitive with current structural approaches. For space structures that must resist buckling under compression or shell bending loads, composite materials offer an attractive approach for providing lightweight, low-cost structural components for future spacecraft. In recognition of the potential weight savings available through structural applications of graphite-epoxy materials, an earlier test program (Reference 1) was undertaken by the ASA to provide a technology base for flat, stiffened graphite-epoxy compression panels and to evaluate their effectiveness in reducing structural weight. The panels used in the earlier test program were designed using an advanced version of the analytical methods developed in (Reference 2) Other tests were conducted with stiffened graphite-epoxy shear panels.


CONCLUSIONS: 1. In loading with a force whose value lies between the long-term and instantaneous critical values, a loss of shell stability by rupture takes place at a certain time after loading. This time is naturally taken as the critical one. 2. Numerical estimates show that the level of the initial irregularities has a very great effect
on the magnitude of the critical time. Therefore, in a theoretical estimate of the critical time it is necessary to take account of them as accurately as possible.

References listed at the end of the paper:

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ABSTRACT: A computer program for the analysis of semi-monocoque structures loaded through a rigid bulkhead is presented. A matrix algebra approach is utilized to generate the governing equations. The program is an efficient and valuable tool for the analysis of aircraft structure components in the preliminary design phase.

ABSTRACT: In recent years, there have been many developments in constitutive relations, finite element idealization, and failure criteria. This paper will try to bring out the impact of the various developments from the point of view of the analyst. The paper is somewhat more extensive in creep-fatigue evaluation than in other areas as a result of the fast breeder reactor program. Inelastic fracture, inelastic buckling, and residual stresses due to fabrication processes, are briefly reviewed. An application in each case is discussed, with emphasis on the difficulties requiring additional work.

ABSTRACT: A spherical submarine hull element is analyzed by means of a nonlinear finite-difference program. The imperfection sensitivity of this stiffened shell is greatly dampened by the structural discontinuities introduced through the stiffened portholes. The influence of shape imperfection or geometric manufacturing tolerance is studied by varying the imperfection amplitude and by changing its distribution (different shapes).
Several grades of steel are considered for the present hull structure as well. The analytical results are presented on various graphs visualizing the buckling characteristics of the present structure. Other simplified analytical tools are reviewed with the purpose of serving as a cross-check. Finally, model test results are compared with the finite-difference results.

ABSTRACT: The current status of inelastic structural analysis is reviewed relative to the needs and requirements for design of elevated temperature nuclear reactor components. The classes of inelastic problems that can be solved in a practical way are identified and the overall scope of ongoing validation programs is reviewed. Three classes of problems are identified where the further development of simplified analysis techniques is necessary to make them tractable for design application.

ABSTRACT: This work describes the development of a curved quadrilateral shell finite element which demonstrates very good convergence properties. A general description is used in deriving the element so that it may be applied to any thin shell problem. The element is shown to be very efficient. It has a total of 36 degrees-of-freedom with 9 at each of the corners of the element. There are several distinct advantages that the element offers for practical applications. Most of the shell elements that have been presented in the past are limited to problems in which the coordinates on the shell surface are orthogonal. The element that is described in the paper is derived using a general description so that it may be applied to any thin shell problem including those in which the shell coordinates are not orthogonal. The degrees-of-freedom at each of the four nodes are the three Cartesian displacements and their first derivatives with respect to the two surface coordinates. The imposition of boundary conditions is simplified since each of the degrees-of-freedom can be associated with a quantity which has a simple physical meaning. During the course of the derivation of the element, the strain displacement relationships are derived in a very simple manner consistent with Love's first approximation for thin shells. The derivation in the paper starts from basic principles and should help to shed some light on the proper form for the bending strain. Two primary contributions are presented in this work. The first is the presentation of a procedure for the development of a general quadrilateral shell element. The second is the simple derivation of the bending strain for the thin shells which apparently has not been presented previously.

ABSTRACT: This paper describes the results of collapse tests on two models of longitudinally and circumferentially stiffened leg sections of an offshore platform. Methods of predicting buckling loads are discussed and predicted platform. Methods of predicting buckling loads are discussed and predicted buckling loads are compared with the model test results.

ABSTRACT: The dynamic response of a pressurized plane strain cylinder is investigated in the case of impulsive distributed loading. The investigation is based on a finite element method which accounts for the influence of internal pressure on the effective stiffness and the response history of a pressurized unconstrained cylindrical shell. The numerical results suggest that significant changes in stiffness occur as functions of internal pressure and the ratio of shell radius to thickness. It is noted that a linear superimposition of the results of a membrane state plus those of an unstressed state subjected to identical dynamic loading does not yield the precise state of stress and deformation in a pressurized cylindrical shell under dynamic loading.


ABSTRACT: A general solution procedure, based on the linear theory, is presented for arbitrary shells of revolution subjected to arbitrary axisymmetric dynamic loads. The equations of motion admit shear deformation and rotational inertia. The numerical solution is obtained by Houbolt's method and by finite differences.


ABSTRACT: The discrete energy method—a special form of finite difference energy approach—is presented as a suitable alternative to the finite element method for the large deflection elastic analysis of plates and shallow shells of constant thickness. Strain displacement relations are derived for the calculation of various linear and nonlinear element stiffness matrices for two types of elements into which the structure is discretized for considering separately energy due to extension and bending and energy due to shear and twisting. Large deflection analyses of plates with various edge and loading conditions and of a shallow cylindrical shell are carried out using the proposed method and the results compared with finite element solutions. The computational efforts required are also indicated.


ABSTRACT: Variational equations are derived for thin elastic shells of arbitrary geometry from their related non-linear modal equations. The advantages of this procedure compared to methods commonly used in engineering applications are discussed. Numerical calculations are carried out for a simply supported circular cylinder to obtain the variation of natural frequencies of the cylinder under internal pressure, and its static buckling stress under uniform axial load. A discrepancy between the results of shell theory and those of three-
dimensional elasticity theory is found and discussed.

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ABSTRACT: The stability of the steady state response of simply supported circular cylinders subjected to harmonic excitation is investigated by using variational equations reduced from “exact” non-linear modal equations. The inertia of the unperturbed vibration motion is included as well as the non-linearities in the steady state resonant response. The existence of a new mechanism of parametric excitation is predicted and the conditions by which it develops are discussed. Unstable regions are established on frequency response plots for different shell geometries. Numerical integration results for unstable conditions indicate considerable overloading of the structure and underline the practical significance of this instability mechanism.


ABSTRACT: A finite element method is presented for the analysis of the vibratory characteristics of laminated orthotropic cylinders. The cylinder may have an arbitrary number of bonded elastic orthotropic cylindrical laminates, each with distinct thickness, density and mechanical properties. The formulation is capable of treating a three-dimensional initial stress state which is radially symmetric. Biot's incremental deformation theory is the basis for this study. A homogeneous, isotropic cylinder was analyzed and these numerical results were in excellent agreement with those from an exact analysis. Additional examples of two geometries of a three-layer composite and a sandwich cylinder are given to further illustrate the influence of the initial stress on the physical behavior of such structures.


ABSTRACT: Cylindrical shells, with wall thickness-to-diameter ratios varying in steps from 1:2000 to 1:500 are used in large floating-roof storage tanks, where buckling under partial vacuum is a potential risk. To examine the validity of several methods of analysis, aluminum models with a nominal diameter of 150 mm were tested. Some models exhibited a sudden buckling, at the pressure predicted by one of the methods of analysis, others deformed at increased rate as the critical pressure was approached. A gradual change in, modal-buckling pattern, under decreasing pressure, was also observed.

References listed at the end of the paper:


ABSTRACT: A simplified method of analysis, capable of predicting the buckling pressure of cylindrical shells with varying degrees of end restraint is presented and compared to published results. The case of the free end is given special attention since no complete analytical solution is known to the authors.

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ABSTRACT: Experimental results are interpreted in the light of numerical analysies, imperfection sensitivity and Design Codes. Two cases are discussed: spherical shells under uniform external pressure and partly filled spherical shells, supported on a continuous equatorial ring. The imperfection sensitivity associated with the first loading case leads to the selection of safety factors that depend on the actual shell stiffness. The second case, in which the load results in a biaxial tension-compression state of stress, is treated approximately in terms of a plate under biaxial load.

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“Comparison between analytical, numerical and experimental determination of dynamic buckling in thin cylindrical shells”, Chapter in Computational Mechanics ’88, pp 793-796, 1988

ABSTRACT: The effect of blast loads on cylindrical shells has been studied by means of approximate analytical methods and by numerical analysis, using commercial programs (ABAQUS). Both axisymmetric and lateral loads have been considered. The results are compared to experiments in which shells, made by electro-depositing copper onto disposable wax molds exposed to an external pressure pulse.

References listed at the end of the paper:
2. C. Ruiz, V.K. Thompson, Modelling of thin-walled shells for buckling investigations by electroplating, Experimental Techniques, to be published.
ABSTRACT: The buckling characteristics of shells with double curvature is an important design consideration of such structures. Aircraft structural components are commonly of the double curvature type. Classical elastic buckling of toroidal shell segments with positive and negative Gaussian curvatures under pressure loading is given by Stein and McElmann. A further investigation of elastic toroidal shells, including bowed-out segments subjected to axial tension and a study of the initial post-buckling behavior, is performed by Hutchinson.


ABSTRACT: The post-buckling behaviour of J.W. Hutchinson’s (1973) plastic buckling model is investigated. The aim is to predict, approximately, the load-deflection curve up to the maximum load. Hutchinson's theory for post-bifurcation behaviour of structures usually fails to predict the behaviour up to the maximum load. An alternative approach is formulated in which the construction of an (approximate) equation for the “locus of maxima” plays a central role. The results of this approach are compared with “exact” numerical solutions.

ABSTRACT: A general solution of Bolotin's differential equations for the dynamic stability of a homogenous isotropic medium is given. This takes the form of displacement functions which express the solution as a sum of dilatational and distortional effects. Using these functions, solutions are found for the vibration of cylinders of finite thickness when initial axial stresses are present. The behaviour of solid rods, simple vibration and simple buckling are all seen to be special cases of the general solution. The results are compared with approximate formulae for the buckling of thin cylinders and it is shown that the known solution for the natural frequency of unloaded cylinders is a particular case.

ABSTRACT: This communication presents a relatively simple formula for the prediction of the initial postbuckling behavior (in the sense of Koiter) of hingeless elastic circular arches of uniform crosssection subjected to a uniform external gas pressure. Calculations are performed on the basis of an asymptotic method which contains elements of the techniques of analysis used by Budiansky and Hutchinson, and Chien.


ABSTRACT: The results obtained in this communication characterize the initial postbifurcation behavior of thin elastic rings subjected to a constant-directional and normal uniform external pressure. They complement the calculated postcritical values presented by Budiansky and Sills in previous publications.


ABSTRACT: An asymptotic method based on Koiter's elastic stability theory is presented for geometrically nonlinear structure analysis; these structures are subjected to a proportional applied load system. An approach that makes possible the choice of the modes which are necessary to obtain a good representation of the reduced energy is developed as an iterative process. The approach is transferred into the framework of the finite element method. Applied to the study of thin walled structures through some sample tests, the method gives, at low cost, numerical results which are in good agreement with the preceding studies.


ABSTRACT: The complementary energy approach for stability analysis of elastic structures under conservative loading is based on Fraeijs de Veubeke's variational principle. The associate equations of neutral equilibrium and stability criterium are presented for arbitrarily large deformations and rotations. When specialized to the structural behavior of thin plates in moderate rotations this functional yields the von Karman equations. Efficient mixed flat shell finite elements are derived from this functional. If the fundamental path is moderately nonlinear, the buckling load and the initial postbuckling behavior can be obtained by an iterative process of Rayleigh-Ritz type, which is based on Koiter's asymptotic approach. Development of the iterative method within the complementary energy principle allows improvement of computational effectiveness and of the rate of convergence, as shown by means of numerical examples.

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ABSTRACT: Uemura and Byon (Int. J. Non-Linear Mech. 13, 1–14, 1978) presented experimental results and a numerical analysis about the secondary buckling of clamped flat plates under uniaxial compression. However, their numerical analysis is based upon an inconsistent flat plate finite element and it does not take into account the important influence of antisymmetric imperfections. This paper presents and discusses F.E.M. results obtained by two computer codes using very different approaches, and compares these results with the experimental ones.


ABSTRACT: Plastic buckling analysis of thin shell structures is generally performed by employing a Newton's type method within an incremental approach. This process becomes more efficient if a good estimate of the critical buckling load is available. This one can be obtained as the solution of an eigenvalue problem that generalizes the elastic bifurcation analysis. The stability matrix of the eigenvalue problem involves an additional term with respect to the elastic bifurcation problem; that is the material stiffness matrix that accounts for the change of the tangent modulus along the fundamental path. The proposed approach is applied to the elastoplastic buckling of spherical caps under pressure.

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ABSTRACT: Implicit-explicit finite-element “mesh partitions” are developed for transient problems of nonlinear mechanics. The methods are shown to have improved implementational properties and may be easily coded into many existing implicit computer programs. The stability and accuracy properties of the methods are discussed, and techniques for improving the accuracy in the explicit group, without adversely affecting stability, are described. Implicit-explicit “operator splitting” methods, which enable the efficient treatment of kinematic constraints (e.g. incompressibility) in transient analysis, are also presented.


ABSTRACT: A nonlinear finite element formulation is presented for the three-dimensional quasistatic analysis of shells which accounts for large strain and rotation effects, and accommodates a fairly general class of nonlinear, finite-deformation constitutive equations. Several features of the developments are noteworthy, namely: the extension of the selective integration procedure to the general nonlinear case which, in particular, facilitates the development of a ‘heterosis-type’ nonlinear shell element; the presentation of a nonlinear constitutive algorithm which is ‘incrementally objective’ for large rotation increments, and maintains the zero
normal-stress condition in the rotating stress coordinate system; and a simple treatment of finite-rotational nodal degrees-of-freedom which precludes the appearance of zero-energy in-plane rotational modes. Numerical results indicate the good behavior of the elements studied.


ABSTRACT: A general nonlinear finite element formulation is given for two-dimensional problems. The formulation applies to the practically important cases of shells of revolution, tubes, rings, beams and frames. The approach is deduced from a corresponding three-dimensional formulation [4] and this enables a simplified implementation, especially with respect to constitutive software. Uniform reduced-integration Lagrange elements are employed and shown to be very effective for the class of problems considered.


ABSTRACT: A previously developed nonlinear finite element shell formulation is generalized to accommodate large membrane strains. The formulation is demonstrated on the bending and inflation of a circular plate and the axisymmetric stretching of an annular plate. Both problems are modeled with a Mooney-Rivlin material and involve large membrane strains.


ABSTRACT: The concept of isogeometric analysis is proposed. Basis functions generated from NURBS (Non-Uniform Rational B-Splines) are employed to construct an exact geometric model. For purposes of analysis, the basis is refined and/or its order elevated without changing the geometry or its parameterization. Analogues of finite element h- and p-refinement schemes are presented and a new, more efficient, higher-order concept, k-refinement, is introduced. Refinements are easily implemented and exact geometry is maintained at all levels without the necessity of subsequent communication with a CAD (Computer Aided Design) description. In the context of structural mechanics, it is established that the basis functions are complete with respect to affine transformations, meaning that all rigid body motions and constant strain states are exactly represented. Standard patch tests are likewise satisfied. Numerical examples exhibit optimal rates of convergence for linear elasticity problems and convergence to thin elastic shell solutions. A k-refinement strategy is shown to converge toward monotone solutions for advection–diffusion processes with sharp internal and boundary layers, a very surprising result. It is argued that isogeometric analysis is a viable alternative to standard, polynomial-based, finite element analysis and possesses several advantages.

References listed at the end of the paper:


ABSTRACT: We have extended the subdivision shell elements of Cirak, Ortiz and Schroder [20] to the finite-deformation range. The assumed finite-deformation kinematics allows for finite membrane and thickness stretching, as well as for large deflections and bending strains. The interpolation of the undeformed and deformed surfaces of the shell is accomplished through the use of subdivision surfaces. The resulting ‘subdivision elements’ are strictly C1-conforming, contain three nodes and one single quadrature point per element, and carry displacements at the nodes only. The versatility and good performance of the subdivision

elements is demonstrated with the aid of a number of test cases, including the stretching of a tension strip; the inflation of a spherical shell under internal pressure; the bending and inflation of a circular plate under the action of uniform pressure; and the inflation of square and circular airbags. In particular, the airbag solutions, while exhibiting intricate folding patterns, appear to converge in certain salient features of the solution, which attests to the robustness of the method.

References listed at the end of the paper:
ABSTRACT: This thesis presents the linear and nonlinear analysis of thin shell structures. The linear formulation is based on three finite elements namely the: four nodes degenerated shell element (DE4), the four nodes flat shell element (FE4) and the nine nodes degenerated shell element (DE9). Each one of these elements has six degrees of freedom per node. Additional elements have been developed; these are: the four nodes element, employing the Mixed Interpolation of Tensorial Components approach (MITC) proposed by Bathe to avoid shear locking applied on DE4 and FE4 , the Non-Conforming Element (NCE) to improve the behavior in bending situations, and the nine nodes element with Selective Reduced Integration (SRI) and Weighted Modified Integration (WMI). These elements are used to overcome the shear and membrane lock in lieu of using reduced integration. The verification of linear formulation was based on using patch test. The DE4 element passes all patch tests except the pure bending test, while the other elements pass the tests partially. Further verification was done by using numerical examples; and the elements perform very well when the results are compared with exact ones as they are in good agreement. The problems of shear and membrane locks result in the divergence of the solution for these shells with increase in the number of elements. A solution is proposed to correct the convergence curve to be asymptotic to the exact solution curve by using extrapolation. This was done by selecting a Weibull model to correlate the displacement and mesh size through the number of joints. The model depends on parameters; the values of which depend on the values of displacements before the divergence occurs. Good results are obtained when applying the method in different numerical examples for the DE4 element.

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ABSTRACT: Many of the formulations of current research interest, including isogeometric methods, the extended finite element method, and meshless methods, use nontraditional basis functions. Some, such as subdivision surfaces, may not have convenient analytical representations. The concept of an element, if appropriate at all, no longer coincides with the traditional definition. Developing new software for each new class of basis functions is a large research burden, especially if the problems involve large deformations, nonlinear materials, and contact. The objective of the current research is to separate as much as possible the generation and evaluation of the basis functions from the analysis, resulting in a formulation that can be...
implemented within the traditional structure of a finite element program but that permits the use of reasonably arbitrary sets of basis functions that are defined only through the input file. Examples of this framework to applications with Lagrange elements, isogeometric elements and XFEM basis functions for fracture are presented.

References listed at the end of the paper:
25. Benson DJ, Bazilevs Y, Hsui MC, Hughes TJR, Isogeometric shell analysis: the

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ABSTRACT: A Reissner–Mindlin shell formulation based on a degenerated solid is implemented for NURBS-based isogeometric analysis. The performance of the approach is examined on a set of linear elastic and nonlinear elasto-plastic benchmark examples. The analyses were performed with LS-DYNA, an industrial, general-purpose finite element code, for which a user-defined shell element capability was implemented. This new feature, to be reported on in subsequent work, allows for the use of NURBS and other non-standard discretizations in a sophisticated nonlinear analysis framework.

References listed at the end of the paper:


ABSTRACT: While studies of post-buckling behavior and load-carrying capacities of thin plates subjected to uniaxial compression have been limited to stable conditions, further post-buckling loading generates an unstable condition. The secondary buckling which occurs with snap-through to higher-order deflections under such unstable conditions has not been analyzed in detail as yet. In the first part of this paper, a thin square plate under uniaxial compression, which is simply supported along four edges, is considered. A method based on the second variation of the total potential energy is then proposed for evaluating the stability of the post-buckling equilibrium state and inevitable secondary buckling is derived analytically. The effects of various factors, such as initial imperfections, assumed virtual displacement pattern, post-buckling deflection pattern and in-plane boundary conditions, on the secondary buckling values are discussed. In part 2, secondary buckling of clamped plates is analyzed by use of the finite element method and the resultant numerical results are compared with experimental results.

ABSTRACT: In Part 1, a theoretical analysis was used to study the secondary buckling of a simply supported plate. In Part 2, a clamped plate is analyzed by the finite element method. The stability criterion for a non-linear post-buckling equilibrium state is evaluated by the sign of the determinant of the stiffness matrix. It should be noted that the secondary buckling loads of clamped plates are unexpectedly smaller than those of simply supported plates and are only one and a half times the primary buckling loads. In previous analyses, only a quarter segment of the plate was considered by assuming a stable equilibrium state with symmetrical mode. However, instability can also be predicted by considering the unsymmetrical mode over the whole plate. Results

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of experimental analysis of secondary instability of clamped square plates under uniaxial compression agreed with the numerical results.


ABSTRACT: An investigation of delamination crack growth in a unidirectional composite laminate under static and fatigue loading conditions is presented. An experimental program was conducted to study failure mechanisms and characterize the crack growth rate; analytical modeling based on microscopic observations was carried out using an advanced singular finite element method of the hybrid-stress model. Using a mixed-mode failure criterion, the delamination growth under a monotonically increasing load can be predicted; the rate of delamination crack propagation under fatigue loading is directly related to the amplitudes of cyclic opening and shearing mode stress intensity factors by a power law relationship.


ABSTRACT: (none given)

References listed at the end of the paper:


ABSTRACT: (none given)

References listed at the end of the paper:

ABSTRACT: (none given)

References listed at the end of the paper:


ABSTRACT: The problem of the buckling of a simply supported thin, elastic, cylindrical panel subjected to a uniform axial compression is studied by constructive methods. In the case of “narrow” panels we obtain near the classical buckling load a description of all stable and unstable buckled states which branch from the unbuckled state. The method also yields useful information on the asymptotic form of the buckled states near the bifurcation load, the exchange of stabilities at the bifurcation point, and whether the buckling at the ends of a narrow panel is “inward or outward”.


ABSTRACT: (none given)

References listed at the end of the paper:
ABSTRACT: Secondary buckling and post-secondary-buckling behaviours are theoretically studied for simply-supported rectangular plates, whose primary buckling modes of deflection contain more than half-waves in the load acting direction. Modal coupling effects more complex than one two-term-coupling effects are incorporated into the secondary buckling and post-secondary-buckling analyses. Then, unstable or stable symmetric secondary branching points are found on the post-primary-buckling paths and “snap through” motions involving an abrupt change in wave-form are shown to be possible. Wave-form variations along post-secondary-buckling paths are also disclosed by means of a numerical analysis of equilibrium paths.


ABSTRACT: This paper is concerned with the numerical solution of systems of equations of discrete variables, which represent the nonlinear behaviour of elastic systems under conservative loading conditions. In particular, an incremental approach to the solution of buckling and snapping problems is explored. The topics that are covered can be summarized as follows:—The computation of nonlinear equilibrium paths with continuation through limit points and bifurcation points.—The determination of critical equilibrium states. Characteristic to the procedures employed is the use of the length of the equilibrium path as control parameter. This feature, together with the second order iteration method of Newton, offers a reliable basis for the procedures described. Actual computations, carried out on a finite element model of a shallow circular arch, illustrate the effectiveness of the methods proposed.


ABSTRACT: Riks [1] has recently proposed a new solution procedure for overcoming limit points. To this end, he adds, to the standard equilibrium equations, a constraint equation fixing the length of the incremental load step in load/deflection space. The applied load level becomes an additional variable. The present paper describes a means of modifying Rik's approach so that it is suitable for use with the finite element method. The procedure is applied in conjunction with the modified Newton-Raphson method in both its original and accelerated forms. The resulting techniques not only allow limit points to be passed, but also, improve the convergence characteristics of the unconstrained iterative procedures. Illustrative examples include the large deflection analysis of shallow elastic shells and the collapse analysis of a stiffened steel diaphragm from a box-girder bridge.

References listed at the end of the paper:


ABSTRACT: The redistribution of stresses in ductile structures, although beneficial from the safety viewpoint, introduces another source of uncertainty, which requires specific methods when the probabilistic approach to reliability evaluation is followed. Practicable procedures have been developed for structures that satisfy the classical assumptions of plastic limit analysis. In particular, two theorems that allow to find rigorous upper and
lower bounds on the probability of full plastic collapse under given loads, are presented. Other methods for probabilistic limit analysis are also indicated, including in particular a specifically developed parametric simulation procedure. The last part of the paper is devoted to the reliability analysis of plastic structures subject to loads varying (slowly) in time. It is recalled first that probabilistic limit analysis can be easily extended to the shakedown—incremental collapse problem, provided the loads vary within a finite domain: however, the significance of such an approach for stochastically varying loads is questioned. In fact, as time increases, the probability also increases that the loads cross any given threshold. Therefore, it is more appropriate to speak of “plastic adaption” rather than “shakedown”, and to focus the attention on the probability of reaching, in any given time interval, a certain permanent deformation. Again, only approximate solutions (in the form of upper and lower bounds) can be found to this question, but this appears to be a more rational and promising approach to the problem.


ABSTRACT: The article discusses characteristic types of nonlinearities in structural systems. Various ways of illustrating such nonlinearities are suggested. Mathematical equations that form the basis for alternative numerical solution algorithms are stated. The use of the current stiffness parameter for characterizing nonlinear systems is discussed. Some new formulations and applications of this parameter are suggested. A new class of solution techniques utilizing simultaneous iteration on the loading parameter as well as the displacements is also proposed. By these techniques it is not necessary to formulate a nonlinear stiffness matrix and incrementation of displacement pattern can be used instead of load incrementation. No special load reversal criterion is normally required for passing limit points.


ABSTRACT: The paper compiles the current status of the finite element method in linear and nonlinear buckling analysis of shells. The classical concept via shell theory, the degeneration method, continuum mechanics based and corotationalformulations used in the displacement approach and the corresponding incremental stiffness expression are briefly described. Some comments on the problem of non-uniqueness and stability of the solution and their practical evaluation are given. A classification of displacement dependent pressure loads is presented discussing the symmetry of the problem. The main characteristics of the different classes of shell elements are outlined. Besides flat and curved elements derived from shell theory the survey concentrates on degenerated elements. A detailed review on the main solution strategies in nonlinear shell analyses is presented. Among these are quasi-Newton methods combined with line search and iteration
techniques in the displacement and load space. Finally selected numerical examples are described applying isoparametric degenerated elements to bifurcation buckling and nonlinear collapse analyses of shells.

References listed at the end of the paper:

ABSTRACT: A computer program called STAR (Shell Transient Asymmetric Response) has been developed for the two-dimensional dynamic response of arbitrary shells. The program is based, in part, on Kempner's shell equations which include nonlinear geometric terms. The partial differential equations of motion have been reduced to a set of time-dependent ordinary differential equations by use of two-dimensional finite difference approximations for derivatives with respect to the shell's middle surface coordinates. An explicit numerical integration method is employed for the solution of the ordinary equations.


A.S. Volmir, “The nonlinear dynamics of plates and shells”, Accession Number: AD0781338, Foreign Technology Div Wright-Patterson AFB, OHIO, Report Date: 16 April 1974

ABSTRACT: The book consists of ten chapters. Chapter I contains the fundamental equations of dynamic theory of large-deflection plates and shells. Chapters II-V examine the various types of vibratory motions of plates and shells. Specific problems pertaining to natural and forced vibrations are apparently presented here for the first time. In the section pertaining to self-induced vibrations, principal attention is given to new data on panel flutter. Chapters VI-IX describe the behavior of thin-walled systems under dynamic loading. It includes an analysis of deformation of plates and shells under rapid and very rapid impact loads of different types. Finally, Chapter X presents some problems of shell and plate dynamics requiring a statistical approach.


ABSTRACT: Application of the DSISR program to recessed shells of revolution is illustrated on the examples of a cylinder with two diametrically-opposite rectangular cutouts and a sphere with a single trapezoidal cutout. The program which is suitable for a wide range of static and dynamic problems was developed for general linear analysis of shells of revolution with arbitrary stiffness and mass density distributions. In the analysis, the equations of motion are derived with the aid of Sanders' theory, and the numerical solution procedure is based on Fourier expansion in the circumferential direction, on finite differences in the meridional direction, and on Houbolt's method in the time domain.

Orhan Gürbüz, “Behavior and analysis of steel liners for prestressed concrete reactor vessels”, Ph.D. dissertation, Dept. of Civil Engineering, Iowa State University, 1974

INTRODUCTION: Prestressed Concrete Reactor Vessels (PCRV's) are structures which contain reactor systems directly without any other intervening pressure barrier. As such, they are continually subject to the
pressure of the primary coolant which is usually a gas. The use of gas-cooled PCRV's has found wide acceptance recently. Today, there are about thirty vessels in operation, under construction or, being planned, all over the world. A PCRV is usually cylindrical in shape and consists of five major components: (1) the concrete structure; (2) the post-tensioning system; (3) the nonprestressed reinforcement; (4) the liner assembly; (5) the thermal control system. The subject matter of this thesis is confined to the fourth component; the others will be discussed only to the extent that they affect the behavior of the liner. One of the important problems in PCRV design is the provision for leak-tightness of the vessel. Since the radioactive coolant must be contained within the vessel cavity, the cavity is always lined with a suitable material. In the United States and abroad, steel liners are used as the primary leakage barrier. There are numerous penetrations in a typical PCRV. These penetrations house mechanical equipment and provide access to reactor interior and, are also lined with steel (Fig. 1). The liner assembly consists of the liner plates, closely spaced anchors and, cooling tubes. The liner plate is essentially a thin shell, rigidly connected to the surrounding concrete by means of continuous (e.g., angles, tees) or discreet (e.g., studs) anchors. Cooling tubes are either square or circular in cross section and are usually welded to the concrete side of the liner. The PCRV liner is in biaxial compression throughout most of its design life. The compressive stress field is due mainly to prestressing loads, shrinkage and creep and, thermal loads. Under operating conditions internal pressure reduces the magnitude of the concrete-imposed compressive strains in the liner. But the resultant stresses are still compressive even under the maximum cavity pressure. In the design of liners, the usual approach is to determine the liner thickness and cooling tube spacing (hence anchor spacing, since anchors are provided between the tubes) considering the construction and heat transfer requirements. Design analyses are then conducted to verify that liner assembly stresses and displacements are within the allowable limits under normal operating and accident conditions. For this purpose, the liner structure is considered as a separate entity, independent of the backing concrete but, subject to concrete-imposed strains and displacements. In design analysis, the problem is considered indirectly, as it affects the behavior of individual liner panels between anchor supports. Stress analysis methods for liners were given in papers presented at Conference on Prestressed Concrete Vessels (1, 2, 3, 4) and First and Second International Conference on Structural Mechanics in Reactor Technology (5, 6). In these and other methods, it is customary to analyze a one-dimensional section of the liner assembly under appropriate loading and boundary conditions. A similar approach was taken in the design of the Fort St. Vrain PCRV liner, the only vessel constructed so far in the United States. In all one-dimensional stress analysis methods, the problem is formulated based on equilibrium at the nodes (the liner-anchor, joint) and compatibility between the nodes. Because of material nonlinearity the problem is usually reduced to solving a set of nonlinear simultaneous equations. Local effects which tend to increase unbalanced forces between liner panels and thus increase anchor forces, must also be considered in the analysis. For this purpose a panel which is weaker in compression than other panels (due to causes such as lower yield point, less thickness, existence of lateral pressure, etc.) is usually termed a "weak" panel, the remainder being "strong" panels. Since such local variations may occur anywhere, it is necessary to consider the most critical weak panel location in the stress analysis so that the magnitude of absolute maximum stresses and displacements can be determined and evaluated in the light of code allowances. The Prestressed Concrete Containment Vessels (PCCV's) are also lined, usually with a thin steel liner and thus present similar design problems. One-dimensional stress analysis methods used in the design of PCCV liners were described in Refs. (7, 8, 9). In Ref. (8) a two-dimensional analysis method, for the analysis of a PCCV or PCRV liner cross section perpendicular to the plane of the liner and including a portion of the backing concrete, was also briefly discussed. The stability of liners in a rigid cavity has been investigated by numerous researchers (10, 11, 12, 13, 14). The analytical models used are of two types: (1) ring or flat strips without anchors (10, 11); (2) rectangular panels or curved strips with anchors (12, 13, 14). Analysis of the former models result in minimum buckling strains at which an alternate equilibrium position exists and thus the liner may buckle into that position with an external disturbance.
Buckling may be prevented by providing anchors at a spacing less than the buckled length for a given strain. The latter models give minimum buckling strains and/or anchor stresses for a known anchor spacing. The above summary indicates that, in the design of PCRV and PCCV liners with closely spaced anchors, it is usual to treat the liner analysis as a stress problem. There are procedures proposed, based on a stability approach, for determining an adequate anchoring system for the liners. The PCRV liner stress analysis problem is considered in this dissertation. Specific objectives include:

1) To evaluate the adequacy of one-dimensional stress analysis methods,
2) To present a more refined, and two-dimensional, stress analysis method, and
3) To present an approximate method with which all local effects may be taken into account in design analysis.

As a basis for evaluating the appropriateness of the stress analysis approach, an overview of current liner design practice is presented in Chapter II. Available stability and stress analysis methods are reviewed and, loading conditions and component behavior are briefly discussed. Considering the fact that most PCRV and PCCV liners have been designed on the basis of a one-dimensional analysis, mainly because of the simplicity and conservativeness of these methods, there is a need to evaluate the adequacy of this approach. Since there is no test available, this evaluation is to be based on a comparison with the more refined analysis. For this purpose, a one-dimensional analysis method, similar to Parker's formulation (5) but using a different solution technique was developed first (Chapter III). A more accurate two-dimensional analysis method was developed next using the finite element approach (Chapter IV). Computer programs were written for both methods. Then a parametric study, based on Fort St. Vrain design data, was conducted using selected parameters (Chapter V). There is also a need for a technique with which the effect of all local variations can be taken into account in design analysis. Some local variations can be considered through modification of the weak panel characteristics while others need to be incorporated in the analytical procedure in some manner. Chapter VI summarizes a technique whereby the effects of various local variations may be studied. The characteristics of a weak panel needed in one-dimensional analysis may be developed using the approximate method presented in Appendix A. The findings and conclusions of this study are intended to apply to general PCRV liner stress analysis. The stress analysis methods discussed in Chapters III and IV are also applicable to PCCV liners. However, due to greater anchor spacing-liner thickness ratio of the PCCV liner panels, the approximate method of strut analysis presented in Appendix A may not be applicable to the case of PCCV liners. Furthermore, some of the local variations discussed in Chapter VI simply do not exist for PCCV liners, although the procedure for taking local effects into account should be applicable to both types of liners.

References listed at the end of the dissertation:

ABSTRACT: The response of the rolling tire is formulated in terms of the natural modes and frequencies of the non-contacting tire for contact loading due to rolling, braking, accelerating or cornering. The tire is viewed as an equivalent thin shell. Formulation is by way of the three-dimensional dynamic Green function of this shell. As the application example, the response of the tire during pure rolling is evaluated. The critical rolling speed at which the tire develops its first large amplitude standing waves is calculated in a novel fashion, showing the relationship between the standing wave phenomenon and natural tire modes and frequencies. Findings underline the need for measuring or calculating higher order tire modes than those considered in what seems to be the present standard practice.

DOI: 10.1002/nme.1620110309

ABSTRACT: The paper presents the theoretical and computational procedures which have been applied in the design of a general purpose computer code for static and dynamic response analysis of non-linear structures. A general formulation of the incremental equations of motion for structures undergoing large displacement finite strain deformation is first presented. These equations are based on the Lagrangian frame of reference, in which constitutive models of a variety of types may be introduced. The incremental equations are linearized for computational purposes, and the linearized equations are discretized using isoparametric finite element formulation. Computational techniques, including step-by-step and iterative procedures, for the solution of non-linear equations are discussed, and an acceleration scheme for improving convergence in constant stiffness iteration is reviewed. The equations of motion are integrated using Newmark's generalized operator, and an algorithm with optional iteration is described. A solution strategy defined in terms of a number of solution parameters is implemented in the computer program so that several solution schemes can be obtained by assigning appropriate values to the parameters. The results of analysis of a few non-linear structures are briefly discussed.


ABSTRACT: A formulation and computer program is developed for the geometrically nonlinear dynamic analysis of shells of revolution under symmetric and asymmetric loads. The nonlinear strain energy expression is evaluated using linear functions for all displacements. Five different procedures are examined for solving the equations of equilibrium, with Houbolt’s method proving to be the most suitable. Solutions are presented for the symmetrical and asymmetrical buckling of shallow caps under step pressure loadings and a wide variety of other problems including some highly nonlinear ones.

ABSTRACT: The natural frequencies and mode shapes for the vibrations of stiffened cylindrical shells with, or without, hemispherical end caps are evaluated. The approach utilizes a theory in which the shell elements and the circumferential stiffeners are considered as separate structures and compatibility is enforced at their junctures. The results are compared with those from orthotropic theory in which the stiffener effects are smeared over the shell. Numerical results are presented for frequencies and mode shapes for several cases of interest. The theoretical results have been compared with a set of experimental results from the Ordnance Research Laboratories and excellent agreement has been found. Comparisons of theory and experiment are presented in this paper.

Chang-Hua Yeh (Dept. of Civil Engineering, University of California, Berkeley, USA), “Large deflection dynamic analysis of thin shells using the finite element method”, UCB/SES-970/18, October 1970
ABSTRACT: An analytical procedure is presented for the evaluation of the nonlinear dynamic response of thin shells of arbitrary geometry. Geometric nonlinearity associated with the finite deflections of the structures is considered; the material is assumed to remain elastic throughout the analysis. The nonlinear dynamic response is obtained using a direct step-by-step integration of the equations of motion.

ABSTRACT: The response of an infinitely long elastic cylindrical shell imbedded in an infinite elastic medium and subjected to internal tractions is obtained. Inextensional and extensional motions are determined due to applied tractions given as step functions in time and varying with the angular coordinate. The interaction effect of the shell and medium is determined by means of compatibility conditions which are expressed as a set of coupled integro-differential equations in each mode and are solved numerically by a forward step integration in time. Numerical results are presented for the response in the axisymmetric mode and for higher modes. The response of the shell-medium system is observed to behave as a damped oscillating system whose long time response approaches that of the corresponding static problem.

ABSTRACT: A general step-by-step solution technique is presented for the evaluation of the dynamic response of structural systems with physical and geometrical nonlinearities. The algorithm is stable for all time increments and in the analysis of linear systems introduces a predictable amount of error for a specified time step. Guidelines are given for the selection of the time step size for different types of dynamic loadings. The method can be applied to the static and dynamic analysis of both discrete structural systems and continuous solids idealized as an assemblage of finite elements. Results of several nonlinear analyses are presented and compared with results obtained by other methods and from experiments.

ABSTRACT: Incremental equations of motion are derived from a Lagrangian variational formulation for the large displacement elastic-plastic and elastic-viscoplastic dynamic analysis of deformable bodies. The material constitutive behaviour is described in terms of the symmetric Piola–Kirchhoff stress and Lagrangian strain
tensors. Degenerate isoparametric elements, permitting relaxation of the Kirchhoff–Love hypothesis, are used in a finite element formulation specialized for the analysis of shells of revolution subjected to axisymmetric loading. The linearized incremental equations of motion are solved using direct integration procedures, with added accuracy obtained from application of equilibrium correction at each step. The effectiveness of the numerical techniques is illustrated by the dynamic response analyses carried out on a shallow spherical cap subjected to uniform external step pressure loadings.


ABSTRACT: The results of carefully-controlled small-scale experiments on the elastic buckling of stiffened plates are presented. Overall and local imperfections have been systematically varied to provide detailed curves of imperfection-sensitivity for geometries spanning the range of interaction between Euler and local plate buckling. The interaction of a third mode associated with the torsional buckling of relatively thin stiffeners is also examined. The analysis of a Shanley model is used to suggest a possible engineering approach to the design problem. This approach is based on a proposed application of the well-known Perry formula in which the material yield stress is simply replaced by the relevant local buckling stress, together with the predicted asymptotic approach to a reduced modulus load.

References listed at the end of the paper:


ABSTRACT: This paper gives an up-to-date account of chaos and fractals, in a popular pictorial style for the general scientific reader. A brief historical account covers the development of the subject from Newton’s laws of motion to the astronomy of Poincaré and the weather forecasting of Lorenz. Emphasis is given to the important underlying concepts, embracing the fractal properties of coast-lines and the logistics of population dynamics. A wide variety of applications include: NASA’s discovery and use of zero-fuel chaotic ‘superhighways’ between the planets; erratic chaotic solutions generated by Euler’s method in mathematics; atomic force microscopy; spontaneous pattern formation in chemical and biological systems; impact mechanics
in offshore engineering and the chatter of cutting tools; controlling chaotic heart-beats. Reference is made to a number of interactive simulations and movies accessible on the web.

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“Probing shells against buckling: a non-destructive technique for laboratory testing”, International Journal of Bifurcation & Chaos, in press in October 2017

ABSTRACT: This paper addresses testing of compressed structures, such as shells, that exhibit catastrophic buckling and notorious imperfection sensitivity. The central concept is the probing of a loaded structural specimen by a controlled lateral displacement to gain quantitative insight into its buckling behaviour and to measure the energy barrier against buckling. This can provide design information about a structure’s stiffness and robustness against buckling in terms of energy and force landscapes. Developments in this area are relatively new but have proceeded rapidly with encouraging progress. Recent experimental tests on uniformly compressed spherical shells, and axially loaded cylinders, show excellent agreement with theoretical solutions. The probing technique could be a valuable experimental procedure for testing prototype structures, but before it can be used a range of potential problems must be examined and solved. The probing response is highly nonlinear and a variety of complications can occur. Here, we make a careful assessment of unexpected limit points and bifurcations, that could accompany probing, causing complications and possibly even collapse of a test specimen. First, a limit point in the probe displacement (associated with a cusp instability and fold) can result in dynamic buckling as probing progresses, as demonstrated in the buckling of a spherical shell under volume control. Second, various types of bifurcations which can occur on the probing path which result in the probing response becoming unstable are also discussed. To overcome these problems, we outline the extra controls over the entire structure that may be needed to stabilize the response.

References listed at the end of the paper:

C.P. Ellinas (1), P. Kaoulla (1), S. Kattura (2) and J.G.A. Croll(1)
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DOI: 10.1007/BF02324668

ABSTRACT: Tee-section columns have been tested under conditions that provide a close relationship between the results so obtained and the behavior of certain classes of stiffened plate structures. It is shown that severe imperfection sensitivity arises when the overall column critical load is coincident, or nearly coincident, with the local torsional critical load of the stiffener. And, although the present results are clearly not directly applicable to stiffened plate design, it is suggested that, if these systems are to be designed with even greater material efficiencies than at present, the interactive mechanics observed could acquire increasing design importance.
Accordingly, suggestions are made as to the form of research needed to provide a rational basis for the design of such ‘optimized’ stiffened plate structures.

References listed at the end of the paper:

DOI: 10.1007/978-3-642-50992-6_29

ABSTRACT: Ship hull structures yearly consume in the order of 15 million tons of steel. An appreciable amount of this goes into parts of the structure which are either designed on the basis of buckling criteria or a combination of stress and buckling criteria, or it is included with no other function than that of preventing buckling of the structure. Most of the ship structures consist of a fairly complex system of stiffened plates which are subjected to hydrostatic and dynamic lateral loads as well as in plane stresses which may be both tensile and compressive in a more or less bi-axial fashion. The theoretical buckling strength of stiffened plates in various bi-axial stress fields is of course reasonably well defined. But there are still some problems related to the influence of initial deviations, the corrections for elasto-plastic behaviour, the influence of lateral loading, and the evaluation of “realistic” boundary conditions. Slender unstiffened or lightly stiffened shells have not been typical for ship structures. However, the present developments of LNG-carriers with very thin shell of revolution type tanks have necessitated development of buckling design criteria both for unstiffened spherical shells and for lightly stiffened cylinders. The importance of the relationship between shape imperfection and reduction (knock down) factor is for both types of shells rather obvious. For circular cylinders even light stiffening gives large increases in the theoretical buckling strength. The extent to which this constitutes a real increase is an important factor for the designer. Typical for the cylinders is also that they operate in the elasto-plastic region. For these and for several other important aspects of buckling, design decisions have had and have to be made. Regrettably the basic theoretical and experimental knowledge is uncomfortably sketchy pointing to a need for further basic and design-oriented research.

References listed at the end of the paper:

ABSTRACT: Using the theory for buckling of laminated, anisotropic, thin plates presented by Whitney and Leissa, optimal designs for simply supported rectangular plates, laminated of composite material and subjected to uniaxial compressive loading, are investigated. Numerical results are presented for optimal-design plates laminated of glass/epoxy, boron/epoxy, and carbon/epoxy composite materials.

INTRODUCTION: A major potential advantage claimed for fibrous composite materials in structural applications is that the material can be "tailored" by proper orientation of the fibers in the various layers so as to optimize the desired structural behavior. Yet the very nature of fibrous composites with their anisotropic elastic behavior has kept such optimal tailoring beyond the reach of most design engineers. In comparison to the numerous analyses available in the literature on buckling of anisotropic plates, very few optimal-design syntheses have been published for this problem. In 1960, Gerard (1) gave a synthesis for uniaxially compressed structurally orthotropic plates, but it was devoted only to longitudinally, transversely, or grid stiffened plates. For composite-material plates, Rothwell (2) presented a crude synthesis using netting analysis for the composite layers. Such an analysis completely neglects the contribution of the matrix material and is known to be in considerable disagreement with experimental results for laminated composite-material plates (3). Recently Hayashi (4) synthesized for maximum uniaxial buckling load in both symmetric cross-ply and symmetric angle-ply plates. However, his synthesis was based on the treatment of the number of axial half waves as a continuous rather than discrete variable. The present synthesis considers both symmetric and unsymmetric laminates subjected to uniaxial compressive loading parallel to two of the plate edges.

References listed at the end of the paper:
8. F. WERREN and C. B. NORRIS, Mechanical Properties of a Laminate Designed to be Isotropic, Forest Products Laboratory, Madison, WI, Rept. 1841, 1953.

ABSTRACT: (None given)

Thompson, J. M. T. (1) and Supple, W. J. (2)
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DOI: 10.1016/0022-5096(73)90015-X

ABSTRACT: It is well-known that a straightforward process of structural optimization often demands the simultaneity of two or more failure modes. It has, however, been emphasized by Koiter and others that this can lead to a dangerous situation in which the nonlinear coupling of two quite stable post-buckling modes can generate highly unstable behaviour and associated imperfection-sensitivity. The question then arises as to how the imperfection-sensitivity might invalidate the apparent optimum, and it is a study of the mechanics of this that is presented here. A two-degree-of-freedom buckling model which exhibits this unexpected coupling action is introduced and its primary and secondary branching characteristics are derived analytically and numerically.

The simultaneity of the primary buckling loads is shown to arise as the solution of a simple but realistic optimization scheme, and the subsequent erosion of this optimum is observed. It is seen that the compound imperfection-sensitivity can quite seriously modify and perhaps destroy the apparent optimum solution, and the key role of secondary bifurcations is delineated.

DOI: 10.1002/nme.1620050207

ABSTRACT: A displacement method of matrix analysis for local instability of plates, stiffened panels and thin-walled columns is presented. The analysis is applicable to stiffened panel and columns for which the cross-section is made up of thin flat plates. For these cases it may be assumed that during buckling deformation no flat component of the cross-section is translated in its own plane and the edge lines at the junctions between flats remain fixed in space. The analysis leads to the standard eigenvalue equation from which the buckling stress can be determined. The elastic and geometrical stiffness matrices derived for this analysis depend on the wavelength of the buckled pattern and this dependence is of a simple form since all coefficients in the resulting stiffness matrices contain the buckling wavelength only as a common factor allowing for considerable simplification in any numerical computations. With this new formulation of local instability analysis very few elements are required to obtain high accuracy for the buckling stress. Several examples illustrating typical applications of this new method have been included.


ABSTRACT: When a thin steel plate with flat stiffeners is loaded either axially or in bending it will eventually undergo large deformations in either Mode I or Mode II, where for Mode I the free edges of the stiffeners have only tensile stresses and for Mode II these stresses are predominantly compressive. Thus Mode I is a plate buckle whereas Mode II is a stiffener buckle. Associated with each mode is a plastic mechanism the load-deflexion curve of which defines a panel’s post-buckling behaviour. These mechanisms are analysed
theoretically and then a study is made of the effects of each parameter. Laboratory tests on large stiffened panels are briefly described.

Ralph E. Ekstrom, “Buckling of Cylindrical Shells Under Combined Torsion and Hydrostatic Pressure,” Experimental Mechanics, 3 (8), 192–197 (1963), DOI: 10.1007/BF02325793

ABSTRACT: Tests conducted to determine the stability of thin cylindrical shells under combined loads show that the nondimensional critical hydrostatic and torsional loads, P and T, follow the parabola P+T^2=1.


ABSTRACT: The development of finite element calculational procedures for thin shell instability analysis has involved the definition of appropriate element representations (i.e. the geometric form of the element and the approximation of displacement and/or stress), constitutive expressions, and computational algorithms. Among these, the status of thin shell finite element representations remains unsettled. This paper therefore emphasizes recent developments in the basic aspects of thin shell finite element analysis and discusses one simplified approach in more detail. Formulative and computational procedures for elastic instability analysis are then summarized and numerical results are shown for the simplified shell element formulation.

References listed at the end of the paper:

ABSTRACT: A finite element method is presented for geometrically nonlinear large displacement problems in thin, elastic plates and shells of arbitrary shape and boundary conditions subject to externally applied concentrated or distributed loading. The initially flat plate or curved shell is idealized as an assemblage of flat, triangular plate, finite elements representing both membrane and flexural properties. The 'geometrical' stiffness of the resulting eighteen degree-of-freedom triangular element is derived from a purely geometrical standpoint. This stiffness in conjunction with the standard small displacement 'elastic' stiffness is used in the linear-incremental approach to obtain numerical solutions to the large displacement problem. Only stable equilibrium configurations are considered and engineering strains are assumed to remain small. Four examples are presented to demonstrate the validity and versatility of the method and to point out its deficiencies.

References listed at the end of the dissertation:

ABSTRACT: The paper presents a special form of finite difference scheme for geometricall nonlinear analysis of one and two dimensional problems. The method uses energy principles to derive a set of nonlinear algebraic equations which are solved by using Newton-Raphson iterative procedure. A study of large deflection and stability behaviour of various structural problems is presented, and results are compared with available exact and approximate solutions.

References listed at the end of the paper: (cannot cut and paste)
initial conditions are presented. A comparison of the results with those obtained in previous studies of the problem is presented and the discrepancies are discussed. References listed at the end of the paper:

---End of Early Contributions to the field of shell buckling ---

End of Section 7

Section 8: There follow many, many citations on buckling and vibration of plates and shells. There is no attempt to alphabetize or to
sort by date. I sometimes attempted to group citations by the same author together. In citations with multiple authors I had to choose which author to “group” with other citations in which that author is included. Sometimes that choice is arbitrary. Sometimes I grouped articles on similar subjects together, but not too often.

Ch. Massonnet and R. Maquoi (University of Liege, Belgium), “Recent progress in the field of structural stability of steel structures”, International Association for Bridge and Structural Engineering (IABSE) Surveys, 1978. ABSTRACT: (Cannot cut and paste the abstract nor the long list of references.)


ABSTRACT: This paper represents a progress report of some of the research that we are conducting in the finite element analysis of thin shell structures. We consider our isoparametric displacement-rotation thin shell element and our discrete-Kirchhoff-theory (DKT) plate/shell element, which we are continuously refining for accurate and effective geometric and materially nonlinear analysis. In the paper we briefly discuss the locking phenomenon of the isoparametric element, the use of this element as a transition element between shell surfaces and in shell-solid transitions, and we give some results using the DKT element.

References listed at the end of the paper:
ABSTRACT: Structural technology of laminated filamentary-composite stiffened-panel structures under combined in-plane and lateral loadings is discussed. Attention is focused on (1) methods for analyzing the behavior of these structures under load and for determining appropriate structural proportions for weight efficient configurations, and (2) effects of impact damage and geometric imperfections on structural performance. Recent improvements in buckling analysis involving combined in-plane compression and shear loadings and transverse shear deformations are presented. A computer code is described for proportioning or sizing laminate layers and cross-sectional dimensions, and the code is used to develop structural efficiency data for a variety of configurations, loading conditions, and constraint conditions. Experimental data on buckling of panels under in-plane compression is presented to validate the analysis and sizing methods and to illustrate structural performance and efficiency obtained from representative structures. Experimental results show that strength of panels under in-plane compression can be degraded by low-velocity impact damage. Mechanisms of impact-damage initiation and propagation are described. Finally, data are presented that indicates the matrix is a significant factor influencing tolerance to impact damage.

References listed at the end of the paper:

ABSTRACT: Three computer programs for nonlinear dynamic analysis, ADINA, STAGS and ILDYN, are compared with regard to accuracy of results and computer utilization. However, only two test cases are studied. The results presented in this report must consequently be handled with care. The main parameters of the test cases are: Thin shell structures, Linear elastic material, Non-linear geometric behaviour, Dynamic analysis, Stepwise linear load function, Unconservative pressure load. The analyses are compared to described test case and experimental measurements and show that nonlinear dynamic analyses may be very sensitive to the formulation of the problem.

(The Paper was presented at the 14th Int. Cong. Theoretical and Applied Mechanics, Delft, The Netherlands, 30 August-4 September 1976.)
ABSTRACT: This paper is concerned with the numerical solution of systems of equations of discrete variables, which represent the nonlinear behaviour of elastic systems under conservative loading conditions. In particular, an incremental approach to the solution of buckling and snapping problems is explored. The topics that are covered can be summarized as follows: — The computation of nonlinear equilibrium paths with continuation through limit points and bifurcation points. — The determination of critical equilibrium states. Characteristic to the procedures employed is the use of the length of the equilibrium path as control parameter. This feature, together with the second order iteration method of Newton, offers a reliable basis for the procedures described. Actual computations, carried out on a finite element model of a shallow circular arch, illustrate the effectiveness of the methods proposed.

Dickson, J. N. (1), Cole, R. T. (1) and Wang, J. T. S. (2)
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DOI: 10.1007/978-1-4684-1033-4_17
ABSTRACT: This paper describes an analysis procedure for use in the design of stiffened laminated composite plates loaded simultaneously by biaxial compression, or tension, and shear acting in the plane of the laminate. The magnitude of the loading is such that the initial buckling limit of the laminated plate is exceeded. The method used is an extension of the shear field theory developed by Koiter for long isotropic plates. General expressions are derived which relate the average stress resultants acting along the edges of the plate to the strains in the stiffeners. The laminate is assumed to possess mid-plane symmetry to eliminate bending-
extensional coupling but the bending-twisting terms $D_{16}$ and $D_{26}$ are retained in the analysis. Stresses resulting from thermal mismatch between stiffener elements and between skin and stiffener are considered. In order to account for manufacturing tolerances and other imperfections, initial eccentricities are imposed in the analysis. Also considered a failure mode is torsional or torsional-flexural buckling of the stiffeners, with the effect of attached skin included.

References listed at the end of the paper:


ABSTRACT: For a number of years, the author has used the finite element method to investigate the collapse strength of thin plated steel structures [1–3]. The work has been directed primarily towards steel bridges which are usually fabricated from engineering steel for which the stress-strain curve exhibits a significant plateau. The collapse behaviour usually involves an interaction between material and geometric non-linearities and is influenced by initial geometric imperfections and residual welding stresses. The present communication describes a number of numerical techniques that the author has developed in order to analyse such structures. The topics covered include approximate yield criteria, accelerated iterative methods and incremental solutions using a ‘length constraint’.

References listed at the end of the paper:

ABSTRACT: This paper describes a method for introducing line searches into the arc-length solution procedure. Such line searches may be used at each iteration to calculate an optimum scalar step-length which scales the normal iterative vector. In practice, a loose tolerance is provided so that on many iterations the line searches are avoided. However on ‘difficult iterations’, the line searches are shown to lead to a substantial improvement in the convergence characteristics. A simple single-parameter acceleration is also developed using line search concepts. The new arc-length method is applied to both the geometrically nonlinear analysis of shallow shells and the materially nonlinear analysis of reinforced concrete beams and slabs. Significant improvements are demonstrated in relation to the standard arc-length method.


SUMMARY: Dynamical aspects of a general nonlinear finite element shell analysis procedure are described. The work extends previous endeavors of the authors on quasistatic plate and shell analysis. Several sample problems of a two- and three-dimensional nature are presented which demonstrate the applicability of the methodology.

References listed at the end of the paper:


C.R. Wouters (Department of Continuum Mechanics, Université Libre de Bruxelles, Belgium), “Geometrically non linear 3-D dynamic analysis of shells”, Computers & Structures, Vol. 15, No. 6, pp 667-672, 1982
DOI: 1016/S0045-7949(82)80008-4

ABSTRACT: This paper presents applications of a new code for shells of arbitrary shape. The geometrically non linear dynamic analysis is based on a total Lagrangian formulation and the direct time integration of the equations of motion. The cost effectiveness of a static condensation is shown and comparison of numerical
results for classical examples of the literature (plates, arches and spherical shells) are presented using a full 3-D code.


ABSTRACT: Pipelines are widely used for the transport of material. While pressure is the dominant sustained design load with gaseous materials, the weight of the contents becomes important with liquid transport and hydraulic solids transport.

References listed at the end of the paper:


INTRODUCTION: In order to produce efficient, reliable designs & to avoid unexpected catastrophic failure of structures of which thin shells are important components, the engineer must understand the physics of shell buckling. The objective of this survey is to convey to the reader a “feel” for shell buckling, whether it be due to nonlinear collapse, bifurcation buckling, or a combination of these modes. This intuitive understanding of instability is communicated by a large number of examples involving practical shell structures which may be
stiffened, segmented, or branched & which have complex wall constructions. With such intuitive knowledge the engineer will have an improved ability to foresee situations in which buckling might occur & to modify a design to avoid it. He or she will be able to set up more appropriate models for tests & analytical predictions. The emphasis here is not on the development of equations for the prediction of instability. For such material the reader is referred to the book by Brush & Almroth. Emphasis is given here to nonlinear behavior caused by a combination of large deflections & plasticity. Also illustrated are stress redistribution effects, stiffener & load-path eccentricity effects, local v. general instability, imperfection sensitivity, & modal interaction in optimized structures. Scattered throughout the text are tips on modeling for computerized analysis. The survey is divided into nine major sections describing: 1) several examples of catastrophic failure of expensive shell structures; 2) the basics of buckling behavior; 3) “classical” buckling & imperfection sensitivity & nonlinear collapse & the appropriateness of linear bifurcation buckling analyses for general shells; 5) bifurcation buckling with significant nonlinear pre-buckling behavior; 6) effects of boundary conditions, load eccentricity, transverse shear deformation, & stable post-buckling behavior; 7) optimization of buckling-critical structures with consequent modal interaction; 8) a suggested design method for axially compressed cylinders with stiffeners, internal pressure, or other special characteristics; & 9) two examples in which sophisticated buckling analyses are required in order to derive improved designs. The paper focuses on static buckling problems.

References listed at the end of that paper:
135 Hoff, N. J. and Soong, T. C., "Buckling of Circular Cylindrical Shells in Axial Compression," SUDAER Rept. 204, Stanford,


ABSTRACT: Coverage has been given to subjects dealing with the strength and stability of columns, including biaxially loaded members and tubular components. Much information is still lacking about laterally unsupported beams, and detailed research needs are outlined for these as well as for steel building frames. A separate section discusses unresolved problems in the stability analysis of shells and shell-like structures, some of which also are pertinent to large-size tubular structures. The research needs of thin-walled, light-gage construction are discussed in one section. Extensive attention is paid to the stability aspects of plate, box and curved girders. Problems related to dynamic stability phenomena are outlined, as are the needs of composite structures. Brief data are given on needed research regarding material properties of steels, local buckling phenomena, and the behavior of stiffened plates.

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ABSTRACT: The paper presents a finite element Mindlin shallow shell formulation. Compared to a previous flat plate formulation it is shown that the addition of a shallow shell capability adds very little extra computational effort. Results are given for the postbuckling behaviour of square and circular plates subject to direct inplane loading and a square plate subject to inplane shear loading. Examples are also presented of the analyses of a shallow truss and cylindrical and spherical shells, all exhibiting snap through behaviour. Agreement with existing solutions is generally good and where possible the results are presented numerically.

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ABSTRACT: A brief survey of weld-induced stresses and deflections in steel-plated structures is given. A finite element approach for analyzing stiffened panels is presented. The stiffener formulation accounts for torsional buckling. Yielding is taken into account and, based on the updated Lagrangian formulation, the effect of large deflections is allowed for. By using the so-called volume approach the development of plastic zones can be followed. The non-linear equations are solved using a combined step-iterative procedure. The examples presented comprise an unstiffened rectangular plate under biaxial compression, and two stiffened panels under uniaxial compression. The effect of initial deflections and stresses is considered.


ABSTRACT: In this paper nonlinear stability of thin elastic circular shallow spherical shell under the action of uniform edge moment is considered by the modified iteration method to obtain second and third approximations to decide the upper and lower critical loads. Results are plotted in curves for the engineering use and are
compared with results of Hu Hai-chang. We also investigate the neighbor situation of the critical point, i.e. the double points of the upper and lower critical loads and denote the range of validity of the second approximation. In the end, we obtain the special case, the design formulas of rigidity and stress as well as the corresponding curves as \( \nu = 0.3 \) of large deflection of circular plate under the same load. These results are also compared with Huang Tse-yen’s.


ABSTRACT: Definitions of plastic and elastic deformation are discussed which are directly related to the physical characteristics of the phenomena and which provide essential uncoupling of elastic and plastic variables. Using finite deformation kinematics and appropriate strain-rate variables in order to carry out total incremental theory, analysis is presented concerning the fact that the total strain rate is not equal to the sum of elastic and plastic rates as is universally assumed. The consequences of this circumstance are examined. It is shown that a conflicting approach to the finite-deformation kinematics of elastic-plastic theory by Nemat-Nasser[4], which generates summable elastic and plastic strain rates, exhibits undesirable features and in particular the associated kinetics does not permit completion of the objective of developing an elastic-plastic constitutive relation on this basis.


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ABSTRACT: The article contains a summary description of ABAQUS, a finite element program designed for general use in nonlinear as well as linear structural problems, in the context of its application to nuclear structural integrity analysis. The article begins with a discussion of the design criteria and methods upon which the code development has been based. The engineering modelling capabilities currently implemented in the program - elements, constitutive models and analysis procedures - are then described. Finally, a few demonstration examples are presented, to illustrate some of the program's features that are of interest in structural integrity analysis associated with nuclear power plants.


ABSTRACT: This paper investigates the general instability of cylindrical shells in which the stiffeners formed spirals along the length and at an arbitrary angle with the axis. Two loading conditions are considered: uniform axial and lateral compressions and torsion. The stress-strain relations of the stiffeners are developed by rotation
of the strain tensor. The buckling determiate is obtained by introducing into the equilibrium equations the
admissible displacement functions consistent with the end constraints, thereby enforcing equilibrium by
satisfying the characteristic equations. The buckling equations are programmed for a computer which searches
through a finite set of stress resultants for assigned values of spiral angle and modes and printed out the
buckling load. The optimum structure weight of the stiffened shell is determined by iterating the design
parameters at the required spiral angle so that the buckling load approaches the applied load as a limit until the
difference between these loads are within the design allowance.

No. 7, pp 662-667, July 1990
ABSTRACT: (none given)
References listed at the end of the paper:
8. Yen Shao-Wen, “Buckling of cylindrical shells with spiral stiffeners under uniform compression and torsion,” Comput. Struct.,11,
No. 6, 587–595 (1980).

Wolfgang Zerna and Ihsan Mungan (Wissenschaftlicher Angestellter, Ruhr-Universitat Bochum, Institut fur
Konstruktiven Ingenieurbau, Bochum, West Germany), “Construction and Design of Large Cooling Towers”,
ABSTRACT: Large natural-draft cooling towers are required for dry-type cooling of power plants having high
capacity. Through the choice of an appropriate offset distance between the axis of the hyperbola and axis of
rotation the stress distribution as well as buckling and vibration behavior can be influenced considerably. In
order to keep the required buckling safety and lowest natural frequency as the dimensions of the cooling tower
shell are increased stiffening of the shell becomes indispensable. Numerical investigations and tests carried out
show clearly that the efficiency of the stiffeners is different, rings being more effective than meridional ribs.
Stiffening rings can be built easily after slight modification of the existing climbing formwork. Reinforced
concrete shells stiffened by rings can compete with cable network structures, even beyond a height of 200 m
(656 ft).

A.M. Vinogradov and Peter G. Glockner (Dept. of Mech. Engrg., Univ. of Calgary, Calgary, Alberta, Canada),
“Buckling of Spherical Viscoelastic Shells”, ASCE Journal of the Structural Division, Vol. 106, No. 1, January
1980, pp. 59-67
ABSTRACT: The creep buckling of thin nonshallow spherical shells is treated, the material of which is
assumed to be isotropic and linearly viscoelastic with special temperature dependence of its mechanical
properties so as to fit the thermorheologically simple body model. The shell is subjected to uniform external
pressure smaller than the classical buckling pressure for corresponding elastic shells. The prebuckling stress
state is assumed to be the membrane state, and total deflections are less than or equal to the shell thickness. The classical stability criteria, uniqueness of equilibrium, is used in formulating the problem, defined by a linear integrodifferential equation in terms of displacement field \( W \), and describing the adjacent equilibrium configuration, and it is assumed to be a function of coordinates and time. A first-step approximation to the governing equation is derived and used to determine the external critical pressure loading as a function of temperature, time, and shell geometry. For a shell made of a three-element model material a “safe load limit” is established.


ABSTRACT: A theoretical and experimental study was undertaken into the crushing behavior of axially compressed short thin-walled open-section columns. The effect of initial geometry of panels as well as distribution and magnitude of shape imperfections on the efficiency of energy absorption was examined. Results of model test on 0.1mm thick aluminum foil specimens have shown that the panels collapsing in the symmetric and asymmetric deformation mode provide respectively, upper and lower bound for the energy absorbed in any other buckling mode. In both of the extreme cases, the crush response of the panel was predicted theoretically with a reasonable accuracy. It is shown that an optimum design of columns against crush can be achieved by introducing a beneficial geometric imperfections of a specified magnitude shape so that the structure will be forced to collapse in the most energy efficient deformation mode.


ABSTRACT: (none given)

References:


ABSTRACT: In this paper, basing on ref. [1] we improved and extended that which is concerned with a view of investigating the finite deflection equations of anisotropic laminated shallow shells subjected to static loads, dynamic loads and thermal loads. We have considered the most general bending-stretching couplings and the shear deformations in the thickness direction, and derived the equilibrium equations, boundary conditions and initial conditions. The differential equations expressed in terms of generalized displacements \( u_0, v_0 \) and \( w \) are obtained. From them, we could solve the problems of stress analysis, deformation, stability and vibration. For some commonly encountered cases, we derived the simplified equations and methods.

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ABSTRACT: A creep buckling analysis of cross-ply symmetric laminated cylindrical panels is given in this paper. By means of theoretical analysis, a method to determine the critical load of creep buckling of the panels with simply supported boundary conditions is obtained.

References listed at the end of the paper:

Kuang-Han Chu (1), B.P. Jain (2) and T.L. Wang (1)
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(2) Sargent & Lundy, Chicago, Illinois, USA


ABSTRACT:


ABSTRACT: A nonlinear formulation of the 9-node shell element is given for large deformation and post-buckling analysis of shells. The formulation is based on updated Lagrangian description and finite deformation constitutive equations. The post-buckling analysis is conducted via either the modified or full Newton-Raphson procedure with a constant-displacement-length method when the limit load of the structure is reached. Several numerical examples are included to demonstrate the post-buckling analysis procedure.


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(2) Faculty of Engineering, Hiroshima University, Higashihiroshima, Hiroshima 724, Japan
ABSTRACT: A theoretical investigation into the effectiveness of a stiffener against the ultimate strength of a stiffened plate is carried out. Series of the buckling analyses, the elastic large deflection analyses and the elastic-plastic large deflection analyses are performed by the analytical method and the finite element method on the stiffened plate under thrust. Experiments are also carried out on the stiffened plate under thrust to confirm the theoretical results. On buckling of a stiffened plate, it is well known that there exists a minimum stiffness ratio of a stiffener to the plate, $\lambda_{B\text{min}}$, which gives the maximum limiting value of the buckling strength. Concerning the ultimate strength it was confirmed that there exists a significant stiffness ratio of a stiffener to the plate, $\lambda_{U\text{min}}$, similar to $\lambda_{B\text{min}}$ for the buckling strength. It was also found that there are three typical collapse modes for the stiffened plate under thrust, that is: (1) MODE OO, overall collapse after overall buckling; (2) MODE LO, overall collapse after local buckling; (3) MODE LL, local collapse after local buckling. Approximatelmethods are proposed to evaluate the ultimate strength and $\lambda_{U\text{min}}$ of a multi-stiffened plate under thrust. The effects of initial imperfections such as welding residual stresses and initial deflection on ultimate strength and $\lambda_{U\text{min}}$ of a stiffened plate under thrust are also discussed.


ABSTRACT: We derive a generalized version of the known system of two simultaneous second order differential equations for the problem of axi-symmetric torsionless deformations of elastic shells of revolution, for finite deformations and including transverse shear deformations and membrane drilling moments. Our generalization, which involves the introduction of a semicomplementary energy density, comes out in a particularly simple and compact form. We furthermore consider the effect of transverse normal stress deformations and discover the possibility of reducing this problem to a system of three simultaneous second order equations, with the supplementary third equation harmoniously adding itself to the two equations without consideration of transverse normal stress deformation effects.


ABSTRACT: The analysis of pipework systems which operate in an environment where local inelastic strains are evident is one of the most demanding problems facing the stress analyst in the nuclear field. The spatial complexity of even the most modest system makes a detailed analysis using finite element techniques beyond the scope of current computer technology. For this reason the emphasis has been on simplified methods. It is the aim of this paper to provide a reasonably complete, state-of-the-art review of inelastic pipework analysis methods and to attempt to highlight areas where reliable information is lacking and further work is needed.


ABSTRACT: Using a thin shell theory developed by Reissner, a nonlinear model for the in-plane bending of a curved pipe is described. It is shown how classical thin shell models of this component can be deduced on
making certain simplifying assumptions concerning the mode of deformation. By way of a numerical nonlinear analysis the problem of Brazier buckling of the curved pipe in pure bending is examined and compared to previous simplified solutions.


ABSTRACT: Advances in the understanding of vibration and buckling behavior of laminated plates made of filamentary composite material are summarized in this survey paper. Depending upon the number of laminae and their orientation, vibration and buckling analyses of composite plates may be treated with: (7) orthotropic theory, (2) anisotropic theory, or (3) more complicated, general theory involving coupling between bending and stretching of the plate. The emphasis of the present overview is upon the last. Special consideration is given to the complicating effects of: inplane initial stresses, large amplitude (nonlinear) transverse displacements, shear deformation, rotary inertia, effects of surrounding media, inplane nonhomogeneity and variable thickness. Nonclassical buckling considerations such as initial imperfections are included, as well as postbuckling behavior.

References listed at the end of the paper:


90. Meffert, D., Berek, H., and Menges, G., Stress deformation behavior of orthotropic plates with initial curvature made of glass fiber-reinforced unsaturated polyester plastics (GFUP) under uniaxial load in the plane of the plate (in German), Bauingenieur, 52 (1977) 211–16.

ABSTRACT: There is considerable confusion in the existing literature as to whether an unsymmetrically laminated, composite plate will remain flat due to the application of inplane compressive or shear loads. If it does not remain flat, then bifurcation buckling would not normally take place, and transverse displacements would occur no matter how small the inplane loads. This paper investigates the conditions under which arbitrarily laminated and arbitrarily loaded plates remain flat, and therefore when buckling can occur. It is demonstrated that for uniform or linearly varying inplane loads no transverse pressure is necessary to keep a plate flat, although edge moments or transverse forces may be required at the boundaries.


ABSTRACT: Some information on the buckling of composite laminated plates is summarized. Loading stresses for buckling orthotropic plate are plotted. Orthotropic plates have fibers parallel to each other and to the edge or a cross ply with fibers in adjacent plies oriented at 90 to each other. Anisotropic and unsymmetric laminate instability are also reviewed. Uniaxial and shear stress buckling parameters for graphite/epoxy angle ply plates are shown in graphs. Test data show that shear deformation effects decrease the buckling stress for plates with a length to thickness ratio of < 30. The buckling characteristic of circular shell panels differs considerably from that of plates. The buckling load increases with the shell curvature, until a maximum value is reached. Data show that, although a shell panel has a higher critical buckling stress than the plate, a decreasing compressive stress is required to maintain equilibrium.

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ABSTRACT: A method is developed for the analysis of free vibration and buckling of generally laminated composite plates having arbitrary edge conditions, such as clamped, simply supported or free. The procedure is an extension of the Ritz method utilizing a strain energy functional containing both bending and stretching effects and accommodating arbitrary ply stacking sequences. Displacement functions are taken in the form of polynomials, and an algorithm for satisfying the geometric boundary conditions is presented. Numerical results are compared with those of other researchers in order to establish the correctness and effectiveness of the method. Some additional new results are also presented.


ABSTRACT: The ‘reduced bending stiffness’ (RBS) method has been used on occasions in the past as a means of simplifying the analysis of the flexural behavior of unsymmetrically laminated composite plates. However, the validity of the method has never been established. This paper makes direct comparisons between relatively simple, exact solutions for the static deflections, buckling loads and vibration frequencies of simply-supported
plates and those arising from the RBS method. Extensive calculations are made for wide ranges of the physical parameters involved (aspect ratio, moduli ratio, lamination orientation angle, numbers of plies). The RBS method is found to yield sufficient accuracy for cross-ply plates, but errors up to 29% are obtained for angle-ply plates constructed with materials currently under development.

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ABSTRACT: This is a summary of the first known work which analyzes the structural behavior of composite plates having nonuniformly spaced fibers. The present investigation is limited to single layer composites having parallel fibers. This results in a plate which is macroscopically orthotropic, but nonhomogeneous. The free vibrations and buckling of such plates subjected to inplane boundary loadings are studied. A plane elasticity problem must first be solved to determine the inplane stresses caused by the applied boundary loading, and these stresses become input to the vibration and buckling problem. Both problems are dealt with by the Ritz method. Numerical results are obtained for six nonuniform distributions of E-glass, graphite and boron fibers in epoxy matrices in simply supported, square plates. The redistributions are seen to increase the buckling load by as much as 38%, and the fundamental frequency by as much as 21%.

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(2) Department of Engineering Mechanics, The Ohio State University, Columbus, OH, USA
ABSTRACT: The effects of changing edge constraints upon the frequencies of shallow shells with rectangular planforms are studied. Attention is focused upon a single edge, with the other three edges remaining completely free. For that edge clamped, simply supported, and free edge conditions are imposed; however, each of these has four possibilities depending upon the existence of either or both types of membrane constraint along the single edge. The Ritz method, assuming algebraic polynomials as displacement functions, is used to obtain accurate results. Frequencies for three types of shallow shells (circular cylindrical, spherical, hyperbolic paraboloidal) are obtained, for two shallowness ratios and two thickness ratios each. Careful attention is paid to the number of rigid body modes (zero frequencies) present, for these enter quite strongly into considerations of the effects of changing edge constraints.

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ABSTRACT: This work presents a three-dimensional (3-D) method of analysis for determining the free vibration frequencies and corresponding mode shapes of truncated hollow cones of arbitrary thickness and having arbitrary boundary conditions. It also supplies the first known numerical results from 3-D analysis for
such problems. The analysis is based upon the Ritz method. The vibration modes are separated into their
Fourier components in terms of the circumferential coordinate. For each Fourier component, displacements are
expressed as algebraic polynomials in the thickness and slant length coordinates. These polynomials satisfy the
geometric boundary conditions exactly. Because the displacement functions are mathematically complete, upper
bound values of the vibration frequencies are obtained that are as close to the exact values as desired. This
convergence is demonstrated for a representative truncated hollow cone configuration where six-digit exactitude
in the frequencies is achieved. The method is then used to obtain accurate and extensive frequencies for two sets
of completely free, truncated hollow cones, one set consisting of thick conical shells and the other being tori
having square-generating cross sections. Frequencies are presented for combinations of two values of apex
angles and two values of inner hole radius ratios for each set of problems.

A. W. Leissa and J. -D. Chang (Department of Engineering Mechanics, The Ohio State University, Columbus,
OH 43210, USA), “Elastic deformation of thick, laminated composite shells”, Composite Structures, Vol. 35,

ABSTRACT: A rigorous theory is derived which governs the linearly elastic deformation of shells made of
laminated composite materials, including shear deformation and rotary inertia effects. The equations presented
are applicable to static and dynamic problems for shells of arbitrary curvature, but constant thickness. Non-
principal shell coordinates (alpha,beta) are used in order that shells with initial twist (Ralphabeta not equal to
infinity) may be straightforwardly accommodated. Equations of motion, boundary conditions and energy
functionals are given for laminates with arbitrary fiber stacking sequences. An accurate theory is developed
based upon the assumptions that terms containing zeta2/RiRj(i,j = alpha,beta) are small in comparison with
unity, where zeta is the thickness coordinate, and Ralpha and Rbeta are radii of curvature. A more simple but
less accurate theory is also given, corresponding to zeta/Ri much less-than 1 (i = alpha,beta). Shallow shell
theories are obtained by setting the LamÈ parameters equal to unity and using projected planform coordinates
(x,y) in place of the shell coordinates (alpha,beta). Further simplification to a Donnell-type shallow shell theory
is also made.

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ABSTRACT: A three-dimensional method of analysis is presented for determining the free vibration
frequencies and mode shapes of hollow cones and cylinders with variable thickness. Displacement components
us, uz, and utheta in the meridional, normal, and circumferential directions, respectively, are taken to be
sinusoidal in time, periodic in theta, and algebraic polynomials in the s and z directions. Potential (strain) and
kinetic energies of the cones and cylinders are formulated, and upper bound values of the frequencies are
obtained by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to
the exact values. Novel numerical results are presented for thick, linearly tapered, hollow cones and cylinders
with completely free boundaries. Convergence to four-digit exactitude is demonstrated for the first five
frequencies of the cones and cylinders. The method is applicable to thin cones and cylinders, as well as thick
and very thick ones.
ABSTRACT: This paper describes three types of situations in structural analysis where singularities at points can greatly influence the global behavior of the configuration: (1) concentrated forces acting upon flat or curved membranes, (2) concentrated moments acting upon plates or shells, and (3) sharp corner singularities in plates and shells. These singularities may have strong effects upon static or dynamic deflections, free vibration frequencies and buckling loads. It is shown that the concentrated forces acting upon flat or curved membranes, or concentrated moments acting upon plates and shells, are improper models, and that correct theoretical analysis indicates that they are meaningless. Examples of sharp corners discussed are (1) the re-entrant corner of a cantilever skew plate, (2) a free circular plate with a V-notch, and (3) the obtuse corners of a simply supported parallelogram plate.

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(2) Department of Mechanical Engineering, Colorado State University, Fort Collins, CO, USA
ABSTRACT: A three-dimensional (3-D) method of analysis is presented for determining the free vibration frequencies and mode shapes of thick, hyperboloidal shells of revolution. Unlike conventional shell theories, which are mathematically two-dimensional (2-D), the present method is based upon the 3-D dynamic equations of elasticity. Displacement components ur, utheta, and uz in the radial, circumferential, and axial directions, respectively, are taken to be sinusoidal in time, periodic in theta, and algebraic polynomials in the r and z directions. Potential (strain) and kinetic energies of the hyperboloidal shells are formulated, and the Ritz method is used to solve the eigenvalue problem, thus yielding upper bound values of the frequencies by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the hyperboloidal shells of revolution. Numerical results are tabulated for 18 configurations of completely free hyperboloidal shells of revolution having two different shell thickness ratios, three variant axis ratios, and three types of shell height ratios. Poisson's ratio (nu) is fixed at 0.3. Comparisons are made among the frequencies for these hyperboloidal shells and ones which are cylindrical or nearly cylindrical (small meridional curvature). The method is applicable to thin hyperboloidal shells, as well as thick and very thick ones.

ABSTRACT: Rayleigh's classical book Theory of Sound was first published in 1877. In it are many examples of calculating fundamental natural frequencies of free vibration of continuum systems (strings, bars, beams, membranes, plates) by assuming the mode shape, and setting the maximum values of potential and kinetic energy in a cycle of motion equal to each other. This procedure is well known as "Rayleigh's Method." In 1908, Ritz laid out his famous method for determining frequencies and mode shapes, choosing multiple admissible displacement functions, and minimizing a functional involving both potential and kinetic energies. He then
demonstrated it in detail in 1909 for the completely free square plate. In 1911, Rayleigh wrote a paper congratulating Ritz on his work, but stating that he himself had used Ritz's method in many places in his book and in another publication. Subsequently, hundreds of research articles and many books have appeared which use the method, some calling it the “Ritz method” and others the “Rayleigh–Ritz method.” The present article examines the method in detail, as Ritz presented it, and as Rayleigh claimed to have used it. It concludes that, although Rayleigh did solve a few problems which involved minimization of a frequency, these solutions were not by the straightforward, direct method presented by Ritz and used subsequently by others. Therefore, Rayleigh's name should not be attached to the method.

ABSTRACT: A parametric study of postbuckled through-width delaminations in laminated coupons was performed. A finite element analysis was developed to analyze the coupons as a combination of linear and geometrically nonlinear components. Because most of the coupon configuration studied behaves linearly, the mixed linear and nonlinear analysis greatly reduced computational costs. The analysis was verified by comparing numerical with exact solutions for simple hypothetical problems. In addition, measured lateral deflections of postbuckled through-width delaminations in laminated coupons were compared with predicted deflections. In the parametric study, stress distributions and strain-energy release rates were calculated for various delamination lengths, delamination depths, applied loads, and lateral deflections. Also, a small number of coupons with through-width delaminations were fatigue tested to obtain delamination growth data. Calculated strain-energy release rates were compared with the observed growth rates to determine the relative importance of the Mode I and Mode II components of energy release. GI was shown to dominate the growth process.

ABSTRACT: Buckling of a delaminated region can cause high interlaminar stresses which, in turn, lead to delamination growth. Hence, buckling strain is an important parameter in assessing the potential for strength loss due to the delamination. The objective of this study was to predict the buckling of an elliptic delamination embedded near the surface of a thick quasi-isotropic laminate. The thickness of the delaminated ply group (the sublaminate) was assumed to be small compared to the total laminate thickness. Finite-element and Rayleigh-Ritz methods were used for the analyses. The Rayleigh-Ritz method was found to be simple, inexpensive, and accurate, except for highly anisotropic delaminated regions. Effects of delamination shape and orientation, material anisotropy, and layup on buckling strains were examined. Results showed that (1) the stress state around the delaminated region is biaxial, which may lead to buckling when the laminate is loaded in tension, (2) buckling strains for multi-directional fiber sublaminates generally are bounded by those for the 0 deg and 90 deg unidirectional sublaminates, and (3) the direction of elongation of the sublaminate that has the lowest buckling strain correlates with the delamination growth direction.

ABSTRACT: In order to formulate the equations for the study here, the Fourier expansions upon the system of orthonormal polynomials are used. It may be considerably convenient to obtain the expressions of displacements as well as stresses directly from the solutions. Based on the principle of virtual work the equilibrium equations of various orders are formulated. In particular, the system of thirddorder is given in detail, thus providing the reference for accuracy analysis of lower-order equations. A theorem about the differentiation of Legendre series term by term is proved as the basis of mathematical analysis. Therefore the functions used are specified and the analysis rendered is no longer a formal one. The analysis will show that the Kirchhoff-Love's theory is merely of the first-order and the theory which includes the transverse deformation but keeps the normal straight is essentially of the first order, too.

References listed at the end of the paper:

ABSTRACT: Computer costs for structural dynamics, rise an order of magnitude over those associated with static analysis. To reduce these costs significantly, a computationally economical triangular plate bending element was developed. This element, designated as the TRP2 element, while simpler than existing high-order accuracy elements, yields results that are sufficiently accurate for engineering analysis. TRP2 is an eighteen degree of freedom triangle. In global coordinates it possesses three translations and three rotations at each vertex. The element linear elastic stiffness matrix was taken from the existing literature. Additional matrices were developed to account for mass properties, applied loads, large deflections and plasticity. Published results that ranged over a spectrum of linear and nonlinear static and dynamic analyses were used in a numerical evaluation of the element. The TRP2 element was found to be capable of yielding results that in most cases were certainly acceptable, and in some cases excellent.


ABSTRACT: The theory of finite rotations in thin shells is developed and many shell relations in terms of finite rotations are presented. Three forms of geometric boundary conditions and energetically compatible static boundary conditions are constructed. Various sets of Eulerian and Lagrangean shell equations are discussed and their consistent simplification within the first-approximation geometrically non-linear theory of isotropic elastic shells is given. A classification of shell problems with small, moderate, large and finite rotations is proposed and appropriate sets of simplified shell equations are presented.

References listed at the end of the paper:
7. Pietraszkiewicz, W., Obroty skonczone i opis Lagrange’a w nieliniowej teorii powłok, Rozprawa habilitacyjna, Biuletyn Instytutu Maszyn Przepływowych PAN, 172(880), Gdansk, 1976.

ABSTRACT: A general approach to the derivation of variational principles is given for the geometrically non-linear theory of thin elastic shells undergoing moderate rotations. Starting from the principle of virtual displacements, a set of sixteen basic free functionals without subsidiary conditions is constructed. From these free functionals and without subsidiary conditions may be generated. As examples, the functionals of the total potential energy and the total complementary energy are derived.

Emmerling, Springer, 1984, pp 76-90, DOI: 10.1007/978-3-642-48013-3_6

ABSTRACT: The present paper deals with geometrically non-linear first approximation Kirchhoff-Love type theories for thin elastic shells undergoing small strains accompanied by moderate, large or unrestricted rotations. All theories will be given in an entirely Lagrangian description. We shall start our considerations with a general theory valid for small strains and arbitrary, unrestricted rotations. Then, this general theory will be simplified for shell problems in which the shell material elements undergo large rotations according to the classification scheme given below. Three variants will be derived which admit large rotations about tangents to the shell middle surface and either large, moderate or small rotations about the normal. Finally, the general shell equations will be simplified for shells undergoing moderate rotations about tangents to the shell middle surface and either moderate or small rotations about the normal. All theories presented here are derivable from variational principles.

References listed at the end of the paper:

ABSTRACT: Equations of equilibrium and four geometric and static boundary conditions are constructed for an entirely Lagrangian non-linear theory of shells. In the case of a linearly-elastic material and conservative surface and boundary loadings the shell relations are derivable as stationarity conditions of the Hu-Washizu free functional. For the geometrically non-linear first-approximation theory of elastic shells several consistently simplified versions of the shell equations are discussed. Several sets of equations for theories of shells undergoing moderate or large/small rotations are presented. The majority of the simplified versions allow an exact variational formulation using a Hu-Washizu free functional. A unified theory of superposition of non-linear deformations in thin shells is outlined and two equivalent incremental formulations of shell equations in the total Lagrangian and the updated Lagrangian descriptions are given.


ABSTRACT: A non-linear bending theory of rubber-like shells undergoing large elastic strains is proposed. The theory is based on a relaxed normality hypothesis and the incompressibility condition. Using series expansion in the normal direction and applying some estimation technique a consistent first approximation and a simplest approximation to the elastic strain energy of the shell are constructed. Lagrangian displacement shell equations are derived and the incremental shell deformation is considered. The numerical results presented for one- and two-dimensional large strain shell problems confirm the accuracy and efficiency of the proposed shell theory.


ABSTRACT: Non-linear problems of thin elastic shells may conveniently be formulated in the Lagrangian description in terms of three displacement components of the reference surface. Assuming that an approximation to an equilibrium state of the shell is known, the explicit form of incremental equations for the correcting increment of displacements, which allows one to calculate the next approximation, is derived for arbitrary configuration-dependent external static loads, and for arbitrary work-conjugate boundary conditions. The derivation is performed applying the Newton-Kantorovich method which is based essentially on successive approximations to the exact solution of some linearized shell problem. As a special case, the ultimate Lagrangian buckling equations for thin shells are constructed.

ABSTRACT: A thorough analysis is presented of the non-linear deformation of the shell lateral boundary surface. The deformation is compatible with the linear distribution of displacements across the shell thickness. It is found that the total rotation of the boundary element can be defined in two ways, by means of two alternative orthonormal triads associated with the deformed shell lateral boundary surface. For both definitions of the rotation, exact expressions for three components of the vector of change of curvature of the boundary contour are derived in terms of shell strain measures. These expressions are then consistently reduced for several particular shell theories.


ABSTRACT: The non-linear theory of thin shell structures with irregularities of geometry, material properties, loading and deformation is developed. The irregular shell is modelled by a reference network being a union of piecewise smooth surfaces and curves, with various fields satisfying relaxed regularity requirements. By transforming the virtual work principle postulated for the entire reference network, we derive the corresponding local field equations and side conditions. Particular attention is paid to formulate the general form of static and kinematic jump conditions at singular geometric and physical curves. Several special kinds of irregularities are considered and some particular forms of the jump conditions are discussed.


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ABSTRACT: We develop the general nonlinear theory of elastic shells with an account of phase transitions in the shell material. Our formulation is based on the dynamically and kinematically exact through-the-thickness reduction of three-dimensional description of the phenomenon to the two-dimensional form written on the shell base surface. In this model shell displacements are expressed by work-averaged translations and rotations of the shell cross-sections. All shell relations are then found from the variational principle of the stationary total potential energy. In particular, we derive the new global dynamic continuity condition at the singular surface curve modelling the phase interface. We also discuss particular forms of the local dynamic continuity conditions at coherent and incoherent interface curves. The results are illustrated by an example of a phase transition in an infinite plate with a circular hole.

References listed at the end of the paper:
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ABSTRACT: We establish the local symmetry group of the dynamically and kinematically exact theory of elastic shells. The group consists of an ordered triple of tensors which make the shell strain energy density invariant under change of the reference placement. Definitions of the fluid shell, the solid shell, and the membrane shell are introduced in terms of members of the symmetry group. Within solid shells we discuss in more detail the isotropic, hemitropic, and orthotropic shells and corresponding invariant properties of the strain energy density. For the physically linear shells, when the density becomes a quadratic function of the shell strain and bending tensors, reduced representations of the density are established for orthotropic, cubic-symmetric, and isotropic shells. The reduced representations contain much less independent material constants to be found from experiments.


ABSTRACT: We formulate the exact, resultant equilibrium conditions for the non-linear theory of branching and self-intersecting shells. The conditions are derived by performing direct through-the-thickness integration in the global equilibrium conditions of continuum mechanics. At each regular internal and boundary point of the base surface our exact, local equilibrium equations and dynamic boundary conditions are equivalent, as expected, to the ones known in the literature. As the new equilibrium relations we derive the exact, resultant dynamic continuity conditions along the singular surface curve modelling the branching and self-intersection as well as the dynamic conditions at singular points of the surface boundary. All the results do not depend on the size of shell thicknesses, internal through-the-thickness shell structure, material properties, and are valid for an arbitrary deformation of the shell material elements.

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“On shear correction factors in the non-linear theory of elastic shells”, International Journal of Solids and
ABSTRACT: Theoretical values of two correction factors \( \pm s = 5/6 \) and \( \pm t = 7/10 \) are established for the respective transverse shear stress resultants and stress couples within the general, dynamically and kinematically exact, six-field theory of elastic shells. These values do not depend on the shell material symmetry, geometry of the base surface, the shell thickness, or any kind of kinematic and/or dynamic constraints. The analysis is based on the complementary energy density following from the transverse shear stresses acting only on the shell cross section. The appropriate quadratic and cubic distributions of the stresses across the thickness allow one to derive the consistent constitutive equations for the transverse shear stress resultants and stress couples with \( \pm s \) and \( \pm t \) as the respective correction factors. Four numerical examples of highly non-linear shell structures illustrate the influence of different values of \( \pm s \) and \( \pm t \) on the results. In particular, some influence of \( \pm t \) is noticed on the placement of bifurcation points. In dynamic problem of flight of three intersecting plates analysed with Newmark-type temporal algorithm, the value of \( \pm t \) influences the moment at which the relative error of total energy of the system begins to grow indefinitely leading to the solution failure.


ABSTRACT: We formulate the complete boundary value problem (BVP) for the geometrically non-linear theory of thin elastic shells expressed entirely in terms of intrinsic field variables—the stress resultants and bendings of the shell reference surface. Applying a perturbation technique the corresponding intrinsic buckling equations are also derived. These intrinsic shell and buckling equations are then consistently simplified in three special cases: (a) the almost inextensional bending state, (b) the almost membrane state, and (c) the bending state. For each special case we derive also consistent sets of dynamic and kinematic boundary conditions expressed entirely through the intrinsic field variables. Additionally, the complete BVP for shells with slowly varying curvatures is formulated in terms of stress and deformation functions. The relatively simple BVPs given here are applicable to highly non-linear problems of flexible shell structures without any restriction of shell geometry, displacements, deflections, and/or rotations.

References listed at the end of the paper:

ABSTRACT: The local buckling of weakly supported thin-walled square tubes under axial compression is studied. By means of asymptotic methods, an expression for the critical pressure is found. The asymptotic results agree well with the numerical results obtained with the finite element method (FEM) and with the sweep method. The dependence of the critical loading on the shell length and on the type of edge supporting is analyzed.


ABSTRACT: Work–conjugate boundary conditions for a class of nonlinear theories of thin shells formulated in terms of displacements of the reference surface are discussed. Applying theorems of the theory of differential forms it is shown that many of the sets of static boundary conditions which have been proposed in the literature do not possess work–conjugate geometric counterparts. The general form of four geometric boundary conditions and their work–conjugate static boundary conditions is constructed and three particular cases are analyzed. The boundary conditions given here are valid for unrestricted displacements, rotations, strains and/or changes of curvatures of the reference surface.

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“Lagrangian nonlinear theory of thin elastic shells with finite rotations”, Proc. of JSCE, No. 344/I-1, April 1984

ABSTRACT: Accurate equilibrium equations and appropriate static and geometric boundary conditions are derived for the geometrically nonlinear theory of shells undergoing finite rotations without restriction to small strains. The principle of virtual work is used to obtain the shell equations in which a nonrational tensor of change of curvature is employed. The introduction of variations of displacement vectors instead of those of displacement components makes it possible to reduce computational efforts for deriving the shell equations. The effects of finite rotations at the shell boundary are strictly taken into account utilizing the total finite rotation vector for the boundary.


ABSTRACT: A nonlinear theory of plates and shells based on only one consistent kinematical approximation is employed to investigate finite strain and large deformation structural problems. The kinematics, expanded with respect to the thickness parameter, include consistently and adequately higher-order terms to allow fibers initially straight to deform nonlinearly in the large deformation range. A full Lagrangean formulation is
considered. Starting from a three-dimensional principle of virtual work, the equilibrium equations and the resultant stresses of the shell together with their incremental form are derived employing an incremental constitutive relation valid for a wide class of rate-independent material. And, to assess the accuracy of the theory adopted, some boundary value problems are solved using a proposed hyperelastic material to model the constitutive behavior of a semi-infinite plate. The analytical and numerical (finite element method) results show good agreements between the exact and the approximate theories.


ABSTRACT: Buckling of axially compressed circular cylindrical shells is examined within the framework of small strain elastoplasticity. A linear bifurcation model is used along with the J2 flow and deformation theories. All four possibilities of simple supports (SS1–SS4) and clamped edges (CL1–CL4) are considered. A general solution is given with special emphasis on the axially symmetric modes. Numerical results show that the weakening effect of the relaxed simple supports (SS1–SS2) is considerably reduced in the plastic range. A detailed comparison with available experimental data points in favour of the deformation theory.


ABSTRACT: We review the geometric rod theory for the case of a naturally straight, linearly elastic, inextensible, circular rod suffering bending and torsion but no shear. Our primary focus is on the post-buckling behaviour of such rods when subjected to end moment and tension. Although this is a classic problem with an extensive literature, dating back to Kirchhoff, the usual approach tends to neglect the physical interpretation of solutions (i.e., rod configurations) to the models proposed. Here, we explicitly compute geometrical properties of buckled rods. In a unified approach, making use of Kirchhoff's dynamic analogy, both the classical helical and the more recently investigated localised buckling are considered. Special attention is given to a consistent treatment of concepts of link, twist and writhe.

References listed at the end of the paper:


ABSTRACT: For an archetypal two-degree-of-freedom forced oscillator, relevant to a large class of mechanical problems, we examine the patterns of bifurcation that govern the internal 1:2 resonance of the system. A knowledge of these bifurcations allows the counter-intuitive suppression and control of escape by internal modal interactions. The bifurcations examined include symmetry-breaking pitchforks, Neimark bifurcations (secondary Hopf bifurcations) to a toroidal attractor, and chaotic crises which trigger dangerous large-amplitude excursions. We particularly focus on the effect that a symmetry-breaking imperfection has on the suppression of escape.

ABSTRACT: An experimental study was conducted to investigate the use of advanced composite materials in unstiffened thin-walled cylindrical structures subjected to hydrostatic pressure. Specifically, graphite/epoxy was looked at for potential application for small submersible pressure hulls. The investigation concentrated on the fabrication, instrumentation, testing, and evaluation of several 12-ply graphite/epoxy cylinders of four different laminate configurations. The test specimens were 18 inches long with radii of 2.76 inches, and each was instrumented with 8 circumferentially and 2 axially mounted strain gages. Data collected from the strain gages throughout the tests were used in a modified Southwell type analysis and an analysis to deduce the buckling mode shape. The Southwell analysis method was shown to have a valid applicability to the buckling of laminated fiber-reinforced composite pressure vessels. A method was developed to use the bending strain data at locations around the centerline of the specimen to deduce the number of, circumferential buckling waves. In addition, 1/2 inch ring specimen were cut from the excess ends of each specimen and tested under two-point compression, yielding information about the material properties of the laminates as fabricated. The hydrostatic tests were designed to verify the results of an analytical and numerical study that was conducted to determine the optimal laminate stacking sequences for buckling considerations. The test results indicate that the classical solution method presented by R.M. Jones produced accurate predictions of buckling strengths and correct relative rankings of the different laminate types.

References listed at the end of the thesis:

ABSTRACT: Many useful thin-walled structures of interest to the U.S. Army, such as rifle barrels, automotive parts, rocket casings, helicopter blades, driveshafts, and containment vessels, are often constructed of layers of anisotropic, filament or fiber-reinforced materials. While many of these structures are subject to severe mechanical, inertial, or thermal loads, they often must be designed to remain elastic. This means that it is particularly important to be able to compute accurately global characteristics, such as buckling loads and natural frequencies, as well as local information such as stresses near holes or edges. Two important, complementary regions of such structures, have been studied, namely, the interior where there are no steep stress gradients, and the edge zone(s) where stress gradients are high. For both regions, simplified, cost-effective asymptotic methods have been developed. These considerations are particularly important in layered, anisotropic structures because many investigators have (1) claimed that higher-order (and hence computationally expensive) beam, plate, or shell theories are needed for such structures and (2) not paid sufficient attention to the particularly severe end effects (breakdown of Saint-Venant's principle) such structures engender. (DTIC)


ABSTRACT: Analyses to predict inelastic buckling of axially loaded thin cylindrical shells are carried out using the finite element technique. The analyses use a bilinear elastic–perfectly plastic material response based upon the associated flow rule of plasticity. Nonlinear geometric effects, combined with initial imperfections, produce load-deflection curves with descending branches for which the limit points are imperfection sensitive. Results from these analyses are compared with two tests of axially loaded cylinders fabricated from 10-gauge (3.4-mm) and 5-mm plate and approximately 1525 mm in diameter. These tests were carried out in the Structural Engineering Laboratory at the University of Alberta. A rational technique for using measured imperfections to obtain effective initial imperfections for use in the analyses is investigated, and is shown to result in accurate predictions of ultimate load.
ABSTRACT: A general sinusoidal stiffness matrix for the buckling analysis of thin, prismatic flat-walled elastic-plastic structures is derived. The constitutive laws of the flow-theory of plasticity associated with smooth yield surfaces are used. The use of this stiffness matrix to predict the buckling stresses and the associated modes is illustrated and some numerical results are used to show the range of applications which can be covered.

References listed at the end of the paper:


ABSTRACT: The paper sketches aspects of nonlinear response and instability behavior of general shell structures, loaded time-invariantly. Starting from their basic mechanical formulations suitable finite element algorithms lead to the computation of highly nonlinear phenomena. Unity of theoretical and numerical concepts is emphasized for a successful tackling.

References listed at the end of the paper:
ABSTRACT: An experimental program to determine the phenomenological aspects of composite-panel failure under simultaneous compressive in-plane loading and low-velocity transverse impact [0-75 m/s (0-250 ft/s)] is described. High-speed photography coupled with the shadow-moiré technique is used to record the phenomenon of failure propagation. The information gained from these records, supplemented by plate sectioning and observation for interior damage, has provided information regarding the failure-propagation mechanism. The results show that the failure process can be divided roughly into two phases. In the first phase the plate is impacted, and the resulting response causes interlaminar separation. In the second phase the local damage spreads to the undamaged portion of the plate through a combination of laminae buckling and further delamination.

References listed at the end of the paper:


ABSTRACT: The effect of the use of the ‘area replacement method’ (ARM) of reinforcing around circular penetrations in a cylindrical shell on the buckling strength of that shell under a uniform axial compressive loading condition is studied both experimentally and analytically. In shells that are of such quality that the penetration reduces the buckling strength, the use of the ARM will increase the buckling strength of the shell, but will not increase it to the unpenetrated value. In any case, the conservative ‘knockdown’ factors suggested for buckling design by the ASME Boiler and Pressure Vessel Code should ensure an adequate margin to failure under this loading condition.

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ABSTRACT: Six steel shells having nuclear containment like features were fabricated and loaded to failure with an offset axial load. The shells (R/t = 500) buckled plastically. Four of the shells had reinforced circular cutouts. These penetrations were sized to cut no ring-stiffener, a single, two- or three-ring stiffeners. Reinforcing and framing around the penetrations were based upon the area-replacement rule of the applicable portion of the ASME Boiler and Pressure Vessel Code and were of a design to simulate actual practice for nuclear steel containments. Prior to testing, imperfections were measured and strain gages were applied to determine information on load distribution at the ends of the cylinder and strain fields at areas likely to buckle. Buckling loads were determined for an axial load applied with an eccentricity of R/2 where R is the cylinder radius. The results showed that the buckling load and mode for the shell having a penetration that did not cut a ring stiffener were essentially the same as those for the unpenetrated shell. The buckling loads for the penetrated shells in which stiffeners were interrupted were less than that for the unpenetrated shells. Results of all tests are compared to numerical solutions carried out using a nonlinear collapse analysis and to the predictions of ASME Code Case N-284.

ABSTRACT: This paper describes the method for and results of, determining the static buckling interaction curves for both ring-stiffened and unstiffened cylindrical geometries that have radius-to-thickness (R/t) ratios and other parameters characteristic of nuclear steel containments. The purpose of developing these test methods and interaction curves is to have this information available for a dynamic buckling study on the same or similar shells that will be directed at answering questions regarding the freezing-in-time analysis method.


ABSTRACT: The problem of dynamic effects for steel containment shells subjected to time-dependent loadings that produce large compressive membrane stresses in the shell wall is considered. Loadings on typical containment structures are reviewed, along with a description of the complete dynamic-buckling problem. Simplifications and the assumptions that are currently used are critically examined and reviewed with respect to buckling analysis. Based on these reviews, three program objectives are defined and the tasks that can accomplish these objectives within a 2-year effort at level funding are outlined in detail.

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ABSTRACT: Buckling of freestanding nuclear steel containment buildings from dynamic base excitation was investigated in a combined experimental/numerical program. A polycarbonate scale model of a containment building was excited with scaled earthquake transients and single-frequency harmonic transients to determine the peak base acceleration levels required to induce buckling. Buckling was identified using recorded signals from strain gages and accelerometers, with high-speed video records, and by audibility. Experimental results are compared with numerical results obtained by using a freezing-in-time technique. The results are preliminary, since several more tests are to be performed. However, the limited data obtained indicate that the freezing-in-time technique approximates the required acceleration levels reasonably well, although not conservatively. Additional experiments are described that will take containment asymmetries into account, as well as use instrumentation that will provide more accurate measures of the occurrence of buckling.


ABSTRACT: A displacement-based versatile and effective finite element is presented for linear and geometric and material nonlinear analysis of plates and shells. The element is formulated by interpolating the element geometry using the mid-surface nodal point coordinates and mid-surface nodal point normals. A total and an updated Lagrangian formulation are presented, that allow very large displacements and rotations. In linear
The effectiveness of the element in practical analysis.

References listed at the end of the paper:


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ABSTRACT: In some earlier communications we presented the formulation of a simple pipe elbow element for linear analysis. In this paper we extend this formulation to include some nonlinear effects. Elastic-plastic conditions can be modeled, and some kinematic nonlinearities (due to large displacement beam behavior) can also be represented. The results of some sample solutions are given to illustrate the use of the element.

References listed at the end of the paper:
1. Adini, A. Analysis of shell structures by the finite element method, PhD Dissertation, Department of Civil Engineering, University of California, Berkeley (1961)


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ABSTRACT: (cannot cut and paste)

ABSTRACT: The objective of this paper is to gain insight into finite element discretizations of shells using the basic shell mathematical model and, in particular, regarding the sources of “locking”. We briefly review the “basic shell mathematical model” and present a formulation of shell finite elements based on this model. These shell finite elements are equivalent to the widely-used continuum mechanics based shell finite elements. We consider a free hyperboloid shell problem, which is known to be difficult to solve accurately. Using a fine mesh of MITC9 elements based on the basic shell mathematical model, a detailed analysis is performed giving the distributions of all strain terms. A similar analysis using the MITC6 shell element shows why this element locks when the shell thickness is very small.

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ABSTRACT: An efficient procedure for the nonlinear analysis of elasto-plastic shells is obtained based on an incremental variational functional of the Hellinger-Reissner type. For computational efficiency an updated Lagrangian description is used, referring the kinematical and mechanical field variables to local corotated coordinate frames. The constitutive equations are given in terms of increments of midsurface strains and curvatures and corresponding stress resultants, thus avoiding the integration over the shell thickness. Two models are considered for the description of subsequent yield surfaces, and modifications are introduced to represent the behaviour of hardening materials. The shell surface is descretized by flat elements of triangular and quadrilateral shape. Relaxing the interelemental continuity requirements, the resulting modified hybrid stress elements are expressed in the standard displacement format of the finite element method. The material models are verified against results obtained by numerical integration through the thickness for the special case of bending and stretching of a beam. Comparative studies for arches, rectangular plates subjected to transverse and inplane loads and cylindrical shells subjected to gravity loading indicate that the accuracy compares favourably with the results obtained by the traditional displacement formulation and numerical integration through the thickness. However, studies on two plastic buckling of axially loaded tubes reveal the need for further studies on the models for hardening materials.


ABSTRACT: This paper presents two numerical modeling approaches to analyze the wrinkles in the space membrane structures. The nonlinear buckling method based on our wrinkle analytical technique incorporating ANSYS thin shell element is used to simulate the wrinkle characteristics in the plane membrane. The explicit time integration method incorporating the AIRBAGS model in LSDYNA code is used to predict the dynamic wrinkle characteristics and the stress state of inflatable membrane structures. Numerical approaches presented
in this paper are applied in two numerical studies. One is the wrinkle analysis of the square plane membrane subjected to symmetric corner tension, and the other is the analysis of the square inflatable membrane airbag under the action of the internal variable inflatable pressure. The detailed wrinkling information, such as wrinkle wavelength, wrinkle amplitude, wrinkle region and the stress state of the wrinkled membrane structures, can be accurately obtained by using the approaches presented in this paper. Comparisons were made with experimental results for the wrinkle shape and distribution. The numerical predictions agreed well with the experimental results. The wrinkling results from the numerical computation can be used to support the studies on the nonlinear behaviors of the space membrane structures.

Changguo Wang, Huifeng Tan and Xingwen Du, “Pseudo-beam method for compressive buckling characteristics analysis of space inflatable load-carrying structures”, Acta Mechanica Sinica, October 2009, ABSTRACT: This paper extends Le van’s work to the case of nonlinear problem and the complicated configuration. The wrinkling stress distribution and the pressure effects are also included in our analysis. Pseudo-beam method is presented based on the inflatable beam theory to model the inflatable structures as a set of inflatable beam elements with a pre-stressed state. In this method, the discretized nonlinear equations are given based upon the virtual work principle with a 3-node Timoshenko’s beam model. Finite element simulation is performed by using a 3-node BEAM189 element incorporating ANSYS nonlinear program. The pressure effect is equivalent included in our method by modifying beam element cross-section parameters related to pressure. A benchmark example, the bending case of an inflatable cantilever beam, is performed to verify the accuracy of our proposed method. The comparisons reveal that the numerical results obtained with our method are close to open published analytical and membrane finite element results. The method is then used to evaluate the whole buckling and the load-carrying characteristics of an inflatable support frame subjected to a compression force. The wrinkling stress and region characteristics are also shown in the end. This method gives better convergence characteristics, and requires much less computation time. It is very effective to deal with the whole load-carrying ability analytical problems for large scale inflatable structures with complex configuration.

Lihong Zhang, Anne Marie Habraken, Amine Ben Bettaieb and Laurent Duchêne, “Parametric study of metal/polymer multilayer coatings for temperature wrinkling prediction”, Journal of Materials Engineering and Performance, Vol. 22, No. 9, pp 2437-2445, September 2013, doi: 10.1007/s11665-013-0541-z ABSTRACT: This article presents an analytic model for the prediction of wrinkling occurring in metal/polymer coatings under particular conditions. Owing to different thermal expansion coefficients (TECs) of the substrate and the different coating layers, temperature variation can induce a compressive stress in the coating. The wrinkling is the material response to the instability caused by this compressive stress. In this study, a reference case was selected: a 0.27-mm-thick steel sheet with a 5-μm-thick polymer layer and, on top of it, a thin aluminum film of 50 nm in thickness. For this reference case, it was observed and predicted by the model that an increase in temperature yielded to the wrinkling of the thin aluminum film. The geometry of the multilayer coating and the properties of the constituent materials are factors able to promote or prevent the wrinkle. To better understand and predict their effects, a sensitivity analysis was carried out with the proposed analytic model. A special attention was devoted to the temperature when wrinkling occurs. The key parameters having a significant influence on the wrinkling temperature were identified. It is concluded that the elastic modulus of the thin aluminum film and that of the polymer, the TEC of the thin film, and the initial stress induced during the processing of the multilayer system all had a significant influence on the wrinkling temperature.
ABSTRACT: Compared with experiments, the J2 deformation theory of plasticity is known to predict plastic buckling with better accuracy than the more accepted incremental J2 flow theory. This paradox is commonly known as the ‘plastic buckling paradox’. In an attempt to analyse this discrepancy, the two mentioned constitutive models were implemented in a non-linear finite element code, along with a third non-associative J2 flow theory. The latter model incorporates a vertex-type plastic flow rule. Using these three constitutive models, the buckling behaviour of plate outstand elements was investigated. Comparisons between the buckling strengths derived are presented. The non-linear static buckling simulations show that the instability introduced by the alternative flow rule of the non-associative model has substantial influence on the buckling behaviour. The acceptance of only small departures from normality was shown to reduce the predicted ultimate capacity of the plates. Furthermore, for plates with small plate slendernesses it was found that the imperfection sensitivity was significantly reduced when using the non-associative flow rule.


ABSTRACT: In this paper the analysis of plastic collapse is executed for a complicated pressure vessel. It is shown that the collapse of the whole vessel depends on the collapse of its details, which are selected in such a way that their collapse takes place independently from each other. Two kinds of collapse modes of the details are recognized: by bulging and by a three-hinge mechanism. It is shown that the collapse of the latter cannot be approximated reasonably by elastic solutions. Following this approach, the collapse of the whole vessel need not be executed. It is shown that for a jacketed construction the jacket cannot be taken as a separate detail because its deformation depends on the stiffness of the component to which it is attached. The collapse of the jacket is pursued in detail. Allowable pressures with respect ot plastic collapse are calculated for a sample vessel.


ABSTRACT: All too often, mechanicists divide themselves into two camps, theoreticians and experimentalists. This unfortunate state of affairs denies us the essential two-sided, realistic view of important physical problems. We must realize that theory cannot exist without suitable experiments, and that experiments cannot be properly designed or used in engineering practice without some form of theory. Thoughtful, penetrating interaction between theoretician and experimentalist is crucial. The truly effective experimentalist must have a strong theoretical background. The truly effective theoretician must have at least a rudimentary, if not a strong, experimental background. Of course, the ideal mechanicist would be neither a theoretician nor an experimentalist, but both simultaneously! The important factor is cross-talk between the two points of view with the objective of achieving a unified view of a phenomenon and its model that can be used to treat behavior beyond that which was observed in experiments. This paper is about the elements that go into making up the
unified viewpoint. Those elements include appreciation of the actual characteristics of the phenomenon studied as determined by experimental techniques and how those characteristics help develop and refine every theory. The point is that experiment is the driving force behind theory.

ABSTRACT: Geometrically perfect plates that are restrained from in-plane expansion when slowly and uniformly heated generally develop compressive stresses and then buckle at a specific temperature. The equivalent mechanical loading concept is used to straightforwardly develop solutions to several fundamental thermal buckling problems involving simple laminated plate configurations and the most simple heating environment, namely uniform heating throughout the plate volume. The analysis is restricted to linear elastic stress-strain behavior and constant orthotropic lamina material properties at a specific temperature. Results are obtained for unidirectional and symmetric cross-ply laminated fiber-reinforced composite rectangular plates that are uniaxially restrained in their plane on two of the four edges, but have no edge rotational restraint on any edge. Those boundary conditions constitute two of the four possible types of simply supported edges that differ only in their in-plane conditions. The results are presented in the form of buckling temperature change from the stress-free temperature (at which no stress is generated against the restraint) versus plate aspect ratio curves festooned for different buckling mode shapes for all laminates. Anomalous examples include unidirectionally laminated plates that actually buckle upon cooling instead of heating and cross-ply laminated plates that do not buckle irrespective of whether they are heated or cooled. Those examples are of interest because of their intriguing possible design applications.

ABSTRACT: During the setup of an experiment, errors may occur. Sources of such errors may be due to several factors which sometimes accumulate and then cause erroneous results. An experimental investigation on buckling of GRP (glass-reinforced-plastic) cylindrical shells, subject to axial compression and/or external pressure loading, has been carried out. At the beginning of the experiment, the initial geometrical imperfections were measured. Because of the small size of these quantities and the great effect these imperfections had on buckling loads, any small errors in the measurement procedure may lead to unreasonable results. Attempts have been made to detect these errors, and to identify and minimize their effect on experimental results. Tables are provided to show a comparison between the final experimental results and the corresponding theoretical ones. References listed at the end of the paper:


ABSTRACT: Koiter's method for initial postbuckling and imperfection sensitivity analysis of elastic structures is conveniently formulated in terms of finite elements. Special care must, however, be taken in the computation of the postbuckling stresses and the postbuckling constant determining the initial curvature of the postbuckling path. The cause of the problem lies in the different degree of approximation of in-plane and lateral displacements and is inevitable in a standard compatible finite element formulation. It is shown that only a minor change in the computation of the postbuckling stresses is needed. The procedure is extended to cover Byskov and Hutchinson's method for cases with nearly simultaneous buckling modes.


ABSTRACT: Basic definitions and relations for stability of elastic discrete systems under one-parameter conservative loads are briefly presented. On the basis of the potential energy functional the incremental FEM equations are derived. Various methods of computation of paths of equilibrium are discussed. These methods are related to evaluation of a curvilinear path either in the configuration space $\mathbb{R}^N$ or in the load-configuration space $\mathbb{R}^{(N+1)}$. The best method seems to be related to computation in $\mathbb{R}^N$ if the arc-type parameter and vector tangent to the equilibrium path are used. This method enables to overcome easily the limit points.
Different stability criteria for computation of critical points are discussed. Tracing of a postbifurcation path of equilibrium is pointed out.


ABSTRACT: The paper is a continuation of Waszczyszyn et al. (in: R. Tadeusiewicz, L. Rutkowski, J. Chojcan (Eds.), Proceedings of the Third Neural Networks and their Applications, TU Czestochowa, Poland, 1997, p. 14), where back-propagation neural networks (BPNNs) were used for predicting the buckling loads for axially compressed cylindrical shells with initial geometrical (manufacturing) imperfections. The paper was based on the measured imperfections and tests on laboratory shell specimens, gathered in the Imperfection Data Bank at the Delft University of Technology (P. II, Report LR-559, TU Delft, Faculty of Aerospace Engineering, Delft, 1988). In the presented paper the idea of data compression is explored. The application of BPNN replicators enables us to significantly reduce the number of inputs so the master BPNN formulated for the buckling load prediction is considerably smaller than BPNNs discussed in Waszczyszyn et al. (1997). It is proved that the compression of imperfection parameters seems to be a new efficient tool for the analysis of experimental data of the problem considered.


ABSTRACT: In this paper a family of dilatant plasticity theories is introduced by considering yield surfaces which change according to a combination of isotropic expansion and kinematic translation. One limiting member of the family is Gurson's (1977) isotropic hardening model, and the other limiting member is a pure kinematic hardening version. The family of constitutive laws is constructed such that all versions coincide for proportional stressing histories. The differences between any two versions show up only under nonproportional stressing histories, such as those encountered in many plastic instability phenomena. Under nonproportional stressing, the kinematic version is significantly “less stiff” than Gurson's isotropic hardening model due to the relatively higher curvature of the kinematic yield surface. This effect is explored in some basic shear localization calculations and is found to have substantial influence on the localization predictions.


ABSTRACT: The results of finite element calculations for a hollow sphere micromodel are used to examine the underlying assumptions and the specific yield functions in the dilatant plasticity theories of Gurson (1977) and Mear and Hutchinson.
ABSTRACT: The effect of void nucleation is incorporated in a recently proposed material model that accounts for a combination of kinematic hardening and isotropic hardening of a porous ductile material. Since each of plastic dilatancy, void nucleation and yield surface curvature have a strong influence on predictions of plastic flow localization, the present material model can be used to study the interaction of these effects. Nucleation controlled by the plastic strain as well as nucleation controlled by the maximum normal stress on the particle-matrix interface are modelled. The predictions of the material model, for various combinations of parameters, are illustrated by analyses of shear band formation under plane strain or axisymmetric conditions, and by analyses of necking in biaxially stretched sheets.

ABSTRACT: Interaction of nearly simultaneous buckling modes in the presence of imperfections is studied. The investigation is concerned with axially stiffened cylindrical shells under axial compression. In these structures, two modes are of particular interest, namely an overall long-wave and a local shortwave buckling mode. Numerical results show that in some cases bending of the stringers in the local mode postbuckling solution plays an important role. Exclusion of this effect, as was done in a previous study by Byskov and Hutchinson, may lead to an overestimation of the carrying capacity of the shell. Furthermore, it is found that apparently reasonable approximations to the postbuckling fields associated with both the local and the overall mode, as well as with the overall mode alone, may lead to inexact values of the buckling load.

ABSTRACT: In some cases, asymptotic methods present an appealing alternative to full nonlinear analyses. In other cases, the value of an asymptotic analysis may merely be that, in a qualitative way, it can characterize the behavior of a structure. Whether an asymptotic method is applied for one or the other purpose it is of interest to attempt an estimation of its range of validity. The present paper addresses this question for an asymptotic method to predict imperfection sensitivity of elastic structures with mode interaction. The particular structure that is investigated possesses an infinity of nearly simultaneous local buckling modes. It is found that very few of these modes need to be taken into account.

ABSTRACT: A number of studies show that nonlinear interaction between a shortwave local panel buckling mode and a longwave overall shell buckling mode usually causes strong imperfection sensitivity in stiffened shells. Interaction is particularly strong for simultaneous or nearly simultaneous modes. Mode interaction
between two overall buckling modes, as well as interaction between two overall and one local mode, has received much less attention. The present study indicates that for certain imperfection combinations, such mode interactions are important. On the other hand, in most cases, interaction between one overall mode and one local mode governs.


ABSTRACT: Exact postbuckling stresses usually vary fairly smoothly. Unfortunately, finite element postbuckling stresses tend to be much less well behaved. The result is that second order postbuckling constants determined by the finite element method may be highly inaccurate. The reason is that in finite element solutions transverse displacements associated with the buckling fields furnish too rapidly varying postbuckling strain contributions, while the postbuckling axial or membrane displacements contribute strain components that are sufficiently smooth, thus creating an internal postbuckling strain and stress mismatch. The present study suggests a modified finite element method that handles the problem, which is a special example of membrane locking, by introducing the postbuckling strains as independent variables. In general, the method provides rather complicated finite element expressions. However, by a suitable choice of interpolating functions, the resulting finite element equations themselves may be found to be the usual ones, and yet provide smooth postbuckling stresses and therefore good values of the postbuckling constants.


ABSTRACT: The buckling load capacity of a form of cellular-walled circular cylindrical shell suggested by fossil shell remains is analyzed. Shells under combined loading of axial compression and external pressure are studied. In particular, the effect of high fluid pressure within the cells on the buckling behaviour of the shell is considered. This study demonstrates that shells of this type with pressurized cells exhibit significantly improved stability and thus appear to have potential in engineering applications, particularly in marine situations.


ABSTRACT: This paper presents an experimental study of the buckling load capacity of a form of cellular-walled circular cylindrical shell suggested by fossil shell remains. Five epoxy model shells were tested in axial compression, external pressure and pressure within the cells. The results confirmed predictions of buckling loads: that is, the shell stability can be significantly improved by pressurising the cells. Thus this form of shell has considerable potential as an engineering structure, particularly in marine situations.

ABSTRACT: A great deal of the behavior of thin-walled cylindrical shells loaded in axial compression can be explained by considering the Yoshimura buckle pattern as a three-dimensional space frame and observing the collapse of that space frame.

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ABSTRACT: This paper presents the results of some tests that were conducted on stringer stiffened epoxy cylindrical shells. The object of the investigation was to determine if the Southwell technique for estimating buckling loads could reasonably be used for the nonlinear collapse of cylindrical shells. The results showed that the technique provides a useful estimate of the buckling load provided care is taken in interpreting the results. In some instances the estimate is likely to be greater than the actual load. Where two buckling modes are encountered at the same time the Southwell technique appears to predict the critical load associated with either mode depending on the deflection parameter being measured as well as on the interpretation of the results.


ABSTRACT: An analytical study has been carried out to determine the effect of axisymmetric shape imperfections on the compressive buckling strength of sandwich cylinders having isotropic facings and orthotropic, shear deformable cores. Buckling solutions are presented as a function of imperfection amplitude, wavelength and the core shear flexibility coefficients. Non-shear deformable cores have also been considered and results compared to isotropic cylinders based on an “equivalent” thickness parameter.

S. Krishnakumar and R. C. Tennyson (University of Toronto, Institute for Aerospace Studies, 4925 Dufferin Street, Downsview, Ontario M3H 5T6, Canada), Effect of impact delaminations on axial buckling of composite cylinders”, in Buckling of shell structures, on land, in the sea, and in the air, edited by J. F. Jullien, Spon Press, 1991, ISBN 1-85166-716-4

ABSTRACT: The development of delaminations induced by low velocity impact and their effect on the axial compressive buckling strength of thin laminated circular cylindrical shells was investigated experimentally. Image Enhanced Backlighting and Structureal Embedded Fiber Optic Sensors were employed for damage assessment. Buckling tests were also conducted on shells with implanted delaminations for comparison purposes and as a means for determining the influence of delamination area on the reduction in buckling strength.

ABSTRACT: The development of delaminations induced by low velocity impact and their effect on the axial compressive buckling strength of thin laminated circular cylindrical shells was investigated experimentally. Image Enhanced Backlighting and Structurally Embedded Fiber Optic Sensors were employed for damage assessment. Buckling tests were also conducted on shells with implanted delaminations for comparison purposes and as a means for determining the influence of delamination area on the reduction in buckling strength. Results are compared with finite difference solutions of the buckling equations and linear stability analysis using the ABSQUS finite element package.


PARTIAL INTRODUCTION: One of the major concerns involving the use of lightweight fibre-reinforced composites is their susceptibility to impact damage. Delamination (or interlaminar fracture), surface spallation and laminate penetration constitute various modes of failure resulting from impact loads. Low-velocity impacts are associated with delamination damage, especially that caused by blunt-headed projectiles. This inter-laminar debonding primarily reduces the local bending stiffness and thus can affect the bending and buckling behavior of the structure. In the latter case, local buckling can induce further delamination growth which can lead to overall global weakening of the structure….. As impact energy is increased, delamination coupled with surface spallation can occur, followed by penetration of the laminate…


ABSTRACT: This paper presents the results of hypervelocity impact tests conducted on graphite/PEEK laminates. Both flat plate and circular cylinders were tested using aluminum spheres of varying size, travelling at velocities from 2–7 km/s. The experiments were conducted at several facilities using light gas guns. Normal and oblique angle impacts were investigated to determine the effect of impact angle, particle energy and laminate configuration on the material damage and ejecta plumes. Correlations were established between an energy parameter and the impact crater size, spallation damage and debris cone angle. Secondary damage resulting from the debris plume on adjacent composite structures was studied using high-speed photography and witness plates. It was observed that for hypervelocity impacts, the debris plume particles have sufficient energy to penetrate adjacent structures and cause major structural damage as well.


ABSTRACT: Some basic problems in the analysis of nonlinear instability for multilayered composite cylindrical shells are discussed. These problems are: the influences of initial imperfections and geometrical nonlinearities of shells; the effects of physical nonlinearity caused by the material nonlinearity of shear modulus; the influences of transverse shearing deformation and the effects of prebuckling deformations on buckling and postbuckling behavior of laminated composite cylindrical shells under various boundary conditions. All these influences are studied under various loading conditions; e.g. axial compression,
hydrostatic pressure, and torsion. Of course, the interaction of these influences is an important and complicated problem. The synthetic analysis of these influences is reported, based on a series of investigated results in recent years on boron--epoxy composites.

ABSTRACT: The effects of prebuckling displacements on the buckling of laminated composite circular cylindrical shells are investigated. Both axial compression and pure torsion are considered for two shell geometries with length to thickness ratios usually associated with container vessels. A clamped prebuckling boundary condition is used for all analysis with four boundary conditions applied during the buckling process. The shell walls are made up of a 6 ply laminate with several symmetric ply orientations. The study was made using the STAGS computer code, utilizing the linear bifurcation branch with linear prebuckling displacements. The results are compared to the buckling loads determined when prebuckling displacements are neglected. It is shown that prebuckling deformations generally tend to decrease the buckling load of a composite shell. It is also shown that prebuckling displacements can cause shell buckling before failure of the fibers occurs.

ABSTRACT: This paper presents results for buckling of a stiffened cylindrical shell with cutouts and both isotropic and composite shells without cutouts acting under end bending moments. The STAGS-C program has been used in the analysis.

ABSTRACT: A finite element analysis is carried out on the buckling of composite cylindrical panels under shear loading. Deep panels are considered, thus requiring a higher order shell theory. A comparison is made with a Galerkin technique which incorporated the Donnell shell theory.

ABSTRACT: The paper presents an approach for a general laminated shell geometry describable by orthogonal curvilinear coordinates. The theory includes a through-the-thickness parabolic distribution of transverse shear stress. Additionally, a simplified approach that allows large displacements and rotations is incorporated. The theory is cast into a displacement-based finite element formulation and then specialized to a cylindrical shell geometry. The theory is then applied to the problem of a transversely loaded isotropic deep arch, and results show a slightly more flexible response compared with published results that are based upon inextensible
assumptions. This problem also indicates that the usual locking associated with shell elements is apparently eliminated.

ABSTRACT: The characteristics of dynamic buckling of a geometrically non-linear cylindrical laminated composite panel subjected to a transverse concentrated step load applied at the center is studied. Attention is focused on the dynamic stability of a finite element discrete structural system. The sufficient condition for dynamic buckling, from the energy transfer consideration, is defined as the smallest load for which an unbounded motion is initiated at one generalized displacement. In other words, the dynamic buckling load associated with that generalized coordinate can be predicted by the intersecting point on the static equilibrium curve and the zero potential energy curve. This dynamic buckling criterion can also be observed by the existence of an inflection point on the generalized displacement response curve. Considering the multi-degree-of-freedom for the entire structure without damping, the dynamic buckling criterion used in a single-degree-of-freedom model gives the lower-bound dynamic buckling estimate, which will be shown in the results of the dynamic buckling analysis for a laminated composite arch. The possibility of parametric resonance due to the transverse concentrated step load on a geometrically non-linear system is discussed. Furthermore, the dynamic effects for different loading rates of the applied concentrated load are examined. Finally, the study of the damping effect, which raises the dynamic buckling load, is included.

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ABSTRACT: A versatile geometrically non-linear curved shell finite element formulation includes exact Green's strain displacement for the inplane strains and linear strain displacement for the transverse shear strains. Additional coupling results for membrane-bending and membrane-transverse shear due to non-linear curvature strain-displacement relations. Additional non-linear terms that are a function of the shell's radius of curvature are also present. The approach is applied to the bifurcation buckling of axially compressed flat plates and transversely pressure-loaded cylindrical shell panels. The method gives a more flexible result for the plates compared to von Kármán non-linearity. Additionally, larger buckling pressures are found for shell panels. The effects of transverse shear flexibility are evident.

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ABSTRACT: Cylindrical shell panels subjected to external pressure are seen in thin semi-monocoque aerospace applications and in the thick-wall pressure hulls of deep-sea submersibles. Both cases are weight-sensitive designs, and therefore, laminated constructions due to their high strength and stiffness-to-weight ratios appear advantageous. In this paper, both linear bifurcation and nonlinear analyses are presented for a wide range of geometries. For shells of high curvature, i.e. a Batdorf parameter, Z, greater than 100, the bifurcation load predicts the onset of instability very accurately as compared to a nonlinear analysis. On the other hand, shallow shells indicate a bifurcation instability where none exists in the nonlinear analysis. The response for some curvatures is significantly altered where transverse shear flexibility apparently has a major influence.

DTIC Accession Number: ADA294792, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA294792
ABSTRACT: A laminated shallow shell approach that includes von Karman geometric nonlinearity and parabolic transverse shear deformation is posed in differential operator form. Trigonometric series are assumed for each of the five shell displacement degrees freedom for the subsequent nonlinear galerkin solution resulting in 5n2 simultaneous algebraic equations where n is the number of displacement terms assumed in the series. The galerkin nonlinear solution is computationally intensive. The response of several laminate geometries subjected to transverse loadings are found. Thicker plates and shells generally exhibit more flexible response compared to thinner geometries in both linear and nonlinear analyses. The nondimensional shell response is examined by using the Batdorf-Stein shell parameter for laminated constructions. Quasi-isotropic shallow shells undergo significant transverse shear flexibility in the thicker geometries as given by the nondimensional shell crown deflection. However, the nondimensional crown deflection in the deeper shell response is not much influenced by shell thickness. For flat plates, geometric nonlinearity lessens the influence of transverse shear flexibility when compared to linear solutions due to membrane stretching resistance.

ABSTRACT: (Cannot cut and paste)

ABSTRACT: An asymptotic procedure is used to derive the nonlinear equations of motion governing the forced dynamic response of an arbitrarily laminated slightly compressible composite shell panel in cylindrical bending. A combination of the Galerkin procedure and the method of multiple time scales is used to construct a uniformly valid asymptotic expansion for the dynamic response of the panel under near-resonant external excitation, and in the presence of a two-to-one internal resonance condition. A qualitative analysis shows that there is a threshold value for the amplitude of excitation, above which the panel exhibits the saturation phenomenon in which the amplitude of the directly excited mode saturates and the coupled mode starts to respond nonlinearly and eventually dominates the response. The force-response curve also exhibits the jump phenomenon.
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ABSTRACT: A geometrically non-linear dynamic shell theory presented by the authors in an earlier work is used to study the non-linear free vibrations of symmetrically laminated cylindrical shell panels. The theory accounts for arbitrary lamination constructions, anisotropy, and slight compression across the thickness. In this paper, this theory is used to derive the equation of motion of the panel with quadratic and cubic non-linearities and symmetric lamination schemes. The symbolic manipulator Mathematica™ is used to perform the Rayleigh-Ritz procedure and derive a single-mode approximation to the vibration of the panel. The Lindstedt-Poincare perturbation technique is used to analyze the resulting non-linear differential equation of motion and study the effects of non-linearities on the dynamics of free vibrations of the panel. A numerical example of a symmetrically laminated graphite/epoxy shell panel is used to demonstrate the procedure. The numerical example shows that non-linearities are of the hardening type and are more pronounced for smaller opening angles. Moreover, it shows that the larger-amplitude motions are dominated by the lower modes.

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ABSTRACT: An analytical study was performed to determine the critical buckling loads and natural frequencies for composite cylindrical shells, including transverse shear effects and constant through-the-
thickness direct strain, epsilonz. A linearized form of Sander's shell equations are derived, including a parabolic transverse shear strain distribution. Higher order laminate constitutive relations are developed. Hamilton's Principle is applied to derive five partial differential equations of motion and the associated boundary conditions, which are then solved using the Galerkin technique. Ply layups of [0/90] and [45/-45] were investigated under three boundary conditions, simply supported, clamped, and a combination simple-clamped. Symmetric and nonsymmetric laminates were investigated. Curvature is shown to have an important effect on all panels investigated due to membrane and bending coupling. Buckling loads for deeper shells are significantly higher than for flat plates. The effect on frequencies is not as great. The behavior of the nonsymmetric laminates was somewhat unexpected. Some results indicate the nonsymmetric laminates to be stiffer than the corresponding symmetric layup.

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ABSTRACT: This paper studies the non-linear free vibrations of simply supported curved orthotropic panels. The panels are modeled using the Donnell-Mushtari-Vlasov shell relationships. A combination of the Galerkin procedure and the Lindstedt-Poincaré perturbation technique is used to construct an approximate solution to the resulting non-linear equations of motion. Algebraic manipulations show that the panel exhibits a non-linear response only when both the involved axial and circumferential modes are axisymmetric. Numerical studies of a Graphite/Epoxy panel show that its response is softening, i.e. the non-linear natural frequency decreases as the amplitude of motion increases. They also show that the lower modes are more non-linear than the higher, mainly flexural modes. The presented results also show that for the studied panels, the non-linear effects are the strongest for shallow, thin, and short panels.

Scott T. Dennis (Department of Engineering Mechanics, Air Force Academy, Colorado Springs, CO, USA),
“Two Dimensional Laminated Shell Theory Including Parabolic Transverse Shear”, Final Report, USAFA-TR-89-6, October 1989, DTIC Accession Number: ADDA 213817
ABSTRACT: The report presents an approach for a general laminated shell geometry describable by orthogonal curvilinear coordinates. The theory includes a through the thickness parabolic distribution of transverse shear stress. Additionally, a simplified approach that allows large displacements and rotations is incorporated. The theory is cast into a displacement based finite element formulation and then specialized to a cylindrical shell geometry. Linear results are compared to exact elasticity solutions of a laminated cylindrical shell in cylindrical bending. The approach predicts displacement and stress for the unidirectional cases very well even for the very thick laminates.

ABSTRACT: A laminated shallow shell approach for circular cylindrical panels that includes von Kármán geometric nonlinearity and parabolic transverse shear deformation is posed in differential operator form. Trigonometric series are assumed for each of the five shell displacement degrees of freedom for the subsequent
nonlinear Galerkin solution resulting in $5n^2$ simultaneous algebraic equations where $n$ is the number of displacement terms assumed in the series. The responses of several laminate geometries subjected to transverse loadings are found. Thicker plates and shells generally exhibit more flexible nondimensional response compared to thinner geometries in both linear and nonlinear analyses. The nondimensional shell response is examined by using the Batdorf-Stein shell parameter for laminated constructions. Quasi-isotropic shallow shells undergo significant transverse shear flexibility in the thicker geometries as given by the nondimensional shell crown deflection. However, the nondimensional crown deflection in the deeper shell response is not much influenced by shell thickness. For flat plates, geometric nonlinearity lessens the influence of transverse shear flexibility when compared to linear solutions due to membrane stretching resistance.


ABSTRACT: The present shell research activities at the Aerospace Engineering Department of the TH Delft are directed towards the development of an improved shell design criteria, which incorporates the latest theoretical findings and makes efficient use of the currently available computational facilities. The establishment of an International Imperfection Data Bank is discussed. Characteristic initial imperfection distributions associated with different fabrication techniques are shown. It is demonstrated that the generation of reliability functions via the Monte Carlo Method, which displays the degrading effect of the expected initial imperfection distribution characteristic of a given fabrication process on the buckling load, offers the means of combining the Lower Bound Design Method with the notion of Goodness Classes. Thus shells manufactured by a process, which produces inherently a less damaging initial imperfection distribution, will not be penalized because of the low experimental results obtained with shells made by another process which produces a more damaging characteristic initial imperfection distribution.

References listed at the end of the paper:

ABSTRACT: This paper deals with the stability problem of axially compressed imperfect orthotropic cylindrical shells. The initial imperfections are represented by a double Fourier series. Approximate solutions are derived for a single axisymmetric, a single asymmetric, a 2-modes and a multimode imperfection model. The effect of boundary conditions is studied by reducing the stability problem to the solution of a 2-point nonlinear boundary value problem. A reliability based stochastic stability approach is described, which makes it possible to include the results of the Imperfection Sensitivity Theory directly into an Improved Shell Design Procedure.

References listed at the end of the paper:


ABSTRACT: The development of “DISDECO”, the Delft Interactive Shell Design Code is described. The purpose of this project is to make the accumulated theoretical, numerical and practical knowledge of the last 20 years readily accessible to users interested in the analysis of buckling sensitive structures. With this open ended, hierarchical, interactive computer code the user can access from his work-station successive programs of increasing complexity. Included are modules that contain Koiter's imperfection sensitivity theory extended to anisotropic shell structures under combined loading. The nonlinear Donnell-type anisotropic shell equations in terms of the radial displacement W and the Airy stress function F are used. The circumferential dependence is eliminated by Fourier decomposition. The resulting sets of ordinary differential equations are solved numerically via the “Shooting Method”. Thus the specified boundary conditions can be enforced rigorously not only in the pre-buckling but also in the buckling and post-buckling problem. Initial results indicate that in order to obtain reliable results for anisotropic shells rigorous enforcing of the edge restraint and of the boundary conditions is indeed a must.

ABSTRACT: The development of “DISDECO”, the Delft Interactive Shell Design Code, is described. The purpose of this project is to make the accumulated theoretical, numerical and practical knowledge of the last 20 years readily accessible to users interested in the analysis of buckling-sensitive structures. With the open ended, hierarchical, interactive computer code the user can access from his work-station successive programs of increasing complexity. Included are modules that contain Koiter’s imperfection sensitivity theory extended to anisotropic shell structures under combined loading. The nonlinear Donnell-type shell equations in terms of the radial displacement $W$ and the Airy stress function $F$ are used. The spatial dependence is eliminated by Fourier decomposition. The resulting sets of algebraic equations form a standard matrix eigenvalue problem. Initial results indicate that an interactive use of these simple modules can greatly facilitate the search for an optimal lay up of composite shells under combined loading.


ABSTRACT: Probabilistic methods are being applied to Koiter formulas in order to derive the reliability of imperfection-sensitive shells, on this occasion by taking into account the randomness of both parameters appearing in the formulas — the initial imperfection and the allowable load. The results indicate the importance of the loading randomness, implying a dramatic reduction in the reliability with respect to traditional derivations which consider only the randomness of the initial imperfections.


ABSTRACT: The establishment of an International Imperfection Data Bank is discussed. Characteristic initial imperfection distributions associated with different fabrication techniques are shown. Using a first-order, second-moment analysis, a stochastic method is presented, whereby the stability of isotropic, orthotropic and anisotropic nominally circular cylindrical shells under axial compression, external pressure and/or torsion possessing general nonsymmetric random initial imperfections can be evaluated. Results of measurements of initial imperfections are represented in Fourier series and the Fourier coefficients are used to construct the second-order statistical properties needed. The computation of the buckling loads is done with standard computer codes and includes a rigorous satisfaction of the specified boundary conditions. It is shown that the proposed stochastic approach provides a means to combine the latest theoretical findings with the practical experiences spanning about 75 years in an optimal manner via the advanced computational facilities currently available.
ABSTRACT: The reliability of imperfection-sensitive shells is derived. The Koiter (asymmetric case) formula is used to construct the failure criterion for the case where the imperfection surface is described by two terms of a double Fourier series with random amplitudes. The effect of the correlation between these variables is also investigated. In some cases exact solutions are derived, while in others, approximate derivations are obtained within the Hasofer-Lind method.

ABSTRACT: A rigorous solution is presented for the case of stiffened anisotropic cylindrical shells with general imperfections under combined loading, where the edge supports are provided by symmetrical or unsymmetrical elastic rings. The circumferential dependence is eliminated by a truncated Fourier series. The resulting nonlinear 2-point boundary value problem is solved numerically via the “Parallel Shooting Method”. The changing deformation patterns resulting from the different degrees of interaction between the given initial imperfections and the specified end rings are displayed. Recommendations are made as to the minimum ring stiffnesses required for optimal load carrying configurations.

ABSTRACT: A rigorous solution is presented for the case of stiffened anisotropic shells with general imperfections under combined axial compression, internal or external pressure and torsion. Donnell type equations are used to describe the behavior of the layered composite shell. The stiffeners are represented by smeared theory and for the discrete end rings, Cohen’s ring equations are used. The circumferential dependence is eliminated by a truncated Fourier series. The resulting 2-point boundary value problem is solved numerically via the “parallel shooting method”. The nonlinear collapse behavior is studied using different combinations of axisymmetric and asymmetric imperfections. Comparison with Koiter type imperfection predictions display the range of validity of the asymptotic results. It is shown that besides initial geometric imperfections also nonuniform harmonically varying boundary conditions can have severe degrading effect on the load carrying capacity of anisotropic shells.

ABSTRACT: The development of “DISDECO”, the Delft Interactive Shell DEsign COde, is described. The purpose of this project is to make the accumulated theoretical, numerical and practical knowledge of the last 20 years readily accessible to users interested in the analysis of buckling of sensitive structures. With this open ended, hierarchical, interactive computer code the use can access successively from his workstation programs of increasing complexity.
ABSTRACT: As a step towards developing a new design philosophy, one that moves away from the traditional empirical approach used today in design, towards a science-based design technology approach, a recent test series of 5 composite shells carried out by Waters [1] at NASA Langley Research Center is used. It is shown how the hierarchical approach to buckling load calculations proposed by Arbocz et al [2] can be used to perform an approach often called “high fidelity analysis”, where the uncertainties involved in a design are simulated by refined and accurate numerical methods. The Delft Interactive Shell Design Code (short: DISDECO) is employed for this hierarchical analysis to provide an accurate prediction of the critical buckling load of the given shell structure. This value is used later as a reference to establish the accuracy of the Level-3 buckling load predictions. As a final step in the hierarchical analysis approach, the critical buckling load and the estimated imperfection sensitivity of the shell are verified by conducting an analysis using a sufficiently refined finite element model with one of the current generation two-dimensional shell analysis codes with the advanced capabilities needed to represent both geometric and material nonlinearities.

References not available at this site

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ABSTRACT: Recent advances in structural analysis and design technology for buckling-critical shell structures are discussed. These advances include a hierarchical analysis strategy that includes analyses that range from classical analysis methods to high-fidelity nonlinear finite element analysis methods, reliability based design methods, the development of imperfection data bases, and the identification of traditional and nontraditional initial imperfections for composite shell structures. When used judiciously, these advances provide the basis for a viable alternative to the traditional and conservative lower-bound design philosophy of the 1960s. These advances also help answer the question of why, after so many years of concentrated research effort to understand the behavior of buckling-critical thin-walled shells, one has not been able to improve on this conservative lower-bound design philosophy in the past.
ABSTRACT: As a step towards developing a new design philosophy, one that moves away from the traditional empirical approach used today in design towards a science-based design technology approach, a test series of 7 isotropic shells carried out by Aristocrat and Babcock at Caltech is used. It is shown how the hierarchical approach to buckling load calculations proposed by Arbocz et al can be used to perform an approach often called 'high fidelity analysis', where the uncertainties involved in a design are simulated by refined and accurate numerical methods. The Delft Interactive Shell DEsign COde (short, DISDECO) is employed for this hierarchical analysis to provide an accurate prediction of the critical buckling load of the given shell structure. This value is used later as a reference to establish the accuracy of the Level-3 buckling load predictions. As a final step in the hierarchical analysis approach, the critical buckling load and the estimated imperfection sensitivity of the shell are verified by conducting an analysis using a sufficiently refined finite element model with one of the current generation two-dimensional shell analysis codes with the advanced capabilities needed to represent both geometric and material nonlinearities.

(no abstract given)

ABSTRACT: A procedure for deriving nondimensional parameters and equations for bifurcation buckling of anisotropic shallow shells subjected to combined loads is presented. First, the Donnell-Mushtari-Vlasov equations governing buckling of symmetrically laminated doubly curved thin elastic shallow shells are presented. Then, the rationale used to perform the nondimensionalization of the buckling equations is presented, and fundamental parameters are identified that represent measures of the shell orthotropy and anisotropy. In addition, nondimensional curvature parameters are identified that are analogues of the well-known Batdorf Z parameter for isotropic shells, and analogues of Donnell’s and Batdorf’s shell buckling equations are presented. Selected results are presented for shear buckling of balanced symmetric laminated shells that illustrate the usefulness of the nondimensional parameters.

ABSTRACT: The buckling and postbuckling behaviour of thin plates with a cut-out and made of advanced composite materials are research topics of great practical importance. For example, composite plate-like subcomponents with cut-outs are being considered for use in many types of aerospace structures owing to their high stiffness-to-weight and strength-to-weight properties. These properties could ultimately yield substantial weight savings for aircraft structures.

References listed at the end of the paper:
ABSTRACT: Results of buckling and nonlinear analyses of the Space Shuttle external tank superlightweight liquid-oxygen (LO2) tank are presented. Modeling details and results are presented for two prelaunch loading conditions and for two full-scale structural tests that were conducted on the original external tank. The results illustrate three distinctly different types of nonlinear response for thin-walled shells subjected to combined mechanical and thermal loads. The nonlinear response phenomena consist of bifurcation-type buckling, short-wavelength nonlinear bending, and nonlinear collapse associated with a limit point. For each case, the results show that accurate predictions of nonlinear behavior generally require a large-scale, high-fidelity finite-element model. Results are also presented that show that a fluid-filled launch-vehicle shell can be highly sensitive to initial geometric imperfections. In addition, results presented for two full-scale structural tests of the original standard-weight external tank suggest that the finite-element modeling approach used in the present study is sufficient for representing the nonlinear behavior of the superlight-weight LO2 tank.

References cited at the end of the paper:

ABSTRACT: A summary of the existing NASA design criteria monographs for the design of buckling-resistant thin-shell structures is presented. Subsequent improvements in the analysis for nonlinear shell response are reviewed, and current issues in shell stability analysis are discussed. Examples of nonlinear shell responses that are not included in the existing shell design monographs are presented, and an approach for including reliability-based analysis procedures in the shell design process is discussed. Suggestions for conducting future shell experiments are presented, and proposed improvements to the NASA shell design criteria monographs are discussed.

References cited at the end of the report:

ABSTRACT: Results of linear bifurcation and nonlinear analyses of the Space Shuttle superlightweight (SLWT) external liquid-oxygen (LO2) tank for an important early booster ascent loading condition are presented. These results for thin-walled linear elastic shells that are subjected to combined mechanical and thermal loads illustrate an important type of response mode that may be encountered in the design of other liquid-fuel launch vehicles. Linear bifurcation analyses are presented that predict several nearly equal eigenvalues that correspond to local buckling modes in the forward ogive section of the LO2 tank. In contrast, the nonlinear response phenomenon is shown to consist of short-wavelength bending deformations in the forward ogive and barrel sections of the LO2 tank that grow in amplitude in a stable manner with increasing load. Imperfection sensitivity analyses are presented that show that the presence of several nearly equal eigenvalues does not lead to a premature general instability mode for the forward ogive section. For the linear bifurcation and nonlinear analyses, the results show that accurate predictions of the response of the shell generally require a large-scale, high-fidelity finite-element model. Results are also presented that show that the SLWT LO2 tank can support loads in excess of approximately 2.6 times the values of the operational loads considered.

References listed at the end of the paper:

ABSTRACT: An analytical, parametric study of the attenuation of bending boundary layers or edge effects in balanced and unbalanced, symmetrically and unsymmetrically laminated thin cylindrical shells is presented for nine contemporary material systems. The analysis is based on the linear Sanders-Koiter shell equations and specializations to the Love-Kirchhoff shell equations and Donnell’s equations are included. Two nondimensional parameters are identified that characterize and quantify the effects of laminate orthotropy and laminate anisotropy on the bending boundary-layer decay length in a very general and encompassing manner. A substantial number of structural design technology results are presented for a wide range of laminated-composite cylinders. For all laminate constructions considered, the results show that the differences between results that were obtained with the Sanders-Koiter shell equations, the Love-Kirchhoff shell equations, and Donnell’s equations are negligible. The results also show that the effect of anisotropy in the form of coupling between pure bending and twisting has a negligible effect on the size of the bending boundary-layer decay length of the balanced, symmetrically laminated cylinders considered. Moreover, the results show that coupling between the various types of shell anisotropies has a negligible effect on the calculation of the bending boundary-layer decay length in most cases. The results also show that, in some cases, neglecting the shell anisotropy results in underestimating the bending boundary-layer decay length and, in other cases, results in an overestimation. An example problem is included in an appendix that demonstrates how to perform the calculations that were used to generate the results of the present study.

References listed at the end of the report:


ABSTRACT: The results of an analytical study of the elastic buckling and non-linear behavior of the liquid-oxygen tank for the new Space Shuttle superlightweight external fuel tank are presented. Selected results that illustrate three distinctly different types of non-linear response phenomena for thin-walled shells which are subjected to combined mechanical and thermal loads are presented. These response phenomena consist of a bifurcation-type buckling response, a short-wavelength non-linear bending response, and a non-linear collapse or “snap-through” response associated with a limit point. The effects of initial geometric imperfections on the response characteristics are emphasized. The results illustrate that the buckling and non-linear response of a geometrically imperfect shell structure subjected to complex loading conditions may not be adequately characterized by an elastic linear bifurcation buckling analysis, and that the traditional industry practice of applying a buckling-load knock-down factor can result in an ultra-conservative design. Results are also presented that show that a fluid-filled shell can be highly sensitive to initial geometric imperfections, and that the use a buckling-load knock-down factor is needed for this case.

Nemeth, M. P. (NASA Langley Research Center, Hampton, Virginia, USA), "Buckling Behavior of Long Anisotropic Plates Subjected to Fully Restrained Thermal Expansion," NASA TP-2003-212131, February 2003. ABSTRACT: An approach for synthesizing buckling results and behavior for long, balanced and unbalanced symmetric laminates that are subjected to uniform heating or cooling and that are fully restrained against thermal expansion or contraction is presented. This approach uses a nondimensional analysis for infinitely long, flexurally anisotropic plates that are subjected to combined mechanical loads and is based on useful nondimensional parameters. In addition, stiffness-weighted laminate thermal-expansion parameters are derived that are used to determine critical temperature changes in terms of physically intuitive mechanical buckling coefficients, and the effects of membrane orthotropy and membrane anisotropy are included. Many results are presented for some common laminates that are intended to facilitate a structural designer’s transition to the use of the generic buckling design curves that are presented in the paper. Several generic buckling design curves are presented that provide physical insight into the buckling response in addition to providing useful design data. Examples are presented that demonstrate the use of the generic design curves. The analysis approach and
generic results indicate the effects and characteristics of laminate thermal expansion, membrane orthotropy and anisotropy, and flexural orthotropy and anisotropy in a very general and unifying manner.

References listed at the end of the report:


ABSTRACT: An approach for synthesizing buckling results and behavior for thin balanced and unbalanced symmetric laminates that are subjected to uniform heating or cooling and elastically restrained against thermal expansion or contraction is presented. This approach uses a nondimensional analysis for infinitely long, flexurally anisotropic plates that are subjected to combined mechanical loads and is based on useful nondimensional parameters. In addition, stiffness-weighted laminate thermal-expansion parameters and compliance coefficients are derived that are used to determine critical temperatures in terms of physically intuitive mechanical-buckling coefficients. The effects of membrane orthotropy and membrane anisotropy are included in the general formulation. Many results are presented for some common laminates that are intended to facilitate a structural designer’s transition to the use of the generic buckling design curves. Several curves that illustrate the fundamental parameters used in the analysis are presented, for nine contemporary material systems, that provide physical insight into the buckling response in addition to providing useful design data. Examples are presented that demonstrate the use of the generic design curves. The analysis approach and generic results indicate the effects and characteristics of elastically restrained laminate thermal expansion or contraction, membrane orthotropy and anisotropy, and flexural orthotropy and anisotropy in a very general and unifying manner.

References listed at the end of the report:

5. Nemeth, M. P., "Buckling Behavior of Long Anisotropic Plates Subjected to Restricted Thermal Expansion and Mechanical...
SUMMARY: Simple formulas for the buckling stress of homogeneous, specially orthotropic, laminated-composite cylinders are presented that are the counterpart of the classical buckling formula for an isotropic cylinder. The formulas are obtained by using nondimensional parameters and equations that facilitate general validation, and are validated against the exact solution for a wide range of cylinder geometries and laminate constructions. The buckling stress is found to be a product of a nondimensional coefficient, that involves only material properties of the wall, with the thickness-to-radius ratio of the cylinder and the effective modulus of the corresponding quasi-isotropic laminate. Unlike the corresponding isotropic-cylinder solution, that is represented by a single equation, two equations that depend on the laminate orthotropy, are needed to obtain the orthotropic-cylinder solution; one for axisymmetric and one for asymmetric buckling modes. Results are presented that establish the ranges of the nondimensional parameters and coefficients used. General results, given in terms of the nondimensional parameters, are presented that encompass a wide range of geometries and laminate constructions. These general results also illustrate a wide spectrum of behavioral trends. Design-oriented results are also presented that provide a simple, clear indication of laminate composition on critical stress, critical strain, and axial stiffness. The particular graphical form of these results that is used in the present study enables rapid trade studies for different design requirements. One conclusion found in the present study is that no buckling stress can be achieved for homogeneous specially orthotropic cylinders that is higher than the corresponding quasi-isotropic layup. Another conclusion is that the higher values of buckling stress are associated with higher values of axial strain. An example is provided to demonstrate the application of these results to thin-walled column designs.

References listed at the end of the report:

SUMMARY: A detailed exposition on a refined nonlinear shell theory that is suitable for nonlinear limit-point buckling analyses of practical laminated-composite aerospace structures is presented. This shell theory includes the classical nonlinear shell theory attributed to Leonard, Sanders, Koiter, and Budiansky as an explicit proper subset that is obtained directly by neglecting all quantities associated with higher-order effects such as transverse-shearing deformation. This approach is used in order to leverage the existing experience base and to make the theory attractive to industry. In addition, the formalism of general tensors is avoided in order to expose the details needed to fully understand and use the theory in a process leading ultimately to vehicle certification.

The shell theory presented is constructed around a set of strain-displacement relations that are based on "small" strains and "moderate" rotations. No shell-thinness approximations involving the ratio of the maximum thickness to the minimum radius of curvature are used and, as a result, the strain-displacement relations are exact within the presumptions of "small" strains and "moderate" rotations. To facilitate physical insight, these strain-displacement relations are presented in terms of the linear reference-surface strains, rotations, and changes in curvature and twist that appear in the classical "best" first-approximation linear shell theory attributed to Sanders, Koiter, and Budiansky. The effects of transverse-shearing deformations are included in the strain-displacement relations and kinematic equations by using analyst-defined functions to describe the through-the-thickness distributions of transverse-shearing strains. This approach yields a wide range of flexibility to the analyst when confronted with new structural configurations and the need to analyze both global and local response phenomena, and it enables a building-block approach to analysis. The theory also uses the three-dimensional elasticity form of the internal virtual work to obtain the symmetrical effective stress resultants that appear in classical nonlinear shell theory attributed to Leonard, Sanders, Koiter, and Budiansky. The principle of virtual work, including "live" pressure effects, and the surface divergence theorem are used to obtain the nonlinear equilibrium equations and boundary conditions.

A key element of the shell theory presented herein is the treatment of the constitutive equations, which include thermal effects. The constitutive equations for laminated-composite shells are derived without using any shell-thinness approximations, and simplified forms and special cases are discussed that include the use of layerwise zigzag kinematics. In addition, the effects of shell-thinness approximations on the constitutive equations are presented. It is noteworthy that none of the shell-thinness approximations appear outside of the constitutive equations, which are inherently approximate. Lastly, the effects of "small" initial geometric imperfections are introduced in a relatively simple manner, and a resume of the fundamental equations are given in an appendix. Overall, a hierarchy of shell theories that are amenable to the prediction of global and local responses and to the development of generic design technology are obtained in a detailed and unified manner.

References listed at the end of the paper:
Institute, Blacksburg, Virginia, 1961.


SUMMARY: Nonlinear and linear-bifurcation buckling equations for elastic, geometrically perfect, right-circular cylindrical shells subjected to combined loads is presented. The loads include compression, shear, and uniform external and hydrostatic pressure. The analysis includes constitutive equations that are applicable to stiffened or unstiffened cylinders made from isotropic or laminated-composite materials. Complete sets of equations are presented for the nonlinear boundary-value problem of shell buckling and the corresponding prebuckling and linear-bifurcation buckling problems that are based on Sanders’ shell theory for "small" strains and "moderately small" rotations. Based on these equations, a three-parameter approximate Rayleigh-Ritz solution and a classical solution to the buckling problem are presented for cylinders with simply supported edges. Extensive comparisons of results obtained from these solutions with published results are also presented for a wide range of cylinder constructions. These comparisons include laminated-composite cylinders with a wide variety of shell-wall orthotropies and anisotropies. Numerous results are also given that show the discrepancies between the results obtained by using Donnell’s equations and variants of Sanders’ equations. For some cases, nondimensional parameters are identified and "master" curves are presented that facilitate the concise representation of results.

References listed at the end of the report: Cannot cut-and-paste for some reason.


ABSTRACT: A non-linear formulation for general, arbitrary, sandwich shells is presented. The formulation accounts for geometric and material non-linear behavior of the shell. The core plasticity is assessed. The first order shear deformation theory is presented as far as the kinematics are concerned. The analysis is based on the displacement formulation of the finite element method and uses the Ahmad shell element with five degrees of freedom per node. The approach is discussed, particularly with reference to a cylindrical shell subjected to transverse load that causes snap buckling.


ABSTRACT: In this work, a finite-element model is presented for geometric non-linear analysis of composite shell structures. It adopts a layered formulation of the Marguerre shell element. The material is assumed to have an orthotropic behaviour. The non-linear incremental equilibrium equations are set using a total Lagrangian displacement formulation of the finite element method and the solution is accomplished using the incremental/iterative Newton–Raphson method as well as a spherical formulation of the arc-length methods. The buckling behaviour of composite shells is analysed as a function of the material orientation and laminate stacking.

A.J.M. Ferreira, C.M.C. Roque and R.M.N. Jorge (Departamento de Engenharia Mecânica e Gestão Industrial, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal),

ABSTRACT: The higher-order shear-deformation theory of laminated orthotropic elastic shells of Vlasov–Reddy is a modification of Sanders’ theory and accounts for parabolic distribution of the transverse shear strains through the thickness of the shell. The Vlasov–Reddy shell theory allows the fulfillment of homogeneous conditions (zero values) at the top and bottom surfaces of the shell. This paper deals with a meshless solution of the Vlasov–Reddy higher-order shell theory. The meshless technique is based on the asymmetric global multiquadric radial basis function method proposed by Hardy and Kansa. This paper demonstrates that this truly meshless method is successful in the analysis of laminated composite shells.

Carla M.C. Roque, Antonio J.M. Ferreira and Renato M.N. Jorge (Department of Engineering Mechanics, University of Porto, Portugal), “Analysis of cylindrical sandwich shells using a meshless method and an optimization technique”, (publisher and date not given in the “pdf” file; most recent reference is dated 2006)

ABSTRACT: The purpose of this work is to use a meshless collocation method with multiquadric radial basis functions (RBFs), the higher order shear deformation theory presented by Khare et al. [1], and optimal values of the shape parameter in the RBFs to analyze static deformations of sandwich cylindrical shells. An optimization technique based on a statistical method is used to choose a shape parameter $c$ on the interpolating multiquadric radial basis function used by the meshless method. This parameter plays a decisive role in the quality of the solution of the boundary value problem and is usually chosen in a trial error basis. The optimization technique here presented allows to obtain a quasi user-independent shape parameter. Although the technique still requires some input by the user, results are encouraging, with the errors produced by the optimal shape parameter being lower than the ones produced by a user defined shape parameter.

References listed at the end of the paper:
Ruth V. Savariego (1), Christophe Geuzaine (1), Patrick Dular (1,2) and Johan Gyselinck (3)
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“Nonlinear time-domain finite-element modeling of thin electromagnetic shells”, CEFC-ATHENS, PB1-10, 2008

ABSTRACT: A nonlinear time-domain extension of the classical linear frequency-domain thin-shell approach is presented. The interface conditions are expressed in terms of the average magnetic flux density throughout the shell thickness and a number of higher-order components. The method is elaborated in the frame of the magnetic vector potential formulation. The nonlinear system of algebraic equations is solved by means of the Newton-Raphson scheme. To validate the new formulation, we consider a magnetic plate placed above a double line carrying a sinusoidal current. Results are compared with those obtained with a fine finite-element model.

References listed at the end of the paper:
Federico M. Mazzolani (1) and Alberto Mandara (2)

(1) Department of Structural Analysis and Design, University of Naples Federico II, Naples, Italy
(2) Department of Civil Engineering, Second University of Naples, Aversa (CE), Italy


ABSTRACT: The paper summarises a part of the of activity of CEN/TC250 SC9 Committee, devoted to the preparation of Eurocode 9 “Design of Aluminium Structures”. The results of a wide imperfection sensitivity F.E.M. analysis, dealing with aluminium cylinders subjected to axial load, uniform external pressure and torsion, are discussed. Numerical simulations have been carried out by accounting for a wide geometrical imperfection spectrum, in order to consider the most dangerous distributions. Results of almost 6000 F.E.M. simulation runs have been used to delineate a numerical data-set for the definition of buckling curves for aluminium alloys shells, to be introduced into the new part prEN1999-1-5 of Eurocode 9. For the sake of homogeneity, the basic layout of prEN1993-1-6 has been referred to as a general framework. Nevertheless, it is shown that buckling curves given in EC3 can not be used for aluminium shells, but require proper modification.

References listed at the end of the paper:

F.M. Mazzolani (1), A. Mandara (2) and G. Di Lauro (2)

(1) Department of Structural Analysis and Design, University Federico II, Naples, Italy
(2) Department of Civil Engineering, Second University of Naples, Aversa, Italy

“Plastic buckling of axially loaded aluminium cylinders: a new design approach”, CIMS 2004, Fourth International Conference on Coupled Instabilities in Metal Structures, Rome, Italy, 27-29 September, 2004

ABSTRACT: The results of a wide F.E.M. analysis on the imperfection sensitivity of axially loaded aluminium cylinders are used to investigate buckling modes occurring in case of relatively thick cylinders (R/t < 200 ÷ 250). The combined effect of geometrical imperfections, inelastic behaviour of material and boundary conditions is considered in order to set-up a refinement of rules given in prEN1993-1-6 dealing with steel shells. The proposal allows for a further exploitation of the cylinder buckling strength in plastic range, which is why it seems rather suited to applications in the field of civil engineering. To this purpose, a special requirement on the initial allowable imperfection level is defined, corresponding to a quality class higher than EC3 class A. Because of its features, the proposal presented herein could be profitably used for the new Part 1-5 “Supplementary rules for shell structures” of Eurocode 9 (prEN1999-1-5), presently under development, which is the very first codification issue at European level dealing with aluminium shell structures.

References listed at the end of the paper:


ABSTRACT: In order to simplify the problem, the equivalent-cylinder assumption has been adopted. The simplified governing equations of sandwich cones we obtain are different from the ones used in previous papers. They can be reduced into the equations of a corresponding sandwich cylinder if the buckle length parameter approaches zero. An analytical study has been carried out to determine the effect of axisymmetric
Shape imperfections on the compressive buckling strength of sandwich cones having isotropic facings and isotropic shear deformable cores. Buckling solutions are presented as a function of imperfection amplitude, wavelength, core shear flexibility coefficients and the small curvature ratio. The well known Koiter formula and circle have been obtained for the first time for sandwich cones.

No abstract is given.

ABSTRACT: Using Schieck and Stumpf’s superposition approach, the kinematics of buckling for continua has been investigated in the present paper. According to the properties of buckling phenomena the concept of “bifurcation configuration” has been introduced, and the total deformation gradient F can be expressed by pre-buckling deformation gradient, $F_{\text{sub-1}}$ and the post-buckling deformation gradient $F_{\text{sub-2}}$, i.e. $F = F_{\text{sub-2}} x F_{\text{sub-1}}$. As an extension, the elasto-plastic deformation has been investigated for the post-buckling stage using Lee and Liu’s multiplicative decomposition, $F = F_{\text{super-e}} x F_{\text{super-p}}$.
References listed at the end of the paper: (Cannot cut and paste them.)

S. B. Filippov, D. N. Ivanov, N. V. Naumova, “Free Vibrations and Buckling of a Thin Cylindrical Shell of Variable Thickness with Curvilinear Edge”, Technische Mechanik, Band 25, Heft 1, (2005), 1–8
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Sergei B. Filippov (St. Petersburg State University, Russia), “Stiffened shell of minimal weight in buckling problems”, AIP Conference Proceedings 1648, 300003 (2015), 22-28 September 2014, Rhodes, Greece
http://dx.doi.org/10.1063/1.4912545
ABSTRACT: Buckling of a thin elastic cylindrical shell stiffened by rings of rectangular cross-sections are considered. The parameters of the shell of the minimal weight, having a given critical external pressure, are found. For the evaluating of the optimal parameters the asymptotic approach is used.
ABSTRACT: Wind loadings govern the design of most cooling towers. Until now, proof of sufficient safety against buckling under wind load has been a major concern for the designers of such shells. In this paper it is demonstrated that a typical cooling tower made of reinforced concrete would not buckle—at least not in the classical sense of the word. Failure would rather be initiated by rapid propagation of cracks in tensile zones followed by temporary stiffening and, finally, by yielding of the reinforcement. The theoretical part of this paper is restricted to a presentation of the constitutive model, discussion of the equation for incremental-iterative ultimate-load analysis and of the condition for instability. The numerical part contains a detailed study of a built hyperbolic cooling tower. It is shown that: (a), buckling loads resulting from linear and geometrically nonlinear prebuckling analyses are considerably larger than the ultimate load; and (b), results based on a certain form of ‘equivalent axisymmetric pressure’ are on the unsafe side of corresponding results from the ‘actual’ wind load. It is also demonstrated that the ‘crack load’, representing a lower bound to the ultimate load, can be estimated by means of a linear-elastic nonaxisymmetric analysis of the cooling tower.

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(1) Dr.-Ing. Wayss & Freytag Ingenieurbau AG, Frankfurt am Main,
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References at the end of the article:

ABSTRACT: The paper presents an optimization method for direct determination of the most unfavorable imperfection of structures by means of ultimate limit states. When analyzing imperfection sensitive structures it turns out that the choice of the shape and size of initial imperfections has a major influence on the response of the structure and its ultimate state. Within the optimization algorithm the objective function is constructed by means of a fully nonlinear direct and first order sensitivity analysis. The method is not limited to small imperfections and also allows the imposition of “technological” constraints on the shape of the imperfection, thus making it possible to avoid unrealistically low ultimate loads. When carefully constructed, the objective function and constraints remain linear enabling the use of numerically efficient and readily available linear programming algorithms. Imperfection analyses are shown for thin-walled girders and a cylinder to demonstrate the applicability and efficiency of the proposed method.


References at the end of the article:

ABSTRACT: In certain structural applications, such as stiffened panels loaded in compression, a better exploitation of the properties of composite materials requires the development of design methodologies that allow the component to work in the post-critical range. This paper describes the results of a research activity with such an objective, carried out at the Department of Aerospace Engineering of the University of Pisa in collaboration with Alenia-Transport Aircraft Group. A group of tests has been carried out on 10 flat stiffened panels, made in composite material, and the results have been analysed with two computer codes, providing useful information concerning their capabilities.


ABSTRACT: This thesis deals with the analytical and experimental studies of the instability of geometrically composite shells of revolution. Different axisymmetric composite shells under uniform external pressure are studied analytically for their use as end-closures of submarine hulls or of pressure vessels. The composite shells studied here are (a) cap:cone end-closures (b) cup-cylinder end-closures and (c) dome-cylinder end-closures. In the cap-cone end-closures a spherical cap is attached to the smaller end of a conical frustum in such a way that the tangent at their junction maintains continuity. In the cup-cylinder end-closure, a spherical cup is attached at an end of a cylinder and in the dome-cylinder end-closure, a spherical dome replaces the spherical cup of the cup-cylinder end-closure. A computer program is developed and enclosed here in the appendix which can find both axisymmetric and asymmetric buckling load of shells of revolution under uniform external pressure. For the study of axisymmetric buckling, the program uses Reissner's theory of large deflection and interprets instability based on the two criteria of Thompson. The non-linear axisymmetric solutions of Reissner's theory are considered as prebuckling solution for asymmetric instability analysis based on eigen-value interpretation. Axisymmetric analyses of the cap-cone end-closure for varying cone height, cone angle (II) and thickness ratio show that increasing the cone angle or thickness ratio leads to decreasing the buckling load. In the case of varying height, the buckling load remains almost the same over a wide range of height and starts decreasing at a certain small height reaching a minimum at zero height when it is a simple spherical cap. The axisymmetric buckling load for cup-cylinder end-closures is found to be much higher than that of the dome-cylinder for the same thickness ratio, cylinder height and cup or dome angle. In the case of dome-cylinder end-closures, it is found that its buckling load is even lower than that of the cylinder. Circumferential stresses at the junction of a cup-cylinder end-closure at the axisymmetric critical load is so high that the failure of this end-closure would always be either due to yielding or asymmetric buckling. A new experimental technique has also been developed for testing the instability of axisymmetric shells. Electrodeposited cap-cone model specimens are tested for instability using this experimental technique. Results of the experiment show that the cap-cone models of tip ratio, r/R, about 0.80 can sustain the highest load and is least imperfection sensitive. The conical portion of the cap-cone end-closures were found to buckle asymmetrically with a number of circumferential lobes. Comparison of the analytical buckling load for both the axisymmetric as well as the asymmetric buckling with the experimental results show that the experimental results are in good agreement with asymmetric buckling load but the axisymmetric buckling loads are found to be about 10 to 15 times higher than the experimental results. At zero cone height, when it is a pure spherical cap with compatible angle (180°-11°), axisymmetric analytical results are found to agree with the experimental results. It is also found that the spherical cap models are highly sensitive to imperfections.

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32. Kalnins, A., "Analysis of Shells of Revolution Subject to Symmetrical and Nonsymmetrical Loads". Journal of Applied Mechanics,


ABSTRACT: The instability under pressure of conical end caps with spherical tips when used as end closures to pressure vessels is studied in this paper. The spherical tip of the conical end cap was assumed to be attached in such a way that continuity of the slope at the cone/sphere junction was maintained. The geometrical parameters of the spherical-tip conical end closure are the ratio r/R; the apex angle of the conical frustum; and the thickness ratio R/h, where r and R are respectively the radius of the cone at the sphere/cone and vessel/cone junctions and h is the thickness of the shell. Governing nonlinear differential equations of axisymmetric deformation which ensure the unique states of lowest potential energy under given pressure have been solved by using the method of multisegment integration, developed by Kalnins and Lestingi. The results show that the critical pressure for the end closure decreases with increasing apex angle at constant values of R/h and r/R. At constant values of _® and R/h, the critical pressure remains constant over a considerable range of r/R and then decreases to a minimum value at r/R = 1Σ0 which corresponds to a purely spherical end cap without the conical extension.

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ABSTRACT: The stability of a toroidal pipe-reducer system is determined here from the solution of non-linear governing equations of axisymmetric deformations of shells of revolution. Numerical solutions are obtained by a modified version of the computer program developed by Uddin for solving the governing equations of axisymmetric shells by the multisegment method of integration. The interpretation of instability of the toroidal reducers is based on Thompson's theorems I and II. Critical pressures for the toroidal reducers are calculated over useful ranges of the curvature ratio, the thickness ratio, and the diameter ratio. It has been found that the critical pressure of these reducers varies almost linearly with the diameter ratio and that the long toroidal reducers are prone to local instability near the larger end. But this critical zone occurs near either one of the two ends as the reducer becomes shorter. The results of stability and stress analysis of toroidal pipe-reducers are compared here with those of conical reducers obtained by Ali and parabolic reducers obtained by Rahman. Comparison shows that toroidal reducers develop uniform stresses of lower magnitude compared to the other two. Further, toroidal reducers are found to sustain higher critical pressure than parabolic reducers except at higher diameter ratio.

Raisuddin Khan (1), M.A. Salam Akanda (2) and Wahhaj Uddin (3), (1) BIT, Chittagong, Bangladesh (2) BUET, Dhaka, Bangladesh (3) Tuskegee University, Tuskegee, AL 36088, USA

ABSTRACT: In this paper, a new experimental technique for the buckling test of shells under external pressure is presented. This technique is simple and determines buckling load very efficiently. It has already been used
extensively in the investigation of buckling load of electroformed spherically conical shells under uniform external pressure. In this method, instead of the conventional monitoring of load and linear displacement of points on a shell, load and change in internal volume of the shell are recorded. Internal volumetric change of a shell is found to be a better indicator of its instability compared to the change in displacements of points on its surface. Volumetric change, a function of all the displacements and rotations contributing to the total change in its configuration, is observed to be a highly magnified indicator of shell deformation encompassing the whole shell, primarily the buckling zones and imperfection locations.

References listed at the end of the paper:
interaction with instability is significant, in that imperfections associated with fabrication of shells reduce the load bearing capacity by a significant amount even when thickness is considerable. A specific buckling analysis is used to predict collapse failure of long pressure vessels and pipelines when they are subjected to external over-pressure. The problem of buckling for variable load conditions is relevant for the optimisation of several Nuclear Power Plant applications as, for instance, the IRIS (International Reactor Innovative and Secure) LWR integrated Steam Generator (SG) tubes. In this paper, we consider in addition to the usual assumptions of thin shell, homogeneous and isotropic material, also the tube geometric imperfections and plastic deformations that may affect the limit load. When all those conditions are considered at present, a complete theoretical analysis was not found in the literature. At Pisa University a research activity is being carried out on the buckling of thin walled metal specimen, with reference to several geometries and two different stainless steel materials. A test equipment (with the necessary data acquisition facility), suitable for carrying out many test on this issue, as well as numerical models implemented on the MARC FEM code, were set up. In this report, the results of the performed analyses of critical pressure load determination with different numerical and experimental approaches are presented. The numerical results obtained are compared with the experimental results, for the same geometry and loading conditions, showing a good agreement between these two approaches.

G. Forasassi, R. Lo Frano (Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Via Diotisalvi, n°2-56126 Pisa, Italy), “Curved thin shell buckling behaviour”, Journal of Achievements in Materials and Manufacturing Engineering, Vol. 23, No. 2 August 2007

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For another version published in 2006 with reversed order of the two authors, see: Journal of Achievements in Materials and Manufacturing Engineering, Vol. 18, Nos. 1-1, September-October 2006

2008 VERSION ABSTRACT: The article presents a study about the buckling behavior of imperfect thin cylindrical shells under lateral pressure. It notes that the behavior of cylindrical shells under external pressure is very sensitive to geometric imperfections. Moreover, when thin shells are subjected to external pressure, the collapse is initiated by yielding. It also emphasizes that buckling phenomenon occurs when most of the strain energy can be converted to the bending energy which requires large deflections. In addition, it discusses the major factors which affect the collapse pressure of pipes such as the diameter-to-thickness ratio, the young's
modulus and the yield stress of the material in the circumference direction. Other details on the buckling behavior of cylindrical shells are discussed.

2008 Version References listed at the end of the paper:

R. Lo Frano and G. Forasassi (Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Italy), “Influence of the curved geometrical shape on the thin shell buckling phenomenon behavior”, Nuclear Engineering and Design, Vol. 239, No. 7, pp 1229-1236, 2009
ABSTRACT: The present paper deals with instabilities of long homogeneous and isotropic thin shells, characterized by geometrical non-linearities and imperfections, with reference to a bent helicoidally geometrical shape of particular interest for the helicoidal steam generators tube bundle. Apparently no data exist in the literature to describe the non-linear buckling behaviour of curved thin shells under external pressure, thus, the theoretical analyses based on the classical linear elastic theory, as expected, might be inadequate to evaluate the collapse load especially if the curvature is rather large. To the purpose of determining the buckling pressure load the effects of a pre-existing level of geometrical and technological imperfection, unavoidably caused by various manufacturing processes were also considered. A numerical analysis, based on detailed three-dimensional finite element (FE) code, was performed on curved thin shell subject to combined pressure and in-plane bending in order to take into account the non-linear geometrical and material properties as well as to assess and quantify their detrimental effects on the buckling phenomenon behaviour. Moreover, at Pisa University a rather intense experimental research activity is being carried out on the buckling of thin-walled tube specimens in the dimensional range suitable for the above mentioned applications. Collapse experiments have demonstrated that the detriment of the mechanical properties resulted in a reduction in the collapse pressure load of about 15% and the obtained results have highlighted also the dependence of the buckling
behaviour on the stress-initial defects/imperfection width (mainly on the diameter-to-thickness or tube/bending diameters ratios) relationship.

Rosa Lo Frano and Giuseppe Forasassi (Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Italy), “Preliminary analysis of the structural effects due to dynamic loads of the isolated next generation lead cooled reactor”, 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20), Espoo, Finland, August 9-14, 2009

ABSTRACT: The main purpose of this preliminary study deals with the evaluation of the structural effects due to the dynamic loads exerted and propagated through the lead coolant during a safety shut down earthquake with reference, as an example, to the isolated ELSY system configuration (CEE-7 Framework Project). Seismic base isolation is increasingly used to protect structures and their contents against dangerous ground motions as well as mitigate the structural effects, on the internals walls and reactor components of the induced dynamic load and of the coupling between coolant and vessel. An adequate predictive numerical modelling, by means a 3-D finite element model, was set up and a non-linear approach was used for the foreseen structural preliminary analyses and simulations of the plant and internals behaviours, in order to describe the interactions among the different subsystems. Moreover the fluid-structure interaction problem, due to the high density of the primary coolant has received a particular attention in relation to the possible hydrodynamic interaction, between lead and the surrounding internals, as well as the sloshing wave motion that may significantly influence the stress level in the reactor pressure vessel. As for the seismic analysis, isolation systems may influence the seismic capacity of as-built structure to reduce the intensity of the propagated seismic loads. Numerical results are presented and discussed highlighting the importance of the fluid-structure interaction effects as well as the isolation technique effectiveness, which is expected to be effective in raising the reliability of internals and vessel structures, during an earthquake event.


ABSTRACT: The current research seeks to demonstrate that an inverse solution approach, leveraging nonlinear finite element analysis with a divide and conquer type stochastic search algorithm, can identify the presence of localized denting imperfections in cylindrical shell structures. This imperfection field identification is achieved using rather sparse displacement measurements taken at safe, service loading conditions. Both the existence and nature of the imperfection field present in a given shell structure instance are determined. These inferred imperfections are subsequently used to make reasonably accurate predictions regarding the actual shell structure strength at ultimate loading.

References at the end of the article:
Christopher J. Stull (1), Jonathan M. Nichols (2) and Christopher J. Earls (3)
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ABSTRACT: It is now widely known that the presence of geometric imperfections in shell structures constitutes an important contribution to the discrepancy between theoretical and experimentally realizable ultimate loads governed by buckling. The present paper describes a method by which an actual initial imperfection field may be estimated using the service load response of a shell structure. The approach requires solving a stochastic inverse problem wherein uncertainty regarding initial imperfection predictions is expressed within the context of a Bayesian posterior distribution. The proposed approach could be applied to condition assessment and performance evaluation activities in practice.


ABSTRACT: The paper takes a phenomenological (topological) look at the Shanley model. Allowable loading sequences of a perfect system are first traced in closed form. By employing the smoothly-varying properties of an associated elastic potential function, comparisons are then made between the asymptotic predictions of a standard perturbation procedure, and a new scheme developed in accordance with the underlying topology. The new scheme is found to converge rapidly to the exact equilibrium paths, indicating compatibility in a global as well as a localized sense.


ABSTRACT: The recognized harmonic buckling modes for the elastic axially-loaded cylinder are by nature symmetric, equal and opposite amplitudes giving equal energy levels. On the other hand, in combination they account for considerable asymmetry, inwards deflection being fundamentally different from outwards; this asymmetry is also apparent in the underlying differential equations, and in the final large-deflection Yoshimura pattern. Taking the view that underlying symmetries are closely linked to the form of bifurcation experienced on buckling, and hence to the gross instability of the phenomenon, the paper thus explores a classic problem in a new light. The wellknown Donnell equations are first employed, the analysis being neatly written in terms of the two variables radial displacement w and stress function phi. An extension is then presented, derived from the full strain-displacement equations appropriate to genuinely large deflections. This makes use of a suite of computer programs, written for a small micro, which handle the required manipulations of multiplication and integration of harmonic functions in algebraic rather than numerical fashion.


ABSTRACT: The paper presents a selective review of modern bifurcation theory and its relationship to structural instability, with consequent implications for structural design. In particular, the complex non-linear analysis that is sometimes found in such work is avoided, by concentrating instead on easily recognizable symmetry properties. Simple spring and rigid-link models, such as the well-known Shanley model, are used to aid description...
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ABSTRACT: Double-scale perturbation analysis of a long elastic cylindrical shell under axial compression reveals a second-order non-linear differential equation for the buckle-pattern amplitude in slow-space. Numerical solution then suggests that the most easily-triggered failure mode is localized along the length. The method is extended to include mode interaction, giving three coupled second-order non-linear differential equations in slow-space. Localized solutions are again found, by combining features of the Lagrangian function with a systematic numerical search procedure. The predicted extent of the localization, about one-and-a-half axial wavelengths when fully developed, compares well with published experiments on long cylinders. Moreover, in contrast to the associated periodic solutions, “square” waves at the minimum critical load are denied; the predominant waveform turns out to be long axially, again as seen experimentally.


ABSTRACT: Localization theory for long continuous structures is extended to the buckling of a thin elastic strut supported by a bilinear elastoplastic medium. It is demonstrated that the form of localization has much in common with the buckling of struts on linear and nonlinear elastic foundations in that the localized response, which is of the greatest practical significance, is accompanied by a myriad of associated less significant solutions including periodic ones. Special shooting techniques are developed to deal with the problem of finding the localized solutions from amongst all competing possibilities.

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ABSTRACT: Buckling is investigated of a long thin cylindrical shell under longitudinal compression as modelled by the von Kármán–Donnell equations. Evidence is reviewed for the buckling being localized to some portion of the axial length. In accordance with this observed behaviour the equations are first approximated circumferentially by a Galerkin procedure, whereupon cross-symmetric homoclinic solutions of the resulting system of ordinary differential equations are sought in the axial direction. Results are compared with experimental and other numerical data. Excellent agreement with experiments is achieved with fewer approximating modes than other methods.

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ABSTRACT: A structural system with an unstable post-buckling response that subsequently restabilizes has the potential to exhibit homoclinic connections from the fundamental equilibrium state to itself over a range of loads, and heteroclinic connections between fundamental and periodic equilibrium states over a different (smaller) range of loads. It is argued that such equilibrium configurations are important in the interpretation of observed behaviour, and govern the minimum possible post-buckling loads. To illustrate this, the classical problem of a long thin axially-compressed cylindrical shell is revisited from three different perspectives: asymptotic conjecture, analogy with nonlinear dynamics, and numerical continuation analysis of a partial spectral decomposition of the underlying equilibrium equations. The nonlinear dynamics analogy demonstrates that the structure of the heteroclinic connections is more complicated than that indicated by the asymptotics: this is confirmed by the numerics. However, when the asymptotic portrayal is compared to the numerics, it turns out to be surprisingly accurate in its Maxwell-load prediction of the practically-significant first minimum to appear in the post-buckling regime.

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ABSTRACT: Experiments have shown that long cylinders buckle into localized patterns axially. It is argued that traditional linear or nonlinear analysis is unlikely to capture such modes, nor the effective buckling load at which such responses stabilize. However, the inherent translational indeterminacy of localized buckling is well captured by considering infinitely long cylinders and seeking homoclinic solutions of the von Kármán Donnell equations. This exploits the dynamical analogy of such structural problems, so that symmetry arguments and numerical techniques developed for dynamical systems may be used. The method is illustrated by successful application to a cylinder which has well documented experimental results.

DOI:10.1137/S1064827597321647

ABSTRACT: This paper concerns numerical computation of localized solutions in partial differential equations (PDEs) on unbounded domains. The application is to the von Kármán--Donnell equations, a coupled system of elliptic equations describing the equilibrium of an axially compressed cylindrical shell. Earlier work suggests that axially localized solutions are the physically preferred buckling modes. Hence the problem is posed on a cylindrical domain that is unbounded axially and solutions are sought which are homoclinic in the axial variable and periodic circumferentially. The numerical method is based on a Galerkin spectral decomposition circumferentially to pose ordinary differential equations (ODEs) in the unbounded coordinate. Methods for location and parameter continuation of homoclinic solutions of ODEs are then adapted, making special use of the symmetry and reversibility properties of solutions observed experimentally. Thus a formally well-posed continuation problem is reduced to a rotational subgroup circumferentially and posed over a truncation of the
half-interval axially. The method for location of solutions makes use of asymptotic approximations where available. More generally, an adaptation of the "successive continuation" shooting method is used in the lowest possible number of circumferential modes, followed by additional homotopies to add more modes by continuation in the strength of nonlinear mode-interaction terms. The method is illustrated step by step to produce a variety of homoclinic solutions of the equations and compute their bifurcation diagrams as the loading parameter varies. Good agreement with experimental data is found. All computations are performed using AUTO. The techniques illustrated here for the von Kármán--Donnell equations are applicable to a wider class of PDEs.

References listed at the end of the paper: (Cannot cut and paste them)


ABSTRACT: We study the deformation of an elastic strut on a nonlinear Winkler foundation subjected to an axial compressive load P. Using multi–scale analysis and numerical methods we describe the localized, cellular, post–buckled state of the system when P is removed from the critical load P = 2. The solutions, and their modulation frequencies, differ significantly from those predicted by weakly nonlinear analysis very close to P = 2. In particular, when P approaches the Maxwell load PM , the localized solutions approach a large–amplitude heteroclinic connection between an unbuckled solution and a periodic solution. An asymptotic description of PM in terms of the system parameters is given. The agreement between the numerical calculations and the asymptotic approximations is striking.

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ABSTRACT: A hypothesis for the prediction of the circumferential wavenumber of buckling of the thin axially-compressed cylindrical shell is presented, based on the addition of a length effect to the classical (Koiter circle) critical load result. Checks against physical and numerical experiments, both by direct comparison of wavenumbers and via a scaling law, provide strong evidence that the hypothesis is correct.

References at the end of the article:
ABSTRACT: A personal view is presented of developments in the non-linear mechanics of structural buckling over more or less the past four decades. The era has been one of unprecedented change and development in the world of science as a whole, and this is acknowledged by describing ways in which the field has interacted strongly with other areas of study, including mathematics, non-linear dynamics and chaos and structural geology. A framework is provided through two key conferences that have emerged as pivotal moments in time when ideas seemed to take shape in a collective sense rather than just with individuals. Throughout most of the paper, the buckling of the axially compressed cylindrical shell is used to illustrate key features, including the breaking of hidden symmetry, localization and snaking solutions leading to a minimum energy periodic state that accords with a revitalized Maxwell stability criterion. The paper closes with some thoughts to the future, including the modelling of layered structures in geology and potential uses of modern composites.

ABSTRACT: Buckling-driven delamination is considered among the most critical failure modes in composite laminates. This paper examines the propagation of delaminations in a beam under pure bending. A pre-developed analytical model to predict the critical buckling moment of a thin sub-laminate is extended to account for propagation prediction, using mixed-mode fracture analysis. Fractography analysis is performed to distinguish between mode I and mode II contributions to the final failure of specimens. Comparison between experimental results and analysis shows agreement to within 5 per cent in static propagation moment for two different materials. It is concluded that static fracture is almost entirely driven by mode II effects. This result
was unexpected because it arises from a buckling mode that opens the delamination. For this reason, and because of the excellent repeatability of the experiments, the method of testing may be a promising means of establishing the critical value of mode II fracture toughness, $G_{IIc}$, of the material. Fatigue testing on similar samples showed that buckled delamination resulted in a fatigue threshold that was over 80 per cent lower than the static propagation moment. Such an outcome highlights the significance of predicting snap-buckling moment and subsequent propagation for design purposes.

References listed at the end of the paper:

ABSTRACT: Similarities and differences between the phenomena of kink banding in compressed layered structures and shear banding in compressed granular media are explored. Simple models are introduced for both, and the focus is directed onto how they can nucleate from the perfectly flat state. A convincing scenario is found for each in which a mode develops from an initial bifurcation into a periodic state, followed by rapid localization under falling load, while retaining decaying but wavy tails. At a certain lower critical load, the tails lose their waviness, and the expected form of the kink or shear band appears. In each case, good numerical evidence is provided for the existence of this form of behaviour. A second potential instability for the layered case is also explored, linked to the appearance of a critical force dipole that overcomes bending stiffness locally at some point along the length. This mode, which should appear with non-wavy decaying tails at the lower of the two critical loads mentioned earlier, proves somewhat elusive. Evidence is found for its existence in the linearized approximation to the layered model, but the search for numerical solutions to the underlying nonlinear equation is hindered by a shortage of suitable boundary conditions.

List of references at the end of the paper:


ABSTRACT: The two- and three-dimensional contact algorithms used in the finite element programs developed at the Lawrence Livermore National Laboratory are described in this paper. We are interested in both static contact and dynamic impact problems and, consequently, have pursued the development of two different algorithms. The first, based on the hydrocode technology of the sixties, is implemented in our two- and three-dimensional explicit finite element codes. The second, a symmetric penalty treatment, is used in our implicit codes and is optional in the explicit codes. The penalty methods are used to obtain solutions to almost all of our structural problems but we find that the hydrocode approach is vastly superior if pressures greatly exceed the yield strength. Examples are provided to show practical applications of both approaches.

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ABSTRACT: In some of our applications we are interested in how a structure behaves after it buckles. When a structure collapses completely, a single surface may buckle enough that it comes into contact with itself. The traditional approach of defining master and slave contact surfaces will not work because we do not know a priori how to partition the surface of the structure. This paper presents a contact algorithm that requires only a single surface definition for its input.
ABSTRACT: This report provides a user's manual for NIKE3D, a fully implicit three-dimensional finite element code for analyzing the finite strain static and dynamic response of inelastic solids, shells, and beams. Spatial discretization is achieved by the use of 8-node solid elements, 2-node truss and beam elements, and 4-node membrane and shell elements. Over twenty constitutive models are available for representing a wide range of elastic, plastic, viscous, and thermally dependent material behavior. Contact-impact algorithms permit gaps, frictional sliding, and mesh discontinuities along material interfaces. Several nonlinear solution strategies are available, including Full-, Modified-, and Quasi-Newton methods. The resulting system of simultaneous linear equations is either solved iteratively by an element-by-element method, or directly by a factorization method, for which case bandwidth minimization is optional. Data may be stored either in or out of core memory to allow for large analyses.

References listed at the end of the manual:


ABSTRACT: A review of contact algorithms under the aspects of mathematical exactness and practical applicability is given. The basic assumptions and possibilities of some of the main algorithms are displayed, and recommendations are given for a synthesis of different approaches. Numerical experiments and comparisons show the efficiency of existing programs.

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ABSTRACT: In this article we discuss the treatment of contact—impact modeling in a large deformation explicit dynamic setting. Such problems are posed mathematically by demanding the usual satisfaction momentum balance equations and boundary conditions for each body separately, while imposing an additional set of constraints that govern the interaction of these bodies with each other. In applying such methods to contact problems we emphasize two requirements: first, that the treatment of contact should follow from the development of the local (weak) and global (strong) forms of the contact equations in the continuum setting. Algorithms developed from this framework are seen to readily handle the three-dimensional multi-body friction case. Second, and equally important especially in large applications is the practical aspect of computing the closest point projection for contact nodes, an essential component of defining the contact constraints. This calculation is global in nature, accounting for the fact that contact—impact involves multiple bodies interacting in unforeseeable ways. These requirements have guided the development of algorithms capable of treating contact—impact in PRONTO3D (M.W. Heinstein, S.W. Attaway, J.W. Swegle, F.J. Mello, A general purpose contact detection algorithm for nonlinear structural analysis codes, SAND92-2141, Sandia National Laboratories, Albuquerque, N-87185, 1992) are discussed in this paper.

CONCLUSIONS: Decisive factors, which have a considerable effect on the stability of cylindrical shells with exfoliations are the area of the region of the exfoliations, the location of the exfoliation region along the thickness and length of the shell, and the nature (discontinuity) of the exfoliation along the length of the shell. The strongest effect on the stability proves to be the exfoliations, equidistant from the annular reinforcing ribs and situated in the neighborhood of the middle surface of the shell. With the arrangement at the end of the shell, what is most dangerous is the discontinuous exfoliation, and in the middle part, continuous exfoliation. The nature of the exfoliation in the circumferential direction does not have a noticeable effect on the critical load of
the total stability of the shell. But we should expect a considerable reduction of the local stability (fracture by separation of the inner layers). The prediction and calculation of such a form of fracture is an independent problem, which has not been considered in the present study. An increase in the value of the opening of exfoliation, which has an effect on the bending stiffness and extension (compression) stiffness leads to a reduction in the critical load. The formulas presented for the critical load can be applied for normalization of the exfoliations. The calculation of such norms assumes the carrying out of a series of tests, as a result of which there should be agreement between calculated and experimental data, and margins of stability are introduced, ensuring reliable operation of shells with defects. The assumption of norms for the defects is economically profitable, since it enables us to use shells having exfoliations whose effects on the critical loads are no significant.

References listed at the end of the paper:


ABSTRACT: The effects of the presence of a delamination on the buckling load of composite laminates under compression are investigated. The linearized buckling analysis for two- and three-dimensional solid finite elements is proposed as an effective and practical tool for the prediction of the critical loads both for bi-dimensional and for tri-dimensional cases. The accuracy of the numerical procedure is assessed by comparing the results with existing analytical solutions obtained from the literature for simple bi-dimensional applications. A tri-dimensional analysis is then presented for the case of a square plate with a circular delamination. The effects of radius and depth of the delamination on the buckling load are also illustrated.

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ABSTRACT: The post-buckling behaviour of compressed composite laminates in presence of a through-width delamination is considered. A 2D finite element procedure is proposed as an effective and practical tool for the nonlinear analysis of the examined structure. An incremental analysis is performed with the introduction of contact constrains to fully account for the real behaviour of the structure. Some illustrating examples are then presented which show the effect of the geometry of delamination on the post-buckling behaviour. Local and global buckled geometries of the deformed structures are also shown corresponding to different levels of the compressive loading.
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ABSTRACT: The present study focuses on the determination of the buckling load and post-buckling behaviour of simply supported laminated composite rectangular panels loaded in shear. The nonlinear structural response is studied with a non-linear finite element approach. In order to determine the accuracy of the procedure, several tests have been performed comparing the finite element solutions for isotropic and laminated composite rectangular panels with existing ones, adopting different sequences of lamination and different length to width ratios. The analysis then considers the behaviour of laminates produced with innovative thermoplastic matrix composites developed in the frame of a national research program.

P Gaudenzi, P Perugini, A Riccio, Post-buckling behavior of composite panels in the presence of unstable delaminations, Composite Structures 51 (3), 301-309, 2001
ABSTRACT: The analysis of the non-linear behavior of delaminated composites panels under compression is considered. A modification to the incremental continuation method (by Riks) for the analysis of the non-linear behavior of damaged composites is proposed to improve the numerical treatment of the analysis of unstable delamination growth. The theoretical formulation of this modification is first presented in conjunction with a general formulation of the continuation method and the modified virtual crack closure technique (MVCCT) for the evaluation of delamination growth. Finally, numerical results for delaminated composite plates through the width and circular delaminations are presented and compared with existing experimental and numerical data.

ABSTRACT: The buckling and postbuckling behaviors of composite laminates with multiple delaminations under uniaxial compression are experimentally studied. The through-width multiple delaminations with triangular shape are used to simulate impact damage. A nonlinear buckling analysis from finite element method is also used to predict the buckling loads that are compared with experimental results. The critical delamination growth loads of multiple delaminations are obtained from postbuckling tests. The difference of single delamination and multiple delaminations on buckling behavior and postbuckling behavior is discussed. The results indicate that the buckling loads obtained by the nonlinear buckling analysis are in reasonable agreement with the experimental values. Experiments have proven that short delaminations distributed under the near-surface, long delamination have no effects on the buckling loads. The critical delamination growth loads of single-delamination specimens are much higher than those of multiple-delamination specimens, and the shape of the triangular multiple delaminations can affect the critical delamination growth loads.

ABSTRACT: Finite element procedures for the analysis of composite structures under compressive loads (buckling and post-buckling) generally are not deployed in books because they are still considered object of research whereas they are deemed as assessed by researchers that focus their papers on restricted audience topics. Therefore, regarding these procedures, a gap exists in literature between what researchers consider as well established and what has been already published. The aim of this paper is to contribute to close this gap by providing an insight in linear and non-linear buckling analyses and in their use with composite structures. Both modelling and analysis considerations are presented and discussed, focusing on what can be considered as best practice when dealing with this kind of problems. Applications (to a stiffened panel and to a wing box) are provided for demonstrating the effectiveness of the procedures presented.

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17. ANSYS 12.1 user manual
20. ASTM D7137/D Standard Test Method for compressive residual strength properties of damaged polymer matrix composites plates

ABSTRACT: An approximate method for analyzing the elastic buckling of Mindlin plates is proposed. The solutions of the differential equations of buckling of Mindlin plate are obtained in discrete forms by applying numerical integration. The discrete solutions give the transverse shear forces, twisting moment, bending moments, rotations and deflection at the all discrete points which are the intersections of the vertical and horizontal equally dividing lines on the plate. In order to confirm the convergency and accuracy of numerical solutions, the buckling loads of simply supported square Mindlin plates are calculated, and the results are compared with other published finite element solutions. As an application, the buckling loads and buckling modes of Mindlin plates with various types of mixed boundaries are calculated.


ABSTRACT: A discrete method is proposed for analyzing the natural vibration problem of rectangular plates with a line hinge. The fundamental differential equations and the solutions of these equations are derived for two parts of the plate, which are obtained by dividing the plate along the line hinge. By transforming these equations into integral equations, and using numerical integration and the continuous conditions along the line hinge, the solutions of the whole plate can be expressed by the unknown quantities on the boundary and the quantities of the rotation along the hinge. The Green function of the deflection problem is used to obtain the characteristic equation of the free vibration. The effects of the position of the line hinge, the aspect ratio, the thickness ratio and the boundary condition on the natural frequency parameters are considered. By comparing the numerical results obtained by the present method with those previously published, the efficiency and accuracy of the present method are investigated.


ABSTRACT: (none given)

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“Reference surface element modelling of composite plate/shell delamination buckling and postbuckling”,
ABSTRACT: A recently developed reference surface element technique is used to model the behaviour of
the buckling and postbuckling of delaminated plates and shells. The technique can be easily incorporated into any
finite element analysis programme for which the beam, plate and shell elements etc. satisfy the Reissner–
Mindlin assumption. In this paper, the reference surface element formulation of a four-node Co quadrilateral
membrane-shear-bending element (ZQUA24) is presented and numerical investigations are performed for
composite plates and shells with various delamination shapes. The numerical results show that the present
technique is simple, reliable and able to model delamination buckling and postbuckling behaviour of laminated
plates or shells. Observations of practical engineering significance are obtained from the study.

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ABSTRACT: The subject of this paper is the buckling of laminated plates, with a pre-existing delamination,
subjected to in-plane loading. Each laminate is modelled as an orthotropic Mindlin plate. The analysis is carried
out by a combination of the finite element and asymptotic expansion methods. By applying the finite element
method, plates with general delamination regions can be studied. The asymptotic expansion method reduces the
number of unknown variables of the eigenvalue equation to that of the equation for a single Kirchhoff plate.
Numerical results for the critical buckling load are presented for several examples. The effects of the shape, size
and position of the delamination on the buckling load are studied through these examples.

G. Steinmetz, F.J. Arendts and R. Nething (Institut für Flugzeugbau, Universität Stuttgart, Pfaffengrundring 31,
7000, Stuttgart 80, West-Germany), “Delamination buckling of laminated plates”, Chapter in Developments in
the Science and Technology of Composite Materials, edited by Fuller, Gruninger, Schulte, Bunsell and
ABSTRACT: The compressive strength of composite plates can be considerably reduced if they are damaged
by delaminations. To study the failure process buckling loads of laminates that contain rectangular, circular and
elliptical delaminations are calculated using two models based on the Rayleigh-Ritz and finite element method.
The influence of several parameters such as stacking sequence, flaw size, flaw location and flaw shape is
investigated and the results are plotted in diagrams. It can be distinguished between local buckling of the
debonded sublamine, buckling of the total plate and an interaction of both cases.
ABSTRACT: Delamination buckling of laminated composite structures with curvature, plays a critical role in affecting the compressive behavior as it may cause localized buckling and the high interlaminar shear and normal stresses at the edges of the buckled regions which often lead to delamination growth. Since an early contribution by Kachanov[1], the delamination buckling problems have received substantial attention in last decade. Chai et al.[2] modelled delamination buckling and crack growth of laminated plates using a simple one-dimensional beam theory. The energy release rate, was computed by evaluating the total potential energy of the plate and differentiating the result with respect to the variable length of delamination which determines the stability characteristics of delamination growth. Whitcomb[3, 4] who is among the first to use a nonlinear finite element method for analyzing local post-buckling of an embedded delamination in laminated plate considered the influence of crack tip mode dependence and contact at delamination buckling in a three-dimensional finite element formulation.

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[8] G. P. Nikishkov and S. N. Atluri, Calculation of fracture mechanics parameters for an arbitrary three dimensional crack by the
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ABSTRACT: Location of delamination is a triggering parameter for structural instability of laminated composites. In this paper, a finite element method is employed to determine the effects of location of delamination on free vibration characteristics of graphite-epoxy cross-ply composite pre-twisted shallow conical shells. The generalized dynamic equilibrium equation is derived from Lagrange’s equation of motion neglecting Coriolis effect for moderate rotational speeds. The formulation is exercised by using an eight noded isoparametric plate bending element based on Mindlin’s theory. Multi-point constraint algorithm is utilized to ensure the compatibility of deformation and equilibrium of resultant forces and moments at the delamination crack front. The standard eigen value problem is solved by applying the QR iteration algorithm. Finite element codes are developed to obtain the numerical results concerning the effects of location of delamination, twist angle and rotational speed on the natural frequencies of cross-ply composite shallow conical shells. The mode shapes are also depicted for a typical laminate configuration. Numerical results obtained from parametric studies of both symmetric and anti-symmetric cross-ply laminates are the first known non-dimensional natural frequencies for the type of analyses carried out here.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: This paper deals with the development of the linearized equation governing the buckling behavior of moderately thick, anisotropic, laminated, and sandwich cylindrical shell panels faced with fiber-reinforced plastic under uniform shear and normal membrane forces. The formulation takes into account the transverse shear flexibility. Two approaches for the approximate solution of the elastic stability equation are developed. The first approach is an analytical approach of the Galerkin type and rests upon the principle of virtual work. The second is a finite-element displacement approach. Some numerical results are presented and compared with other results from the open literature.

References listed at the end of the paper:

30 Greenberg, J. B. and Stavsky, Y., "Stability and Vibration of Compressed, Aeolotropic, Composite Cylindrical Shells," Journal of

ABSTRACT: In a recent paper, the author has developed the equations governing the elastodynamic behaviour of moderately thick multilayered anisotropic plates by making use of a displacement field which allows a non-linear variation of the inplane displacements through the laminate thickness and fulfils a priori the static and geometric continuity conditions. In the present paper, the author specializes those results by developing a third-order shear deformation plate model with continuous interlaminar stresses. To show the accuracy and reliability of the proposed approach, closed-form solutions are given and compared with results from three-dimensional elasticity and other approximate bidimensional plate models with and without continuous interlaminar stresses. Based on the numerical investigation conducted, the proposed approach appears to work very well.

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PARTIAL ABSTRACT: A theory of multilayered anisotropic plates featuring interlaminae imperfections in the form of interlayer slips is presented. The theory rests upon a representation of the displacement field which: i) fulfills a priori the transverse shear stress continuity conditions at each interface of the laminate and the free traction on the top and bottom external planes of the plate, ii) satisfies the requirement of continuous displacements at the perfectly bonded interfaces, and iii) allows for jumps in the in-plane displacements when slip-type interlayer imperfections are present. Numerical results illustrating their implications upon the linear and nonlinear static response of laminated plates are displayed and pertinent conclusions are…

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ABSTRACT: The role of mesh design in the post-buckling analysis of delamination in composite laminates is addressed in this paper. The determination of the strain energy release rate (SERR) along the crack front is central to the analysis. Frequently, theoretical analysis is limited to treatment of the problem in two dimensions, since considerable complexity is encountered in extending the analysis to three dimensions. However, many practical problems of embedded delamination in composite laminates are inherently three-dimensional in nature. Although in such cases, the finite element (FE) method can be employed, there are some issues that must be examined more closely to ensure physically realistic models. One of these issues is the effect of mesh design on the determination of the local SERR along the delamination front. There are few studies that deal
with this aspect systematically. In this paper, the effect of mesh design in the calculation of SERR in two-dimensional (2D) and three-dimensional (3D) FE analyses of the post-buckling behavior of embedded delaminations is studied and some guidelines on mesh design are suggested. Two methods of calculation of the SERR are considered: the virtual crack closure technique (VCCT) and crack closure technique (CCT). The 2D analyses confirm that if the near-tip mesh is symmetric and consists of square elements, then the evaluation of the SERR is not sensitive to mesh refinement, and a reasonably coarse mesh is adequate. Despite agreement in the global post-buckling response of the delaminated part, the SERR calculated using different unsymmetrical near-tip meshes could be different. Therefore, unsymmetrical near-tip meshes should be avoided, as convergence of the SERR with mesh refinement could not be assured. While the results using VCCT and CCT for 2D analyses agree well with each other, these techniques yield different quantitative results when applied to 3D analyses. The reason may be due to the way in which the delamination growth is modeled. The CCT allows simultaneous delamination advance over finite circumferential lengths, but it is very difficult to implement and the results exhibit mesh dependency. Qualitatively, however, the two sets of results show similar distributions of Mode I and Mode II components of the SERR. This is fortunate, since the VCCT is relatively easy to implement.

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“Delamination buckling and propagation analysis of honeycomb panels using a cohesive element approach”,

ABSTRACT: The cohesive element approach is proposed as a tool for simulating delamination propagation between a facesheet and a core in a honeycomb core composite panel. To determine the critical energy release rate (Gc) of the cohesive model, Double Cantilever Beam (DCB) fracture tests were performed. The peak strength (sigma c) of the cohesive model was determined from Flatwise Tension (FWT) tests. The DCB coupon test was simulated using the measured fracture parameters, and sensitivity studies on the parameters for the cohesive model of the interface element were performed. The cohesive model determined from DCB tests was then applied to a full-scale, 914 x 914 mm (36 x36 in.) debond panel under edge compression loading, and results were compared with an experiment. It is concluded that the cohesive element approach can predict delamination propagation of a honeycomb panel with reasonable accuracy.

References listed at the end of the paper:

ABSTRACT: An energy functional for a structure on a nonlinear softening foundation is worked into two different lagrangian forms, in fast and slow space respectively. The developments originate independently of the underlying differential equation, and carry some quite general features. In each case, the kinetic energy is an indefinite quadratic form. In fast space, this leads to an escape phenomenon with fractal properties. In slow space, kinetic energy is added to a potential contribution that is familiar from modal formulations. Together, and in conjunction with a recent set of numerical experiments, they illustrate the extra complexities of localized, as opposed to distributed periodic, buckling.

ABSTRACT: A long structural system with an unstable (subcritical) post-buckling response that subsequently restabilizes typically deforms in a cellular manner, with localized buckles first forming and then locking up in sequence. As buckling continues over a growing number of cells, the response can be described by a set of
lengthening homoclinic connections from the fundamental equilibrium state to itself. In the limit, this leads to a heteroclinic connection from the fundamental unbuckled state to a post-buckled state that is periodic. Under such progressive displacement the load tends to oscillate between two distinct values. The paper is both a review and a pointer to future research. The response is described via a typical system, a simple but ubiquitous model of a strut on a foundation which includes initially-destabilizing and finally-restabilizing nonlinear terms. A number of different structural forms, including the axially-compressed cylindrical shell, a typical sandwich structure, a model of geological folding and a simple link model are shown to display such behaviour. A mathematical variational argument is outlined for determining the global minimum postbuckling state under controlled end displacement (rigid loading). Finally, the paper stresses the practical significance of a Maxwell-load instability criterion for such systems. This criterion, defined under dead loading to be where the pre-buckled and post-buckled state have the same energy, is shown to have significance in the present setting under rigid loading also. Specifically, the Maxwell load is argued to be the limit of minimum energy localized solutions as end-shortening tends to infinity.

References listed at the end of the paper:

ABSTRACT: A variational model is formulated that accounts for the localization of deformation due to buckling under pure bending of thin-walled elastic tubes with circular cross-sections. Previous studies have successfully modelled the gradual process of ovalization of the cross-section with an accompanying progressive reduction in stiffness but these theories have had insufficient freedom to incorporate any longitudinal variation in the tube. Here, energy methods and small-strain nonlinear elastic theory are used to model the combined effects of cross-section deformation and localized longitudinal buckling. Results are compared with a number of case studies, including a nanotube, and it is found that the model gives rise to behaviours that correlate well with some published physical experiments and numerical studies.

References listed at the end of the paper:
procedure, critical buckling loads and mode shapes being found by an ‘exact strip’ algorithm. The analysis is a postbuckling reserve of strength, which is mainly due to str

Marc Fischer, David Kennedy (Cardiff School of Engineering, Cardiff University, PO Box 686, The Parade, Cardiff CF24 3TB, United Kingdom), “Local Postbuckling Analysis Of Curved Aerospace Structures”, ICAS 2000 Congress, no date or publisher given in the pdf file, 2000?

ABSTRACT: Minimum mass design of aerospace structures is greatly enhanced by allowing for their postbuckling reserve of strength, which is mainly due to stress re-distribution within the structure following buckling in a local mode. The paper first outlines a geometrically non-linear analysis for longitudinally compressed panels, in which the ratio of postbuckling to prebuckling axial stiffness is established by an iterative procedure, critical buckling loads and mode shapes being found by an ‘exact strip’ algorithm. The analysis is
illustrated by its application to a simply supported, curved, stiffened panel. The paper next describes an incremental approach to the local postbuckling analysis of longitudinally stiffened cylindrical shells loaded by longitudinal compression and/or a bending moment. The shell is modelled as a collection of skin/stiffener portions, for each of which the critical buckling load and stiffness ratio are determined. Next the axial loads in each portion due to the applied loads are calculated under linear elastic assumptions, so that it is possible to determine which portion will buckle first. Thereafter the buckled portion is modelled with a reduced stiffness, so that the location of the shell’s neutral axis changes and is found by an iterative improvement to a method originally developed by Bruhn.

References listed at the end of the paper:


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“VICONOPT: Program for exact vibration and buckling analysis or design of prismatic plate assemblies”,


ABSTRACT: A summary is given of key features of the computer program VICONOPT, which covers prismatic assemblies of anisotropic plates exactly for buckling and vibration analysis and also for design subject to buckling constraints.

References listed at the end of the paper:


SUMMARY: The aim of this thesis is to investigate the local and global buckling behaviour of delaminated composite plates using exact stiffness analysis. Several attempts are made to model delamination with the accuracy of detailed 3D finite element analysis (FEA) but substantially improved computational efficiency. Investigation of local buckling behaviour is performed using the exact stiffness program VICONOPT, giving
good comparative results and substantially less solution times compared to those of FEA. Extending this approach to global buckling behaviour poses limitations and difficulties in retaining computational efficiency. Several techniques are introduced to study global buckling behaviour while requiring less solution time than FEA. The advantages and disadvantages of these techniques are discussed. Finally, an improved smeared stiffness method is derived which results from simplification of the total potential energy expression for the plate. This simplification avoids expensive computational effort while maintaining results of good accuracy (within 2%-3% of FEA results). This method can be employed for modelling delaminations of different shape and size located anywhere in the composite plate.

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ABSTRACT: For a structure subjected to an intermediate velocity impact in which the duration of loading is in the order of milliseconds and in excess of the period of its first free vibration mode there is a relationship between impact duration and buckling load. Although this relationship results in higher buckling loads for shorter duration impacts, the precise nature of the correlation depends on a number of other factors, one of which is geometry. Since the design of many lightweight structures subject to dynamic loading in this intermediate range is based on the use of a static buckling load to which a load factor is then applied, it is essential that this factor accurately represents the relationship between the two and takes of account of any variations. Failure to do so will at least result in an over designed structure and at worst in catastrophic failure.

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[2] Engineering Sciences Data Unit (ESDU): Flat Panels in Shear. Buckling of long panels with transverse stiffeners. ESDU 02.03.02 (1971).

Mahdi Damghani, David Kennedy and Carol Featherston (Cardiff School of Engineering, Queen’s Buildings,

ABSTRACT: The critical buckling of composite plates with through-the-length delaminations is studied using exact stiffness analysis and the Wittrick–Williams algorithm. Computational efficiency is achieved by avoiding discretisation into elements, making the method suitable for preliminary aircraft design. Numerical results for longitudinal, transverse and shear loading show a transition from global to local buckling modes as the delamination width is increased. The critical buckling strength is dramatically reduced as the delamination is moved towards the plate surface, but is relatively insensitive to its widthwise location or to the edge conditions. The results are compared with finite element analysis.


ABSTRACT: Recent developments in optical techniques have allowed accurate representations of the geometry of test specimens to be obtained. These enable the nature of geometric imperfections resulting from manufacture or set-up to be captured in a form which allows them to be incorporated directly into models generated to predict the behaviour of the structure. This study examines the effect of such imperfections on the behaviour of a series of panels, simply supported along all four edges, and subject to uniaxial compressive in-plane loading. In each case, digital image correlation is used to determine the initial profile and set-up of the panel and to monitor its behaviour during test. The data are used to automatically generate a series of meshes representative of each of the specimens tested, suitable for finite element analysis. Comparison of the results obtained from these analyses with those found during the experiments modelled shows an improved correlation when compared with standard techniques for assessing imperfection sensitivity. Set-up is straightforward, and models can be obtained quickly based on the data collected.


ABSTRACT: The post-buckling behavior of a stiffened panel is investigated in this paper. Firstly, the buckling mode of the stiffened panel is obtained using the linear buckling eigenvalue method. Then, the collapsing strength of the stiffened panel is calculated using the ultimate strength method based on large deflection orthotropic plate theory. In addition, nonlinear finite element analysis is performed to predict the post-buckling behavior of the stiffened panel. By comparing the model prediction and the analytical results of ultimate strength, it is shown that good accuracy can be achieved, especially for the method referring to membrane stress in mid-thickness of equivalent orthotropic plate. It suggests that the proposed method can predict the ultimate strength of whole stiffened panel accurately and effectively.


ABSTRACT: Computer programs which model the static, dynamic and aeroelastic response of wing structures, and which permit optimisation of such structures, have been under development for more than 30 years. However, the industrial application of these programs remains small. This paper provides an overview of some of the existing optimisation methods which may be applied at various stages during the design of wing
structures. An indication of the variety of design variables, constraints and objective functions available within these methods is given. Some general conclusions are drawn, about both the limitations and potential application of such structural optimisation techniques.

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doi: INIST-CNRS, Cote INIST : 214, 35400010064955.0230
ABSTRACT: The suitability of using the efficient, linear elastic design software VICONOPT for the analysis of a stiffened panel with a postbuckling reserve of strength is investigated. A longitudinally compressed panel, which initially buckled in a local skin mode, was analyzed with allowance being made for the effects of an initial overall imperfection. The panel was also analyzed using the nonlinear finite element package ABAQUS. and four laboratory specimens that represent the panel were tested to failure. The similarity of the experimental failure with the VICONOPT and ABAQUS predictions indicates that VICONOPT can give satisfactory analysis results for use in preliminary design.

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ABSTRACT: Postbuckling results are presented for isotropic stiffened panels loaded in compression. Comparisons are made between single-bay and double-bay finite element (FE) models (where bay denotes a repeating portion, between supports, in the load/length direction) and a new strut model, following a Shanley-type approach, for single-bay and multibay panels. The strut model has been incorporated within the strip program VIPASA with CONstrains and OPTimization (VICONOPT) to design a multibay example panel with postbuckling reserve of strength in its skins, assuming linear elastic material properties. The panel has been shown by VICONOPT to have a stiffener buckling failure mode when an overall sinusoidal imperfection causing increased stiffener compression is present. The failure is confirmed by the double-bay FE model, which is shown to be an imperfect representation of the multibay case. Single-bay analysis using the strut model shows good agreement with the single-bay FE results. The VICONOPT code is able to design a metallic panel of realistic dimensions and loading using 50 strip elements (compared with the 9600 shell elements required by the finite element model) but cannot correctly account for material nonlinearity. The important phenomenological difference between postbuckling of single-, double-, and multibay panel models are indicated.

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ABSTRACT: A phenomenological overview of the buckling and postbuckling of fully and partially delaminated struts is developed using a simple four-degree-of-freedom nonlinear Rayleigh-Ritz formulation. Bifurcation analysis indicates that instability occurs in general at an asymmetric point of bifurcation. After bifurcation, realistic solutions are seen to follow the stable part of the postbuckling path, with the unstable branch being denied by contact between the contributing laminates. Depending on the geometry and position of
the delamination, thoroughly stable (thin-film), effectively neutral (overall), or potentially unstable (mixed-mode) buckling can occur in the postbuckling range. Numerically obtained equilibrium solutions of the model are found to compare well with those obtained using the finite element code ABAQUS. Critical delamination depths, where the response undergoes a change in form, are discovered at positions of secondary bifurcation. The multiplicity of equilibrium solutions that arise at such points are seen to cause possible problems of path selection for standard finite element routines.

ABSTRACT: The paper presents a bilevel strategy for the efficient optimum design of composite stiffened panels using VICONOPT, a fast-running optimization package based on linear eigenvalue buckling theory, and embracing practical composite design rules. Panel level optimization finds a minimum weight cross-sectional geometry based on a substitution of equivalent orthotropic plates for laminated plates. Optimization at the laminate level finds stacking sequences satisfying laminate design rules. VICONOPT models are validated with ABAQUS finite element models, and with experimental compressive testing of two blade-stiffened panels. The buckling and postbuckling behavior of the two panels, with initial buckling in the stiffeners and skin, respectively, is investigated in a high load and high strain range. The bilevel strategy is evaluated by the design of a relatively short Z stiffened panel which has been manufactured and tested, and also by design of a long wing cover panel with combined loads. The weight saving from the wing cover panel is 13% compared with an existing datum design. This demonstrated that the strategy is efficient, reliable, and extendable into the long panel range.

ABSTRACT: Composite stiffened panel optimization is typically a mixed discrete-continuous design problem constrained by buckling and material strength. Previous work applied a bi-level optimization strategy to the problem by decomposing the mixed problem to continuous and discrete levels to reduce the optimization search space and satisfy manufacturing constraints. A fast-running optimization package, VICONOPT, was used at the continuous optimization level where the buckling analysis was accurately and effectively performed. However, the discrete level was manually adjusted to satisfy laminate design rules. This paper develops the strategy to application on continuously long aircraft wing panels subjected to compression and lateral pressure loading. The beam-column approach used to account for lateral loading for analysis during optimization is reported. A genetic algorithm is newly developed and applied to the discrete level for automated selection of laminated designs. The results that are presented show at least 13% weight saving compared with an existing datum design.
References listed at the end of the paper:

ABSTRACT: The design of composite structures against buckling presents two major challenges to the designer. First, the problem of laminate stacking sequence design is discrete in nature, involving a small set of fiber orientations, which complicates the solution process. Therefore, the design of the stacking sequence is a combinatorial optimization problem which is suitable for genetic algorithms. Second, many local optima with
comparable performance may be found. Most optimization algorithms find only a single optimum, while often a designer would want to obtain all the local optima with performance close to the global optimum. Genetic algorithms can easily find many near optimal solutions. However, they usually require very large computational costs. Previous work by the authors on the use of genetic algorithms for designing stiffened composite panels revealed both the above strength and weakness of the genetic algorithm. The present paper suggests several changes to the basic genetic algorithm developed previously, and demonstrates reduced computational cost and increased reliability of the algorithm due to these changes. Additionally, for a stiffened composite panel considered in this study, we present designs lighter by about 4% compared to previously obtained results.

References listed at the end of the paper:

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DOI: 10.1016/j.compstruct.2012.04.024

ABSTRACT: The present work develops an optimization procedure for a geometric design of a composite material stiffened panel with conventional stacking sequence using static analysis and hygrothermal effects. The procedure is based on a global approach strategy, composed by two steps: first, the response of the panel is obtained by a neural network system using the results of finite element analyses and, in a second step, a multi-objective optimization problem is solved using a genetic algorithm. The neural network implemented in the first step uses a sub-problem approach which allows to consider different temperature ranges. The compression load and relative humidity of the air are assumed to be constants throughout the considered temperature range. The mass, the hygrothermal expansion and the stresses between the skin and the stiffeners are defined as the optimality criteria. The presented optimization procedure is shown to yield the optimal structure design without compromising the computational efficiency.

References listed at the end of the paper:
Results indicate the model can predict both the strain at which delaminations in the dominantly sublaminates propagate from their original sites and the stability with ±45° dominated sublaminates placed above the delamination in order to prove the applicability of the model to sublaminates with high anisotropy. Results indicate the model can predict both the strain at which delaminations in the coupons with 0° and ±45° dominated sublaminates propagate from their original sites and the stability with


ABSTRACT: Previously, the authors have developed a modelling methodology that establishes a threshold strain below which damage propagation will not occur in laminates subject to Compression After Impact (CAI). In order to validate this methodology, a number of quasi-istropic coupons each containing a circular artificial delamination have been tested in axial compression. These coupons had 0°, ±45° and 90° dominated thin sublaminates placed above the delamination in order to prove the applicability of the model to sublaminates with high anisotropy. Results indicate the model can predict both the strain at which delaminations in the coupons with 0° and ±45° dominated sublaminates propagate from their original sites and the stability with
which propagation occurred. Analysis of the coupon with a $90^\circ$ dominated sublamine was inconclusive due to an unexpected experimental propagation mode. For all coupons delamination propagation was in the direction of the dominant fibre direction in the sublamine. The established methodology is shown to be suitable for assessing the damage tolerance of composite laminates.

References listed at the end of the paper:

ABSTRACT: A Rayleigh–Ritz energy method application is proposed to calculate the buckling onset and bending behavior of flat rectangular anisotropic composite stiffened panels submitted to any combination of in-plane loads (biaxial compression and shear) and pressure. Panels may consist in any kind of anisotropic laminate. Thickness, lay-up and material property changes are allowed along both longitudinal and transverse directions and transverse shear effects are considered using a first order theory. Stiffeners, idealized as offset beams, can also be placed in both directions. Simply supported edges are the assumed boundary conditions for the panel. Nevertheless, additional restrictions can be added by means of the definition of certain torsional or flexural stiffness at the edges. Therefore, clamped conditions or any other condition between clamped and simply supported can be analyzed. The consideration of all these features, together with the potentially high computational performances of the Rayleigh–Ritz method compared with the classical finite elements analyses, enables a wide application in real aircraft structures, such as CFRP (composite fiber reinforced plastic) torque box covers and spars with elevated performances and accuracy. Comparisons with finite element methods and tests in real structures are shown.

References listed at the end of the paper:

Petrov, M.B. and Tesfa, B, “Application of Legendre’s associated equation to the problem of shell buckling”, Sinet (ISSN 0379-2897, Vo. 17, No. 2, pp 125-134, December, 1994


ABSTRACT: An extensive experimental investigation of buckling of conical shells that are supported only along their lower edge and that are loaded by the weight of a liquid leads to diagrams and formulas which can be used directly in the design of such shells. The margin of safety to be applied, the influence of welding stresses and the limitations on the validity of the formulas for structures with different boundary conditions are discussed.

References listed at the end of the paper:

ABSTRACT: The major part of an investigation that began about 15 years ago consisted in testing 75 spherical model domes made of microconcrete. Some were subjected to rapidly increasing uniform radial pressure until they buckled, and some were subjected to a radial pressure held constant until they buckled (two of the latter specimens have not yet failed, ten years after the constant load was applied). Non-linear calculations reflecting the effects of the rapid loading and of the loading of long duration have been carried out and their results have been compared with the data obtained experimentally. The numerical results do not support GERARD’s and KOLLAR’s creep buckling hypothesis, while the set of experimental results of the long-term loading tests supports the hypothesis quite well in a statistical sense.

References listed at the end of the paper:
ABSTRACT: The main purpose of the paper is to confront the buckling failure of the conical steel tank of a water tower with buckling formulae resulting from experimental and theoretical research. The collapse corroborates those formulae, which had been published before. The designer of the water tower had relied on a solution to a different, somewhat similar buckling problem. The fact showed that solution to be unconservative for the shell as constructed. The shell buckling formula used by the designer was not accompanied by an imperfection limitation qualifying its applicability. On account of the adverse effect of shape defects of shells on their buckling strength, the writer believes the lack of such a limitation to be potentially dangerous.

ABSTRACT: Two aspects of the finite element analysis of mid-plane symmetrically laminated anisotropic plates are considered in this paper. The first pertains to exploiting the symmetries exhibited by anisotropic plates in their analysis. The second aspect pertains to the effects of anisotropy and shear deformation on the accuracy and convergence of shear-flexible displacement finite element models. Numerical results are presented which show the effects of increasing the order of approximating polynomials and of using derivatives of generalized displacements as nodal parameters.

ABSTRACT: A computational algorithm, based on the combined use of mixed finite elements and classical Rayleigh–Ritz approximation, is presented for predicting the nonlinear static response of structures; The fundamental unknowns consist of nodal displacements and forces (or stresses) and the governing nonlinear finite element equations consist of both the constitutive relations and equilibrium equations of the discretized structure. The vector of nodal displacements and forces (or stresses) is expressed as a linear combination of a small number of global approximation functions (or basis vectors), and a Rayleigh–Ritz technique is used to approximate the finite element equations by a reduced system of nonlinear equations. The global approximation functions (or basis vectors) are chosen to be those commonly used in static perturbation technique; namely a nonlinear solution and a number of its path derivatives. These global functions are generated by using the finite element equations of the discretized structure. The potential of the global–local mixed approach and its advantages over global–local displacement finite element methods are discussed. Also, the high accuracy and effectiveness of the proposed approach are demonstrated by means of numerical examples.

ABSTRACT: A two-stage global-local approach is presented for predicting the collapse behavior of shells. The first stage is that of spatial discretization wherein the shell is discretized by using finite elements (or finite differences) which cover the entire region of the shell. In the second stage the vector of unknown nodal
parameters is expressed as a linear combination of small number of global functions (or basis vectors). A Rayleigh-Ritz (or Bubnov-Galerkin) technique is then used to approximate the nonlinear equations of the discretized shell by a reduced system of nonlinear algebraic equations. For the case of loading applied by means of axial end shortening, a scalar function is introduced which measures the degree of nonlinearity of the structure. Also, a quantitative measure for the error of the reduced system of equations is proposed. The effectiveness of the proposed technique for predicting the collapse behavior of shells is demonstrated by means of a numerical example of the elastic collapse of a cylindrical shell with a rectangular cutout.

References listed at the end of the paper:

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“Mixed models and reduced/selective integration displacement models for nonlinear shell analysis”,
doi: 10.1002/nme.1620181002
ABSTRACT: Simple mixed models are developed for the geometrically nonlinear analysis of shells. A total Lagrangian description of the shell deformation is used, and the analytical formulation is based on a form of the nonlinear shallow shell theory with the effects of transverse shear deformation and bending-extensional coupling included. The fundamental unknowns consist of eight stress resultants and five generalized displacements of the shell, and the element characteristic arrays are obtained by using the Hellinger-Reissner mixed variational principle. The polynomial interpolation (or shape) functions used in approximating the stress resultants are, in general, of different degree than those used for approximating the generalized displacements. The stress resultants are discontinuous at the element boundaries and are eliminated on the element level. The equivalence and ‘near-equivalence’ between the mixed models developed herein and displacement models based on reduced/selective integration of both transverse shear and extensional energy terms is discussed. The use of reduction methods in conjunction with the mixed models is outlined and the advantages of mixed models
over displacement models are delineated. Analytic expressions are derived for the rigid-body and spurious (or zero energy) models for the various mixed models and their equivalent displacement models. Also, the advantages of mixed models over equivalent displacement models are outlined. Numerical results are presented to demonstrate the high accuracy and effectiveness of the mixed models developed, and to compare their performance with other mixed models reported in the literature.


ABSTRACT: Status and some recent advances in the application of reduction methods to instability analysis of structures are summarized. The aspects of reduction methods discussed herein include: (a) multiple-parameter reduction methods for instability analysis of structures subjected to combined loads; (b) use of mixed models in conjunction with reduction methods for instability analysis; and (c) application of reduction methods to instability problems with displacement-dependent and nonconservative loadings. Numerical examples are presented to demonstrate the effectiveness of reduction methods in instability analysis. Also, research areas which have high potential for application of reduction methods are identified.


ABSTRACT: A multiple-parameter reduced basis technique and a problem-adaptive computational algorithm are presented for the bifurcation and post-buckling analyses of composite plates subjected to combined loadings. The computational algorithm can be conveniently divided into three distinct stages. The first stage is that of determining the stability boundary. The plate is discretized by using displacement finite element models and the analysis region is reduced by exploiting the special symmetries exhibited by the response of the plate. The vector of unknown nodal displacements is expressed as a linear combination of a small number of path derivatives (derivatives of the nodal displacements with respect to path parameters), and a Rayleigh-Ritz technique is used to approximate the finite element equations by a small system of algebraic equations. The reduced equations are used to determine the stability boundary of the plate. In the second stage, a nonlinear solution in the vicinity of the stability boundary is obtained by using a bifurcation buckling mode as a predictor, and a set of reduced equations is generated. In the third stage, the reduced equations are used to trace post-buckling paths corresponding to various combinations of the load parameters. The potential of the proposed approach is discussed and its effectiveness is demonstrated by means of a numerical example of laminated composite plate subjected to combined compressive and shear loadings.


ABSTRACT: Reduction method and computational procedures are presented for reducing the size of the analysis model and the number of degrees of freedom used in predicting the non-linear response of symmetric anisotropic panels. The two key elements of the method are (a) operator splitting, or decomposition of the
characteristic arrays of the finite element model into sums of orthotropic and non-orthotropic contributions, (b) application of a reduction method through the successive use of the finite element method and the classical Rayleigh-Ritz technique. The finite element method is first used to generate a small number of global approximation vectors (or modes). Then the amplitudes of these modes are computed by using the classical Rayleigh-Ritz technique. The global approximation vectors are selected to be those commonly used in single (or multiple) parameter perturbation techniques, namely a non-linear solution corresponding to zero non-orthotropic arrays and a number of its derivatives with respect to an anisotropic tracing parameter (and possibly, to a load or arc-length parameter in the solution space). The size of the analysis model used in generating the global approximation vectors is identical to that of the corresponding orthotropic structure. The effectiveness of the proposed reduction method is demonstrated by means of a numerical example, and its potential for solving quasi-symmetric non-linear problems of anisotropic panels is discussed.


ABSTRACT: An efficient preconditioned conjugate gradient (PCG) technique and a computational procedure are presented for the analysis of symmetric anisotropic structures. The technique is based on selecting the preconditioning matrix as the orthotropic part of the global stiffness matrix of the structure, with all the nonorthotropic terms set equal to zero. This particular choice of the preconditioning matrix results in reducing the size of the analysis model of the anisotropic structure to that of the corresponding orthotropic structure. The similarities between the proposed PCG technique and a reduction technique previously presented by the authors are identified and exploited to generate from the PCG technique direct measures for the sensitivity of the different response quantities to the non-orthotropic (anisotropic) material coefficients of the structure. The effectiveness of the PCG technique is demonstrated by means of a numerical example of an anisotropic cylindrical panel.


ABSTRACT: An efficient computational strategy is presented for reducing the cost of the stress and free vibration analyses of laminated anisotropic shells of revolution. The analytical formulation is based on a form of the Sanders-Budiansky shell theory including the effects of both the transverse shear deformation and the laminated anisotropic material response. The fundamental unknowns consist of the eight strain components, the eight stress resultant and the five generalized displacements of the shell. Each of the shell variables is expressed in terms of trigonometric functions (Fourier series) in the circumferential co-ordinate, and a three-field mixed finite element model is used for the discretization in the meridional direction. The shell response associated with a range of Fourier harmonics is approximated by a linear combination of a few global approximation vectors, which are generated at a particular value of the Fourier harmonic, within that range. The full equations of the finite element model are solved for only a single Fourier harmonic, and the response corresponding to the other Fourier harmonics is generated using a reduced system of equations with considerably fewer degrees of freedom.
ABSTRACT: An efficient procedure is presented for repetitive analysis of structures, with large numbers of degrees of freedom and design variables, as they are progressively modified during the automated optimum design process. The three key elements of the procedure are: (a) lumping of the large number of design variables into a single tracing parameter; (b) operator splitting or additive decomposition of the different arrays in the governing finite element equations of the modified structure into the corresponding arrays of the original structure plus correction terms; and (c) application of a reduction method through the successive use of the finite element method and the classical Bubnov-Galerkin technique. The reanalysis procedure is applied to the linear static and free vibration problems of framed structures. Changes in both the sizing and shape (configuration) design variables are considered. For static problems the similarities between the proposed procedure and the preconditioned conjugate gradient technique are identified and are exploited to provide a physical meaning for the preconditioned residual vectors. The effectiveness of the proposed procedure is demonstrated by means of numerical examples.

ABSTRACT: A review is given of recent advances in two aspects of the numerical simulation of the buckling and postbuckling responses of composite structures. The first aspect is exploiting non-traditional symmetries exhibited by composite structures; and strategies for reducing the size of the model and the cost of the buckling and postbuckling analyses in the presence of symmetry-breaking conditions (e.g. asymmetry of the material, geometry, and/or loading). The second aspect pertains to the prediction of onset of local delamination in the postbuckling range and accurate determination of transverse shear stresses in the structure. The accuracy and effectiveness of the strategies developed are demonstrated by means of a numerical example.

ABSTRACT: A study is made of the effects of variation in the lamination and geometric parameters of multilayered anisotropic (nonorthotropic) plates on the accuracy of the static and vibrational responses predicted by eight modeling approaches, based on two-dimensional shear-deformation theories. Two key elements distinguish the present study from previous studies reported in the literature: (1) the standard of comparison is taken to be the exact three-dimensional elasticity solutions, and (2) quantities compared are not limited to gross response characteristics (e.g. vibration frequencies, strain energy components, average through-the-thickness displacements and rotations), but include detailed through-the-thickness distributions of displacements, stresses and strain energy densities.

ABSTRACT: A computational procedure is presented for the geometrically nonlinear analysis of aircraft tires. The tire was modeled by using a two-dimensional laminated anisotropic shell theory with the effects of variation in material and geometric parameters included. The four key elements of the procedure are: (1) semianalytic finite elements in which the shell variables are represented by Fourier series in the circumferential direction and piecewise polynomials in the meridional direction; (2) a mixed formulation with the fundamental unknowns consisting of strain parameters, stress-resultant parameters, and generalized displacements; (3) multilevel operator splitting to effect successive simplifications, and to uncouple the equations associated with different Fourier harmonics; and (4) multilevel iterative procedures and reduction techniques to generate the response of the shell.


ABSTRACT: A computational procedure is presented for the geometrically nonlinear analysis of aircraft tires. The tire was modeled by using a two-dimensional laminated anisotropic shell theory with the effects of variation in material and geometric parameters included. The four key elements of the procedure are: 1) semianalytic finite elements in which the shell variables are represented by Fourier series in the circumferential direction and piecewise polynomials in the meridional direction; 2) a mixed formulation with the fundamental unknowns consisting of strain parameters, stress-resultant parameters, and generalized displacements; 3) multilevel operator splitting to effect successive simplifications, and to uncouple the equations associated with different Fourier harmonics; and 4) multilevel iterative procedures and reduction techniques to generate the response of the shell.

References listed at the end of the paper:


ABSTRACT: A study is made of the thermal postbuckling response of composite stiffeners subjected to prescribed edge displacement and a temperature rise. The flanges and web of the stiffeners are modeled by using two-dimensional plate finite elements. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the plate. A reduction method is used in conjunction with mixed finite element models for determining the postbuckling response of the stiffeners. Sensitivity derivatives are evaluated and used to study the effects of variations in the different lamination and material parameters of the stiffeners on their postbuckling response characteristics. Numerical studies are presented for anisotropic stiffeners with Zee and channel sections.


ABSTRACT: Novel computational strategies are presented for the analysis of large and complex structures. The strategies are based on generating the response of the complex structure using large perturbations from that of a simpler model, associated with a simpler structure (or a simpler mathematical/discrete model of the original structure). Numerical examples are presented to demonstrate the effectiveness of the strategies developed.


ABSTRACT: A study is made of the effects of variation in the lamination and geometric parameters of multilayered composite cylinders on the accuracy of the static and vibrational responses predicted by eight modeling approaches, based on two-dimensional shear-deformation shell theories. The standard of comparison is taken to be the exact three-dimensional elasticity solutions, and the quantities compared include both the gross response characteristics (e.g. vibration frequencies, strain energy components, average through-the-thickness displacements and rotations): and detailed, through-the-thickness, distributions of displacements, stresses and strain energy densities. Based on the numerical studies conducted, a predictor -corrector approach, used in conjunction with the first-order shear-deformation theory (with five displacement parameters in the predictor phase), appears to be the most effective among the eight modeling approaches considered. For multilayered orthotropic cylinders the response quantities obtained by the predictor corrector approach are shown to be in close agreement with the exact three-dimensional elasticity solutions for a wide range of lamination and geometric parameters. The potential of this approach for predicting the response of multilayered shells with complicated geometry is also discussed.

ABSTRACT: A study is made of the postbuckling response of composite plates subjected to combined axial and thermal loadings. The analysis is based on a first-order shear deformation, von Kármán-type nonlinear plate theory. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the plate. An efficient reduction method is used in conjunction with mixed finite element models for determining the stability boundary and the postbuckling response of the plate. Sensitivity derivatives are evaluated and used to study the sensitivity of the postbuckling response to variations in the different lamination and material parameters of the plate. Numerical results are presented showing the effects of variations in the material characteristics and fiber orientation of individual layers on the postbuckling response of the plate.

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ABSTRACT: A study is made of the thermomechanical buckling and postbuckling responses of flat unstiffened composite panels. The panels are subjected to combined temperature change and applied edge displacement. The analysis is based on a first-order shear deformation, von-Karman type nonlinear plate theory. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the plate. An efficient multiple-parameter reduction method is used in conjunction with mixed finite element models, for determining the stability boundary and postbuckling response. The reduction method is also used for evaluating the sensitivity coefficients which measure the sensitivity of the buckling and postbuckling responses to variations in the different lamination and material parameters of the panel. Numerical results are presented showing the effects of variations in the laminate stacking sequence, fiber orientation, number of layers and aspect ratio of the panels on the thermomechanical buckling and postbuckling responses and their sensitivity.


ABSTRACT: A study is made of the buckling and postbuckling responses of flat, unstiffened composite panels subjected to various combinations of mechanical and thermal loads. The analysis is based on a first-order shear deformation von Kármán-type plate theory. A mixed formulation is used with the fundamental unknowns consisting of the strain components, stress resultants and the generalized displacements of the plate. The stability boundary, postbuckling response and the sensitivity coefficients are evaluated. The sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the different
lamination and material parameters of the panel. Numerical results are presented for both solid panels and panels with central circular cutouts. The results show the effects of the variations in the fiber orientation angles, aspect ratio of the panel, and the hole diameter (for panels with cutouts) on the stability boundary, postbuckling response and sensitivity coefficients.

References listed at the end of the paper:


ABSTRACT: The research work presented here deals with the problems of geometrically nonlinear analysis of thin shell structures. The specific objective was to develop geometrically nonlinear formulations, using Discrete-Kirchhoff Curved Triangular (DKCT) thin shell elements. The DKCT elements, formulated in the natural curvilinear coordinates, based on arbitrary deep shell theory and representing explicit rigid body modes, were successfully applied to linear elastic analysis of composite shells in an earlier research work. A detailed discussion on the developments of classical linear and nonlinear shell theories and the Finite Element applications to linear and nonlinear analysis of shells has been presented. The difficulties of developing converging shell elements due to Kirchhoff's hypothesis have been discussed. The importance of formulating shell elements based on deep shell theory has also been pointed out. The development of shell elements based on Discrete-Kirchhoff's theory has been discussed. The development of a simple 3-noded curved triangular thin shell element with 27 degrees-of-freedom in the tangent and normal displacements and their first-order derivatives, formulated in the natural curvilinear coordinates and based on arbitrary deep shell theory, has been described. This DKCT element has been used to develop geometrically nonlinear formulation for the nonlinear analysis of thin shells. A detailed derivation of the geometrically nonlinear (GNL) formulation, using the DKCT element based on the Total Lagrangian approach and the principles of virtual work has been presented. The techniques of solving the nonlinear equilibrium equations, using the incremental methods has been described. This includes the derivation of the Tangent Stiffness matrix. Various Newton-Raphson solution algorithms and the associated convergence criteria have been discussed in detail. Difficulties of tracing the post buckling
behavior using these algorithms and hence the necessity of using alternative techniques have been mentioned. A detailed numerical evaluation of the GNL formulation has been carried out by solving a number of standard problems in the linear buckling and GNL analysis. The results compare well with the standard solutions in linear buckling cases and are in general satisfactory for the GNL analysis in the region of large displacements and small rotations. It is concluded that this simple and economical element will be an ideal choice for the expensive nonlinear analysis of shells. However, it is suggested that the element formulation should include large rotations for the element to perform accurately in the region of large rotations.


ABSTRACT: A combined numerical and experimental study is carried out for the postbuckling behavior of a stiffened composite panel. The panel is rectangular and is subjected to static in-plane compression on two opposite edges to the collapse level. Nonlinear - large deflection - plate theory is employed, together with an experimentally based failure criterion. It is found that the stiffened composite panel can exhibit significant postbuckling strength.

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Ahmed K. Noor, W. Scott Burton and Jeanne M. Peters (Center for Computational Structures Technology, University of Virginia, NASA Langley Research Center, Hampton, VA 23681, USA), “Hierarchical adaptive
ABSTRACT: Some recent advances in the hierarchical modeling strategies are reviewed with special emphasis on applications to multilayered composite panels. Discussion focuses on the key elements of hierarchical adaptive modeling; multimodel predictor and corrector modeling procedures; potential for solving large complex problems; and the needed development to realize this potential. Numerical studies are presented for free vibrations of thermally-stressed multilayered composite panels and structural sandwiches with composite face sheets demonstrating the effectiveness of the multimodel predictor–corrector modeling approaches.

ABSTRACT: A computational procedure is presented for evaluating the sensitivity coefficients of the viscoplastic response of structures subjected to dynamic loading. A state of plane stress is assumed to exist in the structure, a velocity strain-Cauchy stress formulation is used, and the geometric non-linearities arising from large strains are incorporated. The Jaumann rate is used as a frame indifferent stress rate. The material model is chosen to be isothermal viscoplasticity, and an associated flow rule is used with a von Mises effective stress. The equations of motion emanating from a finite element semi-discretization are integrated using an explicit central difference scheme with an implicit stress update. The sensitivity coefficients are evaluated using a direct differentiation approach. Since the domain of integration is the current configuration, the sensitivity coefficients of the spatial derivatives of the shape functions must be included. Numerical results are presented for a thin plate with a central circular cutout subjected to an in-plane compressive loading. The sensitivity coefficients are generated by evaluating the derivatives of the response quantities with respect to Young's modulus, and two of the material parameters characterizing the viscoplastic response. Time histories of the response and sensitivity coefficients, and spatial distributions at selected times are presented.

ABSTRACT: A study is made of the effects of variation in the material and geometric parameters of curved sandwich panels on the accuracy of the static response predicted by nine different modeling approaches based on two-dimensional shell theories. The standard of comparison is taken to be the exact three-dimensional thermoelasticity solutions, and the quantities compared include gross response characteristics (e.g. strain energy components, average through-the-thickness displacements and rotations); detailed, through-the-thickness distributions of displacements and stresses; and sensitivity coefficients of the response quantities (derivatives of response quantities with respect to material and geometric parameters of the sandwich structure). Extensive numerical studies are conducted to assess the accuracy of both the global and detailed response characteristics and their sensitivity coefficients obtained by nine two-dimensional modeling approaches. For accurate determination of detailed through-the-thickness distributions such as transverse stresses, either high-order discrete three-layer models or predictor-corrector approaches are required. The potential of predictor-corrector approaches for predicting the thermomechanical response of sandwich panels and shells with complicated geometry is also discussed.
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“THERMOMECHANICAL POSTBUCKLING OF MULTILAYERED COMPOSITE PANELS WITH CUTOUTS”, COMPOSITE STRUCTURES, VOL. 30, NO. 4, 1995, PP. 369-388, DOI: 10.1016/0263-8223(94)00055-7

ABSTRACT: The results of a study of the detailed thermomechanical postbuckling response characteristics of flat unstiffened composite panels with central circular cutouts are presented. The panels are subjected to combined temperature changes and applied edge loading (or edge displacements). The analysis is based on a first-order shear deformation plate theory. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the plate. The postbuckling displacements, transverse shear stresses, transverse shear strain energy density, and their sensitivity coefficients are evaluated. The sensitivity coefficients measure the sensitivity of the post-buckling response to variations in the different lamination and material parameters of the panel. Numerical results are presented showing the effects of the variations in the hole diameter, laminate stacking sequence, fiber orientation, and aspect ratio of the panel on the thermomechanical postbuckling response and its sensitivity to changes in panel parameters.


PARTIAL INTRODUCTION: The physical understanding and numerical simulation of the buckling and postbuckling responses of laminated anisotropic plates have been the focus of intense efforts because of the extended use of fibrous composites in aerospace, automotive, shipbuilding and other industries, and the need to establish the practical limits of the load-carrying capability of structures made from these materials….
ABSTRACT: A detailed study is made of the buckling and postbuckling responses of composite panels with central circular cutouts subjected to various combinations of mechanical and thermal loads. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation through the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness, and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included. The stability boundary, postbuckling response and the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Extensive numerical results are presented for composite panels with central circular cutouts subjected to combined edge shortening, edge shear and temperature change. The results show the effects of variations in the hole diameter; the aspect ratio of the panel; the laminate stacking sequence and the fiber orientation on the stability boundary, postbuckling response and sensitivity coefficients.


ABSTRACT: The results of a detailed study of the nonlinear and postbuckling responses of curved unstiffened composite panels with central circular cutouts are presented. The panels are subjected to applied edge displacements and temperature changes. The analysis is based on a first-order shear-deformation Sanders-Budiansky type theory with the effects of large displacements, moderate rotations, transverse shear deformation and laminated anisotropic material behavior included. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the nonlinear response to variations in three sets of interrelated parameters; namely, the panel stiffnesses, the material properties of the individual layers, and the material properties of the constituents (fibers, matrix, interface and interphase). Numerical results are presented for cylindrical panels with central circular cutouts subjected to edge shortening and uniform temperature change, showing the effects of variations in the panel curvature, hole diameter, laminate stacking sequence and fiber orientation, on the nonlinear and postbuckling panel responses, and their sensitivity to changes in the various panel, layer and micromechanical parameters.


ABSTRACT: The results of a detailed study of the buckling and postbuckling responses of composite panels with central circular cutouts are presented. The panels are subjected to combined edge shear and temperature change. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation throughout the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included. The stability boundary,
postbuckling response and hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Numerical results are presented for composite panels with central circular cutouts subjected to combined edge shear and temperature change, showing the effects of variations in the hole diameter, laminate stacking sequence and fiber orientation, on the stability boundary and postbuckling response and their sensitivity to changes in the various panel parameters.

ABSTRACT: The results of a detailed study of the nonlinear and postbuckling responses of curved unstiffened composite panels with central circular cutouts are presented. The panels are subjected to uniform temperature change and an applied in-plane edge shear loading. The analysis is based on a first-order shear-deformation Sanders-Budiansky type theory with the effects of large displacements, moderate rotations, transverse shear deformation and laminated anisotropic material behavior included. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated. Numerical results are presented for cylindrical panels with central circular cutouts and are subjected to uniform temperature change and an applied in-plane edge shear loading. The results show the effects of variations in the panel curvature, hole diameter, laminate stacking sequence and fiber orientation, on the nonlinear and postbuckling panel responses, and their sensitivity to changes in the various panel, layer and micromechanical parameters.

ABSTRACT: The results of a detailed study of the buckling and postbuckling responses of composite panels with skewed stiffeners are presented. The panels are subjected to applied edge displacements and temperature changes. A first-order shear-deformation geometrically nonlinear shallow-shell theory that includes the effects of laminated anisotropic material behavior is used to model each section of the stiffeners and the skin. A mixed formulation is used in the analysis with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in three sets of interrelated parameters; namely, the panel stiffnesses; the effective material properties of the individual layers; and the constituent material parameters (fibers, matrix, interface and interphase). Numerical results are presented for rectangular panels with open section I-stiffeners, subjected to edge shortening and uniform temperature change. The results show the effects of variations in the material properties of the skin and the stiffener on the buckling and postbuckling responses of the panel, as well as on the sensitivity coefficients.

ABSTRACT: The history, recent developments and trends in computational structures technology (CST) are summarized. Discussion focuses on development of CST software and goals of CST activities. Some recent advances in a number of CST areas are described, including discretization techniques and element technology; computational material modeling; modeling of composite, sandwich and smart structures; computational tools and methodologies for life management; transient response analysis; numerical simulation of frictional contact/impact response; articulated structural dynamics; non-deterministic modeling and analysis methods; qualitative analysis and simulation; neuro-computing; hybrid techniques; error estimation and adaptive improvement strategies; strategies for solution of coupled problems; sensitivity analysis; integrated analysis and design; strategies and numerical algorithms for new computing systems; model generation facilities; and application of object-oriented technology. Research areas in CST that have high potential for meeting the future technological needs are identified.

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ABSTRACT: A two-phase approach and a computational procedure are presented for predicting the variability in the nonlinear response of composite structures associated with variations in the geometric and material parameters of the structure. In the first phase, hierarchical sensitivity analysis is used to identify the major parameters, which have the most effect on the response quantities of interest. In the second phase, the major parameters are taken to be fuzzy parameters, and a fuzzy set analysis is used to determine the range of variation of the response, associated with preselected variations in the major parameters. The effectiveness of the procedure is demonstrated by means of a numerical example of a cylindrical panel with four T-shaped stiffeners and a circular cutout.

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ABSTRACT: A study is made of the variability in the nonlinear response of three stiffened composite panels associated with variations in their geometric and material parameters. The three panels have a cylindrical skin with either four or five T-shaped stiffeners. Two of the panels have a notch and the third panel has a circular cutout. Hierarchical sensitivity analysis is used to identify the major parameters at the micro-mechanical, layer, laminate and sub-component levels. The major parameters are then taken to be fuzzy parameters, and a fuzzy set analysis is used to determine the range of variation of the response associated with pre-selected variations in
the major parameters.

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ABSTRACT: Research on the mechanics of composite structures at NASA’s Langley Research Center is discussed. The advantages and limitations of special purpose and general purpose analysis tools used in research are reviewed. Future directions in computational structural mechanics are described to address analysis shortcomings. Research results on the buckling and postbuckling of unstiffened and stiffened composite structures are presented. Recent investigations of the mechanics of failure in compression and shear are reviewed. Preliminary studies of the dynamic response of composite structures due to impacts encountered during crash-landings are presented. Needs for future research are discussed.

ABSTRACT: A study of thermal buckling of stiffened cylindrical shells with the proportions of a preliminary supersonic transport fuselage design (1970) is presented. The buckling analysis is performed using an axisymmetric shell-of-revolution code, BOSOR4. The effects of combined mechanical (axial loading) and thermal loading (heated skins) are investigated. Results indicate that the location of longitudinal eccentric stiffening has a very large effect on the thermal buckling strength of longitudinally stiffened shells, and on longitudinally stiffened shells with rings.

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ABSTRACT: Simple experiments on self-weight buckling of thin, open-top, fixed-base, small-scale silicone rubber cylindrical shells are presented in this article. The buckling heights were found to be proportional to thickness raised to the power of approximately 1.5, compared to 1.0 as in the classical theory. A non-linear finite-element analysis of self-weight buckling showed that there is a ‘post-buckling plateau’ load corresponding to the experimental buckling loads. Moreover, the results of the present experiments showed very little ‘scatter’ in the buckling heights, compared to the large scatter in the experimental data from the literature on the buckling of thin cylindrical shells under axial compressive load (which also have buckling stress
proportional to thickness raised to the power of approximately 1.5), although there were measurable imperfections in terms of thickness variations. These observations somehow defy the accepted hypothesis of ‘imperfection-sensitivities’ in shell buckling. The most obvious explanation of the difference is that the open-topped shells of the present study are statically determinate, whereas the usual closed-ended shells of tests reported in the literature are statically indeterminate; the possibility of high initial stresses may explain the scatter in the experimental observations in the literature.

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ABSTRACT: The Southwell plot is a well-known technique for determining experimentally the elastic critical load of a structure, without having to subject the structure to loading in the vicinity of critical. But several authors have suggested that when the structure is a beam which undergoes lateral-torsional buckling, a modified version of the Southwell plot is called for. In this paper we demonstrate that the modified form of the Southwell plot is not needed, and that the standard version is indeed satisfactory. We do this by plotting and re-plotting some experimental data; by drawing attention to some very clear work by Meck; and by explaining the practical coupling between the variables describing the lateral deflection and the rotation when lateral-torsional buckling occurs. Finally, we examine an argument based on symmetry which appears to support the idea that a modification of the standard Southwell plot is needed in the case of lateral-torsional buckling: but we show that a correct deployment of the argument from symmetry leads to the conclusion that the modified form of the Southwell plot is valid only for special, unrealistic cases.

References listed at the end of the paper:


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“Some New Thoughts on the Buckling of Thin Cylindrical Shells”, XXI ICTAM, 15-21 August 2004, Warsaw,
Zia ul Rehman Tahir and Parthasarathi Mandal (School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK), “Effect of Asymmetric Meshing on the Buckling of Composite Laminated Cylindrical Shells”, ICAMS-2011: International Conference on Advanced Modeling and Simulation, November 28-30, 2011, Islamabad, Pakistan

ABSTRACT: This paper presents the details of a numerical study of buckling and post buckling behaviour of laminated carbon fiber reinforced plastic (CFRP) thin-walled cylindrical shell under axial compression using asymmetric meshing technique (AMT) by ABAQUS. AMT is considered to be a new perturbation method to introduce disturbance without changing geometry, boundary conditions or loading conditions. Asymmetric meshing affects both predicted buckling load and buckling mode shapes. Cylindrical shell having lay-up orientation \([0^\circ/45^\circ/-45^\circ/0^\circ]\) with radius to thickness ratio (R/t) equal to 265 and length to radius ratio (L/R) equal to 1.5 is used. A series of numerical simulations (experiments) are carried out with symmetric and asymmetric meshing to study the effect of asymmetric meshing on predicted buckling behaviour. Asymmetric meshing technique is employed in both axial direction and circumferential direction separately using two different methods, first by changing the shell element size and varying the total number elements, and second by varying the shell element size and keeping total number of elements constant. The results of linear analysis (Eigenvalue analysis) and non-linear analysis (Riks analysis) using symmetric meshing agree well with analytical results. The results of numerical analysis are presented in form of non-dimensional load factor, \(\Lambda\), which is the ratio of buckling load using asymmetric meshing technique to buckling load using symmetric meshing technique. Using AMT, load factor has about 2% variation for linear eigenvalue analysis and about 2% variation for non-linear Riks analysis. The behaviour of load end-shortening curve for pre-buckling is same for both symmetric and asymmetric meshing but for asymmetric meshing curve behaviour in post-buckling becomes extraordinarily complex. The major conclusions are: different methods of AMT have small influence on predicted buckling load and significant influence on load displacement curve behaviour in post buckling; AMT in axial direction and AMT in circumferential direction have different influence on buckling load and load displacement curve in post-buckling.

References listed at the end of the paper:

3. Wardle, B.L., Buckling and damage resistance of transversely loaded composite shells, in Department of Aeronautics and Astronautics. 1998, Massachusetts Institute of Technology, Cambridge.
ABSTRACT: A numerical study is presented on buckling and post buckling behaviour of laminate d carbon fiber reinforced plastic (CFRP) thin-walled cylindrical shells under axial compression using asymmetric meshing technique (AMT). Asymmetric meshing technique is a perturbation technique to introduce disturbance without changing geometry, boundary conditions or loading conditions. Asymmetric meshing affects predicted buckling load, buckling mode shape and post-buckling behaviour. Linear (eigenvalue) and non-linear (Riks) analyses have been performed to study the effect of asymmetric meshing in the form of a patch on buckling behaviour. The reduction in the buckling load using Asymmetric meshing technique was observed to be about 15%. An isolated dimple formed near the bifurcation point and the size of which increased to reach a stable state in the post-buckling region. The load-displacement curve behaviour applying asymmetric meshing is quite similar to the curve obtained using initial geometric imperfection in the shell model.

References listed at the end of this paper:


ABSTRACT: AMT is a perturbation technique to introduce disturbance in the model without changing geometry, boundary conditions or loading conditions. Asymmetric meshing technique is employed in the form of a band along circumferential direction of the shell model. The elements size in the band is reduced as compared with the rest of shell to produce asymmetry in the meshing and four magnitudes of asymmetry in meshing are used. Asymmetric meshing affects predicted buckling load, buckling mode shape and post-buckling behaviour. The reduction in the buckling load using AMT was observed to be about 20%. An isolated dimple formed near the bifurcation point and the size of which increased to reach a stable state in the post-buckling region. The load-displacement curve behaviour applying asymmetric meshing is quite similar to the curve obtained by introducing initial geometric imperfection in the shell model.


ABSTRACT: Asymmetric meshing is a perturbation introduced in the numerical model without changing geometry, loading or boundary conditions. Asymmetric meshing is employed in the form of a band along axial direction of the shell model, the elements size in the axial band is reduced as compared with the rest of shell to produce asymmetry in the meshing and four amplitudes of asymmetry are used in a particular band. Asymmetric meshing affects predicted buckling load, buckling mode shape and post-buckling behaviour. The reduction in the buckling load using asymmetric meshing was observed to be about 18%, which depends mainly on area of asymmetric meshing and less on different magnitudes of asymmetry in the same area. The load-displacement curve behaviour using asymmetric meshing technique is quite similar to the curve obtained by introducing geometric imperfection in the shell model.

References listed at the end of the paper:
DOI: https://doi.org/10.2514/1.26698
agree well with analytical results. The results of numerical analysis are presented in form of non-linear analysis (Eigenvalue analysis) and symmetric meshing to study the effect of asymmetric meshing on predicted buckling load and buckling mode shapes. Cylindrical shell having lay-up orientation \([0^\circ/\pm 45^\circ/0^\circ] \) with radius to thickness ratio \((R/t)\) equal to 265 and length to radius ratio \((L/R)\) equal to 1.5 is analysed numerically. A series of numerical simulations (experiments) are carried out with symmetric and asymmetric meshing to study the effect of asymmetric meshing on predicted buckling behaviour. Asymmetric meshing technique is employed in both axial direction and circumferential direction separately using two different methods, first by changing the shell element size and varying the total number elements, and second by varying the shell element size and keeping total number of elements constant. The results of linear analysis (Eigenvalue analysis) and non-linear analysis (Riks analysis) using symmetric meshing agree well with analytical results. The results of numerical analysis are presented in form of non-dimensional.
load factor, which is the ratio of buckling load using asymmetric meshing technique to buckling load using symmetric meshing technique. Using AMT, load factor has about 2% variation for linear eigenvalue analysis and about 2% variation for non-linear Riks analysis. The behaviour of load end-shortening curve for pre-buckling is same for both symmetric and asymmetric meshing but for asymmetric meshing curve behaviour in post-buckling becomes extraordinarily complex. The major conclusions are: different methods of AMT have small influence on predicted buckling load and significant influence on load displacement curve behaviour in post-buckling; AMT in axial direction and AMT in circumferential direction have different influence on buckling load and load displacement curve in post-buckling.

References listed at the end of the paper:


PARTIAL ABSTRACT: This paper describes an experimental and numerical study that is part of a research project aiming at improving the knowledge of buckling behaviour of composite shell structures. The experimental equipment and the methodologies for systematic data acquisition in buckling tests on composite cylindrical shells under axial compression and torsion, applied individually and in combination, are described. Typical results of the first tests performed on carbon-epoxy laminated cylinders are presented, in terms of diagrams, post-buckling patterns and two-dimensional Fourier analysis….

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“Buckling of axially compressed fiber composite cylindrical shells due to impulsive loading”, in Spacecraft structures, materials and mechanical testing, Proceedings of a European Conference held at Braunschweig, Germany, 4-6 November 1998. Paris: European Space Agency (ESA), ESA-SP, Vol. 428, 1999,
PARTIAL ABSTRACT: Dynamic buckling of thin-walled CFRP shell structures due to impulsive loading is investigated. Computations for axially compressed cylindrical shells are performed by commercially available finite element codes. The effect of laminate set-up on the buckling load of cylindrical shells, the influence of boundary conditions and the sensitivity to geometric imperfections are analysed for static and dynamic buckling loads. The time history of impulsive loading with finite duration and constant in magnitude is varied, and the corresponding dynamic buckling loads are related to the quasi-static buckling loads.


ABSTRACT: This paper deals with the buckling and post-buckling behaviour of carbon fibre reinforced plastic cylindrical shells under axial compression. The finite element analysis is used to investigate this problem and three different types of analysis are compared: eigenvalue analysis, non-linear Riks method and dynamic analysis. The effect of geometric imperfection shape and amplitude on critical loads is discussed. A numerical–experimental correlation is performed, using the results of experimental buckling tests. The geometric imperfections measured on the real specimens are accounted for in the finite element model. The results show the reliability of the method to follow the evolution of the cylinder shape from the buckling to the post-buckling field and good accuracy in reproducing the experimental post-buckling behaviour.


ABSTRACT: To improve a helicopter design concept, which meets structural and crashworthiness requirements, a research program is undertaken to study the energy absorption capability of a subfloor structure. In particular, crash tests are performed on the subfloor structure and on the intersection elements, which are components of the structure and can create high deceleration peak loads at the cabin floor level causing dangerous inputs to the occupants. Then the structures are analysed by a commercial explicit finite element code, PAM-CRASH, using detailed geometrical models, suitable materials models and the appropriate definition of contact forces and rivets. The analysis shows that the load-shortening diagrams present a good correlation to the experimental data and that the structural collapse predictions correspond closely to the observed behaviour during the experimental tests. Consequently the finite element analysis can be used to aid the designers in evaluating the crashworthiness of different structural concepts and can therefore be an important mean of reducing development costs.


ABSTRACT: This paper deals with the definition of a post-buckling optimisation procedure for the design of composite stiffened panels subjected to compression loads. The optimised structures are then characterised by a
local skin buckling between the stiffeners and by a high ratio between the collapse load and the buckling load. To overcome too expensive analyses from a computational point of view, an optimisation procedure is developed. It is based on a global approximation strategy, where the structure response is given by a system of neural networks trained by means of finite element analyses, and on genetic algorithms, that results particularly profitable due to the presence of integer variables. The optimisation procedure reduces considerably the computational costs, offers a complete separation between the system modelling and the optimisation problem and shows that a local skin buckling between the stiffeners allows a weight reduction equal to 18%.


ABSTRACT: This paper describes an experimental investigation of the elastic dynamic buckling of carbon fiber reinforced plastic cylindrical shells subjected to pulse axial compression. The critical impulse is applied using a horizontal crash sled, so to obtain axial compression shape similar to a half-sine and duration of the impact load of approximately 0.1 s. The test results are reported and analyzed. The dynamic buckling load of the initially imperfect shell is related to its static buckling load and the ratio is less than unity. Since the common practice is to assume that dynamic buckling loads are higher than the static ones, which means that static design is safe, extra caution and careful design is recommended.

References listed at the end of the paper:

ABSTRACT: Experimental data obtained from buckling and post-buckling tests performed until collapse on three stiffened composite cylindrical shells are described. The shells, different in the skin and in the stiffeners lay-up, were expressly designed for working in the post-buckling field. The outer and inner surfaces are scanned before the tests, in order to determine the initial geometric imperfections and the thickness variations. After that, the shells are tested using a position control mode until collapse, two of them under axial compression and one under torque. The diagrams of axial load versus displacement and of torsion versus rotation are recorded in real time during the tests. To monitor the first buckling load and the evolution of the buckling shape, five laser displacement sensors are employed. The test results show the strength capacity of these structures to work in the post-buckling range. Indeed neither failure mechanisms nor any other hazards are visible in the post-buckling range. On the other hand, the collapse, due to the failure of the stringers, is sudden and destructive.


ABSTRACT: The paper deals with dynamic buckling due to impulsive loading of thin-walled carbon fiber reinforced plastics (CFRP) shell structures under axial compression. The approach adopted is based on the equations of motion, which are numerically solved using a finite element code (ABAQUS/Explicit) and using numerical models validated by experimental static buckling tests. To study the influence of the load duration, the time history of impulsive loading is varied and the corresponding dynamic buckling loads are related to the quasi-static buckling loads. To analyse the sensitivity to geometric imperfections, the initial geometric imperfections, measured experimentally on the internal surface of real shells, are introduced in the numerical models. It is shown numerically that the initial geometric imperfections as well as the duration of the loading period have a great influence on the dynamic buckling of the shells. For short time duration, the dynamic buckling loads are larger than the static ones. By increasing the load duration, the dynamic buckling loads decrease quickly and get significantly smaller than the static loads. Since the common practice is to assume that dynamic bucking loads are higher than the static ones, which means that static design is safe, careful design is
recommended. Indeed, taking the static buckling load as the design point for dynamic problems might be misleading.


ABSTRACT: First, the test equipment used for various types of buckling experiments in the Department of Aerospace Engineering at the Politecnico di Milano is presented. It can apply axial and torsion loading, separately and in combination, using displacement control. Then, the results of an experimental investigation on stiffened shells and curved panels, made from graphite-epoxy are presented. The experimental data acquired during the first non-destructive buckling tests and during the final destructive failure tests demonstrate clearly the strength capacity of these structures to work in the postbuckling range, allowing further weight savings. The results show that the structures are able to sustain load in the postbuckling range without any damage. On the negative side, the collapse is sudden and destructive. The measured data are also useful for the development and validation of analytical and numerical high-fidelity methods. These validated analysis tools can provide design criteria that are less conservative than the existing ones.


ABSTRACT: This work presents the buckling optimization of composite stiffened panels loaded in compression and shear. The procedure relies on the coupled use of an analytical formulation for the structural analysis together with an optimization based on genetic algorithms. The analytical formulation allows the assessment of the local buckling behavior of panels with blade, J, T and hat stiffener cross sections. The out-of-plane buckling deflections on the skin and the stiffener are represented by trigonometric shape functions, and the governing equations are derived referring to the minimum potential energy principle and the method of Ritz. The formulation is used to obtain optimal configurations in terms of skin and stiffener lay-ups, stiffener cross section and geometry. Constraints can be imposed on the structural response in terms of buckling load and prebuckling stiffness as well as on technological requirements. The optimal design is presented for the buckling load maximization of a flat hat stiffened panel loaded in compression and shear, and for the minimum weight under buckling constraints of a curved panel with open section stringers loaded in compression. Analytical results are then compared with finite element analyses.

Reference listed at the end of the paper:
ABSTRACT: The paper presents an analytical formulation for the post-buckling analysis of composite aeronautical panels with omega stiffeners loaded in compression and shear. The formulation relies on an energy principle and the method of Ritz. In the first step, the panel is an assembly of plate elements, and the buckling analysis is performed. In the second step, the panel is an elastically restrained skin, and the post-buckling behaviour is studied. The comparisons with finite element analyses and experimental results from the literature reveal the ability of the formulation to assess the post-buckling response.

References listed at the end of the paper:
DOI: 10.1142/9781786344335_0006
ABSTRACT: A semi-analytical method for the buckling and postbuckling analysis of composite-stiffened panels is presented. The method is formulated in the context of a variational framework and is based on the method of Ritz. Two levels of approximation are introduced, consisting of a plate assembly representation for the buckling analysis and an elastically restrained panel for the postbuckling assessment. Two aeronautical panels with open-section and closed-section stringer profiles are analyzed, illustrating the comparison with finite element predictions and with experimental data taken from the literature. The results indicate that accurate predictions can be obtained in terms of buckling loads, postbuckling reduction in stiffness, and out-of-plane deflections with an analysis time of the order of a few seconds.

ABSTRACT: An experimental and numerical investigation was conducted to study the skin-stiffener separation of single T-shape stiffener specimens in post-buckling condition. Three specimens were manufactured with a centrally located Teflon insert, and were loaded in compression until collapse. Deformation patterns and separation evolution were monitored during the tests. To measure the full-field displacements and the strain distributions of the specimens, digital image correlation system was used. Skin-stiffener separation was observed and measured with an ultrasound system. Finite element analyses were conducted to capture interlaminar damage mechanism based on Virtual Crack Closure Technique. The numerical analysis well predicted the post-buckling deformation and the skin-stiffener separation behaviour. The close correlation between the experimental and numerical results allows for further exploitation of strength reserve in post-buckling region and wider design options for the next generation of composite aircraft designs.

Carlos G. Davila and Chiara Bisagni, “Fatigue life and damage tolerance of postbuckled composite stiffened structures with indentation damage”, Journal of Composite Materials, 52(7):002199831771578, June 2017 DOI: 10.1177/0021998317715785
ABSTRACT: The fatigue life and damage tolerance of composite stiffened panels with indentation damage are investigated experimentally using single-stringer compression specimens. The indentation damage was induced to one of the two flanges of the stringer of every panel. The advantages of indentation compared to impact are the simplicity of application, less dependence on boundary conditions, better controllability, and repeatability of the imparted damage. The tests were conducted using advanced instrumentation, including digital image correlation, passive thermography, and in situ ultrasonic scanning. Specimens with initial indentation damage ranging between 32 and 56 mm in length were tested quasi-statically and in fatigue, and the effects of cyclic load amplitude and damage size were studied. A means of comparison of the damage propagation rates and collapse loads based on a stress intensity measure and the Paris law is proposed. The stress intensity measure provides the means to compare the collapse loads of specimens with different damage types and damage sizes, while the Paris law is used to compare the damage propagation rates in specimens subjected to different cyclic
loads. This approach enables a comparison of different tests and the potential identification of the effects that influence the fatigue lives and damage tolerance of postbuckled structures with defects.


ABSTRACT (From Alfano’s 2016 thesis): Cylindrical shells are widely used in primary structures of space launch vehicles. Due to the high imperfection sensitivity, buckling behavior of shells under axial compression exhibits a great discrepancy between theory and experiments. In order to meet the demand of aerospace industry for improved design criteria, a unified framework, the probability-based methodology, for probabilistic buckling analysis of axially-compressed shells is developed, illustrating it with application to two structures of Ariane 5 launcher. They are sandwich composite shells made of same material, but with different stacking sequence and geometric dimensions. One of them is also studied with the presence of three circular cut-outs. The methodology combines the Stress-Strength Interference Method and the Latin Hypercube Method to determine a probabilistic buckling factor, once the probability that shell withstands axial load without undergoing buckling is specified. Such a factor accounts for influence of manufacturing and in-service imperfections, but depends on required reliability, on sample size and on considered imperfections. Different sources of imperfections, modeled by literature, are introduced into the analysis independently and jointly. The main advantage of the methodology is the versatility as it can be used for buckling investigation of laminated composite shells and sandwich composite shells including different types of imperfections. In particular, the methodology allows for incorporating directly experimental data representative of shells of interest. To show this, buckling of an experimental shell is investigated by the probabilistic methodology using measured imperfections. An alternative method, the chaos approach, for buckling analysis of axially-compressed shells is derived using concepts of the chaos, with application to one of the studied shells. The goal is to obtain an erosion profile as function of increasing axial load. It illustrates concisely the degradation due to imperfections of the load-carrying capability of shells. The approach could be adopted when test-origination database of imperfections is not available to achieve a first assessment of the imperfection sensitivity of shells.

Chiara Bisagni and Michela Alfano, “Chaos theory applied to buckling analysis of composite cylindrical shell”, 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, South Korea, June 2016


ABSTRACT: The durability and damage tolerance of postbuckled composite structures are issues that are not completely understood and remain difficult to predict due to the nonlinearity of the geometric response and its interaction with local damage modes. A research effort was undertaken to investigate experimentally the quasi-static and fatigue damage progression in single-stringer compression specimens. Three specimens were manufactured with a co-cured hat stringer, and an initial defect was introduced with a Teflon film inserted between one flange of the stringer and the skin. Pre-test finite element analyses were conducted using the virtual
crack closure technique to select the range of defect sizes to be considered and the load levels to be applied during the fatigue tests. The tests were monitored with digital image correlation, passive thermography, and ultrasound systems. After an initial opening and extension of the Teflon-induced embedded defect, the specimens sustained a high number of cycles. It was observed that when the skin/stringer separation develops in the opposite flange, it propagates rapidly within a small number of cycles and causes the collapse of the specimen. These test results contribute to a better understanding of the complex response phenomena exhibited by postbuckled stiffened structures subjected to fatigue loads in the postbuckling range.

Haim Abramovich (Technion – Israel Institute of Technology) and Chiara Bisagni (Delft University of Technology), “Behavior of curved laminated composite panels and shells under axial compression”, Progress in Aerospace Sciences 78, June 2015, DOI: 10.1016/j.paerosci.2015.05.008
ABSTRACT: The buckling and post-buckling behavior of curved cylindrical stringer-stiffened laminated composite and metal panels had been investigated both numerically and experimentally. The results were compared to those of cylindrical stringer-stiffened laminated composite shells to yield a way of determining the optimal structure to be used for axial compression loading. For the present tested structures, the composite panels showed the best load-weight ratio.

Thomas Ludwig, Mathias Doreille, Silvio Merazzi, Riccardo Vescovini and Chiara Bisagni, “Dynamic finite element simulations of composite stiffened panels with a transverse-isotropic viscoelastic energy dissipation model”, Progress in Aerospace Sciences 78, June 2015, DOI: 10.1016/j.paerosci.2015.06.001
ABSTRACT: This paper presents a methodology for predicting the damped response and energy dissipation of laminated composite structures, subjected to dynamic loads. Starting from simple coupon tests to characterize the material, the numerical simulation of damping properties is made possible by a novel linear viscoelastic model that has been developed and implemented in the finite element code B2000++. A nonlinear optimization procedure is adopted to fit experimental data and define the exponential Maxwell parameter model. To illustrate the potentialities of the method, the post-buckling analysis of a relatively complex aeronautical panel is presented, accounting not only for geometric nonlinearities, but also for viscoelastic effects. The results illustrate the effects due to material dissipation, their relation to the effects of inertia, and the influence of geometric imperfections on the response of the panel.

Chiara Bisagni (Delft University of Technology), “Overview of the DAEDALOS project”, Progress in Aerospace Sciences 78, June 2015, DOI: 10.1016/j.paerosci.2015.05.007
ABSTRACT: The “Dynamics in Aircraft Engineering Design and Analysis for Light Optimized Structures” (DAEDALOS) project aimed to develop methods and procedures to determine dynamic loads by considering the effects of dynamic buckling, material damping and mechanical hysteresis during aircraft service. Advanced analysis and design principles were assessed with the scope of partly removing the uncertainty and the conservatism of today's design and certification procedures. To reach these objectives a DAEDALOS aircraft model representing a mid-size business jet was developed. Analysis and in-depth investigation of the dynamic response were carried out on full finite element models and on hybrid models. Material damping was experimentally evaluated, and different methods for damping evaluation were developed, implemented in finite element codes and experimentally validated. They include a strain energy method, a quasi-linear viscoelastic material model, and a generalized Maxwell viscous material damping. Panels and shells representative of
typical components of the DAEDALOS aircraft model were experimentally tested subjected to static as well as dynamic loads. Composite and metallic components of the aircraft model were investigated to evaluate the benefit in terms of weight saving.

Chiara Bisagni (Delft University of Technology), Composite cylindrical shells under static and dynamic axial loading: An experimental campaign”, Progress in Aerospace Sciences 78, October 2015, pp 107-115
https://doi.org/10.1016/j.paerosci.2015.06.004
ABSTRACT: The results of an experimental investigation performed at the Politecnico di Milano inside the European project DAEDALOS on three composite cylindrical shells are here presented. At first, static buckling tests were performed under axial compression. Then, two types of dynamic tests were carried out: modal tests at different load levels before buckling and dynamic buckling tests applying an axial shortening of short duration. At the end, one shell was statically tested until final failure. The tests allow to understand the behavior of thin-walled cylindrical shells subjected to axial compression both in static and dynamic conditions. The results show the strength capacity of these structures to work in the post-buckling range with a capacity to sustain a load that is about 40% of the buckling load. The modal tests at different load levels allowed to observe that an increase of the load determines a reduction of the modal frequency and an increase of the damping. Large deformations are obtained before the final failure with out-of-plane displacements of almost 40 mm and a shortening equal to about 26 times the buckling shortening.


ABSTRACT: This paper describes the analysis and the minimum weight optimisation of a fuselage composite panel made from carbon/epoxy material and stiffened by five omega stringers. The panel investigated inside the European project MAAAXIMUS is studied using a fast tool, which relies on a semi-analytical procedure for the analysis and on genetic algorithms for the optimisation. The semi-analytical approach is used to compute the buckling load and to study the post-buckling response. Different design variables are considered during the optimisation, such as the stacking sequences of the skin and the stiffener, the geometry and the cross-section of the stiffener. The comparison between finite element and fast tool results reveals the ability of the formulation to predict the buckling load and the post-buckling response of the panel. The reduced CPU time necessary for the analysis and the optimisation makes the procedure an attractive strategy to improve the effectiveness of the preliminary design phases.

Chiara Bisagni (Delft University of Technology), “An analytical formulation for the prediction of buckling and post-buckling of composite panels and shells”, Third MIT Conference on Computational Fluid and Solid Mechanics, Boston, USA, June 2015
ABSTRACT: The paper gives an overview of some research activities regarding buckling of composite structures performed in Italy in the last years. In particular, the activities performed at Politecnico di Milano, at Politecnico di Torino and at Università di Pisa are here presented. Some investigations were performed on structures manufactured by Agusta/Westland and by Alenia Aeronautica, while other researches were funded by the Italian Ministry of Research, and other ones were funded by the European Commission within European Projects.

References listed at the end of the paper:

ABSTRACT: The present paper describes the results of an experimental and numerical investigation on a composite laminated helicopter tailplane, whose lower panels are subjected to buckling phenomena during its lifetime. The structure is made of woven carbon fibers, unidirectional carbon fibers, and honeycomb. Two different types of lower laminate composite panels are investigated: Z stringer-stiffened panels and L stringer-stiffened panels. During the tests, measurements are taken using a load cell, potentiometers, strain gauges, and moiré fringes. First, three Z stringer-stiffened and three L stringer-stiffened laminate composite lower panels are tested up to 85% of the target load. Then, the last L stringer-stiffened panel is tested until collapse. Buckling occurs at 63% of the target load, whereas the collapse happens at 90%. At the same time, the finite element analyses of the tailplane structures with both Z stringer-stiffened and L stringer-stiffened panels are performed, simulating the dynamic of a slow compression test, using LS-DYNA. The finite element results are compared with the experimental data, obtaining a good numerical-experimental correlation. Numerically, the collapse of the structure is predicted at 93% of the target load, whereas experimentally it happened at 90%.


ABSTRACT: This paper presents a fast tool that can be used during the preliminary design of isotropic and composite stiffened panels subjected to axial compression. It consists of two modules, one for the analysis and one for the optimization. The analysis is performed by implementing an analytical formulation to obtain the linearized buckling load and to study the nonlinear postbuckling field. In particular, closed-form solutions are derived for the linearized local and global buckling loads, and a semi-analytical procedure is implemented for the study of the nonlinear local postbuckling field. The optimization is based on genetic algorithms and allows
taking into account buckling and postbuckling requirements with reduced computational time. Two examples regarding the minimum weight optimization of an isotropic panel and a composite panel are discussed and verified by means of finite element eigenvalue and nonlinear analyses. The total time required for the analysis and the optimization is of the order of a few minutes, and the difference between the analytical and numerical results is below 9% for the buckling load and below 3% for the postbuckling stiffness.

References listed at the end of the paper:
Chiara Bisagni and Riccardo Vescovini (Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy), ‘Analytical formulation for local buckling and post-buckling analysis of stiffened laminated panels”, Thin-Walled Structures 47 (2009) 318–334

ABSTRACT: This paper presents an analytical formulation for the study of linearized local skin buckling load and nonlinear post-buckling behaviour of isotropic and composite stiffened panels subjected to axial compression. The skin is modelled as a thin plate introducing Donnell-Von Kármán and Kirchhoff hypothesis and applying classical lamination theory, while the stiffeners are considered as torsion bars. The first part of the work deals with the study of linearized buckling load, and two analytical solutions are presented: one is based on Kantorovich method and the other one on Ritz method. The second part of the work regards the development of a semi-analytic This paper presents an analytical formulation for the study of linearized local skin buckling load and nonlinear al formulation for the study of the post-buckling field, using a variational approach and applying Ritz method. Results are compared with a serie of finite element analysis. It is shown that analytical buckling loads differ from numerical ones for less than 12%, and that force–displacement curves are well predicted. A computer program called stiffened panels analysis (StiPAn) is developed on the basis of the presented formulation. It allows quick analysis of stiffened laminated panels and is suited to be used in optimization routines for preliminary design.

References cited at the end of the paper:


ABSTRACT: Analysing the collapse of skin-stiffened structures requires capturing the critical phenomenon of skin-stiffener separation, which can be considered analogous to interlaminar cracking. This paper presents the development of a numerical approach for simulating the propagation of interlaminar cracks in composite structures. A degradation methodology was introduced in MSC.Marc, which involved the modelling of a structure with shell layers connected by user-defined multiple-point constraints (MPCs). User subroutines were written that employ the virtual crack closure technique (VCCT) to determine the onset of crack growth and modify the properties of the user-defined MPCs to simulate crack propagation. Methodologies for the release of failing MPCs are presented and are discussed with reference to the VCCT assumption of self-similar crack growth. The numerical results obtained by using the release methodologies are then compared with experimental data for a double-cantilever beam specimen. Based on this comparison, recommendations for the future development of the degradation model are made, especially with reference to developing an approach for the collapse analysis of fuselage-representative structures.

References listed at the end of the paper:
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ABSTRACT: Advanced fibre-reinforced polymer composites have seen a rapid increase in use in aircraft structures in recent years. However, significant conservatism is applied in the design of composite aerospace structures, largely due to the inability of current analysis tools to accurately capture the effect of damage. In this work, the design of fuselage-representative composite structures for postbuckling applications is demonstrated, accounting for damage initiation and growth. An analysis methodology is applied that was developed to capture the critical damage mechanisms leading to collapse of these structures. The analysis methodology is used to investigate the effect of size and location of a pre-existing interlaminar damage region in a postbuckling composite structure design. A pre-damage configuration suitable for experimental investigation is selected. Experimental results are presented of the selected panel configuration tested to collapse in compression, and compared with numerical predictions.

References listed at the end of the paper:


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ABSTRACT: Experimental and numerical investigations were conducted into the damage growth and collapse behaviour of composite blade-stiffened structures. Four panel types were tested, consisting of two secondary-bonded skin–stiffener designs in both undamaged and pre-damaged configurations. The pre-damaged configurations were manufactured by replacing the skin–stiffener adhesive with a centrally located, full-width Teflon strip. All panels were loaded in compression to collapse, which was characterised by complex post-buckling deformation patterns and ply damage, particularly in the stiffener. For the pre-damaged panels, significant crack growth was seen in the skin–stiffener interface prior to collapse, which caused a reduction in load-carrying capacity. In the numerical analysis of the undamaged panels, collapse was predicted using a ply failure degradation model, and a global–local approach that monitored a strength-based criterion in the skin–stiffener interface. The pre-damaged models were analysed with ply degradation and a method for capturing interlaminar crack growth based on multi-point constraints controlled using the Virtual Crack Closure Technique. The numerical approach gave close correlation with experimental results, and allowed for an in-depth analysis of the damage growth and failure mechanisms contributing to panel collapse. The successful prediction of collapse under the combination of deep post-buckling deformations and several composite damage mechanisms has application for the next generation of composite aircraft designs.

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ABSTRACT: The European Commission Project COCOMAT (Improved MATerial Exploitation at Safe Design of Composite Airframe Structures by Accurate Simulation of COllapse) is a currently running four-year project that aims to exploit the large strength reserves of composite structures through a more accurate prediction of collapse. Accordingly, one of the COCOMAT work packages involves the design of test panels with a focus on investigating the progression of composite damage mechanisms. This paper presents the collaborative results of some of the partners for this task. Different design alternatives were investigated for fuselage-representative test panels. Non-linear structural analyses were performed using MSC.Nastran (Nastran) and ABAQUS/Standard (Abaqus). Numerical predictions were also made applying a stress-based adhesive degradation model, previously implemented into a material user subroutine for Abaqus. Following this, a fracture mechanics analysis using Nastran was performed along all interfaces between the skin and stiffeners, to examine the stiffener disbonding behaviour of each design. On the basis of the structural and fracture mechanics analyses, a design was selected as being the most suitable for the experimental investigation within COCOMAT. Though the COCOMAT panels have yet to be manufactured and tested, experimental data on the structural performance and damage mechanisms were available from a separate project for a panel identical to the selected design. This data was compared to the structural, degradation and fracture mechanics predictions made using non-linear finite element solutions, and the application of the design within the COCOMAT project was discussed.
References listed at the end of the paper:


ABSTRACT: The elastic buckling and postbuckling behaviour of eccentrically stiffened plates are evaluated analytically. The effects of lateral boundary conditions and of stiffener eccentricity relative to the plate plane are emphasized. Attention is confined to global buckling; local plate and local stiffener buckling effects are neglected. A simplified direct energy approach is used together with Marguerre's plate theory. Critical buckling loads are found which are generally higher than those obtained with a simple Euler column model. A simple closed-form solution is found for the postbuckling curve which for small imperfection levels coincides with the classical Koiter solution. The buckling behaviour is found to be asymmetric with loads generally in excess of the critical load in the advanced postbuckling region.

Eirik Byklum and Jørgen Amdahl (Department of Marine Structures, Norwegian University of Science and Technology, N-7491, Trondheim, Norway), “Nonlinear buckling analysis and ultimate strength prediction of stiffened steel and aluminium panels”, The Second International Conference on Advances in Structural Engineering and Mechanics, Busan, Korea, August, 2002

ABSTRACT: A computational model for buckling and postbuckling analysis of stiffened panels is developed. The model provides fast and accurate results for use in design of ships and offshore structures. The loads
considered are in-plane compression or tension, shear force, and lateral pressure. Deflections are represented by trigonometric functions, and the principle of minimum potential energy is applied. Geometrical nonlinearities are accounted for using large deflection plate theory. Material nonlinearity is not taken into account, since the onset of yielding is taken as the capacity limit. Various computations have been performed for verification of the proposed model, and comparisons are made with nonlinear finite element methods.


ABSTRACT: A computational model for analysis of local buckling and postbuckling of stiffened panels is derived. The model provides a tool that is more accurate than existing design codes, and more efficient than nonlinear finite element methods. Any combination of biaxial in-plane compression or tension, shear, and lateral pressure may be analysed. Deflections are assumed in the form of trigonometric function series. The deformations are coupled such that continuity of rotation between the plate and the stiffener web is ensured, as well as longitudinal continuity of displacement. The response history is traced using energy principles and perturbation theory. The procedure is semi-analytical in the sense that all energy formulations are derived analytically, while a numerical method is used for solving the resulting set of equations, and for incrementation of the solution. The stress in certain critical points are checked using the von Mises yield criterion, and the onset of yielding is taken as an estimate of ultimate strength for design purposes.


ABSTRACT: Direct application of geometrical non-linear plate theory is the main concept in the new Panel Ultimate Limit State (PULS) stiffened panel models recently recognized by Det Norske Veritas as part of the new rules and standards for ships and offshore constructions. The focus is on assessment of the ultimate capacity limit, rather than the more traditional elastic buckling limit. The method is streamlined for rules based on modern ultimate limit state design principles. The models are validated against non-linear FE analyses and laboratory experiments. Comparison against existing codes used by Classification Societies are included.

References listed at the end of the paper:


Eirik Byklum (1), Eivind Steen (1) and Jørgen Amdahl (2)
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ABSTRACT: A computational model for global buckling and postbuckling analysis of stiffened panels is derived. The loads considered are biaxial in-plane compression or tension, shear, and lateral pressure. Deflections are assumed in the form of trigonometric function series, and the principle of stationary potential energy is used for deriving the equilibrium equations. Lateral pressure is accounted for by taking the deflection as a combination of a clamped and a simply supported deflection mode. The global buckling model is based on Marguerre’s nonlinear plate theory, by deriving a set of anisotropic stiffness coefficients to account for the plate stiffening. Local buckling is treated in a separate local model developed previously. The anisotropic stiffness coefficients used in the global model are derived from the local analysis. Together, the two models provide a tool for buckling assessment of stiffened panels. Implemented in the computer code PULS, developed at Det Norske Veritas, local and global stresses are combined in an incremental procedure. Ultimate limit state estimates for design are obtained by calculating the stresses at certain critical points, and using the onset of yielding due to membrane stress as the limiting criterion.

References listed at the end of the paper:

ABSTRACT: The buckling capacity of steel plates stiffened with T shape stiffeners was investigated experimentally and analytically. The test specimens, 2000 mm long, were fabricated with a 500×10 mm plate stiffened with a WT 125×12.5 stiffener. The experimental program was designed to investigate the effect of unloaded edges boundary restraint, combination of in-plane and out-of-plane load, and imposed plate damage on the buckling capacity of stiffened steel plates. The residual stresses were measured in a representative test specimen and initial imperfections were measured for each test specimen. The residual stresses and the measured initial imperfections were included in the finite element model. A large deformation and finite strain analysis was performed using the finite element code ABAQUS. The finite element analysis was found to predict very accurately both the behaviour and capacity of stiffened steel plate panels. Stiffener tripping and plate buckling modes were equally well predicted.

Joergen Amdahl, “Buckling and ultimate strength of marine structures”, Chapter 5, Buckling of Cylindrical Shells”, TMR4205, MTS-2005.01.18

PARTIAL INTRODUCTION: Stiffened and unstiffened cylindrical shells are important structural elements in offshore structures. They are very often subjected to compressive stresses and must be designed against buckling criteria. The buckling behaviour is usually more violent than it is for plate and column structures. References listed at the end of the paper:

/5.1/"Buckling Strength Analysis" Classification Note No. 30.1, Det Norske Veritas, July 1982.


ABSTRACT: The stability of plates stiffened with tee-shape stiffeners was investigated using a finite element model. Four series of stiffened plate panels were modeled using a finite strain four-node shell element. The model was validated using the results of tests on full-size stiffened plate specimens and was subsequently used to perform the study of various parameters presented in this paper. The parameters investigated are: the shape and magnitude of initial imperfections in the plate; residual stress magnitude and direction of applied uniform bending; plate slenderness ratio; plate aspect ratio; and plate to stiffener cross-sectional area ratio. The effect of the investigated parameters on the axial load carrying capacity and the mode of failure of stiffened plates is investigated both in the elastic and inelastic ranges. A comparison of these results with design guidelines formulated by Det norske Veritas and the American Petroleum Institute indicates that the guidelines are generally conservative for cases where initial imperfection magnitudes do not exceed the guidelines' prescribed maximum.

References listed at the end of the paper:

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ABSTRACT: The stability of steel plates stiffened with tee-shape sections under uniaxial compression and combined uniaxial compression and bending was investigated using a finite element model. The emphasis of the work presented in this paper was to find the parameters that uniquely describe the strength and behaviour of stiffened steel plates. A finite element model, validated using the results of tests on full-size stiffened plate panels, was used to investigate the scale effect for five dimensionless parameters. The parameters investigated were: the transverse slenderness of the plate, the slenderness of the web and flange of the stiffener, the ratio of torsional slenderness of the stiffener to the transverse slenderness of the plate, and the stiffener-to-plate area ratio. Average magnitude residual stresses and initial imperfections were assumed for this study. A parametric study covering a wide range of dimensionless parameters indicated that stiffened steel plates do not fail by stiffener tripping unless a bending moment is applied to create flexural compressive stresses in the stiffener. Although plate buckling and overall buckling were found to lead to a very stable post-buckling behaviour, the interaction between these two buckling modes was found to give rise to a sudden loss of capacity following initial plate buckling. The plate transverse slenderness, the stiffener slenderness-to-plate slenderness ratio, and the stiffener-to-plate area ratio were found to have a significant effect on this behaviour. A comparison of the numerical analysis results with API and DnV design guidelines indicates that the guidelines predict stiffened steel plate capacity with various degrees of success, depending on the governing mode of failure. Neither guidelines address the potential interaction-buckling phenomenon.
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ABSTRACT: This paper presents part of a series of investigations of the behaviour of steel plates stiffened with tee-shape stiffeners and loaded with axial compressive forces with or without bending moments. These elements typically form bridge decks, ship hulls, ship decks and heavy haul equipment walls. Earlier work by the authors validated a non-linear large deformation-finite strain elasto-plastic finite element model by comparison of the model with the results of sophisticated full-scale physical experimental trials under different load combinations. A parametric study carried out using the finite element model is presented in the following. The study deals with the response of stiffened plate elements under combined uniaxial compression and bending moment. The parameters investigated were the transverse slenderness of the plate, the slenderness of the web and flange of the stiffener, the ratio of torsional slenderness of the stiffener to the transverse slenderness of the plate, and the stiffener to plate area ratio. Average magnitude residual stresses and initial imperfections were assumed. The parametric study indicated that the plate transverse flexural slenderness is the most influential parameter affecting both the strength and behaviour of stiffened steel plates for all the failure modes observed under combined compression and bending. The ratio of stiffener torsional slenderness to plate transverse flexural slenderness, $\beta_4$, affected both the strength and behaviour of only the stiffened plates failing by stiffener tripping. A comparison of the numerical analysis results with American Petroleum Institute and Det Norske Veritas design guidelines indicates that the guidelines predict stiffened steel plate capacity with various degrees of success, depending on the governing mode of failure.


ABSTRACT: In this thesis a post processing tool for finite element analysis was developed to perform buckling checks on stiffened steel panels. The tool can perform buckling checks on rectangular, orthogonal stiffened plates including different panel sizes and openings. The procedure is completely automatic and is consequently conducive to reduction of engineering time. The tool detects geometrical and material properties from a finite element model and determines design loads based on stress results of a finite element analysis. The approach is in accordance with guidelines from design codes and therefore results can be considered to be verified according to the design code in question. The tool has been adapted to the American Bureau of Shipping guide for buckling and ultimate strength assessment for offshore structures. The tool is compared to the ABS plate buckling tool of the commercial software SDC Verifier. Results show that the developed tool does not need as fine finite element mesh as the ABS plate buckling tool of the SDC Verifier to predict accurate buckling factors. Furthermore for general cases up to 25% reduction of buckling factors can be obtained with the developed tool compared to the SDC Verifier.

References listed at the end of the paper:
Elisabeth Slettum (Faculty of Mathematics and Natural Sciences, University of Oslo), “A Semi-Analytical Model for Buckling of Stiffened Cylindrical Shells”, Master’s degree thesis, June 2013, (Supervisor Associate Professor Lars Brubak)

SUMMARY: Cylindrical shells are common configurations within the technology. The transition from the side to the bottom on a ship has the shape of a fourth of a cylindrical shell. Both ring and stringer stiffeners can be added to the shell for support. Buckling of this type of structure is an important area of interest. The main purpose of this thesis has been to make a semi-analytical model that can describe how a ring stiffened shell and stringer stiffened shell respond during buckling. A variety of loads have been subjected to the shell model. Simple analytical expressions do not exist for clamped shells or shells subjected to shear and numerical methods must be used. The development of the model has been done by use of linear buckling theory and an energy method, the Rayleigh Ritz method. The model has been programmed in Fortran. Eigenvalues and associated eigenmodes have been found. The semi-analytical model has been verified against the finite element analysis software Abaqus. The results from the models were in good agreement with each other. The apply of the semi-analytical model on a bilge structure showed a deviation in the results. A small difference in the boundary conditions, with the element model being stiffer due to the edges being held straight, was causing the deviation. The difference in the results from the semi-analytical model and the element model was smaller for the ring stiffened shell than for the unstiffened shell and the stringer stiffened shell. The buckling load calculated by the semi-analytical model were on the conservative side compared with the element model.

References listed at the end of the paper:

ABSTRACT: A total potential energy approach has been employed in conjunction with the Rayleigh-Ritz method to study the stability behaviour of generally laminated composite plates with all edges simply supported and subjected to in-plane loading conditions. Thorough comparison with exact solutions for some classes of laminated composite plates subjected to uniaxial compression and biaxial compression are presented to verify the theoretical prediction of the present analysis. Lastly parametric studies on the combination of the various in-plane loads, i.e. biaxial compression and uniaxial compression with shear, on practical laminated composite plates are presented. The buckling results for a symmetric angle-ply laminated composite plate are also discussed.


ABSTRACT: A closed-form expression to determine the effective flexural modulus for a laminated composite beam is derived and presented in this paper. An approach based on the established Euler—Bernoulli beam theory with the proposed effective flexural modulus to predict the buckling load of the laminated composite beam is also presented in detail. The problem of a laminated beam with no delamination and that with a single through-the-width delamination is analysed. The results obtained using the current expression are compared with those obtained using existing expressions found in the literature. Results from a non-linear finite-element analysis are also presented and included in the comparison. The parameters investigated include ply orientation, number of layers, delamination length, support conditions, and material property. The comparison of results showed that the current estimated effective flexural stiffness expression yields a good lower bound solution for predicting the buckling load of both the perfect and the delaminated laminated composite beam.

ABSTRACT: This article reports the structural responses of generally laminated composite columns subjected to uni-axial compression and transverse load. Closed-form expressions were developed and are presented in this contribution to analyse buckling and bending responses of generally laminated composite beams with various boundary supports. The expressions were developed using a combination of the Euler—Bernoulli beam and the classical lamination theory. In addition, the results of a complementary experimental study are presented and are used to validate the analytical models. The comparison of the analytical results with the experimental results shows good correlation in general. Some interesting preliminary results obtained in the analysis of the beam-column are also presented, noted, and discussed.


ABSTRACT: The post-buckling behaviour of anisotropic stiffened panels with initial imperfections is investigated. Since buckling of the skin between the stiffeners often occurs first, a non-linear analysis is developed for symmetric panels under biaxial compression in order to obtain the out-of-plane panel deflection in the post-buckling range. The non-linear differential equations are expressed in terms of the out-of-plane displacement and the Airy function. They are solved with the Galerkin method for various boundary conditions by imposing an edge displacement control. The theoretical and experimental results obtained by the present analysis show that the transverse load can greatly influence the buckling loads and halfwave number. Since no experimental results have been found in the literature, several tests have been carried out on graphite/epoxy blade stiffened panels 900 mm long and 620 mm wide applying simultaneously biaxial compression loads with several combined ratios. An eccentricity results between longitudinal and transverse load, because the longitudinal compression is applied along the centroidal axes of the stiffened section while the transverse compression is applied to the skin panel. The correlation between the experimental and analytical results has been quite good; the experimental results demonstrate the influence of eccentricity of the transverse load on panel deflection in the pre- and post-buckling range.


ABSTRACT: A systematic study of theoretical methods for predicting the ultimate hull girder strength of ships is carried out based on long-time theoretical and experimental work in authors group. An integrated framework of non-linear finite element analysis, a locally improved idealized structural unit method (ISUM), a simplified method (SM) in which average stress–strain relationship is derived using beam-column theory, along with an advanced analytical method (AM) which is coupled with an elastic-plastic method (EPM which is a combination of elastic large deflection analysis and rigid plastic analysis) of ultimate buckling strength of stiffened panels and suitable for biaxial bending and non-symmetric structures of damaged ship hulls, are used to perform a comparative study of ultimate hull girder strength of a 300,000 dwt large double hull tanker. The calculation results are also compared with single step procedure of common structural rules (CSR) for double hull tankers and comparative analysis of calculation methods of ultimate hull girder strength is carried out in many ways.

ABSTRACT: The new simple design equations for predicting the ultimate compressive strength of stiffened plates with initial imperfections in the form of welding-induced residual stresses and geometric deflections were developed in this study. A non-linear finite element method was used to investigate on 60 ANSYS elastic–plastic buckling analyses of a wide range of typical ship panel geometries. Reduction factors of the ultimate strength are produced from the results of 60 ANSYS inelastic finite element analyses. The proposed design equations have been developed based on these reduction factors. For the real ship structural stiffened plates, the most general loading case is a combination of longitudinal stress, transverse stress, shear stress and lateral pressure. The new simplified analytical method was generalized to deal with such combined load cases. The accuracy of the proposed equations was validated by the experimental results. Comparisons show that the adopted method has sufficient accuracy for practical applications in ship design.


ABSTRACT: An analytical method based on the modal expansion technique was developed to predict the vibro-acoustic response of both unidirectionally and bidirectionally stiffened flat panel. This paper presents the response to diffuse acoustic field (DAF) and turbulent boundary layer (TBL) excitations in terms of their joint acceptance. Numerical results for the dynamic and acoustic responses are compared with finite element method (FEM) and boundary element (BEM) results for stiffened panel with complex and eccentrically shaped stiffeners subject to point force excitation. A theoretical prediction of the transmission loss (TL) is also compared with laboratory measurements conducted on flat panels representing aircraft models as well as with hybrid statistical energy analysis (SEA)–FEM periodic model. The results confirm that the stiffened panel has the same acoustic response as the skin without stiffeners at frequencies where the structural wavelengths are equal to the spacing between the stiffeners. In addition, the transmission loss is lowered by the presence of the stiffeners at some particular region of frequencies below the critical frequency with respect to the unstiffened panel.

Knight, Norman F, Jr and Starnes, James H, Jr, “Postbuckling behavior of axially compressed graphite-epoxy cylindrical panels with circular holes”, American Society of Mechanical Engineers, Joint Pressure Vessels and Piping/Applied Mechanics Conference, San Antonio, TX; United States; 17-21 June 1984

ABSTRACT: The results of an experimental and analytical study of the effects of circular holes on the postbuckling behavior of graphite-epoxy cylindrical panels loaded in axial compression are presented. The STAGSC-1 general shell analysis computer code is used to determine the buckling and postbuckling response of the panels. The loaded, curved ends of the specimens were clamped by fixtures and the unloaded, straight edges were simply supported by knife-edge restraints. The panels are loaded by uniform end shortening to several times the end shortening at buckling. The unstable equilibrium path of the postbuckling response is obtained analytically by using a method based on controlling an equilibrium-path-arc-length parameter instead of the traditional load parameter. The effects of hole diameter, panel radius, and panel thickness on
postbuckling response are considered in the study. Experimental results are compared with the analytical results and the failure characteristics of the graphite-epoxy panels are described.


ABSTRACT: Results of an experimental and analytical study of the postbuckling behavior of selected graphite-epoxy cylindrical panels loaded in axial compression are presented. The postbuckling response and failure characteristics of the panels are described. The postbuckling response of each specimen is typical of axially-compressed cylindrical shells and curved panels in that a severe reduction in load occurs at buckling. Failure of all panels initiated near regions with severe local bending gradients. Analytical results from a nonlinear general shell finite element analysis computer code correlate well with typical experimental results up to buckling. Measured initial geometric imperfections were included in the postbuckling analysis. Analytically-determined stress distributions in the postbuckling response were used with failure criteria to identify the load level and the location of first-ply failure.


ABSTRACT: Factors influencing the nonlinear response prediction of composite panels are described. The role of these factors in performing test-analysis correlation for composite panels is discussed and demonstrated using selected configurations for which experimental data have been previously published. Advanced formulations and analysis methods are providing structural analysts with better tools to aid the development of understanding the complexities associated with composite structural design and analysis.

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ABSTRACT: The prediction of the ultimate load-carrying capability for compressively loaded shell structures is a challenging nonlinear analysis problem. Selected areas of finite element technology research and nonlinear solution technology are assessed. Herein, a finite element analysis procedure is applied to four cylindrical shell collapse problems which have been used by computational structural mechanics researchers in the past. This assessment will focus on a number of different shell element formulations and on different approaches used to account for geometric nonlinearities. The results presented confirm that these aspects of nonlinear shell analysis can have a significant effect on the predicted nonlinear structural response. All analyses were performed using a single software system which allowed a convenient assessment of different element formulations with a consistent approach to solving the discretized nonlinear equations.

Rengarajan, G. (1), Aminpour, M. A. (2) and Knight, N. F. (3),
(1) Clemson University, Clemson, SC 29634-0921, U.S.A
ABSTRACT: An improved 4-node quadrilateral assumed-stress hybrid shell element with drilling degrees of freedom is presented. The formulation is based on Hellinger–Reissner variational principle and the shape functions are formulated directly for the 4-node element. The element has 12 membrane degrees of freedom and 12 bending degrees of freedom. It has 9 independent stress parameters to describe the membrane stress resultant field and 13 independent stress parameters to describe the moment and transverse shear stress resultant field. The formulation encompasses linear stress, linear buckling and linear free vibration problems. The element is validated with standard test cases and is shown to be robust. Numerical results are presented for linear stress, buckling, and free vibration analyses.


ABSTRACT: The goal of this research project is to develop assumed-stress hybrid elements with rotational degrees of freedom for analyzing composite structures. During the first year of the three-year activity, the effort was directed to further assess the AQ4 shell element and its extensions to buckling and free vibration problems. In addition, the development of a compatible 2-node beam element was to be accomplished. The extensions and new developments were implemented in the Computational Structural Mechanics Testbed COMET. An assessment was performed to verify the implementation and to assess the performance of these elements in terms of accuracy. During the second and third years, extensions to geometrically nonlinear problems were developed and tested. This effort involved working with the nonlinear solution strategy as well as the nonlinear formulation for the elements. This research has resulted in the development and implementation of two additional element processors (ES22 for the beam element and ES24 for the shell elements) in COMET. The software was developed using a SUN workstation and has been ported to the NASA Langley Convex named blackbird. Both element processors are now part of the baseline version of COMET.

N. Jaunky (1), N.F. Knight Jr (1) and D.R. Ambur (2)
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ABSTRACT: An improved smeared stiffener theory for stiffened panels is presented that includes skin-stiffener interaction effects. The neutral surface profile of the skin-stiffener combination is developed analytically using the minimum potential energy principle and statics conditions. The skin-stiffener interaction is accounted for by computing the bending and coupling stiffness due to the stiffener and the skin in the skin-stiffener region about a shift in the neutral axis at the stiffener. Buckling load results for axially stiffened, orthogrid, and general grid-stiffened panels are obtained using the smeared stiffness combined with a Rayleigh-Ritz method and are compared with results from detailed finite element analyses.
Knight, Norman F, Jr and Nemeth, Michael P (editors), “Stability Analysis of Plates and Shells”, NASA no. 19980019011. In: AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference ABSTRACT: This special publication contains the papers presented at the special sessions honoring Dr. Manuel Stein during the 38th AIAA /ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference held in Kissimmee, Florida, Apdl 7-10, 1997. This volume, and the SDM special sessions, are dedicated to the memory of Dr. Manuel Stein, a major pioneer in structural mechanics, plate and shell buckling, and composite structures. Many of the papers presented are the work of Manny's colleagues and co-workers and are a result, directly or indirectly, of his influence. Dr. Stein earned his Ph.D. in Engineering Mechanics from Virginia Polytechnic Institute and State University in 1958. He worked in the Structural Mechanics Branch at the NASA Langley Research Center from 1943 until 1989. Following his retirement, Dr. Stein continued his involvement with NASA as a Distinguished Research Associate.

Norman F. Knight, Jr and Yunqian Qi (Department of Aerospace Engineering, Old Dominion University, Norfolk, VA 23529-0247, USA), “On a consistent first-order shear-deformation theory for laminated plates”, Composites Part B: Engineering, Vol. 28, No. 4, 1997, pp. 397-405, doi:10.1016/S1359-8368(96)00058-3 ABSTRACT: This paper systematically states the consistent first-order shear-deformation theory for laminated plates recently proposed by Qi and Knight. It assumes that only in an average sense does a straight line originally normal to the midplane remain straight and rotate relative to the normal of the midplane, and in a local sense a slight displacement perturbation around the average rotated line is also permitted after deformation. Since the curved line is very shallow, the present theory still approximates linear in-plane and constant transverse displacements through the thickness just as Reissner and Mindlin's first-order shear-deformation theory does. Reissner and Mindlin's theory leads to uniform transverse shear strain distributions by employing pointwise strain displacement relationships, and satisfies the transverse shear constitutive relationships only in an average corrected form. In contrast, Qi and Knight's theory accounts for variable transverse shear strain distributions by enforcing pointwise constitutive relationships, and relates transverse shear strains to kinematic unknowns only in a weighted-average form. Through-the-thickness transverse shear strains are thus consistent with the stress counterparts and their transverse-shear-stress-weighted-average values are just the nominal-uniform transverse shear strains which correspond to the average rotations. The new theory combines the advantages of several prevailing 2D laminated plate theories while overcoming their drawbacks. Numerical results for the cylindrical bending problem of orthotropic laminated plates exhibit excellent agreement between Qi and Knight's theory and Pagano's 3D exact elasticity results.

Norman F. Knight, Jr and Yunqian Qi (Department of Aerospace Engineering, Old Dominion University, Norfolk, Virginia 23529-0247, U.S.A.), “Restatement of first-order shear-deformation theory for laminated plates”, International Journal of Solids and Structures, Vol. 34, No. 4, February 1997, pp. 481-492, doi:10.1016/S0020-7683(96)00032-7 ABSTRACT: A restatement of the first-order shear-deformation theory of plates is offered and verified numerically by exact 3-D elasticity results. Based on a more appropriate physical assumption, the restated theory innovatively interprets its variables and applies elasticity equations in a more pertinent manner. It assumes physically that only in some average sense does a straight line originally normal to the midplane remain straight and rotate relative to the normal of the midplane after deformation. Hence the in-plane displacement is still approximated, in an average sense, as linear and the transverse deflection as constant through the plate thickness. The associated nominal-uniform transverse shear strain directly derived from these displacement field assumptions is identified as the weighted-average transverse shear strain through the plate
thickness, with the corresponding transverse shear stress as the weighting function, while the actual transverse shear strain is permitted to vary through the thickness and satisfies the constitutive law with its stress counterpart. Likewise, the average rotation of the line is identified as its weighted-average value, instead of the one evaluated from a linear regression of the inplane displacement with the least-square method. Examination of bending energy and transverse shear energy supports this interpretation. In addition, an effective transverse shear stiffness parameter is identified and proven appropriate. This restated first-order, shear-deformation theory yields accurate local as well as global response predictions without employing a shear-correction factor.

Knight, Norman F, Jr and Starnes, James H, Jr, “Developments in Cylindrical Shell Stability Analysis”, NASA no. 19980019015. Stability Analysis of Plates and Shells; UNITED STATES; 1998

ABSTRACT: Today high-performance computing systems and new analytical and numerical techniques enable engineers to explore the use of advanced materials for shell design. This paper reviews some of the historical developments of shell buckling analysis and design. The paper concludes by identifying key research directions for reliable and robust methods development in shell stability analysis and design.

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“Optimal design of general stiffened composite circular cylinders for global buckling with strength constraints”, Composite Structures, Vol. 41, Nos. 3-4, March-April 1998, pp. 243-252,
doi:10.1016/S0263-8223(98)00020-8

ABSTRACT: A design strategy for optimal design of composite grid-stiffened cylinders subjected to global and local buckling constraints and strength constraints was developed using a discrete optimizer based on a genetic algorithm. An improved smeared stiffener theory was used for the global analysis. Local buckling of skin segments were assessed using a Rayleigh-Ritz method that accounts for material anisotropy. The local buckling of stiffener segments were also assessed. Constraints on the axial membrane strain in the skin and stiffener segments were imposed to include strength criteria in the grid-stiffened cylinder design. Design variables used in this study were the axial and transverse stiffener spacings, stiffener height and thickness, skin laminate stacking sequence and stiffening configuration, where stiffening configuration is a design variable that indicates the combination of axial, transverse and diagonal stiffener in the grid-stiffened cylinder. The design optimization process was adapted to identify the best suited stiffening configurations and stiffener spacings for grid-stiffened composite cylinder with the length and radius of the cylinder, the design in-plane loads and material properties as inputs. The effect of having axial membrane strain constraints in the skin and stiffener segments in the optimization process is also studied for selected stiffening configurations.

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ABSTRACT: A design strategy for optimal design of composite grid-stiffened panels subjected to global and local buckling constraints is developed using a discrete optimizer. An improved smeared stiffener theory is used for the global buckling analysis. Local buckling of skin segments is assessed using a Rayleigh-Ritz method that
accounts for material anisotropy and transverse shear flexibility. The local buckling of stiffener segments is also assessed. Design variables are the axial and transverse stiffener spacing, stiffener height and thickness, skin laminate, and stiffening configuration, where the stiffening configuration is herein defined as a design variable that indicates the combination of axial, transverse, and diagonal stiffeners in the stiffened panel. The design optimization process is adapted to identify the lightest-weight stiffening configuration and stiffener spacing for grid-stiffened composite panels given the overall panel dimensions, in-plane design loads, material properties, and boundary conditions of the grid-stiffened panel.

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ABSTRACT: A buckling formulation for anisotropic variable-curvature panels is presented in this paper. The variable-curvature panel is assumed to consist of two or more panels of constant curvature where each panel may have a different curvature. Bezier functions are used as Ritz functions. Displacement (C0), and slope (C1) continuities between segments are imposed by manipulation of the Bezier control points. A first-order shear-deformation theory is used in the buckling formulation. Results obtained from the present formulation are compared with those from finite element simulations and are found to be in good agreement.

PARTIAL INTRODUCTION: The objectives of this paper are to present a brief overview of the finite element method, to review selected finite element analysis techniques as applied to determining the nonlinear postbuckling and collapse response of elastic structures, and to describe selected application problems. First, some of the fundamental concepts associated with finite element approximations are described. Second, the basic equations of nonlinear solid mechanics are given for the case of small strain, large elastic deformation including a brief discussion of laminate theory for composite structures. Third, different variational formulations are presented along with their finite element models. Then solution techniques for nonlinear systems (both static and dynamic) are discussed. The traditional approach of nonlinear finite element analysis using a Newton-Raphson approach is reviewed. Reduction methods for nonlinear problems such as the global function approach and the reduced basis approach are summarized. Next, selected applications are described, and finally some concluding remarks are made.

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ABSTRACT: Three new buckling models have been incorporated into PANDA2, a program for minimum weight design of stiffened composite panels and shells: (1) buckling of unstiffened panels or unstiffened
portions of panels with use of double-trigonometric series expansions for buckling modal displacement components, u, v, w; (2) general buckling of cylindrical stiffened panels with both rings and stringers treated as discrete beams; and (3) inter-ring buckling of cylindrical panels based on a discretized single module model containing discretized ring segments and a discretized skin-smeared-stringer cylindrical surface to which the ring is attached. Examples are provided of buckling of certain isotropic and laminated composite flat and cylindrical unstiffened and stiffened panels and shells for which the predictions from the modified PANDA2, formerly unacceptably inaccurate, are compared with predictions from STAGS, a general-purpose finite element code. The new comparisons demonstrate that the modified PANDA2 is now well qualified for preliminary design in particular cases for which it previously yielded unreliable designs and designs that were overly conservative. The optimum design of a composite ring and stringer-stiffened cylindrical shell derived by PANDA2 is evaluated with the use of STAGS. The optimum design of an isotropic hydrostatically compressed internally T-ring stiffened cylindrical shell optimized by PANDA2 is evaluated with the use of the shell-of-revolution code BOSOR4. There is good agreement between PANDA2 predictions and STAGS and BOSOR4 predictions for buckling of the optimized designs.


ABSTRACT: Buckling loads of circular cylindrical laminated composite panels are obtained using Sanders–Koiter (e.g. Sanders, 1959; Koiter, 1959), Love (e.g. Love, 1927) and Donnell (e.g. Loo, 1957) shell theories with a first-order, shear-deformation approach and a Rayleigh–Ritz method that accounts for different boundary conditions and material anisotropy. Results obtained using Sanders–Koiter, Love, Donnell shell theories are compared with those obtained from finite element simulations, where the curved panels are modeled using nine-node quadrilateral continuum-based shell elements that are independent of any shell theory. Comparisons with finite element results indicate that Donnell’s theory could be in error for some lamination schemes and geometrical parameters.

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ABSTRACT: Non-linear analyses are difficult simulations to perform and place increased demands not only on the computational systems but also on the analyst. The number of possible problems and/or difficulties increases significantly compared to those for linear elastic analyses. Combined material and geometric non-linearities challenge the analyst and the solution algorithms. Progressive failure and damage propagation for composite structures result in even more complexities due to the discrete, abrupt changes in local material stiffness. Analysts need to interrogate the computed solutions carefully based on their understanding of structural mechanics, material behavior, computational procedures and non-linear phenomena to distill correct physics from such simulations. This paper describes the computational strategy incorporated into the STAGS non-linear finite element analysis code with special emphasis on progressive failure analysis of laminated composite structures. Results for selected laminated composite structures are used to demonstrate the PFA

ABSTRACT: The design process is rapidly evolving as the twenty-first century begins. Advanced aerospace systems are becoming increasingly more complex, and customers are demanding lower cost, higher performance, and high reliability. Increased demands are placed on the design engineers to collaborate and integrate design needs and objectives early in the design process to minimize risks that may occur later in the design development stage. The Mars Sample Return/Earth Entry Vehicle has stringent design requirements imposed due to mission objectives. These requirements in turn necessitate the mitigation of uncertainties and risk associated with the system design and mission. Characterization of material response accounting for damage, delaminations, and manufacturing flaws, and understanding their influence on structural integrity to meet mission objectives are critical. Extreme environment loading conditions due to re-entry and impact on the earth’s surface using a passive impact energy management system require detailed mathematical models and advanced analysis tools based on verified constitutive models. The design process becomes a balancing process between risk and consequences. High-performance systems require better understanding of system sensitivities much earlier in the design process to meet these goals. This understanding is developed through enhanced concept selections, reduced uncertainty, and enhanced analytical tools. However, the cornerstone of the design process is the design engineer. The knowledge, skills, intuition, and experience of an individual design engineer will need to be extended significantly for the next generation of aerospace system designs. Then a collaborative effort involving the designer, rapid and reliable analysis tools and virtual experts representing the knowledge capture of technical disciplines, manufacturing processes, mission profile, and/or system performance will result in advanced aerospace systems that are safe, reliable, and efficient. This paper discusses the evolution, status, needs and directions for rapid modeling and analysis tools for structural analysis. First, the evolution of computerized design and analysis tools is briefly described. Next, the status of representative design and analysis tools is described along with a brief statement on their functionality. Then technology advancements to achieve rapid modeling and analysis are identified. Finally, potential future directions including possible prototype configurations are proposed.

Some of the more than 200 references at the end of the report (only those pertaining to the buckling of shells):

ABSTRACT: Bearing-load response for a pin-loaded hole is studied within the context of two-dimensional finite element analyses. Pin-loaded-hole configurations are representative of mechanically connected structures, such as a stiffener fastened to a rib of an isogrid panel, that are idealized as part of a larger structural component. Within this context, the larger structural component may be idealized as a two-dimensional shell finite element model to identify load paths and high stress regions. Fastener modeling within these analysis models is often of low fidelity and limitations need to be assessed. Finite element modeling and analysis aspects of a pin-loaded hole are considered in the present paper including the use of linear and nonlinear springs to simulate the pin-bearing contact condition. For a repeating unit of a square domain with a center circular hole, the effects of hole diameter and degree of elastic restraint provided by material surrounding the hole are considered. These effects are found to affect the local response by changing it from a bearing-dominated response for small holes to a plane-stress-dominated ligament response for larger holes. For a T-shaped coupon specimen configuration, the pin-loaded-hole case resulted in higher local stresses around the hole, while the open-hole case generated high stresses along the majority of the free edge of the T-specimen web. Simulating pin-connected structures within a two-dimensional finite element analysis model using nonlinear spring or gap elements provides an effective way for accurate prediction of the local effective stress state and peak forces.

References listed at the end of the paper:
ABSTRACT: Experimental and analysis results for a curved, stiffened aluminum fuselage panel tested in a combined loads test machine with combined internal pressure, axial compression, and torsional shear loads are described. The experimental and analytical strain results for the panel with and without discrete source damage are presented. The effect of notch tip geometry on crack growth predictions is addressed. The crack growth trajectory predictions for the panel are presented for the applied loading conditions at failure. (Unfortunately, the pdf file does not permit cutting and pasting the 10 references listed at the end of the 4-page file.)

ABSTRACT: The results of an analytical and experimental study of the nonlinear response of thin, unstiffened, aluminum cylindrical shells with a long longitudinal crack are presented. The shells are analyzed with a nonlinear shell analysis code that accurately accounts for global and local structural response phenomena. Results are presented for internal pressure and for axial compression loads. The effect of initial crack length on the initiation of stable tearing and unstable crack growth in typical shells subjected to internal pressure loads is predicted using geometrically nonlinear elastic-plastic finite element analyses. The results of these analyses and of the experiments indicate that the pressure required to initiate stable tearing and unstable tearing in a shell subjected to internal pressure loads decreases as the crack length increases. The effects of crack length on the prebuckling, buckling and postbuckling responses of typical shells subjected to axial compression are also described. For this loading condition, the crack length is held constant. The results of the analyses illustrate the influence of crack length on shell buckling instabilities. The experimental and analytical results correlate well.


ABSTRACT: The results of an experimental and analytical study of the effects of initial imperfections on the buckling response of thin unstiffened graphite-epoxy cylindrical shells with and without a cutout, and with three different shell-wall laminates, are presented. Results that identify the individual and combined effects of traditional initial geometric shell-wall imperfections, and nontraditional shell-wall thickness variations, shell-end geometric imperfections, and variations in loads applied to the ends of the shells on the shell buckling and nonlinear responses, are included. The shells have been analyzed with a robust nonlinear finite-element analysis code for shells that accurately accounts for these effects on the buckling and nonlinear responses of the shells. The analysis results generally correlate well with the experimental results. The nonlinear analysis results are also compared with the results from a traditional linear bifurcation buckling analysis that is commonly used for...
shell design. The results suggest that the nonlinear analysis procedure can be used for determining accurate, high-fidelity, design knockdown factors for shell buckling and collapse. A discussion of how this high-fidelity nonlinear analysis procedure can be used to form the basis for a shell analysis and design approach that addresses some of the critical shell-buckling design criteria and design considerations for composite shell structures is included.


ABSTRACT: The results of a numerical study to assess the effect of skin buckling on the internal load distribution in a stiffened fuselage panel, with and without longitudinal cracks, are presented. In addition, the impact of changes in the internal loads on the fatigue life and residual strength of a fuselage panel is assessed. A generic narrow-body fuselage panel is considered. The entire panel is modeled using shell elements and considerable detail is included to represent the geometric-nonlinear response of the buckled skin, cross section deformation of the stiffening components, and details of the skin-stringer attachment with discrete fasteners. Results are presented for a fixed internal pressure and various combinations of axial tension or compression loads. Results illustrating the effect of skin buckling on the stress distribution in the skin and stringer, and fastener loads are presented. Results are presented for the pristine structure, and for cases where damage is introduced in the form of a longitudinal crack adjacent to the stringer, or failed fastener elements. The results indicate that axial compression loads and skin buckling can have a significant effect on the circumferential stress in the skin, and fastener loads, which will influence damage initiation, and a comparable effect on stress intensity factors for cases with cracks. The effects on stress intensity factors will influence damage propagation rates and the residual strength of the panel.

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12 Young, R. D., Rose, C. A., and Starnes, J. H., Jr., “Nonlinear Bulging Factors for Longitudinal and Circumferential Cracks in


ABSTRACT: Results of a geometrically nonlinear finite element parametric study to determine curvature correction factors or “bulging factors” that account for increased stresses due to curvature for longitudinal and circumferential cracks in unstiffened pressurized cylindrical shells are presented. Geometric parameters varied in the study include the shell radius, the shell wall thickness, and the crack length. The major results are presented in the form of contour plots of the bulging factor as a function of two nondimensional parameters: the shell curvature parameter, Lambda, which is a function of the shell geometry, Poisson’s ratio, and the crack length; and a loading parameter, Eta, which is a function of the shell geometry, material properties, and the applied internal pressure. These plots identify the ranges of the shell curvature and loading parameters for which the effects of geometric nonlinearity are significant. Simple empirical expressions for the bulging factor are then derived from the numerical results and shown to predict accurately the nonlinear response of shells with longitudinal and circumferential cracks. The numerical results are also compared with analytical solutions based on linear shallow shell theory for thin shells, and with some other semi-empirical solutions from the literature, and limitations on the use of these other expressions are suggested.

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4 Folias, E. S., “Asymptotic Approximations to Crack Problems in Shells,” Mechanics of Fracture - Plates and Shells with Cracks, G.


ABSTRACT: Analysis methodologies for predicting fatigue-crack growth from rivet holes in panels subjected to cyclic loads and for predicting the residual strength of aluminum fuselage structures with cracks and subjected to combined internal pressure and mechanical loads are described. The fatigue-crack growth analysis methodology is based on small-crack theory and a plasticity induced crack-closure model, and the effect of a corrosive environment on crack-growth rate is included. The residual strength analysis methodology is based on the critical crack-tip-opening-angle fracture criterion that characterizes the fracture behavior of a material of interest, and a geometric and material nonlinear finite element shell analysis code that performs the structural analysis of the fuselage structure of interest. The methodologies have been verified experimentally for structures ranging from laboratory coupons to full-scale structural components. Analytical and experimental results based on these methodologies are described and compared for laboratory coupons and flat panels, small-scale pressurized shells, and full-scale curved stiffened panels. The residual strength analysis methodology is sufficiently general to include the effects of multiple-site damage on structural behavior.

References listed at the end of the paper:


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ABSTRACT: The crack-tip-opening angle or displacement (CTOA/CTOD) fracture criterion is one of the oldest fracture criteria applied to fracture of metallic materials with cracks. During the past two decades, the use of elastic–plastic finite-element analyses to simulate fracture of laboratory specimens and structural components using the CTOA criterion has expanded rapidly. But the early applications were restricted to two-dimensional analyses, assuming either plane-stress or plane-strain behavior, which lead to generally non-constant values of CTOA, especially in the early stages of crack extension. Later, the non-constant CTOA values were traced to inappropriate state-of-stress (or constraint) assumptions in the crack-front region and severe crack tunneling in thin-sheet materials. More recently, the CTOA fracture criterion has been used with three-dimensional analyses to study constraint effects, crack tunneling, and the fracture process. The constant CTOA criterion (from crack initiation to failure) has been successfully applied to numerous structural applications, such as aircraft fuselages and pipelines. But why does the “constant CTOA” fracture criterion work so well? This paper reviews the results from several studies, discusses the issues of why CTOA works, and discusses its limitations.


ABSTRACT: This paper reviews some of the advances that have been made in stress analyses of cracked aircraft components, in the understanding of the fatigue and fatigue-crack growth process, and in the prediction of residual strength of complex aircraft structures with widespread fatigue damage. Finite-element analyses of
cracked structures are now used to determine accurate stress-intensity factors for cracks at structural details. Observations of small-crack behavior at open and rivet-loaded holes and the development of small-crack theory has lead to the prediction of stress-life behavior for components with stress concentrations under aircraft spectrum loading. Fatigue-crack growth under simulated aircraft spectra can now be predicted with the crack-closure concept. Residual strength of cracked panels with severe out-of-plane deformations (buckling) in the presence of stiffeners and multiple-site damage can be predicted with advanced elastic-plastic finite-element analyses and the critical crack-tip-opening angle (CTOA) fracture criterion. These advances are helping to assure continued safety of aircraft structures.

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James H. Starnes, Jr and Cheryl A. Rose (NASA Langley Research Center), “Stable tearing and buckling responses of unstiffened aluminum shells with long cracks”, http://dl.acm.org/citation.cfm?id=887529 , 1998 NASA Technical Report (Number not given), NASA Langley Technical Report Server; Presented at the Second Joint DoD/FAA/NASA Conference on Aging Aircraft, Williamsburg, Virginia, August 31 – September 3, 1998 ABSTRACT: The results of an analytical and experimental study of the nonlinear response of thin, unstiffened, aluminum cylindrical shells with a long longitudinal crack are presented. The shells are analyzed with a nonlinear shell analysis code that accurately accounts for global and local structural response phenomena. Results are presented for internal pressure and for axial compression loads. The effect of initial crack length on the initiation of stable crack growth and unstable crack growth in typical shells subjected to internal pressure loads is predicted using geometrically nonlinear elastic-plastic finite element analyses and the crack-tip-opening angle (CTOA) fracture criterion. The results of these analyses and of the experiments indicate that the pressure required to initiate stable crack growth and unstable crack growth in a shell subjected to internal pressure loads decreases as the initial crack length increases. The effects of crack length on the prebuckling, buckling and postbuckling responses of typical shells subjected to axial compression loads are also described. For this loading condition, the crack length was not allowed to increase as the load was increased. The results of the analyses and of the experiments indicate that the initial buckling load and collapse load for shell subjected to axial compression loads decrease as the initial crack length increases. Initial buckling causes general instability or collapse of a shell for shorter initial crack lengths. Initial buckling is a stable local response mode for longer initial crack lengths. This stable local buckling response is followed by a stable postbuckling response, which is followed by general or overall instability of the shell.
References listed at the end of the paper: (cannot cut and paste them)

ABSTRACT: The results of a numerical study of the nonlinear response of thin unstiffened aluminum cylindrical shells with a longitudinal crack are presented. The shells are analyzed with a nonlinear shell analysis code that accurately accounts for global and structural response phenomena. The effects of initial crack length on the prebuckling, buckling and postbuckling responses of a typical shell subjected to axial compression loads, and subjected to combined internal pressure and axial compression loads are described. Both elastic and elastic-plastic analyses are conducted. Numerical results for a fixed initial crack length indicate that the buckling load decreases as the crack length increases for a given pressure load, and that the buckling load increases as the internal pressure load increases for a given crack length. Furthermore, results indicate that predictions from an elastic analysis for the initial buckling load of a cracked shell subjected to combined axial compression and internal pressure loads can be unconservative. In addition, the effect of crack extension on the initial buckling load is presented.

References listed at the end of the paper:

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ABSTRACT: A comparative study of different modeling approaches for predicting sandwich panel buckling response is described. The study considers sandwich panels with anisotropic face sheets and a very thick core. Results from conventional analytical solutions for sandwich panel overall buckling and face-sheet-wrinkling type modes are compared with solutions obtained using different finite element modeling approaches. Finite element solutions are obtained using layered shell element models, with and without transverse shear flexibility, layered shell/solid element models, with shell elements for the face sheets and solid elements for the core, and sandwich models using a recently developed specialty sandwich element. Convergence characteristics of the shell/solid and sandwich element modeling approaches with respect to in-plane and through-the-thickness discretization, are demonstrated. Results of the study indicate that the specialty sandwich element provides an accurate and effective modeling approach for predicting both overall and localized sandwich panel buckling response. Furthermore, results indicate that anisotropy of the face sheets, along with the ratio of principle elastic moduli, affect the buckling response and these effects may not be represented accurately by analytical solutions. Modeling recommendations are also provided.

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ABSTRACT: A design strategy for optimal design of composite grid-stiffened structures with variable curvature subjected to global and local buckling constraints is developed using a discrete optimizer. An improved smeared stiffener theory is used for the global buckling analysis. Local buckling of skin segments is assessed using a Rayleigh–Ritz method that accounts for material anisotropy and transverse shear flexibility. The local buckling of stiffener segments is also assessed. Design variables are the axial and transverse stiffener spacing, stiffener height and thickness, skin laminate, and stiffening configuration. Stiffening configuration is herein defined as a design variable that indicates the combination of axial, transverse and diagonal stiffeners in the stiffened panel. The design optimization process is adapted to identify the lightest-weight stiffening configuration and stiffener spacing for grid-stiffened composite panels given the overall panel dimensions, in-plane design loads, material properties, and boundary conditions of the grid-stiffened panel or shell.

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ABSTRACT: Experimental and analytical results are presented for progressive failure of stiffened composite
panels with and without a notch and subjected to in-plane shear loading well into the postbuckling regime. Initial geometric imperfections are included in the finite element models. Ply damage modes such as matrix cracking, fiber-matrix shear, and fiber failure are modeled by degrading the material properties. Experimental results from the test include strain full-field data from a video image correlation system in addition to other strain and displacement measurements. Results from nonlinear finite element analyses are compared with experimental data. Good agreement between experimental data and numerical results is observed for the stitched stiffened composite panels studied.

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ABSTRACT: Progressive failure analyses results are presented for composite curved panels with and without a circular cutout and subjected to axial compression loading well into their postbuckling regime. Ply damage modes such as matrix cracking, fiber-matrix shear, and fiber failure are modeled by degrading the material properties. Results from finite element analyses are compared with experimental data. Good agreement between experimental data and numerical results are observed for most part of the loading range for the structural configurations considered. Modeling of initial geometric imperfections may be required to obtain accurate analysis results depending on the ratio of the cutout width to panel width.

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“Intralaminar and interlaminar progressive failure analyses of composite panels with circular cutouts”, Composite Structures, Vol. 64, No. 1, April 2004, pp. 91-105, doi:10.1016/S0263-8223(03)00217-4
ABSTRACT: A progressive failure methodology is developed and demonstrated to simulate the initiation and material degradation of a laminated panel due to intralaminar and interlaminar failures. Initiation of intralaminar failure can be by a matrix-cracking mode, a fiber-matrix shear mode, and a fiber failure mode. Subsequent material degradation is modeled using damage parameters for each mode to selectively reduce lamina material properties. The interlaminar failure mechanism such as delamination is simulated by positioning interface elements between adjacent sublaminates. A nonlinear constitutive law is postulated for the interface element that accounts for a multi-axial stress criteria to detect the initiation of delamination, a mixed-mode fracture criteria for delamination progression, and a damage parameter to prevent restoration of a previous cohesive state. The methodology is validated using experimental data available in the literature on the response and failure of quasi-isotropic panels with centrally located circular cutouts loaded into the postbuckling regime. Very good agreement between the progressive failure analyses and the experimental results is achieved if the failure analysis includes the interaction of intralaminar and interlaminar failures.
ABSTRACT: Buckling of simply supported rectangular sandwich plate with multi-blade stiffeners is addressed herein. The main objective was to present and validate an approximate, semi-analytical computational model for such plates subjected to in-plane loading. The faceplates are modeled as shear-deformable plates using first-order shear deformation plate theory (SDPT). The core of the sandwich panel is treated as three-dimensional body. The stiffeners were added at the upper faceplates and modeled as simple beams with flexural stiffness only against out-of-plane bending. Nonlinear finite element analysis was used to verify the accuracy of the presented model. The results of the presented model are, in most cases, found to be in a good agreement with fully nonlinear finite element analysis results. The presented model allows for a very efficient analysis with relatively high numerical accuracy and low computational efforts compared to fully nonlinear finite element analysis results. A number of applications have been described, with the aim of demonstrating the capability and versatility of the presented approach.

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Mallela, U. and A. Upadhyay, 2006. Buckling of laminated composite stiffened panels subjected to in-plane shear: A parametric

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ABSTRACT: Buckling of simply supported square orthotropic plates with multi-blade stiffeners is addressed herein. An approximate, semi-analytical model for such plates subjected to in-plane loading is derived. The optimal buckling load of simply supported laminated composite blade-stiffened panels with circular cutouts is predicted using Finite Element Analysis. In this optimization, the design variables were the cutout size, cutout location, fiber orientation angles, number and locations of stiffeners. Three types of in-plane loading were considered; namely, uniaxial, biaxial and shear loading. Based on the model studies, the total increase in the buckling load due to the presence of cutouts and stiffeners can reach up to 5 times in uniaxial loading, 7 times in biaxial loading and 2 times in shear loading compared to perfect plates. Several other imperative findings are identified based upon the various parameters influencing the buckling behavior. Guidelines for the optimal stiffeners' configurations and cutouts' proportioning are developed.

References listed at the end of the paper:

ABSTRACT: The vibrations of stiffened cylindrical shells having axisymmetric or asymmetric initial geometrical imperfections and axial preload are analyzed. The analysis is based on a solution of the von Kármán-Donnell non-linear shell equations, an “exact” solution of the compatibility equation, and a first order approximation by the Galerkin method of the equilibrium equation. The stiffeners are closely spaced and “smeared” stiffener theory is employed. The results of an extensive parametric study carried out on shells similar to those used in vibration and buckling tests at the Technion show that stiffening of the shell will lower the imperfection-sensitivity of its free vibrations, but the decrease depends on the type of stiffening (strings or rings), the mode shapes of the vibration and the imperfection, the stiffener strength and eccentricity. The imperfection-sensitivity decrease, caused by the stiffeners, is greater for vibration mode shapes with high imperfection-sensitivity than for other vibration mode shapes. The sensitivity differences between stringer and ring-stiffened shells depend especially on the vibration and the imperfection mode shapes, and on their coupling. Small imperfections change the natural frequencies of stiffened shells in the same directions as for isotropic shells, but to a smaller extent. The frequency dependence on the external load is also strongly affected by the imperfection mode shape. The results correlate well with earlier ones for isotropic shells.

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ABSTRACT: Non-linear static deformation, combined with small vibrations in its vicinity, of an imperfect cylindrical panel under axial loading, is studied within a single-degree-of-freedom treatment. The frequency of the small vibrations vanishes at the limit load. This conclusion is proved to be valid for a system with any other non-linearity as well. Special emphasis is placed on the influence of initial imperfections on the vibration frequencies.

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“Dynamics of a thin cylindrical shell under impact with limited deterministic information on its initial

ABSTRACT: This study deals with the dynamics and failure of a thin circular cylindrical shell with axisymmetric initial imperfections. In contrast to earlier studies, the uncertainty involved in the initial imperfections is described by convex modelling: a non-probabilistic, set-theoretical approach. This methodology is useful when only limited information is available on the distribution of the uncertain events. The most significant N Fourier coefficients are assumed to fall in an ellipsoidal set in N-dimensional Euclidean space. We evaluate the maximum total displacement as a function of the shape of the ellipsoid.

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ABSTRACT: This paper is devoted to a fundamental problem of accounting for parameter uncertainties in random vibrations of structures. In contrast to the overwhelming majority of random vibration studies where perfect knowledge is assumed for the parameters of the excitation, this crucial conjecture is dispensed with. The probabilistic characteristics of the excitation are assumed to be given as depending on some parameters which are not known in advance. We postulate that some imprecise knowledge is available; namely, that these parameters belong to a bounded, convex set. In the case where this convex set is represented by an ellipsoid, closed form solutions are given for the upper and lower bounds of the mean-square displacement of the structures. For the first time in the literature the system uncertainty in the random vibrations is dealt with as an ‘anti-optimization’ problem of finding the least favorable values of the mean-square response. The approach developed here opens a new avenue for tackling parameter uncertainty which is often encountered in various branches of engineering.

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ABSTRACT: Buckling of initial imperfection sensitive structure — column on a non-linear elastic foundation — is investigated. A criterion based on the concept of “modal buckling load” is proposed to determine which modes should be included in the analysis when the weighted residuals method is utilized to calculate the limit load — maximum load the structure can support — for a given initial deflection. For stochastic analysis, a random field model is suggested for the uncertain initial imperfection, and Monte Carlo simulations are performed to obtain the probability density of the buckling load and the reliability of the column. Finally, a non-stochastic convex model of uncertainty is employed to describe a situation when only limited information is available on uncertain initial deflection, and the minimum buckling load is obtained for this model. The results from both the stochastic and the non-stochastic approaches are derived and critically contrasted.

ABSTRACT: A refined second-order method is presented for structural reliability analysis. Exact and approximate reliability solutions are obtained for a circular shaft subject to random bending moments and a random torque. The comparison of the approximate results with exact ones shows that the first-order approximation is only applicable to the case where the failure surface is “far” from the origin, while the suggested second-order approximation yields quite accurate results even if the failure surface is “close” to the origin.

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ABSTRACT: The present paper reviews recent developments in two major areas of structural sensitivity analysis: sensitivity of static and transient response; and sensitivity of vibration and buckling eigenproblems. Recent developments from the standpoint of computational cost, accuracy, and ease of implementation are presented. In the area of static response, current interest is focused on sensitivity to shape variation and sensitivity of nonlinear response. Two general approaches are used for computing sensitivities: differentiation of the continuum equations followed by discretization, and the reverse approach of discretization followed by differentiation. It is shown that the choice of methods has important accuracy and implementation implications. In the area of eigenproblem sensitivity, there is a great deal of interest and significant progress in sensitivity of problems with repeated eigenvalues. The paper raises the issue of differentiability and continuity that is inherent to the repeated eigenvalue case.

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ABSTRACT: In many cases precise probabilistic data are not available on uncertainty in loads, but the magnitude of the uncertainty can be bound. This paper proposes a design approach for structural optimization with uncertain but bounded loads. The problem of identifying critical loads is formulated mathematically as an optimization problem in itself (called anti-optimization), so that the design problem is formulated as a two-level optimization. For linear structural analysis it is shown that the antioptimization part is limited to consideration of the vertices of the load-uncertainty domain. An example of a ten-bar truss is used to demonstrate that we cannot replace the anti-optimization process by considering the largest possible loads.

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(1) Center for Computational Mechanics, Jilin University of Technology, Changchun, People's Republic of China
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ABSTRACT: In this paper, we present a method for computing upper and lower bounds of the natural frequencies of a structure with parameters which are unknown, except for the fact that they belong to given intervals. These parameters are uncertain, yet they are not treated as being random, since no information is available on their probabilistic characteristics. The set of possible states of the system is described by interval matrices. By solving the generalized interval eigenvalue problem, the bounds on the natural frequencies of the structure with interval parameters are evaluated. Numerical results show that the proposed method is extremely effective.

References listed at the end of the paper:

ABSTRACT: This selective review (with emphasis on the word “selective”) gives only a taste of extensive research that has been conducted since 1759 when Leonhard Euler posed, apparently for the first time, a boundary value problem. Since then numerous studies have been conducted for rods, Bernoulli-Euler beams, Bresse-Timoshenko beams, Kirchhoff-Love and Mindlin-Reissner plates and shells and structures analyzed via finer, higher-order theories. This selective review classifies the solutions as belonging to either of three main classes: (1) direct problems, (2) semi-inverse problems, (3) inverse problems. In addition, some new closed-form solutions are reported, that have been obtained via posing an inverse vibration problem. Due to the huge body of literature, author limits himself with discussing classic theories of structures.

References listed at the end of the paper:
There are 774 references, too many to include here.
Isaac Elishakoff (1), Kevin Dujat (2) and Maurice Lemaire (2)
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ABSTRACT: In this note we deal with the approximate solution of the buckling problem of a clamped-free double-walled carbon nanotube. First the finite difference method is utilized to solve this case. Then this approach is verified by solving the buckling problem of a double-walled carbon nanotube that is simply supported at both ends for which the exact solution is available.
References listed at the end of the paper:

Isaac Elishakoff (1), Benedikt Kriegesmann (2), Raimund Rolfes (2), Christian Hühne (3), and Alexander Kling (3).
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(2) University of Hannover, Germany
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ABSTRACT: Hybrid optimization and antioptimization of the buckling load of composite cylindrical shells is conducted. The methodology, which has been developed in previous works, is applied to a set of cylindrical
composite shells, tested at the German Aerospace Center. Furthermore, the existing approach is enhanced to fit within the design-optimization scheme. The shells possess traditional imperfections in the form of Fourier series coefficients of their initial imperfection profile. Additionally, two nontraditional imperfections are included in the analysis. The available experimental data are enclosed by either 11-dimensional hyperrectangle or hyperellipsoid. The minimum buckling load of the ensemble of such shells is determined by the antioptimization procedure. Then, this minimum load is maximized by varying the laminate angle. It is shown that the proposed method is a viable and relatively simple alternative to probabilistic approaches and successfully supplements them. It is shown that the proposed method is a successful supplement to probabilistic methods and the deterministic single-buckle approach because it is deterministic in nature and thus could appeal to engineers and investigators alike, and it takes into account the actual scatter of input data.

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ABSTRACT: This paper investigates the buckling mode localization in the periodic multi-span beam with disorder occurring in an arbitrary single span. The analytical finite difference calculus is used in conjunction with the conventional displacement method to derive the transcendental equations from which buckling load is calculated. The underlying treatment is general and the solution thus obtained is exact. Numerical results show that the buckling mode is highly localized in the vicinity of the disordered span of the beam.

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ABSTRACT: This investigation deals with the buckling problem of a column with random geometric imperfection, resting on a nonlinear elastic foundation. In contrast to most of the earlier studies, it is assumed that the column is subjected to a random axial compression. The random initial imperfection is expressed in terms of buckling modes with coefficients obeying the truncated normal distribution. The external load is modeled as a random variable with the extreme-value distribution. An improved simulation technique with high computational efficiency is employed to obtain the probability of failure of the structure. Statistical analysis of the simulation data is proposed, and the final result is given in the form of confidence interval, which can be used directly in engineering design.

Isaac Elishakoff (Dept. of Mechanical Engineering, Florida Atlantic University, Boca Raton, Florida, USA), “Random vibration of structures: a personal perspective”, Applied Mechanics Reviews, VBoI. 48, No. 12, pp
Some topics in random vibration of structures are reviewed. For this occasion three topics are chosen: (a) effect of cross correlations in linear vibration of continuous structures, (b) effect of choice of deterministic theory describing the dynamic behavior of the structure, (c) new versions of stochastic linearization of nonlinear continuous structures. The essay attempts to partially answer a familiar but still nagging question “Now that I’m here, where am I?”


ABSTRACT: Stochastic approach and non-stochastic, convex modeling of uncertainty are critically contrasted. First some drawbacks of the probabilistic methods are discussed, attributable to lack of sufficiently accurate data; then the effect of human error in constructing a probabilistic model for input quantities is elucidated. Extensive quotations from pertinent works of Freudenthal, who is rightfully considered as an architect of modern reliability theory, are utilized to explain some doubts he himself experienced about probabilistic methods. His hints are realized in modern convex modeling of uncertainty, which the writer is advocating and advancing. A set-theoretical, convex description of uncertainty is discussed in detail. Uncertainty is described as a set of constraints unlike the classical probabilistic approach. Moreover, instead of conventional optimization studies, where the minimum possible responses are sought, here an uncertainty modeling is developed as an “anti-optimization” problem of finding the least favorable response under the constraints within the set-theoretical description. The question of how the output quantities of such an anti-optimization process vary when the global knowledge on the uncertainties increases is considered in detail. Response variability of viscoelastic structures is evaluated. Combined probabilistic-convex modeling is proposed for situations where the input quantities should be modeled as stochastic ones, but some of their probabilistic characteristics are unknown but bounded.

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ABSTRACT: In this paper we present a closed-form solution for vibrational imperfection sensitivity-the effect of small imperfections on the vibrational frequencies of perturbed motion around the static equilibrium state of Augusti's model structure (a rigid link, pinned at one end to a rigid foundation and supported at the other by a linear extensional spring that retains its horizontality as the system deflects). We also treat a modified version of that model with attendant slightly different dynamics. It is demonstrated that the vibrational frequency decreases as the initial imperfections increase.

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ABSTRACT: In this study, it is demonstrated through a simple example of the Roorda-Koiter frame that the unavoidable dissimilarity in the distribution of elastic moduli may further reduce the load-carrying capacity in addition to the well-recognized effect of initial geometric imperfections.

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ABSTRACT: Buckling problems of two types of multi-span elastic plates with transverse stiffeners are considered using a method based on the finite difference calculus. The discreteness of the stiffeners is accounted for. It is found that the torsional rigidity of the stiffener plays an important role in the buckling mode pattern. When the torsional rigidity is properly adjusted, the stiffener can act as an isolator of deformation for the structure at buckling so that the deflection is only limited to a small area.

References listed at the end of the paper:


Isaac Elishakoff (Department of Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431-0991, USA), “Uncertain buckling: its past, present and future”, International Journal of Solids and Structures, Vol. 37, No. 46-47, November 2000, pp. 6869-6889, doi:10.1016/S0020-7683(99)00318-2 ABSTRACT: An authoritative review on stochastic buckling of structures was written by Amazigo some quarter century ago. The present review summarizes some of the developments which took place since then. A brief overview of the effect of uncertainty in the initial geometric imperfections, elastic moduli, applied forces, and thickness variation is given. For the benefit of the thoughtful reader, the review is of critical nature.

Isaac Elishakoff (Department of Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431-0991, USA), “Euler’s problem revisited: 222 years later”, Meccanica, Vol. 36, No. 3, pp 265-272, May 2001 ABSTRACT: This paper furnishes several closed-form solutions for the buckling eigenvalue problem of the
columns with variable flexural rigidity along the axis. The column is either under uniformly distributed axial load or under concentrated compressive load.

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Fulvio Tonon (1), Alberto Bernardini (2) and Isaac Elishakoff (3)
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ABSTRACT: This paper elucidates that for rigorous analysis of many engineering structures, three seemingly unrelated concepts, namely probability, fuzziness and anti-optimization, ought to be utilized. This is in order to take into account the uncertainty in the actual values of the basic variables or on the models employed to evaluate the structure-expected behaviour. In this case, it is possible and reasonable to use the three paradigms in a combined manner. Some examples are given to illustrate these ideas.

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ABSTRACT: Probabilistic and non-probabilistic, anti-optimization analyses of uncertainty are contrasted in this study. Specifically, the comparison of these two competing approaches is conducted for an uniform column, with initial geometric imperfection, subjected to an impact axial load. The reliability of the column is derived for the cases when the initial imperfections possess either (a) uniform probability density, (b) truncated exponential density or (c) generic truncated probability density. The problem is also analyzed in the context of an interval analysis. It is shown that in, the most important near-unity reliability range these two approaches tend to each other. Since the interval analysis constitutes a much simpler procedure than the probabilistic approach, it is argued that the former is advantageous over the latter in some circumstances.


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employed by engineers, but in the new light. The safety factor apparently for the first time in the literature. The aim of the paper is to present the safety factor that is uniformly led to a considerable literature dedicated to the probabilistic interpretation of the safety factor. The present utilization of long time ago as a ratio of the yield stress to the so-called safety factor to provide the region for the safe utilization of the structure. Thus the uncertainty is introduced into practice by the “back door”. This observation called safety factor to provide the region for the safe utilization of the structure. Thus the uncertainty is introduced into practice by the “back door”. This observation led to a considerable literature dedicated to the probabilistic interpretation of the safety factor. The present paper deals with the novel aspect of elucidation of the concept of safety factor through the theory of fuzzy sets, apparently for the first time in the literature. The aim of the paper is to present the safety factor that is uniformly employed by engineers, but in the new light. The safety factor in the fuzzy setting is introduced. The ideas are
illustrated on two strength of material problems; simple examples are chosen so as to allow for clearer illustration of ideas.

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ABSTRACT: In this paper we study axisymmetric buckling of radially graded circular plates. The flexural rigidity is considered to be a suitably varying function of the radial coordinate. The problem is posed as a semi-inverse one. The buckling mode is selected first, then the variation of the flexural rigidity consistent with the buckling mode is determined. Apparently for the first time in the literature, closed-form solutions are found. Such solutions allow the design of a circular plate whose buckling load is at least the pre-specified one. Such a design appears to find much applications in various fields of engineering.

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Martin Bechthold (Harvard University School of Design), New stone shells: design and robotic fabrication”, Proceedings of the International Association for Shell and Spatial Structures (IASS), Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures, 28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain

ABSTRACT: The research explores the design and analysis of a thin marble shell that incorporates the latest developments in fabrication technology and computational analysis. Natural stone, one of the oldest and most traditional building materials, is used in innovative ways by manipulating it with a 6-axis robotic waterjet. The research studies techniques for the robotic perforation and surfacing of natural stone, with a particular focus on marble. The work was conducted in collaboration with Monica Ponce de Leon and Wes McGee at the Harvard Graduate School of Design (GSD). Small tests panels explore how transparency and translucency of stone can
be generated through robotic waterjet cutting. A prototypical stone shell is designed to further explore the design potential encountered in the small test pieces. The shell is post-tensioned and stiffened with metal stiffeners. Finite-element analysis (FEA) serves as a primary technique to conduct a detailed structural analysis of the shell.

References listed at the end of the paper:

Demetris Pentaras (Department of Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL, USA; later Cyprus Institute of Technology), “Vibration, buckling and impact of carbon nanotubes”, Ph.D. dissertation, Isaac Elishakoff (advisor), College of Engineering and Computer Science, Florida Atlantic University, Boca Raton, Florida, April 2009

ABSTRACT: Natural frequencies of the double and triple-walled carbon nanotubes are determined exactly and approximately for both types. Approximate solutions are found by using Bubnov-Galerkin and Petrov-Galerkin methods. For the first time explicit expressions are obtained for the natural frequencies of double and triple-walled carbon nanotubes for different combinations of boundary conditions. Comparison of the results with recent studies shows that the above methods constitute quick and effective alternative techniques to exact solution for studying the vibration properties of carbon nanotubes. The natural frequencies of the clamped-clamped double-walled carbon nanotubes are obtained; exact solution is provided and compared with the solution reported in the literature. In contrast to earlier investigation, an analytical criterion is derived to establish the behavior of the roots of the characteristic equation. Approximate Bubnov-Galerkin solution is also obtained to compare natural frequencies at the lower end of the spectrum. Simplified version of the Bresse-Timoshenko theory that incorporates the shear deformation and the rotary inertia is proposed for free vibration study of double-walled carbon nanotubes. It is demonstrated that the suggested set yields extremely accurate results for the lower spectrum of double-walled carbon nanotube. The natural frequencies of double-walled carbon nanotubes based on simplified versions of Donnell shell theory are also obtained. The buckling behavior of the double-walled carbon nanotubes under various boundary conditions is studied. First, the case of the simply supported double-walled carbon nanotubes at both ends is considered which is amenable to exact solution. Then, approximate methods of Bubnov-Galerkin and Petrov-Galerkin are utilized to check the efficacy of these approximations for the simply supported double-walled carbon nanotubes. Once the extreme accuracy is demonstrated for simply supported conditions, the approximate techniques are applied to two other cases of the boundary conditions, namely to clamped-clamped and simply supported-clamped double-walled carbon nanotubes. For the first time in the literature approximate expression for the buckling loads are reported for these boundary conditions. The dynamic deflection of a single-walled carbon nanotube under impact loading is analyzed by following a recently study reported on the energy absorption capacity of carbon nanotubes under ballistic impact.

References listed at the end of the dissertation:


ABSTRACT: This review paper deals with two problems in structural engineering dynamics; one is deterministic, the other is of stochastic nature. One problem is linear, the other is nonlinear. Authors have a biased preferential view on these problems because of their active involvement in the discussed research topics.
Still, these two problems reflect, at least in a small manner, some developments in this vast and fascinating field. The first part deals with deterministic linear vibrations of double-walled carbon nanotubes either in classical or refined setting; the second part is devoted to the nonlinear random vibrations of structures.

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ABSTRACT: Natural frequencies of triple-walled carbon nanotubes (TWCNTs) are determined both exactly and approximately. For the case of a TWCNT simply supported at its ends, closed-form solutions are obtained. It is shown that there are three series of natural frequencies corresponding to the cubic polynomial equation for natural frequency squares. For a TWCNT that has other boundary conditions approximate Bubnov–Galerkin and Petrov–Galerkin methods are used with simple polynomial functions. Each of these methods yields three natural frequencies corresponding to the lower end of each frequency spectrum.

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Isaac Elishakoff (1) and Simon Bucas (2)
(1) Dept. of Mechanical Engineering, Florida Atlantic University, Boca Raton, FL
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ABSTRACT: This study deals with the Bubnov-Galerkin method applied to the buckling of clamped-free double-walled carbon nanotubes (DWCNTs) subjected to a concentrated compressive load at the free end. It was found that at least four comparison functions are needed in order to obtain accurate results.

References listed at the end of the paper:
failure mode associated with these structures is buckling. This failure mode is further subdivided into ‘local skin and/or stiffener buckling’, and ‘universal buckling’. In this paper buckling investigation of a grid stiffened composite cylinder is presented using analytical model, Finite elements model and experimentation. The cylinder under discussion has orthotropic stiffeners integrally made with an orthotropic shell. All the buckling analysis is based on a uniaxial compressive load condition.

References listed at the end of the thesis:

Samuel Kidane (1), Guoqiang Li (1), Jack Helms (1), Su-Seng Pang(1) and Eyassu Woldesenbet (2)
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ABSTRACT: Stiffened cylindrical shells are the major components of aerospace structures. In this study global buckling load for a generally cross and horizontal grid stiffened composite cylinder was determined. This was accomplished by developing an analytical model for determination of the equivalent stiffness parameters of a grid stiffened composite cylindrical shell. This was performed by taking out a unit cell and smearing the forces and moments due to the stiffeners onto the shell. Based on this analysis the extensional, coupling and bending matrices (A, B and D matrices, respectively) associated with the stiffeners were determined. This stiffness contribution of the stiffeners was superimposed with the stiffness contribution of the shell to obtain the equivalent stiffness parameters of the whole panel. Making use of the energy method the buckling load was solved for a particular stiffener configuration. Buckling test was also performed on a stiffened composite cylinder and compared with analytical results. Finally, using the analytical model developed, parametric analysis of some of the important design variables was performed and based on these results conclusions were drawn.

References listed at the end of the paper:

ABSTRACT: An improved smeared method is developed to model the buckling problem of an isogrid stiffened composite cylinder. In this model the stiffness contributions of the stiffeners is computed by analyzing the force and moment effect of the stiffener on a unit cell. The equivalent stiffness of the stiffener/shell panel is computed by superimposing the stiffness contribution of the stiffeners and the shell. The equivalent stiffness parameters are then used to calculate the buckling load of the stiffened cylinder. A 3-D finite-elements model is also built that takes into consideration the exact geometric configuration and the orthotropic properties of the stiffeners and the shell. Experimental analysis is also performed to compliment the two analytical methods used to determine the buckling load of the stiffened cylinder. Results of the three types of analyses methods are compared. Finally a parametric study is carried out and general conclusions are drawn regarding optimum configurations of the different parameters of the grid-stiffened cylinder.

References taken from Kidane’s 2002 Master’s thesis):

ABSTRACT: In steel structures like vessels or offshore constructions shells are often not as thin as in aircraft and space constructions. The rather thick-walled shells which are stressed in the elastic-plastic range are of great importance. To take this fact into account the plastic range was introduced in the codes for shell buckling during the past years. Compared to the number of experiments in the elastic range there are unfortunately only a few tests performed in the plastic range. And these few ones are not even well documented. Especially there is a lack of exact values of the yield stresses of the materials being used.

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P.J. Dowling, J.E. Harding, N. Agelidis and W. Fahy (Dept. of Civil Engineering, Imperial College, London), “Buckling of orthogonally stiffened cylindrical shells used in offshore engineering”, in Buckling of Shells, pp 239-273, 1982

ABSTRACT: This paper presents the results of tests on a series of small and large scale stringer stiffened cylinder models. Emphasis is placed on the fabrication techniques, methods of imperfection measurement and subsequent testing. A discussion of the resulting data and a comparison with available design rules have also been included.

References listed at the end of the paper:
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Partial ABSTRACT: This Paper examines the failure, under hydrostatic and lateral pressure loading, of three small-scale fabricated cylinders reinforced by light ring stiffeners. The ring stiffeners were designed so that overall failure involving both panel and ring buckling would be likely to occur...

J.E. Harding (University of Surrey, Guildford, UK), “The behavior and design of cylindrical shell structures”, in Stability Problems of Steel Structures, Vol. 323 of the series CISM International Centre for Mechanical Sciences, pp. 173-221, 1992

ABSTRACT: The buckling and collapse behaviour of shells is a complex subject about which numerous books have been written. This chapter is intended to serve as a simple introduction to the behaviour and design of a restricted class of shells, namely cylindrical shells stiffened by ring or orthogonal stiffeners. The treatment is non-mathematical with an emphasis on explaining the behaviour of the components. This is demonstrated by reference to the results of numerical analyses. The geometries considered are typical of the main leg components of offshore rig legs and where specialist design rules are mentioned they are taken from the area of offshore design.

References listed at the end of the paper:
ABSTRACT: Offshore jacket structures are composed of tubular members. As offshore structures go deeper into the ocean, the water pressure on these tubular elements is increased. This paper discusses the effect of external and internal pressure on the buckling behavior of the circular cross section tubular elements or pipes. The linear and nonlinear buckling behaviors of the tubular members with circular cross section were considered. Material and geometry nonlinearities were included in the analysis. The nonlinear buckling was found to be significantly affected by the water pressure. The paper also introduces a parametric study on the change in buckling load with the change of different parameters.

ABSTRACT: A sequential linear programming method with a simple move-limit strategy is used to investigate the following three important buckling optimization problems of composite shells: (1) optimization of fiber orientations for maximizing buckling resistance of composite shells without cutouts; (2) optimization of fiber orientations for maximizing buckling resistance of composite shells with circular cutouts; and (3) optimization of cutout geometry for maximizing buckling resistance of a composite shell. From the results of optimization study, it has been shown that, given a structural geometry, loading condition and material system, the buckling resistance of a cylindrical composite shell is strongly influenced by fiber orientations, end conditions, the presence of cutout and the geometry of cutout.

Hsuan-Teh Hu (Department of Civil Engineering National Cheng Kung University 1 University Road Tainan, Taiwan Republic of China), “Buckling analyses of fiber composite laminate plates with material nonlinearity”,
ABSTRACT: A nonlinear material constitutive model, including a nonlinear in-plane shear formulation and a failure criterion for fiber-composite laminate materials, is employed to carry out finite-element buckling analyses for composite plates under uniaxial compressive loads. It has been shown that the nonlinear in-plane shear together with the failure criterion have significant influence on the buckling behavior of composite laminate plates.

ABSTRACT: Based on linear and nonlinear in-plane shear formulations for fiber-composite laminate materials, finite-element buckling analyses for composite plates under uniaxial compression and biaxial compression and for composite shells under end compression and hydrostatic compression are presented. It has been shown that the nonlinear in-plane shear has significant influence on the buckling and postbuckling responses of composite plates and shells, specially for those with [45/-45]_{2S} layup.

Hsuan-Teh Hu (Department of Civil Engineering, National Cheng Kung University, Tainan, Taiwan 70301, R.O. China), “Buckling analyses of fiber-composite laminate shells with material nonlinearity”, Journal of Composites Technology & Research, JCTRER, Vol. 15, No. 3, Fall 1993, pp. 202-208
ABSTRACT: A nonlinear material constitutive model, including a nonlinear in-plane shear formulation and a failure criterion for fiber-composite laminate materials is employed to carry out finite-element buckling analyses for composite shells under hydrostatic compressive loads. It has been shown that the nonlinear in-plane shear together with the failure criterion have significant influence on the buckling behavior of composite shells.

ABSTRACT: The buckling strengths of fiber-composite laminate shells with a given material system are maximized with respect to fiber orientations using a sequential linear programming method together with a simple move-limit strategy. While a modified Riks nonlinear solution algorithm is utilized to analyse the buckling and postbuckling behaviour of composite shells, both linear and nonlinear in-plane shear formulations are employed to form the finite-element constitutive matrix for fiber-composite laminate. Results of the optimization study for simply supported composite cylindrical shells using both linear and nonlinear in-plane shear formulations are presented.

References listed at the end of the paper:
Hsuan-Teh Hu and Zhong-Zhi Chen (Department of Civil Engineering, National Cheng Kung University, Tainan, Taiwan 701, R.O.C.), “Buckling optimization of unsymmetrically laminated rectangular plates with a given material system and subjected to combined lateral and inplane loads are maximized with respect to fiber orientations by
using a sequential linear programming method together with a simple move-limit strategy. Significant influence of plate aspect ratios, central circular cutouts, lateral loads and end conditions on the optimal fiber orientations and the associated optimal buckling loads of unsymmetrically laminated plates has been shown through this investigation.

ABSTRACT: Elastic stability of skew composite laminate plates subjected to uniaxial inplane compressive forces has been studied. The critical buckling loads of the skew laminate plates are carried out by the bifurcation buckling analysis implemented in finite element program ABAQUS. The effects of skew angles, laminate layups, plate aspect ratios, plate thicknesses, central circular cutouts, and edge conditions on the buckling resistance of skew composite laminate plates are presented.

Hsuan-Teh Hu and Jiing-Sen Yang (Department of Civil Engineering and Sustainable Environment Research Center, National Cheng Kung University, 1 University Road, Tainan 701, Taiwan, ROC), “Buckling optimization of laminated cylindrical panels subjected to axial compressive load”, Composite Structures, Vol. 81, No. 3, December 2007, pp. 374-385, doi:10.1016/j.compstruct.2006.08.025
ABSTRACT: The buckling resistance of fiber-reinforced laminated cylindrical panels with a given material system and subjected to uniaxial compressive force is maximized with respect to fiber orientations by using a sequential linear programming method together with a simple move-limit strategy. The significant influences of panel thicknesses, curvatures, aspect ratios, cutouts and end conditions on the optimal fiber orientations and the associated optimal buckling loads of laminated cylindrical panels have been shown through this investigation.

ABSTRACT: The fundamental frequencies of fiber-reinforced laminated cylindrical shells with a given material system are maximized with respect to fiber orientations by using the golden section method. The significant effects of shell thickness, shell length, cutout and end condition on the maximum fundamental frequencies and the associated optimal fiber orientations are demonstrated.

ABSTRACT: A nonlinear material constitutive model, including a nonlinear in-plane shear formulation and the Tsai- Wu failure criterion, for fiber-composite laminate materials is employed to carry out finite element buckling analyses for composite laminate skew plates under uniaxial compressive loads. The influences of laminate layup, plate skew angle and plate aspect ratio on the buckling resistance of composite laminate skew plates are presented. Comparing with the linearized buckling loads of the skew plates, one can observer that the
nonlinear in-plane shear together with the failure criterion have significant influence on the ultimate loads of the composite laminate skew plates with $[\pm \theta]_{10S}$ and $[\pm \theta/90/0]_{5S}$ layups but not the $[\alpha/0]_{10S}$ layup.

-------- PANDA2 references

-------- References to stiffened panel and shell programs other than PANDA2


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end of references to programs other than PANDA2
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ABSTRACT: A procedure is presented for designing uniaxially stiffened panels made of composite material and subjected to combined inplane loads. The procedure uses a rigorous buckling analysis and nonlinear mathematical programming techniques. Design studies carried out with the procedure consider hat-stiffened and corrugated panels made of graphite-epoxy material. Combined longitudinal compression and shear and combined longitudinal and transverse compression are the loadings used in the studies. The capability to tailor the buckling response of a panel (i.e., design a panel so that it will have specified buckling loads at various buckling wavelengths) is also explored. Finally, the adequacy of another, simpler, analysis-design procedure is examined. The report demonstrates that a panel design procedure with a high-quality buckling analysis and with complete generality of constraints is practical. Such a procedure can be used to avoid failure from complex buckling modes and to determine mass and proportions of panels for multiple design load conditions and constraints.

References listed at the end of the report:
1. Peterson, James P., “Structural Efficiency of Aluminum Multiweb Beams and Z-Stiffened panels reinforced with filamentary
boron-epoxy composite”, NASA TN D-5856

W.J. Stroud and M.S. Anderson (NASA Langley Research Center, Hampton, Virginia, USA), “PASCO: Structural panel analysis and sizing code, capability and analytical foundations”, 1980 (publisher not given; perhaps a NASA Technical Note?, ProQuest-CSA)
ABSTRACT: A computer code denoted PASCO which can be used for analyzing and sizing uniaxially-stiffened composite panels is described. Buckling and vibration analyses are carried out with a linked-plate analysis computer code denoted VIPASA, which is incorporated in PASCO. Sizing is based on nonlinear mathematical programming techniques and employs a computer code denoted CONMIN, also incorporated in PASCO. Design requirements considered are initial buckling, material strength, stiffness, and vibration frequency. The capability of the PASCO computer code and the approach used in the structural analysis and sizing are described.

ABSTRACT: The stiffened composite structural panel analysis and sizing code designated 'PASCO' encompasses both the generality required for the exploitation of composite materials' design flexibility and an accurate buckling analysis for the detection of complex buckling modes. PASCO can accordingly design for buckling, frequency, material strength, and panel stiffness requirements. Attention is given to an additional thermal loading design capability. Design studies illustrate the importance of the multiple load condition capability when thermal loads are present.


ABSTRACT: Local stiffener and skin pocket buckling prediction by special PASCO modeling technique: Correlation to test data
YIN, DAHN | TRAN, V U M | SWIFT, PATRICKM
(SEE N89-24626 18-39); UNITED STATES; 1989
ABSTRACT: Waffle panels are often used on fuselage structures such as that of the Space Shuttle. The waffle panel design is an efficient design for carrying biaxial, in-plane, and shear loads. The WAFFLE program was designed for application on waffle panels. The Panel Analysis and Sizing Code (PASCO) program was designed for analyzing and sizing uniaxially stiffened panels. The application of the PASCO program in conjunction with the WAFFLE program is discussed to account for both the fillet radius and the presence of stiffness in both directions. The results of the tests are used to verify that these adjustments are valid and necessary if accurate analysis of the waffle panel is to be achieved.


Wong, K. F. W. and Weaver, P. M. (University of Bristol, Bristol BS8 1TR, UK), “Approximate solution for the compression buckling of fully-anisotropic cylindrical shells”, 45th AIAA Structures, Structural Dynamics & Materials Conference, April 2004, Palm Springs, California
doi: INIST-CNRS, Cote INIST : 214, 3540001343834.0200
ABSTRACT: The circular cylindrical thin-walled shell is a fundamental building block of many structures, such as aircraft fuselages. When used with laminated composites, highly efficient structures can be designed. As a result, the analytical treatment of cylindrical shells has received significant attention over recent decades. However, most of the works carried out in this area concern isotropic materials or orthotropic laminates, that is, those with no couplings. The present analysis develops a closed-form, yet simple solution for the linear buckling of laminated circular cylindrical shell, from the Donnell's model, including all available couplings. Although the usefulness of a linear solution for predicting buckling loads is questionable, its worth is in initial sizing and layup selection during the early stages of design. The resulting model could be used to examine the usefulness of different couplings that are not yet well understood. It is found that extension/shear coupling results in torsional movement of the cylinder, which, when restricted, induces a secondary torsional loading on the cylinder, thus reducing its overall buckling load by up to 50%. When not restricted, extension/shear couplings generally increase buckling loads.

Weaver, P. M., On optimisation of long anisotropic flat plates subject to shear buckling loads, 45th AIAA SDM Conference, April 2004

Diaconu, C. G. and Weaver, P. M., Approximate solution and optimum design for postbuckling of infinite laminated composite plates subjected to compression loading, 45th AIAA SDM Conference, April 2004

ABSTRACT: FASOR (Field Analysis of Shells of Revolution) is a user-oriented code for the analysis of stiffened, laminated axisymmetric shells. Very general shell geometries are allowed in that the reference surface meridian may form a branched, multi-circuit figure. Modes of response treated are linear asymmetric and geometrically nonlinear axisymmetric prebuckling, and asymmetric buckling and vibration under static axisymmetric loads. Bifurcation buckling under asymmetric loads is also treated by using a symmetrized prebuckling state based on the linear response of a user-specified meridian. For each mode of response, the user may specify any combination of orthotropic or anisotropic material properties with classical or transverse shear deformation shell theories. FASOR employs a numerical integration method (called the field method) whereby a numerically unstable linear boundary-value problem (all modes of response reduce to a sequence of such problems) is converted into two successive numerically stable initial-value problems. In this context, numerical stability means that round-off errors introduced at each step of the integration process tend to decay out. As a consequence, solution accuracy is controlled essentially by a single number, the truncation error tolerance, which is satisfied by automatically adjusting the size of each integration step. The field method thus eliminates
the need for mesh generation required by finite element and finite difference methods, and the associated problem of numerical convergence. It also provides for automatic determination of response storage points so as to obtain a uniformly valid discrete approximation of the continuous response. In this paper the field method is briefly described, basic aspects of the mathematical model are discussed, the organization of input data is presented, and input and plot output are given for specific examples.


ABSTRACT: An integrated computer program entitled Field Analysis of Shells of Revolution (FASOR) currently under development for NASA is described. When completed, this code will treat prebuckling, buckling, initial postbuckling and vibrations under axisymmetric static loads as well as linear response and bifurcation under asymmetric static loads. Although these modes of response are treated by existing programs, FASOR extends the class of problems treated to include general anisotropy and transverse shear deformations of stiffened laminated shells. At the same time, a primary goal is to develop a program which is free of the usual problems of modeling, numerical convergence and ill-conditioning, laborious problem setup, limitations on problem size and interpretation of output. The field method is briefly described, the shell differential equations are cast in a suitable form for solution by this method and essential aspects of the input format are presented. Numerical results are given for both unstiffened and stiffened anisotropic cylindrical shells and compared with previously published analytical solutions.


ABSTRACT: Critical in-plane normal and shear loads of rectangular anisotropic laminated plates are presented. These were calculated using the shell code FASOR, which includes the effect of transverse shear deformation. For simply-supported orthotropic laminates with midplane symmetry normal buckling loads are verified by a closed-form solution derived from transverse shear deformation plate theory. Results are compared to previously published solutions from three-dimensional elasticity theory and classical plate theory.


ABSTRACT: A computer program for the analysis of stress, nonlinear collapse and bifurcation buckling of hybrid bodies of revolution (BOSOR6) is used for the prediction of failure of axially compressed cylinders containing frangible joints. Plasticity and moderately large deflections are included in the analytical models. The structure in the immediate neighborhoods of the frangible joint notches is modeled with use of eight-node solid isoparametric finite elements of revolution and the rest of the structure is modeled with use of computationally efficient thin shell elements. Theoretical predictions are compared to test results. Certain aspects of the test specimens and boundary conditions remain unknown, and parameters in the analytical models are established and varied in order to reveal what these test conditions must have been. For reasonable values of these parameters, theoretical and experimental joint failure loads agree to within 2%.

ABSTRACT: The BOSOR5 computer program for elastic plastic buckling of shells of revolution is used for calculation of bifurcation buckling of cold bent and welded ring-stiffened cylinders under external pressure. Residual stresses and deformations from cold bending and welding are included in the model for buckling under service loads by introduction of these manufacturing processes as functions of a time-like parameter which ensures that the material in the analytical model experiences the proper sequence of loading prior to and during application of the service loads. The cold bending process is first simulated by a thermal loading cycle in which the temperature varies linearly through the shell wall thickness, initially increasing in time to simulate cold bending around a die and then decreasing in time to simulate springback to a final somewhat larger design radius. The welding process is subsequently simulated by the assumption that the material in the immediate neighborhoods of the welds is cooled below the ambient temperature by an amount that leads to weld shrinkage amplitudes typical of those observed in tests. Buckling loads are calculated for a configuration including and neglecting the cold bending and welding processes. These predictions are compared to values obtained from tests on two nominally identical specimens, one carefully machined and the other fabricated by cold bending the shell and then welding machined ring stiffeners to it.


ABSTRACT: The purpose of the many examples of buckling presented here is to give the reader a physical feel for shell buckling. Section 1 contains a brief description of two kinds of buckling, collapse and bifurcation. Section 2 concerns shell structures in which the cause of failure is nonlinear collapse due to either large deflections or to both large deflections and nonlinear material behavior. Section 3 gives examples of axisymmetric shells in which failure is due to bifurcation buckling. Section 4 provides examples that illustrate the effects of boundary conditions and eccentric loading on bifurcation buckling of shells of revolution. Section 5 is devoted to combined loading of cylindrical shells and nonsymmetric loading of shells of revolution. Section 6 is on bifurcation buckling and collapse of ring-stiffened shells with emphasis given to cylindrical shells. Section 7 contains several illustrations of buckling of prismatic shells and panels, that is, structures that have a cross section that is constant in one of the coordinate directions. Section 8 focuses on the sensitivity of predicted buckling loads to initial geometrical imperfections. Section 9 demonstrates axisymmetric collapse and bifurcation buckling of bodies of revolution that consist of combinations of thin shell segments and solid segments to which shell theory cannot be applied with sufficient accuracy.


ABSTRACT: A summary of previous work is first presented. Then an axisymmetric model is presented in which the bending of an infinite straight or curved pipe with external or internal pressure is simulated by thermal loading. The model includes geometric and material nonlinearity in the prebuckling analysis and bifurcation buckling from the nonlinear prebuckled state. Comparisons with tests on straight pipes and elbows are given. The calculations are performed with use of a slightly modified version of the BOSOR5 computer
program. Qualitative agreement with test results is demonstrated.


ABSTRACT: Results of nonlinear finite element analysis of several axially compressed, ring-stiffened, steel, cylindrical shells are presented, including comparisons with tests conducted at the Los Alamos National Laboratory. The specimens, all with radius-to-thickness ratio of about 450, have reinforced circular openings that cut across various numbers of ring stiffeners. The cylinders are loaded by enforced axial displacement applied to thick end plates halfway between the axis of revolution and the cylindrical shell wall. Measured imperfections are included in the analysis of a ring-stiffened specimen without any cutout. Inclusion of the imperfection field reduces the predicted collapse load by only eight per cent. Reinforced openings that cut one, two and three rings reduce the collapse load by 14, 21, and 22 per cent, respectively.


ABSTRACT: An analysis and an interactive computer program are described through which minimum weight designs of composite, elastic-plastic, stiffened, cylindrical panels can be obtained subject to general and local buckling constraints and stress and strain constraints. The panels are subjected to arbitrary combinations of in-plane axial, circumferential and shear resultants. Nonlinear material effects are included if the material is isotropic or has stiffness in only one direction (as does a discrete or a smeared stiffener). Several types of general and local buckling modes are included as constraints in the optimization process, including general instability, panel instability with either stringers or rings smeared out, local skin buckling, local crippling of stiffener segments, and general, panel and local skin buckling including the effects of stiffener rolling. Certain stiffener rolling modes in which the panel skin does not deform but the cross section of the stiffener does deform are also accounted for. The interactive PANDA system consists of three independently executed modules that share the same data base. In the first module an initial design concept with rough (not necessarily feasible or accurate) dimensions are provided by the user in a “conversational” mode. In the second module the user decides which of the design parameters of the concept are to be treated by PANDA as decision variables in the optimization phase. In the third module the optimization calculations are carried out. Examples are provided in which optimum designs obtained by PANDA are compared to those in the literature.


ABSTRACT: This paper opens with a general discussion of terms in an energy functional which might be the basis from which equations governing stress, stability, and vibration analyses are derived. The energy expression includes strain energy of the shell and discrete stiffeners, kinetic energy of the shell and stiffeners, constraint conditions with Lagrange multipliers, and other terms arising from the change in direction of applied loads during deformation. Brief discussions are included of the coupling effect between bending and extensional energy needed for the analysis of layered composite shells or elastic-plastic shells, nonlinear terms,
The form that the energy expression takes upon discretization of the structure. A section follows in which the energy formulation for stress, stability, and vibration analyses of an elastic curved beam is given, including thermal effects, moderately large rotations, boundary conditions, and distributed and concentrated loads. The matrix notation and type of discretization are introduced here which will later be used for the analysis of shells of revolution. Terms in the local element stiffness, mass, and load-geometric matrices are derived in terms of nodal point displacements, and it is shown how these local matrices are assembled into global matrices. The purpose of the section is to demonstrate the procedure for derivation of the analogous equations and quantities for shells of revolution or more complex structures. The next section is on elastic shells of revolution. It opens with a summary of what computer programs exist for stress, buckling, and stability analyses of such structures. The assumptions on which these programs are based are listed and the various components of the energy functional, such as strain energy of the shell and discrete rings, are identified and derived in terms of nodal point displacements. Included are a derivation of the constitutive law for anisotropic shell walls and a formulation of nonlinear constraint conditions, which are required for the treatment of segmented or branched shells with meridional discontinuities between segments or branches. Derivations of terms in the global stiffness and load-geometric matrices and the force vector are given, with tables tracing the origin of each term. The computational strategy for calculation of critical bifurcation buckling loads in the presence of prebuckling nonlinearities is given, with an example of buckling under axial compression of a very thin cylinder. This is a simple problem to formulate but a difficult one to solve numerically, owing to the existence of closely spaced eigenvalues corresponding to nonsymmetric buckling at loads close to the load corresponding to nonlinear axisymmetric collapse. A description of various pitfalls encountered in the search for the lowest bifurcation buckling load is given, including estimates of the critical number of circumferential waves in the buckling mode. Computerized formulations and run times are compared for various discretization methods, including finite difference energy models and standard finite element models, with an example showing comparisons of rate of convergence with increasing nodal point density and computer times required to form stiffness matrices. Hybrid bodies of revolution are discussed next. By “hybrid” is meant a body of revolution with both one-dimensionally and two-dimensionally discretized regions. The formulation is particularly useful for the stress, buckling, and vibration analyses of branched shells or ring-stiffened shells in which one is particularly interested in local effects within a distance equal to a shell wall thickness of a branch or ring. An appropriate strategy for the solution of nonlinear problems with simultaneous geometric nonlinearity and path-dependent material properties is described, including the development of the incremental constitutive law for the tangent stiffness method of treatment of elastic-plastic structures. The two-dimensionally discretized regions are modeled with use of 8-node isoparametric quadrilaterals of revolution. Details are presented on the formulation of constraint conditions for compatibility at junctions between rotationally symmetric shell segments (one-dimensionally discretized regions) and solid segments (two-dimensionally discretized regions). The paper closes with a summary of linear equations for general shells. Surface coordinates, the first and second fundamental forms, and the definition of a shell are introduced, and the assumptions corresponding to Love's first approximation are identified. The differences in commonly used or referenced formulations are listed, including differences with regard to kinematic relations, expressions for total strain anywhere in the thickness of the shell wall, and expressions for stress and moment resultants. Comments are offered on which theory is the most suitable for engineering estimates.

ABSTRACT: A theory based on minimum potential energy for the bifurcation buckling of elastic or elastic-plastic isotropic or elastic composite, flat or cylindrical, ring- and stringer-stiffened panels subjected to combined in-plane loads is derived. Equations are given for general instability, panel instability and local instability of panels with fully populated 6 x 6 thickness-integrated constitutive matrices. Also derived are equations for crippling and rolling of stiffeners. The theory has been implemented in user-friendly, interactive computer programs called PANDA and PANDA2 for the minimum-weight design of panels. These programs have been described in previous papers.


ABSTRACT: PANDA2 finds minimum weight designs of laminated composite flat or curved cylindrical panels or cylindrical shells with stiffeners in one or two orthogonal directions. The panels or shells can be loaded by as many as five combinations of in-plane loads and normal pressure. The axial load can vary across the panel. Constraints on the design include crippling, local and general buckling, maximum tensile or compressive stress along the fibers and normal to the fibers in each lamina, and maximum in-plane shear stress in each lamina. Local and general buckling loads are calculated with the use of either closed-form expressions or discretized models of panel cross sections. An analysis branch exists in which local post buckling of the panel skin is accounted for. In this branch a constraint condition that prevents stiffener popoff is introduced into the optimization calculations. Much of this paper represents a tutorial run through the PANDA2 processors for a hat-stiffened panel under combined axial compression, in-plane shear and normal pressure. Examples follow in which results from PANDA2 are compared with those in the literature and those obtained with the STAGS and EAL computer programs. Results of an extensive study are given for an optimized, blade-stiffened panel design so that it buckles locally at about 10% of the design load. The axially stiffened panel is subjected to pure axial compression, pure normal pressure, combined axial compression and normal pressure, and combined axial compression and residual stresses and deformations that arise from a simulated curing process. An example is provided of a design process applied to a ring and stringer stiffened cylindrical shell similar in geometry and loading to the 2/3 interstage of the ARIANE 4 booster.


ABSTRACT: A theory based on minimum potential energy for the nonlinear equilibrium of composite, stringer-stiffened, imperfect panels subjected to combined in-plane loads is derived. The normal displacement \( w(x, y) \) is assumed to have the form \( W(Y)\sin\left(\frac{x}{L}\right) \) in which \( x \) is the coordinate along the axis of the stringers, \( Y \) is the coordinate in the plane of the panel skin normal to \( x \), \( f_m \) is the slope of the nodal lines in the local buckling pattern in the panel skin, and \( L \) is the half-wavelength of the local bifurcation buckling mode. The function \( W(y) \) is obtained from a series expansion of the buckling modal normal displacement field obtained from a model in which the cross-section of a panel module is discretized as in the BOSOR4 analysis of shells of revolution. Nonlinear strain-displacement relations analogous to those developed in 1946 by Koiter for perfect panels are extended to handle panels with imperfections in the form of the critical local bifurcation buckling mode. The theory is incorporated into the PANDA2 computer program for minimum weight design. The nonlinear theory for the prediction of behavior of locally imperfect panels appears to be properly implemented in PANDA2, since there is excellent agreement between PANDA2 and STAGS for the case of a
uniformly axially compressed, imperfect, rectangular, isotropic panel loaded to four times the local bifurcation buckling load. The theory captures reasonably well the nonlinear modal interaction effect described in many papers published by Koiter, Hutchinson, Thompson, Tvergaard and others in the 1970s. There is good agreement between these previous theories, PANDA2 results and tests. Locally and globally imperfect panels can be automatically optimized with PANDA2, as demonstrated for the case of a blade-stiffened, imperfect, aluminum panel. The inclusion of local and global imperfections with amplitudes likely to occur in practice does not appear to affect dramatically the behavior nor the optimum design of axially stiffened panels that behave approximately as wide columns in the general instability mode of failure. Optimum designs of imperfect blade-, tee- and hat-stiffened panels are compared. Some recent modifications to the PANDA2 computer program are briefly described.

ABSTRACT: A number of struts or straps support a rigid, delicate mass (dewar) which must be successfully launched and maintained in orbit for a long time at a very low temperature. The support system must be designed so that the heat flow into the mass is minimized subject to constraints on minimum allowable natural frequency of the mass during launch, minimum natural frequency of the mass in orbit, maximum allowable stress in any support member during launch, and no buckling or slackening of any support member during launch. A user-friendly system of computer programs called DEWAR is described by means of which optimum designs can be obtained for a support system consisting of simple tension straps or simple tubes, or support systems with a passive thermal disconnect feature through which the thermal conductance is greatly reduced during the transition from the launch condition to the orbital condition. Most of the present paper consists of a sample case in which DEWAR is used in the tutorial mode.

ABSTRACT: The purpose of GENOPT (GEneral OPTimization) is to enable an engineer to create a user-friendly system of programs for analyzing and/or optimizing anything. The application of GENOPT is not limited to the field of structural mechanics. GENOPT is designed to handle problems with small data bases, not large finite element models, although it might well be used to provide a user-friendly “shell” within which any analysis could be done. GENOPT is ideal for generating programs for optimizing objects the behavior (stress, buckling, vibration, etc.) of which can be expressed by relatively simple tables or formulas such as those that appear in handbooks, or for optimizing objects the behavior of which has been previously encoded in existing subroutines. The optimizer used in GENOPT, created by Vanderplaats, is called ADS. Two examples are presented, one relatively simple, the other more complex.

ABSTRACT: The computer program PANDA2 for minimum weight design of composite, stiffened cylindrical
or flat panels made of composite material is described. The capability of PANDA2 has been expanded to handle truss-core sandwich panels. The new capability is demonstrated in this paper with an example: minimum weight design of a truss-core sandwich panel under axial compression, in-plane shear, and normal pressure. At the design load the panel is in a locally postbuckled state.

ABSTRACT: Local buckling and postbuckling of panels stiffened by stringers and rings and subjected to combined in-plane loads is explored with the use of a single module model that consists of one stringer and a width of panel skin equal to the stringer spacing. The cross-section of the skin-stringer module is discretized and the displacement field is assumed to vary trigonometrically in the axial direction. Local imperfections in the form of local buckling modes and overall initial axial bowing of the panel are included in the numerical model. The local postbuckling theory, based on early work of Koiter, is formulated in terms of buckling modal coefficients derived from integrals of products of the discretized displacement field and its derivatives. The principle of minimum potential energy is used to derive nonlinear algebraic equilibrium equations in terms of four unknowns, the amplitude f of the postbuckling displacement field, a postbuckling ‘flattening’ parameter a, the slope m of the nodal lines in the postbuckling displacement field, and an axial wavelength parameter N. The nonlinear equations are solved by Newton's method. An elaborate strategy is introduced in which the incidence of non-convergence is minimized by removal and re-introduction of the unknowns f, a, m, N on a one-by-one basis. This nonlinear theory has been implemented in the PANDA2 computer program, which finds minimum-weight designs of stiffened panels made of composite materials. PANDA2 is used to find the minimum weight of a cylindrical panel made of isotropic material with rectangular stringers mounted on thickened bases. The panel is optimized for three load sets, axial compression with negative axial bowing, axial compression with positive axial bowing, and combined axial compression and in-plane shear with no axial bowing. The optimum design is loaded well beyond local buckling for each load set. Critical margins of the optimized design include maximum allowable effective stress, bending-torsion buckling and general instability. The optimum design is evaluated by application of a general-purpose finite element program, STAGS, to finite element models generated by PANDA2 for each of the three load sets. The agreement of results between PANDA2 and STAGS is good enough to qualify PANDA2 as a preliminary design tool.

ABSTRACT: A minimum-weight design of a T-stiffened panel is found with the PANDA2 program. The panel, subjected to axial compression, in-plane shear, and normal pressure, is designed for service in its locally postbuckled state. A program called STAGSMODEL has been written for transforming output from PANDA2 to input for STAGS, a general-purpose nonlinear finite element code. STAGS is then used to evaluate the optimum design. Agreement between results obtained with PANDA2 and STAGS is reasonable for this very complex, very nonlinear problem. Therefore, PANDA2 qualifies as a preliminary design tool for panels operating in their locally postbuckled states.

ABSTRACT: Minimum-weight designs of T-stiffened and hat-stiffened panels made of laminated composite material are found with the PANDA2 program. The panels, subjected to axial compression, in-plane shear, and normal pressure, are designed for service in their locally postbuckled states. A program called STAGSMODEL is used for transforming output from PANDA2 to input for STAGS, a general-purpose nonlinear finite element code. STAGS is then used to evaluate the optimum designs. Agreement between results obtained with PANDA2 and STAGS is reasonable for these very complex, very nonlinear problems. Therefore, PANDA2 appears to qualify as a preliminary design tool for composite panels operating in their locally postbuckled states.


ABSTRACT: PANDA2 is a computer program for the minimum weight design of stiffened, composite, flat or cylindrical, perfect or imperfect panels and shells subjected to multiple sets of combined in-plane loads, normal pressure, edge moments, and temperature. The panels can be locally postbuckled. Recent additions to PANDA2 include implementation of: Sanders-type shell equations as a user-specified choice in addition to the Donnell equations, a 'global' optimizer processor, SUPEROPT, which in a single long run finds optimum designs from several different starting designs, and Arbocz' (1993) extension of Koiter's (1963) special theory for computation of buckling load factors for perfect anisotropic cylindrical shells and knockdown factors for axisymmetrically imperfect shells. Also incorporated are the ability to handle a new truss-core sandwich configuration and isogrid-stiffened panels and shells. Examples given.


ABSTRACT: The PANDA2 computer program for minimum-weight design of stiffened composite panels is expanded to handle optimization of ring and stringer stiffened cylindrical panels and shells with local, inter-ring, and general buckling modal imperfections in the form of buckling modes, any combination of which may be present: local (buckling between adjacent stringers and rings), inter-ring (buckling between rings with stringers bending with the panel skin), and general (buckling in which both stringers and rings bend with the panel skin). Stresses and buckling load factors of the imperfect panels are computed with use of the assumption that the amplitudes of the buckling modal imperfections grow hyperbolically with increasing load factor according to the formula AMP(i) = EIG(i)/(EIG(i) - 1), in which AMP(i) is a factor to be multiplied by the initial buckling modal imperfection and EIG(i) represents the critical load factor for the ith type of buckling mode (i = 1 = local buckling, i = 2 = inter-ring buckling, i = 3 = general buckling). Buckling load factors corresponding to local, inter-ring, and general buckling of the imperfect panel are computed with use of the maximum radius of curvature that develops in whatever portion of the panel (between stiffeners, inter-ring, overall) is being considered in the calculations and including redistribution of stress resultants over panel skin and stiffener cross-sections caused by prebuckling...
bending. Stress constraints in the optimization problem are computed including local, inter-ring, and general bending stresses generated by the growth of the initial local, interring, and general imperfections. These bending stresses are added to the stresses from other sources (thermal, in-plane loading, normal pressure, curing, redistribution of membrane stresses from overall prebuckling bending of the imperfect panel). Minimum-weight designs for various imperfect unstiffened and stiffened cylindrical shells derived by PANDA2 are evaluated with use of the STAGS general-purpose finite element code. The agreement of results from PANDA2 and STAGS appears to qualify PANDA2 for the preliminary design of imperfect, stiffened, composite cylindrical shells.


ABSTRACT: GENOPT, a program that writes user-friendly optimization code, and BOSOR4, a program for stress, buckling, and vibration analysis of segmented branched stiffened shells of revolution, are combined to create a capability to optimize specific classes of shells of revolution. GENOPT and BOSOR4 and recent improvements to them are described. An example is provided of an aluminum cylindrical shell with a wavy wall and with ring stiffeners. In the example the objective of the optimization is minimum weight, and the design constraints include stress, buckling, and modal vibration. In the report from which this paper is condensed an Appendix is provided in which a very simple example is employed to demonstrate in detail how a user can create a capability to optimize any shell of revolution.


ABSTRACT: The PANDA2 computer program has been modified to permit minimum weight design of imperfect panels with riveted Z-shaped stiffeners for service in a load regime in which the panel is in its locally postbuckled state. Perfect and imperfect panels optimized with PANDA2 are evaluated via nonlinear STAGS analyses. The agreement between predictions by PANDA2 and STAGS is sufficient to qualify PANDA2 as a preliminary design tool for panels with riveted Z-shaped stringers. Optimum designs for panels with Z-shaped stringers are compared to those with J-shaped and T-shaped stringers.

References listed at the end of the paper:


[22] Bushnell, D.: ../panda2/doc/panda2.news, a continually updated file distributed with PANDA2 that contains a log of all significant modifications to PANDA2 from 1987 through the present.


ABSTRACT: PANDA2 is a code for the minimum-weight design of perfect and imperfect elastic stiffened panels and shells made of composite laminates and subjected to multiple sets of in-plane loads, edge moments, normal pressure, and temperature. The scope of PANDA2 is increased to include global optimization and the capability to handle isogrid stiffening. The enhanced program is used to find global optimum designs of internally T-isogrid and internally T-ring stiffened perfect and imperfect isotropic cylindrical shells under uniform external pressure. For the cases studied, it is found that for the perfect optimized shells the isogrid stiffening is important but the rings are not, whereas the opposite holds for the optimized shells with an initial general buckling modal imperfection of amplitude equal to one per cent of the shell radius.

ABSTRACT: PANDA2, a computer program for the minimum-weight design of elastic perfect and imperfect stiffened cylindrical panels and shells under multiple sets of combined loads, is used to obtain optimum designs of uniformly axially compressed elastic internal T-ring and external T-stringer stiffened cylindrical shells with initial imperfections in the form of the general buckling mode. The optimum designs generated by PANDA2 are verified by STAGS elastic and elastic-plastic finite element models produced automatically by a PANDA2 processor called STAGSUNIT. Predictions from STAGS agree well with those from PANDA2. Improvements to PANDA2 during the past year are summarized. Seven different optimum designs are obtained by PANDA2 under various conditions. The most significant condition is whether or not PANDA2 is permitted automatically to make the initial user-specified amplitude of the general buckling modal imperfection directly proportional to the axial halfwavelength of the critical general buckling mode. A survey is conducted over (m,n) space to determine whether or not the critical general buckling modal imperfection shape computed by PANDA2 with (m,n)critical (m=axial, n=circumferential) halfwaves is the most harmful imperfection shape. It is found that indeed (m,n)critical is, for all practical purposes, the most harmful imperfection mode shape if PANDA2 is permitted automatically to make the general buckling modal imperfection amplitude directly proportional to the axial halfwavelength of the critical general buckling mode (inversely proportional to m). It is concluded that for axially compressed, stiffened, globally imperfect cylindrical shells the optimum designs obtained with the condition that PANDA2 is NOT allowed to change the initial user-specified imperfection amplitude are probably too heavy. One of the cases investigated demonstrates that the optimum design of a perfect shell obtained via the commonly used condition that a likely initial imperfection be replaced by an increase in the applied load by a factor equal to the inverse of a typical knockdown factor is too heavy. A new input index, ICONSV, is introduced into PANDA2 by means of which optimum designs of various degrees of conservativeness can be generated. Optimum designs are obtained with ICONSV = -1, 0, and +1, which represent increasing degrees of conservativeness in the PANDA2 model. It is concluded that, when obtaining optimum designs with PANDA2, it is best to allow PANDA2 to enter its branch in which local postbuckling...
behavior is determined, thereby avoiding the generation of designs that may be unsafe because of excessive local bending stresses in the panel skin and stiffener parts. In most cases both nonlinear static and nonlinear dynamic analyses are required in order to obtain collapse loads with STAGS. A table is included that demonstrates how to use STAGS to evaluate an optimum design obtained by PANDA2. In most cases the elastic STAGS models predict collapse in one of the ring bays nearest an end of the cylindrical shell. With the effect of elastic-plastic material behavior included in the STAGS models, collapse most often occurs in an interior ring bay where the finite element mesh is the most dense.


ABSTRACT: GENOPT, a program that can be used to optimize anything, and BIGBOSOR4, a program for stress, buckling, and vibration analysis of segmented, branched, stiffened, elastic shells of revolution, are combined to a capability to optimize a specific kind of shell of revolution: an internally isogrid-stiffened elastic ellipsoidal shell subjected to uniform external pressure. Optimum designs are obtained for isogrid-stiffened and unstiffened axisymmetrically imperfect and perfect titanium 2:1 ellipsoidal shells. The decision variables are the shell skin thickness at several user-selected meridional stations, the height of the isogrid stiffeners at the same meridional stations, the spacing of the isogrid stiffeners (constant over the entire shell), and the thickness of the isogrid stiffeners (also constant over the entire shell). The design constraints involve maximum stress in the isogrid stiffeners, maximum stress in the shell skin, local buckling of an isogrid stiffener, local buckling of the shell skin between isogrid stiffeners, general nonlinear bifurcation buckling, nonlinear axisymmetric collapse, and maximum normal displacement at the apex of the dome. Optimum designs first obtained by GENOPT are subsequently evaluated by the use of STAGS, a general-purpose finite element computer program. It is found that in order to obtain reasonably good agreement between predictions from BIGBOSOR4 and STAGS it is necessary to model the ellipsoidal shell as an "equivalent" ellipsoidal shell consisting of a spherical cap and a series of toroidal shell segments that closely approximates the true ellipsoidal meridional shape. The equivalent ellipsoidal shell is optimized with up to four axisymmetric buckling modal imperfections, each imperfection shape assumed to be present by itself. Computations include both plus and minus axisymmetric buckling modal imperfection shapes. At each design cycle and for the plus and minus version of each axisymmetric imperfection shape the following analyses are conducted: 1. linear general axisymmetric bifurcation buckling analysis (in order to obtain the axisymmetric linear buckling modal imperfection shapes), 2. nonlinear axisymmetric stress analysis at the design pressure, 3. nonlinear axisymmetric collapse analysis, and 4. nonlinear non-axisymmetric bifurcation buckling analysis. For each axisymmetric imperfection shape the design margins include an axisymmetric collapse margin, a general buckling margin, a margin involving the normal displacement of the apex of the shell, and local skin and stiffener stress margins and local skin and stiffener buckling margins within two approximately equal meridional regions of the equivalent ellipsoidal shell.

There is generally good agreement of the predictions from STAGS and from BIGBOSOR4 for the elastic behavior of the perfect stiffened and unstiffened optimized shells and for the behavior of the imperfect stiffened optimized shells with axisymmetric buckling modal imperfections. Optimization with the use of only axisymmetric buckling modal imperfections has a disadvantage in the case of the unstiffened imperfect shell under certain conditions: the optimum design of the axisymmetrically imperfect unstiffened shell evolves in such a way that, according to predictions from STAGS, a non-axisymmetric buckling modal imperfection with the same amplitude as an axisymmetric buckling modal imperfection causes collapse of the shell at an external pressure far below the design pressure. This disadvantage is easily overcome if, during optimization cycles, the
unstiffened shell wall in the neighborhood of the apex is forced to remain thick enough so that local axisymmetric buckling does not occur primarily at and near the apex but instead occurs primarily in the remainder of the shell. An extensive study of some of the previously optimized elastic shells is conducted with STAGS including elastic-plastic material properties. The effect on collapse pressure of initial imperfections in the form of off-center residual dents produced by load cycles applied before application of the uniform external pressure is determined and compared with the effect on collapse pressure of imperfections in the form of non-axisymmetric and axisymmetric linear buckling modes, especially the non-axisymmetric linear buckling modal imperfection with n=1 circumferential wave, which seems to be the most harmful imperfection shape for optimized externally pressurized ellipsoidal shells. For the optimized unstiffened shell it is found that a residual dent that locally resembles the n=1 linear buckling modal imperfection shape is just as harmful as the entire n=1 linear buckling modal imperfection shape.


ABSTRACT: GENOPT/BIGBOSOR4 is applied to the problem of an axially compressed perfect elastic cylindrical shell the wall of which is a composite truss-core sandwich. The truss-core sandwich is constructed of trapezoidal core tubes that are sandwiched between two face sheets. At the junction of the core webs and the face sheets are “noodle” regions that are filled with unidirectional composite material. The design constraints are local buckling, general buckling, and five stress constraints for each material. Local and general buckling are computed from BIGBOSOR4 models in which the "huge torus" prismatic representation of the cylindrical shell is employed. In both the local and general buckling models the "huge torus" representation of the cylindrical shell consists of a number of identical modules of the cross section of the truss-core sandwich wall that are strung together along the curved meridian of the "huge torus". The rather elaborate 22-segment module used for local buckling includes small curved and straight segments that occur at the corners of the trapezoidal tool around which the truss-core is wrapped during the fabrication process. The presence of "noodles" that fill the prismatic triangular-like gaps between adjacent trapezoids is accounted for.


ABSTRACT: GENOPT/BIGBOSOR4 is applied to the problem of perfect elastic spherical or cylindrical “shells” the complex inflatable wall of which is a webbed sandwich. The spherical or cylindrical “shell” is stabilized by uniform pressure applied between its inner and outer walls and subjected to uniform pressure applied to its outermost wall. This paper is analogous to [1]. The distance between the inner and outer walls of the optimized spherical balloons is smaller than that for the optimized cylindrical balloons. The pre-buckling behavior of the spherical balloons is “crankier” (more nonlinear) than that of the cylindrical balloons with the result that certain special strategies have to be introduced in order to permit the generation of optimum designs via the GENOPT processor called SUPEROPT. General buckling modes of the type observed in optimized cylindrical balloons have so far not been observed in any spherical balloons, optimized or not. Local buckling modes include both axisymmetric modes and non-axisymmetric modes with many circumferential waves. Since [1] was written new versions of the “balloon” software, behavior.balloon and bosdec.balloon, have been created by means of which both cylindrical and spherical balloons and balloons with either radial webs or truss-like
 webs can all be optimized and analyzed with use of the same “balloon” software. Since [1] was
produced a new behavioral constraint has been added that involves a load factor corresponding to the initial loss
of tension in any of the segments of the balloon wall. This new behavioral constraint is related to initial
wrinkling of the balloon, which is a type of buckling that pertains to both cylindrical and spherical balloons.
Optimum designs are found for balloons made of polyethylene terephthalate, which has a maximum allowable
stress of 10000 psi and weight density, 0.1 lb/in³, and for balloons made of a much stronger and lighter
fictitious carbon fiber cloth, which has much higher maximum allowable tensile and compressive stresses,
75600 psi and 59600 psi, respectively, and lower weight density, 0.057 lb/in³. The optimized weights of the
balloons made of the much stronger and lighter fictitious carbon fiber cloth are 15 to 20 times lighter than those
made of polyethylene terephthalate. A section is included showing optimized designs of cylindrical balloons
made of the fictitious carbon fiber cloth, which is not included as a material option in [1]. Some peculiarities of
the pre-buckling deformations and general buckling modes of optimized spherical and cylindrical balloons
made of fictitious carbon fiber cloth are displayed. These optimized balloons, which have much thinner walls
than the optimized balloons made of polyethylene terephthalate, exhibit significant spurious local “zig-zag”
components of pre-buckling and bifurcation buckling modal displacements. Convergence studies with respect to
the number of nodal points used for each segment of the balloons indicate that this spurious local “zig-zag”
characteristic does not have a major influence on the prediction of the overall behavior of the balloons.
Therefore, it appears that the optimized designs are valid despite the spurious local “zig-zag” characteristic,
which disappears with increasing numbers of nodal points used in each segment of a balloon wall.

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“Optimization of Propellant Tanks Supported by Optimized Laminated Composite Tubular Struts”, AIAA
Paper 2013-1479, AIAA 54th Structures, Structural Dynamics and Materials Meeting, April 8-12, 2013,
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ABSTRACT: The propellant tank is a shell of revolution completely filled with liquid hydrogen (LH2). This
propellant tank is to be launched into space. During launch it is subjected to high axial and lateral accelerations.
The tank is supported by a system of struts that consist mainly of tubes with laminated composite walls. This
strut-supported tank system is optimized via GENOPT/BIGBOSOR4 in the presence of two loading cases: (1)
10 g axial acceleration and 0 g lateral acceleration and (2) 0 g axial acceleration and 10 g lateral acceleration. In
addition to the g-loading the tank has 25 psi internal ullage pressure and the tank wall is 200 degrees cooler than
the wall of the launch vehicle from which it is supported by the struts. In the BIGBOSOR4 modal vibration
model the mass of the propellant is "lumped" into the tank wall, a conservative model. The tank/strut system is
optimized in the presence of the following constraints: (1) the minimum modal vibration frequency must be
greater than a given value; (2) five stress components in each ply of the laminated composite wall of the strut
tubes shall not exceed five specified allowables; (3) no strut tube shall buckle as a column; (4) no strut tube
shall buckle as a thin cylindrical shell; (5) the maximum effective (vonMises) stress in the tank wall shall not
exceed a specified value; (6) the tank wall shall not buckle; (8) the maximum force in a strut during the launch-
hold phase of a mission shall not exceed a specified value. The objective to be minimized is in general a
weighted combination of the normalized mass of the empty tank plus the normalized conductance of the support
system: Objective= W x (normalized empty tank mass) + (1-W) x (normalized strut conductance), in which W
is a user-selected weight between 0.0 and 1.0. Two propellant tank/strut systems are optimized: (1) a long tank
with two "rings" of struts, an aft ring and a forward ring, and (2) a short tank with only one "ring" of struts. It is
emphasized that the tank/strut combination is optimized as a single system. The flexibility of the propellant tank
is accounted for and found to be significant for optimized tank/strut systems. The flexibility of the launch vehicle to which the tank/strut system is attached is neglected: the ends of the supporting struts attached to the launch vehicle are assumed to be attached to rigid "ground". Parameter studies are conducted in which optimum designs are obtained as a function of the number of strut pairs attached to the tank. During optimization linear theory is used throughout. Predictions for certain of the optimized tank/strut designs obtained here are compared with those from the general-purpose finite element code, STAGS. The agreement between the predictions of GENOPT/BIGBOSOR4 and STAGS qualifies the use of GENOPT/BIGBOSOR4 for preliminary design in the particular cases studied here.

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ABSTRACT: The propellant tank is a shell of revolution completely filled with liquid hydrogen (LH2). This propellant tank is to be launched into space. During launch it is subjected to high axial and lateral accelerations. The tank is supported by one or two conical skirts each of which consists of five segments: two short segments near each end of the skirt and a central long segment that has a laminated composite wall. Each of the short segments nearest the ends of the skirt has an isotropic one-layered wall with tapered thickness. Each short segment next to each short end segment is multi-layered with the extreme layers consisting of tapered isotropic material and the remaining internal, contained layers consisting of the same laminated composite wall as the long central segment. This tank/skirt system is optimized via GENOPT/BIGBOSOR4 in the presence of two loading cases: (1) 10 g axial acceleration and 0 g lateral acceleration and (2) 0 g axial acceleration and 10 g lateral acceleration. In addition to the g-loading the tank has 25 psi internal ullage pressure, the tank wall is 200 degrees cooler than the wall of the launch vehicle from which it is supported by the conical skirt(s), and there exists axisymmetric meridionally non-uniform cooling of the skirts. In the BIGBOSOR4 modal vibration model the mass of the propellant is "lumped" into the tank wall, a conservative model. The tank/skirt system, a multi-segment branched shell of revolution, is optimized in the presence of the following constraints: (1) the minimum modal vibration frequency of the tank/skirt(s) system must be greater than a given value; (2) five stress components in each ply of the laminated composite wall of the conical skirt(s) shall not exceed five specified allowables; (3) the conical skirt(s) shall not buckle; (4) the maximum effective (von Mises) stress in the tank wall shall not exceed a specified value; (5) the tank wall shall not buckle. The objective to be minimized is in general a weighted combination of the normalized mass of the empty tank plus the normalized conductance of the support system: Objective = W x (normalized empty tank mass) + (1-W) x (normalized strut conductance), in which W is a user-selected weight between 0.0 and 1.0. Two propellant tank/skirt systems are optimized: (1) a long tank with only one supporting skirt joined to the tank at the midlength of the tank and (2) the same long tank with two supporting skirts, an aft skirt and a forward skirt. It is emphasized that the tank/skirt(s) combination is optimized as a single branched shell of revolution. The flexibility of the launch vehicle to which the tank/skirt(s) system is attached is neglected: the ends of the supporting skirt(s) attached to the launch vehicle are assumed to be attached to rigid "ground". Linear theory is used throughout. Predictions for the optimized tank/skirt designs obtained here are compared with those from the general-purpose finite element code, STAGS. The agreement between the predictions of GENOPT/BIGBOSOR4 and STAGS qualifies the use of GENOPT/BIGBOSOR4 for preliminary design in the particular cases studied here.
ABSTRACT: We want to determine the minimum amount of material required to span a distance of width $= WIDTH$ for an axially compressed, unstiffened, prismatic metallic wall or panel of length $= LENGTH$. The prismatic panel has a complex “corrugated” cross section. The width of the complex “corrugated” panel is composed of a number of “major” cylindrical segments, each of which may be divided into a number of cylindrical “sub-segments”. Each segment and each sub-segment is a sector of a little cylindrical shell the generators of which run in the axial direction. In addition there exists an overall arching over the entire width of the panel. The several little cylindrical segments/sub-segments are joined generator to generator in series. The entire unstiffened “corrugated” panel can be fabricated without any welding. Half of the width of the panel is included in the BIGBOSOR4 model used for optimization, with symmetry and anti-symmetry conditions imposed at its mid-width, $WIDTH/2$. The GENOPT/BIGBOSOR4 system is used to build the model and to perform the optimization. The minimum weight of the panel is determined in the presence of the following behavioral constraints: 1. The panel shall not buckle locally, 2. The panel shall not buckle in a general mode that is symmetric at the plane of symmetry, 3. The panel shall not buckle in a general mode that is anti-symmetric at the plane of symmetry, 4. Each little cylindrical segment of the panel shall not buckle in a “classical” mode, and 5. The maximum stress in the wall of the panel shall be less than a specified value. The numerical analysis is extended to flat or curved panels of any width with repeating complex cross sections. An optimized cross-section profile with reflected and multiple repeating complex sections is mapped onto a cylindrical surface, and the buckling characteristics and weight of this complexly corrugated cylindrical shell are compared with those of an optimized “equivalent” cylindrical shell with external T-shaped stringers, an “equivalent” optimized cylindrical shell with a truss-core sandwich wall, and an optimized “equivalent” cylindrical shell with uniform corrugations. It is found that the optimized complexly corrugated cylindrical shell weighs less than these other three optimized “equivalent” cylindrical shells that have different wall constructions. Optimized complexly corrugated panels with cylindrical segments the geometry of which varies across its width weigh about 12-14 per cent less than optimized uniformly corrugated panels, such as a standard corrugated panel. The existence of sub-segments does not lead to panels that weigh less than panels without sub-segments. The gradient-based optimizer used in the GENOPT/BIGBOSOR4 system (“ADS” by Vanderplaats) has difficulty finding “global” optimum designs for panels with many cylindrical segments. Several of the optimized designs determined with GENOPT/BIGBOSOR4 are verified by comparison with predictions from the general-purpose computer program STAGS. The agreement between the predictions of GENOPT/BIGBOSOR4 and STAGS qualifies the use of GENOPT/BIGBOSOR4 for optimization in the particular cases studied here. The behavior of optimized configurations with “corners” (discontinuous slope in the “width-wise” direction) between major cylindrical segments are compared with that of configurations in which these “corners” have been smoothed by the introduction of transitional fairing segments. A program called HUGEBOSOR4 is developed to handle cases with up to 2950 segments.


ABSTRACT: The content of this volume is related to the choice of knockdown factors to be used in the design of containment vessels. The presently used design recommendations are based on experimental results pertaining to shells subjected to uniform static loading. Relatively few experiments have been performed on fabricated shells typical of civil engineering structures. A variety of factors have some effect on the imperfection sensitivity of shell structures, such as ratios between basic dimensions, degree of stiffening, inelastic deformation, duration and uniformity of loading. Therefore, it is hardly possible to collect sufficient empirical information to allow for the development of truly satisfactory design procedures. It is suggested here that the situation can be greatly improved if numerical experimentation based on computer analysis of shells with random imperfections is used to enlarge the basis for the procedures. A distinction is made between more or less deterministic imperfections inherent in the manufacturing process and truly random imperfections. The utilization of numerical results to verify or modify code recommendations is demonstrated for ring stiffened inelastic shell segments. Some effects on buckling of nonuniformity in loading are discussed.


ABSTRACT: A semiimplicit dynamic relaxation technique for solution of the nonlinear structural equilibrium equation is presented. A previously presented basic transient response analysis algorithm is employed, permitting use of one solution method and one software module for both static and dynamic analyses. A theoretical comparison of the method with explicit dynamic relaxation techniques shows that it offers a substantially improved convergence property without additional computational overhead.


ABSTRACT: A new corotational procedure is developed which enables existing finite element formulations to be used in problems that contain arbitrarily large rotations. Through the use of a nonsingular large rotation vector, the contribution of the rigid body motion of the element to the total displacement field is removed before element computations are performed, with the result that almost any element can be easily upgraded to handle large rotations. This paper contains a derivation of the theory, an outline of the implementation into the STAGS code, and a demonstration of performance for problems involving large rotations and moderate strains. (Referenced by other researchers 144 times as of August 2011)

ABSTRACT: A new approach for enforcing invariance to rigid body motion is introduced. This invariance property is derived in terms of a projection matrix, P, which depends on the rigid body modes and acts on nodal forces, f, independent of the element formulation. The invariance property takes the form $f = P^{\text{transpose}}f$. Moreover, the same transformation enforces equilibrium of the element internal force vector when it is not initially satisfied. An equivalent transformation using P is also derived for the element stiffness matrix. This approach has been applied to a number of established elements, and is used to solve two text examples that expose deficiencies of elements. Numerical results indicate marked improvement in the performance of the elements tested.

(Referenced by other researchers 66 times as of August 2011)


ABSTRACT: The solution of bifurcation problems with closely-spaced critical points is achieved by first separating the singular part of the equation system encountered during a Newton iteration and carrying the Taylor expansion of the reduced system out to higher order. This separation is accomplished by transforming the equation system into an equivalent system in which some of the original unknowns are replaced with an equal number of modal amplitude coefficients. This method was used to continue the analysis of two significant example problems well past multiple bifurcation points, allowing a detailed examination of postbuckling behavior in the presence of modal interaction.


ABSTRACT: A systematic procedure is presented that may be used to extend the capabilities of an existing linear finite element to accomodate finite rotation analysis. This procedure is a generalization of the work presented in Computers and Structures, Volume 30, pp. 257–267. The basis of our approach is the element-independent co-rotational algorithm, where the element rigid body motion (translations and rotations) is separated from the deformational part of its total motion. The variation of this co-rotational relation results in a projector matrix, with the property that a consistent internal force vector is invariant under its action. The consistent tangent stiffness matrix is shown to depend on this invariance condition through the derivative of the projector. This results in an unsymmetric tangent matrix whose anti-symmetric part depends on the out-of-balance force vector. In this paper we prove that using the symmetric part of the tangent matrix, the Newton
iteration retains its quadratic rate of convergence. This approach has been used to solve a number of large rotation test example problems. The results demonstrate that it is possible to analyze structures undergoing large rotations within a general co-rotational framework, using simple and economical finite elements. The resulting improvements in the performance of these simple elements are brought about through the use of convenient software utilities as pre- and post-processors to the element routines.


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“The numerical simulation of the collapse process of axially compressed cylindrical shells with measured imperfections”, Delft University Aerospace Engineering Report LR-705, 1992, uuid: c94a0f5d-7d62-4e07-9eda-bd22ff66b5e2
ABSTRACT: A numerical computation of the collapse process of a cylindrical shell under prescribed edge displacement is discussed. The shell chosen for the computational experiment was manufactured, measured, and tested some twenty years ago. The purpose of the study is to compute the static, pre-collapse loading path and the subsequent snap (dynamic process) to the post buckling state. The test specimen is an integrally machined stringer stiffened cylindrical shell. The wave pattern in the pre-collapse state was observed to be dominated by a mode of one half wave in the axial direction and 9 waves in the circumferential direction. In the post buckling state after the snap, one half wave in the axial direction and ten full waves in the circumferential direction were observed. The simplifications applied in the model concern the adaptation of symmetry in the imperfection pattern and deformation after the load is applied.

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ABSTRACT: A finite element procedure is presented for the analysis of the buckling and postbuckling behavior of cracks in plates loaded in tension. The procedure proposed is applied to the problem of the centrally cracked plate in tension where the loading direction is perpendicular to the crack faces. The results of the analysis show that the buckling deformations can cause a considerable amplification of the stress intensity around the crack tip. This effect, which is due to a redistribution of the stress field in the plate, increases with the length of the crack.

ABSTRACT: A method for computing the energy release rate for cracks of varying length in a typical stiffened metallic fuselage under general loading conditions is presented. Reliable analytical methods that predict the structural integrity and residual strength of aircraft fuselage structures containing cracks are needed to help to understand the behavior of pressurized stiffened shells with damage, to determine the safe life of such a shell. The models used in the simulation are derived from an extensive analysis of a fuselage barrel section subjected to operational flight loads. Energy release rates are computed as a function of the length of the crack, its location, and the crack propagation mode.


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ABSTRACT: This paper is an investigation into the merits of an hybrid procedure for the numerical simulation of transient buckling problems. The procedure consists of the combination of a classical path-following method with a transient integration method where the first method is used for the quasi static (stable) parts of the simulation and the second method for the parts of the simulation that belong to the transient domain. It is shown that the success of the procedure is guaranteed by a proper formulation of the so-called matching conditions that define the transition from one mode of operation to the other. The chosen strategy turns out to be very robust and it has as an added advantage that it can be applied with relative ease. The power of the approach is demonstrated with the presentation of two simulations: The mode jumping problem of a plate strip and the collapse of a thin-walled composite cylinder in compression.


Eduard Riks (SMR Biel), “On the Purpose and Limitations of Buckling Analysis”, - cocomat.de (no date or publisher given; most recent reference cited is 2003.)
ABSTRACT: The discussion in this presentation is restricted to mechanical systems that are conservative or quasi-conservative. By quasi conservative we mean that the notion of conservatism holds as long as the changes of state occur infinitely slow. If changes of state occur with a finite rate of deformation, dissipative forces may
come into play.
Classic elastic stability theory studies the behavior of engineering structures under the influence of their service loads with a special focus on the determination of the (maximum) load these structures can carry. This maximum load is determined by geometrical effects that result from the state of deformation and not (in the first place) by material failure mechanisms. It is important to realize that the classical theory is restricted to quasi static loading conditions. The load carrying capacity in this setting is reached at the deformation state at which any further increase of the loading will result in the destruction of the structure. The state where this change is about to occur is called the collapse state, the limit state, or the state of loss of stability. The theory categorizes these states also as (proper) limit points and unstable bifurcation points.

In early applications of the theory, the actual collapse process -- called snap through or snap buckling -- was not deemed to be of particular interest and simply not considered. It should be added that the analytical tools in those days were not capable of solving the nonlinear partial differential equations of motion so that this transient phenomenon could be calculated. In fact, most applications remained restricted to the solution of the quasi-nonlinear buckling equations that arise when the pre-buckling state can be taken to be a linear function of the load intensity.

Thus before the age of “computational mechanics”, in the beginning of the 20th century, applications of stability theory remained restricted to problems that exhibited an initially linear pre-buckling state. This state of affairs did not change with the appearance of the perturbation theory of elastic stability conceived by Koiter. A milestone in the development of the concept of buckling, this development offered a considerable gain in understanding of the way stability is lost or maintained at a bifurcation point. It explained the consequences of these properties for the behaviour of structures loaded into the neighborhood of such a point. It also provided a systematic derivation of an ordered sequence of linearized equations that determine the shape of the most important bifurcations that can be encountered. However, with the analytical means available at that time, these equations were no more accessible to computation than the well established linearized buckling equations. As a consequence, applications of Koiter’s general theory remained also restricted to problems with a linear pre-buckling state. It was the advent of the computer and the surge of the numerical treatment of the classical theories of solid mechanics that gradually offered possibilities in computation that nobody would or could have dreamed of before. This revolution opened an approach in the solution of nonlinear equations that removed the necessity to restrict the analysis to initial linear behavior. It also removed the restriction to “static analysis only”. This means that the traditional assessment of the load carrying capacity on the basis of a quasi static loading process can presently be amended by transient analysis and even replaced by it. Moreover, these advances have now also paved the way to consider non classical definitions of stability loss. In particular, buckling induced by transient loading of short duration is presently studied as a possible potential critical loading case for certain buckling problems that are encountered in practice.


ABSTRACT: Reliable analytical methods that predict the structural integrity and residual strength of aircraft fuselage structures containing cracks are needed to help to understand the behavior of pressurized stiffened shells with damage, so that it becomes possible to determine the safe life of such a shell. Of special importance is the ability to determine under what conditions local failure, once initiated, will propagate. In this paper we shall present a reliable and efficient method for computing the energy release rate for cracks of varying length in a typical stiffened metallic fuselage under general loading conditions. The models used in the simulation are derived from an extensive analysis of a fuselage barrel section subjected to operational flight loads. Energy
release rates are computed as a function of the length of the crack, its location, and the crack propagation mode.

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ABSTRACT: PANDA2 is a computer program for the minimum weight design of stiffened composite, flat or cylindrical, perfect or imperfect panels and shells subject to multiple sets of combined in-plane loads, normal pressure, edge moments and temperature. STAGS is a general nonlinear finite element code that is specifically designed to analyze especially difficult stability problems in shell structures. Weight optimization of stiffened panels can be particularly troublesome when local buckling is allowed to occur in the precollapse state. For these systems, designs may be affected by interaction between local modes, a mechanism that manifests itself as mode jumping and is difficult to characterize. In this paper we describe how in PANDA2 mode jumping is detected and suppressed in optimized panels. Two axially compressed blade stiffened panels optimized by PANDA2 for service in the far postbuckling regime were numerically tested by STAGS. Mode jumping was permitted to occur below the design load in the first panel and suppressed in the second. Results obtained by STAGS are in reasonably good agreement with predictions by PANDA2. The first panel exhibits mode jumping well below the design load. Application of STAGS to this panel reveals that even though the mode jump involves little change in potential energy it generates large amplitude oscillating stresses with significant stress reversal that might well cause fatigue and delamination.

DOI: 10.1007/BF02737118

ABSTRACT: This paper concerns the theory and implementation of a numerical procedure that is capable of solving the collapse process of a structure when it is loaded past its ultimate carrying strength. The procedure is a combination of two generally available methods: A path following method for the quasi static part of the solutions and a transient method for the dynamic part. The simulation of a compression test on a thin walled cylindrical shell with a local imperfection is provided to demonstrate the effectiveness of the strategy employed.

References listed at the end of the paper:
The Netherlands.


ABSTRACT: Oblique line contact algorithms are developed in this research to simulate local buckling around a crack due to crack edges contacting. The contact algorithms are based on a large-displacement and geometrically nonlinear response. A penalty function in terms of the minimum distance between two contacting lines is introduced in the proposed method to determine the contact conditions. The STAGS finite element code is employed to show the results of two cantilevered beams that experience line-to-line contact.


ABSTRACT: The finite strip method has successfully been applied for the calculation of the buckling load of stiffened panels in wing box structures. This article describes an implementation of the finite strip method that extends the scope of the analysis of the determination of the post-buckling stiffness of these panels.


ABSTRACT: Although the first known solution of a buckling problem was given by the outstanding Swiss ‘natural philosopher’ Leonhard Euler (1744), buckling theory as an engineering subject is an outgrowth of a development that was established during the last century. The overview of the present knowledge regarding the computational analysis of buckling problems is here given in the context of the theory's most important historical developments.

ABSTRACT: The buckling behaviour of complete spherical shells and spherical caps is explained and test results are extensively reviewed. The development of the theory up to the point where theoretical and experimental results agree is presented. The treatment is confined to completely elastic material.

References listed at the end of the paper:


ABSTRACT: Explicit analyses of flexural-torsional buckling of open thin-walled FRP beams, local buckling of rotationally restrained orthotropic composite plates subjected to biaxial linear loading and associated
applications of the explicit solution to predict the local buckling strength of composite structures (i.e., FRP structural shapes and sandwich cores), and delamination buckling of laminated composite beams are presented. Based on nonlinear plate theory, of which the shear effect and beam bending-twisting coupling are included, the buckling equilibrium equations of flexural-torsional buckling of pultruded FRP composite I- and channel beams are established using the second variational principle of total potential. The critical buckling loads for different span lengths are measured through experiments and compared with analytical solutions and numerical finite element results. A parametric study is conducted to evaluate the effects of the load location, fiber orientation, and fiber volume fraction on the buckling behavior.

The first variational formulation of the Ritz method is used to establish an eigenvalue problem for local buckling of composite plates elastically restrained along their four edges and subjected to a biaxial linear load, and the explicit solution in terms of rotational restraint stiffness is presented with a unique harmonic shape function. A parametric study is conducted to evaluate the influences of the biaxial load ratio, rotational restraint stiffness, aspect ratio, and flexural-orthotropy parameters on the local buckling stress resultants of various rotationally-restrained plates. The applicability of the explicit solutions of restrained composite plates is illustrated in the discrete plate analysis of two types of composite structures: FRP structural shapes and sandwich cores.

The delamination buckling formulas are derived based on the rigid, semi-rigid, and flexible joint deformation models according to three corresponding bi-layer beam theories (i.e., conventional composite, shear-deformable bi-layer, and interface-deformable bi-layer, respectively). Numerical simulation is carried out to validate the accuracy of the formulas, and the parametric study of the shear effect is conducted to demonstrate the improvement of flexible joint model. The explicit buckling solutions developed facilitate design analysis and optimization of FRP composite structures and provide simplified practical design equations and guidelines for buckling analyses.

References listed at the end of the thesis:


Head, P.R., 1996. Advanced composites in civil engineering - a critical overview at this high interest, low use stage of development, Proceedings of ACMBS, M. El-Badry, ed., Montreal, Quebec, Canada, pp. 3-15.


Loughlan, J, and Ata, M., 1997. The behavior of open and closed section carbon fiber composite beams subjected to constrained...
18:1(42-50).

ABSTRACT: This paper considers the elastic unilateral buckling of rectangular mild steel plates that are restrained elastically and subjected to bending and axial actions. A variational formulation of the Ritz method using linear combinations of harmonic functions for the buckling deformations is used to establish an eigenproblem to determine the plate local buckling coefficients. The motivation for the study is the retrofit of reinforced concrete beams by gluing and then bolting steel plates to the sides of the beam. Such plates, when acting compositely with the concrete beam, are subjected to predominantly bending and axial actions which may cause unilateral local buckling. Whereas the bolts provide complete restraint against buckling at discrete points, the glue may also inhibit local buckling between these nodal points since it acts as a continuous elastic restraint. The influence of the glue stiffness, support conditions and plate proportions on the unilateral buckling of such plates are assessed.


Summary: Aircraft structures, both metallic and composite, are often stiffened with thin-walled sections of
various shapes to resist compression loads efficiently. Analysis of these structures can be challenging, and empirical methods are often used for design purposes. Since initial buckling is not necessarily indicative of structural failure, the analysis must be carried into the post-buckling range, where geometric and material nonlinearities are present. Final failure in this context is called crippling, which corresponds to the maximum load carried by the section.

In this paper, the nonlinear capabilities of MSC Nastran SOL 400 are used to perform post-buckling analysis of graphite/epoxy composite I-section stiffeners. After performing an eigenvalue buckling analysis, initial imperfections in the shape of the buckling modes are applied to the model to start the large displacement analysis. Composite material failures are modeled using the Progressive Failure Analysis (PFA) feature of SOL 400. Results are plotted as load-displacement curves, and crippling failure is defined as the maximum load carried. Results are compared to published test data as well as MIL-HDBK-17 design equations.

References listed at the end of the report:

D.L. Bonanni (Survivability, Structures and Materials Directorate, Naval Surface Warfare Center (formerly David Taylor Research Center), Bethesda, Maryland, USA), “Stability analysis of thick-section composite cylinders under hydrostatic pressure including three-dimensional effects and nonlinear material response”, ASTM STP1185, January 1994

ABSTRACT: Recent studies of thick-section laminated composite materials and structures have suggested that there is a need for three-dimensional (3-D) structural analysis methods which include the nonlinear material response of the constituents. The work described in this paper integrates a 3-D micromechanics-based nonlinear constitutive model for laminated composite materials into 3-D structural analyses performed with the ABAQUS general purpose finite element code. The nonlinear model and its incorporation into ABAQUS are described. The method is demonstrated through 3-D stability analyses of thick, unstiffened AS4/3501-6 carbon/epoxy circular cylinders under external hydrostatic pressure. The results of two-dimensional (2-D) shell finite element analyses of these cylinders are also presented for comparison. The cylinders analyzed are geometrically identical and are subjected to the same loading and boundary conditions. Five different ply layups are considered, including cross-ply, quasi-isotropic, and [±45°]. Modeling the nonlinear material response is found to reduce the predicted cylinder collapse load by up to 50% when layers oriented at ±45° to the cylinder axis are present in the laminate. The role of material nonlinearity in the plane of the laminate versus through-thickness nonlinearity is discussed for the cylinders analyzed.

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ABSTRACT: Postbuckling analysis is essential to predict the capacity of composite plates carrying considerable additional load before the ultimate load is reached, and manufacturing-induced geometric imperfections often reduce the load-carrying capacity of composite structures. A higher-order finite strip method based on the higher-order shear deformation plate theory is developed for postbuckling analysis of laminated composite plates with initial geometric imperfection subjected to progressive end shortening. The arbitrary nature of initial geometric imperfection induced during manufacturing is accounted for in the analysis. Nonlinear equilibrium equations are solved by a Newton-Raphson procedure. Examples of postbuckling analyses of unsymmetric cross-ply, angle-ply, and arbitrary laminates are presented, and the accuracy and performance of the method are examined. The numerical higher-order finite strip method presented can be used as an accurate and efficient tool for postbuckling analysis of imperfect composite plates.

References listed at the end of the paper:


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“Lightweight design for thin-walled cylindrical shell based on action mechanism of bamboo node”, ASME
ABSTRACT: Lightweight design is needed for many engineering structures, but conventional design methods cannot always meet requirements. Natural organisms have developed many types of structures with excellent properties and ingenious construction, and they can provide many new design ideas. In this paper, a thin-walled cylindrical shell, one of the most common structures, is designed to resist buckling based on the study of bionics. First, the structure and function of bamboo node are described, and a statistical analysis of internode length-to-diameter ratio in bamboo is performed to investigate structural characteristics of bamboo node. Then, through buckling analysis of three relevant experimental models, the action mechanism of bamboo node is investigated, and two rules for application of this structure in engineering are proposed. Finally, a bionic design method is introduced, and a lightweight design for a thin-walled cylindrical shell based on this method is presented. A comparison between the bionic shell and a conventional one shows that the weight was reduced by as much as 20.5%.

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“Geometrically Non-linear Finite Element Analysis of Thick Plates and Shells”, Chapter in Elasto-Plastic and Damage Analysis of Plates and Shells, Springer, 2008, pp 77-90, DOI: 10.1007/978-3-540-79351-9_4

ABSTRACT: (none given)

References listed at the end of the paper:


ABSTRACT: An explicit elastic stability analysis for local buckling of fiber-reinforced plastic (FRP) structural shapes is presented. Flange of pultruded FRP wide-flange sections is modeled as a discrete panel with elastic restraint at one unloaded edge and free at the other unloaded edge [restrained-free (RF) condition] and subjected to uniform distributed axial in-plane force along simply supported loaded edges. By considering a linear combination of simply supported-free and clamped-free boundary displacement fields as an interpolation function of the RF buckling, a variational formulation of the Ritz method is used to establish an eigenvalue problem, and a flange critical local buckling coefficient is determined. An explicit solution is obtained for local compressive buckling strength of orthotropic panels with the RF condition and is expressed in term of the coefficient of elastic restraint based on the flexibility of flange-web connection. The explicit predictions are in good agreements with experimental data, exact transcendental solutions, and finite-element analyses for local buckling of FRP wide-flange columns. The formulation developed in this paper is the first attempt in the literature for explicit buckling analysis of orthotropic plates with RF condition and can facilitate the local buckling analysis and design of open FRP structural profiles (e.g., I and channel shapes).

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ABSTRACT: A combined analytical and experimental study of flexural–torsional buckling of pultruded fiber-reinforced plastic (FRP) composite cantilever I-beams is presented. An energy method based on nonlinear plate theory is developed for instability of FRP I-beam, and the formulation includes shear effect and bending–twisting coupling. Three different types of buckling mode shape functions of transcendental function, polynomial function, and half simply supported beam function, which all satisfy the cantilever beam boundary conditions, are used to obtain the eigenvalue solution, and their accuracy in the analysis are investigated in relation to finite element results. Four different geometries of FRP I-beams with cantilever beam configurations and with varying span lengths are experimentally tested under tip loads to evaluate their flexural–torsional buckling response. The loads are applied at the centroid of the tip cross-sections, and the critical buckling loads are obtained by gradually adding weight onto a loading platform. A good agreement among the proposed analytical solutions, experimental testing, and finite element method is obtained, and simplified explicit
formulas for flexural–torsional buckling of cantilever beams with applied load at the centroid of the cross-section are developed. The effects of vertical load position through the cross-section, fiber orientation and fiber volume fraction on buckling behavior are also studied. The proposed analytical solutions can be used to predict the flexural–torsional buckling loads of FRP cantilever beams and to formulate simplified design equations.

References listed at the end of the paper

E. Suhir (Physical Sciences and Engineering Research Division, Bell Laboratories, Murray Hill, NJ 09074 Department of Electrical Engineering, University of California, Santa Cruz, CA 95064 Department of Mechanical Engineering, University of Maryland, College Park, MD 20742 Department of Electronic Materials, Technical University, Vienna, Austria ERS Co., Los Altos, CA 94024), “Elastic stability of a cantilever beam (rod) supported by an elastic foundation, with application to nano-composites”, J. Appl. Mech., Vol. 79, No. 1, 011009, December 2011, DOI: 10.1115/1.4005190

ABSTRACT: A simple analytical (“mathematical”) predictive model is developed with an objective to establish the condition of elastic stability for a compressed cantilever beam (rod) of finite length lying on a continuous elastic foundation. Based on the developed model, practical guidelines are provided for choosing the adequate length of the beam and/or its flexural rigidity and/or the spring constant of the foundation, so that the beam remains elastically stable. The obtained solution can be used, perhaps with some additional assumptions and modifications, for the assessment of the critical force for high-modulus and low-expansion fibers (including nano-fibers) embedded into a low-modulus and high-expansion medium (matrix). Composite systems are often fabricated at elevated temperatures and operated at lower temperature conditions. It is imperative that an embedded fiber remains elastically stable, i.e., does not buckle as a result of the thermal contraction mismatch of its material with the material of the matrix. If buckling occurs, the functional (e.g., thermal) and/or the structural (“physical”) performance of the composite might be compromised.


ABSTRACT: Ring and stringer stiffened perfect and imperfect angle-ply cylindrical shells under combined axial compression and in-plane shear are optimized with a program called PANDA2 for the minimum weight design of stiffened panels, and the optimum designs are then evaluated with use of a general purpose finite element code called STAGS. The good agreement between PANDA2 and STAGS predictions for the nonlinear collapse of imperfect stiffened shells justifies the use of PANDA2 for preliminary design. A new PANDA2 processor called STAGSUNIT automatically generates STAGS input files for cylindrical panels and shells with both stringers and rings that have various open cross sections such as Blades, Zees, Jays, Tees and Is. In STAGSUNIT the edge conditions are formulated so that STAGS models of subdomains of a long cylindrical shell with many stiffeners can be constructed that do not have artificial prebuckling stress concentrations near the edges that might significantly affect predictions of bifurcation buckling and nonlinear collapse of the subdomain. Many STAGS models of optimized shells and subdomains of shells with Blade, Zee, and Tee stiffening are generated and explored, both with respect to linear bifurcation buckling and nonlinear collapse. The behavior of shells with an initial imperfection in the form of a general buckling mode of the imperfect shell is described from a physical point of view. Some difficulties encountered during this project are described.


ABSTRACT: The PANDA2 computer program generates minimum-weight designs of ring and stringer stiffened flat or cylindrical composite panels subjected to multiple sets of load combinations. PANDA2 is described with emphasis on the many different stress and buckling constraints that can affect the evolution of a design during optimization cycles, on the way that imperfections are treated, on certain difficulties that
imperfections may cause during optimization cycles, and on difficulties encountered during attempts to evaluate optimum designs with the use of the STAGS general purpose finite element program. Details are given on how PANDA2 determines the effect of an initial buckling modal imperfection on the load bearing capability of a ring and stringer stiffened cylindrical shell. Numerical results pertain to a metallic cylindrical shell with external T-shaped stringers and external T-shaped rings subjected to combined axial compression, external pressure and in-plane shear (torque). The maximum allowable stress is set very high so that stress constraints do not affect the evolution of the global optimum design in this example. Minimum-weight designs are determined for this shell with an initial imperfection in the form of the critical general buckling mode. Modifications to PANDA2 are described which overcome some of the difficulties associated with the determination of a global optimum design in the presence of an initial general buckling modal imperfection. Further modifications to PANDA2 are described which lead to less conservative global optimum designs than was previously the case. The optimum designs obtained by PANDA2 are evaluated by comparisons with predictions from STAGS for various finite element models generated automatically with a PANDA2 processor called STAGSUNIT. The agreement between PANDA2 and STAGS predictions for a global optimum design obtained by PANDA2 is good enough to qualify PANDA2 for the optimum design of imperfect stiffened cylindrical panels and shells under combined loads.


ABSTRACT: The results of an analytical study of the nonlinear response of stiffened fuselage shells with long cracks are presented. The shells are modeled with a hierarchical modeling strategy and analyzed with a nonlinear shell analysis code that maintains the shell in a nonlinear equilibrium state while the crack is grown. The analysis accurately accounts for global and local structural response phenomena. Results are presented for various combinations of internal pressure and mechanical loads, and the effects of crack orientation on the shell response are described. The effects of combined loading conditions and the effects of varying structural parameters on the stress-intensity factors associated with a crack are presented.

References listed at the end of the paper:
Young, Richard D. (1) and Rankin, Charles C. (2)
(1) Lockheed Martin Engineering and Science Services, Hampton, Virginia
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ABSTRACT: Advanced modeling and analysis capabilities of a state-of-the-art general purpose finite element code, developed for nonlinear structural analysis of launch vehicles, are described. In particular, the application of these capabilities to nonlinear analyses of the new Space Shuttle superlightweight external liquid-oxygen tank are presented that can be used as a guide for conducting similar analyses on future launch vehicles. A typical prelaunch loading condition with combined thermal and mechanical loads is considered, and applications of the advanced modeling and analysis capabilities to linear bifurcation buckling and nonlinear static analyses are presented. The results for this problem illustrate a localized short-wavelength bending response, and show that a high-fidelity model is required to represent the behavior accurately. A mesh refinement strategy is presented that is based on the linear bifurcation buckling analyses and does not require respecification of the shell wall properties and load. Specifically, mesh refinement is simplified by using user-written subroutines to describe the spatial distribution of complex shell wall properties and loading conditions.

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ABSTRACT: Finite element models of sandwich structures are often based on classical sandwich theory which reduces the essentially three-dimensional composite — a combination of two high strength faces separated by a light weight core — to a two-dimensional, deformable reference surface to which certain appropriate stiffness properties against stretch, bending and transverse shear are attached. The simplification introduced in this way is well established, but it suffers from a number of drawbacks that restricts its range of applicability rather severely. The drawbacks concern among others, the kinematic and dynamic boundary conditions that prohibit a realistic application of the loading along the edges. They also concern the inability of this model to study local effects such as buckling of the faces. In the present paper, we demonstrate how, with a relatively simple means, a sandwich model can be introduced that does not suffer from the deficiencies mentioned above. Moreover, this improved model provides the possibility to study the detrimental effect of delamination of the faces, and/or, decohesion zones between the core and faces, on the buckling strength of sandwich compression panels. The modification proposed here makes use of existing shell finite elements that are standard in many finite element codes. These shell elements are used to model the deformation of the faces of the sandwich, while the coupling between the two shell components is carried out by applying an appropriate penalty function that represents the deformation of the core. In this paper, we describe this model in some detail and solve an example problem involving the buckling of a sandwich plate with a partially debonded face plate.

P.J. Denrijer and E. Riks, “A finite element analysis of cracks in a thin walled cylinder under internal pressure”, (no publisher or date given by ProQuest-CSA, 1987?)
ABSTRACT: Finite element models for the analysis of the behavior of longitudinal cracks in a pressurized thin
walled cylindrical shell were defined with the STAGSC-1 finite element code and used to study the possibilities of an analysis of cracks present in stiffened cylinders. In contrast to the problem of a crack in a flat plate in tension, the problem of a crack in a cylinder is governed by geometrical nonlinear effects from the onset. This is clearly brought out by the analysis results. They show that for cracks with a large aspect ratio, the linear theory grossly overestimates the intensity of the crack tip singularity. The results also show that the finite element method holds considerable promise in this area of crack mechanics. This is illustrated by the solution of a problem which concerns a centrally cracked plate loaded in the post buckling range.

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ABSTRACT and PARTIAL INTRODUCTION:
This paper discusses some computational tools, recently developed, that are useful in the assessment of the residual strength of fuselage shells damaged by through cracks.

1. Introduction
Fuselages can accumulate damage in the form of through cracks in the outer containment shell. The prediction of the way these cracks propagate under service loads is therefore an important issue in the assessment of the residual strength of such a shell. This paper is focused on some of the tools of analysis recently developed that are capable to assess the effect of this type of damage.

A through crack in a pressurized shell is known to be dominated by the following influence factors: (i) the curvature, which is the principal reason the crack faces bulge out; (ii) a geometrically nonlinear effect that usually, but not always, alleviates crack tip loading; and, (iii) the ductility of the material, so that a plastic zone develops in front of the crack tip and absorbs a part of the energy that must be supplied to force the crack to advance.

References listed at the end of the paper:
ABSTRACT: The capability of the computer program PANDA2 to generate minimum-weight designs of stiffened panels and cylindrical shells is enhanced to permit the adding of substiffeners with rectangular cross sections between adjacent major stringers and rings. As a result many new buckling margins exist that govern buckling over various domains and subdomains of the doubly stiffened panel or shell. These generally influence the evolution of the design during optimization cycles. The substiffeners may be stringers and/or rings or may form an isogrid pattern. The effects of local, inter-ring, and general buckling modal imperfections can be accounted for during optimization. Perfect and imperfect cylindrical shells with external T-shaped stringers and T-shaped rings and with and without substrings and subrings and under combined axial compression, external pressure, and in-plane shear are optimized by multiple executions of a "global" optimizer called SUPEROPT. It is found that from the point of view of minimum weight there is little advantage of adding substiffeners. However, with substiffeners present the major stringers and rings are spaced farther apart at the optimum design than is so when there are no substiffeners. The weight of a cylindrical shell with substiffeners is much less sensitive to the spacing of the major T-shaped stringers than is the case for a cylindrical shell without substiffeners. The optimum designs obtained by PANDA2 are evaluated by comparisons with buckling loads obtained from a general-purpose finite element program called STAGS. Predictions from STAGS agree well with those from PANDA2.


ABSTRACT: (Cannot cut and paste)

ABSTRACT: Results of a geometrically nonlinear finite element parametric study to determine curvature correction factors or “bulging factors” that account for increased stresses due to curvature for longitudinal and circumferential cracks in unstiffened pressurized cylindrical shells are presented. Geometric parameters varied in the study include the shell radius, the shell wall thickness, and the crack length. The major results are presented in the form of contour plots of the bulging factor as a function of two nondimensional parameters: the shell curvature parameter, Lambda, which is a function of the shell geometry, Poisson’s ratio, and the crack length; and a loading parameter, Eta, which is a function of the shell geometry, material properties, and the applied internal pressure. These plots identify the ranges of the shell curvature and loading parameters for which the effects of geometric nonlinearity are significant. Simple empirical expressions for the bulging factor are then derived from the numerical results and shown to predict accurately the nonlinear response of shells with longitudinal and circumferential cracks. The numerical results are also compared with analytical solutions based on linear shallow shell theory for thin shells, and with some other semi-empirical solutions from the literature, and limitations on the use of these other expressions are suggested.


ABSTRACT: The results of an experimental and analytical study of the effects of initial imperfections on the buckling and postbuckling response of unstiffened thin-walled compression-loaded graphite-epoxy cylindrical shells are presented. The shells considered in the study have four different shell-wall laminates and two different shell-radius-to-thickness ratios. The shell-wall laminates include two different orthotropic laminates and two different quasi-isotropic laminates. The shell-radius-to-thickness ratios include shell-radius-to-thickness ratios equal to 100 and 200. The results identify the effects of traditional and nontraditional initial imperfections on the nonlinear response characteristics and buckling loads of the shells. The traditional imperfections include the geometric shell-wall mid-surface imperfections that are commonly discussed in the literature on thin shell buckling. The nontraditional imperfections include shell-wall thickness variations, local shell-wall ply-gaps associated with the fabrication process, shell-end geometric imperfections, nonuniform applied end loads, and variations in the boundary conditions including the effects of elastic boundary conditions. A high-fidelity nonlinear shell analysis procedure that accurately accounts for the effects of these traditional and nontraditional imperfections on the nonlinear response characteristics and buckling loads of the shells is described. The analysis procedure includes a nonlinear static analysis that predicts the stable response characteristics of the shells, and a nonlinear transient analysis that predicts the unstable response characteristics. The results of a local shell-wall stress analysis used to estimate failure stresses are also described.


ABSTRACT: A parametric study of the effects of test-fixture-induced initial prestress and elastic edge restraints on the prebuckling and buckling responses of a compression-loaded, quasi-isotropic curved panel is presented.
The numerical results were obtained by using a geometrically nonlinear finite element analysis code with high-fidelity models. The results presented show that a wide range of prebuckling and buckling behavior can be obtained by varying parameters that represent circumferential loaded-edge restraint and rotational unloaded-edge restraint provided by a test fixture and that represent the mismatch in specimen and test-fixture radii of curvature. For a certain range of parameters, the panels exhibit substantial nonlinear prebuckling deformations that yield buckling loads nearly twice the corresponding buckling load predicted by a traditional linear bifurcation buckling analysis for shallow curved panels. In contrast, the results show another range of parameters exist for which the nonlinear prebuckling deformations either do not exist or are relatively benign, and the panels exhibit buckling loads that are nearly equal to the corresponding linear bifurcation buckling load.

Overall, the results should also be of particular interest to scientists, engineers, and designers involved in simulating flight-hardware boundary conditions in structural verification and certification tests, involved in validating structural analysis tools, and interested in tailoring buckling performance.

References listed at the end of the paper:


ABSTRACT: The development of DISDECO, the Delft Interactive Shell DEsign COde is described. The purpose of this project is to make the accumulated theoretical, numerical and practical knowledge of the last 25 years or so readily accessible to users interested in the analysis of buckling sensitive structures. With this open ended, hierarchical, interactive computer code the user can access from his workstation successively programs of increasing complexity. The computational modules currently operational in DISDECO provide the
prospective user with facilities to calculate the critical buckling loads of stiffened anisotropic shells under combined loading, to investigate the effects the various types of boundary conditions will have on the critical load, and to get a complete picture of the degrading effects the different shapes of possible initial imperfections might cause, all in one interactive session. Once a design is finalized, its collapse load can be verified by running a large refined model remotely from behind the workstation with one of the current generation 2-dimensional codes, with advanced capabilities to handle both geometric and material nonlinearities.


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ABSTRACT: A FORTRAN IV, large capacity, computer program has been developed to determine collapse loads and bifurcation loads for linear and nonlinear prebuckling behavior for fiber-reinforced, laminated, rectangular plates and panels under general loading systems and boundary conditions. The program is based on the principle of total potential energy and uses finite-differences in the discretization process. Whole-station spacing has been used to calculate the strain energy associated with an area-element and an orthogonal finite-difference grid that provides for variable spacings in perpendicular directions is incorporated. Numerical results are presented that compare favorably with results obtained via the general computer program STAGS. Other numerical results are presented that illustrate the types of boundary conditions, applied loads, cut-outs and initial geometric imperfections that can be handled by the present program. A brief study of the effect of panel construction and initial geometric imperfections on the buckling behavior of fiber-reinforced panels is presented.


ABSTRACT: Attention is given to the structural efficiencies obtainable with optimally designed graphite/epoxy wing rib panel configurations that are potentially economically manufacturable. Some ribs are commonly used as fuel cell closeout panels, and are accordingly subjected to out-of-plane pressure loads in addition to the in-plane axial compressive and shear loads resulting from the wing loading. The present minimum-weight panel designs satisfy buckling and strength constraints for wing rib panels subjected to a wide range of combined load conditions.


ABSTRACT: Development of an algorithm to perform the optimal sizing of buckling resistant, imperfect, anisotropic ring-stiffened cylinders subjected to axial compression, torsion, and internal pressure is presented. An axisymmetric, geometrically nonlinear prebuckling equilibrium configuration is assumed and both stress and stability constraints are considered. The enforcement of stability constraints is treated in a way that does not require any eigenvalue analysis. Case studies performed using a combination of penalty function and feasible direction optimization methods indicate that the presence of the axisymmetric initial imperfection in the cylinder wall can significantly affect the optimal designs. Weight savings associated with the addition of two rings to the unstiffened cylinder and/or the addition of internal pressure is substantial when torsion makes up a significant fraction of the combined load state.

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17. Simitses, G.J.; Giri, J. 1978: Minimum weight design of stiffened cylinders subject to torsion combined with axial compression and without lateral pressure. Comp. & Struct. 8, 19–30


ABSTRACT: An automated procedure for designing minimum-weight composite panels subject to a local damage constraint under tensile loading was developed. A finite element program based on linear elastic fracture mechanics for calculating stress intensity factors (SIF) was incorporated in the design cycle. Panel fracture toughness was obtained by using a strain based criterion. A general purpose mathematical optimization algorithm was used for the weight minimization. Analytical sensitivity derivatives of the SIF employing the adjoint variable technique was used to enhance the computational efficiency of the procedure. Design results for both unstiffened and stiffened plates are presented.
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ABSTRACT: An experimental and analytical study was carried out to investigate the buckling and failure characteristics of stiffened compression-loaded panels with holes, and to assess the validity of analytical models used for the design of such panels. Graphite-epoxy panels with four equally spaced blade stiffeners were fabricated with a laminate stacking sequence optimally designed for stiffened panels without holes. Panels with different hole sizes and panels without holes were tested. Failure of all panels initiated at or near the stiffeners, in regions with severe local bending gradients. Finite element analysis using a quarter-panel model with boundary conditions to simulate the experiment was used to predict the prebuckling and buckling behavior. Analytical results correlate well with experimental results.

ABSTRACT: Derivatives of buckling loads of stiffened panels with respect to ply thicknesses are easy to calculate. Consequently, such derivatives are often available in computer programs that calculate buckling loads of composite structures. These derivatives can be used to construct approximations of the dependence of the buckling load on ply thicknesses. The present work demonstrates the use of derivatives of buckling loads with respect to ply thicknesses to approximate the effects of changes in stacking sequence and ply orientations on buckling load of a laminate. Examples of unstiffened and stiffened panels are used to demonstrate the effectiveness of the proposed approximation.

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ABSTRACT: Buckling and postbuckling analyses of circular laminated composite plates with delaminations are presented. An axisymmetric finite element model based on a layer-wise laminated composite plate theory is developed to formulate the problem. Geometric nonlinearity in the sense of von Kármán and imperfections in the form of initial global deflection and initial delamination openings are included. A simple contact algorithm which precludes the physically inadmissible overlapping between delaminated surfaces is proposed and incorporated into the analysis. Numerical results are obtained addressing the effects of the initial imperfections, the number of delaminations and their sizes on the critical buckling load and buckling mode shapes, as well as postbuckling responses.

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K. Chauncey Wu (1), Zafer Gürdal (2) and James H. Starnes, Jr. (1)
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ABSTRACT: Results of an analytical and experimental study to characterize the structural response of two compression-loaded variable stiffness composite panels are presented and discussed. These variable stiffness panels are advanced composite structures, in which tows are laid down along precise curvilinear paths within each ply and the fiber orientation angle varies continuously throughout each ply. The panels are manufactured from AS4/977-3 graphite-epoxy pre-preg material using an advanced tow placement system. Both variable stiffness panels have the same layup, but one panel has overlapping tow bands and the other panel has a constant-thickness laminate. A baseline cross-ply panel is also analyzed and tested for comparative purposes. Tests performed on the variable stiffness panels show a linear prebuckling load-deflection response, followed by a nonlinear response to failure at loads.

References listed at the end of the paper:
The introduction of advanced tow-placement machines has made it possible to fabricate novel variable-stiffness composite structures where the fiber orientation angle varies continuously within each ply and throughout the structure. This manufacturing capability allows designers of composites to use the fiber orientation angle as design variable in their analysis, not only for each ply as with conventional composites, but at each point within a ply. Consequently, beyond the improvements that can be accomplished with traditional composites with straight fibers, the directional material properties of composites can be fully exploited to improve the laminate performance. In this paper, design tailoring for the pressure pillowing problem of a fuselage panel bounded by two frames and two stringers is addressed using tow-placed steered fibers. The panel is modeled as a two-dimensional plate loaded by out-of-plane pressure and in-plane loads. A Python-ABAQUS script is developed to perform the linear and geometrically nonlinear finite element analyses of variable-stiffness panels. The design objective is to determine the optimal fiber paths within each ply of the laminate for maximum load carrying capacity and for maximum buckling capacity. Simulated-annealing algorithm is used to solve the optimization problems. Optimal designs are obtained for different loading cases and boundary conditions. As a basis of comparison, a practical constant-stiffness quasi-isotropic design is used. Numerical results indicate that by placing the fibers in their optimal spatial orientations within each ply, the load carrying capacity and the buckling load of the structure can be substantially improved compared with traditional straight fiber designs. It is shown that laminates optimized for maximum failure load have buckling loads that are higher than those for quasi-isotropic laminates. On the other hand, laminates optimized for maximum buckling load fail at load levels lower than laminates optimized for maximum failure load. However, the failure loads of those laminates may still be higher than those for their quasi-isotropic counterparts.

References listed at the end of the paper:


ABSTRACT: There is a renewed interest in grid-stiffened composite structures; they are not only competitive with conventional stiffened constructions and sandwich shells in terms of weight but also enjoy superior damage tolerance properties. In this paper, both global and local structural instabilities are investigated for grid-stiffened composite panels using homogenization theory. Characteristic cell configurations with periodic boundary constraints are employed for orthogrid- and isogrid-stiffened shells in order to smear the stiffened panel into an equivalent unstiffened shell. Homogenized properties corresponding to classical lamination theory are obtained by matching the strain energy of the stiffened and equivalent cells. Global buckling analysis is carried out based on the homogenized shell properties. Bloch wave theory is adopted to calculate the local buckling load of grid-stiffened shells, where the interaction of adjacent cells is fully taken into account. Moreover, instead of considering skin buckling and stiffener crippling separately, as is commonly done, the skin and stiffeners are assembled together at the level of the characteristic cell. The critical instabilities can be captured whether they are related to the skin or stiffener or their interaction. The proposed combination of global/local models can also be used to predict the material failure of a structure. Numerical examples of orthogrid- and isogrid-stiffened isotropic panels show that the local buckling loads predicted by the proposed method match finite element calculations better than semi-analytical methods based on assumptions and idealisations. The proposed method is further validated using typical configurations of flat composite panels and circular composite cylinders.

References cited at the end of the paper:

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ABSTRACT: The model problem proposed to study the buckling of stratified geological layers consists of a linearly elastic plate, capable of accommodating finite rotations, resting over an inviscid and buoyant fluid. The Lyapunov–Schmidt–Koiter decomposition is applied to construct the bifurcated equilibrium solutions. The asymptotic analysis of the post-buckling reveals a decrease in the magnitude of the lateral compressive force during an overall shortening of the stratified structure. Buckling and post-buckling are not influenced by the presence of a vertical stress gradient in the elastic plate.


ABSTRACT: The aim of this work is to investigate the influence of axial load uncertainties on the nonlinear vibrations of simply-supported cylindrical shells. The axial load is composed by both harmonic deterministic and random terms; the random term depends on the parameters of the harmonic deterministic load. Donnell’s nonlinear shallow shell equations in terms of the in-plane and transversal displacements are used to study the nonlinear vibrations of the shell. To discretize the partial differential equations of motion, first, a general expression for the transversal displacement is obtained by a perturbation procedure which identifies all modes that couple with the linear modes through the quadratic and cubic terms in the equations of motion. Then, a particular solution is selected which ensures the convergence of the response up to very large deflection. Finally, the in-plane displacements are obtained as a function of the transversal displacement by solving the in-plane equations analytically. So, the proposed solution satisfies all boundary, continuity and symmetry conditions. Substituting the modal expansion of the transversal displacement into the equation of motion and applying the Galerkin’s method, a discrete system in time domain is obtained. Several numerical strategies are used to study the nonlinear behavior of the shell under an axial load with uncertainties. Special attention is given to the influence of the random term on the parametric instability and escape loads.

References listed at the end of the paper:
ABSTRACT: Cylindrical shells exhibit a dense frequency spectrum, especially near the lowest frequency range. In addition, due to the circumferential symmetry, frequencies occur in pairs. So, in the vicinity of the lowest natural frequencies, several equal or nearly equal frequencies may occur, leading to a complex dynamic behavior. So, the aim of the present work is to investigate the dynamic behavior and stability of cylindrical shells under axial forcing with multiple equal or nearly equal natural frequencies. The shell is modelled using the Donnell nonlinear shallow shell theory and the discretized equations of motion are obtained by applying the Galerkin method. For this, a modal solution that takes into account the modal interaction among the relevant modes and the influence of their companion modes (modes with rotational symmetry), which satisfies the boundary and continuity conditions of the shell, is derived. Special attention is given to the 1:1:1:1 internal resonance (four interacting modes). Solving numerically the governing equations of motion and using several tools of nonlinear dynamics, a detailed parametric analysis is conducted to clarify the influence of the internal resonances on the bifurcations, stability boundaries, nonlinear vibration modes and basins of attraction of the structure.

References listed at the end of the paper:

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ABSTRACT: In recent papers, the authors have presented Generalized Beam Theory (GBT) formulations specifically designed for performing efficient (i) linear analyses of steel-concrete composite bridges [1] and (ii) elastoplastic collapse analyses of thin-walled steel members [2, 3]. This paper presents an extension of these previous formulations that includes non-linear reinforced concrete material behaviour, aiming at analysing, accurately and efficiently, steel-concrete composite beams. In particular, steel beam and rebar plastification is implemented, together with concrete cracking(crushing and shear-lag effects. Several illustrative examples are
presented and discussed. For validation and comparison purposes, results obtained with shell/solid finite element models are provided.

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Kazi Md Abu Sohel, Jat Yuen Richard Liew and Min Hong Zhang (Dept. of Civil Engineering, National University of Singapore), “Analysis and design of steel-concrete composite sandwich systems subjected to extreme loads”, Frontiers of Structural and Civil Engineering, Vol. 5, No. 3, pp 278-293, 2011
DOI: 10.1007/s11709-011-0120-z

ABSTRACT: This paper presents the design guide based on analytical, numerical and experimental investigation of Steel-concrete-steel (SCS) sandwich structural members comprising a lightweight concrete core with density ranging from 1300 to 1445 kg/m³ subjected to static, impact and blast loads. The performance of lightweight sandwich members is also compared with similar members with normal weight concrete core and ultra high strength concrete core (f_c = 180 MPa). Novel J-hook shear connectors were invented to prevent the separation of face plates from the concrete core under extreme loads and their uses are not restricted by the concrete core thickness. Flexural and punching are the primary modes of failure under static point load. Impact test results show that the SCS sandwich panels with the J-hook connectors are capable of resisting impact load with less damage in comparison than equivalent stiffened steel plate panels. Blast tests with 100 kg TNT were performed on SCS sandwich specimens to investigate the key parameters that affect the blast resistance of SCS sandwich structure. Plastic yield line method is proposed to predict the plastic capacity and post peak large deflection of the sandwich plates. Finally, an energy balanced model is developed to analyze the global behavior of SCS sandwich panels subjected to dynamic load.

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ABSTRACT: This paper deals with optimization of the buckling load for laminated composite structures. A new methodology has been developed where thermal residual stresses introduced in the manufacturing process are included in the buckling analysis. The thermal effects are also included in the calculation of the buckling load sensitivities, and it is therefore possible to “tailor” the thermal residual stresses in order to increase the buckling load. Rectangular plates and circular cylindrical shells subjected to axial compression are considered. The structures are optimized twice; the first time the thermal residual stresses are ignored in the optimization, and the second time the thermal residual stresses are included in the optimization. These two sets of optimizations give two important results. Firstly, it is possible to increase the buckling load for the structures significantly when the thermal residual stresses are taken into account. Secondly, structures which have been optimized ignoring the effects of thermal residual stresses, may have a buckling load which is much less than expected when the effects of the thermal residual stresses are included.


PARTIAL INTRODUCTION: When considering a structural system, perhaps one of the crucial problems facing the designer is the identification of those phenomena that are important. For example, there are quite different concerns if the predominant loads are compressive rather than tensile; compressive loads may lead to crushing, whereas tensile load may lead to necking phenomena. If materials are ductile or brittle there are different concerns; questions of yielding and flow may dominate for ductile materials, whereas flaw sensitivity may dominate for brittle materials. This is the context within which buckling or stability considerations should be taken. The conditions that always give the warning when a stability analysis may be necessary can be summarized quite easily: the structure must be subjected to compressive loads, and the structure must be thin. As contradictory as it may seem, these criteria are very precise and yet often ambiguous. Although thinness is absolutely essential for buckling, how “thin” is thin may be debatable. In a similar manner, identifying compressive loading situations may seem straightforward. However, some care must be exercised because a variety of loading situations may lead to compression. For example, shear buckling is quite common; in terms of principal stresses a pure shear results in a biaxial stress state with tensile and compressive principal normal stresses. It is the compressive component that causes buckling….

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ABSTRACT: The optimal design of composite sandwich plates in which the facesheets are composed of a carbon fiber/epoxy net is considered. The objective of the work is to obtain minimum mass designs while maintaining constraints on the first natural frequency and selected facesheet stress components. The facesheets are assumed to be composed of an orthotropic net of unidirectional composite fiber strips and the optimal
design (the least mass design) is achieved by changing the strip widths and the spacings between them. It is demonstrated that varying the spatial fiber strip distribution can lead to significant structural advantages; in the example presented, a 32% facesheet mass reduction is achieved.


ABSTRACT: Buckling around an interfacial crack in a clamped sandwich plate is studied. The layers of the plate are assumed to be linearly viscoelastic, isotropic, and homogeneous. The investigations are carried out within the framework of a piecewise homogeneous body model with the use of a three-dimensional linearized theory of stability. The corresponding boundary value problems are solved numerically by employing the FEM and the Laplace transform. The calculated critical times are presented for various problem parameters. In this case, the upper and lower layers are assumed to be viscoelastic and are described by Rabotnov operators, whereas the midlayer is regarded as purely elastic. The influence of rheological parameters on the critical time is also analyzed.

References listed at the end of the paper:
SUMMARY: A thin solid film or coating bonded to a solid substrate may be in a state of residual stress due to mismatch in thermal expansion coefficient between the film and the substrate or other effects. If the residual stress is compressive, the tendency for film buckling is suppressed by the relatively high stiffness of the substrate. However, at a flaw in the interfacial bonding between the film and substrate, buckling of the film can and does occur. The focus here is on the process of delamination buckling under these circumstances, including dynamic effects. For an interfacial defect of a certain size, the compressive force in the film may exceed the buckling load, in which case the buckling process is inherently dynamic. Both cases of plane strain and axially symmetric deformation are considered, and propagation of the buckle is permitted provided that an energy balance separation condition is satisfied. Post-bifurcation response of the film is described by means of the von Karman plate theory. Hamilton’s principle is applied to obtain an approximate representation of the deformation in terms of two generalized coordinates, namely, the midpoint deflection of the buckled region and the size of the buckled region. Dynamic effects included are the transient deformation from the bifurcation state to the post-buckling configuration and the possibility of buckle nucleation due to waves impinging on the film from within the substrate. Histories of transient buckle deflection and buckle width are determined for representative material parameters.

References listed at the end of the paper:

ABSTRACT: We present the mechanics of folding surface-layer wrinkles on a soft substrate, i.e. inter-touching of neighbouring wrinkle surfaces without forming a cusp. Upon laterally compressing a stiff layer attached on a finite-elastic substrate, certain material nonlinearities trigger a number of bifurcation processes to form multi-mode wrinkle clusters. Some of these clusters eventually develop into folded wrinkles. The first bifurcation of the multi-mode wrinkles is investigated by a perturbation analysis of the surface-layer buckling on a pre-stretched neo-Hookean substrate. The post-buckling equilibrium configurations of the wrinkles are then trailed experimentally and computationally until the wrinkles are folded. The folding process is observed at various stages of wrinkling, by sectioning 20–80 nm thick gold films deposited on a polydimethylsiloxane substrate at a stretch ratio of 2.1. Comparison between the experimental observation and the finite-element analysis shows that the Ogden model deformation of the substrate coupled with asymmetric bending of the film predicts the folding process closely. In contrast, if the bending stiffness of the film is symmetric or the substrate follows the neo-Hookean behaviour, then the wrinkles are hardly folded. The wrinkle folding is applicable to construction of long parallel nano/micro-channels and control of exposing functional surface areas.

References listed at the end of the paper:
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ABSTRACT: The aim of this chapter is to review the studies on buckle delamination in compressively stressed thin films over substrates by pulling together experimental and theoretical analysis. The general phenomena shown in delamination buckles of compressively stressed films were discussed from the onset to propagation over the substrates. The experimental observations were characterized by the delamination conditions and buckle morphologies. Then, the related mechanics for buckle delamination were provided with a theoretical solution for simple buckle configurations and a numerical solution for nonlinear buckle. Based on the experimental and theoretical analysis, the buckle configuration was applied to fluidic channels by precisely controlling buckle width within the desired area by adjusting interface adhesion.

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K.G. Muthurajan, K. Sankaranarayanasamy, S.B. Tiwari and B. Nageswara Rao, 2006. Post-buckling of a Thin Film Strip Delamination in a Composite Laminate. Trends in Applied Sciences Research, 1: 48-60. ABSTRACT: Studies are made to understand the delamination growth of general laminates with general loading conditions. Post-buckling solutions are obtained for a laminate with clamped ends applicable to thin film strip delamination in a base laminate under uniform membrane loads. The strain energy release rate at the crack-tip (G) is derived in terms of the critical equivalent base laminate strain at the onset of the buckling ($\epsilon^*_{cr}$) and the applied equivalent strain ($\epsilon^*$). It is also expressed in terms of the maximum amplitude ($W_{max}$) of the delaminated layer. A Griffith-type fracture criterion with constant specific fracture energy ($G_c$) of the material is used to govern the delamination growth. The stability characteristics of the delamination growth are discussed. The maximum amplitude ($W_{max}$) of the delaminated layer increases with the applied load without enhancement in the length of the delamination for the values of G less than $G_c$. Initiation of the delamination growth can be expected when the value of G is very close to $G_c$. References listed at the end of the paper:

Haitao Han, Zixing Lu and Jordan Zhen Zhang (School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, 100191, Beijing, People’s Republic of China), “Solutions of beam-shaped-function for analysis of composite plates with embedded delaminations”, Archive of Applied Mechanics, Vol. 82, No. 4, pp 573-589, April 2012

ABSTRACT: Based on beam-shaped-function, the analytical solution for composite plates with arbitrary embedded delaminations is presented. The deflection function of the delaminated plate is composed by those of beams with the corresponding loading and support conditions, which can be easily and accurately derived from the beam analysis, and the deflection amplitude is derived by the minimum potential energy principle. The closed form solutions of displacements, stresses, and energy release rate of a composite plate containing an arbitrarily embedded rectangular delamination are obtained and compared with the three-dimensional finite element results to validate the accuracy of this present method. Furthermore, the influences of delamination depth, length, central position, and modulus mismatch ratio ($E_1/E_2$) of the upper and lower sublamine on the energy release rate are discussed.

References listed at the end of the paper:

ABSTRACT: Taking the longitudinal deformation into consideration, a two-dimensional beam theory is proposed, and a new layered beam model is established subsequently for composite laminates with multiple through-the-width delaminations. The undelaminated portion is regarded as separate beams along the layer interfaces, and the interface continuities are satisfied using the generalized variational principle. Comparisons of the present analytical solutions with three-dimensional finite element results and classical beam model solutions are made to verify the accuracy and efficiency of the present model. The effects of the geometrical parameters of the delamination on the deflection and the energy release rate are discussed.


ABSTRACT: Results related to the buckling delamination of elastic and viscoelastic composite plates are reviewed and analyzed. They have been obtained during the last fifteen years by the author and his students. The plates contain cracks whose faces have initial infinitesimal imperfections. The evolution of the imperfections under compression of the plates is studied, and the values of critical parameters are determined from a criterion of initial imperfection. The study is performed with the use of 3D geometrically nonlinear field equations. In the present paper, the historical background of the problems is outlined considered, general remarks about the field equations and solution method are made, and problems related to the plane strain state are reviewed.

References listed at the end of the paper:

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ABSTRACT: In this paper, the formation of buckling and delamination of sandwiched stacking of Ti/Cu/Si thin film are investigated. The crystallization structures, the composition of the Cu/Ti thin films, and the surface morphology are measured during annealing. The results show that the solid-phase reaction between Cu and Ti occurs at the interface. Buckling is initiated in the thin film annealed at 600°C. The volume expansion promotes the buckling and further produces microcracks. With increasing volume expansion, there are cavities formed in the middle layer when the annealing temperature is up to 700°C. Finally, thin film is delaminated from the substrate.

References listed at the end of the paper:


ABSTRACT: Instability failure mode of nearly cylindrical sandwich shell was investigated by theoretical calculation. Finite Element Analysis and finally verified by two test specimens. During the test, information regarding snap-through, buckling mode and post buckling behaviour were collected. These indications were obtained by using the F/S method.

PARTIAL INTRODUCTION: The instability and the failure mode of nearly cylindrical sandwich shells, loaded in torsion, were investigated by theoretical calculation, Finite Element Analysis and verified by three parametric test specimens. Limited studies on composite wing boxes have been reported (Ref. 1-3), but they are all for solid laminate skins and none for thin composite sandwich shell skins. The purpose of this work was to develop a method for the analysis for the prediction of instability (buckling) and collapse (failure) of lightweight sandwich shells. The results are to be used in the design of GA (general aviation) structures.

References listed at the end of the paper:

Roberto Vitali (1), Oung Park (1), Raphael T. Haftka (1), Bhavani V. Sankar (1) and Cheryl A. Rose (2) (1) University of Florida Department of Aerospace Engineering, Mechanics and Engineering Science 231 Aerospace Building, P.O. Box 116250 Gainesville, FL 32611-6250 (2) NASA Langley Research Center Hampton, VA 23681-0001

ABSTRACT: The paper describes a design study for the structural optimization of a typical bay of a blended wing body transport. A hat stiffened laminated composite shell concept is used in the design. The geometry of the design is determined with the PANDA2 program, but due to the presence of varying axial loads, more accurate analysis procedure is needed. This is obtained by combining the STAGS finite element analysis program with response surface approximations for the stresses and the buckling loads. The design procedure results in weight savings of more than 30 percent, albeit at the expense of a more complex design. The response surface approximations allow easy coupling of the structural analysis program to the optimization program in
the widely available Microsoft EXCEL spreadsheet program. The response surface procedure also allows the optimization to be carried out with a reasonable number of analyses. In particular, it allows combining a large number of inexpensive beam-analysis stress calculations with a small number of the more accurate STAGS analyses.

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Oung Park (1), Raphael T. Haftka (1), Bhavani V. Sankar (1), James H. Starnes, Jr. (2), and Somanath Nagendra (3)
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ABSTRACT: A combined analytical and experimental study of a blade-stiffened composite panel subjected to axial compression was conducted. The study first examined the effects of the differences between a simple model used to design the panel and the actual experimental conditions. It was found that the large imperfection used in the design process compensated for the simplifying assumptions of the design model, and the experimental failure load was only 10% higher than the design load. Next, finite element analyses were performed in order to correlate analytical and experimental results. The buckling loads from finite element analyses agreed well with the experimental failure loads. However, substantial differences were found in the out-of-plane displacements of the panel. Finite element simulations of nonuniform load introduction with general contact definitions improved correlation between the measured and predicted out-of-plane deformations.

Reference listed at the end of the paper
http://doi.ieeecomputersociety.org/10.1109/ISUMA.2003.1236176
ABSTRACT: This paper explores reliability-based designs of isogrid stiffened panels. Uncertainties in material properties and geometric manufacturing uncertainties are represented by random variables. Due to the multiple failure modes in the stiffened panels, polynomial response surface approximation are fit to the most critical safety margins in the panel. Probability of failure is calculated by Monte Carlo simulation using the polynomial response surfaces. A probabilistic sufficiency factor approach is employed to facilitate the design optimization.

ABSTRACT: The design of reusable launch vehicles is driven by the need for minimum weight structures. Preliminary design of reusable launch vehicles requires many optimizations to select among competing structural concepts. Accurate models and analysis methods are required for such structural optimizations. Model, analysis, and optimization complexities have to be compromised to meet constraints on design cycle time and computational resources. Stiffened panels used in reusable launch vehicle tanks exhibit complex buckling failure modes. Using detailed finite element models for buckling analysis is too expensive for optimization. Many approximate models and analysis methods have been developed for design of stiffened panels. This dissertation investigates the use of approximate models and analysis methods implemented in PANDA2 software for preliminary design of stiffened panels. PANDA2 is also used for a trade study to compare weight efficiencies of stiffened panel concepts for a liquid hydrogen tank of a reusable launch vehicle. Optimum weights of stiffened panels are obtained for different materials, constructions and stiffener geometry. The study investigates the influence of modeling and analysis choices in PANDA2 on optimum designs. Complex structures usually require finite element analysis models to capture the details of their response. Design of complex structures must account for failure modes that are both global and local in nature. Often, different analysis models or computer programs are employed to calculate global and local structural response. Integration of different analysis programs is cumbersome and computationally expensive. Response surface approximation provides a global polynomial approximation that filters numerical noise present in discretized
analysis models. The computational costs are transferred from optimization to development of approximate models. Using this process, the analyst can create structural response models that can be used by designers in optimization. It allows easy integration of analysis models in optimization. The dissertation investigates use of response surface approximations for integrating structural response obtained from a global analysis in the local optimization of stiffened panels. In addition, response surfaces are used for correcting structural response predictions from a low fidelity model with a few expensive detailed finite element analyses.

References listed at the end of the dissertation:


Lamberti, L. (1), Venkataraman, S. (2), Haftka, R. T. (3) and Johnson, T. F. (4)
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ABSTRACT: Preliminary sizing of structural components in the conceptual design phase of new aerospace vehicles requires a large number of structural optimizations. Use of detailed finite element models for global optimization of stiffened shell structures is not affordable. Designers have to compromise between the complexity in the structural analysis model (e.g. small models or linear analysis) and that of the optimization method (local versus global optimization). When designing new concepts where good initial designs are not available, global design optimization needs to be performed, and this is not currently possible with complex models. In this paper, we discuss the use of simple analysis methods for performing global optimization of stiffened shell structures. We demonstrate the efficiency of using approximate analysis models by using PANDA2 for a practical design trade study. Often approximate models are based on assumptions that are not satisfied throughout the design space. Hence, such models require constraints that will keep the designs in regions where the analysis assumptions are valid. We illustrate with examples situations where such design constraints result in sub-optimal designs. We conclude that performing global optimization using approximate methods can permit a greater exploration of the design space than the use of local optimization with complex models.

ABSTRACT: Rapid increases in computer processing power, memory and storage space have not eliminated computational cost and time constraints on the use of structural optimization for design. This is due to the constant increase in the required fidelity (and hence complexity) of analysis models. Anecdotal evidence seems to indicate that analysis models of acceptable accuracy have required at least six to eight hours of computer time (an overnight run) throughout the last thirty years. This poses a severe challenge for global optimization or reliability-based design. In this paper, we review how increases in computer power were utilized in structural optimization. We resolve problem complexity into components relating to complexity of analysis model, analysis procedure and optimization methodology. We explore the structural optimization problems that we can solve at present and conclude that we can solve problems with the highest possible complexity in only two of the three components of model, analysis procedure or optimization. We use examples of optimum design of composite structures to guide the discussion due to our familiarity with such problems. However, these are supplemented with other structural optimization examples to illustrate the universality of the message.

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ABSTRACT: Nonlinear problems such as transient dynamic problems exhibit structural responses that can be discontinuous due to numerous bifurcations. This hinders gradient-based or response surface-based
optimization. This paper proposes a novel approach to split the design space into regions where the response is continuous. This makes traditional optimization viable. A convex hull approach is adopted to isolate the points corresponding to unwanted bifurcations in the design space. The proposed approach is applied to a tube impacting a rigid wall representing a transient dynamic problem. Since nonlinear behavior is highly sensitive to small variations in design, reliability-based design optimization is performed. The proposed method provides the designer an optimal design with a prescribed dynamic behavior.

References listed at the end of the paper:

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“A convex hull approach for the reliability-based design optimization of nonlinear transient dynamic problems”,
ABSTRACT: Nonlinear transient dynamic problems exhibit structural responses that might be discontinuous due to numerous critical points. The discontinuous behavior hinders classical gradient-based or response surface-based optimization. However, these discontinuities help to classify the system’s responses and identify regions of the design space corresponding to distinct dynamic behaviors. In this paper, data mining techniques are employed to group the responses into clusters. The regions of the design space corresponding to the clusters of unwanted behaviors are delimited with convex hulls. This allows an explicit definition of the boundaries of the failure region in terms of the design variables. In addition, the identification of response clusters, within which the responses might be considered continuous, enables the use of traditional response surface approximation for optimization. The proposed approach is applied to the reliability-based design of a tube impacting a rigid wall, which is optimized for a prescribed dynamic behavior.

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ABSTRACT: Buckling of thin walled welded structures is one of the most common failure modes experienced by these structures in-service. The study of such buckling, to date, has been concentrated on experimental tests, empirical models and the use of numerical methods such as the Finite Element Method (FEM). Some researchers have combined the FEM with Artificial Neural Networks (ANN) to study both open and closed section structures but these studies have not considered imperfections such as holes, weld seams and residual stresses. In this paper, we have used a combination of FEM and ANN to obtain predictive models for the critical buckling load and lateral displacement of the center of the profile under compressive loading. The study was focused on ordinary Rectangular Hollow Sections (RHS) and on the influence of geometric imperfections while taking residual stresses into consideration.

References listed at the end of the paper:
ABSTRACT: Spatial variability in material properties and in the coefficient of thermal expansion (CTE) in particular can have detrimental effects on thermally induced buckling by lowering the buckling load. Worst-case effects of this variability were studied by anti-optimization on a plate subjected to thermal loading for up to 20% variation in CTE around a fixed mean. Finite element analyses were used to construct a response surface approximation of the buckling eigenvalues as function of the spatial variations of the CTE. Optimizing the spatial variations for lowest buckling eigenvalue led to worst-case CTE distributions with respect to the thermal buckling studied. It was found that for the same CTE mean these distributions could lead to up to 10% lower eigenvalues. Such anti-optimal distributions tend to lead to higher than average CTE along the centerline of the plate, which increases the pre-buckling stresses in those area which from the buckling point of view are the most sensitive to high stresses. For composites, CTE variations were also assumed to be caused by variations in fiber volume fraction, which would also affect moduli and Poisson ratio. The worst distribution of fiber volume fraction led to a reduction in eigenvalues of only about 4.3%, meaning that fiber volume fraction induced CTE variations have much milder effects on thermal buckling than independent CTE variations, due to the effects of individual material properties variations partially cancelling each other out.

References listed at the end of the paper:


ABSTRACT: An experimental program to determine the response of thin-walled steel projectiles to the impact with concrete targets was recently conducted. The projectiles were fired against 41-MPa concrete targets at an impact velocity of 290 m/s. This article contains an outline of the experimental program, an examination of the results of a typical test, and predictions of projectile deformation by classical shell theory and computational simulation. Classical shell analysis of the projectile indicated that the predicted impact loads would result in circumferential buckling. A computational simulation of a test was conducted with an impact/penetration model created by linking a rigid-body penetration trajectory code with a general-purpose finite element code. Scientific visualization of the resulting data revealed that circumferential buckling was induced by the impact conditions considered.

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(2) Mechanical Engineering, National Chung-Hsing University, Taiwan, Republic of China
ABSTRACT: The vibrational behavior of geometrically imperfect single and multilayered composite double-curved shallow panels subjected to a system of tangential compressive/tensile edge loads in the pre- and postbuckling ranges is investigated. The effects of transverse shear deformations, lamination, the character of in-plane boundary conditions, and of transverse normal stress are incorporated and their influence is emphasized. Numerical illustrations enabling one to compare the obtained results based on higher order and first order shell theories with their classical counterparts, based on the Love-Kirchhoff model are presented and conclusions related to their range of applicability are outlined.
References listed at the end of the paper:


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ABSTRACT: The paper presents a new technique for the prediction of buckling loads of structural elements with postbuckling unstable characteristics such as cylindrical shells. The technique introduced is based on the cubic parametric curve defined by the Hermite form, which is described in the paper. The technique requires as input the data obtained from vibration tests carried out on structural elements under compressive loading, specifically, the values of the applied load and the square of the measured corresponding natural frequency of vibration. The proposed technique is applied to a simplified cylindrical shell model and two cylindrical shells. A comparison between the predicted and the exact values of the buckling loads is presented for each case discussed in the paper, highlighting the accuracy of the proposed technique.

References listed at the end of the paper:
Dongdong Wang and Huikai Peng (Department of Civil Engineering, Xiamen University, Xiamen, Fujian, 361005, China), “A Hermite reproducing kernel Galerkin meshfree approach for buckling analysis of thin plates”, Computational Mechanics, Vol. 51, No. 6, pp 1013-1029, June 2013

Abstract: A Hermite reproducing kernel Galerkin meshfree approach is proposed for buckling analysis of thin plates. This approach employs the Hermite reproducing kernel meshfree approximation that incorporates both the deflectional and rotational nodal variables into the approximation of the plate deflection and the $C^1$ continuous approximation requirement for the Galerkin analysis of thin plates can be easily achieved herein. The strain smoothing operation is consistently introduced to construct the smoothed rotation and curvature fields which appear in the weak form governing the thin plate buckling. The domain integration of the weak form is carried out by the method of sub-domain stabilized conforming integration with the smoothed measures of rotation and curvature, as leads to an efficient discrete meshfree formulation for the eigenvalue problem of thin plate buckling. A series of benchmark buckling problems are presented to assess the proposed algorithm and the results uniformly demonstrate the present approach is very effective and it performs superiorly compared to the conventional Galerkin meshfree formulations whose domain integration are performed by Gauss quadrature rules.

References listed at the end of the paper:

ABSTRACT: A higher-order, geometrically nonlinear theory of transversely isotropic symmetrically laminated composite plates is formulated and their post-buckling behavior is analysed. The numerical illustrations emphasize the role played by transverse shear deformation, transverse normal stress, higher-order effects and the character of in-plane boundary conditions. The results obtained within the present higher-order theory are compared with those of first-order transverse shear deformation and classical (Kirchhoff) theory, and conclusions on their range of applicability and the influence of various parameters are outlined.


ABSTRACT: A higher-order, geometrically nonlinear theory of transversely isotropic symmetrically laminated composite plates is formulated and their post-buckling behavior is analysed. The numerical illustrations emphasize the role played by transverse shear deformation, transverse normal stress, higher-order effects and the character of in-plane boundary conditions. The results obtained within the present higher-order theory are compared with those of first-order transverse shear deformation and classical (Kirchhoff) theory, and conclusions on their range of applicability and the influence of various parameters are outlined.


ABSTRACT: This paper discusses the thermally-induced geometrically nonlinear response of symmetrically laminated composite plates. The plate response is due to a temperature increase that is uniform in the plane of the plate but has a slight gradient through the thickness. The case of a completely uniform temperature increase but with an initial out-of-plane imperfection in the plate is also considered. Because they are closely allied
problems, thermal buckling and postbuckling are discussed. Using variational methods in conjunction with a Rayleigh-Ritz formulation, these responses are investigated for two laminates, a \((\pm 45/0/90)\) s and a \([+45/-45/0/2]s\) under two different simple support conditions, fixed and sliding. The effects of the principal material axes not being aligned with the edges of the plate, referred to here as material axis skewing, are also investigated. The study concludes that while differences between buckling temperatures for the two support conditions are small, support conditions can have a large influence on the thermally-induced nonlinear response. In general, plates with fixed simple supports deflect out-of-plane more than plates with sliding simple supports. In addition, support conditions can influence modal interaction. Skewing of the material axes decreases the buckling temperatures of both laminates and, like fixed support conditions, causes increased deflections. Skewing also influences modal interaction.


ABSTRACT: This study discusses the results of a layer-by-layer analysis of a thick-walled cross-ply graphite-epoxy cylinder subjected to external hydrostatic pressure. The analysis, which is valid away from the ends of the cylinder and is based on a generalized plane deformation elasticity solution for each layer, considers inter- and intralaminar stresses. Cylinders with 102 layers and radius to wall thickness ratios of 5 and 10 are studied. The influence of curing stresses are evaluated. For possible application to testing, the response of a thick laminated ring is compared to the response of a cylinder. The idea of smearing the 102 layers into an equivalent single layer is discussed and the results of a smeared analysis are compared with the layer-by-layer analysis. Finally, the responses of glass-epoxy and metallic cylinders are compared with the response of the graphite-epoxy cylinder. The primary findings of the study are: (1) the radial strain distribution through the thickness of the graphite-epoxy cylinder changes from extension at the inner radius to compression at the outer radius. This is different than the radial strain distributions through the glass-epoxy and metallic cylinders. The radial strains for these cylinders are everywhere extensional. (2) The magnitude of the curing stresses are much smaller than the stresses due to hydrostatic pressure. (3) The smearing technique works very well, the response predicted by the single-layer analysis being indistinguishable from the response predicted by the layer-by-layer analysis. (4) The high level of orthotropy of the graphite-epoxy causes a higher fiber loading than occurs for glass-epoxy. This effect could amplify any imperfections, e.g., fiber waviness, in the compressively loaded fibers and could lead to premature failure.


ABSTRACT: This paper explores the gains in buckling performance that can be achieved by deviating from the conventional straightline fiber format and considering the situation whereby the fiber orientation in a layer, or a group of layers, can vary from point to point in the plane of the plate. The particular situation studied is a simply-supported square plate with a centrally located hole loaded in compression. By using both a sensitivity analysis and a gradient-search technique, fiber orientation in a number of regions of the plate are selected so as to increase the buckling load relative to baseline straightline designs. The sensitivity analysis is used to determine which regions of the plate have the most influence on buckling load, and the gradient search is used to find the design that is believed to represent the absolute maximum buckling load for the conditions prescribed. Convergence studies and sensitivity of the final design are discussed. By examining the stress resultant contours, it is shown how the curvilinear fibers move the load away from the unsupported hole region of the plate to the supported edges, thus increasing the buckling capacity. The tensile capacity of the improved buckling design is investigated, and it is shown that both tensile capacity and buckling capacity can be improved with the curvilinear fiber concept.


ABSTRACT: The geometrically nonlinear Donnell shell theory is applied to the problem of stable bending of thin-walled circular cylinders. Responses are computed for cylinders with a radius-to-thickness ratio of 50 and length-to-radius ratios of 1 and 5. Four laminated composite cylinders and an aluminum cylinder are considered. Critical moment estimates are presented for short cylinders for which compression-type buckling behavior is important, and for very long cylinders for which the cross-section flattening, i.e., Brazier effect, is important. A finite element analysis is used to estimate the critical end rotation in addition to establishing the range of validity of the prebuckling analysis. The radial displacement response shows that the character of the boundary layer is significantly influenced by the geometric nonlinearities. Application of a first ply failure analysis using the maximum stress criterion suggests that in nearly all instances material failure occurs before buckling. Failure of the composite cylinders can be attributed to fiber breakage. Striking similarities are seen between the prebuckling displacements of the bending problem and axial compression problem for short cylinders.


ABSTRACT: A numerical and experimental investigation of the bending behavior of six eight-ply graphite-
epoxy circular cylinders is presented. Bending is induced by applying a known end-rotation to each end of the cylinders, analogous to a beam in bending. The cylinders have a nominal radius of 6 inches, a length-to-radius ratio of 2 and 5, and a radius-to-thickness ratio of approximately 160. A (+/- 45/0/90)S quasi-isotropic layup and two orthotropic layups, (+/- 45/0 sub 2)S and (+/- 45/90 sub 2)S, are studied. A geometrically nonlinear special-purpose analysis, based on Donnell's nonlinear shell equations, is developed to study the prebuckling responses and gain insight into the effects of non-ideal boundary conditions and initial geometric imperfections. A geometrically nonlinear finite element analysis is utilized to compare with the prebuckling solutions of the special-purpose analysis and to study the buckling and post buckling responses of both geometrically perfect and imperfect cylinders. The imperfect cylinder geometries are represented by an analytical approximation of the measured shape imperfections. Extensive experimental data are obtained from quasi-static tests of the cylinders using a test fixture specifically designed for the present investigation. A description of the test fixture is included. The experimental data are compared to predictions for both perfect and imperfect cylinder geometries. Prebuckling results are presented in the form of displacement and strain profiles. Buckling end-rotations, moments, and strains are reported, and predicted mode shapes are presented. Observed and predicted moment vs. end-rotation relations, deflection patterns, and strain profiles are illustrated for the post buckling responses. It is found that a geometrically nonlinear boundary layer behavior characterizes the prebuckling responses. The boundary layer behavior is sensitive to laminate orthotropy, cylinder geometry, initial geometric imperfections, applied end-rotation, and non-ideal boundary conditions. Buckling end-rotations, strains, and moments are influenced by laminate orthotropy and initial geometric imperfections. Measured buckling results correlate well with predictions for the geometrically imperfect specimens. The postbuckling analyses predict equilibrium paths with a number of scallop-shaped branches that correspond to unique deflection patterns. The observed postbuckling deflection patterns and measured strain profiles show striking similarities to the predictions in some cases. Ultimate failure of the cylinders is attributed to an interlaminar shear failure mode along the nodal lines of the postbuckling deflection patterns.

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ABSTRACT: A numerical and experimental study of the behavior of unstiffened thin-walled graphite-epoxy cylindrical shells subjected to bending loads is presented. Eight-ply quasi-isotropic and orthotropic shells were subjected to bending in a special test fixture. The experimental prebuckling, buckling, and postbuckling responses are compared to predictions from geometrically nonlinear analyses. It is found that a geometrically nonlinear boundary layer behavior characterizes the prebuckling responses. Discrepancies between predicted and observed strain amplitudes indicate that shape imperfections and other localized imperfections influence the prebuckling responses, causing a reduction in the predicted buckling resistance. Ultimate failure is attributed to excessive postbuckling deformations.

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ABSTRACT: The geometrically nonlinear Donnell shell theory is used to determine the prebuckling response of short thin-walled laminated circular cylinders in bending. Bending is induced by a known rotation of the clamped cylinder ends. The equilibrium equations and strain-displacement equations are manipulated so the governing partial differential equations are in first-order form. Using the separation of variables technique, along with a harmonic expansion in the circumferential direction, these first-order partial differential equations are converted to first-order ordinary differential equations. These equations are solved numerically using a finite-difference procedure and prebuckling responses are computed for cylinders with a radius: thickness ratio of 160 and length: radius ratios of 2 and 5. The range of validity of the prebuckling solution is limited by the critical, or previous term buckling, next term end rotation, which is estimated by the simple classical method. The use of the classical estimate is justified by comparing it with more rigorous approaches. Three laminated composite cylinders are considered: an axially stiff [−0/45/0]s layup, a circumferentially stiff [−45/0/90]s layup, and a quasiisotropic [0/45/90]s layup. The displacement response is discussed for each cylinder as a function of axial and circumferential location, with particular emphasis on the character of the radial displacement and the boundary layer associated with the nonlinear response. Comparisons with a geometrically linear analysis are made. An analog with the axial compression problem is developed and valuable information about boundary layer length as a function of laminate material properties and applied end rotation is presented. In addition, the role of the laminate Poisson's ratio ν(xθ) on the displacement behavior is discussed.

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ABSTRACT: The results from semianalytical predictions and experiments are used to study the response of composite cylinders with elliptical cross sections haded with internal pressure. The results for ellipses are contrasted to the case of circular cylinders. The semianalytical approach is based on the methods of Marguerre, Rayleigh-Ritz, and Kantorovich, the radius of curvature end the displacements being approximated by expansions in harmonic series in the circumferential arc-length coordinate, and the coefficients of the displacement series being unknown functions of x that are solved for using the finite-difference method. The experiments are described and results for a circular and an elliptical quasi-isotropic cylinder loaded to 1 atm internal pressure are compared with predictions. Correlations between the predictions and the experiments are, in general, quite good.


ABSTRACT: A computationally efficient analysis capability for the geometrically non-linear response of compressively loaded prismatic plate structures was developed. Both a "full" finite strip solution procedure and a "reduced" solution procedure were implemented in a FORTRAN 90 computer code, and comparisons were
made with results available in the technical literature. Both the full and reduced solution procedures were demonstrated to provide accurate results for displacement and strain quantities through moderately large post-buckling loads. The full method is a non-linear finite strip analysis of the semi-analytical, multi-term type. Individual finite strips are modeled as balanced and symmetric laminated composite materials which are assumed to behave orthotropically in bending, and the structure is loaded in uniaxial or biaxial compression. The loaded ends of the structure are assumed to be simply supported, and geometric shape imperfections may be modeled. The reduced solution method makes use of a reduced basis technique in conjunction with the full finite strip analysis. Here, the potentially large set of non-linear algebraic equations produced by the finite strip method are replaced by a small set of system equations. In the present implementation, the basis vectors consist of successive derivatives of the non-linear solution vector with respect to a loading parameter. Depending on the nature of the problem....

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ABSTRACT: Results of a numerical parametric study of the prebuckling and postbuckling response of tailored composite stiffened panels with axial-shear coupling are presented. In the stiffened panels, axial-shear stiffness coupling is created by rotating the stiffener orientation and tailoring the skin laminate anisotropy. The panels are loaded in axial compression and the effects of stiffener orientation and skin anisotropy on the panel stiffness, buckling parameters, and axial-shear coupling response are described. Results are obtained from a nonlinear general shell finite element analysis computer code. The prebuckling and postbuckling responses can be affected by both the stiffener orientation and skin laminate anisotropy, and the effects are different and load dependent. The results help identify different mechanisms for axial-shear coupling, and show that a load-dependent structural response can be controlled by selecting appropriate stiffener and skin parameters.

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11 Nemeth, M. P., “Importance of Anisotropy on Buckling of Compression-Loaded Symmetric Composite Plates,” AIAA Journal,

ABSTRACT: This paper briefly discusses the influences of through-thickness thermal expansion, a misaligned ply, and a resin-rich slightly thicker ply on the deformations of a curved composite laminate during cool down from the cure temperature. Both two-dimensional and three-dimensional level finite-element analyses are used. The deformations are categorized as to radial and tangential deformations and twist, and for each of the three influences, these deformations are quantified. An additional outcome of the study is an indication of the level of analysis needed to study each of these three influences.

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ABSTRACT: The response characteristics of composite cylinders constructed in four circumferential segments are discussed. Two cylinder configurations, referred to as axially stiff and circumferentially stiff cylinders, are studied. Numerical results from STAGS finite element analyses are presented and include predicted radial displacements and selected stress resultants. Compressive loading into the postbuckling range by an axial endshortening is considered. The results show that, as the endshortening increases toward the buckling value, some segments of the cylinders begin to develop axial wrinkles, whereas other segments remain relatively unwrinkled. For the two cylinders considered here, the wrinkling of the segments is correlated with the level of axial stress resultant supported in the segment. Load drops of 20 and 57% for the axially stiff and circumferentially stiff cylinders, respectively, are predicted for levels of endshortening beyond the buckling values. The postbuckled cylinders are characterized by regions of large localized inward dimples and outward ridges in the radial displacement pattern. These regions are sites of large-magnitude axial and transverse shear stress resultants.

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ABSTRACT: By varying the thickness of the cylinder wall with circumferential position, the axial buckling capacities of homogeneous, isotropic cylindrical shells with elliptical cross sections are improved. The classic buckling stress relation for a uniform-thickness homogeneous, isotropic circular cylindrical shell is applied to cylinders with elliptical cross sections. It is assumed that this relation can be used to design the wall thicknesses
of elliptical cylinders as a function of circumferential location to compensate for the negative effects of the variation of the radius of curvature with circumferential location. Three variable-thickness elliptical cylinder designs are proposed, and analytical expressions for the thickness variation, cross-sectional area, axial buckling stress, axial buckling stress resultant, and axial buckling load for each design are derived. Predictions from the analytical development are then compared with finite element analyses of the three designs. So-called small and large cylinders with three values of eccentricity are considered. The comparisons between the finite element results and the analytic predictions are quite good. It is shown that considerable improvement in axial buckling capacity can be achieved with the thickness-tailoring technique, and in some cases the axial capacity of the circular cylinder with the same circumference is achieved.


ABSTRACT: A novel re-defining of the orthotropic material properties in terms of a so-called associated geometric mean isotropic (GMI) material is used to develop a thorough buckling analysis of an axially-loaded orthotropic circular cylinder. A membrane prebuckling condition is assumed and an expression for the buckling stress is derived in terms of cylinder geometry, orthotropic material properties, and the number of waves in the buckling deformation pattern in the axial and circumferential directions. By assuming the number of waves in each direction are real-valued variables, as opposed to integers, conditions which result in stationary values of the buckling stress are sought, and once found, examined for their character as regards representing minima, maxima, or saddle points. Three quite different buckling characteristics are predicted, the particulars depending on the shear modulus of the orthotropic material relative to that of the associated GMI material. It is shown that if the shear modulus of the orthotropic material is greater than the shear modulus of the associated GMI material, the cylinder buckles into a unique axisymmetric deformation pattern. If the shear modulus of the orthotropic material is less than the shear modulus of the associated GMI material, the cylinder buckles into a unique nonaxisymmetric deformation pattern. If the shear modulus of the orthotropic material is exactly equal to the shear modulus of the associated GMI material (this is the situation for an isotropic cylinder), the cylinder can buckle into either axisymmetric or nonaxisymmetric deformation patterns. Moreover it is shown that, in this case, there exists a number of deformation patterns, all at essentially the same stress level. Closed-form lower-bound expressions for the buckling stress are developed using the adopted notation, the value of the shear modulus relative to the shear modulus of the GMI material determining which expression is applicable. The results of this analysis are applied to a circular cylinder constructed of a lattice structure consisting of helical and circumferential ribs, a so-called orthogrid lattice cylinder, where it is assumed that the ribs of the lattice structure are dense enough to be able to represent the elastic properties of the lattice with an equivalent homogenized orthotropic material. An isogrid cylinder, where the helical rib angle is 30° relative to the axial direction, is a special case. The orthotropic cylinder analysis is reformulated in terms of the material properties of the ribs and the angle of the helical ribs. For this situation the isogrid case is the GMI material, and the rib angle determines whether the shear modulus of the equivalent orthotropic material is greater than or less than the GMI material. This translates into the character of the buckling deformations depending directly on the rib angle.

References listed at the end of the paper:
ABSTRACT: The equations for the free vibration of an elliptic cylindrical shell of constant thickness were derived using a Ritz approach. A higher order shell theory is employed that includes the effects of shear deformation, rotary inertia, and symmetric and antisymmetric thickness stretch deformations. The frequency-wavenumber spectrum has seven branches: flexural, extensional, torsional, two thickness shear, and two thickness stretch. The resulting seven coupled algebraic equations are symmetric and positive definite. The shell has a constant thickness, $h$, finite length, $L$, and is “simply supported” at its ends, $(z = 0, L)$, where $z$ is the axial coordinate. The elliptic cross-section is defined by the shape parameter, $a$, and the half-length of the major axis, $I$. The modal solutions are expanded in a doubly infinite series of comparison functions in terms of circular functions in the angular and axial coordinates. Numerical results for the natural frequencies were obtained for two values of $h/I$ and $L/I$, and various shape parameters, including the limiting case of a simply supported cylindrical shell ($a \approx 100$).


ABSTRACT: Accurate analysis concerning static instability and reliable appointment of the buckling loads is important for safe design of thin-walled shell structures. Real shells contain geometric imperfections and other deviations from nominal values which have to be considered, as for buckling analyses on the basis of ideal
conditions extreme discrepancies between prediction and test data can result. This thesis deals with the buckling behaviour of thin-walled, unstiffened cylinders under pure axial compression because of their extraordinary sensitivity to imperfections in the shell geometry. The parameters required for an application of real imperfections in a buckling analysis are difficult to be specified. And measured values of real imperfections for the design of any new cylinder shell are hardly available. In the absence of such data in most cases buckling patterns are used that result for perfect geometry and whose buckling patterns can be described with harmonic displacement functions. For safe shell design that imperfection shape is significant which yields the minimum buckling load. But, in general neither the geometry nor the amplitudes of the buckling patterns which contribute to the most damaging imperfection shape are known a priori. In addition, the monotone wavelike dimples forming the buckling patterns of perfect cylinders enclose the entire shell surface, and hence localized irregularities like single dents or bulges of different amplitude are insufficiently included. Consequently, due to the lack of adequate imperfections parameters, cylindrical shells still have to be designed by use of reduction factors to be applied to the analytical buckling loads for perfect cylinders. These reduction factors consider smallest empirical values and therefore provide critical loads which appear to be rather conservative. Moreover, such instructions exist for steel and other isotropic shell materials but not for laminated composite cylinders, for instance.

For these reasons the thesis on hand focusses on cylinders having localized imperfections in form of local inward or outward dimples. To investigate the influences of a single initial dimple on the instability behaviour of such cylinders, and separate from any effect of other irregularities, discrete parametric dents or bulges were added to FE models of unstiffened circular cylinders of otherwise perfect geometry. The chosen shape of a parametric dimple allowed to investigate the influence of its initial amplitude, its initial axial height, its initial circumferential width, and its axial position systematically and independently of other parameters. With regard to the absence of practical design recommendations for laminated composite cylinders the thesis on hand covers analyses of isotropic as well as of laminated CFRP shells.

Several parameter studies were conducted for a number of cylinders having dimples of different initial amplitude but fixed initial circumferential width and axial height. In addition, for a few cylinders and for some predefined initial amplitudes the initial axial height and circumferential width to the dimple was searched which reduce the axial cylinder stability the most. Finally the influence of the relative position of a second identical dent to the load carrying capacity was investigated. These series of analyses aimed at investigating whether there are single, localized initial dimples which reduce the nominal axial buckling load of an unstiffened circular cylinder more than imperfections derived from classical buckling patterns of ideal shells, and whether there is a worst geometry of such a single dimple imperfection. Further: is the instability behaviour the same for isotropic shells as for laminated composite shells having such a localized dimple imperfection? And, is there an important interaction between two initial dimples?

The dimple-parameter studies required a large amount of static and transient dynamic FE analyses. Most of the calculations performed were nonlinear buckling analyses, i.e. nonlinear static stress analyses under consideration of large displacements and rotations using Updated Lagrangian formulations with additional linear eigenvalue calculations, conducted after a selected number of small loading steps to determine the stability of pre-buckling states of stress and deformation. To manage the large number of shells with different bucking loads and behaviour considered, the nonlinear buckling analysis was adapted for an adaptive load step control which utilizes the intermediately extracted eigenvalues. For a selection of cylinders and dimples additional nonlinear transient dynamic analyses were conducted in order to research into the particular deformation processes of such shells under axial loading. Because of the relatively slow compression velocities assumed the implicit "single-step Houbolt" method for time integration was preferred to the more common explicit operators. To reduce the number of time increments needed for stepwise convergence significant inertia damping was introduced.
In a classical analysis, for ideal, thin-walled unstiffened isotropic circular cylinders of medium length under pure axial compression the load-carrying capacity can be predicted analytically by means of simple equations. These equations follow from solving the coupled partial differential equations for equilibrium and compatibility in simply-supported cylinder with harmonic functions. There are also closed-form solutions of the Donnell-type shell equations available for thin-walled orthotropic composite cylinders. Such a classical analysis, however, is applicable exclusively for perfect cylinder geometry.

For the imperfection shapes and sizes considered no test results were available against which the FE analysis results could have been benchmarked. Instead, they are supported by convincing results of such calculations for similar cylinders with perfect geometry and for laminated CFRP cylinders with their measured imperfections included. The results of the ideal cylinders could be compared with values achieved with classical analyses, whereas for the analysis results of the CFRP shells with measured imperfections test data was available for comparisons.

The asymmetrically laminated CFRP cylinders analysed stem from a preceding European project which focused on the correlation of measured buckling loads of test cylinders with analytical and numerical buckling load predictions. The FE analyses of these shells have shown that for such cylinders calculated buckling loads close to test values may be attained if measured imperfections are included in the analysis. It was further found that the consideration of imperfections requires the use of FE analysis methods which take geometric nonlinearity into account. The nonlinear buckling and transient dynamic FE analyses of these CFRP cylinders with perfect geometry and with measured imperfections applied finally provided the basis for the FE analyses of such cylinders having a single localized dimple.

The FE analyses of cylinders with an initial local dent or bulge yielded particular deformation processes including different local buckling phenomena which were hardly known from unstiffened circular cylinders with neither perfect geometry nor with imperfections distributed over the entire shell surface. Nevertheless, by means of systematic parameter variation some interrelationships between the results and the nominal dimensions of the cylinder and the dimple could be derived.

The initial circumferential curvature of a shell in the dimple plays a decisive role in the deformation process of the cylinders and in the run of their FE analyses. The differences in the behaviour pattern and the initial curvature led to a distinction between "shallow" and "deep" dents. Shallow dents with an initial amplitude smaller than a certain marginal depth provoke a distinct local buckling with a sudden snapping inwards of the dent to form a local flattened shell strip of reduced geometric axial stiffness. Deep dents, in turn, result in a continuous local flattening of the shell without any dynamic local-buckling incident prior to the total cylinder collapse.

Localized, shallow dents of particular initial circumferential width and axial height reduce the buckling load as much as axisymmetric inward dimples of identical initial amplitude. And a non-axisymmetric, shallow dent of adequate initial width and height may be as damaging as an imperfection-pattern that is given by a classical buckling mode of initial amplitude that is half the initial amplitude of the dent. Further, localized non-axisymmetric bulges impair the load carrying capacity less than localized dents of the same absolute initial amplitude, width, and height. Finally, the buckling load of a cylinder with single localized dent is only little different from that of a cylinder having two dents of identical size.

For isotropic cylinders the initial axial heights of dimples that reduces the buckling load the most for a preselected initial depth is close to the wavelength for classical axisymmetric buckling of a perfect cylinder. The initial circumferential widths of the worst dent is between two to three times the initial height, whereas the worst bulge is always axisymmetric.

The studies yielded that the cylinder length is also decisive for the local deformation processes of the shell in and in the adjacency of the initial dimples (local buckling) observed. The design recommendations in standards and literature considered for thin-walled, unstiffened isotropic cylinders under axial compression are
conservative if the nominal radius and wall-thickness as well as the nominal cylinder length are taken into account.

For the laminated cylinders investigated accurate and general predictions of minimal buckling loads and of critical dimple dimensions could not be derived on basis of the cylinder geometry alone as the buckling behavior patterns of such shells depend strongly on the laminate stacking. However, there was no indication that any laminated cylinder with any non-axisymmetric dimple results in a lower buckling load than anisotropic cylinder of identical radius, length and wall thickness also having a non-axisymmetric dimple.

References listed at the end of the dissertation:
(Cannot easily cut and paste the references.)

DOI: 10.1016/S0045-7825(02)00504-2
ABSTRACT: The implementation of the element free Galerkin method (EFG) for spatial thin shell structures is presented in this paper. Both static deformation and free vibration analyses are considered. The formulation of the discrete system equations starts from the governing equations of stress resultant geometrically exact theory of shear flexible shells. Moving least squares approximation is used in both the construction of shape functions based on arbitrarily distributed nodes as well as in the surface approximation of general spatial shell geometry. Discrete system equations are obtained by incorporating these interpolations into the Galerkin weak form. The formulation is verified through numerical examples of static stress analysis and frequency analysis of spatial thin shell structures. For static load analysis, essential boundary conditions are enforced through penalty method and Lagrange multipliers while boundary conditions for frequency analysis are imposed through a weak form using orthogonal transformation techniques. The EFG results compare favorably with closed-form solutions and that of finite element analyses.

Maurizio Paschero, “Improvement of the axial buckling capability of elliptical cylindrical shells”, Dissertation submitted to Virginia Polytechnic Institute and State University, March 2008 (See also, AIAA Journal, Vol. 47, No. 1, 2009, pp. 142-156)
ABSTRACT: A rather thorough and novel buckling analysis of an axially-loaded orthotropic circular cylindrical shell is formulated. The analysis assumes prebuckling rotations are negligible and uses a unique re-defining of the orthotropic material properties in terms of a so-called geometric mean isotropic (GMI) material. Closed-form expressions for the buckling stress in terms of cylinder geometry and orthotropic material properties are presented, the particular closed form depending on the specific character of the orthotropic material relative to the GMI material. With the formulation, the specific character of the buckling deformations - e.g., axisymmetric or nonaxisymmetric, the number of axial and circumferential waves - can be established. By using the maximum radius of curvature of an elliptical cross section in this formulation, the analysis is used to demonstrate the detrimental effects of an elliptical cross section on axial buckling capacity when compared to a circular cross section with the same circumference. Using the circumferentially-varying radius of curvature of an elliptical cross section, the analysis is then further used as the basis for developing two methods for improving the axial buckling capacity of elliptical cylinders. The first approach involves varying the wall thickness of an isotropic elliptical cylinder with circumferential position. Uniformly stable elliptical cross sections which preserve the same critical stress, critical load, or volume of an axially loaded circular cylinder of the same circumference are designed with the formulation. The second approach involves maintaining a
uniform wall thickness but varying the orthotropic material properties with circumferential position. This approach is applied to a cylindrical lattice structure where it is assumed that the ribs are dense enough to be able to describe the lattice structure by means of an equivalent homogenized material. The orthotropic properties of the homogenized material are varied by varying the lattice rib angle with circumferential position. Considerable recovery of the axial buckling capacity of the variable-rib-angle design elliptical cylinder compared to the same cylinder constructed in isogrid fashion is demonstrated. In fact, recovery relative to an isogrid circular cylinder of the same circumference is demonstrated. For both approaches confirming finite element models are used to verify the findings. The two different approaches are compared, and finally the two approaches are recognized as special cases of a more general design philosophy.

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(2) Delft University of Technology, The Netherlands

“Experimental study of nonlinear vibrations of thin-walled cylindrical shells”, ICAS 2000 Congress

ABSTRACT: Large amplitude vibration tests of thin-walled aluminum cylindrical shells were performed to validate results of theoretical analysis. The tests were carried out on four shells with practically clamped-clamped boundary conditions, two of them were perfect and the other two with built-in imperfections. The vibration behaviors of shell responses at large amplitudes of interest are the dependence of resonant frequency on the response levels and the possibility of response in the form of traveling waves. Parameters of the study were axial loads, geometric imperfections of the shell, excitation levels and direction of excitation frequency sweep. Comparison between the experimental and the theoretical results showed good agreements qualitatively.

References listed at the end of the paper:


ABSTRACT: Curved panels constructed of laminated graphite-epoxy composite material are of potential interest in airframe fuselage applications. An understanding of structural response at elevated temperatures is required for anticipated future high speed aircraft applications. This study concentrates on the response of unstiffened, curved composite panels subjected to combinations of thermal and mechanical loading conditions. Mechanical loading is due to compressive end-shortening and thermal loading is due to a uniform temperature increase. Thermal stresses, which are induced by mechanical restraints against thermal expansions or contractions, cause buckling and postbuckling panel responses. Panels with three different lamination sequences are considered, including a quasi-isotropic laminate, an axially soft laminate, and an axially stiff laminate. These panels were chosen because they exhibit a range of stiffnesses and a wide variation in laminate coefficients of thermal expansion. The panels have dimensions of 10 in. by 10 in. with a base radius of 60 in. The base boundary conditions are clamped along the curved ends, and simply supported along the straight edges. Three methods are employed to study the panel response, including a geometrically nonlinear Rayleigh-Ritz solution, a finite element solution using the commercially available code STAGS, and an experimental program. The effects of inplane boundary conditions and radius of curvature are studied analytically, along with consideration of order of application in combined loading. A substantial difference is noted in the nonlinear load vs. axial strain responses of panels loaded in end-shortening and panels loaded with uniform temperature change, depending on the specific lamination sequence, boundary conditions, and radius of curvature. Experiments are conducted and results are presented for both room temperature end-shortening tests and elevated temperature tests with accompanying end-shortening. The base finite element model is modified to include measured panel thicknesses, boundary conditions representative of the experimental apparatus, measured initial geometric imperfections, and measured temperature gradients. With these modifications, and including an inherent end displacement of the panel present during thermal loading, good correlation is obtained between the experimental and numerically predicted load vs. axial strain responses from initial loading through postbuckling.

References listed at the end of the paper:

**Thermal Response Review Papers (Nicole Breivik’s PhD dissertation references)**


**Axial Compression of Curved Panels (Nicole Breivik’s PhD dissertation references)**


**Thermal Response of Curved Panels (Nicole Breivik’s PhD dissertation references)**


**Thermal-Structural Testing (Nicole Breivik’s PhD dissertation references)**

**Computational Aids (Nicole Breivik’s PhD dissertation references)**
General Topics (Nicole Breivik’s PhD dissertation references)


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ABSTRACT: The buckling and postbuckling responses of unstiffened cylindrically curved composite panels are studied using the finite element code STAGS and a geometrically nonlinear Rayleigh–Ritz solution. Loading is either through axial end-shortening at a fixed spatially uniform temperature, or it is temperature-induced due to the thermal stresses that arise when the spatially uniform temperature is increased while axial end displacement is restrained to be zero. Comparisons are made between two sets of boundary conditions and three laminates. Buckling and postbuckling responses are found to be strongly dependent on material orthotropy and are substantially affected by the amount of circumferential restraint along the straight edge boundaries.


ABSTRACT: A parametric study of the buckling behavior of infinitely long symmetrically laminated anisotropic plates that are subjected to linearly varying edge loads, uniform shear loads, or combinations of these loads is presented. The study focuses on the effects of the shape of linearly varying edge load distribution, plate orthotropy, and plate flexural anisotropy on plate buckling behavior. In addition, the study examines the interaction of linearly varying edge loads and uniform shear loads with plate flexural anisotropy and orthotropy. Results obtained by using a special purpose non-dimensional analysis that is well suited for parametric studies of clamped and simply supported plates are presented for [±theta]s thin graphite-epoxy laminates that are representative of spacecraft structural components. Also, numerous generic buckling-design charts are presented for a wide range of nondimensional parameters that are applicable to a broad class of laminate constructions. These charts show explicitly the effects of flexural orthotropy and flexural anisotropy on plate buckling behavior for linearly varying edge loads, uniform shear loads, or combinations of these loads. The most important finding of the present study is that specially orthotropic and flexurally anisotropic plates that are subjected to an axial edge load distribution that is tension dominated can support shear loads that are larger in magnitude than the shear buckling load.
References listed at the end of the report:

Carl R. Schultheisz (1) and Anthony M. Waas (2)
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(2) Associate Professor, Department of Aerospace Engineering, University of Michigan, FXB Bldg, Ann Arbor, MI 48109-2118, U.S.A.
ABSTRACT: When structures made of composite materials are designed to be used in load bearing applications, a primary consideration is the evaluation of their load carrying capacity in compression. To this end, a vast number of research investigations, whose main objective is linked to ascertaining the compressive strength of a composite structure has been carried out and/or is currently being performed. Apart from its practical significance, the complexity associated with the task of predicting compression strength is the main reason for the overt attention this problem is receiving. One such difficulty has been associated with testing. When laboratory tests are carried out to determine compression strength, structural instabilities dictated by the geometry of the structure may interfere with material strength dictated by the mechanical properties of the constituents and their alignment and geometry (needed to describe the microstructure of the material). In addition stress concentrations may occur at undesirable locations. In Part I, issues pertaining to compression testing and micromechanical failure theories are reviewed.

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ABSTRACT: In Part I of this two part sequence, issues related to compression testing of composites and micromechanical failure models were reviewed. The present paper (Part II) is written with a focus on understanding experimental studies that have been carried out to illuminate those micromechanical influences that affect compression strength. The use of model composites to study compression failure is discussed. The advantages and disadvantages of the many different experimental techniques to measure fiber strengths are presented. Many suggestions for future investigations are given.


ABSTRACT: Thin-walled cylinders, used in a variety of engineering applications, are often subjected to situations where the applied loading is not limited to a single loading type. The introduction of multiple loads alters the stability characteristics of the system in a manner that must be understood to maintain structural integrity and abide by safety regulations. The present study investigates the elastic buckling response of thin-walled cylindrical shells under a combination of torsional loads and circumferentially-varying thermal loads. References listed at the end of the paper:


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ABSTRACT: The stability theories energetically associated with different finite strain measures are equivalent if the tangential moduli are transformed as a function of the stress. However, for homogenized soft-in-shear composites, they can differ greatly if the material is in small-strain and constant elastic moduli measured in small-strain tests are used. Only one theory can then be correct. The preceding variational energy analysis showed that, for sandwich columns and elastomeric bearings, respectively, the correct theories are Engesser’s and Haringx’s, associated with Green’s and Almansi’s Lagrangian strain tensors, respectively. This analysis is reviewed, along with supporting experimental and numerical results, and is then extended to arbitrary multiaxially loaded homogenized soft-in-shear orthotropic composites. It is found that, to allow the use of constant shear modulus when the material is in small strain, the correct stability theory is associated with a general Doyle–Ericksen finite strain tensor of exponent m depending on the principal stress ratio. Further it is
shown that the standard updated Lagrangian algorithm for finite element analysis, which is associated with Green’s Lagrangian finite strain, can give grossly incorrect results for homogenized soft-in-shear structures and needs to be generalized for arbitrary finite strain measure to allow using constant shear modulus for critical loads at small strain.

References listed at the end of the paper:
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ABSTRACT: The previous energetic variational analysis of critical loads and of the choice of finite strain measure for structures very weak in shear, remaining in a state of small strain, is extended to the initial postcritical behavior. For this purpose, consideration of the transverse deformation is found to be essential. It is shown that imperfection sensitivity of such structures, particularly laminate-foam sandwich plates, can arise for a certain range of stiffness and geometric parameters, depending on the proper value of parameter m of the Doyle–Ericksen finite strain tensor, as determined in the previous analysis. The bifurcation is symmetric and Koiter’s 2/3-power law is followed. The analytical predictions of maximum load reductions due to imperfection sensitivity are verified by finite element simulations. The possibility of interaction between different instability modes, particularly lateral deflection and bulging, is also explored, with the conclusion that lateral deflection dominates in common practical situations.

References listed at the end of the paper:

ABSTRACT: The dynamic axial crush response of circular cell polycarbonate honeycombs was studied for 3-cell and 7-cell specimens experimentally and through finite-element (FE) simulation. The experiments were conducted using two loading methods: (i) the wave loading device (WLD) method and (ii) the direct impact method (DIM). The specimens were subjected to crush velocities of about 12000 mm per second in the WLD method and 5000 mm per second in the DIM. The two methods were used to obtain a fairly wide range of input velocities. The collapse sequence and displacement information of the specimens were captured using a high-speed camera. The mode of collapse was through progressive concertina-diamond fold formation over a fairly constant state of load, which is referred to as the crush load. The crushing was simulated using an explicit FE analysis using ABAQUS, with geometrically imperfect 3-cell and 7-cell honeycomb models that incorporated the rate-dependent properties of polycarbonate. The FE results were found to agree well with the experimental results in terms of overall force-displacement plots, thus providing a basis to extract energy absorption estimates from the models and to draw comparisons between the 3-cell and 7-cell response behaviour. Moreover, the dynamic crush results were compared against a quasi-static axial crush response to demonstrate the presence of rate effects.

References listed at the end of the paper:

ABSTRACT: A sandwich beam buckling problem is studied here using two-dimensional elasticity to model the beam constituents. The global and local instability of such a beam with orthotropic constituents under various boundary conditions are investigated. The face sheet and the core are assumed to be linear elastic orthotropic continua. General buckling deformation modes of the sandwich beam subjected to uniaxial compressive loading are considered. The appropriate incremental stress and conjugate incremental finite-strain measure for the instability problem of the sandwich beam, and the corresponding constitutive model are addressed. It is shown that a sandwich beam having a core with a negligible stiffness compared to the face sheets is prone to fail by edge buckling. The present analysis is compared with several previous analytical studies and corresponding experimental results. Finite-element analyses are carried out for comparison against the theoretical predictions. The formulation used in the finite-element code is discussed in relation to the formulation adopted in the theoretical derivation.

References listed at the end of the paper:

ABSTRACT: This paper is concerned with two issues that arise in the finite element analysis of 3D solids. The first issue examines the objectivity of various stress rate conjugacy. Remedies to fix the errors in the numerical solution strategy are given.

References listed at the end of the paper:


Wooseok Ji (1), Anthony M. Waas (1) and Zdenek P. Bazant (2)
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"On the importance of work-conjugacy and objective stress rates in finite deformation incremental finite element analysis", Journal of Applied Mechanics, Vol. 80, 041024-1-9, July 2013, DOI: 10.1115/1.4007828

ABSTRACT: This paper is concerned with the elastic stability of a sandwich beam panel using classical elasticity. An exact solution for the buckling problem of a sandwich panel (wide beam) in uniaxial compression is presented. Various formulations that correspond to the use of different pairs of energetically conjugate stress and strain measures for the infinitesimal elastic stability of the sandwich panel are discussed. Results from the present two-dimensional analyses to predict the global and local buckling of a sandwich panel are compared with previous theoretical and experimental results. A new finite element formulation for the bifurcation buckling problem is also introduced. In this new formulation, terms that influence the buckling load, which have been omitted in popular commercial codes are pointed out and their significance in influencing the buckling load is identified. The formulation and results presented here can be used as a benchmark solution to establish the accuracy of numerical methods for computing the buckling behavior of thick, orthotropic solids.

References listed at the end of the paper:

Conclusion and suggestions for further work:

An analytical method for predicting global and wrinkling instabilities of a sandwich beam is presented. The sandwich beam is modeled as a 2D-linear elastic continuum. Field equations representing a solid slightly deformed from a state of initial stress and under conditions of plane strain is adopted in the analysis. The results obtained yield the buckling stress and the associated wavelength. The results have shown that the buckling stress for the anti-symmetrical deformation mode is always lower than that of the symmetrical one. The buckling behavior of the two modes is parameterized according to the ratio of core thickness to the face sheet thickness. The results are compared with previous experimental results, theoretical analyses, and a finite element analysis prediction. Since the present analysis has fewer assumptions than previous analyses, the limitations of previous investigation are discussed for different combination of geometry and material properties. The results presented here, which have been verified by finite element analysis and compared against experimental results, reproduce the buckling behavior accurately for a wide range of material and geometric parameters. The results that have been presented here are a good prediction of the overall behavior of a sandwich beam in a uniaxial compressive load environment regardless of the core modulus and thickness ratio. In particular, for thick face sheets and for relatively stiff cores, the present model is found to be more accurate than previous models that assume beam like behavior for the face sheets and neglect the axial load carrying capability of the core. The results from finite element analysis have verified the findings of the present analytical model. In addition the correct formulation of the 2D elastic sandwich column problem has been presented along with a FE formulation of the problem. The latter has revealed deficiencies in the formulation adopted by popular commercial codes (for example ABAQUS). An analytical prediction of dynamic buckling is also presented in this thesis. Dynamic buckling of a structure under uniaxial impact compression is studied. Fully coupled equations of inplane and out-of-plane motions are solved to find the condition of the onset of dynamic buckling. There exists a critical time for the axial strain to satisfy the emergence of the buckling deformation. The bifurcation condition is derived for the simple Euler-Bernoulli beam as well as the sandwich beam. Experimental studies are also performed to investigate the failure mechanism of the sandwich structure under axial impact loading. The sequential responses of the sandwich specimens reveal that the structure initially experiences the axial deformation only until the buckling deformation emerges at a certain load value corresponding to the critical time. FE analysis is also performed to simulate the dynamic response and it is found that there exist a sudden increase of the bending deformation after numerous superpositions of axial strain waves. The dynamic buckling analysis presented here has numerous potential applications in various fields. The analysis is not dependent on the beam response, but is derived quantitatively so that it is adaptable to various engineering applications. The dynamic buckling analysis can be extended further for better understanding of more complex material under dynamic loading. The analysis can be improved considering inelastic behavior of the material, orthotropic material, shear deformation, and various combinations of material and geometric properties for the sandwich structure. The analysis combined with fracture mechanics can be used to explain the failure mechanism of the sandwich structure under axial loading. The latter is suggested for future work. In addition, extension of the Euler-Bernoulli model to a Timoshenko beam model is suggested for the impact buckling problem, so that shear deformation effects can be accounted for. Adopting the work of Von Karman [34], the effects of column plasticity on the “critical time to buckle” can be captured and this is also suggested for future work. Finally, it is
possible to develop a sandwich beam FE model that includes cohesive zone models for the face sheet-core interface. Such a model in conjunction with an explicit FE code can be used to obtain a comprehensive response model for the sandwich beam impact problem.

References listed at the end of the thesis:


Wooseok Ji and Anthony M. Waas (Department of Aerospace Engineering, Composite Structures Laboratory,
University of Michigan, Ann Arbor, MI 48109), “The two-dimensional elasticity solution for the buckling of a thick orthotropic ring under external pressure loading”, Journal of Applied Mechanics, Vol. 81, 011005-1-12, January 2014, DOI: 10.1115/1.4023682

ABSTRACT: This paper is concerned with the 2D elasticity solution for the buckling of a thick orthotropic ring under external hydrostatic pressure loading. The bifurcation buckling problem is first formulated using two methods, distinguished by the manner in which the external work done by the pressure loading during the buckling transition is treated. In doing so, the correct buckling equations and associated traction boundary conditions are derived. The resulting sets of equations and associated boundary conditions are then cast in a weak form, amenable to a numerical solution using the finite element method. The necessity of using the correct pairs of energetically conjugate stress and strain measures for the buckling problem is pointed out. Errors in using the incorrect traction boundary condition and terms that influence the buckling load and that have been omitted in popular commercial codes are pointed out and their significance in influencing the buckling load is identified. Results from the present two-dimensional analysis to predict the critical pressure are compared with previous theoretical results. The formulation and results presented here can be used as the correct benchmark solution to establish the accuracy in computing the buckling load of thick orthotropic composite structures, of contemporary interest, due to the increased use of thick-walled composite shell type structures in diverse engineering applications.

References listed at the end of the paper:
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ABSTRACT: Results from a study of the effects of cutouts and laminate construction on the prebuckling and initial postbuckling stiffnesses, and the effective widths of compression-loaded laminated-composite and aluminum square plates are presented. An effective-width concept is derived for plates with and without cutouts, and experimental and nonlinear finite-element analysis results are presented. Behavioral trends are compared for seven plate families and for cutout-diameter-to-plate-width ratios up to 0.66. A general compact design curve that can be used to present and compare the effective widths for a wide range of laminate constructions is also presented. A discussion of how the results can be used and extended to include certain types of damage, cracks, and other structural discontinuities or details is given. Several behavioral trends are described that initially appear to be nonintuitive. The results demonstrate a complex interaction between cutout size and plate orthotropy that affects the axial stiffness and effective width of a plate subjected to compression loads.

References listed at the end of the report:

ABSTRACT: Results from a numerical study of the response of thin-walled compression-loaded quasi-isotropic laminated composite cylindrical shells with unreinforced and reinforced square cutouts are presented. The effects of cutout reinforcement orthotropy, size, and thickness on the non-linear response of the shells are described. A high-fidelity non-linear analysis procedure has been used to predict the non-linear response of the shells. The analysis procedure includes a non-linear static analysis that predicts stable response characteristics of the shells and a non-linear transient analysis that predicts unstable dynamic buckling response characteristics. The results illustrate the complex non-linear response of a compression-loaded shell with an unreinforced cutout. In particular, a local buckling response occurs in the shell near the cutout and is caused by a complex non-linear coupling between local shell-wall deformations and in-plane destabilizing compression stresses near the cutout. In general, reinforcement around a cutout in a compression-loaded shell can retard or eliminate the local buckling response near the cutout and increase the buckling load of the shell. However, results are presented that show how certain reinforcement configurations can cause an unexpected increase in the magnitude of local deformations and stresses in the shell and cause a reduction in the buckling load. Specific cases are presented that suggest that the orthotropy, thickness, and size of a cutout reinforcement in a shell can be tailored to achieve improved buckling response characteristics.

Mark W. Hilburger (NASA Langley Research Center, Hampton, Virginia 23681-2199, USA), “Buckling and failure of compression-loaded composite laminated shells with cutouts”, One of the AIAA Structures Meetings after 2005 (date not given in the pdf file; latest reference is dated 2005)

ABSTRACT: Results from a numerical and experimental study that illustrate the effects of laminate orthotropy on the buckling and failure response of compression-loaded composite cylindrical shells with a cutout are presented. The effects of orthotropy on the overall response of compression-loaded shells is described. In general, preliminary numerical results appear to accurately predict the buckling and failure characteristics of the shell considered herein. In particular, some of the shells exhibit stable post-local-buckling behavior accompanied by interlaminar material failures near the free edges of the cutout. In contrast another shell with a different laminate stacking sequence appears to exhibit catastrophic interlaminar material failure at the onset of local buckling near the cutout and this behavior correlates well with corresponding experimental results.

References listed at the end of the paper:
ABSTRACT: Results from a numerical study of the buckling response of two different orthogrid stiffened circular cylindrical shells with initial imperfections and subjected to axial compression are used to compare three different lower bound buckling load prediction techniques. These lower bound prediction techniques assume different imperfection types and include an imperfection based on a mode shape from an eigenvalue analysis, an imperfection caused by a lateral perturbation load, and an imperfection in the shape of a single stress-free dimple. The STAGS finite element code is used for the analyses. Responses of the cylinders for ranges of imperfection amplitudes are considered, and the effect of each imperfection is compared to the response of a geometrically perfect cylinder. Similar behavior was observed for shells that include a lateral perturbation load and a single dimple imperfection, and the results indicate that the predicted lower bounds are much less conservative than the corresponding results for the cylinders with the mode shape imperfection considered herein. In addition, the lateral perturbation technique and the single dimple imperfection produce response characteristics that are physically meaningful and can be validated via testing.

References listed at the end of the paper:

ABSTRACT: The problem of designing a cutout in a load bearing structural member in the form of a shell, such that the cut structure maintains its stress state with a minimal departure from the stress state of the uncut structure is addressed herein. Symmetrically laminated composite circular cylindrical shells under hydrostatic compression and axial pressure are considered. Shallow thin shell (Donnell shell theory) lamination theory is utilized. The original (uncut) stiffness of the shell structures is recovered considerably by appropriately designing an edge reinforcement around the cutout. The buckling load of the designed shells are analyzed via the finite element method. An experimental investigation has been carried out to verify some of the results obtained from the finite element analysis. In the work presented, the reinforcement is modeled as a one-dimensional rod/beam type structural element.

ABSTRACT: An analysis-based approach for developing shell buckling design factors for cylindrical shells that accurately accounts for the effects of initial geometric imperfections is presented. To develop this approach, measured initial geometric imperfection data from six laboratory-scale graphite-epoxy shells are used to determine a manufacturing-process-specific imperfection signature for these shells. This imperfection signature is then used as input into nonlinear finite element analyses. The imperfection signature represents a “first approximation” mean imperfection shape that is suitable for developing preliminary design data. Comparisons of test data and analytical results obtained by using several different imperfection shapes are presented for
selected shells. These imperfection shapes include the actual measured imperfection shape of the test specimens, a “first approximation” mean imperfection shape with plus or minus one standard deviation in the shape, and a linear-bifurcation-mode imperfection shape. In addition, buckling interaction curves for composite shells subjected to combined axial compression and torsion loading are presented that were obtained by using the various imperfection shapes in the analyses. A discussion on the development of experimentally validated nonlinear finite element analyses is also presented. Overall, the results indicate that the proposed analysis-based approach presented herein, for developing reliable preliminary design criteria, has the potential to provide improved, less conservative buckling load estimates, and to reduce the weight and cost of developing buckling-resistant shell structures.

Hilburger, M. W. (1 and 3), Britt, V. O. (2), and Nemeth, M. P. (3)
(1) National Research Council, Washington, DC 20418, USA
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(3) NASA Langley Research Center, MS 190, Hampton, VA 23681-0001, USA,
“Buckling Behavior of Compression-Loaded Quasi-Isotropic Curved Panels With a Circular Cutout,”
doi:10.1016/S0020-7683(00)00114-1
ABSTRACT: Results from a numerical and experimental study of the response of compression-loaded quasi-isotropic curved panels with a centrally located circular cutout are presented. The numerical results were obtained by using a geometrically nonlinear finite element analysis code. The effects of cutout size, panel curvature and initial geometric imperfections on the overall response of compression-loaded panels are described. In addition, results are presented from a numerical parametric study that indicate the effects of elastic circumferential edge restraints on the prebuckling and buckling response of a selected panel and these numerical results are compared to experimentally measured results. These restraints are used to identify the effects of circumferential edge restraints that are introduced by the test fixture that was used in the present study. It is shown that circumferential edge restraints can introduce substantial nonlinear prebuckling deformations into shallow compression-loaded curved panels that can result in a significant increase in buckling load.

doi: 10.1002/9780470686652.eae178
ABSTRACT: Guidelines on the development of a successful test plan for large-scale, aerospace vehicle shell buckling tests with particular attention given to defining test objectives and requirements are presented. In addition, some of the more challenging aspects of test planning, test operations, test article, and test apparatus design are discussed, and recommendations on instrumentation and control system setup for buckling tests and including state-of-the-art measurement approaches and technologies are provided. In many cases, actual examples are given. This chapter is intended to provide the first time as well as the experienced test engineer or project manager with experiences and lessons learned from recent large-scale aerospace vehicle development test activities at NASA.

Mark W. Hilburger (NASA Langley Research Center, Hampton, VA, USA), “Developing the next generation shell buckling design factors and technologies”, AIAA Paper AIAA 2012-1686, 53rd AIAA Structures,
Structural Dynamics and Materials Meeting, Honolulu, Hawaii, April 2012

ABSTRACT: NASA’s Shell Buckling Knockdown Factor (SBKF) Project was established in the spring of 2007 by the NASA Engineering and Safety Center (NESC) in collaboration with the Constellation Program and Exploration Systems Mission Directorate. The SBKF project has the current goal of developing less conservative, robust shell buckling design factors (a.k.a. knockdown factors) and design and analysis technologies for light-weight stiffened metallic launch vehicle (LV) structures. Preliminary design studies indicate that implementation of these new knockdown factors can enable significant reductions in mass and mass-growth in these vehicles and can help mitigate some of NASA’s LV development and performance risks. In particular, it is expected that the results from this project will help reduce the reliance on testing, provide high-fidelity estimates of structural performance, reliability, robustness, and enable increased payload capability. The SBKF project objectives and approach used to develop and validate new design technologies are presented, and provide a glimpse into the future of design of the next generation of buckling-critical launch vehicle structures.

References listed at the end of the paper:
The Ritz method is selected to solve the non-criterion.

eigenvalue problem that can be used to predict the instability behavior, the latter using the neutral equilibrium stationary conditions of the total potential energy in order to obtain the non-

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are able to take into account both geometric and load imperfections, which are recognized to be among the main

imperfection sensitive structures. From t

order to present and discuss some of the main deterministic approaches currently used for the design of

shells under various loads and boundary conditions will be proposed. An introduction is given to the reader in

investigated and new semi-analytical models capable to predict the static and the instability response of these shells under various loads and boundary conditions will be proposed. An introduction is given to the reader in order to present and discuss some of the main deterministic approaches currently used for the design of imperfection sensitive structures. From this introduction it will become clear the need for non-linear tools that are able to take into account both geometric and load imperfections, which are recognized to be among the main factors affecting the load carrying capacity of the shells under discussion.

The complete non-linear strain equations are derived using two Equivalent Single-Layer Theories: the Classical Laminated Plate Theory and the First-order Shear Deformation Theory. The non-linear terms will be identified corresponding to Donnell’s, Sanders’ and Timoshenko and Gere’ assumptions, but the discussion will focus on Donnell’s and Sanders’ equations. The resulting strain- displacement equations will then be applied to the stationary conditions of the total potential energy in order to obtain the non-linear static equations and the eigenvalue problem that can be used to predict the instability behavior, the latter using the neutral equilibrium criterion.

The Ritz method is selected to solve the non-linear set of equations and a new set of appropriate approximation


ABSTRACT: The non-linear buckling of unstiffened laminated composite cones and cylinders will be investigated and new semi-analytical models capable to predict the static and the instability response of these shells under various loads and boundary conditions will be proposed. An introduction is given to the reader in order to present and discuss some of the main deterministic approaches currently used for the design of imperfection sensitive structures. From this introduction it will become clear the need for non-linear tools that are able to take into account both geometric and load imperfections, which are recognized to be among the main factors affecting the load carrying capacity of the shells under discussion.

The complete non-linear strain equations are derived using two Equivalent Single-Layer Theories: the Classical Laminated Plate Theory and the First-order Shear Deformation Theory. The non-linear terms will be identified corresponding to Donnell’s, Sanders’ and Timoshenko and Gere’ assumptions, but the discussion will focus on Donnell’s and Sanders’ equations. The resulting strain- displacement equations will then be applied to the stationary conditions of the total potential energy in order to obtain the non-linear static equations and the eigenvalue problem that can be used to predict the instability behavior, the latter using the neutral equilibrium criterion.

The Ritz method is selected to solve the non-linear set of equations and a new set of appropriate approximation
functions for the displacement field is proposed, in order to simulate axial compression, torsion, pressure, load asymmetry, any arbitrary surface or concentrated loads; and any load case combining these loads. Elastic constraints are used to produce a wide range of boundary conditions, covering the four types of boundary conditions commonly used in the literature.

Two methods to solve the non-linear static equations are discussed: Newton-Raphson with line search and Riks; both presented in the full form, where the tangent stiffness matrix is calculated at every iteration; and in the modified form, where the tangent stiffness matrix is updated at the beginning of each load increment (or arc-length increment) and kept constant along the iterations.

An analytical integration scheme is proposed for the linear stiffness matrices and a numerical integration scheme proposed for the non-linear stiffness matrices. The analytical integration schemes assume constant laminate properties over the whole conical/cylindrical surface. For conical shells a novel approximation is proposed in order to efficiently perform the analytical integration of the linear stiffness matrices.

Detailed convergence analyses are presented and the proposed models are verified with finite element results, models available from the literature and test results from the literature. All the developed tools and algorithms are presented in detail and made available to the reader online.

References listed at the end of the dissertation:

[71] F. Shadmehri, Buckling of laminated composite conical shells; theory and experiment, Montreal, Quebec, Canada: PhD thesis, Concordia University, 2012.


Mariano A. Arbelo (1), Annemarie Herrmann (2), Saullo G.P. Castro (1), Regina Khakimova (3), Mark W. Hilburger (4) and Richard Degenhardt (3)
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(4) NASA Langley Research Center, Hampton, Virginia 23681, USA
ABSTRACT: The important role of geometric imperfections on the decrease of the buckling load for thin-walled cylinders had been recognized already by the first authors investigating the theoretical approaches on this topic. However, there are currently no closed-form solutions to take imperfections into account already during the early design phases, forcing the analysts to use lower-bound methods to calculate the required knock-down factors (KDF). Lower-bound methods such as the empirical NASA SP-8007 guideline are commonly used in the aerospace and space industries, while the approaches based on the Reduced Stiffness Method (RSM) have been used mostly in the civil engineering field. Since 1970s a considerable number of experimental and numerical investigations have been conducted to develop new stochastic and deterministic methods for calculating less conservative KDFs. Among the deterministic approaches, the single perturbation load approach (SPLA), proposed by Hühne, will be further investigated for axially compressed fiber composite cylindrical shells and compared with four other methods commonly used to create geometric imperfections: linear buckling mode-shaped, geometric dimples, axisymmetric imperfections and measured geometric imperfections from test articles. The finite element method using static analysis with artificial damping is used to simulate the displacement controlled compression tests up to the post-buckled range of loading. The implementation of each method is explained in details and the different KDFs obtained are compared. The study is part of the European Union (EU) project DESICOS, whose aim is to combine stochastic and deterministic approaches to develop less conservative guidelines for the design of imperfection sensitive structures.

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“Investigation of buckling behavior of composite shell structures with cutouts”, Applied Composite Materials,
ABSTRACT: Thin-walled cylindrical composite shell structures can be applied in space applications, looking for lighter and cheaper launcher transport system. These structures are prone to buckling under axial compression and may exhibit sensitivity to geometrical imperfections. Today the design of such structures is based on NASA guidelines from the 1960’s using a conservative lower bound curve generated from a database of experimental results. In this guideline the structural behavior of composite materials may not be appropriately considered since the imperfection sensitivity and the buckling load of shells made of such materials depend on the lay-up design. It is clear that with the evolution of the composite materials and fabrication processes this guideline must be updated and or new design guidelines investigated. This need becomes even more relevant when cutouts are introduced to the structure, which are commonly necessary to account for access points and to provide clearance and attachment points for hydraulic and electric systems. Therefore, it is necessary to understand how a cutout with different dimensions affects the buckling load of a thin-walled cylindrical shell structure in combination with other initial geometric imperfections. In this context, this paper present some observations regarding the buckling load behavior vs. cutout size and radius over thickness ratio, of laminated composite curved panels and cylindrical shells, that could be applied in further recommendations, to allow identifying when the buckling of the structure is dominated by the presence of the cutout or by other initial imperfections.

References listed at the end of the paper:

ABSTRACT: A preliminary design tool for metallic stiffened fuselage cylindrical panels subjected to longitudinal compression has been developed and validated by comparison to test results. Several methodologies for stiffened panel buckling and failure predictions were examined and evaluated. An appropriate level of analysis fidelity was determined for different failure modes and design details. Results from panel tests conducted to verify analytical methods used to design the Gulfstream V aircraft were presented. The panels were representative of four general skin/stringer configurations on the aircraft. Finite Element analyses and standard analytical methods were used to predict panel failure loads. The accuracy of the finite element analysis predictions was dependent upon the level of detail included in the model. The inclusion of such details as fasteners had a significant effect on the predicted failure load. The omission of such complexities from the finite element model led to unconservative failure predictions. Standard analytical methods were found to be more efficient than finite element methods and produced conservative panel failure loads. Improvements for a preliminary design tool were identified to reduce conservatism in failure predictions and thereby reduce structural weight.

Starnes, James H., Jr. ; Hillburger, Mark W., “Using High-Fidelity Analysis Methods and Experimental Results to Account for the Effects of Imperfections on the Buckling Response of Composite Shell Structures”, March 2003, http://handle.dtic.mil/100.2/ADP014170
ABSTRACT: The results of an experimental and analytical study of the effects of initial imperfections on the buckling response of unstiffened thin-walled compression-loaded graphite-epoxy cylindrical shells are presented. The analytical results include the effects of traditional and nontraditional initial imperfections and uncertainties in the values of selected shell parameters on the buckling loads of the shells. The nonlinear structural analysis results correlate very well with the experimental results. The high-fidelity nonlinear analysis procedure used to generate the analytical results can also be used to form the basis of a new shell design procedure that could reduce the traditional dependence on empirical results in the shell design process.
References listed at the end of the paper:

ABSTRACT: The results of an experimental and analytical study of the effects of initial imperfections on the buckling and postbuckling response of three unstiffened thin-walled compression-loaded graphite-epoxy cylindrical shells with different orthotropic and quasi-isotropic shell-wall laminates are presented. The results identify the effects of traditional and non-traditional initial imperfections on the non-linear response and buckling loads of the shells. The traditional imperfections include the geometric shell-wall mid-surface imperfections that are commonly discussed in the literature on thin shell buckling. The non-traditional imperfections include shell-wall thickness variations, local shell-wall ply-gaps associated with the fabrication process, shell-end geometric imperfections, non-uniform applied end loads, and variations in the boundary conditions including the effects of elastic boundary conditions. A high-fidelity non-linear shell analysis procedure that accurately accounts for the effects of these traditional and non-traditional imperfections on the non-linear responses and buckling loads of the shells is described. The analysis procedure includes a non-linear static analysis that predicts stable response characteristics of the shells and a non-linear transient analysis that predicts unstable response characteristics.

ABSTRACT: The results of an experimental and analytical study of the effects of initial imperfections on the buckling response and failure of unstiffened thin-walled compression-loaded graphite-epoxy cylindrical shells are presented. The shells considered in the study have six different shell-wall laminates two different shell-radius-to-thickness ratios. The shell-wall laminates include four different orthotropic laminates and two different quasi-isotropic laminates. The shell-radius-to-thickness ratios include shell-radius-to-thickness ratios equal to 100 and 200. The numerical results include the effects of traditional and nontraditional initial imperfections and selected shell parameter uncertainties. The traditional imperfections include the geometric shell-wall mid-surface imperfections that are commonly discussed in the literature on thin shell buckling. The nontraditional imperfections include shell-wall thickness variations, local shell-wall ply-gaps associated with the fabrication process, shell-end geometric imperfections, nonuniform applied end loads, and variations in the boundary conditions including the effects of elastic boundary conditions. The cylinder parameter uncertainties considered include uncertainties in geometric imperfection measurements, lamina fiber volume fraction, fiber and matrix properties, boundary conditions, and applied end load distribution. Results that include the effects of these traditional and nontraditional imperfections and uncertainties on the nonlinear response characteristics, buckling loads and failure of the shells are presented. The analysis procedure includes a nonlinear static analysis that predicts the stable response characteristics of the shells and a nonlinear transient analysis that predicts the unstable response characteristics. In addition, a common failure analysis is used to predict material failures in the shells.

[70] Hilburger, M. W., Nemeth, M. P., and Starnes, J. H., Jr. (NASA Langley Research Center, Hampton,
ABSTRACT: An analysis-based approach for developing shell buckling design criteria for laminated-composite cylindrical shells that accurately account for the effects of initial geometric imperfections is presented. With this approach, measured initial geometric imperfection data from six graphite-epoxy shells are used to determine a manufacturing-process-specific imperfection signature for these shells. This imperfection signature is then used as input into nonlinear finite-element analyses. The imperfection signature represents a "first-approximation" mean imperfection shape that is suitable for developing preliminary-design data. Comparisons of test data and analytical results obtained by using several different imperfection shapes are presented for selected shells. These shapes include the actual measured imperfection shape of the test specimens, the "first-approximation" mean imperfection shape, with and without plus or minus one standard deviation, and the linear-bifurcation-mode imperfection shape. In addition, buckling interaction curves for composite shells subjected to combined axial compression and torsion loading are presented that were obtained by using the various imperfection shapes in the analyses. A discussion of the nonlinear finite-element analyses is also presented. Overall, the results indicate that the analysis-based approach presented for developing reliable preliminary-design criteria has the potential to provide improved, less conservative buckling-load estimates, and to reduce the weight and cost of developing buckling-resistant shell structures.

ABSTRACT: This study addresses the effect of thickness variation on the stability of the composite cylindrical shells under axial compression. Various lamination configurations and three commonly used composite materials are considered. Numerical results show that certain types of thickness variation patterns can greatly reduce the classical buckling load. Results indicate that the most detrimental effect of the thickness variation occurs when the wave number of the thickness variation is twice that of the classical buckling mode. For this case, an asymptotic formula is established by use of a computer algebra, which relates the buckling load reduction rate to the thickness variation parameter.

[72] Li, Y. W., Elishakoff, I., Starnes, J. H., Jr., and Shinozuka, M., Prediction of natural frequency and buckling load variability due to uncertainty in material properties by convex modeling, Fields Institute Communications, American Mathematical Society, Vol. 9, pp. 139-154 (1996)


ABSTRACT: (cannot cut and paste)

Abramovich, H. and Zarutskii, V., “Stability of open circular cylindrical shells reinforced with longitudinal
ABSTRACT: We obtain exact and approximate solutions to buckling problems for circular cylindrical open shells hinged at all edges and quasiregularly reinforced with discrete longitudinal ribs. It is shown that analogous solutions to natural-vibration problems for such shells can easily be found.

References listed at the end of the paper:


ABSTRACT: A nonlinear two-degree-of-freedom system is considered to simulate the peculiar behavior of stringer-stiffened cylindrical shells under nonuniform axial compression, which was observed in recent tests where the characteristic curves (eigenfrequency squared versus load) were nonmonotonic and decreasing steeply when approaching the critical load. Correlation is traced between the characteristic curves and equilibrium paths. It is shown that for particular nonzero values of load eccentricity, bifurcations are observed instead of the usual limit points. Nonunique stable post-buckling equilibrium paths are pointed out. The general properties of characteristic curves are discussed.


ABSTRACT: Eight curved blade stringer-stiffened composite panels were tested under axial compression to obtain the "first" buckling and postbuckling behavior till collapse. Except for one panel, used as a reference panel, all of the panels had stringers without dropoff layers. Four panels contained either artificial damage or
both artificial and impact-induced damage. Cyclic/repeated buckling was applied well in a relatively "deep" postbuckling region. It was demonstrated that neither repeated buckling, within the number of cycles applied in the present program, nor artificial damage and impact-induced damage, which were introduced into the panels, resulted in stiffness degradation of the panels. No premature failure of any of the tested panels was observed within their expected life cycle, i.e. exposure to a few hundred cycles deep in the postbuckling region, even in the presence of either type or a combination of the damage. All of the tested panels sustained repeated postbuckling loading till they were subjected to static loading aimed at determining their collapse loads. In spite of the present design, i.e. stiffeners with no dropoff plies aimed amongst others at providing a mechanism for initiating stiffener debonding, no skin-stringer separation was encountered till collapse of the panels. It was found that composite stringer-stiffened panels can be safely and repeatedly loaded in their deep postbuckling range with no degradation in their stiffness. Damage, due to either manufacturing or impact, which usually will result in rejection of a structural element, affected neither the load-carrying capacity nor the capability to withstand repeated loading in the relatively very deep postbuckling range within the present designed life cycle of the element. It was realized that manufacturing complexities and consequently costs can be reduced by employing a simplified design configuration where the use of a dropoff ply of the stringer base has been eliminated.


ABSTRACT: An extensive test series on circular cylindrical laminated composite stringer-stiffened panels subjected to axial compression, shear loading introduced by shear and combined axial compression and shear was carried out at the Technion, Israel. The test program was an essential part of an ongoing effort undertaken by the POSICOSS project (improved postbuckling simulation for design of fibre composite stiffened fuselage structures) aiming at design of low cost, low weight airborne structures that was initiated and supported by the Fifth European Initiative Program. The first part of this test series, dealing with panels PSC1–PSC9 (blade-stiffened), has already been summarized and published. The results of the tests with panels BOX1–BOX4 (blade- and J-stiffened) have also been reported and published. These tests dealt with two identical stiffened panels, combined together by two flat nonstiffened aluminum webs, to form a torsion box, thus enabling application of shear tractions, through introduction of torsion, and combined axial compression and shear. The present manuscript aims at describing test results and relevant numerical studies on the buckling and postbuckling behavior of another set of four panels, AXIAL1–AXIAL4, stiffened by J-type stringers. Based on the experimental studies carried out within the framework of the POSICOSS project and reported in the literature and on the present study design guidelines were formulated and presented. Accompanying supporting calculations were presented as well; they were performed with a “fast” calculation tool developed at the Technion, and based on the effective width method modified to handle laminated circular cylindrical stringer-stiffened composite panels.

References listed at the end of the paper:


H. Abramovich (1), C. Bisagni (2), and P. Cordisco (2),
“Effect of cyclic post-buckling loads on CFRP panels,” 2008 (publisher not given in the “pdf” file)

ABSTRACT: Experimental results obtained on four carbon fiber composite stiffened curved panels subjected to static and cyclic compression and shear loadings are discussed. Two of the four panels presented an initial delamination obtained with Teflon inserts between stringers and skin. Panels were assembled in two closed boxes using flat aluminum plates. This solution allows the application of shear on each panel by applying torque on the box. The first box was obtained using undamaged panels, while the second one assembling damaged panels. Results are described in terms of axial load vs. shortening curve, torque vs. rotation curve, deformed shape and strain measurements. Boxes were subjected to a cyclic post-buckling torque, allowing the investigation of the effect of cyclic buckling in terms of global and local behavior. The obtained results show that this kind of structures can well work in the post-buckling field even if during their operative life the buckling load is reached thousands of times.

References listed at the end of the paper:

H. Abramovitch (Technion-Israel Institute of Technology, Israel), “Experimental studies of stiffened composite panels under axial compression, torsion and combined loading”,

PARTIAL ABSTRACT: Experimental results on the behavior of nine single panels and of four torsion boxes, each comprising of two stringer-stiffened cylindrical graphite-epoxy composite panels are presented. These were tested under axial compression, torsion and combined loading. The buckling and postbuckling behavior of these single panels and torsion boxes demonstrated consistent results. Prior to performing the buckling tests, the initial geometric imperfections of the panels and boxes were scanned and recorded. The tests were complemented by finite element calculations, which were performed for each panel and box. These detailed calculations have also assisted in identifying critical regions of the boxes and the boxes were reinforced accordingly to avoid premature failure. The investigation on the single panels revealed a good correlation between the predictions of the finite element codes and the experimental results…

References listed at the end of the paper:


ABSTRACT: In a number of applications, the actual boundary conditions at the ends of a cylinder are not taken into account properly when the structure is being designed against buckling. For example, in the design of submersibles the older theoretical treatments assume that bulkheads are present at the ends of the cylinders, whereas this form of construction is not always used. The purpose of the investigation described here is to study the effect of realistic boundary conditions on the elastic buckling pressure of unstiffened cylinders with torispherical or hemispherical end closures. In the present study only perfect, initially stress-free, structures are
considered and their theoretical buckling pressures are obtained from a variational finite-difference program written for the digital computer. The numerical results presented were obtained from a limited parametric survey of the problem. In the main, linear buckling theory was used. However, as is shown, this can sometimes lead to unsafe predictions. The buckling pressures for the cylinders with hemispherical end closures, as predicted by the variational finite-difference technique, are also compared with a modified von Mises formula with corrections for the end closures. The agreement between the two sets of predictions was good within the range of the survey.

ABSTRACT: Elastic and elastic-plastic buckling pressures for internally-pressurized 2:1 ellipsoidal shells with diameter-thickness ratios in the range 750 < D/t < 1500 are given in the paper. The effects of σ\textsubscript{m}, E and linear strain hardening on the buckling pressures were investigated and both flow and deformation theories utilized. Some experimental/theoretical correlations are also given. The elastic p\textsubscript{cr} \_s differ from some which have been published recently and the elastic-plastic p\textsubscript{cr} \_s are believed to be new. For steel shells, flow and deformation theories sometimes gave contradictory buckling predictions but this was not the case with the aluminum shells which were investigated.

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ABSTRACT: The elastic-plastic buckling of internally pressurized torispherical shells is considered in some detail in the paper. The effects of geometric parameters (r/D, RS/D and D/t) and material properties (σ\textsubscript{m}, E and the strain-hardening coefficient) on the elastic-plastic internal buckling pressures were investigated using the BOSOR 5 program. Based on the results of the parametric study, approximate formulas for predicting the elastic-plastic internal buckling pressures are suggested. These should be useful to designers.

ABSTRACT: With the aid of the non-linear shell buckling computer program BOSOR 4, the internal pressures at which elastic circumferential buckling (or wrinkling) take place in thin torispherical shells have been calculated. The maximum equivalent (or effective) stresses in the shells in the axisymmetric pre-buckled state were also obtained…

ABSTRACT: Thin metallic torispherical shells are used frequently in many industries as end closures on cylinders subjected to internal pressure and, for those torispheres which have diameter/thickness ratios greater than 400, elastic–plastic internal pressure buckling may occur. As yet, however, code rules to assist the designer with this buckling problem are not available in either the UK or the USA and one of the aims of this paper is to help to correct this situation. Elastic–plastic internal buckling pressures, for a range of perfect torispherical geometries and obtained with the aid of a sophisticated computer program, are given in the first part of the paper. These pcr's are then utilized (a) to develop a relatively simple equation for predicting the internal buckling pressures of torispherical shells and (b) to assess the accuracy of another, even simpler, approximate buckling equation which was suggested recently.


ABSTRACT: The elastic-plastic buckling pressures of three (the ‘optimum’ and two others) 2:1 torispherical shells subjected to internal pressure are compared with the corresponding $p_r$ for the 2:1 ellipsoidal shell. This is done for $207 \text{ N/mm}^2 \leq \sigma_{yp} \leq 620 \text{ N/mm}^2$ and over the diameter-thickness range $750 < D/t < 1250$. The result of the comparison is that the 2:1 ellipsoidal shape appears to have about 25% more buckling resistance than the 2:1 torispherical shape. Whether one can rely on this 25% margin in practice depends on the accuracy of the shape verification procedure. Some examples are discussed to illustrate the problem.

References listed at the end of the paper:


SUMMARY: Some simple approximate equations for predicting the buckling pressures of internally-pressurised perfect torispheres are given and compared with experimental results obtained on (i) small machined aluminium alloy models and (ii) large ‘as-manufactured’ stainless steel heads. The agreement between theory and test was reasonably satisfactory. Based on these results, a possible procedure for the design of these ‘as-fabricated’ heads is outlined and evaluated. The axisymmetric plastic collapse mode in these heads is also discussed briefly.

References listed at the end of the paper:
39. Wunderlich, W.: See written discussion of Ref. [5].
49. AD-Merkblatt B3: Dished ends subjected to internal or external pressure. Verein der Tech. Überwachungs-Vereine e.v. (VdTUV), Essen, 1977.


ABSTRACT: Vertical liquid-filled cylindrical shells which are subjected to horizontal seismic loads can fail by buckling in shear. One example where this might arise in the nuclear industry is with the primary vessel in a fast breeder reactor (LMFBR) and design criteria are, therefore, needed to prevent its occurrence. In the present paper, the static analogue of the foregoing problem is considered and experimental results on the plastic buckling of short, steel cantilevered cylindrical shells subjected to transverse edge shearing loads are presented. In addition, a simple quadratic equation is suggested for predicting the plastic shear buckling loads. The agreement between the experimental shear loads at the inception of buckling and the predictions of the proposed design equation is excellent for the limited range of geometries investigated.


ABSTRACT: In the diameter-to-thickness range 250 < D/t < 1000, internally pressurized torispherical shells can fail either by plastic buckling or by axisymmetric yielding. However, the present Code rules cater only for the axisymmetric yielding mode and they also restrict the D/t ratios to being less than 500. The rules are based on limit analysis results and these can be conservative for this problem. With regard to internal pressure buckling, there are as yet no design rules in either the American or the British pressure vessel Codes to prevent its occurrence. To provide guidance for a more accurate formulation of design rules for both of these failure modes over the range 300 < D/t < 1500, the authors have made a series of calculations to determine the values of Pcr (the internal buckling pressure) and Pc (the axisymmetric yielding pressure) for perfect torispherical
shells. The availability of these results, obtained with a finite-deflection shell theory, enables curves to be drawn showing when buckling is the controlling failure mode and when axisymmetric yield controls. …

ABSTRACT: The buckling of welded steel cylindrical shells under the combined action of external pressure and axial compressive loads is of considerable interest to the offshore oil and nuclear industries. However, test results on this subject are scarce and some design rules which have been proposed recently have not been validated experimentally, especially in the plastic buckling region. In order to check these rules, and suggest others, interactive buckling tests were conducted at Liverpool University on cylindrical shells having R/t = 100. One series of tests consisted of 19 machined and stress-relieved steel models having L/R ratios of 0.33, 0.74 and 1.45. The results obtained on these near-perfect machined models were compared with theoretical predictions of the behaviour of perfect cylindrical shells and the agreement between the two was good. The other series consisted of 21 welded steel models and had geometric ratios which were similar to the machined ones. The linear interaction equation \( Sp + Sx = 1 \) was used to predict the failure loads of these welded steel models and the predictions were safe in all cases. However, for some combined loading cases the linear equation was rather conservative and, in consequence, some non-linear interaction equations were investigated. These seem promising for design purposes. Irrespective of whether a linear or a non-linear equation is chosen for design, more tests will be needed to establish the scatter bands of the interactive buckling curves for various values of R/t. Some tests were also carried out on (a) the effect of the loading path on the failure loads and (b) models with localized dents. Other topics discussed in the paper are: the effects of residual stresses and initial geometric imperfections, the general procedure adopted by Codes to predict buckling loads and some discrepancies between the predictions of various Codes.

(cannot cut and paste the abstract)

G.D. Galletly (1), J. Blachut (1) and J. Kruzelecki (2)
(1) Department of Mechanical Engineering, University of Liverpool
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ABSTRACT: Plastic buckling/collapse pressures for externally pressurized imperfect hemispherical shells were calculated for several values of the yield point, the radius-thickness ratio, and the amplitude of the initial imperfections at the pole. The well-known elastic-plastic shell buckling program, BOSOR5, was used in the calculations, and two axisymmetric initial imperfection shapes were studied, a localized increased-radius type and a Legendre polynomial…. 
G. D. Galletly (1), J. Kruzelecki (2), D. G. Moffat (1), B. Warrington (1)
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ABSTRACT: The test results obtained on 24 externally-pressurised torispherical steel shells are given in this paper. The knuckle radius-to-diameter ratio of the domes varied from 0.06 to 0.18 and the spherical cap radius-to-thickness ratios were between 75 and 335. Initial shape and thickness measurements were carried out on all the torispheres and a summary of this information is given. The BOSOR5 shell buckling program was employed to predict the buckling/collapse pressures of all the domes; both perfect domes and those with axisymmetric imperfections were considered. The correlation between the theoretical predictions and the experimental results was, in general, very good. The main conclusions of the present investigation are: (i) that some of the experimental buckling pressures were lower than those obtained by multiplying the BS 5500 design values by a safety factor of 1.5, and (ii) that those torispheres with sharp knuckle radii failed by plastic collapse in the knuckle region and the collapse pressures were not very sensitive to initial geometric imperfections. It thus appears that the BS 5500 rules relating to the strength of shallow torispheres subjected to external pressure need to be amended, and that the tolerances on geometric shape for cases which are likely to be imperfection-insensitive should be reconsidered.


ABSTRACT (cannot cut and paste abstract)


ABSTRACT: Perfect clamped torispherical shells subjected to external pressure are analysed in the paper using the BOSOR5 shell buckling program. Various values of the knuckle radius-to-diameter ratio (r/D) and the spherical cap radius-to-thickness ratio (Rs/t) were studied, as well as four values of sigma_y, the yield point of the material. Buckling/collapse pressures, modes of failure and the development of plastic zones in the shell wall were determined. A simple diagram is presented which enables the failure mode in these shells to be predicted. The collapse pressures, pc, were also plotted against the parameter….


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ABSTRACT: Various shell buckling problems have been studied in the Department of Mechanical Engineering at Liverpool over the past decade. The background to these problems, and the work carried out on them at Liverpool, is discussed briefly in this paper. The shell types which have been investigated are doubly-curved shells (torispheres and hemispheres) and cylinders (mainly unstiffened but some with ring stiffeners). The principal applied loading has been uniform pressure (internal or external) but transverse edge shear and axial compression loads on cylinders have also been studied.

References listed at the end of the paper:
30. CODAP, Code Français de Construction des Appareils à Pression SNCT, AFIAP (10, avenue Hoche, Paris).
46. DASl (Deutscher Ausschuss fur Stahlbau), Richtlinie 013, Beulsicher-heimsnachweise fur Schalen, July 1980, Cologne, Germany.


51. Blachut, J., Galletly, G. D. and Moreton, D. N. “Buckling of Near-Perfect Steel Torispherical and Hemispherical Shells Subjected to External Pressure”, to be published in J. AIAA.


ABSTRACT: (cannot cut and paste)

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ABSTRACT: (cannot cut and paste)
ABSTRACT (cannot cut and paste abstract)

ABSTRACT: Experimental and numerical results on seven 580 mm diameter, spun steel, hemispherical shells subjected to external pressure are discussed in the paper. The average wall thickness of the shells varied from 0.37mm to 2.5mm. Careful shape and thickness measurements on all the shells were obtained and utilised in several types of analysis (2-D Finite Element, best-fit axisymmetric, axisymmetric with a local fattening, etc.). None of the analysis techniques employed proved to be entirely reliable insofar as predicting the collapse strength of the spun steel hemispheres. For example, the ratios of the experimental to the 2-D FE numerical collapse pressures were between 0.56 and 1.21. The test results were also compared with the ECCS design curve and it is shown that one should use the minimum shell thickness for design purposes and not rely on the average wall thickness (three test results plotted below the design curve when the average wall thickness was used).

ABSTRACT: (cannot cut and past abstract)

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(1) Department of Mechanical Engineering, University of Liverpool, PO Box 147, Liverpool L69 3BX, U.K.
(2) Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, U.K.
ABSTRACT: A recent innovation in the design of submersibles is the employment of a series of circular pipes to form part of the pressure hull. These pipes serve as storage for gaseous oxygen, which is mixed with fuel oil to drive a diesel engine in a closed-cycle mode. One of the structural design problems with these vessels is the calculation of the local buckling pressure of the hull and in this paper this is tackled by isolating a short section of the vessel. Two adjacent toroids were considered first, together with their connecting annular segments. Then three toroids were considered. The loading was external pressure on the external surface of the vessel plus the axial thrust caused by the pressure on the end closures. The stress distributions, elastic plastic buckling pressures and mode shapes were determined using the variational finite-difference BOSOR5 program. Factors investigated for the 2-torus case were: the shape of the connecting segments, the constraint conditions at the contact point between the toroids and the influence of the yield stress. The results of the investigation showed that: (i) the local buckling pressure of the 3-torus structure was almost the same as that of the 2-torus case; and
(ii) cylindrical connecting segments gave a higher buckling pressure than circular toroidal ones. A simple approximate method for calculating the local buckling pressure of the 2-torus shell structure was also checked. It turned out to be conservative, giving a buckling pressure which was about three-quarters of the BOSOR 5 value.

ABSTRACT: When perfect, externally pressurized complete circular toroidal shells buckle, the minimum buckling pressure pc occurs in the axisymmetric n = 0 mode, with pc for n = 2 being only slightly larger. In the present paper, the effects of axisymmetric initial geometric imperfections on reducing pc for the perfect shell are investigated. Various types of imperfection are studied, i.e. localized flat spots, smooth dimples, sinusoids and buckling mode shapes. The principal geometry investigated was R/b = 10, b/t = 100, although other geometries were also considered. The maximum decrease in buckling resistance….

ABSTRACT: It was predicted recently that some complete toroidal shells of elliptical cross-section would buckle when subjected to internal pressure. As yet there is no experimental evidence for this, so two independent shell buckling programs (BOSOR and INCA) were employed to calculate the internal buckling pressures for some test cases. The agreement between the results of the two programs is very good, with both programs predicting that buckling occurs. Calculations were also carried out by using BOSOR on complete toroids having cross-sections in the form of prolate (k=a/b>1.0) ellipses. The ranges of the parameters were: R/b=4 and 10, b/t=50, 100 and 200, and 1.3<k<2.5. The shells were assumed to be perfect, made from steel and to behave elastically. The buckling pressures and circumferential wavenumbers are given in tabular form and some are plotted graphically. The deformed shapes of some typical cross-sections prior to buckling are also illustrated, along with the buckling modes.

ABSTRACT: This paper summarizes the results of numerical studies into the effects of initial geometric imperfections on the elastic buckling behaviour of steel circular and elliptic toroidal shells subjected to follower-type external pressure. The types of initial imperfection studied are (a) axisymmetric localized ones and (b) sinusoidal buckling modes. The principal localized imperfections studied are (i) circular increased-radius "flat spots" and (ii) smooth dimples. The buckling pressures pc of circular toroidal shells were not very sensitive to initial imperfections. With elliptic toroids, whether the shell was sensitive to initial imperfections or not depended on the ratio k(a/b) of major to minor radii of the section. The shells on the ascending part of the pc versus k curve behaved like circular toroidal shells, i.e. they were not sensitive to initial imperfections. However, the behaviour of elliptic toroids on the descending part of the pc versus k curve was very different. The
numerical results quoted in the paper are for limited ranges of the geometric parameters. It would be useful to extend these ranges, to explore the effects of plasticity and to conduct model tests on imperfect steel models to verify the conclusions of the numerical studies.

ABSTRACT: Optimal meridional shape and thickness distributions in a filament wound dome closure were investigated in order to increase shell buckling strength under static external pressure. The meridional shape was sought amongst generalized ellipses. The variable thickness profile was obtained through appropriate stacking sequence of continuously wound pre-preg carbon in polar mode. Significant increases in the collapse pressures were obtained for some analysed configurations. The collapse strength of optimally wound domes was then compared with quasi-isotropic lay-up of woven and vacuum bagged closures having the same mass and meridional shape. The latter models were, in many cases, stronger than their wound counterparts. The complex method of Box was used as an optimizer. Bifurcation buckling, axisymmetric snap-through and first ply failure were included in the evaluation procedure.

J. Blachut and G. Galletly, “Progressive collapse of composite shells”, March 1994-October 1997 research project at the University of Liverpool, Engineering and Physical Sciences Research Council (EPSRC) Reference: GR/J14622/01
ABSTRACT: Progressive collapse of this externally-pressurised doubly-curved composite shells, from woven cloth, is to be investigated. This includes development of theoretical/numerical model(s) for the post first ply failure region. The numerical predictions of the difference in strength between the first-ply failure (FPF) and the last-ply failure pressures will be compared with experiments. The behaviour of composite shells in the post FPF region is of great practical importance. We aim here to capture the correct mechanisms of failure and reliable predictions of same backed by experiment.

ABSTRACT: The paper considers barreling of a mild steel cylindrical shell as a way of improving its load carrying capacity when subjected to static external pressure. Numerical results show that the load carrying capacity can be increased from 1.4 to 40 times above the load capacity of mass equivalent cylinders. The effect of end boundary conditions on the ultimate load is examined together with sensitivity of buckling loads to initial geometric imperfections.

ABSTRACT: An effort is made to parametrically establish the maximal compressive axial buckling load of a 'bowed out' shell whose wall thickness and shell volume are maintained constant. Buckling load increase is due to the change in the shell meridional curvature. While there is no dramatic increase in the buckling load, gains of up to 20 percent can be achieved through curvature shaping of the kind presently employed.

J. Blachut (Department of Mechanical Engineering, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, U.K.), “Combined axial and pressure buckling of shells having optimal positive Gaussian curvature”,
ABSTRACT: The optimal curvature of a monocoque toroidal, clamped-clamped shell under axial compression and external pressure is sought under static stability constraints. The material is assumed to be either elastic or elastic-plastic and nonlinear prebuckling effects are included. The results of this parametric study are presented for length/radius ratios varying from 0.5 to 4.0 and radius/thickness varying from 100 to 1000.

J. Blachut (Department of Mechanical Engineering, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, U.K.), “Optimally shaped torispheres with respect to buckling and their sensitivity to axisymmetric imperfections”, Computers & Structures, Vol. 29, No. 6, 1988, pp. 975-981, doi:10.1016/0045-7949(88)90323-9
ABSTRACT: A discrete version of dynamic programming is used to optimise elastic-plastic externally pressurised torispheres. Step-wise redistribution of mass along the meridian is allowed with an arbitrary number of segments. The optimally shaped torispheres seem to be sensitive to initial axisymmetric geometrical imperfections to the same extent as spherical caps/hemispheres—unlike torispheres with uniform thickness. The full advantage of 15–50% increase in buckling pressure requires shape control to a considerable degree of accuracy.

ABSTRACT: Parabolic and cubic splines together with circular arcs are used to approximate the meridional shapes of multisegmental, axisymmetric, externally pressurized domes. Bifurcation buckling, axisymmetric collapse and fibre first ply failure are considered as possible mechanisms of dome collapse. The objective is to maximize the lowest collapse pressure for a constant wall thickness, given the material and the through thickness lamination sequence. The optimization procedure is based on the complex method of Box and the geometrically nonlinear analysis uses the classical lamination theory. The largest increase in the failure load is obtained for segments made out of circular arcs. A generalized ellipse is also used as a possible meridional profile.

ABSTRACT: Sensitivity of bifurcation buckling, first-ply failure (FPF) and last-ply failure (LPF) to the different modelling methods of woven cloth is examined numerically for a range of torispherical shells. Axisymmetric and two two-dimensional models are used for externally pressurized multi-ply domes. In the first two-dimensional model, angles between warp and weft directions on torispheres are obtained through an optical projection of an initially orthogonal woven net. In the second type of modelling, a planar/orthogonal mapping is preserved on the torispherical geometry. Bifurcation buckling seems to be insensitive to the method of modelling. Results for FPF show that differences between axisymmetric and planar models can be as high as 50%, whilst the differences for optical and planar models can reach 30%. The magnitude of LPF pressures is also sensitive to the two-dimensional modelling method adopted. Ultimate collapse loads, associated with LPFs and based on optical modelling, are up to 30% higher than those obtained for planar modelling for carbon cloth.


ABSTRACT: The effect of knuckle size and length of the cylindrical flange on the buckling strength of externally pressurised torispheres with a sharp knuckle is examined numerically. Both elastic and elastic–perfectly plastic modelling is used. It is illustrated how sensitivity of the load-carrying capacity to the boundary conditions can be removed by the adoption of a large enough knuckle or a cylindrical flange of appropriate length. Experimental results available for the sharp knuckle domes are collected and 10 new tests are carried out on machined steel domes. Two tests on spun torispheres are also included. The tests demonstrate that the safety margin as used for externally pressurised hemispheres and deep torispheres is inadequate for sharp knuckle torispheres with a 6% knuckle.


ABSTRACT: This article contains a survey of some of the recent literature on the structural integrity of metallic and composite domed closures subjected to external or internal pressure. The article refers to other recent reviews and gives a general overview of recent and current research with which the author has been directly or indirectly concerned. For externally pressurized heads this includes correlation between experimental and numerical results, imperfection sensitivity, low buckling resistance of shallow torispheres, and modelling of wound and handdraped multi-ply composite domes. For internally pressurized heads, the topics include the plastic buckling paradox, plastic loads and first cycle shakedown pressures. Structural optimization of vessel closures is also mentioned in the article.


ABSTRACT: The paper presents results of a numerical study into the buckling resistance of geometrically perfect and imperfect steel toroidal shells with closed cross-sections. Elastic and elastic-plastic buckling analyses of shells subjected to uniform external pressure were carried out for a range of geometries, boundary conditions and material properties. Toroids with circular and elliptical cross-sections were investigated. Elastic-plastic analyses carried out for toroids with circular cross-sections allowed identifying shell configurations,
which fail by bifurcation buckling or by collapse. An appropriate equation is proposed for identification of configurations for which either bifurcation or collapse governs the shell’s stability. The proposed equation supplements Jordan’s long-standing design formula, which is applicable to elastic buckling only. The obtained results show that toroids with an elliptical cross-section can be much stronger than shells with a circular cross-section. Calculations identified geometries possessing the largest load carrying capacity. It was found numerically that on both sides of ‘the peak performance geometry’ there is a different failure mechanism which in turn, as it is discussed in the paper, leads to different imperfection sensitivity. A simple design curve is provided for the separation of these two regions. Within each region, the paper provides simple design equations for the elastic buckling strength of geometrically perfect toroids with elliptical cross-sections. Imperfection sensitivities of elastic and elastic-plastic buckling loads to initial, localised and global shape deviations from perfect geometry are given for typical shells with circular and elliptical cross-sections. Initial geometric imperfections in the form of the eigenmode, ‘a single wave’ extracted from the eigenmode and inward dimple modelled by a cosine function in both R-circumferential and r-meridional directions are studied.

J. Blachut (Department of Mechanical Engineering, Applied Mechanics Division, The University of Liverpool, Liverpool L69 3GH, UK), “Application of simulated annealing to optimal barreling of externally pressurised shells”, ICAAISE ’01 Proceedings of the eighth international conference on The application of artificial intelligence to civil and structural engineering computing, Civil-Comp Press, 2001

ABSTRACT: The load carrying capacity, of externally pressurised and optimally shaped metallic shell, has been increased by 40 % over the performance of an equivalent cylinder. The optimal geometry has been sought within a class of generalised ellipses by the application of simulated annealing algorithm. The optimal solution has been verified experimentally by collapsing two, nominally identical, CNC-machined, mild steel shells at about 17 MPa. The wall thickness of the optimal shell was about 2.6 mm, its height was about 100 mm and its diameter was 200 mm. The effect of initial geometric imperfections on the ultimate load is also discussed. The comparison of theoretical and experimental results is good.


ABSTRACT: Current interest in non-gradient optimization can be attributed to two, distinct developments. The first stems from studying natural processes and the second from fast progress in the computing environment. The first has resulted in new optimization techniques like simulated annealing, tabu search and genetic algorithms whilst the second has made many of the existing zero order methods computationally affordable. This chapter discusses simulated annealing, tabu search, dynamic programming, random methods and other heuristics. A variety of illustrative examples is provided together with practical examples drawn from structural mechanics.

References listed at the end of the paper:

Details of collapse tests of two cylindrical and four bowed out mild steel shells are provided. The diameter of the tested shells was about 200 mm, their length varied from 75 to 100 mm whilst the wall thickness was about 3 mm. Experimental buckling/collapse pressures varied from 8 to 22 MPa. Zero radial displacements and zero rotations have been implemented at both ends of all tested shells. The sensitivity of buckling/collapse pressures to the initial, eigenmode type geometric imperfections has been assessed for both cylindrical and bowed out geometries. It appears that barrelling does not necessarily increase the sensitivity of buckling pressure to shape deviations from perfect geometry. Good agreement has been obtained between experimental results on these computer numerically controlled (CNC)-machined models and numerical predictions. Results show that, on a like-for-like basis, barrels were able to support a pressure 85% higher than mass equivalent cylinders.


The paper discusses the load-carrying capacity of toroidal shells with closed circular cross section and loaded by static external pressure. Details about the manufacturing, pre-experiment measurements and testing of three, nominally different, steel toroids are provided. Two of them were manufactured from mild steel by spinning two halves and then welding them around the inner and outer equatorial perimeters. The third one has been assembled by welding four 90-deg stainless elbows. The outer diameter of these models was about 300 mm and the wall thickness varied from 2.0 to 3.0 mm. The hoop radius-to-thickness ratio, r/t, varied from about 15 to 30. The experimental collapse pressures were in the range from 4 to 8 MPa. Comparisons with numerical results are also provided.


The load carrying capacity, of externally pressurised and optimally shaped metallic shell, has been increased by 40% over the performance of an equivalent cylinder. The optimal geometry has been sought within a class of generalised ellipses by the application of simulated annealing algorithm. The optimal solution has been verified experimentally by collapsing two, nominally identical, CNC-machined, mild steel shells at about 17 MPa. The wall thickness of the optimal shell was about 2.6 mm, its height was about 100 mm and its diameter was 200 mm. The effect of initial geometric imperfections on the ultimate load is also discussed. The comparison of theoretical and experimental results is good.


This contribution details buckling tests and numerical results for shallow spherical caps subjected to static and uniform external pressure. Six mild steel caps were carefully CNC-machined from a solid billet. Three caps were designed to fail elastically with the remaining three failing within the plastic range. Caps’ shallowness parameter, λ, varied from 3.5 to 5.5, and radius-to-thickness ratio varied from 300 to 1800. References listed at the end of the paper:

ABSTRACT: Results of a parametric study into buckling and first ply failure of bowed out cylinders, subjected to static external pressure, are discussed. It is shown that substantial pressure increases can be achieved through barreling. This can be further enhanced by varying the lamination angles. The effect of imperfections in lamination angles, and the effect of top/bottom edge boundary conditions on the buckling strength are also discussed.


ABSTRACT: Results of a numerical and experimental study into buckling performance of multi-segment pressure hull subjected to uniform hydrostatic pressure are discussed. Constituents of multi-segment configurations are bowed-out cylindrical shells with, and without flanges. Details about five collapse tests of laboratory scale mild steel, CNC machined models are given. Segments were about 200 mm diameter, 100 mm long and had uniform wall thickness of 3 mm. Experimental collapse pressures were in the range from 12 to 20 MPa. Numerical collapse pressures agreed well with those obtained during experiments.


ABSTRACT: Details are given of a numerical and experimental study into buckling of steel ellipsoidal domes loaded by static external pressure. A range of geometries and thicknesses of domes is examined, as is the influence of different boundary conditions. Shells are examined on the basis of having the same mass. The main focus of the study is on prolate domes, i.e., those taller than a hemisphere of the same base radius. Numerical predictions are confirmed by pressurizing six laboratory scale prolate domes to destruction. Details are given of the manufacture and test procedure for the domes. The adverse effects of variations in shape and wall thickness are discussed, and finite element predictions are made for geometrically imperfect domes. Correlation between the two sets of results is good. Numerically and experimentally obtained results are related to the current design codes: ASME Boiler and Pressure Vessel Code, Sec. VIII, Division 2 (described hereon as ASME VIII), PD5500, and ECCS recommendations (ASME B&PV Code, 2004 ed., Sec. 8, Division 2, New York, NY; BSI 2003 “Published Document PD5500: Specification for Unfired Pressure Vessels,” BSI London; European
ABSTRACT: The paper details numerical and experimental study on elastic buckling of cylindrical shells, which at present make no provision for prolate domes. Suggestions are made for the possible inclusion of such domes into the standards.

References listed at the end of the paper:
17 ASME B&PV Code, 2004 ed., Sec. 8, Division 2, New York, NY.


ABSTRACT: The paper details numerical and experimental study on elastic buckling of cylindrical shells caused by external pressure, a horizontal edge force and combined action of both. The following three geometries of vertical cylinders are considered: (i) circular cylinders, (ii) concentric circular cylinders, and (iii) cylinders with elliptical cross-section. In total, test results on nineteen shells are given. The experimental data is benchmarked against the FE predictions of buckling loads. Good agreement has been obtained between the experimental results and numerical predictions for all tested shells except for buckling of the concentric cylinders loaded by the horizontal edge force. Possible reasons for discrepancies are discussed. The paper offers insight into buckling performance of vertical cylinders subjected to combined loading, and in the case of concentric cylinders, into the interaction between the inner and outer shells. Some of the interaction
features, not immediately obvious, are discussed.

References listed at the end of the paper:
1. Athiannan K., Palaninathan R., 2004, Buckling of cylindrical shells under transverse shear, Thin-Walled Structures, 42, 1307-1328
15. Yao J.C., Jenkins W.C., 1970, Buckling of elliptic cylinders under normal pressure, AIAA J., 8, 1, 22-27


ABSTRACT: The load bearing capacity has been computed for axially compressed mild steel cylinders with non-uniform axial length. The initial geometric imperfection had a sinusoidal shape along the compressed edge. Computations were carried out for the radius-to-thickness ratio, 165 less-than-or-equals, slant R/t less-than-or-equals, slant 1000, the length-to-radius ratio, L/R "a 2.4, and the ratio of axial amplitude of imperfections to the wall thickness, 0 less-than-or-equals, slant A/t less-than-or-equals, slant 6.0. The contact problem between a rigid plate and a deformable cylinder was successfully benchmarked against experimental data on axially-perfect aluminium cylinders and also against predictions of other proprietary software. Buckling strength showed an astonishing sensitivity to axial imperfections in cylinders. Within the studied range, this could be nearly five times more severe than in the case of geometric imperfections in the shell’s generator, modelled with eigenmode type shape deviations of the same amplitude. The usual sequence of failure modes seen in compressed cylinders, i.e. asymmetric bifurcation followed by axisymmetric collapse is also no longer the case for some geometrical configurations. In particular, asymmetric bifurcation buckling can appear on the post-collapse path. This in turn can lead to mode jumping, i.e. the shell might not reach collapse and instead it can snap to the asymmetric mode at a much lower load than the predicted collapse. This has not been reported for metallic shells but it has recently been actively pursued for composite shells.


ABSTRACT: Eighteen mild steel cylinders with the length-to-radius ratio, L/R ≈ 2.4 and with the radius-to-wall
thickness ratio, R/t ≈ 185 were collapsed by axial compression. Cylinders had variable length at one end of sinusoidal profile. The magnitude of axial imperfection-to-wall thickness ratio, 2A/t, was varied between 0.05 and 1.0. Experimental results show that buckling strength strongly depends on the axial amplitude of imperfection. On average imperfect cylinders, with 2A/t = 1.0, are able to support 49% of experimental buckling load obtained for geometrically perfect model. The largest sensitivity of buckling strength was associated with small amplitude of imperfection in axial length. For example, for axial length imperfection amounting to 25% of wall thickness the buckling strength was reduced by 40%. It appears that the number of sinusoidal waves in the imperfection profile plays a secondary role, i.e., its role in reducing the buckling strength is not a dominant factor. The paper provides experimental details and comparisons with numerical results.


ABSTRACT: This paper considers the determination of plastic instability pressure in toroidal shells under internal uniform pressure. Analytical and numerical approaches, as well as verification by experiments, are presented. This work is inspired by Mellor’s treatment (1983, Engineering Plasticity, Ellis Horwood Ltd., Chichester; 1960, “The Ultimate Strength of Thin-Walled Shells and Circular Diaphragms Subjected to Hydrostatic Pressure,” Int. J. Mech. Sci., 1, pp. 216–228; 1962, “Tensile Instability in Thin-Walled Tubes,” J. Mech. Eng. Sci., 4(3), pp. 251–256), which assumed that plastic instability occurs at the maximum load. A closed-form formula of plastic instability condition is derived analytically. This expression for toroidal shells turns out to be the general case of spherical and cylindrical shells given by Mellor. Then the corresponding pressure is obtained by semianalytical analysis for a material with the strain hardening characteristic, s = A(B+e)^n. For the numerical approach, plastic instability pressure is the maximum pressure at which a small pressure increment causes a very large deformation. This is identified by the slope of pressure—change of volume curve approaching zero. Both approaches predict the onset of instability at the inner equator point. Experimental results of two nominally identical stainless steel toroidal shells correlated well to both approaches in terms of the magnitude of pressure and failure location.


ABSTRACT: The paper provides results of a numerical and experimental investigation into static stability of externally pressurised hemispherical and torispherical domes. Hybrid wall of considered domes includes steel–aluminium, titanium–aluminium and copper–steel–copper configurations. Buckling-collapse tests were conducted on domes manufactured from copper–steel–copper layered material. Details are provided of manufacture of domes, pre-test measurements, testing, and the FE analysis of measured geometries of domes. Five pairs of laboratory scale domes were tested. Each pair had nominally identical geometry. Total wall thickness of copper–steel–copper domes was about 1.1 mm. Inner and outer layers were copper, each 0.05 mm thick. Both types of heads, i.e., hemispherical and torispherical were manufactured from flat sheets using spinning. The (radius-to-wall-thickness)-ratio, R/t, was in the range from 40 to 200. Two values of the (knuckle-radius-to-diameter)-ratio in torispheres were used, i.e., 10% and 17%. Single, quasi-static incremental loading was applied in all cases. The end of load carrying capacity was sudden and well defined. Values of experimental buckling pressures varied from 1.7 to 10 MPa.

ABSTRACT: This paper studies the static stability of metal cones subjected to combined, simultaneous action of the external pressure and axial compression. Cones are relatively thick; hence, their buckling performance remains within the elastic-plastic range. The literature review shows that there are very few results within this range and none on combined stability. The current paper aims to fill this gap. Combined stability plot, sometimes called interactive stability plot, is obtained for mild steel models. Most attention is given to buckling caused by a single type of loading, i.e., by hydrostatic external pressure and by axial compression. Asymmetric bifurcation bucklings, collapse load in addition to the first yield pressure and first yield force, are computed using two independent proprietary codes in order to compare predictions given by them. Finally, selected cone configurations are used to verify numerical findings. To this end four cones were computer numerically controlled-machined from a solid steel billet of 252 mm in diameter. All cones had integral top and bottom flanges in order to mimic realistic boundary conditions. Computed predictions of buckling loads, caused by external hydrostatic pressure, were close to the experimental values. But similar comparisons for axially compressed cones are not so good. Possible reasons for this disparity are discussed in the paper.

References listed at the end of the paper:


ABSTRACT: The paper considers the buckling of short, and relatively thick, mild steel conical shells subjected to the combined action of external pressure and axial compression. Past results on axially compressed cones and on cones subjected to hydrostatic external pressure are compared with fresh test results on equivalent, axially compressed cylinder and with the equivalent cylinder subjected to external hydrostatic pressure. The paper contains both numerical and experimental results. Details about experiments, numerical modelling and computed estimates of the load carrying capacity of analyzed shells are given. Results of this study suggest that the concept of equivalent cylinders is not applicable to short master-cones. Combined stability plots have also been derived for the master-cone and equivalent cylinders. They provide not only the failure envelopes but also the yield envelopes and spread of plastic zones. The paper also brings into the light a useful design tool proposed by Esslinger and van Impe [8], and applicable to elastic–plastic buckling of cones subjected to external hydrostatic pressure.

ABSTRACT: Five laboratory scale models have been machined from 250 mm steel billet. The nominal wall thickness was, t = 2 mm, the semi-vertex angle, beta = 14 deg. Their (large radius, r₂, to-wall-thickness)-ratio was r₂/t ≈ 50, and the (height, h, to large-radius)-ratio was h/r₂ ≈ 1.0. Under axial compression, two nominally identical cones collapsed at F_{coll} ≈ 230 kN. Further two models were subjected to lateral pressure, and one shell to hydrostatic pressure. The magnitudes of their bifurcation pressure were, p_{bif} ≈ 4.7 MPa. Experimental results compare very well with numerical estimates of collapse and asymmetric bifurcation buckling. But the goodness of the comparison strongly depends on the modeling strategy.


ABSTRACT: Buckling of shallow spherical shells subjected to external pressure has been exploited, for example, in pressure safety devices. Shallow spherical caps have also been used as mirrors and more recently they have been considered as energy concentrators in space applications. Hence there is a renewed interest in their static stability performance. This paper addresses two issues: (1) buckling performance of caps, with shallowness parameter, lambda, varying from 3.5 to 7.5, and (2) the effect of boundary conditions on the buckling strength. In the first case, for elastic buckling of caps, there is a sudden drop in the buckling strength for small magnitude of cap's geometrical parameter lambda, i.e., for lambda ≈ 4.0. This has recently been reconfirmed for steel caps. However, it is not clear whether this drop can be eliminated or reduced in caps made from composites mainly through the lamination sequence and also by appropriate supporting of the caps perimeter—as typically used in inflatable space antenna. The current paper examines spherical caps made from composites subjected to quasi-static external pressure. The effect of different lamination sequences on the buckling strength is examined for a range of the shallowness parameter. In the second part, it is proposed to use a closed toroidal shell as means of supporting the cap's perimeter. The supporting toroidal shells can be of different cross-section, i.e., circular or elliptical. The toroids can also be internally pressurized, differently laminated, etc. Additionally the point of attachment can be chosen in such a way that buckling load is as large as possible. The effect of some of these parameters on the buckling pressures is quantified. This is an entirely numerical study.


ABSTRACT: Three types of imperfections are analysed in the current paper, and they are: (i) Initial geometric imperfections, i.e., deviations from perfect geometry, (ii) Variations in the wall thickness distribution, and (iii) Imperfect boundary conditions. It is assumed that cones are subject to: (a) axial compression only, (b) radial pressure only, and (c) combined loading, i.e., axial compression and external pressure acting simultaneously. Buckling strength of imperfect cones is obtained for all of the cases above. It is shown that the buckling strength is differently affected by imperfections, when cones are subjected to axial compression or to radial external pressure. The response to imperfections along the combined stability envelope is also provided, and these results are first of this type. The finite element analysis, using the proprietary code is used as the numerical tool. Cones are assumed to be from mild steel and the material is modelled as elastic perfectly plastic. Geometrical imperfection profiles are affine to eigenshapes. A number of them are tried in calculations, as well as the effect
of them being superimposed. The results indicate that imperfection amplitude and its shape strongly affect the load carrying capacity of conical shells. Also, it is shown that the buckling loads of analyzed cones are more sensitive when subjected to combined loading as compared to their sensitivity under single load conditions. At the next stage, uneven thickness distribution along the cone slant was considered. Variation of wall thickness was assumed to vary in a piece-wise constant fashion. This appears to have a large effect on the buckling strength of cones under axial compression only as compared with that of cones subjected to radial external pressure only. Finally, the effect of variability of boundary conditions on failure load of cones was investigated for two loading conditions, i.e., for axial compression and for radial pressure, only. Results indicate that change of boundary conditions influences the magnitude of buckling load. For axially compressed cones the loss of buckling strength can be large (about 64% for the worst case (beta = 30 deg, the cone not restrained at small radius end). Calculations for radial pressure indicate that the loss of buckling strength is not as acute — with 34% for the worst case (beta = 40 deg, relaxed boundary conditions at the larger radius end). This is an entirely numerical study but references to accompanying experimental programme are provided.


ABSTRACT: This is the first study into elastic-plastic buckling of unstiffened truncated conical shells under simultaneously acting axial compression and an independent external pressure. This is both a numerical and experimental study. Domains of combined stability are obtained using the finite element method for a range of geometrical parameters. Cones are clamped at one end and free to move axially at the other end, where all the other degrees of freedom remain constrained. Shells are assumed to be from mild steel and the material is modeled as elastic perfectly plastic. The FE results indicate that the static stability domains remain convex. The failure mechanisms, i.e., asymmetric bifurcation and axisymmetric collapse are discussed together with the spread of plastic strains through the wall thickness. Also, the combined stability domains are examined for regions of purely elastic behavior and for regions where plastic straining exists. The latter is not convex and repercussions of that are discussed. The spread of plastic strain is computed for a range of the (radius-to-wall-thickness) ratios. Experimental results are based on laboratory scale models. Here, a single geometry was chosen for validation of numerically predicted static stability domain. Parameters of this geometry were assumed as follows: the ratio of the bigger radius, r2 , to the smaller radius, r1 , was taken as (r2 /r1 ) = 2.02; the ratio of radius-to-wall-thickness, (r2 /t), was 33.0, and the cone semiangle was 26.56 degrees, while the axial length-to-radius ratio was (h/r2 ) = 1.01. Shells were formed by computer numerically controlled machining from 252 mm diameter solid steel billet. They had heavy integral flanges at both ends and models were not stress relieved prior to testing. Details about the test arrangements are provided in the paper.

References listed at the end of the paper:

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(This paper received at the Pressure Vessels and Piping Conference in Anaheim in July 2014 the Journal of Pressure Vessel Technology G.E.O. Widera Literature Award for the Outstanding Technical Paper.)

ABSTRACT: The paper provides details about tests on six steel cones. Test models were machined from 250 mm diameter billet. All cones had substantial and integral top and bottom flanges in order to secure well defined boundary conditions. Experimental data were obtained for: (i) two cones subjected to axial compression, (ii) two cones subjected to external pressure, and (iii) the remaining two models subjected to combined action of external pressure and axial compression. Apart from axisymmetric modeling of tested cones, true geometry with true wall thickness was also used in calculations. Theoretical failure loads were obtained for: (i) elastic perfectly plastic, (ii) engineering stress–strain, and (iii) true stress–true strain modeling of steel. The latter approach coupled with measured geometry and wall thickness secured safe predictions of the collapse loads in all cases. Comparisons of experimental collapse loads with estimates given by ASME and ECCS design codes are included. It is seen here that the ASME and ECCS rules provide a safety margin of about 100% against the collapse (except 50% for axial compression in the case of the ECCS).

J. Blachut (Department of Mechanical Engineering, University of Liverpool, PO Box 147, Brownlow Hill, Liverpool L69 3BX, UK), “Combined stability of geometrically imperfect conical shells”, Thin-Walled Structures, Vol. 67, pp. 121-128, June 2013, DOI: 10.1016/j.tws.2013.02.007

ABSTRACT: The paper examines the influence of axisymmetric, bulge-type shape imperfections in conical shells on buckling strength. Mild steel cones are subjected to axial load, lateral pressure, and any combination of both. Imperfection sensitivity of buckling load along the entire interactive plot for (i) inward shape deviations, (ii) outward shape deviations and (iii) both inward and outward shape imperfections is examined numerically. For all three cases the worst possible scenario is sought through the application of structural optimization. The latter employs Tabu search algorithm coupled with the FE re-analysis tool. It is shown that both inward and outward imperfections can significantly reduce the load carrying capacity. But the largest shrinkage of the interactive diagram is obtained for the case of co-existing inward and outward initial shape imperfections.

Andreas Taras, “Contribution to the development of consistent stability design rules for steel members”, Ph.d dissertation, Technical University of Graz, Austria, 2010

ABSTRACT: This thesis is concerned with open questions relating to the accuracy and safety of buckling design rules for steel members. It identifies a series of inconsistencies in the current practice of design of these members against instability and comes up with novel solutions to overcome them. The accuracy of design rules is addressed for the buckling modes of lateral-torsional, torsional-flexural and in-plane beam-column buckling. It is shown that the load-carrying capacity of steel members for these modes can be assessed with great accuracy on the basis of simple, case-specific second order (Ayrton-Perry) equations. Thereby, it is of paramount importance that the proposed design equations are calibrated to accurately reflect the results of materially and geometrically non-linear GMNIA FEM calculations. For the purposes of determining how accurately a formulation reflects the true mechanical behaviour of a certain member in a buckling mode, these GMNIA calculations are inevitably of deterministic nature, but are conveniently carried out on “model members” that inherently reflect a certain,desired safety level through their assumptions regarding imperfections and geometry. By doing so, the same, consistent procedure was finally adopted for the development of design rules for these buckling modes as for the most-studied and best-understood benchmark
case of flexural column buckling. Accordingly, also the resulting design formulae are both formally and mechanically consistent with the benchmark case.

Aspects of safety were addressed both implicitly through the above-mentioned development procedure and explicitly by the use of reliability assessments on the basis of Monte Carlo simulations and First Order Reliability Methods. Random number generation and numerical tests were used to answer some questions related to the nexus between fabrication tolerances and specified imperfections for design. Specifically, the impact of changes to the curvature tolerances of compression members was quantified by the use of these methods. Additionally, the possibility was addressed to move away from “semi-deterministic” buckling rules calibrated onto “model member” GMNIA calculations, and to directly base the calibration of buckling rules on “constant reliability curves”. Such curvatures can be obtained from a combination of numerical GMNIA and probabilistic FORM calculations.

Finally, a systematic development procedure for buckling design rules for steel members is proposed, which allows for a consistent expansion of the findings of this thesis to other buckling modes.

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ABSTRACT: This thesis is concerned with the study of the elastic-plastic buckling of short and relatively thick conical shells subjected to combined loading, i.e., axial compression and external pressure acting simultaneously. This is both numerical and experimental study. Within the context of numerical study, a
nonlinear finite element calculations were carried out in order to obtain: (i) the failure loads of cones under axial compression only, external pressure only and under combined loading, (ii) the spread of plastic strain and the effect of strain hardening of the material on failure loads, and (iii) the sensitivity of buckling loads to initial geometric imperfections or to structural defects under various loading conditions. The thesis provides results of extensive FE calculations. An experimental programme involved tests on thirteen conical specimens CNC machined with integral top and bottom flanges from 252mm diameter steel billet. The specimens were made from mild steel material with average yield stress of 230.6 MPa, Young's modulus of 21 0490 MPa and Poisson's ratio of 0.281. Prior to tests, the existing test rig had to be significantly modified and instrumented in order to accommodate independent/combined loadings. The test procedure has been developed and successfully implemented. Two models were subjected to axial compression, with further two subjected to external pressure. The remaining nine cones were subjected to combined action of axial compression and external pressure. Experimental results were compared with predictions of failure loads obtained from the existing design codes. For the case of axial compression an extension of the design rules is outlined in order to widen the range of applicability. For the case of external pressure, the test data compared well with the theoretical work by Esslinger and Van Impe, [40]. At the same time the test data highlighted how inadequate estimates of the load carrying capacity are given by the design codes. The case of combined loading, i.e., axial compression and external pressure is only covered by ASME code case 2286-2, [157], and experimental data does not exist. The current study provides the first and much needed test data. The thesis also looks into the concept of equivalent cylinder. Numerical results point out to the fact that this approach is unsuitable for combined stability scenario (axial compression and external pressure). Experimental data is also compared with predictions given by the Finite Element calculations. Details about various approaches to modeling material properties, shape, wall thickness distribution, and boundary conditions are discussed. The quality of FE models is assessed by comparing the FE predictions of the load carrying capacity with the test data.


ABSTRACT: This paper considers the buckling behaviour of commonly used shell structures in the offshore and oil industry. Three types of shells subjected to external pressure were examined, and they are: (i) torispheres, (ii) circular cylinders and (iii) truncated cones. It is assumed that shells are made from steel and the material is modeled as elastic material behaviour. Buckling strength for cases of different prebuckling/perturbation load and different edge support were obtained. In the case of transfer, results indicate that the magnitude of prebuckling/perturbation load has a significant effects on the bifurcation pressure. Whilst, changing the edge support has no effect on the buckling load. For the case of circular cylinder and cone, numerical calculation reveals that the magnitude of the prebuckling/perturbation load does not affect the bifurcation pressure. Whereas, in the case of different edge support, for a convergent solution to be obtained, the edge support must be either pinned or fully clamped at both ends. This is purely numerical study but the results of bifurcation pressure were compared with available data in open literature.

References listed at the end of the paper:

Abstract: Effect of torispherical head on the buckling of pressure vessels was investigated by finite element (FE) method. The FE method with use of nonlinear buckling analysis was applied to predict the critical buckling Load. The influences of geometrical parameter such as thickness, knuckle radius and diameter of cylindrical part, on the buckling of heads have been studied. The Arc Length method which can control the load level, the length of the displacement increment and the maximum displacement was been used. By verification performed with the European Convention for Constructional Steelwork (ECCS) code, it was confirmed that the nonlinear buckling analysis could assure accurate results for buckling strength. It was shown that geometrical imperfections had little effect on buckling strength.

ABSTRACT: In analysis of the removal of offshore jackets an important failure mode is buckling. In current practice, a buckling check involves manual determination of the buckling lengths of each frame member. It is estimated that 5 to 10% of the man-hours in structural analysis of removal projects is spend on checking and correcting buckling lengths. Fortunately, an alternative method is available that does not require determining buckling lengths. In this paper it is shown how this method can be derived from the NORSOK standard for tubular steel frame structures. The method is demonstrated in a removal analysis of an offshore jacket. It is concluded that this method can be successfully applied.

ABSTRACT: Finite element analysis has been carried on composite pipes of length-to-internal diameter ratio of 5 and internal diameter-to-thickness ratio of 20 to assess their strength when subjected to a combination of external pressure and axial compression. The effect of the winding angle of the fibre reinforcements on the buckling and first-ply failure loads of the pipes have been examined. It is shown that the optimum winding angle of the fibres varies according to the ratio of hoop-to-axial membrane stresses in the pipes. In the case of hydrostatic external pressure loading of the pipes, the optimum angle is close to 80° instead of 55° reported elsewhere for internal pressure loading.

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ABSTRACT: The outline of a procedure to calculate the buckling and material failure loads of axisymmetric composite shells and cylinders subjected to uniform pressure is presented. It is shown that conventional axisymmetric shell analysis programs have to overcome the limitation of the uniform thickness and fibre orientation circumferentially. The procedure uses this limitation to useful effect by modelling a given problem as a series of shells having uniform thickness and material properties associated with the different meridians of the shell. It is thus possible to employ one-dimensional axisymmetric shell analysis to solve effectively three-dimensional shell problems. In order to demonstrate the viability of the proposed method, three hemispherical domes prepared from two, four and six layers of woven carbon rovings in epoxy resin matrix were tested to failure under the action of external pressure loading. The domes were selected to give both buckling and material modes of failure and their failure loads were compared with those predicted by the method described herein. It is shown that for the thinnest dome having only two layers, the failure mode is bifurcation buckling with a high number of circumferential waves. The mode of failure changes to snap-through axisymmetric collapse when the number of layers is increased to four. A further addition of two layers in the dome changes the failure mode to material collapse. Theoretical prediction of the failure loads based on geometrically perfect structures and average compression properties tended to vary in the range 1.37–1.83 of the experimental values. Thus there was a reasonable agreement between the two sets of results after allowing for the scatter in compressive properties of the material and the sensitivity to geometric imperfections of thin domes.

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ABSTRACT: The necking of an elastic-plastic circular plate under uniform radial tensile loading is investigated both within the framework of the three-dimensional theory and within the context of the plane-stress approximation. Attention is restricted to axisymmetric deformations of the plate. The material behavior is described by two different constitutive laws. One is a finite-strain version of the simplest flow-theory of
plasticity and the other is a finite-strain generalization of the simplest deformation theory, which is employed as a simple model of a solid with a vertex on its yield surface. For an initially uniform plate made of an incompressible material, bifurcation from the uniformly stretched state is studied analytically. The regimes of stress and moduli where the governing axisymmetric three-dimensional equations are elliptic, parabolic or hyperbolic are identified. The plane-stress local-necking mode emerges as the appropriate limiting mode from the bifurcation modes available in the elliptic regime. In the elliptic regime, the main qualitative features of the bifurcation behavior are revealed by the plane-stress analysis, although three-dimensional effects delay the onset of necking somewhat. For the deformation theory employed here, the first bifurcation modes are encountered in the parabolic regime if the hardening-rate is sufficiently high. These bifurcations are not revealed by a plane-stress analysis. For a plate with an initial inhomogeneity, the growth of an imperfection is studied by a perturbation method, by a plane-stress analysis of localized necking, and by numerical computations within the framework of the three-dimensional theory. When bifurcation of the corresponding perfect plate takes place in the elliptic regime, the finite element results show that the plane-stress analysis gives reasonably good agreement with the numerical results. When bifurcation of the corresponding perfect plate first occurs in the parabolic regime, then a bifurcation of the imperfect plate is encountered, that is, the finite element stiffness matrix ceases to be positive definite.

ABSTRACT: The buckling behaviour is investigated for an axially compressed elastic-plastic cylindrical panel of the type occurring in stiffened shells. The bifurcation stress is determined analytically and an asymptotically exact expansion is obtained for the initial post-bifurcation behaviour in the plastic range. For panels with small initial imperfections the behaviour is analysed asymptotically on the basis of the hypoelastic theory that results from neglecting the effect of elastic unloading. The imperfection-sensitivity of an elastic-plastic panel is also computed numerically by a linear incremental method, and the results are compared with the results of the asymptotic analysis. For a low hardening material the panel is found to be imperfection-sensitive in the whole range of curvatures considered, whereas for a high hardening material the panel is only imperfection-sensitive if the curvature exceeds a certain value.

ABSTRACT: The creep buckling behaviour is investigated for simply supported rectangular plates under axial compression. In addition to creep also elastic and plastic deformations are accounted for. The initial creep buckling behaviour at small deflections is analysed by a perturbation method, and this solution is used to obtain a simple, rough estimate of the life time. Numerical solutions for the plate creep buckling are obtained by an iterative incremental method. Based on these results the effect of the creep exponent and various effects of plasticity are discussed. The failure times obtained numerically are compared with the time estimates based on a symptotic theory and with critical times predicted in earlier investigations.

Viggo Tvergaard (Department of Solid Mechanics The Technical University of Denmark, DK-2800 Lyngby, Denmark), “Plastic buckling of axially compressed circular cylindrical shells”, Thin-Walled Structures, Vol. 1,
ABSTRACT: For elastic-plastic cylindrical shells with initial axisymmetric imperfections bifurcation into a non-axisymmetric shape is analysed. The shell material is represented by a phenomenological plasticity theory that accounts for the formation of a vertex on subsequent yield surfaces. The influence of various geometric and material parameters is investigated for a wide range of radius-to-thickness ratios. It is shown that for the thicker shells bifurcation generally occurs beyond the maximum axial compressive load. A few analyses for shells with additional non-axisymmetric imperfections show the unstable post-bifurcation behaviour and the sensitivity to imperfections of more general shapes.

ABSTRACT: The influence of buckling pattern localization on the collapse mode of axially compressed elastic-plastic circular cylindrical shells is investigated. Initial imperfections are assumed to be axisymmetric and the possibility of bifurcation into a non-axisymmetric shape is analysed. For sufficiently thin-walled shells bifurcation occurs before the load maximum: but in more thick-walled shells the axisymmetric deformations are stable beyond the maximum load, at which localization into a single outward buckle takes place. It is found that localization delays bifurcation considerably, such that sufficiently thick-walled shells will collapse in an axisymmetric mode. The theoretical predictions are compared with a number of published experimental results.

ABSTRACT: Plastic buckling theory is presented, starting with the general theory of uniqueness and bifurcation for elastic-plastic solids. Also asymptotic procedures for estimating the initial post-bifurcation behaviour and the imperfection-sensitivity are presented, based on the classical elastic-plastic solid. The effect of other elastic-plastic constitutive descriptions on bifurcation and post-bifurcation behaviour is discussed. Several numerical analyses of the plastic buckling of plate — or shell structures are reviewed, and special attention is given to the localization of buckling patterns that often occurs as a secondary bifurcation. Finally, the effect of material strain-rate sensitivity on the prediction of plastic instabilities is discussed in some detail.

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ABSTRACT: Localization of an initially periodic buckling pattern is investigated for an axially compressed elastic–plastic cylindrical panel of the type occurring between axial stiffeners on cylindrical shells. The phenomenon of buckling localization and its analogy with plastic flow localization in tensile test specimens is discussed in general. For the cylindrical panel, it is shown that buckling localization develops shortly after a maximum load has been attained, and this occurs for a purely elastic panel as well as for elastic–plastic panels. In a case where localization occurs after a load maximum, but where subsequently the load starts to increase
again, it is found that near the local load minimum, the buckling pattern switches back to a periodic type of pattern. The inelastic material behavior of the panel is described in terms of J2 corner theory, which avoids the sometimes unrealistically high buckling loads predicted by the simplest flow theory of plasticity.

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ABSTRACT: Weld-induced residual stresses in shell structures tend to give earlier onset of plastic yielding and to reduce the critical buckling load. Geometrical imperfections may also have a detrimental effect on the load carrying capacity. The interaction between these two kinds of imperfections is studied here for various longitudinally welded cylindrical shell structures, with focus on short wave local buckling modes. It is found that structures with reduced bifurcation loads due to residual stresses show less sensitivity to geometrical imperfections, and after buckling mode deflections of the order of the shell thickness, the residual stresses play no role at all.


ABSTRACT: Free vibrations of turbine blades are analysed numerically by means of a general shell theory. The effect of centrifugal force is taken into account, and it is found possible to examine a wide class of blades. The continuous shell problem is discretized through a finite difference energy method, working on a simple rectangular grid mapped onto the blade surface by parameter functions. Three examples are shown, all of which are compared with previous investigations. One example considers an actual blade from the last stage of a steam turbine, while another considers a compressor blade.


ABSTRACT: This work presents a model to predict the flexural behavior of reinforced concrete slabs, combining the Mazars damage model for simulation of the loss of stiffness of the concrete during the cracking process and the Classical Theory of Laminates, to govern the bending of the structural element. A variational formulation based on the principle of virtual work was developed for the model, and then treated numerically according to the Finite Difference Energy Method, with the end result a program developed in Fortran. To validate the model thus proposed have been simulated with the program, some cases of slabs in flexure in the literature. The evaluation of the results obtained in this study demonstrated the capability of the model, in view of the good predictability of the behavior of slabs in flexure, sweeping the path of equilibrium to the rupture of the structural element. Besides the satisfactory prediction of the behavior observed as positive aspects of the model to its relative simplicity and reduced number of experimental parameters necessary for modeling. References listed at the end of the paper:
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ABSTRACT: The derivation for the nonlinear bending response of finite length composite tubes exhibiting cross-sectional deformations associated with Brazier's flattening effect is presented using classical shell theory. Semi-membrane constitutive theory is used to simplify the analysis and local buckling on the compressive side of the tube is investigated based on the axial stress and local curvature on the compressive side of the cylinder. The nonlinear system is solved numerically and results are obtained for various combinations of material and geometric parameters as well as end conditions. Results of the present investigation are compared with published finite element solutions and approximate analytical solutions for the Brazier effect of finite length tubes.


ABSTRACT: An analytical method is proposed for the solution of geometrically nonlinear Brazier problem for thin-wall pipes with initial cross-sectional shape imperfection in the case of action of pressure. Geometrical equations relating displacement components to strains and equilibrium equations taking into account change in the curvature of pipe cross section and axis have been derived. A solution in a first approximation for dimensionless flexibility parameter is presented, the exactness of which is illustrated by numerous examples. For the case of joint action of external bending moment and pressure, a limit curve of the critical moment value
as a function of pressure value has been obtained.


PARTIAL ABSTRACT: An investigation of the possible performance improvements of thin circular cylindrical shells through the use of the variable stiffness concept is presented. The variable stiffness concept implies that the stiffness parameters change spatially throughout the structure. This situation is achieved mainly through the use of curvilinear fibers within a fiber-reinforced composite laminate, though the possibility of thickness variations and discrete stiffening elements is also allowed. These three mechanisms are incorporated into the constitutive laws for thin shells through the use of Classical Lamination Theory. The existence of stiffness variation within the structure warrants a formulation of the static equilibrium equations from the most basic principles. The governing equations include sufficient detail to correctly model several types of nonlinearity, including the formation of a nonlinear shell boundary layer as well as the Brazier effect due to nonlinear bending of long cylinders. Stress analysis and initial buckling estimates are formulated for a general variable stiffness cylinder. Results and comparisons for several simplifications of these highly complex governing equations are presented so that the ensuing numerical solutions are considered reliable and efficient enough for in-depth optimization studies. Four distinct cases of loading and stiffness variation are chosen to investigate possible areas of improvement that the variable stiffness concept may offer over traditional constant stiffness and/or stiffened structures.

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15. Olmedo, R., “Compression and Buckling of Composite Panels with Curvilinear Fibers,” M.S. Thesis, Virginia Polytechnic

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ABSTRACT: The past developments on tow-placement technology led to the production of machines capable of controlling fibre tows individually and placing them onto the surface of a laminate with curvilinear topology. Due to the variation of properties along their surface, such structures are termed variable-stiffness composite panels. In previous experimental research tow-steered panels have shown increased buckling load capacity as compared with traditional straight-fibre laminates. Also, numerical analyses by the authors showed that first-ply failure occurs at a significant higher load level. The focus of this paper is to extend those analyses into the postbuckling progressive damage behaviour and final structural failure due to accumulation of fibre and matrix damage. A user-developed continuum damage model implemented in the finite element code ABAQUS is employed in the simulation of damage initiation and material stiffness degradation. In order to correctly predict the buckling loads of tow-steered panels under compression, it is of crucial importance to take into account the residual thermal stresses resulting from the curing process. Final failure of tow-steered panels in postbuckling is predicted to within 10% difference of the experimental results. Curvilinear-fibre panels have up to 56% higher strength than straight-fibre laminates and damage initiation is also remarkably postponed. Tow-steered designs also show more tolerance to central holes than traditional laminates.
ABSTRACT: Machines capable of individually controlling fibre tows and placing them onto the surface of a laminate with curvilinear topology are available nowadays. Due to the variation of properties along their surface, such structures are termed variable-stiffness composite panels. Experimental research demonstrated that properly designed tow-steered panels buckle at higher loads than traditional straight-fibre laminates. Also, numerical analyses by the authors demonstrated that first-ply failure of these designs is remarkably postponed.

The focus of this paper is to extend those analyses into the postbuckling progressive damage behaviour and final structural failure. A user-developed continuum damage model implemented in the finite element code ABAQUS is employed in the characterisation of damage initiation and propagation. As with damage initiation, failure of curvilinear-fibre panels is remarkably postponed as compared with straight-fibre laminates. Tow-steered panels also show to be more tolerant to notches than traditional laminates. By taking into account the residual thermal stresses, not only predicted and experimented buckling loads show remarkable agreement but also predicted final failure loads of tow-steered panels in postbuckling are within 12% of the experimental results.

References listed at the end of the paper:
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“Variable stiffness composite panels: Effects of stiffness variation on the in-plane and buckling response”,

ABSTRACT: Descriptions of fiber orientation variation for flat rectangular composite laminates that possess variable stiffness properties are introduced. The simplest definition employs a unidirectional variation based on a linear function for the fiber orientation angle of the individual layers. Analyses of variable stiffness panels for in-plane and buckling responses are developed and demonstrated for two distinct cases of stiffness variations. The first case assumes a stiffness variation in the direction of the loading, and numerical results indicate small improvements in buckling load for some panel configurations due to favorable distribution of the transverse stresses over the panel planform. The second case varies the stiffness perpendicular to the loading, and provides a much higher degree of improvement due to the re-distribution of the applied loads. It is also demonstrated that the variable stiffness concept provides a flexibility to the designer for trade-offs between overall panel stiffness and buckling load, in that there exist many configurations with equal buckling loads yet different global stiffness values, or vice versa.

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ABSTRACT: One of the primary advantages of using fibre-reinforced laminated composites in structural design is the ability to change the stiffness and strength properties of the laminate by designing the laminate
stacking sequence in order to improve its performance. This procedure is typically referred to as laminate tailoring. Traditionally, tailoring is done by keeping the fibre orientation angle within each layer constant throughout a structural component. Allowing the fibres to follow curvilinear paths within the plane of the laminates constitutes an advanced tailoring option that can lead to modification of load paths within the laminate to result in more favourable stress distributions and improve the laminate performance.

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“Variable-Stiffness Composite Panels: Effects Of Stiffness Variation On The Buckling And Failure Responses”, 7th EUROMECH Solid Mechanics Conference J. Ambrosio et.al. (eds.) Lisbon, Portugal, 7–11 September 2009

ABSTRACT: The traditional approach to the problem of stress concentrations around cutouts in composite structures is to locally increase the laminate thickness in order to smooth out the stress peak. Often, this practice attracts more loads to the cutout region besides increasing part weight. A more effective solution is to avoid the stress concentrations altogether by using fibre-steered laminates. The production of composites in this format is practical nowadays due to capabilities of advanced fibre-placement technology. This paper shows that it is possible to design and manufacture composite panels whose buckling and failure responses are insensitive to the existence of a central hole. This cutout insensitivity does not involve an increase in structural mass, but only the steering of the fibres in the plane of the laminate, in order to promote the redistribution of the loading towards the supported edge sections of the panel.

References listed at the end of the paper:

ABSTRACT: A generalized reciprocal approximation is presented for design of variable-stiffness laminated composite panels for maximum buckling load. The buckling load is expanded in terms of the inverse of the stiffness tensor. For discretized panels such an approximation has the important property of being separable, which allows the maximization to be carried out at each discrete node separate from the others. This makes the algorithm particularly suited to parallel computations. The sensitivity analysis is performed exactly using an adjoint method, requiring only one back substitution using the already factored in-plane stiffness matrix with different right hand sides to compute the sensitivities for all design variables. A conforming CLPT finite element is used for the buckling analysis of rectangular plates and the proposed reciprocal approximation is used to update fiber orientation angles at each finite element node. Numerical results obtained for rectangular plates show that significant improvements can be gained in the buckling load by allowing the stiffness properties to vary spatially. The case of repeated eigenvalues is handled using a dual formulation.


ABSTRACT: Fiber-reinforced composite conical shells with given geometry and material properties are optimized for maximum fundamental frequency. The shells are assumed to be built using an advanced tow-placement machine, which allows in-plane steering of the fibers, resulting in a variable-stiffness structure. In this paper, different path definitions for variable-stiffness shells are provided and used to optimize conical shells for maximum fundamental frequency, while manufacturing constraints that apply for tow placement are taken into account in the process. The influence of manufacturing constraints on the performance is shown; and improvements of variable-stiffness conical shells over conventional, constant-stiffness shells are demonstrated.
ABSTRACT: A fiber-reinforced cylindrical shell with given geometry and material properties is optimized for maximum load-carrying capability under bending. The shell is assumed to be built using an advanced fiber-placement machine, which allows in-plane steering and overlapping of fibers, resulting in a so-called variable-stiffness shell. The design methodology for strength and stiffness variation in circumferential direction by means of fiber placement is explained and restrictions on the manufacturability are specified. Implementation in the commercially available finite element package ABAQUS® for structural analysis is described. Subsequently, the cylinder is optimized to carry a maximum buckling load under bending, while applying a strength constraint. Constraints on the global stiffness are imposed by means of comparison with a baseline quasi-isotropic shell, while a matrix dominated lay up is avoided at all locations in the laminate in order to ensure that the laminate is strong enough in all directions in case a hole is present. Optimization is done using a surrogate model in order to minimize the amount of finite element analyses. Improvements of up to 17% are obtained by changing the load path. The tension side is made stiffer and the compression side softer in longitudinal direction by changing the fiber orientation from near zero at the upper (tension) side to higher fiber angles at the lower (compression) side, such that load is relieved from the compression side. This results in a higher load-carrying capability of the cylinder.

References listed at the end of the paper:


ABSTRACT: Underwater vehicles that operate in deep waters require a pressure hull to maintain the sufficient strength and stiffness against external hydrostatic pressure. We investigated the validity of the finite element method (FEM) that is applied to a buckling analysis of the filament-wound composite cylinder, subjected to an external hydrostatic pressure. Two methods were suggested for the buckling analysis of a filament-wound thick composite cylinder under hydrostatic pressure: using the equivalent properties of the composite, and using stacking sequence. The hydrostatic pressure test was conducted to verify the FEA. Test results were compared with the previous results obtained by FEM on the buckling of a filament-wound composite cylinder under hydrostatic pressure. FEM analysis results were in good agreement with the test results. The difference between FEM results and the test results was approximately 1 to 5%.

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“Buckling of filament-wound composite cylinders subjected to hydrostatic pressure for underwater vehicle applications”, Composite Structures, Vol. 92, No. 9, August 2010, pp. 2241-2251, Special Issue: Fifteenth International Conference on Composite Structures, doi:10.1016/j.compstruct.2009.08.005
ABSTRACT: The buckling and failure characteristics of moderately thick-walled filament-wound carbon–epoxy composite cylinders under external hydrostatic pressure were investigated through finite element analysis and testing for underwater vehicle applications. The winding angles were [±30/90]FW, [±45/90]FW and [±60/90]FW. ACOS, an in-house finite element program, successfully predicted the buckling pressure of filament-wound composite cylinders with 2 to 23% deviation from the test results. The analysis and test results showed that the cylinders do not recover the initial buckling pressure after buckling and that this leads directly to the collapse. Major failure modes in the test were dominated by the helical winding angles.

ABSTRACT: Progressive failure analysis based on the complete unloading method was conducted to investigate the crippling failure of carbon/epoxy composite stiffeners under axial compression. A modified arc-length algorithm was incorporated into a nonlinear finite element method to trace the equilibrium path after local buckling. For the validation of the finite element method, several carbon/epoxy Z-section stiffeners were tested in compression. The finite element results on the buckling and crippling stresses showed good agreement with the experimental results.
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Han-Gi Son, Deepak Kumar, Yong-Bin Park, Jin-Hwe Kweon and Jin-Ho Choi, “Structural design and analysis of composite aircraft fuselage used to develop AFP technology”, Proceedings of the Seventh International Symposium on Mechanics, Aerospace and Information Engineering, Hakone Pax Yoshino, Japan, February 21-23, 2013

ABSTRACT: Increasing use of composite materials in aircraft structure aims in reducing the structural weight significantly. In order to exploit the advantage of composite materials especially to manufacture fuselage structure can be efficiently developed by Automatic Fiber Placement (AFP) technology. In this regard, design of composite materials for fuselage structure has been needed. In this study, stacking sequence of skin, stringer and frame has been designed. The skin and frame stacking sequence are designed as [45/90/-45/0/45/0/-45]s and [90/45/-45]s, respectively. The numbers of stringer have been decided on the basis of already published papers. Material selected for fuselage is T800/3900-2 tape lamina. The sizing of stringer (T-shape) and frame (C-shape) has been decided on the basis of Denis Howe’s methods. One ply thickness is taken as 0.1905 mm. The design is modeled in CATIA V5 and imported in FEM code MSC. Patran and Nastran. The meshing is critical near the joint, so, mesh transition between the skin and stringer and skin and frame has been matched. The analysis has been done for internal pressure, shear load, bending moment, torsional load and axial compressive buckling, respectively. It has been observed from the analysis that designed fuselage can withstand internal pressure 75.5 kPa, shear load 13.86x10^6 N, bending moment 8.05x10^6 N-m and axial compressive force 504.150 kN, individually.

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ABSTRACT: This work is concerned with the finite element modeling of Nomex honeycomb core and carbon/epoxy composite laminate face sandwich panel structures. One objective is the identification of a material model for the honeycomb’s constituent material by model comparison with experimental test results. A detailed model of the panel structure, including the geometry of the honeycomb, was constructed. This model was loaded in the same fashion as corresponding 3-point flexure, 4-point flexure and compression experimental load tests. Linear isotropic and orthotropic Nomex material models were evaluated by comparing simulation results with test results. Both the isotropic and orthotropic linear material model can make the model agree reasonably well with 3-point flexion test results alone. When those 3-point flexion test identified material model parameters are used in the 4-point flexion and compression test models, they yield about 60% and 90% stiffer results than experiment, respectively. The modeling strategy used in this work along with the material models evaluated thus appears to provide unsatisfactory precision. In spite of this, the orthotropic material model gave the best fit to experimental results from the parameter sets evaluated.

References listed at the end of the paper:


ABSTRACT: Nomex honeycomb core composite sandwich panels are widely used in aircraft structures. Detailed meso-scale finite element modeling of the honeycomb geometry can be used to analyze sandwich inserts, vibration response, and complex combined loading cases. The accuracy of a meso-scale honeycomb modeling technique for static load cases was evaluated. A rectangular honeycomb core was modeled with perfect hexagon honeycomb cells. Compression and shear tests simulations with linear and non-linear solutions were performed for four core densities. The simulated moduli and buckling strengths were recorded. These results were compared to property data published by honeycomb manufacturers. The simulated maximum honeycomb wall stresses at the manufacturer predicted core strengths were also recorded. The honeycomb walls’ first compression deformation mode shape was observed. Sinusoidal small imperfections were then introduced in the honeycomb geometry based on that deformation mode shape. These imperfections provided a better match to manufacturer compressive modulus data while having a limited impact on the shear moduli. The
simulated properties did not exactly match manufacturers’ shear and compression data together for all the core densities. Modeling the honeycomb cells with rounded corners and with increased thickness at the cell junctions are potential strategies to improve the accuracy.


ABSTRACT: BIGBOSOR4 is used in an optimization loop in which the dimensions of a typical axially oriented weld land and the cross-section dimensions of reinforcing Tee-shaped stringers along the two straight edges (generators) of the weld land are decision variables. The optimization is carried out in a GENOPT context. Any number of equally spaced identical T-stiffened weld lands in a 360-degree cylindrical shell can be accommodated. The weld lands are embedded in an internally stiffened "acreage" cylindrical shell that has been previously optimized by PANDA2. The previously optimized "acreage" cylindrical shell has internal "acreage" stringers and internal "acreage" rings with rectangular cross sections. The spacings, heights, and thicknesses of the internal "acreage" stiffeners are not decision variables for the optimization problem in which the weld land and its reinforcing edge Tstringers are optimized. The design constraints for the cylindrical shell with the T-stiffened weld lands are: 1. general buckling, 2. inter-ring buckling, and 3. stress. The prebuckled state is assumed to be uniform end shortening, with the membrane axial compression in each segment of the structure proportional to the axial membrane stiffness of that segment. The prebuckled state is assumed to be a membrane state: no prebuckling bending. The entire shell structure is fabricated of the same material. In the model for general buckling the previously optimized "acreage" rings and stringers are smeared out and the cylindrical shell is simply supported at its ends. In the model for inter-ring buckling adjacent "acreage" rings are replaced by simple supports, that is, a length of shell equal to the ring spacing is analyzed, and the previously optimized "acreage" stringers are smeared out. The maximum stress in the weld-land-edge-stringer region is computed as if there were no prebuckling bending (membrane compression only). The cylindrical shell is modeled as a 180-degree segment of a huge torus, with symmetry conditions applied along the generators at zero and at 180 degrees. In the GENOPT examples studied here there are three identical T-stiffened weld lands spaced at 120 degree intervals. The adequacy of the optimized "acreage" cylindrical shell with and without the optimized T stiffened weld lands is evaluated with various STAGS finite element models. There is good agreement between predictions from the GENOPT/BIGBOSOR4 model and the various STAGS models.

--------References from the CV of Professor Y. Goldfeld of the Technion, Haifa, Israel


ABSTRACT: The stability pattern of shells is governed by a set of nonlinear partial differential equations. The solution procedure can be simplified, and fast and accurate predictions of the critical buckling load obtained, with the aid of a multilevel approach. Under this approach the lower levels are implemented by means of the perturbation technique, with the nonlinear prebuckling deformation disregarded, and a linear set of equations solved for each state. It turns out, however, that in these circumstances the prediction may differ depending on the chosen formulation. In an attempt to find the reasons for these differences, the linear bifurcation buckling behavior of laminated cylindrical shells was examined via two well-known formulations, with u–v–w and w–F as the unknowns. A third, mixed formulation, was found the most reliable in predicting the buckling behavior.


ABSTRACT: The sensitivity of laminated conical shells to imperfection is considered, via the initial post-buckling analysis, on the basis of three different shell theories: Donnell’s, Sanders’, and Timoshenko’s. Unlike isotropic conical shells or laminated cylindrical shells, in the case of laminated conical shells the thickness and the material properties vary with the shell coordinates, which complicates the problem considerably. The main objective of the study is to investigate the influence of the variation of the stiffness coefficients on the buckling behavior and on the imperfection sensitivity of laminated conical shells. It is felt that by finding the various parameters that influence the shell’s imperfection sensitivity, it is possible to improve the behavior of the whole structure. A special Level-1 computer code ISOLCS (Imperfection Sensitivity of Laminated Conical Shells) had been developed. ISOLCS calculates the classical buckling load and the imperfection sensitivity via Koiter’s theory of laminated conical shells with consideration to the variation of the material properties in the shell’s coordinates. The range of validity of the Level-1 predictions by ISOLCS is verified by the Level-3 code STAGS-A.


ABSTRACT: The buckling behavior of a filament-wound laminated conical shell is thoroughly investigated by consideration of the variation of the stiffness coefficients. To date, all analyses of laminated conical shells have been undertaken with constant stiffness coefficients in the laminate constitutive relations, usually under the assumption of nominal material properties taken from the midlength of the cone. The main object of the study is to investigate the influence of the variation of the stiffness coefficients on the buckling behavior of laminated conical shells. An analytical and computational model was developed to calculate the variation of the stiffness coefficients under the assumption that, in the case of filament-wound truncated conical shells, the fiber orientation changes using a geodesic path. The model was added to the computer code STAGS-A to calculate the buckling behavior of the laminated conical shell.

ABSTRACT: A hierarchical high-fidelity analysis procedure is adopted for predicting the critical buckling load of filament wound laminated conical shells. This hierarchical procedure includes three levels of fidelity for the analysis. Level-1 assumes that the shell buckling load can be predicted by using simply supported boundary condition with a linear membrane prebuckling solution. Level-2 includes the effects of a nonlinear prebuckling solution and the effects of different boundary conditions. Level-3 includes the nonlinear interaction between nearly simultaneous buckling modes and the effects of boundary imperfections. For the Level-1 analysis a computer code BOLCS had been developed. BOLCS calculates the buckling load of laminated conical shells by a linear bifurcation analysis. The buckling behavior obtained by BOLCS is compared for various load cases with Level-3 solutions calculated by the two-dimensional nonlinear code STAGS-A. The effects of the assumptions and approximations used for the two solutions are discussed. In addition, the influence of the in-plane boundary condition on the buckling behavior of laminated conical shells under axial compression is investigated. It is found that the in-plane boundary condition at the large end of the shell has a major effect on the buckling behavior.


ABSTRACT: Optimum laminate configuration for minimum weight of filament-wound laminated conical shells is investigated subject to a buckling load constraint. In the case of a composite laminated conical shell, due to the manufacturing process, the thickness and the ply orientation are functions of the shell coordinates, which ultimately results in coordinate dependence of the stiffness matrices (A,B,D). These effects influence both the buckling load and the weight of the structure and complicate the optimization problem considerably. High computational cost is involved in calculating the buckling load by means of a high-fidelity analysis, e.g. using the computer code STAGS-A. In order to simplify the optimization procedure, a low-fidelity model based on the assumption of constant material properties throughout the shell is adopted, and buckling loads are calculated by means of a low-fidelity analysis, e.g. using the computer code BOCS. This work proposes combining the high-fidelity analysis model (based on exact material properties) with the low-fidelity model (based on nominal material properties) by using correction response surfaces, which approximate the discrepancy between buckling loads determined from different fidelity analyses. The results indicate that the proposed multi-fidelity approaches using correction response surfaces can be used to improve the computational efficiency of structural optimization problems.

References listed at the end of the paper:

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ABSTRACT: The present study concentrates on the optimization of geometrically nonlinear shell structures using the multipoint approximation approach. The latter is an iterative technique, which uses a succession of approximations for the implicit objective and constraint functions. These approximations are formulated by means of multiple regression analysis. In each iteration the technique enables the use of results gained at several previous design points. The approximate functions obtained are considered to be valid within a current subregion of the space of design variables defined by move limits. A geometrically nonlinear curved triangular thin shell element with the corner node displacements and the mid-side rotations as degrees of freedom is used for the FE analysis. The influence of initial shape imperfections on the optimum designs is investigated. Imperfections are considered as a shape distortion proportional to the lowest buckling modes of the perfect structure. Displacement, stress, and stability constraints are taken into account. To prevent finite element solutions from becoming unstable during the optimization process, a simple strategy for avoiding passage of stability points is applied. Some numerical examples are solved to show the practical use and efficiency of the technique presented.

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19. Toropov, V.V.; Filatov, A.A.; Polynkin, A.A. 1993: Multiparameter structural optimization using FEM and multipoint explicit approximation. Struct. Optim. 6, 7–14
SUMMARY: In this thesis a curved triangular finite shell element is described based on the Kirchhoff-Love hypothesis. Using this element, thin shell structures can be analysed in the nonlinear field. The element has twelve degrees of freedom, namely, nine displacement components and three rotations about the element sides. The membrane strains and the changes of curvature, just like the tangential stress resultants and the tangential stress couples, are taken to be consant over the element. In addition to a comprehensive discussion of geometrical nonlinearities, it is also pointed out how to incorporate time independent plasticity in a consistent way. In Chapter 1 a general introduction is given, in which a number of finite element approaches to shell analysis are mentioned, while further some historical background of the present study is outlined. In Chapter 2 a short review of the usual nonlinear shell theory is presented. By introducing a number of error estimates, suitable expressions for a shallow part of a shell are derived. In Chapter 3 the just-mentioned expressions are applied to obtain the actual finite element formulation. A key role is played by a second-order interpolation for the initial geometry and the displacement component in the direction perpendicular to the plane determined by the vertices of the element. Furthermore, attention is paid to inter-element continuity of the displacements and the rotations of the normal to the shell middle surface, while the requirement that rigid body motions must be described correctly is also emphatically taken into consideration. Due to the way of calculating the changes of curvature, the incremental rotations have to remain moderate. In Chapter 4 a recapitulation of constitutive rate equations for time-independent small strain elastoplasticity is given, together with a discussion of possible solution strategies. The three-dimensional nature of the fraction model is illustrated and the implications of using a three-dimensional stress state instead of a two-dimensional one are taken into account. In Chapter 5 a number of demonstrative examples are shown. They deal with a variety of analysis types, from linear to both geometrically and physically nonlinear, including dynamics. All solutions are compared with semi-analytical or other finite element solutions known from the literature. In the Appendices A.1 and A.2 an alternative method for calculating the changes of curvature, which is also valid for finite rotational increments, and some aspects concerning the Tresca yield criterion are mentioned, respectively.

A. Bout and F. Van Keulen (Faculty of Mechanical Engineering and Marine Technology, Dept. of Engineering Mechanics, Delft University of Technology, The Netherlands), “A mixed element for geometrically and physically nonlinear shell problems”, (publisher and date not given in the pdf file; most recent citation is dated 1991)
ABSTRACT: A triangular element for geometrical and physical nonlinear shell problems is described. The degrees of freedom are 18 displacement components and 6 rotation-like scalars. A key role in the description is played by a flat reference triangle through the vertices of the element. The governing equations are derived by means of the principle of virtual work, using constitutive equations based on a layered model. The performance of the element is illustrated by two sample problems.

ABSTRACT: The objective of this article is to study the solvability of variational problems of both geometrically and physically nonlinear theory of thin non-sloping shells of zero Gaussian curvature with rigidly fixed edge. The characteristic property of this article is the fact that the solvability of problems is proved in a functional space which differs from spaces of displacements and forces. Solvability conditions of the problem are obtained without assumptions on smallness of components of the outer load. Similar problems for sloping shells were considered in [1]. The physically nonlinear problems for non-sloping shells whose middle surface is formed by rotation, a convex developable surface, were studied in [2], [3].

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ABSTRACT: A structural optimization algorithm is developed for truss and beam structures undergoing large deflections against instability. The method combines the nonlinear buckling analysis using the displacement control technique, with the optimality criteria approaches. Several benchmark case studies illustrate the procedure and the results are compared with examples reported in the literature. It is shown that a design based on the generalized eigenvalue problem (linear buckling) highly underestimates the optimum mass or overestimates the buckling load for these types of structures, so a design based on the linear buckling analysis may result in catastrophic failure. The effect of geometrical nonlinearities and element imperfections has also been studied.

References listed at the end of the paper:


ABSTRACT: Optimum laminate configuration for the maximum buckling load of filament-wound laminated conical shells is investigated. In the case of a laminated conical shell, the thickness and the ply orientation (the design variables) are functions of the shell coordinates, influencing both the buckling load and the weight of the structure. Thus, optimization can be performed by maximization of the buckling load for a specific weight, or
by minimization of the weight of the structure under the constraint of applied buckling load. Due to the complex nature of the problem a preliminary investigation is made into the characteristic behavior of the buckling load with respect to the volume as a function of the ply orientation. The exact buckling load is calculated by means of the computer code STAGS-A (Structural Analysis of General Shells [Almroth BO, Brogan FA, Meller E, Zele F, Petersen HT. Collapse analysis for shells of general shape, user's manual for STAGS-A computer code. Technical report AFFDL TR-71-8; 1973]) by adding a user written subroutine WALL, see Ref. [Goldfeld Y, Arbocz J. Buckling of laminated conical shells taking into account the variations of the stiffness coefficients. AIAA J 2004; 42(3):642–649]. The optimization problem is solved using response surface methodology.


ABSTRACT: The sensitivity of laminated cylindrical shell to imperfection is considered, via the initial post-buckling analysis, on the bases of Sanders’ theory. A general code is developed and used in studying the effect of the stretching–bending coupling (B) and the flexural (D) stiffness matrices on the buckling and the post-buckling behavior of the shell, thereby improving its behavior.


doi: 214, 35400009945776.0160

ABSTRACT: Bifurcation buckling analysis of laminated cylindrical shells is presented on the basis of three different shell theories: Donnell's (Donnell, L. H., Stability of Thin-Walled Tubes under Torsion, NACA TR-479, 1933), Sanders's (Sanders, J. L., Jr., Nonlinear Theories of Thin Shells, Quarterly Journal on Applied Mathematics, Vol. 21, No. 1, 1963, pp. 21-36), and Timoshenko's (Timoshenko, S., Theory of Elastic Stability, McGraw-Hill, New York, 1961). Formulations in terms of the displacement components and of the Airy stress function and normal displacement are examined. The partial differential equations are derived via the variational principle and solved with variables expanded in Fourier series in the circumferential direction and presented as finite differences in the axial direction. The buckling behavior of an angle-ply laminated cylindrical shell under different modes of loading was investigated parametrically, showing-in contrast to its isotropic counterparts-a discrepancy between the two formulations.
ABSTRACT: Most of the previous research on buckling and stability of shell structures is confined to \( u-v-w \) or \( w-F \) formulation, which are limited either by accuracy or by the chosen kinematic theory. In this work, an alternative mixed formulation is proposed for general laminated shells of revolution and calculated for different shell theories. Its principle consists in choosing the set of unknown functions as the obtainable boundary conditions from the variational formulation. The main advantage of the mixed formulation is direct involvement of the stiffness matrices, without their derivatives. This quality is most important in complicated woven-fabric procedures when the derivative functions of the fiber orientations are not available or the constitutive functions have discontinuities. The proposed formulation is validated and demonstrated for filament-wound laminated conical shells with variable material properties.

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References from the CV of Professor Johann Arbocz of the Technical University of Delft

ABSTRACT: A hierarchical high-fidelity analysis methodology for predicting the critical buckling load of compression-loaded thin-walled isotropic shells is described. This hierarchical procedure includes three levels of fidelity for the analysis. Level 1 assumes that the buckling load can be predicted by the classical shell solution with simply supported boundary condition, and with a linear membrane prebuckling solution. Level 2 includes the effects of a nonlinear prebuckling solution and the effects of traditional clamped or simply supported boundary conditions. Level 3 includes the nonlinear interaction between nearly simultaneous buckling modes and the effects of boundary imperfections and general boundary conditions. Various deterministic and probabilistic approaches are used to account for the degrading effects of unavoidable shell-wall geometric imperfections. The results from the three solution levels are compared with experimental results, and the effects of the assumptions and approximations used for the three solution levels are discussed. This hierarchical analysis approach can be used in the design process to converge rapidly to an accurate prediction of the expected buckling load of a thin-shell design problem.

ABSTRACT: A probability-based analysis method for predicting buckling loads of compression-loaded laminated composite shells is presented, and its potential as a basis for a new shell-stability design criterion is demonstrated and discussed. In particular, a database containing information about specimen geometry, material properties, and measured initial geometric imperfections for a selected group of laminated-composite cylindrical shells is used to calculate new buckling-load “knockdown factors.” These knockdown factors are shown to be substantially improved and hence much less conservative than the corresponding deterministic knockdown factors that are presently used by industry. The probability integral associated with the analysis is evaluated by using two methods; that is, by using the exact Monte Carlo method and by using an approximate first-order second-moment method, yields results that are conservative for the shells considered. Furthermore,
the results show that the improved, reliability-based knockdown factor presented always yields a safe estimate of the buckling load for the shells examined.


ABSTRACT: As a step towards developing a new design philosophy, one that moves away from the traditional empirical approach used today in design towards a science-based design technology approach, a test series of 5 lightly stiffened orthotropic shells carried out by Singer, Arbocz and Babcock at Caltech is used. In earlier publications a hierarchical high-fidelity analysis procedure for predicting the critical buckling load of compression-loaded thin-walled shells is described. This hierarchical procedure includes three levels of fidelity for the analysis, Level-1 assumes that the shell buckling load can be predicted by the classical solution with simply supported boundary condition, and with a linear membrane prebuckling solution. Level-2 includes the effects of a nonlinear prebuckling solution and the effects of boundary conditions. Level-3 is a two-dimensional analysis, which includes the nonlinear interaction between nearly simultaneous buckling modes. As a final step in the hierarchical analysis approach, in the present paper the Level-3 buckling load prediction based on the experimentally measured initial imperfections are verified by the experimental buckling loads. Since the simulated buckling loads yield a lower bound to the experimental buckling loads of all five shells tested, it is believed that the proposed hierarchical analysis procedure can be used in the design process to rapidly converge to an accurate prediction of the expected buckling load of a thin-shell design problem.


ABSTRACT: Multi-level high-fidelity analysis is recognized as a viable strategy for obtaining improved safe knock-down factors based on the so-called “manufacturing signature” of a fabrication process. This approach is implemented in the hierarchical interactive computer code, DISDECO, the Delft, Interactive Shell Design Code, which enables interactive investigation of the various aspects of the nonlinear response of thin-walled shells. The goal of the research reported in this paper is the development of accurate inheritance of computed results from low-level parametric analysis modules through intermediate approximate analysis levels to high-level large general purpose computer codes. Accurate fitting, interpolation and extrapolation of computed results as
well as reformulating to accommodate alternate computational methods are major requirements. The inheritance methods are demonstrated by the hierarchical analysis of the collapse behavior of a stringer stiffened cylindrical shell.


PARTIAL ABSTRACT: Because of their favourable strength over weight ratios thin-walled stiffened or unstiffened, metallic or composite shells are widely used structural elements in many applications in the aerospace, the off-shore, the maritime, the process-technology and other civil engineering fields. Unfortunately, thin-walled shells are also often very prone to buckling instabilities. In the 1960s, the engineering community in the United States was facing the urgent problem of having to devise reliable design procedures for both the ballistic missile program of the US Air Force and the launch vehicles of the NASA space program. ...


------- WEBSITE fgg.uni-lj.si (University of Ljubljana, Slovenia, ESDEP WG)
------- REFERENCES LECTURE 6.1 “Concepts of stable and unstable equilibrium”


------- REFERENCES LECTURE 6.6.2 “Buckling of real structural elements II


------- REFERENCES AND ADDITIONAL READING, LECTURE 8.9 “Design of stringer-stiffened cylindrical shells”


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ABSTRACT: Energy distribution within the critical modes of a classical energy eigenvalue analysis for circular cylindrical seashells under external pressure shows that a significant contribution to the stability of the shell is derived from membrane stiffness. It is argued from physical reasoning that the unstable post-critical behavior is the result of the loss of this membrane stiffness. To account for the combined effect of mode coupling and imperfections in eroding this membrane stiffness, a simplified theoretical analysis is described in which appropriate terms in the membrane potential energy are neglected. It is shown, by comparison with the writers’ experiments, and with a collection of data found in the literature, that this reduced stiffness method provides lower bounds which, for shells with moderate imperfections, are reliable lower bounds of the experimental buckling pressures in the modes observed to trigger buckling. This lower boundedness combined with the conceptual and analytic simplicity of the reduced stiffness method make it a particularly attractive basis for the design.


ABSTRACT: A re-examination of some 240 past experiments on the general elastic buckling of axially loaded stringer stiffened cylinders suggests that the observed buckling behaviours exhibited a degree of imperfection sensitivity considerably higher than that so often ascribed to them. It is demonstrated how the underestimation of these experimental knock-downs may have resulted from the use of theoretical models insufficiently
representative of test conditions. By incorporating a more precise modelling of the test shells the present analyses show how, contrary to a widely held belief, the potential knock-down factors for general elastic buckling can approach those of the isotropic cylinder. Furthermore, despite the relatively perfect nature of many of the test shells, the recently described ‘reduced stiffness analysis’ method provides lower bounds of the observed experimental scatter that are sufficiently reliable to recommend this method as a basis for future design.


ABSTRACT: Re-examination of some 85 past experiments on the elastic buckling of axially loaded ring stiffened cylinders shows the existence of two distinctive behavioural regimes. Lightly stiffened cylinders, like isotropic cylinders, buckle into non-axisymmetric modes having long axial wavelengths at loads that are sensitive to the precise magnitudes of small initial imperfections. Heavily stiffened cylinders are characterised by snap buckling into axisymmetric modes which, for elastic behaviour at least, show only limited sensitivity to initial imperfections. Each of these characteristics is shown to be predicted by the recently developed ‘reduced stiffness analysis’ method, which, despite the relatively perfect nature of test specimens, predicts reliable lower bounds to the experimental scatter. Taken together with the previously demonstrated empirical validity of the reduced stiffness analysis for the prediction of buckling modes and lower bounds to buckling loads for both isotropic and stringer stiffened cylinders, the present comparisons provide further support to the recommendation that this method be considered as an alternative basis for future design.

References listed at the end of the paper:


ABSTRACT: This paper reports a study carried out on behalf of the U.K. Dept. of Energy to update its Guidance Notes relating to the buckling design of offshore steel structures. The results presented here refer to stringer and orthogonally stiffened cylinders and are compared with the predictions from various design codes. Conclusions are predictions from various design codes. Conclusions are drawn as to the validity and conservativeness of the code recommendations.

A.C. Walker, Y. Segal and S. McCall (Dept. of Mechanical Engineering University of Surrey, Guildford, UK), “The buckling of thin-walled ring-stiffened steel shells”, in Buckling of Shells, pp 275-304, 1995

SUMMARY: The buckling of thin-walled cylindrical shells subject to various types of combined loading is of current interest to engineers engaged in offshore engineering practice. This paper considers the inter-ring buckling of cylinders when subject simultaneously to pressure and axial loading. Some example results from an experimental research programme on steel models are presented and compared to the interaction diagrams proposed by other researchers.

References listed at the end of the paper:
25. Walker, A.C.; Andronicou, A. Buckling of ring stiffened shells subject to pressure and axial loading. To be published.
30. Miller, C.D. Summary of buckling tests on fabricated steel cylindrical shells in U.S.A. Imperial College Conference on offshore structure April 1981.

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ABSTRACT: A reduced stiffness theoretical analysis of imperfection sensitive elastic buckling for end supported cooling tower-type shells, provides lower bounds of experimentally recorded buckling pressures. Classical analysis of these shells with the same empirically realistic boundary support conditions, in contrast, provides unreliable upper bounds of test buckling pressures. By attempting to attribute this imperfection sensitivity to notionally weakened boundary conditions, past interpretations may have provided non-conservative advice for the estimation of design buckling pressures. The reduced stiffness method provides a simple, alternative basis for designing against imperfection sensitive buckling.

ABSTRACT: This paper shows how the analysis of minimum, quasi-static, buckle propagation pressures for subsea pipelines may be exactly formulated in terms of the characteristics of ring collapse. A simple mechanistic approach to ring collapse is described which enables the rational incorporation of the effects of material strain hardening. Theoretical predictions resulting from this analysis are shown to reproduce past
empirically observed propagation pressures; they also successfully predict the variations in the forms of ring collapse modes resulting from differing strain-hardening properties. Upon suitable non-dimensionalisation this analysis shows how predicted propagation pressures may be represented in terms of just one composite material and geometric ‘propagation parameter’. This eliminates the need for recourse to empirically fitted design curves and allows resolution of certain anomalies experienced in past analyses. It emphasises the need for more complete information regarding material strain-hardening properties if test results are to be properly interpreted. Most importantly, the present analysis offers the potential for future design of pipelines being at once more rationally and parametrically complete, and yet compact and simple to apply.

C.P. Ellinas (1) and J.G.A. Croll (2)  
(2) Civil Engineering Department, University College, London, U.K.  
ABSTRACT: A recently developed procedure for predicting the elastoplastic axisymmetric collapse of cylinders subjected to combinations of axial compression and pressure loading is described. This allows the modelling of radial pressure induced deformations, boundary effects and initial geometric imperfections in terms of an equivalent imperfection in a “column type” bifurcation analysis. Together with the incorporation of a more rational means of specifying initial geometric tolerances, it is used to develop compact design-orientated procedures for predicting safe design loads for this form of elastoplastic collapse of cylinders.


K. Matsumoto (1), S. Yamada (1), H.T. Wang (2) and J.G.A. Croll (2)  
(1) Toyohashi University of Technology, Toyohashi, Japan  
(2) University College London, U.K.  
ABSTRACT: This paper deals with buckling of thin-walled cylindrical shells under compression. It is well-known that axially compressed cylindrical shells have buckling behaviour which is very sensitive to initial geometric imperfections. However, current approaches using mathematical algorithms to optimise the linearised classical critical loads with respect to many design variables, generally ignore the potential reductions in elastic load carrying capacities that result from the initial imperfections. They present major problems for incorporation into design processes and often involve excessive computational effort. Adopting 6-ply symmetric, glass-epoxy cylindrical shells, this paper carries out classical buckling analysis for perfect shells and nonlinear analysis for imperfect shells. In addition the present paper applies an alternative lower bound design concept called the reduced stiffness method. By confirming the correspondence between the lower bounds of nonlinear buckling analysis and the reduced stiffness analysis, it suggested that the reduced stiffness method could provide an important basis for design.  
References listed at the end of the paper:  


ABSTRACT: Thin metallic shells have long been adopted as major structural components in weight-sensitive applications, especially in marine engineering. Imperfection sensitive buckling is a critical design factor when these structures are loaded in compression. Traditional experimental design method depends on deriving lower bounds to the scatter of large sets of test results. This paper aims to present an analytical approach, the so-called reduced stiffness method (RSM) to the lower-bound buckling of thin-metallic shells. The validity of the RSM for the prediction of the safe lower bounds to the buckling of thin shells is verified through carefully controlled finite element analysis and the comparative studies confirm the reliability of the RSM.


ABSTRACT: An elastic, nonlinear, Ritz analysis has been developed to allow investigation of the imperfect behavior of axially compressed orthotropic fiber reinforced polymer cylindrical shells. In a particular mode, buckling loads are shown to be strongly influenced by the constitutive material coefficients and are sensitive to initial geometric imperfections. Just as for the previously analyzed isotropic cylindrical shells, the reduced stiffness criteria are shown to provide close lower bounds to the imperfection sensitive elastic buckling loads. The potential benefits in the use of the reduced stiffness theoretical results to allow specification of the optimal designs are illustrated.

References listed at the end of the paper:
Seishi Yamada, “Theory and application of shell buckling mechanics”, (Publisher and Date unknown, possibly 2011, The most recent citation is dated 2008)

ABSTRACT: (Cannot cut and paste it.)

Krishna Kumar Bhetwal (1), Seishi Yamada (1), Yukihiro Matsumoto (1) and James G. A. Croll (2)
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ABSTRACT: In this paper, the strengthening of thin-walled metallic shells with the application of CFRP (carbon fibre reinforced polymer) has been investigated. To lower down the downside of the lower stiffness exhibited by CFRP shells and to diminish the major problem associated with steel shells, a new composite sandwich structure has been introduced in this paper and effect of CFRP reinforcements under axial compression has been studied through three kinds of analytical procedures; the linear Eigen value problem, the modified RS (reduced stiffness) analysis and the fully nonlinear numerical experiment. With these multiple treatments it has been suggested that recently developed modified RS analysis which effectively compute the lower bounds provides the significant information to evaluate the buckling capacity of reinforced shells that display the unstable behaviour and imperfection-sensitivity than the general RS Analysis. This paper also illustrates the application of the methodology to cases of axially loaded shells with varying thickness of veneers of CFRP.

References listed at the end of the paper:

ABSTRACT: The imperfection sensitive buckling loads of fibre reinforced polymeric (FRP) composite cylindrical shells under axial compression can be optimised with respect to many material and geometric parameters. Current approaches, using mathematical algorithms to optimise the linearised classical critical loads with respect to many design variables, generally ignore the potential reductions in elastic load carrying capacities that result from the severe sensitivities of buckling loads to the effects of initial imperfections. This paper applies a lower-bound design philosophy called the reduced stiffness method (RSM) to the optimisation design of FRP shell buckling. A physical optimisation in terms of parametric studies is carried out for simply supported, 6-ply symmetric, glass-epoxy circular cylindrical shells under uniform axial load. It is shown that under the guidance of RSM, safe lower-bound buckling loads can be enhanced greatly by choosing appropriate combinations of design parameters. It is demonstrated how this approach encourages the delineation of those components of the shell’s membrane and bending stiffness that are important and those that are unimportant within each of the prospective buckling modes. On this basis, it is argued that the RSM provides not only a safe but also a more rational strategy for better design decision making.

References listed at the end of the paper:

ABSTRACT: Methods are proposed for the determination of the optional ply angle variation through the thickness of symmetric angle-ply shells of uniform thickness. These methods use continuous piecewise-linear segment approximations or discontinuous piecewise-constant segment approximations to the ply angle function. A mathematical programming (MP) problem is formulated using segment ply angles and thicknesses as design variables. A special MP algorithm, capable of treating multiple objective functions, combined with a critical mode search is used to solve this problem. The procedure is applied to the maximization of the minimum natural frequency or buckling load of a thin, simply supported, circular, cylindrical, angle-ply shell. Results show large performance gains result from the use of optimal variable ply angle configurations, compared to an optimal constant ply angle. The continuously variable ply angle approximation is particularly effective.


ABSTRACT: The free vibration characteristics of a submarine hull have an important influence on the noise signature. A submarine hull, or portion of one, can frequently be idealised as a ring stiffened cylinder subjected to external loading from the surrounding water, for the purposes of vibration analysis. The modal behaviour of ring stiffened cylinders is reviewed, including the effect of external pressure loading and added mass effects from surrounding fluid. The existing unclassified literature is inadequate in its coverage of the problem and these shortcomings are discussed, in order to identify the requirements for further work in order to be able to satisfactorily analyse a submarine hull structure.

----- ARA
Anonymous, “Dynamic Buckling of Shells” (an abstract, not a paper)
ABSTRACT: SRI performed experiments and analyses on impulsively loaded thin cylindrical aluminum shells. The cosine distributed external impulsive loads drive the shell inward producing compressive circumferential stresses and pulse buckling on the loaded side of the shell. These buckles produce strain concentrations that govern the eventual fracture of the structure. Thus the buckling response needs to be correctly modeled to predict failure. Predicting the buckling response of thin shells is difficult because most finite element models do not include the physical characteristics of the problem that initiate instabilities. A methodology was developed to accurately predict the buckling response of the thin shell structures by incorporating either the measured imperfections in the structure and loading, or accurate statistical approximations to the imperfections. A cross section of a dynamically pulse buckled thin cylindrical shell and the calculated response are shown in Figure 1. In the calculation, we used the measured imperfections in the cylinder shape to initiate the buckling. The buckling response can clearly seen on the loaded (front) side of the cylinder and is accurately reproduced in the
calculation. These modeling techniques, developed for analysis of pulse buckling of thin aerospace shell structures, have been used in other structural applications. These include analysis of crash energy management structures for vehicles, static axial collapse of cylinders, and dynamic buckling of thick shells. One example application for thick shells is the buckling that occurs in explosively formed penetrators (EFPs) as shown in Figure 2. Understanding and modeling the processes that lead to dynamic plastic buckling in EFP liners allows the designer to control the buckling process to gain enhanced aerostability.

References:


ABSTRACT: Thin cylindrical shells were tested under axial compression beyond the critical buckling load. Both pretest and posttest finite element calculations were performed to calculate the buckling loads and post-buckling deformations. Finite element simulations of the shell included pretest measured imperfections in shell geometry and asymmetry in the axial load. Results show that the axial collapse load is sensitive to imperfections in both the shell geometry and the load distribution. Careful modeling of the imperfections resulted in accurate predictions of the buckling load and postbuckling deformations for the shells.

References listed at the end of the paper:

ABSTRACT: When a cylindrical shell is subjected to dynamic impulsive loading in radial direction and the ratio of radius-to-thickness exceeds a special value, the cylindrical shell will produce elastic dynamic buckling. This paper which is based on the results of some relative experiments, assumes deformation mode and utilizes Lagrange method to analyse the elastic pulse buckling of a thin cylindrical shell with a finite length under a cosine impulse. The dynamic buckling equations are derived and solved by numerical method. The results of calculation are compared with some relative calculation results which were obtained by other authors. References listed at the end of the paper:


ABSTRACT: In the traditional buckling analysis of rectangular plates the classical thin plate theory is generally applied, so neglecting the plating shear deformation. It seems quite clear that this method is not totally appropriate for the analysis of thick plates, so that in the following the two variable refined plate theory proposed by Shimpi (2006), that permits to take into account the transverse shear effects, is applied for the buckling analysis of simply supported isotropic rectangular plates, compressed in one and two orthogonal directions. The relevant results are compared with the classical ones and, for rectangular plates under uniaxial compression, a new direct expression, similar to the classical Bryan’s formula, is proposed for the Euler buckling stress. As the buckling analysis is a widely diffused topic for a variety of structures, such as ship ones, some applications for plates uniformly compressed in one and two orthogonal directions are presented and the relevant theoretical results are compared with those ones obtained by a FEM analysis, carried out by ANSYS, to show the feasibility of the presented method.

V. Piscopo, “Buckling analysis of rectangular plates under the combined action of shear and uniaxial stresses”, World Academy of Science, Engineering and Technology, Vol. 4, 2010-10-4

ABSTRACT: In the classical buckling analysis of rectangular plates subjected to the concurrent action of shear and uniaxial forces, the Euler shear buckling stress is generally evaluated separately, so that no influence on the shear buckling coefficient, due to the in-plane tensile or compressive forces, is taken into account. In this paper the buckling problem of simply supported rectangular plates, under the combined action of shear and uniaxial forces, is discussed from the beginning, in order to obtain new project formulas for the shear buckling coefficient that take into account the presence of uniaxial forces. Furthermore, as the classical expression of the shear buckling coefficient for simply supported rectangular plates is considered only a “rough” approximation, as the exact one is defined by a system of intersecting curves, the convergence and the goodness of the classical
solution are analyzed, too. Finally, as the problem of the Euler shear buckling stress evaluation is a very important topic for a variety of structures, (e.g. ship ones), two numerical applications are carried out, in order to highlight the role of the uniaxial stresses on the plating scantling procedures and the goodness of the proposed formulas.


ABSTRACT: An efficient beam-column approach, using an improved step-by-step numerical method, is developed in the current research for studying the ultimate strength problems of stiffened panels with two load cases: 1) under longitudinal compression, and 2) under transverse compression. Chapter 2 presents an improved step-by-step numerical integration procedure based on (Chen and Liu, 1987) to calculate the ultimate strength of a beam-column under axial compression, end moments, lateral loads, and combined loads. A special procedure for three-span beam-columns is also developed with a special attention to usability for stiffened panels. A software package, ULTBEAM, is developed as an implementation of this method. The comparison of ULTBEAM with the commercial finite element package ABAQUS shows very good agreement.

The improved beam-column method is first applied for the ultimate strength analysis of stiffened panel under longitudinal compression. The fine mesh elasto-plastic finite element ultimate strength analyses are carried out with 107 three-bay stiffened panels, covering a wide range of panel length, plate thickness, and stiffener sizes and proportions. The FE results show that the three-bay simply supported model is sufficiently general to apply to any panel with three or more bays. The FE results are then used to obtain a simple formula that corrects the beam-column result and gives good agreement for panel ultimate strength for all of the 107 panels. The formula is extremely simple, involving only one parameter: the product $\lambda \Pi_{\text{orth}}^2$.

Chapter 4 compares the predictions of the new beam-column formula and the orthotropic-based methods with the FE solutions for all 107 panels. It shows that the orthotropic plate theory cannot model the “crossover” panels adequately, whereas the beam-column method can predict the ultimate strength well for all of the 107 panels, including the “crossover” panels. The beam-column method is then applied for the ultimate strength analysis of stiffened panel under transverse compression, with or without pressure. The method is based on a further extension of the nonlinear beam-column theory presented in Chapter 2, and application of it to a continuous plate strip model to calculate the ultimate strength of subpanels. This method is evaluated by comparing the results with those obtained using ABAQUS, for several typical ship panels under various pressures.

References listed at the end of the dissertation:


ABSTRACT: Three blade-stiffened CFRP panels with co-cured stiffener webs, manufactured by means of an elastomeric mould, have been tested under compressive load. Several Bragg grating sensors have been surface bonded on two of the stiffened panels and have been embedded into the stiffener webs of the third panel. The Bragg grating sensors measured the strain distribution in the stiffener web and in the skin panels. The buckling onset was clearly detected in every case, the post-buckling behaviour can be tracked, but the information is heavily dependent on the right choice of the sensor position and the buckling mode. To calibrate the system, and to evaluate the influence of different curing pressures, and the use of unidirectional or fabric prepreg material, tensile test specimens were made on flat panels. The strain measurements provided by the optical fibre sensors in tensile tests were compared with the strain measurements provided by conventional clamp extensometers.


ABSTRACT: The nonlinear stiffness equations that predict local and post-local buckling of plates and plate assemblies are given. These equations are validated by accurate predictions of independent test results. The elastic local buckling of longitudinally stiffened web plates in combined bending and compression is considered. Graphs which may be used to predict the optimum position of a stiffener are presented. The relationship between the area and second moment of area of a stiffener of finite dimensions that optimizes the local buckling coefficient is given for various eccentricities of end load. The post-local buckling of a longitudinally stiffened plate in uniform compression and pure bending is also considered. It is shown that the provision of a longitudinal stiffener, of proportions to enforce a node at the plate–stiffener junction, enhances significantly the postbuckling response of the plate with regard to the serviceability limit state, particularly for the case of pure bending.


ABSTRACT: The buckling of an elastic plate with arbitrary shape flush-mounted on a rigid wall and deforming under the action of a uniform tangential load due to an overpassing simple shear flow is considered. Working under the auspices of the theory of elastic instability of plates governed by the linear von Kármán equation, an eigenvalue problem is formulated for the buckled state resulting in a fourth-order partial differential equation with position-dependent coefficients parameterized by the Poisson ratio. The governing equation also describes the deformation of a plate clamped around the edges on a vertical wall and buckling under the action of its own weight. Solutions are computed analytically for a circular plate by applying a Fourier series expansion to derive an infinite system of coupled ordinary differential equations and then implementing orthogonal collocation, and numerically for elliptical and rectangular plates by using a finite-element method. The eigenvalues of the resulting generalized algebraic eigenvalue problem are bifurcation points in the solution space, physically representing critical thresholds of the uniform tangential load above which the plate buckles and wrinkles due to the partially compressive developing stresses. The associated eigenfunctions representing possible modes of deformation are illustrated, and the effect of the Poisson ratio and plate shape is discussed.

References listed at the end of the paper:

T. Morimoto and Y. Tanigawa (Dept. of Mechanical Systems Engineering, Osaka Prefecture University, Japan),

SUMMARY: A linear buckling analysis is carried out for orthotropic inhomogeneous rectangular plates under uniform in-plane compression. It is assumed that material inhomogeneities of Young's modulus and shear modulus of elasticity are continuously changed in the thickness direction with the power law of the coordinate variable, while Poisson's ratio is assumed to be constant. The buckling equation can be successfully constructed as the linearized von Kármán plate model by introducing the newly defined position of the reference plane which enables us to easily deal with the problem. The critical buckling loads of the simply supported rectangular plate are presented using the derived fundamental relations. Effects of material inhomogeneity, material orthotropy, aspect ratio, width-to-thickness ratio and load ratio are discussed.

References listed at the end of the paper:

3. Feldman, E., Aboudi, J. 1997 Buckling analysis of functionally graded plates subjected to uniaxial loading Compos. Struct.382936
OVERVIEW: Whereas the classical theory of plates is limited to situations in which deflections of the plate are small compared with the plate thickness, the von Kármán theory considered here has been shown to be valid for problems in which the transverse deflection is of the same order as the plate thickness, although small in comparison with the other plate dimensions. This theory makes use of the nonlinear strain–displacement relations in which quadratic terms in the slopes of the plate middle surface are retained but is otherwise consistent with the basic assumptions of the classical theory. The associated governing equations of motion for homogeneous isotropic plates and heterogeneous anisotropic plates are presented. Both the displacement formulation and the stress-function formulation addressed here entail coupled, nonlinear differential equations, and due to their complexity, it is generally necessary to employ approximations...

References listed at the end of the paper:


ABSTRACT: Thermally-induced large-deflection behaviors of laminates, including flat plates and cylindrical and doubly-curved panels, are investigated. The finite element technique based on the first-order shear deformation theory is employed to predict the shell response. Post-critical equilibrium paths are traced using the arc-length and the Riks methods. Laminate strength is also predicted, based upon the Tsai-Wu criterion.
ABSTRACT: The presence of elevated temperature and absorbed moisture can alter significantly the structural response of fibre-reinforced laminated composites. A hygrothermal environment causes degradation in both strength and constitutive properties, particularly in the case of fibre-reinforced polymeric composites. Furthermore, associated hygrothermal expansion, either alone or in combination with mechanically induced deformation, can result in buckling, large deflections, and excessively high stress levels. Consequently, it is often imperative to consider environmental effects in the analysis and design of laminated systems.

References listed at the end of the paper:


ABSTRACT: Based on both moderate and finite rotation bending theories of thin elastic shells including shear deformation, adaptive non-linear static finite element analysis is treated within a displacement approach and h-adaptivity. The a posteriori error indicator given by Rheinboldt, gained by linearization, is investigated in order to decide whether the deformations influence the indicator explicitly and how parameter dependent problems (like the Reissner-Mindlin model) behave in the process of adaptation. In order to achieve overall consistency, dimensional adaptivity (to 3-D elasticity) is implemented within disturbed subdomains, especially at supports. Results are that Rheinboldt’s error indicator is valid under certain restrictions but not directly at bifurcation points and that robustness is not improved by adaptation. Nested quadrilateral finite elements are used for studying pre- and post-buckling states of plates and shells.

References listed at the end of the paper:
ABSTRACT: Power generation is one of the thrust areas for priority investment in developing countries. Cooling towers have become essential structures in many of the super thermal and nuclear power plants. Much technology transfer is taking place at an international level in the areas of thermal and structural design of natural draught cooling towers in concrete. One of the more controversial topics in such technology transfer is buckling safety of the hyperboloidal cooling tower shell. This paper presents a comparative evaluation of the recommendations, in this area, of some of the important national and international codes of practice, by way of case studies on five different cooling towers.

ABSTRACT: Analyses to predict inelastic buckling of axially loaded thin cylindrical shells are carried out.
using the finite element technique. The analyses use a bilinear elastic-perfectly plastic material response based upon the associated flow rule of plasticity. Nonlinear geometric effects, combined with initial imperfections, produce load-deflection curves with descending branches for which the limit points are imperfection sensitive. Results from these analyses are compared with two tests of axially loaded cylinders fabricated from 10-gauge (3.4-mm) and 5-mm plate and approximately 1525 mm in diameter. These tests were carried out in the Structural Engineering Laboratory at the University of Alberta. A rational technique for using measured imperfections to obtain effective initial imperfections for use in the analyses is investigated, and is shown to result in accurate predictions of ultimate load.


ABSTRACT: Solution procedures based on arc-length control have been among the most successful to be applied in nonlinear structural analysis. However, in the course of applying this type of procedure to postbuckling analysis of pipe segments, the writers experienced difficulties with the occurrence of complex roots arising from the arc-length constraint equation and with determining the direction of the load increment. In this paper, modified formulations of the arc-length control criterion and the loading criterion are proposed to address these problems. Applications of the procedures are shown to be successful for postbuckling analysis of pipe segments. Their effectiveness in following and advancing on the equilibrium path for both snap-through and snap-back behavior is illustrated.


ABSTRACT: A method is presented to incorporate the local buckling behavior of line pipe, determined from three-dimensional large deformational elastic-plastic shell analysis, into an interactive soil-structure beam model of a pipeline. The finite element model for the analysis of the pipe as a shell is described and the influence on the results of the buckling analysis of various load combinations are examined from the point of view of buckling configurations, moment-curvature curves and cross-sectional deformations. A method of extracting the stiffness properties of the pipe from these analyses is then described and a technique for determining stiffness coefficients from these properties is developed.


1305

-----ABAQUS Underground pipe buckling
Journal of the Brazilian Society of Mechanical Sciences and Engineering
ABSTRACT: A quasi-bifurcation theory of dynamic buckling and a simple flow theory of plasticity are employed to analyze the axisymmetric, elastic-plastic buckling behavior of buried pipelines subject to seismic excitations. Using the seismic records of the 1971 San Fernando earthquake, a series of numerical results have been obtained, which show that, at strain rates prevalent in earthquakes, the dynamic buckling axial stress or strain of a buried pipe is only slightly higher than that of static buckling.

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ABSTRACT: The paper proposes a new approach of predicting the bifurcation points of elastic-plastic buckling of plates and shells, which is obtained from the natural combination of the Lyapunov’s dynamic criterion on stability and the modified adaptive Dynamic Relaxation (maDR) method developed recently by the authors. This new method can overcome the difficulties in the applications of the dynamic criterion. Numerical results show that the theoretically predicted bifurcation points are in very good agreement with the corresponding experimental ones. The paper also provides a new means for further research on the plastic buckling paradox of plates and shells.

References listed at the end of the paper:


ABSTRACT: Initial imperfections have long been acknowledged as having an effect on the behavior of shell structures, affecting both the global and local behavior. Yet, despite their significance, initial imperfections are rarely included in analytical models for pipelines. This is usually because of the complicated nature of initial imperfections, the difficulty in measuring them, and the small amount of available literature that describes their geometry. Some recent investigations at the University of Alberta in Edmonton have focused on the effect of initial imperfections on the behavior of segments of line pipe. Imperfections measured across the inside surface of pipe test specimens were incorporated into a finite element model that was developed to predict the experimental behavior of the specimens tested under combined loads of internal pressure, axial load and
bending moment. Test-to-predicted ratios for the load carrying capacity of the test specimens had a mean value of 1.035 with a coefficient of variation of 0.047. The improvements in the accuracy of the finite element analysis models that include the initial imperfection pattern indicate their importance in modeling the experimental behavior. Once the importance of initial imperfections was established, idealized patterns were developed to simplify numerical modeling. This paper presents the results of different patterns investigated for both plain and girth-welded segments of line pipe and provides recommended simplified assumed initial imperfection patterns.


Yaw-Jeng Chiou and Shue-Yeong Chi, “Beam and Shell Modes of Buckling of Buried Pipes Induced by Compressive Ground Failure”, ASCE Lifeline Earthquake Engineering (1995), pp. 176-183

ABSTRACT: The buckling of buried pipeline induced by compressive ground failure was investigated. Both the beam mode of buckling and local shell mode of buckling, and their interactions were studied. The pipeline response was analyzed numerically. The results agree qualitatively with past researches and possess satisfactory comparisons with actual case histories. The relations of critical buried depth versus ratio of pipe diameter to thickness for buried pipe with different imperfections and various soil foundations were established.

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ABSTRACT: A shell model which takes into account the dynamic interaction terms for the earthquake behaviour of buried pipes is presented. A more realistic ground motion input for seismic waves is chosen in the analysis. Then a parametric study is conducted to investigate the effects of pipe radius, slenderness of the pipe, soil stiffness and wave propagation velocity on the modal amplitudes.


ABSTRACT: The Donnell and Flügge forms of the stability equations of cylindrical shells are employed to analyze the axisymmetric, elastic quasi-static buckling of buried pipelines subject to seismic excitations. Using shell dimensions and the stiffness of the soil medium surrounding the pipe as parameters, a series of numerical results are obtained, which shows that no significant half sine wave occurring in the circumferential direction for relatively long pipes when axial buckling load reaches its minimum. It also is shown that for a given pipeline an increase in soil stiffness causes a decrease in wavelength of the critical-load instability mode and, consequently, causes an increase in axial critical load.


ABSTRACT: This paper deals with the tensile failure of buried pipelines subject to abrupt fault movements. The pipe is modeled as a thin cylindrical shell which is essentially semi-infinite. The Sanders nonlinear shell theory is used with the inclusion of soil effects, and a simple flow theory of plasticity. A number of parametric studies are carried out and discussed to identify some design parameters of buried pipelines.

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ABSTRACT: An analysis method for the buckling process of a pipe section with a random pipelay imperfection is proposed. Four basic lateral modes, acquired by finite-element (FE) eigenvalue buckling analysis, are combined to provide the needed grid configurations for describing a real pipelay imperfection and an arc-length algorithm is used to analyze the snap-through process of the shell-element-grid model under nonlinear frictional boundary conditions. This paper also presents evaluation methods for the lateral buckling of two types of pipe-in-pipe systems that are used in the offshore oil and gas industry. For evaluating the buckling and postbuckling of compliant pipe-in-pipe systems FE analyses were carried out to judge the occurrence of the system buckling and furthermore to check postbuckling stresses induced in the buckles. The calculated results of the modified Riks algorithm indicate that only when high temperature would not trigger an abrupt short-wavelength buckle and when no yielding has been induced in the unavoidable long-wavelength buckles, the thermal stability and safety of compliant pipe-in-pipe systems can be proved. In the non-compliant pipe-in-pipe systems, firstly
small-amplitude buckles of the carrier pipe may occur in the annulus between carrier pipe and casing pipe and the contact forces between the spacers and the casing pipe may drive the buckle of the pipe-in-pipe systems on the seabed. Based on the classical analytical solution of pipe buckling, four potential buckling modes corresponding to finite-element models are developed to evaluate the stability and the postbuckling strength of such pipe-in-pipe systems.

References listed at the end of the paper:

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ABSTRACT: The currently valid worldwide standards allow for taking into consideration plastic deformations in order to achieve a higher degree of utilization. The maximum plastic strains, which can be allowed for steel pipes subjected to internal pressure and additional loads, are particularly interesting. In this paper results of investigations on the elasto-plastic bearing behavior of steel pipelines subjected to internal pressure and bending are presented. Four-point bending tests on eight steel pipes were carried out in order to make the buckling analysis in the elasto-plastic range possible. Finite-element-models were checked by test results for the application on buried pipelines. Taking into account bedding conditions of the pipeline in the soil was made possible. Furthermore, an analytical method based on the differential equation for beams with longitudinal tensile force and variable bending stiffness was developed. It is suitable to determine the elasto-plastic bearing capacity for internal pressure and bending. The collapse due to plastic shell buckling is considered by a limit criterion based on critical strains.

References listed at the end of the paper:

ABSTRACT: A new kind of tower construction, calling hybrid tower, is developed for offshore wind energy converters. The tower sections consist of two steel shells which are bonded together with a core material. The core between the inner an outer steel face increases the stability of the shells. In comparison with linear buckling analyses the validity of a laminate composite shell theory was proven. With model scale tests the stability of sandwich shells was analyzed against shell buckling due to axial compression and compared to tests with steel shells. Optical measurements were used to record the geometrical imperfections and to import the imperfect geometry of such shells in FE-models. Furthermore, a comparison of critical buckling loads was carried out with numerical solutions. The test series show a significant increase in bearing capacity for sandwich cylinders, which depends on the compressive strength of the core materials. The sandwich shells with a grout as core material show a catastrophic post buckling like steel shells. In contrast to this the elastomer core supports a ductile post buckling. The failure criteria for all variants of tested sandwich shells is more a local failure due to the steel faces called face wrinkling and not a global shell buckling.


ABSTRACT: The cylindrical shell with rectangle stiffeners was usually utilized in coal mine refuge chambers. Aiming at the buckling deformation of thin cylindrical shell under uniform axial compression, finite element analysis software ANSYS was employed to set up the optimization model of stiffened cylindrical shell, and the sequential linear programming method was executed to optimize the thickness of shell and the sizes of stiffener. The mechanical property after optimization was compared with the theoretical value of no-stiffener shell with equal volume, and reasonable stiffener distribution was obtained while the optimization results of five different longitudinal and circumferential stiffener patterns were gained. The results showed that the shell’s mechanical capacity of axial compression was basically not improved when the stiffeners were too sparse or overcrowded. Nevertheless, in the condition of reasonable stiffeners distribution, it could be improved by approximately 50%. The stiffener pattern and optimal results obtained in this paper are useful for refuge chamber’s shell design.

ABSTRACT: Lightweight yet stiff and strong lattice structures are attractive for various engineering applications, such as cores of sandwich shells and components designed for impact mitigation. Recent breakthroughs in manufacturing enable efficient fabrication of hierarchically architected microlattices, with dimensional control spanning seven orders of magnitude in length scale. These materials have the potential to exploit desirable nanoscale-size effects in a macroscopic structure, as long as their mechanical behavior at each appropriate scale – nano, micro, and macro levels – is properly understood. In this letter, we report the nanomechanical response of individual microlattice members. We show that hollow nanocrystalline Ni cylinders differing only in wall thicknesses, 500 and 150 nm, exhibit strikingly different collapse modes: the 500 nm sample collapses in a brittle manner, via a single strain burst, while the 150 nm sample shows a gradual collapse, via a series of small and discrete strain bursts. Further, compressive strength in 150 nm sample is 99.2% lower than predicted by shell buckling theory, likely due to localized buckling and fracture events observed during in situ compression experiments. We attribute this difference to the size-induced transition in deformation behavior, unique to nanoscale, and discuss it in the framework of “size effects” in crystalline strength.


ABSTRACT: The John equations are used to model the buckling of a simply-supported elastic spherical cap that is subjected to a constant uniform external load $\lambda$. The Liapunov-Schmidt method is used to solve these equations. We show that solutions possessing circular, pear-shaped, elliptical, triangular, square-shaped, pentagonal and a variety of other symmetries branch from the unbuckled state of the shell. The stability of these solutions is discussed. Some numerics that complement the analytical results are also included.

References listed at the end of the paper:

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ABSTRACT: Pumpkin balloon designs such as the constant-bulge-angle design, the constant-bulge-radius design, and hybrids of these design schemes have been used in an attempt to achieve a cyclically symmetric pumpkin-like shape when fully inflated. A number of flight balloons that were built based on these three design concepts encountered deployment problems. . . . Currently, NASA’s approach to superpressure balloon design uses a constant-stress model developed at NASA Goddard Space Flight Center. To fully understand the mechanism behind cleft formation in pumpkin balloons and to explore the constant-stress design space, NASA’s Balloon Program Office carried out a series of inflation tests in 2007 involving four 27-meter-diameter 200-gore pumpkin balloons. . . . In an effort to gauge constant-stress design susceptibility to deployment problems, we carry out a number of parametric studies and assess the stability landscape of the constant-stress design space. In our studies, we examine two types of top end-fitting boundary conditions, one restrictive and one less restrictive, that help to define a cleft-free design envelope. . . . To study scaling effects, we consider a
14-million-cubic-foot design. Our analysis suggest that as one scales up the balloon, the size of the cleft-free envelope shrinks.


SUMMARY: The post-buckling behavior of an elastic spherical shell is studied for large axisymmetric deformations. The complete post-buckling path is given for the experimentally confirmed single dimple solution in a load-deformation diagram, making use of the methods of local bifurcation theory, singular perturbation analysis and numerical analysis. From the specific form of the post-buckling path with its predominating unstable part follows the strong imperfection sensitivity of the shell structure.

References listed at the end of the paper:
Solution a nearly total understanding of the complete axisymmetric buckling behavior of the perfect Shell. I will shortly comment on this at the end of the paper.

References listed at the end of the paper:


ABSTRACT: For the axisymmetric buckling problem of a complete spherical shell we are able to give a complete imperfection sensitivity analysis for the most complicated case to occur, namely that of a double eigenvalue, if we restrict our analysis to nonlinear terms of quadratic order, which is correct mathematically as the bifurcation system turns out to be two determinate. As we make a classical bifurcation analysis our results are strictly local and therefore are of restricted practical importance in two respects. Firstly we do not take care of the fact that we have closely spaced eigenvalues. We comment on this in chapter 7. Secondly we are not able to show that the experimentally observed single dimple solution (Fig. 8) is one of the stable solutions found from our bifurcation equations up to terms of third order.

References listed at the end of the paper:

ABSTRACT: A constructive method is developed to establish the existence of buckled states of a thin, flat elastic plate that is rectangular in shape, simply supported along its edges, and subjected to a constant compressive thrust applied normal to its two short edges. Under the assumption that the stress function and the deformation of the plate are described by the nonlinear von Kármán equations, the approach used yields information regarding not only the number of buckled states near an eigenvalue of the linearized problem, but also the continuous dependence of such states on the load parameter and the possible selection of that buckled state “preferred” by the plate. In particular, the methods used provide a rigorous approach to studying the existence of buckled states near the first eigenvalue of the linearized problem (that is, near the “buckling load”) even when the first eigenvalue is not simple.

References listed at the end of the paper:


ABSTRACT: A method is outlined to obtain the “preferred” buckled states of a (complete) spherical shell under uniform external pressure. The shell model investigated is that of the John equations, a system of six nonlinear partial differential equations. Methods in bifurcation theory and group representations are used to reduce the problem to a finite-dimensional problem whose solutions generate buckled states that are “preferred” in a certain least-energy sense. Asymptotic methods and Newton's method are used in some special cases to relate the “preferred” buckled states obtained by the above approach to actual buckled states observed in experimental studies.

References listed at the end of the paper:


SUMMARY: A finite element method of mixed type is proposed to solve the Dirichlet problem of the von Kármán equations. Existence and convergence of the approximate solution are proved.

References listed at the end of the paper:


SUMMARY: The purpose of this paper is to study the approximation of the Von Karman equations by the mixed finite element scheme of Miyoshi and to follow the solutions arcs at a neighbourhood of the first eigenvalue of the linearized problem. This last problem is solved by a continuation method.

References listed at the end of the paper:
2. Begis, D.: Etude numérique de l'écoulement d'un fluide viscoplastique de Bingham par une méthode de Lagrangien augmenté. Rapport LABORIA 355, IRIA Rocquencourt
ABSTRACT: In preparing a Swedish handbook on stability of shell structures it was contended that present design codes and recommendations, with few exceptions, employ rather crude rules and also severe tolerance limits especially concerning spherical domes manufactured on site. A re-evaluation of test results available for metal domes subjected to external pressure was made with the aim of establishing a more refined procedure to determine a safe knock-down function to be applied to classical linear buckling strength. In the treatment of the test results a computer program was used allowing a statistical analysis.

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“Stability analysis of plates and doubly curved shallow shell structures using finite element methods and applications of MSC/NASTRAN”, (publisher and date not given in the pdf file. Most recent citation is dated 1995.)

ABSTRACT: A variational formulation of doubly curved shallow shells is presented. The analysis used Reissner’s two-field variable variational principle with the transverse displacement w and Airy stress function $F$ as field variable. Euler-Lagrange equations and boundary conditions are obtained. A finite element based on this variational principle preserving $C^1$ continuity is formulated, and your eigenvalues for free vibrations and buckling analyses are obtained. Applications for free vibrations and buckling analysis in MSC/NASTRAN model are given as well as their respective geometry shape. Several numerical calculations are presented. The results obtained are discussed and are compared with previous analytical solutions and numerical calculations.

References listed at the end of the paper:

ABSTRACT: A method is presented for formulating stiffness terms and thermal coefficients of stiffened, fiber-reinforced composite panels. The method is robust enough to handle panels with general cross sectional shapes, including those which are unsymmetric and/or unbalanced. Nonlinear, temperature and load dependent constitutive material data of each laminate are used to ‘build-up’ the stiffened panel membrane, bending, and membrane-bending coupling stiffness terms and thermal coefficients. New thermal coefficients are introduced to quantify panel response from through-the-thickness temperature gradients. A technique of implementing this capability with a single plane of shell finite elements using the MSC/NASTRAN analysis program (FEA) is revealed that provides accurate solutions of entire airframes or engines with coarsely meshed models. An example of a composite, hat-stiffened panel is included to demonstrate errors that occur when an unsymmetric panel is symmetrically formulated as traditionally done. The erroneous results and the correct ones produced from this method are compared to analysis from discretely meshed three-dimensional FEA.


DTIC Accession Number: ADA443229, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA443229

ABSTRACT: The benefits of a software package which couples with the MSC/NASTRAN FEA program is presented. The software, called HyperSizer, performs panel and beam structural sizing optimization with metallic and composite materials. Applications in the aerospace and transportation industries are presented. The aerospace application, an X-34x experimental vehicle, emphasizes capabilities and accuracy required for a high speed flight, thermomechanical environment. The transportation application emphasizes practical and inexpensive capabilities suitable for a cost driven, manufacturing oriented environment.

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Buckling Analysis and Optimization of Stiffened Cylindrical Shells under Uniform Axial Compression
Journal Key Engineering Materials (Volumes 462 - 463)
Volume Fracture and Strength of Solids VII
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Authors Xing Hua Chen, Lian Chun Long
Keywords Axial Compression, Buckling, Loading Capacity, Optimization, Stiffened Cylindrical Shell
Abstract Thin cylindrical shells are widely used in modern structures. When the structures are under axial compression, inflectional destruction happens early. In order to design reasonable and reliable shell structures, stiffened cylindrical shells are applied in the dissertation, ANSYS, an valid finite element analysis software, is employed to redevelop and set up parameter calculation model, subjected to volume and variables value range restriction, the structure’s critical buckling load is the objective, and the serial linear programming optimization procedure is executed as well as the optimized thickness of shell and the size of stiffeners are gained accordingly. The critical buckling load of the structure is obviously increased after optimization, and the feasibility of this method is validated due to the comparison with the numerical and theoretical result.

--------http://www.fgg.uni-lj.si/kmk/esdep/master/wg01b
University of Lubxxxx Buckling lecture ESDEP WG 1B: Lecture 1B.8: Learning from Failures

ABSTRACT: Research results concerning the simulation of the crushing behaviour of composite systems with energy absorption characteristics are presented in the present work. The study is focused on the ‘tensor skin’ concept, an energy absorbing composite system that was originally developed to improve the crashworthiness of helicopters under water impact and which is promising for utilization in the construction of the lower part of
composite fuselage aircraft. The ‘tensor skin’ concept comprises a folded or corrugated composite construction, which upon loading unfolds by forming ‘plastic hinges’, leading to an increase in the load bearing capability of the structure. The numerical modelling issues and the critical aspects of the simulation are discussed. Verification of the numerical simulation procedure is performed by experimental work. The experimental results utilized to assess and validate the numerical procedure were derived within the European Research Project ‘Design for Crash Survivability – CRASURV’ (BRITe – Aeronautics Area). The results of the simulations are generally in good agreement with experimental data.

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ABSTRACT: The purpose of this paper is to present an efficient engineering methodology for solving the problem of non-linear (NL) damage and post-buckling of large-scale structures, which is of high importance mainly for the aircraft industry. The methodology takes advantage of the capabilities of finite element substructuring technique in the simulation of large/complex structures and exploits the advantages of local-global analysis logic. The main innovation deals with the appropriate modification of superelement method, such that it can deal with NL behaviour and efficiently model the entire large-scale structure. In this study, the proposed methodology is demonstrated in the treatment of geometrical non-linearity and its efficiency is assessed in the case of a large-scale fuselage section.


ABSTRACT: A methodology for the analytical assessment of local buckling and post-buckling behavior of isotropic and orthotropic stiffened plates is presented. The approach considers the stiffened panel segment located between two stiffeners, while the remaining panel is replaced by equivalent transverse and rotational springs of varying stiffness, which act as elastic edge supports. A two-dimensional Ritz displacement function (pb-2 Ritz) is utilized in the solution of the local buckling problem of isotropic and laminated symmetric composite panels with arbitrary edge boundary conditions. The buckling analysis of the segment provides an accurate and conservative prediction of the panel local buckling behavior. Consequently, the developed methodology is extended in the prediction of the post-buckling response of stiffened panels of which the skin has undergone local buckling. Of high importance for the calculation of the post-buckling behavior is the selection of appropriate boundary conditions for the structural members analyzed. A comparison of the present methodology results to respective finite element (FE) results has shown a satisfactory agreement.

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ABSTRACT: In this paper an outline is given of a theoretical approach which is able to predict the equilibrium behaviour of thin-walled, pin-ended, I-section columns after local buckling. The extreme changes in cross-sectional shape that occur during overall bending of the locally buckled column are accounted for quite easily in the analysis by the inclusion of several local deflection shape functions. The changes in cross-sectional shape that occur during the pure compression phase of behaviour, prior to overall bifurcation, are also accounted for in the analysis. The Rayleigh-Ritz method is used to obtain local buckling loads and a semi-energy method is employed to describe post-buckling interaction behaviour. It is shown that, although all columns exhibit stable equilibrium behaviour after local buckling, the quality of the equilibrium at failure due to overall bifurcation, can be unstable to varying degrees depending on geometry. It is also shown that the theoretical predictions of equilibrium behaviour and ultimate loads are significantly influenced by the number of local deflection shape functions incorporated in the post-buckling analysis. If insufficient functions are employed in the solution, a considerable overestimate of stiffness and hence ultimate load can result. The analysis is able to accommodate eccentricity of applied loading and column axis imperfection in which case, overall bending would occur from the onset of loading. A study is made of the effect of column axis imperfection on the ultimate carrying capability of thin-walled I-section columns and it is shown that, I-sections are appreciably sensitive to this mode of imperfection over a wide design range. Results are presented in the paper in the form of load-deflection equilibrium curves and ultimate load-slenderness plots. A comparison of the theory with independent experimental work is also included and agreement is seen to be good.

References listed at the end of the paper:

ABSTRACT: In the present contribution a novel fast design tool is developed to enable the calculation of critical buckling loads of large structural components comprising stiffened composite panels. In more detail the development of analytical closed form solution for the local buckling problem of a stiffened plate is treated as the buckling of the skin segment enclosed by two consecutive stringers. In this case the effect of the stringers to the skin is modeled by applying appropriate elastic restraints as boundary conditions. The elastic restraints are derived and determined considering the bending and torsional stiffness of the stringers. The solution of the skin local buckling problem is obtained utilizing the Rayleigh-Ritz method. Additionally, the developed closed form solution is extended to the interesting case of anisotropic stiffened panels. Finally, the validation of the analytical results is obtained comparing them with the respective numerical, and a satisfactory correlation is achieved.

ABSTRACT: A stiffened panel demonstrator component typical of that used in the shipbuilding industry was conceived to demonstrate the advantages of three dimensional laser processing using robot manipulated 4kW Nd:YAG lasers. BS EN 10025:1991 Grade S275JR (formally BS 4360: Grade 43D) material in the 6-8mm-thickness range was used. Initial parameter development preceded the fabrication of a 1mx1m test panel and the eventual production of a 4.8mx1.9m full size panel section for destructive testing. Equipment set-up, joint design, effect of fit-up, processing techniques and distortion are described. The completed panel was used to compare the level of distortion induced between laser and conventional arc welding processes, before being used to conduct a similar buckling test comparison.

ABSTRACT: The design wall thickness of many corrugated silos and tanks is governed by the vertical compressive strength of the wall. This paper presents a precise theoretical study of the collapse strengths of cylindrical corrugated shells under axial compression and axial compression combined with internal pressure. Two simple models to describe the collapse strength are proposed, and each is shown to be approximately valid for a certain range of geometries. The true collapse strength is determined using a large displacement elastic-plastic finite element analysis for doubly curved shells of revolution. The form of the corrugation profile is accurately modelled and the collapse strength is found precisely by following the complete loading and unloading paths of the load-deflection curve. Simple design recommendations are given.


ABSTRACT: A very large literature exists on the static analysis of thin shell structures, covering elastic stress states, elastic buckling, plastic collapse and elastic-plastic failures. Modern approaches to these problems usually involve the use of computer programs to perform a variety of different alternative types of calculation. However, the way in which different analyses should be used in the design process has received much less attention until recently. The new European Standard for the Strength and Stability of Shells sets out a philosophical framework that accommodates the results of both algebraic analysis and different levels of sophistication in computer analyses. This paper describes the philosophy on which the new standard is based, and outlines the way in which the various analyses should be used, when applied in design practice. It also identifies some of the remaining difficulties which pose challenges of definition and interpretation, and which need debate in the scientific community.

References listed at the end of the paper:

ABSTRACT: Metal silos and tanks are subject to axial compressive stresses in their cylindrical shell walls. The buckling strength is very sensitive to geometric imperfections in the wall. The most regular and well-defined imperfection is the local depression adjacent to a circumferential weld, caused by the plate rolling process and shrinkage of the weld. This paper examines the elastic buckling strengths of thin cylindrical shells under axial compression, with imperfections arising at circumferential welded joints. The effects of the welded joint depression amplitude, the shell radius-to-thickness ratio, a change of shell plate thickness at the weld, and internal pressurization are all examined. The study is confined to cylinders with a radius-to-thickness ratio in excess of 100, as thicker shells are rare for these structures. It is shown that a welded joint depression is one of the most deleterious practical imperfection forms currently known.

ABSTRACT: Conical shells are often joined to cylindrical shells as end closures, reducers or roofs. Under a variety of loading conditions, the intersection between the large end of a cone and a cylinder is subject to a large circumferential compressive force which can lead to its failure by buckling. The problem may be idealized as a cone-cylinder intersection under a radial inward ring load. This paper first investigates the elastic buckling strength of thin cone-cylinder intersections under a radial inward ring load and develops simple and accurate equations for the prediction of buckling mode and strength. The ability of ring-loaded intersections to conservatively represent intersections under a variety of other loading conditions for their buckling behaviour is then explored. The ring load idealization is shown to be generally conservative, but may become rather conservative for some loading conditions such as uniform internal pressure. The strength of cone-cylinder intersections under uniform internal pressure is examined in detail in the final part of the paper and approximate strength equations are also developed, as this loading condition is important for pressure vessel and piping applications.

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ABSTRACT: A study is presented of the out-of-plane buckling strength of rings attached to cone-cylinder intersections. Simple formulae which can be used to estimate the stiffness of the rotational restraint provided by adjacent shell walls are first developed from a finite element parametric study. These formulae are then combined with an existing closed-form solution based on thin-walled member theory to predict the flexural-torsional buckling strength of rings with an elastic rotational restraint. Numerical results are obtained for angle section rings from the closed-form solution and a finite element shell buckling analysis which is able to model cross-section distortion. Comparisons between the two approaches show that when the restraint stiffness is small, they agree with each other closely. Beyond a certain level of restraint stiffness, the buckling strength predicted by the finite element analysis falls increasingly below that given by the closed-form solution due to cross-section distortion and approaches the strength of an inner edge clamped ring. The paper concludes with suggestions for safely approximating the stiffness of the shell wall rotational restraint for use in design.


ABSTRACT: In many practical applications, thin shells are in contact with soils or other solids. Such situations arise in cylindrical bulk solid storage silos, above-ground and underground liquid storage tanks, underground pipelines, ballistic missiles filled with solid propellants, and concrete-filled steel tubular columns. As a result, many studies have been carried out on the analysis and behavior of shells on elastic foundations. However, little has been done on shells on nonlinear elastic foundations, despite the fact that foundation behavior is generally nonlinear. This paper presents a finite element formulation for the buckling analysis of shells of revolution on nonlinear elastic foundations. To achieve a versatile foundation model, the foundation reaction–displacement relationship is represented by a number of discrete data points (referred to as the Discrete-Point or DP Model in this paper). Any specific nonlinear functions such as polynomials can be treated as special cases of this model and accurately represented by a sufficiently large number of data points. The validity and capability of the present analysis are demonstrated through numerical comparisons. The paper also presents the first set of verified numerical results for buckling of shells on nonlinear elastic foundations, which can be used to benchmark results from other sources in the future.


ABSTRACT: Theories for the out-of-plane buckling of rings under uniform circumferential compression are well established. However these theories are not applicable to rings in column-supported bins where the circumferential stress in the ring varies significantly over the cross-section and around the circumference. This paper deals with the out-of-plane buckling of annular plate rings in column-supported bins and tanks. The stress distributions in such rings are first examined using a finite element shell analysis. A closed-form solution for the buckling of rings under non-uniform circumferential stresses is then derived. Numerical results from the closed-
form solution are compared with those from a finite element shell buckling analysis, and close agreement is found. The significant effect of stress non-uniformity on the buckling predictions is demonstrated. Finally, simplified equations are given which are suitable for structural design purposes, and which closely model the predictions of the more rigorous solution.


ABSTRACT: Large modern steel silos are either elevated or supported on the ground. The main structural components are a cylindrical body, stiffeners (rings and stringers etc), a roof, and in the case of elevated silos, a hopper and supporting column. Silo structures are designed chiefly as containers, therefore the load from the contained material comprises the major part of the load which silos experience. The stored bulk solid exerts both internal pressure and downward frictional drag on the wall, the latter causing a potential for buckling of the wall. In addition to loading the wall by gravity, the bulk solid has a strengthening effect against buckling under axial compression. This is because, unlike fluids, bulk solids have finite strength and stiffness. The effect of imperfections on the buckling strength of cylinders under axial compression has been studied extensively in the past, as has the effect of internal pressure. The stiffening effect due to bulk solids in silos has, however, not been systematically studied. In this thesis a study of the stability of thin-walled steel silos is presented. The strengthening effect of the bulk solid is modelled theoretically using a Winkler foundation. The theoretical studies are carried out using the finite element technique. The formulation of an isoparametric doubly curved shell element for the linear elastic static analysis of shells of revolution with attached elastic restraints along the three curvilinear directions is described first. Non-symmetric loads are decomposed into Fourier components. The linear elastic buckling analysis is followed by the analysis of the shell-spring system under axisymmetric load, and nonlinear large-displacement and material analysis. Linear analysis is often not sufficient to describe the real behaviour of shells. Non-linear effects from both the change of geometry and stresses which exceed the elastic limit may need to be considered. This formulation, including the effect of restraints, is given. The analysis includes full non-linearity on both shell geometry and material. The effect of non-linear springs is taken into account in the formulation. Recently-developed non-linear strain-displacement relations for thin shells of revolution are used. An efficient and accurate state determination algorithm is adopted. The arc-length method implemented by other researchers is used to trace both the pre- and post-collapse load deflection curve. Non-symmetric bifurcation including prebuckling large deflections is given, after the primary equilibrium state is reached. The linear and non-linear analyses are applied to a number of example problems of restrained shells. Results are compared with published theoretical and numerical results, wherever it is possible. Several comprehensive theoretical studies of the buckling and collapse of steel silo shells are performed using the finite element analysis developed in this thesis. A study of silos filled with bulk solids with axisymmetric imperfections caused by weld joint depressions is firstly given. Attempt is made to relate any buckling strength gain of the shell wall by bulk solids to the mechanical properties of bulk solids, which has been a difficult task. A comprehensive study of the collapse failure of light gauge steel silos made of thin corrugated sheets is made. One of the common failure modes in thin corrugated silos is that in which a few corrugations are squashed together to form a fold. Two simple collapse mechanisms are presented, each valid for a range of geometry. The proposed theories are verified using the finite element technique. Another common failure mode for silos built of thin corrugated sheets is buckling of wall under axial or circumferential compression. The wall is idealised as an orthotropic shell. The orthotropic properties are therefore important to the stability analysis of corrugated shells. A number of expressions have been proposed in the past for the orthotropic properties of a flat corrugated sheet. The circumferential curvature influences these properties. A numerical study using the finite element analysis is given in this thesis for the accurate definition of these properties, and the results are
compared with existing proposals. Finally, tests of thin steel model cylinders filled with different bulk materials are conducted under several load conditions. The purpose of the experiments is to measure the strength gains of cylinders filled with bulk solids and compare with predictions of the finite element studies of restrained cylinders. Three series of tests were conducted: (a) Empty cylinders under axial compression; (b) Cylinders filled with pressurised water under axial compression; and (c) Cylinders filled with bulk solids under axial compression. Two types of bulk solids are selected; one is the relatively softer wheat and the other the stiffer Sydney sand. The bulk solids inside the models are stressed to different levels to achieve different ratios of axial and hoop stress in the wall. The results indicate that the buckling strength of the wall can be increased significantly by the presence of bulk solids, and in some cases, it can be well above the classical buckling stress for a perfect cylinder under axial compression. Information on the quasi-elastic behaviour of bulk solids inside silos is limited. A study is presented here to add to the available data. The mechanical properties of sand and wheat inside silos are given and compared with predictions suggested in the design specifications and in the literature.

J.M. Rotter and P.T. Jumikis (School of Civil and Mining Engineering, University of Sydney), “Nonlinear strain-displacement relations for axisymmetric thin shells”, Research report / University of Sydney, School of Civil and Mining Engineering ; no. R563, 1988

ABSTRACT: Nonlinear deformation and stability analyses are based on nonlinear relations between the strains and the corresponding displacements of the body. Many attempts have been made to develop nonlinear strain-displacement relations for thin shells, and many of these are quoted in specialised form for shells of revolution. Shells of revolution have many more applications than most other shell forms, so it is natural that specialised analyses should be developed for them. The differences between existing nonlinear relations for thin shell lie principally in the number of terms which have been rejected using the assumption that they would be unimportant. The purpose of rejecting these small terms has usually been to produce simple relations which could be used in algebraic or classical theories. In modern finite element analysis, there is little advantage in reducing the number of terms slightly, but a theory which has omitted a term which is vital in even a small number of practical structures has a major flaw. This paper describes a new set of nonlinear strain-displacement relations for thin shells, subject to large displacements with moderate rotations, and which retains more terms than most existing theories. The new relations are proposed only for use in finite element calculations. The chief difference between the new relations and previous work is the recognition that nonlinear strains arising from products of in-plane strain terms may be important in certain buckling problems. It is shown that the widely-used relations of Sanders (1963) lead to the wrong answer for a simple practical problem, and that this disadvantage is overcome by the present formulation.


A Review of the paper dated 19 May, 2009:
This is the first known study that defines the strength of a cylindrical shell under internal pressure and axial load leading to an elastic-plastic stability failure in the Elephant's Foot mode. The paper gives design equations that have been widely adopted into standards to cover this failure mode. It is easy to read and is worth studying if you are concerned with elephant's foot buckling.

ABSTRACT: Elevated steel silos commonly consist of a cylindrical shell, a conical hopper, and a skirt. At the intersection of these shell segments, a ring is often provided to sustain the high circumferential compressive stress developed. The cone/cylinder/skirt/ring junction, known as the transition, may fail by plastic collapse under the large circumferential compression. In this paper, an elastic-plastic large-deflection finite element analysis is employed to study the plastic collapse behavior of this junction. A typical structure is first examined to study the distribution of stresses, the effect of large deflections, the formation of a plastic collapse mechanism, and the collapse process. A simple theory proposed by Rotter, which is based on a reinterpretation of the classical limit analysis of ring-loaded cylinders, is next outlined and its background further clarified. An improved version of Rotter's equation, which applies to a wider range of geometries, is then proposed for use in design.

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“Buckling in thin elastic cylinders on column supports”, in Buckling of shell structures on land, in the sea, and in the air, edited by J. F. Jullien, Elsevier, 1991

PARTIAL ABSTRACT: Elevated silos and tanks are often supported on a number of columns. The discrete supports of the columns induce high stresses adjacent to the column terminations. In particular very high meridional compressive stresses arise above the column termination, and these can lead to buckling of the shell at a load much lower than that for a uniformly supported shell. This paper presents a brief summary of recent theoretical work on the elastic buckling strength of column-supported cylinders...

J.G. Teng and Hong-Wei Ma (Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China), “Elastic buckling of ring-stiffened cone–cylinder intersections under internal pressure”, International Journal of Mechanical Sciences, Vol. 41, No. 11, November 1999, pp 1357-1383

ABSTRACT: Cone–cylinder intersections are commonly found in pressure vessels and piping. Examples include conical end closures to cylindrical vessels and conical reducers between cylinders of different radii. In the case of a cone large end-to-cylinder intersection under internal pressure, the intersection is subject to a large circumferential compressive force. Both the cone and the cylinder may be thickened near the intersection to resist this compression, but it is often convenient and necessary to augment further the strength of the intersection using an annular plate ring stiffener. Under this large circumferential compression, the intersection may fail by elastic buckling, plastic buckling or plastic collapse. This paper describes an investigation of the elastic buckling strength of ring-stiffened cone–cylinder intersections. Two buckling modes are identified: a shell mode for thin intersections with a shallow cone (a cone with its apex half angle approaching 90°) and/or a relatively stocky ring stiffener, and a ring mode for other cases. An existing elastic buckling approximation for annular plate rings in steel silos is found to be applicable to the intersection when it buckles in the ring mode. New approximate design equations are also established for the shell mode. In addition, simple expressions are identified which relate the number of circumferential buckling waves to the geometric parameters of the intersection.
ABSTRACT: Fibre-reinforced polymer (FRP) jackets have been widely used to confine reinforced concrete (RC) columns for enhancement in both strength and ductility. This paper presents the results of a recent study in which the benefit of FRP confinement of hollow steel tubes was explored. Axial compression tests on FRP-confined steel tubes are first described. Finite element modelling of these tests is next discussed. Both the test and the numerical results show that FRP jacketing is a very promising technique for the retrofit and strengthening of circular hollow steel tubes. In addition, finite element results for FRP-jacketed thin cylindrical shells under combined axial compression and internal pressure are presented to show that FRP jacketing is also an effective strengthening method for such shells failing by elephant’s foot collapse near the base.

References listed at the end of the paper:

ABSTRACT: Shell structures are widely used in a great variety of applications from space rockets to domestic food and drink containers. Civil engineers are principally concerned with steel shell structures such as silos, tanks, pipelines, chimneys, towers and masts, though other examples may be found in offshore structures and stadium roofs. This paper describes the treatment of terrestrial shell structures in Eurocode 3: Steel structures. It outlines the principles which are guiding the development of the standard, the range of applications covered, and some details of the current proposals. The axially compressed cylindrical shell is then chosen as an example illustrating the range of real problems which need to be addressed, and the paucity of current data on many aspects of these problems. This example is also used to outline the complexity involved even in this one area, recent progress and current needs.

J. Michael Rotter (University of Edinburgh, Scotland, UK, School of Civil and Environmental Engineering), “Pressures, Stresses and Buckling in Metal Silos containing Eccentrically Discharging Solids”, Greiner Institute for Steel and Shell Structures, TU Graz, 2001

ABSTRACT: The eccentric discharge of stored solids from moderately slender metal silos has caused many dramatic and catastrophic buckling failures. Despite these many failures, eccentric discharge failures are poorly understood even by specialists in shell structures, and the cause of failure is often misinterpreted. In particular, buckles occurring well up the wall of a silo are often thought to be difficult to explain. This paper sets out the theory of pressures occurring in silos under eccentric pipe flow where part of the flow channel is in contact with the silo wall. It then uses pressures predicted by this theory to analyse an example structure, with different flow channel geometries. The stress patterns are seen to be such that local axial compression buckles are likely to occur well up the wall, and it is found that certain sizes of flow channel are critically dangerous to the structural integrity of the silo shell.

References listed at the end of the paper:
ACI 313 ADP (1989), Alternate Design Procedure, Discussion document before ACI Committee 313 on Concrete Bins, Silos and Bunkers for Storing Granular Materials, ACI, Detroit.
J. Michael Rotter, “Advanced computer calculations in the design of shell structures”, Advances in Steel Structures (ICASS '02), Proceedings of the Third International Conference on Advances in Steel Structures 9–11 December 2002, Hong Kong, China, 2002, pp. 27–42, doi:10.1016/B978-008044017-0/50006-8

ABSTRACT: The high efficiency of shell structures leads them to be widely used in a huge variety of applications: food and drink containers, cars and vehicles, aircraft and spacecraft, and large storage structures. Steel shell structures are most used in civil engineering as silos, tanks, pipelines, chimneys, towers and masts. Offshore structures present another example.


PARTIAL ABSTRACT: Cylindrical shell structures are often subjected to compressive stresses in the direction of the cylinder axis, which can be either uniform or varying throughout the cylinder. The buckling strength of a thin cylindrical shell under axial compression is particularly sensitive to imperfections in the shell, and the changing patterns of behaviour with changing geometry, loading and boundary conditions make the axially compressed cylinder a classical exemplar for behaviours that may be found in a less marked form in other structures or in shells under other loading conditions. For these reasons, the axially compressed cylinder has probably been the most extensively studied of all shell buckling conditions, giving a wealth of evidence from both experimental and theoretical work.


ABSTRACT: Metal cylindrical bins, silos and tanks are thin shell structures subject to internal pressure from stored materials together with axial compression from the frictional drag of stored materials on the walls and horizontal loads. The governing failure mode is frequently buckling under axial compression. The internal pressure exerted by the stored fluids or solids can significantly enhance the buckling strength, but high internal pressures lead to severe local bending near the base. Local yielding then precipitates an early elastic-plastic
buckling failure. This failure mode, commonly known as “elephant's foot buckling”, has received relatively little attention to date and until recently was often ignored in tank and silo design. This problem is an unusual buckling condition, because it involves very high tensile stresses in one direction, coupled with rather small compressive stresses in the orthogonal direction. Thus, although it is a buckling failure involving considerable plasticity, it occurs at low buckling stresses and under conditions that appear to be classically “slender”. The normal concatenation of “slender” with “elastic” in buckling formulations does not apply at all here. This paper describes alternative approaches to the formulation of design rules for the elastic-plastic instability and collapse of axially-loaded internally-pressureurised thin cylindrical shells adjacent to the base support. The differences between the different approaches arise from different conceptual models for the manner in which an elastic-plastic slender structure instability should be treated.

References listed at the end of the paper:

ABSTRACT: Externally bonding of fibre reinforced polymer (FRP) composites has become a popular technique for retrofitting existing structures worldwide. Extensive research has been conducted in the last two decades on various topics such as strengthening concrete, masonry and timber structures as well as metallic structures. The vast majority of these studies have focussed on the failure strength, rather than on stability considerations. A study is currently being conducted at Edinburgh University on the strengthening of thin metal shell structures using FRP composites. This paper presents a numerical study of the buckling behaviour of FRP strengthened thin cylindrical shells with an axisymmetric imperfection. The results show that the buckling strength of the shell under axial loading can be significantly increased by using only a small amount of FRP in the critical area of the imperfection. This outcome indicates that this technique is indeed very effective and economical for enhancing the buckling strength of thin shell structures, especially under conditions where a local defect causes the shell to fail the tolerance requirement.

References listed at the end of the paper:

ABSTRACT: Thin metallic shell structures such as silos and tanks are susceptible to buckling failure which is usually very sensitive to local imperfections. The strengthening of such thin shells has previously been rather difficult if not impossible. Welding additional metal plates to the existing structure is not easy and can be prohibitive for health and safety reasons if the structure contains materials like harmful chemicals, flammables, explosive liquids or gases. Welding also introduces imperfections and residual stresses which may reduce the buckling strength of the structure. The authors have recently proposed to strengthen such structures using externally bonded FRP. This paper presents a numerical study of the buckling behavior of cylindrical metal shells with a dent and strengthened with FRRP. The results show that the scheme is very effective and economical.


ABSTRACT: Thin metal cylindrical shell structures such as silos and tanks are susceptible to an elastic–plastic instability failure at the base boundary known as elephant's foot buckling, due to its characteristic deformed shape. This form of buckling occurs under high internal pressure accompanied by axial compression in the shell structure. This is a common failure mode for tanks under earthquake loading. Another common situation is in a silo where the silo wall is subjected to both normal pressures from the stored granular solid and vertical compressive forces developed from the friction between the stored solid and the silo wall. This paper presents a novel method of strengthening cylindrical shells against elephant's foot buckling in which a small amount of fibre-reinforced polymer (FRP) composite, used at a critical location, can effectively eliminate the problem and increase the buckling strength. The strengthened shell is analysed using linear elastic bending theory in this preliminary study. Within the scope of this research, the strengthening effect is shown to be sensitive to the thickness, height and location of the FRP sheet. The issue of optimal FRP strengthening to allow the shell to attain pure membrane-state deformation is examined in detail as strengthening with too much and too little FRP are both undesirable. Both pinned-based and fixed-based shells are examined and their responses are compared.


ABSTRACT: Silos and tanks are probably the commonest form of large engineering shell structure in service, but their placement on industrial sites and out of the public eye often leads them to be neglected by researchers and the public alike. The high rate of structural failure in these structures is a strong indication of the extensive range of issues that must be understood by the designer and the complexity of their behavior. This paper outlines some of the most critical aspects of the loading, structural behavior and failure modes of silos and tanks, and points in many places towards the need for additional research to permit better regulation of these very varied and complex structures.

References listed at the end of the paper:


ABSTRACT: The most serious loading condition for slender thin-walled metal silos has long been recognized to be the condition of discharge, with eccentric discharge causing more catastrophic failures than any other. Two key reasons for this high failure rate are the difficulties in characterizing the pressure distribution caused by eccentric solids flow, and in understanding the associated unsymmetrical stresses in the silo wall. Few studies have addressed either the linear elastic behavior of such a silo or its buckling failure under eccentric discharge. In this study, the eccentric discharge pressures are characterized using the new rules of the European Standard EN 1991-4 on Silos and Tanks. This novel description of unsymmetrical pressures permits a study of the structural behavior leading to buckling during eccentric discharge, including the critical effects of change of geometry and imperfection sensitivity, to be undertaken using geometrically and materially nonlinear computational analyses. The mechanics of the behavior are found to be quite complicated. A silo which is safe under axisymmetric loading is found to be susceptible to catastrophic stability failure under eccentric discharge.

References listed at the end of the paper:


ABSTRACT: Eccentric discharge in slender metal silos is known to be one of the most critical load conditions, responsible for many silo buckling disasters in the past. The high failure rate may be significantly attributed to difficulties in devising a suitable wall pressure representation for this condition. Where the flow of stored solids is eccentric and has partial contact with the wall in a slender silo, the solid exerts much lower pressures than the adjacent stationary solid. This pressure drop leads to very high local axial compression and causes buckling failure. Experimentally measured pressures indicate that a significant rise in pressure may occur just outside the flow channel, but its form and magnitude are not yet well understood because very detailed and expensive instrumentation is needed to obtain data that can define it. This paper explores the nonlinear structural behaviour and buckling of a slender metal silo with and without specific inclusion of an adjacent rise in pressure, to determine whether it is a necessary part of any design pressure representation. To assist this investigation, the mechanics of the nonlinear behaviour of a cylindrical silo under this load condition is explored using the analogy of a propped cantilever slice-beam. Advantage is taken of a particular load condition that leads, by chance, to buckling at the same load factor for both linear and geometrically nonlinear analyses. This special case permits the detrimental effect of wall flattening and the beneficial effect of the changing prebuckling stress pattern to be explored to give a deeper insight into the behaviour. The slice-beam analogy may also be generalised to describe the nonlinear behaviour of any thin-walled cylindrical shell under meridional strip-like loads acting on part of the circumference.

References listed at the end of the paper:
ABAQUS 6.9 [Computer software]. Providence, RI, Dassault Systèmes Simulia.


ABSTRACT: Modern procedures for the design of shell structures against buckling have their basis in analytical studies of axisymmetric shell geometries under the very simple load cases of uniform compression, external pressure and torsion. Studies of more complex but realistic stress states were based on prebuckling analyses using either membrane theory or linear bending theory because even these involved considerable mathematical complexity. As a result, only limited conclusions for practical design could be drawn and the effects of geometric nonlinearity could not be assessed. With recent advances in computing power and nonlinear finite element programs, it is now possible to undertake nonlinear analyses of complex load patterns that would have been very difficult to do only a decade or so ago.

References listed at the end of the paper:

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ABSTRACT: Many problems in structural mechanics involve complex principal stress fields that are not orthogonal to the geometric axis of the structure. Such problems are often analysed with finite elements, but the quality of a finite element solution may be sensitive to the orientation of the mesh with respect to the principal axes of stress. This paper presents the outline of a procedure to generate well-structured inclined quadrilateral finite element meshes for the analysis of thin plate and shell structures. The procedure was developed using the commercial FE pre-processor ABAQUS CAE and the Python script language, though it may readily be applied in any pre-processor which supports an external scripting functionality. A set of mesh convergence studies using linear buckling analyses are presented on four benchmark problems with known analytical solutions to illustrate the effect of inclined meshes on the accuracy of the computed solution. These illustrations are intended to raise an awareness of the subtle but important relationship between mesh and stress field orientation.
and are presented for the benefit of practising finite element analysts in structural engineering.

References listed at the end of the paper:

ABSTRACT: This paper presents an initial study of the effects of an accidental eccentric flow channel that sometimes develops in the conical hopper of a metal storage silo. A simple assumed pressure regime is adopted, based on studies of eccentric discharge in cylindrical silos, and the structural actions are analysed using shell membrane theory. The results are verified against a finite element analysis. A set of equations is derived which give the complete membrane stress state in the hopper under such an unsymmetrical pressure regime. Under symmetrical loading, silo hoppers are subject to biaxial tension, with failure normally governed by material rupture due to tensile meridional membrane stresses. It is found that the eccentric flow channel leads to dramatically increased meridional membrane stresses at the transition. Compressive membrane stresses are also found near the hopper outlet and at the sides of the flow channel near the transition. A reasonably close correlation is found between the derived membrane theory equations in a right circular conical hopper and linear elastic finite element predictions.

References listed at the end of the paper:
[18] Rotter JM. Pressures, stresses and buckling in metal silos containing eccentrically discharging solids. Festschrift Richard Greiner, celebration volume for the 60th birthday of Prof. Richard Greiner  Institute for Steel and Shell Structures, TU Graz,


ABSTRACT: The buckling strength of a thin cylindrical shell is important in many applications in civil engineering. On the one hand, current design rules are principally based on an empirical interpretation of test data and hence very simple loading conditions are applied. On the other hand, experimental and theoretical observations show significant stress non-uniformity and hence a deviation from the buckling strength expected under uniform load. Reliable quantification of this effect is still challengingly difficult. This paper explores a typical thin cylindrical silo shell under localized axial compression. Two different buckling phenomena are identified with corresponding, and distinct, buckling mode forms. The influence of geometric imperfections on the buckling strength of the shell is also considered. INTRODUCTION Cylindrical silo shells are subject to vertical stresses in their walls as a consequence of friction between the stored solid and the wall. Shell buckling under axial compression is normally the controlling design consideration especially for steel silos. The classical buckling strength (Lorenz, 1908; Timoshenko, 1910; Southwell, 1914) continues to be treated as a practical reference load for such shells. On the one hand, Janssen theory (1895) remains the dominant method of defining silo pressures for design. On the other hand, more recent experimental (Pieper, on silo loading show significant non-uniform deviations from the classical theory even under careful symmetrical filling. Unsymmetrical loads on silo walls lead to high local axial compression (Rotter, 1986a; Rotter, 1998). The buckling strength under an axial compression that acts over only a part of the circumference is significantly reduced, but has been scarcely explored at all (Rotter, 1986a; Rotter, 1986b; Ansourian, 1992; Rotter, 1997). A recent investigation by Cai et al. (2002) is the first known study to examine this problem systematically. The present paper details some of the results from their study.

References listed at the end of the paper:
ABSTRACT: This paper explores the results of full-scale bending tests of thick spiral welded steel tubes in the slenderness range of $d/t = 73.5$ to 101.5. The experimental investigations reveal unused bending capacities for such tubes compared to existent design rules and support the need for the development of improved and more efficient design recommendations. The results of the bending tests together with the investigations of the initial geometric quality of the specimens' surfaces suggest that the influence of spiral welding on the bearing behaviour is negligible in case of the investigated thick-walled specimens.

References listed at the end of the paper:
INTRODUCTION: Recent work in the field of semi-analytical methods used for the nonlinear analysis and design of stiffened plates with buckling problems have shown an important and alternative tool that provide an efficient and understandable response [1–4]. Nowadays two computational programs use the semi-analytical method to analyse the post-buckling behaviour of plates and to predict their ultimate strength. The computer program ALPS/ULSAP [5], which uses a semi-analytical method previously known as the incremental Galerkin method [6] and the computer program PULS [7] developed at Det Norske Veritas (DNV) and accepted as general buckling code for ship and offshore platform structures as part of the DNV specifications [8]. The existing semi-analytical models are restricted to stiffened plates supported by rigid transverse and longitudinal girders. This type of arrangement is typical in ship, aircraft, tanks and offshore platform structures where it is assumed that the analysed stiffened plate is simply supported and the in-plane displacements perpendicular to the edges are constrained to remain straight in all edges. Generally, in bottom flanges of steel box girder bridges there are no neighbouring panels in the longitudinal edges to provide this kind of constraint and it is more conservative to consider the longitudinal edges with fully free in-plane displacements that are characteristic of edges free from stresses. This paper presents a computational semi-analytical model for the post-buckling analysis and ultimate strength prediction of stiffened plates under longitudinal uniform compression. The possibility of considering fully free in-plane displacements at longitudinal edges (or unloaded edges) is the innovation of this model over existing models. Comparisons between the semi-analytical model and nonlinear finite element model results are presented.

References listed at the end of the paper:


ABSTRACT: A solution for the elastic and inelastic local buckling of flat rectangular plates with centerline boundary conditions subjected to non-uniform in-plane compression and shear stress is presented. The loaded edges are simply supported, the longitudinal edges may have any boundary conditions and the centerline is simply supported with a variable rotational stiffness. The Galerkin method, an effective method for solving differential equations, is applied to establish an eigenvalue problem. In order to obtain plate buckling coefficients, combined trigonometric and polynomial functions that satisfy the boundary conditions are used. The method is programmed, and several numerical examples including elastic and inelastic local buckling, are presented to illustrate the scope and efficacy of the procedure. The variation of buckling coefficients with aspect ratio is presented for various stress gradient ratios. The solution is applicable to stiffened plates and the flange of the I-shaped beams that are subjected to biaxial bending or combined flexure and torsion and shear stresses, and it is important to estimate the reduction in elastic buckling capacity due to stress gradient.

ABSTRACT: This paper outlines key aspects of the new European Standard on the Strength and Stability of Metal Shells EN 1993-1-6 with its extended commentary and expansion in the fifth edition of the European Recommendations on Shell Buckling. This European design standard is the first to be strongly oriented toward numerical analyses in design, with clear distinctions between different classes of both analysis and fabrication. It presents a different style of standard: Each limit state is defined in a separate chapter, but all shell geometries are treated and all analysis types are used within each chapter. The strength evaluation criteria differ according to the calculation that has been made. This new structure, with its new paradigm that permits generalization of the design procedure for all thin shells, geometries, load cases, boundary conditions, and qualities, represents a major step forward. It also offers the opportunity for future research studies of shell structures to be undertaken within a coherent conceptual framework that is completely general. The EN 1993-1-6 standard goes a long way toward bridging the gap between the computational engineering mechanics and structural engineering design communities. Unfortunately, this European standard EN 1993-1-6 has a complex and extensive background that cannot be stated within the document so the European Recommendations on Shell Stability, now published in its fifth edition, gives an extensive commentary, many expanded rules, and many additional geometries and load cases that are not formally presented within the standard itself. The development of both EN 1993-1-6 and the recommendations has been the work of the Eurocode shell structures development committee CEN/TC250/SC3/PT4 and the European Convention for Constructional Steelwork committee (ECCS) TWG 8.4. It is presented here by the convener of these two committees. This paper explains the reasoning behind several particular choices that have been taken in developing the standard, occasionally running counter to traditional views. It also identifies several tricky issues that have not been addressed well in the shell buckling literature but that have arisen through the attempts to achieve completely general rules and which need imaginative answers to ensure a fully consistent treatment of all systems. It is hoped that this paper will assist researchers and designers to understand the rules and recommendations and will encourage researchers to undertake and present their work in a manner that permits its rapid adoption into the new standardized design procedures.

References listed at the end of the paper:

ABSTRACT: Metal silos used to store granular solids often take the form of a cylindrical shell with an aspect ratio in the range 2<H/D<6. It has long been recognised that the most serious load case for all silos is probably the condition of eccentric discharge of its stored solid, but in circular metal silos this is especially true. More
failures have occurred under this condition than any other. This high failure rate is chiefly due to the complexity of the pressures exerted by an eccentrically discharging granular material, and the difficulty in understanding the pattern of stresses that develops in a shell wall under such unsymmetrical pressure regimes. The nonsymmetric behaviour of a shell structure under unsymmetrical pressures is not at all well described in the voluminous shell structures literature, and only a few studies have explored the mechanics leading to high local stresses which in turn lead to buckling failure under eccentric discharge. This study follows an earlier initial exploration by Sadowski and Rotter (2010) [2], in which buckling in a moderately slender perfect silo was explored. Here, the work is taken further to explore a very slender structure, and to investigate the imperfection sensitivity of this failure mode. The pressures caused by eccentric discharge are characterised using the new rules of the European Standard EN 1991-4 (2006) [1] that define the actions in silos and tanks. Using this new improved description of unsymmetrical eccentric discharge pressures, it is now possible to perform relatively realistic calculations relating to this common but complicated shell buckling condition. The shell buckling calculations described here employ a pressure distribution formulated with the assumption of a parallel-sided flow channel and are undertaken using geometrically and materially nonlinear analyses in accordance with the European Standard EN 1993-1-6 (2007) [25] on the strength and stability of shells. The paper explores the structural behaviour of a slender silo under eccentric discharge, leading to buckling and including the critical effects of changes of geometry and imperfection sensitivity.

References listed at the end of the paper:

ABSTRACT: The current European standards for the design of thin-walled metal silos require the designer to use a complex combination of rules covering many different aspects of loading, structural behaviour and strength. Each individual rule was often developed autonomously, usually with implicit and undocumented conservative assumptions. When combined, the overall factor of safety of a designed silo may be significantly different from that guaranteed by the standard, making it difficult to reproduce the design rules in a numerical calculation that does not include the same implicit assumptions. This paper explores the behaviour of five thin-walled cylindrical silos with stepwise-varying wall thickness and aspect ratios varying from very squat to very slender, all custom-designed for and analysed under the EN 1991–4 concentric discharge loading condition. The aspect ratio plays a deciding role in both the behaviour and design of silos, and it is important to ascertain that a finding that is valid for one is transferable to the others. The nonlinear finite element analyses reveal that the computed load factor exceeds the partial safety factor in design by a large factor over a wide range of aspect ratio, suggesting that the overall design process is particularly conservative. The reasons for these discrepancies are explored. This paper is the first of a pair. The second paper explores the behaviour of the same set of example silos under the EN 1991–4 eccentric discharge loads, with fundamentally different conclusions.

References listed at the end of the paper:
However the structural consequences of its application are currently largely unknown. The behaviour of a silo condition appears in a regulat

ABSTRACT: The phenomenon of eccentric discharge is widely recognised as the most dangerous condition for thin-walled metal silos and the cause of many catastrophic buckling failures. A realistic pressure model for this condition appears in a regulating standard for the first time in EN 1991-4 (2006) on Actions on Silos and Tanks. However the structural consequences of its application are currently largely unknown. The behaviour of a silo


ABSTRACT: The phenomenon of eccentric discharge is widely recognised as the most dangerous condition for thin-walled metal silos and the cause of many catastrophic buckling failures. A realistic pressure model for this condition appears in a regulating standard for the first time in EN 1991-4 (2006) on Actions on Silos and Tanks. However the structural consequences of its application are currently largely unknown. The behaviour of a silo

subjected to these pressures is certainly very dependent on the aspect ratio of the silo, the granular solid properties and the discharge channel geometry. This paper explores the behaviour of four thin-walled cylindrical silos with stepwise-varying wall thickness and aspect ratios varying from intermediate to very slender, subject to the codified EN 1991-4 eccentric discharge pressures. It is shown that a silo design that was found to be very safe under the EN 1991-4 concentric discharge pressures becomes very unsafe under eccentric discharge. Further, as it is known that the aspect ratio has an important effect on the flow pattern in discharging granular solids, and that slender silos exhibit very different flow patterns from squat silos, it is currently not certain whether a suitable range of aspect ratio over which the codified eccentric discharge model is to be applied has been prescribed in the standard. This paper is the second of a pair. In the first, the behaviour of a set of example silos under the EN 1991-4 concentric discharge condition was studied. The same example silos are studied here under eccentric discharge.

References listed at the end of the paper:
ABSTRACT: Large quantities of particulate solids and fluids are stored in cylindrical metal shell silos and tanks with a vertical axis. Such metal silos and tanks are often required to be elevated above ground level to permit trains, trucks or conveying systems to be placed beneath a hopper from which the solid or fluid is withdrawn. Elevated silos must be supported, and access requirements often mean that the supports must be local (either on columns or supported from an elevated floor system). The connection of a local support to an elevated cylindrical metal silo shell is a long-standing difficult problem in shell analysis, and most designs are based on simple ideas using past experiences of successes and failures. Smaller silo structures are often supported on local brackets attached to the side of the shell, but very few investigations of the behaviour or strength of such an arrangement have ever been made. This thesis presents a comprehensive investigation into the behaviour of a cylindrical steel shell that is discretely supported on several brackets, each rigidly connected to a stiff column or floor. The study has been conducted within the framework of the European Standard for Shell Structures (EN1993-1-6, 2006), which requires that the two reference strengths of the small displacement theory plastic collapse resistance and the linear bifurcation critical elastic resistance should both be evaluated to establish the context in which more sophisticated analyses are judged, and to provide a rapid means of producing reliable but simple design information. Therefore this thesis begins with a thorough investigation of the predictions of these two reference strengths for these structures, discovering the challenges inherent in this methodology and finally developing equations that can be used in hand calculations intended for the simple evaluation of the reference strengths for a wide variety of geometries. The influence of geometric nonlinearity is next explored, both with and without geometric imperfections. The results pose some interesting questions concerning the relative importance of geometric nonlinearity and geometric imperfections in shell buckling problems where the stress field is far from uniform. In the final part of the investigation, analyses are conducted that include both material and geometric nonlinearity with and without geometric imperfections. The results of these analyses are presented and analysed in the context of interaction capacity curves. Following this extensive parametric investigation using linear and nonlinear analyses of all kinds, design recommendations are formulated so that bracket supports of this type can be used on thin cylindrical shells of any thickness and with any bracket dimensions necessary to transmit the loads. Finally, proposals are made for key future research investigations.

References listed at the end of the dissertation:


ABSTRACT: Cylindrical shells of stepwise variable wall thickness are widely used for cylindrical containment structures, such as vertical-axis tanks and silos. The thickness is changed because the stress resultants are much larger at lower levels. The increase of internal pressure and axial compression in the shell is addressed by increasing the wall thickness. Each shell is built up from a number of individual strakes of constant thickness. The thickness of the wall increases progressively from top to bottom. Whilst the buckling behaviour of a uniform thickness cylinder under external pressure is well defined, that of a stepped wall cylinder is difficult to determine. In the European standard EN 1993-1-6 (2007) and Recommendations ECCS EDR5 (2008), stepped wall cylinders under circumferential compression are transformed, first into a three-stage cylinder and thence into an equivalent uniform thickness cylinder. This two-stage process leads to a complicated calculation that depends on a chart that requires interpolation and is not easy to use, where the mechanics is somewhat hidden, which cannot be programmed into a spreadsheet leading to difficulties in the practical design of silos and tanks. This paper introduces a new "weighted smeared wall method", which is proposed as a simpler method to deal with stepped-wall cylinders of short or medium length with any thickness variation. Buckling predictions are made for a wide range of geometries of silos and tanks (unanchored and anchored) using the new hand calculation method and compared both with accurate predictions from finite element calculations using ABAQUS and with the current Eurocode rules. The comparison shows that the weighted smeared wall method provides a close approximation to the external buckling strength of stepped wall cylinders for a wide range of short and medium-length shells, is easily programmed into a spreadsheet and is informative to the designer.


ABSTRACT: Cylindrical shells are widely used in civil engineering. Examples include cooling towers, pipelines, nuclear containment vessels, steel silos and tanks for storage of bulk solids and liquids, and pressure vessels. The loading condition for these shells is quite varied depending on the function of the shell. Axial compression, global bending, external or internal pressure and wind loading are some of the most common loading forms for realistic structures. The failure of these cylindrical shell structures is often controlled by elastic or elastic-plastic buckling failure. Yield failure may occur in thick cylinders in some situations. A cylindrical shell under different loading conditions may display quite different buckling behaviour. The objective of this thesis is to investigate the characteristics of different buckling behaviours of cylindrical shell structures under axial compression, global bending, uniform external pressure and wind pressure. Some challenging practical problems in the design of these shell structures are explored. This thesis is expected to have some far-reaching impacts in defining how to design cylindrical shell structures to give them adequate strength to resist extreme events. Many aspects will be based on the latest Eurocode (EN 1993-1-6, 2007) and Recommendations (ECCS EDR5, 2008). The results show both some strength and some weaknesses in the Eurocode in design of shell structures. New methods are proposed for some practical problems. Some new conclusions and suggestions are derived and are expected to provide some useful knowledge for the improvement of the Eurocode in cylindrical shell design in general.

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Hongyu Li (University of Edinburgh), “Analysis of steel silo structures on discrete supports”, Ph.D. dissertation, University of Edinburgh, College of Science & Engineering, School of Engineering & Electronics, 1994

ABSTRACT: The objective of this thesis is to broaden current knowledge of the strength and buckling/collapse of shells, with special reference to steel silo structures on discrete supports, and thus to provide design guidance of practical value for future silo design and construction and to develop new research aspects for further investigation. A linear elastic solution of the cylindrical shell bending equations is presented for local loadings, with special attention to local longitudinal distributed loadings. Algebraic expressions for the displacements and stresses induced by a rectangular patch of longitudinal load on a simply supported cylindrical shell are derived using double Fourier series. The solution of this problem is general, and therefore can be applied to cylindrical shells under local I loadings in any direction and with different boundary conditions. Linear elastic analyses of discretely supported perfect cylinders under axial compression are presented using the finite element method. The pre-buckling meridional membrane stress distribution above the support centreline is examined in detail, and is followed by investigations of the linear bifurcation behaviour of the cylinders. The effects on the stress distribution and the buckling strength of different loading patterns and different geometric configurations are extensively examined. Geometrically nonlinear elastic buckling analyses are also performed using large
deflection theory. Both perfect and imperfect cylinders are studied with various geometric configurations and under different loading conditions. The nonlinear elastic buckling behaviour, the buckling strength and the buckling configuration are thoroughly investigated for discretely supported cylinders. Further studies extend the work into the plastic range. Discretely supported cylinders obeying the von Mises yield criterion are analysed. Limit analyses of perfect cylinders are first conducted using small deflection theory. Geometrically nonlinear elastic-plastic collapse analyses of both perfect and imperfect cylinders are performed next. Studies of different loading conditions and parametric studies of varying geometries and material strengths are presented in both types of analysis. The nonlinear elastic-plastic behaviour of discretely supported cylinders is thus explored. A complete silo which consists of a cylindrical shell, a conical roof hopper and a conical discharge hopper is briefly examined, with the aim of exploring the applicability of the established cylinder model in the elastic buckling analysis of silo structures. Finally, the conclusions drawn from this research are summarised and recommendations are also made for further research on locally supported shells.

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ABSTRACT: Steel silos are widely used as long-term or short-term containers for the storage of granular solids, of which a huge range are stored, from flour to iron ore pellets, coals, cement, crushed rocks, plastic pellets, chemical materials, sand, and concrete aggregates. The radius to thickness ratio for silos is in the range of 200 to 3000, so they fall into the category of thin shells, for which failure by buckling is the main concern and requires special attention in design. The primary aim of this thesis is to investigate the possible application of Fibre Reinforced Polymer (FRP) as a new repair and strengthening technique to increase the buckling capacity of thin metallic cylindrical shells. Extensive research has been conducted on the use of fibre reinforced polymer (FRP) composites to strengthen concrete, masonry and timber structures as well as metallic beams. However, all these studies were concerned with failure of the structure by material breakdown, rather than stability. As a result, this thesis marks a major departure in the potential exploitation of FRP in civil engineering structures. Many analyses of cylindrical shells are presented in the thesis. These are all focussed on strengthening the shell against different failure modes. Two loading conditions were explored: uniform internal pressure accompanied by axial load near a base boundary, and axial loads with geometric imperfections. For the latter, local imperfections are usually critical, and two categories of imperfection were studied in detail: an inward axisymmetric imperfection and a local dent imperfection. For the first loading condition, which leads to elephant’s foot buckling, an analytical method was used to derive general equations governing the linear elastic behaviour of a cylindrical shell that has been strengthened with FRP subject to internal pressure and axial compression. It was used to identify optimal application of the FRP. All the later studies were conducted using nonlinear finite element analysis (using the ABAQUS program) to obtain extensive predictions of many
conditions causing shell buckling and the strengthening effect of well-placed FRP. In all the cases studied in this thesis, it was shown that a small quantity of FRP composite, applied within a small zone, can provide a significant enhancement of the resistance to buckling failure of a thin metal cylinder. These calculations demonstrate that this new technique is of considerable practical value. However, it is clear that not all the relevant questions have been fully answered, so the author poses appropriate questions and makes suggestions for future work.

References listed at the end of the dissertation:


ABSTRACT: An isoparametric shell element has been developed capable of linear response to the imposed loads. The original formulation, which was written for static and dynamic analyses, was extended to embrace linear buckling problems. A variety of numerical examples were attempted in order to assess the adaptability of the element to different geometrical representations. Despite serious size limitations of the computer, the accuracy of the predicted buckling loads was found to be satisfactory.

-------Fatih Bazman, Monday, 17 August 2009 blog:
Shell Buckling Calculations
The buckling behaviour of shells is not widely known and simple procedures for analysis of buckling of shells are available only to a very limited extent in design codes. Although AWWA D100 considers the buckling effects in itself, API 650 doesn't investigate any buckling behaviour of shell structure. Storage tank designers must be consider the buckling behaviour due to self weight, vacuum load, wind load and seismic load effects on shell. At the present time, several papers or standards are available:
- Det Norske Veritas: DNV-RP-C202: Buckling Strength of Shells
- DIN 1880 Part 4: Structural Steelwork Analysis of Safety Against Buckling of Shells
- ASME Code Case N-284: Metal Containment Shell Buckling Design Methods, Miller C.D. 1991,
In my opinion, DIN 1880 Part 4 has more practical solutions instead of others.

Fuat Tinis, Fatih Bazman, GAMA Industrial Plants Manufacturing & Erection Corp., 06791, Ankara, Turkey.
“Stiffening of thin cylindrical silo shell against buckling loads, 12th International Conference on Machine Design and Production, September 2006, Kusadasi, Turkey
ABSTRACT: Buckling is one of the important criteria to be checked in silo design. Buckling behaviour of silos can be analyzed with finite element methods or analytical methods which are developed for cylindrical shells. In this study, buckling analysis of a silo which is also supporting another structure is analyzed with eigenvalue solution by using finite element method and one of these analytical methods. The results obtained by using these two methods are compared.

-------Glenn A. Hrinda, NASA Langley Research Center
ABSTRACT: Shell-buckling knockdown factors (SBKF) have been used in large cylindrical shell structures to account for uncertainty in buckling loads. As the diameter of the cylinder increases, achieving the manufacturing tolerances becomes increasingly more difficult. Knockdown factors account for manufacturing imperfections in the shell geometry by decreasing the allowable buckling load of the cylinder. In this paper, large-diameter (33 ft) cylinders are investigated by using various SBKF's. An investigation that is based on finite-element analysis (FEA) is used to develop design sensitivity relationships. Different manufacturing
imperfections are modeled into a perfect cylinder to investigate the effects of these imperfections on buckling. The analysis results may be applicable to large-diameter rockets, cylindrical tower structures, bulk storage tanks, and silos.

References listed at the end of the paper:


----------Anonymous from the ARA Company, Mountain View, CA;

**Buckling Analysis of Shell Structures**

Predicting the buckling response of thin shells in structural simulations is difficult because most models do not include the physical characteristics of the problem that initiate instabilities. For shell structures, the character of the buckling and load levels that lead to instability are governed by the nonuniformities or imperfections in either the structure or loading. A methodology was developed to accurately predict the buckling response of the thin shell structures by incorporating either the measured imperfections in the structure and loading or accurate statistical approximations to the imperfections. This analysis approach has been applied successfully to a variety of buckling problems. One application is the analysis of dynamic pulse buckling of impulsively loaded thin cylindrical aluminum shells. The cosine distributed external impulsive loads drive the shell inward, producing compressive circumferential stresses and pulse buckling on the loaded side of the shell. These buckles produce strain concentrations that govern the eventual fracture of the structure. Thus, the buckling response needs to be correctly modeled to predict failure. A cross section of a dynamically pulse buckled thin cylindrical shell and the calculated response are shown in Figure 1. In the calculation, we used the measured imperfections in the cylinder shape to initiate the buckling. The buckling response can clearly be seen on the loaded (front) side of the cylinder and is accurately reproduced in the calculation. These modeling techniques have also been applied to other structural applications, including analysis of crash energy management structures for vehicles, static axial collapse of cylinders, and dynamic buckling of thick shells. One example application for thick shells is the buckling that occurs in explosively formed penetrators (EFPs), as shown in Figure 2. Understanding and modeling the processes that lead to dynamic plastic buckling in EFP liners allows the designer to control the buckling process to gain enhanced aerostability.

References


ABSTRACT: A finite difference solution is presented for elastic wave propagation in laminated composite hollow tubes under axial plane strain, subjected to a radially symmetric pressure pulse at the inner surface. The solution is applied to two-layered cross-ply and angle-ply AS4/3501-6 graphite/epoxy cylinders, and to homogeneous monoclinic cylinders. The effects of pulse time duration, stacking sequence, ply angle and stiffnesses on the resulting displacement, stresses (radial, hoop, axial and shear) and dynamic stress concentration factor are studied.

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ABSTRACT: The dynamic plastic buckling of cylindrical shells (rings) subjected to general initial impulsive velocity and subjected to impulsive loading is studied based on the energy criterion. A simple analysis method is given and the formulas of critical mode numbers, n cr, and critical impulsive velocity, v cr, are obtained.


ABSTRACT: This paper is devoted to the derivation and the analysis of vibrations of shallow spherical shell subjected to large amplitude transverse displacement. The analog for thin shallow shells of von Karman’s theory for large deflection of plates is used. The validity range of the approximations is assessed by comparing the analytical modal analysis with a numerical solution. The specific case of a free edge is considered. The governing partial differential equations are expanded onto the natural modes of vibration of the shell. The problem is replaced by an infinite set of coupled second-order differential equations with quadratic and cubic non-linear terms. Analytical expressions of the non-linear coefficients are derived and a number of them are found to vanish, as a consequence of the symmetry of revolution of the structure. Then, for all the possible internal resonances, a number of rules are deduced, thus predicting the activation of the energy exchanges between the involved modes. Finally, a specific mode coupling due to a 1:1:2 internal resonance between two companion modes and an axisymmetric mode is studied.

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(1) Structural Mechanics and Coupled Systems Laboratory, CNAM, 2 rue Conte, 75003 Paris, France
(2) ENSTA-UME, Chemin de la Huniere, 91761 Palaiseau Cedex, France
“Non-linear modal interactions in free-edge thin spherical shells: measurements of a 1:1:2 internal resonance”, in Computational Fluid and Solid Mechanics, K.J. Bathe (Editor), Paper no. 120-221, 2005
ABSTRACT: This study is devoted to the experimental validation of a theoretical model of large amplitude vibrations of thin spherical shells described in Thomas et al.[1]. A specific mode coupling due to a 1:1:2 internal resonance between an axisymmetric mode and two companion asymmetric modes is especially addressed. The structure is forced with a sinusoidal signal of frequency close to the natural frequency of the axisymmetric mode. The experimental setup, which allows precise measurements of the vibration amplitudes of the three involved modes, is presented. Experimental resonance curves showing the amplitude of the modes as functions of the driving frequency are compared to the theoretical ones. A good qualitative agreement is obtained with the predictions given in the model. The quantitative discrepancies are discussed and an improvement of the model is proposed.
References listed at the end of the paper:

ABSTRACT: The aim of the present paper is to compare two different methods available for reducing the complicated dynamics exhibited by large amplitude, geometrically nonlinear vibrations of a thin shell. The two methods are: the proper orthogonal decomposition (POD), and an asymptotic approximation of the nonlinear normal modes (NNMs) of the system. The structure used to perform comparisons is a water-filled, simply supported circular cylindrical shell subjected to harmonic excitation in the spectral neighbourhood of the fundamental natural frequency. A reference solution is obtained by discretizing the partial differential equations (PDEs) of motion with a Galerkin expansion containing 16 eigenmodes. The POD model is built by using responses computed with the Galerkin model; the NNM model is built by using the discretized equations of motion obtained with the Galerkin method, and taking into account also the transformation of damping terms. Both the POD and NNMs allow to reduce significantly the dimension of the original Galerkin model. The computed nonlinear responses are compared in order to verify the accuracy and the limits of these two methods.

For vibration amplitudes equal to 1.5 times the shell thickness, the two methods give very close results to the original Galerkin model. By increasing the excitation and vibration amplitude, significant differences are observed and discussed. The response is investigated also for a fixed excitation frequency by using the excitation amplitude as bifurcation parameter for a wide range of variation. Bifurcation diagrams of Poincare maps obtained from direct time integration and calculation of the maximum Lyapunov exponent have been used to characterize the system.

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ABSTRACT: Reduced-order models are essential to study nonlinear vibrations of structures and structural components. The natural mode discretization is based on a two-step analysis. In the first step, the natural modes of the structure are obtained. Because this is a linear analysis, the structure can be discretized with a very large number of degrees of freedom. Then, in the second step, a small number of these natural modes are used to discretize the nonlinear vibration problem with a huge reduction in the number of degrees of freedom. This study finds a recipe to select the natural modes that must be retained to study nonlinear vibrations of an angle-ply laminated circular cylindrical shell that the author has previously studied by using admissible functions defined on the whole structure, so that an accuracy analysis is performed. The higher-order shear deformation theory developed by Amabili and Reddy is used to model the shell.

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ABSTRACT: The problem of a thin spherical linearly-elastic shell, perfectly bonded to an infinite linearly-elastic medium is considered. A constant axisymmetric stress field is applied at infinity in the matrix, and the displacement and stress fields in the shell and matrix are evaluated by means of harmonic potential functions. In order to examine the stability of this solution, the buckling problem of a shell which experiences this deformation is considered. Using Koiter’s nonlinear shallow shell theory, restricting buckling patterns to those which are axisymmetric, and using the Rayleigh–Ritz method by expanding the buckling patterns in an infinite series of Legendre functions, an eigenvalue problem for the coefficients in the infinite series is determined. This system is truncated and solved numerically in order to analyse the behaviour of the shell as it undergoes buckling, and to identify the critical buckling stress in two cases — namely where the shell is hollow and the stress at infinity is either uniaxial or radial.

References listed at the end of the paper:
Partial text from the given page:

shells are needed, especially for shells made of advanced composite materials. Shell-buckling design criteria have a history steeped in empiricism. From approximately 1930 to 1967, many shell-buckling experiments were conducted on metallic shells. Typically, the experiments yielded buckling loads that were substantially lower than the corresponding analytical predictions, which were based on simplified linear bifurcation analyses of geometrically perfect shells with nominal dimensions and idealized support conditions. The primary source of discrepancy between corresponding analytical predictions and experimental results is attributed to small deviations from the idealized geometry of a shell, known as initial geometric imperfections. Empirical design factors, known as "knockdown" factors, were determined from these test data and were to be used in conjunction with linear bifurcation analyses for simply supported shells to adjust or "knockdown" the unconservative analytical prediction. This approach to shell design remains prominent in industry practice, as evidenced by the extensive use of the NASA space vehicle design recommendations. Recent advancements in digital computers, high-fidelity structural analysis tools and testing technologies are enabling the development of a new shell buckling design philosophy, namely, analysis-based knockdown factors. Key enabling technology developments and their implementation in ongoing NASA Shell Buckling Knockdown Factor development activities are presented in this lecture. In addition, the development of a refined shell-buckling preliminary-design criteria that is based on high-fidelity nonlinear finite-element analyses that include the effects of a manufacturing-process-specific geometric imperfection signature is presented.

(No references given. This is not a paper, just an abstract.)


ABSTRACT: Validity of the assumptions relating the applicability of continuum shell theories to the global mechanical behavior of carbon nanotubes is examined. The present study focuses on providing a basis that can be used to qualitatively assess the appropriateness of continuum-shell models for nanotubes. To address the effect of nanotube structure on their deformation, all nanotube geometries are divided into four major classes that require distinct models. Criteria for the applicability of continuum models are presented. The key parameters that control the buckling strains and deformation modes of these classes of nanotubes are determined. In an analogy with continuum mechanics, mechanical laws of geometric similitude are presented. A parametric map is constructed for a variety of nanotube geometries as a guide for the applicability of different models. The continuum assumptions made in representing a nanotube as a homogeneous thin shell are analyzed to identify possible limitations of applying shell theories and using their bifurcation-buckling equations at the nano-scale.


ABSTRACT: This part of the edited volume highlights trends in recent publications by providing examples of important research papers in different areas of nanoscale mechanics. Research papers on novel applications of carbon nanotubes, nanocomposites, nanodevices, quantum anti-dots, and other nanostructures are noted. References listed at the end of the paper:

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ABSTRACT: The buckling behaviors of double-walled carbon nanotubes (DWCNTs) under torsion are investigated by using molecular dynamics (MD) simulations. The effect of length on the torsional buckling behaviors of DWCNTs is examined for the first time. The simulation results show that the DWCNTs experience gradual or simultaneous buckling deformations depending on their lengths. In addition, the effect of the inner tube in a DWCNT on its torsional buckling behavior is also examined. The presence of the inner tube triggers van der Waals (vdW) interactions between it and the outer tube and thus leads to a stiffening effect of the DWCNT against torsional deformation. Whether the ends of the inner tube are free or fixed and whether it is subject to a torque or not, the critical torque and the critical torsional angle of the outer tube are only marginally affected.


ABSTRACT: Carbon nanotubes (CNTs) have potential applications in various fields of science and engineering due to their extremely high elasticity, strength, and thermal and electrical conductivity. Owing to their hollow
and slender nature, these tubes are susceptible to buckling under a compressive axial load. As CNTs can undergo large, reversible post-buckling deformation, one may utilize this postbuckling response of CNT to manufacture mechanical energy storage devices at the nano-scale, or use it as a nano-knife or nano-pump. It is therefore important to understand the buckling behavior of CNTs under a compressive axial load. Experimental investigations on CNT buckling are very expensive and difficult to perform. As such, researchers often rely on molecular dynamics (MD) simulations, or continuum mechanics modeling to study their mechanical behaviors. In order to develop a good continuum mechanics model for buckling analysis of CNTs, one needs to possess adequate experimental or MD simulation data for its calibration. For “short” CNTs with small aspect ratios (B10), researchers have reported different critical buckling loads/strains for the same CNTs based on MD simulations. Moreover, existing MD simulation data are not sufficiently comprehensive to allow rigorous benchmarking of continuum-based models. This chapter presents extensive sets of MD critical buckling loads/strains for armchair single-walled CNT (SWCNTs) and double-walled CNTs (DWCNTs), with various aspect ratios less than 10. These results serve to address the discrepancies found in the existing MD simulations, as well as to offer a comprehensive database for the critical buckling loads/strains for various armchair SWCNTs and DWCNTs. The Adaptive Intermolecular Reactive Bond Order (AIREBO) potential was adopted for MD simulations. Based on the MD results, the Young’s modulus, Poisson’s ratio and thickness for an equivalent continuum cylindrical shell model of CNTs are calibrated. The equivalent continuum shell model may be used to calculate the buckling loads of CNTs, in-lieu of MD simulations.

References listed at the end of the paper:

ABSTRACT: An elastic double-shell model is presented for infinitesimal buckling of a double-walled carbon nanotube embedded in an elastic matrix under axial compression. The analysis is based on a Winkler model for the surrounding elastic medium and a simplified model for the van der Waals interaction between the inner and outer nanotubes. An explicit formula is derived for the critical axial strain, which indicates the effects of the surrounding elastic matrix combined with the intertube van der Waals forces. In particular, the present model predicts that the critical axial strain of the embedded double-walled nanotube is lower than that of an embedded single-walled nanotube under otherwise identical conditions. This implies that inserting an inner tube lowers the critical axial strain of an embedded single-walled carbon nanotube, although the total critical compressive force could be increased due to the increase in the cross-sectional area of the nanotube. The reduced critical axial strain is attributed to the intertube slips between the inner and outer tubes. This result indicates that embedded multi-walled carbon nanotubes could be even more susceptible to infinitesimal axial buckling than embedded single-walled carbon nanotubes.


ABSTRACT: This paper studies axially compressed buckling of an individual multiwall carbon nanotube subjected to an internal or external radial pressure. The emphasis is placed on new physical phenomena due to combined axial stress and radial pressure. According to the radius-to-thickness ratio, multiwall carbon nanotubes discussed here are classified into three types: thin, thick, and (almost) solid. The critical axial stress and the buckling mode are calculated for various radial pressures, with detailed comparison to the classic results of singlelayer elastic shells under combined loadings. It is shown that the buckling mode associated with the minimum axial stress is determined uniquely for multiwall carbon nanotubes under combined axial stress and radial pressure, while it is not unique under pure axial stress. In particular, a thin N-wall nanotube (defined by the radius-to-thickness ratio larger than 5) is shown to be approximately equivalent to a single layer elastic shell whose effective bending stiffness and thickness are N times the effective bending stiffness and thickness of singlewall carbon nanotubes. Based on this result, an approximate method is suggested to substitute a multiwall nanotube of many layers by a multilayer elastic shell of fewer layers with acceptable relative errors. Especially, the present results show that the predicted increase of the critical axial stress due to an internal radial pressure appears to be in qualitative agreement with some known results for filled singlewall carbon nanotubes obtained by molecular dynamics simulations.

ABSTRACT: This paper examines applicability and limitations of simplified models of elastic cylindrical shells for carbon nanotubes. The simplified models examined here include Donnell equations and simplified Flugge equations characterized by an uncoupled single equation for radial deflection. These simplified elastic shell equations are used to study static buckling and free vibration of carbon nanotubes, with detailed comparison to exact Flugge equations of cylindrical shells. It is shown that all three elastic shell models are in excellent agreement (with relative errors less than 5%) with recent molecular dynamics simulations for radial breathing vibration modes of carbon nanotubes, while reasonable agreements for various buckling problems have been reported previously for Donnell equations. For general cases of buckling and vibration, the results show that the simplified Flugge model, which retains mathematical simplicity of Donnell model, is consistently in better agreement with exact Flugge equations than Donnell model, and has a significantly enlarged range of applicability for carbon nanotubes. In particular, the simplified Flugge model is applicable for carbon nanotubes (with relative errors around 10% or less) in almost all cases of physical interest, including some important cases in which Donnell model results in much larger errors. These results are significant for further application of elastic shell models to carbon nanotubes because simplified shell models, characterized by a single uncoupled equation for radial deflection, are particularly useful for multiwall carbon nanotubes of large number of layers.


ABSTRACT: Based on a multiple-shell model, a comprehensive investigation has been performed on the effect of three dimensional factors, i.e., aspect ratio, the innermost radius, and the number of layers, on buckling behavior of multiwall carbon nanotubes (MWCNTs) under axial compression or radial pressure. In contrast to previous shell models, which use the single Donnell equation [Wang et al, ASME J. Appl. Mech. 71, 622 (2004)] and thus are only adequate for buckling of MWCNTs of relatively small aspect ratio (e.g., not larger than 10), the present shell model based on the simplified Flugge equation [Wang et al, ASME J. Appl. Mech. 71, 622 (2004)] allows for the study of buckling behavior of MWCNTs without any limitation on their aspect ratios. In addition, the pressure dependence of the interlayer van der Waals interaction coefficient (defined as the second derivative of the interlayer potential energy-interlayer spacing relation) has been considered for pressure-induced buckling of MWCNTs. The relevance of the present shell model for buckling of MWCNTs has been confirmed by the good agreement between the present shell model and available discrete models or experiments. Here, distinct buckling behaviors under axial compression or radial pressure are identified for long and short MWCNTs, separated by a certain critical value of aspect ratio. On the other hand, while the critical buckling load usually changes monotonically with the innermost radius an optimum value of the number of layers associated with the maximum critical buckling pressure is obtained for MWCNTs under radial pressure. In particular, the present shell model shows that the three dimensional factors effecting buckling of MWCNTs are generally interacting with, rather than being independent of, one another.
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ABSTRACT: We report experimental observations of shell buckling instabilities in freestanding, vertically aligned multiwalled carbon nanotubes subjected to uniaxial compression. Highly ordered and uniform arrays of carbon nanotubes embedded in an alumina matrix were fabricated and subjected to uniaxial compression using a nanoindenter. The buckling load was found to be on the order of 2 _ºN for nanotubes with 25 nm outer radius, 13 nm inner radius, and heights of 50 and 100 nm. Good agreement was found between the experimental observations and the predictions of linear elastic shell buckling theory.

ABSTRACT: Although the mechanical behavior of carbon nanotubes has been studied extensively in recent years, very few experimental results exist on the shell buckling of nanotubes, despite its fundamental importance in nanotube mechanics and applications. Here we report an experimental technique in which individual multiwalled carbon nanotubes were axially compressed using a nanoindenter and the critical shell-buckling load was measured. The results are compared with predictions of existing continuum theories, which model multiwalled carbon nanotubes as a collection of single-walled shells, interacting through van der Waals forces. The theoretical models significantly underpredict the experimental buckling load.

References listed at the end of the paper:
ABSTRACT: In this article, we present recent progress in selected areas of carbon nanotube mechanics. First, we present the authors’ experimental work on shell buckling mechanics of multi-walled carbon nanotubes using nanoindentation. A comparison with existing elastic theories showed that the shell theories under-predict the buckling loads by as much as 50%. We then present an investigation of electromechanical coupling in carbon nanotubes by focusing on phonon frequency shifts as a result of charge injection. Raman spectroscopic measurements of the electromechanical couplings under varied but controlled charge injection conditions are analyzed, and the close agreement between the model results and the measured Raman peak shifts suggests that geometrical changes of charged carbon nanotubes previously observed or speculated in different experiments can indeed originate from the simple quantum effects described herein.

Akita, Seiji, Nishio, Mitsumasa and Nakayama, Yoshikazu (Dept. of Physics & Electroics, Osaka Prefecture University, Sakai, Japan), “Buckling of carbon nanotubes under axial compression”, International Conference on Microprocesses and Nanotechnology, 25-28 October 2005, pp. 74-75, DOI: 10.1109/IMNC.2005.203744
ABSTRACT: We have investigated the axial buckling of a multiwall nanotube by changing its number of layers. Young's moduli of nanotubes with different inner hollow diameters are estimated to be 0.77 TPa and 0.80 TPa from the Euler's buckling model, respectively. This good agreement implies that the Euler's buckling model is applicable to the analysis of the axial buckling behaviors of the nanotubes. The MD simulations for the buckling behaviors of the triple- and the double-walled nanotubes are also consistent with the continuum analysis. Consequently, the multi-shells composing multiwall nanotubes can be treated as a single shell with a thickness for whole shells.

References at the end of the paper:

ABSTRACT: Experiments were conducted in which multiwalled carbon nanotubes were subjected to uniaxial compression and shell-buckling loads were measured. A comparison with existing theoretical models shows that the predictions are about 40–50% smaller than the experimentally measured buckling loads. This is in contrast to the classical elastic shell studies in which the experimental values were always substantially lower than the predicted values due to imperfection sensitivity. It is proposed that the discrepancy between the predicted and measured value might be due to imperfections in the multiwalled nanotubes in the form of sp³ bonds between the tube walls, which introduce shear coupling between them. An analytical model is presented to estimate the effect of the shear coupling on the critical buckling strain, which shows that the contribution from shear coupling increases linearly with the effective shear modulus between the walls. Further, this
contribution increases with the number of walls; the increment from each additional wall progressively decreases.

References listed at the end of the paper:

Markus J. Buehler (1), Yong Kong (2), Huajian Gao (2) and Yonggang Huang (3)
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ABSTRACT: (none given)
References listed at the end of the paper:

ABSTRACT: Debonding of a single CNT (carbon nanotube) from the midway or one end of a CNT rope is studied in this paper. The analysis of buckling-driven debonding of an individual CNT is based on an elastic beam model, while the local debonding growth, stability and arrest are explained by the energy release rate criterion. The debonding from a preloaded CNT rope is driven by excess energy released from the unbuckled to the buckled state of an individual CNT. Some interesting debonding behaviors are displayed for varying dimensions, compression strain and van der Waals (vdW) adhesive energy. The growth of the debonding may be stable, unstable or unstable growth followed by a stable growth when an initial debonding CNT rope is loaded.
many manipulate matter on the nanometer scale. We have studied, through molecular dynamics simulations, using a

ABSTRACT: Proximal probe technology has provided researchers with new ways to investigate and manipulate matter on the nanometer scale. We have studied, through molecular dynamics simulations, using a many-body empirical potential, the indentation of a hydrogen-terminated, diamond (111) surface, with a

References listed at the end of the paper:
proximal probe tip that consists of an open, hydrogen-terminated, (10,10) carbon nanotubule. The simulations showed that upon indenting 1.8 Å, the tubule deforms but returns to its original shape upon retraction. The Young’s modulus of the tubule was determined using the predicted Euler buckling force and was found to be comparable to measured and calculated values. In a second series of simulations, an open (10, 10) nanotubule was heated to 4500 K and allowed to close. We find that at this temperature the resulting cap contains numerous imperfections, including some not mentioned previously in the literature.

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ABSTRACT: Triangular lattices were assembled on spherical surfaces and caps via thermal stress engineering on core/shell microstructures. The lattices on a complete spherical surface, when the total number is small, contain uniquely fivefold disclinations, whereas scars consisting of pentamer-heptamer chains emerged when more vertices are available (>360). Disclination-free pattern were obtained on caps, revealing the defect management strategy in nature. All the experimental observations can be explained by numerical studies to Thomson’s problem [ J. J. Thomson, Philos. Mag. 7, 237 (1904) ]. These results can help understand the various patterns assembled on curved surfaces, and be of essential importance for the en masse fabrication of nanostructures on pliable substrates.


ABSTRACT: In this work the electromechanical buckling and postbuckling responses of a circular cylindrical shallow shell are analyzed. The cylindrical shell is subjected to a radial axi-symmetric electrostatic field that is generated by setting voltage difference between an exterior elastic thin shallow cylinder and an inner infinitely stiff solid cylinder. The nonlinear prebuckling state of the cylinder is considered in order to increase the accuracy of the analysis. The prebuckling, buckling and postbuckling states are solved by implementing the perturbation asymptotic approach. The critical electromechanical buckling voltage and the stability of the postbuckling states are solved for a wide range value of the geometrical parameters of the elastic shell, such as radius-thickness ratio, the radius-length ratio and the ratio between the radius of the interior stiff cylinder and the exterior cylindrical shell. The numerical results show that the initial electromechanical postbuckling of the shell is unstable for all the considered range of parameters.


ABSTRACT: Author(s):
We report atomistic studies of single-wall carbon nanotubes with very large aspect ratios subject to compressive loading. These long tubes display significantly different mechanical behavior than tubes with smaller aspect ratios. We distinguish three different classes of mechanical response to compressive loading. While the deformation mechanism is characterized by buckling of thin shells in nanotubes with small aspect ratios, it is replaced by a rod-like buckling mode above a critical aspect ratio, analogous to the Euler theory in continuum mechanics. For very large aspect ratios, a nanotube is found to behave like a flexible macromolecule which tends to fold due to vdW interactions between different parts of the carbon nanotube. This suggests a shell-rod-wire transition of the mechanical behavior of carbon nanotubes with increasing aspect ratios. While continuum mechanics concepts can be used to describe the first two types of deformation, statistical methods will be necessary to describe the dynamics of wire-like long tubes.

ABSTRACT: Control over the composition, shape, spatial location and/or geometrical configuration of semiconductor nanostructures is important for nearly all applications of these materials. Here we report a mechanical strategy for creating certain classes of three-dimensional shapes in nanoribbons that would be difficult to generate in other ways. This approach involves the combined use of lithographically patterned surface chemistry to provide spatial control over adhesion sites, and elastic deformations of a supporting substrate to induce well-controlled local displacements. We show that precisely engineered buckling geometries can be created in nanoribbons of GaAs and Si in this manner and that these configurations can be described quantitatively with analytical models of the mechanics. As one application example, we show that some of these structures provide a route to electronics (and optoelectronics) with extremely high levels of stretchability (up to ~100%), compressibility (up to ~25%) and bendability (with curvature radius down to ~5 mm).

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ABSTRACT: We have studied the scaling of controlled nonlinear buckling processes in materials with dimensions in the molecular range (i.e., about 1 nm) through experimental and theoretical studies of buckling in individual single-wall carbon nanotubes on substrates of poly(dimethylsiloxane). The results show not only the ability to create and manipulate patterns of buckling at these molecular scales, but also, that analytical continuum mechanics theory can explain, quantitatively, all measurable aspects of this system. Inverse calculation applied to measurements of diameter-dependent buckling wavelengths yields accurate values of the Young's moduli of individual SWNTs. As an example of the value of this system beyond its use in this type of molecular scale metrology, we implement parallel arrays of buckled SWNTs as a class of mechanically stretchable conductor.

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(37) Lier, G. V.; Alsenoy, C. V.; Doran, V. V.; Geerlings, P. Chem. Phys. Lett. 2000, 326, 181-185.
ABSTRACT: Local buckling can form microcorrugations in thin films on elastomeric substrates, to yield an effective type of mechanical stretchability in otherwise rigid, brittle materials, with many application possibilities. For large area films or relatively thin substrates, however, global Euler buckling, as opposed to local buckling, can be observed in experiments. This paper describes analytically the mechanics of local and global buckling of one-dimensional thin films or two-dimensional thin membranes on elastomeric substrates. The critical condition separating these two buckling modes is obtained analytically, and it agrees well with experiments and numerical simulations.

References listed at the end of the paper:


ABSTRACT: Based on the finite-deformation shell theory for carbon nanotubes established from the interatomic potential and the continuum model for van der Waals (vdW) interactions, we have studied the buckling of double-walled carbon nanotubes subjected to compression or torsion. Prior to buckling, the vdW interactions have essentially no effect on the deformation of the double-walled carbon nanotube. The critical
buckling strain of the double-wall carbon nanotubes is always between those for the inner wall and for the outer wall, which means that the vdW interaction decelerates buckling of one wall at the expenses of accelerating the buckle of the other wall.


ABSTRACT: This paper discusses the size dependence of the hardness with respect to the depth and the radius of the indenter for multiple walled carbon nanotubes. Results show a peculiar size influence on the hardness, which is explained via the shear resistance between the neighboring walls during the buckling of the multiwalled nanotubes.

Key words: Toupin-Mindlin theory, nanoindentation, size effects, buckling carbon nanotubes

References listed at the end of the paper:

ABSTRACT: We use Reddy's third order plate theory to study buckling and steady state vibrations of a simply supported functionally gradient isotropic polygonal plate resting on a Winkler–Pasternak elastic foundation and subjected to uniform in-plane hydrostatic loads. Young's modulus and the Poisson ratio for the material of the plate are assumed to vary only in the thickness direction. Effects of rotary inertia are considered. The problem of determining the critical buckling load or the vibration frequency of the plate is found to be analogous to that of ascertaining the frequency of a membrane clamped at the edges and whose shape coincides with that of the plate. The critical buckling load and the vibration frequency are shown to be positive. Some available results for plates symmetric about the mid-plane can be retrieved from the present analysis.

References listed at the end of the paper:

ABSTRACT: The dynamic buckling of thin isotropic thermoviscoplastic cylindrical shells compressed with a uniform axial velocity prescribed at the end faces is investigated analytically and numerically. In the first part of the paper, the stressed/deformed state of a shell is assumed to have buckled if infinitesimal perturbations superimposed upon it grow. Cubic algebraic equations are derived for both the initial growth rate of the perturbation and its wavenumber. The wavenumber corresponding to the maximum initial growth rate of a perturbation introduced at an axial strain of 0.1 is taken to determine the buckling mode. The computed buckling modes are found to match well with those listed in the available experimental data. A thermoviscoplastic constitutive relation is used to delineate the influence of material parameters on the buckling behavior. In the second part of the paper, the finite element method is used to analyze the collapse of an imperfect circular cylindrical tube with axial velocity prescribed at one of its flat end faces with the other end face kept fixed. The influence of initial randomly located imperfections on the buckling behavior is investigated and discussed.

References listed at the end of the paper:

ABSTRACT: Buckling of single-walled and multiwalled carbon nanotubes (SWNTs and MWNTs, respectively) due to axial compressive loads has been studied by molecular mechanics simulations, and results compared with those from the analysis of equivalent continuum structures using Euler buckling theory and the finite element method. It is found that a MWNT of large aspect ratio (length/diameter) buckles as a column with axial strain at buckling given reasonably well by the Euler buckling theory applied to the equivalent continuum structure. However, a MWNT of low aspect ratio buckles in shell wall buckling mode with the axial strain at buckling corresponding to the highest axial strain at buckling of one of its constituent SWNTs. A finite element model has been developed that simulates van der Waals forces by truss elements connecting nodes on adjacent walls of a MWNT; the axial strain at buckling from it is close to that obtained from the MM simulations but the two sets of mode shapes are different.

References listed at the end of the paper:

Buckling of a simply supported three-layer circular cylindrical shell under axial compressive load is studied. The inner and outer layers of the shell are comprised of the same homogeneous and isotropic material, and the middle layer is made of an isotropic functionally graded (FG) material whose Young's modulus varies either affinely or parabolically in the thickness direction from its value for the material of the inner layer to that of the outer layer. The solution is expressed in terms of trigonometric functions that identically satisfy displacement type boundary conditions at the edges. Buckling loads for different values of the geometric parameters and the variation in material parameters of the middle layer are computed. Numerical results show that buckling modes are symmetric in the circumferential coordinate, and the buckling load decreases with an increase in the radius to thickness ratio, and increases with an increase in the average value of Young's modulus of the middle layer. The increase in the length to radius ratio has no effect on the buckling load, and it increases the axial wave number of the buckled shapes.

References listed at the end of the paper:


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ABSTRACT: Buckling of a simply supported three-layer circular cylindrical shell under axial compressive load is studied. The inner and outer layers of the shell are comprised of the same homogeneous and isotropic material, and the middle layer is made of an isotropic functionally graded (FG) material whose Young's modulus varies either affinely or parabolically in the thickness direction from its value for the material of the inner layer to that of the outer layer. The solution is expressed in terms of trigonometric functions that identically satisfy displacement type boundary conditions at the edges. Buckling loads for different values of the geometric parameters and the variation in material parameters of the middle layer are computed. Numerical results show that buckling modes are symmetric in the circumferential coordinate, and the buckling load decreases with an increase in the radius to thickness ratio, and increases with an increase in the average value of Young's modulus of the middle layer. The increase in the length to radius ratio has no effect on the buckling load, and it increases the axial wave number of the buckled shapes.

References listed at the end of the paper:

References listed at the end of the paper:

ABSTRACT: We use molecular statics simulations with the embedded atom method potential to delineate yielding (material instability) and buckling (structural instability) in gold nanowires deformed axially in compression. It is found that both local (stacking faults) and global instabilities occur when the gold nanowire yields but only global instabilities occur when the nanowire buckles. Furthermore strong surface effects reorient the lattice structure which significantly increases Young’s modulus in the axial direction and cause a nanowire of relatively small slenderness ratio (e.g., 14) to buckle. Upon complete unloading of the nanowires, the average axial stress and the total potential energy revert to their values in the reference configuration for the nanowires that buckled but not for the one that yielded.

References listed at the end of the paper:
ABSTRACT: Analytical relations between the critical buckling load of a functionally graded material (FGM) Timoshenko beam and that of the corresponding homogeneous Euler–Bernoulli beam subjected to axial compressive load have been derived for clamped–clamped (C–C), simply supported–simply supported (S–S) and clamped–free (C–F) edges. However, no such relation is found for clamped–simply supported (C–S) beams. For C–S beams, the transcendental equation has been derived to find the critical buckling load for the FGM Timoshenko beam which is similar to that for a homogeneous Euler–Bernoulli beam. For the FGM beams Young’s modulus, E, and Poisson’s ratio, μ, are assumed to vary through the thickness. The significance of this work is that for the C–C, S–S and C–F FGM Timoshenko beams, the critical buckling load can be easily found from that of the corresponding homogeneous Euler–Bernoulli beam and two constants whose values depend
upon the through-the-thickness variations of E and m. For the C–S FGM Timoshenko beam the transcendental equation for the determination of the critical buckling load is similar to that for the corresponding homogeneous Euler–Bernoulli beam.

References listed at the end of the paper:


ABSTRACT: The solution of viscoplastic axisymmetrical buckling of a complete thin spherical shell subjected to radial pressure impulse is presented. Analytically, the problem is formulated as a superposition of small perturbations on the basic unperturbed motion. The amplitudes of perturbed motion are restricted to be so small that the homogeneous compressive deformation predominates over the local bending. This condition allows the constitutive equations to be linearized by the expansion into Taylor's series in the vicinity of unperturbed motion. As a result, a set of two linear partial differential equations of the fifth order is obtained for describing
the perturbed motion of the shell. The functional coefficients of these equations are determined by the solution for the unperturbed motion. The governing set of equations is solved using the series of Legendre's functions. As a result, for the time-dependent amplitudes in the series, the set of two ordinary equations with variable coefficients is arrived at. It turns out that certain harmonics grow very rapidly and cause the shell to exhibit a characteristic wrinkled shape which is characterized by a critical mode number. This property of the amplitudes is used to determine the threshold impulse that a shell can tolerate without excessive deformation. The influence of the meridional displacement on the magnitude of radial displacement, buckling mode and critical impulse is investigated. Also, the influence of the viscosity and the initial imperfections of the geometry and loading is shown. The numerical results for a steel shell are presented diagrammatically.


ABSTRACT: The paper develops a direct, intrinsic approach to the equilibrium equations of bodies coated by a thin film with a nonlinear shell like structure. The forms of the equations in the reference and actual configurations are considered. The equations are shown to coincide with those obtained by using coordinate systems on the film or on the thin shell.

References listed at the end of the paper:

ABSTRACT: The solution of viscoplastic buckling of a complete thin spherical shell subjected to impulse pressure is given. The nonlinear flow law is assumed and the influence of elevated temperature on the magnitude of displacements, buckling mode and threshold impulse is discussed. The special cases of bucking modes are also considered. The numerical results are presented diagrammatically for a steel shell loaded by a radial impulse.


ABSTRACT: Viscoplastic material behavior could influence the inelastic collapse and buckling loads of shell structures due to the strain rate dependence of the flow stress and through pre-buckling creep deformations and inelastic unloading. An examination of these effects is performed by incorporating the unified elastic-viscoplastic constitutive equations of Bodner-Parton into the BOSOR-5 computer program of Bushnell for the deformation and buckling of axisymmetric shells subjected to both pressure and thermal loadings. The combined computer program enables consideration of both time-dependent geometrical and material effects on the pre-buckled state and the instability condition. In particular, the procedure enables the determination of a bifurcation-type lower bound on the buckling load. A few numerical exercises were performed to illustrate the various effects, including that of temperature dependence of the viscoplastic properties.


ABSTRACT: The small deformation elastic-viscoplastic constitutive equations of Bodner-Partom are modified to model strong non-proportional loading paths such as experienced in corner turning tests and certain cases of inelastic buckling. An essential generalization is made to the flow rule, causing the magnitude and direction of plastic strain rate to become an explicit function of deviatoric total strain rate as well as of stress and hardening variables. With this and other modifications, the equations indicate some of the important characteristics of the response to abrupt changes in the loading direction. These are: (a) a reduced effective shear modulus; (b) a transient drop in the effective stress; and (c) a transient non-coaxiality of the plastic strain rate relative to the
deviatoric stress. Predictions of the modified theory compare reasonably well with experimental values for inelastic torsional buckling of axially compressed cruciform columns and for corner turning tests.


ABSTRACT: The buckling of structures of elastic-viscoplastic materials is a stability problem that does not admit a realistic bifurcation formulation in the classical manner. In the absence of imperfections and inertial effects, the standard bifurcation criterion leads only to elastic buckling since an instantaneous jump in strain rate would develop at the critical condition. However, an expression for the “short time” inelastic tangent modulus at the pre-buckling strain rate can be developed from an appropriate incremental constitutive theory and this can be used in the quasi-static bifurcation buckling condition appropriate to the structure and loading. Such a buckling value can be interpreted as a lower bound on the actual instability condition. For the case of structures with initial imperfections, the calculation of local inelastic tangent moduli at the current state should lead to close correspondence between bifurcation and instability. Under creep conditions, the procedure gives approximate creep buckling times for both perfect and initially imperfect structures. For situations where the buckling mode generates abrupt changes in the multiaxial stress state, modifications to the reference constitutive theory are required to properly represent the governing physics. In this manner, the procedure seems capable of indicating buckling values consistent with test results without relying on a “deformation” type plasticity theory.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: Large deformation behavior and post-buckling modes of single-walled carbon nanotubes are studied numerically by using traditional continuum shell theory and eigenvalue buckling methodology with elasticity parameters obtained by atomistic methods incorporated. Comparison with molecular mechanics and an atomistic-based continuum membrane method shows that the continuum shell theory is convenient and efficient in predicting the post-buckling behavior of the nanotubes subjected to axial compression, torsion and...
bend loads, providing that the elasticity parameters of the tube are obtained from atomistic theory. Higher-order buckling modes, which are difficult to be obtained by molecular mechanics, have been analyzed as well.


ABSTRACT: Buckling of nanotubes has been studied using many methods such as molecular dynamics (MD), molecular mechanics, and continuum-based shell theories. In MD, motion of the individual atoms is tracked under applied temperature and pressure, ensuring a reliable estimate of the material response. The response thus simulated varies for individual nanotubes and is only as accurate as the force field used to model the atomic interactions. On the other hand, there exists a rich literature on the understanding of continuum mechanics-based shell theories. Based on the observations on the behavior of nanotubes, there have been a number of shell theory-based approaches to study the buckling of nanotubes. Although some of these methods yield a reasonable estimate of the buckling stress, investigation and comparison of buckled mode shapes obtained from continuum analysis and MD are sparse. Previous studies show that the direct application of shell theories to study nanotube buckling often leads to erroneous results. The present study reveals that a major source of this error can be attributed to the departure of the shape of the nanotube from a perfect cylindrical shell. Analogous to the shell buckling in the macro-scale, in this work, the nanotube is modeled as a thin-shell with initial imperfection. Then, a nonlinear buckling analysis is carried out using the Riks method. It is observed that this proposed approach yields significantly improved estimate of the buckling stress and mode shapes. It is also shown that the present method can account for the variation of buckling stress as a function of the temperature considered. Hence, this can prove to be a robust method for a continuum analysis of nanosystems taking in the effect of variation of temperature as well.

References listed at the end of the paper:
ABSTRACT: This exercise is intended to provide a direct correlation between the axial compressive buckling of elastic thin-walled cylinders and the response of a mechanical model that exhibits a peak load at large deformation. The model is similar, but more general, to those used by Budiansky and Hutchinson and by Kounadis and associates to illustrate dynamic buckling behavior of imperfection sensitive nonlinear systems. Here, an empirical relation between observed static shell buckling loads and the shell geometry is used to characterize the restraining spring parameter of the model. The resulting model indicates realistic imperfection sensitivity of the load-deflection relation and, as a good physical analogy, provides insight into the shell buckling mechanism. Specifically, from the perspective of the model, shell buckling is viewed as a local event governed by shallow arch-like behavior where the extent of the arch depends on the shell geometry. This implies that the specific geometry of local axial imperfections of the shell (out of straightness) might be more important than that of circumferential imperfections (out of roundness) for shell buckling under axial loading. Moreover, use of an imperfection slope factor rather than an imperfection displacement term might be more suitable for actual shells in some cases. In addition, the model analogy indicates that the buckling (peak) load also depends on the shell geometry and that the bifurcation load serves only as a reference value. A comparison is made to Koiter’s approximate formula for axially compressed isotropic shells.

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ABSTRACT: The torsional buckling of a double-walled carbon nanotube embedded in an elastic medium is studied in this paper. The effects of surrounding elastic medium and van der Waals forces between the inner and outer nanotubes are taken into account. Using continuum mechanics, an elastic double-shell model is presented for the torsional buckling of a double-walled carbon nanotube. Based on the model, a condition is derived in terms of the buckling modes of the shell and the parameters describing the effect of van der Waals interaction and surrounding elastic medium. A simplified analysis is also carried out estimate the critical torque for torsional buckling of the double-walled carbon nanotube.

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ABSTRACT: (cannot easily cut and paste)


ABSTRACT: In view of the fact that microtubules exhibit strong anisotropic elastic properties, an orthotropic elastic shell model for microtubules is developed to study buckling behavior of microtubules. The predicted critical pressure is found to agree well with recent unexplained experimental data on pressure-induced buckling of microtubules [Needleman et al., Phys. Rev. Lett. 93, 198104 (2004); Biophys. J. 89, 3410 (2005)] which are lower than that predicted by the isotropic shell model by four orders of magnitude. General buckling behavior of microtubules under axial compression or radial pressure is studied. The results show that the isotropic shell model greatly overestimates the buckling loads of microtubules, except columnlike axially compressed buckling of long microtubules (of length-to-diameter ratio larger than, say, 150). In particular, the present results also offer a plausible explanation for the length dependency of flexibility of microtubules reported in the literature.

Related Papers:
Vibration of microtubules as orthotropic elastic shells
C Wang, C Ru, A Mioduchowski in Physica E: Low-dimensional Systems and Nanostructures (2006)
Buckling and postbuckling of radially loaded microtubules by nonlocal shear deformable shell model.
Elastic Buckling of Orthotropic Plates Under Varying Axial Stresses
Ashraf Badir, Hurang Hu, Abdouramane Diallo (1997)
Buckling of a long cylindrical shell containing an elastic core
G Herrmann in AIAA Journal (1965)
Buckling of a long cylindrical shell surrounded by an elastic medium
Michael J Forrestal, George Herrmann in International Journal of Solids and Structures (1965)

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doi: 10.1088/0964-1726/14/1/029

ABSTRACT: This paper presents the research on the stability analysis of carbon nanotubes (CNTs) via elastic continuum beam and shell models. The estimation of the flexural stiffness of a single-walled nanotube (SWNT) via the elastic beam model is proposed based on the postulate analyzed and provided in the paper. The validation of the stiffness is conducted with the ab initio calculations of the vibration of a SWNT. Based on the stiffness proposed, the stability analysis of CNTs is further conducted and validated with the well-cited research results by Yakobson and his collaborators. In addition, more predictions of various buckling phenomena of carbon nanotubes by beam and shell models are provided and studied. Finally, the kink phenomenon in a SWNT under pure bending is discussed via the continuum model. It is hoped that this paper will pave the way toward a better understanding of the application of continuum models in the stability and dynamics analysis of carbon nanotubes.

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ABSTRACT: Nonlocal elastic beam and shell models are developed and applied to investigate the small scale effect on buckling analysis of carbon nanotubes (CNTs) under compression. General and explicit solutions are derived and expressed in terms of the solutions via local or classical elastic models, in which the scale effect is not accounted, to reveal the small scale effect on CNTs buckling results. The dependence of the scale effect with respect to the length, radius, and buckling modes of CNTs is clearly established and observed from the universal solutions derived in the manuscript. It is clearly seen from the results that the buckling solutions for CNTs via local continuum mechanics are overestimated and hence the scale effect is indispensable in providing more accurate results for mechanical behaviors of CNTs via continuum mechanics.

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ABSTRACT: Continuum mechanics models for the torsional buckling of carbon nanotubes (CNTs) are developed in the Letter. The applicability of these models is investigated for CNTs with different aspect ratios. In particular, molecular dynamics simulations are conducted to verify the feasibility of the models for moderately long CNTs.


ABSTRACT: The buckling of short double-walled carbon nanotubes subjected to compression is investigated through molecular dynamics in the paper. The inner wall is discovered to have helically aligned buckling mode while the outer wall is reported to have shell buckling mode with kinks. Such buckling modes are attributed to the interaction of the two walls via the van der Waals effect. In addition, a buckling strain higher than the buckling strains of two constituent inner and outer walls is found in the double-walled tube within a certain size range. The causes for such a phenomenon are analyzed and discussed.

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ABSTRACT: The small-scale effect on the torsional buckling of multi-walled carbon nanotubes coupled with temperature change is investigated in this paper. A nonlocal multiple-shell model for the multi-walled carbon nanotubes surrounded an elastic medium under torsional and thermal loads is established, and then general solutions are obtained from the governing equations. The influence of the nonlocal effect on critical shear force and change in temperature is investigated. It is demonstrated that the critical shear force could be overestimated by the classical continuum theory and the nonlocal effect on critical buckling force decreases as the change in temperature increases at room or low temperature but increases as the change in temperature increases at higher temperature. Meanwhile, the effect of small size-scale is dependent on the buckling mode under different thermal environments. It is also shown that the innermost radius and the number of layer can affect the small-scale effect on critical change in temperature and buckling shear force. When the ratio of tube length and outmost radius are given, the critical shear force in each layer decreases and the nonlocal effect on the critical shear force becomes weaker as the innermost radius and the layer number increase.

References listed at the end of the paper:
Zhang, C. L. and Shen, H. S., “Buckling and postbuckling analysis of single-walled carbon nanotubes in thermal environments via molecular dynamics simulation”, Carbon, 44(13), 2608-2616, 2006

ABSTRACT: Buckling and postbuckling analysis of single-walled carbon nanotubes (SWCNTs) with (n,n)- and (n,0)-helicity, when acted upon by the destabilizing loads of axial compression, torsion and external pressure, is presented by using molecular dynamics simulation. Based on the interatomic interactions given by Brenner and Lennard–Jones potentials, the molecular dynamics method is used to determine the postbuckling equilibrium paths as well as the variation of strain energy. Temperature changes and van der Waals interaction forces between the opposite walls of SWCNTs are both taken into account. Comprehensive numerical results for armchair (12,12)- and zigzag (21,0)-tubes are presented. The results reveal that the effect of van der Waals interactions on the postbuckling behavior of SWCNTs under axial compression can be negligible, while the additional van der Waals forces will affect the postbuckling equilibrium paths of SWCNTs under torsion and external pressure when the deformation of the tube is sufficiently large. The results also show that the temperature change has a significant effect on the postbuckling response of SWCNTs under axial compression, but it has a small effect in the loading case of torsion. In contrast, it only has a less effect on the postbuckling response of SWCNTs under external pressure.


ABSTRACT: In this paper, the buckling behavior and critical axial pressure of double-walled carbon nanotubes (DWCNTs) with surrounding elastic medium are investigated. A double-shell (circular cylindrical shell) model is presented and the effects of surrounding elastic medium on the outer tube and the van der Waals forces between two adjacent tubes are taken into account. The analysis and the numerical solution method are based on the classical theory of plates and shells and the Galerkin method. Equations are derived for the critical axial forces and pressures of DWCNTs; the critical axial forces and pressures are calculated for different axial half sine wavenumbers and circumferential sine wavenumbers and compared with those for single-walled carbon nanotubes (SWCNTs). Results indicate that the critical axial force of a DWCNT is higher than that of an SWCNT, but the critical axial pressure of a DWCNT is lower than the critical axial pressure of a SWCNT. Although the critical axial force of a DWCNT decreases as the axial half sine wavenumbers increase, it rises as the circumferential sine wavenumbers increase.


ABSTRACT: This paper studies the pure axially compressed buckling and combined loading effects of a cylindrical shell and an individual single-walled carbon nanotube (SWCNT). The results of finite element (FE)
simulations of SWCNT using the ANSYS software are presented, and are compared with the classical (local) and continuum (nonlocal) mechanical theories. Critical axial stress and deflections are calculated for all the cases. Two types of buckling are considered in this study, namely, the shell buckling which depends on the radius-to-thickness ratio, and the column buckling which is controlled by the length-to-diameter ratio.


ABSTRACT: The torsional and axially compressed buckling of an individual embedded multi-walled carbon nanotube (MWNTs) subjected to an internal and/or external radial pressure was investigated in this study. The emphasis is placed on new physical phenomena which are due to both the small length scale and the surrounding elastic medium. Multiwall carbon nanotubes which are considered in this study are classified into three categories based on the radius to thickness ratio, namely, thin, thick, and almost solid. Explicit formulas are derived for the van der Waals (vdW) interaction between any two layers of an MWNT based on the continuum cylindrical shell model. In most of the previous studies, the vdW interaction between two adjacent layers was considered only and the vdW interaction among other layers was neglected. Moreover, in these works, the vdW interaction coefficient was treated as a constant that was independent of the radii of the tubes. However, in the present model the vdW interaction coefficients are considered to be dependent on the change of interlayer spacing and the radii of the tubes. The effect of the small length scale is also considered in the present formulation. The results show that there is a unique buckling mode \((m,n)\) corresponding to the critical shear stress. This result is obviously different from what is expected for the pure axially compressed buckling of an individual multi-walled carbon nanotube.

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ABSTRACT: This paper presents an assessment of continuum mechanics (beam and cylindrical shell) models in the prediction of critical buckling strains of axially loaded single-walled carbon nanotubes (SWCNTs). Molecular dynamics (MD) simulation results for SWCNTs with various aspect (length-to-diameter) ratios and diameters will be used as the reference solutions for this assessment exercise. From MD simulations, two distinct buckling modes are observed, i.e. the shell-type buckling mode, when the aspect ratios are small, and the beam-type mode, when the aspect ratios are large. For moderate aspect ratios, the SWCNTs buckle in a mixed beam–shell mode. Therefore one chooses either the beam or the shell model depending on the aspect ratio of the carbon nanotubes (CNTs). It will be shown herein that for SWCNTs with long aspect ratios, the local Euler beam results are comparable to MD simulation results carried out at room temperature. However, when the SWCNTs have moderate aspect ratios, it is necessary to use the more refined nonlocal beam theory or the Timoshenko beam model for a better prediction of the critical strain. For short SWCNTs with large diameters, the nonlocal shell model with the appropriate small length scale parameter can provide critical strains that are in good agreement with MD results. However, for short SWCNTs with small diameters, more work has to be done to refine the nonlocal cylindrical shell model for better prediction of critical strains.

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ABSTRACT: The axially compressed buckling of a double-walled carbon nanotube surrounded by an elastic medium using the energy and the Rayleigh-Ritz methods is investigated in this paper. In this research, based on the elastic shell models at nano scale, the effects of the van der Waals forces between the inner and the outer tubes, the small scale and the surrounding elastic medium on the critical buckling load are considered. Normal stresses at the outer tube medium interface are also included in the current analysis. An expression is derived relating the external pressure to the buckling mode number, from which the critical pressure can be obtained. It is seen from the results that the critical pressure is dependent on the outer radius to thickness ratio, the material parameters of the surrounding elastic medium such as Young’s modulus and Poisson’s ratio. Moreover, it is shown that the critical pressure descend very quickly with increasing the half axial wave numbers.

References listed at the end of the paper:


ABSTRACT: (FMLs) subjected to low-velocity impact. The deflection to thickness (w/h) ratio has been identified through the governing equations of the plate that are solved using the first-order shear deformation theory as well as the Fourier series method. With the help of a two degrees-of-freedom system, consisting of springs-masses, and the Choi’s linearized Hertzian contact model the interaction between the impactor and the plate is modeled. Thirty-one experiments are conducted on samples of different layer sequences and volume fractions of Al plies in the composite Structures. A reliable fitness function in the form of a strict linear mathematical function constructed. Using an ordinary least square method, response regression coefficients estimated and a zero-one programming technique proposed to optimize the FML plate behavior subjected to any technological or cost restrictions. The results indicated that FML plate behavior is highly affected by layer sequences and volume fractions of Al plies. The results also showed that, embedding Al plies at outer layers of the structure significantly results in a better response of the structure under low-velocity impact, instead of embedding them in the middle or middle and outer layers of the structure.

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ABSTRACT: We propose a method to estimate the natural frequencies of the multi-walled carbon nanotubes (MWCNTs) embedded in an elastic medium. Each of the nested tubes is treated as an individual bar interacting
with the adjacent nanotubes through the inter-tube Van der Waals forces. The effect of the elastic medium is introduced through an elastic model. The mathematical model is finally reduced to an eigen value problem and the eigen value problem is solved to arrive at the inter-tube resonances of the MWCNTs. Variation of the natural frequencies with different parameters are studied. The estimated results from the present method are compared with the literature and results are observed to be in close agreement.

References listed at the end of the paper:

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ABSTRACT: The small-scale effect on the torsional buckling of a double-walled carbon nanotube (DWCNT) embedded on Winkler and Pasternak foundations is investigated in this study using the theory of nonlocal elasticity. The effects of the surrounding elastic medium, such as the spring constant of the Winkler type and the shear constant of the Pasternak type, as well as the van der Waals (vdW) forces between the inner and the outer nanotubes are taken into account. Finally, based on the theory of nonlocal elasticity and by employing the continuum models, an elastic double-shell model is presented for the nonlocal torsional buckling load of a DWCNT. It is seen from the results that the shear constant of the Pasternak type increases the nonlocal critical torsional buckling load, while the difference between the presence and the absence of the shear constant of the Pasternak type becomes large. It is shown that the nonlocal critical buckling load is lower than the local critical buckling load. Moreover, a simplified analysis is carried out to estimate the nonlocal critical torque for the torsional buckling of a DWCNT.

References listed at the end of the paper:

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“Thermal buckling analysis of double-walled carbon nanotubes considering the small-scale length effect”,
Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,
ABSTRACT: In this article, the buckling analysis of a double-walled carbon nanotube (DWCNT) subjected to a
uniform internal pressure in a thermal field is investigated. The effects of the temperature change, the
surrounding elastic medium based on the Winkler model, and the van der Waals forces between the inner and
the outer tubes are considered using the continuum cylindrical shell model. The small-length scale effect is also
included in the present formulation. The results show that there is a unique buckling mode corresponding to
each critical buckling load. Moreover, it is shown that the non-local critical buckling load is lower than the local
critical buckling load. It is concluded that, at low temperatures, the critical buckling load for the infinitesimal
buckling of a DWCNT increases as the magnitude of temperature change increases whereas at high
temperatures, the critical buckling load decreases with the increasing of the temperature.

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“Postbuckling Equilibrium Path of a Long Thin-Walled Cylindrical Shell (Single-Walled Carbon Nanotube)
January 2011, pp. 79-86
ABSTRACT: In this paper, an elastic shell model is presented for postbuckling prediction of a long thin-walled
cylindrical shell under axial compression. The Ritz method is applied to solve the governing equilibrium
equation of a cylindrical shell model based on the von-Karman type nonlinear differential equations. The
postbuckling equilibrium path is obtained using the energy method for a long thin-walled cylindrical shell.
Furthermore, the postbuckling relationship between the axial stress and end-shortening is investigated with
different geometric parameters. Also, this theory is used for postbuckling analysis of a single-walled carbon
nanotube without considering the small scale effects. Numerical results reveal that the single-walled carbon
nanotube under axial compression has an unstable postbuckling behavior.
References listed at the end of the paper:
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M. Bodaghi and A.R. Saidi (Department of Mechanical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran), “Thermoelastic buckling behavior of thick functionally graded rectangular plates” Archive of Applied Mechanics, Vol. 81, No. 11, pp 1555-1572, November 2011

ABSTRACT: Thermoelastic buckling behavior of thick rectangular plate made of functionally graded materials is investigated in this article. The material properties of the plate are assumed to vary continuously through the thickness of the plate according to a power-law distribution. Three types of thermal loading as uniform temperature raise, nonlinear and linear temperature distribution through the thickness of plate are considered. The coupled governing stability equations are derived based on the Reddy’s higher-order shear deformation plate theory using the energy method. The resulted stability equations are decoupled and solved analytically for the functionally graded rectangular plates with two opposite edges simply supported subjected to different types of thermal loading. A comparison of the present results with those available in the literature is carried out to establish the accuracy of the presented analytical method. The influences of power of functionally graded material, plate thickness, aspect ratio, thermal loading conditions and boundary conditions on the critical buckling temperature of aluminum/alumina functionally graded rectangular plates are investigated and discussed in detail. The critical buckling temperatures of thick functionally graded rectangular plates with various boundary conditions are reported for the first time and can be served as benchmark results for researchers to validate their numerical and analytical methods in the future.

References listed at the end of the paper:

ABSTRACT: In this paper, the dynamic stability of single- and double-walled carbon nanotubes (SWCNT and DWCNT) under dynamic axial loading is investigated using the continuum mechanics model and the minimum total energy method. The natural frequencies of the SWCNT and the critical dynamic axial load of the SWCNT and DWCNT are obtained using the Rayleigh-Ritz method. The effects of the elastic medium and the van der Waals forces between the two layers in the DWCNT are taken into account using the Winkler model and Lennard-Jones theory, respectively. The effect of the small length scale is also considered using the Eringen Model. The critical dynamic axial load is increased by inserting an inner carbon nanotube (CNT) into an isolated CNT embedded in an elastic medium.

References listed at the end of the paper:
ABSTRACT: Using principle of minimum total potential energy approach in conjunction with Rayleigh-Ritz method, the electro-thermo-mechanical axial buckling behavior of piezoelectric polymeric cylindrical shell
reinforced with double-walled boron-nitride nanotube (DWBNNT) is investigated. Coupling between electrical and mechanical fields are considered according to a representative volume element (RVE)-based micromechanical model. This study indicates how buckling resistance of composite cylindrical shell may vary by applying thermal and electrical loads. Applying the reverse voltage or decreasing the temperature, also, increases the critical axial buckling load. This work showed that the piezoelectric BNNT generally enhances the buckling resistance of the composite cylindrical shell.

References listed at the end of the paper:


ABSTRACT: This paper investigates the effect of partially filled foam core on the behavior of buckling in a thin-walled cylindrical shell. Previous studies have focused on 100% infill or simply used a fixed thickness of foam core. However, this may not be the optimum arrangement in terms of design. To further investigate this, a theoretical analysis is carried out using the Rayleigh–Ritz approximation, and a new formula is proposed to predict the critical buckling stress of an infill ranging from 0% up to 100% rigid. The proposed formula agrees well with works reported in the literature. It also shows that filling a foam core in a thin-walled cylindrical shell can enhance its resistance to buckling failure. Meanwhile, a simplified formula is provided to the practicing engineer. The paper concludes that an excessive increase in foam core thickness beyond 10% of outer radius is inefficient due to extra cost and weight.


ABSTRACT: Using principle of minimum total potential energy approach in conjunction with Rayleigh-Ritz method, the electro-thermo-mechanical axial buckling behavior of piezoelectric polymeric cylindrical shell reinforced with double-walled boron-nitride nanotube (DWBNNT) is investigated. Coupling between electrical and mechanical fields are considered according to a representative volume element (RVE)-based micromechanical model. This study indicates how buckling resistance of composite cylindrical shell may vary by applying thermal and electrical loads. Also, applying the reverse voltage or decreasing the temperature, increases the critical axial buckling load. This work showed that the piezoelectric BNNT enhances on the whole the buckling resistance of the composite cylindrical shell.

References listed at the end of the paper:
ABSTRACT: Using harmonic differential quadrature (HDQ) method, nonlinear vibrations and instability of a smart composite cylindrical shell made from piezoelectric polymer of polyvinylidene fluoride (PVDF) reinforced with boron nitride nanotubes (BNNTs) are investigated while clamped at both ends and subjected to combined electro-thermo-mechanical loads and conveying a viscous-fluid. The mathematical modeling of the cylindrical shell and the resulting nonlinear coupling governing equations between mechanical and electrical fields are derived using Hamilton’s principle based on the first-order shear deformation theory (FSDT) in conjunction with the Donnell's non-linear shallow shell theory. The governing equations are discretized via HDQ method, and solved to obtain the resonant frequencies and critical flow velocities associated with divergence and flutter instabilities as well as re-stabilization of the system. Results indicate that the internal moving fluid plays an important role in the instability of the cylindrical shell. Application of a smart material such as PVDF improves significantly the stability and vibration of the system.

References listed at the end of the paper

http://www.science-gate.com/IJAAS.html

ABSTRACT: Nonlinear vibration of embedded polymeric pipes reinforced with single-walled carbon nanotubes (SWCNTs) is investigated in the present work. The classical cylindrical shell theory is used for mathematical modeling of structure. The pipe is subjected to thermal and magnetic loads. The surrounding elastic foundation is simulated with spring constant of Winkler-type and shear constant of Pasternak-type. Mori-Tanaka model is applied in order to obtain the characteristics of the equivalent composite. Based on energy method and Hamilton's principal, the motion equations are derived and solved numerically for calculating the nonlinear frequency utilizing the differential quadrature method (DQM). The effects of different parameters such as volume percent of SWCNTs, geometrical parameters of shell and elastic foundation on the vibration of pipe are investigated. Results showed that with increasing the volume percent of SWCNTs in pipe, the frequency of structure increases.

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ABSTRACT: In this paper, we apply the asymptotic analysis to thin piezoelectric shells in the framework of geometrically exact formulation. The formal mathematical approach used here is based neither on geometrical nor on mechanical assumptions and rigorously justifies the limiting constitutive nonlinear-two-dimensional equations. More precisely, we formally obtain two-dimensional membrane and flexural models written on the middle surface of the shell. We show that the coupling between the limit displacement field and the limit electric potential inherent to piezoelectricity appears in the membrane model but not in the flexural model. Finally, we suggest a “full” new model for piezoelectric shells using membrane and flexural effects.

PARTIAL INTRODUCTION: This paper aims at extending the range of applicability of the now classic equations of quasi-shallow shells. To this end, the condition of quasi-shallowness is replaced by the weaker assumption of slow variation of curvatures over the middle surface — an assumption first proposed by Duddeck [4] in the context of linear theory and then exploited by Łukasiewicz (see [5]) in a series of papers concerning both linear and nonlinear shell problems. We borrow from Duddeck his refined expression for membrane forces in terms of a strain function which, contrary to quasi-shallow shells, takes account of the Gaussian curvature.

The second of Duddeck's variables, the normal deflection of the midsurface, turns out to be unsuitable for the intended displacement-free theory and is not used. Instead, we express the bending strains through a strain function, finding the appropriate formula from Duddeck's stress function by noting a static-geometric analogy between membrane forces and bending strains. Compared with Koiter's strain function ("curvature function" in his terminology), our new formula is only slightly more complicated….

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"A nonlinear theory for shells with slowly varying thickness", (Publisher/date not given in the pdf file. The most recent date cited is 2006 or 2008)

ABSTRACT: We study the Γ-limit of 3d nonlinear elasticity for shells of small, variable thickness, around an arbitrary smooth 2d surface.

INTRODUCTION: The following question receives large attention in the current literature on elasticity [1]: which theories of thin objects (rods, plates, shells) are predicted by the 3d nonlinear theory? For plates, this problem has been extensively studied through Γ-convergence; first by LeDret and Raoult [5], leading to a
rigorous derivation of the membrane theory, and later by Friesecke, James and Mueller [4], for the Kirchhoff, von Karman and linear theories. In this framework, much less has been done for shells. The membrane and the bending theories were obtained in [6] and [2], respectively. More recently, the generalized von Karman and linear theories have been rigorously introduced and justified by the authors in [7]. In this paper, we present these last new results, in an extended version for shells with variable thickness and mid-surface.

References listed at the end of the paper:

M. Lewicka, M.G. Mora, M.R. Pakzad, Shell theories arising as low energy Γ-limit of 3d nonlinear elasticity, after 2006
ABSTRACT: We discuss the limiting behavior (using the notion of Γ-limit) of the 3d nonlinear elasticity for thin shells around an arbitrary smooth 2d surface. In particular, under the assumption that the elastic energy of deformations scales like $h^4$, $h$ being the thickness of a shell, we derive a limiting theory which is a generalization of the von Kármán theory for plates.

Marta Lewicka (Dept. of Mathematics, University of Minnesota, Minneapolis), “A note on convergence of low energy critical points of nonlinear elasticity functionals, for thin shells of arbitrary geometry”, ESAIM: Control, Optimization and Calculus of Variations, Vol. 17, No. 2, pp 493-505, 2011, DOI: 10.1051/cocv/2010002
ABSTRACT: We prove that the critical points of the 3d nonlinear elasticity functional on shells of small thickness $h$ and around the mid-surface $S$ of arbitrary geometry, converge as $h \to 0$ to the critical points of the von Kármán functional on $S$, recently proposed in [Lewicka et al., Ann. Scuola Norm. Sup. Pisa Cl. Sci. (to appear)]. This result extends the statement in [Müller and Pakzad, Comm. Part. Differ. Equ.33 (2008) 1018–1032], derived for the case of plates when $S \subset \mathbb{R}^2$. The convergence holds provided the elastic energies of the 3d deformations scale like $h^4$ and the external body forces scale like $h^3$.

Herve Le Dret and Annie Raoult, “Variational convergence for nonlinear shell models with directors and related semicontinuity and relaxation results” (publisher and date not given in the pdf file; most recent citation is dated 1998)
ABSTRACT: We use a variational convergence method to study the consistency of various Cosserat hypotheses in shell theory with the limit nonlinear membrane model derived from three-dimensional elasticity. In the course of the analysis, we introduce a generalization of quasiconvexity that is suitable for problems of the calculus of variations with two vectorial unknowns, one of which appears through its gradient, the other one
through its value, in a weak $W^{1,p} \times L^p$ framework.

References listed at the end of the paper:


References listed at the end of the paper:


ABSTRACT: Nonlinear buckling response of a composite cylindrical shell made of polyvinylidene fluoride (PVDF), is investigated. A two-dimensional smart model surrounded by an elastic foundation subjected to combined electro-thermo-mechanical loading is considered. The nonlinear strain terms based on Donnell’s theory are taken into account using the first shear deformation theory. The Hamilton’s principle is employed to obtain coupled differential equations, containing displacement and electric potential terms. Harmonic differential quadrature method (HDQM) is applied to obtain the critical buckling load for clamped supported mechanical and free electric potential boundary conditions at both ends of the smart cylinder. Results indicate that the critical buckling load increases when piezoelectric effect is considered.

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ABSTRACT: Nonlinear buckling of bonded double-walled boron nitride nanotubes (DWBNNTs) under combined electro-thermo–mechanical loadings based on the nonlocal piezoelectricity theory and Euler–Bernoulli beam (EBB) model is presented in this paper. Coupled DWBNNTs are embedded in an elastic medium that is simulated as a Pasternak foundation. Using the Lennard-Jones model, the van der Waals interaction between 2 layers of DWBNNTs is taken into account. Considering the von Kármán geometric nonlinearity, Hamilton’s principle, and charge equation, higher order governing equations are derived and solved by differential quadrature method (DQM). The detailed parametric study is conducted, focusing on the remarkable effects on the behavior of nonlinear buckling loads. The results indicated that the small-scale parameter, elastic medium, boundary conditions, electric potential, aspect ratio, and different vibration phases play an important role in the nonlinear buckling of smart elastically coupled systems. In addition, it is found that the trend of figures has good agreement with those of previous research. The results of this work could be used in the design and manufacture of nano/micro-electro–mechanical systems.

References listed at the end of the paper:


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A. Salehi-Khojin and N. Jalili (Smart Structures and Nanoelectromechanical Systems Laboratory, Department of Mechanical Engineering, Clemson University, Clemson, SC 29634-0921, USA), “Buckling of boron nitride nanotube reinforced piezoelectric polymeric composites subject to combined electro-thermo-mechanical loadings”, Compos. Sci. Tech., 68 (2008) 1489–1501, DOI: 10.1016/j.compscitech.2007.10.024
ABSTRACT: Unlike widely used carbon nanotubes, boron nitride nanotubes (BNNTs) have shown to possess stable semiconducting behavior and strong piezoelectricity. Such properties along with their outstanding mechanical properties and thermal conductivity, make BNNTs promising candidate reinforcement materials for a verity of applications especially nanoelectronic and nanophotonic devices. Motivated by these abilities, we aim to study the buckling behavior of BNNT-reinforced piezoelectric polymeric composites when subjected to combined electro-thermo-mechanical loadings. For this, the multi-walled structure of BNNT is considered as elastic media and a set of concentric cylindrical shells with van der Waals interaction between them. Using three-dimensional equilibrium equations, Donnell shell theory is utilized to show that the axially compressive resistance of BNNT varies with applying thermal and electrical loads. Also, a new equivalent spring constant model of piezoelectric matrix under electro-thermo-mechanical loadings is developed according to the concept of Whitney–Riley model. Results indicate that the support of piezoelectric matrix significantly enhances the buckling resistance of BNNT. Alternatively, the effect of BNNT piezoelectric property on the buckling behavior of composites is demonstrated. Furthermore, it is demonstrated that the supporting effect of elastic medium depends on the direction of applied voltage and thermal flow. More specifically, it is shown that applying direct and reverse voltages to BNNT changes the buckling loads for any axial and circumferential wavenumbers. Such capability could be uniquely utilized when designing BNNT-reinforced composites for structural vibration control applications.

M. Mohammadimehr, M. Moradi, A. Loghman (Department of Solid Mechanics, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran), “Influence of the Elastic Foundation on the Free Vibration and Buckling of Thin-Walled Piezoelectric-Based FGM Cylindrical Shells Under Combined Loadings”, Journal of Solid Mechanics, Vol. 6, No. 4 pp 347-365, 2014
ABSTRACT: In this paper, the influence of the elastic foundation on the free vibration and buckling of thin-walled piezoelectric-based functionally graded materials (FGM) cylindrical shells under combined loadings is investigated. The equations of motion are obtained by using the principle of Hamilton and Maxwell's equations
and the Navier's type solution used to solve these equations. Material properties are changed according to power law in the direction of thickness. In this study, the effects of Pasternak elastic foundation coefficients and also the effects of material distribution, geometrical ratios and loading conditions on the natural frequencies are studied. It is observed that by increasing Pasternak elastic medium coefficients, the natural frequencies of functionally graded piezoelectric materials (FGPM) cylindrical shell always increases. The mode shapes of FGPM cylindrical shell has been shown in this research and the results show that the distribution of the radial displacements is more significant than circumferential and longitudinal displacements.

References listed at the end of the paper:


ABSTRACT: By means of ping-pong balls, the dynamic buckling behaviours of thin-walled spherical shells under impact loading are studied both experimentally and numerically. First, the quasi-static tests were conducted on an MTS tester, in which the ball was compressed onto a PMMA plate. Apart from the force-displacement relationship, the evolution of the contact zone between the ball and the plate was obtained by a digital camera. In the impact tests, ping-pong balls were accelerated by an air-gun and then impinged onto a rigid plate with the velocity ranging 10-45 m/s. The local dynamic buckling processes of the ball were recorded by a high-speed digital camera, from which the impact duration, the maximum contact diameter, as well as the contact diameter at snap-through buckling under different impact velocities were obtained. It is found that with the same size of contact zone, the dynamic energy absorption of the ball is much larger than that in the quasi-static tests. To understand the dynamic effects in the impact process, numerical simulations were performed by using different material properties and different impact velocities. The comparison between the experimental and numerical results show that the kinetic energy absorption of the ball is induced by the strain-rate effect, local vibration of the ball and viscous-elastic effect, respectively.

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ABSTRACT: This paper considers the elastic buckling of rectangular Mindlin plates that are subjected to partially distributed in-plane edge loadings. A numerical algorithm based on the radial point interpolation method (RPIM) is proposed for the solution of such plates. The pre-buckling stresses are first determined using the RPIM based on a two-dimensional (2-D) elastic plane stress problem. The buckling load intensity factors for rectangular plates that incorporate these predetermined pre-buckling stresses are then computed via the RPIM based on the Mindlin plate theory. Numerical examples of the plates with various boundaries and subjected to different partially distributed in-plane edge loadings are presented. Shear-locking of the buckling load is
studied. The results demonstrate the high accuracy of the proposed RPIM.

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ABSTRACT: This paper employs the atomic-scale finite element method (AFEM) to study critical strain of axial buckling for carbon nanotubes (CNTs). Brenner et al. “second-generation” empirical potential is used to model covalent bonds among atoms. The computed energy curve and critical strain for (8, 0) single-walled CNT (SWNT) agree well with molecular dynamics simulations. Both local and global buckling are achieved, two corresponding buckling zones are obtained, and the global buckling behavior of SWNT with a larger aspect ratio approaches gradually to that of a column described by Euler's formula. For double-walled CNTs with smaller ratio of length to outer diameter, the local buckling behavior can be explained by conventional shell theory very well. AFEM is an efficient way to study buckling of CNTs.


ABSTRACT: Carbon nanotubes subject to large deformations reversibly switch into different morphological patterns. Each shape change corresponds to an abrupt release of energy and a singularity in the stress-strain curve. These transformations, simulated using a realistic many-body potential, are explained by a continuum shell model. With properly chosen parameters, the model provides a remarkably accurate “roadmap” of nanotube behavior beyond Hooke's law.

References listed at the end of the paper:
[15] This explains why the detailed calculations [16,17] did not reveal significant effects of helicity on elastic properties; it also

ABSTRACT: Graphene is an ultimate membrane that mixes both flexibility and mechanical strength, together with many other remarkable properties. A good knowledge of the elastic properties of graphene is prerequisite to any practical application of it in nanoscopic devices. Although this two-dimensional material is only one atom thick, continuous-medium elasticity can be applied as long as the deformations vary slowly on the atomic scale and provided suitable parameters are used. The present paper aims to be a critical review on this topic that does not assume a specific pre-knowledge of graphene physics. The basis for the paper is the classical Kirchhoff-Love plate theory. It demands a few parameters that can be addressed from many points of view and fitted to independent experimental data. The parameters can also be estimated by electronic structure calculations. Although coming from diverse backgrounds, most of the available data provide a rather coherent picture that gives a good degree of confidence in the classical description of graphene elasticity. The theory can than be used to estimate, e.g., the buckling limit of graphene bound to a substrate. It can also predict the size above which a scrolled graphene sheet will never spontaneously unroll in free space.

References listed at the end of the paper:
References listed at the end of the paper:


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ABSTRACT: This paper presents the buckling analysis of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) plates under various in-plane mechanical loads, using the element-free kp-Ritz method. The first-order shear deformation plate theory is applied and a set of mesh-free kernel particle functions are used to approximate two-dimensional displacement fields. Effective properties of materials of the plates reinforced by single-walled carbon nanotubes (SWCNTs) are estimated through a micromechanical model based on either the Eshelby–Mori–Tanaka approach or the extended rule of mixture. Comparison study and numerical simulations with various parameters are conducted to assess efficacy and accuracy of the present method for analysis of buckling of SWCNT-reinforced composite plates. Results demonstrate that the change of carbon nanotube volume fraction, plate width-to-thickness ratio, plate aspect ratio, loading condition and temperature have pronounced effects on buckling strength of CNTRC plates as well as the boundary condition. References listed at the end of the paper:


ABSTRACT: This paper investigates the transverse and torsional wave in single- and double-walled carbon nanotubes (SWCNTs and DWCNTs), focusing on the effect of carbon nanotube microstructure on wave dispersion. The SWCNTs and DWCNTs are modeled as nonlocal single and double elastic cylindrical shells. Molecular dynamics (MD) simulations indicate that the wave dispersion predicted by the nonlocal elastic cylindrical shell theory shows good agreement with that of the MD simulations in a wide frequency range up to the terahertz region. The nonlocal elastic shell theory provides a better prediction of the dispersion relationships than the classical shell theory when the wavenumber is large enough for the carbon nanotube microstructure to have a significant influence on the wave dispersion. The nonlocal shell models are required when the wavelengths are approximately less than 2.3x10^-9 and 0.95x10^-9 m for transverse wave in armchair (15,15) SWCNT and torsional wave in armchair (10,10) SWCNT, respectively. Moreover, an MD-based estimation of the scale coefficient ε0 for the nonlocal elastic cylindrical shell model is suggested. Due to the small-scale effects of SWCNTs and the interlayer van der Waals interaction of DWCNTs, the phase difference of the transverse wave in the inner and outer tube can be observed in MD simulations in wave propagation at high frequency. However, the van der Waals interaction has little effect on the phase difference of transverse wave.

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Q. Wang (Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6), “Compressive buckling of carbon nanotubes containing polyethylene molecules”,

ABSTRACT: The instability of a carbon nanotube containing a polyethylene molecule subjected to compression is investigated using molecular dynamics. A decrease up to 35% in the buckling strain of the (6,6) and (10,10) carbon nanotube/polymer structures due to the attractive van der Waals interaction between the tube wall and the polymer molecule is reported. In particular, the decrease in the buckling strain of the (6,6) carbon nanotube/polymer structure is attributed to the initiation of two flattenings on the tube wall. Simulations show that the buckling strain of the structure is insensitive to the number of units of the polymer molecule.

ABSTRACT: The discovery of a buckling instability of a single-walled carbon nanotube wrapped by a polyethylene molecule subjected to compression is reported through molecular mechanics simulations. A decrease up to 44% in the buckling strain of the nano-structure owing to the van der Waals interaction between the two molecules is uncovered. A continuum model is developed to calculate both the interaction between the tube and the polymer and the decreased buckling strain of the structure by fitting the molecular mechanics results.

ABSTRACT: In this study, single-walled carbon nanotubes were generated in their perfect state as finite element models in the MSC.Marc software. The buckling behaviour and resonant frequency modes of the two limiting cases of carbon nanotubes, i.e. the armchair and zigzag models, were studied. The obtained results were compared with the classical analytical solutions related to a similar continuum structure of a hollow cylinder. The buckling behaviour of single-walled carbon nanotubes under cantilever boundary conditions proved to be almost identical to the prediction of the classical Euler equation. Furthermore, there was very good agreement between the analytical and finite element results of the studied single-walled carbon nanotubes; though the achieved value of the first mode of frequency, obtained from the finite element results, was more accurate than the higher modes.

References listed near the end of the paper:
ABSTRACT: The three-dimensional theory of stability of a carbon nanotube (CNT) in a polymer matrix is presented. The results are obtained on the basis of the three-dimensional linearized theory of stability of deformable bodies. Flexural and helical (torsional) buckling modes are considered. It is proved that the helical (torsional) buckling modes occur in a single CNT (the interaction of neighboring CNTs is neglected) and do not occur in nanocomposites (the interaction of neighboring CNTs is taken into account).

ABSTRACT: The results obtained in setting up a theory of stability of fibrous and laminated composites in the case where the plane ? is in an arbitrary position are analyzed. The plane ? is formed by the points of a buckling mode that have equal phases relative to the line of compression. This theory follows from the linearized three-dimensional theory of stability of deformable bodies and is used to determine the critical compressive load and the associated position of the plane ?. Numerical examples are presented. A brief historical sketch is given.

ABSTRACT: This paper reports the elastic buckling behavior of carbon nanotubes. Both axial compression and bending loading conditions are considered. The modeling work employs the molecular structural mechanics approach for individual nanotubes and considers van der Waals interaction in multi-walled nanotubes. The effects of nanotube diameter, aspect ratio, and tube chirality on the buckling force are investigated. Computational results indicate that the buckling force in axial compression is higher than that in bending, and the buckling forces for both compression and bending decrease with the increase in nanotube aspect ratio. The trends of variation of buckling forces with nanotube diameter are similar for single-walled and double-walled carbon nanotubes. Compared to a single-walled nanotube of the same inner diameter, the double-walled carbon nanotube shows a higher axial compressive buckling load, which mainly results from the increase of cross-sectional area, but no enhancement in bending load-bearing capacity. The buckling forces of nanotubes predicted by the continuum beam or column models are significantly different from those predicted by the atomistic model.

ABSTRACT: A meshfree method based on the reproducing kernel particle approximate is employed for the free vibration and buckling analyses of shear-deformable plates. In this approach, the first order Mindlin/Reissner plate theory (FSDT) is used, and the displacement shape functions are constructed using the reproducing kernel approximation satisfying the consistency condition. The essential boundary conditions are enforced by a transformation method. Numerical examples considering various aspect ratios, skew angles and boundary conditions are demonstrated to show the validity of the proposed method, and satisfactory results were obtained when comparisons are made with the exact and other available numerical results existing in the literature.


ABSTRACT: A new atomistic structural model is developed here for graphene sheets based on the stiffnesses from the REBO potential. Using this model, the flexural vibration natural frequencies and buckling loads of rectangular single-layer graphene sheets of different sizes, chiralities and boundary conditions are calculated. The newly developed atomistic structural model is verified by comparing the calculated fundamental natural frequencies for small-sized graphene sheets with those obtained from ab initio density functional theory (DFT) frequency analysis. The vibration and buckling analysis results are also compared with those of an earlier atomistic structural model based on the AMBER potential as well as the equivalent continuum model for graphene sheets. Through this study, it is observed that graphene sheets display very slight anisotropic characteristics in flexural vibration and buckling. Also, it is shown that the atomistic structural model cannot be replaced by a classical equivalent continuum model such as a plate model. Most significantly, we verify that the new atomistic structural model based on the REBO potential predicts more accurate natural frequencies and buckling loads for graphene sheets, which are considerably lower than those predicted by the earlier atomistic structural model based on the AMBER potential.

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ABSTRACT: Explicit formulas are derived for the van der Waals (vdW) interaction between any two layers of a multi-walled carbon nanotube (CNT). Based on the derived formulas, an efficient algorithm is established for the buckling analysis of multi-walled CNTs, in which individual tubes are modeled as a continuum cylindrical shell. The explicit expressions are also derived for the buckling of double-walled CNTs. In previous studies by
Ru (J. Appl. Phys. 87 (2000b) 7227) and Wang et al. (Int. J. Solids Struct. 40 (2003) 3893), only the vdW interaction between adjacent two layers was considered and the vdW interaction between the other two layers was neglected. The vdW interaction coefficient was treated as a constant that was not dependent on the radii of the tubes. However, the formulas derived herein reveal that the vdW interaction coefficients are dependent on the change of interlayer spacing and the radii of the tubes. With the increase of radii, the coefficients approach constants, and the constants between two adjacent layers are about 10% higher than those reported by Wang et al. (Int. J. Solids. Struct. 40 (2003) 3893). In addition, the numerical results show that the vdW interaction will lead to a higher critical buckling load in multi-walled CNTs. The effect of the tube radius on the critical buckling load of a multi-walled CNT is also examined.

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ABSTRACT: Buckling and postbuckling behaviors of multi-walled carbon nanotubes (MWCNTs) under a compressive force are studied. MWCNTs are modeled by Donnell’s shallow shell nonlinear theory with the allowance of van der Waals (vdW) interaction between the walls. It is shown herein that the buckling load decreases while the buckling strain increases as the innermost radius of MWCNT increases. For the postbuckling behavior, the shortening-load curves show an initial steep gradient that gradually level up when the radius of the innermost tube changes from a small value to a large value. However, the deflection-load curves are almost level for various radii of MWCNTs. In addition, the analytical results showed that the shortening-load curves are almost linear but the deflection-load curves are nonlinear and the stability of MWCNTs can be enhanced by adding tubes.

References listed at the end of the paper:
nm are proposed and optimized based on molecular dynamics simulation, in which the second-generation Tersoff-Brenner potential and Lennard-Jones (12-6) potential are used to characterize the intratube interatomic interaction and the intertube van der Waals (vdW) interaction, respectively. Then, a multishell continuum model that is combined with a refined vdW force model is used to carry out the buckling analysis of abnormal MWNTs (including two-, four-, and six-walled MWNTs) and to investigate the effect of the vdW interaction of abnormal MWNTs. The numerical results show that the effect of the vdW interaction is more significant for abnormal MWNTs than for normal MWNTs and that the vdW interaction of abnormal MWNTs cannot be neglected. The critical buckling strains of abnormal MWNTs are greatly enhanced compared with those of normal MWNTs, which suggests that abnormal MWNTs may be excellent candidates as enforced fibers of nanocomposites.


Abstract: This paper investigates size-effects in the torsional response of single walled carbon nanotubes (SWCNTs) by developing a modified nonlocal continuum shell model. The purpose is to facilitate the design of devices based on SWCNT torsion by providing a simple, accurate and efficient continuum model that can predict the corresponding buckling loads. To this end, Eringen’s equations of nonlocal elasticity are incorporated into the classical models for torsion of cylindrical shells given by Timoshenko and Donnell. In contrast to the classical models, the nonlocal model developed here predicts non-dimensional buckling torques that depend on the values of certain geometric parameters of the CNT, allowing for the inclusion of size-effects. Molecular dynamics simulations of torsional buckling are also performed and the results of which are compared with the classical and nonlocal models and used to extract consistent values of shell thickness and the nonlocal elasticity constant (e0). A thickness of 0.85 Å and nonlocal constant values of approximately 0.8 and 0.6 for armchair and zigzag nanotubes respectively are recommended for torsional analysis of SWCNTs using nonlocal shell models. The size-dependent nonlocal models together with molecular dynamics simulations show that classical shell models overestimate the critical buckling torque of SWCNTs and are not suitable for modeling of SWCNTs with diameters smaller than 1.5 nm.


Abstract
An analysis-based approach for developing shell-buckling design criteria for laminated-composite cylindrical shells that accurately accounts for the effects of initial geometric imperfections is presented. With this approach, measured initial geometric imperfection data from six graphite-epoxy shells are used to determine a manufacturing-process-specific imperfection signature for these shells. This imperfection signature is then used as input into nonlinear finite-element analyses. The imperfection signature represents a "first-approximation" mean imperfection shape that is suitable for developing preliminary-design data. Comparisons of test data and analytical results obtained by using several different imperfection shapes are presented for selected shells. Overall, the results indicate that the analysis-based approach presented for developing reliable preliminary-design criteria has the potential to provide improved, less conservative buckling-load estimates, and to reduce the weight and cost of developing buckling-resistant shell structures.

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No.4-5, June, 2002, pp. 723-744.

ABSTRACT: Description of a casting technique for fabricating high-quality plastic structural models, and review of results regarding the use of such specimens to parametrically study the effect of base ring stiffness on the critical buckling pressure of a ring-stiffened conical shell. The fabrication technique involves machining a metal mold to the desired configuration and vacuum-drawing the plastic material into the mold. A room-temperature curing translucent thermoset epoxy was the casting material selected. A shell of revolution computer program which employs a nonlinear axisymmetric prebuckling strain field to obtain a bifurcation buckling solution was used to guide the selection of configurations tested. The shell experimentally exhibited asymmetric collapse behavior, and the ultimate load was considerably higher than the analytical bifurcation prediction. The asymmetric buckling mode shape, however, initially appeared at a pressure near the analysis bifurcation solution.

J. G. Williams and R. C. Davis, “Buckling experiments on stiffened cast-epoxy conical shells A casting technique for manufacturing high-quality shell specimens with complex geometry is described and experimental and theoretical results are presented for a pressure-loaded ring-stiffened conical shell”, Experimental Mechanics, Vol. 15, No. 9, 1975, pp. 329-338, DOI: 10.1007/BF02318873
ABSTRACT: This paper describes a casting technique for fabricating high-quality plastic structural models and presents results on the use of such specimens to parametrically study the effect of base-ring stiffness on the critical buckling pressure of a ring-stiffened conical shell. The fabrication technique involves machining a metal mold to the desired configuration and vacuum drawing the plastic material into the mold. A room-temperature-
curing translucent thermoset epoxy was the casting material selected. The casting technique allows many high-quality specimens to be produced and each specimen is capable of being repeatedly tested without failure. The conical shell was modified for successive tests by machining the epoxy base-ring configuration to reduce its stiffness. A shell-of-revolution computer program which uses a nonlinear axisymmetric prebuckling strain field to obtain a bifurcation-buckling solution was used to guide the selection of configurations tested. The shell experimentally exhibited asymmetric collapse behavior and the ultimate load was considerably higher than the analytical bifurcation prediction. The asymmetric buckling-mode shape, however, initially appeared at a pressure near the analysis-bifurcation solution. Comparison of experimental and analytical prebuckling strains at pressure magnitudes below the initiation of asymmetric collapse showed good agreement.

References listed at the end of the paper:


ABSTRACT: A 3-m-diameter by 3-m-long corrugated cylindrical shell with external stiffening rings was tested to failure by buckling. The corrugation geometry for the graphite-epoxy composite cylinder wall was optimized to withstand a compressive load producing the relatively low maximum load intensity of 157.6 kN/m without buckling. The resulting mass per unit of shell-wall area, including stiffening rings and fasteners, was 1.96 kg/sq m. The cylinder-test load achievement of 101 percent of design ultimate demonstrates a substantial mass-saving potential over available data for corrugated aluminum shell designs. Future space missions will require low-mass structures to achieve maximum payloads. For such structures that must carry compression loads
without buckling, graphite-epoxy materials offer an attractive approach to providing the needed low-mass structural components. Preliminary design studies of lightly loaded shells, using minimum-mass structural-sizing codes, indicate that ring-stiffened graphite-epoxy corrugated shells can, like corrugated graphite epoxy panels offer a mass-saving potential of 20 to 40 percent over aluminum shell-wall design concepts. To evaluate the merits of a corrugated graphite-epoxy cylindrical shell and to develop a design data base for lightweight space structures, a program was initiated to design, fabricate, and test a 3-m-diameter by 3-m-long corrugated ring-stiffened graphite-epoxy cylinder. The preliminary design for the cylinder was generated using a minimum-mass structural-sizing code to carry an ultimate axial-compression loading intensity of 157.6 kN/m. The preliminary design for the shell was modified and verified by testing subcomponent specimens as described. The purpose of this paper is to present the results from the test of the cylinder.


Buckling analysis is carried out in compliance with the French design code RCC-MR. As per this, it is required to determine the critical buckling load multipliers for the various load combinations and ensure that these multipliers should be more than the minimum values specified…..For the theoretical buckling analysis, the computer codes available at Indira Gandhi Centre for Atomic Research such as CAST3M…..From citation given on the website, http://www.ebook2you.net/ebook/shell-buckling-pdf.php


ABSTRACT: Thin aluminum-alloy cylinders were tested under different combinations of torque and circumferentially varying axial thermal stress. The methods of application of the required loads and the measuring techniques employed are discussed. The buckling process is described and interaction curves are presented.

References listed at the end of the paper:
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(2) Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands
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ABSTRACT: The stiffness coefficients of a laminated conical shell, orthotropic, or in some more general mode, are usually assumed to be constant. It is shown that due to the geometry of the conical surface, in connection with the filament winding process necessary to build the laminated conical shell, this can never be achieved. To calculate the varying stiffness coefficients of a laminated conical shell the geometry of the shell and the winding process needed to build the shell must be taken into account. A method to calculate those stiffness coefficients is proposed. The geodesic paths, which are the practical ways to position the fibers, are especially examined. Of course stiffeners can also be placed on these paths. However, other paths are also examined. Stiffeners, for example, can be placed on these paths for optimization purposes. The stiffness coefficients of a laminated conical shell vary always and are functions of the coordinates of the shell. It is shown that by proper filament winding process these functions can be made to be functions of the longitudinal coordinate only.


ABSTRACT: (none given)

References listed at the end of the paper:

ABSTRACT: A finite element model is presented for analyzing the strength and stability of sandwich shells of arbitrary configuration with an adhesion failure zone between the core and one of the facings. The model is based on the assumptions that both facings are laminated Timoshenko-type composite shells, only transverse shear stresses in the core and normal stresses in the thickness direction have nonzero values, a free slip in the tangential plane in the adhesion failure zone and unilateral contact along the normal are possible, and the prebuckling state in the stability problem is linear. Biquadratic nine-node approximations for all functions and numerical integration were used. The displacements and rotation angles of the normals toward the facings as well as stresses in the core are taken as global degrees of freedom. The algebraic problem is solved using a special step-by-step procedure of determining the contact area in the scaling zone and employing unilateral constraints for some of the unknowns. Numerical examples are also given.

References listed at the end of the paper:


ABSTRACT: This paper presents computational models for simulating the behaviour of reinforced concrete structures which exhibit a combination of geometric and material nonlinearity. The nonlinear finite element model is described and methods are presented for the solution of the nonlinear equilibrium equations using arc-length procedures. In order to examine the performance of the finite element model and the solution procedures, examples are presented which involve material and geometric nonlinearity with snap-through and/or snap-back behaviour.

References listed at the end of the paper:


ABSTRACT: We propose a method for investigation of the stability of shells under the action of forces and thermal factors that is based on relations of the geometrically nonlinear theory of elasticity and the moment scheme of finite elements. For the case of uniformly heated restrained cylinders, we demonstrate the efficiency of the method and the validity of the results obtained. We analyze the distinctive features of deformation of the investigated class of shells.

References listed at the end of the paper:


ABSTRACT: (none given)

References:
1. É. I. Grigolyuk and V. V. Kabanov, Shell Stability [in Russian], Nauka, Moscow (1978).

ABSTRACT: Submersible structures consist merely of simple and double curvature thin-walled shells. For this kind of structure, collapse occurs due to the combined nonlinear action of buckling and plasticity of material. Load-carrying capacity may then be assessed mainly by two approaches: experimental investigations and step-by-step numerical procedures. In nonlinear analyses, the results obtained are influenced by the magnitude of the load increment adopted. Solution procedures are then required in order to choose adequate parameters for material failure description as well as elastic nonlinearity. The aim of this paper is to carry out a suitable numerical procedure whose reliability does not depend on the finite-element code adopted.


ABSTRACT: Experiments are carried out into the deformation and stability of a reinforced conical shell in local loading with concentrated forces applied to the ring of the larger base, in both longitudinal and transverse directions. The dependence of the distribution of strains in the shell and critical loads on the number of forces and the conicity node (24 shells were tested) were obtained. Strains in the tested shells were calculated. Comparison of the calculated and experimental results shows that they are in satisfactory agreement.

References listed at the end of the paper:
5. V. V. Novozhilov, Theory of Thin Shells [in Russian], Sudpromgiz, Leningrad (1951).


ABSTRACT: The article explains a method of numerical calculation of the stability of imperfect conical shells with helical reinforcement under uniform external pressure. It also investigates the effect of the amplitude of local initial imperfections on the critical loads.

References listed at the end of the paper:

ABSTRACT: The survey is devoted to problems on the stability and load-carrying capacity of imperfect shells in a nonhomogeneous stress-strain state. Methods recently developed at the Institute of Mechanics (Kiev, Ukraine) are briefly described. The approaches proposed are based on the generalized Euler criterion. Special attention is focused on numerical methods. The stability and load-carrying capacity of shells with symmetric and asymmetric, local and regular imperfections are considered. The data presented are compared with the well-known theoretical results and experimental data. At the end of the review, an analytical method (of reduced stiffness) is presented for predicting the lower bounds of sensitivity to imperfection in elastic buckling of longitudinally compressed stiffened shells with a nearly cylindrical shape.

References listed at the end of the paper:

ABSTRACT: A procedure is proposed whereby critical loads for elastic near-cylindrical shells are determined with the use of equations in terms of displacements. An analytical expression has been derived for the assessment of critical stresses in momentless smooth shells. A contribution of individual components of the total potential energy of such shells to stabilization or destabilization of the strain state is analyzed graphically. Dimensionless critical stresses are assessed with respect to classical ones as determined for ideal cylindrical shells. The data obtained are compared with the known experimental results.
References listed at the end of the paper:

ABSTRACT: The stability of equilibrium of a layered composite circular conical truncated shell loaded with uniform external pressure is investigated. A parametric analysis of the critical pressure intensities is carried out with allowance for the transverse shear, the moment character of the subcritical state of equilibrium, and the subcritical strains.
List of references at the end of the paper:

ABSTRACT: An experimental study into the stability of ribbed cylindrical and conical shells is described. It is shown that when the equivalent rigidity introduced earlier is chosen as an argument in the formula for calculation of the critical stresses at the stage of shell design, this formula has the form of a linear function.

References listed at the end of the paper:

ABSTRACT: The paper proposes a technique for stability analysis of anisotropic laminated thin shells of revolution made of a composite with one plane of symmetry. The technique is used for numerical analysis of truncated cones made of binder-impregnated filaments continuously wound along geodesic lines. It is shown
that the effect of low symmetry on the critical loads depends not only on the number of laminas, but also on the cone angle.

References listed at the end of the paper:


ABSTRACT: The paper outlines a numerical method for stability analysis of cylindrical shells with initial imperfections. We solve a nonlinear buckling problem for a cylindrical shell with variable wall thickness under surface pressure. The imperfections of the shell are modeled as the first buckling mode. A probabilistic approach is used to determine the reliability against buckling of the cylindrical shell with the probability density of initial imperfections represented by uniform distribution, triangular distribution, or Gaussian distribution.

References listed at the end of the paper:
3. Vertical Reservoirs for Oil Storage under a Saturation Vapor Pressure of no Higher than 93.3 kPa [in Ukrainian], Departmental Building Code VBN V.2.2-58.2-94, Derzhkomoftogaz Ukrainy (1994).
References listed at the end of the paper:


ABSTRACT: Results from theoretical and experimental investigations into the nonlinear deformation (geometrical nonlinearity, plastic deformation, creep) and critical states (limit loads, buckling) of shell-frame systems with geometric imperfections are analyzed. The presence of prestresses is allowed. Diverse effects of various geometrical imperfections and plastic deformation for different load histories are studied. New qualitative effects of the mutual influence of these factors are established. Relevant experimental results are outlined.


22. È. I. Grigolyuk and V. V. Kabanov, Shell Stability [in Russian], Nauka, Moscow (1978).


A. Kadir Yavuz and S. Leigh Phoenix (Cornell University), “Buckling stability of adhesively bonded composite

ABSTRACT: A mathematical model is developed for buckling stability of an adhesively bonded composite conical shell system consisting of carbon fiber in a polyimide (PI) matrix. The conical shell is modeled by two orthotropic layers bonded together with a PI adhesive. In-plane compressive and external surface pressure loads are applied. The adhesive layer is modeled by mechanical linear normal and shear springs. The Galerkin method is applied to analyze the buckling stability of the structure as an eigenvalue problem to give critical buckling loads and corresponding mode shapes. Parametric studies are performed to show effects of system parameters on buckling stability of the system.


ABSTRACT: A Donnell type theory is developed for finite deflection of closely stiffened truncated laminated composite conical shells under arbitrary loads by using the variational calculus and smeared-stiffener theory. The most general bending-stretching coupling and the effect of eccentricity of stiffeners are considered. The equilibrium equations, boundary conditions and the equation of compatibility are derived. The new equations of the mixed-type of stiffened laminated composite conical shells are obtained in terms of the transverse deflection and stress function. The simplified equations are also given for some commonly encountered cases.

References listed at the end of the paper:


ABSTRACT: In this paper, based on the mixed-type theory developed by the same authors[11], a theoretical analysis is presented for the stability of laminated composite circular conical shells under external pressure. The
formulas for critical external pressure are obtained by using the potential energy variation principle. Very good agreement is shown between the theoretical prediction of critical external pressure and the experimental data. Finally, the influence of some parameters on critical external pressure is discussed numerically. The mixed-type theory developed by the same authors[1] and the results obtained in this paper are very useful in aerospace engineering design.

References listed at the end of the paper:


ABSTRACT: The results of FEM calculations of stability of thin–walled spherical shells are presented. A static and dynamic stability analysis was conducted. Hemispherical shells and spherical caps with various dilation angles, subjected to external pressure, were considered. For each shell calculated, various boundary conditions of support were analyzed: joint, fixed and elastically fixed support. In the calculations, an axisymmetric and random discretization of the model was accounted for. As a result of the calculations conducted for static loads, values of upper critical pressures and buckling modes of the shells were obtained. The results were presented for various shell thicknesses. The FEM solutions were compared to the available results obtained with analytical and numerical methods, showing a good conformity. Dynamic calculations were conducted for a triangular pulse load. On the basis of the Budiansky–Roth dynamic criterion of stability loss, values of upper dynamic critical pressures were obtained. Shell buckling modes were determined as well.

References listed at the end of the paper:

ABSTRACT: The paper deals with an analysis of the dynamic response of the isotropic conical shell subjected to rectangular or triangular pulse loading. This problem was solved with the Bubnov–Galerkin analytical–numerical method, using a two–parameter function of deflection. In the equations of dynamic equilibrium, an orthotropic material was taken into consideration. Moreover, pressure loading and compression force were included. The solution results were compared with the finite element method, using ANSYS 11.

References listed at the end of the paper:


ABSTRACT: The thin conical and spherical shell structures subjected to pulse loading were considered. The influence of shell geometrical parameters and pulse loading parameters such as its amplitude, direction and duration on the dynamic response was analyzed. The calculations were conducted for two material models: linearly elastic and elastic plastic. To solve the problem of dynamic response of shell structures the ANSYS software based on finite element method was employed.

References listed at the end of the paper:
INTRODUCTION: A thin plate or thin-walled constructions are used in the sports industry, automotive, aerospace and civil engineering. As an example of such structural elements snowboard, skis, poles may be mentioned, as well as all kinds of crane girders, structural components of automobiles (car body sheathing or all longitudinal members), aircraft fuselages and wings, supporting structures of the walls and roofs of large halls and warehouses. All the above structures, as well as many others which can be regarded as a thin, exhaust carrying capacity not by exceeding the allowable stresses but by the stability loss. Therefore, not only critical load but also the postbuckling behaviour of thin-walled structures subjected to static and dynamic load is essential knowledge for designers. The use of more accurate mathematical models allows to explore the phenomena occurring after the loss of stability and to describe more precisely their behaviour. Engineers and designers need guidelines to construct as well as quick and easy software to use for analyse the behaviour of thin-walled structures. Therefore, the author of this chapter decided to explore this issue, propose a mathematical model and the method of analysis of orthotropic thin-walled structures subjected to static and dynamic load.


ABSTRACT: The subject of this monograph is a study of buckling and postbuckling behaviour of thin plates and thin-walled structures with flat walls, subjected to static and dynamic load.

205 References included at the end of the introduction:

On Composite Materials, Gold Coast, Queensland Australia
80. Koiter WT, Pignataro M (1976) A general theory for the interaction between local and overall buckling of stiffened panels. WTHD, Report No. 556, Delft University
93. Koning C, Taub J (1934) Impact buckling of thin bars in the elastic range hinged at both ends. NACA TM 748
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120. Lekhnitskii S (1947) Anisotropnyje plastinki. Moscow—Leningrad
· 137. March H (1942) Buckling of flat plywood plates in compression, shear or combined compression and shear. Forest Products Laboratory Rep. 1316
· 160. Seydel E (1933) The critical shear load of rectangular plate. NACA TM 705
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178. Taub J (1934) Impact buckling of thin bars in the elastic range for any end condition. NACA TM 749
185. Thielemann W (1950) Contributions to the problem of buckling of orthotropic plates with special reference to plywood NACA TM 1263
References listed at the end of the paper:

5. Koiter WT (1976) General theory of mode interaction in stiffened plates and shell structures. WTHD Report 590, Delft University, Netherlands
ABSTRACT: The finite element method is used here to validate the analytical–numerical method presented in Chapter 3 [See the previous entry]. The basic assumption and the used equations for thin plates in both the methods (ANM—the analytical–numerical method, FEM—the finite element method) are identical, but the way of solution is different. To apply a program based on the finite element method as a numerical experiment, confirming or verifying the theoretical analysis or the analysis based on the analytical–numerical method, it is important to create an appropriate model. A properly chosen finite element type, a rational mesh density and appropriate boundary conditions play a significant role in obtaining the calculation results close to the reality. References listed at the end of the paper:
1. ANSYS 11.1 html online documentation, SAS IP, Inc, 2007

ABSTRACT: Dynamic stability, or better, dynamic buckling (sometimes referred to as a dynamic response) means a loss of stability of the structure subjected to pulse load. Especially, it can act along the axis of the column or in the plane of the plate. It should be mentioned that for the ideal uniformy compressed structures (without any geometrical imperfection) the critical buckling amplitude of pulse loading leads to infinity. Therefore, the dynamic buckling can be analysed only for structures with initial geometrical imperfections. In such a case, the critical value of dynamic load does not have a bifurcation character, thus it has to be determined on the basis of the assumed criterion. Some the most popular and some new criterion allowing to determine dynamic buckling is presented in this chapter.

References listed at the end of the paper:
7. Coan JM (1951) Large-deflection theory for plates with small initial curvature loaded in edge compression. ASME J Appl Mech 18:143–151
Tomasz Kubiak, “Thin-walled columns”, Chapter 7 in Static and Dynamic Buckling of Thin-Walled Plate Structures, edited by Tomasz Kubiak, Springer, 2013, pp 141-158

**ABSTRACT:** The chapter deals with static buckling, postbuckling behaviour and dynamic buckling of thin-walled column with open cross-section made of isotropic and orthotropic material. The analysed columns were subjected to compressed load. The results was obtained using finite element method and analytical-numerical method.

References listed at the end of the paper:
8. SAS IP, Inc (2007) ANSYS 11.1 html online documentation


**ABSTRACT:** The results of the dynamic buckling analysis of girders subjected to torsion are presented in this chapter. All the results of numerical calculations to be discussed further were obtained with finite element method commercial software. Girders with square cross-sections and different lengths were considered. A little attention is paid to thin-walled structures with flat wall subjected to bending or torsion. It was therefore decided to fill this gap by conducting an analysis of thin-walled girders with closed cross-section and behaviour of such structures subjected to torsion impulse of finite duration.

References listed at the end of the paper:
7. SAS IP, Inc (2007) ANSYS 11.1 html online documentation

Radoslaw J. Mania (Dept. of Strength of Materials and Structures, Technical University of Lodz, Poland), “Strain-rate effect in dynamic buckling of thin-walled isotropic columns”, Mechanics and Mechanical
ABSTRACT: The aim of this paper is the analysis of strain–rate sensitivity in dynamic stability of thin–walled isotropic columns of closed rectangular cross–section, subjected to in–plane pulse loading of finite duration. The analysis is performed with the FE Method application. The full Lagrange strain tensor is assumed and various material characteristics are applied. The First Shear Deformation Theory displacement field is employed for the solution as well as the viscoplasticity constitutive model for material behavior under high strain rate loading. In the performed analysis the strain–rate effect influence on the dynamic buckling load is examined and also the initial imperfections of walls, pulse shape and pulse duration. The applications of some dynamic criteria are compared as well.

References listed at the end of the paper:
distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRC beam are assumed to be graded in the thickness direction. The SWCNTs are assumed aligned, straight and with a uniform layout. Exact solutions are presented to study the thermal buckling behavior of beams made of a symmetric single-walled carbon nanotube reinforced composite with surface-bonded piezoelectric layers. The critical temperature load is obtained for the nonlinear problem. The effects of the applied actuator voltage, temperature, beam geometry, boundary conditions, and volume fractions of carbon nanotubes on the buckling of piezoelectric CNTRC beams are investigated.


ABSTRACT: During the past few decades, a number of conical tanks have collapsed in various locations around the globe. Previous studies attributed the reason of collapse to inadequate thickness of the conical vessel especially at the bottom part. Most of the previous studies focused on studying the stability of conical tanks under the effect of only hydrostatic pressure. The current study focuses on studying the combined effect of wind loading and hydrostatic pressure on the stability of conical tanks. The study is conducted numerically, using a three-dimensional finite element model that is developed in-house. The critical imperfection shapes leading to minimum buckling capacity of conical shells under wind load alone, and under the combined effect of wind load and hydrostatic pressure, are determined. The study shows that a non-axisymmetric imperfection shape leads to minimum buckling capacity of empty conical tanks subjected to wind loads, while an axisymmetric distribution is noticed in the case of conical tanks under the combined effect of wind loads and hydrostatic pressure. In addition, the current study assesses the adequacy of an existing design procedure, which accounts for hydrostatic pressure, when the combination of hydrostatic pressure and wind load is considered. References listed at the end of the paper:

Doubravka Stredova and Petr Tomek (Department of Mechanics, Materials and Machine Parts, University of Pardubice, Czech Republic), “Experimental model of conical shell under external pressure”, Special Issue 2, Vol. VI, May 2011

ABSTRACT: This article deals with the loss of stability of the experimental model of the conical shell subjected to an external pressure. Experiment with real specimens is based on the numerical analysis, which it was performed in (3). The problem is limited to a case of the simply supported conical shell. The main task is to verify the numerical analysis results and the method of the preparation of the experimental models. Fully nonlinear analysis of the conical shells GMNA is performed in a computer program COSMOS/M based on the Finite Element method (FEM).

References listed at the end of the paper:
(5) FEM Computer program COSMOS/M, version 2.95, (2007).

Petr Tomek (Department of Mechanics, Materials and Machine Parts, University of Pardubice, Czech Republic), “Influence of the initial imperfections on the strength and stability of thin-walled structures”, Ph.D. Dissertation, 2012

PARTIAL SUMMARY: Doctoral dissertation focuses on the influence of initial geometric imperfections on the loss of stability spherical caps stiffened by circumferential ring. Investigated area is limited to simply supported spherical caps with the final stiffness in the radial direction. The described problem is mostly solved by numerical analyses in the environment of program COSMOS/M [5] and CosmosWorks [6]. Verification of the results of numerical analysis performing the experiment is currently still ongoing. Preparation of experiments and the development of the test equipment are described in the doctoral dissertation. First tests of the loss of stability test specimens were performed on the test equipment. [To date] results of the experiments [have been] used to modify test equipment and method of production of test specimens.

References listed at the end of the dissertation:

ABSTRACT: Based on the Von Karman large deflection theory of shallow shell, the problem of nonlinear stability of symmetrically FGM shallow conical shells under the action of mechanical and thermal loads is investigated. The nonlinear governing equation under the united action of mechanical and thermal loads of FGM shallow conical shells whose physical parameters change with the power rate is derived and solved by the modified iteration method. The nonlinear characteristic relation of load, deflection and temperature is obtained. The extremum buckling principle is employed to determine the critical buckling load. The influences of gradient constants, geometric parameters and temperature differences on buckling are discussed as well.

ABSTRACT: An experimental study of repeated buckling of shear panels, which represents the first phase of a more comprehensive program is presented. Two similar typical Wagner beams were tested under cyclic loading not exceeding 70% of the predicted ultimate static load, one tested as a cantilever and one loaded symmetrically at three points. The aim of these pilot tests was better understanding of the physical phenomena and evaluation of the experimental methods for future tests. The appropriate location and precautions for use of strain gages to measure the stress concentrations at the edges of the diagonal of tension were determined, and the suitability of the shadow moire technique for deflection measurements was ascertained. It was found that cyclic loading at a fairly high load level causes significant structural changes in the shear panels that affect the failure of the beam.


ABSTRACT: A method has been developed for analysis of the vibration and buckling of preloaded stiffened cylindrical panels with different boundary conditions along the straight edges, including elastic restraints. In the analysis linear, “smeared” stiffener, Flügge type theory is used. A computer program VIBUPAL has been developed. The method has been verified by comparison with results available for limited cases and very good agreement has been obtained.


ABSTRACT: The measurement of initial geometric imperfections of stringer-stiffened cylindrical shells on a laboratory scale is reviewed and recent results are presented. Buckling loads are predicted by the multimode analysis and are compared with experimental results. The concept and purpose of an international imperfection data bank is outlined and the activity of the Technion branch is described. An evaluation of the characteristics of shells from their measured imperfection record is attempted.

ABSTRACT: Analytical studies with the ADINA computer code were performed to determine the Dynamic Load Amplification Factor (DLF) of metal beams and plates subjected to axial in-plane impact compression loading. The results were compared with experimental ones and those yielded by self developed finite differences programs. The influences of initial geometric imperfections, as well as duration of loading on the DLF were evaluated. As anticipated, the DLFs were usually higher than unity. However, in a few cases, in the presence of certain magnitudes of initial geometric imperfection and for loading durations close to the first natural period in bending, DLFs smaller than unity were observed.


ABSTRACT: The recent developments in shell buckling experiments are surveyed and related to a review of the progress in the seventies. Model fabrication, imperfection measurements, boundary conditions, nondestructive testing, combined loading, postbuckling behavior, composite shells and other aspects of shell buckling tests are discussed. The motivation for experiments and the conclusions drawn in the previous review are reassessed.

References listed at the end of the paper:
66. Singer, J. and Segal, Y.: Direct prediction of the buckling load of stiffened cylindrical shells from vibration tests. TAE Report 405, Technion, Israel Inst. of Technology, Dept. of Aeronautical Eng., (to be published).

ABSTRACT: The vibration-correlation technique, VCT for definition of real boundary conditions, and the method of repeated buckling were employed for nondestructive generation of improved interaction curves for buckling of stringer-stiffened circular-cylindrical shells subjected to a combined axial compression and external-pressure state of loading. Thirteen shells were tested, five on clamped boundary conditions and eight on nominal simple supports. The study also included an assessment of the influence of the order of loading on the behavior of the shells before and at buckling as a result of the nonlinear interaction. It has been shown that the VCT and repeated buckling approach are feasible for closely stiffened shells and are adequate tools for the derivation of more realistic buckling interaction curves. It appears that the sequence of loading, constant axial compression first and then increasing the external pressure until buckling occurs, or the reverse order of loading, does not influence the buckling loads.

References listed at the end of the paper:
ABSTRACT: The role of experiments in buckling and postbuckling studies of structures is examined. The essential elements of the experimental approach are discussed for a simple buckling test — a column under axial compression — and typical modern techniques are enumerated. The theory of modeling and its applications are summarized. The problems of buckling and postbuckling experiments for plates and shells are then discussed in detail, with emphasis on comparison with theoretical results and recent developments like initial imperfection measurements, definition of boundary condition and nondestructive methods.

References listed at the end of the paper:


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65. Grove, T., and Didrikson, T., Buckling experiments on 4 large ring-stiffened cylindrical shells subjected to axial compression and lateral pressure, Det Norske Veritas, Report No. 77-431, 1977.

ABSTRACT: The present experimental study aims at providing better inputs for improvement of the buckling load predictions of stiffened cylindrical shells subjected to combined loading. The work focuses on two main factors which considerably affect the combined buckling load of stiffened shells, namely initial geometric imperfections and boundary conditions. Six shells with nominal simple supports were tested under various combinations of combined loading. The Vibration Correlation Technique (VCT) is employed to define the real boundary conditions. The initial geometric imperfections of the integrally stiffened shells are measured in the present experiments in situ and are used as inputs to a multimode analysis which yields the appropriate “knockdown” factor for various combinations of axial compression and external pressure. Thus when employing the repeated buckling method for obtaining interaction curves, each point on the curve is adjusted (using the multimode analysis) for the measured degradation of the shell and this results in improved interaction curves and reduced experimental scatter. The measured geometrical imperfections of the preloaded shells can also serve as a contribution to International Imperfection Data Bank for future studies on the correlation between the manufacturing method of the shell and its geometric imperfections.

I. Patlashenko and T. Weller (Faculty of Aerospace Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel), “Cubic B-spline collocation method for nonlinear static analysis of panels under mechanical and...

ABSTRACT: This study presents the cubic B-spline collocation method for solution of one- and two-dimensional nonlinear boundary problems, describing the behavior of panels subjected to mechanical and thermal loadings. Snap-through of panels under pressure loading, and nonlinear thermally-induced response of panels are considered. Available results, yielded by other solution methods, were compared with those obtained by the proposed method. The accuracy, as well as efficiency of the present approach are verified.


ABSTRACT: The application of the spline collocation method, using the cubic B-splines technique, was extended to solve two-dimensional problems, and employed to determine the pre- and postbuckling behavior of laminated panels subjected to mechanical and heating induced loadings. Transverse shear deformation effects were included in the analysis. The accuracy of the method was validated and its efficiency and adequacy to solve problems, concerned with moderate and thin-walled (which may experience “shear-locking”) shell type structures under the above types of loadings, were shown. Examples, demonstrating the capability of the method to satisfactorily provide the buckling loads and postbuckling branches of multilayered panels under axial, pressure and uniform heating type loadings, are presented.


ABSTRACT: The buckling and postbuckling behaviors of perfect and imperfect antisymmetrically angle-ply laminated composite plates under uniaxial compression have been studied by perturbation technique which takes deflection as its perturbation parameter.

In this paper, the effects of in-plane boundary conditions, angles, total number of layers and initial geometric imperfection on the postbuckling behavior of laminated plates have been discussed.

References listed at the end of the paper:
References listed at the end of the paper:


Recent developments in shell buckling experiments are reviewed and related to earlier investigations. The motivation for buckling experiments on shells in the era of the digital computer, analysed by the author in two previous reviews, is re-examined and evaluated. The historical development of shell buckling tests is briefly traced and the interaction of theory, experiments and numerical studies in developing better understanding of buckling and postbuckling phenomena is emphasized. Some significant measurement problems are briefly discussed. The role of initial imperfections and their measurement is outlined, as well as the effect of boundary conditions. Nondestructive test methods for shell buckling are briefly mentioned. Finally, areas of shell buckling experimentation that deserve attention in coming years are enumerated.


ABSTRACT: The development of techniques for measuring geometric imperfections is traced from the sixties to the present day. First, the early laboratory experiments that initiated the concepts and developed the basic techniques are outlined. Imperfection measurements of large and full-scale shells are then considered, including those performed in industry. Modern, more sophisticated, semi-automated measurement techniques as well as imperfection data banks are discussed. Finally, a design methodology which includes the correlation of realistic imperfections with manufacturing techniques is outlined, and ways are indicated of inclusion of the relevant imperfection data into design methods.

Josef Singer, Haim Abramovich and Tanchum Weller (Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel), “The prerequisites for an advanced design methodology in shells prone to buckling”, in New approaches to structural mechanics, shells, and biological structures, edited by

ABSTRACT: The performance goals of future aerospace vehicles will require an unprecedented degree of structural efficiency, which can be obtained by an advanced design methodology, often called “high-fidelity analysis”. Such a methodology combines accumulated geometrical, material and loading imperfections and boundary-condition data with the available computer codes. The prerequisite for a successful application of such a high fidelity analysis to shell type structures is the existence of data banks of measured imperfections and data on the effective boundary conditions. These data banks have to be not only extensive, but also well correlated with the relevant manufacturing processes, loading conditions and practical end fixtures. The experimental work on stiffened metal shells that produced the available data banks is briefly reviewed and their present limitations are emphasized. The urgent need for coordinated extensive international efforts by industry and research laboratories to measure imperfections and effective boundary conditions, and correlate them with experimental buckling loads as well as fabrication processes, is emphasized. Nondestructive vibration correlation techniques are also briefly discussed as a means for determining the effective boundary conditions. Finally, assuming that the necessary prerequisites will become available, the consecutive stages of the advanced design methodology are outlined.

References listed at the end of the paper:


ABSTRACT: The present experimental study aims at providing better inputs for improvement of the buckling load predictions of stiffened cylindrical shells subjected to combined loading. The work focuses on two main factors which considerably affect the combined buckling load of stiffened shells, namely geometric imperfections and boundary conditions. Six shells with nominal simple supports were tested under various combinations of axial compression and external pressure. The vibration correlation technique is employed to define the real boundary conditions. The geometric imperfections of the integrally stiffened shells are measured in the present experiments in situ and are used as inputs to a multimode analysis which yields the corresponding “knockdown” factor for various combinations of loading. Thus, when employing the repeated buckling procedure for obtaining interaction curves, each point on the curve is adjusted (using the multimode analysis) for the measured “new” surface of the shell and this results in more realistic interaction curves. The geometrical imperfections of the preloaded shells can also serve as an input to the International Imperfection Data Bank for future studies on the correlation between the manufacturing method of the shell and their geometric imperfections.


ABSTRACT: The dynamic buckling of cylindrical stringer stiffened shells was investigated both numerically and experimentally. A new criterion to define the numerical “dynamic” buckling load was developed yielding consistent results. The ADINA finite element code was applied to simulate the static and dynamic buckling loads of the shells. It was shown numerically that when the period of the applied loading (half-wave sine)
equals half the lowest natural period of the shell, there is a slight drop in the dynamic load amplification factor (DLF). The DLF is defined, as the ratio of the dynamic buckling to the static buckling of the shell. This factor drops below unity, when the ratio of the given sound speed in solids, c, to the velocity developed axially due to the applied dynamic loading, approaches unity. It means that, for this particular loading period, the dynamic buckling load would be lower than the static one. It was shown numerically that the shape of the loading period, half-wave sine, a shape encountered during the tests, as well as the initial geometric imperfections have a great influence on the dynamic buckling of the shells. The relatively simple test set-up design to cause a shell to buckle dynamically did not fulfill our expectations. Although, the process leading to eventually the dynamic buckling of the shell worked properly, still no test results were obtained to form a sound experimental database for this phenomenon. Based on the numerical predictions, correct guidelines were formulated for better test procedures to be applied in future tests, which will be reported in due time.


PARTIAL ABSTRACT: Stiffened shells, and in particular stiffened circular cylindrical shells, are usually very efficient structures that have many applications in civil, aerospace, marine, petrochemical and mechanical engineering...


ABSTRACT: This paper provides a novel approach to the geometrically nonlinear analysis of shells by deriving the geometric stiffness matrix by load perturbing the linear equilibrium equations in their finite element formulation. Rotations are considered as finite, and rigid body motion is elegantly removed to result in pure elastic deformations that enable stress retrieval via linear constitutive relations. Simple three-noded triangular elements that have proven successful in linear analysis will thus transform to powerful nonlinear elements.

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ABSTRACT: The aim of this paper is to present the buckling analysis of a laboratory tested composite panel under axial compression by means of a simple shell finite element that is developed and presented herein. The tests were performed in the Aircraft Structure Laboratory of the Faculty of Aerospace Engineering at the Technion. Buckling is achieved via incremental geometrically nonlinear analysis and monitoring of the tangent stiffness matrix at each increment. The performance of the finite element is further validated by solving a complex multi-snap example from the literature.
ABSTRACT: This paper is concerned with the development of the geometric stiffness matrix of thick shell finite elements for geometrically nonlinear analysis of the Newton type. A linear shell element that is comprised of the constant stress triangular membrane element and the triangular discrete Kirchhoff Mindlin theory (DKMT) plate element is ‘upgraded’ to become a geometrically nonlinear thick shell finite element. Perturbation methods are used to derive the geometric stiffness matrix from the gradient, in global coordinates, of the nodal force vector when stresses are kept fixed. The present approach follows earlier works associated with trusses, space frames and thin shells. It has the advantage of explicitness and clear physical insight. A special procedure, tailored to triangular elements is used to isolate pure rotations to enable stress recovery via linear elastic constitutive relations. Several examples are solved. The results compare well with those available in the literature.


ABSTRACT: The present study deals with "dynamic buckling", where a composite cylindrical shell, which is subjected to an axial impact load, loses its stability once its lateral transient behaviour becomes unbounded in response to the applied impulsive load. Under this type of loading, a structure may survive suddenly applied loads, the amplitudes of which may exceed by many times its static buckling capacity before reaching its critical conditions, provided the loading duration is short enough. Hence, the load intensity is loading duration dependent, where the prescribed loading amplitude determines its maximum safe time of application. In the case under consideration, triggering of "dynamic buckling" is only possible in presence of relatively small lateral initial geometric imperfections, or lateral coupled deformations stemming from the cylinder skin constitutive relations. Instability in these cases results from continuous amplification of either the imperfections or the coupled deformations once they exceed permissible critical arbitrarily prescribed values of stress/strains or deformations. Therefore, definition of "dynamic buckling" is arbitrary and consequently there is no unique criterion as yet for determination of "dynamic buckling", nor guidelines for design of dynamic buckling resistant structures exist. A criterion that lends itself to a rational definition of "dynamic buckling" has been proposed by Budiansky and Hutchinson. It defines simplified means for determination of the critical dynamic loading, and in essence is analogous to ones employed in the definition of static buckling load of an imperfect structure. Thus, it provides means for comparison between static and dynamic buckling loads corresponding to a given structure; however the analogy is incomplete since in the dynamic case the loading and the structural response are time dependent. In light of the above discussion wide range parametric numerical studies have been undertaken in the present study to assess the influence of shell wall configuration and its initial geometrical imperfections on the dynamic buckling capacity and behaviour of thin walled composite shells, as well as on the loading duration of the shell, which in turn also affects the critical load capacity. In performing
these evaluations the Budiansky and Hutchinson criterion has been adopted for determination of the shell critical dynamic load. Cylindrical structures are very sensitive to the presence of initial geometric imperfections. The effect of identical imperfections on dynamic buckling is compared with their influence on static buckling. For this purpose, initial geometric imperfections, the shapes of which correspond to the first static buckling mode of the perfect shell have been employed. The amplitude of this mode is treated as a free parameter in this assessment. Previous theoretical and experimental studies on dynamic buckling of beams and plates have indeed demonstrated that the shorter the duration $n$ of loading, the higher the resistance to dynamic buckling of these structural elements, and significantly higher than the respectively static buckling load, i.e. there exists a dynamic load amplification factor, D.L.F. However, in the neighbourhood of loading durations corresponding to the period of the first natural bending vibration D.L.F.'s smaller than one have been observed, namely the dynamic buckling load is smaller than the static one. Consequently, special attention is given in the present study to the buckling behaviour of cylinders subjected to axial impacts of duration in this particular range.


ABSTRACT: The effective width method that is widely applied for the analysis of isotropic planar stringer-stiffened panels has been extended to laminated composite stringer-stiffened circular cylindrical panels. The approach was modified and adapted to handle curved composite structures. Panels stiffened by blade type stiffeners, J-form stiffeners and T-form stiffeners were considered in the present study. Bending buckling of the stiffeners, their torsional buckling, combined bending and torsion buckling and local buckling of the stringers were accounted for in the investigation. Using the proposed extended effective width method, a MATLAB based software code TEW1 was developed and implemented. To validate this code, predictions obtained by it were compared with experimental results and with finite element calculations. Good agreement between the present proposed method, experiments and finite element simulations was found, thus yielding an efficient, simple to apply and fast engineering code to be used in design and optimization stages.


ABSTRACT: The performances of the air transport sector as a whole have almost reached a stage of leveling off. New breakthrough design concepts and technologies are needed to introduce a new era of air flight. Air transport demands are predicted to double in the next 10 – 15 years and triple in 20 years time. Involved with it, both the European and American aeronautical industries expect an operating cost reduction of 20% in the mean period followed by a further reduction of 50% in the long run [1]. These extreme expectations can be understood and realized based on the actual and future design scenarios of basic aeronautical structures – a laminated composite stringer stiffened panel presented in Figure 1, where the axial compression load vs. end shortening behaviors of such a structure is depicted. This schematic figure summarizes the vision of the COCOMAT consortium [1-2], namely improved material exploitation of laminated composite airframe structures by accurate simulation of postbuckling and collapse. It is only natural to attempt achieving the above expectations by narrowing the large conservative gap traditionally accepted between the ultimate and the collapse load capacities, thus, yielding the future design scenario as depicted in Fig.1. To realize this target, it is necessary to develop the appropriate tools to be able to
correctly predict the behavior of a laminated composite stringer stiffened shell in the deep postbuckling region, at the collapse load, which is characterized by separation between the skin and the stringers, delaminations, crack propagations and matrix failure, as well as to understand its behavior under repeated buckling. During its normal service life, a fuselage, which is composed of many curved laminated composite stringer stiffened panels, may experience a few hundreds of buckling-postbuckling cycles. Although it is well recognized that CFRP stiffened structures are capable of withstanding very deep post-buckling, yielding collapse loads equal to three - four times their buckling load (see for example typical Refs. [4-6]), there exists scarce knowledge in the literature about the effects of repeated buckling on the global behavior of the panels composing such fuselages. The data found in the literature is dealing with simple structures and loadings [7-8]. Very few results are available (for example [9, 20]) on how repeated buckling under combined loading influences the non-linear behavior of aluminum cylindrical shells and CFRP aeronautical panels and their collapse modes, and on how far into the post-buckling region it is possible to increase loading without loosing structural safety.

Therefore, in light of the above, it is the aim of the present manuscript, to contribute to the basic understanding and knowledge of the above topic, by summarizing the experimental and numerical results that were experienced and obtained within the COCOMAT consortium, during the years 2003-2008.

References listed at the end of the paper:
with composite webs bonded to an aluminum alloy frame, whereas the axial compression specimens were “I” and “J” stiffened cocured composite panels. The test results demonstrate that composite stiffened panels are less fatigue sensitive than comparable metal ones. In the shear panels repeated buckling, even when causing extensive damage, does not reduce the residual strength by more than 20 percent. For the axial compression panels no reduction in residual strength was observed. Safe design of stiffened Graphite/Epoxy panels well beyond their initial buckling is therefore feasible. This can lead to more efficient structures.


ABSTRACT: It is well known [1] that non-closely stiffened panels can have considerable postbuckling reserve strength, enabling them to carry loads significantly in excess of their initial buckling load. If appropriately designed, their load carrying capacity will even appreciably exceed that corresponding to an equivalent weight unstiffened shell (i.e. a shell of identical radius and thicker skin and which is also more sensitive to geometrical imperfections). In these shells, initial buckling of their panels takes place in a local mode, i.e. skin buckling between stiffeners, and not in an overall mode, i.e., an Euler or wide column mode. The design of aerospace structures places great emphasis on exploiting the behavior and on mass minimization of such panels to reduce lifecycle costs. An optimum (minimum mass) design approach based on initial buckling, stress or strain, and stiffness constraints, typically yields an idealized structural configuration characterized by almost equal critical loads for local and overall buckling. This, of course, results in little postbuckling strength capacity and susceptibility to premature failure. However, an alternative optimum design approach can be imposed to achieve lower mass designs for a given loading by requiring the initial local buckling to occur considerably below the design load and allowing for the response characteristics known to exist in postbuckled panels [2] i.e. capability to carry loads higher than their initial buckling load. To meet the requirements of low structurally weight, advanced lightweight laminated composite elements are increasingly being introduced into new designs of modern aerospace structures for enhancing both their structural efficiency and performance. In recognition of the numerous advantages that composites offer, there is a steady growth in replacement of metallic components by composite ones in marine structures, ground transportation, robotics, sports and other fields of engineering. Many theoretical and experimental studies have been performed on buckling and postbuckling behavior of flat stiffened composite panels (see for example Refs.3-8). Recently, a wide body of description and detailed data on buckling and postbuckling tests has been compiled [9] (see chaps.12-14). However, studies on cylindrical composite shells and curved stiffened composite panels are still quite scarce (see for example Refs.10-15). Most of them have been discussed in detail in Ref. 9 (see chap. 14). In light of the above discussion, it has been suggested that permitting postbuckling to take place under ultimate load of fuselage structures, i.e. alleviation of design constraints, may provide a means for meeting the objectives for the design of next generation aircraft, where the demand is reduction of weight without prejudice to cost and structural life (see paper Vision 2020 of the European Community). This approach has been undertaken in an experimental study (Improved P0stbuckling SImulation for Design of Fibre COmposite Stiffened Fuselage Structures - POSICOSS project) as a part of an ongoing effort on design of low cost low weight airborne structures initiated by the 5th European Initiative Program. It was aimed at supporting the development of improved, fast and reliable procedures for analysis and simulation of postbuckling behavior of fiber composite stiffened panel of future generation fuselage structures and their design. Within the POSICOSS project, the Technion performed a long test series, on curved laminated composite stringer stiffened panels under axial compression, shear load introduced by torsion and combined axial compression and shear. The buckling and
postbuckling behavior of these panels was recorded till their final collapse. The first part of this test series, dealing with panels PSC1-PSC9 was summarized in Ref. 16. The results of the tests with panels BOX1-BOX4, which deal with two identical panels, combined together by two flat non-stiffened aluminum panels, to form a torsion box,…. 

References listed at the end of the paper:


PARTIAL ABSTRACT: Experimental results on the behavior of nine single panels and of four torsion boxes, each comprising of two stringer-stiffened cylindrical graphite-epoxy composite panels are presented. These were tested under axial compression, torsion, and combined loading. The buckling and postbuckling behavior of these single panels and torsion boxes demonstrated consistent results. Prior to performing the buckling tests, the initial geometric imperfections of the panels and boxes were scanned and recorded. The tests were complemented by finite element calculations, which were performed for each panel and box…


ABSTRACT: Carbon nanotube (CNT)-reinforced polymer composites have attracted great attention due to their exceptionally high strength. Their high strength can be affected by the presence of defects in the nanotubes used as reinforcements in practical nanocomposites. In this article, a new three-phase molecular structural mechanics/finite element (MSM/FE) multiscale model is used to study the effect of CNT vacancy defects on the stability of single-wall (SW) CNT-polymer composites. The nanotube is modeled at the atomistic scale using MSM, whereas the interphase layer and polymer matrix are analyzed by the FE method. The nanotube and polymer matrix are assumed to be bonded by van der Waals interactions based on the Lennard-Jones potential. Here, two of the most commonly used buckling regimes of CNTs, called column and shell buckling, are considered. To study the stability of the nanocomposites, the buckling onset strain is calculated for perfect and defected CNTs in the polymer nanocomposites. The results reveal that the presence of vacancy defects causes a decrease in the axial buckling strain of SWCNT-polymer composites. Meanwhile, this decrease is much more noticeable in the case of the column buckling mode. Also, it is shown that decreasing the CNT diameter causes a reduction in the onset buckling strain of defected nanocomposites. Finally, the role of the interphase layer on the stability behavior of these nanocomposites is discussed. It is concluded that the existence of a more compact layer than the polymer chains coated on the nanotube can enhance drastically the buckling behavior of these nanocomposites (about 35%).

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ABSTRACT: The mechanical stability of conductive, single-walled carbon nanotubes (SWCNTs) under applied electric field and compressive loading is investigated. The distribution of electric charges on the nanotube surface is determined by employing a method based on the classical electrostatic theory. For mechanical stability analysis, a hybrid atomistic-structural element is proposed, which takes into account the nonlinear features of the stability. Nonlinear stability analysis based on an iterative solution procedure is used to determine the buckling force. The coupling between electrical and mechanical models is accomplished by adding Coulomb interactions to the mechanical model. The results show that in the presence of uniform axial electric fields, stability of SWCNTs under compressive axial loading increases. Also, the effects of CNT geometry on the mechanical stability in the presence of electric fields are studied and the dependence of the increase in the stability of the nanotube on length and diameter is shown.

M. Jabbarzadeh, R. Naghdabadi and M. Tahani, “Corotational Lagrangian formulation for elastic and elastic-plastic large deformation analysis using FEM”, Archive of SID, 2006

ABSTRACT: In this paper a corotational Lagrangian finite element method is presented to analyze the geometric and material nonlinearity problems using degenerated shell and solid elements. The formulation is based on the updated Lagrangian conjugate stress and strain tensors with the linear and nonlinear terms to eliminate the approximation of the Cauchy stress in the finite element formulation. Linear work hardening and the Prandtl-Reuss flow rule along with the von-Mises yield criterion are used to model material nonlinearity. To investigate the accuracy and computational efficiency of the formulation some examples in the elastic and elastic-plastic regime are presented. Also, the results obtained from this method are compared with those available using other corotational finite element formulations. (in Arabic)


DOI: 10.1007/s11431-012-4995-2

ABSTRACT: Based on the consistent symmetrizable equilibrated (CSE) corotational formulation, a linear triangular flat thin shell element with 3 nodes and 18° of freedom, constructed by combination of the optimal membrane element and discrete Kirchhoff triangle (DKT) bending plate element, was extended to the geometric nonlinear analysis of thin shells with large rotation and small strain. Through derivation of the consistent tangent stiffness matrix and internal force vector, the corotational nonlinear finite element equations were established. The nonlinear equations were solved by using the Newton-Raphson iteration algorithm combined with an automatic load controlled technology. Three typical case studies, i.e., the slit annular thin plate, top opened hemispherical shell and cylindrical shell, validated the accuracy of the formulation established in this paper.

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ABSTRACT: On the basis of the finite element corotational formulation for geometric nonlinear static analysis of thin shells with large rotation and small strain established before and from the generalized-α time integration algorithm, the energy conserving and decaying algorithms for corotational formulation nonlinear dynamic response analysis of thin shells are established in this paper. Responses are solved by means of a predictor-corrector procedure. In the case of ignoring the structural damping, the conserving or decaying total energy of structure and the controllable numerical damping for high frequency responses can ensure the numerical stability of the algorithm. The inertial parts are linearly interpolated directly in the fixed global coordinate system by using the element nodal displacement in the global coordinate system for obtaining the constant mass matrix, while the elastic parts adopt the corotational formulation. Hence, the whole formulation obtained in this paper is element independent. Through three typical numerical examples, the performances of the algorithm in this paper were compared with those of the classical Newmark and HHT-α algorithms to indicate that the algorithm in this paper could accurately solve nonlinear dynamic responses of thin shells with large displacements and large rotations.
ABSTRACT: The nonlinear static and dynamic response of circular and annular plates under electrostatic, thermal, and combined loading is investigated. The main motivation for the study of these phenomena is providing fundamental insights into the mechanics of micro-electro-mechanical-systems (MEMS). MEMS devices are usually miniaturization of the corresponding macro-scale devices. The basic mechanics of the components of many MEMS devices can be modeled using conventional structural theories. Some of the most used and actively researched MEMS devices - namely pressure sensors and micropumps - use circular or annular diaphragms as principle components. The actuation and sensing principles of these devices are usually electrostatic in nature. Most MEMS devices are required to operate under wide environmental conditions, thus, a study of thermal effects on the performance of these devices is a major design consideration. There exists a wide arsenal of analytic, semi-analytic, and numerical tools for nonlinear analysis of continuous systems. The present work uses different tools for the analysis of different types of problems. The selection of the analysis tools is guided by two principles. The first consideration is that the analysis should reveal the fundamental mechanics and dynamics of the problem rather than simply generating numerical data. The second consideration is numerical efficiency. Guided by the same principles, the basic structural model adopted in this work is the von-Karman plate model. This model captures the basic nonlinear phenomena in the plate with minimal complexity in the equations of motion, thus providing a balance between simplicity and accuracy. We address a wide array of problems for a variety of loading and boundary conditions. We start by analyzing annular plates under static electrostatic loading including the variation of the plate natural frequencies with the applied voltage. We also analyze parametric resonances in plates subjected to sinusoidally varying thermal loads. We investigate the prebuckling and postbuckling static thermal response and the corresponding variation of the natural frequencies. Finally, we close by investigating the problem of a circular plate under a combination of thermal and electrostatic loading. The results of this investigation demonstrate the importance of including nonlinear phenomena in the modeling of MEMS devices both for correct quantitative predictions and for qualitative description of operations.

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In this paper, eight sets of popularly employed benchmark problems are identified and their deflection curves. In most, if not all, of the previous work on finite element formulation and nonlinear solution procedures, results of geometric nonlinear benchmark problems of shells are presented in the form of load-deflection curves. In this paper, eight sets of popularly employed benchmark problems are identified and their...
detailed reference solutions are obtained and tabulated. It is hoped that these solutions will form a convenient basis for subsequent comparison and that the tedious yet inaccurate task of reconstructing data points by graphical measurement of previously reported load-deflection curves can be avoided. Moreover, the relative convergent difficulty of the problems are revealed by the number of load increments and the total number of iterations required by an automatic load incrementation scheme for attaining the converged solutions under the maximum loads.

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ChaoRong Li, Xiaona Zhang and Zexian Cao (Institute of Physics, Chinese Academy of Sciences, Post Office Box 603, 100080 Beijing, China), “Triangular and Fibonacci Number Patterns Driven by Stress on Core/Shell
ABSTRACT: Fibonacci number patterns and triangular patterns with intrinsic defects occur frequently on nonplanar surfaces in nature, particularly in plants. By controlling the geometry and the stress upon cooling, these patterns can be reproduced on the surface of microstructures about 10 micrometers in diameter. Spherules of the Ag core/SiOx shell structure, possessing markedly uniform size and shape, self-assembled into the Fibonacci number patterns (5 by 8 and 13 by 21) or the triangular pattern, depending on the geometry of the primary supporting surface. Under proper geometrical constraints, the patterns developed through self-assembly in order to minimize the total strain energy. This demonstrates that highly ordered microstructures can be prepared simultaneously across large areas by stress engineering.

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ABSTRACT: We use numerical simulations to show how noninteracting hard particles binding to a deformable elastic shell may self-assemble into a variety of linear patterns. This is a result of the nontrivial elastic response to deformations of shells. The morphology of the patterns can be controlled by the mechanical properties of the surface, and can be fine-tuned by varying the binding energy of the particles. We also repeat our calculations for a fully flexible chain and find that the chain conformations follow patterns similar to those formed by the nanoparticles under analogous conditions. We propose a simple way of understanding and sorting the different structures and relate it to the underlying shape transition of the shell. Finally, we discuss the implications of our results.

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ABSTRACT: The current study reports the use of buckling structures as a measure of film elasticity on physisorbed, solid-supported polymer-tethered lipid monolayers consisting of phospholipids and poly(ethylene glycol) (PEG) lipopolymers. These monolayer systems, built using the Langmuir–Blodgett (LB) technique, exhibit buckles over a wide range of lipopolymer concentrations. Systematic quantitative analysis of the buckling structures using epifluorescence microscopy and atomic force microscopy reveals that increased lipopolymer concentrations are associated with higher area fractions of buckling regions. Quantitative analyses of buckling profiles show, furthermore, that enhanced lipopolymer concentrations lead to increased buckling widths without notably altering buckling amplitude. On the basis of these experimentally determined buckling parameters, we are able to derive a metric between elastic properties and buckling structures in the polymer-tethered lipid monolayer system. This is achieved by combining mean-field calculations of elastic properties of polymer-tethered lipid membranes with buckling theory of an Euler column. Our findings are significant because they provide new insight into the fascinating materials properties of polymer-lipid supramolecular assemblies and represent a tool for the characterization of elastic properties in complex biomembrane-mimicking film architectures with buckling structures.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0810443105/DCSupplemental

ABSTRACT: Many natural fruits and vegetables adopt an approximately spheroidal shape and are characterized by their distinct undulating topologies. We demonstrate that various global pattern features can be reproduced by anisotropic stress-driven buckles on spheroidal core/shell systems, which implies that the relevant mechanical forces might provide a template underpinning the topological conformation in some fruits and plants. Three dimensionless parameters, the ratio of effective size/thickness, the ratio of equatorial/polar radii, and the ratio of core/shell moduli, primarily govern the initiation and formation of the patterns. A distinct morphological feature occurs only when these parameters fall within certain ranges: In a prolate spheroid, reticular buckles take over longitudinal ridged patterns when one or more parameters become large. Our results demonstrate that some universal features of fruit/vegetable patterns (e.g., those observed in Korean melons, silk gourds, ribbed pumpkins, striped cavern tomatoes, and cantaloupes, etc.) may be related to the spontaneous buckling from mechanical perspectives, although the more complex biological or biochemical processes are involved at deep levels.

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ABSTRACT: A thin metal film vapor deposited on thick elastomer substrate develops an equi-biaxial compressive stress state when the system is cooled due to the large thermal expansion mismatch between the elastomer and the metal. At a critical stress, the film undergoes buckling into a family of modes with short wavelengths characteristic of a thin plate on a compliant elastic foundation. As the system is further cooled, a highly ordered herringbone pattern has been observed to develop. Here it is shown that the herringbone mode constitutes a minimum energy configuration among a limited set of competing modes.

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ABSTRACT: The wrinkling of a stiff thin film bonded on a soft elastic layer and subjected to an applied or residual compressive stress is investigated in the present paper. A three-dimensional theoretical model is presented to predict the buckling and postbuckling behavior of the film. We obtained the analytical solutions for the critical buckling condition and the postbuckling morphology of the film. The effects of the thicknesses and elastic properties of the film and the soft layer on the characteristic wrinkling wavelength are examined. It is found that the critical wrinkling condition of the thin film is sensitive to the compressibility and thickness of the soft layer, and its wrinkling amplitude depends on the magnitude of the applied or residual in-plane stress. The bonding condition between the soft layer and the rigid substrate has a considerable influence on the buckling of the thin film, and the relative sliding at the interface tends to destabilize the system.

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Xiaoling Zhang (1), Qingduan Meng (1), Qian Yu (1), Liwen Zhang (1) and Yanqiu Lv (2)
“Thermal buckling analysis in InSb focal plane arrays detector”, Journal of Mechanical Science and Technology, Vol. 27, No. 6, pp 1809-1813, June 2013

ABSTRACT: When exploring the buckling mechanism in indium antimonide (InSb) detector, the global square checkerboard buckling pattern reappears in finite element simulation results. The contributions from the three layered materials to the deformations along the Z-direction are systematically analyzed. Analysis of results shows that the buckling deformation originated from the thermal difference between silicon readout integrated circuits (silicon-ROIC) and the intermediate layer directly above. Furthermore, the buckling pattern is determined by indium bumps array. After passing through the 10 μm intermediate layer, the deformation amplitude is significantly reduced from 2.23 μm to 0.24 μm. Afterwards, passing upward through the 10 μm InSb chip, the maximal deformation is further decreased to 0.09 μm.

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ABSTRACT: The English-language dictionary defines wrinkles as “small furrows, ridges, or creases on a normally smooth surface, caused by crumpling, folding, or shrinking”. In this paper we review the scientific aspects of wrinkling and the related phenomenon of buckling. Specifically, we discuss how and why
wrinkles/buckles form in various materials. We also describe several examples from everyday life, which demonstrate that wrinkling or buckling is indeed a commonplace phenomenon that spans a multitude of length scales. We will emphasize that wrinkling is not always a frustrating feature (e.g., wrinkles in human skin), as it can help to assemble new structures, understand important physical phenomena, and even assist in characterizing chief material properties.

References listed at the end of the paper:


We have measured the multi-scale wrinkling that occurs along the edge of torn plastic sheets. The plastic deformations induced by tearing define a new metric on the sheet, which then relaxes elastically. The resultant patterns of wrinkles correspond to a superposition of waves of different wavelengths. Measurements of the variation of the pattern as a function of the distance from the edge reveal a set of transitions, each of which adds a new mode to the cascade. The wavelengths \( \lambda \) in the cascade depend on both a geometrical length scale, \( L_{\text{geo}} \), given by the metric near the
sheet’s margin, and the sheet thickness $t$: $\lambda \propto t^{0.3}L^{0.7}$. This scaling implies vanishingly short geo
wavelengths in the limit $t \to 0$. A possible geometrical origin of this behavior is discussed. Finally, we show that
our measurement and analysis techniques are applicable to the study of some wavy patterns of leaves.
Measurements of metric properties of leaves indicate that some leaves form waves through a spontaneous
wrinkling like that in the plastic sheets, rather than through an explicit three-dimensional construction.

References listed at the end of the paper:

[18] In power spectra of profiles $z(x,y)$, such as in Fig. 3(b), peaks corresponding to higher modes appear less and less well defined.
These modes are not periodic with respect to the lab’s x coordinate but are periodic modulations of the curved base-line formed by the
longer wavelengths, on which they are superimposed. Therefore, we obtain the amplitude of a given mode $A_n$, by comparing two
profiles: The first - the “base line” - is the surface profile at a given y that consists of modes of lower order than $n$ (obtained by
filtering all $i \geq n$ modes out of $z(x)$). The second is the same profile with the nth mode (obtained by filtering out all $i > n$ modes). The
root mean square of distances between the two curves (measured perpendicularly to the local tangent to the “base line”) gives the
amplitude when divided by $\sqrt{2}$.

Reza Ansari, Saeed Rouhi and Ayoub Shahnazari, “Vibrational analysis of single-walled carbon
nanotube/graphene junctions using finite element modeling”, “The European Physical Journal Applied Physics,
Vol. 76, 20402, 2016, DOI: 10.1051/epjap/2016160173

ABSTRACT: Current study concerns the vibrational behavior of single-walled carbon nanotube/graphene
junctions using the finite element method. The effects of different parameters including nanotube and graphene
geometry/boundary conditions on the vibrations of nanotube/graphene junction are investigated. Two types of
junctions are considered. In the first type, the nanotube is connected to one side of graphene, while in the
second type, both sides of the graphene are connected to nanotubes. It is shown that increasing the height-to-
length ratio of graphene results in decreasing the fundamental natural frequency of the junctions. When the
boundary conditions are imposed on the graphene, increasing the radius of carbon nanotube leads to decreasing
the frequency. Moreover, the frequencies of the second type models are larger than those of the first type.

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ABSTRACT: Wafer-scale strained bilayer graphene is demonstrated by employing a silicon nitride (Si$_3$N$_4$) stressor layer. Different magnitudes of compressive stress up to 840 MPa were engineered by adjusting the Si$_3$N$_4$ deposition recipes, and different strain conditions were analyzed using Raman spectroscopy. The strained graphene displayed significant G peak shifts and G peak splitting with 16.2 cm$^{-1}$ and 23.0 cm$^{-1}$ of the G band and two-dimensional band shift, which corresponds to 0.26% of strain. Raman mapping of large regions of the graphene films found that the largest shifts/splitting occurred near the bilayer regions of the graphene films. The significance of our approach lies in the fact that it can be performed in a conventional microfabrication process, i.e., the plasma enhanced chemical vapor deposition system, and thus easily implemented for large scale production.

Qiming Wang and Xuanhe Zhao, “A three-dimensional phase diagram of growth-induced surface instabilities”, Scientific Reports, Vol. 5, 8887, March 2015, DOI: 10.1038/srep08887
ABSTRACT: A variety of fascinating morphological patterns arise on surfaces of growing, developing or aging tissues, organs and microorganism colonies. These patterns can be classified into creases, wrinkles, folds, period-doubles, ridges and delaminated-buckles according to their distinctive topographical characteristics. One universal mechanism for the pattern formation has been long believed to be the mismatch strains between biological layers with different expanding or shrinking rates, which induce mechanical instabilities. However, a general model that accounts for the formation and evolution of these various surface-instability patterns still does not exist. Here, we take biological structures at their current states as thermodynamic systems, treat each
instability pattern as a thermodynamic phase, and construct a unified phase diagram that can quantitatively predict various types of growth-induced surface instabilities. We further validate the phase diagram with our experiments on surface instabilities induced by mismatch strains as well as the reported data on growth-induced instabilities in various biological systems. The predicted wavelengths and amplitudes of various instability patterns match well with our experimental data. It is expected that the unified phase diagram will not only advance the understanding of biological morphogenesis, but also significantly facilitate the design of new materials and structures by rationally harnessing surface instabilities.

References listed at the end of the paper:
References listed at the end of the paper:
ABSTRACT: A large number of authors in the past have concluded that the flow theory of plasticity tends to overestimate significantly the buckling load for many problems of plates and shells in the plastic range, while the deformation theory generally provides much more accurate predictions and is consequently used in practical applications. Following previous numerical studies by the same authors focused on axially compressed cylinders, the present work presents an analytical investigation which comprises the broader and different case of nonproportional loading. The analytical results are discussed and compared with experimental and numerical findings and the reason for the apparent discrepancy on the basis of the so-called “buckling paradox” appears once again to lie in the overconstrained kinematics on the basis of the analytical and numerical approaches present in the literature.
ABSTRACT: Here, we study hierarchy of graphene wrinkles induced by thermal strain engineering and demonstrate that the wrinkling hierarchy can be accounted for by the wrinklon theory. We derive an equation $\lambda = (ky)^{0.5}$, explaining evolution of wrinkling wavelength $\lambda$ with the distance to the edge $y$ observed in our experiment by considering both bending energy and stretching energy of the graphene flakes. The prefactor $k$ in the equation is determined to be about 55nm. Our experimental result indicates that the classical membrane behavior of graphene persists down to about 100nm of the wrinkling wavelength.


ABSTRACT: Wrinkling is a ubiquitous phenomenon in two-dimensional membranes. In particular, in the large-scale growth of graphene on metallic substrates, high densities of wrinkles are commonly observed. Despite their prevalence and potential impact on large-scale graphene electronics, relatively little is known about their structural morphology and electronic properties. Surveying the graphene landscape using atomic force microscopy, we found that wrinkles reach a certain maximum height before folding over. Calculations of the energetics explain the morphological transition and indicate that the tall ripples are collapsed into narrow standing wrinkles by van der Waals forces, analogous to large-diameter nanotubes. Quantum transport calculations show that conductance through these “collapsedwrinkle” structures is limited mainly by a density-of-states bottleneck and by interlayer tunneling across the collapsed bilayer region. Also through systematic measurements across large numbers of devices with wide “foldedwrinkles”, we find a distinct anisotropy in their electrical resistivity, consistent with our transport simulations. These results highlight the coupling between morphology and electronic properties, which has important practical implications for large-scale high-speed graphene electronics.

Dayong Chen (1), Shengqiang Cai (2), Zhigang Suo (2) and Ryan C. Hayward (1)
(1) Department of Polymer Science and Engineering, University of Massachusetts, Amherst
(2) School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts
ABSTRACT: In a soft elastic film compressed on a stiff substrate, creases nucleate at preexisting defects and grow across the surface of the film like channels. Both nucleation and growth are resisted by the surface energy, which we demonstrate by studying creases for elastomers immersed in several environments—air, water, and an aqueous surfactant solution. Measurement of the position where crease channeling is arrested on a gradient thickness film provides a uniquely characterized strain that quantitatively reveals the influence of surface energy, unlike the strain for nucleation, which is highly variable due to the sensitivity to defects. We find that these experimental data agree well with the prediction of a scaling analysis.


ABSTRACT: Soft tissues growing under constraint often form creases. We adopt the model of growth that factors the deformation gradient into a growth tensor and an elastic deformation tensor, and show that the critical conditions for the onset of creases take a remarkably simple form. The critical conditions are illustrated with tubes of tissues growing either inside a rigid shell or outside a rigid core. By comparing the critical conditions for the onset of wrinkles, we show that the creases are the preferred type of instability. Furthermore, deep creases in a tube are simulated by using the finite-element method, and the number of creases in the tube is estimated by minimizing the free energy.


ABSTRACT: As the thinnest atomic membrane, graphene presents an opportunity to combine geometry, elasticity, and electronics at the limits of their validity. We describe the transport and electronic structure in the neighborhood of conical singularities, the elementary excitations of the ubiquitous wrinkled and crumpled graphene. We use a combination of atomistic mechanical simulations, analytical geometry, and transport calculations in curved graphene, and exact diagonalization of the electronic spectrum to calculate the effects of geometry on electronic structure, transport, and mobility in suspended samples, and how the geometry-generated pseudomagnetic and pseudoelectric fields might disrupt Landau quantization.


ABSTRACT: In this paper, the shear wrinkles of a rectangular membrane under the pretension were analyzed firstly. A critical shear distance was then obtained based on the tension field theory. An expression between the wavelength and the amplitude of the membrane wrinkles were developed using the Von Karman large deflection formula. The simulation flow of the membrane wrinkles were also established using the nonlinear post-buckling analytical method. The results indicated that the wrinkle was firstly generated on both sides of the membrane and then extended to the center. The wrinkle amplitude increased with the shear distance increases. The wrinkle formation and expansion were effectively resisted by increasing the initial pretension. Buckling mode of the shear membrane was unstable in the post-buckling process and the secondary buckling phenomenon was obviously observed. The theoretical and numerical results were compared to verify the rationality of the theoretical and simulation results.

Pil J. Yoo, Kahp Y. Suh, Hyewon Kang, and Hong H. Lee (Seoul National University, Korea), “Polymer
ABSTRACT: We report the critical effects the deformational stress from the elastic nature of a confined polymer layer has during the relaxation process on the buckling of thin metal-polymer bilayer systems (less than 100 nm) even above the temperature at which the polymer is in the liquid flow region. In contrast with what is generally believed, the dispersion force does not play a significant role in the buckling. We also find that the final wrinkled waves take on the shape of wormlike islands. The coarsening leading to the island structure is driven by the growth in amplitude of the dominant wave at the expense of less dominant ones.

References listed at the end of the paper:

[14] Equation (2) is valid for initial perturbation of the film or \( h_0 = \alpha x \). The normal component contributing to the stress is given by \( \tau_{xx} \sin^2 \theta \cos^2 \theta x \alpha_\sigma \sin \theta \sigma_0 \), where \( \tan \theta_0 = \alpha / 0 \).


ABSTRACT: Wrinkles occur due to a mechanical instability when sufficient strain is applied to an incompressible thin film attached to a deformable substrate. For wrinkles made with a polymer film supported on a soft elastomer, the amplitude is directly proportional to the wavelength and the square root of the applied strain. This dependence has been confirmed with ideal substrates where the global strain is homogeneously distributed, but the influence of strain inhomogeneity has not been considered previously. We use the contact line wrinkling technique to prepare polystyrene thin films with periodic regions of different wrinkle amplitudes, hence strains, on soft substrates. We find that an inhomogeneously strained surface approaches amplitude homogeneity globally upon the application of sufficiently large strains. We derive relationships to describe this process, providing fundamental knowledge of the wrinkling mechanism.
ABSTRACT: Wrinkling of spherical surfaces represents a promising pathway for the formation of complex hierarchical structures and patterns. Using a swelling-based approach, we demonstrate the relationship between applied compressive stress, radius of curvature, and wrinkle pattern morphology. Surface features with spherical curvature are fabricated on poly(dimethylsiloxane) elastomers and a stiff surface oxide layer is generated using UV–ozone treatment. Swelling of this surface layer with ethanol vapor results in the formation of periodic wrinkles on the spherical caps. The radius of curvature is found to influence the critical wrinkling stress of the system, allowing cap size to independently dictate wrinkle morphology from non-wrinkled caps at small radii, through hexagonal dimple and long ridge structures as the cap radius increases. A similar transition is observed at constant radius by varying the UV–ozone treatment time, which affects the oxide film thickness and composition. The influence of curvature on the critical wrinkling stress is confirmed by modulating the atmospheric concentration of ethanol, and measuring the applied stress for the lowest concentration for which wrinkling occurs.

ABSTRACT: Wrinkled surfaces are ubiquitous in Nature and can be used in a large range of applications such as improved adhesives, microfluidic patterns, or as metrology instruments. Despite wide-ranging applications, existing methods do not permit local pattern control since all existing methods impose extensive compressive strains. In this article, we describe a new process that exploits the local deformation of a soft substrate as it stretches to form an adhesive interface with a thin polymer film. The wrinkle pattern is effectively a measurement of the strain-field created during the adhesion process, which shows a strong dependence on the speed of attachment. We develop simple scaling arguments to describe this velocity dependence and a critical velocity above which wrinkles do not form. Notably, our approach allows us to define the surface pattern “wrinkle-by-wrinkle”, thus permitting the creation of single wrinkles. Intricate patterns on laterally extensive length scales can also be produced by exploiting the shape of the contact line between the film and the substrate. This level of control—the placement of single features of prescribed trajectory—which is not present in any other method of thin film wrinkling, is absolutely necessary for any realistic, scalable application.

ABSTRACT: Osmotically-driven surface buckling is a simple method for introducing controlled micro- and nano-scale topography onto material surfaces. To achieve a fundamental understanding of the buckling process and a library of the equilibrium and kinetically-trapped structures that can be attained, we observe the growth processes of a buckling silicate plate rigidly attached to an elastomeric substrate. The primary variable is the lateral extent of the silicate plate which is shown to dictate the location of buckle initiation, and thus the resulting morphology of the final buckled structure. We present a model to qualitatively describe the radial stress profile within the plate, based on both the diffusion-controlled local osmotic stress and the ability of the plate to transfer this stress to the relatively unconfined region surrounding it. These results and insights provide lessons for controlling the order and arrangement of buckled microstructures.

ABSTRACT: Surface buckling instabilities, particularly wrinkles, are spontaneously occurring surface patterns that can cover large areas and have the potential to modify the adhesion of surfaces in a systematic manner; however, the impact of these wrinkled features is not understood quantitatively. We utilize a novel fabrication process to form aligned wrinkles from polystyrene and polydimethylsiloxane and quantify their adhesion using contact adhesion tests. Wrinkle amplitudes range from 0.3 μm to 11.4 μm and wavelengths range from 6.2 μm to 74.0 μm, and these two parameters are tuned independently. The maximum separation force of a flat cylindrical probe from a wrinkled surface depends non-linearly on the wrinkle geometry, as described by both amplitude and wavelength. Additionally, results are presented for a set of adhesion experiments conducted on single, macroscopic cylinders using small circular flat probes to mimic the contact of individual wrinkles. A simple scaling is presented that incorporates geometric parameters, testing geometry and materials properties to predict the separation force. This relationship is shown to be in good agreement with the experimental data.


ABSTRACT: Wrinkles and strain localized features are observed in many natural systems and are useful surface patterns for a wide range of applications, including optical gratings and microfluidic devices. However, the transition from sinusoidal wrinkles to more complex strain localized features, such as delaminations or folds, is not well understood. In this paper, we investigate the onset of wrinkling and strain localizations in a model system of a glassy polymer film attached to a surface of an elastomeric substrate. We show that careful measurement of feature amplitude as a function of applied strain allows not only the determination of wrinkle, fold, or delamination onset but also allows clear distinction between each type of feature. We observe that amplitude increases discontinuously as delamination occurs; whereas, the amplitude for a fold deviates gradually compared to the amplitude for a nearby wrinkle as a function of applied strain. The folds observed in these experiments have an outward morphology from the surface, in contrast to folds that form into the plane for a film floating on a liquid substrate. A deformation mode map is presented, where the measured critical strain for localization is compared for films with thickness ranging from 5 nm to 180 nm.


http://dx.doi.org/10.2514/6.2007-1818

ABSTRACT: In this study, geometrically non-linear shell element post-buckling analysis was performed to study the wrinkling behavior of creased square membranes under corner loads. To instigate the out-of-plane wrinkle deformation, the finite element meshes were seeded with semi-random geometrical imperfection, and "STATIC,STABILIZE" option was used to stabilize the solution procedure. A pristine membrane and creased membranes with various initial deployment angles were considered. The local and global wrinkle formation was studied as increasing the ratio of corner loads. The effect of load level and the development of separate wrinkles along the crease line were also discussed.

ABSTRACT: In this paper, geometrically non-linear post-buckling analyses were performed to study the effect of sheet thickness on the crease-wrinkle interaction. A square sheet configuration with a single transverse crease was modeled using thin shell elements. The analysis proceeded by initially providing a realistic deployed state of a creased membrane sheet. Then an uneven corner loading was applied to introduce wrinkling. The effects of the induced anisotropy from the crease on the fine-scale detail of the wrinkle evolution, as a function of sheet thickness, loading, and crease deployment angle were systematically investigated.


ABSTRACT: The present paper provides insight into the crease-wrinkle interaction through a numerical analysis of a square sheet configuration, i.e., a thin membrane with small but finite bending stiffness (induced here by the crease). The analysis proceeds by initially providing a realistic deployed state of a creased membrane sheet. Then an uneven corner loading is applied to introduce wrinkling. The effects of the induced anisotropy from the crease on the fine-scale detail of the wrinkle evolution, as a function of crease orientation, loading, and crease deployment angle are presented. Then a brief study is performed by replacing selected crease cases with a seam. The results of the study have ramifications for the surface topology, global static shape, and dynamic response of large, lightly-loaded membranes in gossamer spacecraft.

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ABSTRACT: Within the frame work of the three-dimensional linearized theory of stability of deformable bodies (LTTSDB), the near-surface buckling instability of a system consisting of a half-plane (substrate), a viscoelastic bond layer, and an elastic covering layer is suggested. The equations of the LTTSDB are obtained from the three-dimensional geometrically non linear equations of viscoelasticity theory by using the boundary-form perturbation technique. By employing the Laplace transform, a method for solving the problem is developed. It is supposed that the covering layer has an insignificant initial imperfection. The stability of the system is considered lost if the imperfection starts to increase and grows indefinitely. Numerical results for the critical compressive force and the critical time are presented.

References listed at the end of the paper:

S.D. Akbarov (1) and R. Tekercioglu (2)
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ABSTRACT: The delamination buckling problem for a rectangular plate made of an orthotropic composite material is studied. The plate contains a band crack whose faces have an initial infinitesimal imperfection. The subsequent development of this imperfection due to an external compressive load acting along the crack is studied through the use of the three-dimensional geometrically nonlinear field equations of elasticity theory for anisotropic bodies. A criterion of initial imperfection is used in determining the critical forces. The corresponding boundary-value problems are solved by employing the boundary-form perturbation technique and the FEM. Numerical results for the critical force are presented.

References listed at the end of the paper:

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ABSTRACT: This paper describes the spontaneous formation of patterns of aligned buckles in a thin film of gold deposited on the surface of an elastomer [poly(dimethylsiloxane), PDMS]. The surface of the elastomer is patterned photochemically into areas differing in stiffness and coefficient of thermal expansion. The gold is deposited while the surface of the patterned elastomer is warm (T > 100 °C). On cooling, shrinkage in the elastomer places the gold film under compressive stress. The buckles relieve this compressive stress. The distribution of stresses and buckle patterns is described during the pre- and postbuckling regimes using solutions from calculations describing a model comprising a thin stiff plate resting on a thick elastic foundation.

References listed as footnotes on various pages of the paper:
(7) A footnote.
ABSTRACT: Upon cooling, a thin metal film deposited on compliant elastomer substrate undergoes equibiaxial compression and begins to buckle at a critical stress. As further cooling occurs, a highly ordered herringbone pattern self-assembles. The preference for the herringbone pattern over other potential modes is demonstrated based on minimum energy arguments. Control of the pre-buckling in-plane stress components may be one way to influence the pattern formation, possibly giving rise to a family of unbalanced herringbone modes that links one-dimensional modes with the balanced herringbone mode.

References listed at the end of the paper:

ABSTRACT: An analysis of the stability of squeezing flows between flat plates (consolidation flows) of viscous liquids reinforced by continuous fibres is presented. The ideal linear fibre-reinforced fluid model is used to model the composite as an incompressible Newtonian fluid reinforced with inextensible fibres. The development of small fibre wrinkles initially present in the preimpregnated plies is analysed using linear stability theory. It is shown that when the flows are lubricated by resin rich layers, two perturbation modes are possible. In the first mode, the wrinkles are of the same form throughout the thickness of the sample while in the second mode they vary linearly with distance from the platens. In both cases the stability depends on the normal components of the applied stress. If the only traction acting in addition to hydrostatic pressure is that due to the squeezing force then the first perturbation mode is stable. This prediction is in agreement with experimental results.

doi: 10.1007/s001700200031
ABSTRACT: Wrinkling that occurs in the stamping of tapered square cups and stepped rectangular cups is investigated. A common characteristic of these two types of wrinkling is that the wrinkles are found at the draw wall that is relatively unsupported. In the stamping of a tapered square cup, the effect of process parameters, such as the die gap and blank-holder force, on the occurrence of wrinkling is examined using finite-element simulations. The simulation results show that the larger the die gap, the more severe is the wrinkling, and such wrinkling cannot be suppressed by increasing the blank-holder force. In the analysis of wrinkling that occurred in the stamping of a stepped rectangular cup, an actual production part that has a similar type of geometry was examined. The wrinkles found at the draw wall are attributed to the unbalanced stretching of the sheet metal between the punch head and the step edge. An optimum die design for the purpose of eliminating the wrinkles is determined using finite-element analysis. The good agreement between the simulation results and those observed in the wrinkle-free production part validates the accuracy of the finite-element analysis, and demonstrates the advantage of using finite-element analysis for stamping die design.


ABSTRACT: The clearances between tube and various dies have a significant and complicated influence on the onset of wrinkling during the rotary draw bending process. To study the effect of clearance on wrinkling, a 3D finite element (FE) model of the process for thin-walled rectangular aluminum alloy tube has been built using the explicit code ABAQUS/Explicit and validated by comparing the experiment. Then, simulation and analysis of the process have been carried out based on the model. The influence laws of clearances between tube and various dies on wrinkling have been studied and the reasonable combination of clearances obtained using the combination method of 3D FE simulation and orthogonal experimental design. The results show that with the increase of tube mandrel clearance, \( \Delta c_m \), and tube bending die clearance, \( \Delta c_b \), the wrinkling wave number decreases rapidly, whereas the wrinkling wave height increases sharply. The effects of tube wiper die clearance, \( \Delta c_w \), and tube pressure die clearance, \( \Delta c_p \), on wrinkling are not significant. The reasonable combination of clearances is \( \Delta c_m = 0.15 \text{ mm}, \Delta c_b = 0 \text{ mm}, \Delta c_w = 0 \text{ mm}, \) and \( \Delta c_p = 0 \text{ mm}. \) These achievements are helpful to the design and optimization of the process.


ABSTRACT: An investigation into material wrinkling failure mechanics of conventional metal spinning and the effects of process parameters and material properties are presented in this paper. By developing finite element (FE) models using the Box-Behnken design of experiments, the effects of six key process and material parameters on the start of material wrinkling have been investigated. These key factors include roller feed per pass, feed rate, blank thickness, tool path profile, material Young’s modulus, yield stress and strain hardening exponent. The results of FE simulation are validated by comparing the modelled roller tool forces and spun part end shape with those measured during a spinning experiment. From FE simulations, large residual stresses in the form of bending moments are found to be present in the flange of the blank, induced by the roller contact. It is found that material wrinkling failure begins when a plastic hinge is formed between the roller and the edge of the blank. It is found that both roller feed per pass and feed rate produce the most significant effect on the initiation of wrinkling failure, as they increase the bending stresses causing a plastic hinge to form more rapidly, thus wrinkling to occur more quickly.
ABSTRACT: A new model is proposed to accurately predict the wrinkling and collapse loads of a membrane inflated beam. In this model, the pressure effects are considered and a modified factor is introduced to obtain an accurate prediction. The former is achieved by modifying the pressure-related structural parameters based on elastic small strain considerations, and the modified factor is determined by our test data. Compared with previous models and our test data, the present model, named as shell-membrane model, can accurately predict the wrinkling and collapse loads of membrane inflated beams.

References listed at the end of the paper:

ABSTRACT: The burning of a sheet of cellulose-based material, such as paper or cloth, involves uneven shrinkage which causes wrinkling. We simulate this geometrically complicated phenomenon by modeling the effects of heat transfer, shrinkage and partial ablation on a thin shell. A strain-limitation technique is applied to a two-layer structure of springs arranged as a body-centered square. Although this structure is over-constrained, convergence can be achieved using a new successive fast projection method. We also remesh the shells.
dynamically to deal with the topological changes that occur as regions burn away.


ABSTRACT: Various geometric sizes and helical types (i.e., armchair, zigzag, and chiral) of single-walled carbon nanotubes (CNTs) are considered in molecular dynamics simulations in order to systematically examine the length-to-radius ratio and chirality effects on the buckling mechanism. The buckling strain is getting smaller as the CNT becomes slender for most nanotubes, which implies that the slender nanotubes have lower buckling resistance regardless of the radius of the CNTs. The applicability of the continuum buckling theory, which has been well developed for thin tubes, on predicting the buckling strain of the CNT is also examined. In general, the corresponding buckling strain and buckling type predicted by the continuum buckling theory could agree reasonably well with simulation results except at the transition region due to the competition of two buckling mechanisms.


PARTIAL INTRODUCTION: Since Iijima reported MWCNTs in 1991, CNTs have captured the intensive attention of researchers worldwide due to the combination of their expected structural perfection, small size, low density, high stiffness, high strength, and excellent electronic properties. CNTs have been widely adopted as microscopic probing tips (Dai et al., 1996; Hafner et al., 2001), nanocomposites reinforcements (Bower et al., 1998; Jin et al., 1998), nanotweezers (Kim & Lieber, 1999), and nanoactuators (Baughman et al., 1999; Fennimore et al., 2003) due to their slender and high aspect ratio structures. Meanwhile, nanotubes are also highly susceptible to buckling under compression, which is a structural instability. Once the buckling of CNTs occurs, the load-carrying capability would suddenly reduce and lead to possible catastrophic failure of the nanotubes, which significantly limit the loading strengths of the probing tips and compressive strengths of nanocomposite structures. Even the physical properties such as conductance of carbon nanotube can be influenced by the occurrence of buckling (Postma et al., 2001). Hence, it is crucial to understand the mechanism of nanotube buckling and even predict the onset of buckling in order to improve the nanotube applications. A review of the relevant literature shows that significant studies have employed both experimental (Falvo et al., 1997; Iijima et al., 1996; Thostenson & Chou, 2004; Waters et al., 2004) and theoretical (Ru, 2000; Yakobson & Avouris, 2001) approaches to investigate the bucking behaviors of CNTs.

References listed at the end of the paper:


ABSTRACT: We carry out systematic molecular mechanics (MM) analyses to study the effect of the displacement increment on the critical buckling strain of single-walled carbon nanotubes (SWCNTs) under axial compression. The SWCNT geometric parameters, such as the tube length, diameter, and chirality, are varied in the numerical studies. The results show that the critical buckling strain of the SWCNTs deduced from the atomistic analyses is highly sensitive to the displacement increment used in the numerical simulation, and such an effect is more obvious for tubes with smaller diameters. Therefore, a reasonable compressive displacement increment should be selected in the atomistic simulations in order to obtain the intrinsic values of the critical buckling strain, which is suggested in this paper. The studies in this paper may be used to explain the contradicting results of the critical compressive buckling strains computed by other MM analyses in the literature.


ABSTRACT: The bending buckling behaviors of single-walled carbon nanotubes (SWCNTs) are systematically investigated by using both molecular dynamics (MD) simulation and finite element method (FEM), to analyze the relationships between critical bending buckling curvature, critical buckling strain and nanotube geometry parameters (e.g., tube diameter, length and chirality). The postbuckling shape of SWCNT and the effect of loading boundary conditions are also discussed. The comparison between MD and FEM simulations shows that the continuum shell model provides some useful insights into the bending buckling mechanisms, yet it cannot quantitatively reproduce the bending buckling behavior of SWCNTs, since the continuum model does not account for the geometrical imperfections in the atomic system that are critical to the onset of buckling. Improvements of continuum models are suggested based on the findings.


ABSTRACT: During the general (conventional) molecular mechanics (GMM) simulation of the buckling of single-walled carbon nanotubes (SWCNTs), the load is displacement controlled and the calculated critical buckling strain is very sensitive to the specific displacement increment and convergence threshold chosen in molecular dynamics (MD) simulations, which may have led to the contradictory and diverged results in the previous studies. In this paper, a targeted-molecular mechanics (TMM) simulation method is proposed to study the buckling behavior of SWCNTs under axial compression, bending, and torsion. Comparing with the GMM method, the TMM technique is independent of the displacement increment and thus the solution is converged. The critical buckling strain computed from the TMM is higher than that from the GMM under axial compression and torsion, and the TMM results are similar to the GMM results upon bending. The TMM result
approaches to the intrinsic critical buckling strain of a perfect tube; in addition, the TMM significantly reduces
the computational cost and thus may be more efficient to study larger systems with atomistic simulations.

P. Waters and A.A. Volinsky (Department of Mechanical Engineering, University of South Florida, 4202 E
Fowler Ave ENB118, Tampa, FL, 33620, USA), “Stress and moisture effects on thin film buckling

ABSTRACT: Deposition processes control the properties of thin films; they can also introduce high residual
stresses, which can be relieved by delamination and fracture. Tungsten films with high 1–2 GPa compressive
residual stresses were sputter deposited on top of thin (below 100 nm) copper and diamond-like carbon (DLC)
films. Highly stressed films store large amounts of strain energy. When the strain energy release rate exceeds
the films’ interfacial toughness, delamination occurs. Compressive residual stresses cause film buckling and
debonding, forming open channels. Profiles of the buckling delaminations were used to calculate the films’
interfacial toughness and then were compared to the adhesion results obtained from the superlayer indentation
test. Tests were conducted in both dry and wet environments and a significant drop in film adhesion, up to 100
times was noticed due to the presence of moisture at the film/substrate interface.

References listed at the end of the paper:
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06T104.
ABSTRACT: As instrument technology is needed for rapid determination of the smaller, thinner and lighter specimens, more stringent demands are related to thin films such as micro-electro-mechanical systems (MEMS), dielectric coatings and electronic packaging. Therefore, the requirement for testing platforms for rapidly determine the mechanical properties of thin films is increasing. Buckling of a film/substrate system could offer a variety of applications, ranging from stretchable electronics to micro-nanoscale metrology. In this paper, a fatigue-loading device has been designed to make the cyclic loading available for investigating the cumulative propagation of thin film buckling. The straight side buckling of thin compressed titanium film with the thickness of 50 nm deposited on organic glass substrates is investigated by using an optical microscope. The cumulative buckling propagation under the cyclic loading of a sequence of peak compression with the frequency 1 Hz is recorded by CCD camera. The buckling extension lengths are calculated by digital image measurement technology.

References listed at the end of the paper:


Guoxin Cao (1), Xi Chen (1), Chaorong Li (2), Ailing Ji (3) and Zexian Cao (3)
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ABSTRACT: We investigated the possibility of controlling thin film buckling patterns by varying the substrate curvature and the stress induced therein upon cooling. The numerical and experimental studies are based on a spherical Ag core/SiO2 shell system. For Ag substrates with a relatively larger curvature, the dentlike triangular buckling pattern comes out when the film nominal stress exceeds a critical value. With increasing film stress and/or substrate radius, the labyrinthlike buckling pattern takes over. Both the buckling wavelength and the critical stress increase with the substrate radius.

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ABSTRACT: Wrinkling is a common everyday occurrence. Over the last decade wrinkling in thin films has become an interesting topic. Nearly all studies to date have focused on the underlying physics or how the wrinkles can be used for a specific application. With more and more devices being created from stacked materials, a need for ways to prevent buckling has arisen. In this article we highlight the prevention of wrinkling in nanoscale thin films.

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ABSTRACT: Self-assembled buckling patterns of thin films on compliant substrates have been subjected to extensive studies and shown great promise in micro-fabrication. However, most previous studies were limited to planar substrates, and the study of buckling of films on curved substrates has not received sufficient attention. With the constraining effect from various types of substrate curvature, numerous new types of buckling morphologies may emerge which not only enable true three-dimensional (3D) fabrication of microstructures and microdevices, but also have important implications for the morphogenesis of quite a few natural and biological systems. We review the scientific aspects of elastic buckling of thin films on several representative curved substrates, emphasizing the critical effect of substrate curvature, its interaction with other material/system parameters, ways to control the buckles based on mechanical and physical principles, and bridge them with prospective applications in biology, biomedical engineering, and small-scale fabrication.


ABSTRACT: Space-saving design is a requirement that is encountered in biological systems and the development of modern technological devices alike. Many living organisms dynamically pack their polymer chains, filaments or membranes inside deformable vesicles or soft tissue-like cell walls, chorions and buds.
Surprisingly little is known about morphogenesis due to growth in flexible confinements—perhaps owing to the daunting complexity lying in the nonlinear feedback between packed material and expandable cavity. Here we show by experiments and simulations how geometric and material properties lead to a plethora of morphologies when elastic filaments are growing far beyond the equilibrium size of a flexible thin sheet they are confined in. Depending on friction, sheet flexibility and thickness, we identify four distinct morphological phases emerging from bifurcation and present the corresponding phase diagram. Four order parameters quantifying the transitions between these phases are proposed.


ABSTRACT: A method to simulate orthotropic behaviour in thin shell finite elements is proposed. The approach is based on the transformation of shape function derivatives, resulting in a new orthogonal basis aligned to a specified preferred direction for all elements. This transformation is carried out solely in the undeformed state leaving minimal additional impact on the computational effort expended to simulate orthotropic materials compared to isotropic, resulting in a straightforward and highly efficient implementation. This method is implemented for rotation-free triangular shells using the finite element framework built on the Kirchhoff–Love theory employing subdivision surfaces. The accuracy of this approach is demonstrated using the deformation of a pinched hemispherical shell (with a 18-degree hole) standard benchmark. To showcase the efficiency of this implementation, the wrinkling of orthotropic sheets under shear displacement is analyzed. It is found that orthotropic subdivision shells are able to capture the wrinkling behavior of sheets accurately for coarse meshes without the use of an additional wrinkling model.

References listed at the end of the paper:


ABSTRACT: The details of development of the stiffness matrix for a doubly curved quadrilateral element suited for static and dynamic analysis of laminated anisotropic thin shells of revolution are reported. Expressing the assumed displacement state over the middle surface of the shell as products of one-dimensional first order Hermite polynomials, it is possible to ensure that the displacement state for the assembled set of such elements,
is geometrically admissible. Monotonic convergence of total potential energy is therefore possible as the modelling is successively refined. Systematic evaluation of performance of the element is conducted, considering various examples for which analytical or other solutions are available.

ABSTRACT: Laminated composite sandwich panels are extensively used in many engineering industries. Stability studies are needed to achieve good structural performance with minimum weight. The work presented in this paper deals with the prediction of elastic buckling loads for composite sandwich rectangular panels with a grid core subjected to axial compression. Kirchhoff-Love assumptions are used and each of the edges is considered to be clamped (C) or simply supported(S). The given panel is idealised as a homogeneous orthotropic plate whose equivalent properties are determined based on the given parameters of the panel. The boundary conditions considered are SCSC, CSCS, SCSS, CSSS, CCCS, CCCS and CCSC. Critical buckling loads are obtained using conventional orthotropic plate theory. A large class of $0^\circ/90^\circ/45^\circ/-45^\circ$ lamination schemes leading to quadridirectional, tridirectional and bidirectional T300/N5208 sandwich panels is examined and merit listed from buckling point of view. Results indicate that by proper choice of lamination scheme, very significant increases in buckling loads compared to quasi isotropic case can be obtained when $a/b < 1$ (the lower the value of $a/b$, the higher the gain) and for $a/b > 2$, the corresponding gains are smaller. For $a/b > 3$, having more $45^\circ$ layers is found to be more advantageous from buckling point of view, whereas for $a/b < 0.75$ having more $0^\circ$ layers is more advantageous.

ABSTRACT: Instability of laminated curved composite beams made of repeated sublaminate construction is studied using finite element method. In repeated sublaminate construction, a full laminate is obtained by repeating a basic sublaminate which has a smaller number of plies. This paper deals with the determination of optimum lay-up for buckling by ranking of such composite curved beams (which may be solid or sandwich). For this purpose, use is made of a two-noded, 16 degrees of freedom curved composite beam finite element. The displacements $u$, $v$, $w$ of the element reference axis are expressed in terms of one-dimensional first-order Hermite interpolation polynomials, and line member assumptions are invoked in formulation of the elastic stiffness matrix and geometric stiffness matrix. The nonlinear expressions for the strains, occurring in beams subjected to axial, flexural and torsional loads, are incorporated in a general instability analysis. The computer program developed has been used, after extensive checking for correctness, to obtain optimum orientation scheme of the plies in the sublaminate so as to achieve maximum buckling load for typical curved solid/sandwich composite beams.

ABSTRACT: Fibre-reinforced composite cylindrical panels are a typical subcomponent used in various aerospace structures. Buckling is one of the important modes of failure of such a panel. Repeated sublaminate
construction is often used in practice to reduce manufacturing errors and to produce more damage-tolerant laminates. In this type of construction, the full laminate is obtained by repeating the basic sublaminate, which has a smaller number of plies. This paper deals with the determination of optimum lay-up for buckling by ranking of such fibre-reinforced plastic composite cylindrical panels (which may be solid, sandwich or stiffened) using the finite element method. The particularized form of a four-noded, 48-dof doubly curved quadrilateral laminated anisotropic thin shell finite element is used. The core/stiffener can be a corrugated composite sheet or a regular grid. The computer program developed has been used, after extensive checking for correctness, to obtain the optimum orientation scheme of the plies in the sublaminate so as to achieve maximum buckling load for typical composite cylindrical panels.

ABSTRACT: Buckling of discretely stiffened composite cylindrical panels made of repeated sublaminate construction is studied using a finite element method. In repeated sublaminate construction, a full laminate is obtained by repeating a basic sublaminate, which has a smaller number of plies. This paper deals with the determination of the optimum lay-up for buckling by ranking of such stiffened (longitudinal and hoop) composite cylindrical panels. For this purpose we use the particularized form of a four-noded, 48 degrees of freedom doubly curved quadrilateral thin shell finite element together with a fully compatible two-noded, 16 degrees of freedom composite stiffener element. The computer program developed has been used, after extensive checking for correctness, to obtain an optimum orientation scheme of the plies in the sublaminate so as to achieve maximum buckling load for a specified thickness of typical stiffened composite cylindrical panels.

ABSTRACT: The buckling of plain and discretely stiffened composite axisymmetric shell panels/shells made of repeated sublaminate construction is studied using the finite element method. In repeated sublaminate construction, a full laminate is obtained by repeating a basic sublaminate, which has a smaller number of plies. The optimum design for buckling is obtained by determining the layup sequence of the plies in the sublaminate by ranking, so as to achieve maximum buckling load for a specified thickness. For this purpose, a four-noded 48-dof quadrilateral composite thin shell element, together with fully compatible two-noded 16-dof composite meridional and parallel circle stiffener elements are used.

ABSTRACT: Fibre-reinforced composites are used in many engineering structures with cylindrical panels being a typical component. Buckling is one of the important modes of failure of such a panel. The work presented in this paper deals with optimizing the orientation of plies in a simply supported composite cylindrical panel so as to achieve maximum buckling load. The panel is assumed to be composed of a repeated sublaminate construction. In this type of construction the basic sublaminate has a smaller number of plies, for example, 8, 6, 4 or 2, and the full panel is obtained by repeating the basic sublaminate. Such a construction is used to avoid
manufacturing errors and to produce damage-tolerant panels resulting from maximum splicing of plies. The buckling loads have been found using an energy method, and optimization of ply orientations in the basic sublaminate is achieved by using the ranking technique proposed by Tsai. The following configurations are considered in the paper: (i) solid laminated panel, (ii) sandwich panel, and (iii) stiffened panel. The sandwich or stiffened panel may have sinusoidally corrugated sheet, hat-type corrugated sheet or regular grid as core or stiffener respectively. The computer program developed was first checked for accuracy by comparing with results available in the literature for isotropic and orthotropic cylindrical panels. Then it was used to optimize the ply orientation in the sublaminate for any specified geometry, material, loading and boundary conditions. It was found that significant gains in buckling loads can be had by choosing the optimum lay-up scheme and that quasi-isotropic lay-up in many cases is far from the optimum.


ABSTRACT: Linear bifurcation buckling of FRP axisymmetric shells with fully compatible FRP meridional and hoop stiffeners is studied using the finite element method. Eccentricity of the stiffeners is taken into account. The composite shell and the stiffener are assumed to be made of a repeated sublaminate construction. This type of construction is used in industry to reduce manufacturing errors and to produce more damage-tolerant laminates. In this type of construction, the sublaminate consists of smaller number of plies and the required thickness of the laminate is obtained by repeating the sublaminate many times. This paper deals with the determination of the optimum lay-up scheme in the sublaminate of a composite axisymmetric shell with composite stiffener elements so as to achieve maximum buckling load for a given geometry, loading and boundary conditions using the finite element method. A four-noded, 48-DOF doubly curved quadrilateral laminated anisotropic thin shell finite element with fully compatible two-noded, 16-DOF meridional stiffener elements (MSE) and parallel circle stiffener elements (PCSE) is used. The buckling loads computed for several cases of shells (solid/stiffened) of positive and negative Gaussian curvatures with different applied loads and boundary conditions compare well with existing results in the literature. Subsequently the computer program has been used to find the optimum lay-up scheme of the plies in the sublaminate so as to achieve maximum buckling load for typical composite solid/stiffened shells.


ABSTRACT: The buckling of plain and discretely stiffened composite axisymmetric shell panels/shells made of repeated sublaminate construction is studied using the finite element method. In repeated sublaminate construction, a full laminate is obtained by repeating a basic sublaminate, which has a smaller number of plies. The optimum design for buckling is obtained by determining the layup sequence of the plies in the sublaminate by ranking, so as to achieve maximum buckling load for a specified thickness. For this purpose, a four-noded 48-dof quadrilateral composite thin shell element, together with fully compatible two-noded 16-dof composite meridional and parallel circle stiffener elements are used.

Sijl, Jeroen and Rozendal, Timo and Overvelde, Marlies and Garbin, Valeria and Dollet, Benjamin and Jong, Nico de and Lohse, Detlef and Versluis, Michel (2009) “Shell buckling increases the nonlinear dynamics of
ultrasound contrast agents at low acoustic pressures”. Journal of the Acoustical Society of America, 125 (4). p. 2680. ISSN 0001-4966

PARTIAL ABSTRACT: The key feature of ultrasound contrast agents in distinguishing blood pool and tissue echoes is based on the nonlinear behavior of the bubbles. Here we investigate the nonlinear properties of the shell which lead to an increased nonlinear bubble response, especially at low acoustic pressures. The microbubbles were studied in free space away from the wall using the Brandaris camera coupled to an optical tweezers setup. The microbubble spectroscopy method (Van der Meer et al., JASA, 121, 648, 2007) was employed to characterize BR-14 microbubbles (Bracco, Geneva). For increasing applied pressures the bubble resonance curves become asymmetrical and the frequency of maximum response decreases, up to 50% at a pressure of 25 kPa. It was found that the skewing of the nonlinear resonance curve is the origin of the so-called thresholding behavior below resonance. Traditional bubble models account for a purely elastic shell predict linear behavior, whereas the shell buckling model by Marmottant et al. . . .


ABSTRACT: Contrast-enhanced ultrasound imaging relies on the nonlinear scattering of microbubbles suspended in an ultrasound contrast agent. The bubble dynamics is described by a Rayleigh-Plesset-type equation, and the success of harmonic imaging using contrast agents has always been attributed to the nonlinear behavior predicted by this equation. A surfactant layer of phospholipids stabilizes the microbubbles and it has always been assumed that the visco-elastic properties of the coating lead to an increased stiffness and additional damping of the radial dynamics, hence to a reduction of the nonlinear response of the bubbles. Here we show that the coating material in fact leads to an increased nonlinear bubble response even at low acoustic pressures where the traditional models for coated as well as uncoated bubbles would only predict linear behavior. For a selection of bubbles we show a pronounced skewness of the resonance curve for increasing pressures to be the origin of the ‘threshold’ behavior, where it appears as if the bubbles are activated only at elevated pressures. Another set of bubbles shows a ‘compression-only’ behavior, where the bubbles are observed to efficiently compress, while their expansion is highly reduced. Moreover, the majority of these bubbles display a very strong subharmonic response. The shell-buckling model by Marmottant et al. accounts for buckling and rupture of the shell and captures all of the above cases for a unique set of the shell parameters, the relevant parameter being the phospholipid concentration at the bubble interface.

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ABSTRACT: Subharmonic behavior of coated microbubbles can greatly enhance the contrast in ultrasound imaging. The threshold driving pressure above which subharmonic oscillations are initiated can be calculated from a linearized Rayleigh-Plesset type equation. Earlier experimental studies on a suspension of phospholipid-coated microbubbles showed a lower threshold than predicted from traditional elastic shell models. Here we present an experimental study of the subharmonic behavior of individual BR-14 microbubbles (Bracco Research) with initial radii between 1.6 and 4.8 micro-m. The subharmonic behavior was studied as a function of the amplitude and the frequency of the driving pressure pulse. The radial response of the microbubbles was recorded with the Brandaris ultrahigh-speed camera, while the resulting acoustic response was measured with a calibrated transducer. It is shown that the threshold pressure is minimum near a driving frequency equal to half the resonance frequency of the bubble, as expected. We found a threshold pressure as low as 10 kPa for certain bubble sizes, which can be explained by the shell buckling model proposed by [Marmottant et al., JASA (2005)]. We show that the origin of subharmonic behavior is a result of the discontinuous transition within the bubble shell from the elastic state to the tensionless buckling state.
Marmottant, Phillippe (1), Bouakaz, Ayache (2), Jong, Nico De. (3) and Quilliet, Catherine (4),
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“Buckling resistance of solid shell bubbles under ultrasound”, Journal of the Acoustical Society of America,
Vol. 129, No. 3, pp. 1231-1239, March 2011, DOI: 10.1121/1.3543943
ABSTRACT: Thin solid shell contrast agents bubbles are expected to undergo different volume oscillating
behaviors when the acoustic power is increased: small oscillations when the shell remains spherical, and large
oscillations when the shell buckles. Contrary to bubbles covered with thin lipidic monolayers that buckle as
soon as compressed: the solid shell bubbles resist compression, making the buckling transition abrupt.
Numerical simulations that explicitly incorporate a shell bending modulus give the critical buckling pressure
and post-buckling shape, and show the appearance of a finite number of wrinkles. These findings are
incorporated in a model based on the concept of effective surface tension. This model compares favorably to
experiments when adjusting two main parameters: the buckling tension and the rupture shell tension. The
buckling tension provides a direct estimation of the acoustic pressure threshold at which buckling occurs.

S. J. Britvec (Institute for Mechanics, University of Bundeswehr, Munich, Germany), “Static and dynamic
buckling of complex hyperstatic pin-connected elastic systems”, in Stability and Optimization of Flexible Space
Structures, pp 157-271, 1995
ABSTRACT: In this chapter we consider hyperstatic lattices composed of three-dimensional space elements
such as tetrahedrons, octahedrons, combinations of cubes and tetrahedrons etc., in which each element is made
of light flexible members joined together by hinged or quasi-hinged (hinge-like) connectors at the nodes. By
giving these members appropriate lengths, the lattice may be shaped into any curved three dimensional array of
space elements, as demonstrated in Fig. 3.1.1. Curved three-dimensional arrays of space elements constitute
shell-type geometrical configurations. Lattices and, in general, structures of this type are called reticulated shells.

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“The geometrically nonlinear stability analysis of the composite reticulated spherical shell”, Spatial Structures, 1996-01, doi: CNKI:SUN:KJJG.0.1996.01.000

ABSTRACT: The geometrically nonlinear stability analysis of the composite reticulated spherical shell is studied in this paper by nonlinear finite element method of composite structure. The tangent stiffness matrices of spaal bea

spatial element and "discrete Kirchhoff" shell element are derived, and the nonlinear load-deflection response of the structure is analyzed by the cylindrical arc-length method. Finally taking a composite reticulated spherical shell with 40m span as an example, the load-deflection response, deflection shapes and critical load are studied in details. The comparison of computed results of composite reticulated spherical shell with those of spherical ribbed shell, plain shell and reticulated shell is also studied. Some useful conclusions are obtained.

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ABSTRACT: This paper was based on the design of Space City, Science & Technology City of Shanghai (STCS). The Space City, the shape of which looks like an ovum, is a single-layered reticulated shell, so the buckling problem should be paid attention to. In this paper, Some nonlinear buckling analyses on two arrangements of the structure were used to solve the puzzle of engineers on the stable problems existing in the structure system of STCS. And the results were used to direct the design and construction.


ABSTRACT: Contrary to the usual procedure, a desired state of stress is assumed and that corresponding
funicular shells shape is obtained. The reticulated domes that are developed from these equivalent shells are called Funicular domes. For shallow shells the governing equation is a Poisson's equation and for deep shells the governing equation is a nonlinear partial differential equation. The Boundary Integral Element method is used to obtain the shape of the funicular reticulated domes. Nonlinear analysis is carried out to investigate the snap through buckling and load deformation response. Numerical examples are solved using the program "NLA" developed.

ABSTRACT: The constitutive model of laminated veneer lumber dealing with the creep and suitable for FE modeling was developed, based on the year-long tension and compression tests of laminated veneer lumber. The constitutive model was incorporated into the commercial FE software ABAQUS by developing a user-defined subroutine UMAT. FE models to predict the long-term behaviour of reticulated laminated veneer lumber shells, buckling in particular, were developed. Buckling analysis of single layer reticulated laminated veneer lumber shells with three-directional mesh was conducted. The interdependent relationship between the creep buckling load and the buckling time of the shells was revealed through the analysis, and the safety load against buckling during service life of the shells was defined.

ABSTRACT: This paper aims to achieve analysis and experiment results that relate to mechanics capability and structural parameter of a special saddle shell of revolution. Theoretically speaking, the saddle shell of revolution consists of a toroidal shell and a spherical shell. The shells simultaneous equations can be solved with harmonious terms. Where, the fundamental equations can be solved by asymptotic exponential perturbation method. The equations of special solution can be solved by Hovozhilovs special solution. This new idea is from a study of some existing solutions of the toroidal shell. The results have been proved by compared with some experimental results. The experiments aims to study the effect caused by change of material parameter, or by change of different geometric dimensions of the saddle shell, which include the change of thickness, the change of radius of shell, and the change of ribs. Finally, the accepted product of the saddle shell were reinforced by a toroidal rib has been submitted.

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ABSTRACT: This paper describes the features of the JET shell element, a new thin shell curved finite element, based on Marguerre's theory. The element is quadrilateral with corner nodes only; each node has six degrees of freedom, i.e. three translations and three rotations. We emphasize here the physical aspects rather than the equations and give an explanation of the element, choice, difficulties encountered and their solutions, the resulting element and its capabilities, through various examples in linear, nonlinear and instability analysis.


ABSTRACT: The single-layer latticed cylindrical shell is one of the most widely adopted space-framed structures. In this paper, free vibration properties and dynamic response to horizontal and vertical seismic waves of single-layer latticed cylindrical shells are analyzed by the finite element method using ANSYS software. In the numerical study, where hundreds of cases were analyzed, the parameters considered included rise-span ratio, length-span ratio, surface load and member section size. Moreover, to better define the actual behavior of single-layer latticed shells, the study is focused on the dynamic stress response to both axial forces and bending moments. Based on the numerical results, the effects of the parameters considered on the stresses are discussed and a modified seismic force coefficient method is suggested. In addition, some advice based on these research results is presented to help in the future design of such structures.

References listed at the end of the paper:

ABSTRACT: To analysis progressive collapse behavior of single-layer reticulated shell under severe earthquake, based on spatial fiber beam element failure criteria, a simulation method on progressive collapse of shell is presented, which account of mechanical properties of components after buckling and damage accumulation effect of combine hardening material. And a computation program is developed correspondingly. At last the method and program proves to be applicable by an example.


PARTIAL ABSTRACT: According to the responses of the single-layer reticulated shell under dynamic loads, this study discusses the relationship between the failure model and the corresponding dynamic load parameters…


DOI: 10.1109/RSETE.2011.5964359

ABSTRACT: The collapse model and state judgment of reticulated shell structures is one of the research focuses of spatial structures. With structure double nonlinearity and material failure strain taken into account and based on LS-DYNA software, the collapse processes of three typical reticulated shell structures are simulated in this paper. And different states are defined in the dynamic collapse processes, including dynamic local buckling, dynamic overall buckling and dynamic whole collapse. By the simulation results, collapse model of reticulated shell structures is proposed, and a reference for space structures design and construction is provided.


ABSTRACT: This paper presents the study on failure mechanism of single-layer saddle-curve reticulated shells subjected to severe earthquake. Failure mode of single-layer saddle-curve reticulated shells is illustrated with the consideration of material damage accumulation. The effects of different parameters on failure characteristics of single-layer saddle-curve reticulated shells are discussed. The influence of substructure upon failure behaviors of single-layer saddle-curve reticulated shells is particularly investigated. It is observed that dynamic strength failure is the failure mode of single-layer saddle-curve reticulated shells. The substructure has great influence on failure characteristics of single-layer saddle-curve reticulated shells subjected to the severe earthquake.

References listed at the end of the paper:
ABSTRACT: The purpose of this study is to determine the buckling load of both continuous spherical shells and reticulated spherical shells using the continuum analogy method empirically and numerically. During the non-linear analysis, a post-buckling plateau and the appearance of a dimple in the shell wall identified the buckling load. By applying the theorem of work and energy to the dimple, an empirical formula to predict the buckling load of thin spherical shells was derived then extended to single-layer reticulated shells. It was observed that the buckling load is proportional to the thickness raised to exponential 2.5. Several finite element modeling and simulations using ABAQUS were conducted to validate the results.

References listed at the end of this paper:


**ABSTRACT:** Nonlinear behavior of single-layer squarely-reticulated shallow spherical shells with geometrical imperfections subjected to a central concentrated (joint) load has been studied in this paper. Using the asymptotic iteration method, an analytical characteristic relationship between the non-dimensional load and central deflection is obtained. The resulting asymptotic solution can be used readily to perform the analysis of parameters and predict the buckling critical load. Meanwhile, numerical examples are presented and effects of imperfection factor and boundary conditions on buckling of the structures are discussed. Comparisons with data based on the finite element method show good exactness of the resulting solution.

**References listed at the end of the paper:**


ABSTRACT: The nonlinear dynamical equations are established by using the method of quasi-shells for three-dimensional shallow spherical shells with circular bottom. Displacement mode that meets the boundary conditions of fixed edges is given by using the method of the separate variable. A nonlinear forced vibration equation containing the second and the third order is derived by using the method of Galerkin. The stability of the equilibrium point is studied by using the Floquet exponent.


ABSTRACT: The single-layer spherical reticulated shell is the structure which is sensitive to imperfections. The initial imperfections reducing structural stability included initial curvature and residual stress of element and installation deviation of nodes. The stress-strain curve concerning the residual stress was got by model CRC, the influence of initial curvature was got by the half-sinusoid and the programs about them were programmed by ANSYS secondary exploitation. Then the stochastic imperfections method about installation deviation of nodes was advanced, meanwhile, a new method was put forward for stability of the single-layer spherical reticulated shell. Comparing with the consistent imperfect buckling analysis method, the precision of the new method was higher. So the new method is better to the stability analysis of single-layer spherical reticulated shell.


ABSTRACT: Based on mechanical characteristics of the single layer latticed shell member, two buckling types of structural compression members are summarized. The pre-buckling and post-buckling mechanical behaviors of the member are simulated by different calculating model, and the member calculating model are founded by which the likely buckle-straighten processes of the member and the form-disappear processes of the plastic hinge can be simulated. Numerical computing results indicate that based on the member calculating model presented in this paper, the changes of member mechanical behaviors and the consequent complex changes of structural bearing capacity in the seismic dynamic responses process of single layer latticed shell can be calculate accurately, and the refined simulation of the full-range dynamic response process for single layer latticed shell subject to dynamic excitation are realized.

ABSTRACT: The collapse processes of three typical long-span reticulated shell structures were simulated using nonlinear dynamic finite element analysis under strong seismic excitations. The plastic kinematic hardening model, which considers failure strain, was adopted for simulating steel. Both geometric and contact nonlinearities were considered in this study. The three failure states—i.e., dynamic local buckling, dynamic overall buckling, and whole collapse—were identified in accordance with the analysis results. Taking the Schwedler reticulated shell structure as an example, seismic waves were applied to the structure in three directions. The critical loads were obtained by the incremental dynamic analysis method (IDAM), and some critical state indices were obtained according to the dynamic responses. The results showed that all the critical indices need to be considered simultaneously in order to judge the dynamic collapse states.


ABSTRACT: Thin spherical shells usually fail due to buckling. An empirical equation to predict their buckling load is derived based on the theorem of work done and energy released in the inversion of a section of a shell and nonlinear finite element (FE) modeling done using ABAQUS to determine their post-buckling behavior. It is observed that the initial buckling is sensitive to initial geometrical imperfections but the post-buckling load is little influenced. Therefore, the post-buckling load is used to predict a more realistic load as compared to classical buckling theory prediction.

References listed at the end of the paper:

ABSTRACT: The critical load of structures sensitive to initial imperfections may be considerably less than the classical buckling load. A method to evaluate the critical load of reticulated shells with rigid joints based on Koiter's general post-buckling theory is introduced. The use of generalized strain-displacement relationships and vector algebra leads to a polynomial representation of the static, buckling and post-buckling equation. As a result, the numerical solution is simplified and consists of solution of systems of linear equations and an eigenvalue problem. The slope of the post-buckling curve is obtained by the aid of which the critical load is computed.

References listed at the end of the paper:


ABSTRACT: In order to produce efficient, reliable design and to avoid unexpected catastrophic failure of structures, the engineer must understand the behaviour of buckling of large span reticulated shell structures. The function and the feature of the Code DDJTJQ, which is a computer program for static and buckling analysis of complex structures using finite element method, and the Code PPTJQ, which is a pre-post processing of DDJTJQ, are briefly introduced. The system has been implemented on microcomputers. An engineering structure, whose thin plate, thin shell and beam are important components, with 2965 degrees of freedom and 655 max. semi-bendwidth is analyzed. The numerical results of global buckling of reticulated shell structure of Jinan Zoo which was designed by Jinan Architectural Designing and Research Institute are given.

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3 Yin Siming, Hu Ying shan, Liu Xu Dong Shaoyun (Architectural Explore and Design Institute of Panzhihua, Sichuan Province 617000); Structural Design And Studies On A Several Prestressed Steel Mesh Roof Of A Sports Centre [J]; INDUSTRIAL CONSTRUCTION; 1998-07
4 Wu Yi; Shen Shizhao; Chen Xin; Nonlinear Stability Analysis of Single Layer Ellipse Parabolic Reticulated Shell[ J]; Journal Of Harbin University Of Civil Engineering And Architecture; 1999-04
ABSTRACT: The influence of eccentric discharge of stored solids in squat silos has been highly valued by many researchers. However, calculation method of lateral pressure under eccentric flowing still needs to be deeply studied. In particular, the lateral pressure distribution on vertical wall could not be accurately recognized mainly because of its asymmetry. In order to build mechanical model of lateral pressure, flow channel and flow pattern of stored solids in squat silo are studied. In this passage, based on Janssen's theory, the method for calculating lateral static pressure in squat silos after eccentric discharge is proposed. Calculative formulae are deduced for each of three possible cases. This method is also focusing on unsymmetrical distribution characteristic of silo wall normal pressure. Finite element model is used to analysis and compare the results of lateral pressure and the numerical results illustrate the practicability of the theoretical method.


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ABSTRACT: The final form of tubular nanofibres produced by the co-electrospinning of two solutions (core/shell) is largely determined by the kinetics governing the buckling phenomenon. The buckling mechanism involves the evaporation of the core solution through a solidified shell resulting in a pressure difference across the fibre shell. Buckling can take place when the pressure drop across the fibre shell exceeds a critical value. In this work the physical conditions leading to fibre buckling are analysed from a kinetic point of view. A time interval, $\Delta t$, during which buckling may occur, is introduced as a single criterion determining the buckling probability. Different core/shell systems were spun by varying the surface tension, viscosity, flow rate, electric field and the diffusion coefficient of the core solvent through the fibre shell. The imaged as-spun nanofibres were analysed statistically to determine the buckling probability, and the corresponding $\Delta t$ values were calculated using the values of the spinning parameters. The obtained data were fitted with an exponential distribution function which afforded determination of the characteristic time to buckling, $t_b$. The results provide a means of predicting the buckling of tubular nanofibres. In particular, one can conclude that the dominant parameter determining the final form of the as-spun tubular nanofibres is the diffusion coefficient of the core solvent through the fibre shell.


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DOI: 10.1016/j.finel.2011.03.014
ABSTRACT: This paper presents a formulation for analysis of thin elastic membranes using a rotation-free shell element within an explicit time integration strategy. The applications presented are isotropic/anisotropic rectangular membranes under shear forces and fabric drapes falling over a pedestal. Results are compared with other numerical results existing in the literature.

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ABSTRACT: The implementation of equilibrium and compatibility conditions along discontinuities in the geometry of thin shells is considered for finite element displacement formulations in which the displacements and their first derivatives are specified as generalised coordinates. A method is proposed in which the transformations of generalised coordinates affect only the element stiffness matrix. Applied to the solution of a
rotationally symmetric shell with discontinuities in the geometric curvature the method is shown to eliminate the numerical disturbances that can otherwise occur in the solution.

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ABSTRACT: The elastic stability of shells or shell-like structures under two independent load parameters is considered. One of the loads is associated to a limit point form of buckling, whereas the second is a bifurcation. A simple one degree of freedom mechanical system is first investigated, for which an analytical solution is possible. Next, a cylindrical shell under the combined action of axial load and localised lateral pressure is studied via a non linear, two-dimensional, finite element discretization. It is shown that both problems display the same general behaviour, with a stability boundary in the load space which is convex towards the region of stability. The results show the need of performing a full non-linear analysis to evaluate the stability boundary for the class of interaction problems considered.

ABSTRACT: A study is presented of the elastic buckling of pressurized complex shells of revolution which are formed by the intersection of cylindrical with spherical or conical shells. The studies are based on the general theory of elastic stability using an asymptotic approximation to the secondary path. An axisymmetric finite element is used for the discretization of the shell. First, the behaviour of the individual components is presented for simply supported and clamped boundary conditions. Next, the complex shells are investigated in terms of the buckling load, the meridional and circumferential shape of the buckling mode, and the initial characteristics of the post-buckling path. The results show that the bifurcation loads of complex shells are lower than those of the individual components; but the post-critical path does not decrease as severely as in the isolated shells.

ABSTRACT: Dynamic instability of simple one-degree-of-freedom systems is studied under two loading parameters: lambda1, associated to a static load, and lambda2, which represents a dynamic load. Two models are considered which correspond to quadratic and cubic non-linearities. The static buckling response of the system shows unstable post-buckling behaviour (bifurcation for lambda2 and limit point for lambda2). Three forms of dynamic load lambda2 are studied: a step, a rectangular and an impulsive loading. The results are represented in terms of interaction curves, which show the relation between the parameters that lead to a critical state. An equivalent problem is also studied to allow for a generalization of the results to arbitrary dynamic
loads of finite duration.

Luis A. Godoy, Genock Portela, Eduardo M. Sosa, Luis E. Suarez, Juan C. Virella, and Raúl Zapata (Department of Civil Engineering and Surveying University of Puerto Rico, Mayaguez, PR 00681-9041, Puerto Rico), “Damage due to buckling in aboveground storage tanks” (publisher not given, date not given in the pdf file. Most recent citation is dated 2001) ABSTRACT: The damage due to buckling in thin-walled, short cylindrical aboveground tanks is discussed in this paper. Various sources of buckling are considered, including wind, earthquake, support settlement and vacuum during emptying of the tank. In all cases the tanks were modeled using finite elements, and the results include the buckling load and associated buckling mode, and the postbuckling equilibrium path. The results have been obtained using the computer packages ABAQUS and ALGOR. Experiments on flexible small-scale tanks with settlement of the supports on a sector of the foundation were conducted. Also, wind tunnel tests were carried out on rigid tanks with and without a roof to evaluate the pressure distribution due to wind. References listed at the end of the paper:

ABSTRACT: The main equations for the equilibrium, stability and critical state analysis of discrete elastic systems are presented following the works of Thompson, but in such a way that the original set of generalized coordinates and loads are preserved in the Total Potential Energy. This introduces differences in the resulting equations in bifurcation analysis but does not introduce any new feature regarding the physics of the problem. The new formulation is approximated by means of a standard finite element approach based on interpolation of displacements, in which the derivatives of the potential energy are approximated. The terms retained are those of moderately large rotation theory. The energy analysis is finally related to the more conventional finite element notation in terms of stiffness matrices, and it is shown how in such a way it can be included in present day codes.

ABSTRACT: The general theory developed in Part 1 of this paper for the finite element stability analysis of structural systems, using perturbation expansions in the vicinity of a critical point, is applied here to the analysis of shells of revolution. The discretization of the shell is performed by means of a semianalytical approximation, and the matrices required for the evaluation of critical points and postcritical equilibrium paths are obtained. Two cases are presented: bifurcation in axisymmetric and in asymmetric buckling modes. The derivatives required for an imperfection analysis are also obtained. A technique of switching between two paths using continuation methods is also discussed, in which the switch is performed using derivatives of the perturbation expansion. Results are presented for bifurcation in axisymmetric and in non-axisymmetric modes, and compared with known solutions or with results from changing the path using continuation methods; good correlation is shown. For structures displaying unstable bifurcation, the influence of load and geometric imperfections is evaluated.


ABSTRACT: The equations that define the load equivalent to an imperfection in the geometry (in the form of a deviation from the as-designed midsurface) of a thin shallow shell are considered. The present formulation defines initial displacements and an initial strain field in order to model the imperfection. It is assumed that deviations involve only initial displacements in the out-of-plane direction. Nonlinear terms in displacements due to the loads are neglected. The complete displacement field is introduced into the equilibrium equations to isolate the equivalent load. It is shown that the complete equivalent load obtained in this way differs from the simplified one employed in the literature due to the presence of nonlinear terms in the initial displacements. (The simplified load is the product of the membrane stress resultants multiplied by the error in geometric curvature of the shell.) An example illustrates the differences of stress resultants obtained from these linear and nonlinear approximations.


ABSTRACT: This paper presents a convenient formulation for the stability analysis of structures using the finite element method. The main assumptions are linear elasticity, a linear fundamental path, and the existence of distinct critical loads (i.e. no coupling between buckling modes occurs). The formulation developed is known as W-formulation, in which the energy is written in terms of a sliding set of incremental coordinates measured with respect to the fundamental path. In the presentation developed here, the only ingredients required to carry out the analysis are the strain-displacement and the constitutive matrices at the element level. The present formulation is compared with the so called V-formulation, in which the displacements refer to the unloaded state. It is shown that under the present assumptions of linear fundamental path, the advantages of the V-formulation are lost and both approaches are similar. An example of a circular plate under in-plane loading
illustrates the procedures. Part II of this paper deals with the application to the post buckling analysis of plate assemblies made of composite materials.


ABSTRACT: In a companion paper the authors presented a convenient formulation for the stability analysis of structures using the finite element method. The main assumptions are linear elasticity, a linear fundamental path and the existence of distinct critical loads. The formulation developed is known as the W-formulation, where the energy is written in terms of a sliding set of incremental coordinates measured with respect to the fundamental path. In the present paper a number of applications of finite elements for post-buckling analysis on composite plate assemblies are presented. Thin-walled composite plates, I-beams, angle sections, and a specially designed box-beam with flanges (unicolumn) are studied in post-buckling when axially loaded. The results are in good agreement with previous studies. Moreover, a parametric study involving critical buckling load and geometry is presented for the case of the unicolumn.

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ABSTRACT: An analytical approximate model, leading to a closed form solution, is presented to account for buckling mode interaction in composite I section columns. Three buckling modes are considered in the analysis: a global mode (Euler mode about the weak axis); a primary local mode (rotation of the flanges and bending of the web); and a secondary local mode (bending of the flanges), which are modeled using analytical functions and four degrees of freedom. The fundamental state is shown to be linear and the three critical states for the isolated modes are found to be stable symmetric bifurcations. Mode interaction analysis in terms of the amplitudes of first order fields is carried out, for the first time, for prismatic sections of composite material. The tertiary (coupled) path involves coupling between the two local modes and it describes the sensitivity to imperfections of the buckling behavior of the composite column. A salient feature of the model presented is the closed form of the resulting solution, which enables the designer to easily perform parametric studies. Also, this is the first buckling mode interaction study for thin-walled composite columns. Numerical examples are presented to validate the results and to show the influence of the geometry and properties of the composite on the interaction phenomenon.

References listed at the end of the paper:

ABSTRACT: In a companion paper the authors presented a convenient formulation for the stability analysis of structures using the finite element method. The main assumptions are linear elasticity, a linear fundamental path and the existence of distinct critical loads. The formulation developed is known as the W-formulation, where the energy is written in terms of a sliding set of incremental coordinates measured with respect to the fundamental path. In the present paper a number of applications of finite elements for post-buckling analysis on composite plate assemblies are presented. Thin-walled composite plates, I-beams, angle sections, and a specially designed box-beam with flanges (unicolon) are studied in post-buckling when axially loaded. The results are in good agreement with previous studies. Moreover, a parametric study involving critical buckling load and geometry is presented for the case of the unicolon.


ABSTRACT: The dynamic instability of discrete, elastic, multiple degree of freedom (d.o.f.) systems under a combination of static and step loads is studied. Conservative, autonomous and holonomic systems are considered, in which the associated static response is a bifurcation under one load parameter, and a limit point under the second parameter. A review of different criteria and algorithms obtained from them for the computation of dynamic buckling loads is first presented, followed by a procedure derived from previous investigations on one d.o.f. systems. The different procedures are applied to a two d.o.f. problem under axial and lateral load, with quadratic and cubic non-linearities. The response in time shows that the system oscillates about the static equilibrium position before dynamic buckling is reached, with the kinetic energy tending to zero as assumed in the static (energy) procedures of stability.

References listed at the end of the paper:
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ABSTRACT: First-ply failure (FPF) of composite thin-walled columns and frames is investigated in the buckled structure. Elastic behavior is assumed during the pre-buckling and buckling states, and along part of the post-buckling equilibrium path. The Tsai-Hill criterion is employed to identify failure of one ply at one specific location. The technique of analysis is based on evaluation of the post-buckling elastic path, and using FPF as a constraint in the analysis. The structure is modeled using a few degrees of freedom to include local and/or overall buckling modes. The theoretical results are compared with experimental bounds and show good agreement for local buckling of isolated columns. There are no experimental results for frames in the literature, but theoretical results are presented for a simple case with asymmetric bifurcation.

ABSTRACT: Pultruded composite structural members with open or closed thin-walled sections are being extensively used as columns for structural applications where buckling is the main consideration in the design. In this paper, global buckling is investigated and critical loads are experimentally determined for various fiber reinforced composite I-beams of long column length. Southwell's method is used to determine the critical buckling load about strong and weak axes. The experimentally determined buckling load is compared with theoretical predictions. A number of observations about testing methodology and data reduction techniques are presented.

References listed at the end of the paper:


ABSTRACT: Column buckling is a major design concern for pultruded composite columns. Interaction between the local (flange) and global (Euler) buckling modes occurs in intermediate length thin-walled columns
with near coincident buckling loads. The interaction of more than one buckling mode induce an unstable tertiary post-buckling path, causing imperfection sensitivity and premature failure. In this work, the existence of buckling-mode interaction is experimentally verified for intermediate length pultruded wide-flange columns subjected to uniaxial compression. Characterization of the interaction mode is done using both conventional testing techniques and the shadow moiré optical technique, allowing for non-contact, full field measurement of the buckling modes.

Luis A. Godoy and Sandra Lopez-Bobonis (Department of Civil Engineering, University of Puerto Rico, Mayagüez, PR 00681-9041, Puerto Rico), “On the collapse of a reinforced concrete digester tank”, (publisher and date not given in the pdf file. Most recent citation is dated 1999.)

ABSTRACT: The investigation following the collapse of a large reinforced concrete dome, which was part of a digester tank, is presented. The shell was constructed in 1987, and had construction errors related to the location of the single layer of reinforcement, which were discovered as a consequence of the collapse. The shell collapsed without the occurrence of any natural hazard. It is believed that a high internal pressure developed on the day of the collapse because of a problem with a valve, which allowed the discharge of large quantities of sewage inside the tank and filled the structure completely. A finite element analysis of the structure shows the stress levels in the structure, and support the hypothesis of a failure mechanism which coupled the construction errors with the internal pressure. Finally, the strengthening of the shell with externally bonded fiber composite sheets is described as a possibility to improve the safety of other tanks in similar situations.

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Luis A. Godoy, “A primer on buckling of tanks”, (chapter in an unidentified book (no publisher nor date given, but latest reference is 2000)
References cited at the end of the paper:

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ABSTRACT: This paper reports theoretical studies on the design sensitivity of problems with geometrically
non-linear behavior leading to buckling and post-buckling of thin-walled structural members. For the class of problems considered, buckling occurs in the form of a stable bifurcation, and it is assumed that changes in the design parameters do not break the bifurcation behavior. The specific focus of the research is the first yield or first failure of the material as part of the sensitivity study of equilibrium states along the post-critical path. The investigation employs a discrete model of a structure in terms of generalized coordinates (suitable for finite element analysis) and a single load parameter; and perturbation techniques to classify the critical state and to approximate the post-critical path. The problem of material behavior is modeled by means of constraints on the post-critical path, based on a yield criterion. For simplicity, the presentation uses the von Mises yield criterion, but other more complex criteria, such as those employed in composite materials (first-ply failure) can also be represented. Two forms of the constraints are formulated, and the problem of sensitivity with respect to changes in a design parameter is discussed. A simple example of a circular plate is presented to illustrate the use of the formulation for the sensitivity with respect to a single design parameter.

Luis A. Godoy and Genock Portela (University of Puerto Rico, Mayaguez Campus, Department of Civil Engineering), “A review of wind-tunnel results of pressures on tank models”, (publisher and date not given in the pdf file; latest reference is 2001)

GENERAL OVERVIEW: The Caribbean Islands are heavily exposed to hurricanes due its geographical location in the Atlantic and Caribbean Seas. Damage due to wind pressure of tanks used for storage different liquids have been observed and studied by different authors (Flores and Godoy (1998), Godoy and Mendez (2001)). Some of the cases studied were found in St. Croix, St. Thomas, and Puerto Rico during Hugo (1989), Marilyn (1995), and Georges (1998), respectively. Studies of wind pressures have taken place since early in the 20th century. During this era, air flow effects were investigated by different authors (H. L. Dryden et. al., 1930). A common problem is the variation of wind pressures depending on tank geometry. Both external wall pressure, as external roof pressure distribution is strongly dependent of the tank geometry. Detailed studies concerning to wind loads on cylinders include wind tunnel tests performed by Maher (1966) to dome-cone and dome-cylinder tanks. The height of hemisphere and spherical dome roofs mounted on cylinders with base diameters of 12 in. or 24 in., was changed to account variation of wind on the roof and wall of the shell. Pressures were measured both in the meridian and parallel axes of the cylinders and different pressure patterns were developed. Purdy et. al. (1967), studied wind pressure distributions on flat-top cylinders. The aspect ratio (h/D) was varied from short (tanks) to long (silos) cylinders to quantify the dimensional effects in pressure distribution. The cylinder diameters were 12 and 24 in., and the heights were increased from 6 in. Numerical approximations were developed based in Fourier cosines series on the surface of the flat roof diameter and along the parallel and meridian axes of the shell. More recent studies concerning to pressure variations around the shells were accomplished by Esslinger et.al. (1971), Gretler (1978), Gorenc (1986), Greiner (1998), and Pircher (1998). Studies based on wind distribution on conical roof tanks were accomplished by Sabransky et.al (1986), and MacDonald et.al (1988). Variations in aspect ratios were considered in the experimental tests and the authors give contours of different pressure coefficients found at different tank sections.

References listed at the end of the paper:

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ABSTRACT: Shell buckling problems belong to the class of geometrically nonlinear behavior, and may be coupled with material nonlinearity of the shell. There are many general-purpose finite element programs that perform geometric and material nonlinear analysis of shells; however, this does not mean that a user can feed data and collect reliable results without a full understanding of the physics of the problem. This paper discusses the theories involved in the explanation and classification of phenomena, and in the prediction of results. Next, those approaches are considered in the practical analysis of one shell form, namely thin-walled steel tanks used to store oil. Results have been obtained with the general-purpose package ABAQUS, and they tend to show that their interpretation requires the use of Koiter’s theory in order to make sense of what is obtained. Some thoughts on possible ways to implement Croll’s lower bound reduced energy approach in practice are given.

References listed at the end of the paper:


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ABSTRACT: An experimental/computational strategy is used in this paper to evaluate the buckling behavior of steel tanks with a dome roof under exposure to wind. First, wind tunnel experiments using small scale rigid models were carried out, from which pressure distributions due to wind on the cylindrical part and on the roof were obtained. Second, a computational model of the structure (using the pressures obtained in the experiments) was used to evaluate buckling loads and modes and to study the imperfection sensitivity of the tanks. The computational tools used were bifurcation buckling analysis (eigenvalue analysis) and geometrical nonlinear analysis (step-by-step incremental analysis). Geometric imperfections and changes in the buckling results due to reductions in the thickness were also included in the study to investigate reductions in the buckling strength of the shell. For the geometries considered, the results show low imperfection sensitivity of the tanks and buckling
loads associated with wind speeds 45% higher than those specified by the ASCE 7-02 standard.

References listed at the end of the paper:

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ABSTRACT: We investigate dynamic buckling of aboveground steel tanks with conical roofs and anchored to the foundation, subjected to horizontal components of real earthquake records. The study attempts to estimate the critical horizontal peak ground acceleration (Critical PGA), which induces elastic buckling at the top of the cylindrical shell, for the impulsive hydrodynamic response of the tank–liquid system. Finite elements models of three cone roof tanks with height to diameter ratios (H/D) of 0.40, 0.63 and 0.95 and with a liquid level of 90% of the height of the cylinder were used in this study. The tank models were subjected to accelerograms recorded during the 1986 El Salvador and 1966 Parkfield earthquakes, and dynamic buckling computations (including material and geometric non-linearity) were carried out using the finite element package ABAQUS. For the El Salvador accelerogram, the critical PGA for buckling at the top of the cylindrical shell decreased with the H/D ratio of the tank, while similar critical PGAs regardless of the H/D ratio were obtained for the tanks subjected to the Parkfield accelerogram. The elastic buckling at the top occurred as a critical state for the medium height and tallest models regardless of the accelerogram considered, because plasticity was reached for a PGA larger than the critical PGA. For the shortest model (H/D=0.40), depending on the accelerogram considered, plasticity was reached at the shell before buckling at the top of the shell.

References listed at the end of the paper:

ABSTRACT: Ground-supported steel tanks experienced extensive damage in past earthquakes. The failure of tanks in earthquakes may cause severe environmental damage and economic losses. This study deals with the evaluation of the elastic buckling of above-ground steel tanks anchored to the foundation due to seismic shaking. The proposed nonlinear static procedure is based on the capacity spectrum method (CSM) utilized for the seismic evaluation of buildings. Different from the standard CSM, the results are not the base shear and the maximum displacement of a characteristic point of the structure but the minimum value of the horizontal peak ground acceleration (PGA) that produces buckling in the tank shell. Three detailed finite element models of tank-liquid systems with height to diameter ratios H/D of 0.40, 0.63, and 0.95 are used to verify the methodology. The 1997 UBC design spectrum and response spectra of records of the 1986 El Salvador and 1966 Parkfield earthquakes are used as seismic demand. The estimates of the PGA for the occurrence of first elastic buckling obtained with the proposed nonlinear static procedure were quite accurate compared with those calculated with more elaborate dynamic buckling studies. For all the cases considered, the proposed methodology yielded slightly smaller values of the critical PGA for the first elastic buckling compared to the dynamic buckling results.

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“Challenges in the computation of lower-bound buckling loads for tanks under wind pressures”, Thin-Walled
ABSTRACT: This paper reports on the implementation of a lower-bound approach for the buckling of imperfection-sensitive shells using general purpose finite element codes. The stability of cylindrical steel tanks under wind pressure is evaluated for two tank configurations: conical roof tanks and open top tanks. For both tank configurations, several geometric relations are considered in order to find the variation of the knock-down factor as the geometry changes. The reduced energy method is implemented to compute a lower-bound for critical wind pressures and the results are compared with the static non-linear analysis carried out on the same models. An alternative way to implement the reduced energy method is presented to improve the results obtained with the proposed methodology.

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ABSTRACT: Shell structures are usually designed by considering their final shape and configuration, so that it is assumed that stability during the construction will be satisfied without further thought. However, evidence from recent collapses of metal tanks under moderate winds shows that this is a matter that requires special attention. This paper reports analytical studies of tanks for the oil industry that failed during their construction in the Argentinean Patagonia under moderate winds. The cylindrical part of the tanks was set up in place with point welding, but the roof was not yet in place at the time of collapse. To understand the mechanism of failure, static, geometrically nonlinear finite element modeling of the tanks was carried out, in which the shell was represented as close as possible to the actual conditions during the construction stage at which it failed. The results show that for the wind velocities prevalent at the time of collapse, an explanation of the failure mechanism can only be achieved by taking into account several special features of the structure under construction, i.e. the localized nature of welding and the influence of the incomplete junction with the bottom plate.

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“Reduced Stiffness Buckling Analysis of Aboveground Storage Tanks with Thickness Changes”, Advances in Structural Engineering Vol. 14 No. 3 2011, pp. 475-487
ABSTRACT: The Reduced Stiffness Analysis (RSA) to compute lower bounds to buckling loads of shells has been employed by a number of researchers as a simple way to evaluate the buckling capacity of shells that display unstable behavior and imperfection-sensitivity. It allows the use of simple eigenvalue analysis, without having to perform incremental nonlinear analysis, and is based on the physical behavior of the shell which recognizes that a significant contribution to the stability of a shell under lateral pressure is provided by its membrane stiffness. Unstable post-critical behavior is associated with the loss of this stabilizing membrane
contribution. Past use of the approach has been mainly restricted to cases of uniform shell thickness and uniform pressures in the circumferential direction, in which case analytical solutions are possible. Recent applications by the authors and other researchers have shown ways to compute the lower bounds using finite element analysis, for which a modified eigenvalue analysis is constructed by neglecting the membrane contributions to the matrix containing the initial stresses. This paper illustrates the application of the methodology to cases of pressure loaded shells with thickness changes in the meridional direction. A semi-analytical finite element code has been employed for the buckling analysis when uniform pressures act on aboveground steel tanks. The tanks are representative of those constructed for the oil industry, with diameter to thickness ratios of the order of 3000, and height to diameter ratios lower than one.

References listed at the end of the paper:


ABSTRACT: This paper reviews the research on the theory of elastic stability published at the end of the 19th century, with emphasis on the work by G. H. Bryan in Cambridge. The state of the studies on structural stability previous to Bryan is reviewed, and two lines of work are identified: one is a general stability of rigid bodies and the other is a collection of case studies of elastic stability. Bryan's theory is discussed next, presenting his arguments based on first energy principles, which led him to strong conclusions. The importance of the word “general” and the idea of having solved the problem in each case are explained. The impact of the contributions made by Bryan, together with the critiques that this generated, is also discussed.

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ABSTRACT: Advances in computational methods to model the nonlinear elastic behavior of shell structures have generated new computer capabilities to solve complex industrial problems. Shell buckling involves a number of specific features not present in other structural forms, such as imperfection-sensitivity, load-sensitivity, mode interaction, and exchange of energy contributions along a nonlinear equilibrium path. However, rather than using increasingly complex tools, it is also desirable to have methods in which the physics of the problem is taken into account to set theoretically loaded models, which can be solved using simpler computational tools. The authors have recently investigated one such strategy, known as Reduced Stiffness Method, in which selected energy components are eroded as a consequence of mode interaction and imperfection-sensitivity. This physical interpretation allows the formulation as an eigenvalue problem, in which the critical loads are lower bounds to experiments or to nonlinear incremental analysis. This paper considers the computational implementation of a reduced stiffness approach to the buckling of axisymmetric shell structures under wind loads. The structural configurations of interest in this work are cylindrical storage tanks with a roof (either flat or conical roof), in which case the thickness is decreased from the bottom to the top of the cylindrical part. A reduced stiffness approach has been implemented in a finite element code for shells of revolution, in which stabilizing membrane components are eliminated on the assumption that they will be eroded due to imperfection-sensitivity and mode interaction. Several strategies are considered depending on the zone of the shell in which elimination of membrane components is made. The code is employed to estimate buckling loads and modes in tanks with various roof configurations. It is shown that there are two aspects that influence the results: first, the existence of zones with different stiffness in the structure, and second, a load with a circumferential variation. The present results are compared with geometrically nonlinear analysis including shape imperfections and with experimental results. The results indicate that a reduction in meridional and torsional membrane components applied on a zone of the shell leads to good results in terms of limit point loads and modes.

References listed at the end of the paper:

ABSTRACT: This paper reports the computational results of an investigation of oil storage tanks with the shape of an open cylindrical shell under thermal loads induced by fire. Interest in this problem has arisen as a consequence of a catastrophic fire that affected an oil storage facility in Puerto Rico in 2009 that caused the failure of 21 large tanks. To identify patterns of deformations that could be expected under various fire conditions, computer modeling has been carried out for one tank geometry. It is assumed that fire occurs outside the tank and induces an increasing temperature field affecting part of the external surface in the circumferential direction. The nonlinear shell response is modeled using finite elements under thermal loads and self-weight. The nonlinear behavior is computed to identify thermal buckling of the shell as a limit point. The response is initially computed for empty tanks, and the influence of various factors is investigated, including the liquid stored, a temperature gradient across the thickness, the circumferential zone affected by fire, and the shell thickness. The results for open tanks show that the location of large out-of-plane displacements attributable to thermal buckling coincides with the heated zone. The importance of thermal gradients in the thickness to the buckling load and mode are shown.

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ABSTRACT: The strategy of Reduced Stiffness (or Reduced Energy) Analysis, in which selected energy components are eliminated to account for mode interaction and imperfection-sensitivity in a simplified way, was developed by Croll and co-workers since the early 1980s. This physical interpretation allows the formulation as an eigenvalue problem, in which the eigenvalue (critical load) is a lower bound to experiments and to nonlinear incremental analysis. This paper considers the computational implementation of both reduced stiffness and reduced energy approaches to the buckling of shell structures by means of perturbation techniques and penalty parameter methods. The structural configurations of interest in this work are cylindrical shells with or without a roof. The reduced stiffness approach has been implemented in a special purpose finite element code for shells of revolution, whereas the reduced energy methodology was implemented in a general purpose finite element code. The present results are compared with geometrically nonlinear analysis including geometric imperfections. Achievements and difficulties in extending the methodologies to complex problems in engineering practice are highlighted.

References listed at the end of the paper:


ABSTRACT: Buckling pressures were measured by collapsing thirteen 4000-gallon steel underground storage tanks using water to generate external pressure. These tanks were built using the minimum shell thickness specified in Underwriter Laboratories Standards UL-58 and UL-1746, reduced wall thickness. The effects on buckling pressure of shell thickness and shell-to-shell weld geometry were measured, as was the effect of internal stiffeners. These buckling pressures were compared with calculated values using standard formulas available in the literature. A predeformation force was applied to the bottom of the test tanks to induce uniform failure modes. A tank “stiffness” was determined from these measurements and correlated with buckling pressure. Measurements were also made on single-wall tanks with a surface coating of fiberglass reinforced plastic and on double-wall steel tanks.


ABSTRACT: In many practical problems, e.g., storage bins, oil tanks, missile shells, launch vehicles, etc., cylindrical shells are subjected to unsymmetrical lateral external load. These shells are usually made of thin sheets of metal; therefore, in many instances these structures have failed due to buckling. In this paper, the stability of cylindrical shells under the action of wind load is investigated. Often these shells are constructed of corrugated steel sheets; therefore, the shells are analyzed by considering the material as orthotropic. This analysis can also be used for other orthotropic materials. The principle of minimum potential energy in conjunction with Ritz’s approach is used. The buckling loads, as well as the buckling configurations, are obtained for short cylinders made of corrugated steel sheets subjected to wind pressure. The present study is made on cylindrical shells of various dimensions, which are simply supported at the base and are open or closed at the top. For practical use, buckling load curves for these shells are given for different length-to-radius and radius-to-thickness ratios.

Zhou Fang, Zhi Ping Chen, Chu Lin Lu, Ming Zeng, “Effect of Weld on Axial Buckling of Cylindrical Shells”, Advanced Materials Research (Volumes 139 - 141), pp 171-175, October 2010, DOI: 10.4028/www.scientific.net/AMR.139-141.171

ABSTRACT: Large oil storage tank (oil tank for short) shells are vulnerable to buckling damage when suffering the seismic loads. Numerical simulation analysis was taken to estimate the effects of the weld form, number and their location to axial buckling stress of cylindrical shells, considering not only the characteristic of welding
processes, but also the effects probably caused by magnitude of residual stress and deformation on elephant foot buckling to oil tanks. It is revealed that the existence of circumferential welds had obvious negative effect on axial buckling critical stress compared with the structure without welds, while the effects of weld number and location were not as much; longitudinal welds had no visible effect on axial buckling critical stress; controlling the residual stress and deformation range caused by circumferential welds should be the key point during the tanks welding process.


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ABSTRACT: Based on two international well accepted design standards, Eurocode 8 Part 4—Tanks, Silos and Pipelines and API Standard 650—Seismic Design of Storage Tanks, the structural response of seismically excited vertical circular cylindrical tanks is analysed from a novel perspective. The common basic assumption, adopted from Haroun-Housner and Veletsos, that a circular cylindrical tank containing liquid behaves like a cantilever beam without deformation of its cross-section is obsolete. Instead the authors consider the shell modal forms in order to generate a refined model. Emphasis is laid on the analysis of the fundamental frequencies for the tank-liquid-system. They are calculated by a new method, based on Galerkin’s approximations for cylindrical shells. As the results differ significantly from those calculated by the proposed formulae in both EC8 and API Standard 650, the new results are compared with tank failures during recent earthquakes. This comparison is astonishing. It can be seen from recent examples of tank damage that most failures are caused by resonance effects, which are taken into account neither in EC8 nor in API Standard 650. And, therefore, we take into account a high safety risk. This leads to the conclusion that the basic assumptions for current design provisions are no longer tenable under the present knowledge of shell theory and shell design, and, therefore should be reconsidered.

ABSTRACT: The earthquake response behaviour of a cylindrical wine storage tank similar to many that were damaged in Livermore, California during the January 1980 earthquake was studied on the University of California shaking table. Tests of the 9.5 ft diameter by 20 ft high tank, with simulated earthquake accelerations up to 0.95 g, induced buckling patterns similar to those observed after the actual earthquake. Observed peak axial compression stresses in the test tank wall were substantially higher than those assumed in typical design standards, demonstrating the need for further study of the buckling problem in tanks free to uplift during earthquake excitation.
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ABSTRACT: The magnitude M = 6.5 Coalinga earthquake of 2 May 1983 caused intense ground shaking throughout the epicentral region. Unanchored cylindrical ground supported tanks located at six sites within this oil producing area were damaged; damages included elephant's foot buckling at the base of three moderate sized tanks, joint rupture and top shell buckling in one large old rivetted tank, bottom plate rupture of a relatively new welded tank and damage to the floating roofs of 11 tanks. Also oil spilled over the top of many tanks and secondary damages occurred in pipe connections, ladders, etc. In this paper an estimate is made of the intensity of ground motion at each of the tank sites, based on strong motion records made during the main shock and the strongest aftershock. Then response parameters specified by current codes are correlated with the damages observed at each tank site. Based on this comparison, it is concluded that current U.S. practice under-estimates the sloshing response of tanks with floating roofs and does not adequately address the uplifting mechanism of unanchored ground supported tanks.

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ABSTRACT: The bulging observed on the wall of a ground supported cylindrical storage tank, located at the Chiba Experimental Station of the University of Tokyo, is investigated. This damage is correlated with a ground motion recording obtained very near the tank base during a moderately strong earthquake that occurred on September 25, 1980 not far from the Chiba Experimental Station. From this correlation the importance of the horizontal excitation in amplitude and direction is clearly established. In addition, good agreement can be seen between the predicted tank wall earthquake performance, derived by an empirical approach proposed by the first author, and the shell deformation observed at the Chiba Experimental Station.

ABSTRACT: This paper details the damage sustained by a number of wine tanks during the San Juan, Argentina, 1977 earthquake. The available ground motion information is used to compare the actual tank performance with that predicted. Two of the tanks examined were located quite near the two accelerographs that recorded the ground motion in the city of San Juan for the main shock. An empirical attenuation formula which describes the intensity of the shaking was derived for this earthquake and used in a quantitative evaluation of the performance of a number of other tanks. By correlating and comparing the observed performance of the anchors and what was predicted we see the predictions are upheld by the actual damage. When the anchoring
system failed during the earthquake the tanks were rendered effectively unanchored. Consequently, the state of stress that results from their base uplift was then examined in conjunction with the tank wall stability approach proposed by the author, and seen to give results consistent with the observed tank wall performance.

ABSTRACT: Generally, we increase the cross sectional area of circular transverse frames or decrease the overall buckling length for increasing the critical buckling load of the ring-stiffened cylindrical shells. However, it is of no use to a large submarine. The curve r-p and formula are presented here, which determines whether the result of ordinary calculated methods is correct or not, estimates the maximum buckling load, determines the thickness of the shell, decides the reinforcements of the structure. There is only one curve. Therefore it is convenient to use. The curve has been checked by both model experiment and exact solution.

Chapter DOI: http://dx.doi.org/10.1017/CBO9780511536656.011
INTRODUCTION: The dynamic analysis of a cylindrical shell experiencing elastic deformation that is comparable to its wall thickness cannot be described within the framework of the linear theory. The same is applied if the liquid free-surface amplitude is relatively large. In both cases, nonlinear analysis should be carried out. The presence of nonlinearities may result in nonlinear resonance conditions that cause complex response characteristics. One of the main difficulties in nonlinear problems of shell–liquid systems is that the boundary conditions are essentially nonlinear. This is in addition to the fact that the strain state of an elastic shell and the shape of the liquid free surface are not known a priori. The treatment of the nonlinear interaction of a liquid–shell system is a nonclassical boundary-value problem and relies on mechanics of deformable solids, fluid dynamics, and nonlinear mechanics. With reference to nonlinear vibrations of cylindrical shells in vacuo, the literature is very rich and reports some controversies regarding the influence of nonlinearities on the shell dynamic behavior. The main results have been reviewed by Vol'mir (1972, 1979), Leissa (1973), Evensen (1974), Kubenko, et al. (1984), Amiro and Prokopenko (1997), and Amabili, et al. (1998b). Some attempts have been made to reconcile the reported discrepancies (see, e.g., Dowell, 1998, Evensen, 1999, and Amabili, et al. 1999c). It is believed that Reissner (1955) made the first attempt to study the influence of large-amplitude vibration for simply supported shells.

H. Moghaddam and S. Sangi (Faculty of Civil Engineering, Sharif University of Technology, Tehran, Iran), “Elephant’s Foot Buckling of Cylindrical Steel Storage Tanks Subjected to Earthquake Excitation”, 6th National Congress on Civil Engineering, April 26-27, 2011, Semnan University, Semnan, Iran
ABSTRACT: Thin metal cylindrical shell structures such as silos and tanks are susceptible to an elastic–plastic instability failure at the base boundary known as elephant’s foot buckling, due to its characteristic deformed shape. This form of buckling occurs under high internal pressure accompanied by axial compression in the shell structure. This work concerns with Theoretical studies on elephant's foot buckle failure of ground-supported, cylindrical liquid storage tanks under horizontal excitation. The buckling loads are obtained from finite elements models and codes and are compared. Theoretical nonlinear seismic analyses are carried out using ANSYS package. Studies are conducted on 13 models of cone roof tanks with height to diameter ratios (H/D)
between 1 and 2, and a liquid level of 85% of the height of the cylinder with and without axial constraint at the point diametrically opposite the loading. The results are compared to which of the codes API 650, NZSEE guidelines and Eurocode 8. The comparisons of analytical buckling loads and those obtained by the codes reveal the following. Tanks designed by the codes API650 and Eurocode 8 tend to be unsafe due to elastic-plastic buckling occurrence of the shell. However, NZSEE guidelines have a near coherence to the analysis results. It is also obtained from the results that constraints at the base of the tank reduces sloshing height while cause the buckling capacity to rise up.

References listed at the end of the paper:

Medhat A. Haroun and Hossam S. Badawi (Department of Civil Engineering, University of California, Irvine, California, USA), “Seismic Behavior of Unanchored Ground-Based Cylindrical Tanks”, Proceedings of Ninth World Conference on Earthquake Engineering, August 2-9, 1988, Tokyo-Kyoto, Japan (Vol. VI)

SUMMARY: A review of the methods of seismic analysis of unanchored liquid storage tanks is presented along with an outline of an ongoing study to model the complex response mechanism of these structures. The study includes: 1. nonlinear static and dynamic analyses of the tank’s base plate under uplifting forces considering the nonlinear contact with the foundation and the underlying soil, the large deformation, and the inelastic response; 2. an analysis of the large-amplitude motion of the liquid and the corresponding hydrodynamic pressures; and 3. an analysis of the coupled response of the liquid, the shell, and the base plate under moderate to severe earthquake motions.

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ABSTRACT: Local uplift of the tank wall is perhaps the most important characteristic of the seismic behaviour of unanchored liquid storage tanks made out of steel. Such uplift is necessary, because unanchored tanks rely primarily on the weight of the liquid resting on an uplifted portion of the base plate to balance the overturning moments that occur during strong shaking. A simplified method of analysis for static lateral loads is developed, based on the assumption that the restraining action of the base plate can be modelled with equivalent, non-linear
springs. This assumption, together with a Fourier decomposition of the displacements, simplifies the problem to the extent that it can be solved on a personal computer. The solutions are compared with those from experiments and those from current U.S. design analysis methods.

ABSTRACT: The diamond - modes of collapse are studied with finite element methods. Both linear and nonlinear analyses are performed on the buckling of a cylindrical shell under axial compression. Among the postbuckling shapes of the cylindrical shell, a number of diamond modes (cos(Ntheta); N = 0, 14, 18, 10, 24 and 28) are found to be possible. The analysis is compared to those conducted by Maewal and Nachbar, Crisfield, and Yoshida et al. Agreement is established in conceiving the deformed shape with circumferential number of 14 as the stable postbuckling mode of the cylindrical shell. The transition from the axisymmetric mode to a diamond mode of collapse is shown to be an instantaneous process triggered in the proximity of the critical state by a small perturbation of the load increment.

ABSTRACT: A Galerkin Finite Element formulation for the dynamic stability analysis of liquid-filled shells is given in this paper. The coupling among the axial and circumferential modes is investigated. The dynamic stability characteristics of two liquid-filled storage tanks subjected to vertical, horizontal and rocking seismic excitations are presented. It is shown that a tall tank tends to buckle at distinct frequencies; and for cos theta-type ground excitation, cos 2theta, cos 3theta and cos 4theta are the dominant modes of failure. On the other hand, in a broad tank, buckling regions overlap each other. In particular, for cos theta-type ground excitation, the dominant buckling modes are cos 6theta to cos 9theta, and also cos 12theta to cos 14theta.

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ABSTRACT: The matrix equation of motion for liquid-filled shells with a particular reference to the influence of ground excitation are derived through a Galerkin/finite element discretization procedure. The modal coupling among the various combinations of axial and circumferential modes are identified. The equations for the dynamic buckling analysis of liquid-filled shells are presented. The buckling criteria of liquid-filled shells subjected to horizontal ground excitation are established. A comparison to available experimental results gives strikingly good agreement. The importance of modal interaction in the axial as well as circumferential directions is also demonstrated. This provides guidelines for a better understanding of dynamic buckling of liquid-filled shells.

S. Li, W. Hao and W. K. Liu (Department of Mechanical Engineering, Northwestern University, 2145 Sheridan
ABSTRACT: In this paper, meshfree simulations of large deformation of thin shell structures is presented. It has been shown that the window function based meshfree interpolants can be used to construct highly smoothed (high order “manifold”) shape functions for three-dimensional (3-D) meshfree discretization/interpolation, which can be used to simulate large deformation of thin shell structures while avoiding ill-conditioning as well as stiffening in numerical computations. The main advantage of such 3-D meshfree continuum approach is its simplicity in both formulation and implementation as compared to shell theory approach, or degenerated continuum approach. Moreover, it is believed that the accuracy of the computation may increase because of using 3-D exact formulation. Possible mechanism to relieve shear/volumetric locking due to the meshfree interpolation is discussed. Several examples have been computed by using a meshfree, explicit, total Lagrangian formulation. Towards to developing a self-contact algorithm, a novel meshfree contact algorithm is proposed in the end.

References listed at the end of the paper:
ABSTRACT: Sheet buckling, a form of instability, is one of the major considerations in the design of part shape, die geometry and processing parameters of sheet metal forming. In this study, an adaptive enrichment meshfree method is developed to capture wrinkling and post-buckling behavior in sheet metal forming. A three-dimensional meshfree continuum approach is applied to the large deformation of plate/shell structures. A stress-based wrinkling predictor is used to predict the onset of buckling within effective compressive regions. Enrichment particles with a proper enrichment function are inserted/deleted in those regions to capture the buckling mode and therefore post-buckling behavior. For verification of the simulation results, a high-resolution wedge strip test is designed to study the onset and post-buckling behavior of a sheet under different boundary conditions.

ABSTRACT: Numerical simulation of sheet metal forming processes is overviewed in this work. Accurate and efficient elements, material modelling and contact procedures are three major considerations for a reliable numerical analysis of plastic forming processes. Two new quadrilaterals with reduced integration scheme are introduced for shell analysis in order to improve computational efficiency without sacrificing accuracy: the first one is formulated for plane stress condition and the second designed to include through-thickness effects with the consideration of the normal stress along thickness direction. Barlat’s yield criterion, which was reported to be adequate to model anisotropy of aluminum alloy sheets, is used together with a multi-stage return mapping method to account for plastic anisotropy of the rolled sheet. A brief revision of contact algorithms is included, specially the computational aspects related to their numerical implementation within sheet metal forming context. Various examples are given to demonstrate the accuracy and robustness of the proposed formulations.
References listed at the end of the paper:


ABSTRACT: To determine the relationship between dynamic instability phenomenon of liquid storage tanks and excitation parameters, from fluid-solid coupling equations with displacement-pressure form, the dynamic stability equations were established for liquid storage tanks under harmonic ground acceleration, in which the fluid-solid coupling effect was considered with added mass matrix and the shell stress change was considered with period-varying geometric stiffening matrix. After order reduction by modal truncation method, above equations were then solved based on Floquet theory to recursively search for the dynamic instability boundary described by the excitation parameters. The Chiba test models were analyzed by the proposed Floquet method, and the analysis results were reexamined based on B-R criterion. The results show that, the dynamic instability boundaries obtained by the Floquet method were consistent with Chiba test results, and agreed well with the estimates of B-R method. Floquet method can obviously improve the computational efficiency of dynamic instability boundary and eliminates the influence of half-wave assumption of shell vibration modes.

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5 CHIBA M, TANI J, HASHIMOTO H, et al. Dynamic stability of liquid-filled cylindrical shells under horizontal excitation, part I:
Hou Chao-sheng and Zhou Wei-yi (School of Civil Engineering, Tianjin University, Tianjin 300072, China), “Nonlinear stability of revolutionary shells with arbitrary variable thickness subjected to axisymmetric distributed line load” Journal of Tianjin University, 2007-07

ABSTRACT: To simplify the complexity of calculating the large deflection of a plate or shell with variable thickness under the action of distributed line load, the solutions of nonlinear stability of revolutionary shells with variable thickness are obtained using the point collocation method with the cubic B-spline function as a trial function. Under the action of distributed line load, upper and lower critical loads of conical shells, spherical shells or quartic polynomial shells with linearly or polynomially variable thickness are obtained. Most solutions are compared with those obtained by other methods (including the finite elements method). As the rise of a spherical shell with uniform thickness reaches 6052 times its thickness, upper critical load of the shell subjected to distributed line load remains convergent. The program written by the spline collection method are accurate and universal.


ABSTRACT: (none given)

References listed at the end of the paper:

Harley Cohen and Franco Pastrone, “Buckling of a cylindrical shell subject to a wrench”, Meccanica, Vol. 28, No. 4, pp 293-301, 1993, DOI: 10.1007/BF00987165

ABSTRACT: We examine the axisymmetric buckling of a generalized Kirchhoff cylindrical shell under an axial wrench. If the shell is non-linear elastic, we provide a boundary value problem amenable to the bifurcation theory of Poincaré. Using this theory we prove a non-uniqueness theorem and obtain the critical loads and critical states. In the hyperelastic case, by exploiting the variational character of the problem, a global existence and non-uniqueness theorem is also proved.

References listed at the end of the paper:


SUMMARY: The dynamic stability of thin, laminated cylindrical shells under combined static and periodic axial forces is studied here using three common thin shell theories, namely Donnell's, Love's and Flügge's shell theories. A normal-mode expansion of the equations of motion yields a system of Mathieu-Hill equations the stability of which is examined using Bolotin's method. The present study examines and compares the effects of the use of the various shell theories on the dynamic stability analysis.

References listed at the end of the paper:
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ABSTRACT: Metal silo walls are often constructed from isotropic plates, and the controlling design condition is buckling under axial compression. It has long been recognised that this buckling strength is highly sensitive to imperfections in the cylindrical shell, but most attention has been paid to geometric imperfections and imperfect boundary conditions. Imperfections in the form of residual stresses have only rarely been investigated, and the challenges facing a rigorous treatment of them have often not been faced. This paper adopts a rigorous treatment technique to investigate residual stresses and their effect on the axial compression buckling strength under elastic conditions. It achieves this by considering consistent stress and displacement fields arising from local geometrical incompatibilities, and adopting their consequent geometric imperfections. The calculations of the strength of imperfect shells with residual stresses are compared with corresponding calculations for the same imperfections but with the residual stresses ‘annealed’ out of the analysis. The results show that consistent residual stresses generally appear to strengthen a thin shell relative to the corresponding strength with only geometric imperfections present.

J.M.F.G. Holst, J.M. Rotter, M. Gillie and M. Munch (School of Civil and Environmental Engineering, University of Edinburgh, Edinburgh, EH9 3JN, UK), “Failure Criteria for Shells on Local Brackets”, Chapter in

ABSTRACT: Several criteria are given in design standards for determining the failure load of cylindrical shell structures. When the loading is nonuniform, a nonlinear finite element analysis is required to capture fully the deformation characteristics of the shell and to obtain a true estimate of the failure load. However, even if a fully nonlinear analysis is performed, the determination of the strength of the shell is not always easily achievable. Several different forms of nonlinear load-deformation behaviour are found. The adequacy of existing design guidelines for obtaining an estimate of the design strength is examined. For certain types of behaviour alternative methods are suggested that may provide a more definitive measure. The numerical results are based on silos supported locally on brackets. The results are, however, more widely applicable to shells under a general set of loads. The bracket-supported silo is used in the calculations as it provides a good example of a simple design, but with a relatively complex pattern of deformations leading to a highly nonuniform stress state.

References listed at the end of the paper:


ABSTRACT: This paper presents theoretical descriptions of the key phenomena that govern the behaviour of composite framed structures in fire. These descriptions have been developed in parallel with large scale computational work undertaken as a part of a research project (The DETR-PIT Project, Behaviour of steel framed structures under fire conditions) to model the full-scale fire tests on a composite steel framed structure at Cardington (UK). Behaviour of composite structures in fire has long been understood to be dominated by the effects of strength loss caused by thermal degradation, and that large deflections and runaway resulting from the action of imposed loading on a ‘weakened’ structure. Thus ‘strength’ and ‘loads’ are quite generally believed to be the key factors determining structural response (fundamentally no different from ambient behaviour). The new understanding produced from the aforementioned project is that, composite framed structures of the type tested at Cardington possess enormous reserves of strength through adopting large displacement configurations. Furthermore, it is the thermally induced forces and displacements, and not material degradation that govern the structural response in fire. Degradation (such as steel yielding and buckling) can even be helpful in developing
the large displacement load carrying modes safely. This, of course, is only true until just before failure when material degradation and loads begin to dominate the behaviour once again. However, because no clear failures of composite structures such as the Cardington frame have been seen, it is not clear how far these structures are from failure in a given fire. This paper attempts to lay down some of the most important and fundamental principles that govern the behaviour of composite frame structures in fire in a simple and comprehensible manner. This is based upon the analysis of the response of single structural elements under a combination of thermal actions and end restraints representing the surrounding structure.


ABSTRACT: The buckling strength of a thin cylindrical shell is important in many applications in civil engineering. On the one hand, current design rules are principally based on an empirical interpretation of test data and hence very simple loading conditions are applied. On the other hand, experimental and theoretical observations show significant stress non-uniformity and hence a deviation from the buckling strength expected under uniform load. Reliable quantification of this effect is still challengingly difficult.

This paper explores a typical thin cylindrical silo shell under localized axial compression. Two different buckling phenomena are identified with corresponding, and distinct, buckling mode forms. The influence of geometric imperfections on the buckling strength of the shell is also considered.

References listed at the end of the paper:
PARTIAL INTRODUCTION: Storage containers are frequently constructed at ports in coastal regions or on reclaimed land where large settlements arise due to poor soil conditions. Uneven settlement beneath a ground-supported tank may occur, leading to several possible failure modes. The commonest causes are the use of non-uniform fill beneath the vessel and the construction of only part of the vessel on ground that has been consolidated by the earlier presence of a tank…. Each failure mode is closely related to a different component of the total settlement. Although the description given in the following outline review is mostly in terms of tank structures, it is equally applicable to all forms of cylindrical metal shells with the axis vertical…If buckling occurs in the tank wall, is it potentially catastrophic or only unsightly…

ABSTRACT: The design of cylindrical metal silos and tanks is often controlled by considerations of buckling under axial compression. Whilst the effects of geometric imperfections on the buckling strength have been extensively explored, few studies have explored the effects of defects in the boundary conditions and the effects of residual stresses have received even less attention. This paper investigates the initiation and development of imperfections caused by local differential settlement at the supported base and their effect on the elastic buckling of a thin cylindrical shell under axial compression. The shells were treated as initially perfect with perfect support, but developing geometric imperfections and residual stresses as a consequence of local displacement at the supported edge and with residual stresses consistent with the induced geometric imperfections. The results raise interesting questions concerning the criteria of failure and appropriate tolerance measurements for constructed cylindrical shells.
ABSTRACT: Thin cylindrical shells used in civil engineering applications are often susceptible to failure by elastic buckling. Most information on shell buckling relates to simple and uniform load cases, but most practical load cases involve stresses that vary very significantly throughout the structure. The buckling strength of an imperfect shell under relatively uniform stresses is much lower than that under locally high stresses, so design proposals have often suggested that designers use the uniform buckling stress strength even for local stresses. However, this leads to enormous overdesign, and many knowledgeable designers use their own very simple rules of thumb to produce safe but unverifiable designs. Unfortunately, very few scientific studies of shell buckling under locally elevated stresses have ever been undertaken. The most critical case is that of a locally axially compressed cylinder. This paper explores the buckling strength of an elastic cylinder in which a locally high, axial membrane stress state is produced far from the boundaries (which can elevate the buckling strength further) and adjacent to a serious geometric imperfection. Care is taken to ensure that there is relatively little influence from local bending phenomena, so that the stress state can mimic that produced by much more complex load cases. The study includes explorations of different geometries, different localisation of the loading and different imperfection amplitudes. The results show an interesting distinction between narrower and wider zones of elevated stresses. The study is a necessary precursor to the development of a complete design rule for the buckling strength under local axial compression.

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“Buckling of Thin Cylindrical Shells Under Locally Elevated Compressive Stresses”, Journal of Pressure Vessel Technology, Bol. 133, No. 1, 011204 (11 pages), December 2010
ABSTRACT: Thin cylindrical shells used in engineering applications are often susceptible to failure by elastic buckling. Most experimental and theoretical research on shell buckling relates only to simple and relatively uniform stress states, but many practical load cases involve stresses that vary significantly throughout the structure. The buckling strength of an imperfect shell under relatively uniform compressive stresses is often much lower than that under locally high stresses, so the lack of information and the need for conservatism have led standards and guides to indicate that the designer should use the buckling stress for a uniform stress state even when the peak stress is rather local. However, this concept leads to the use of much thicker walls than is necessary to resist buckling, so many knowledgeable designers use very simple ideas to produce safe but unverified designs. Unfortunately, very few scientific studies of shell buckling under locally elevated compressive stresses have ever been undertaken. The most critical case is that of the cylinder in which locally high axial compressive stresses develop extending over an area that may be comparable with the characteristic size of a buckle. This paper explores the buckling strength of an elastic cylinder in which a locally high axial membrane stress state is produced far from the boundaries (which can elevate the buckling strength further) and adjacent to a serious geometric imperfection. Care is taken to ensure that the stress state is as simple as possible, with local bending and the effects of internal pressurization eliminated. The study includes explorations of different geometries, different localizations of the loading, and different imperfection amplitudes. The results show an interesting distinction between narrower and wider zones of elevated stresses. The study is a necessary precursor to the development of a complete design rule for shell buckling strength under conditions of locally varying axial compressive stress.

ABSTRACT: The strength of metal cylinders is well known to be highly sensitive to the presence of imperfections. Attention has long been focused on geometric imperfections, but some recent studies have examined the effect of including the residual stress state relating to the formation of these imperfections in assessing the buckling strength of the shell. This paper looks first at how the imposition of a local geometrical incompatibility on a long narrow circumferential region of the shell surface leads to the formation of dimple imperfections and how these, in turn, affect the buckling strength of the shell. As an example, a case study of a thin cylindrical steel tank is presented, where lack of fit and weld shrinkage have caused local dimpling of the shell. Some results are presented from an analysis of this tank, which successfully uses several of the procedures applied in studying the fundamental cases of misfits.


ABSTRACT: The general theory of an elastic Cosserat surface due to Green and Naghdi, along with some kinematic results from the theory of superposed small deformations on a large deformation of an elastic Cosserat surface, are applied to study axisymmetric buckling of a cylindrical elastic shell under axial compression. An eigencondition is determined for a sinusoidal buckling mode in an infinitely long shell which illustrates the dependence of the buckling load on the pre-buckling deformation and on shear deformation in the superposed buckling deformation.


ABSTRACT: Relying on the concept of a Cosserat continuum, the reduction of the three-dimensional equations of a shell body to two-dimensions is carried out in a direct manner by considering the Cosserat continuum to be a two-dimensional surface. By that, a non-linear shell theory, including transverse shear strains, with exact description of the kinematical fields is derived. The strain measures are taken to be the first and the second Cosserat deformation tensors allowing for an explicit use of a three parametric rotation tensor. Thus, inplane rotations, also called drilling degrees of freedom, are included in a natural way. The structure of the configuration space is discussed and two possible definitions of it are given equipped once with a Killing metric and once with an Euclidean one. A partially mixed variational principle is proposed on the base of which an efficient hybrid finite-element formulation, which does not exhibit locking phenomena, is developed. Various numerical examples of shell deformations at finite rotations, with excellent element performance, are presented.

Carlo Sansour (Technische Hochschule Darmstadt, Fachgebiet Maschinenelemente und Akustik, Magdalenenstr. 4, 64289, Darmstadt, Germany), “Large strain deformations of elastic shells constitutive
ABSTRACT: This paper is concerned with the constitutive modelling of large elastic strains with applications to shells. The shell theory itself is characterized by seven degrees of freedom and enjoys the following features: (1) it circumvents the use of a rotation tensor preserving the Euclidean structure of the configuration space and (2) it is capable to the application of a three-dimensional constitutive law. In addition, an elastic finite strain constitutive law is developed which: (1) covers the whole range of deformation experimentally given by Treloar and (2) is formulated in terms of invariants avoiding the use of principal stretches. The second feature means that the model is generalizable to anisotropic material behaviour, and that it allows for straightforward computations of the tangent operator making the whole theory well suited for large strain computations. In addition to the four-node and nine-node displacement-based finite elements, an enhanced strain finite element is examined. Its efficiency is compared with that of displacement-based element formulations. Different examples of large strain shell deformations are presented. It is shown that the application of the enhanced strain concept in the nonlinear constitutive range limits severely the stability of computation.

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“A Shell Theory with Scale Effects, Higher Order Gradients, and Meshfree Computations”, Chapter in Recent Developments and Innovative Applications in Computational Mechanics, pp 107-114, 2011, DOI: 10.1007/978-3-642-17484-1_13

ABSTRACT: In recent times, scale effects have been given great attention due to the fact that they characterise the material behaviour at lower scales. The later being considered an important area of research in material sciences and engineering. Many applications, however, are concerned with so-called thin domains (e.g. thin films, nano tubes) which makes it more effective to run the computations via a shell theory. Hence the motivation to develop a shell theory which includes in a natural way scale effects. This is done by extending and modifying previous 3-d generalized formulations of the authors [5] to accommodate for the shell. Applications are discussed for the buckling of thin shells at small scales.

References listed at the end of the paper:

P. Wriggers (T. H. Darmstadt, Darmstadt, Germany), “Continuum mechanics, nonlinear finite element

ABSTRACT: This three lectures course will give a modern concept of finite-element-analysis in nonlinear solid mechanics using material (Lagrangian) and spatial (Eulerian) coordinates. Elastic response of solids is treated as an essential example for the geometrically and material nonlinear behavior. Furthermore a brief introduction in stability analysis and the associated numerical algorithms will be given. A main feature of these lectures is the derivation of consistent linearizations of the weak form of equilibrium within the same order of magnitude, taking also into account the material laws in order to get Newton-type iterative algorithms with quadratic convergence. The lectures are intended to introduce into effective discretizations and algorithms based on a well founded mechanical and mathematical analysis.

References listed at the end of the paper:
DOI: 10.1002/nme.1620371503

ABSTRACT: A numerical time-integration scheme for the dynamics of non-linear elastic shells is presented that simultaneously and independent of the time-step size inherits exactly the conservation laws of total linear, total angular momentum as well as total energy. The proposed technique generalizes to non-linear shells recent work of the authors on non-linear elastodynamics and is ideally suited for long-term/large-scale simulations. The algorithm is second-order accurate and can be immediately extended with no modification to a fourth-order accurate scheme. The property of exact energy conservation induces a strong notion of non-linear numerical stability which manifests itself in actual simulations. The superior performance of the proposed scheme method relative to conventional time-integrators is demonstrated in numerical simulations exhibiting large strains coupled with a large overall rigid motion. These numerical experiments show that symplectic schemes often regarded as unconditionally stable, such as the mid-point rule, can exhibit a dramatic blow-up in finite time while the present method remains perfectly stable.


ABSTRACT: Investigation of nonlinear static and dynamic response of solids and structures requires knowledge about the stability behaviour. In general we have to detect singular points (e.g. limit or bifurcation points) or the global loss of stability and furthermore one has to be able to follow nonlinear solution paths. References listed at the end of the paper:


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ABSTRACT: This paper presents a general formulation of thin incompressible membranes and investigates the behavior of soft biotissues using the finite element method. In particular the underlying hyperelastic model is chosen to examine the highly non-linear constitutive relation of blood vessels which are considered to be perfectly elastic, homogeneous and (nearly) incompressible. First, the stress-deformation relation and the elastic tangent moduli are derived in a very general material setting which is subsequently specified for blood vessels in terms of Green-Lagrangian strains. Based on the principle of virtual work the finite element equations are provided and briefly discussed. Consistent linearization of the weak form of equilibrium and the external pressure term ensures a quadratic convergence rate of the iterative solution procedure. On the computational side of this work an effort was undertaken to show a novel approach on the investigation of soft tissue biomechanics. Representative numerical analyses of problems in vascular mechanics are discussed that show isochoric finite deformations (large rotations and large strains). In particular, a numerical simulation of the interaction between an inflated balloon catheter and a plaque deposit on the wall of a blood vessel is presented.

ABSTRACT: Author's own experimental and theoretical researches on buckling of shells of revolution are summarized with special emphasis on the conceptual approach behind them. Effect of the biaxial stress states is depicted in form of interaction diagrams. Design formulas based on these concepts and computations carried out for reinforced concrete hyperboloidal cooling tower shells allow the erection of very large and thin cooling towers which meanwhile have reached the 200m limit in height.

E.L. Jansen (Faculty of Aerospace Engineering, Delft University of Technology, Kluysterweg 1, HS 2629, Delft, Netherlands), “Non-stationary flexural vibration behaviour of a cylindrical shell”, International Journal of
ABSTRACT: An analytical/numerical method involving a small number of generalized coordinates is presented for the analysis of the non-linear vibration and dynamic stability behaviour of imperfect anisotropic cylindrical shells. The small amplitude vibration mode is characterized by \( m \) axial half-waves and \( n \) circumferential full waves. The radial excitation is assumed to have the same spatial distribution as the small amplitude vibration mode. For large excitations, a coupled mode response can occur, consisting of the directly excited “driven mode” and the so-called “companion mode”. The latter has the same spatial form as the driven mode, but is circumferentially 90 degrees out-of-phase. Donnell-type governing equations are used and classical laminate theory is employed. The assumed modes approximately satisfy “simply supported” boundary conditions. A formulation is used which can account for a possible skewedness of the asymmetric modes. Certain axisymmetric modes which are essential for a satisfactory description of the non-linear behaviour are also included in the assumed deflection function. The effect of axial and torsional inertia, including the inertia effect of a ring or disk at the loaded end of the shell, can be taken into account approximately. Viscous modal damping is included in the analysis. The shell is statically loaded by axial compression, radial pressure, and torsion. A two-mode imperfection model, consisting of an axisymmetric and an asymmetric mode, is used. The static state response is assumed to be affine to the given imperfection. In order to find approximate solutions for the dynamic state equations, Hamilton's principle is applied to derive a set of modal amplitude equations. The dynamic response is obtained via numerical time integration of the set of non-linear ordinary differential equations. The coupled mode non-linear vibration behaviour of an axially loaded isotropic shell is simulated using this approach. Non-stationary vibrations, where the response drifts between single mode and different types of coupled mode solutions, are observed in a small frequency region near resonance.


ABSTRACT: We present in this paper a simple finite element implementation of Koiter’s perturbation analysis for initial post-buckling of general shell structures. The calculation of post-buckling curvature coefficients shows converge problems when careless finite element implementation of Koiter’s analysis is carried out. Instead of using special formulations, we show that reasonably accurate results can be obtained by extending an existing linear triangular shell element with a nonlinear strain contribution derived from simple linear displacement shape functions. The resulting constant strains alleviate locking phenomena in the calculation of the post-buckling coefficients. Numerical results are shown to validate the proposed approach.

References listed at the end of the paper:


ABSTRACT: Analytical–numerical models to analyse the flexural vibration behaviour of anisotropic cylindrical shells are presented. The two models (denoted as Level-1 and Level-2 Analysis) have different levels of complexity and can be used to study the influence of important parameters, such as geometric imperfections, static loading, and boundary conditions. A specific anisotropic shell is used in the calculations in this paper. The influence of the imperfection shape and amplitude on the natural frequency is investigated for this shell via both the Level-1 and the Level-2 Analysis. Imperfections with the shape of the “lowest vibration mode” give a decrease of the natural frequency with increasing imperfection amplitude. The results of the Level-2 Analysis for the effect of imperfections on the natural frequency are in reasonable agreement with Finite Element calculations.


ABSTRACT: In this paper a multi-mode finite element implementation of Koiter’s initial post-buckling theory with the inclusion of the pre-buckling nonlinearity is presented. Using this implementation a multi-mode initial post-buckling analysis of an axially loaded composite cylindrical shell has been carried out with a small number of representative modes. The implementation has been done in a general purpose finite element code. Results are compared with results from semi-analytical perturbation analysis and from finite element based fully nonlinear analysis.

References listed at the end of the paper:


ABSTRACT: This paper presents a finite element formulation of Koiter's initial post-buckling theory using a multi-mode approach. Initial post-buckling theory provides direct information about the imperfection sensitivity of a structure under compressive loading, and is also the basis of a nonlinear reduced order model. The objective of the present work is to illustrate the capability of the implementation for buckling analysis of shell structures including modal interaction. A coupled mode initial post-buckling analysis for a composite cylindrical shell under axial compression, including the effect of a nonlinear pre-buckling state, has been carried out using a small number of representative modes. For small imperfection amplitudes the limit-point buckling loads obtained with the reduced order model compare reasonably well with full model nonlinear analysis, illustrating that a fast prediction of the coupled mode response of imperfect shells is possible using the approach proposed.

References listed at the end of the paper:
Eelco Jansen (1), Tanvir Rahman (2) and Zafer Gurdal (3)

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ABSTRACT: A finite element formulation of a reduction method for dynamic stability analysis of imperfection-sensitive shell structures is presented. The reduction method makes use of a perturbation approach, initially developed for static buckling and later extended to dynamic buckling analysis. The single mode dynamic buckling analysis and its extension to parametric excitation analysis are described. The approach is available within a general purpose finite element code. Characteristic results for the parametric excitation analysis of a composite cylindrical shell are shown.

References listed at the end of the paper:

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ABSTRACT: In this paper a finite element formulation of a reduction method for dynamic buckling analysis of imperfection-sensitive shell structures is presented. The reduction method makes use of a perturbation approach, initially developed for static buckling and later extended to dynamic buckling analysis. The implementation of a single-mode dynamic buckling analysis in a general purpose finite element code is described. The effectiveness of the approach is illustrated by application to the dynamic buckling of composite cylindrical shells under axial and radial step loads. Results of the reduction method are compared with results available in the literature. The results are also compared with full model finite element explicit dynamic analysis, and a reasonable agreement is obtained.

References listed at the end of the paper:

ABSTRACT: This paper aims to show that effective and reliable computer codes can be obtained by a suitable finite element implementation of the Koiter's perturbation method. However, careful attention has to be paid to all the implementation details in order to avoid kinematical inconsistencies that can strongly affect the results.

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“The direct prediction of buckling loads of shells under axial compression using VCT – Towards an upgraded approach”, 29th Congress of the International Council of the Aeronautical Sciences, St. Petersburg, Russia, September 7-12, 2014

ABSTRACT: The availability of a Vibration Correlation Technique (VCT) for nondestructive determination of buckling loads of cylindrical shells has obvious advantages. Earlier, a semi-empirical VCT approach has been developed and applied successfully for the prediction of the buckling load of closely stiffened aluminum shells. In the present paper, a possibility to support and improve the estimates of this semi-empirical VCT approach by means of the application of analysis tools is proposed. Two semi-analytical models with different levels of complexity will be used for this purpose. In the two approaches employed, both the nonlinear effect of the static state and the nonlinear effect of the geometric imperfections are represented. These two methods form the basis of an extension of the existing semi-empirical Vibration Correlation Technique for shells, to a VCT in which vibration measurements and analysis tools are combined. In this paper, the capability of the analysis tools which can be used to improve the VCT is illustrated.

References listed at the end of the paper:


ABSTRACT: A method of localization is proposed to lower the high order of equations in FEM calculation for the stability of a complex thin-walled structure. The localized analysis enables us to obtain both the upper and lower limits for the bifurcating point in a whole linear-elastic structural system, as well as an approximate solution to asymptotic post-buckling problem. Some numerical examples are included.

References listed at the end of the paper:

G.M.A. Schreppers (1) and C.M. Menken (2)
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(2) Department of Mechanical Engineering, Eindhoven University of Technology, The Netherlands
“Mode-reduction applied to initial post-buckling behavior”, Chapter in DIANA Computational Mechanics ’94, pp 287-296, 1994

ABSTRACT: This paper presents a perturbation approach for analyzing the (initial) post-buckling behavior of elastic structures. In this perturbation a small number of buckling modes is taken into account. This approach results in a potential energy function which is defined in terms of amplitudes of the selected modes. The post-buckling displacement field is solved from the reduced set of equilibrium equations where the unknowns are the amplitudes of the Euler modes which are selected for the asymptotic expansion. To perform this technique the segment PERTUR in module *EULER is designed in DIANA 6.0. The theory of this segment and two calculating examples are demonstrated.

References listed at the end of the paper:
2. DIANA 5.1 User’s Manual.

Hae-Young Jung, Jong-Rae Cho and Won-Byung Bae, “Buckling analysis of composite cylindrical shell using numerical analysis method”, Transactions of the Korean Society of Mechanical Engineers A, 01/2012; 36(1).
ABSTRACT: The objective of this paper is to predict the buckling pressure of a composite cylindrical shell using buckling formulas (ASME 2007, NASA SP 8007) and finite element analysis. The model in this study uses a stacking angle of [0/90]12t and USN 125 composite material. All specimens were made using a prepreg method. First, finite element analysis was conducted, and the results were verified through comparison with the hydrostatic pressure buckling experiment results. Second, the values obtained from the buckling formula and the buckling pressure values obtained from the finite element analysis were compared as the stacking angle was changed in increments from to . The linear and nonlinear results of the finite element analysis were consistent with the results of the experiment, with a safety factor of 0.85-1. Based on the above result, the ASME 2007 formula, a simplified version of the NASA SP-8007 formula, is regarded as a buckling formula that provides a reliable safety factor.


ABSTRACT: The non-linear dynamic behavior of suddenly loaded composite shells is the subject of this research. The objective of the research is two-fold: (1) to characterize the apparently random physical behavior sometimes observed in the finite element analysis as either numerical instability, chaotic behavior, or both; and (2) to develop criteria for choosing time steps for the finite element model, referred to as DSHELL. This displacement based finite element code is capable of dynamic analysis of plates, arches, and cylindrical shells undergoing large displacements and moderately large rotations during deformation. DSHELL uses a 36-DOF isoparametric shell element to obtain numerical results. A simplified shell model (MSHELL) is developed to provide a shell analog that requires much less computer time to run than the full-up finite element model. The results of the investigations using this simplified model are then applied toward understanding behavior seen in the finite element code. The simplified model and the composite shell exhibit chaotic behavior after collapse. For loads not sufficient to cause collapse, the composite shell experiences oscillations at the panel edges of a type associated with near-chaotic behavior. Significant in-plane oscillations (parametric resonances) are exhibited by the suddenly-loaded composite shell. Extensive use of the Fast Fourier Transform (FFT) is made to investigate behavior of the MSHELL and DSHELL models in the frequency domain. The composite shell is compared to an isotropic shell of identical physical dimensions and static collapse strength, showing the primary effect of isotropy to be increased flexibility in all displacement directions. A method is developed using MSHELL for choosing appropriate time steps for analyses using DSHELL. References listed at the end of the thesis.


ABSTRACT: The Implicit Corotational Method or simply ICM is a powerful tool for defining geometrically nonlinear structural models. Its main feature is the possibility of obtaining nonlinear models starting from linear ones in an easy and automatic fashion. This has great potential because the literature is full of linear theories while, conversely, satisfactory nonlinear models are not widely available. (text omitted) Our aim is to show that the ICM, by decoupling the kinematical coherency from the elastic response, can make a useful contribution to
this also allow us to directly recover the results provided by the tradition. The method is based on the polar decomposition theorem and the corotational description of motion, which is directly applied at the continuum level. (text omitted) The theoretical features of the ICM are presented and its main items are discussed referring to some implementations to planar and spatial beam and thin plate models. (text omitted) The FEM implementation is provided for both nonlinear 3D beam and plate models. For the beam model (based on Saint Venant theory) the assumptions about the rotation parameters and the details on handling finite rotations are given clearly. The accuracy of some finite elements that differ for the interpolation laws assumed for the kinematics and statics fields and for the interpolations strategy is pointed out. For the plate model (based on Kirchoff hypothesis) the proposed finite element is implemented in asymptotic FEM code. A large amount of numerical analysis is performed, also comparing beam and plate based solutions. The good agreement between them shows the accuracy and capability of the proposed approach for numerical implementations.

References listed at the end of the dissertation:
[50] R. Casciaro, G. Garcea, A. Madeo, 'Elastic postbuckling analysis; how to recover accurate nonlinear structural models from the linear ones'. 8th World Congress on Computational Mechanics, June 30 - July 5, 2008 Venice, Italy.
[51] G. Garcea, A. Madeo, G. Zagari, R. Casciaro, 'Geometrically nonlinear 3D beam model based on Saint Venant rod theory'. 8th


ABSTRACT: In our previous paper the implicit corotational method (ICM) was presented as a general procedure for recovering objective nonlinear models fully reusing the information obtained by the corresponding linear theories. The present work deals with the implementation of the ICM as a numerical tool for the finite element analysis of nonlinear structures using either a path-following or an asymptotic approach. Different aspects of the FEM modeling are discussed in detail, including the numerical handling of finite rotations, interpolation strategies, and equation formats. Two mixed finite elements are presented, suitable for nonlinear analysis: a three-dimensional beam element, based on interpolation of both the kinematic and static fields, and a rotation-free thin-plate element, based on a biquadratic spline interpolation of the displacement and piece-wise constant interpolation of stress. Both are frame invariant and free from nonlinear locking. A numerical investigation has been performed, comparing beam and plate solutions in the case of thin-walled beams. The good agreement between the recovered results and the available theoretical solutions and/or numerical benchmarks clearly shows the correctness and robustness of the proposed approach as a general strategy for numerical implementations.

References listed at the end of the paper:


ABSTRACT: We investigate a geometrically exact membrane model with respect to its capabilities in describing buckling and wrinkling. The concept is distinct from traditional ones by the introduction of an artificial viscosity related to an adjusted orthonormal frame (rotations). In this way our model is able to capture the detailed geometry of wrinkling while the balance of force equations remains elliptic throughout. The movement of rotations is given by a local evolution equation. We discuss the consistent linearization of the model and the local update of rotations. Numerical examples are presented, which demonstrate the effectiveness of the new model for predicting wrinkles in membranes undergoing large deformation.

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“Implicit Corotational Method: analysis of slender panels assemblages”, (no publisher or date given. Most recent reference is dated 2009)
ABSTRACT: In some recent works, it has been shown that the Implicit Corotational Method (or simply ICM) is a powerful and consolidated approach for recovering nonlinear models starting from the corresponding linear ones both in the cases of continuum and discrete problems (see [1, 2, 3]). The method is based on the polar decomposition theorem and the corotational description of motion, which is directly applied at the continuum level. By referring to the linear stress solution as Biot tensor in corotational frame and using a mixed variational formulation, we obtain an automated way of using the information gained by the linear model in the nonlinear context. Since linearized model are always available it is easy to obtain, by this way, the corresponding nonlinear models in a form convenient for numerical implementations. A similar picture holds when the approach is directly applied to the finite element discretization. In this case, starting from a linear finite element, the methods give the corresponding nonlinear, frame indifferent, finite element interpolation. As good and accurate is the linear finite element as good will be the corresponding nonlinear one. On the other hand, in the last years high-performance plate finite elements, based on hybrid stress formulation and which exhibit a good behavior in the linear/elastic context, have been developed (see [4, 5, 6] and references therein) showing that they are in general simple, stable, locking–free. On the contrary, the developments of so good finite elements for the geometrically nonlinear case is in general more difficult. The idea of the present work is then to reuse these finite elements in a nonlinear context using the ICM. For this purpose, the format of the element has been rearranged to be suitable for ICM implementation and a specialized corotational algebra for the plate model has been developed [7]. The implementations are carried out in both contexts of path–following and asymptotic approaches, extending the FE codes KASP and RASP already available and aimed at asymptotic and path–following analysis, respectively, of slender panels assemblages (see [8] and related references).

References listed at the end of the paper:
This paper shows that the FEM implementation of Koiter's asymptotic method [W.T. Koiter, On the stability of elastic equilibrium, 1970, Ph.D. Thesis, Delft, 1945. English transl. NASA TT-F10, 883, 1967, AFFDL-TR70-25] outlined by Casciaro et al. [Finite element asymptotic analysis of slender elastic structures: a simple approach, Int. J. Num. Meth. Eng. 35 (1992) 1397–1426] provides accurate and reliable results in the critical and post-critical analysis of non-linear elastic structures. Care, however, does have to be taken in implementing (apparently) minor details to avoid locking effects which adversely affect accuracy and which can destroy the method reliability. As the effects related to the finite element interpolation have been discussed before this paper focuses on the non-linear locking due to the use, implicit in the method, of finite distance extrapolations. Within this scope, it is shown that perturbation algorithms based on compatible formulations can imply a strong critical and post-critical locking when analysing structures characterized by high stiffness ratios in the presence of moderate pre-critical rotations. On the contrary, perturbation algorithms based on independent extrapolations of displacements and stresses furnish reliable results in excellent agreement with those provided by step-by-step analysis, at a small fraction of its computational cost.

ABSTRACT: Finite element asymptotic post-buckling analysis, being based on fourth-order expansions of the strain energy, requires that nonlinear structural modeling be accurate to same order, at least with respect to the rigid motions of the elements. A corotational description is proposed here as a general tool to satisfy this requirement of objectivity, by referring each element to a local frame which moves (rotates) with the element, so filtering its rigid motion. In this description nonlinearity of the problem derives essentially from the change of reference, from the global fixed frame to the local one, the strain energy being governed by their relative rotations. In finite kinematics, this noticeably complicates the algebra for obtaining exact expressions of its variations. Quite simple, basic expressions for the first four corotational derivatives of the strain energy are provided, allowing the set up of a fourth-order accurate asymptotic analysis starting from standard finite elements based on linear or simplified nonlinear local modelings. The formulation is implemented for the analysis of 3D beam assemblages and several numerical results are presented and discussed showing the effectiveness and robustness of the proposed approach in reproducing the nonlinear equilibrium path in both cases of monomodal and coupled multimodal buckling.


ABSTRACT: A path-following non-linear elastic analysis for structures composed of assemblages of flat slender elastic panels is presented. The proposed path-following method employs FEM technology and a
kinematical model to analyse these structures using a Koiter asymptotic approach. As a result it is possible to verify the accuracy achieved by the asymptotic method. The proposed mixed path-following formulation is both efficient and robust with regards to the locking extrapolation phenomenon that strongly affects compatible formulations. The use of an HC finite element makes it possible to avoid the problem of the finite rotations in the space, maintaining a high degree of continuity and making the numeric formulation simple and efficient.

Giovanni Garcea, Antonio Madeo, Giuseppe Zagari, Emira Lanari (Dipartimento di modellistica per l’ingegneria, University of Calabria, Italy), “Implicit Corotational Method: FEM implementation”, ECSM 2009, Lisbon, Portugal

ABSTRACT: The Implicit Corotational Method (ICM) is a powerful and consolidated approach for recovering objective and suitable for FEM implementation nonlinear models fully reusing the corresponding linear ones [1, 2]. An appropriate stress/strain (Biot) representation for the description of the nonlinear elastic continuum, the use of corotational algebra for splitting the body motion into rigid and deformative parts and some assumptions on the reinterpretation of linear theory in the nonlinear context, constitute the basis of the ICM. An important feature of the method is the possibility of obtaining a tool that allow an easy FEM implementation. Different kinds of interpolation strategies (Total and Updated Lagrangian, Corotational) are used within the approach. A standard format and an automated way of implementing the nonlinear models into the FEM context based on the use of algebraic manipulator and aimed at path-following or asymptotic analyses have been developed [3]. The FEM implementation is provided for 3D beam and plate models recovered using ICM. For the 3D beam model, based on Saint Venant theory [2], the assumptions about the rotation parameters and the details on handling finite rotations are given clearly. The accuracy of some mixed finite elements that differ for the interpolation laws assumed for the kinematics and statics fields and for the interpolations strategy is pointed out. For the thin plate model, based on Kirchoff hypothesis [1], the proposed finite element is implemented as specialized one in asymptotic FEM code (see [7]). A numerical investigation has been performed, also comparing beam and plate based solutions in the case of thin–walled beams. The good agreement between the recovered results with the theoretical ones and the numerical benchmarks, shows clearly the correctness and capability of the proposed approach for numerical implementations.

References listed at the end of the paper:
ABSTRACT: The Implicit Corotational Method (ICM) is powerful and consolidated approach for recovering frame invariant nonlinear models. An appropriate stress/strain (Biot) representation for the description of the nonlinear elastic continuum, the application of corotational algebra for splitting the body motion into rigid and deformative parts and a reinterpretation of linear theory in the nonlinear context, constitute the basis of the ICM. An important feature of the method is the possibility of obtaining a tool that allows an easy FEM implementation. Different kinds of interpolation strategies (Total and Updated Lagrangian and Corotational) are used within the ICM. A standard format and an automated way of implementing the nonlinear models into the FEM context have been developed and used for path-following or asymptotic analyses. The work presents some FEM applications regarding 3D beam and plate models recovered using ICM. A numerical investigation has been performed, also comparing beam and plate based solutions in the case of thin-walled beams. The good agreement between the recovered results with the theoretical ones and the numerical benchmarks, clearly shows the suitability and capability of the proposed approach for numerical implementations.

References listed at the end of the paper:
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“Finite rotation shell elements for nonlinear statics and dynamics”, European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2000), Barcelona, 11-14 September, 2000

ABSTRACT: In this work we consider geometrically exact shell model subjected to finite rotations. We present some developments on handling constrained finite rotations that are of direct use in nonlinear static and dynamic finite element analysis of smooth shells. Relationships between different preferred parametrizations of constrained finite rotations are first given in a form of commutative diagrams. Incremental rotation vector for smooth shells is presented as the most suitable parameter for the standard incremental solution strategy as well as for the construction of the time-stepping schemes. An appropriate consideration is given to construct the corresponding Newmark implicit time stepping schemes for constrained rotations.

References listed at the end of the paper:

14. A. Ibrahimbegovic, Stress resultant geometrically exact shell theory for finite rotations and its finite element implementation,
ABSTRACT: A simple non-linear stress resultant shell finite element is presented. The underlying shell theory is developed from the three-dimensional continuum theory via standard assumptions on the displacement field. A model for thin shells is obtained by approximating terms describing the shell kinematics is consistently linearized, leading to the Newton-Raphson numerical procedure, which preserves quadratic rate of asymptotic convergence. A range of linear and non-linear tests is provided and compared with available solutions to illustrate the approach.

References listed at the end of the paper:


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A. D. Lanzo (DiSGG, Università della Basilicata, 85100 Potenza, Italy), “A Koiter's perturbation strategy for the imperfection sensitivity analysis of thin-walled structures with residual stresses”, Thin-Walled Structures, Vol. 37, No. 1, May 2000, pp. 77-95, doi:10.1016/S0263-8231(00)00008-2
ABSTRACT: This paper suggests a strategy for the imperfection sensitivity analysis of elastic thin-walled structures with notable residual stresses. The analysis is carried out by means of a Koiter's perturbation approach. The concept of imperfection, traditionally associated with geometric and load factors, is extended in this paper to the residual stresses. The strategy is implemented in a FEM code. A comparison of the obtained results allows a discussion on the accuracy and the influence of the different coefficients connected to the asymptotic analysis of the residual stresses.

ABSTRACT: This paper provides a review of recent research advances and trends in the area of stability of unstiffened circular cylindrical shells subjected to general non-uniform axial compressive stresses. Only the more important and interesting aspects of the research, judged from a personal viewpoint, are discussed. They can be crudely classified into four categories: (1) shells subjected to non-uniform loads; (2) shells on discrete supports; (3) shells with intended cutouts/holes; and (4) shells with non-uniform settlements.

cutouts/holes; and (4) shells with non-uniform settlements.

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68. ISO 11697, 1995: Bases for design of structures-loads due to bulk materials.

ABSTRACT: This paper presents a finite element study of the non-linear buckling behaviour of column-supported steel cylinders. Both perfect and imperfect shells are examined. High compressive stresses develop in the vicinity of the column support and these can lead to buckling of the shell at a load much lower than that for a uniformly supported shell. Imperfections are shown to play an important role in reducing the buckling load even when the structure is supported on a small number of columns.

References listed at the end of the paper:

Anonymous, Lecture 8.9: Design of stringer-stiffened cylindrical shells, ESDEP WG 8, “Plates and Shells”, fgg.uni-lj.si (University of Ljubljana, Slovenia).

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Mousa Khalifa Ahmed, Department of Mathematics, Faculty of Science at Qena, South Valley University, 83523 Qena, Egypt, “Elastic Buckling Behaviour of a Four-Lobed Cross Section Cylindrical Shell with Variable Thickness under Non-Uniform Axial Loads”, Mathematical Problems in Engineering Volume 2009 (2009), Article ID 829703, 17 pages, doi:10.1155/2009/829703

ABSTRACT: The static buckling of a cylindrical shell of a four-lobed cross section of variable thickness subjected to non-uniform circumferentially compressive loads is investigated based on the thin-shell theory. Modal displacements of the shell can be described by trigonometric functions, and Fourier's approach is used to separate the variables. The governing equations of the shell are reduced to eight first-order differential equations with variable coefficients in the circumferential coordinate, and by using the transfer matrix of the shell, these equations can be written in a matrix differential equation. The transfer matrix is derived from the nonlinear differential equations of the cylindrical shells by introducing the trigonometric series in the longitudinal direction and applying a numerical integration in the circumferential direction. The transfer matrix approach is used to get the critical buckling loads and the buckling deformations for symmetrical and antisymmetrical shells. Computed results indicate the sensitivity of the critical loads and corresponding buckling modes to the thickness variation of cross section and the radius variation at lobed corners of the shell.

References listed at the end of the paper:
Fourier’s approach is used to separate the variables. The vibration equations of the shell are reduced to eight first-order differential equations in the circumferential coordinate, and by using the transfer matrix of the shell,
these equations can be written in a matrix differential equation. The transfer matrix is derived from the nonlinear differential equations of the cylindrical shells by introducing the trigonometric functions in the longitudinal direction and applying a numerical integration in the circumferential direction. The proposed method is used to get the vibration frequencies and the corresponding mode shapes of symmetrical and antisymmetrical type-modes. Computed results indicate the sensitivity of the frequency parameters and the bending deformations to the geometry of the non-uniformity of the shell, and also to the radius of curvature at the lobed corners.


ABSTRACT: The objective of this paper is to study the elastic buckling characteristics of an axially loaded cylindrical shell of a three lobed cross section of variable thickness subjected to combined compression and bending loads based on the thin-shell theory and using the computational transfer matrix method. Modal displacements of the shell can be described by trigonometric functions and Fourier’s approach is used to separate the variables. The governing equations of the shell are reduced to eight first-order differential equations with variable coefficients in the circumferential coordinate, and by using the transfer matrix of the shell, these equations can be written in a matrix differential equation. The transfer matrix is derived from the non-linear differential equations of the cylindrical shells by introducing the trigonometric function in the longitudinal direction and applying a numerical integration in the circumferential direction. The computational transfer matrix method is used to get the critical buckling loads and the buckling deformations for symmetrical and antisymmetrical buckling-modes. Computed results indicate the sensitivity of the critical loads and corresponding buckling modes to the thickness variation of cross-section and the radius variation at lobed corners of the shell.


ABSTRACT: This paper presents the transfer matrix analysis of nonlinear dynamic response of stiffened thin shells in resonance regions of vibration. Considered is the interaction of geometric and physical nonlinearities. Direct time integration procedures to solve the equations of motion are used. Corresponding incremental transfer matrices are formulated in an updated Lagrangian reference mesh. Illustrative numerical example is presented, showing the influence of studied nonlinear interactions in resulting dynamic response of thin shells.


ABSTRACT: The present paper is concerned with the nonlinear finite solution of the postbuckling instability behaviour of thin shell structures in resonance regions of vibration. The development of reliable and efficient techniques for handling the dynamic postbuckling behaviour is emphasized. An illustrative solution associated with the postbuckling resonance response of thin shells is presented.

Alexander Tesar (Institute of Construction and Architecture, Slovak Academy of Sciences, Dubravska cesta 9,
ABSTRACT: Some research results of failure behaviour of carbon fiber composites are presented. The solution of material instability on the basis of fiber kinking theory is adopted for the treatment of the failure process. The micromechanical modeling adopting the FETM-approach is used for a numerical analysis of the problem. Some numerical and experimental results with an actual application are submitted in order to demonstrate the efficiency of the approaches suggested.

ABSTRACT: In this paper, the Flügge's shell theory is modeled and the transfer matrix approach is used to investigate the elastic buckling behaviour of a cylindrical shell with a four lobed cross section with reduced thickness over part of its circumference under axial compressive loads. Modal displacements of the shell can be described by trigonometric functions and Fourier's approach is used to separate the variables. The buckling equations of the shell are reduced to eight first-order differential equations in the circumferential coordinate, and by using the transfer matrix of the shell, these equations can be written in a matrix differential equation. The transfer matrix is derived from the differential equations of the cylindrical shells by introducing the trigonometric functions in the longitudinal direction and applying a numerical integration in the circumferential direction. The method is used to get the critical buckling loads and the buckling deformations for symmetrical and antisymmetrical shells. Computed results indicate the sensitivity of the buckling loads and the corresponding buckling deformations to the geometry of the non-uniformity of the shell, and also to the radius of curvature at the lobed corners.

Mousa Khalifa Ahmed (Dept. of Mathematics, Faculty of Science at Qena, South Valley University, Qena City, Egypt), “Vibration and Buckling Approximation of an Axially Loaded Cylindrical Shell with a Three Lobed Cross Section Having Varying Thickness”, Applied Mathematics, Vol. 2, No. 3, March 2011, doi: 10.4236/am.2011.23039
ABSTRACT: On the basis of the thin-shell theory and on the use of the transfer matrix approach, this paper presents the vibrational response and buckling analysis of three-lobed cross-section cylindrical shells, with circumferentially varying thickness, subjected to uniform axial membrane loads. A Fourier approach is used to separate the variables, and the governing equations of the shell are formulated in terms of eight first-order differential equations in the circumferential coordinate, and by using the transfer matrix of the shell, these equations are written in a matrix differential equation. The transfer matrix is derived from the non-linear differential equations of the cylindrical shells with variable thickness by introducing the trigonometric series in the longitudinal direction and applying a numerical integration in the circumferential direction. The natural frequencies and critical loads beside the mode shapes are calculated numerically in terms of the transfer matrix elements for the symmetrical and antisymmetrical vibration modes. The influences of the thickness variation of crosssection and radius variation at lobed corners of the shell on the natural frequencies, mode shapes and critical loads are examined.

References listed at the end of the paper:
Mousa Khalifa Ahmed (Dept. of Mathematics, Faculty of Science at Qena, South Valley University, Egypt),

“Computational buckling of a three-lobed cross section cylindrical shell with variable thickness under combined compression and bending loads”, International Journal of Mechanical Engineering Research and Development (IJMERD), Vol. 3, No. 1, pp. 11-27, January-March 2013, ISSN 2248-9347(print), ISSN 2248-9355(Online)

ABSTRACT: The objective of this paper is to study the elastic buckling characteristics of an axially loaded cylindrical shell of a three-lobed cross section of variable thickness subjected to combined compression and bending loads based on the thin-shell theory and using the computational transfer matrix method. Modal displacements of the shell can be described by trigonometric functions and Fourier’s approach is used to separate the variables. The governing equations of the shell are reduced to eight first-order differential equations with variable coefficients in the circumferential coordinate, and by using the transfer matrix of the shell. These equations can be written in a matrix differential equation. The transfer matrix is derived from the non-linear differential equations of the cylindrical shells by introducing the trigonometric function in the longitudinal direction and applying a numerical integration in the circumferential direction. The computational transfer matrix method is used to get the critical buckling loads and the corresponding buckling deformations for symmetrical and antisymmetrical buckling modes. Computed results indicate the sensitivity of the critical loads and corresponding buckling modes to the thickness variation of cross-section and the radius variation at lobed corners of the shell.


ABSTRACT: In this paper, the framework of the Flügge's shell theory, the transfer matrix approach and the Romberg integration method has been employed to investigate the buckling analysis of radial loaded oval cylindrical shell with parabolically varying thickness along of its circumference. Trigonometric functions are used to form the modal displacements of the shell and Fourier's approach is used to separate the variables. The mathematical analysis is formulated to overcome the difficulties related to mode coupling of variable curvature and thickness of the shell. Using the transfer matrix of the shell, the buckling equations of the shell are reduced to eight first-order differential equations in the circumferential coordinate and rewritten in a matrix form and solved numerically. The proposed model is adopted to get the critical buckling loads and the corresponding buckling deformations for the symmetrical and antisymmetrical modes of buckling. The influences of the shell geometry, orthotropic parameters, ovality parameter, and thickness ratio on the buckling parameters and the bending deformations are presented for different type-modes of buckling.


ABSTRACT: For the first time, a new cross-section profile and efficient method are developed for the vibration analysis of isotropic and orthotropic cylindrical shells having circumferentially varying profile of a cardioid cross-section expressed as an arbitrary function, under thermal gradient effect. The governing equations of orthotropic cylindrical shells with varying thermal gradient around its circumference are derived as a boundary-value problem and solved numerically as an initial-value problem, based on the framework of Flügge's shell theory, transfer matrix approach and Romberg integration method. As a semi-analytical procedure, the trigonometric functions are used with Fourier's approach to approximate the solution in the longitudinal
direction and also to reduce the two-dimensional problem to one-dimensional one. The thermal gradient is assumed to arise due to the variation of Young's moduli and shear modulus, along the circumferential direction of the shell. The results are obtained to indicate the effects of cardioid cross-section on the natural frequencies and corresponding mode shapes in the thermal environment as well as the sensitivity of the vibration behavior to the thermal gradient ratio and the orthotropy of the shell is also investigated for different types of vibration modes. In general, close agreement between the obtained results and those of other researchers has been found.

Mousa Khalifa Ahmed (Dept. of Mathematics, Faculty of science at Qena, South Valley University, Egypt), “How the thermal gradient affects the vibration behavior of a spinning orthotropic oval cylindrical shell”, International Journal of Applied Mechanics, Vol. 7, No. 4, August 2015

ABSTRACT: Based on the framework of Flügge's shell theory, transfer matrix approach and Romberg integration method, we investigated how the thermal gradient affects the vibration behavior of rotating isotropic and orthotropic oval cylindrical shells. The governing equations of orthotropic oval cylindrical shells, under parabolically varying thermal gradient around its circumference, with consideration of the effects of initial hoop tension and centrifugal forces due to the rotation are derived, and they are put in a matrix differential equation as a boundary-value problem. As a semianalytic solution, the trigonometric functions are used with Fourier's approach to approximate the solution in the longitudinal direction, and also to reduce the two-dimensional problem in to an one-dimensional one. Using the transfer matrix approach, the equations can be written in a matrix differential equation of first-order and solved numerically as an initial-value problem. The proposed model is applied to get the natural frequencies and vibratory displacement of the symmetrical and antisymmetrical vibration modes. The sensitivity of the vibration behavior to the rotational speed, the thermal gradient, the ovality and orthotropy of the shell is studied for different type-modes of vibration. The present method is found to be accurate when compared with the results available in the literature.

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Nimal Rajapakse, Alireza Nojeh, Simon Fraser University, Burnaby, Canada

ABSTRACT:
Recently, nano devices have been developed which use Carbon Nanotubes (CNTs) as structural elements. To define the range of applicability of CNTs in such devices, it is important to investigate failure modes such as the axial buckling limit. Classical continuum models are inaccurate as they are unable to account for the size-effects in such devices. In this work, a modified nonlocal continuum shell model for the axial buckling of CNTs is proposed and compared with a nonlocal model for torsional buckling. This is done through modifying classical continuum models by incorporating basic concepts from nonlocal elasticity. Furthermore, molecular dynamics (MD) simulations are performed on a range of nanotubes with different diameters. Compared to classical models, the modified nonlocal models provide a much better fit to MD simulation results. Using MD simulation results for axial buckling, values of the nonlocal constant and shell thickness are calculated.

ABSTRACT: The development of a new approach based on the energy principle is presented to study the free vibration of shallow conical shells. In the numerical procedure, a set of orthogonally generated and kinematically oriented shape functions, which satisfies the geometric boundary conditions at the outset, is proposed to overcome the mathematical complexity in expressing the geometry and variable surface curvature of these shells. To establish the accuracy of this method, convergence and comparison studies have been carried out. In this study, the effects of various shell parameters on the fundamental and higher mode frequencies are investigated. It is found that monotonic increases in the fundamental nondimensional frequency parameter occurs when the cone vertex angle or base subtended angle is increased independently for the cantilever conical shell. The fundamental frequency parameter also becomes higher for the fully clamped conical shell with higher panel-length to cone-length (a/s) ratio. A set of first published vibration mode shapes is also presented.

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ABSTRACT: A mesh-free radial basis function (RBF) method is employed for the buckling analysis of non-uniformly loaded thick plates. The field variables are approximated using a set of scattered nodes in the problem domain. The number of nodes and nodal distribution in the problem domain can be easily changed without a complex procedure for desired computational accuracy. The shape functions possess the ‘partition of unity’ properties. Based on the two-dimensional (2D) plane stress problem, a variational form of the static system of equations is formulated in terms of displacements, and is discretised. The initial (i.e., pre-buckling) stresses are obtained by solving the discrete system of equations. Based on the first-order shear deformation plate theory, a variational form of the plate problem with previously obtained initial stresses is established and discretised as the eigenvalue equation. The buckling loads of circular, trapezoidal and skew plates are presented. The present results have good convergence and are in good agreement with the finite element solutions. The present mesh-free radial basis function method is effective for the buckling analysis of non-uniformly loaded plates.

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ABSTRACT: Buckling behavior of single-walled and multiwalled carbon nanotubes is studied under axial compression in this work. Brenner’s “second generation” empirical potential is used to describe the many-body
short-range interatomic interactions for single-walled carbon nanotubes, while the Lennard Jones model for the van der Waals potential is added for multiwalled carbon nanotubes. Single-, two-, three-, and four-walled nanotubes are considered in the simulations in order to examine the effects of the number of layers on the structural properties of the multiwalled nanotubes. Results indicate that there exists an optimum diameter for single-walled nanotubes at which the buckling load reaches its maximum value. The buckling load increases rapidly with the increase of the diameter up to the optimum diameter. A further increment beyond this diameter results in a slow decline in buckling load until a steady value is reached. The effects of layers on the buckling load of multiwalled nanotubes are also examined.

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ABSTRACT: This paper presents thermal buckling and post-buckling analyses for moderately thick laminated rectangular plates that contain functionally graded materials (FGMs) and subjected to a uniform temperature change. The theoretical formulation employs the first-order shear deformation theory and accounts for the effect of temperature-dependent thermoelastic properties of the constituent materials and initial geometric imperfection. The principle of minimum total potential energy, the differential quadrature method, and iterative algorithms are used to obtain critical buckling temperatures and the post-buckling temperature-deflection curves. The results are presented for both symmetrically and unsymmetrically laminated plates with ceramic/metal functionally graded layers, showing the effects of temperature-dependent properties, layup scheme, material composition, initial imperfection, geometric parameters, and boundary conditions on buckling temperature and thermal post-buckling behavior.

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ABSTRACT: The material properties of functionally graded materials (FGMs) possess inherent randomness due to their complicated fabrication process, in which the total control of various design parameters is often impossible. The present work investigates the effect of this randomness on the elastic buckling of FGM rectangular plates which are resting on an elastic foundation and subjected to uniform in-plane edge compressions. The interaction between the plate and foundation is included in the formulation with a two-parameter Pasternak model. The elastic material properties (including the Young’s modulus and Poisson’s ratio of each constituent material) and the foundation stiffness parameters are modeled as independent random variables. First-order shear deformation plate theory and a mean-centered first-order perturbation procedure are
used to examine the stochastic characteristics of the buckling load. Typical results are presented for plates with aluminum/zirconia two-phase functionally graded material to show the influence of variation in material constants and foundation stiffness parameters, volume fraction index, edge in-plane forces, side-to-thickness ratio, and plate aspect ratio on the second-order statistics of buckling loads.

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“Thermo-mechanical post-buckling of FGM cylindrical panels with temperature-dependent properties”

ABSTRACT: This paper presents thermo-mechanical post-buckling analysis of cylindrical panels that are made of functionally graded materials (FGMs) with temperature-dependent thermo-elastic properties that are graded in the direction of thickness according to a simple power law distribution in terms of the volume fractions of the constituents. The panel is initially stressed by an axial load, and is then subjected to a uniform temperature change. The theoretical formulations are based on the classical shell theory with von-Kármán–Donnell-type nonlinearity. The effect of initial geometric imperfection is also included. A differential quadrature (DQ) based semi-analytical method combined with an iteration process is employed to predict the critical buckling load (where it is applicable) and to trace the post-buckling equilibrium path of FGM cylindrical panels under thermo-mechanical loading. Numerical results are presented for panels with silicon nitride and nickel as the ceramic and metal constituents. The effects of temperature-dependent properties, volume fraction index, axial load, initial imperfection, panel geometry and boundary conditions on the thermo-mechanical post-buckling behavior are evaluated in detail through parametric studies.

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ABSTRACT: This paper presents a mesh-free Galerkin method for the free vibration and stability analyses of stiffened plates via the first-order shear deformable theory (FSDT). The model of a stiffened plate is formed by (1) regarding the plate and the stiffener separately, (2) imposing displacement compatible conditions between the plate and the stiffener so that displacement fields of the stiffener can be expressed in terms of the mid-surface displacement of the plate, and (3) superimposing the strain energy of plate and stiffener. Because there are no meshes used in this method, the stiffeners can be placed anywhere on the plate and need not be placed along the mesh lines. Several numerical examples are computed by this method to show its accuracy and convergence. The present results demonstrate good agreement with the existing solutions given by other researchers and the ANSYS. Influences of support size and order of the complete basis functions on the numerical accuracy are also investigated.
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ABSTRACT: A Ritz method based on kernel particle approximation for the field variables is proposed for the postbuckling analysis of laminated composite plates. The first-order shear deformation plate theory (FSDT) is employed to model the plate flexure. The Ritz method is used to obtain the discretized non-linear equations. A geometrically non-linear analysis is used to trace the postbuckling paths of the plate. Typical numerical examples including isotropic plates, and cross-ply and angle-ply laminated composite plates have been solved using the proposed method. The results are in close agreement with the series solution as well as previous finite element results available in the literature.

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ABSTRACT: A hybrid continuum mechanics and molecular mechanics model is developed to predict the compressive buckling strain and load for the inelastic buckling of armchair and zigzag carbon nanotubes. The effectiveness of the hybrid model is demonstrated by comparisons of buckling results from the model, molecular dynamics simulations, and continuum models by other work.

References listed at the end of the paper:
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“Geometrically nonlinear analysis of cylindrical shells using the element-free kp-Ritz method”, Engineering Analysis with Boundary Elements, Vol. 31, No. 9, September 2007, pp. 783–792,
doi:10.1016/j.enganabound.2007.01.003

ABSTRACT: In this paper, the geometrically nonlinear analysis of cylindrical shells is carried out using the element-free kp-Ritz method. The first-order shear deformation shell theory, which can cater for both thin and relatively thick shells, is utilized in the present study. Meshfree kernel particle functions are employed to
approximate the two-dimensional displacement field. The nonlinear equilibrium equations are formulated by applying the Ritz procedure to the energy functional of shells. The Newton–Raphson method and the arc length technique are used to determine the load–displacement path. To validate the accuracy and stability of this method, convergence studies based on the support size and number of nodes were performed. Comparisons were also made with the existing results available in the open literature, and good agreement is obtained.


ABSTRACT: The bending buckling of single-walled carbon nanotubes (SWCNTs) is studied in the theoretical scheme of the higher order gradient continuum. The deformation of the underlying lattice vectors is approximated with an extended Cauchy–Born rule in which the effect of the second order deformation gradient is considered, and the continuum constitutive responses are determined by minimizing the energy of the representative cell. A mesh-free method is developed to implement the numerical modeling of SWCNTs, and their bending buckling behavior is numerically simulated with the developed method. The results are compared with those obtained with a full atomistic simulation, and it is revealed that the developed mesh-free method can accurately exhibit the bending deformation of SWCNTs. Different types of carbon nanotubes (CNTs) are studied, and the buckling mechanism is investigated.

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ABSTRACT: This paper employs the atomic-scale finite element method to study bending buckling of single-walled carbon nanotubes (SWNTs). As the bending angle increases, kinks will appear and the morphology of the SWNT will change abruptly. The (15, 0) SWNT changes into a one-kinked structure, and finally contains two kinks; while the (10, 0) SWNT changes into a one-kinked structure, then into a two-kinked one, and finally contains three kinks. Strain energy grows initially as a quadratic function of bending angle, then increases gradually slowly, and finally changes approximately linearly. The energy releases suddenly at morphology bifurcations and the amount depends on degree of morphology change. The simulation shows that the appearance of kinks associated with the large deformation nearby reduces the slope of the strain energy curve in the post-buckling stages and hence increases the flexibility of the SWNTs.

References listed at the end of the paper:


ABSTRACT: In this paper, the linearly conforming radial point interpolation method is extended for geometric nonlinear analysis of plates and cylindrical shells. The Sander’s nonlinear shell theory is utilized and the arc-length technique is implemented in conjunction with the modified Newton–Raphson method to solve the nonlinear equilibrium equations. The radial and polynomial basis functions are employed to construct the shape functions with Delta function property using a set of arbitrarily distributed nodes in local support domains. Besides the conventional nodal integration, a stabilized conforming nodal integration is applied to restore the deformability and to improve the accuracy of solutions. Small rotations and deformations, as well as finite strains, are assumed for the present formulation. Comparisons of present solutions are made with the results reported in the literature and good agreements are obtained. The numerical examples have demonstrated that the present approach, combined with arc-length method, is quite effective in tracing the load-deflection paths of snap-through and snap-back phenomena in shell problems.

References listed at the end of the paper:
ABSTRACT: The buckling response of functionally graded ceramic-metal cylindrical shell panels under axial compression and thermal load is presented here. The formulation is based on the first-order shear deformation shell theory and element-free kp-Ritz method. The material properties of shell panels are assumed to vary through their thickness direction according to a power-law distribution of the volume fraction of constituents. Approximations of the displacement field are expressed in terms of a set of mesh-free kernel particle functions. A stabilized conforming nodal integration approach is employed to estimate the bending stiffness, and the shear and membrane terms are evaluated using a direct nodal integration technique to eliminate membrane and shear locking for very thin shells. The mechanical and thermal buckling responses of functionally graded shell panels are investigated, and the influences of the volume fraction exponent, boundary conditions, and temperature distribution on their buckling strengths are also examined.

References listed at the end of the paper:


ABSTRACT: This paper presents a mechanical and thermal buckling analysis of metal and ceramic functionally graded conical shell panels using the element-free kp-Ritz method. The formulation is based on the first-order shear deformation shell theory, which accounts for the transverse shear strains and rotary inertia, and mesh-free kernel particle functions are employed to approximate the two-dimensional displacement fields. The effective material properties of the functionally graded conical shell panels are assumed to be smooth and continuous through their thickness direction, and are determined according to a power-law distribution of the volume fractions of their constituents. Convergence studies are performed in terms of the number of nodes, and comparisons between the current solutions and those reported in the literature are provided to verify the accuracy of the proposed method. Three types of functionally graded conical shell panels, Al/ZrO2, SUS304/Si3N4, and Al2O3/Ti6Al4V are selected for study, and the effects of the volume fraction, boundary condition, semi-vertex angle, length-to-thickness ratio, and temperature-dependent material properties on the buckling strength are discussed in detail.
ABSTRACT: Stability problems for cylindrical shells under various loading modes were considered in numerous papers. A detailed analysis of such problems can be found, e.g., in the monograph [1]. We refer to the solutions presented in this monograph as classical. For long cylindrical shells in axial compression, one of the buckling modes is the purely beam flexural mode similar to the classical buckling mode of a straight rod. It is well known that it can be studied by using the nonlinear or linearized equations of the membrane theory of shells. In [2], it was shown that, on the basis of such equations constructed starting from the noncontradictory version of geometrically nonlinear elasticity relations in the quadratic approximation [3], under the separate action of the axial compression, external pressure, and torsion, there are also previously unknown nonclassical buckling modes, most of which are shear ones.

In the present paper, we show that the use of the above equations for cylindrical shells under compression and external pressure with simultaneous pure torsion or bending permits revealing the earlier unknown torsional, beam flexural, and beam torsional-flexural buckling modes, which are nonclassical, just as those found in [2]. The second of these buckling modes is realized when axially compressing forces are formed in the shell with simultaneous torsion, and the third of them is realized under compression combined with pure bending. It was found that, earlier than the classical buckling modes, the torsional buckling modes can be realized for relatively short shells with small shear rigidity in the tangent plane, while the second and third buckling modes can be realized for relatively long shells.


ABSTRACT: (cannot cut and paste)

K. T. Hautala Consulting KORTES Ltd., Finland, 2003 The Steel Construction Institute, “Buckling Reduction Factors for Stainless Steel Shell Structures”

ABSTRACT: The material behaviour of stainless steel strongly differs from that of mild steel beyond the proportional limit. Consequently, the buckling behaviour of mild steel structures and stainless steel structures will differ from each other in so far as for any given stainless steel structure of medium slenderness, i.e. belonging to the ‘elastic-plastic’ region, the buckling capacity is lower than for a comparable mild steel structure of identical shape and area. This paper shows numerical buckling reduction factors for stainless steel shell structures. Firstly some buckling strength curves of European standards are numerically reproduced using simple substitute imperfections. Proposals are then made for modification of standards in order to include stainless steels. Preliminary new proposals are made for modelling of material behaviour of stainless steels and buckling design of shell structures under meridional compression.

References listed at the end of the paper:

ABSTRACT: In the construction of chimneys and tubular masts adjacent cylindrical shells often have to be built with different radii according to the global bending moment or operational requirements. With a steep conical shell in between a cylinder-cone-cylinder intersection is built. This paper reports on a numerical study on the buckling stability of these structures. Unstiffened and ring-stiffened structures are considered, where the rings are attached to the edges of the cone or set off into the adjacent cylindrical shells. It is shown that the critical load of the entire structure remains under the critical load of a straight cylinder, even if heavy stiffeners are used and local buckling is relevant.


ABSTRACT: The assessment of imperfections is most important for determining the load-bearing capacity of a thin-walled shell structure. Different ways of modelling imperfections are discussed in this paper and steel silo shells are used as an application. Buckling tests were performed on different types of model shell - standard quality and high quality with reduced heat input during welding. For the numerical studies two different approaches were used as well: an axisymmetric approach with substitute geometric imperfections and an FEM approach, where the nodal coordinates were derived from surveying the specimen. It was found that there is considerable gain in the buckling strength due to the presence of the granular solid. The larger the initial imperfections in the shell the greater the gain in strength compared to the empty cylinder. The modelling of the unevenness of the edges with uneven dead loading is also discussed.

ABSTRACT: The stress distribution in thinwalled shell structures with concentrated edge loads was investigated by means of FEA. Using the concept of effective width an 'angle of load spread' can be defined under which the load spreads from the loaded edge into the shell. Due to the usual constraints along the bottom, there is a non-critical zone along the edge, where no buckles will develop. If the stress peak remains limited to a small non-critical strip above the support it cannot trigger buckling and can be excluded from further considerations as well. Using this information the critical locus can be determined where the first buckle will form. The format of the stability check is according to German Standard DIN 18800 part 4. Because the effects of the concentrated edge loads are followed explicitly in the model, the empirical knock-down factor does not need to account for uneven edge load distribution. Therefore it is suggested, to increase K2 by a factor of 1.67. For plastic buckling special advice is given.


ABSTRACT: This paper reports on wind loaded shell structures. The description of the wind pressure distribution around the shell circumference is discussed. Five different structural models to determine the relevant axial membrane stresses of wind loaded shells are presented. An example is presented for which the axial membrane stress distributions are calculated according to the given models. The results are compared and discussed.

References listed at the end of the paper:


ABSTRACT: Thin walled short cantilever cylinders, such as supply-air-chimneys, silos or tanks, develop a shell-type distribution of membrane forces when subjected to natural wind. A structural analysis by hand involves a Fourier decomposition of the circumferential wind pressure distribution and a separate calculation for each harmonic, using an appropriate shell theory. With this classical method simple boundary conditions at the bottom edge of the shell, such as ‘pinned’ or ‘clamped’, can be modelled only. The use of a finite element code – if available – gives possibility to account for more realistic conditions at the bottom of the structure, such as
elastic flanges and anchors or unilateral contact. In designing silos, tanks or chimneys however, as often encountered by the authors, structural engineers use beam theory to determine stress resultants and anchor forces, may this be due to lack of time or due to ignorance. Those who determine ‘real’ anchor forces obtain dimensions, which they feel to be inadequate and which are so much in excess of beam-theory-anchors that there should be much more failures with ‘beam-designed-anchors’. In the present paper some evidence on this apparent contradiction is given and a practical design approach is suggested.

ABSTRACT: Commercial FEA packages became increasingly wide spread in design offices. Being general purpose software, these packages may easily be used to model a tank or a silo by an engineer, who might not be sufficiently experienced to do proper strength and stability checks by hand. Thus, the authors see very often FEA-based design, which does not meet the state of the art. This was the motivation for the present article. Based on the needs of practical design of a steel or aluminium tank or silo, rules are given for the application of the finite element method. These include general considerations about deriving a structural model. As well, hints are given as to when a hand calculation (DBF = design by formulae) could be less time consuming than a FEA. For practical application of FEA, issues are covered like modelling and meshing of the global structure, modelling of imperfections, material properties, welds and loads. The specific needs of documentation for shell structures is discussed, i. e. splitting the obtained stresses in membrane and bending and in meridional and circumferential parts. Finally, three examples of industrial applications are described shortly.

ABSTRACT: Open cylindrical steel tanks for the storage of liquids tend to be rather thin-walled because they are primarily designed for the circumferential tensile stresses from hydrostatic internal pressure. It is desirable to take advantage of the postbuckling strength of the thin cylindrical wall when designing the empty tank against wind load. The theoretical external pressure carrying behaviour of edge-stiffened thin-walled cantilever shells is discussed with regard to both bifurcation and postbuckling phenomena. For experimental verification, a series of postbuckling tests on cylindrical PVC and steel specimens with large radius/thickness ratio (r/t=2500) under internal underpressure and under a “wind-like” load arrangement has been carried out. Based on the numerical and experimental results, recommendations are put forward for an economic postbuckling strength design strategy. They are compared with existing design rules in tank codes.

ABSTRACT: The state-of-the-art of available knowledge about the stability design of steel shell structures is discussed. Specific stress is put on the various approaches to a numerically based stability design. The European Prestandard ENV 1993-1-6 (the “Shell Eurocode”) is briefly described.

References listed at the end of the paper:


ABSTRACT: Tubular structural components are used in a large variety of civil engineering structures, e.g. for off-shore platforms, chimneys, pipelines, bridge arches or wind turbine towers. They are often subjected to combined loading inducing membrane compressive stress states which – in case they are not thick-walled – implies the danger of loss of local structural stability (shell buckling). However, existing design codes show significant shortcomings for interactive shell buckling. Therefore, a comprehensive experimental and numerical study on cylindrical shells has been performed which leads to an improved design proposal for interactive buckling under combined loading.

ABSTRACT: Circular cylindrical shells made of steel are used in a large variety of civil engineering structures, e.g. in off-shore platforms, chimneys, silos, tanks, pipelines, bridge arches or wind turbine towers. They are often subjected to combined loading inducing membrane compressive and/or shear stress states which endanger the local structural stability (shell buckling). A comprehensive experimental and numerical investigation of cylindrical shells under combined loading has been performed which yielded a deeper insight into the real buckling behaviour under combined loading. Beyond that, it provided rules how to simulate numerically the realistic buckling behaviour by means of substitute geometric imperfections. A comparison with existing design codes for interactive shell buckling reveals significant shortcomings. A proposal for improved design rules is put forward.


H. Schmidt and Th. A. Winterstetter, “Cylindrical shells under combined loading: Axial compression, external
PARTIAL INTRODUCTION: Circular cylindrical shells made of steel are used in a variety of engineering structures, for example, tanks, chimneys, offshore platforms, pipelines, silos or wind turbine towers. The design against tensile hoop stresses (containments) or against tubular bending stresses (tower-type structures) often results in very thin shell walls which implies the danger of failure by instability due to compressive and/or shear forces (shell buckling). The behavior of cylindrical shells under each of the fundamental loads of axial compression, external pressure and pure torsion…. is well understood. However, in almost all cases the actions on the structure do not induce such a simple fundamental membrane stress state, but a combination of them, including membrane stress variations in axial and circumferential direction and stress peaks at different locations….


ABSTRACT: A subsea pipeline laid onto a flat seabed will buckle laterally from a combination of pressure and temperature due to the pipeline’s ‘out-of-straightness’. The pipeline will tend to buckle laterally due to horizontal imperfections associated with the pipeline laying process, and the horizontal frictional restraint force is less than the pipeline submerged weight. The lateral buckling may take place as a dynamic ‘snap’ if the out-of-straightness, or imperfection, in the pipeline length is small. The pipeline ‘snap’ will result in dynamic motion. Seabed soil friction factors, in both axial and lateral directions, are also parameters which govern the lateral buckling, beside the size of the initial out-of-straightness. All of these parameters will influence the lateral buckling, and under which conditions dynamic buckling behaviour can occur. This paper investigates the influence of these different parameters and their effect on the onset of dynamic buckling.

References listed at the end of the paper:


ABSTRACT: A study on the free vibration and linear buckling analyses of thick plates is described in this article. In order to determine the natural frequencies and buckling loads of plates, a plate element is developed by using isogeometric approach. The Non-uniform B-spline surface (NURBS) is used to represent both plate geometry and the unknown displacement field of plate. All terms required in isogeometric formulation are consistently derived by NURBS definition. The capability of the present plate element is demonstrated by using several numerical examples. From numerical results, it is found to be that the present isogeometric element can predict accurate natural frequencies and buckling loads of plates.
References listed at the end of the paper:


ABSTRACT: In standard stability investigations of structures applying the finite element method usually the bifurcation and snap-through points – so-called stability points – are detected. However, for practical design purposes not only the stable state of equilibrium itself is significant but also the robustness of the state against finite perturbations in contrast to infinitesimal perturbations. The sensitivity measure, which quantifies this robustness, can be investigated by introducing perturbations at certain load levels and considering the perturbed motion. Some sensitivity studies are performed for simple stability problems as well as for realistic structures (cylindrical shells) under different loading conditions. Further scalar parameters based on Liapunov Characteristic Exponents are developed to allow a better judgment of the motion after introducing perturbations and a more efficient analysis of the complex response (see Ewert/Schweizerhof[7]).

K. Schweizerhof, E. Ewert, Institut für Mechanik Universität Karlsruhe
Universität Karlsruhe 76131 Karlsruhe, Germany, “Stability and Sensitivity of Shell-Like Structures Considering Imperfections and Contact”, 8th. World Congress on Computational Mechanics (WCCM8) 5th
ABSTRACT: In standard stability investigations of structures applying the finite element method usually bifurcation and snap-through loads – so-called singular or stability points – are detected, see e.g. [4],[6],[7]. It is well-known that for complex structures like cylindrical shells these loads depend strongly on the geometrical and other imperfections, see [8],[9],[10]. It has been shown in [1] that the singular points and the corresponding modes vary significantly for small deviations of the approximated geometry using different ansatz-functions. Furthermore investigations in [1] have shown that the converging behavior for imperfect structures is non-monotone. Particular limitations exist for the stability analysis of shell structures which involve contact between parts or with surrounding objects. In the end it could be followed that stability points and the corresponding loading determined numerically by static stability analysis are often of limited use for design purposes. In contrast to the loading obtained for singular points the so-called post-buckling loads, which are the stable equilibrium states in the post-buckling region, are rather independent of geometrical imperfections and of approximation order, see [1]. Therefore it is advantageous to use post-buckling loads for design purposes instead of loads obtained for singular points. Since the applicability of static analyses in the computation of post-buckling paths like proposed e.g. in [5] is rather limited, it is favorable to model the complete loading and deformation behavior by a time dependent process, see [3], [2], [11], [12]. The major advantage of a purely transient analysis is the complete simulation of the buckling process as it happens in reality. This is possible with moderate numerical effort, since the matrices used in the solution are usually better conditioned compared to pure static analysis. In addition, this allows to take the changing boundary conditions as found in contact situations properly into account. For practical design purposes not only the equilibrium state itself is significant but also the ”robustness” of such states against finite perturbations in contrast to infinitesimal perturbations. In the case of systems with many equilibrium states at a defined load level finite perturbations can transfer the mechanical system from a stable equilibrium state to another equilibrium state or in some cases even to an unbounded motion initiating buckling. Then a sensitivity measure can be defined as the reciprocal value of the minimum perturbation energy, necessary for this transfer S = 1/Wper,min, see [2]. In the present paper stability and sensitivity studies are performed for simple stability problems (beams) and finally for rather general shell structures involving geometrical imperfections and in particular contact.

References listed at the end of the paper:

PARTIAL INTRODUCTION: The crack problems of shells have been in recent years subject to increasing interest. Various initial value problems for cylindrical shells containing different types of cracks have been studied by Erdogan and his associates, and Chilver and Hayman have initiated an extensive study of the effect of degeneracy on the stability performance of rods and shell structures [1-3]. Such investigations result partly from dramatic structural collapses, such as that of the reinforced concrete cooling towers at Ferryridge in Yorkshire [4]...


ABSTRACT: A simple concept for studying the lower stability limit of shell structures which is based on the theory of isometric transformation of surfaces is outlined. The influence of imperfection on the lower stability limit is discussed in the case of axially compressed cylindrical shells.


ABSTRACT: Recent advances in buckling localization based on the theory of solitons and deterministic chaos are discussed and subsequently utilized in conjunction with a geometrical approach to buckling of elastic shells in order to obtain an engineering estimation of the actual buckling load.


ABSTRACT: The paper draws attention to an interesting connection between the randomness of localized buckling forms of elastic structures, solitons and deterministic chaos of dynamic systems.


ABSTRACT: (none given)

References listed at the end of the paper:
Nonlinear dynamics of a post-buckled beam: a parametric space investigation

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“Nonlinear dynamics of a post-buckled beam: a parametric space investigation” (publisher and date not given in

the pdf file

ABSTRACT: The nonlinear response of an aircraft panel due to acoustic and thermal loading is computationally expensive using traditional finite element methods. This has lead to the use of several reduced-order modal model development methods for such systems. In this paper, we first provide a historical review of the nonlinear phenomenon associated with the post-buckling response due to thermal-acoustic loading with specific emphasis on snap-through response. Next, a parametric space investigation is presented to study the effect of thermal gradient and/or preload on the post-buckling dynamic behavior of a clamped-clamped beam system. This paper studies a single mode approximation of the clamped-clamped beam. These reduced order models are based on the implicit condensation method. First the parametric space investigation is conducted to identify the stability of the periodic solutions for both models. The effect of harmonic excitation is presented in terms of the bifurcation diagram with specific focus on the effect of initial pre-load parameter. Finally, some conclusions about the response to multi-frequency excitation are presented in terms of the numerical bifurcation diagrams.

References listed at the end of the paper:


ABSTRACT: Linear stability of the cylindrical shell with the strong cover filled by the soft core is investigated. Such structures are usually elements of the vehicle bumpers. They are used for dissipating the crash energy. The analysis is focused on finding the most waved buckling form due to the parameters of the structure. An analytical approach is employed in this investigation instead of a numerical one. The standard Lagrangian energy algorithm is expressed in Mathematica formalism.


ABSTRACT: The present paper discusses a method to estimate the elasto-plastic buckling loads of two-way
grid shells. The method first applies the concept of shell analogy to derive linear buckling loads in a mathematical form, second calculates the generalized slenderness of buckling of members using linear buckling loads, and finally estimates the elasto-plastic buckling loads based on the concept of column strength curves in terms of generalized slenderness. In the mathematical form for linear buckling loads, the in-plane shear rigidity is reconfirmed to be the most important together with the out-of-plane bending rigidities. The buckling strength in elasto-plastic region, based on the present method, is compared with those obtained by elasto-plastic nonlinear analysis and verified very accurate. Nonlinear analysis and verified very accurate.

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ABSTRACT: In general, the stiffened plates consisting of steel plate elements are unavoidably accompanied by initial imperfections such as residual stresses and initial deflections, which have considerable effects on their ultimate strength. Therefore, it is needed for designing them to develop more rational method taking the ultimate strength influenced by initial imperfections into account rather than the conventional design method being on the basis of the linear elastic buckling theory. From this point of view, this study aims to evaluate rigorously the ultimate strength of orthogonally stiffened plate with initial imperfections under uniaxial in-plane compression. The elasto-plastic finite element method is applied to attain this purpose. By a happy combination of modal analytical technique and conventional finite element method, much reduction of the degree of freedom can be expected to be realized herewith. Some numerical calculations are performed by means of this rigorous method to examine the exactness of the analysis. Moreover, the numerical results are compared with the experimental ones.


Abstract: The present paper aims to propose a method to evaluate elasto-plastic buckling strength of two-way grid shells, using mathematical formulas for linear buckling derived based on the continuum shell analogy. The paper is organised from two principal points of view. In the first discussion, we derive two formulas for linear buckling of two-way grid shells by substituting the equivalent continuum rigidity into the buckling formulas for orthotropic shells. The applicability of the formulas is verified using several structural examples by comparison with the other proposed formulas and FEM results. In the second discussion, based on the concept of column buckling, an effective approach to estimate elasto-plastic buckling strength of two-way grid shells is demonstrated. In the estimation procedure, the buckling formulas derived in the first discussion are effectively applied to obtain the generalised slenderness.


ABSTRACT: A study of the free vibration of finite cylinders with elliptical cross section under external
pressure is presented. The buckling pressure is obtained as a special case in the free vibration analysis. The elliptical cross section is considered to be composed of two circular arcs, and the equations of a circular cylindrical shell are applied. Numerical examples are presented to examine the effect of out-of-roundness on the natural frequencies and the buckling pressure.


ABSTRACT: The vibration of cylindrical shells subjected to initial stresses is studied on the basis of a shell theory including shear deformation and rotatory inertia. The original equation system with five unknowns is reduced to one in three unknowns. An analysis is carried out for cylindrical shells with simply supported ends and the effects of initial stresses as well as shear deformation and rotatory inertia on the frequencies and the buckling forces are examined, and results are compared with those obtained by using classical thin shell theory. Results for initially unstressed shells are compared with those obtained by using the Mirsky-Herrmann theory.

Kaoru Shirakawa and Tohru Tamada, “Vibration and Buckling of Cylindrical Shell under External Pressure”, ABSTRACT: The vibration problems of finite cylindrical shells under external pressure are studied based on the equations developed by Flugge. The buckling pressure is obtained as a special case in the vibration analysis. Numerical results are presented for nine different sets of boundary conditions, and their effects on the characteristics of vibration and buckling are examined with regard to the mode shapes and the geometrical parameters of cylindrical shells.

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3) K. Forsberg, AIAA, 2, 2150 (1964).
5) R. von Mises, ZVDI, 58, 750 (1914).
6) S. B. Batdorf, NACA, TR. 874, 17 (1947).
13) K. Sezawa, Shindogaku (Vibrations), Iwanami (1932).

principal shortcoming in the analysis. The problem has been simplified by applying axial tensile load and external press to simple cylindrical shell specimen and observing the buckling load for various nonproportional load-paths. Results are compared to numerical predictions (BOSOR5) using classical type plasticity models such as [...] deformation and [...] incremental theory. Significant discrepancy was found attributed to inadequate modeling of the nonlinear material behavior. The effects of geometrical imperfections and large deflections were found to insignificant, thereby leading to an idea [...] of the discrepancy between test and theory is due to a use of inadequate plastic model. The introduction of the Southwell plot into elastic shell buckling problem reduced the already minor effects of geometric imperfections. The Christoffersen-Hutchinson corner theory model was introduced into BOSOR5 in its simplest form as presented by Poh-Sang Lam. Results obtained with this model, which allows corners to form on an initially smooth yield surface, displayed better agreement with experimental data. However, increased computational time and problems related to abrupt changes in load-path at the corner are a major concern at this present time.


ABSTRACT: The predictions for plastic buckling of shells are significantly affected by the plasticity model employed, in particular in the case of nonproportional loading. A series of experiments on plastic buckling of cylindrical aluminum alloy shells under biaxial loading (external pressure and axial tension), with well-defined loading and boundary conditions, was therefore carried out to provide experimental data for evaluation of the suitability of different, plasticity models. In the experiments, initial imperfections and their growth under load were measured and special attention was paid to buckling detection and load path control. The Southwell plot was applied with success to smooth the results. The results show that axial tension decreases resistance to buckling under external pressure in the plastic region due to Isqosofteningrsquo of the material behavior. Comparison with numerical calculations using J2 deformation and incremental theories indicate that both theories do not predict correctly plastic buckling under nonproportional loading.

References listed at the end of the paper:

ABSTRACT: Buckling of elastic-plastic cylindrical shells axially struck with a mass is discussed. The effect of stress wave fronts travelling along the shell is taken into account. This allows us to cast some more light on the mechanism of progressive buckling. Only axisymmetric buckling modes are considered. The analysis is based on the Kirchhoff-Love hypotheses. As a constitutive law, the rate independent elasto-plastic relations with linear strain hardening and von Mises yield condition are adopted. A method for calculating bifurcation times and buckling modes is presented. Numerical examples are given.

ABSTRACT: The buckling phenomena of the subducting lithosphere due to the sphericity or the earth are studied by a nonlinear finite element method, and the results are compared with the buckling experiments by Yamaoka et al. (1986b). The subduction or the lithosphere is modeled by a hemispherical shell squeezed at its circumferential edge. For simplicity, two parameters are employed in scaling the subducting lithosphere. One is the thickness or the lithosphere and the other is the length or its deformable portion (i.e., the length of the descending slab). Uniform inward load is applied to the free circumferential edge or the deformable portion. At the opposite edge (i.e., at the trench), built-in boundary condition is imposed; no displacements and no rotations are allowed. Investigations are made mainly on the following three subjects: (I) How do the two parameters control the wavelength of buckling? The results show that shorter waves are associated with thinner and shorter shells. The irregularities such as tears or seamounts do not alter the buckling wavelength very much. (2) How do shells deform in their postbuckling state. Sharp cusps pointing outward appear in the postbuckling undulation without any irregularities in shell property and in applied load. The shape or the cuspidal undulation is quite similar to that of the actual subducting lithosphere. (3) Can buckling take place in the subducting lithosphere under likely conditions in the earth? The examination is made with respect to the buckling load, the shell deflection, and the buckling wavelength. The results strongly suggest that the arcuate shapes of subduction zones are in fact generated by buckling or the subducting lithosphere.

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ABSTRACT: The lithospheric plate is a spherical shell rather than a plane plate. A spherical shell must buckle when it is bent inward. We examined the possibility of lithospheric buckling upon subduction. The lithosphere with its subducted portion is simulated by a hemispherical elastic shell bent inward at its circumferential edge by a uniform radial load. The buoyancy force acting on the lithosphere seaward of the trench is simulated by
clamping the shell along a parallel. The deformable portion between the loaded and clamped edges corresponds to the subducting slab of lithosphere. Buckling analyses were made using the techniques of a linear stability analysis and a finite element method. The wavelength of buckling depends on the thickness of the shell and the length of its deformable portion: a longer wavelength is associated with a thicker shell and a longer deformable portion. By scaling the shell thickness and the length of the deformable portion to the elastic thickness of lithosphere and the length of subducting slab, respectively, the wavelength of buckling can be compared favourably to the length of one unit of arcuate trench in a chain-like continuation of island arcs. The load to be applied for initiation of buckling is called the critical load: a lower critical load is associated with a thinner shell with a longer deformable portion. The excess weight of subducting slab provides a load large enough to initiate lithospheric buckling at a relatively early stage of subduction. Radial displacement of the circumferential edge at the critical state is an order of magnitude smaller than the depth of the leading edge of the Wadati-Benioff zone, indicating that most of the present subducting lithospheres are under a postbuckling state. Undulation of the shell in the postbuckling state is not purely sinusoidal but a successive continuation of arcs with cusps in between, invoking the continuation of arcuate deep-sea trenches with cusps at their junctions. The cuspathe feature of island arc chains is thus a natural consequence of lithospheric buckling and does not require any such irregularities as seamounts colliding with a trench. Collision of seamounts, however, can aid buckling greatly if they are aligned along a trench at an interval not very different from the inherent buckling wavelength.

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ABSTRACT: We investigated the buckling response of a faulted elastic plate under horizontal compression using the finite element technique to better understand the effect of faults on the elastic behavior of a plate. We studied the effect of changes in fault spacing, depth and dip on the effective Young's modulus, buckling stress and wavelength. Our model consists of a thick elastic plate whose entire upper surface is cut by evenly spaced faults. We impose either an initial sinusoidal deformation with a fixed wavelength or a random deformation to the grid. A fault is represented as a free surface with no resolved shear stress and is allowed to slip in a specified direction using the method of ‘slippery nodes’. With the assumption of free slip on the faults, our model results represent an end member case in which the buckling wavelength and buckling stress are minimized by the presence of the faults.

In our models, fault depth was varied from 0 to 75% of the plate thickness. As strain increases, the grid deforms by antisymmetric flexural folding and the initial imposed wavelength of deformation is modified such that the new buckling wavelength emerges. Our results show that the effective Young's modulus is a decreasing function of fault depth and an increasing function of fault spacing. In addition, buckling of the plate occurs at a lower stress for greater fault depths. Buckling wavelength is independent of the initial deformation wavelength however, it is modified by the presence of faults. For a plate with closely spaced faults extending through at least 75% of the plate, buckling occurs at a wavelength one half as large as that for a continuous plate. Buckling stress is not independent of the initial deformation wavelength, rather it increases slightly with increasing difference between the initial deformation wavelength and the buckling wavelength.

Analytical models that approximate or ignore the effect of faulting can have large errors in calculation of the buckling stress. More importantly, modeling the observed wavelength of deformation in a faulted region with analytical solutions for continuous plates may result in a significant underestimate of elastic thickness. Fault dip
does not strongly affect either the effective Young's modulus or the buckling wavelength. Thus, the buckling response should be the same for a plate cut by a low angle fault or a high angle fault.

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ABSTRACT: Numerical methods for the computation of singular points of nonlinear equations \( G(u, \lambda, \mu) = 0 \) are discussed, where \( \lambda \) and \( \mu \) are real parameters. Simple and double limit points are treated in some detail and numerical algorithms are presented and applied to elastic shell stability problems. The case of simple symmetry breaking bifurcation points is also treated with applications to nonsymmetric bifurcation from axisymmetric states of deformation of shells of revolution.


ABSTRACT: The ‘static-geometric analogy’ in thin shell structures is a formal correspondence between equilibrium equations on the one hand and geometric compatibility equations on the other. It is well known as a fact, but no satisfactory explanation of its basis has been given. The paper gives an explanation for the analogy, within the framework of shallow-shell theory. The explanation is facilitated by two innovations: (i) separation of the shell surface conceptually into separate stretching (S) and bending (B) surfaces; (ii) use of change of Gaussian curvature as a prime variable. Various limitations of the analogy are pointed out, and a scheme for numerical calculation which embodies the most useful features of the analogy is outlined.


ABSTRACT: The classical buckling of a thin-walled circular cylindrical shell which is subjected simultaneously to uniform bending moment and internal pressure is investigated in an approximate fashion by assuming an appropriate eigenmode and obtaining a “best-fit” solution of the resulting equations. In this way, explicit formulae are derived for critical loading combinations and for the characteristics of the modal form. These formulae agree reasonably well with a wide range of numerical data previously obtained by Seide and Weingarten. A feature of the scheme is that it is feasible to interpret the results in physical terms, and to envisage the roles of bending, twisting and stretching in the critical solution.


ABSTRACT: This paper discusses in a general way some aspects of the theory of shell structures, and the nature of the theory itself. It emphasises the importance of the interaction between bending and stretching effects in shells, and shows that the “two surface” model of shells provides a useful way of investigating this interaction at both the conceptual and the computational level. A cylindrical shell under various simple kinds of loading demonstrates how the key dimensionless groups emerge from this type of analysis.
Some fresh light is thrown on the famous controversy between Love and Rayleigh on the vibration of simple shells. Various problems which arise in the numerical computation of shell structures are discussed. The paper concludes with some general remarks.


ABSTRACT: This paper commemorates the publication in 1888 of A.E.H. Love’s paper on thin elastic shells. It discusses Love’s relationship with Rayleigh and others, and assesses the historical significance of the work.


ABSTRACT: It is well known that the buckling load of a thin cylindrical shell under axial compression depends significantly on the initial imperfection of the specimen. In this paper we focus attention on the effect of imperfections in the form of a particular kind of damage on the load-carrying capacity of a thin cylindrical shell. The study is an experimental one. The specimens used were steel drinks cans having a radius/thickness ratio of about 350. The damage was introduced by pressing in an indentation by hand and then pushing it out again: this left two locally damaged regions in the shell; and the level of damage could be characterised by the width of the initial indentation. The specimens were tested under eccentric axial compression. Careful visual observations were made of the behaviour of the shells in the damaged regions. In general, as the load increased a small dimple near the damaged zone grew in size, and turned gradually into a diamond shape. When the width of such a dent reached 25 mm, the can collapsed catastrophically. The nominal stress level in the region of the dent at buckling was around 0.24 of the classical buckling stress, whereas the buckling stress level for undamaged cans was 0.5±0.1 of the classical value.


ABSTRACT: Simple experiments on self-weight buckling of thin, open-top, fixed-base, small-scale silicone rubber cylindrical shells are presented in this article. The buckling heights were found to be proportional to thickness raised to the power of approximately 1.5, compared to 1.0 as in the classical theory. A non-linear finite-element analysis of self-weight buckling showed that there is a ‘post-buckling plateau’ load corresponding to the experimental buckling loads. Moreover, the results of the present experiments showed very little ‘scatter’ in the buckling heights, compared to the large scatter in the experimental data from the literature on the buckling of thin cylindrical shells under axial compressive load (which also have buckling stress proportional to thickness raised to the power of approximately 1.5), although there were measurable imperfections in terms of thickness variations. These observations somehow defy the accepted hypothesis of ‘imperfection-sensitivity’ in shell buckling. The most obvious explanation of the difference is that the open-topped shells of the present study are statically determinate, whereas the usual closed-ended shells of tests reported in the literature are statically indeterminate; the possibility of high initial stresses may explain the scatter in the experimental observations in the literature.

ABSTRACT: The widely accepted theory of buckling of thin cylindrical shells under axial compressive loading emphasises the sensitivity of the buckling load to the presence of initial imperfections. These imperfections are conventionally taken to be minor geometric perturbations of a shell which is initially stress-free. The original aim of the present study was to investigate the effect on the buckling load of imperfections in the form of local initial stress, which are probably more typical of practice than purely geometric ones. Experiments were performed on a vertical “melinex” cylinder of diameter about 0.9 m and height about 0.7 m, with radius/thickness ratio about 1800. The upper and lower edges of the cylinder were clamped to end discs by means of circumferential belts, an arrangement that allowed states of self-stress to be introduced to the shell readily by means of local “uplift” at the base. The upper disc was made sufficiently heavy to buckle the shell, and it was supported by a vertical central rod under screw control. Many buckling tests were performed. Surprisingly, the buckling loads were generally at the upper end of the range of fractions of the classical buckling load that have been found in many previous experimental studies. Even when the local uplift at the base caused a local “dimple” to be formed before the shell was loaded, the buckling load was relatively high. A surface-scanning apparatus allowed the geometric form of the shell to be monitored, and the progress of such a dimple to be followed; and it was found that a dimple generally grew in size and migrated in a stable fashion up the shell as the load increased, until a point was reached when unstable buckling occurred. These unexpected and paradoxical features of the behaviour of the experimental shell may be attributed to the particular boundary conditions of the shell, which provide in effect statically determinate support conditions. This study raises some new issues in the field of shell buckling, both for the understanding of buckling phenomena and for the rational design of shells by engineers against buckling.

References listed at the end of the paper:
ABSTRACT: The classical theory of buckling of axially loaded thin cylindrical shells predicts that the buckling stress is directly proportional to the thickness $t$, other things being equal. But empirical data show clearly that the buckling stress is actually proportional to $t^{1.5}$, other things being equal. As is well known, there is wide scatter in the buckling-stress data, going from one half to twice the mean value for a given ratio $R/t$. Current theories of shell buckling explain the low buckling stress—in comparison with the classical—and the experimental scatter in terms of “imperfection-sensitive”, non-linear behaviour. But those theories always take the classical analysis of an ideal, perfect shell as their point of reference. Our present principal aim is to explain the observed $t^{1.5}$ law. So far as we know, no previous attack has been made on this particular aspect of thin-shell buckling. Our work is thus breaking new ground, and we shall deliberately avoid taking the classical analysis as our starting point. We first point out that experiments on self-weight buckling of open-topped cylindrical shells agree well with the mean experimental data mentioned above; and then we associate those results with a well-defined post-buckling “plateau” in load/deflection space, that is revealed by finite-element studies. This plateau is linked with the appearance of a characteristic “dimple” of a mainly inextensional character in the deformed shell wall. A somewhat similar post-buckling dimple is also found by quite separate finite-element studies when a thin cylindrical shell is loaded axially at an edge by a localised force; and it turns out that such a dimple grows under a more-or-less constant force that is proportional to $t^{2.5}$, other things being equal. This 2.5-power law can be explained by analogy with the inversion of a thin spherical shell by an inward-directed force. Thus, the deformation of such a shell is generally inextensional except for a narrow “knuckle” or boundary layer in which the combined local elastic energy of bending and stretching is proportional to $t^{2.5}$, other things being equal. Similarly, the modes of deformation in the post-buckling dimples in a cylindrical shell are practically independent of thickness, except in the highly deformed boundary-layer regions which separate the inextensionally distorted portions of the shell. These ideas lead in turn to an explanation of the $t^{1.5}$ law for the post-buckling stress of open-topped cylindrical shells loaded by their own weight. We attribute the absence of experimental scatter in the self-weight buckling of open-topped cylindrical shells to the statical determinacy of the situation, which allows a post-buckling dimple to grow at a well-defined “plateau load”. Conversely, the large experimental scatter in tests on cylinders with closed ends may be attributed to the lack of statical determinacy there. Our paper contains several arguments that are not mathematically water-tight, in contrast to many reports in the field of mechanics of structures. We plead that the problem which we have tackled is so difficult that the only way forward is one of “over-simplification”. We hope that our work will be judged not with respect to its absence of mathematical precision, but by the light which it sheds upon the problem under investigation.
References listed at the end of the paper:

Georges Duvaut (1), F. Lene (2) and A. Noureddine (2)
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ABSTRACT: Lattice structures are often made in the form of thin-walled cylindrical shells reinforced with helical and circumferential ribs. In this research, an integrated equivalent stiffness model is developed to describe such a structure. The structure is defined by the following independent design variables: thickness of the lattice layer, angle of helical ribs, spacing of helical ribs, thicknesses of ribs, thickness of the skin, angle-ply of the skin. Method of Moving Asymptotes (MMA) is used to model a cylindrical lattice shell with external laminated skin. Compression axial force and global and local buckling of the shell are considered. Solution methodology is described. A numerical example of optimization of the design variables to provide the minimum value of the shell mass and to satisfy the following constraint: acting compression axial force should not cause the general buckling of the shell neither the local buckling of the helical ribs, is given. The proposed model
allows analysis of the lattice structures and is not based on the finite element method which is still of little use for overall design due to model complexity and the inability to easily changes rib geometry (angle, spacing).


ABSTRACT: This paper simulates dynamic responses of single-layer elliptical paraboloid latticed shells under impact based on rate-dependent isotropic hardening material model, master-slave contact point searching method and penalty function method. Node displacement and structural energy are analyzed under impact of freely falling with certain initial height. The dynamic buckling of plasticity is judged according to the dynamic responses. The effects of all kinds of parameters (such as span, rise-to-span ratio and cross-sectional areas of members etc.) are analyzed on the structural dynamic buckling. The results show that the displacements of characteristic nodes, stain energy and total energy of the structure increase all of a sudden. The vertical stiffness of the latticed shells strengthens and critical momentums are enhanced with rise-to-span ratio's aggrandizement, and cross-sectional areas of members increasing. Supporting condition has a slight effect on critical loads and the latticed shells are sensitive highly to initial geometric imperfection.

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ABSTRACT: Many papers which treat the dynamic instability of shell structures under step load have been published, but there are few papers which deal with dynamic buckling under a load with periodic characteristics, especially considering damping. Dynamic buckling behavior under periodic excitation is different from that of step excitation. In this paper, the damping influence on dynamic buckling for shell-like shallow trusses is numerically investigated under up-and-down excitation, that is, step, sinusoidal and seismic excitations, and compared with the static critical load. The results show that, considering the damping, dynamic buckling loads become higher than the case of no damping, and the indirect snapping responds more sensitively than the direct snapping by the damping effect, except in the vicinity of the main resonance region.


SYNOPSIS: An iterative approach is suggested to calculate the critical loads of single-layer shallow domes with initial stochastic geometrical imperfections. The tangent stiffness matrix of an element with a small initial curvature is also presented in this paper.

T. Nishimura , K. Morisako and S. Ishida, “Numerical analysis of rotational buckling in gusset plate type joints
of timber lattice dome under several loading conditions”, Journal of the International Association for Shell and Spatial Structures (J. IASS), Vol. 39, No. 2, April 1998

ABSTRACT: Numerical study of critical behaviors of a timber lattice dome with steel gusset plate type joints under several loading conditions is conducted using the spatial beam-column FEM developed by the authors. The good accuracy of this numerical method is verified by the simulation of the full-scale physical test of the timber lattice dome in EXPO’90 Osaka, in which the rotational buckling of the node joint composed of six steel gusset plates has previously been observed. The numerical data of strain in one of the steel plates suggest that the rotational buckling was induced by lateral elastic buckling of plates. Under the loading conditions adopted here, the initial critical behavior of the lattice dome was neither overall snap-through of the dome nor buckling of individual wooden members but was invariably the rotational buckling of the node joints.

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PARTIAL ABSTRACT: This paper concentrates on the mathematical modeling of nonlinear mechanics of thin-walled structures in view of associated finite element formulations. This means that we will primarily focus on formulations for structural models as prerequisite for derivation of finite elements, rather than specific ‘elementology’. The main emphasis is put on shells, including the special case of flat plates, turning into shells anyway in the nonlinear regime. The derivations are kept as general as possible, including thick and layered shells (laminated or sandwich structures), as well as anisotropic and inhomogeneous materials from the outset. Throughout Section 4.4, we will specify the corresponding restrictions and assumptions to obtain the classical 5-parameter shell formulation predominantly used for standard shell problems in the context of finite element analysis. In most part of the text, we restrict ourselves to static problems within the framework of geometrically nonlinear elasticity, neglecting time dependence and inertia effects. The extension into the materially nonlinear area is a straightforward procedure. It is believed that this does not mean a too strong restriction in view of the underlying motivation. It is a well cultivated tradition to let review articles start with the remark that a complete overview of existing methods and appropriate literature is utterly impossible. The multitude of existing concepts, methods, and implementations, as well as scientific papers, text books, and yet other review articles would effectively prohibit an exhaustive overview…


ABSTRACT: The purpose of this study is to investigate the characteristics of the connector having an influence on the elasto-plastic buckling load of ball-jointed single layer latticed domes. As analytic model, domes are composed of tubular member elements, balls and joints. The joint system of members in the single layer latticed domes has an influence on buckling load. Generally, the joint is assumed to be pin or rigid joint for the simplification of analysis. But the mero system that is used mostly for the spatial structures has intermediate properties between pin joint and rigid joint. Several studies based on the property of this semi-rigid joint are
"Experiment and elasto-plastic buckling analysis of ball-jointed single layer reticulated domes" by Suzuki, "Elasto-plastic buckling loads of latticed shells with elastic springs at both ends of members" by Kato and "Loading test and elasto-plastic buckling analysis of a single layer latticed dome" by Ueki and so on.


ABSTRACT: Single layer latticed domes are lightweight and elegant structures that provide cost-effective solutions to cover the large areas without intermediate supports. The topological design of these structures present difficulty due to the fact that the number of joints and members as well as the height of the dome keeps on changing during the design process. This makes it necessary to automate the numbering of joints and members and the computation of the coordinates of joints in the dome. On the other hand the total number of joints and members in a dome is function of the total number of rings exist in the dome. Currently no study is available that covers the topological design of dome structures that give the optimum number of rings, the optimum height of crown and the tubular cross-sectional designations for the dome members under the given general external loading. The algorithm presented in this study carries out the optimum topological design of single layer lattice domes. The serviceability and strength requirements are considered in the design problem as specified in BS5950. The algorithm takes into account the nonlinear response of the dome due to effect of axial forces on the flexural stiffness of members. The optimum solution of the design problem is obtained using coupled genetic algorithm. Having the total number of rings and the height of crown as design variables provides the possibility of having a dome with different topology for each individual in the population. It is shown in the design example considered that the optimum number of joints, members and the optimum height of a geodesic dome under a given external loading can be determined without designer’s interference.


ABSTRACT: The purpose of this paper is to analyze a squared lattice cylindrical shell under compressive axial load and to optimize the geometric parameters to achieve the maximum buckling load. Also a comparison between buckling loads of a squared lattice cylinder and a solid hollow cylinder with equal weight, length and outer diameter is performed to reveal the superior performance of the squared lattice cylindrical shells. A cylindrical lattice shell includes circumferential and longitudinal rods with geometric parameters such as cross-section areas of the rods, distances and angles between them. In this study, the governing differential equation for buckling load which can be presumed as a criterion for designing lattice structures with a specific weight is derived and is used as an objective function in genetic algorithm (GA) method to calculate the optimum geometric parameters of the shell. The optimum parameters were modelled in finite element method (FEM) in order to verify the buckling loads obtained from GA. In another effort, the FEM was applied to analyze the solid hollow cylinders. The results demonstrate relatively close agreement between the buckling loads obtained from GA and FEM for such shells. It was also shown that latticed cylinders have better performance to carry compressive axial loads than the equivalent solid hollow cylinders with equal weights, lengths and outer diameters. The studies reported in this paper have been carried out for a single squared lattice shell without using two-side skins. However, using skins can give better performance in carrying compressive axial loads. The results in this paper show that this type of effective, economical lightweight and functional structures could
be applied as inter-stages, inter-tanks, aircraft fuselage, rocket motor cases, pressure vessels and other elements of civil engineering structures in order to have greater strength and lower weight. Squared lattice cylindrical shell with optimum geometric design could provide the chance for eliminating the stiffeners of shells in aerospace structures in order to decrease the weight and increase the load-bearing capacity.


ABSTRACT: In this paper, the buckling analysis of a multilayered composite cylindrical shell which volume fraction of its fiber varies according to power law in longitudinal direction, due to applied compressive axial load is studied. Rule of mixture model and reverse of that are employed to represent elastic properties of this fiber reinforced functionally graded composite. Strain displacement relations employed are based on Reissner-Naghd-Berry’s shell theory. The displacement finite element model of the equilibrium equations is derived by employing weak form formulation. The Lagrangian shape function for in-plane displacements and Hermitian shape function for displacement in normal direction to the surface of mid-plane are used. Then, finite element code is written in MATLAB based on stated method to obtain the critical axial buckling load. Numerical results show that despite having the same layout and average volume fraction of fibers, the critical axial buckling load of functionally graded composite cylindrical shell is more than that of traditional composite in which the volume fraction of its fiber is constant throughout the shell.

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ABSTRACT: This paper presents the formulation and numerical buckling analysis of a circular cylindrical composite shell comprising of fibers made of functionally graded material (FGM). The material properties of the fibers vary through the shell length according to a power-law distribution of the volume fraction. That is the fiber material properties vary from the metal on the one end to the ceramic up to the middle of the shell then from the ceramic to the metal towards the other end of the shell. Based on the first order shear deformation theory (FSDT) the governing equations of the shells are derived. Then to determine the buckling load of the composite shell over simply supported edges these equations are solved using the generalized differential quadrature method. The obtained results for an isotropic shell are compared with those given in the literature. Very good agreement is seen. Then, the effects of geometric parameters and FG power index are also investigated on the magnitude of the buckling load through number of examples. The study of the obtained results shows that any decrease in the value of FG power index will lead to a better buckling behavior of the composite shell.

References listed at the end of the paper:

ABSTRACT: Thin-walled tube bending is an advanced technology for producing precision bent tube parts in aerospace, aviation and automobiles, etc. With increasing demands of bending tubes with a larger tube diameter and a smaller bending radius, wrinkling instability is a critical issue to be solved urgently for improving the bending limit and forming quality in this process. In this study, by using the energy principle, combined with analytical and finite element (FE) numerical methods, an energy-based wrinkling prediction model for thin-walled tube bending is developed. A segment shell model is proposed to consider the critical wrinkling region, which captures the deformation features of the tube bending process. The dissipation energy created by the reaction forces at the tube–dies interface for restraining the compressive instability is also included in the prediction model, which can be numerically calculated via FE simulation. The validation of the model is performed and its physical significance is evaluated from various aspects. Then the plastic wrinkling behaviors in thin-walled tube bending are addressed. From the energy viewpoint, the effect of the basic parameters including the geometrical and material parameters on the onset of wrinkling is identified. In particular, the influence of multi-tools constraints such as clearance and friction at various interfaces on the wrinkling instability is obtained. The study provides instructive understanding of the plastic wrinkling instability and the model may be suitable for the wrinkling prediction of a doubly-curved shell in the complex forming process with contact conditions.

PREFACE: This document is described as the 5th Edition of the ECCS European Recommendations for the Buckling of Steel Shells. It is the successor to the 4th Edition, published in 1988, which was very different in style, format and content, though some of the regulatory requirements of the 4th Edition are here retained in the 5th Edition. In the 20 years since the publication of the 4th Edition in 1988, much has changed in the field of metal shell buckling. Extensive research has been undertaken, much new knowledge has been developed, and powerful computational modelling has transformed the field, though much design is still conducted by hand calculation. These changes are reflected in this 5th Edition.

Aleksandrs Korjakins, Institute of Materials and Structure, Riga Technical University, Patricia Kara, Kaspars Kalnins, “Buckling and post-buckling analyses of stiffened composite shells with inter-laminar damages”, 5th European LS-DYNA Users Conference, (year? 2004 or after) (Not allowed to copy portions of the document without a password from the owner, and I’m not willing to type the abstract or the list of references).


ABSTRACT: In this study sandwich-walled cylindrical shells with aluminum pyramidal truss core of constant curvature suitable for functional applications were fabricated employing an interlocking fabrication technique for the metallic core. The skins were made of carbon-fiber reinforced composites and co-cured with the metallic truss core. Thereafter, axial compression tests on some representative samples were carried out to investigate the failure modes of these structures and compared with an analytical failure map developed to account for Euler buckling, shell buckling, local buckling between reinforcements and face-crushing. The experimental data closely matched the analytically predicted behavior of the cylinders. In particular, it was found that local buckling and face crushing modes can exist together and are the most important modes of failure of the fabricated structure. In addition, a study on the bending response of semi-cylindrical samples is also presented using a combination of analytical modeling, three-point bending experiments and finite element (FE) based simulations. The aluminum pyramidal cores of these samples were also constructed using the novel interlocking method before curing them with composite face sheets to fabricate the final structure. A theoretical model was developed to analyze the experiments and develop failure criteria. Three failure modes: i) Face wrinkling, ii) Face crushing, and iii) Debonding between face sheet and truss cores, were considered and theoretical relationships for predicting the collapse load associated with each mode were developed. The experiments were carried out on two sets of specimens with differing face sheet thickness which clearly indicated the important role played by core debonding in determining the peak load of the structure. Localized buckling instabilities were also reported for samples with thinner face sheets. The role of debonding in determining strength was further highlighted by a comparison with FE simulations with suppressed debonding. This study highlighted the superior structural performance and failure properties of these structures thus demonstrating their suitability for their integration into the next generation of ultralight multifunctional systems.
DOI: 10.1007/s00419-006-0053-5

ABSTRACT: Axial compression of aluminium spherical shells of $R/t$ values ranging from 25 to 43 was performed under central loading. Quasi-static tests were conducted on an INSTRON machine (model 1197) of 50 T capacity. Spherical shells were tested to identify their modes of collapse and to study the associated energy absorption capacity. In experiments all the spherical shells were found to collapse due to formation of an axisymmetric inward dimple associated with a rolling plastic hinge. A Finite Element computational model of development of the axisymmetric mode of collapse is also presented. Experimental and computed results of the deformed shapes and their corresponding load–compression and energy–compression curves were presented and compared to validate the computational model. The computed variations of the different strains and stresses were also studied. On the basis of the computational results mechanics of the development of the axisymmetric inward dimple mode of collapse has been presented, analysed and discussed.

References listed at the end of the paper:


ABSTRACT: Experimental investigations and numerical simulations are performed in order to numerically predict the buckling behaviour of thin composite laminated specimens. Experiments are aimed at two objectives: the first is to completely characterize the carbon/epoxy material under simple loading configurations, the second is to test this material in buckling and post-buckling situations. The data collected with the first campaign of experiments are used to obtain the strength parameters required to define a damage model based on the failure theory by Tsai-Wu. This model is implemented in a Finite Element (FE) code and numerical simulations of buckling are executed for unidirectional and cross-ply laminates; results are in good agreement with experiments both in terms of determination of the critical loads and prediction of failure during post-buckling.

References listed at the end of the paper:
and stresses are plotted. The buckling load is increasing with increase in thickness. The hinge stresses and loads are considerably reduced with nonlinear analysis. The effect of thickness on buckling load analysis is extended for circular members. The stresses and results are compared with theoretical results to check Finite element validity. The results are very close and better results. Both Shell63 in elastic range and shell43 in plastic range are used for analysis. The elliptical members are fine meshed to get scaling options are used to built the elliptical members. The structure is divided to ease map meshing. Initially element techniques in the nonlinear domain. In the present work both cylindrical and elliptical members are available for nonlinear range. So these problems are solved by the advances in computer technology with Finite element techniques, analysis of these problems is possible which is difficult in earlier days. Formulae’s are available based on experimental techniques for linear range and not work. Due to the advances in the Finite element techniques, analysis of these problems is possible which is difficult in earlier days. Formulae’s are available based on experimental techniques for linear range and not work. Due to the advances in computer technology with Finite element techniques, analysis of these problems is possible which is difficult in earlier days. Formulae’s are available based on experimental techniques for linear range and not work. Due to the advances in computer technology with Finite element techniques, analysis of these problems is possible which is difficult in earlier days. Formulae’s are available based on experimental techniques for linear range and not work.

ABSTRACT:


ABSTRACT: Buckling is a critical phenomenon in structural failure. Buckling is the failure of structures under compression load. Also buckling strength of structures depends on many parameters like supports, linear materials, composite or nonlinear material etc. Also buckling behavior is influenced by thermal loads and imperfections. Analyzing all these conditions is difficult task. So few parameters are considered for the present work. Due to the advances in the Finite element techniques, analysis of these problems is possible which is difficult in earlier days. Formulae’s are available based on experimental techniques for linear range and not available for nonlinear range. So these problems are solved by the advances in computer technology with Finite element techniques in the nonlinear domain. In the present work both cylindrical and elliptical members are considered for buckling strength. Initially both the members are created using Ansys top down approach. Scaling options are used to built the elliptical members. The structure is divided to ease map meshing. Initially one end constrained and other free condition is considered for analysis. The structure is fine meshed to get better results. Both Shell63 in elastic range and shell43 in plastic range are used for analysis. The elliptical results are compared with theoretical results to check Finite element validity. The results are very close and analysis is extended for circular members. The stresses and loads are very high with linear analysis. But the stresses and loads are considerably reduced with nonlinear analysis. The effect of thickness on buckling load and stresses are plotted. The buckling load is increasing with increase in thickness. The hinged boundary

conditions shows higher buckling strength compared to the initial boundary conditions for both elliptical and cylindrical members. The problem executed in the time domain also indicates the stresses reaching to the yield point and converging towards the critical loads. All results are represented with necessary graphical and pictorial plots.

References listed at the end of the paper:

K. Kalnins, J. Auzins and R. Rikards (Institute of Materials and Structures, Riga Technical University, Riga, Latvia), “A fast simulation procedure for ribbed composite structures with material degradation”, Mechanics of Composite Materials, Vol. 43, No. 3, pp 225-232, May 2007 ABSTRACT: A fast simulation procedure for axially loaded ribbed composite structures is suggested based on the response surface methodology (RSM). The assessment of material degradation in terms of stiffness reduction in the skin-stringer zone is carried out to ensure the design reliability, thus acquiring a fast simulation procedure for an efficient and reliable analysis of the behaviour of axially loaded ribbed composite panels in their postbuckling state.

References listed at the end of the paper:


ABSTRACT: The buckling of imperfect composite cylinders under concentric and eccentric compression is investigated experimentally and numerically, with particular attention given to the imperfection sensitivity of the shells. A series of glass-fiber-reinforced plastic cylinders have been tested under different load eccentricities to validate the corresponding nonlinear numerical analyses performed in this study. A good agreement between the experimental and numerical results was achieved through use of the ABAQUS/Explicit finite-element code and the introduction of initial imperfections. Both the experimental and the numerical results show that the knockdown factor increases as the loading eccentricity grows.

References listed at the end of the paper:
ABSTRACT: This experimental and numerical study focuses on the buckling problem of cylindrical composite shells under pulse loads. Series of experiments have been performed to determine buckling loads of the laminated cylinders under different axial loading rates. Numerical models of the tested specimens have been elaborated and good agreement between experimental and numerical results has been achieved. The numerical models have been used to study the buckling behavior of the cylinders at loading rates much higher than could be achieved experimentally. Additionally, the influence of imperfections on dynamic buckling behavior of the laminated shells has been studied numerically.

References listed at the end of the paper:

ABSTRACT: This thesis is focused on the investigation of the changes in the buckling behaviour of various composite shells due to dynamic, rapid loading. Currently, the structural design procedures of lightweight structures incorporate assumption of the loads as quasistatic, while maintaining reliability by applying conservative safety coefficients. Different investigations show that in various cases of dynamic loading the buckling loads can be both higher and lower than the static buckling load. Therefore, correct consideration of the load dynamics in the design procedure would lead to safer and more efficient structures. A reliable, experimentally validated analysis approach is required in order to benefit from the weight-saving potential of dynamically loaded composite structures, while maintaining the reliability. However, only few experimental investigations on dynamic buckling of composite structures have been performed because of the complexity of such experiments. In present thesis, the dynamic buckling of composite shells has been investigated experimentally and numerically, and an appropriate experimentally validated modelling approach has been proposed. Chapter 1 gives review of the accumulated knowledge in dynamic buckling of thin-walled structures. The key pioneering research has been reviewed along with the publications describing the current state-of-the-art in the field. It has been revealed that surprisingly few experimental studies have been attempted in dynamic buckling of composite shells, with most researchers resorting to the analytical and numerical investigations only. Chapter 2 contains the relevant information about the experimental and numerical methods used within this thesis. The experimental investigations have been performed on cylindrical composite shells using hydraulically actuated loading frames and a drop tower. The main numerical tool used in this thesis is the ABAQUS/Explicit finite element software. Chapter 3 describes the static buckling behaviour of the selected specimens as a reference for the comparison with the dynamic buckling behaviour. The imperfection sensitivity of the cylindrical shells has been addressed by measuring the geometrical imperfections of the specimens and
using this data in the numerical analyses. Chapter 4 contains the results of experimental and numerical investigations of dynamic buckling of composite cylinders. Gradually and suddenly applied loads, as well as half-sine shaped pulse loads have been considered and the influence of the load parameters on the buckling behaviour of the shells has been revealed. Chapter 5 expands the research to stiffened curved composite panels. The results have been obtained for various loading patterns using numerical models validated with the results of static buckling experiments.

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162


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ABSTRACT: It has been long recognized that the buckling behaviour of thin-walled pressure vessels, subjected to axial loading, is characterized by a bifurcation on an asymmetrical mode. It is also known that the carrying capacity of this type of structure greatly depends on geometrical imperfections characterizing the surface. This drastic effect of geometrical faults leads to a conservative design in most cases. In the design of the principal cryotechnic stage of the launcher Ariane 5, a thin-walled vessel was studied under complex loading conditions combining: pressurization, axial loading and a shear force coupled to a bending moment. Thus, the risk of buckling requires a precise estimation of pressure effects on geometrical imperfections. This is performed in two different cases: in the case of a non-stiffened configuration, and with the presence of axial stiffeners.

References listed at the end of the paper:


ABSTRACT: The effects of geometrical imperfections on the critical load of elastic cylindrical shells when subjected to axial compression are studied through analytical modelling. In addition to distributed defects of both axisymmetric or asymmetric forms, emphasis is put on the more severe case of localized defects satisfying the axial symmetry. The Von Kármán - Donnell shell equations were used. The obtained results show that shell strength at buckling varies very much with the defect amplitude. These variations are not monotonic in general. They indicate however a clear reduction of the shell critical load for some defects revealed as the most dangerous ones. The proposed method does not consider the complete coupled situation that may arise from interactions between several localized defects. It facilitates nevertheless straightforward initializing of closer analyses if such couplings are to be taken into account by means of special numerical approaches, because it enables fast a priori selection of the most hazardous isolated defects.

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“Buckling of elastic cylindrical shells considering the effect of localized axisymmetric imperfections”, Thin-
ABSTRACT: The effect of localized axisymmetric initial imperfections on the critical load of elastic cylindrical shells subjected to axial compression is studied through analytical modeling. Some classical results regarding sensitivity of shell buckling strength with respect to distributed defects having axisymmetric or asymmetric forms are recalled. Special emphasis is placed after that on the more severe case of localized defects satisfying axial symmetry by displaying an analytical solution to the Von Kármán–Donnell shell equations under specific boundary conditions. The obtained results show that the critical load varies very much with the geometrical parameters of the localized defect. These variations are not monotonic in general. They indicate, however, a clear reduction of the shell critical load for some defects recognized as the most hazardous isolated ones. Reduction of the critical load is found to reach a level which is up to two times lower than that predicted by general distributed defects.

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RÉSUMÉ: Les structures cylindriques élastiques sont des constructions courantes dans les domaines de l’ingénierie civile et mécanique. Ces structures à parois minces peuvent occasionner un ébavouissement lorsqu’elles sont soumises à la compression axiale. L’ébavouissement limite à un grand degré leurs performances en termes de résistance. Ce phénomène dépend énormément des imperfections initiales distribuées ou localisées géométriques qui sont présentes sur la structure de la coque. Les imperfections géométriques localisées ont en général été obtenues par l’assemblage de la coque par le soudage de strakes. Dans cet essai, une étude de la fiabilité de la résistance d’ébavouissement en prenant en compte la variation de la coque a été effectuée. Les imperfections géométriques localisées étaient choisies pour être entrantes et avoir une forme triangulaire ou onde. L’interaction entre trois imperfections localisées avait également été considérée. Approach: Un logiciel spécifique était utilisé permettant d’analyser le problème d’ébavouissement de la coque à travers le procédé d’Éuler linéaire. Un ensemble de cinq facteurs y compris les rapports d’aspect de la coque, les caractéristiques de l’imperfection et la distance séparant les imperfections localisées avaient été trouvés pour gérer le problème. Un paramétrage a été effectué pour déterminer leur influence relative sur la déformation de la coque. L’analyse de fiabilité a été menée à l’aide de la méthode de premier ordre. Résultats: L’imperfection ondulée a été trouvée plus sévère que celle triangulaire dans la gamme de faible amplitude des imperfections. Il a été montré par comparaison avec le cas unique que la diminution de la charge critique est obtenue pour trois imperfections interactives. La distance inter-imperfections a été trouvée de grande importance sur l’indice de fiabilité. Conclusion/Recommandations: Dans la gamme de paramètres examinés, la fiabilité a été trouvée d’augmenter avec la distance séparant les imperfections géométriques localisées. Cela peut aider à effectuer un design optimal des strakes assemblés.

References listed at the end of the paper:
for short and thin shells. Two interacting imperfections were found to be more severe than a single imperfection. The obtained results have shown that amplitude and wavelength have major effects, part

ABSTRACT: Buckling of cylindrical shells under axial compression is an important problem. The buckling load is affected by the initial geometric imperfections. Several studies have been performed to investigate the effect of initial geometric imperfections on the buckling load of cylindrical shells. The imperfections of entering triangular form were assumed to be positioned symmetrically at the middle shell length. The buckling load was assessed in terms of shell aspect ratios, imperfection amplitude and wavelength, and the distance separating the imperfections. The obtained results have shown that amplitude and wavelength have major effects, particularly for short and thin shells. Two interacting imperfections were found to be more severe than a single imperfection.
imperfection, but the distance separating them has small influence.


ABSTRACT: A thin-walled pressurised cylindrical shell is sensitive to buckling phenomena when it experiences locally a compressive stress. It is often considered that its behaviour under bending is rather similar to pure compression, but very few are the experimental investigations that precise the real behaviour of a thin pressurised cylinder submitted to a bending load. A large amount of experimental results is presented here, obtained on thin shells (550<\(R/t<1450\)) of moderate length (\(L/R\approx 2\)). The evolution of the cylinders' behaviour that has been recorded when internal pressure increases is outlined. It is shown that one must distinguish between local buckling and global collapse of the structure. A comparison of our experimental data to design recommendations given by two standards (NASA SP8007 and Eurocode 3) is finally achieved, putting in advance safety margins provided by these codes.


ABSTRACT: Experimental and numerical methods are used to study the stability problem of cylindrical shells with cut-outs. The paper presents parametric research of the shape (square, rectangular, circular), the dimensions (axial and circumferential sizes, diameter) of the hole. The effect of the location and the number of the holes are also studied. The analysis indicates that the critical load is sensitive to the opening angle or circumferential size of the hole. The function (critical load-opening angle) is linear for large openings and independent of the geometrical imperfections of the shell. However for small openings, it is necessary to take into account the coupling between the initial geometrical imperfections and the openings. The linear approach does not fit because of the importance of the evolution of the displacements near the openings. These results will be used for the development of European rules.


ABSTRACT: Aggressive environments can provoke corrosion of thin cylindrical shells widely used in different engineering applications. Localised decrease of shell thickness usually causes buckling load reduction. Recently in 1994, Koiter et al. investigated the influence of modal thickness variation on a buckling load of an axially compressed shell. The thickness variation is assumed to be axisymmetrical and sufficiently small. In this paper Koiter et al. show that thickness imperfection can provoke a loss of buckling load which is, for small imperfection amplitude, a linear function.

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ABSTRACT: Stability of imperfect elastic cylindrical shells which are subjected to uniform axial compression is analyzed by using the finite element method. Multiple interacting localized axisymmetric initial geometric imperfections, having either triangular or wavelet shapes, were considered. The effect of a single localized geometric imperfection was analyzed in order to assess the most adverse configuration in terms of shell aspect ratios. Then two or three geometric imperfections of a given shape and which were uniformly distributed along the shell length were introduced to quantify their global effect on the shell buckling strength. It was shown that with two or three interacting geometric imperfections further reduction of the buckling load is obtained. In the ranges of parameters that were investigated, the imperfection wavelength was found to be the major factor influencing shell stability; it is followed by the imperfection amplitude, then by the interval distance separating the localized imperfections. In a wide range of parameters this last factor was recognized to have almost no effect on buckling stresses.


ABSTRACT: Reliability assessment of buckling limit state for imperfect stiffened panels made from elastic homogenous and isotropic material and subjected to uniform axial compression was performed in this work. The stiffened panel was assumed to suffer a single localized geometric imperfection having the form of a rectangular depression patch that is situated either on a web or a segment of the panel. A parametric study was performed with regards to the buckling strength variations for both perfect and imperfect panels as affected by the defect depth and position. Imperfect panels were generated by placing a depression square of fixed size and variable depth at various locations of the web and the plate. The obtained results have shown that buckling strength of stiffened panels is largely affected by the system geometric parameters and the defect characteristics. For an imperfect stiffened panel with a defect present either on a web or a segment, a drastic reduction of the buckling stress was obtained. The relative influence of defect position and depth was found to depend on whether the defect is located on a web or a segment of the stiffened panel. For a given configuration of the panel, focus was done on the effect of uncertainties affecting the plate geometric dimensions, the defect characteristics and the applied loading. These parameters were assumed to be random variables. Their means and standard deviations were assumed to be known, while no prior information is available about their densities of probabilities. First Order Reliability Method was applied to a response surface representation of the buckling limit state which was derived through quadratic polynomial regression of finite element results that were collected according to a full factorial design of experiment table built on the key intervening factors. The influence of the distributions of probabilities chosen to model the problem uncertainties for the perfect and imperfect stiffened panels was analyzed. It was found that these modify significantly reliability results.

References listed at the end of the paper:


ABSTRACT: Sixteen torispherical heads were tested under internal pressure. These heads, which were 500 mm in diameter, had diameter/thickness ratios ranging from 330 to 1000. They were all prepared by spinning mild steel plates. Deflections along the axis and in the knuckle area were recorded. The most practical result is the buckling pressure and this can be exceeded without fracturing the head. The tests show that the buckling pressure is relatively unaffected by geometric imperfections. These experimental results are used to assess the validity of the different plastic bifurcation analysis methods. Five different methods were employed using the CASTEM general-purpose computer program. The method based on the incremental theory of plasticity proved to be incapable of correctly predicting head buckling. If this method is modified by replacing the elastic shear modulus by the secant modulus, the results obtained show good agreement with experimental results.

ABSTRACT: The Liquid Metal Fast Breeder Reactor poses special problems in the design and construction of its important components. Its low pressures permit utilization of less expensive, thin cross-sections. But the high temperatures result in serious thermal stress and buckling problems. This paper describes the buckling design rules for the French Fast Reactor design for Class I and II components. The paper contains a simplified analysis method, offers experimental validation, and a comparison with the ASME Section III code.

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PARTIAL INTRODUCTION: In Liquid Metal Fast Breeder Reactors (LMFBR) potential shear buckling failures of the primary vessel, induced through seismic excitations, have to be considered. The problem is particularly severe in pool type reactors due to their large size, radius of approximately 10 m, coupled with small wall thicknesses of 50 mm and less. In addition, the primary vessel material, typically 316 stainless steel, has a low yield strength at the normal operating temperatures of around 400 degrees C to 500 degrees C. These characteristics tend to make the structure relatively flexible and subject to potential elasto-plastic shear buckling failure…
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ABSTRACT: A modal method of analysis is used to determine the response of an infinitely long stiffened cylindrical shell of revolution to a transient lateral pressure produced by an underwater explosion and propagating in an acoustic fluid. The shell is initially immersed, hence prestressed by the external hydrostatic pressure. A theory of dynamic buckling is then developed for cylindrical shells subjected to transverse pressure pulses of different durations.

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ABSTRACT: The plastic bifurcation buckling pressures of 60 internally-pressurised, perfect, complete toroidal shells of elliptical cross-section are given in the present paper, assuming elastic, perfectly plastic, material behaviour. The shell buckling programs employed in the computations were BOSOR 5 and INCA. Denoting the major-to-minor axis ratio by $k$, the numerical results show that the plastic buckling pressures are considerably lower than their elastic counterparts in the range $1.25 \leq k \leq 1.5$ and are approximately equal to them for $k=2.5$. A limited study of the effects of non-axisymmetric initial geometric imperfections on the buckling pressures of the shells was also carried out using the INCA code. For the four cases studied the post-buckling behaviour was stable. This means that designers can use the buckling pressures given herein for perfect shells as a basis for their initial designs.

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ABSTRACT: Imperfection sensitivity of thin shells of constant thickness was widely studied during the last 50 years (J.G. Teng, Appl. Mech. Rev. 1996:49(4)). Recently, Koiter et al. (Int. J. Solids Struct. 1994:31(6):797–805) investigated the influence of axisymmetric modal thickness variation on the buckling load of an axially compressed shell. In this paper, the influence of harmonic thickness variation in the circumferential direction on thin cylindrical shell buckling under external pressure is analysed by means of FE bifurcation analysis. Two different FE codes were used, one with quasi-axisymmetrical multimodal Fourier analysis (A. Combescure, Etude de la stabilité des coques minces sous chargements complexes dans INCA. Rapport DMT/94-460, in French, 1994; Modélisation des coques axissymétriques avec imperfection quelconque: L’élément COMI (in French). Rapport DMT/97-189, 1997; Schauder B. Flambage des Coques Cylindriques en Fléxion. Thèse de doctorat, INSA de Lyon, in French, 1997), and the second one with 3D shell elements. A new quasi-
axisymmetric element (COMI) is presented. It uses Fourier series expansion in the circumferential direction coupled with a full numerical integration around the circumference, which allows any variation of thickness or of initial imperfections.

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ABSTRACT: This paper concerns the influence of thickness imperfections on the nonlinear buckling of cylinders under uniform external pressure. The material is assumed to behave elastically. A parametric study is performed using the COMI finite element, which allows to perform nonlinear analyses of shells of revolution with any kind of nonaxisymmetric initial imperfection. Let us assume that the perfect shell buckles with a Fourier mode $m$ and that the initial thickness imperfection is on Fourier mode $1$, $m$ or $2m$. As shown in a previous study on linear buckling of cylinders with thickness imperfections, $1$ and $2m$ are the most harmful thickness imperfections. We show that the nonlinear pre-buckling does not affect the buckling pressures very much. We then study the coupling with geometrical imperfections. We show that the geometry and thickness imperfections have a multiplicative effect on the decrease in buckling load in the nonlinear range. Finally, we show that if one uses only the measured outer radius of a shell to input initial imperfections, very different nonlinear buckling pressures can be obtained under the assumptions that the imperfection is purely geometric, purely thickness, or a combination of both.

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ABSTRACT: The buckling behavior of thin-walled pressurized cylinders under bending load is investigated through an intensive experimental campaign on thin shells ($550 < R/t < 1450$) of moderate length ($L/R$ about equal to 2.0). The experimental buckling behavior of pressurized shells under bending is somewhat similar to the behavior under axial compression: for low pressurization cases, the load-carrying capacity is strongly sensitive to geometrical imperfections, whereas above a sufficiently high level of pressure, the buckling occurs for a stress value close to the theoretical prediction. A major difference between bending and pure compression lies in the post-critical behavior; the reaching of the critical load under bending is accompanied by wrinkles or buckles confined to a small area around the (maximally) compressed fiber. It allows, in the case of sufficiently pressurized cases, stress redistribution around the buckling zone. Therefore the collapse moment is much higher than the bifurcation moment, in contrast to the case of pure axial compression. In a second section, non-linear finite element analyses are carried out to simulate the conducted tests. The numerical model correctly follows the experimental results.


ABSTRACT: The objective of this work is to answer the following question: Is a multilayer shell model always
appropriate for the prediction of the buckling of a thin structure? In order to do that, we chose to analyze the buckling of a three-layer cylindrical tube in uniform axial compression. We compared three approaches for the calculation of the theoretical buckling load: a fully analytical formula, a Fourier series buckling model of a multilayer axisymmetric shell and a calculation based on a mechanical mesh of the axisymmetric medium of the middle layer. This analysis shows that two buckling modes are in competition: a global beam mode and a local skin buckling mode (wrinkling) which develops when the stiffness of the middle layer is quite small. The critical loads can be estimated analytically for both types of modes, leading to a critical length under which the cylinder fails by skin buckling; otherwise, it fails in beam mode. Then the problem was solved by finite elements using two models: first, a multilayer axisymmetric shell model, then a model with two types of elements in each section (an 8-node axisymmetric element for the middle layer, and axisymmetric shell elements for the two skins). We showed that both models can predict the beam mode, but only the latter was capable of predicting the skin buckling mode. Similar results are proposed for the prediction of the buckling of a three-layer cone under internal pressure. We also compared the formulations for geometrically nonlinear problems with nonlinear materials and showed that in such problems the nonlinearities cause even more pronounced differences. This clearly raises the question of the choice of the type of finite element for the prediction of buckling in a multilayer structure in which some layers have only a small relative stiffness. The analytical solution and the analysis of the nonlinear response in the case of the cone confirm that the poor prediction of the skin buckling mode is due to a failure to account for the flexibility perpendicular to the mean surface.

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ABSTRACT: A series of fabric-reinforced concrete shells are tested for buckling under uniform normal pressure in an air chamber. The test results are compared with previous experimental results for steel-reinforced concrete shells, and are used to provide a tentative design procedure for fabric-reinforced spherical shells. The design procedure is illustrated with an example, comparing results with the results obtained by design methods for steel-reinforced shells described in earlier studies. Experiments to maximize buckling stiffness per unit material cost in the shell cross section are summarized. Practical limitations on shapes of fabric-reinforced shells are described as well as their buckling sensitivity to variables in construction procedure.

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“Nondestructive Load Predictions of Concrete Shell Buckling”, ASCE J. Struct. Engrg. 115, 1191 (1989 );
ABSTRACT: Nondestructive test methods are evaluated for predicting the buckling capacity and buckling location of fabric-reinforced concrete shells. The load-deformation methods consist of measuring vertical deflections of 10-20 points on the shell surface under increasing vacuum pressures, curve fitting of the deflection-pressure response at each point, calculating a characteristic pressure on each curve, and using the lowest such calculated pressure as a predictor of shell buckling capacity. The curve fits are updated at each pressure increment and the test is continued to a pressure equal to a safe fraction of predicted buckling load,
based on prior testing experience. Predicted and actual buckling pressures are compared for six experimental shells. The chosen method was selected from a comparison of four extrapolation methods, based on its least standard deviation between predicted and actual buckling pressures for the six shells. Vacuum tests can also indicate approximate buckling locations, for installing reinforcing arches before placing shells in service, and provide an inexpensive means for proof loading shells to any specified overload factor.


ABSTRACT: A degenerated 9-node-shell element and interpolation formulation for stress resultant vectors were utilized in this work. Selected experiments previously performed by the second author on the elastic buckling of clamped thin-walled shallow spherical shells under external pressure are compared with the present finite element analytical results. The measured geometric initial imperfection distributions are incorporated in the finite element analytical procedure. Good agreement between the numerical simulations and the experimental measurements of not only maximum loads but also displacement distributions were obtained.


ABSTRACT: In contrast with the pressure buckling of a complete cylinder, even a perfect cylindrical shell panel displays a complex form of nonlinear snap buckling behaviour. The prebuckling nonlinearity has been understood to be induced by the total equivalent imperfections involving the potential-load-induced imperfection and the actual geometric imperfection. Based on this concept, an alternative estimation procedure of the elastic and elastoplastic buckling load-carrying capacities is proposed and the resulting simple equations and formulae for design are represented.

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ABSTRACT: An elastic nonlinear Ritz analysis is used to investigate the behavior of axially loaded imperfect cylindrical shells. It is shown how the initially positive contributions arising from the shells membrane energy are eroded with increasing levels of both deformations and imperfections. This loss of membrane energy is shown to be responsible for the notoriously imperfection sensitive buckling of the shell. Extensive parameter studies demonstrate the existence of a well-defined lower bound to buckling loads and the dominance of characteristic incremental deformation modes as this lower bound is approached. For the first time the physically based hypotheses of the reduced stiffness method are theoretically demonstrated. Furthermore, it is shown how a slightly modified form of the reduced stiffness method provides very close predictions of the lower bounds to buckling loads.

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ABSTRACT: A rational design evaluation procedure is investigated for the elastic overall buckling load carrying capacity of single layer cylindrical lattice shell roof structures. The nature of the imperfection sensitivity of these structures is for the first time reviewed in this paper. This allows the development of the reduced stiffness buckling analytical concept for the lattice shells based upon the introduction of a simple lower bound estimation equation through the use of the so-called continuum shell analogy theory. The linear and nonlinear buckling loads found from conventional finite element analyses are compared with the present estimations. Finally, the elastic-plastic load carrying capacity estimation method through the use of the present elastic lower bound criteria is also proposed.

References listed at the end of the paper:

ABSTRACT: In this paper, dynamic buckling of a martensitic transformation dominated super-elastic TiNi thin cylindrical shell under single loading was studied and analyzed. The results showed that the buckling mode was mainly the non-axisymmetric diamond model, and recovered when unloading, and related with martensitic transformation and the behavior of the transformation hinge, and was significantly different from the traditional elastic-plastic cylindrical shell. The article also discussed that the influence of the length-to-diameter rate and boundary conditions on buckling mode, specific energy, critical instability threshold, and so on. The study showed, as length and boundary conditions changed, TiNi thin cylindrical shells showed a variety of buckling modal development. Under the same boundary condition, Se was reduced as length-diameter ratio increased, had the similar law with the quasi-static compression experiments. But the specific energy of a TiNi thin cylindrical shell was greater than that in the quasi-static compression experiments.


ABSTRACT: The containment vessel of a nuclear power plant, the LMFBR reactor vessel, and a tall cylindrical tower are thin cylindrical shell structures with large diameter. Therefore, development of an evaluation technology for dynamic buckling for these structures due to wind or seismic loading is becoming very important. Some research works are found recently, but the analysis generally needs unpractical huge CPU time. The development and the utility of a practical dynamic buckling analysis code using FEM, in which lumped masses and initial imperfection etc. can be taken into account, are reported here.

Nine references to papers published 1984 – 1991 given at the end of the paper (could not “cut and paste”).


ABSTRACT: The paper considers the buckling of complete spherical shells. The main purpose could be, as a basis for real design, to find the lower critical load. Three scientists developed the idea that the buckled shape of the shell is the isometrically transformed shape of the original shell surface. Applying this idea using rotationally symmetric buckled shape the lower critical load can be calculated fairly easily for spherical shells. In reality the buckled shape has rather discrete rotation symmetry. Considering this kind of buckled shape is the main task of our research. Some preliminary results related to this buckling form will be presented here.

References:
ABSTRACT: Metal silos used to store granular solids often take the form of a cylindrical shell with an aspect ratio in the range 2 < H/D < 6. It has long been recognized that the most serious load case for silos is the condition of eccentric discharge of its stored solid, and more failures have occurred under this condition than any other. Two of the chief reasons for this high failure rate are the difficulty in characterizing the pressure distribution caused by eccentric solids flow, and the difficulty in understanding the pattern of stresses that develops in a shell wall under such unsymmetrical pressure regimes. The nonsymmetric behavior of a shell structure under such a loading condition is not at all well described in the voluminous shell structures literature, and only a few studies have explored the mechanics leading to high local stresses which in turn lead to buckling failure under eccentric discharge. In this study, the pressures caused by eccentric discharge are characterized using the new rules of the European Standard EN 1991-4 [5] that defines the Actions in Silos and Tanks. Using this new improved description of unsymmetrical pressures, it is now possible to perform relatively realistic calculations relating to this common but complicated shell buckling condition. The calculations described here are part of a wider study believed to be the first of its kind and are undertaken using geometrically and materially nonlinear analyses in accordance with the European Standard EN 1993-1-6 [6] on Strength and Stability of Shells. The paper explores the structural behavior leading to buckling during eccentric discharge, including the critical effects of changes of geometry and imperfection sensitivity.

ABSTRACT: This paper aims to develop practical design equations and charts estimating the buckling strength of the cylindrical shell and tank subjected to axially compressive loads. Both geometrically perfect and imperfect shells and tanks are studied. Numerical analysis is used to evaluate buckling strength. The modeling method, appropriate element type and necessary number of elements to use in numerical analysis are recommended. According to the results of the parametric study of the perfect shell, the buckling strength decreases significantly as the diameter-to-thickness ratio increases, while it decreases slightly as the height-to-diameter ratio increases. These results are different from those in the case of columns. The buckling strength of the perfect tank placed on an extremely soft foundation and a stiff foundation increases by up to 1.6% and 5.6%,
respectively, compared with that of the perfect shell. The buckling strength of the shell and tank decreases significantly as the amplitude of initial geometric imperfection increases. Convenient and sufficiently accurate design equations and charts used for estimating buckling strength are provided.

References listed at the end of the paper:


ABSTRACT: The free vibration problem of a thin cross-ply composite laminated circular cylindrical panel subjected to arbitrary combinations of axial and circumferential initial compressions is studied. The equations of motion are derived, in the framework of the Donnell-type theory, in terms of the panel middle surface displacements components. Closed form solutions are obtained, for simply-supported panels, and numerical results for both antisymmetric and unsymmetric laminated cross-ply panels are presented.

References listed at the end of the paper:

ABSTRACT: The free vibration problem of a thin composite cross-ply laminated non-circular cylindrical shell subjected to an axial compression is studied. The equations of motion are derived, in the framework of the Donnell-type theory, in terms of the shell middle surface displacement components. The differential equations of motion have variable coefficients and they are solved by employing Galerkin's method. As an application, the problem of the free vibrations and buckling of cross-ply laminated oval cylinders is studied. Numerical results for antisymmetric and unsymmetric cross-ply laminated shells of graphite-epoxy are presented and discussed.

ABSTRACT: The buckling and free vibration problem of a thin composite antisymmetric angle-ply laminated circular cylindrical shell is studied. The Donnell-type equations of motion, in terms of the shell middle surface displacement components, are used and solved approximately by means of Galerkin's method. Numerical results are presented and the expectation that the bending-stretching coupling phenomenon rapidly dies out as the number of layers increases is confirmed.

ABSTRACT: For a generally anisotropic laminated thin elastic non-circular cylindrical shell, subjected to a combined loading, the equations of motion of a second approximation Flugge-type theory are derived and expressed in terms of the shell middle-surface displacement components. As an application, for the free vibration problem of a cross-ply laminated non-circular cylindrical shell subjected to S2 simply supported edge boundary conditions, these equations are solved by employing the method of Galerkin. For a family of regular antisymmetric cross-ply laminated oval shells, numerical results are obtained and discussed. Comparisons are also made between some of the obtained results and corresponding results obtained from the solution of the quasi-shallow shell Donnell-type equations of motion.

ABSTRACT: The free vibration problem of thin elastic cross-ply laminated circular cylindrical panels is considered. For this problem, a theoretical unification as well as a numerical comparison of the thin shell theories most commonly used (in engineering applications) is presented. In more detail, the problem is formulated in such a way that by using some tracers, which have the form of Kronecker's deltas, the stress-
strain relations, constitutive equations and equations of motion obtained produce, as special cases, the corresponding relations and equations of Donnell's, Love's, Sanders' and Flugge's theories. By using a closed form solution, obtained for simply supported panels, a comparison of corresponding numerical results obtained on the basis of all of the aforementioned shell theories is attempted.


ABSTRACT: The present paper is concerned with the development and certain applications of a refined shear deformable theory suitable for the dynamic analysis of laminated anisotropic plates as well as cylindrical shells of either circular or non-circular configuration. The theory accounts for parabolic variation of transverse shear strains and it is capable of satisfying zero shear traction boundary conditions at the external shell or plate surfaces, and makes no use of transverse shear correction factors. It can be considered as a transverse shear deformable analogue of the classical laminate Donnell-type and Love-type shell theories while, through certain new definitions of force and moment resultants, the higher order moment and transverse shear force resultants occurring acquire some physical substance. Under certain conditions, some dynamical problems studied earlier by the present author are considered as applications of the refined theory developed. As a further application, the present theory is employed for the study of the free vibration problem of antisymmetric angle-ply laminated closed circular cylindrical shells. This problem is solved by two different mathematical techniques; namely, the helical modal pattern approach and an approach based on Galerkin's method. Numerical results based on both solutions obtained are presented and compared and the efficiency of both approaches, with regard to the prediction of the natural frequencies of vibration, is discussed.


ABSTRACT: A general two-dimensional theory, suitable for the static and/or the dynamic analysis of transverse shear deformable laminated plates, is presented. This displacement-based theory is capable of satisfying continuity of both displacements and transverse shear stresses at the plate material interfaces. The derivation of its governing differential equations is based on the application of Hamilton's principle in conjunction with the method of Lagrange multipliers. Moreover, this new theory is capable of accounting for unlimited multiple choices of continuous displacement distributions, through the plate thickness, while, starting with the smallest possible number of independent displacement components (five, for a shear deformation theory), it is capable of further operating with as many degrees of freedom as desired. With such a double-infinite freedom, it is concluded that for the analysis of the particular laminated plate considered one may start with the solution of the governing equations of the 5-degrees-of-freedom theory derived for relatively simple choices of through-the-thickness displacement distributions. Then, either increasing the number of the degrees of freedom or reforming, suitably, the aforementioned displacement distributions, one may iteratively improve the efficiency of the theory until a sufficient degree of accuracy is achieved for the results obtained.

ABSTRACT: This paper deals with the buckling problem of antisymmetric angle-ply laminated circular cylindrical panels subjected to a uniform axial compression. Since a flat plate configuration occurs as a particular case of the cylindrical panel geometry (zero shallow angle parameter), the corresponding flat plate problem is studied as a particular case of the problem considered. The theoretical analysis is based on a nonlinear theory developed in a previous paper (Soldatos, 1992), which accounts for parabolically distributed transverse shear strains through the shell thickness. The linearized differential equations, governing the buckling behavior of a simply supported panel, are solved on the basis of Galerkin’s method. Comparisons of corresponding numerical results, based on both the refined shell theory employed and a classical Love-type shell theory, show the influence of transverse shear deformation on the buckling loads of such laminated composite panels.


ABSTRACT: This paper deals with a refined formulation of a general, geometrically nonlinear, shear deformable, static plate theory which allows a multiple choice of trial displacement and, consequently, stress distributions through the plate thickness. This is achieved with the incorporation, into a basic trial displacement approximation, of a general function of the transverse coordinate. An appropriate choice of the derivative of that function is, essentially, adequate for an a posteriori control of the transverse shear strain and stress distributions. However, a particular choice of that general function is not provided, leaving, therefore, the theory in its most general form. The development of the theory is based on the concept of small strains and moderate rotations. Its force and moment equilibrium equations are derived variationally, on the basis of the principle of the total potential energy. Under certain conditions, the present nonlinear theory becomes analogous to several linear and nonlinear plate theories available in the literature, in the sense that it can easily adopt and make use of their main characteristics.


ABSTRACT: A successive approximation method proposed and applied in connection with static and dynamic analyses of homogeneous isotropic, orthotropic and cross-ply laminated hollow cylinders and cylindrical panels is outlined and its applicability is extended in connection with corresponding thermoelastic analyses. Nevertheless, the method is further applied in connection with the buckling problem of simply supported hollow cylinders and cylindrical panels subjected to certain external mechanical loadings. To deal with finite cylinders subjected to more complicated loading that simply supported edge conditions, an approach is outlined which is suitable for corresponding analyses of hollow cylinders having fixed edge boundaries.

ABSTRACT: It is well known that composite thin-walled structures are considerably more sensitive in transverse deformation effects than corresponding structures made from isotropic materials. However, buckling studies of composite cylinders and cylindrical shells are mainly based on two-dimensional shell theories. It is only very recently that three-dimensional buckling analyses of composite cylinders subjected to certain mechanical loading have appeared in the literature [1–4].

References listed at the end of the paper:

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ABSTRACT: This paper extends the applicability of the Ritz-type method presented in a previous publication [1] towards an advanced study of the influence of the edge boundary conditions on the vibration characteristics of complete, cross-ply laminated cylindrical shells. The analysis is based on a combination of the Ritz method with appropriate, complete bases of orthonormal polynomials and its subsequent application on the energy functional of the love-type version of a unified shear-deformable shell theory. As a result, two different kinds of shear deformable Love-type shell theories are employed, including versions that either fulfil or violate the continuity of the interlaminar stresses through the shell thickness. Apart from the study of the physical problem itself, several features related to the theoretical model as well as to the analytical procedure are further addressed and investigated. As far as the modelling is concerned, particular emphasis is given to the version of the parabolic shear-deformable shell theory that considers continuity of interlaminar stresses. Moreover, the relation of this version of the theory as well as its performance with respect to the corresponding older version that violates this continuity requirement [8] is further investigated. It is concluded that the accurate modelling of the interlaminar stress distribution may become a serious issue for further investigation, as it already is for the stress analysis of laminated composite structural elements.

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ABSTRACT: This paper extends the applicability of a new stress analysis method (Soldatos KP, Watson PA. Acta Mech 1997;123:163–186) towards the accurate prediction of stresses within cross-ply laminated doubly curved shell segments having a rectangular plan-form. The method is based on the successful incorporation of three-dimensional elasticity information for stress distributions into a two-dimensional five-degrees-of-freedom shallow shell theory. This successful matching is achieved by means of a set of two shape functions, which are incorporated within the two-dimensional shell model whereas their form depends on the particular problem considered. In the present case, two different sets of shape functions are developed and tested, one of which is more accurate than the other is, the later being however simpler than the former.


ABSTRACT: This paper develops complex potential formalisms for the solution of the bending problem of inhomogeneous anisotropic plates, on the basis of the most commonly used refined plate theories. Being an initial step in that direction, it works out such formalisms only in connection with the bending problem of shear deformable homogeneous plates as well as plates having a special type of inhomogeneity along their thickness direction. The adopted type of inhomogeneity is however still general enough to include certain classes of plates made of functionally graded material as well as the classes of cross- and angle-ply symmetric laminates as particular cases. The basic formalism, similar to that developed by Stroh in plane strain elasticity, is detailed in relation with the equilibrium equations of a generalized plate theory that accounts for the effects of transverse shear deformation and includes conventional, refined theories as particular cases. Some interesting specializations, related to the most important of those conventional plate theories, are then presented and discussed separately. Hence, the outlined formalisms provide, for the first time in analytical form, the general solution of the partial differential equations associated with the most commonly used refined, elastic plate theories.


ABSTRACT: The initial postbuckling behavior and imperfection sensitivity of truss-type structures in which the joints do not transmit moments is determined by means of the Lyapunov-Schmidt-Koiter approach. Such structures possess local buckling modes involving the buckling of individual members, and global modes involving axial deformations of all members but no member buckling. Of particular interest is the case in which through optimization (or otherwise) a number of local and global modes are coincident. The worst shape of imperfection for this case is determined from the bifurcated equilibrium branch on which the load drops most rapidly. It is shown that this critical bifurcated branch initially involves the buckling of one member only. The general theory is illustrated by a number of examples involving two- and three-dimensional lattice columns. The leading order asymptotic results for these examples are compared to exact results obtained by tracking the appropriate equilibrium branch numerically.
References listed at the end of the paper:


ABSTRACT: Beginning with the work of Koiter in 1945, valuable insights into the postbuckling behavior of structures have been gained by Lyapunov-Schmidt decomposition of the displacements followed by an asymptotic expansion about the bifurcation point. Here this methodology is generalized to include nonlinear prebuckling behavior, as well as multiple, not necessarily coincident buckling modes. The expansion of the reduced equilibrium equations is performed about a reference point (which need not coincide with any of the bifurcation points), and applies no matter whether the modes are coincident, closely spaced, or well separated. From a variety of possible decompositions of the admissible space of displacements, two are incorporated into a finite element program. Theoretical considerations, and numerical examples in which asymptotic results are compared to ‘exact’ results, indicate that one of the decompositions has some important advantages over the other. Examples include a shallow arch, and a beam on elastic foundation problem exhibiting symmetry-breaking modal interaction.

References listed at the end of the paper:


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ABSTRACT: Buckling and imperfection sensitivity are the primary considerations in analysis and design of thin shell structures. The objective here is to develop accurate and efficient capabilities to predict the postbuckling behavior of shells, including imperfection sensitivity. The approach used is based on the Lyapunov–Schmidt–Koiter (LSK) decomposition and asymptotic expansion in conjunction with the finite element method. This LSK formulation for shells is derived and implemented in a finite element code. The method is applied to cylindrical and spherical shells. Cases of linear and nonlinear prebuckling behavior, coincident as well as non-coincident buckling modes, and modal interactions are studied. The results from the asymptotic analysis are compared to exact solutions obtained by numerically tracking the bifurcated equilibrium branches. The accuracy of the LSK asymptotic technique, its range of validity, and its limitations are illustrated.

ABSTRACT: The problem of a tube under pure bending is first solved as a generalised plane strain problem. This then provides the prebifurcation solution, which is uniform along the length of the tube. The onset of wrinkling is then predicted by introducing buckling modes involving a sinusoidal variation of the displacements along the length of the tube. Both the prebuckling analysis and the bifurcation check require only a two-dimensional finite element discretisation of the cross-section with special elements. The formulation does not rely on any of the approximations of a shell theory, or small strains. The same elements can be used for pure bending and local buckling a prismatic beam of arbitrary cross-section. Here the flow theory of plasticity with isotropic hardening is used for the prebuckling solution, but the bifurcation check is based on the incremental moduli of a finite strain deformation theory of plasticity. For tubes under pure bending, the results for limit point collapse (due to ovalisation) and bifurcation buckling (wrinkling) are compared to existing analysis and test results, to see whether removing the approximations of a shell theory and small strains (used in the existing analyses) leads to a better prediction of the experimental results. The small strain analysis results depend on whether the true or nominal stress–strain curve is used. By comparing small and finite strain analysis results it is found that the small strain approximation is good if one uses (a) the nominal stress–strain curve in compression to predict bifurcation buckling (wrinkling), and (b) the true stress–strain curve to calculate the limit point collapse curvature. In regard to the shell theory approximations, it is found that the three-dimensional continuum theory predicts slightly shorter critical wrinkling wavelengths, especially for lower diameter-to-wall-thickness (D/t) ratios. However this difference is not sufficient to account for the significantly lower wavelengths observed in the tests.


ABSTRACT: Wrinkle formation at electromagnetic tube compression was simulated using finite element (FE) method. Three-dimensional (3D) calculations were performed using a staggered coupling scheme between the electromagnetic and structural sides of the problem. Introducing the tube’s contour imperfections into the FE model makes the simulation of the wrinkle formation possible. The results show good correspondence with the experiments.

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ABSTRACT: Buckling load sensitivity calculations in the shell-of-revolution program FASOR are discussed. This development is based on Koiter's initial postbuckling theory, which has been generalized to include the effect of stiffness changes, as well as geometric imperfections. The implementation in FASOR is valid for anisotropic, as well as orthotropic, shells. Examples are presented for cylindrical panels under axial compression, complete cylindrical shells in torsion, and antisymmetric angle-ply cylindrical panels under edge
Shear.


ABSTRACT: Based on small-deflection buckling equation, a weighted solution for critical load is presented. Usually, it is very difficult to solve the equation for general problems, especially those with complicated boundary conditions. Axisymmetric problem was studied as an example. Influencing factors were found from the equation and averaged as the buckling load by introducing weights. To determine those weights, some special known results were applied. This method solves general complicated problems by using the solutions of special simple problems, simplifies the solving procedure and expands the scope of solvable problem. Compared with numerical solution, it also has fine precision.

References listed at the end of the paper:

A. Kiehne, P. Horst, Institute of Aircraft Design and Lightweight Structures, TU Braunschweig Hermann-Blenk-Straße 35, 38108 Braunschweig Germany, “Buckling Analysis Of Non-Rectangular Stiffened Shell Structures” (publisher and date not given)
www.ifl.tu-braunschweig.de/pdf/Ki_Ho_06_DGLR.pdf

ABSTRACT: Usually, fuselage structures are stiffened by longitudinal and circumferential structural elements in a way that rectangular fields evolve. In the case of modern manufacturing technologies for aircraft structures, new topologies can be produced and possibly replace a conventional fuselage design. This paper deals with the buckling analysis of metallic non-rectangular stiffened structures with triangular skin panels. In order to assess the benefits, the buckling behaviour of triangular and rectangular stiffened structures due to various load combinations is compared.

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ABSTRACT: Purpose – In former work, test results of cracks in aluminium panels under cyclic shear buckling showed that cracks in the tensile stress field of a buckle propagate. The main influencing factor for the crack growth rate is the maximum principle stress. A simplified approach for crack propagation analyses based on this finding showed limitations for application on larger cracks because it disregarded the increasing out-of-plane deformation for larger cracks as well as stress redistributions. The purpose of this paper is to improve the results of the simplified approach with the help of finite element method (FEM).

Design/methodology/approach – An approach for crack propagation based on FEM is presented taking into account the mutual interaction of cracks and buckling. The finite element (FE) model, which is described in detail, respects the boundary conditions of the test-set-up. Different initial crack positions, loads and panel thicknesses are analyzed. Results of the stress intensity factors KI calculated by the ABAQUS FE model provide a function which is used to run a crack propagation analysis based on Forman law.

Findings – The results of the FE-based crack propagation solution are in good agreement with test results and improve the prediction of the simplified approach. It is not restricted in terms of panel thickness, crack position or applied shear load.

Research limitations/implications – Limitations of the FE-based crack propagation solution compared to the experimental results are discussed. These are, the sensitivity of crack propagation analyses to initial crack length and deviations of the experimental settings from the ideal FE model.

Originality/value – The interaction of cracks and buckling in aluminium shells is mainly disregarded both in research and industrial work, but can be of interest considering, accidental damages in fuselage side shells. Cracks propagate under shear load as it was shown in former work. The FE modeling of the tests presented in this paper proves the mutual interactions of crack propagation and buckling deformation.


ABSTRACT: Reliable and accurate method of the experimental buckling prediction of thin-walled cylindrical shell under an eccentric load is presented. The experimental arrangement and specimens are discussed in detail, including the measurement of the geometric imperfections of the specimen's surface using a coordinate measuring machine. Different FE models, in terms of complexity, are used to simulate the experiment arrangement in an attempt to get a good agreement with the experimental buckling loads and study the effect of measured initial geometric imperfections, load eccentricity, load eccentricity position along the shell's circumferential direction and different experimental arrangement that influence the boundary conditions. It has been demonstrated that FE models with simplified rigid support conditions overestimate the prediction of the experimental buckling load even though these models included the effects of the measured initial geometric imperfections and load eccentricity. By contrast, FE models with realistically modeled support conditions achieved the best result. The average deviation "_1.59% from the experimental buckling loads was achieved using the FE model simulating the mounting devices as elastic bodies and with surface-to-surface contact interaction behavior on the support. The presented work also demonstrated the strong influence of the eccentric load position along the imperfect shell's circumferential direction on the buckling of the thin-walled shell.

Robert Sliz, Prof. Ing. Stanislav Holy, CSc., Ing. Miroslav Spaniel, Czech Technical University, Technická 4, Praha 6, 166 36 , Czech Republic, “Numerical Analysis of Buckling of Thin-walled Shell”, (publisher and date not given).
ABSTRACT: The aim of this study is numerical investigation of the sensitivity of buckling load of thin-walled shell under uniform axial compression load on different kinds of initial geometric imperfection and comparison with the experimental results [1]. Finite Element Method has been used in this research followed the method from [1] and general conclusions applied for thin-walled structures, especially about element types used for such problem, describes in [2].

References given at the end of the note:

R. Palaninathan and K. Athiannan, “Investigations on stability of cylindrical shells under axial compression”, 1995. (notice of untrustworthy web site, so could not get publisher or abstract)


ABSTRACT: The conventional degenerated shell element which involves numerical integration in three dimensions becomes inefficient when applied to multilayered shells. For the computational efficiency, layered element based on the explicit integration through thickness assumes importance. The explicit integration becomes possible due to the assumption concerning the variation of inverse Jacobian through the thickness. Depending on the level of approximation, whether linearly varying or constant Jacobian inverse along the thickness, three models are discussed. Examples of stress analysis and classical buckling are considered for the comparative studies relating to the computational efficiency and numerical accuracy. The model, which assumes linear variation of Jacobian inverse through thickness with further approximations is seen to be the best from numerical accuracy and computational efficiency points of view.


ABSTRACT: This paper presents experimental studies on buckling of cylindrical shell models under axial and transverse shear loads. Tests are carried out using an experimental facility specially designed, fabricated and installed, with provision for in-situ measurement of the initial geometric imperfections. The shell models are made by rolling and seam welding process and hence are expected to have imperfections more or less of a kind similar to that of real shell structures. The present work thus differs from most of the earlier investigations. The measured maximum imperfections are of the order of plus or minus 3 x thickness. The buckling loads obtained experimentally are compared with the numerical buckling values obtained through finite element method (FEM). In the case of axial buckling, the imperfect geometry is obtained in four ways and in the case of transverse shear buckling, the FE modelling of imperfect geometry is done in two ways. The initial geometric imperfections affect the load carrying capacity. The load reduction is considerable in the case of axial compression and is marginal in the case of transverse shear buckling. Comparisons between experimental buckling loads under axial compression, reveal that the extent of imperfection, rather than its maximum value, in a specimen influences the failure load. Buckling tests under transverse shear are conducted with and without axial constraints. While differences in experimental loads are seen to exist between the two conditions, the
numerical values are almost equal. The buckling modes are different, and the experimentally observed and numerically predicted values are in complete disagreement.

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“Buckling of cylindrical shells under transverse shear”, Thin-Walled Structures, Vol. 42, No. 9, September
Xiang Lin, “Buckling of extensively welded steel cylindrical shells under axial compression”, Ph.D. dissertation, Dept. of Civil and Structural Engineering, Hong Kong Polytechnic University, 2004

ABSTRACT: Thin cylindrical shells in large civil engineering steel shell structures such as steel silos and tanks are subject to both axial compression and internal pressure. Buckling under axial compression often governs their design. These shells are commonly constructed by joining a large number of rolled panels using many short vertical welds and continuous circumferential welds. This fabrication method leads to unique geometric imperfections which have been argued to be severely detrimental to the shell axial buckling strength. In addition, welding-induced residual stresses in these shells may also have a significant effect on this buckling strength. A review of the existing literature reveals that few previous studies have examined the buckling behavior of these shells with a rigorous treatment of the geometric imperfections and residual stresses in these shells. This thesis presents both theoretical and experimental studies aimed at correcting this important deficiency in existing knowledge. The first part of the thesis, consisting of Chapters 3-5, presents the results of theoretical studies into the characteristics of geometric imperfections measured in three large steel silos at Port Kembla, Australia, and their effect on buckling strength. In order to accurately represent these imperfections measured at non-uniformly spaced sampling points, a new iterative Fourier decomposition method was proposed. The traditional Fourier decomposition method cannot produce accurate Fourier representations, and the reasons for this difficulty are clarified in the thesis. This new iterative method was then employed in deducing accurate Fourier series representing the measured imperfections. It is explained in the thesis that these real imperfections, due to their non-zero values at the boundaries, can only be accurately represented using half-wave cosine series in the meridional direction, an important phenomenon overlooked by all previous researchers. The characteristics of the imperfections are next examined by studying the spectra of the deduced Fourier series, including both 1D and 2D Fourier series. It is shown that the dominant components of the imperfections in each shell are in the lower Fourier terms, with some of these components being closely associated with the weld pattern. Finite element analyses of the three silo shells (referred to as Shells A, B, and C) showed that these shells have buckling strengths which are much lower than those of shells with many known forms of imperfections. A systematic parametric study revealed that the buckling strength of Shell A is dominated by significant axisymmetric imperfections, while those of Shells B and C are governed by highly complex imperfections.
non-symmetric imperfections. Based on the specification of Eurocode 3, an automated computer procedure was developed to numerically 'measure' the local dimples and out-of-roundness of these shells. This was undertaken to determine the quality classes of the three shells so that their buckling strengths as predicted by Eurocode 3 could be found. A comparison between the predictions of the code and finite element results from nonlinear analyses reveals that the existing rule in Eurocode 3 is too optimistic about shells of Class A but too pessimistic about shells of Classes B and C. While detailed measurements of imperfections are available for the three large silos, the residual stresses in these shells due to welding are unknown. As residual stresses may have a significant effect on the buckling strength, an experimental study aimed at an indirect evaluation of this effect is presented in Chapters 6-8. In this experimental study, an innovative two-stage model fabrication technique was proposed and implemented with a sophisticated experimental set up for the fabrication of small models simulating large cylindrical shells with many welds. Three model shells were fabricated and tested under axial compression, each of which had a different weld pattern. The initial geometric imperfections in these model shells were precisely measured and decomposed into Fourier series. The imperfections were also found to be dominated by lower Fourier terms and closely associated with the weld patterns. The buckling loads of the model shells are very low compared to the value of a corresponding perfect shell, demonstrating the serious deleterious effect of the imperfections in these shells. Finite element buckling loads obtained from non-linear analyses with the measured imperfections accurately modeled are also presented. These buckling loads are close but slightly lower than the experimental buckling loads, indicating that the effect of residual stresses and other factors in these shells is small but beneficial, and may be safely ignored. Finally, a parametric study is presented in Chapter 9, in which the buckling behavior and strength of the three real silo shells under the combined action of axial compression and internal pressure were explored. Nonlinear finite element analyses revealed that the strengths of Shell A are considerably lower than those of Shells B and C, as the dominant imperfection components are significantly axisymmetric in Shell A, but are highly non-symmetric in Shells B and C. Comparisons between the finite element results and the predictions of Eurocode 3 indicate that the code overestimates the failure strengths of Shell A considerably. Modifications to the existing design rule are thus presented to achieve safe predictions.

Vishwanath Hegadekatte and Yahai Shi, “Buckling of beverage cans under axial loading”, SIMULIA India Regional Users Meeting, 2011

ABSTRACT: Wrinkling is one of the major defects in sheet metal forming processes. It may become a serious obstacle to implementing forming process and assembling the parts, and may also play a significant role in the wear of the tool. Wrinkling is a local buckling phenomenon that results from compressive stresses (compressive instability) e.g., in the hoop direction for axisymmetric systems such as beverage cans. In the present work, we have studied the buckling of ideal (no imposed imperfections like dents) beverage cans under axial loading both by laboratory testing and finite element analysis. Our laboratory test showed that 2 out of 11 cans fail by sidewall buckling. We have developed finite element models to study the effect of a couple of manufacturing parameters on the buckling of beverage cans. Further we have studied the buckling of dented beverage cans under axial compression through both laboratory testing and finite element analysis using Abaqus and LS-Dyna. Our results show that Abaqus did not predict sidewall buckling during axial compression of beverage cans while LS-Dyna predicted buckling in a few cases.

Pattaramon Jongpradist, Rattharong Rojbunsongsri, Thoatsanope Kannerdtong and Somchai Wongwises (Dept. of Mechanical Engineering, King Mongkut’s University of Technology Thonburi, Bangkok, Thailand), “Parametric study and optimization of a food can corrugation design using a response surface method”, Journal
of Mechanical Science and Technology, Vol. 27, No. 7, pp 2043-2052, July 2013

ABSTRACT: This paper presents the parametric design and functional optimization of a thin-walled food container with a corrugated surface. The configuration of the can corrugation should be designed to minimize the use of raw material subject to the constraints of the targeted structural performance. In the present study, the failure behaviors and the buckling strengths of a commercial food can under paneling pressure and axial loading are investigated with a series of experiments and finite element analyses. Full factorial design is implemented to study the effects of the geometric parameters of the corrugation (e.g., depth, radius, spacing and number of beadings) on its strength. Parameter optimization using a rotatable central composite design is employed to identify an optimal corrugation design by approximating the response surfaces of the can strength in terms of the significant design variables. The obtained surfaces are derived through the analysis of variance, and the suitability of the response is justified. A light-weight can body is then achieved by reduction of the can body thickness according to the required strength characteristics. Finite element analysis of the optimal model is also performed to confirm the predicted results. By using the proposed procedure, the can-body weight can be reduced by up to 12% compared with the original design.

References listed at the end of the paper:
Caitríona de Paor, Department of Civil and Environmental Engineering, University College Cork (UCC),
ABSTRACT: Thin-walled structures, also known as shells, combine light weight with high strength and are used in a diverse range of fields including aerospace engineering, civil engineering and chemical engineering. Common applications of these shells include oil and gas storage tanks, powder or liquid storage tanks in pharmaceutical plants as well as airplane frames and ship bodies. Although these thin-walled shells have a wide variety of uses, this research is motivated by storage tank collapse in the process industry. Thin-walled cylindrical tanks common in the food and biotechnology sectors are prone to buckling (or inward collapse) due to accidentally induced internal vacuum. During the sterilisation process, steam can condense, causing a reduction in volume. This results in an equivalent increase in external pressure, triggering collapse, or buckling of the tank. Such a collapse, if it occurs, tends to be catastrophic resulting in the complete destruction of the vessel (see Fig.1). Notwithstanding that the basis of this type of failure is understood and can generally be averted, it is still a regular occurrence, often due to the inadvertent closure of line control valves during a sterilisation cycle.
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ABSTRACT: The buckling capacity of thin cylindrical shells subject to uniform external pressure is investigated in this paper. Thin cylindrical shells are known to be highly sensitive to geometric and material imperfections such as wall thickness variation, non-circularity and random geometric imperfections. The effect of imperfection on the buckling load is studied using finite element (FE) models and laboratory experiments. Imperfection measurements are taken on small scale steel cans and these measurements are modelled and analysed using a geometrically non-linear static finite element analysis. The cans are then tested in the laboratory and the results compared with those predicted by the FE models and theory.
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varying thickness subjected to uniform external pressure”. Thin-Walled Structures, 44(8), pp. 904–909.


ABSTRACT: Analysis of indenting, buckling and piercing of aluminum beverage cans using both physical testing and computer simulation was performed in order to develop a better understanding of the sidewall structural strength of the cans. This understanding can be used to help design better cans and/or improve manufacturing processes. Simulation of the sidewall indentation was done with an impacting sphere. Parameters investigated included the sphere size and velocity, and the impact height along the sidewall. Buckling simulation of the dented can was then performed. Results from the deformed can buckling model compared well with physical testing based on buckled geometry, buckling load, and external work to buckle. Severe damage to a can that might occur during the manufacturing process was investigated by studying piercing of the can sidewall. Impacts of 5 and 10 m/s were performed with both blunt (flat) and sharp (45° tip) steel rods. It was found that separated elements with tied nodal constraints more accurately represent the failure behavior of the can subjected to a piercing load than merged element nodes. It was also found that the more crushing a can
undergoes before piercing occurs, the more energy the can material absorbs. However, there is an upper limit to the crushing based on the speed and shape of the impactor.

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“Model validation for the collapse of spherical shells” (publisher and date not given in the pdf file. The most recent citation is 2003.)

ABSTRACT: There is a growing need to quantify the level of credibility that can be associated with model predictions. Model verification and validation (V&V) is a methodology for the development of models that can be used to make engineering predictions with quantified confidence. Model V&V procedures are needed by government and industry to reduce the time, cost and risk associated with component and full-scale testing of products, materials, and weapons. Consequently, the development of guidelines and procedures for conducting a V&V program are currently being defined by a broad spectrum of researchers. This paper describes an ongoing effort to validate a model that predicts the collapse load of a spherical shell structure. Inherent variations in geometric shape and material parameters are included in the uncertainty model. Results from a recently completed probabilistic validation test to measure the variation in collapse load are compared to the predicted collapse load variation.

References listed at the end of the paper:
1. NESSUS Version 7.55, Southwest Research Institute, July 2003.

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ABSTRACT: The collapse of shell-shaped membranes due to buckling is investigated experimentally using droplets of latex suspension left to dry. The evaporation of water, limited by diffusion in air, first leads to the formation, on the surface, of a spheroidal envelope of gel. During the later evolution, spontaneous buckling of this envelope occurs. The later evolution leads to a large-amplitude invagination and for certain concentrations to a transition to a toroidal shape. This specific evolution of a spheroidal envelope, linked with its inhomogeneous mechanical properties, is similar to that observed during the gastrulation of sea-urchin embryos.

References listed at the end of the paper:
[12] The free diffusion coefficient of colloidal particles for dilute and non-interacting systems is given by \( D = k_B T/6 \eta a \), where \( a \) is the particle diameter and \( \eta \) the solvent viscosity.
[13] This process was observed in the drying of a hydro-soluble polymer solution, Dextran, deposited on super-hydrophobic substrates. In that case, the resulting rigid glassy shell being transparent, the growth of a basal bubble inside the drop is observed directly.


ABSTRACT: We herein present the results of a study of the direct fabrication of buckled patterns in flexible organic light-emitting devices (FOLEDs) that had a conducting polymer anode on a polyethersulfone substrate. These patterns were produced spontaneously by the thermal deposition of an aluminum cathode on an electroluminescent (EL) composite layer. The polymer used for the anode was modified poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) and the EL layer was composed of a solution-processable small molecular composite including phosphorescent Iridium complex mixed with a poly(vinylcarbazole) host. It is shown that FOLEDs produced with buckled patterns can exhibit a luminance as high as ca. 14,900 cd/m² with a peak efficiency of 50.5 cd/A. The patterned structure formed by the buckling of the EL layer allows FOLEDs to be produced with a high peak external quantum efficiency of 15% with an increase in light extraction by a factor of ca. 3.1. These results show that spontaneous buckling yields patterned structures that offer considerable promise for the production of high performance, reproducible and reliable FOLEDs.
E Bagherizadeh, Y Kiani, M.R and M Sadighi. (Department of Mechanical Engineering, Amirkabir University, Hafez street Tehran), “Elastic buckling of FGM cylindrical shell surrounded by an elastic foundation”, 2nd International Conference on Composites: Characterization, Fabrication and Application, 1983 (should the date be 2013?).

ABSTRACT: This research inspects the elastic buckling of FGM cylindrical shell, resting on two-parameters elastic foundation, subjected to external pressure load. Material properties of functionally graded cylindrical shell are graded in the thickness direction according to a power law direction. Theoretical formulations are derived based on the classical shell theory. The effects of shell geometry, volume fraction exponent, and foundation parameters on critical buckling load of FGM cylindrical shells are investigated. It is inferred from the results that the elastic foundation postpones the critical buckling load and swifts mode shapes of elastic buckling.


ABSTRACT: In this article, non-linear stability analysis of monomorph functionally graded piezoelectric material beams is investigated based on the Ritz formulation of the finite elements method. Each thermo–electro–mechanical property of the beam is assumed to be graded across the thickness based on a power law form. Geometrically non-linear behaviour of the structures is included based on the von-Karman simplifications of the complete Green strain tensor. Timoshenko beam theory and trigonometric distribution of electrical potential assumptions are held to obtain the governing equations, describing the equilibrium state of the beam. Non-linear equilibrium equations are solved based on both Newton–Raphson and Picard iterative techniques. It is shown that response of a monomorph functionally graded piezoelectric material beam cannot be considered as a bifurcation-point behaviour. While in some types of boundary conditions, there are critical temperatures through the load–deflection path of the beam.

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ABSTRACT: Based on the Donnell theory of shells combined with the von-Karman type of geometrical nonlinearity, three coupled equilibrium equations for a through-the-thickness functionally graded cylindrical shell embedded in a two parameter Pasternak elastic foundation are obtained. Equivalent properties of the shell are obtained based on the Voigt rule of mixture in terms of a power law volume fraction for the constituents. Properties of the constituents are considered to be temperature dependent. The temperature profile through the shell thickness is obtained by means of the central finite difference method. Linear prebuckling analysis is performed to obtain the prebuckling forces of the cylindrical shell. Stability equations are derived based on the well-known adjacent equilibrium criterion. Three coupled partial differential stability equations are solved with the aid of a hybrid Fourier-GDQ method. After validating the numerical results, some parametric studies are conducted to investigate the influence of various parameters, especially foundation interaction. It is shown that
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ABSTRACT: In the present work, genetic algorithm (GA) and artificial neural networks (NN) are used to...
optimize the stacking sequence of a laminated cylindrical shell with natural frequency and buckling load as the objective functions. Vibration analysis is based on fully three dimensional elasticity equations and the stability solution is presented using equations governed by the Donnell type of approximation. Artificial neural network models are developed and tested to predict the natural frequency and buckling load of the structure. A genetic algorithm then uses the trained neural network prediction models to obtain the maximum fundamental frequency and critical buckling load, simultaneously. Optimization is performed for the shell geometry with different sets of thickness to radius and length to radius ratios. The results obtained, using the NN-GA combination are compared with those using the GA directly. A satisfactory verification is observed meanwhile a considerable reduction is achieved in computational time.

References listed at the end of the paper:


ABSTRACT: This paper is concerned with the elastic buckling of stiffened cylindrical shells by rings and
stringers made of functionally graded materials subjected to axial compression loading. The shell properties are assumed to vary continuously through the thickness direction. Fundamental relations, the equilibrium and stability equations are derived using the Sander’s assumption. Resulting equations are employed to obtain the closed-form solution for the critical buckling loads. The results show that the inhomogeneity parameter and geometry of shell significantly affect the critical buckling loads. The analytical results are compared and validated using the finite element method.


ABSTRACT: The static stability analysis of stiffened functionally graded cylindrical shells by isotropic rings and stringers subjected to axial compression is presented in this paper. The Young's modulus of the shell is taken to be function of the thickness coordinate. The fundamental relations, the equilibrium and stability equations are derived using the Sander's assumption. Resulting equations are employed to obtain the closed-form solution for the critical axial loads. The effects of material properties, geometric size and different material coefficient on the critical axial loads are examined. The analytical results are compared and validated using the finite element model.

References listed at the end of the paper:


ABSTRACT: The buckling analysis of stiffened cylindrical shells by rings and stringers made of functionally graded materials subjected to axial compression loading is presented. It is assumed that the material properties vary as a power form of the thickness coordinate variable. The fundamental relations, the equilibrium and stability equations are derived using the first order shear deformation theory. Resulting equations are employed
to obtain the critical buckling loads. The effects of the material properties and geometry of shell on the critical buckling loads are examined. Excellent agreement with the results in the literature indicates the correctness of the proposed closed form solution.

Reference listed at the end of the paper:

ABSTRACT: The nonlinear strain-displacement relations in general cylindrical coordinates are simplified by Sander's assumptions for the cylindrical shells and substituted into the total potential energy function for thermoelastic loading. The Euler equations are then applied to the functional of energy, and the general thermoelastic equations of nonlinear shell theory are obtained and compared with the Donnel equations. An improvement is observed in the resulting equations as no length limitations are imposed on a thin cylindrical shell. The stability equations are then derived through the second variation of potential energy, and the same improvements are extended to the resulting thermoelastic stability equations. Based on the improved equilibrium and stability equations, the magnitude of thennoelastic buckling of thin cylindrical shells under different thermal loadings is obtained. The results are extended to short and long thin cylindrical shells.

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doi: 10.1080/014957399280733
ABSTRACT: In this article the buckling of specially orthotropic laminated composite cylindrical shells is investigated. The nonlinear equilibrium equations based on the Sander's assumption of simplified nonlinear strain-displacement relations and the linearized stability equations for a circular cylindrical thin shell are considered. The equations include the rotations and transverse shear force. The resulting equations are improved compared to the Donnell stability equations. The mechanical and thermal buckling loads of a thin composite circular cylindrical shell based on Donnell and improved stability equations are obtained.

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**ABSTRACT:** The nonlinear strain-displacement relations for thin orthotropic plates are considered and substituted into the potential energy function of thermoelastic loadings. The Euler equations are then applied to the functional of energy, and the general thermoelastic equations of thin orthotropic plates are obtained. The stability equations are then derived through the second variation of the potential energy function. The thermal loadings include the uniform temperature rise, axial temperature difference, and the gradient temperature through the thickness. The thermoelastic buckling of a thin plate under these thermal loadings is investigated. The results are extended to isotropic and orthotropic thin plates with and without imperfections.

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**ABSTRACT:** Buckling, free and forced vibration analyses of orthotropic plates are studied numerically using Isogeometric analysis. The present formulation is based on the classical plate theory (CPT) while the NURBS basis function is employed for both the parametrization of the geometry and the approximation of plate deflection. An efficient and easy-to-implement technique is used for imposing the essential boundary conditions. Numerical examples for free and forced vibration and buckling of orthotropic plates with different boundary conditions and configurations are considered. The numerical results are compared with other existing solutions to show the efficiency and accuracy of the proposed approach for such problems.


**ABSTRACT:** Thermoelastic stability of thin perfect spherical shells based on deep and shallow shell theories is presented. To derive the equilibrium and stability equations according to deep shell theory, Sanders's nonlinear kinematic relations are substituted into the total potential energy function of the shell and the results are extremized by the Euler equations in the calculus of variation. The same equations are also derived based on quasi-shallow shell theory. An improvement is obtained for equilibrium and stability equations related to the deep shell theory in comparison with the same equations related to shallow shell theory. Approximate one-term solutions that satisfy the boundary conditions are assumed for the displacement components. The Galerkin-Bubnov method is used to minimize the errors due to this approximation. The eigenvalue solution of the stability equations is obtained using computer programs. For several thermal loads it is found that the deep shell theory results are slightly more stable as compared to the shallow shell theory results under the same thermal loads. The results are compared with the Algor finite element program and other known data in the literature.

M. M. Najafizadeh (2) and M. R. Eslami (1)
ABSTRACT: This study presents the buckling analysis of radially loaded solid circular plate made of functionally graded material. The edge of the plate is either simply supported or clamped and the plate is assumed to be geometrically perfect. The equilibrium and stability equations, derived through variational formulation, are used to determine the prebuckling forces and critical buckling loads. The equations are based on Love–Kirchhoff hypothesis and the Sander's non-linear strain-displacement relation. The results are verified with the known results in the literature.


ABSTRACT: Equilibrium and stability equations of a rectangular plate made of functionally graded material under thermal loads are derived, based on the classical plate theory. When it is assumed that the material properties vary as a power form of the thickness coordinate variable, z, and when the variational method is used, the system of fundamental differential equations is established. The derived equilibrium and stability equations for functionally graded plates are identical with the equation for homogenous plates. Buckling analysis of functionally graded plates under four types of thermal loads is carried out, resulting in closed-form solutions. The buckling loads are reduced to the critical buckling temperature relations for functionally graded plates with linear composition constituent materials and homogeneous plates. The results are validated with the reduction of the buckling relations for functionally graded plates to those of isotropic homogeneous plates given in the literature.


ABSTRACT: Equilibrium and stability equations of a rectangular plate made of functionally graded material (FGM) under thermal loads are derived, based on the higher order shear deformation plate theory. Assuming that the material properties vary as a power form of the thickness coordinate deformation variable z and using the variational method, the system of fundamental partial differential equations is established. The derived equilibrium and stability equations for functionally graded plates (FGPs) are identical to the equations for laminated composite plates. A buckling analysis of a functionally graded plate under four types of thermal loads is carried out and results in closed-form solutions. The critical buckling temperature relations are reduced to the respective relations for functionally graded plates with a linear composition of constituent materials and homogeneous plates. The results are compared with the critical buckling temperatures obtained for functionally graded plates based on classical plate theory given in the literature. The study concludes that higher order shear deformation theory accurately predicts the behavior of functionally graded plates, whereas the classical plate theory overestimates buckling temperatures.

ABSTRACT: In this article, the thermal buckling loads of cylindrical shells of functionally graded material are considered. Derivation of equations are based on the first-order shell theory and the Sanders kinematic equations. The derived equilibrium and stability equations for the functionally graded cylindrical shell are identical with the equations for homogeneous shells expressed in the form of forces and moments per unit length. Assuming that the material properties vary linearly through the thickness direction, the system of fundamental partial differential equations in terms of the displacement components is established. Buckling analysis of functionally graded cylindrical shells under two types of thermal loads with simply supported boundary conditions are carried out. Results are obtained in the analytical form. The results are validated with the known data in the literature.


ABSTRACT: A thermal buckling analysis of an imperfect functionally graded cylindrical shell is considered using the Wan-Donnell model for initial geometrical imperfections. Derivation of the equations is based on the first-order classical shell theory using the Sanders nonlinear kinematic relations. Results for the buckling loads are obtained in the closed form. The effects of shell geometry and volume fraction exponent of functionally graded material on the buckling load are investigated. The results are validated with known data in the literature.


ABSTRACT: In this paper, thermal instability of shallow spherical shells made of functionally graded material (FGM) is considered. The governing equations for a thin spherical shell based on the Donnell-Mushtari-Vlasov theory are obtained. The equations are derived using the Sanders simplified kinematic relations and variational method. It is assumed that the mechanical properties vary linearly through the shell thickness. The constituent material of the functionally graded shell is assumed to be a mixture of ceramic and metal. Analytical solutions are obtained for three types of thermal loading including Uniform Temperature Rise (UTR), Linear Radial Temperature (LRT), and Nonlinear Radial Temperature (NRT). The results are validated with the known data in the literature.

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ABSTRACT: A thermal buckling analysis is presented for functionally graded cylindrical shells that are integrated with surface-bonded piezoelectric actuators and are subjected to the combined action of thermal load and constant applied actuator voltage. The material properties are assumed to vary as a power form of the thickness coordinate. Derivation of the equations is based on the higher-order shear deformation shell theory
using the Sanders nonlinear kinematic relations. Results for the buckling temperatures are obtained in the closed form solution. The effects of the applied actuator voltage, shell geometry, and volume fraction exponent of functionally graded material on the buckling temperature are investigated. The results for simpler states are validated with known data in the literature.


ABSTRACT: Elastic buckling analysis of imperfect FGM cylindrical shells under axial compression in thermal environments is carried out, using two different models for geometrical imperfections. The material properties of the functionally graded shell are assumed to vary continuously through the thickness of the shell according to a power law distribution of the volume fraction of the constituent materials, also temperature dependency of the material properties is considered. Derivation of equations is based on classical shell theory using the Sanders nonlinear kinematic relations. The stability and compatibility equations for the imperfect FGM cylindrical shell are obtained, and the buckling analysis of shell is carried out using Galerkin’s method. The novelty of the present work is to obtain closed form solutions for critical buckling loads of the imperfect FGM cylindrical shells, which may be easily used in engineering design applications. The effects of shell geometry, volume fraction exponent, magnitude of initial imperfections, and environment temperature on the buckling load are investigated. The results reveal that initial geometrical imperfections and temperature dependency of the material properties play major roles in dictating the bifurcation point of the functionally graded cylindrical shells under the action of axial compressive loads. Also results show that for a particular value of environment temperature, critical buckling load is almost independent of volume fraction exponent.

References listed at the end of the paper:

- H.-S. Shen, “Thermal postbuckling behavior of functionally graded cylindrical shells with temperature-dependent

ABSTRACT: Thermal and mechanical instability of truncated conical shells made of functionally graded material (FGM) is studied in this paper. It is assumed that the shell is a mixture of metal and ceramic that its properties change as a function of the shell thickness. The governing equations are based on the first-order shell theory and the Sanders nonlinear kinematics equations. The results are obtained for a number of thermal and mechanical loads and are validated with the known data in the literature.

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ABSTRACT: The thermomechanical instability of truncated conical shells made of functionally graded material under different uniform temperature rises is studied in this paper. It is assumed that the shell is a mixture of metal and ceramic, where its properties change as functions of the shell thickness. The mechanical properties of metal and ceramic are assumed to be temperature dependent. The governing equations are based on the first-order theory of shells and the Sanders non-linear kinematics equations. The results are obtained under different thermal conditions for three types of mechanical loading, namely hydrostatic pressure, axial compressive loading, and their combination. The results are validated with the known data in the literature.

A. Hafezalkotob and M.R. Eslami (Thermoelasticity Center of Excellence, ME Department, Amirkabir University of Technology, Tehran, Iran), “Thermomechanical buckling of simply supported shallow FGM spherical shells with temperature-dependent material”, Archive of SID, ISME (publisher and date not given in the pdf file; latest reference is 2009.)

ABSTRACT: The thermomechanical buckling of simply supported thin shallow spherical shells made of functionally graded material is presented in this paper. A metal-ceramic functionally graded shell with a power law distribution for volume fraction is considered, where its properties vary gradually through the shell thickness direction from pure metal on the inner surface to pure ceramic on the outer surface. The mechanical properties of the metal and ceramic are assumed to be temperature dependent. The governing equations are derived using the first-order shell theory of Love and Kirchhoff, the Donnell-Mushtari-Vlasov kinematics
equations, and the calculus of variations. The analytical results are obtained for various types of loadings. The detailed results are compared and validated with the known data in the literature.

References listed at the end of the paper:


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ABSTRACT: Thermal instability of deep spherical shells made of functionally graded material (FGM) is studied in this paper. The governing equations are based on the first-order theory of shells and the Sanders nonlinear kinematics equations. It is assumed that the mechanical properties are linear functions of thickness coordinate. The constituent material of the functionally graded shell is assumed to be a mixture of ceramic and metal. The analytical solutions are obtained for three types of thermal loadings including the uniform temperature rise (UTR), the linear radial temperature (LRT), and the nonlinear radial temperature (NRT). Results are validated with the known data in literature.


ABSTRACT: A thermal buckling analysis is presented for functionally graded rectangular plates that are integrated with surface-bonded piezoelectric actuators and are subjected to the combined action of thermal load and constant applied actuator voltage. The temperature-dependent material properties of the functionally graded plate are assumed to vary as a power form of the thickness coordinate. Derivation of the equations is based on the third-order shear deformation plate theory. Results for the critical buckling temperatures are obtained in closed-form solution, which are convenient to be used in engineering design applications. The effects of the applied actuator voltage, plate geometry, and volume fraction exponent of the functionally graded material on the buckling temperature are investigated.

References listed at the end of the paper:


ABSTRACT: In this study, the mechanical buckling of functionally graded material cylindrical shell that is embedded in an outer elastic medium and subjected to combined axial and radial compressive loads is investigated. The material properties are assumed to vary smoothly through the shell thickness according to a power law distribution of the volume fraction of constituent materials. Theoretical formulations are presented based on a higher-order shear deformation shell theory (HSDT) considering the transverse shear strains. Using the nonlinear strain–displacement relations of FGMs cylindrical shells, the governing equations are derived. The elastic foundation is modelled by two parameters Pasternak model, which is obtained by adding a shear layer to the Winkler model. The boundary condition is considered to be simply-supported. The novelty of the
present work is to achieve the closed-form solutions for the critical mechanical buckling loads of the FGM cylindrical shells surrounded by elastic medium. The effects of shell geometry, the volume fraction exponent, and the foundation parameters on the critical buckling load are investigated. The numerical results reveal that the elastic foundation has significant effect on the critical buckling load.

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ABSTRACT: Thermal buckling analysis of deep imperfect functionally graded (FGM) spherical shell is considered in this paper. A mixture of ceramic and metal is considered for the FGM shell and the material properties, such as the modulus of elasticity and coefficient of thermal expansion, vary by a power law function through the thickness. Employing the Sanders non-linear kinematic relations, total potential energy function is derived and the equilibrium and stability equations are obtained for the imperfect shell. Approximate solutions satisfying the simply supported boundary condition are assumed and using the Galerkin method the error due to the approximation is minimized. The geometrically imperfect shell is considered and three types of thermal loadings, such as the uniform temperature rise (UTR), linear temperature rise through the thickness (LTR), and non-linear temperature rise through the thickness (NLTR) are considered and their associated buckling temperatures are obtained. The effects of different temperature functions and the magnitude of initial geometric imperfection are examined on the thermal buckling loads of the shell.


ABSTRACT: Thermal instability of shallow spherical shells made of functionally graded material (FGM) and surface-bonded piezoelectric actuators is studied in this paper. The governing equations are based on the first order theory of shells and the Sanders nonlinear kinematics equations. It is assumed that the property of the functionally graded materials vary continuously through the thickness of the shell according to a power law distribution of the volume fraction of the constituent materials. The constituent material of the functionally graded shell is assumed to be a mixture of ceramic and metal. The analytical solutions are obtained for three types of thermal loadings and constant applied actuator voltage. Results for simpler states are validated with the known data in the literature.


ABSTRACT: Thermal instability of deep spherical shells made of functionally graded material and surface-bonded piezoelectric actuators is studied in this article. The governing equations are based on the classical shell theory and the Sanders nonlinear kinematic equations. It is assumed that the property of the functionally graded materials varies continuously through the thickness of the shell, according to a power law distribution of the volume fraction of the constituent materials. The constituent material of the functionally graded shell is
assumed to be a mixture of ceramic and metal. The analytical solutions are obtained for three types of thermal loadings and constant applied actuator voltage. Results for simpler states are validated with the known data in the literature.

M.R. Eslami and J. Torabi, “Thermal buckling of functionally graded truncated conical shells”, 20th Annual Conference of Mechanical Engineering, (publisher and date not given)

ABSTRACT: In this paper, linear thermal buckling of a thin functionally graded material (FGM) truncated conical shell subjected to the uniform temperature rise loading is presented. Material properties of the FGM shell are assumed to vary continuously through the thickness direction. Equilibrium and stability equations are obtained based on the variational approach considering the first order shell theory and Sander's nonlinear kinematics equations. Galerkin method is adopted to obtain the critical buckling temperature difference of the conical shell. The results are compared with the known data in the literature. Upon the numerical results, effects of various parameters such as semi-vertex angel and FG parameter of material distribution are investigated on thermal instability of the conical shell.


DEFINITIONS: One of the failure phenomena in thin circular shells is instability due to buckling. When the conical shells with simply supported boundary conditions are subjected to thermal loads, due to the temperature changes, compressive stresses may be produced and lead to the buckling of the shell. Recent achievements in material engineering are the development of smart materials, such as piezoelectric structures. In this entry, thermal buckling analysis of isotropic conical shells embedded with piezoelectric layers and subjected to uniform temperature rise is investigated. The governing equations are obtained based on the variational approach and the Donnell and Sanders shell theories. Immovable simply supported boundary conditions are assumed at both ends of the cone. Considering membrane solutions of linear equilibrium equations and the effect of piezoelectric layers, the prebuckling force resultants are obtained. Finally, the Galerkin method is applied to stability equ..

References listed at the end of the paper:


“ABSTRACT”: API Standard 650 has provisions for addressing some of the storm related issues that affect storage tanks. Storage Tanks Vulnerabilities:
• Wind Issues... –Shell Buckling –Tank Overturning –Roof Damage
• Flooding Issues... –Floating Off of Foundation –Shell Buckling

Summary:
• Design for the expected conditions (primarily wind)
• Maintain your tanks
• A well maintained tank will fair better than a ragged tank.
• Add liquid to prevent flotation, overturning, wind buckling, & shell buckling from external pressure (rising water)
• A full tank will fair better than an empty tank.
Some very nice photographs of very large buckled tanks.


ABSTRACT: The buckling of thin shells is in general very sensitive to imperfections. A consistent numerical analysis for the determination of the buckling load has to consider the “correct” imperfections. Instead of assuming load or deformation imperfections, a new approach is presented which applies to the minimum of perturbation energy with respect to all possible disturbance patterns as criteria for the stability degree of the shell. Thus, by starting from the perfect shell the engineer may compute the least energy necessary to reach the critical state of equilibrium and may introduce this approach for determining safety against buckling. A nonlinear eigenvalue problem is solved to find the adjacent buckling mode of smallest energy. The concept has been developed so far only for elastically buckling shells of arbitrary shape. As examples to demonstrate the method, cylindrical shells under axial loads are investigated.

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ABSTRACT: We revisit the classical problem of the buckling of a long thin axially compressed cylindrical shell. By examining the energy landscape of the perfect cylinder we deduce an estimate of the sensitivity of the shell to imperfections. Key to obtaining this is the existence of a mountain pass point for the system. We prove the existence on bounded domains of such solutions for all most all loads and then numerically compute example mountain pass solutions. Numerically the mountain pass solution with lowest energy has the form of a single dimple. We interpret these results and validate the lower bound against some experimental results available in the literature.

References listed at the end of the paper:

References:


Jiri Horák, “Buckling of a Cylinder” (self-published, 2009?)

ABSTRACT: Everybody knows how to make a Coke can ready for recycling - step on it, squash it. One also knows that the can resists the squashing up to a certain point, then it suddenly buckles. The can is an example of a thin cylindrical shell. The process of buckling of such shells has not yet been completely understood. One of the main questions is how big is the load that the shell can withstand before it buckles. . .

References:


ABSTRACT: A strategy is presented, in which the common load incrementation is replaced by a creep type process. The load path approximation is governed by an artificial damping, which is outlined for direct search for stable equilibrium states, detailed path tracing and stability check of the solution by perturbed damping. The damping schemes are shown on examples of snapping structures in the elastic and plastic range.

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ABSTRACT: A perturbation strategy is outlined, which enables systematic calculation of secondary solution paths in the nonlinear solution manifold of thin-walled imperfection-sensitive structures. The strategy consists of three steps. First, the perturbation pattern is determined, second its critical amplitude is calculated to reach a secondary path and third the iteration to the secondary path itself is performed. The steps are formulated by means of constraints in the solution space. Examples are given for application to arches, plate strips and shells.

ABSTRACT: Among all mechanical joining processes, welding has been employed for its advantage in design flexibility, cost saving, reduced overall weight and enhanced structural performance. However, for structures made of relatively thin components, welding can introduce significant buckling distortion which causes loss of dimensional control, structural integrity and increased fabrication costs. Different parameters can affect buckling behavior of welded thin structures such as, heat input, welding sequence, dimension of structure. In this work, a 3-D thermo elastic-viscoplastic finite element analysis technique is applied to evaluate the effect of shell dimensions on buckling behavior and entropy generation of welded thin shells. Also, in the present work, the approximated longitudinal transient stresses which produced in each time step, is applied to the 3D-eigenvalue analysis to ratify predicted buckling time and corresponding eigenmode. Besides, the possibility of buckling prediction by entropy generation at each time is investigated and it is found that one can predict time of buckling with drawing entropy generation versus out of plane deformation. The results of finite element analysis show that the length, span and thickness of welded thin shells affect the number of local buckling, mode shape of global buckling and post-buckling behavior of welded thin shells.
References listed at the end of the paper:
Abstract: Ten cylindrical pressure vessels with torispherical ends, all of the same constant nominal thickness, were tested under internal pressure to observe the buckling behaviour of the toroidal knuckle. All specimens were of constant internal cylinder diameter to thickness ratio of 531.5. The sphere radius was equal to the cylinder diameter and only the torus radius was varied. Buckling was detected by rotating probes at the sphere/torus junction and at the mid-point of the torus. The buckling pressure increased with increasing torus radius and the two specimens with the largest torus radii did not buckle. For all specimens, the change of meridional shape with increase in pressure was measured. For one specimen, strain gauges were used to study the variation of circumferential strain on the inside and outside surface at the sphere/torus junction due to variation in thickness round the circumference. A simple theoretical expression for the buckling pressure, similar to the Rankine formula for a strut, is suggested.


ABSTRACT: Hamilton Principle was used to derive the general governing equations of nonlinear dynamic stability for laminated cylindrical shells in which factors of nonlinear large deflection, transverse shear and longitudinal inertia force were included. Equations were solved by variational method. Analysis reveals that under the action of dynamic load, laminated cylindrical shells will fall into a state of parametric resonance and enter into the dynamic unstable region that causes dynamic instability of shells. Laminated shells of three typical composites were computed: i.e. T300/5 208 graphite epoxy, E-glass epoxy, and ARALL shells. Results show that all factors will induce important influence for dynamic stability of laminated shells. So, in research of dynamic stability for laminated shells, to consider these factors is important.
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“Theoretical studies on dynamic stability of composite laminated cylindrical shells subjected to periodic loading”, Proceedings of the School of Engineering of Tokai University, 26, 50, 2001, Tokai University  
ABSTRACT: This paper deals with the problem of dynamic stability of angle-ply and cross-ply laminated cylindrical shells subjected to periodic axial compressive loading, external pressure and hydrostatic pressure. Several cases of the dynamic stability problem for composite laminated cylindrical shells are solved explicitly. The solutions for the prebuckling motion and the perturbated motion are obtained by the use of Galerkin's method. Calculations are carried out for composite laminated cylindrical shells and the instability regions are determined by utilizing Mathieu's equation. The inevitability of dynamically unstable behavior is proved analytically and the effects of various factors, such as static buckling, load ratio, number of layers, stacking sequence, vibrated amplitude, fundamental frequency, lamination angle, dimension of cylinder and dynamic unstable mode, are clarified.  

ABSTRACT: The parametric instability characteristics of doubly curved panels subjected to various in-plane static and periodic compressive edge loadings, including partial and concentrated edge loadings are studied using finite element analysis. The first order shear deformation theory is used to model the doubly curved panels, considering the effects of transverse shear deformation and rotary inertia. The theory used is the extension of dynamic, shear deformable theory according to the Sander’s first approximation for doubly curved shells, which can be reduced to Love's and Donnell's theories by means of tracers. The effects of static load factor, aspect ratio, radius-to-thickness ratio, shallowness ratio, boundary conditions and the load parameters on the principal instability regions of doubly curved panels are studied in detail using Bolotin's method. Quantitative results are presented to show the effects of shell geometry and load parameters on the stability boundaries. Results for plates and cylindrical shells are also presented as special cases and are compared with those available in the literature.  

ABSTRACT: The parametric resonance characteristics of laminated composite doubly curved panels subjected to various in-plane static and periodic compressive edge loadings, including partial and concentrated edge loading are studied using finite element analysis. The first order shear deformation theory is used to model the doubly curved panels, considering the effects of transverse shear deformation and rotary inertia. The theory used is the extension of dynamic, shear deformable theory according to the Sander’s first approximation for doubly curved laminated shells, which can be reduced to Love’s and Donnell’s theories by means of tracers. The effects of number of layers, static load factor, side to thickness ratio, shallowness ratio, boundary
conditions, degree of orthotropy, ply orientations and various load parameters on the principal instability regions of doubly curved panels are studied in detail using Bolotin’s method. Quantitative results are presented to show the effects of shell geometry, lamination details and load parameters on the stability boundaries. Results of plates and cylindrical shells are also presented as special cases and are compared with those available in the literature.

ABSTRACT: The parametric instability behaviour of curved panels with cutouts subject ed to in-plane static and periodic compressive edge loadings are studied using finite element analysis. The first order shear deformation theory is used to model the curved panels, considering the effects of transverse shear deformation and rotary inertia. The theory used is the extension of dynamic, shear deformable theory according to Sanders’ first approximation for doubly curved shells, which can be reduced to Love's and Donnell's theories by means of tracers. The effects of static and dynamic load factors, geometry, boundary conditions and the cutout parameters on the principal instability regions of curved panels with cutouts are studied in detail using Bolotin's method. Quantitative results are presented to show the effects of shell geometry and load parameters on the stability boundaries. Results for plates are also presented as special cases and are compared with those available in the literature.

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(1) Assistant Professor, Dept. of Civil Engineering, National Institute of Technology, Rourkela, India.
(2) Professor, Dept. of Aerospace Engineering, Indian Institute of Technology, Kharagpur, India.
ABSTRACT: The present investigation deals with the dynamic stability behavior of laminated composite curved panels with cutouts subjected to in-plane static and periodic compressive loads, analyzed using the finite element method. A generalized shear deformable Sanders’ theory with tracers is used in this study. Numerical results obtained for vibration and buckling of composite panels with cutouts compare well with literature. The principal dynamic instability region of composite perforated panels is obtained using Bolotin’s approach. The study reveals that curved panels with cutouts depict higher stiffness with the addition of curvatures. The laminated hyperbolic paraboloid panel shows the highest stiffness with the onset of instability at higher excitation frequencies. The effect of curvature in laminated composite curved panels is reduced with an increase in size of the cutout. The principal instability regions are influenced by the lamination parameters. Thus, the laminate construction, coupled with cutout geometry, can be used to the advantages of tailoring during design of composite structures for practical applications.

S. K. Sahu, M. K. Rath and R. Sahoo (Department of Civil Engineering, NIT, Rourkela-769008, Orissa, India), “Parametric Instability of Laminated Composite Doubly Curved Shell Panels Subjected to Hygrothermal Environment”, (publisher and date not given in the pdf file. The most recent citation is dated 2003.)
ABSTRACT: The dynamic stability behavior of laminated composite shells subjected to hygrothermal loadings are studied in the present investigation. A simple laminated model is developed for the vibration and stability analysis of laminated composite shells subjected to hygrothermal conditions. A computer program based on
FEM in MATLAB environment is developed to perform all necessary computations. An eight-node isoparametric element is employed in the present The analysis with five degrees of freedom per node. Element elastic stiffness matrices, mass matrices, geometric stiffness matrix due to mechanical and hygrothermal loads and load vectors are derived using the principle of minimum potential energy. Quantitative results are presented to show the effects of curvature, ply-orientation, degrees of orthotropy and static load factors of laminate on dynamic stability of composite shells for different temperatures and moisture concentrations.

References listed at the end of the paper:


ABSTRACT: This article deals with the stability analysis of angle-ply laminated composite twisted panels using the finite element method. Here, a eight-noded isoparametric quadratic shell element is used to develop the finite element procedure. To investigate the vibration and stability behavior of twisted panels, the effect of various geometrical parameters like angle of twist, aspect ratio, lamination parameters, shallowness ratio, etc. are studied. The influence of various parameters on the vibration and stability characteristics of twisted panels have been examined. Numerical results are presented to show the effects of pretwist angles, geometry, and lamination details on the stability characteristics of twisted plates.

References listed at the end of the paper:
PARTIAL ABSTRACT: The twisted cantilever panels have significant applications in wide chord turbine blades, compressor blades, fan blades, particularly in gas turbines. This range of practical applications demands a proper understanding of their vibration, static and dynamic stability characteristics. Due to its significance, a large number of references deal with the free vibration of twisted plates. Structural elements subjected to in-plane periodic forces may lead to parametric resonance, due to certain combinations of the values of load parameters. The instability may occur below the critical load of the structure under compressive loads over wide ranges of excitation frequencies. Composite materials are being increasingly used in turbo-machinery blades because of their specific strength, stiffness and these can be tailored through the variation of fiber orientation and stacking sequence to obtain an efficient design. Thus the parametric resonance characteristics of laminated composite twisted cantilever plates have significant applications in wide chord turbine blades, compressor blades, fan blades, particularly in gas turbines. This range of practical applications demands a proper understanding of their vibration, static and dynamic stability characteristics. Due to its significance, a large number of references deal with the free vibration of twisted plates. Structural elements subjected to in-plane periodic forces may lead to parametric resonance, due to certain combinations of the values of load parameters. The instability may occur below the critical load of the structure under compressive loads over wide ranges of excitation frequencies. Composite materials are being increasingly used in turbo-machinery blades because of their specific strength, stiffness and these can be tailored through the variation of fiber orientation and stacking sequence to obtain an efficient design. Thus the parametric resonance characteristics of laminated composite twisted cantilever plates...

References listed at the end of the paper:


ABSTRACT: The static stability of the curved panels subjected to varieties of non-uniform loading including partial and concentrated in-plane compressive edge loading is studied using finite element method, considering the effects of transverse shear deformation and rotary inertia. An eight nodded quadratic isoparametric element is employed in the present analysis. The study reveals that the stability behaviour of the flat and curved panels is greatly influenced by the geometry, boundary conditions, the type and position of loads.

ABSTRACT: The present study deals with the dynamic stability of laminated composite pre-twisted cantilever panels. The effects of various parameters on the principal instability regions are studied using Bolotin's approach and finite element method. The first-order shear deformation theory is used to model the twisted curved panels, considering the effects of transverse shear deformation and rotary inertia. The results on the dynamic stability studies of the laminated composite pre-twisted panels suggest that the onset of instability occurs earlier and the width of dynamic instability regions increase with introduction of twist in the panel. The instability occurs later for square than rectangular twisted panels. The onset of instability occurs later for pre-twisted cylindrical panels than the flat panels due to addition of curvature. However, the spherical pre-twisted panels show small increase of nondimensional excitation frequency.

References listed at the end of the paper:


ABSTRACT: The buckling and vibration analysis of cross-ply laminated cantilever twisted plates are investigated. The analysis is carried out using the finite element method with first order shear deformation theory. An eight-nodded isoparametric quadratic element is employed in the present analysis with five degrees of freedom per node. The element elastic stiffness matrix, mass matrix and load vector are derived using the principle of Stationery Potential Energy. Plane stress analysis is carried out using the finite element method to determine the stresses and these are used to formulate the geometric stiffness matrix. The overall stiffness and mass matrices are obtained by assembling the corresponding element matrices using skyline technique. The eigenvalues are determined using subspace iteration scheme. Extensive results are presented to show the effects of various parameters such as aspect ratio, number of layers, angle of twist, ply orientation, etc on the buckling and vibration behavior of cross-ply laminated twisted cantilever plates. It was noticed that both the non-dimensional buckling and frequency parameter decreased with the increase in the angle of twist of the plate. The non-dimensional frequency parameters as well as buckling loads also increase with increase in the number of layers of the plate. There is significant decrease in the buckling load of the plate with increase of aspect ratio unlike the frequencies of vibration. These can be used to advantage in tailoring of laminated cross-ply twisted cantilever plates.
ABSTRACT: The present paper deals with the study of the vibration, buckling and parametric instability characteristics of general laminated cross-ply pre-twisted cantilever flat and curved panels. The effects of angles of pre-twist, aspect ratio, static load factor, and the lamination parameters of the cross-ply twisted curved panels on the principal instability regions are studied using Bolotin's approach. An eight-noded isoparametric quadratic shell element with five degrees of freedom per node is used to develop the finite element procedure. The first order shear deformation theory is used to model the twisted cross-ply curved panels considering the effects of transverse shear deformation and rotary inertia. The linear part of the strain is used to derive the elastic stiffness matrix and the non-linear part of the strain is used to derive the geometric stiffness matrix. The global matrices are obtained by assembling the corresponding element matrices using skyline technique. Subspace iteration method is used throughout to solve the eigenvalue problem. Reduced integration technique is adopted in order to avoid possible shear locking. Based on the parametric studies, it is found that the instability behavior of twisted cross-ply cantilever panels is greatly influenced by the geometry, material, angle of twist and lamination parameters. So, this can be used to advantage in tailoring during design of cross-ply twisted cantilever panels.

ABSTRACT: This paper reviews most of the research done in the field of tensile buckling characteristics pertaining to aerospace structural elements with special attention to local buckling and parametric excitation due to periodic loading on plate and shell elements. The concepts of buckling in aerospace structures appear as the result of the application of a global compressive applied load or shear load. A less usual situation is the case, in which a global tensile stress creates buckling instability and the formation of complex spatial buckling pattern. In contrast to the case of a pure compression or shear load, here the applied macroscopic load has no compressive component and is thus globally stabilizing. The instability stems from a local compressive stress induced by the presence of a defect, such as a crack or a hole, due to partial or non-uniform applied load at the far end. This is referred to as tensile buckling. This paper discusses all aspects of tensile buckling, theoretical and experimental. Its far reaching applications causing local instability in aerospace structural components are discussed. The important effects on dynamic stability behaviour under locally induced periodic compression have been identified and influences of various parameters are discussed. Experimental results on simple and combination resonance characteristics on plate structures due to tensile buckling effects are elaborated. References listed at the end of the paper:


Susumu Toda (National Aerospace Laboratory, Tokyo, Japan), “Buckling of cylinders with cutouts under axial compression” (Experimental results are presented for circular cylindrical shells with both reinforced and unreinforced holes under axial compression), Experimental Mechanics, Vol. 23, No. 4, 1982, pp. 414-417, doi: 10.1007/BF02330057

ABSTRACT: An experimental study was carried out to clarify the effects of circular holes on the buckling of circular cylinders under axial compression. The effect of reinforcements was also examined by placing thin annular plates around the cutouts. Tests were performed on polyester shells with radius-to-thickness ratio of 400 and 100 and with two diametrically opposed circular holes. If a hole is small enough, there are no appreciable effects on the buckling strength of the cylinder. However larger cutouts result in a significant reduction of the buckling load. When doublers are placed around the holes, the buckling load approaches the value for the complete cylinder with no cutouts as the stiffening volume increases.

References listed at the end of the paper:

S.K. Sahu (1) and P.K. Datta (2)
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ABSTRACT: The parametric resonance characteristics of laminated composite curved panels subjected to various in-plane periodic concentrated edge loadings are studied using finite element analysis. The first order shear deformation theory is used to model the curved panels, considering the effects of transverse shear deformation and rotary inertia. The effects of number of layers, static load factor, boundary conditions and ply orientations for different positions of loading on the principal instability regions of curved panels are studied in detail using Bolotin's method. Quantitative results are presented to show the effects of shell geometry, lamination details and load parameters on the stability boundaries.

References listed at the end of the paper:

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ABSTRACT: This paper deals with the study of tensile buckling, vibration and dynamic stability behaviour of multilaminated curved panels subjected to uniaxial in-plane point and patch tensile edge loadings by using the finite element method. The effect of first order shear deformation theory is used to model the doubly curved panels. Numerical results have been established through convergence and comparison with the published data from the literature. The effects of load position, number of layers, lamination angles, thickness ratio, aspect ratio and shell geometries of the panel are considered in the analysis and results are discussed.

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ABSTRACT: The tensile buckling and vibration behaviour of curved panels of square planform subjected to combinations of tension-tension, tension-compression and compression-compression edge loadings have been studied using the finite element method. The first order shear deformation theory is used to model the doubly curved panels, considering the effects of transverse shear deformation and rotary inertia. The theory used is extended from the dynamic, shear deformable theory based on the Sander’s first approximation for doubly curved shells, which can be reduced to Love’s and Donnell’s theories by means of tracers. The in-plane non-uniform stress field has been analysed under plane-stress conditions with reasonable accuracy. The effects of biaxial concentrated and patch loading on the edges are also considered in the analysis.

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ABSTRACT: This paper deals with the study of vibration and dynamic instability characteristics of laminated composite doubly curved panels subjected to non-uniform follower load, using finite element approach. First order shear deformation theory is used to model the doubly curved panels, considering the effects of shear deformation and rotary inertia. The formulation is based on the extension of dynamic, shear deformable theory according to Sanders’ first approximation for doubly curved laminated shells, which can be reduced to Love’s and Donnell’s theories by means of tracers. The modal transformation technique is applied to reduce the number of equilibrium equations for subsequent analysis. Structural damping is introduced into the system in terms of viscous damping. Instability behaviour of curved panels have been examined considering the various parameters such as width of edge load, load direction control, damping, influence of fiber orientation and lay up sequence etc. The results show that under follower loading the panel may lose its stability due to either flutter or divergence, depending on the system parameters.
Buckling and dynamic instability analysis of stiffened shell panels are investigated in this paper. The eight-noded isoparametric degenerated shell element and a compatible three-noded curved beam element are used to model the shell panels and the stiffeners, respectively. As the usual formulation of degenerated beam element is found to overestimate the torsional rigidity, an attempt has been made to reformulate it in an efficient manner. Moreover, the new formulation for the beam element requires five degrees of freedom per node as that of shell element. The method of Hill's infinite determinant is applied to analyze the dynamic instability regions. Numerical results are presented through convergence and comparison with the published results from the literature. The effects of various parameters like shell geometry, stiffening scheme, static and dynamic load factors, stiffener size and position, and boundary conditions are considered in buckling and dynamic instability analysis of stiffened panels subjected to uniform in-plane harmonic loads along the boundaries.

ABSTRACT: The static and dynamic instability characteristics of stiffened shell panels subjected to uniform in-plane harmonic edge loading are investigated in this paper. The eight-noded isoparametric degenerated shell element and a compatible three-noded curved beam element are used to model the shell panels and the stiffeners, respectively. As the usual formulation of degenerated beam element is found to overestimate the torsional rigidity, an attempt has been made to reformulate it in an efficient manner. Moreover, the new formulation for the beam element requires five degrees of freedom per node as that of shell element. The method of Hill's infinite determinant is applied to analyze the dynamic instability regions. Numerical results are presented through convergence and comparison with the published results from the literature. The effects of various parameters like shell geometry, stiffening scheme, static and dynamic load factors, stiffener size and position, and boundary conditions are considered in buckling and dynamic instability analysis of stiffened panels subjected to uniform in-plane harmonic loads along the boundaries.

ABSTRACT: The dynamic instability characteristics of stiffened shell panels subjected to partial in-plane harmonic edge loading are investigated in this paper. The eight-noded isoparametric degenerated shell element and a compatible three-noded curved beam element are used to model the shell panels and the stiffeners, respectively. As the usual formulation of degenerated beam element is found to overestimate the torsional rigidity, an attempt has been made to reformulate it in an efficient manner. Moreover, the new formulation for the beam element requires five degrees of freedom per node as that of shell element. The method of Hill's infinite determinant is applied to analyze the dynamic instability regions. Numerical results are presented through convergence and comparison with the published results from the literature. The effects of parameters like loading type and shell geometry are considered in the dynamic instability analysis of stiffened panels subjected to non-uniform in-plane harmonic loads along the boundaries. The tension buckling aspect of the stiffened panels are also considered and the dynamic stability behavior due to tensile in-plane edge loading is studied for the concentrated load.

ABSTRACT: Delaminations may reduce the buckling load of the laminated structure greatly. In this paper, various examples were analyzed by using the model in part I. First, by comparing with the results of the classical theory and first-order shear-deformation theory, the model was validated and the usable range of each theory was pointed out. Three different buckling modes of delaminated shell were considered. The influence of different ratios of radius to thickness, boundary condition and length, depth and position of the delamination on
the buckling load was analyzed. Finally, the buckling analysis of delaminated orthotropic shell and the influences of ply orientation of the material on the buckling load of a delaminated shell were given.

1789


ABSTRACT: An analytical methodology is presented for predicting the buckling initiation of delaminated composite plates. Both global and local sublaminate buckling deformation modes are predicted for rectangular plates of any thickness. The global behavior of the delamination zone is accounted for by summing the individual stiffness contributions of each sublaminate constituting the delamination zone. This allows for the delamination zone to be treated as a single plate when performing global buckling predictions. Local buckling predictions are obtained by modeling a sublaminate adjacent to the surface as a separate elliptical plate. These analytical predictions compare closely with the results of detailed finite element models investigating several cases of delaminated plates. The methodology presented is found to be accurate for the cases considered and versatile as it can accommodate plates of any aspect ratio and having arbitrarily sized and located delaminations.


ABSTRACT: This paper contributes newly developed closed-form buckling solutions for generic one-edge-free problems common to partially disbanded composite structures. These solutions are shown to be accurate by comparison with experimentally measured buckling loads which are also reported in this paper. The buckling of partially disbanded regions in adhesive joints is a safety concern due to the potential for ensuing buckling-driven disbond growth. In order to design structures to be tolerant to these flaws, closed-form expressions that predict buckling load have been developed based on a one-edge-free buckling model. Comparison of the closed-form predictions with the finite element results verifies the accuracy of the solutions. Validation of these analyses was achieved by comparison with the experimentally determined buckling loads. These were measured to fall within a range of predicted values, as defined by the choice of boundary condition opposite the disbonded flange-free-edge: either clamped or simply-supported. Assumption of either boundary condition provides upper-and lower-bound predictions of buckling in partially disbanded joint flange configurations.


PARTIAL ABSTRACT: This paper investigates how geometrical imperfections, which in most cases are present for impacted laminates, affect the postbuckling behaviour of delaminated composite plates under compression. Delaminations are one of the most frequently appearing material damage due to impact. The influence of different shapes of the geometrical imperfections on the response has been studied. The program system, DEBUGS, which is developed and specialized to simulate delamination buckling and growth, is used for the analyses. DEBUGS is based on the finite element program ADINA. It is found that the geometrical
imperfections influence the buckling behaviour, and thus also possibly the initiation of delamination growth. A more accurate model of delamination buckling of impact-damaged laminated composites should thus include a feature where the initial shape of the composite may be varied, e.g. in a model where the material degradation in the impact damaged zone is modeled.

ABSTRACT: The influence of impact damage on the structural performance of composite laminates was investigated by a joint effort and included nondestructive evaluation (NDE), mechanical testing and analysis. The impacted NASA Industry Standard Compression After Impact test specimen was chosen. Damage characterization incorporated ultrasonic and radiographic methods. Computerized and manual ultrasonic testing from both sides of the test panels provided accurate information on the damaged area. The findings were confirmed by a destructive X-ray microfocus technique combined with an opaque penetrant for damage enhancement. From the NDE data, a simplified damage model was constructed and analyzed for strength and stability. Failure loads and modes were predicted and compared to compression after impact test results. Preliminary tests showed very good agreement.

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ABSTRACT: Delamination buckling analysis of laminates is of considerable interest to the mechanical and materials engineering sectors, as well as having wider applications in geology and civil engineering. With advances in computing power, the ability to model ever increasingly complex problems at more detailed levels becomes more of a reality. However, many of the common finite element packages, with the exception of all but the most specialized, do not perform particularly well where complex non-linear problems are dealt with. In many cases, these packages can fail to determine the full range of solutions or accurately predict the properties and geometry of the final state. This is particularly the case where large deformations and buckling of laminates are considered. Because of this, many researchers prefer to use what they perceive to be more reliable techniques, such as the symbolic computation of the underlying differential equations, rather than finite element approaches. The use of finite element packages is further frustrated by the steep learning curve and implicit restrictions imposed by using third-party software. In this paper, a finite element approach and an energy formulation method are considered and used to model the delamination buckling in a geometrically constrained system. These methods are compared with experimental results and their relative merits are discussed. In particular, the accuracy and the ability to represent the geometry of the buckled system are discussed. Both the finite element approach and the energy formulation are described in detail and the numerical results are compared.

ABSTRACT: Shell structures have been widely used in engineering applications such as pipelines, aerospace and marine structures, and cooling towers. Occurring suddenly and generally inadvertently due to its nature, buckling is one of the main failure considerations in the design of these structures. Presence of defects, such as cracks, corrosion pits, blow-out holes, in shell structures may severely compromise their buckling behavior and jeopardize the structural integrity.

In this study, a numerical investigation on the buckling behavior of a cracked cylindrical shell reinforced with an elastic liner and subjected to combined axial compression was carried out. The effect of supporting liner on the buckling behavior of the cracked shell at different crack sizes and orientations were investigated. In the next step, the buckling behavior of a cracked cylindrical shell with an elastic liner subjected to the internal pressure and axial compression was studied. Different buckling modes of the cracked shell, including global, transition and locales modes are identified for different loading conditions.

The results showed that longitudinal crack has a more detrimental effect on the buckling strength of the cylindrical shell in cylinders with no elastomeric liner or with elastomeric liners with low relative stiffness. In addition, cylinders with elastomeric liners of high relative stiffness circumferential crack have a more detrimental effect on the buckling strength of the cylindrical shell.

The finite element analysis also showed that increasing the thickness of the supporting layer or increasing its stiffness, can significantly increase the critical crack size at each angle. The shells reinforced with elastic liners subjected to the internal pressure and axial compression shown that the internal pressure does not affect the overall buckling behavior of perfect cylindrical shells. For circumferential crack, the internal pressure increases the buckling load of the cylindrical shell. In contrast, for longitudinal crack, the internal pressure decreases the buckling load of the cylindrical shell. We found that the critical buckling load of the cracked cylinder with various thicknesses of the elastomeric liner can be expressed at each crack angle by a single parameter, namely stretching stiffness ratio of liner and shell layers.

References listed at the end of the paper:

A. Vaziri (1) and H.E. Estekanchi (2)

ABSTRACT: Linear eigenvalue analysis of cracked cylindrical shells under combined internal pressure and axial compression is carried out to study the effect of crack type, size and orientation on the buckling behavior of cylindrical thin shells. Two types of crack are considered; through crack and thumbnail crack. Our calculations indicate that depending on the crack type, length, orientation and the internal pressure, local buckling may precede the global buckling of the cylindrical shell. The internal pressure, in general, increases the buckling load associated with the global buckling mode of the cylindrical shells. In contrast, the effect of internal pressure on buckling loads associated with the local buckling modes of the cylindrical shell depends mainly on the crack orientation. For cylindrical shells with relatively long axial crack, buckling loads associated with local buckling modes of the cylindrical shell reduce drastically on increasing the shell internal pressure. In contrast, the internal pressure has the stabilizing effect against the local buckling for circumferentially cracked cylindrical shells. A critical crack length for each crack orientation and loading condition is defined as the shortest crack causing the local buckling to precede the global buckling of the cylindrical shell. Some insight into the effect of internal pressure on this critical crack length is provided.

References listed at the end of the paper:

ABSTRACT: Potential sensitivity of the buckling behavior of cracked composite cylindrical shells to service life cracking is explored by carrying out linear buckling analysis. Computational models of cracked composite cylindrical shells are developed by exploiting a special meshing scheme in which the element size is reduced incrementally from the element size employed in the uncracked region by approaching the crack tip. The effect of crack size and orientation, as well as the composite ply angle on the buckling behavior of cylindrical shells under axial compression is investigated. The results provide some insight into designing a composite laminate, which enhances the load capacity of cylindrical shells and minimizes their potential sensitivity to the presence of defects.

References listed at the end of the paper:

ABSTRACT: The response of low-dimensional solid objects combines geometry and physics in unusual ways, exemplified in structures of great utility such as a thin-walled tube that is ubiquitous in nature and technology. Here we provide a consequence of this confluence of geometry and physics in tubular structures: our analysis shows that the persistence of a localized pinch in an elastic pipe whose effect decays as an oscillatory exponential with a persistence length that diverges as the thickness of the tube vanishes, which we confirm using simulations and simple experiments. The result is more a consequence of geometry than material properties, and is thus equally applicable to carbon nanotubes as it is to oil pipelines.


ABSTRACT: The dried raisin, the crushed soda can, and the collapsed bicycle inner tube exemplify the nonlinear mechanical response of naturally curved elastic surfaces with different intrinsic curvatures to a variety of different external loads. To understand the formation and evolution of these features in a minimal setting, we consider a simple assay: the response of curved surfaces to point indentation. We find that for surfaces with zero or positive Gauss curvature, a common feature of the response is the appearance of faceted structures that are organized in intricate localized patterns, with hysteretic transitions between multiple metastable states. In contrast, for surfaces with negative Gauss curvature the surface deforms nonlocally along characteristic lines that extend through the entire system. These different responses may be understood quantitatively by using numerical simulations and classified qualitatively by using simple geometric ideas. Our ideas have implications for the behavior of small-scale structures.


ABSTRACT: Emergence of new technological applications, in addition to the constantly growing interest in biological materials has accentuated the importance of studying the mechanics of highly deformed shells. The key challenge is the intricate interplay of physics and geometry, which leads to a mechanical response much different from the response of solid objects. The quest to understand the underlying phenomena has spawned theoretical and experimental studies, which have helped in understanding the underlying mechanisms of deformation and response of shells. Here, we use numerical simulations to study the response of shells when they are deformed deeply into the nonlinear regime. We use computational models to study the mechanics of highly deformed elastic shells in several classical problems: indentation of elastic spherical caps by a flat rigid plate and a rigid sharp indenter and pure bending of circular and oval cylinders. These assays are used to highlight some of the key aspects of the mechanics of highly deformed elastic shells, while an overview of the current state-of-the-art and suggestions for future research on this subject are also provided.

References listed at the end of the paper:
[76] Brazier LG. On the flexure of thin cylindrical shells and other “thin sections”. In: Proceedings of the royal society, Series A 116,
ABSTRACT: We study the formation of localized structures formed by the point loading of an internally pressurized elastic shell. While unpressurized shells (such as a ping-pong ball) buckle into polygonal structures, we show that pressurized shells are subject to a wrinkling instability. We study wrinkling in depth, presenting scaling laws for the critical indentation at which wrinkling occurs and the number of wrinkles formed in terms of the internal pressurization and material properties of the shell. These results are validated by numerical simulations. We show that the evolution of the wrinkle length with increasing indentation can be understood for highly pressurized shells from membrane theory. These results suggest that the position and number of wrinkles may be used in combination to give simple methods for the estimation of the mechanical properties of highly pressurized shells.


ABSTRACT: Thin-walled structural components, such as plates and shells, are used in several aerospace, naval, nuclear power plant, pressure vessels, mechanical and civil structures. Due to their high slenderness, the safety assessment of such structural components requires to carefully assess the buckling collapse which can strongly
limit their bearing capacity. For very thin plate, buckling collapse can occur under shear, compression or even under tension. In the latter case, fracture or plastic failure can also take place instead of elastic instability. In the present paper, the effects of a central straight crack on the buckling collapse of rectangular elastic thin-plates—characterized by different boundary conditions, crack length and orientation—under compression, tension or shear loading are analysed. Accurate FE numerical parametric analyses have been performed to get the critical load multipliers in such loading cases. Moreover the effect of crack faces contact is examined and discussed. Some useful conclusions related to the sensitivity to cracks of the buckling loads for thin plates, especially in the case of shear stresses, are drawn. Cracked plates under tension are finally considered in order to determine the most probable collapse mechanism among fracture, plastic flow or buckling and some failure-type maps are determined.

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Babak Haghpanah Jahromi and Ashkan Vaziri (Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115, USA), “Instability of cylindrical shells with single and multiple cracks under axial compression”, Thin-Walled Structures Vol. 54 (2012) 35–43, doi:10.1016/j.tws.2012.01.014

ABSTRACT: Linear eigenvalue buckling analysis was carried out for singly and doubly cracked cylindrical thin shells under axial compression using the finite element method. First, the effect of crack size and orientation on the buckling behavior of an axially loaded shell with a single crack was studied. Then, the buckling behavior of a cylinder with two parallel longitudinal cracks was investigated. Two different buckling shapes with cross-sectional deformation profiles that resemble letters M (symmetric) and N (anti-symmetric) were identified as the first buckling modes of the cylinder. The exchange between these local buckling modes due to variation of crack size and spacing was illustrated. The transition between these two buckling shapes can be used to estimate the ‘maximum interaction distance’ of the cylinder cracks—the separation distance beyond which the two cracks do not interact in affecting the buckling load of the cylindrical shell. The influence of shell thickness and crack length on the maximum interaction distance was quantified for cylinders with two co-centered (i.e., parallel offset) or collinear longitudinal cracks. Additional simulations were carried out for cylinders with multiple symmetrically spaced longitudinal cracks to show how the behavior of single and double cracks can give the buckling load and mode shape of cylinders with multiple cracks.

References listed at the end of the paper:

ABSTRACT: More recently, we have been studying the emergence and evolution of point and linear-like loci of localization on thin shells indented well into the nonlinear regime. For large enough indentation, sharp points of localized curvature form, which we refer to as 's-cones' (for shell-cones), in contrast with their developable cousins in plates, 'd-cones'. Through experiments and FEM, we have found that the shape of the indenter has a significant effect on the mechanical response and that there is a qualitative difference between sharp and blunt indenters. Given the importance of geometry and the scale-invariance of this problem, our results should find uses at the microscale, e.g. for AFM, where it is crucial to understand how the curvature of the tip, relative to the object being indented, affects the mechanical response.

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ABSTRACT: Elastic liners are used for in situ repair and retrofitting of pipes as a cost effective alternative to the replacement of damaged parts and sections. In this paper, we studied the role of an elastic liner on the buckling behavior of a cracked cylindrical shell using finite element method. A special meshing scheme that could mimic the stress singularity at the crack tip was employed to model the cracked shells. Linear eigenvalue analysis was carried out to study the effect of crack geometry (length and orientation) as well as the material properties and thickness of the elastic liner on the buckling load and buckling shape of the cylindrical shell. We considered a combination of axial compression and internal pressure which is a typical loading for pipelines and pressurized liquid-retaining structures. Our results show that cracked shell's strength and mode of buckling for different crack length and orientations can be largely influenced by thickness and relative stiffness of the liner layer. In particular we report a gradual transition from local to global instability due to these size and orientation effects. Finally, the role of internal pressure on structural stability and local buckling of cracked shells, which strongly depends on the crack orientation and liner thickness, is discussed.

References listed at the end of the paper:
ABSTRACT: An approach to obtain analytical closed-form expressions for the macroscopic ‘buckling strength’ of various two-dimensional cellular structures is presented. The method is based on classical beam-column end-moment behaviour expressed in a matrix form. It is applied to sample honeycombs with square, triangular and hexagonal unit cells to determine their buckling strength under a general macroscopic in-plane stress state. The
results were verified using finite-element Eigenvalue analysis.

References listed at the end of the paper:


Iwan A.T. Schaap (1), Carolina Carrasco (2), Pedro J. de Pablo (2), Frederick C. MacKintosh (1) and Christoph F. Schmidt (1)

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ABSTRACT: We tested the mechanical properties of single microtubules by lateral indentation with the tip of an atomic force microscope. Indentations up to about 3.6 nm, i.e., 15% of the microtubule diameter, resulted in an approximately linear elastic response, and indentations were reversible without hysteresis. At an indentation force of around 0.3 nN we observed an instability corresponding to an approximately 1-nm indentation step in the taxol-stabilized microtubules, which could be due to partial or complete rupture of a relatively small number of lateral or axial tubulin-tubulin bonds. These indentations were reversible with hysteresis when the tip was retracted and no trace of damage was observed in subsequent high-resolution images. Higher forces caused substantial damage to the microtubules, which either led to depolymerization or, occasionally, to slowly reannealing holes in the microtubule wall. We modeled the experimental results using finite-element methods and find that the simple assumption of a homogeneous isotropic material, albeit structured with the characteristic protofilament corrugations, is sufficient to explain the linear elastic response of microtubules.

References listed at the end of the article:


from continuum mechanics have a similarity with the two-dimensional Stokes flows, and we use a nonlinear stream function for the exact treatment of the incompressibility constraint. A free energy approach allows the extension both to arbitrary hyperelastic strain energies and to additional interactions, such as surface energies. We find that, at constant volumetric growth, the threshold for a wavy instability is completely governed by the amount of growth. Nevertheless, the determination of the wavelength at threshold, which scales with the initial thickness of the gel layer, requires the coupling with a surface effect. Our findings, which are valid in proximity of the threshold, are compared to experimental results. The proposed treatment can be extended to weakly nonlinearities within the aim of the theory of bifurcations.


ABSTRACT: Static deflection as well as free and forced nonlinear vibration of thin square plates made of hyperelastic materials are investigated. Two types of materials, namely rubber and soft biological tissues, are considered. The involved physical nonlinearities are described through the Neo-Hookean, Mooney-Rivlin, and Ogden hyperelastic laws; geometrical nonlinearities are modeled by the Novozhilov nonlinear shell theory. Dynamic local models are first built in the vicinity of a static configuration of interest that has been previously calculated. This gives rise to the approximation of the plate’s behavior in the form of a system of ordinary differential equations with quadratic and cubic nonlinear terms in displacement. Numerical results are compared and validated in the static case via a commercial finite element software package: they are found to be accurate for deflections reaching 100 times the thickness of the plate. The frequency shift between low- and large-amplitude vibrations weakens with an increased initial deflection.

References listed at the end of the paper:
ABSTRACT: Static and dynamic responses of a circular cylindrical shell made of hyperelastic arterial material are investigated. The material is modeled as a combination of Neo-Hookean and Fung hyperelastic materials. Two pressure loads are implemented: distributed radial force and deformation-dependent pressure. The static responses of the shell under these two different loads differ essentially at moderate strains, while the behavior is similar for small loads. The main difference is in the axial displacements that are much larger under distributed radial forces. Free and forced vibrations around pre-loaded configurations are analyzed. In both cases the nonlinearity of the single-mode (driven mode) response of the pre-loaded shell is quite weak but a resonant regime with co-existing driven and companion modes is found with more complicated nonlinear dynamics. References listed at the end of the paper:

(cannot easily cut and paste the references.)

ABSTRACT: The shape of plants and other living organisms is a crucial element of their biological functioning. Morphogenesis is the result of complex growth processes involving biological, chemical and physical factors at different temporal and spatial scales. This study aims at describing stresses and strains induced by the production and reorganization of the material. The mechanical properties of soft tissues are modeled within the framework of continuum mechanics in finite elasticity. The kinematical description is based on the multiplicative decomposition of the deformation gradient tensor into an elastic and a growth term. Using this formalism, the authors have studied the growth of thin hyperelastic samples. Under appropriate assumptions, the dimensionality of the problem can be reduced, and the behavior of the plate is described by a two-dimensional surface. The results of this theory demonstrate that the corresponding equilibrium equations are of the Föppl–von Kármán type where growth acts as a source of mean and Gaussian curvatures. Finally, the cockling of paper and the rippling of a grass blade are considered as two examples of growth-induced pattern formation.

ABSTRACT: Generation of shapes in biological tissues is a complex multiscale phenomenon. Biochemical details of cell proliferation, death and mobility can be incorporated within a continuum mechanical framework by specifying locally the amplitude and direction of growth. For tissues exhibiting an elastic behavior, equilibrium shapes of growing bodies can be evaluated through the minimization of an appropriate energy. This model is applied to thin shells and plates, a geometry relevant to nuts and pollen grains but also leaves, petals and algae.
Localized growth of layered tissues

ABSTRACT: Due to their structural heterogeneity, stratified media usually lose their initial symmetry when they grow. Mismatching expansions between distinct layers create elastic stresses that lead to the emergence of wavy patterns. In the context of morphogenesis, this process of constrained growth has been used to explain patterns in biological soft-layered tissues such as the fingerprints of the skin. Discovery of morphogens has however revealed that growth is not always a homogeneous process and can be highly localized. Spatially concentrated growth processes are thought to be responsible for the formation of various structures, from placodes in the chicken embryo to nevus and skin tumours. On a different ground, the processing of complex textured surfaces requires to understand the connection between the local variation of mass and the resulting surface profile. In this paper, we investigate a model of a locally growing thin sheet bound to a soft infinite substrate. We show that, in two dimensions, bending effects select the shape of the growing sheet, therefore preventing the fabrication of an arbitrary surface. In three dimensions, the high energetic cost of stretching sets a stronger constraint on the attainable patterns and provides a simple relation between the profile of the surface and the local properties of the growth process.
ABSTRACT: Using swelling hydrogels, we study the evolution of a thin circular artificial tumor whose growth is confined at the periphery. When the volume of the outer proliferative ring increases, the tumor loses its initial symmetry and bifurcates towards an oscillatory shape. Depending on the geometrical and elastic parameters, we observe either a smooth large-wavelength undulation of the swelling layer or the formation of sharp creases at the free boundary. Our experimental results as well as previous observations from other studies are in very good agreement with a nonlinear poroelastic model.

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ABSTRACT: Morphologies of soft materials in growth, swelling or drying have been extensively studied recently. Shape modifications occur as the size varies transforming ordinary spheres, cylinders and thin plates into more or less complex objects. Here we consider the genesis of biofilm patterns when a simple disc containing initially bacteria with moderate adhesion to a rigid substrate grows according to very simple rules. The initial circular geometry is lost during the growth expansion, contour undulations and buckling appear, ultimately a rather regular periodic focussing of folds repartition emerges. We theoretically predict these morphological instabilities as bifurcations of solutions in elasticity, characterized by typical driving parameters established here. The substrate plays a critical role limiting the geometry of the possible modes of instabilities and anisotropic growth, adhesion and toughness compete to eventually give rise to wrinkling, buckling or both. Additionally, due to the substrate, we show that the ordinary buckling modes, vertical deviation of thin films, are not observed in practice and a competitive pattern with self-focussing of folds can be found analytically. These patterns are reminiscent of the blisters of delamination in material sciences and explain recent observations of bacteria biofilms. The model presented here is purely analytical, is based on a neo-Hookean elastic energy, and can be extended without difficulties and applied to polymer materials.

References listed at the end of the paper:
ABSTRACT: The stability of the wrinkling mode experienced by a compressed half-space of neo-Hookean material is investigated using analytical and numerical methods to study the post-bifurcation behavior of periodic solutions. It is shown that wrinkling is highly unstable due to the nonlinear interaction among the multiple modes associated with the critical compressive state. Concomitantly, wrinkling is sensitive to exceedingly small initial imperfections that significantly reduce the compressive strain at which the instability occurs. The study provides insight into the connection between wrinkling and an alternative surface mode, the finite amplitude crease, or sulcus. The shape of the critical combination of wrinkling modes has the form of an incipient crease, and a tiny initial imperfection can trigger a wrinkling instability that collapses into a crease.

Reference cited at the end of the paper:
ABSTRACT: A soft dielectric membrane is prone to snap-through instability. We present theory and experiment to show that the instability can be harnessed to achieve giant voltage-triggered deformation. We mount a membrane on a chamber of a suitable volume, pressurize the membrane into a state near the verge of the instability, and apply a voltage to trigger the snap without causing electrical breakdown. For an acrylic membrane we demonstrate voltage-triggered expansion of area by 1692%, far beyond the largest value reported in the literature. The large expansion can even be retained after the voltage is switched off.

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ABSTRACT: The creasing instability of elastomer films under compression is studied by a combination of experiment and numerical simulation. Experimentally, we attach a stress-free film on a much thicker and stiffer pre-stretched substrate. When the substrate is partially released, the film is uniaxially compressed, leading to formation of an array of creases beyond a critical strain. The profile of the folded surface is extracted using confocal fluorescence microscopy, yielding the depths, spacings, and shapes of creases. Numerically, the onset and development of creases are simulated by introducing appropriately sized defects into a finite-element mesh and allowing the surface of the film to self-contact. The measurements and simulations are found to be in excellent agreement.

References listed at the end of the paper:


ABSTRACT: In the emerging field of soft machines, large deformation of soft materials is harnessed to provide functions such as regulating flow in microfluidics, shaping light in adaptive optics, harvesting energy from ocean waves, and stretching electronics to interface with living tissues. Soft materials, however, do not provide
all of the requisite functions; rather, soft machines are mostly hybrids of soft and hard materials. In addition to requiring stretchable electronics, soft machines often use soft materials that can deform in response to stimuli other than mechanical forces. Dielectric elastomers deform under a voltage. Hydrogels swell in response to changes in humidity, pH, temperature, and salt concentration. How does mechanics meet geometry, chemistry, and electrostatics to generate large deformation? How do molecular processes affect the functions of transducers? How efficiently can materials convert energy from one form to another? These questions are stimulating intriguing and useful advances in mechanics. This review highlights the mechanics that enables the creation of soft machines.

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ABSTRACT: Soft, elastic materials are capable of large and reversible deformation, readily leading to various modes of instability that are often undesirable, but sometimes useful. For example, when a soft elastic material is compressed, its initially flat surface will suddenly form creases. While creases are commonly observed, and have been exploited to control chemical patterning, enzymatic activity, and adhesion of surfaces, the conditions for the formation and disappearance of creases have so far been poorly controlled. Here we show that a soft elastic bilayer can snap between the flat and creased states repeatedly, with hysteresis. The strains at which the creases form and disappear are highly reproducible, and are tunable over a large range, through variations in the level of pre-compression applied to the substrate and the relative thickness of the film. The introduction of bistable flat and creased states and hysteretic switching is an important step to enable applications of this type of instability.

References listed at the end of the paper:
ABSTRACT: Theory and experiment are presented to show that an interface between two soft materials under compression can form creases, a type of bifurcation distinct from wrinkles. While creases bifurcate from a state of flat interface by a deformation localized in space and large in amplitude, wrinkles bifurcate from a state of flat interface by a deformation nonlocal in space and infinitesimal in amplitude. The interfacial creases set in at a lower critical compression than interfacial wrinkles, but higher than surface creases. The condition for the onset of interfacial creases is scale-free, and is calculated in terms of elastic moduli, pre-strains and applied strains.

References listed at the end of the paper:


Dian Yang (1,2), Bobak Mosadegh (1,3), Alar Ainla (1), Benjamin Lee (1), Fatemeh Khashai (1), Zhigang Suo (2,4), Katia Bertoldi (2,4) and George M. Whitesides (1,3,4)

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“Buckling of elastomeric beams enables actuation of soft machines”, Advanced Materials, 2015, DOI: 10.1002/adma.201503188

ABSTRACT: This article demonstrates the utility of a special type of non-linear behavior—the reversible, cooperative torsion, and collapse of a set of elastomeric beams (fabricated as one connected piece) under pressure. Understanding the motions exhibited in these systems started with observations and analyses by Boyce and co-workers of cooperative transformations in the shapes of patterns of through-holes cut into elastomeric slabs, on applying external pressure to these structures in the plane of the slab. Our work extends these studies, and greatly increases the ability of this kind of system, by using negative pressure (e.g., vacuum) applied to an elastomeric structure containing a number of elastic beams and interconnected, deformable cavities sealed within a thin elastomeric membrane. When negative pressure is applied, cooperative interactions among the components of the structure cause its elements (beams) to bend and buckle in ways that produce a range of useful motions. Buckling of materials is ordinarily considered an undesired mode of mechanical and structural failure, as it often causes permanent damage to structural components (e.g., metal frames, concrete pillars). The buckling of elastomeric materials, however, is reversible, and can provide useful new functions when designed properly. One such useful function is a rotary motion that provides a torque.

References listed at the end of the paper:

ABSTRACT: When a stiff film on a soft substrate is compressed, the surface of the film forms wrinkles, with tunable wavelengths and amplitudes that enable a variety of applications. As the compressive strain increases, the film undergoes post-wrinkling bifurcations, leading to period doubling and eventually to formation of localized folds or ridges. Here we study the post-wrinkling bifurcations in films on pre-stretched substrates. Through a combination of experiments and simulations, we demonstrate that pre-stretched substrates not only show substantial shifts in the critical strain for the onset of post-wrinkling bifurcations, but also exhibit qualitatively different post-wrinkled states. In particular, we report on the stabilization of wrinkles in films on pre-tensioned substrates and the emergence of ‘chaotic’ morphologies in films on pre-compressed substrates.
Subject to compression, elastic materials may undergo bifurcation of various kinds. A homogeneous material forms creases, whereas a bilayer consisting of a stiff film and a compliant substrate forms wrinkles. Here, we show several new types of bifurcation behavior for bilayers consisting of films and substrates of comparable elastic moduli. Depending on the ratios of moduli and thicknesses of the two materials, the critical strain for the onset of creases can be either smaller or larger than that for the onset of wrinkles. When the critical strain for the onset of creases is lower than that of wrinkles, creases can be subcritical or supercritical. When the critical strain for the onset of wrinkles is lower than that of creases, wrinkles can further channel to creases at a strain much lower than the critical strain for the onset of creases in a homogeneous material. Experiments, conducted with bilayer polydimethylsiloxane (PDMS) structures subject to compressive loading, show that the different types of bifurcation behavior agree with the theoretical
predictions.

References listed at the end of the paper:


ABSTRACT: Fingerprints (epidermal ridges) have been used as a means of identifications for more than 2000 years. They have also been extensively studied scientifically by anthropologists and biologists. However, despite all the empirical and experimental knowledge, no widely accepted explanation for the development of epidermal ridges on fingers, palms and soles has yet emerged. In this article we argue that fingerprint patterns are created as the result of a buckling instability in the basal cell layer of the fetal epidermis. Analysis of the well-known von Karman equations informs us that the buckling direction is perpendicular to the direction of greatest stress in the basal layer. We propose that this stress is induced by resistance of furrows and creases to the differential growth of the basal layer and regression of the volar pads during the time of ridge formation. These ideas have been tested by computer experiments. The results are in close harmony with observations. Specifically, they are consistent with the well-known observation that the pattern type is related to the geometry of the fingertip surface when fingerprint patterns are formed.

References listed at the end of the paper:
ABSTRACT: Cortical folding, characterized by convex gyri and concave sulci, has an intrinsic relationship to the brain's functional organization. Understanding the mechanism of the brain's convoluted patterns can provide useful clues into normal and pathological brain function. In this paper, the cortical folding phenomenon is interpreted both analytically and computationally, and, in some cases, the findings are validated with experimental observations. The living human brain is modeled as a soft structure with a growing outer cortex and inner core to investigate its developmental mechanism. Analytical interpretations of differential growth of the brain model provide preliminary insight into critical growth ratios for instability and crease formation of the developing brain. Since the analytical approach cannot predict the evolution of cortical complex convolution after instability, non-linear finite element models are employed to study the crease formation and secondary morphological folds of the developing brain. Results demonstrate that the growth ratio of the cortex to core of the brain, the initial thickness, and material properties of both cortex and core have great impacts on the morphological patterns of the developing brain. Lastly, we discuss why cortical folding is highly correlated and consistent by presenting an intriguing gyri-sulci formation comparison.

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ABSTRACT: Mechanical instabilities in soft materials, specifically wrinkling, have led to the formation of unique surface patterns for a wide range of applications that are related to surface topography and its dynamic tuning. In this progress report, two distinct approaches for wrinkle formation, including mechanical stretching/releasing of oxide/PDMS bilayers and swelling of hydrogel films confined on a rigid substrate with a depth-wise modulus gradient, are discussed. The wrinkling mechanisms and transitions between different wrinkle patterns are studied. Strategies to control the wrinkle pattern order and characteristic wavelength are suggested, and some efforts in harnessing topographic tunability in elastomeric PDMS bilayer wrinkled films for various applications, including tunable adhesion, wetting, microfluidics, and micro-lens arrays, are highlighted. The report concludes with perspectives on the future directions in manipulation of pattern formation for complex structures, and potential new technological applications.


ABSTRACT: Physically self-assembled microstructures can be realized by utilizing the stress relief process in buckling that usually leads to the formation of random wrinkles. This physical self-assembly occurs when the wrinkle formation is guided by a periodic pattern on an elastomeric mold that is simply placed on the surface of a bilayer of metal on polymer, which is then heated above its glass-transition temperature.

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Thin film encapsulated by elastomeric substrates in wrinkled powder coatings.

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Yan-Ping Cao, Bo Li and Xi-Qiao Feng (Institute of Biomechanics and Medical Engineering & Center for Nano and Micro Mechanics, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China),
ABSTRACT: Constrained swelling or shrinkage of such soft materials as elastomers, polymeric hydrogels, and biological tissues can create various surface patterns through surface wrinkling and subsequent morphological evolution. Here we study, both theoretically and numerically, the swelling-driven surface wrinkling and pattern evolution of cylindrical elastomers with core–shell structure. The results demonstrate that the system may buckle into different morphologies under different geometric and material parameters. When the swelling of the shell or the shrinkage of the core reaches a threshold, the cylindrical surface will first buckle into a periodically buckling pattern. With further swelling/shrinkage, wrinkle-to-fold transition may occur, rendering a period-doubling surface topography. The energetic mechanisms underlying this process of wrinkling pattern evolution are analyzed. This study not only benefits the understanding of the morphogenesis in soft materials and tissues (e.g., tumors), but also opens a new avenue for the fabrication of multi-periodic or aperiodic patterns on curved surfaces through self-organization.

Vishnesh Ranjan Kar, Nonlinear Thermoelastic Static Vibration and Buckling Behaviour of Functionally Graded Shell Panel. PhD thesis, Biju Patnaik Central Library, National Institute of Technology, Rourkela, Odisha, 2015 (Supervisor: Dr. Subrata Kumar Panda)

ABSTRACT: Functionally graded material (FGM) has created the interest of many researchers due to its tailor-made material properties. FGMs are the advanced form of composites that exhibit an inhomogeneous character especially designed for the high-temperature applications such as aircraft engines, rocket heat shields, thermal barrier coatings, heat exchanger tubes, etc. This material has been developed by taking the gradual variation of metal and ceramic constituents in a very efficient manner to suit the needs of the engineering structure. The effective material properties of the FGM follow the rule-based grading of two counterparts as discussed above, metals and ceramics. Shell structures made of FGMs are subjected to different kind of loading during their service life, and the structural responses (deformations, buckling/post-buckling, and linear/nonlinear natural frequencies) are affected considerably due to that. In this regard, a general nonlinear mathematical model has been developed for the FGM doubly curved shell panel using Green-Lagrange geometrical nonlinear kinematics in the framework of the higher-order shear deformation theory. The effective material properties of FGM shell panels are evaluated using Voigt’s micromechanical model via the power-law distribution. The material properties each constituent are assumed to be temperature-dependent. In addition, to achieve the true flexure of the structure, all the nonlinear higher-order terms are included in the mathematical model. The system governing equation of the FGM structure is obtained using the variational principle, and the direct iterative method is employed to compute the desired nonlinear responses in conjunction with suitable isoparametric finite element steps. The convergence behaviour of the proposed numerical model has been checked and validated further by comparing the responses with those available published literature. The linear and the nonlinear flexural, free vibration and the buckling responses of the FGM single/doubly curved shell panels are examined under thermo-mechanical loading. Finally, the effects of different geometrical and material parameters, support conditions, loading types on the deflection, frequency and critical buckling load parameter of the FGM single/doubly curved shell panels are examined and discussed in detail. This is also believed that the present study would be beneficial to the analysis and the design of FGM structure and/or structural component for real-life problems.

The following papers are prepared based on the work presented in the thesis:


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Alijani, F., Amabili, M., Karagiozis, K., Bakhtiari-Nejad, F. (2011a) Nonlinear vibrations of functionally graded doubly curved


Huang, H., Han, Q. (2010b). Nonlinear dynamic buckling of functionally graded cylindrical shells subjected to time-dependent axial load. Composite Structures 92:593–598.


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spherical shell panel, Steel and Composite


ABSTRACT: This work focuses on the static analysis of functionally graded (FGM) and laminated doubly-curved shells and panels resting on nonlinear and linear elastic foundations using the Generalized Differential Quadrature (GDQ) method. The First-order Shear Deformation Theory (FSDT) for the aforementioned moderately thick structural elements is considered. The solutions are given in terms of generalized displacement components of points lying on the middle surface of the shell. Several types of shell structures such as doubly-curved shells (elliptic and hyperbolic hyperboloids), singly-curved (spherical, cylindrical and conical shells), and degenerate panels (rectangular plates) are considered in this paper. The main contribution of this paper is the application of the differential geometry within GDQ method to solve doubly-curved FGM shells resting on nonlinear elastic foundations. The linear Winkler-Pasternak elastic foundation has been considered as a special case of the nonlinear elastic foundation proposed herein. The discretization of the differential system by means of the GDQ technique leads to a standard nonlinear problem, and the Newton-Raphson scheme is used to obtain the solution. Two different four-parameter power-law distributions are considered for the ceramic volume fraction of each lamina. In order to show the accuracy of this methodology, numerical comparisons between the present formulation and finite element solutions are presented. Very good agreement is observed. Finally, new results are presented to show effects of various parameters of the nonlinear elastic foundation on the behavior of
functionally graded and laminated doubly curved shells and panels.

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A.H. Sofiyev, N. Kuruoglu, Natural frequency of laminated orthotropic shells with different boundary conditions and resting on the Pasternak type elastic foundation, Compos. Part B Eng. 42 (2011), 1562–1570.


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E. Viola, F. Tornabene, N. Fantuzzi, DiQuMASPAB Software, DICAM Department, Alma Mater Studiorum—University of Bologna (http://software.dicam.unibo.it/diqumaspab-project).


ABSTRACT: The dynamic response of functionally graded skew shell is investigated using a C₀ finite element formulation. Reddy's higher order theory has been employed to perform the analysis and the volume fractions of the ceramic and metallic components are assumed to follow simple linear distribution law. The present study attempts to focus mainly on the influence of skew angle on frequency parameter and displacement of shell panel with various geometries. Comprehensive numerical results are demonstrated for cylindrical, spherical and hypar shells for different boundary conditions and skew angles. The findings obtained for functionally graded skew shell panels are new and can be used as benchmark for researchers in this field.

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Karson Brooks, Mir Jalil Razavi, Xianqiao Wang and Jason Locklin (Dept. of Chemistry, College of
Engineering and the Center for Nanoscale Science and Engineering, University of Georgia, Athens, Georgia 30602, USA), “Nanoscale surface creasing induced by post-polymerization modification”, NANO, Vol. xxx, No. xx, pp 000-000, 2015 or 2016 (in press), DOI: 10.1021/acs.nano.5b04144

ABSTRACT: Creasing in soft polymeric films is a result of substantial compressive stresses that trigger instability beyond a critical strain and have been directly related to failure mechanisms in different materials. However, it has been shown that programming these instabilities into soft materials can lead to new applications, such as particle sorting, deformable capillaries, and stimuli-responsive interfaces. In this work, we present a method for fabricating reproducible nanoscale surface instabilities using reactive microcontacting printing (μCP) on activated ester polymer brush layers of poly(pentafluorophenyl acrylate). The sizes and structures of the nanoscale creases can be modulated by varying the grafting density of the brush substrate and pressure applied during μCP. Stress is generated in the film under confinement due to the molecular weight increase of the side chains during post-polymerization modification, which results in substantial in-plane growth in the film and leads to the observed nanoscale creases.

References listed at the end of the paper:

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ABSTRACT: Although buckling instabilities in elastic solids have been known for a long time, high interest in this phenomenon is relatively recent. The current and prospective applications in flexible electronics, materials with tunable surface properties (adhesion and wettability), responsive photonic and phononic structures, and reinforced nanocomposites led to a surge in the interest in buckling instabilities. In fact, some of the applications, such as flexible electronics and metrology, have advanced at a tremendous pace only within the past few years. In this review, we discuss some of the most recent progress in the fundamental understanding of buckling instabilities in periodic multi-component polymer materials and porous polymer structures. We also discuss how the buckling can be localized to predetermined regions and hence form periodic instability patterns. Finally, we present several recent examples where buckling instabilities have been employed as a patterning tool to realize complex surface arrays of various materials.

ABSTRACT: Non-Euclidean plates are plates (“stacks” of identical surfaces) whose two-dimensional intrinsic geometry is not Euclidean, i.e., cannot be realized in a flat configuration. They can be generated via different mechanisms, such as plastic deformation, natural growth or differential swelling. In recent years there has been a concurrent theoretical and experimental progress in describing and fabricating non-Euclidean plates (NEP). In particular, an effective plate theory was derived and experimental methods for a controlled fabrication of responsive NEP were developed. In this paper we review theoretical and experimental works that focus on shape selection in NEP and provide an overview of this new field. We made an effort to focus on the governing principles, rather than on details and to relate the main observations to known mechanical behavior of ordinary plates. We also point out to open questions in the field and to its applicative potential.

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ABSTRACT: The mechanical deformation characteristics of living cells are known to influence strongly their chemical and biological functions and the onset, progression and consequences of a number of human diseases. The mechanics of the human red blood cell (erythrocyte) subjected to large deformation by optical tweezers forms the subject of this paper. Video photography of the cell deformed in a phosphate buffered saline solution at room temperature during the imposition of controlled stretching forces, in the tens to several hundreds picoNewton range, is used to assess experimentally the deformation characteristics. The mechanical responses of the cell during loading and upon release of the optical force are then analysed to extract the elastic properties
of the cell membrane by recourse to several different constitutive formulations of the elastic and viscoelastic behavior within the framework of a fully three-dimensional finite element analysis. A parametric study of various geometric, loading and structural factors is also undertaken in order to develop quantitative models for the mechanics of deformation by means of optical tweezers. The outcome of the experimental and computational analyses is then compared with the information available on the mechanical response of the red blood cell from other independent experimental techniques. Potential applications of the optical tweezers method described in this paper to the study of mechanical deformation of living cells under different stress states and in response to the progression of some diseases are also highlighted.

ABSTRACT: This paper conducts three-dimensional, nonlinear finite element analysis to investigate the results of using different solution methods and the influence of initial imperfections and material plasticity on failure modes and maximum load of various Z-shaped column lengths; it also compares the column buckling responses between various lengths, each with different initial imperfections. Further analyses include investigating the element suitability and computational costs. Results showed that both displacement control method and Riks method are fully capable of receiving promising results from this analysis. In terms of the effects of initial imperfection and material plasticity on the maximum load that column could carry, the imperfection is the major contributing factor when the column is long whereas the plasticity is the major contributing factor when the column is short.

ABSTRACT: In this paper it has been shown that the buckling strength of Columns may be evaluated by a function of ultimate stress, which is obtained by using Limit Analysis Method to analyse the function of bending moment resulted from the axial compressive forces and transverse load acting on the columns. Because of the effects of column's initial deflection and the nonlinear relationship between stress and strain on the bending moment are accounted for in this paper by some proper mathematical-physical parameters, therefore the ultimate stress function established on the basis of strength point of view can illustrate the buckling problem of columns more simply and completely than classical theory of stability. In this paper the ultimate stress function is expressed in nondimensional form, so it may be used as principle of model experiment to evaluate the stability of various structures, such as beams, plates, cylindrical and spherical shells and etc. The good agreement between the experimental data of spherical shells and the nondimensional ultimate stress demonstrates that the difficulty in evaluating stability of spherical shells, which exists in classical theory of stability for a long time, may be solved.

Bantle, S. (Gesellschaft fuer Technisch Orientiertes Rechnen m.b.H. (TOR), Nuernberg (Germany, F.R.)); Calli, H.; Jeschke, J. (Kraftwerk Union A.G., Offenbach am Main (Germany, F.R.), “Local stability at nozzles in spherical shells subjected to bending moments and axial forces”, Seventh International Seminar on Computational Aspects of the Finite Element Method (CAFEM-7) in conjunction with the Seventh International Conference on Structural Mechanics in Reactor Technology (SMiRT-7), Chicago, IL, USA, 22-26 August, 1983
ABSTRACT: The stability of spherical shells including nozzles and reinforced rounds has been investigated theoretically for the loading external force and overturning moment. Limit loads have been established for several geometries emphasizing the overturning moment.


ABSTRACT: In this paper an elastic stability analysis has been developed for spherical shell segments with fixed or horizontally removable edges. The shells are subjected to external hydrostatic pressure or the combination load, namely, hydropressure and frictional resistance. And when these forces act nonconservatively on the surfaces of the shells. It is shown, the dynamic (flutter type) instabilities as well as static (divergence type) instabilities often take place. The authors consider that these analytical results give some contributions to the study of elastic shell stability.

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ABSTRACT: The dynamic buckling behavior of a complete spherical shell made of a bilinear or work-hardening material and under a uniform external impulsive loading is investigated. A quasi-bifurcation theory and a minimum principle are employed to determine, respectively, the onset of the dynamic buckling process and the post-bifurcation nonlinear behavior. Numerical results are obtained for a number of elastic and elastic-plastic cases. The results indicate there is a softening effect in the plastic deviated stress-strain relationship which makes the spherical shell less stable. Furthermore, the higher order terms in stress and strain measures and the coupling of symmetric and asymmetric modes of motion cannot be neglected in the post-bifurcation analysis.

ABSTRACT: In this paper, a theory for large deflection of symmetrically laminated composite cylindrically orthotropic shallow spherical shells including transverse shear is proposed. The nonlinear stability of the symmetrically laminated cylindrically orthotropic shallow spherical shell with a rigidly clamped edge under the action of a uniform pressure is studied by the modified iteration method. The analytic solution for critical loads of the shell is obtained, and it can be applied directly to engineering.

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ABSTRACT: Thin shells are prone to fail by buckling. In most of the practical situations, shell structures have membrane stresses as well as bending stresses and the response of these shells becomes nonlinear. Linearization of the nonlinear equilibrium equations gives rise to an algebraic eigenvalue problem, solving which, buckling load is obtained. Eigenvalue buckling analysis is computationally much cheaper than nonlinear analysis involving tracing the load-deflection path and finding the corresponding collapse load. But buckling loads obtained by eigenvalue buckling analysis are always overestimated, and for systems with large prebuckling rotations this approach may give highly unconservative results. For better prediction of the actual buckling load of a structure, a new methodology involving the proper combination of eigenvalue buckling analysis and geometric nonlinear analysis is used here. This method is computationally cheaper than nonlinear buckling analysis but more reliable than linear buckling analysis. The methodology is used to calculate the buckling load of shells of revolution. The conical frustum shell element with two nodal circles is used in the present study. Also discussed is how to include the effect of initial geometric imperfection in buckling analysis.

ABSTRACT: The nonlinear stability of composite conical shell under external pressure was studied. The Donnell type governing equations were developed for general anisotropic composite conical shells. The partial differential equations with variable coefficients were changed into differential equations with constant coefficients by means of selecting appropriate displacement function and changing coordinate system which can be solved easily. The stress functions were strictly deduced from compatible equations by the displacement function selected. The stability of orthotropic composite conical shell under external pressure was calculated by means of Galerkin method and the formulas were obtained for the post buckling equilibrium displacement figure curves.

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ABSTRACT: Conical steel shells are fairly widely used as elevated water tanks. However, the current code of practice in North America for the design of such reservoir structures provides an obsolete method for
ascertaining their adequacy to resist hydrostatic loadings. Moreover, there are no provisions available for handling liquid-filled conical tanks subjected to seismic forces. The lack of appropriate design methods could not have been demonstrated more vividly when in December of 1990, an elevated conical water tower failed by buckling when being filled for the first time. The steel vessel, located in Fredericton, New Brunswick, is claimed to have "exploded" by eyewitnesses. The work of this thesis, then, was motivated by this failure. It involves non-linear stability analysis of liquid-filled conical steel vessels possessing geometric imperfections and residual stresses, and which can be subjected to hydrostatic and seismic loading. To achieve this, a finite element formulation is developed based on a consistent shell element which is free from spurious shear modes known to exist in the isoparametric shell elements. The consistent shell element employed also exhibits excellent performance in the analysis of plates and shells in the small displacement range. This element is extended to include both geometric and material non-linearities as well as non-linear dynamic analysis. The non-linear finite element model developed is general and can be applied to any thin or thick shell problem. Numerical testing of the non-linear model through static and dynamic analysis of different plate and shell problems indicates the continued excellent performance of the consistent shell element in the non-linear range. Hydrostatically loaded conical steel vessels are modelled using the consistent shell element. Static stability analyses of conical shells with different geometric imperfection patterns are undertaken and the results indicate that the presence of axisymmetric imperfections leads to the lowest limit load for the structure. The sensitivity of the hydrostatically loaded conical vessels to geometric imperfections and residual stresses is investigated by considering three cases: (i) analysis of perfect vessels, (ii) same as case (i) but with axisymmetric geometric imperfections of the order of the thickness of the shell, (iii) same as case (ii) but with the addition of residual stresses due to welding. The results from these analyses indicate that the liquid-filled conical shells are significantly sensitive to geometric imperfections, and that yielding precedes elastic buckling for tanks having practical dimensions. The non-linear dynamic (stability) analysis of elevated liquid-filled conical vessels subjected to both horizontal and vertical accelerations, but free from rocking motion, is then considered. The boundary integral method is used to formulate the fluid added-mass matrix resulting from the impulsive component of the hydrodynamic pressure. This is added to the mass matrix of the shell structure to perform free vibration as well as nonlinear time history analyses for elevated liquid-filled conical tanks treated as either perfect or axisymmetrically imperfect. Tanks with different dimensions and imperfection levels are subjected to an appropriately scaled real input ground motion. Some of these elevated structures exhibit inelastic behaviour and generally develop a localized buckle near the bottom of the vessel which leads to the overall instability of the structure. In general, time history analyses indicate that liquid-filled conical tanks, often possessing apparently adequate safety factors under hydrostatic loading, may not be safe under seismic loading. Therefore, a proper modelling procedure along with time dependent analysis must be followed in order to design such tanks safely. The finite element model developed in this thesis is a means provided for such a purpose.
imperfection patterns are undertaken, and the results indicate that the presence of axisymmetric imperfections leads to the lowest limit load for the structure. The sensitivity of the hydrostatically loaded conical vessels to geometric imperfections and residual stresses is investigated by considering inelastic analyses of three cases: (1) perfect vessels; (2) same as case 1, but with axisymmetric geometric imperfections of the order of the thickness of the shell; and (3) same as case 2, but with the addition of residual stresses due to welding. Results of these analyses indicate that liquid-filled conical shells are quite sensitive to geometric imperfections and that yielding precedes elastic buckling for tanks having practical dimensions.

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ABSTRACT: Conical steel shells are widely used as water containments for elevated tanks. However, the current codes for design of water structures do not specify any procedure for handling the seismic design of such structures. In this paper, a numerical model is developed for studying the stability of liquid-filled conical tanks subjected to seismic loading. The model involves a previously formulated consistent shell element with geometric and material non-linearities included. A boundary element formulation is derived to obtain the hydrodynamic pressure resulting from both the horizontal and the vertical components of seismic motion acting on a conical tank which is prevented from rocking. The boundary element formulation leads to a fluid added-mass matrix which is incorporated with the shell element formulation to perform non-linear dynamic stability analysis of such tanks subjected to both horizontal and vertical components of ground motion. Although, the formulation was developed for conical vessels, it is general and can be easily modified to study the stability of any liquid-filled shell of revolution subjected to seismic loading. The accuracy of fluid added-mass formulation was verified by performing the free vibration analysis of liquid-filled cylindrical tanks and comparing the results to those available in the literature.

ABSTRACT: The buckling of laminated composite shells subjected to transverse load is investigated. The geometrical non-linear analysis is carried out using the finite element method based on a higher-order shear deformation theory. An eight noded degenerated isoparametric shell element with nine degrees of freedom at each node is considered. The geometric non-linear behaviour and the collapse pressures with the associated mode shapes are presented for simply supported symmetrically and anti-symmetrically laminated spherical shell panels subjected to uniform normal pressure.

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“Buckling Load Characteristic of Conical Shells under Various End Conditions”, 17th Annual Conference of
Mechanical Engineering Network of Thailand, 15-17 October 2003, Prachinburi, Thailand

ABSTRACT: This paper is aimed to investigate the buckling load characteristic of conical shells subjected to axial loading. It was focused on the effect of end conditions, which are believed to promote the buckling resistance of structures. The study was carried out by means of experiment and structural model (FEA). The experimental result was, then, compared with the FEA and good agreement was achieved. The result suggested the strength of conical shells may be enhanced by constraining at the end. Particularly, the top constrained cones provide considerable high strength improvement (3%-10%).

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ABSTRACT: The axisymmetric nonlinear stability of a shallow conical shell with a spherical cap was studied using the point collocation method with the cubic B-spline function as a trial function. Formulas were set up to consider arbitrary variable shell thickness and different boundary and loading conditions. A FORTRAN program was written to determine the critical loads and trace the stable parts of the equilibrium paths of the shell by method of gradually applied load. The upper and lower critical loads obtained in this technical note for some specific cases with constant shell thickness are of very good accuracy and agree very well with known solutions and finite-element method results. The method was then expanded successfully to arbitrary variable shell thickness and different boundary and loading conditions.


ABSTRACT: Thermal buckling and free vibration analyses of multi-layered composite conical shells based on a layerwise displacement theory are performed. The Donnell’s displacement-strain relationships of conical shell structure are applied. The natural frequencies are compared with the ones existing in the previous literature for laminated conical shells with several cone semi-vertex angles. Moreover, the thermal buckling behaviors of the laminated conical shell are investigated to consider the effect of the semi-vertex angle, subtended angle, and radius to thickness ratio on the structural stability.


ABSTRACT: The vaulted roofs of oil storage tank are usually designed as shallow spherical shells subjected to external pressure, and have been widely observed that these shallow spherical shells undergo varying degrees of corrosion in service periods. It is important to assessment the stability of these local thinned shallow spherical roofs due to corrosion for preventing them from occurring unexpected buckling failure. In this paper, the uniform eroded part of a shallow spherical oil tank vaulted roof is simplified as a shallow spherical shell with elastic supports. Based on the simplification, a general approach to compute critical pressure of eroded shallow spherical shell is proposed. The modified iteration method that considers the large deformation of shell is used to solve the problem of nonlinear stability of the shallow spherical shells, and then a second-order approximate analytical solution is obtained. The critical pressure calculated by this method is consistent with the classical numerical results and nonlinear finite element method, and the computing errors are less than 10%. It shows that the presented method is feasible.

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imperfections in the column specimens and the test rig. At the shortest column height, the onset of local
behaviour of such members is investigated to provide a basis for future assessment of de

ABSTRACT: We discuss the stability of icosadeltahedral shells subjected to a uniform external load in the form of an isotropic pressure. We demonstrate that there exists a universal critical buckling pressure scaling form that defines a locus of buckling instabilities. The parameter that uniquely determines this scaling form is shown to be the Föppl–von Karman number of nonpressurized shells. Numerical results are interpreted in terms of scaling forms for buckling instabilities of spheres and cylinders under isotropic mechanical pressure, and are applied to the case of viruses under osmotic pressure.

References listed at the end of the paper:

8. We contrast outward buckling in the LMN case, thus without any external forcing, with inward buckling that we analyze here, in the presence of external isotropic pressure acting on the shell. We refer to the latter also simply as buckling, where the meaning is clear and there is no possibility of confusion.


ABSTRACT: This paper concerns polymeric composite columns manufactured by the pultrusion process. The behaviour of such members is investigated to provide a basis for future assessment of design methods. The minor-axis buckling characteristics of twelve wide-flange columns are presented. The main parameters varied are height (6·3 m, 4·8 m and 3·3 m) and nominal cross-sectional dimensions (152 × 152 × 9·53 mm, 203 × 203 × 9·53 mm and 203 × 203 × 12·7 mm). Deformation and failure characteristics are presented. It is found that theoretical Euler critical buckling loads generally correlate well with maximum test loads and critical loads derived from Southwell plots. A detailed discussion is presented to show that differences are due to imperfections in the column specimens and the test rig. At the shortest column height, the onset of local
compression flange buckling is found to lower resistance by way of modal-coupling with the global bending deformation.


ABSTRACT: In practice, large diameter, thin wall shells of revolution are never fabricated with constant diameters and thicknesses over the entire length of the assembly. These initial geometric imperfections have significant effect on the load carrying capacity of cylindrical shells. The cylindrical shell in the study is flue gas desulphurization (FGD) “vessel” which is a large hybrid tank-vessel-stack assembly in a major Canadian refinery. The function of the FGD vessel is to contain and support a proprietary process that utilizes an ammonium sulphate scrubbing system to produce environmentally friendly air emissions. FGD vessel stack has internal diameter of 6.1m, height of 45.34m and wall thickness of 9.525mm. Initial imperfections in FGD vessel is in the form of wall thickness variations. FGD wall thickness at 144 points along the circumference and elevation are measured. Monte Carlo method is employed to generate the measured data again. Test of significance is carried out to see the accuracy of the data generated. This Monte Carlo algorithm can be used to create data for any type of shell without spending time in actual measurements. Next, load carrying capacity of shell is determined considering imperfections to be axisymmetric and then asymmetric. Fourier decomposition is used to interpret imperfections as structural features can be easily related to the different components of imperfections. Further, double Fourier series is used to represent asymmetric initial geometric imperfections. The ultimate objective of these representations is to achieve a quantitative assessment of the critical buckling load considering the small axisymmetric and asymmetric deviations from the nominal cylindrical shell wall thickness. Analysis of cylindrical shells when used as pressure vessels and are under external pressure is also carried out. Comparison of reliability techniques that employ Fourier series representations of random axisymmetric and asymmetric imperfections in axially compressed cylindrical shells and shells under external pressure with evaluations prescribed by ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2 is also carried out.

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ABSTRACT: The uncertainty of geometric imperfections in a series of nominally equal I-beams leads to a variability of corresponding buckling loads. Its analysis requires a stochastic imperfection model, which can be derived either by the simple variation of the critical Eigenmode with a scalar random variable, or with the help of the more advanced theory of random fields. The present paper first provides a concise review of the two different modeling approaches, covering theoretical background, assumptions and calibration, and illustrates their integration into commercial finite element software to conduct stochastic buckling analyses with the Monte Carlo method. The stochastic buckling behavior of an example beam is then simulated with both stochastic models, calibrated from corresponding imperfection measurements. The simulation results show that for different load cases, the response statistics of the buckling load obtained with the Eigenmode based and the random field based models agree very well. A comparison of our simulation results with corresponding
Eurocode 3 limit loads indicates that the design standard is very conservative for compression dominated load cases.

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ABSTRACT: Presented are results from geometric non-linear finite element analyses to examine the lateral torsional buckling (LTB) resistance of a Pultruded fibre reinforced polymer (FRP) I-beam when initial geometric imperfections associated with the LTB mode shape are introduced. A data reduction method is proposed to define the limiting buckling load and the method is used to present strength results for a range of beam slendernesses and geometric imperfections. Prior to reporting on these non-linear analyses, Eigenvalue FE analyses are used to establish the influence on resistance of changing load height or displacement boundary conditions. By comparing predictions for the beam with either FRP or steel elastic constants it is found that the former has a relatively larger effect on buckling strength with changes in load height and end warping fixity. The developed finite element modelling methodology will enable parametric studies to be performed for the development of closed form formulae that will be reliable for the design of FRP beams against LTB failure.


ABSTRACT: An experimental and analytical research on shear buckling of a comparably large polymer composite I-section is presented. It is known that shear buckling load of a large span composite beam is difficult to determine experimentally. In order to sensitively detect shear buckling of the tested I-section, twenty strain rosettes and eight displacement sensors were applied and attached on the web and flange surfaces. The tested specimen was a pultruded composite beam made of vinylester resin, E-glass, carbon fibers and micro-fillers. Various coupon tests were performed before the shear buckling test to obtain fundamental material properties of the I-section. An asymmetric four-point bending loading scheme was utilized for the shear test. The loading scheme resulted in a high shear and almost zero moment condition at the center of the web panel. The shear buckling load was successfully determined after analyzing the obtained test data from strain rosettes and displacement sensors. An analytical approach was also performed to verify the experimental results and to support the discussed experimental program.

References listed at the end of the paper:

ABSTRACT: Electrostatic properties and stability of charged virus-like nano-shells are examined in ionic solutions with monovalent and multivalent ions. A theoretical model based on a thin charged spherical shell and multivalent ions within the "dressed multivalent ion" approximation, yielding their distribution across the shell and the corresponding electrostatic (osmotic) pressure acting on the shell, is compared with extensive implicit Monte-Carlo simulations. It is found to be accurate for positive or low negative surface charge densities of the shell and for sufficiently high (low) monovalent (multivalent) salt concentrations. Phase diagrams involving electrostatic pressure exhibit positive and negative values, corresponding to an outward and an inward facing force on the shell, respectively. This provides an explanation for the high sensitivity of viral shell stability and self-assembly of viral capsid shells on the ionic environment.


ABSTRACT: The inorganic analogs of carbon fullerenes and nanotubes, like MoS2 and BN, are reviewed. It is
argued that nanoparticles of 2D layered compounds are inherently unstable in the planar configuration and prefer to form closed cage structures. The progress in the synthesis of these nanomaterials, and, in particular, the large-scale synthesis of BN, WS2 and V2O5 nanotubes, are described. Some of the electronic, optical and mechanical properties of these nanostructures are reviewed. The red-shift of the energy gap with shrinking nanotube diameter is discussed as well as the suggestion that zigzag nanotubes exhibit a direct gap rather than an indirect gap, as is prevalent in many of the bulk 2D materials. Some potential applications of these nanomaterials are presented as well, most importantly the superior tribological properties of WS2 and MoS2 nested fullerene-like structures (onions).

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ABSTRACT: Recent findings of linear carbon-atom chains (C-chains) inside carbon nanotubes have stimulated considerable interest. In this work, molecular dynamics (MD) simulation and an elastic string–elastic shell model is adopted to study radial pressure-induced buckling of single-walled carbon nanotubes (SWCNT) filled with a C-chain. The continuum model predicts that the C-chain increases critical buckling pressure considerably (about 40%–160%) for SWCNTs of diameters ranging from 0.68 to 0.72 nm, in reasonable quantitative agreement with the prediction of MD simulation. In particular, the MD simulation confirms that the originally circular cross section of filled SWNTs becomes elliptical after buckling, as predicted by the continuum model.

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ABSTRACT: The deformation of thin spherical shells by applying an external pressure or by reducing the volume is studied by computer simulations and scaling arguments. The shape of the deformed shells depends on the deformation rate, the reduced volume V/V0 and the Foppl-von Karman number gamma. For slow deformations the shell attains its ground state, a shell with a single indentation, whereas for large deformation rates the shell appears crumpled with many indentations. The rim of the single indentation undergoes a shape transition from smooth to polygonal for gamma approximately 7000(deltaV/V0)^(-3/4). For the smooth rim the elastic energy scales like gamma^(1/4) whereas for the polygonal indentation we find a much smaller exponent, even smaller than the exponent 1/6 that is predicted for stretching ridges. The relaxation of a shell with multiple indentations towards the ground state follows an Ostwald ripening type of pathway and depends on the compression rate and on the Foppl-von Karman number. The number of indentations decreases as a power law with time t following ….(formula with lots of symbols and powers).
References listed at the end of the paper:
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[31] von Kármán Th and Tsien H-S 1939 The buckling of spherical shells by external pressure J. Aeronaut. Sci. 7 43-50
[34] Gompper G and Kroll D M 1997 Network models of fluid, hexatic and polymerized membranes J. Phys.: Condens. Matter. 9 8795-834
[41] Vliegenthart G A and Gompper G 2006 Mechanical deformation of spherical viruses with icosahedral symmetry Biophys. J. 91 834-41


ABSTRACT: We studied the elastic properties and mechanical stability of viral capsids under external force-loading with computer simulations. Our approach allows the implementation of specific geometries corresponding to specific phages, such as φ29 and cowpea chlorotic mottle virus. We demonstrate how, in a combined numerical and experimental approach, the elastic parameters can be determined with high precision. The experimentally observed bimodality of elastic spring constants is shown to be of geometrical origin, namely the presence of pentavalent units in the viral shell. We define a criterion for capsid breakage that explains well the experimentally observed rupture. From our numerics we find a crossover from $\gamma^{2/3}$ to $\gamma^{1/2}$ for the dependence of the rupture force on the Föppl-von Kármán number, $\gamma$. For filled capsids, high internal pressures lead to a stronger destabilization for viruses with buckled ground states versus viruses with unbuckled ground states. Finally, we show how our numerically calculated energy maps can be used to extract information about the strength of protein–protein interactions from rupture experiments.


ABSTRACT: A series of hollow biodegradable polymeric microcapsules were prepared, of which their susceptibility to ultrasound was used for triggered release. High speed imaging of the ultrasound experiments showed a strong correlation between the acoustic pressure needed to activate these microcapsules and their shell
thickness to diameter ratio. Based on this information a selective triggering of capsules with two different shell thickness to diameter ratios was successfully performed. The capsules were mixed in a single system and were activated independently from each other by a differentiation in acoustic pressure levels. This application is of great interest in the field of drug delivery, since this system allows for localized multiple drug releases in a selective fashion.

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ABSTRACT: The localization of deformation is a simple consequence of the fact that bending a thin sheet is energetically cheaper than stretching it. Thus, on examining a crumpled piece of paper, we find that it is made of nearly-planar or cylindrically curved regions folded along line-like stretched ridges or point-like conical singularities. Since the real crumpled paper problem is fairly difficult to deal with, we investigate two simple model experiments where one or two singularities are isolated and studied. When a cylindrical panel is axially compressed, a crease terminated by two conical type singularities appears. The length of this crease is selected by the width of the panel when the length and the thickness of the panel are kept constant. We study also a single conical singularity. This is achieved by pushing a thin sheet into a hollow cylinder similar to pushing coffee-filter paper in a funnel. We measured the singularity energy of the plate, or the work required to form a scar in the sheet. A simple model is proposed to understand the energetics of the crease formation.

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ABSTRACT: Forced crumpling of stiff self-avoiding sheets is studied by discrete element simulations. Simulations display stress condensation and scaling of ridge energy in agreement with theoretical expectations for elastic and frictionless sheets, and extends such behavior to elasto-plastic sheets. Crumpling of ideally elastic and frictionless sheets is compared to that of elasto-plastic sheets and sheets with friction.


ABSTRACT: When a thin elastic sheet crumple’s, the elastic energy condenses into a network of folding lines and point vertices. These folds and vertices have elastic energy densities much greater than the surrounding areas, and most of the work required to crumple the sheet is consumed in breaking the folding lines or “ridges.” To understand crumpling it is then necessary to understand the strength of the ridges. In this work, we consider
the buckling of a single ridge under the action of inward forcing applied at its ends. We demonstrate a simple scaling relation for the response of the ridge to the force prior to buckling. We also show that the buckling instability depends only on the ratio of strain along the ridge to the curvature across it. Numerically, we find for a wide range of boundary conditions that ridges buckle when our forcing increases their elastic energy by 20% over their resting state value. We also observe a correlation between neighbor interactions and the location of initial buckling. Analytic arguments and numerical simulations are employed to prove these results. Implications for the strength of ridges as structural elements are discussed.

References listed at the end of the paper:
REFERENCES listed at the end of the paper:

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DOI: 10.1103/PhysRevLett.90.074302

ABSTRACT: The wrinkling of thin elastic sheets occurs over a range of length scales, from the fine scale patterns in substrates on which cells crawl to the coarse wrinkles seen in clothes. Motivated by the wrinkling of a stretched elastic sheet, we deduce a general theory of wrinkling, valid far from the onset of the instability, using elementary geometry and the physics of bending and stretching. Our main result is a set of simple scaling laws; the wavelength of the wrinkles \( \lambda \) approximately \( K^{-1/4} \), where \( K \) is the stiffness due to an "elastic substrate" effect with a multitude of origins, and the amplitude of the wrinkle \( A \) approximately \( \lambda \). These could form the basis of a highly sensitive quantitative wrinkling assay for the mechanical characterization of thin solid membranes.

ABSTRACT: Subject to a compressive membrane force, a film bonded to a compliant substrate often forms a pattern of wrinkles. This paper studies such wrinkles in a layered structure used in several recent experiments. The structure comprises a stiff film bonded to a compliant substrate, which in turn is bonded to a rigid support. Two types of analyses are performed. First, for sinusoidal wrinkles, by minimizing energy, we obtain the wavelength and the amplitude of the wrinkles for substrates of various moduli and thicknesses. Second, we develop a method to simultaneously evolve the two-dimensional pattern in the film and the three-dimensional elastic field in the substrate. The simulations show that the wrinkles can evolve into stripes, labyrinths, or herringbones, depending on the anisotropy of the membrane forces. Statistical averages of the amplitude and wavelength of wrinkles of various patterns correlate well with the analytical solution of the sinusoidal wrinkles.


ABSTRACT: The radial stretching of a hollow thin membrane without compressive strength is considered within the framework of the small strain tension field theory. For each type of the uniform boundary conditions, the loading plane is partitioned into the domains of biaxial tension, tension field and buckling. The extent of these domains critically depends on the value of the Poisson’s coefficient and on the aspect ratio of the membrane. The stress and displacement fields are determined at an arbitrary stage of loading, when the outer biaxially stressed (taut) annulus surrounds the inner (tension field) portion of the membrane, characterized by continuously distributed infinitesimal wrinkles. The growth of the tension field as the loading increases is analyzed. It is shown that, depending on the Poisson’s coefficient and the aspect ratio of the membrane, the tension field may or may not spread throughout the whole membrane. For the fixed outer boundary, and the applied tension or a negative displacement at the inner boundary, and for a particular combination of the material and geometric parameters, the tension field instantly spreads to a specific depth within the membrane, dependent on the Poisson’s ratio and the outer radius of the membrane, remaining constant during further increase of the loading.

References listed at the end of the paper:
ABSTRACT: The wrinkled geometry of thin films is known to vary appreciably as the applied stresses exceed their buckling threshold. Here we derive and analyze a minimal, nonperturbative set of equations that captures the continuous evolution of radial wrinkles in the simplest axisymmetric geometry from threshold to the far-from-threshold limit, where the compressive stress collapses. This description of the growth of wrinkles is different from the traditional post-buckling approach and is expected to be valid for highly bendable sheets. Numerical analysis of our model predicts two surprising results. First, the number of wrinkles scales anomalously with the thickness of the sheet and the exerted load, in apparent contradiction with previous predictions. Second, there exists an invariant quantity that characterizes the mutual variation of the amplitude and number of wrinkles from threshold to the far-from-threshold regime.


ABSTRACT: (none given)

List of references at the end of the paper:


Karamanos SA, Tassoulas JL (Dept. of Civil Engineering, University of Texas at Austin). Tubular members I:

ABSTRACT: This paper presents a finite-element technique for the analysis of tubular member stability under combined external pressure and structural loads. A tube element is developed for the purposes of this research. While polynomial (quadratic) interpolation is used in the longitudinal direction, Fourier series expansions of the displacement components are adopted at the nodal cross sections. The formulation accounts for large inelastic deformation and recognizes initial imperfections and residual stresses. To trace unstable equilibrium paths, arc-length procedures are implemented. A simple, yet effective estimate of the contribution of external pressure to the tube element stiffness matrix, particularly significant in the analysis of slender tubes, is included. Preliminary results regarding the behavior of tubular members subjected to pressure and bending are reported and discussed. The effects of initial imperfections and residual stresses on the response to pressure along with bending are summarized. Finally, the influence of residual stresses on thrust-moment interaction in tubular beam-columns is examined briefly.


ABSTRACT: The present paper examines instabilities of long thin elastic tubes. Both initially straight and initially bent tubes are analyzed under in-plane bending. Tube response, a combination of ovalization instability and bifurcation instability (buckling), is investigated using a nonlinear finite element (FE) technique, which employs polynomial functions in the longitudinal tube direction and trigonometric functions to describe cross-sectional deformation. It is demonstrated that the interaction between the two instability modes depends on the value and the sign of the initial tube curvature. The ovalization of initially bent tubes is examined in detail and, in particular, the case of opening moments. Furthermore, the paper emphasizes on bifurcation instability. It is shown that buckling may occur prior to or beyond the ovalization limit point, depending on the value of the initial curvature. Using the nonlinear FE formulation, the location of bifurcation on the primary path is detected, post-buckling equilibrium paths are traced, and the corresponding wavelengths of the buckled configurations are calculated. Moreover, results over a wide range of initial curvature values are presented, extending the findings of previous works. Finally, several analytical approaches, introduced in previous research works, are also employed to estimate the moments causing ovalization and bifurcation instability. These approaches are based on nonlinear flexible shell theory or simplified ring analysis. The efficiency and accuracy of those analytical methods with respect to the nonlinear FE formulation are examined.

N. Silvestre and D. Camotim, “Vibration behaviour of axially compressed cold-formed steel members”, Steel and Composite Structures, Vol. 6, No. 3, pp 221-236, 2006

ABSTRACT: (Cannot cut and paste it)

N. Silvestre and D. Camotim (University of Lisbon), “Bending instabilities of carbon nanotubes”, Chapter in book that is not identified in the pdf file, January 2009, DOI: 10.1007/978-3-642-00980-8_49

ABSTRACT: This paper presents an investigation on the buckling behaviour of single-walled carbon nanotubes (NTs) under bending and unveils several aspects concerning the dependence of critical bending curvature on the NT length. The buckling results are obtained by means of non-linear shell finite element analyses using ABAQUS code. It is shown that eigenvalue analyses do not give a correct prediction of the critical curvature of NTs under bending. Conversely, incremental-iterative non-linear analyses provide a better approximation to the
molecular dynamics results due to the progressive ovalization of the NT cross-section under bending. For short NTs, the limit curvature drops with the increasing length mostly due to the decreasing influence of end effects. For moderate to long tubes, the limit curvature remains practically constant and independent on the tube length. An approximate formula based on the Brazier expression is proposed to predict the limit curvature.

References listed at the end of the paper:


Evangelos Giakoumatos (Dept. of Mechanical Engineering, University of Thessaly, Greece), “Nonlinear finite element analysis of steel pipe elements under pressure and bending”, Diploma Thesis, July 2002

ABSTRACT: The work investigates the response of elbows under in-plane bending and pressure, through nonlinear finite element tools, supported by experimental results from real-scale tests. The finite element analysis is mainly based on a nonlinear three-node "tube element", capable of describing elbow deformation in a rigorous manner, considering geometric and material nonlinearities. Furthermore, a nonlinear shell element from a general-purpose finite element program is employed in some special cases. Numerical results are compared with experimental data from steel elbow specimens. The comparison allows the investigation of important issues regarding deformation and ultimate capacity of elbows, with emphasis on relatively thin-walled elbows. The results demonstrate the effects of pressure and the influence of straight pipe segments. Finally, using the numerical tools, failure of elbows under bending moments is examined (cross-sectional flattening or local buckling), and reference to experimental observations is made.

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ABSTRACT: The paper investigates the response of elbows under in-plane bending and pressure, through nonlinear finite element tools, supported by experimental results from real-scale tests. The finite element analysis is mainly based on a nonlinear three-node "tube element," capable of describing elbow deformation in a rigorous manner, considering geometric and material nonlinearities. Furthermore, a nonlinear shell element from a general-purpose finite element program is employed in some special cases. Numerical results are compared with experimental data from steel elbow specimens. The comparison allows the investigation of important issues regarding deformation and ultimate capacity of elbows, with emphasis on relatively thin-
walled elbows. The results demonstrate the effects of pressure and the influence of straight pipe segments. Finally, using the numerical tools, failure of elbows under bending moments is examined (cross-sectional flattening or local buckling), and reference to experimental observations is made.

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ABSTRACT: The paper examines the nonlinear elastic-plastic response of internally pressurized 90 deg pipe elbows under in-plane and out-of-plane bending. Nonlinear shell elements from a general-purpose finite element program are employed to model the inelastic response of steel elbows and the adjacent straight parts. The numerical results are successfully compared with real-scale experimental measurements. The paper also presents a parametric study, aimed at investigating the effects of diameter-to-thickness ratio and moderate pressure levels on the ultimate bending capacity of 90 deg elbows, focusing on the failure mode (local buckling or cross-sectional flattening) and the maximum bending moment. Special attention is given to the response of 90 deg elbows under out-of-plane bending moments.

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ABSTRACT: Mechanical damage in steel pipelines in the form of local buckles due to excessive bending deformation may severely threaten their structural integrity. The present paper describes experimental and numerical research conducted to assess the structural condition of buckled pipes, subjected to both bending and internal pressure. Fatigue failure under repeated loading is mainly investigated, whereas pipe burst due to internal pressure is also examined. Three full-scale buckled pipe specimens are tested under pressure and bending loads to determine their structural capacity. In addition, using nonlinear finite element tools, an extensive parametric study is conducted to determine the critical locations at the buckled area at which maximum strain variation occurs, as well as to investigate the influence of several geometrical and mechanical parameters. Using the maximum strain range from the finite element computations and a simple S-N approach, reasonable predictions are obtained for the number of cycles to failure observed in the tests. The results of the present study demonstrate that, under repeated loading, fatigue failure occurs in the buckled area at the location of maximum strain range. It is also found that the burst pressure may not be affected by the presence of buckles.

SUMMARY: The research examines instabilities of long pressurized thin elastic tubes. The material is isotropic or transversely-isotropic, and it is modeled through a hypo-elastic constitutive equation. Both initially straight and initially bent tubes are analyzed under in-plane bending and pressure. Tube response, a combination of
ovalization instability and bifurcation instability (buckling), is investigated using a nonlinear finite element technique, which employs polynomial functions in the longitudinal tube direction and trigonometric functions to describe cross-sectional deformation. It is demonstrated that the interaction between the two instability modes depends on the value and the sign of the initial tube curvature. The work emphasizes on bifurcation instability. It is shown that buckling may occur prior to or beyond the ovalization limit point, depending on the value of the initial curvature. Using the nonlinear finite element formulation, the location of bifurcation on the primary path is detected, post-buckling equilibrium paths are traced, and the corresponding wavelengths of the buckled configurations are calculated for a range of initial curvature values and in terms of pressure. Results over a wide range of initial curvature values are presented. The effects of anisotropy on the buckling moment, the buckling mode and the post-buckling response are also examined. Finally, an analytical approach is also employed to estimate the bending moment causing bifurcation instability. The approach is based on the DMV shell equations considering pre-buckling solutions from simplified ring analysis. The efficiency and accuracy of the analytical method with respect to the nonlinear finite element formulation are examined.

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ABSTRACT: The buckling of isotropic rings under external pressure has attracted the interest of researchers since late 1950s. The formula for critical fluid buckling pressure of thin rings is very well known. This formula was directly extended to account for homogeneous orthotropic rings as well. The buckling of orthotropic cylindrical shells was also a subject of interest since the 1960s. However, the formulations developed, to date, require numerical solutions to obtain the critical pressure. In this work, a generalized closed form analytical formula for the buckling of thin orthotropic multi-angle laminated rings/long cylinders is developed. Standard energy based formulation is used to express the kinematics and equilibrium equations. Classical lamination theory is implemented to introduce the constitutive equations of thin shells. These equations are statically condensed, in terms of the ring's boundary conditions, to produce effective axial, coupling and flexural rigidities for the cases of rings and long cylinders. The critical buckling pressure may be calculated by hand using the derived equation in terms of these effective elastic rigidities. Comparisons are made with some existing results. Parametric studies are conducted to compare the present results with those of the buckling equations implemented by design standards. Various fiber orientations and stacking sequences are considered.

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ABSTRACT: An overview of buckling and postbuckling behavior of pipes and tubes is presented, with particular emphasis on nonlinear finite element modeling. Classical bifurcation solutions for isotropic elastic cylinders under external pressure and bending are presented first. Subsequently, the stability of metal tubes and pipes under bending and external pressure is examined, and comparison with available experimental data is conducted. Finally, the behavior of composite cylinders under external pressure is presented, and the important
issue of delamination is thoroughly discussed.


ABSTRACT: The present paper focuses on the structural stability of long uniformly pressurized thin elastic tubular shells subjected to in-plane bending. Using a special-purpose non-linear finite element technique, bifurcation on the pre-buckling ovalization equilibrium path is detected, and the post-buckling path is traced. Furthermore, the influence of pressure (internal and/or external) as well as the effects of radius-to-thickness ratio, initial curvature and initial ovality on the bifurcation moment, curvature and the corresponding wavelength, are examined. The local character of buckling in the circumferential direction is also demonstrated, especially for thin-walled tubes. This observation motivates the development of a simplified analytical formulation for tube bifurcation, which considers the presence of pressure, initial curvature and ovality, and results in closed-form expressions of very good accuracy, for tubes with relatively small initial curvature. Finally, aspects of tube bifurcation are illustrated using a simple mechanical model, which considers the ovalized pre-buckling state and the effects of pressure.

References listed at the end of the paper:

ABSTRACT: The present paper investigates buckling of cylindrical shells of transversely-isotropic elastic material subjected to bending, considering the nonlinear prebuckling ovalized configuration. A large-strain hypoelastic model is developed to simulate the anisotropic material behavior. The model is incorporated in a finite-element formulation that uses a special-purpose “tube element”. For comparison purposes, a hyperelastic model is also employed. Using an eigenvalue analysis, bifurcation on the prebuckling ovalization path to a uniform wrinkling state is detected. Subsequently, the postbuckling equilibrium path is traced through a continuation arc-length algorithm. The effects of anisotropy on the bifurcation moment, the corresponding curvature and the critical wavelength are examined, for a wide range of radius-to-thickness ratio values. The calculated values of bifurcation moment and curvature are also compared with analytical predictions, based on a heuristic argument. Finally, numerical results for the imperfection sensitivity of bent cylinders are obtained, which show good comparison with previously reported asymptotic expressions.


ABSTRACT: The present paper investigates structural response and buckling of long unstiffened thin-walled cylindrical steel shells, subjected to bending moments, with particular emphasis on stability design. The cylinder response is characterized by cross-sectional ovalization, followed by buckling (bifurcation instability), which occurs on the compression side of the cylinder wall. Using a nonlinear finite element technique, the bifurcation moment is calculated, the post-buckling response is determined, and the imperfection sensitivity with respect to the governing buckling mode is examined. The results show that the buckling moment capacity is affected by cross-sectional ovalization. It is also shown that buckling of bent elastic long cylinders can be described quite accurately through a simple analytical model that considers the ovalized prebuckling configuration and results in very useful closed-form expressions. Using this analytical solution, the incorporation of the ovalization effects in the design of thin-walled cylinders under bending is thoroughly examined and discussed, considering the framework of the provisions of the new European Standard EN1993-1-6.

ABSTRACT: The present paper investigates the structural stability of thin-walled steel cylinders surrounded by an elastic medium, subjected to uniform external pressure. A two-dimensional model is developed, assuming no variation of load and deformation along the cylinder axis. The cylinder and the surrounding medium are simulated with nonlinear finite elements that account for both geometric and material nonlinearities. Cylinders of elastic material within a rigid boundary are considered first, and the numerical results are compared successfully with available closed-form analytical predictions. Subsequently, the external pressure response of confined thin-walled steel cylinders is examined, in terms of the initial out-of-roundness of the cylinder, the initial gap between the cylinder and the medium, and the stiffness of the surrounding medium. Numerical results are presented in the form of pressure-deformation equilibrium paths, and show a rapid drop of pressure after reaching the maximum pressure level, as well as a significant imperfection sensitivity. A plastic-hinge mechanism is developed that results in a closed-form expression and illustrates the post-buckling response of the cylinder in an approximate manner. The distributions of plastic deformation, as well as the variation of cylinder-medium contact pressure around the cylinder cross-section are also depicted and discussed. Furthermore, the effects of uniform vertical preloading on the maximum pressure sustained by the cylinder are examined. Finally, the numerical results show good comparison with a simplified closed-form expression, proposed elsewhere, which could be used for design purposes.


ABSTRACT: Thin-walled steel cylinders surrounded by an elastic medium, when subjected to uniform external pressure may buckle. In the present paper, using a two-dimensional model with nonlinear finite elements, which accounts for both geometric and material nonlinearities, the structural response of those cylinders is investigated, toward developing relevant design guidelines. Special emphasis is given on the response of the confined cylinders in terms of initial imperfections; those are considered in the form of initial out-of-roundness of the cylinder and as an initial gap between the cylinder and the medium. Furthermore, the effects of the deformability of the surrounding medium are examined. The results indicate significant imperfection sensitivity and a strong dependency on the medium stiffness. The numerical results are employed to develop a simple and efficient design methodology, which is compatible with the recent general provisions of European design recommendations for shell buckling and could be used for design purposes.

References listed at the end of the paper:

ABSTRACT: Motivated by practical engineering applications, the present study investigates the structural behavior and stability of thin-walled steel cylindrical shells with lateral confinement under two main types of loading, namely external pressure and longitudinal bending, both resulting in structural failure. The present work emphasizes on structural stability in terms of buckling, post-buckling and imperfection sensitivity. The investigation is computational using advanced finite element tools through the employment of a general-purpose finite element program. The cylindrical shells under consideration and the corresponding confinements are simulated with nonlinear finite elements that account for both geometric and material nonlinearities. An extensive literature review on the examined mechanical issues is conducted for the evaluation and assessment of available analytical solutions and experimental data. A numerical simulation methodology is developed and verified in order to model the shell and the interaction with the confinement. Shells of elastic material are considered first, offering the possibility of comparing the numerical results with available closed-form or simplified analytical predictions. Subsequently, the buckling response of steel shells is examined and the results are compared with available experimental data. For the case of external pressure loading, the numerical results are presented in the form of pressure-deformation equilibrium paths, and show an unstable post-buckling response beyond the point of ultimate pressure capacity, indicating significant imperfection sensitivity on the
value of the maximum pressure. The effects of the diameter-to-thickness ratio \((D/t)\), the yield stress, the interface friction, and the medium deformability on the structural response are examined. It is demonstrated that even for rigid confinement medium, the maximum (buckling) pressure is well below the pressure that causes plastification of the entire cylinder (referred to as yield pressure). Finally, based on the numerical results, a simplified and efficient methodology is developed which is compatible with the recent general provisions of European design recommendations for shell buckling, and could be used for design purposes. For the case of longitudinal bending loading of confined cylinders, the analysis refers to the case of the so-called lined pipes, focusing on the behavior of the thin-walled inner pipe (liner) which interacts with the outer pipe. Using a numerical simulation, the stresses and deformations in the compression zone are monitored, with emphasis on possible detachment of the liner from the confining medium, and on the formation of wrinkles. Furthermore, the development of liner ovalization, bending moment, local hoop curvature, axial stress, and hoop stress with increasing level of bending are investigated. The effects of liner thickness, friction, liner prestressing, and stiffness of the confining medium on the buckling curvature and wavelength are investigated. The sensitivity of response on the presence of initial wrinkling imperfections is investigated. Finally, the effect of external pressure on the mechanical response is discussed. The present study aims at establishing the theoretical basis for understanding and solving a significant number of structural instabilities related to confined cylindrical shells, which are encountered often in numerous practical engineering applications.


ABSTRACT: Motivated by practical engineering applications, the present paper examines the mechanical response of thin-walled cylinders surrounded by a rigid or deformable medium, subjected to uniform external pressure. Emphasis is given to structural stability in terms of buckling, postbuckling, and imperfection sensitivity. The present investigation is computational and employs a two-dimensional model, where the cylinder and the surrounding medium are simulated with nonlinear finite elements. The behavior of cylinders made of elastic material is examined first, and a successful comparison of the numerical results is conducted with available closed-form analytical solutions for rigidly confined cylinders. Subsequently, the response of confined thin-walled steel cylinders is examined. The numerical results show an unstable postbuckling response beyond the point of maximum pressure and indicate severe imperfection sensitivity on the value of the maximum pressure. A good comparison with limited available test data is also shown. Furthermore, the effects of the deformability of the surrounding medium are examined. In particular, soil embedment conditions are examined, with direct reference to the case of buried thin-walled steel pipelines. Finally, based on the numerical results, a comparison is attempted between the present buckling problem and the problem of “shrink buckling.” The differences between those two problems of confined cylinder buckling are pinpointed, emphasizing the issue of imperfection sensitivity.

References listed at the end of the paper:


Other papers co-authored by Vasilikis and Karamanos:

Summary of the work described in the 5 papers just listed:
The research examines the mechanical behavior of lined pipes and investigates extensively the wrinkling of such pipes under bending loading with or without the presence of external pressure. Lined pipe, also referred to as “mechanically clad pipe”, is a new and promising technological solution in energy pipeline applications where the structural integrity of oil and gas steel pipelines requires erosion damage protection from oil or gas pollutants. Lined pipe is a double-wall pipe, consisting of a load-bearing high-strength, low-alloy carbon steel outer pipe, lined with a thin-walled sleeve made from a corrosion-resistant material referred to as “liner” pipe. Lined pipes are produced through an appropriate manufacturing procedure, consisting of heating the outer pipe, inserting the liner and pressurizing it until both pipes come in contact, and finally cooling the outer pipe. Considering the liner pipe as a thin-walled cylindrical shell prone to buckling, the lateral confinement due to the deformable outer pipe constitutes a paramount parameter for its mechanical behavior. In the present investigation, the problem is solved numerically, using nonlinear finite elements capable at simulating the lined pipe and the interaction between the liner and the outer pipe. Nonlinear geometry with large strains is taken into account, and the material of both pipes is elastic-plastic. The lined pipe is considered either stress-free (snug-fit pipe, SFP) or with an initial stress (tight-fit pipe, TFP). The thermo-hydraulic manufacturing process of the lined pipe is simulated to determine the liner hoop prestressing. First, an ovalization bending analysis of the lined pipe is conducted, where a slice of the pipe between two adjacent cross-sections is considered excluding the possibility of buckling. In this analysis, the stress and deformation of the liner in the compression zone is monitored, with emphasis on possible detachment of the liner from the outer pipe. Using a simple buckling hypothesis, it is possible to estimate the curvature at which liner wrinkling would occur. Subsequently, a three-dimensional analysis is conducted to examine buckling of the liner in the form of a uniform wrinkling pattern.
The curvature at which buckling occurs and the corresponding buckling wavelength are determined for different thicknesses of the liner and outer pipe. Furthermore, the transition from a uniform wrinkling configuration to a secondary bifurcation with more localized deformations is investigated, and reference to experimental observations is made. Next, the effects of initial imperfections on the structural behavior of lined pipes are investigated. Subsequently, the effect of the prestressing on the critical wavelength and the buckling curvature is examined. A comparison with available experimental results is conducted in terms of wrinkle height development and the corresponding buckling wavelength. Finally, the structural behavior of lined steel pipes under bending in the presence of external pressure is examined. The results of the present research can be used for safer design of lined pipes in pipeline applications.

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“So on the seismic behavior and design of liquid storage tanks”, COMPDYN2011, III ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, M. Papadrakakis, M. Fragiadakis and V. Plevris (Editors), Corfu, Greece, 25-28 May, 2011

ABSTRACT: The paper examines some special issues on the structural behaviour of upright cylindrical liquid storage tanks, which are widely used in industrial facilities and for water storage. Two main design standards are considered: EN 1998-4, a relatively new standard, and Appendix E of API 650, which has been through substantial amendments and revisions in its new version (11th edition, 2007). There are significant differences between the two specifications, which are due to the fact that there exist several controversial issues on this subject, open to further research. These issues are (a) the number of modes necessary to estimate accurately the convective seismic force due to the hydrodynamic behaviour of the liquid containment; (b) the appropriate combination of the impulsive and the convective component of seismic force; (c) the uplifting behaviour of unanchored tanks, with emphasis on the base plate behaviour and the increase of meridional compression; (d) the choice of an appropriate reduction (behaviour) factor for calculating both the impulsive and the convective force; (e) the calculation of hydrodynamic hoop stresses due to liquid hydrodynamic motion; (f) the design of tanks against buckling at the top due to liquid sloshing; (g) the importance of nonlinear wave sloshing effects. The present paper is aimed at addressing the above issues based mainly on numerical simulations. To simulate the tank shell and its structural behaviour, general-purpose finite element software ABAQUS is employed, whereas to examine hydrodynamic effects, an in-house numerical technique is developed. Existing data from previous investigations are also considered. The results are aimed at better understanding of liquid storage tank seismic behaviour, bridging the gap between the two major design standards (EN 1998-4 and API 650-Appendix E), towards safer seismic design of industrial facilities.

References listed at the end of the paper:
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ABSTRACT: The purpose of this study is to investigate the large strain and stress analysis for pipe elbows subjected to in-plane bending moments. A finite element model for the bend was constructed and loaded taking geometric and material nonlinearities into account using (ABAQUS) nonlinear finite element code. The initiation of yielding for the opening and closing cases appears at the inside surface of the elbow crown. However, further loading causes a significant difference in strain distribution and deformed shapes. The limit moment for the opening cases is higher than that for closing due to the geometric stiffening effects.


ABSTRACT: The purpose of this work is to study the load-carrying capacity of pipe bends, with different pipe bend factor (h) values, under out-of-plane moment loading; and to investigate the effect of internal pressure on the limit moments in this loading mode. The finite element method is used to model and analyze a standalone, long-radius pipe bend with a 16-in. nominal diameter, and a 24-in. bend radius. A parametric study is performed in which the bend factor takes ten different values between 0.0632 and 0.4417. Internal pressure is incremented by 100 psi for each model, until the limit pressure of the model is reached. The limit moments were found to increase when the internal pressure is incremented. However, beyond a certain value of pressure, the effect of pressure is reversed due to the additional stresses it engenders. Expectedly, increasing the bend factor leads to
an increase in the value of the limit loads. The results are compared to those, available in the literature, of a similar analysis that treats the in-plane loading mode. Pipe bends are found to have the lowest load-carrying capacity when loaded in their own plane, in the closing direction. They can sustain slightly higher loads when loaded in the out-of-plane direction, and considerably higher loads under in-plane bending in the opening direction.

ABSTRACT: This article covers the general behaviour of a straight uniform pipe, with built-in open ends, subject to internal pressure and in plane bending or curvature. It is intended as a summary of the basic equations driving the unintuitive phenomena of bending and instability of pipes under internal pressure. The analysis covers in addition the investigation of opposite pressure stabilisation effects that can be observed in some orthotropic material pipes like composite pressure hoses.

References listed at the end of the paper:

ABSTRACT: The experimental part of a study which deals with the response and stability of thin-walled tubes under cyclic bending histories is presented (see [7] for theory). Aluminum and steel tubes are cyclically bent in pure bending into the plastic range. It is found that under curvature-symmetric loading histories the tube progressively ovalizes to a critical value at which it buckles. This critical value of ovalization is approximately equal to the value obtained just prior to buckling under monotonic bending. The influence of the material and geometric parameters of the tubes on the phenomenon is studied. It is shown that for the materials studied, the phenomenon can drastically reduce the life expectancy of tubes in the range of D /t of 15 to 80.

Daniel Peter Miller, “Buckling failure boundary for cylindrical tubes in pure bending”, Master’s thesis, Mechanical Engineering, Brigham Young University, April 2012
ABSTRACT: Bending of thin-walled tubing to a prescribed bend radius is typically performed by bending it
around a mandrel of the desired bend radius, corrected for spring back. By eliminating the mandrel, costly setup time would be reduced, permitting multiple change of radius during a production run, and even intermixing different products on the same line. The principal challenge is to avoid buckling, as the mandrel and shoe are generally shaped to enclose the tube while bending. Without the shaped mandrel, buckling will likely occur sooner, that is, at larger bend radii. A test apparatus has been built for arborless bending. It has been used to determine the limits of bend radius, wall thickness, material properties, etc. on buckling. Key to the process is a set of moveable clamps, which grip the tube and rotate to produce the bend. A complex control system moves the clamps radially to maintain pure bending, without superimposing tension or compression. A series of tests were performed to document the safe region of operation to avoid buckling. Charts have been created to assist the operator, as well as the design engineer, in determining the minimum bend radius. Similar tests will be required for each additional tube size, thickness, material, etc.

References listed at the end of the thesis:

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“Behavior of Thin-walled circular hollow section tubes subjected to bending”, Thin Walled Struct 73:281–289, December 2013, DOI: 10.1016/j.tws.2013.08.014

ABSTRACT: Thin-walled steel circular hollow sections (CHS) are widely used in wind turbine towers. The tower tubes are mainly subjected to bending. There have been a few experimental studies on the bending behavior of thin-walled CHS steel tubes. This paper describes a series of bending tests to examine the influence of section slenderness on the inelastic and elastic bending properties of thin-walled CHS. In addition, the influence of stiffeners welded in the steel tube is considered. Sixteen bending tests were performed up to failure on different sizes of CHS with diameter-to-thickness ratio (D/t) varying from 75 to 300. The experimental results showed that the specimens with small diameter-to-thickness ratios failed by extensive plastic deformation on the central part of the tube. With the increase of diameter-to-thickness ratio, the local buckling phenomena became more pronounced. The stiffeners in the steel tubes increased the load carrying capacity and improved the ductility of the specimens. The experimental results were compared with current design guidelines on thin-walled steel members in AISC-LRFD, AS4100 and European Specification. It was found that the test results agreed well with the results based on AS4100 design code.

References listed at the end of the paper:
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DOI: 10.1177/073664413491442

ABSTRACT: This article is concerned with the numerical modelling and analysis of the mechanical behaviour of composite pipes used for offshore oil and gas applications. Specifically, the bending of the reinforced thermoplastic pipes during the reeling process of reel-lay installation is modelled using non-linear finite-element procedures. In particular, the possible buckling of the reeled composite pipes has been investigated. Composite pipes reinforced with one angle-ply and two angle-ply layers are considered and the effects of different diameter-to-thickness ratios and different angle-ply combinations on the mechanical behaviour of these pipes have been studied.

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“Buckling analysis of high-temperature pressurized pipelines with soil-structure interaction”, Journal of the
ABSTRACT: High-temperature pressurized pipelines design requires special attention, as restrained thermal stresses are high. Due consideration should be given to thermal expansion, as stresses in bends of expansion loops are significant. Also, the modeling of the soil-pipe interaction using soil characteristics, especially friction and lateral resistance, is important when analyzing high-temperature pipelines. This paper describes a numerical procedure for the analysis of global and local buckling behavior of high temperature pressurized buried pipelines. Results of finite element calculations are presented and discussed.


ABSTRACT: Deformation of a spherical shell adhering onto a rigid substrate due to van der Waals attractive interaction is investigated by means of numerical minimization of the sum of the elastic and adhesion energies. The conformation of the deformed shell is governed by two dimensionless parameters Cs/epsilon and Cb/epsilon, where Cs and Cb are respectively the stretching and the bending constants, and epsilon is the depth of the van der Waals potential. As a function of Cb/epsilon, we find both continuous and discontinuous buckling transitions for small and large Cs/epsilon, respectively, which is analogous to van der Waals fluids or gels. Some scaling arguments are employed to explain the adhesion induced buckling transition.


ABSTRACT: Deformation of a spherical shell adhering onto a rigid substrate due to van der Waals attractive interaction is investigated by means of numerical minimization (conjugate gradient method) of the sum of the elastic and adhesion energies. The conformation of the deformed shell is governed by two dimensionless parameters, i.e., Cs/epsilon and Cb/epsilon where Cs and Cb are respectively the stretching and the bending constants, and epsilon is the depth of the van der Waals potential between the shell and substrate. Four different regimes of deformation are characterized as these parameters are systematically varied: (i) small deformation regime, (ii) disk formation regime, (iii) isotropic buckling regime, and (iv) anisotropic buckling regime. By measuring the various quantities of the deformed shells, we find that both discontinuous and continuous buckling transitions occur for large and small Cs/epsilon, respectively. This behavior of the buckling transition is analogous to van der Waals liquids or gels, and we have numerically determined the associated critical point. Scaling arguments are employed to explain the adhesion induced buckling transition, i.e., from the disk formation regime to the isotropic buckling regime. We show that the buckling transition takes place when the indentation length exceeds the effective shell thickness which is determined from the elastic constants. This prediction is in good agreement with our numerical results. Moreover, the ratio between the indentation length and its thickness at the transition point provides a constant number (2–3) independent of the shell size. This universal number is observed in various experimental systems ranging from nanoscale to macroscale. In particular, our results agree well with the recent compression experiment using microcapsules.

“Dynamics of Snapping Beams and Jumping Poppers”, A. Pandey, D.E. Moulton, D. Vella, and D.P. Holmes,
ABSTRACT: We consider the dynamic snapping instability of elastic beams and shells. We show that the stretchability of the arch plays a critical role in determining not only the post-buckling mode of deformation, but also the timescale of snapping, and the frequency of the arch's vibrations about its final equilibrium state. We show that the growth rate of the snap-through instability, and its subsequent ringing frequency, can both be interpreted physically as the result of a sound wave in the material propagating over a distance comparable to the radius of curvature of the arch. Finally, we extend our analysis of the ringing frequency of indented arches to understand the 'pop' heard when everted shell structures snap-through to their stable state. Remarkably, we find that not only are the scaling laws for the ringing frequencies in these two scenarios identical, but also the respective prefactors are numerically close; this allows us to develop a master curve for the frequency of ringing in snapping beams and shells.

D.P. Holmes, iMechanica - Journal Club, February 2012
Welcome to February 2012's Journal club, which will include a discussion on elastic instabilities for form and function. Not long ago, the loss of structural stability through buckling generally referred to failure and disaster. It was a phenomenon to be designed around, and rarely did it provide functionality*. The increasing focus on soft materials, from rubbers and gels to biological tissues, encouraged scientists to revisit the role of elastic instabilities in the world around us and inspired their utilization in advanced materials. Now the field of elastic instabilities, or extreme mechanics, brings together the disciplines of physics, mechanics, mathematics, biology, and materials science to extend our understanding of structural instabilities for both form and function. In this journal club, we're going to look at research on the wrinkling, crumpling, and snapping of soft or slender structures.

ABSTRACT: Soft materials, e.g. biological tissues and gels, undergo morphological changes, motion, and instabilities when subjected to external stimuli. Tissues can exhibit residual internal stresses induced by growth, and generate elastic deformations to move in response to light or touch, curl articular cartilage, aid in seed dispersal, and actuate hygromorphs, such as pine cones. Understanding the dynamics of such osmotically driven movements, in the influence of geometry and boundary conditions, is crucial to the controlled deformation of soft materials. We examine how thin elastic plates undergo rapid bending and buckling instabilities after exposure to a solvent that swells the network. A circular disc bends and buckles with multiple curvatures, and a large-amplitude traveling wave rotates azimuthally around the disc.

ABSTRACT: A polymer film draping over a point of contact will wrinkle due to the strain imposed by the underlying substrate. The wrinkle wavelength is dictated by a balance of material properties and geometry; most directly the thickness of the draping film. At a critical strain, the stress in the film will localize, causing hundreds of wrinkles to collapse into several discrete folds. In this paper, we examine the deformation of an axisymmetric sheet and quantify the force required to generate a fold. The onset of folding, in terms of a critical force or displacement, scales as the thickness to the four-ninth power, which we predict from the energy balance of the system. The folds increase the tension in the remainder of the film causing the radial stress to increase, thereby decreasing the wavelength of the remaining wrinkles.

ABSTRACT: The topographic control of pattern features is of great interest for a range of applications including the generation of ultrahydrophobic surfaces, microfluidic devices, and the control and tuning of adhesion. In these areas, surface patterning is achieved by a variety of techniques including: photolithography, imprint lithography, and surfaces wrinkling. In this paper, we present a scalable patterning method based on surface plate buckling, or crumpling, to generate a variety of topographies that can dynamically change shape and aspect ratio in response to stimuli.

List of references at the end of the paper:


ABSTRACT: The responsive mechanism of the Venus flytrap has captured the interest of scientists for centuries. Although a complete understanding of the mechanism controlling the Venus flytrap movement has yet to be determined, a recent publication highlights the importance of geometry and material properties for this fast, stimuli-responsive movement. Specifically, the movement is attributed to a snap-through elastic instability whose sensitivity is dictated by the length scale, geometry, and materials properties of the features. Here, we use lessons from the Venus flytrap to design surfaces that dynamically modify their topography. We present a simple, biomimetic responsive surface based on an array of microlens shells that snap from one curvature to another when a critical stress develops in the shell structure.

S-L Fok, University of Manchester Manchester School of Engineering UK,

ABSTRACT: Elastic buckling of a spherical shell, embedded in an elastic material and loaded by a far-field hydrostatic pressure is analysed using the energy method together with a Rayleigh—Ritz trial function. For
simplicity, only axisymmetric deformations are considered and inextensional buckling is assumed. The strains within the structure that are pre-critical are assumed to be small for the linear theory to be applicable. An expression is derived relating the pressure load to the buckling mode number, from which the upper-bound critical load can be determined. It is found that the presence of the surrounding elastic medium increases the critical load of the shell and the corresponding buckling mode number. However, the results also show that the strain of the shell at the point of instability may not be small for typical values of material and geometric constants.

References
MacRobert, T. M.Spherical Harmonics, 1927 (Methuen, London).

ABSTRACT: This paper considers dynamic buckling of a harmonically base-excited vertical cylindrical shell carrying a top mass. Based on Donnell’s nonlinear shell theory, a semi-analytical model is derived which exactly satisfies the (in-plane) boundary conditions. This model is numerically validated through a comparison with quasi-static and modal analysis results obtained using finite element modelling. The steady-state nonlinear dynamics of the base-excited cylindrical shell with top mass are examined using both numerical continuation of periodic solutions and standard numerical time integration. In these dynamic analyses the cylindrical shell is preloaded by the weight of the top mass. This preloading results in a single unbuckled stable static equilibrium state. A critical value for the amplitude of the harmonic base-excitation is determined. Above this critical value, the shell exhibits an instationary beating type of response with time intervals showing severe out-of-plane deformations (it buckles dynamically). Similar as for the static buckling case, the critical value highly depends on the initial imperfections present in the shell.

References listed at the end of the paper:
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doi:10.1016/j.jsv.2010.02.007
ABSTRACT: Considering both an experimental and a numerical approach, the dynamic stability of a harmonically base-excited thin orthotropic cylindrical shell carrying a top mass is examined. To be able to compare the experimentally obtained results with numerical results, a semi-analytical coupled shaker-structure model is derived. Using the semi-analytical model, it is shown that the dynamic stability analysis of the base-excited cylindrical shell with top mass should be concentrated near a low frequency resonance, corresponding to a mode, in which axial vibrations of the (cylindrical shell with) top mass dominate. In this frequency region, the shell may exhibit an aperiodic beating type of response, if some critical value of the amplitude of the harmonic base-excitation is exceeded. This beating response is characterized by severe out-of-plane deformations. The experimental results qualitatively confirm the numerical observations.

ABSTRACT: In this thesis a theoretical investigation of the nonlinear vibrations of imperfect thin-walled cylindrical shells is presented, which is aimed at two objectives. The first one is to investigate the influence of initial geometric imperfections on the nonlinear vibration behaviour of shells, while the second one is to investigate the effect of different boundary conditions. Donnell shallow shell equations are used with the appropriate damping, inertial and initial geometric imperfection terms included. Galerkin's procedure and the method of averaging are employed in order to reduce the problem to the solution of nonlinear algebraic and nonlinear ordinary differential equations, respectively. Numerical solutions indicate that the initial geometric imperfections have strong influence on the nonlinear vibrations of shells if certain coupling conditions are satisfied. The imperfections may not only significantly change the natural frequencies and the degree of non-linearity, but also may change the vibration behaviour. Results show that the effect of boundary conditions on the nonlinear vibrations of shells may be significant especially for shorter shells .

doi:10.1006/jsvi.1996.0827
ABSTRACT: In this paper, the non-linear vibration and dynamic instability of thin shallow spherical and conical shells subjected to periodic transverse and in-plane loads are investigated. The Marguerre type dynamic equations used for the analysis of shallow shells, when treated by the Galerkin method, will result in a system of total differential equations in the time functions, known as Duffing and Mathieu equations, from which the
various kinds of non-linear vibration and dynamic instability are determined by using numerical methods. Numerical results are presented for axisymmetric vibrations and dynamic instabilities of shallow spherical and conical shells with (a) clamped and (b) supported edge conditions. As numerical examples, non-linear vibration frequencies and instability regions for shells are determined. The effects of static load as well as static snap-through buckling on the instability are also investigated.


ABSTRACT: A system of governing equations for non-linear vibrations of heated sandwich shallow shells is derived using Hamilton's principle in combination with Reissner-Hellinger's variational principle. The system contains four unknown functions which characterize the deflection, the Airy stress function and the shearing displacements. For a rectangular simply supported shallow shell due to a temperature difference between the upper and lower faces and prevented from inplane motions on the contour, the governing time equation is derived by means of a Galerkin procedure applied to the field equation of the vertical motion. Numerical results are shown in the graphs.


ABSTRACT: An analytical study of buckling of rectangular sandwich plates, stressed uniaxially by uniform shortening beyond the elastic limits of component materials, is presented. The analysis is based on the inelastic behavior according to both the $J_2$-incremental and $J_2$-deformation theories of plasticity. Taking the loaded edges as simply supported, the governing equations are solved for (a) plates simply supported on all four sides, and (b) plates simply supported on three sides and free on the fourth side. The theory gives rise to two sets of boundary conditions, each representing “simple support”. It is shown that these alternative choices lead to significantly different predictions of the buckling load in the case of sandwich plates simply supported on three sides and free on the fourth, unloaded side. The presented analysis can be specialized to elastic buckling of sandwich plates, and also to elastic or plastic buckling of homogeneous (one-material) plates with or without the transverse shear effects.


ABSTRACT: This paper reports on the development of finite element formulations and computer programs for modelling free and constrained inflation of thin polymeric sheets in the context of thermoforming of plastic articles. In recognition of the generally time-dependent viscoelastic behaviour of polymers, and the large strains encountered in thermoforming applications, the material is modelled as non-linear viscoelastic. For this purpose the constitutive relation proposed by Christensen is adopted, assuming the relaxation function to be exponential. Most of the published work on non-linear viscoelastic membranes deals with simple axisymmetric geometries, while the finite element formulations presented in this work are for both axisymmetric and non-axisymmetric membrane inflations, including contact against constraining surfaces. Both frictionless and slipless idealizations
of contact conditions are studied. The finite element solutions of free and constrained inflations of circular membranes serve as illustrative examples for the axisymmetric case, while those for elliptical membranes demonstrate the non-axisymmetric cases. Comparison of the finite element results with the analytical solutions obtained (Appendix 1) for some simple free and constrained inflation problems shows good agreement.

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ABSTRACT: Finite element semidiscrete approximations on nonlinear dynamic shallow shell models is considered. It is shown that the algorithm leads to global optimal rates of convergence. The result presented in the paper improves upon the existing literature where the rates of convergence were derived for small initial data only [19].

References listed at the end of the paper:
Liu Chang-Jiang, ZhengZhou-Lian, HuangCong-Bing, He Xiao-Ting, Sun Jun-Yi, and Chen Shan-Lin

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ABSTRACT: This paper investigated the nonlinear stability problem of dished shallow shells under circular line loads. We derived the dimensionless governing differential equations of dished shallow shell under circular line loads according to the nonlinear theory of plates and shells and solved the governing differential equations by combing the free-parameter perturbation method (FPPM) with spline function method (SFM) to analyze the nonlinear instability modes of dished shallow shell under circular line loads. By analyzing the nonlinear instability modes and combining with concrete computational examples, we obtained the variation rules of the maximum deflection area of initial instability with different geometric parameters and loading action positions and discussed the relationship between the initial instability area and the maximum deflection area of initial instability. The results obtained from this paper provide some theoretical basis for engineering design and instability prediction and control of shallow-shell structures.

References listed at the end of the paper:

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ABSTRACT: A simple and computationally efficient numerical approach is employed in this study for free vibrations of complicated shaped layered shells of revolution. Each layer of the shell is assumed to be constructed from an orthotropic material. The effects of shear deformation and rotary inertia have been included in the formulation, where stiffness and consistent mass matrices are evaluated using reduced integration technique. The approach yields accurate results for shells, if the mid-surfaces are represented by a series of mutually tangential circular arcs. Numerical examples include the natural frequencies and corresponding mode shapes of three-layered freely supported circular cylindrical shells, clamped shallow spherical shells and a cylindrical shell closed by a torispherical head.

ABSTRACT: This paper deals with the free flexural vibration of laminated quadrilateral plates and shallow shells using the Rayleigh–Ritz method. Equations are derived using the first order shear deformation theory of plates and shells. Nonlinearity is present only in the in-plane strain components. The transverse shear strains, curvature and inertial terms are linear. The geometry is mapped using the natural coordinates. Admissible displacement fields are constructed by taking the product of two simple polynomials in each of the two parametric coordinates. By controlling the coefficients of these polynomials, the geometric boundary conditions are satisfied. Numerical results are presented for the four-layer angle-ply plates and cylindrical shallow shells supported on trapezoidal boundary. The influences of the large amplitude and also of the geometry on the natural frequency are examined.

ABSTRACT: An analysis is presented for the vibration and stability of a circular cylindrical shell subjected to a torque. The displacements of a circular shell are written in a series of beam eigenfunctions satisfying the boundary conditions. The kinetic and strain energies of the shell are evaluated analytically, and the frequency equation of the shell is derived by the Ritz method. The method is applied to circular cylindrical shells under two types of boundary conditions at the edges; the natural frequencies and the divergence torques are calculated numerically, and the effects of the thickness ratio, length ratio and edge conditions on the vibration and stability are studied.

Gen Yamada, Toshihiro Irie and Mitsuo Tsushima (Department of Mechanical Engineering, Faculty of Engineering, Hokkaido University, Sapporo, 060 Japan), “Vibration and stability of orthotropic circular cylindrical shells subjected to axial load”, J. Acoust. Soc. Am. 75, 842 (1984); http://dx.doi.org/10.1121/1.390594
ABSTRACT: An analysis is presented for the vibration and stability of an orthotropic circular cylindrical shell subjected to an axial static load by use of the transfer matrix approach. The applicability of the thin-shell theory is assumed, and the governing equations of free vibration of the shell are written in a matrix differential equation by using the transfer matrix of the shell. Once the matrix has been determined by a solution to the equation, the natural frequencies and the critical loads are calculated numerically in terms of the elements of the matrix for a given set of boundary conditions at the edges. This method is applied to orthotropic circular cylindrical shells simply supported at the edges, and the effects of the length ratio, orthotropy, and axial load on the vibration and stability are studied.

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ABSTRACT: This paper examines non-linear free vibration characteristics of first and second vibration modes of laminated shallow shells with rigidly clamped edges. Non-linear equations of motion for the shells based on the first order shear deformation and classical shell theories are derived by means of Hamilton's principle. We apply Galerkin's procedure to the equations of motion in which eigenvectors for first and second modes of linear vibration obtained by the Ritz method are employed as trial functions. Then simultaneous non-linear ordinary differential equations are derived in terms of amplitudes of the first and second vibration modes. Backbone curves for the first and second vibration modes are solved numerically by the Gauss–Legendre integration method and the shooting method respectively. The effects of lamination sequences and transverse shear deformation on the behavior are discussed. It is also shown that the motion of the first vibration mode affects the response for the second vibration mode.

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ABSTRACT: This paper presents the response of symmetric crossply laminated shallow shells with an internal resonance omega2 approximately equal to omega3, where omega2 and omega3 are the linear natural frequencies of the asymmetric vibration modes (2,1) and (1,2), respectively. Galerkin's procedure is applied to the nonlinear governing equations for the shells based on the von Kármán-type geometric nonlinear theory and the first-order shear deformation theory, and the shooting method is used to obtain the steady-state response when a driving frequency Omega is near omega2. In order to take into account the influence of quadratic nonlinearities, the displacement functions of the shells are approximated by the eigenfunctions for the linear vibration mode (1,1) in addition to the ones for the modes (2,1) and (1,2). This approximation overcomes the shortcomings in Galerkin's procedure. In the numerical examples, the effect of the (1,1) mode on the primary resonance of the (2,1) mode is examined in detail, which allows us to conclude that the consideration of the (1,1) mode is indispensable for analyzing nonlinear vibrations of asymmetric vibration modes of shells.

T.L.C. Chen and C.W. Bert (Mechanical Engineering, The University of Oklahoma, Norman, Oklahoma),

ABSTRACT: A linear stability analysis is presented for a thin-walled, circular cylindrical shell of orthotropic material conveying a swirling flow. Shell motion is modeled by using the dynamic orthotropic version of the Sanders shell theory and fluid forces are described by inviscid, incompressible flow theory. The critical flow velocities are determined for piping made of composite and isotropic materials conveying swirling water. Fluid rotation strongly degrades the stability of the shell/fluid system, i.e. increasing the fluid rotating speed severely decreases the critical flow velocity.


ABSTRACT: Consideration is given to problems of nonlinear stability of inertial collapse of spherical and cylindrical shells filled with a viscous incompressible fluid homogeneous in density. Using Lyapunov’s direct method, we determine: 1) the necessary and sufficient condition for stability of spherically symmetrical inertial collapse of a thick spherical shell with respect to finite disturbances of symmetry of the same type and 2) absolute stability of cylindrically symmetrical inertial collapse of a cylindrical shell relative to finite disturbances of the same symmetry.

References listed at the end of the paper:


ABSTRACT: This paper deals with the dynamics of a cluster of parallel flexible cylinders in a cylindrical channel in the presence of an axially flowing fluid. The equations of motion are derived, taking into account inviscid and viscous hydrodynamic coupling of small arbitrary motions of the cylinders. Solutions of the equations of motion yield the eigenfrequencies and modal shapes of the system. For sufficiently high flow velocities the system loses stability by divergence and flutter, similarly to a solitary cylinder in unbounded flow; however, the critical flow velocities are much lower, as proximity to other cylinders and to the channel wall severely destabilize the system.


ABSTRACT: This paper presents an analytical model for the dynamics and stability of coaxial cylindrical shells conveying incompressible or compressible fluid in the inner shell and in the annulus between the two shells. Shell motions are described by Flügge's thin-shell equations and the fluid forces are determined by means of linearized potential flow theory and formulated with the aid of generalized force Fourier transform techniques. Calculations have been conducted with two flexible shells or with one replaced by an identical rigid
cylinder, with inner or annular flow, or both, mainly with incompressible flows but also with compressible ones; with steel or rubber shells conveying either water or air. It is found that, for the systems studied, annular flow destabilizes the system at lower flow velocities than flow in the inner shell and that the stability threshold is lower when both shells are flexible. The critical flow velocities are in the range of interest for industrial systems. The effect of compressibility is found to be small.

ABSTRACT: In this paper the dynamics and stability characteristics of coaxial cylindrical shells containing incompressible, viscous fluid flow are examined in contrast to previous studies where the fluid has been considered to be inviscid. Specifically, upstream pressurization of the flow (to overcome frictional pressure drop) and skin friction on the shell surfaces are taken into account, generating time-mean normal and tangential loading on the shells. Shell motions are described by Flügge’s thin shell equations, suitably modified to incorporate the time-mean stress resultants arising from viscous effects. The fluctuating fluid forces, coupled to shell vibration, are determined entirely by means of linearized potential flow theory and formulated with the aid of generalized-force Fourier-transform techniques. It is found that the effect of viscosity in the annular flow generally tends to destabilize the system, vis-à-vis inviscid flow, whereas viscous effects in the inner flow stabilize the system. These effects can be quantitatively very important, so that, generally, neglect of viscous effects cannot be justified.

ABSTRACT: This paper considers analytically the dynamics of a flexible cylinder in a narrow coaxial cylindrical duct, subjected to annular flow. In the present analysis, in contrast to existing theory, the viscous forces are not derived by an adaptation of Taylor’s unconfined-flow relationships, but by a systematic, albeit approximate, solution of the Navier-Stokes equations, which accounts for the unsteady viscous effects much more fully than heretofore; it is found that, for very narrow annuli, the contribution of these unsteady viscous forces to the overall unsteady forces on the cylinder can be much larger than that of the steady skin friction and pressure-drop effects alone. The present analysis also differs from existing theory in that the in-viscid forces are not derived via the slender-body approximation, and hence the analysis is also applicable to bodies of relatively small length-to-radius ratio. The dynamics and stability of typical systems with fixed ends is investigated, concentrating mainly on viscous effects and comparing the results with those of previous work. It is found that, as the annular gap becomes narrower, the system loses stability by divergence at smaller flow velocities, provided the gap size is such that inviscid fluid effects are dominant. For very narrow annuli, however, where viscous forces predominate, this trend is reversed, and further narrowing of the annular gap has a stabilizing effect on the system; furthermore, in some cases the system loses stability by flutter rather than divergence.

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“Low-dimensional model for nonlinear vibration of circular cylindrical shells”, (publisher and date not given in
the pdf file. Most recent reference is dated 1998.)

ABSTRACT: The response-frequency relationship in the vicinity of a resonant frequency, the occurrence of travelling wave response and the presence of internal resonances are investigated for simply supported, circular cylindrical shells. Donnell's nonlinear shallow-shell theory is used. The boundary conditions on radial displacement and the continuity of circumferential displacement are exactly satisfied. The problem is reduced to a system of ordinary differential equations by means of the Galerkin method. The mode shape is expanded by using four degrees of freedom. The effect of internal dense fluid is studied. The solution is obtained by the Method of Normal Forms. Comparison of a three and a four degree-of-freedom model is performed. A water-filled shell presenting the phenomenon of 1:1:1:2 internal resonances is investigated; specific Normal Forms are developed for this study.

References listed at the end of the paper:


ABSTRACT: (none given by ASME)

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ABSTRACT: The non-linear vibration of simply supported, circular cylindrical shells is analysed. Geometric non-linearities due to finite-amplitude shell motion are considered by using Donnell's non-linear shallow-shell theory; the effect of viscous structural damping is taken into account. A discretization method based on a series expansion of an unlimited number of linear modes, including axisymmetric and asymmetric modes, following
the Galerkin procedure, is developed. Both driven and companion modes are included, allowing for travelling-wave response of the shell. Axisymmetric modes are included because they are essential in simulating the inward mean deflection of the oscillation with respect to the equilibrium position. The fundamental role of the axisymmetric modes is confirmed and the role of higher order asymmetric modes is clarified in order to obtain the correct character of the circular cylindrical shell non-linearity. The effect of the geometric shell characteristics, i.e., radius, length and thickness, on the non-linear behaviour is analysed: very short or thick shells display a hardening non-linearity; conversely, a softening type non-linearity is found in a wide range of shell geometries.

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ABSTRACT: The study presented is an investigation of the non-linear dynamics and stability of simply supported, circular cylindrical shells containing inviscid incompressible fluid flow. Non-linearities due to large-amplitude shell motion are considered by using the non-linear Donnell's shallow shell theory, with account taken of the effect of viscous structural damping. Linear potential flow theory is applied to describe the fluid–structure interaction. The system is discretized by Galerkin's method, and is investigated by using a model involving seven degrees of freedom, allowing for travelling wave response of the shell and shell axisymmetric contraction. Two different boundary conditions are applied to the fluid flow beyond the shell, corresponding to: (i) infinite baffles (rigid extensions of the shell), and (ii) connection with a flexible wall of infinite extent in the longitudinal direction, permitting solution by separation of variables; they give two different kinds of dynamical behaviour of the system, as a consequence of the fact that axisymmetric contraction, responsible for the softening non-linear dynamical behaviour of shells, is not allowed if the fluid flow beyond the shell is constrained by rigid baffles. Results show that the system loses stability by divergence.

References listed at the end of the paper:
Part I of this study, are studied by using a code based on the collocation method. The validation of the present
results is checked by comparing the obtained solutions with those of the literature and, if possible, with
an analytical solution. The nonlinear sction of the study is organized as follows:

**ABSTRACT:**

The non-linear vibration of a cylindrical shell containing a flowing fluid is investigated. Both modal and point
excitations have been considered. The model is suitable to study simply supported shells with and without axial
constraints. Donnell's non-linear shallow-shell theory is used. The boundary conditions on radial displacement and
the continuity of circumferential displacement are exactly satisfied. The radial deflection of the shell is expanded by
using a basis of seven linear modes. The effect of internal quiescent, incompressible and inviscid fluid is investigated.
The equations of motion, obtained in Part I of this study, are studied by using a code based on the collocation method. The validation of the present
model is obtained by comparison with other authoritative results. The effect of the number of axisymmetric modes used in the expansion on the response of the shell is investigated, clarifying questions open for a long time. The results show the occurrence of travelling wave response in the proximity of the resonance frequency, the fundamental role of the first and third axisymmetric modes in the expansion of the radial deflection with one longitudinal half-wave, and limit cycle responses. Modes with two longitudinal half-waves are also investigated.

References listed at the end of the paper:

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ABSTRACT: The response of simply supported circular cylindrical shells to harmonic excitation in the spectral neighbourhood of one of the lowest natural frequencies is investigated by using improved mode expansions with respect to those assumed in Parts I and II of the present study. Two cases are studied: (1) shells in vacuo;
and (2) shells filled with stagnant water. The improved expansions allow checking the accuracy of the solutions previously obtained and giving definitive results within the limits of Donnell's non-linear shallow-shell theory. The improved mode expansions include: (1) harmonics of the circumferential mode number n under consideration, and (2) only the principal n, but with harmonics of the longitudinal mode included. The effect of additional longitudinal modes is absolutely insignificant in both the driven and companion mode responses. The effect of modes with 2n circumferential waves is very limited on the trend of non-linearity, but is significant in the response with companion mode participation in the case of lightly damped shells (empty shells). In particular, the travelling wave response appears for much lower vibration amplitudes and presents a frequency range without stable responses, corresponding to a beating phenomenon. A liquid (water) contained in the shell generates a much stronger softening behaviour of the system. Experiments with a water-filled circular cylindrical shell made of steel are in very good agreement with the present theory.

References listed at the end of the paper:

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ABSTRACT: (none given)
ABSTRACT: The non-linear dynamics and stability of simply supported, circular cylindrical shells containing inviscid, incompressible fluid flow is analyzed. Geometric non-linearities of the shell are considered by using the Donnell's non-linear shallow shell theory. A viscous damping mechanism is considered in order to take into account structural and fluid dissipation. Linear potential flow theory is applied to describe the fluid–structure interaction. The system is discretized by Galerkin's method and is investigated by using two models: (i) a simpler model obtained by using a base of seven modes for the shell deflection, and (ii) a relatively high-dimensional dynamic model with 18 modes. Both models allow travelling-wave response of the shell and shell axisymmetric contraction. Boundary conditions on radial displacement and the continuity of circumferential displacement are exactly satisfied. Stability, bifurcation and periodic responses are analyzed by means of the computer code AUTO for the continuation of the solution of ordinary differential equations. Non-stationary motions are analyzed with direct integration techniques. An accurate analysis of the shell response is performed by means of phase space representation, Fourier spectra, Poincaré sections and their bifurcation diagrams. A complex dynamical behaviour has been found. The shell bifurcates statically (divergence) in absence of external dynamic loads by using the flow velocity as bifurcation parameter. Under harmonic load a shell conveying flow can give rise to periodic, quasi-periodic and chaotic responses, depending on flow velocity, amplitude and frequency of harmonic excitation.

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ABSTRACT: In the present study, the dynamic stability of simply supported, circular cylindrical shells subjected to dynamic axial loads is analysed. Geometric nonlinearities due to finite-amplitude shell motion are considered by using the Donnell’s nonlinear shallow-shell theory. The effect of structural damping is taken into account. A discretization method based on a series expansion involving a relatively large number of linear modes, including axisymmetric and asymmetric modes, and on the Galerkin procedure is developed. Axisymmetric modes are included; indeed, they are essential in simulating the inward deflection of the mean oscillation with respect to the equilibrium position and in describing the axisymmetric deflection due to axial loads. A finite length, simply supported shell is considered; the boundary conditions are satisfied, including the contribution of external axial loads acting at the shell edges. The effect of a contained liquid is investigated. The linear dynamic stability and nonlinear response are analysed by using continuation techniques and direct simulations.

References listed at the end of the paper:


ABSTRACT: The vibration response of a thin circular cylindrical panel to harmonic excitation in the neighborhood of the first three natural frequencies has been measured for different force levels. The experimental boundary conditions approximate (i) on the curved edges: zero radial, axial and circumferential displacements; all rotations were allowed; (ii) on the straight edges: zero radial and axial displacements; all rotations and circumferential displacements were allowed. The different levels of excitation permitted reconstruction of the relatively strong, softening type non-linearity of the panel.


ABSTRACT: Large-amplitude (geometrically non-linear) vibrations of circular cylindrical shells subjected to radial harmonic excitation in the spectral neighbourhood of the lowest resonances are investigated. The Lagrange equations of motion are obtained by an energy approach, retaining damping through Rayleigh's dissipation function. Four different non-linear thin shell theories, namely Donnell's, Sanders–Koiter, Flügge–Lur’e-Byrne and Novozhilov's theories, which neglect rotary inertia and shear deformation, are used to calculate the elastic strain energy. The formulation is also valid for orthotropic and symmetric cross-ply laminated composite shells. The large-amplitude response of perfect and imperfect, simply supported circular cylindrical shells to harmonic excitation in the spectral neighbourhood of the lowest natural frequency is computed for all these shell theories. Numerical responses obtained by using these four non-linear shell theories are also compared to results obtained by using the Donnell's non-linear shallow-shell equation of motion. A validation of calculations by comparison with experimental results is also performed. Both empty and fluid-filled shells are investigated by using a potential fluid model. The effects of radial pressure and axial load are also studied. Boundary conditions for simply supported shells are exactly satisfied. Different expansions involving from 14 to 48 generalized co-ordinates, associated with natural modes of simply supported shells, are used. The non-linear equations of motion are studied by using a code based on an arclength continuation method allowing bifurcation analysis.

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ABSTRACT: The present paper focuses on the theory and experiments for geometrically nonlinear vibrations of shell type structures made of traditional and advanced materials. Closed shells, curved panels and rectangular plates made of isotropic, sandwich and laminated composite materials are studied. Several original aspects of nonlinear vibrations of shells and panels including the effects of geometric imperfections, geometry and boundary conditions have been addressed and consistent reduced-order models essential to capture shell dynamics are obtained. The numerical analysis is based on multi-dimensional Lagrangian approach and pseudo arc-length continuation technique is used for bifurcation analysis. Moreover, the experimental analysis, an example of the set-up is shown in Figure 1, is carried out following a stepped-sine testing procedure and by increasing and decreasing the excitation frequency in very small steps at specific force amplitudes controlled in a closed-loop. Comparisons between experimental results and numerical simulations are performed and show good agreement for shells and panels oscillating at large-amplitude vibrations.

References listed at the end of the paper:


ABSTRACT: This study presents experimental results on the non-linear dynamics and stability characteristics of a thin-walled clamped-clamped circular cylindrical shell in contact with fluid. It also discusses theoretical results for simply-supported shells conveying inviscid and incompressible fluid. The non-linear Donnell shallow shell theory, with structural damping, is used to describe the large-amplitude shell vibrations. The interaction between the flowing fluid and the shell structure is formulated with linear potential flow theory. The aim of the experimental study was to gather for the first time important data points of the critical flow velocity for instability and maximum flexural displacement, and to analyze the experimental results to validate the theoretical model. The experimental study involved two set-ups: one containing a clamped-clamped silicone rubber shell and flowing air in internal and external flow configurations, and the second an aluminum shell and water as the flowing fluid. The interaction between the shell and the fully developed flow, in both cases, gives instabilities in the form of divergence at sufficiently high flow velocities. The experimental results show a softening type nonlinear behaviour with a large hysteresis in the velocity for the onset and cessation of divergence.

References listed at the end of the paper:


ABSTRACT: Large-amplitude (geometrically nonlinear) vibrations of circular cylindrical panels with rectangular base, simply supported at the four edges and subjected to radial harmonic excitation in the spectral neighbourhood of the lowest resonances are investigated. Two different nonlinear strain–displacement relationships, from the Donnell's and Novozhilov's shell theories, are used to calculate the elastic strain energy. In-plane inertia and geometric imperfections are taken into account. The solution is obtained by Lagrangian approach. The nonlinear equations of motion are studied by using (i) a code based on arclength continuation method that allows bifurcation analysis and (ii) direct time integration. Numerical results are compared to those available in the literature and convergence of the solution is shown. Interaction of modes having integer ratio among their natural frequencies, giving rise to internal resonances, is also discussed.


ABSTRACT: Large amplitude (geometrically non-linear) vibrations of doubly curved shallow shells with rectangular base, simply supported at the four edges and subjected to harmonic excitation normal to the surface in the spectral neighbourhood of the fundamental mode are investigated. Two different non-linear strain–displacement relationships, from the Donnell's and Novozhilov's shell theories, are used to calculate the elastic strain energy. In-plane inertia and geometric imperfections are taken into account. The solution is obtained by Lagrangian approach. The non-linear equations of motion are studied by using (i) a code based on arclength continuation method that allows bifurcation analysis and (ii) direct time integration. Numerical results are compared to those available in the literature and convergence of the solution is shown. Interaction of modes having integer ratio among their natural frequencies, giving rise to internal resonances, is discussed. Shell stability under static and dynamic load is also investigated by using continuation method, bifurcation diagram from direct time integration and calculation of the Lyapunov exponents and Lyapunov dimension. Interesting phenomena such as (i) snap-through instability, (ii) subharmonic response, (iii) period doubling bifurcations and (iv) chaotic behaviour have been observed.


ABSTRACT: Large-amplitude vibrations of circular cylindrical panels (open shells) subjected to harmonic excitation are numerically and experimentally investigated. The Donnell nonlinear strain–displacement relationships are used to describe the geometric nonlinearity; in-plane inertia is taken into account. Specific boundary conditions, with zero transverse displacement at the panel edges and free or elastically restrained in-plane displacements, not previously considered, have been introduced in order to model the experimental boundary conditions. The nonlinear equations of motion are obtained by the Lagrange equations with multi-mode approach, and are studied by using a code based on the pseudo-arclength continuation method. Two thin circular cylindrical panels of different dimensions and made of stainless steel have been experimentally tested in the laboratory for several excitation amplitudes in order to characterize the nonlinearity. The dimensions of the two panels have been chosen in order to have the fundamental mode with one and two circumferential half-
waves, respectively. Numerical results are able to reproduce the experimental results with high accuracy for both panels. The effect of geometric imperfections on the trend of nonlinearity and on natural frequencies is shown; convergence of the solution with the number of generalized coordinates is numerically verified.

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ABSTRACT: In this paper, the nonlinear stability of circular cylindrical shells subjected to internal incompressible flow is studied by means of the Donnell nonlinear shallow shell equations and a linear fluid–structure interaction model. Specifically, the effect of varying the thickness-to-radius (h/R) and length-to-radius (L/R) ratios is investigated. In general, the system loses stability by a subcritical pitchfork bifurcation, leading to a stable divergence of increasing amplitude with flow; no oscillatory solutions are found. Increasing the value of the circumferential wavenumber for shells with the same h/R ratio reduces the natural frequency and enhances the subcritical behaviour of the shell. Interesting results are found for different L/R cases in which the solution changes from subcritical to supercritical nonlinear behaviour.

References listed at the end of the paper:
Some of the references listed at the end of the paper:


INTRODUCTION: Most of studies on large-amplitude (geometrically nonlinear) vibrations of circular cylindrical shells used Donnell's nonlinear shallow-shell theory to obtain the equations of motion, as shown in Chapter 5. Only a few used the more refined Sanders-Koiter or Flügge-Lur'e-Byrne nonlinear shell theories. The majority of these studies do not include geometric imperfections, and some of them use a single-mode approximation to describe the shell dynamics. This chapter presents a comparison of shell responses to radial harmonic excitation in the spectral neighborhood of the lowest natural frequency computed by using five different nonlinear shell theories: (i) Donnell's shallow-shell, (ii) Donnell's with in-plane inertia, (iii) Sanders-Koiter, (iv) Flügge-Lur'e-Byrne and (v) Novozhilov theories. These five shell theories are practically the only ones applied to geometrically nonlinear problems among the theories that neglect shear deformation. Donnell's shallow-shell theory has already been used in Chapter 5, and the numerical results presented there are used for comparison. Shell theories including shear deformation and rotary inertia are not considered in this chapter. The results presented are based on the study by Amabili (2003).

Some of the references listed at the end of the paper:

34. I. I. Vorovich 1999 Nonlinear Theory of Shallow Shells. Springer-Verlag, New York, USA.

(Note: Many additional citations are given, but several of them seem to be repetitions of the citations just listed.)
INTRODUCTION: Doubly curved shells are largely used in aeronautics and aerospace and are subjected to dynamic loads that can cause vibration amplitudes of the order of the shell thickness, giving rise to significant nonlinear phenomena. In order to reduce the weight, traditional materials are often substituted with laminated panels. This justifies the study of nonlinear vibrations of isotropic and laminated curved panels. Nonlinear (large amplitude) forced vibrations of doubly curved shallow-shells are initially studied by using Donnell's theory retaining in-plane inertia and the Lagrange equations. The effect of the geometry and curvature are investigated for isotropic shells. Then, nonlinear free vibrations of laminated composite shells are studied by using both the Donnell and the first-order shear deformation theories in order to compare numerical results. It is observed that a shear deformation theory should be adopted for moderately thick laminated shells for which the ratio between the thickness and the largest of the in-plane curvilinear dimensions is equal or larger than 0.04. The stability of a spherical shell under static normal load is discussed. Finally, the example of buckling analysis of the external tank of the NASA space shuttle, taking into account the effect of initial geometric imperfections, is performed following the study of Nemeth et al. (2002).

INTRODUCTION: Circular cylindrical shells are very stiff structural elements with optimal use of the material. Therefore, they are also very light. This is one of the reasons why they are used for rockets (see Figure 13.1). Similarly to other thin-walled structures, the main strength analysis of circular cylindrical shells is a stability analysis; in fact, these structural elements buckle much before the failure stress of the material is reached. In this chapter, the stability and the postcritical behavior of circular cylindrical shells under the action of axial static and periodic loads are investigated. Because of the strongly subcritical nature of the pitchfork bifurcation associated with buckling, even if the static compression load is much smaller than the critical load, shells collapse under small perturbation with a jump from the trivial equilibrium configuration to the stable bifurcated solution. Moreover, circular cylindrical shells subjected to axial loads are highly sensitive to geometric imperfections. Periodic axial loads generate large-amplitude asymmetric vibrations due to period-doubling bifurcation of axisymmetric small-amplitude vibration. Period-doubling bifurcation arises for frequency of axial load close to twice the natural frequency of an asymmetric mode; this is usually referred as parametric instability. In fact, most of the studies are based on Donnell's nonlinear shallow-shell theory, so that axial loads do not appear directly in the equations of motion obtained with this shell theory, where only radial loads are directly inserted. They appear through boundary conditions, giving the so-called parametric excitation in the equation of motion.

ABSTRACT: The geometrically nonlinear forced vibrations of laminated circular cylindrical shells are studied by using the Amabili–Reddy higher-order shear deformation theory. An energy approach based on Lagrange equations, retaining modal damping, is used in order to obtain the equations of motion. An harmonic point
excitation is applied in radial direction and simply supported boundary conditions are assumed. The equations of motion are studied by using the pseudo-arclength continuation method and bifurcation analysis. A one-to-one internal resonance is always present for a complete circular cylindrical shell, giving rise to pitchfork bifurcations of the nonlinear response with appearance of a second branch with travelling wave response and quasi-periodic vibrations. The numerical results obtained by using the Amabili–Reddy shell theory are compared to those obtained by using an higher-order shear deformation theory retaining only nonlinear term of von Kármán type and the Novozhilov classical shell theory.

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“ABSTRACT: Human aortas are subjected to large mechanical stresses because of blood flow pressurization and through contact with the surrounding tissue. It is essential that the aorta does not lose stability by buckling with deformation of the cross-section (shell-like buckling) (i) for its proper functioning to ensure blood flow and (ii) to avoid high stresses in the aortic wall. A numerical bifurcation analysis employs a refined reduced-order model to investigate the stability of a straight aorta segment conveying blood flow. The structural model assumes a nonlinear cylindrical orthotropic laminated composite shell composed of three layers representing the tunica intima, media and adventitia. Residual stresses because of pressurization are evaluated and included in the model. The fluid is formulated using a hybrid model that contains the unsteady effects obtained from linear potential flow theory and the steady viscous effects obtained from the time-averaged Navier–Stokes equations. The aortic segment loses stability by divergence with deformation of the cross-section at a critical flow velocity for a given static pressure, exhibiting a strong subcritical behaviour with partial or total collapse of the inner wall. Preliminary results suggest directions for further study in relation to the appearance and growth of dissection in the aorta.

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ABSTRACT: The non-linear dynamics and stability of simply supported, circular cylindrical shells containing inviscid, incompressible fluid flow is analyzed. Geometric non-linearities of the shell are considered by using the Donnell's non-linear shallow shell theory. A viscous damping mechanism is considered in order to take into account structural and fluid dissipation. Linear potential flow theory is applied to describe the fluid–structure interaction. The system is discretized by Galerkin's method and is investigated by using two models: (i) a simpler model obtained by using a base of seven modes for the shell deflection, and (ii) a relatively high-dimensional dynamic model with 18 modes. Both models allow travelling-wave response of the shell and shell axisymmetric contraction. Boundary conditions on radial displacement and the continuity of circumferential displacement are exactly satisfied. Stability, bifurcation and periodic responses are analyzed by means of the
computer code AUTO for the continuation of the solution of ordinary differential equations. Non-stationary motions are analyzed with direct integration techniques. An accurate analysis of the shell response is performed by means of phase space representation, Fourier spectra, Poincaré sections and their bifurcation diagrams. A complex dynamical behaviour has been found. The shell bifurcates statically (divergence) in absence of external dynamic loads by using the flow velocity as bifurcation parameter. Under harmonic load a shell conveying flow can give rise to periodic, quasi-periodic and chaotic responses, depending on flow velocity, amplitude and frequency of harmonic excitation.

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ABSTRACT: The static and dynamic behavior of a compressed circular cylindrical shell having geometric imperfections is analyzed. The analysis is mainly performed by means of the Donnell’s nonlinear shallow-shell theory. However, the refined Sanders shell theory is also used for comparison. A suitable expansion of the radial displacement, able to describe both buckling and dynamic behaviors is developed; the effect of geometric imperfections is accounted for by means of a modal representation. The response of the shell subjected to a sinusoidal axial excitation at its ends, giving rise to a parametric excitation, is considered. The effect of imperfections on the critical value of the dynamic load, that causes the loss of stability of the system, is analyzed. Interesting nonlinear dynamic phenomena are observed: direct resonance with softening behavior and parametric instability with period doubling response.

References listed at the end of the paper:


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ABSTRACT: In the present paper the dynamic stability of circular cylindrical shells subjected to static and dynamic axial loads is investigated. Both Donnell’s nonlinear shallow shell and Sanders–Koiter shell theories have been applied to model finite-amplitude static and dynamic deformations. Results are compared in order to evaluate the accuracy of these theories in predicting instability onset and post-critical nonlinear response. The effect of a contained fluid on the stability and the post-critical behaviour is analyzed in detail. Geometric imperfections are considered and their influence on the dynamic instability and post-critical behaviour is investigated. Chaotic dynamics of pre-compressed shells is investigated by means of nonlinear time-series techniques, extracting correlation dimension and Lyapunov exponents.

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ABSTRACT: The dynamics of a circular cylindrical shell carrying a rigid disk on the top and clamped at the base is investigated. The Sanders–Koiter theory is considered to develop a nonlinear analytical model for moderately large shell vibration. A reduced order dynamical system is obtained using Lagrange equations: radial and in-plane displacement fields are expanded by using trial functions that respect the geometric boundary conditions. The theoretical model is compared with experiments and with a finite element model developed with commercial software: comparisons are carried out on linear dynamics. The dynamic stability of the system is studied, when a periodic vertical motion of the base is imposed. Both a perturbation approach and a direct numerical technique are used. The perturbation method allows to obtain instability boundaries by means of elementary formulae; the numerical approach allows to perform a complete analysis of the linear and nonlinear response.


ABSTRACT: In the present paper, the dynamic stability of circular cylindrical shells is investigated; the combined effect of compressive static and periodic axial loads is considered. The Sanders–Koiter theory is applied to model the nonlinear dynamics of the system in the case of finite amplitude of vibration; Lagrange equations are used to reduce the nonlinear partial differential equations to a set of ordinary differential equations. The dynamic stability is investigated using direct numerical simulation and a dichotomic algorithm to find the instability boundaries as the excitation frequency is varied; the effect of geometric imperfections is investigated in detail. The accuracy of the approach is checked by means of comparisons with the literature.


ABSTRACT: The present paper is focused on the experimental and theoretical analysis of circular cylindrical shells under base excitation. The shell axis is vertical, it is clamped at the base and connected to a rigid body on the top; the base provides a vertical seismic-like excitation. The goal is to investigate the shell response when a resonant harmonic forcing is applied: the first axisymmetric mode is excited around the resonance at relatively low frequency and low amplitude of excitation. A violent resonant phenomenon is experimentally observed as well as an interesting saturation phenomenon close to the previously mentioned resonance. A theoretical model is developed to reproduce the experimental evidence and provide an explanation of the complex dynamics observed experimentally; the model takes into account geometric shell nonlinearities, electrodynamic shaker equations and the shell shaker interaction.

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ABSTRACT: The axisymmetric buckling behavior of clamped shallow spherical shells under uniform pressure is investigated using Marguerre's shallow-shell equations of 1939. The deflected shape of the shell as well as the stress function are described by linear combinations of Bessel functions and modified Bessel functions that satisfy all the relevant boundary and continuity conditions. The buckling characteristics of these caps are examined using a fully nonlinear Galerkin solution procedure, a classical bifurcation analysis, and a reduced-stiffness bifurcation analysis. This allows the elucidation of the imperfection sensitivity and nonlinear behavior of this important class of shell structures. A systematic parametric analysis highlights the interplay between these contrasting approaches, and demonstrates the lower boundedness of the reduced-stiffness analytical procedure for predicting imperfection-sensitive elastic-collapse pressures and its potential importance as a design methodology. A simple closed-form solution is given for this analytical lower bound. This compares favorably with a large collection of available experimental results but demonstrates the variability and possible inadequacies in some of the existing design rules for spherical shell structures.


ABSTRACT: Based on Donnell shallow shell equations, the nonlinear vibrations and dynamic instability of axially loaded circular cylindrical shells under both static and harmonic forces is theoretically analyzed. First the problem is reduced to a finite degree-of-freedom one by using the Galerkin method; then the resulting set of coupled nonlinear ordinary differential equations of motion are solved by the Runge–Kutta method. To study the nonlinear behavior of the shell, several numerical strategies were used to obtain Poincaré maps, Lyapunov exponents, stable and unstable fixed points, bifurcation diagrams, and basins of attraction. Particular attention is paid to two dynamic instability phenomena that may arise under these loading conditions: parametric excitation of flexural modes and escape from the pre-buckling potential well. Calculations are carried out for the principal and secondary instability regions associated with the lowest natural frequency of the shell. Special attention is given to the determination of the instability boundaries in control space and the identification of the bifurcational events connected with these boundaries. The results clarify the importance of modal coupling in the post-buckling solution and the strong role of nonlinearities on the dynamics of cylindrical shells.

References listed at the end of the paper:

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ABSTRACT: The non-linear vibrations and instabilities of cylindrical shells under pulsating axial loads are investigated using Donnell’s shallow shell equations. Based on physical and mathematical reasoning, a meaningful low dimensional model is derived and used together with Galerkin method to obtain a set of coupled non-linear equations of motion. Particular attention is paid to the investigation of modal interaction between non-linear vibration modes with equal or nearly equal natural frequencies and to its influence on parametric instability and snap-through buckling. A parametric analysis using continuation techniques identifies the relevant bifurcations connected with the modal interaction and highlights their relevance in design.


ABSTRACT: This paper discusses the non-linear oscillations and dynamic instabilities of thin walled shells subjected to harmonic loads. Due to the presence of strong non-linearities and high sensitivity to small variations in control parameters, thin shells may display a complex dynamic behavior and, despite the recent advances in this field, there is still a lack of satisfactory solutions to this class of problems. There are several complicated issues relating to the dynamics of such structures. In this work some of these topics are addressed, namely shell discretization processes, influence of modal coupling on non-linear vibration modes, modal interaction between different non-linear vibration modes, imperfection sensitivity and fractal basin boundaries. To this end, the theory for quasi-shallow shells is used to study the non-linear vibrations and instabilities of thin cylindrical shells under axial load.


ABSTRACT: This paper discusses the derivation of discrete low-dimensional models for the non-linear vibration analysis of thin shells. In order to understand the peculiarities inherent to this class of structural problems, the non-linear vibrations and dynamic stability of a circular cylindrical shell subjected to dynamic axial loads are analyzed. This choice is based on the fact that cylindrical shells exhibit a highly non-linear behavior under both static and dynamic axial loads. Geometric non-linearities due to finite-amplitude shell motions are considered by using Donnell’s nonlinear shallow shell theory. A perturbation procedure, validated in previous studies, is used to derive a general expression for the non-linear vibration modes and the discretized equations of motion are obtained by the Galerkin method. The responses of several low-dimensional models are compared. These are used to study the influence of the modelling on the convergence of critical loads, bifurcation diagrams, attractors and large amplitude responses of the shell. It is shown that rather low-dimensional and properly selected models can describe with good accuracy the response of the shell up to very large vibration amplitudes.

References listed at the end of the paper:
The transient and steady state stability of cylindrical shells under harmonic axial loads is investigated through the evolution of basins of attraction. Both parametric instability and steady state basins of attraction but must be considered with care when transient stability is of interest. Based on these results, the behavior of the shell under harmonic axial load is investigated through the evolution of basins of attraction. Both parametric instability and escape from a safe pre-buckling well are considered. It is shown that damping has a beneficial influence on the magnitude of the steady-state basins of attraction but must be considered with care when transient stability is of interest.

ABSTRACT: The transient and steady-state instability of an axially loaded cylindrical shell is discussed in the present paper. Donnell's shallow shell theory is used and the shell spatial discretization is obtained by the Galerkin method. First, an alternative vision of the buckling problem through the evolution and erosion of safe basins using energy and geometric considerations is presented, using an autonomous conservative low dimensional but qualitatively consistent model. Then, the response of the corresponding dissipative system is studied in terms of transient and steady-state behavior. Based on these results, the behavior of the shell under harmonic axial load is investigated through the evolution of basins of attraction. Both parametric instability and escape from a safe pre-buckling well are considered. It is shown that damping has a beneficial influence on the magnitude of the steady-state basins of attraction but must be considered with care when transient stability is of interest.
This paper investigates the large deformations of an extended thick cylindrical tube under internal pressure. The methodology presented in this work is particularly suited to structural systems liable to unstable bifurcation.
pressure, with emphasis on the static nonlinear behavior and instabilities of the shell. Thick elastic tubes that undergo large elastic deformations under internal pressure can exhibit novel instabilities. After some deformation, part of the tube becomes highly deformed taking the form of a bulge, while the remainder appears almost unchanged. This local instability phenomenon corresponds to a limit point along the nonlinear equilibrium path. After the onset of these highly nonuniform deformations, the local bulge initially grows with a marked decrease in internal pressure while the rest of the tube unloads. First, a detailed experimental analysis is carried out involving different geometries and initial axial forces and the influence of the axial force and of the internal pressure on the critical pressure is investigated. The shell used in the experiments is composed of an isotropic, homogeneous and hyperelastic rubber, which is modeled as a Mooney–Rivlin incompressible material, described by two elastic constants. These constants are obtained by comparing the experimental and numerical solutions for the shell under axial tension. The governing shell equations are solved numerically using the finite-element method, using the program ABAQUS. The experimental results are, as shown in the paper, in satisfactory agreement with the numerical analysis.

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ABSTRACT: Structural systems liable to asymmetric bifurcation usually become unstable at static load levels lower than the linear buckling load of the perfect structure. This is mainly due to the imperfections present in real structures. The imperfection sensitivity of structures under static loading is well studied in literature, but little is know on the sensitivity of these structures under dynamic loads. The aim of the present work is to study the behavior of an archetypal model of a harmonically forced structure, which exhibits, under increasing static load, asymmetric bifurcation. First, the integrity of the system under static load is investigated in terms of the evolution of the safe basin of attraction. Then, the stability boundaries of the harmonically excited structure are obtained, considering different loading processes. The bifurcations connected with these boundaries are identified and their influence on the evolution of safe basins is investigated. Then, a parametric analysis is conducted to investigate the influence of uncertainties in system parameters and random perturbations of the forcing on the dynamic buckling load. Finally, a safe lower bound for the buckling load, obtained by the application of the Melnikov criterion, is proposed which compare well with the scatter of buckling loads obtained numerically.

References listed at the end of the paper:

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ABSTRACT: In formulating mathematical models for dynamical systems, obtaining a high degree of qualitative correctness (i.e. predictive capability) may not be the only objective. The model must be useful for its intended application, and models of reduced complexity are attractive in many cases where time-consuming numerical procedures are required. This paper discusses the derivation of discrete low-dimensional models for the nonlinear vibration analysis of thin cylindrical shells. In order to understand the peculiarities inherent to this class of structural problems, the nonlinear vibrations and dynamic stability of a circular cylindrical shell subjected to static and dynamic loads are analyzed. This choice is based on the fact that cylindrical shells exhibit a highly nonlinear behavior under both static and dynamic loads. Geometric nonlinearities due to finite-amplitude shell motions are considered by using Donnell's nonlinear shallow-shell theory. A perturbation procedure, validated in previous studies, is used to derive a general expression for the nonlinear vibration modes and the discretized equations of motion are obtained by the Galerkin method using modal expansions for the displacements that satisfy all the relevant boundary and symmetry conditions. Next, the model is analyzed via the Karhunen–Loève expansion to investigate the relative importance of each mode obtained by the perturbation solution on the nonlinear response and total energy of the system. The responses of several low-dimensional models are compared. It is shown that rather low-dimensional but properly selected models can describe with good accuracy the response of the shell up to very large vibration amplitudes.

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“Influence of Geometry on the Dynamic Buckling and Bifurcations of Cylindrical Shells”, SDSS’Rio 2010 Stability snd Ductility of Steel Structures E. Batista, P. Vellasco, L. de Lima (Eds.) Rio de Janeiro, Brazil, September 8 - 10, 2010
ABSTRACT: In this work, Donnell’s nonlinear shallow shell equations are used to study the dynamic buckling and bifurcations of simply supported cylindrical shells subjected to axial or lateral load. A modal expansion with eight degrees of freedom containing the fundamental, companion, axially asymmetric and five axi-symmetric modes is used to describe the lateral displacement of the shell. The Galerkin method is used to obtain the nonlinear equations of motion which are, in turn, solved by the Runge-Kutta method. Several studies on the nonlinear dynamics of cylindrical shells are found in literature but they are restricted to specific geometries. In this paper we intend to study through a detailed parametric analysis the influence of the shell geometry, specifically Batdorf’s parameter, length to radius ratio and radius to thickness ratio on the main nonlinear dynamic characteristics of the shell.

References listed at the end of the paper:
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ABSTRACT: In this work, Donnell’s non-linear shallow shell equations are used to study the dynamic instability of perfect simply supported orthotropic cylindrical shells with internal flowing fluid and subjected to either a compressive axial static pre-load plus a harmonic axial load or a harmonic lateral pressure. The fluid is assumed to be non-viscous and incompressible and the flow, isentropic and irrotational. An expansion with eight degrees of freedom, containing the fundamental, companion, gyroscopic, and four axi-symmetric modes is used to describe the lateral displacement of the shell. The Galerkin method is used to obtain the non-linear equations of motion which are solved by the Runge–Kutta method. A detailed parametric analysis clarifies the influence of the orthotropic material properties on the non-linear buckling and vibration characteristics of the shell. Numerical methods are used to identify the effect of the fluid flow and applied loads control parameters on the bifurcations and stability of the shell motions.

References listed at the end of the paper:

an axially pre-loaded, partially fluid-filled cylindrical shell. The Donnell non-linear shallow shell theory is used to study the nonlinear vibrations of the shell. For this, the Galerkin method is used, together with a suitable expansion that takes into account the main nonlinear interactions, to discretize the shell. The resulting nonlinear equations of motion are solved by numerical integration. The fluid is assumed to be non-viscous and incompressible and its inertial effects on the shell surface are obtained by the potential flow theory. A detailed parametric analysis is carried out to demonstrate the influence of the fluid height within the shell on the parametric instability load and on the snap-through buckling load in the main parametric resonance region. Using bifurcations diagrams, the main bifurcation events associated with these stability boundaries are identified. The influence of the different types of bifurcation and fluid height on the safety is also discussed.

References listed at the end of the paper:


ABSTRACT: In this work, Donnell’s non-linear shallow shell equations are used to study the dynamic instability of imperfect simply supported orthotropic cylindrical shells with internal flowing fluid and subjected to a compressive axial static pre-load plus a harmonic axial load. The fluid is assumed to be non-viscous and incompressible and the flow isentropic and irrotational. An expansion with eight degrees of freedom, containing the fundamental, companion, gyroscopic and five axi-symmetric modes is used to describe the lateral displacement of the shell. The geometric imperfections are described by the same expansion as the lateral displacement and the Galerkin method is used to obtain the non-linear equations of motion which are, in turn, solved by the Runge-Kutta method. Numerical methods are used to identify the most important bifurcations as the fluid flow is varied, special attention is given to the influence of the material properties and the influence of initial geometric imperfection on the global stability of the system.

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ABSTRACT: A theoretical analysis is presented for determining the elastic non-linear vibrations of a prestressed thin-walled cylindrical shell filled with an ideal fluid. For the vibrations of the shell itself, the dynamic version of the Sanders non-linear equations for the case of moderately small rotations is employed. Modal expansions are used for the displacements of the shell middle surface that are required to satisfy the “classical simply supported” boundary conditions and the circumferential periodicity condition. The fluid is taken as non-viscous and incompressible, and the coupling between the deformable shell and this medium is taken into account. The velocity potential is expanded in terms of harmonic functions which satisfy the Laplace equation term by term. The Galerkin method is used to reduce the problem to a system of coupled algebraic non-linear equations for the modal amplitudes. Solutions are presented to show the effects of fluid and shell parameters on the non-linear vibrations of the shell.

model of a parametrically excited cylindrical shell”, Nonlinear Dynamics, Vol. 63, pp. 61-82

ABSTRACT: In this paper the global dynamics and topological integrity of the basins of attraction of a parametrically excited cylindrical shell are investigated through a two-degree-of-freedom reduced order model. This model, as shown in previous authors’ works, is capable of describing qualitatively the complex nonlinear static and dynamic buckling behavior of the shell. The discretized model is obtained by employing Donnell shallow shell theory and the Galerkin method. The shell is subjected to an axial static pre-loading and then to a harmonic axial load. When the static load is between the buckling load and the minimum post-critical load, a three potential well is obtained. Under these circumstances the shell may exhibit pre- and post-buckling solutions confined to each of the potential wells as well as large cross-well motions. The aim of the paper is to analyze in a systematic way the bifurcation sequences arising from each of the three stable static solutions, obtaining in this way the parametric instability and escape boundaries. The global dynamics of the system is analyzed through the evolution of the various basins of attraction in the four-dimensional phase space. The concepts of safe basin and integrity measures quantifying its magnitude are used to obtain the erosion profile of the various solutions. A detailed parametric analysis shows how the basins of the various solutions interfere with each other and how this influences the integrity measures. Special attention is dedicated to the topological integrity of the various solutions confined to the pre-buckling well. This allows one to evaluate the safety and dynamic integrity of the mechanical system. Two characteristic cases, one associated with a sub-critical parametric bifurcation and another with a super-critical parametric bifurcation, are considered in the analysis.

References listed at the end of the paper:


PARTIAL ABSTRACT: Using Donnell non-linear shallow shell equations in terms of the displacements and the potential flow theory, this work presents a qualitatively accurate low dimensional model to study the nonlinear dynamic behavior and stability of a fluid-filled cylindrical shell under lateral pressure and axial loading. First, the reduced order model is derived taking into account the influence of the driven and companion modes. For this a modal solution is obtained by a perturbation technique which satisfies exactly the in-plane equilibrium equations and all boundary, continuity, and symmetry conditions. Finally, the equation of motion in the transversal direction is descritized by the Galerkin method.…. References listed at the end of the paper:

6. Pellicano, F.: Dynamic stability and sensitivity to geometric imperfections of strongly compressed circular cylindrical shells under
ABSTRACT: In this work, by using the Galerkin-iterative method, the non-linear free and forced vibrations of rectangular plates are investigated. This method gives the eigenfunctions for the lateral displacements of plates with different sets of boundary conditions. Special attention is given to the frequency-amplitude relations and to the parametric instability boundaries of rectangular plates in the force control space.


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ABSTRACT: A smart laminate model developed using the nonlinear piezoelectric model, i.e., electroelastic and electrostrictive effects, and von Kármán type geometric nonlinearity is proposed. On the basis of the proposed model, the analytical solutions for extensional and bending deformations of symmetrically constructed piezoelectric laminates under large electric fields are calculated. A comparison between the present nonlinear extension deformation of a piezoelectric laminated plate and the induced strain model shows that more realistic results are obtained with the present model. Numerical simulation reveals that the calculated results agree well with the experimental data.

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ABSTRACT: In this paper, a detailed analysis is conducted to study the influence of the geometric parameters, boundary conditions as well as initial imperfections on the nonlinear response and imperfection sensitivity of L-frames. An efficient nonlinear finite element formulation for the analysis of planar elastic frames is used together with incremental-iterative strategies. This enables one to obtain the highly nonlinear equilibrium paths exhibited by L-frames under certain loading conditions and identify the bifurcation and limit points along these equilibrium paths. These results provide some insight as to the source and mechanism of asymmetric bifurcation and imperfection sensitivity in frames thus helping engineers to evaluate the importance of geometric nonlinearities in the analysis and design of slender elastic frames.

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“Dynamic instability of cylindrical shells subjected to sudden step loads”, Proceedings of the 19th International Congress of Mechanical Engineering, November 5-9, 2007, Brasilia DF, Brazil

ABSTRACT: In this work the nonlinear behavior of a simply supported cylindrical shell under a sudden axial step load of infinite duration is investigated. The shell is modelled through the nonlinear shell theory of Donnell and the discretized equations of motion are obtained by the method of Galerkin based on a low dimensional modal solution derived in previous publications by the authors. The shell is initially considered to be at rest inside a potential well associated with the stable pre-buckling configuration. The effects of small initial geometric imperfections on the shell behavior is presented. The variation of the dynamic buckling load as a function of the geometric imperfection using Budiansky’s stability criterion is evaluated. It is observed that the escape occurs in the neighborhood of the saddle point that defines the frontier of the stable region. The erosion of the safe region of the basin of attraction with the load increment is also investigated. The sudden reduction of the safe region highlights the imperfection sensitivity of the shell under this type of load.

ABSTRACT: In the present study, the large-amplitude vibrations and stability of a perfect circular cylindrical shell subjected to axial harmonic excitation in the neighborhood of the lowest natural frequencies are investigated. Donnell’s shallow shell theory is used and the shell spatial discretization is obtained by the Ritz method. An efficient low-dimensional model presented in previous publications is used to discretize the continuous system. The main purpose of this work is to discuss the use of basins of attraction as a measure of the reliability and safety of the structure. First, the nonlinear behavior of the conservative system is discussed and the basin structure and volume is understood from the topologic structure of the total energy and its evolution as a function of the system parameters. Then, the behavior of the forced oscillations of the harmonically excited shell is analyzed. First the stability boundaries in force control space are obtained and the bifurcation events connected with these boundaries are identified. Based on the bifurcation diagrams, the probability of parametric instability and escape are analyzed through the evolution and erosion of basin boundaries within a prescribed control volume defined by the manifolds. Usually, basin boundaries become fractal. This together with the presence of catastrophic subcritical bifurcations makes the shell very sensitive to initial conditions, uncertainties in system parameters, and initial imperfections. Results show that the analysis of the evolution of safe basins and the derivation of appropriate measures of their robustness is an essential step in the derivation of safe design procedures for multiwell systems.

References listed at the end of the paper:
dynamics and instabilities of axially loaded fluid behavior. The aim of this paper is to investigate the influence of these internal resonances on the nonlinear natural frequencies, several equal or nearly equal frequencies may occur, leading to a complex dynamic behavior. The aim of this paper is to investigate the influence of these internal resonances on the nonlinear dynamics and instabilities of axially loaded fluid-filled cylindrical shells. For this, a modal solution that takes into account the internal resonances is presented. The results are compared with those obtained by other methods, and good agreement is found. The method is then applied to a specific case study, and the results are shown to be in excellent agreement with experimental data. ABSTRACT: Cylindrical shells exhibit a dense frequency spectrum, especially near the lowest frequency range. In addition, due to the circumferential symmetry, frequencies occur in pairs. So, in the vicinity of the lowest natural frequencies, several equal or nearly equal frequencies may occur, leading to a complex dynamic behavior. The aim of this paper is to investigate the influence of these internal resonances on the nonlinear dynamics and instabilities of axially loaded fluid-filled cylindrical shells. For this, a modal solution that takes into account the internal resonances is presented. The results are compared with those obtained by other methods, and good agreement is found. The method is then applied to a specific case study, and the results are shown to be in excellent agreement with experimental data.


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ABSTRACT: Cylindrical shells exhibit a dense frequency spectrum, especially near the lowest frequency range. In addition, due to the circumferential symmetry, frequencies occur in pairs. So, in the vicinity of the lowest natural frequencies, several equal or nearly equal frequencies may occur, leading to a complex dynamic behavior. The aim of this paper is to investigate the influence of these internal resonances on the nonlinear dynamics and instabilities of axially loaded fluid-filled cylindrical shells. For this, a modal solution that takes
into account the modal interaction among the relevant modes and satisfies the boundary and continuity conditions of the shell is derived. The shell is modeled using the Donnell nonlinear shallow shell theory and the discretized equations of motion are obtained by applying the Galerkin method. The shell is assumed to be completely filled with a dense fluid. The fluid is assumed to be incompressible and non-viscous and its irrotational motion is described by a velocity potential that satisfies the Laplace equation and relevant boundary and continuity conditions. Solving numerically the governing equations of motion, a detailed parametric analysis is conducted to clarify the influence of the internal resonances on the bifurcations, stability boundaries and nonlinear vibration modes.

References listed at the end of the paper:


ABSTRACT: This work investigates the influence of Young’s modulus, shells thickness, and geometrical imperfection uncertainties on the parametric instability loads of simply supported axially excited cylindrical
shells. The Donnell nonlinear shallow shell theory is used for the displacement field of the cylindrical shell and the parameters under investigation are considered as uncertain parameters with a known probability density function in the equilibrium equation. The uncertainties are discretized as Hermite-Chaos polynomials together with the Galerkin stochastic procedure that discretizes the stochastic equation in a set of deterministic equations of motion. Then, a general expression for the transversal displacement is obtained by a perturbation procedure which identifies all nonlinear modes that couple with the linear modes. So, a particular solution is selected which ensures the convergence of the response up to very large deflections. Applying the standard Galerkin method, a discrete system in time domain that considers the uncertainties is obtained and solved by fourth-order Runge-Kutta method. Several numerical strategies are used to study the nonlinear behavior of the shell considering the uncertainties in the parameters. Special attention is given to the influence of the uncertainties on the parametric instability and time response, showing that the Hermite-Chaos polynomial is a good numerical tool.


ABSTRACT: Slender structural systems liable to unstable buckling usually become unstable at load levels lower than the linear buckling load of the perfect structure. In some cases, experimental buckling loads can be just a small fraction of the theoretical critical load. This is mainly due to the imperfections present in real structures. The imperfection sensitivity of structures under static loading is well studied in the literature, but little is known on the sensitivity of these structures under dynamic conditions. In a dynamic environment not only geometric imperfections but also initial conditions (disturbances), physical and geometrical system parameters uncertainties and excitation noise influence the bifurcation scenario and basins of attraction. The aim of this work is to investigate the influence of inherent uncertainties of real systems and load noise on the dynamic integrity and stability of their solutions in a dynamic environment. To illustrate the system sensitivity, an archetypal model of slender systems liable to unstable buckling is used. Special attention is given to the influence of uncertainties and random noise on the basins of attraction of the system and consequently on the integrity measures of the unforced and forced system. The Melnikov criterion, erosion profiles based on different integrity measures and stochastic differential equations and polynomial chaos are discussed as possible tools to obtain reliable lower bounds for design.

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ABSTRACT: In this work the influence of geometry, load and material properties on the non-linear vibrations of a simply supported viscoelastic circular cylindrical shell subjected to lateral harmonic load is studied. Donnell’s non-linear shallow shell theory is used to model the shell, assumed to be made of a Kelvin-Voigt material type, and a modal solution with six degrees of freedom is used to describe the lateral displacements. The Galerkin method is applied to derive a set of coupled non-linear ordinary differential equations of motion. Obtained results show that the viscoelastic dissipation parameter has significant influence on the instability loads and resonance curves.

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Colin G. Foster (Department of Civil and Mechanical Engineering, University of Tasmania, GPO Box 252C, Hobart, Tasmania, 7001, Australia), “Interaction of buckling modes in thin-walled cylinders” (Results of combined load tests in buckling thin-walled cylinders show that existing published data may be inadequate), Experimental Mechanics, Vol. 21, No. 3, 1981, pp. 124-128, doi: 10.1007/BF02326369
ABSTRACT: This paper presents a summary of some recent buckling tests conducted on thin-walled cylinders. These tests were made with the cylinders in axial compression, hoop compression, torsion and combinations of all three. Results show that presently available design material on the interaction of buckling modes may need to be updated.

References listed at the end of the paper:

ABSTRACT: Collapse loads for thin walled cylinders loaded in axial compression can be estimated by considering the buckling failure of equivalent space frames. These loads are presented in the form of a design chart where the collapse load for any cylinder can be determined provided the radius to thickness ratio of the cylinder and the size of the shape defects in the cylinder are known. It is demonstrated how these defects can be evaluated by an optical examination of a proof loaded cylinder. There is good agreement between estimated collapse loads for cylinders with known shape defects and measured collapse loads.

ABSTRACT: Experiments on the axial compression buckling of high-quality epoxy cylindrical shells with imposed dimple-type defects are described. Additionally, a technique for the manufacture of high-quality epoxy conical shells which buckle at loads approaching the classical critical load is presented. For both types of shells,
prebuckling deformations have been monitored optically. The sizes of defects determined from the optical examination when applied in the space-frame approach to shell buckling have led to predicted knock-down factors which are remarkably consistent with measured knock-down factors (i.e., the ratio of actual collapse to classical critical load).

References listed at the end of the paper:

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ABSTRACT: In this paper an optical technique for the measurement of radial deformation in circular cylindrical shells is discussed. The technique is a modification and improvement on an earlier method, using a conical mirror of simple geometry to view a grating reflected from the inner surface of the shell. The new system allows more precise alignment of the components of the optical system with the shell. Fringes obtained by superposition as in the Ligtenberg moiré method, or deviations of lines from a regular pattern in a
photographic image provide a measure of the slope changes on the surface of the shell. Theoretical relations are presented for three grid orientations, at least two of which have to be used in conjunction to determine the two components of slope. Illustrations for the use and accuracy of the technique are presented for two cases. In the first, deflections due to a tilt of the axis of the test shell are measured; in the second, deformations associated with a radial point load applied at the free end of a cylindrical shell with one end built in are determined.

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“Measurement of axisymmetric prebuckling deformations in axially compressed cylindrical shells”,
ABSTRACT: This paper describes tests that were conducted on high-quality circular cylindrical shells loaded in axial compression. During the loading sequence the shells were continuously examined by an optical technique employing reflected grid lines. Because of the high sensitivity of the optical system, axisymmetric-ripple-type prebuckling deformations were detected even though the shells collapsed into the conventional dimple-type buckle pattern. Although this axisymmetric-type deformation is predicted by theoretical considerations only limited evidence of its existence has been previously reported.

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(2) Department of Civil and Mechanical Engineering, University of Tasmania, GPO Box 252C, Hobart, Tasmania, 7001, Australia
ABSTRACT: The influence of large localized geometric imperfections on the stability and axial load carrying capacity of thin isotropic circular cylindrical shells was investigated experimentally. Diamond shaped “Yoshimura facet type” dimples were introduced in otherwise near perfect cylinders, and their behavior under compressive load was monitored using a whole-field grid reflection technique. Buckling tests were conducted to determine the effects of shell geometry and variations in the size and number of defects. An empirical formula was developed for estimating the degradation in buckling strength caused by single or multiple local facet type defects.

S. Krishnakumar and C. G. Foster, “Axial load capacity of cylindrical shells with local geometric defects”
ABSTRACT: The effect of local geometric defects on the buckling load of axially compressed thin circular cylindrical shells is investigated experimentally. Defects, in the form of diamond-shaped local dimples, similar to the buckles of the Yoshimura pattern, were introduced in otherwise near perfect isotropic epoxy shells by locally heating the shell wall. The behavior of the defects under load was monitored optically using a special whole-field grid-reflection technique. The effects of variations in shell geometry and defect size are also
investigated. In general, the results indicate that the effect of local diamond-shaped defects on the stability of the axially loaded cylinder is not as detrimental as that of the global initial imperfections hitherto investigated.


FOREWORD: This Guide for the Buckling and Ultimate Strength Assessment of Offshore Structures is referred to herein as “this Guide”. This Guide provides criteria that can be used in association with specific Rules and Guides issued by ABS for the classification of specific types of Offshore Structures. The specific Rules and Guides that this Guide supplements are the latest editions of the following.

- Rules for Building and Classing Offshore Installations [for steel structure only]
- Rules for Building and Classing Mobile Offshore Drilling Units (MODUs)
- Rules for Building and Classing Single Point Moorings (SPMs)
- Rules for Building and Classing Floating Production Installations (FPIs) [for non ship-type hulls].

In case of conflict between the criteria contained in this Guide and the above-mentioned Rules, the latter will have precedence.


ABSTRACT: The objective of this paper is to perform dynamic nonlinear analysis of shell structures using a vector form intrinsic finite element (VFIFE). The procedures of VFIFE are designed to carry out a vector-mechanics-based theory, vector form analysis in which a fundamental concept called point value description is proposed. It enables VFIFE to deliberately treat the shell problems with large deflections, large overall motions and even fragmentations. The interaction forces amid particles are complemented by the generalized forces evaluated by a triangular element of VFIFE family recently developed using physical modeling procedures. In this paper, the problems with large overall motion, large deflection, nonlinear material property and contact/impact are further tested to justify the performance of the element on highly nonlinear analysis. It is reveals that the VFIFE element has good reliability and accuracy on solving shell problems with multiple nonlinearities.


ABSTRACT: Cylindrical shells, unstiffened or stiffened with rings and/or stringers are commonly used in offshore structures as main loading-carrying members. Comprehensive theoretical work and experimental studies on the buckling behavior of cylindrical shells have been carried out in the past. The increasing offshore application of stiffened cylindrical shells has raised some new challenges that need to be addressed. This paper provides the fundamental principles and technical background of the ABS buckling strength assessment criteria for cylindrical shells applied in offshore structures. The accuracy of ABS buckling criteria for assessing the cylindrical shells is established by benchmarking the results against an extensive database of test results assembled by American Bureau of Shipping. The results are also compared against current recognized offshore standards, such as API Bulletins 2U and DnV CN30.1. It is demonstrated that the ABS criteria provide very effective and sufficiently accurate predictions for the cylindrical shell buckling
calculations.

References listed at the end of the paper:


OUTLINE:
11.1 Introduction
Overview * Production Practice * Scope * Limitations * Stress Components for Stability Analysis and Design * Materials * Geometries, Failure Modes, and Loads * Buckling Design Method * Stress Factor * Nomenclature
11.2 Allowable Compressive Stresses for Cylindrical Shells Uniform Axial Compression * Axial Compression Due to Bending Moment * External Pressure * Shear * Sizing of Rings (General Instability)
11.3 Allowable Compressive Stresses For Cones Uniform Axial Compression and Axial Compression Due to Bending * External Pressure * Shear * Local Stiffener Buckling
11.4 Allowable Stress Equations For Combined Loads For Combination of Uniform Axial Compression and Hoop Compression * For Combination of Axial Compression Due to Bending Moment, M, and Hoop Compression * For Combination of Hoop Compression and Shear * For Combination of Uniform Axial Compression, Axial Compression Due to Bending Moment, M, and Shear, in the Presence of Hoop Compression, * For Combination of Uniform Axial Compression, Axial Compression Due to Bending Moment, M, and Shear, in the Absence of Hoop Compression
11.5 Tolerances for Cylindrical and Conical Shells Shells Subjected to Uniform Axial Compression and Axial Compression Due to Bending Moment * Shells Subjected to External Pressure * Shells Subjected to Shear
11.6 Allowable Compressive Stresses Spherical Shells * Toroidal and Ellipsoidal Heads
11.7 Tolerances for Formed Heads

References listed at the end of the paper:
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ABSTRACT: The pressure hulls of submersibles are frequently designed to BS5500 which evolved from RN submarine design. In this, failure by local interframe shell collapse is sought as a basis for design since the strength predictions are based on good experimental data. Overall modes of failure involving frame bending or tripping are avoided because of their greater shape sensitivity. This is achieved by a combination of higher safety factors and/or conservative assumptions.


ABSTRACT: A Level 1 code format is proposed for the buckling design of ring-stiffened cylindrical shells under external pressure. Depth independent partial safety factors to be applied to the resistance (collapse pressures) are proposed for the four relevant collapse modes (Interframe Shell Collapse, Frame Yield, Plate Yield and Frame Tripping), covering design and fabrication factors. A partial safety factor to be applied to the load (external pressure), and varying with the design pressure and the maximum expected overdiving, is proposed to cover operational factors. For deep diving vessels or in cases in which the risk of overdiving is not relevant, it is proposed that the overall safety factors used in design may be smaller than those presently recommended. In order to obtain such partial safety factors, different aspects of strength modeling and Structural Reliability had to be addressed. On the strength modeling side, the work was focused on the frame collapse modes. Seventy two experimental results were compiled, corresponding to machined models failing by elastic General Instability. Finite Element (FE) meshes were validated in view of mesh studies and experimental results and further used in parametric studies. The effect of boundary conditions on the elastic General Instability pressure \( p(n) \) was investigated in view of both experiments and results of the FE models. Statistical properties were obtained for the model uncertainty associated with \( p(n) \). Thirty five experimental results were compiled corresponding to welded models failing by General Instability. FE models were validated in view of the most relevant of these experiments as well as in view of other numerical results found in the literature. A closed form solution for the elastic Frame Tripping pressure, based on energy methods and showing good agreement with FE and other numerical results, was introduced. FE parametric studies showed the effects of
initial tilting angles of up to 4 degrees to be considerably less harmful than an initial o-o of 0.5%R, supporting the use of a modified Tangent Modulus approach for inelastic Tripping. On the Structural Reliability side, different reliability methods were reviewed, implemented and compared and the possibility of obtaining the failure probability in case of overdiving (or as a function of the external pressure in general) was verified, using any of the above methods. Notional safety levels of various types of existing structures were reviewed and target safety levels were proposed for externally pressurized, internally ring-stiffened cylinders in the four modes under consideration. Finally, partial safety factor optimization was carried out to obtain the partial safety factors.

ABSTRACT: Ring frame design is the aspect least well treated in the available design codes for orthogonally stiffened cylinders, particularly where axial load is dominant. Recent advances in this particular area are reviewed, together with the relevant theory and experiments. Detailed Finite Element analyses of a typical TLP column, as well as of its redesigned version, are presented and the results are compared with present prediction methods.

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ABSTRACT: This paper addresses the problem of designing ring frames in externally pressurised cylinders to avoid sideways tripping. A closed form solution is proposed for the elastic tripping pressure, including the effect of the rotational constraint provided by the shell to the toe of the web as well as the web deformation effect. Such theory compared reasonably well with numerical results given by ABAQUS as well as BOSOR4 and N9E. The differences become unimportant when a column curve is used for inelastic tripping, calculated with a structural tangent modulus approach. A safety factor for preliminary design is proposed based on parametric studies.

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ABSTRACT: The work presented in this paper forms part of a broader task in establishing a guide to serve as technical documentation for buckling and ultimate strength assessment of various types of marine structural components using the best state-of-the-art knowledge for extreme environmental loading. This paper concentrates on buckling and ultimate strength assessment of ring stiffened shells and ring and stringer stiffened shells involving various modes of buckling and under various loading like axial compression, radial pressure and combined loading. Comparisons are made with screened test data, which have realistic imperfections and various radius to thickness ratio values in the range generally used in offshore structures. The statistical data of
model uncertainty factors in terms of bias and coefficient of variation (COV) are calculated and may be used in a further reliability study. Comparisons are also made with the codified rules, API BUL 2U and DNV buckling strength of shells.

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ABSTRACT: The paper gives the results of an experimental study on three sets of AMT aluminum alloy cylindrical shells under axial impact. The length of the shell is 100 mm. Three different thicknesses 1.00mm, 1.42mm, and 2.00mm are used, and the shell is fixed on a jig and struck by a moving mass M (54gm.). The influence of different impact velocities on buckling behavior is discussed (see Fig. 2 and photographs 1, 2). It is found that when the impact velocity is less than a certain critical value Vc1, eq. (4), the shell will only exhibit uniform plastic deformation in both the axial and radial directions and does not produce sinusoidal waves. Vc1 is the critical velocity usually discussed in the literature, when this velocity is exceeded, the shell buckles. When the impact velocity exceeds another critical value Vc2, the shell will further change from the axisymmetric mode into a non-uniform type of large deformation. The shell shortens greatly and it begins to lose its load carrying capacity. We believe that this second critical velocity is also quite important in the study of dynamic plastic buckling characteristics. An approximate theoretical formula for estimating Vc2 based on strain rate reversal (violation of eq. 5) is given by eq. (7).

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Zhang Yanjiao (Huadong Institute of Technology) and Han Mingbao (Peking University); “An Experimental Study Of Instability Of Cylindrical Shells Under External Pressure And Axial Impact”; Explosion and Shock Waves; 1988-02

ABSTRACT: A dynamic plastic buckling analysis of three AMT aluminum alloy circular cylindrical shell with different thickness under external pressure and axial impact is presented in this paper. Experiments discover the presence of a critical speed vc2. which is corresponding to the collapse of the shell with large deformation and not the same as usually mentioned the critical speed vc1. In this paper the emphases of study are buckling mode and the relationship between vc2 and parameters of the axial deformation and the thickness of the shell.

ABSTRACT: Generally, thin cylindrical shells are susceptible for geometrical imperfections like non-circularity, non-cylindricity, dents, swellings etc. All these geometrical imperfections decrease the static buckling strength of thin cylindrical shells, but in this paper only effect of a dent on strength of a short (L / D "<1 and R/t = 280) stainless steel cylindrical shell is considered for analysis. The dent is modeled on the FE surface of perfect cylindrical shell for different angles of inclination and sizes at half the height of cylindrical shell. The cylindrical shells with a dent are analyzed using non-linear static buckling analysis. From the results it is found that in case of shorter dents, size and angle of inclination dents do not have much effect on static buckling strength of thin cylindrical shells, where as in the case of long dents, size and angle of inclination of dents have significant effect. But both short and long dents reduce the static buckling strength drastically.


ABSTRACT: One of the common failure modes of thin cylindrical shell subjected external pressure is buckling. The buckling pressure of these shell structures are dominantly affected by the geometrical imperfections present in the cylindrical shell which are very difficult to alleviate during manufacturing process. In this work, only three types of geometrical imperfection patterns are considered namely (a) eigen affine mode imperfection pattern, (b) inward half lobe axisymmetric imperfection pattern extended throughout the height of the cylindrical shell and (c) local geometrical imperfection patterns such as inward dimple with varying wave lengths located at the mid-height of the cylindrical shell. ANSYS FE non-linear buckling analysis including both material and geometrical non-linearities is used to determine the critical buckling pressure. From the analysis it is found that when the maximum amplitude of imperfections is 1t, the eigen affine imperfection pattern gives out the lowest critical buckling pressure when compared to the other imperfection patterns considered. When the amplitude of imperfections is above 1t, the inner half lobe axisymmetric imperfection pattern gives out the lowest critical buckling pressure when compared to the other imperfection patterns considered.

References at the end of the paper:
ABSTRACT: Thin plate structures are more widely used in many engineering applications as one of the structural members. Generally, buckling strength of thin shell structures is the ultimate load carrying capacity of these structures. The presence of cracks in a thin shell structure can considerably affect its load carrying capacity. Hence, in this work, static buckling strength of a thin square plate with a centre or edge crack under axial compression has been studied using general purpose Finite Element Analysis software ANSYS. Sensitivity of static buckling load of a plate with a centre or a edge crack for crack length variation and its vertical and horizontal orientations have been investigated. Eigen buckling analysis is used to determine the static buckling strength of perfect and cracked thin plates. First, bifurcation buckling loads of a perfect thin plate with its mode shapes from FE eigen buckling analysis are compared with analytical solution for validating the FE models. From the analysis of the cracked thin plates, it is found that vertical cracks are more dominant than horizontal cracks in reducing buckling strength of the thin plates. Further, it is also found that as the crack length increases, buckling strength decreases.

References listed at the end of the paper:

ABSTRACT: It is well known that thin cylindrical shell structures have wide applications as one of the important structural elements in many engineering fields and its load carrying capacity is decided by its buckling strength which in turn predominantly depends on geometrical imperfections present in it. Geometrical imperfections can be classified as local and distributed geometrical imperfections. But in this work, only local geometrical imperfection namely dent is considered for analysis. The main aim of this study is to determine the more influential dimensional parameter out of two dent dimensional parameters, one is the extent of dent present over a surface area and the other is dent depth, which affect the buckling strength of the cylindrical shells drastically. To account for the parameter “extent of dent present over an area”, the dent is considered as circular dent and its amplitude is considered as dent depth. For this purpose, finite element (FE) models of cylindrical shells with a circular dent at half the height of cylindrical shells having different dent sizes are generated. These FE models are analyzed using ANSYS non-linear buckling analysis. It is concluded that extent of dent present over an area is more influential than dent depth. To verify this conclusion further, FE models of cylindrical shells with two circular dents at half the height of cylindrical shell placed at 180° apart having different dent sizes are generated and analyzed.

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Hautala KT. (2003) Buckling reduction factors for stainless steel structures
ABSTRACT: Generally, thin cylindrical shells are susceptible for geometrical imperfections like non-circularity, non-cylindricity, dents, swellings, etc. All these geometrical imperfections decrease the static buckling strength of thin cylindrical shells, but in this paper only effect of a dent on strength of a short (Lc/Rc, vert, similar1, Rc/t=117, 175, 280) cylindrical shell is considered for analysis. The dent is modeled on the FE surface of perfect cylindrical shell for different angles of inclination and sizes at half the height of cylindrical shell. The cylindrical shells with a dent are analyzed using non-linear static buckling analysis. From the results it is found that in case of shorter dents, size and angle of inclination of dents do not have much effect on static buckling strength of thin cylindrical shells, whereas in the case of long dents, size and angle of inclination of dents have significant effect. But both short and long dents reduce the static buckling strength drastically. It is also found that the reduction in buckling strength of thin cylindrical shell with a dent of same size and orientation increases with increase in shell thickness.


ABSTRACT: Thin shell structures are efficient structures because of their high load-carrying capacity and small weight. Thin plates are one of the common structural elements. Their load-carrying capacity mainly depends on their buckling behavior, which is in turn affected by the imperfections present in them. Dent is one of the common geometrical imperfections in thin shell structures, which may be formed in the plate as an impact of sharp objects, among other reasons. Using ANSYS nonlinear FEA, the present work conducts a numerical study of the effect of various dent parameters on the ultimate strength of a thin plate, with a longitudinal or a transverse dent located centrally on the plate, under uniaxial compressive loading with simply supported boundary conditions.

References listed at the end of the paper:
the effect of single dent. It is found that the effect of two short dents and its nearness effect seem to be negligible compared with analysis and their buckling behaviours are compared with that of cylindrical shell with a short circumferential centre distance between the dents. These cylindrical shells are analysed using non linear FE modelled on the FE surface of perfect cylindrical shell at half the height of the cylindrical shell by varying the dents on the buckling behaviour of thin short stainless steel cylindrical shell is studied in detail. The dents are modelled on the FE surface of perfect cylindrical shell at half the height of the cylindrical shell by varying the centre distance between the dents. These cylindrical shells are analysed using non linear FE static buckling analysis and their buckling behaviours are compared with that of cylindrical shell with a short circumferential dent. It is found that the effect of two short dents and its nearness effect seem to be negligible compared with the effect of single dent in reducing the buckling strength of cylindrical shell.

ABSTRACT: In this paper, individual and combined effects of distributed and local geometrical imperfections on the limit load of an isotropic, thin-walled cylindrical shell under axial compression are investigated. First eigen affine mode shape imperfection pattern (FEAMSIP) is taken as distributed geometrical imperfections and dent as local geometrical imperfections. Limit load of the cylindrical shells are determined using non-linear static finite-element analysis module of general purpose FE software ANSYS. A parametric study on the effect of both imperfection patterns is done by varying the size and orientation of the dent. From the numerical results obtained, it is found that distributed geometrical imperfections namely, FEAMSIP have more influence on buckling strength than local geometrical imperfections namely dent.


ABSTRACT: One of the common failure modes of thin cylindrical shell subjected to external pressure is buckling. The buckling pressure of these shell structures are dominantly affected by the geometrical imperfections present in the cylindrical shell which are very difficult to alleviate during manufacturing process. Dent is one of the common geometrical imperfections present in thin shell structures which may be formed due to mechanical damage caused by accidental loading or impact. In this work, influence of various dent parameters (dent length, dent width, dent depth and angle of orientation of the dent) on the critical buckling pressure of thin cylindrical shells with a centrally located dent is studied using non-linear static finite-element analysis of ANSYS under external pressure with simply supported boundary conditions at the top and bottom edges of the thin cylindrical shell.

References listed at the end of the paper:


ABSTRACT: Generally, thin cylindrical shells are susceptible for geometrical imperfections like non-circularity, non-cylindricity, dents, swellings etc. All these geometrical imperfections decrease the static buckling strength of thin cylindrical shells. In this work, neighbourhood effect of two circumferential short dents on the buckling behaviour of thin short stainless steel cylindrical shell is studied in detail. The dents are modelled on the FE surface of perfect cylindrical shell at half the height of the cylindrical shell by varying the centre distance between the dents. These cylindrical shells are analysed using non linear FE static buckling analysis and their buckling behaviours are compared with that of cylindrical shell with a short circumferential dent. It is found that the effect of two short dents and its nearness effect seem to be negligible compared with the effect of single dent in reducing the buckling strength of cylindrical shell.


ABSTRACT: Thin steel plates are widely used in many structural applications because of its high load carrying capacity with less weight. The load carrying capacity of thin plates mainly depends on its buckling behavior which in turn is affected by the imperfections present in it. Dent is one of the common geometrical imperfections present in thin steel structures which may be formed due to mechanical damage caused by accidental loading or impact. In this work, influence of various dent parameters (dent length, dent width, dent depth and angle of orientation of the dent) on the static ultimate strength of thin square plates of different thicknesses under uniaxial compressive loading is studied. The dent is modeled on the FE surface of perfect thin square plate of size 1000 mm (of different thickness) for different sizes and angles of orientation of the dent at the center of the plate. These dented plates are analyzed using non-linear static buckling analysis of general purpose FE software ANSYS V12. From the results obtained, it is found that both shorter and longer dents reduce the ultimate strength drastically. But in case of shorter dents, variation of ultimate strength of dented plates due to variation of size and angle of orientation of dents is insignificant, whereas in the case of longer dents, size and angle of orientation of dents have significant effect. It is also found that the reduction in ultimate strength of thin plates with a dent of same size and orientation increases with increase in shell thickness.

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ABSTRACT: One of the common failure modes of thin cylindrical shells subjected to external pressure is buckling. The critical buckling pressures of these shell structures are mainly affected by the geometrical imperfections present in the cylindrical shell which are very difficult to alleviate during manufacturing process. Dent is one of the common geometrical imperfections present in thin shell structures which may be formed due to mechanical damage caused by accidental loading or impact. In this work, numerical parametric study is carried out to study the influence of dent parameters of centrally located dent (dent length, dent width, dent depth and angle of orientation of the dent), cylindrical shell parameters (L/R ratio and R/t ratio) and yield stress on the critical buckling pressure of externally pressurized thin dented cylindrical shells with simply supported boundary conditions at both top and bottom edges using non-linear static finite-element analysis of ANSYS.


ABSTRACT: The exact relation between strain and displacement is given for nonlinear deformation of thin shell. The fundamental formula of large deformation when the deflection is on the same class with the thickness of the shell is derived after simplified rationally. The fundamental formula of large deformation when the deflection is on the same class with the length of the shell is derived exactly for cylinder shell deformed cylindrical shaped.

References listed at the end of the paper:

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ABSTRACT: An incremental variational formulation and a curved-shell element were proposed in the companion paper. In this part, the material model and solution techniques are discussed in detail. The strain-hardening plastic approach is employed to model the compressive behavior of the concrete. A dual criterion is considered for yielding and crushing in terms of stresses and strains, which is completed with a tension cut-off representation. Both the crack interface effects and dowel action are accounted for by using an average shear
modulus, and a full bond is assumed at the steel-concrete interface. A total Lagrangian approach making use of the second Piola-Kirchhoff stress tensor is employed in this analysis. An incremental and iterative modified Newton-Raphson scheme is used for the solution of nonlinear problem. An energy criterion in terms of both forces and displacements is implemented. The applicability and validity of this analytical model incorporating both geometrical and material nonlinearities is amply demonstrated through several numerical examples. The solution technique proposed in this paper has been shown to be successful in preventing the drifting of the solution in incremental process.

ABSTRACT: The cylindrical shells under global bending with different geometric parameters display different failure behavior. The size of typical buckles under axial compressive stress regimes is rather small and extends over a very small zone, with the axial compressive stress reaching the critical value. The first estimate of the elastic buckling strength in bending is the condition in which the most compressed fiber reaches the buckling stress for uniform axial compression. For short cylinders, local bifurcation buckling occurs at the middle of the most compressed side of the shell, and geometric nonlinearity has a little effect on the buckling strength, while for medium-length and long cylinders, the geometric nonlinearity and the ovalization of the cross-section should be considered. This paper explores the failure behavior in elastic cylinders in pure bending.

ABSTRACT: On the project background of the large-scale thin-walled cylindrical shells of a practical desulphurizing absorption tower, the investigations are conducted into the buckling mode and buckling capacity of the large-scale thin-walled cylindrical shells under wind loading by nonlinear finite element methods. In the buckling path, it firstly presents the buckling mode similar to that of the stocky cylinder under uniform external radial compression. In the post-buckling stage, the snap-through takes place, the buckling mode turns to being similar to the axial compressive buckling mode of the medium-height cylinder that horizontal buckles occur in the upper half of the front area. The buckling capacity of the cylindrical shells of desulphurizing tower is some more than the linear elastic buckling pressure of the cylinder under uniform radial pressure.

ABSTRACT: During the years 1994 – 1999 a European research project under the title “Design and Validation of Imperfection-Tolerant Laminated Shells” (DEVILS) was carried out. In this project 11 European partners were involved. A goal of the project was an analytical and experimental study of the buckling behavior of thin-walled carbon fibre reinforced polymer (CFRP) laminated shells under combined axial and torsion loading. An
additional aim was to compose a guideline for the dimensioning of such shells. This paper deals with the experimental and the analytical work conducted by DLR (Institute of Structural Mechanics, Braunschweig), ETH Zurich (former Institute of Lightweight Structures and Ropeways) and EMPA Dübendorf (Department of Polymers/Composites) in that project. The study was aimed at the determination of buckling loads of circular cylindrical shells of different laminate lay-ups. Nine shells were tested at DLR in Braunschweig for axial compression and at EMPA in Dübendorf under axial load and under combined axial compression and superimposed torsion. To determine the geometrical quality the internal and external surfaces of the specimens were mapped. ETH used photogrammetry and laser scanning prior to loading, while EMPA applied coordinate measurements for the unloaded shells and Moiré projection to monitor the lateral deflection of the cylindrical wall during loading and after buckling. At DLR strain measurements were performed to assess regularity of the load distribution throughout the loading. The investigation showed that buckling loads of cylinders which are imperfection-sensitive under axial loading may not be so sensitive to combined loads. Furthermore, it was found that the stiffness eccentricity of the laminate played a significant role on the magnitude of the axial buckling load, while for combined loads this effect was somewhat reduced. This paper contains the results of those tests and also the comparison with results of analytical investigations and FE modeling. The obtained data can be used as benchmark reference.


ABSTRACT: On the basis of extensive buckling tests and analytical and numerical buckling analyses for composite cylinders it became desirable to provide a recommendation for the most reliable evaluation of stability limits for imperfect CFRP cylinders subjected to axial compression. This paper reports on different approaches including linear, non-linear and dynamic non-linear FE analysis results and discusses the related effects and potential difficulties.


ABSTRACT: This article deals with the linear static and buckling analysis of an asymmetric square sandwich plate with orthotropic stiffness properties in the face layers. Two analytical formulations related to thin and thick face layers, respectively, have been taken from (Zenkert, D. (1995). An Introduction to Sandwich Construction, Chameleon Press Ltd, London, UK (ISBN 0 947817 77 8)), slightly modified to account for unequal faces, orthotropic properties in the face layers, and individual Poisson’s ratios, and applied to square sandwich plates of 1 m lateral dimension and a variety of different face layer thickness. All cases assume simply supported edges. The obtained deflections and buckling loads are compared with the results of a 3D analysis (Meyer-Piening, H.-R. (2004). Application of the Elasticity Solution to Linear Sandwich Beam, Plate and Shell Analyses, J. of Sandwich Structures & Materials, 6(4): 295-312) and of finite element calculations. The objectives of this study are to gain insight into the limits of validity of the published formulas in view of unequal thick face layers and orthotropic properties. The obtained results are meant to serve as a benchmark for further studies.

PARTIAL INTRODUCTION: In systems with a large aspect ratio, a band of solutions with different wavenumbers \( q \) may exist above the instability threshold. …

References listed at the end of the paper:


ABSTRACT: We present a new asymptotic-numerical method for the buckling analysis of imperfect elastic structures. It improves the classical estimate given by the theories of postbuckling or of perturbed bifurcation. By this way, we are able to compute numerically a class of nonlinear problems by inverting only one stiffness matrix.

R. Abdelmoula (1), N. Damil (2), M. Potier-Ferry (3)
ABSTRACT: The influence of distributed and/or localized imperfections on the buckling load is analysed within the framework of cellular bifurcation theory. We propose analytical formulae for the reduction of the critical buckling pressure of those shells in the presence of various types of imperfections.

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ABSTRACT: This paper deals with the buckling of thin cylindrical shells with very large Batdorf parameters under external pressure. We first perform a simplified analysis from which we obtain explicit formulae for the critical load. An asymptotic analysis is carried out with a view to determining the effects of the boundary conditions on the critical loads and buckling shapes. The inverse of the Batdorf parameter is the convenient small parameter of the analysis. Among the whole set of boundary conditions, the axial boundary conditions are found to have crucially important at the first order. This analysis also shows the existence of boundary layers in which the remaining boundary conditions are only significant at the second order, at the very most.

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ABSTRACT: We revisit the delicate problem of choosing an appropriate constitutive law to model buckling of thin walled structures. The classical flow and deformation theories are compared with a micromechanical model. We establish that a polycrystalline modelling is able to explain why the deformation theory is better than the flow theory to predict plastic buckling. This comparison is achieved for a simple buckling problem, with a view to design characterization tests for the evaluation of the tangent stiffness matrix.

References listed at the end of the paper:


Sami Abdelkhalek (1,2), Hamid Zahrouni (2), Michel Potier-Ferry (2), Nicolas Legrand (3), Pierre Montmitonnet (1) and Pascal Buessler (3)

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ABSTRACT: Severe thin strip cold rolling conditions usually induce heterogeneity of in-bite plastic deformation always translated to irregular stress field. This stress field may dwell sufficiently compressive in several out-of-bite areas to cause buckling (flatness defects) which generates stress reorganisation in rolled strip and probably affects the bite zone. Hence, out-of-bite buckling, in-bite elastic-(visco)plastic deformation and thermo-mechanical roll-stack/strip interaction may be strongly coupled. However, a completely coupled model providing realistic rolled strip shape specially when flatness defects occur is not easy to establish. This call for two ways of flatness defect modelling in thin strip rolling: with a completely coupled approach but using a simple buckling criterion, or using an uncoupled approach by chaining strip rolling model calculation with shell element models presenting good buckling computing capabilities. Our objective is the improvement of the flat product rolling – specialized FEM software Lam3/Tec3 [1] using Counhaye simple buckling criterion [3] and
Asymptotic Numerical Method (ANM) for shell element model [9,10] respectively with coupled and uncouple approaches detailed in the present paper. These two approaches bring computed stress profiles to very good agreement with experiments and the most important result at this stage is the weak influence of buckling on in-bite stress and strain fields providing a more rigorous justification of the traditional decoupled methods [2,5-8]. References listed at the end of the paper:


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ABSTRACT: In many industrial conditions, light thin titanium shells are well used under various severe loading conditions. It is of interest to know the real conditions that govern the instability of a cracked panel subject to buckling loads in order to conserve as maximum as possible the strength of the structure. Several parameters can be varied in order to achieve this objective. The aim of this study is to determine the evolution of these parameters in order to achieve optimal crack propagation conditions while keeping these parameters within “reasonable” limits of physical and economic feasibility. For the purpose of the current study the considered structure can be regarded as thin cylindrical shell of radius r, thickness t with an initial through crack of length a. The titanium cylindrical shell is sealed on one edge and compression is applied on the other. An additional applied pressure can generates a stress and deformation field around the crack tip that has bending stresses and membrane stresses and appears as a bulge around the crack area. This paper give details of a simulation with FEA numerical analysis that determine governing instability conditions of a Titanium shell under particular loading conditions and to put in light the effect of bulging on the stress intensity factor at the crack tips. This bulging factor measures the severity of the stress intensity in the bulged crack compared to a plane shell subjected to equivalent loading conditions.
Michel Potier-Ferry (Laboratoire de Physique et Mécanique des Matériaux, Université de METZ, Ile du Saulcy, 57045, Metz, France), “Foundations of elastic postbuckling theory”, Chapter in Buckling and Post-Buckling, Vol. 288 of the series Lecture Notes in Physics, pp. 1-82

ABSTRACT: In this paper we present the elastic postbuckling theory, but we introduce two modifications with respect to its classical statement. First, we account for the influence of symmetries. Second, the singularities will be classified according to their robustness, what was introduced by Catastrophe Theory. Various recent progresses are discussed; mathematical foundations of the energy criterion, buckling of structures with a large aspect ratio, contribution of catastrophe theory ...

References listed at the end of the paper:
Ahmad Elhage-Hussein (1), Michel Potier-Ferry (1) and Noureddine Damil (2)

ABSTRACT: In the framework of the cellular bifurcation theory, we investigate the effect of distributed and/or localized imperfections on the buckling of long cylindrical shells under axial compression. Using a double scale perturbative approach including modes interaction, we establish that the evolution of amplitudes of instability patterns is governed by a non-homogeneous second order system of three non-linear complex equations. The localized imperfections are included by employing jump conditions for their amplitude and permitting discontinuous derivatives. By solving these amplitude equations, we show the influence of distributed and/or localized imperfections on the reduction of the critical load. To assess the validity of the present method, our results are compared to those given by two finite element codes.

ABSTRACT: In this paper the buckling and post-buckling of elastic structures taking into account large rotations are investigated using an asymptotic-numerical method. The critical points are detected by two different ways: first by a bifurcation indicator, second by analysing the poles of a Padé approximant. The first step of the post-buckling branch is computed starting from the bifurcation point and using an extended system. The remaining bifurcating branch is followed by the same algorithm as for the fundamental path. Several
examples are tested to show the effectiveness of the proposed method.

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“Buckling of a functionally graded coating with an embedded crack bonded to a homogeneous substrate”,
doi: 10.1007/s10704-006-9031-8

ABSTRACT: In an attempt to simulate buckling of nonuniform coatings, we consider the problem of an embedded crack in a functionally graded coating bonded to a homogeneous substrate subjected to a compressive loading. The coating is graded in the thickness direction and the material gradient is orthogonal to the crack direction which is parallel with the free surface. The loading consists of a uniform compressive strain applied away from the crack region. The graded coating is modeled as a nonhomogeneous medium with an isotropic stress-strain law. Using a nonlinear continuum theory and a suitable perturbation technique, the plane strain problem is reduced to an eigenvalue problem describing the onset of buckling. Using integral transforms, the resulting plane elasticity equations are converted analytically into singular integral equations which are solved numerically to give the critical buckling strain and the corresponding crack opening displacement shapes. The main objective of the paper is to study the influence of material nonhomogeneity on the buckling resistance of the graded layer for various crack positions and coating thicknesses.

References listed at the end of the paper:

F. Khouli, R.G. Langlois and F.F. Afagh (Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Ontario, Canada), “Analysis of active closed cross-section slender beams based on asymptotically correct thin-wall beam theory”, Smart Materials and Structures, Vol. 18, No. 1, January 2007

ABSTRACT: An asymptotically correct theory for multi-cell thin-wall anisotropic slender beams that includes the shell bending strain measures is extended to include embedded active fibre composites (AFCs). A closed-form solution of the asymptotically correct cross-sectional actuation force and moments is obtained. Active thin-wall beam theories found in the literature neglect the shell bending strains, which lead to incorrect predictions for certain cross-sections, while the theory presented is shown to overcome this shortcoming. The theory is implemented and verified against single-cell examples that were solved using the University of Michigan/Variational Beam Sectional Analysis (UM/VABS) software. The stiffness constants and the actuation vector are obtained for two-cell and three-cell active cross-sections. The theory is argued to be reliable for efficient initial design analysis and interdisciplinary parametric or optimization studies of thin-wall closed cross-section slender beams with no initial twist or obliqueness.

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ABSTRACT: Based on a non-linear stability model, analytical solutions are derived for simply supported beam-column elements with bi-symmetric I sections under combined bending and axial forces. An unique compact closed-form is used for some representative load cases needed in design. It includes first-order bending distribution, load height level, pre-buckling deflection effects and presence of axial loads. The proposed solutions are validated by recourse to non-linear FEM software where shell elements are used in mesh process. The agreement of the proposed solutions with bifurcations observed on non-linear equilibrium paths is good. It is proved that classical linear stability solutions underestimate the real resistance of such element in lateral buckling stability especially for I section with large flanges. Numerical study of incidence of axial forces on lateral buckling resistance of redundant beams is carried out. When axial displacements of a beam are prevented
important tension axial forces are generated in the beam. This results in important reduction of displacements and for some sections, the beam behaviour becomes non-linear without any bifurcation.

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ABSTRACT: New results are presented for the finite element analysis of wrinkling in curved elastic membranes under-going large deformation. Concise continuum level governing equations are derived in which singularities are eliminated. A simple and efficient algorithm with robust convergence properties is established to find the real strain and stress of the wrinkled membrane for Hookean materials. The continuum theory is implemented into a finite element code. Explicit formulas for the internal forces and the tangent stiffness matrix are derived. Numerical examples are presented that demonstrate the effectiveness of the new theory for predicting wrinkling in membranes undergoing large deformation.

ABSTRACT: Thin-film membrane structures are under consideration for use in many future gossamer spacecraft systems. Examples include sunshields for large-aperture telescopes, solar sails, and membrane optics. The development of capabilities for testing and analyzing pretensioned, thin-film membrane structures is an important and challenging aspect of gossamer spacecraft technology development. Results are presented from experimental and computational studies performed to characterize the wrinkling behavior of thin-film membranes under mechanical loading. The test article is a 500-mm-square Kapton membrane subjected to symmetric corner loads. Data are presented for loads ranging from 0.49 to 4.91 N. The experimental results show that as the load increases the number of wrinkles increases, while the wrinkle amplitude decreases. The computational model uses a finite element implementation of Stein–Hedgepeth membrane wrinkling theory to predict the behavior of the membrane. Comparisons were made with experimental results for the wrinkle angle and wrinkled region. There was reasonably good agreement between the measured wrinkle angle and the predicted directions of the major principle stresses. The shape of the wrinkled region predicted by the finite element model matches that observed in the experiments; however, the size of the predicted region is smaller that that determined in the experiments.

ABSTRACT: A buckling solution and a non-linear post buckling solution were employed for the wrinkling analysis of a tensioned Kapton square membrane. The buckling solution with significantly reduced bending stiffness creates localized buckling modes accounting for the wrinkle formation in the membrane. The non-linear post buckling solution with an updated Lagrangian scheme describes the detailed wrinkle evolution during the loading process. Simulations show wrinkle amplitudes decrease as the tension load increases. The wrinkle number and distribution remain stable until loads exceed a certain level, then new wrinkles occur usually by splitting from existing wrinkles. The evolution of existing wrinkles and formation of new wrinkles in simulations are consistent with experimental observations.
References listed at the end of the paper:

ABSTRACT: In this paper three fundamental issues regarding modeling and analysis of wrinkled membranes are addressed. First, a new membrane model with viable Young's modulus and Poisson's ratio is proposed, which physically characterizes stress relaxation phenomena in membrane wrinkling, and expresses taut, wrinkled and slack states of a membrane in a systematic manner. Second, a parametric variational principle is developed for the new membrane model. Third, by the variational principle, the original membrane problem is converted to a non-linear complementarity problem in mathematical programming. A parametric finite element discretization and a smoothing Newton method are then used for numerical solution. The proposed membrane model and numerical method are capable of delivering convergent results for membranes with a mixture of wrinkled and slack regions, without iteration of membrane stresses. Three numerical examples are provided.

ABSTRACT: The computational challenge in dealing with membrane systems is closely connected to the lack of bending stiffness that constitutes the main feature of this category of structures. This manifests numerically in badly conditioned or singular systems requiring the use of stabilized solution procedures, in our case of a ‘pseudo-dynamic’ approach. The absence of the flexural stiffness makes the membrane very prone to local instabilities which manifest physically in the formation of little ‘waves’ in ‘compressed’ areas. Current work presents an efficient, sub-iteration free ‘explicit’, penalty material based, wrinkling simulation procedure suitable for the solution of ‘static’ problems. The procedure is stabilized by taking full advantage of the pseudo-dynamic solution strategy, which allows to retain the elemental quadratic convergence properties inside the single solution step. Results are validated by comparison with published results and by setting up ‘numerical experiments’ based on the solution of test cases using dense meshes.

ABSTRACT: This paper reviews conventional wrinkle models for anisotropic membrane and shows the
A new wrinkle model is proposed which assumes virtual shear as well as virtual elongation of the membrane to estimate the real strain in the wrinkled region. This model coincides with the other models if the virtual shear and elongation is determined so that the strain energy is minimized. Another wrinkle/slack model is proposed for the dynamic analysis of thin isotropic membrane undergoing large overall motion with wrinkle and slack. It can take into account the residual compressive stress in the wrinkled and slack regions, i.e. the stiffness in the post-buckling state. It is shown that the proposed model is a generalization of the conventional ones. Finite element formulation of the proposed model is described. Furthermore, the energy momentum conservation framework is constructed for the proposed membrane element, which achieves the unconditionally stable time integration. The total of the proposed method enables us to compute the overall motion of thin isotropic membrane such as the deployment of folded membrane, which has been one of the most difficult problems in aerospace engineering.


ABSTRACT: A simple computer implementation of membrane wrinkle behaviour is presented within the classical elastic plane stress constitutive model. In the present method, a projection technique is utilized for modelling of the wrinkle mechanisms, in which the total strains in wrinkled membranes are decomposed into elastic and zero-strain energy parts, and a projection matrix that extracts the elastic parts from the total strains is derived. The resulting modified elasticity matrix that represents the stress–strain relations in wrinkled membranes is thus obtained as product of the classical elasticity matrix and the projection matrix. The modified elasticity matrix is straightforward to implement within the context of the finite element method. Numerical examples are presented to demonstrate the accuracy and effectiveness of the proposed method.

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ABSTRACT: In this paper, a new technique using slowly variable Fourier coefficients and the asymptotic Landau–Ginzburg approach are re-discussed and compared. The aim is to define simple macroscopic models describing the influence of local wrinkling on membrane behaviour. This question is analyzed by considering the simple example of a beam resting on a non-linear Winkler foundation.

References listed at the end of the paper:


This paper presents a detailed experimental study of the formation and evolution of the wrinkle pattern that form in flat elastic and isotropic membranes under the action of in-plane tension. The experiments were carried out on a cruciform specimen stretched along two uncoupled axes using various loading paths. The wrinkled shapes of the membrane were digitized by using a full-field measurement based on the fringe analysis method. Over this experiment, several phenomena were observed: the mechanism of wrinkle division, the influence of the membrane thickness on the wrinkle pattern, and the reproducibility of a kinematic configuration of wrinkles. The main result is that non-unique wrinkle shapes have been observed over repeated experiments for nominally identical boundary conditions. The uncertainty of the experimental wrinkle shape has been explained using comparison with the results of a post-buckling finite element analysis.

References listed at the end of the paper:


ABSTRACT: Membrane modeling in the presence of wrinkling is revisited from a multi-scale point of view. In the engineering literature, wrinkling is generally accounted at a macroscopic level by nonlinear constitutive laws without compressive stiffness, but these models ignore the properties of wrinkles, such as their wavelength, size and spatial distribution. A new multi-scale approach is discussed that belongs to the family of Ginzburg-Landau bifurcation equations. By using the method of Fourier series with variable coefficients, several nonlinear macroscopic models are derived that couple the membrane response with equations governing the evolution of the wrinkles. Contrary to previous approaches, these macroscopic models are completely deduced from the “microscopic” shell model without any phenomenological assumptions. Some analytical and numerical solutions are discussed that prove the relevance of the presented modeling. A new
class of models has been established. It permits to predict the characteristics of the wrinkles and their influence on membrane behavior.

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ABSTRACT: This paper presents a detailed Finite Element Analysis study of the formation and evolution of wrinkle pattern that observed in stretched thin membranes. The model problem is set up under the various load conditions. As a precondition for wrinkling, development of compressive stresses in the transverse direction is found to depend on both the length-to-width aspect ratio & thickness of the rectangular membrane. Shape and size of wrinkle also depends on applied tensile strain and shear strain. The analysis has been done in two parts; in first part we see the effect of thickness of membrane and number of element variation on number of wrinkles and eigenvalue frequency. In second part, two-dimensional stress analysis is performed under the plane-stress condition to finding out stretch-induced stress distribution patterns in the elastic membrane. The analysis has been carried out on the rectangular membrane with tensile loading with assuming imperfections in the structure with the ABAQUS a commercially available finite element package. Wrinkling patterns are presented to show how wrinkle formation with increasing shear loads, tensile loads, membrane thickness and number of elements.

References listed at the end of the paper:


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ABSTRACT: Mechanics of tympanic membrane (TM) is crucial for investigating the acoustic transmission through the ear. In this study, we studied the wrinkling behavior of tympanic membrane when it is exposed to mismatched air pressure between the ambient and the middle ear. The Rayleigh–Ritz method is adopted to analyze the critical wrinkling pressure and the fundamental eigenmode. An approximate analytical solution is obtained and validated by finite element analysis (FEA). The model will be useful in future investigations on how the wrinkling deformation of the TM alters the acoustic transmission function of the ear.


ABSTRACT: We investigate the buckling behavior of thin cylindrical shape-memory shells at room temperature, using a modified split Hopkinson bar and an Instron hydraulic testing machine. The quasi-static buckling response is directly observed using a digital camera with a close-up lens and two back mirrors. A high-speed Imacon 200 framing camera is used to record the dynamic buckling modes. The shape-memory shells with an austenite-finish temperature less than the room temperature, buckle gradually and gracefully in quasi-static loading, and fully recover upon unloading, showing a superelastic property, whereas when suitably annealed, the shells do not recover spontaneously upon unloading, but they do so once heated, showing a shape-memory effect. The gradual and graceful buckling of the shape-memory shells is associated with the stress-induced martensite formation and seems to have a profound effect on the unstable deformations of thin structures made from shape-memory alloys.

References listed at the end of the paper:

ABSTRACT: To investigate the buckling behavior of thin and relatively thick cylindrical shape-memory shells, uniaxial compression tests are performed at a 295 K initial temperature, using the CEAM/UCSD's modified split Hopkinson bar systems and an Instron hydraulic testing machine. The quasi-static buckling response of the shells is directly observed and recorded using a digital camera with a close-up lens and two back mirrors. To document the dynamic buckling modes, a high-speed Imacon 200 framing camera is used. The shape-memory shells with an austenite-finish temperature of $A(f) = 281$ K, buckle gradually and gracefully in quasi-static loading, and fully recover upon unloading, showing a superelastic property, whereas when suitably annealed, the shells do not recover spontaneously upon unloading, but they do so once heated, showing a shape-memory effect. The thin shells had a common thickness of 0.125 mm a common outer radius of 2.25 mm (i.e., a common radius, $R$, to thickness, $t$, ratio, $R/t$, of 18). A shell with the ratio of length, $L$, to diameter $D$ ($L/D$) of 1.5 buckled under a quasi-static load by forming a nonsymmetric chessboard pattern, while with a $L/D$ of 1.95 the buckling started with the formation of symmetrical rings which then changed into a nonsymmetric chessboard pattern. A similar buckling mode is also observed under a dynamic loading condition for a shell with $L/D$ of 2. However thicker shells, with 0.5 mm thickness and radius 4 mm ($R/t = 8$), buckled under a dynamic loading condition by the formation of a symmetrical ring pattern. For comparison, we have also tested shells of similar geometry but made of steel and aluminum. In the case of the steel shells with constrained end conditions, the buckling, which consists of nonsymmetric (no rings) folds (chessboard patterns), is sudden and catastrophic, and involves no recovery upon unloading. The gradual buckling of the shape-memory shells is associated with the stress-induced martensite formation and seems to have a profound effect on the unstable deformations of thin structures made from shape-memory alloys.

References listed at the end of the paper:


Sia Nemat-Nasser (1), Mahmoud Reza Amini (1), Jeom Yong Choi (2) and Jon Isaacs (1)
(1) Center of Excellence for Advanced Materials, Department of Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, CA 92093-0416, United States
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ABSTRACT: We report experiments and simulations of the dynamic and quasistatic compressive response of single and hex-arrayed thick aluminum tubes. The investigation aims to further characterize how tube-based sandwich structures absorb energy. First, we study by compression tests the quasistatic buckling of single tubes of 7075 aluminum, an alloy showing sufficient ductility and plasticity to make it potentially a good choice for energy absorbing devices. The experiments show geometry-dependent buckling modes. The corresponding finite element numerical simulations correlate well and will help estimate the maximum load level, and the buckling and postbuckling responses. Second, we study the dynamic buckling of sandwiched, hex-arrayed 3003 aluminum tubes. The simulations and experimental results correlate well and show a remarkable increase in energy absorbing capacity, which is caused by the postbuckling interaction of neighboring tubes. They also show that, as the tube spacing is decreased, the overall energy absorbed increases significantly. We also simulate how varying tube length and thickness affect the buckling of the array under dynamic loading.

References listed at the end of the paper:
S. Nemat-Nasser (1) and Jeam Yong Choi (2), Jon B. Isaacs (1) and David W. Lischer (1)
(1) Center of Excellence for Advanced Materials, University of California, San Diego
(2) POSCO, Pohang, South Korea
ABSTRACT: To investigate the buckling behavior of thin and relatively thick cylindrical shape-memory shells, uniaxial compression tests are performed at a 295 K initial temperature, using the CEAM/UCSD’s modified split Hopkinson bar systems and an Instron hydraulic testing machine. The quasi-static buckling response of the shells is directly observed and recorded using a digital camera with a close-up lens and two back mirrors. To document the dynamic buckling modes, a high-speed Imacon 200 framing camera is used. The shape-memory shells with an austenite-finish temperature of $A_f = 281$ K, buckle gradually and gracefully in quasi-static loading, and fully recover upon unloading, showing a superelastic property, whereas when suitably annealed, the shells do not recover spontaneously upon unloading, but they do so once heated, showing a shape-memory effect. The thin shells had a common thickness of 0.125 mm a common outer radius of 2.25 mm (i.e., a common radius, $R$, to thickness, $t$, ratio, $R/t$, of 18). A shell with the ratio of length, $L$, to diameter, $D$ $L/D$ of 1.5 buckled under a quasi-static load by forming a nonsymmetric chessboard pattern, while with a $L/D$ of 1.95 the buckling started with the formation of symmetrical rings which then changed into a nonsymmetric chessboard pattern. A similar buckling mode is also observed under a dynamic loading condition for a shell with $L/D$ of 2. However, thicker shells, with 0.5 mm thickness and radius 4 mm $R/t=8$, buckled under a dynamic loading condition by the formation of a symmetrical ring pattern. For comparison, we have also tested shells of similar geometry but made of steel and aluminum. In the case of the steel shells with constrained end conditions, the buckling, which consists of nonsymmetric (no rings) folds (chessboard patterns), is sudden and catastrophic, and involves no recovery upon unloading. The gradual buckling of the shape-memory shells is associated with the stress-induced martensite formation and seems to have a profound effect on the unstable deformations of thin structures made from shape-memory alloys.
Karman nonlinear displacement–strain relationships are applied to consider large deflections due to thermal loads. The cylindrical arc-length method is used to take account of the snapping phenomenon which is an unstable behavior observed in the shell panels. A nonlinear finite element procedure based on Brinson's model is developed to investigate the behaviors of shape memory alloy (SMA) wire. The results of numerical analysis show that the recovery stresses of SMA wires can enhance the stiffness of structure and the SMAHC shell panel exhibits superior behaviors of thermal post-buckling compared to the conventional composite panel. It is also shown that embedding SMA wires in a composite structure can prevent the unstable post-buckling behavior.

Xinzhen He, Huadong Yong and Youhe Zhou (Key Laboratory of Mechanics on Disaster and Environment, Department of Mechanics and Engineering Science, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, People's Republic of China), “The characteristics and stability of a dielectric elastomer spherical shell with a thick wall”, Smart Materials and Structures, Vol. 20, No. 5, 2011, doi:10.1088/0964-1726/20/5/055016
ABSTRACT: When a voltage is applied between the internal and external surface of a dielectric elastomer spherical shell, positive charges appear on one surface and negative charges on the other. This gives rise to Coulomb forces between opposite charges, generating a pressure. Thus, the shell reduces in thickness and stretches in area, and a higher electric field is produced. This positive feedback may make the shell continually thin down, eventually causing electrical instability. In this paper we use the neo-Hookean model and the Arruda–Boyce model to analyze the electromechanical instability of the thick-walled shell respectively. The electric field in the shell is inhomogeneous and varies with the radius of the shell. The instability in spherical shells with different thicknesses and boundary conditions is discussed. When the elastomer obeys the Arruda–Boyce model, the stability is related to the parameter $n$. The spherical shell will appear with snap-through instability and pull-in instability for different values of the parameter $n$.

Guanghui Shi, Qingsheng Yang and Qiang Zhang (Beijing Univ. of Technology, China), “Investigation of buckling behavior of carbon nanotube/shape memory polymer composite shell”, Proc. SPIE 8409, Third International Conference on Smart Materials and Nanotechnology in Engineering, 840916 (April 2, 2012); doi:10.1117/12.923313
ABSTRACT: Shape memory polymer (SMP) is a class of smart materials used in intelligent biomedical devices and industrial application as sensors or actuators for their ability to change shape under a predetermined stimulus. Carbon nanotube (CNT)/shape memory polymer (SMP) composites demonstrate good mechanical properties and shape memory effect. In this work, a model of CNT/SMP composite shell with a vaulted cross-section was established. This composite shell structure could further elevate the recovery stress of CNT/SMP composites. The folding properties of CNT/SMP composite shell structure were analyzed by finite element method and the influence of structural parameters on the buckling behavior of the shell was studied using the energy conservation principle. The results indicate that vaulted cross-section shell had unique mechanical properties. The structural parameters, such as the vaulted radius and the total length have a great impact on buckling moment of the shell. This shell structure is expected to achieve effective control of buckling and deploying process, relying on the special shape memory property of SMP and high elastic modulus CNTs. Moreover, it could also largely avoid the vibration problem during the deploying process.

Mahmoud Reza Amini and Sia Nemat-Nasser (Center of Excellence for Advanced Materials Department of Mechanical and Aerospace Engineering University of California, San Diego, 9500 Gilman Drive, La Jolla, CA

ABSTRACT: Shape-memory alloys can sustain relatively large strains and fully recover without noticeable residual strains. This is referred to as superelasticity. We have been studying quasi-static and dynamic buckling of relatively thin circular cylindrical shells consisting of shape-memory alloys in order to understand the response when used as the core of the sandwich structures. The work consists of experimental characterization of the buckling process, as well as numerical simulation. For comparison, we have also studied both dynamic and quasi-static buckling of aluminum tubes of similar dimensions. This presentation will focus on numerical simulation of dynamic buckling of these tubes and correlation with experimental observations.

References listed at the end of the paper:


ABSTRACT: The analysis of imperfect, stiffened, thin circular cylindrical shells, subjected to suddenly applied pressure, is presented. Moreover, a solution scheme for the complete (including post-limit point behavior) static analysis is described. The concept of dynamic stability is discussed for suddenly loaded structures. In addition, a fairly complete review of the reported works on the subject is presented. Results are presented for a ring-stiffened geometry. These include critical dynamic loads, critical static loads (limit point loads), as well as minimum post-limit point loads.


ABSTRACT: The problem of instability of imperfect, laminated, circular cylindrical shells under the action of
uniform axial compression is investigated. The analysis is based on nonlinear kinematic relations where the
effect of transverse shear deformation is taken into account. The buckling is assumed to be elastic and the
geometry to have initial geometric imperfections. The kinematic relations, governing equations and the related
boundary conditions for the nonlinear analysis are derived and presented. A solution methodology has been
developed and employed in generating results. The imperfection sensitivity is investigated. The results obtained
indicate that geometric imperfections have little effect on the limit point load for moderately thick cylindrical
shells.

A. Tabiei and Y. Jiang (Department of Aerospace Engineering and Engineering Mechanics, University of
Cincinnati, Cincinnati, OH 45221-0070, U.S.A.), “Instability of laminated cylindrical shells with material non-
doi:10.1016/S0020-7462(97)00030-9
ABSTRACT: An analytical methodology is presented to study the post-buckling behavior of laminated
cylindrical shells under axial compression and lateral pressure. Non-linear inplane stress-strain relations for
transverse (E22) and shear (G12) modulus is considered. The user defined material subroutine UMAT in finite
element analysis package, ABAQUS, with an updated Lagrangian formulation, and large displacement and
small strain kinematic relations, is employed in this study. Numerical analyses are conducted to demonstrate the
effect of material non-linearity and stacking sequence on the post-buckling behavior of laminated shells.

Romil Tanov and Ala Tabiei (Center of Excellence in LS-DYNA Analysis University of Cincinnati, Cincinnati,
OH 45221-00700, “Static and Dynamic Buckling of Laminated Composite Shells”, Mechanics of Composite
ABSTRACT: This paper presents the results from numerical investigation of the behavior of cylindrical
laminated shells subjected to suddenly applied loading. A numerical approach is used combining the finite
element method with two different stability criteria namely the Budiansky-Roth and the phase-plane buckling
criteria. In the finite element analysis an explicit time integration scheme is used implemented in the LS-DYNA
commercial code. The response of the composite shells has been investigated at the presence and absence of
static preloading. Results are presented for different values of the shell length, imperfection factors, stacking
sequence, and laminae orientation, and for different static preloading magnitudes. Based on the presented
results important conclusions can be drawn concerning the shell behavior and its sensitivity to different system
parameter variations.
References listed at the end of the paper:
Papers on Instability of Shell Structures, NASA TN D-1510.
Impact”, Technical
Vol. 32, pp. 81-88.


ABSTRACT: The present work concentrates on the development of correct representation of the transverse shear strains and stresses in Mindlin-type displacement-based shell finite elements. The formulation utilizes the robust standard first-order shear deformation shell finite element for implementation of the proposed representation of the transverse shear stresses and strains. In this manner the need for the shear correction factor is eliminated. In addition, modification to any existing shell finite element for the correct representation of transverse shear quantities is minimal. Some modifications to correct Mindlin-type elements are presented in the literature. These modifications correct the distribution of the transverse shear stresses only and use the constant transverse shear strains through the thickness. As compared to the above, the present formulation uses the correct distribution and is consistent for both transverse shear stresses as well as transverse shear strains.


ABSTRACT: The ultimate goal of the present research is to come up with an accurate and efficient analysis
approach for composite and sandwich shells, which is simple enough to be capable of implementing into a FE code without significantly affecting its computational efficiency, and at the same time gives good accuracy in predicting the behavior of layered shells. It has to be capable of accurately modeling both overall behavior, and the local distribution of strains and stresses in all layers and all constituents in the composite laminae. Two different approaches are utilized in the attempt to fulfill the final research objective of the present work. First, a homogenization procedure for the FE analysis of sandwich shells is developed. The procedure works on the material constitutive level. A homogenization of the sandwich shell is performed at each call of the corresponding constitutive subroutine. Thus the sandwich nature of the problem is hidden from the main FE program. As a consequence there is no need to develop a new shell element formulation, but instead the available homogeneous shell elements in the utilized FE code can be used for the analysis of sandwich shells. However, the defined homogenization procedure works with first order shear deformable shell elements, which sets a limit to the accuracy with which the transverse distribution of the unknowns is represented. To overcome this, a higher order shear deformable shell element is formulated and implemented into a general nonlinear explicit FE code. Using the differential equilibrium equations and the interlayer requirements, special treatment is developed for the transverse shear, resulting in a continuous, piecewise quartic distribution of the transverse shear stresses through the shell thickness. A similar approach is applied to the transverse normal stresses, which are represented by a continuous piecewise cubic function. The FE implementation is cast into a 4-noded quadrilateral shell element with 9 degrees of freedom per node. Only C0 continuity of the displacement functions is required in the shell plane, which makes the present formulation applicable to the most popular 4-noded bilinear isoparametric shell elements. Expressions are developed for the critical time step of the explicit time integration for orthotropic homogeneous and layered shells based on the developed third order formulation. Finally, to be able to analyze shells with woven composite layers, two micromechanical models for analysis of woven fabric composites are developed. Both models utilize the representative volume cell approach and divide a representative unit of the woven lamina into sub-cells of homogeneous material. Starting with the average strains in the representative volume cell and based on continuity requirements at the sub-cell interfaces, the strains and stresses in the composite constituents are determined as well as the average stresses in the lamina. Equivalent homogenized material properties are also determined. Their very good accuracy together with the simplicity of formulation makes these models attractive for the nonlinear FE analysis of composite laminates and can be efficiently utilized in explicit and implicit FE codes. The formulations developed within the research provide an efficient analysis approach to layered shells including sandwich shells with composite facings. Furthermore, the developed micromechanical models can be used to determine the stress and strain fields in the composite layer constituents. This would enable important strength and durability phenomena as failure, damage, and property degradation of the constituents to be included into the FE analysis of layered shells.


ABSTRACT: The presence of cracks or similar imperfections can considerably reduce the buckling load of a shell structure. In this paper, buckling analysis of cylindrical shells with a longitudinal crack is presented. Numerical buckling analyses of cylindrical shells were performed using FEM, and verified by experiment. The numerical analyses and experiments were conducted for several crack lengths and radius of curvature, and two different boundary conditions were applied, i.e. simply support and clamp in all sides. The results show the effect of the presence of crack to the critical buckling load of the shells. There are good agreements between experimental and numerical results.
DOI: 10.4028/www.scientific.net/KEM.306-308.49
ABSTRACT: The presence of cracks or similar imperfections can considerably reduce the buckling load of a shell structure. In this paper, buckling analysis of cylindrical shells with a longitudinal crack is presented. Numerical buckling analyses of cylindrical shells were performed using FEM, and verified by experiment. The numerical analyses and experiments were conducted for several crack lengths and radius of curvature, and two different boundary conditions were applied, i.e. simply support and clamp in all sides. The results show the effect of the presence of crack to the critical buckling load of the shells. There are good agreements between experimental and numerical results.

Jiantao Liu; Pingan Du; Mingjing Huang; Yaobing Xiao; Sch. of Mech. Eng., Univ. of Electron. Sci. & Technol. of China, Chengdu, China.
ABSTRACT: The theoretical analysis of finite element method for buckling phenomenon to finite-sized shell structure is first introduced. Then, a real application using a probe for detecting the pressure inside turboprops is analyzed thoroughly with ANSYS10.0, including section profile, dimensions, and local characteristics. Based on the solved results, several rules between critical load and influence factors are obtained, which would be helpful for similar structures design and application. Finally, several useful conclusions about the best profile and ratio between dimensions are obtained.

ABSTRACT: A reduced stiffness method is presented for the estimation of lower bounds to the imperfection sensitive general buckling of axially loaded, orthotropically stiffened, elastic cylinders. It predicts many previously inexplicable empirical observations and provides lower bounds to the scatter of available test buckling loads, thus becoming useful as a design tool.

ABSTRACT: Buckling of pressure loaded cylindrical panels is investigated using a fully nonlinear Ritz solution procedure and a classical bifurcation analysis of an idealized model. The dialectic between these two contrasting approaches is shown to produce greater understanding than if either one of them were to be used alone. Apart from illuminating the specific buckling behavior of the pressure loaded panel and demonstrating the lower boundedness of the reduced stiffness analytical procedure, the paper suggests that a similar interplay between classical and numerical analysis could be useful in elucidating behavior and providing design analysis procedures for many other shell buckling problems.
Seishi Yamada (1) and J. G. A. Croll (2)
(1) Toyohashi University of Technology, Toyohashi 441, Japan
(2) Department of Civil and Environmental Engineering, University College London, London WC1E 6BT, U.K.
ABSTRACT: Nonlinear Ritz analysis is used to investigate the elastic buckling behavior of pressure loaded cylinders. Careful analysis of the energy changes during the buckling process allows definition of a reduced stiffness theoretical model. This reduced stiffness model provides a convenient means for estimating lower bounds to the imperfection sensitive elastic buckling behavior.

ABSTRACT: The ‘reduced stiffness method’ for the analysis of shell buckling was developed to overcome a trend towards increasingly sophisticated analysis that has become divorced from its basically simple underlying physics. This paper outlines the developments of the reduced stiffness method from its origins in the late 1960s, through its experimental confirmation, generalisation and elaboration over the past 20 years, to its more recent consolidation using carefully controlled non-linear numerical experiments. It is suggested that the method has now reached a stage where it could profitably be adopted as a basis for an improved shell buckling design methodology.

(no abstract given)

J. G. A. Croll (1) and G. D. Gavrilenko (2)
(1) University College, London, UK
(2) Timoshenko Institute of Mechanics, National Academy of Sciences of Ukraine, Kiev, Ukraine
ABSTRACT: The reduced-stiffness method is used to establish the lower bounds of buckling loads for stringer- or ring-stiffened cylindrical shells. The numerical results obtained by using this method are compared with the experimental data. We also consider the problem of applicability of the reduced-stiffness method in design practice as well as the prospects for its development and generalization.

References listed at the end of the paper:

J.G.A. Croll: The following text is most of a July 8, 2013, email message from J. G. A. Croll to Chris Calladine and Mike Thompson, with copies to Allan McRobie, John Hutchinson, Isaac Elishakoff, Giles Hunt, Alan Champneys, Gert Van Der Heijden, Mark Peletier, David Bushnell:
I have been arguing the case for the remarkably simple and effective reduced stiffness method for more than 40 years. For the first 15 or so years the theory was founded upon simple mechanics reasoning and some remarkably good correlations between its predictions and experimental observation, for wide classes of shell buckling problem. You may also recall that at the IUTAM Symposium we held in London (1982) Professor Yamaki brought over a number of his co-workers who presented to the best of my understanding the first fully non-linear analysis of axial load shell buckling; this reproduced in every detail carefully conducted experimental observation on shells for which the precise form of the initial geometric imperfections had been recorded. After the IUTAM Symposium I contacted Prof. Yamaki to suggest we undertake a joint research programme to see if the predictions from reduced stiffness theory could be reproduced through carefully controlled numerical experiment in which the levels and forms of initial imperfection could be systematically varied in order to accurately identify the lower bounds. Yamaki’s response was to send to London one of the young researchers, Dr Seishi Yamada, who had developed their so successful non-linear shell buckling analysis algorithm. Seishi spent a year working with me in I think 1986 and we had been working together since in what I believe has been an extremely successful collaboration. This has allowed the identification of the imperfection sensitive lower bounds for most of the classical shell buckling problems, and most gratifyingly the relevance of the reduced stiffness theory in predicting these lower bounds. For his remarkable contributions Seishi was awarded a Gold medal by the Japan Architectural Institute.

Were it not for Seishi’s tragic and untimely death a few weeks ago I would probably have not taken the time to respond to the dialogue your very interesting paper has generated. After all, if more than 200 papers by increasingly large numbers of independent workers has not convinced you and others of the relevance of the RSM [Reduced Stiffness Method], it is unlike any short email within the context of this discussion will change too many minds! But I have to say I have found it difficult to understand why so many good friends and colleagues have found it so difficult to accept the beautiful simplicity of the RSM and the remarkable effectiveness of its predictions.

I would of course welcome the chance to enter into any discussion as to the relevance of the RSM with your contributors.

Ciao, Jim

ps here is a selection of articles describing various contributions showing the relevance of the RSM; some of these might be of interest.
1. (with A H Chilver) Approximate Estimation of the Stability of Cooling Towers under Wind Loading, Int. Assoc. Shell Structures Colloquium, Brussels, May, 1971. This was the first use of what I then characterised as a quasi-inextensional theory of shell buckling. This was extended and presented to TWSG in:

2. Towards Simple Estimates of Shell Buckling Loads, presented to Thin Walled Structures Study Group, Cranfield, March, 1972. Later that year I spent a few weeks presenting similar papers at a number of German universities including Darmstadt where colleagues of Prof Kloppel urged me to publish the work in der Stahlbau. I submitted this in late 1972 only to find the paper sat upon until 1975! It eventually appeared:

3. Towards Simple Estimates of Shell Buckling Loads, Der Stahlbau: Part I, Heft 8, August 1975; Part II, Heft 9, September 1975. While the work to this point was able to explain buckling of pressure loaded shells there was clearly something missing for the explanation of axially loaded rotationally symmetric shells – including axially loaded cylinders. It was this problem I asked Ronaldo Batista to address in his PhD research. The result was I believe extremely important and allowed the method to be extended to this thorny old problem. See for example:


5. (with R C Batista) A Design Approach to the Buckling of Cylinders under External Pressure, International Conference on Thin Walled Structures, 3-6 April 1979, University of Strathclyde. It was around this time that I tried to get some research council funding under the umbrella of the Marine technology Programme only to find that the approach was rejected on the grounds that it did not cover the problem of plasticity which was clearly so important for the shell scantlings being used in the offshore context. For this reason a couple of papers were prepared showing how easily the method could be extended to provide lower bounds to the elastic-plastic buckling. See for example:


16. (with S Yamada) 'Non-linear Buckling Response of Pressure Loaded Cylindrical Panels and its
Interpretation for Design', Technology Report of Tohoku University, 153, March 1988, 71-95. This was the first joint work from the collaboration with Seishi Yamada. It was quickly followed by others including:


21. (with Yamada, S) Buckling and Post-buckling Buckling Characteristics of Pressure Loaded Cylinders, J Applied Mechanics, ASME, 60, 1993, 290-299. This was an important work that demonstrated the relevance of the RSM to the buckling of pressure loaded shells.


30. (with Yamada, S) Contributions to Understanding the Buckling of Axially Compressed Cylinders, J of Applied Mechanics, ASME, 66, 1999, 299-309. This was an important work that demonstrated the relevance of the Batista extension to the RSM to handle the additional stabilizing membrane energy terms experienced with axially loaded cylinders.

31. (with Ohga, M et alia) Elastic Buckling Strengths of Cylindrical Sandwich Shells under External Pressure, xxxx

32. (with Ohga, M and Nakamura, D) Buckling Strength of Spherical Sandwich Shells by Reduced Stiffness Method, xxxx, 45, 1999, 1-6.


ABSTRACT: We consider parametrically excited vibrations of shallow cylindrical panels. The governing system of two coupled nonlinear partial differential equations is discretized by using the Bubnov–Galerkin method. The computations are simplified significantly by the application of computer algebra, and as a result low dimensional models of shell vibrations are readily obtained. After applying numerical continuation techniques and ideas from dynamical systems theory, complete bifurcation diagrams are constructed. Our principal aim is to investigate the interaction between different modes of shell vibrations under parametric excitation. Results for system models with four of the lowest modes are reported. We essentially investigate periodic solutions, their stability and bifurcations within the range of excitation frequency that corresponds to the parametric resonances at the lowest mode of vibration.


DOI: 10.1007/s11029-007-0032-0

ABSTRACT: Based on the discrete-structural theory of thin plates and shells, a variant of the equations of buckling stability, containing a parameter of critical loading, is put forward for the thin-walled elements of a layered structure with a weakened interfacial contact. It is assumed that the transverse shear and compression stresses are equal on the interfaces. Elastic slippage is allowed over the interfaces between adjacent layers. The stability equations include the components of geometrically nonlinear moment subcritical buckling conditions for the compressed thin-walled elements. The buckling of two-layer transversely isotropic plates and cylinders under axial compression is investigated numerically and experimentally. It is found that variations in the kinematic and static contact conditions on the interfaces of layered thin-walled structural members greatly affect the magnitude of critical stresses. In solving test problems, a comparative analysis of the results of stability calculations for anisotropic plates and shells is performed with account of both perfect and weakened contacts between adjacent layers. It is found that the model variant suggested adequately reflects the behavior of layered thin-walled structural elements in calculating their buckling stability.

References listed at the end of the paper:

ABSTRACT: This master thesis involves the design of a roof for a basketball arena, which has a capacity of 20,000 spectators and it needs to be designed as a concrete shell structure. The size of the stadium is large enough to demand a long spanned shell structure. This thesis attempts to find an elegant solution to this problem, which combines aesthetic and structural beauty with efficiency during construction. These points are judged to be important aspects of a complete structural design. A literature study is done in an attempt to create a plan for the design of the shell roof. The general theory of shells is studied to understand their forms, structural behaviour and modes of failure. This helps the designer to understand the mechanics of shells which heavily influence the design procedure. Prominent shell designers of yesteryears and some of their projects are the next object of interest. Existing basketball arenas are also examined to find out the loading requirements for the roof in this thesis. The literature study is concluded by gathering details of high strength concrete and finite element software, both of which are relatively new in the shell industry. A design procedure is defined based on the findings of the studies mentioned above. The shell is chosen to be designed as a spherical dome. The initial geometrical details are stipulated after conducting sightline analysis, capacity calculations and hanging model analysis. Varying values of the span and thickness are chosen, leading to multiple design formulation, one of which is chosen based on a linear stability analysis. The selected design is then structurally investigated with inclusion of nonlinear effects and imperfections. The above mentioned process is executed using a combination of different softwares, for modelling, meshing and analyzing. Once the structural behaviour has been verified, the stresses are checked and the design is finalized by defining the structural framework, and proposing the paneling and connection details.

References listed at the end of the thesis:
ABSTRACT: A study is presented of internal auto-parametric instabilities in the free non-linear vibrations of a cylindrical shell, focused on two modes (a concertina mode and a chequerboard mode) whose non-linear interaction breaks the in–out symmetry of the linear vibration theory: the two mode interaction leads to preferred vibration patterns with larger deflection inwards than outwards, and at internal resonance, significant energy transfer occurs between the modes. A Rayleigh–Ritz discretization of the von Kármán–Donnell equations leads to the Hamiltonian and transformation into action-angle co-ordinates followed by averaging provides readily a geometric description of the modal interaction. It was established that the interaction should be most pronounced when there are slightly less than $2\sqrt{N}$ square chequerboard panels circumferentially, where $N$ is the ratio of shell radius to thickness.

A.A. Popov (School of Mechanical, Materials and Manufacturing Engineering and Management, University of Nottingham, University Park, Nottingham NG7 2RD, UK), “The application of Hamiltonian dynamics and averaging to nonlinear shell vibration”, Computers & Structures, Vol. 82, Nos. 31-32, December 2004, pp.2659-2670, Special Issue: Nonlinear Dynamics of Continuous Systems, doi:10.1016/j.compstruc.2004.03.078

ABSTRACT: Internal auto-parametric instabilities in the nonlinear vibration of undamped and unloaded cylindrical shells are discussed. The focus is on the coupling between a few simple modes that can combine to break the in–out symmetry and give an energetically favourable pattern of deformation. When the ratio of the natural frequencies is close to a resonance, internal auto-parametric instability triggers energy transfer between
some of the modes. A Rayleigh–Ritz discretization of the von Kármán–Donnell equations leads to the Hamiltonian and transformation into action-angle coordinates followed by averaging provides readily a geometric description of the modal interaction. It is established that the interaction should be most pronounced between concertina and chequerboard modes with no energy transfer between the chequerboard modes. A simple mechanical system that exhibits similar dynamics is the extensible (spring) spherical pendulum.

ABSTRACT: We suggest the theoretical fundamentals of the method of reduced stiffness for the determination of the lower bounds of sensitivity of longitudinally compressed shells whose shapes are close to cylindrical to imperfections of the shape under the conditions elastic buckling. The theoretical and experimental data demonstrating the validity of the method of reduced stiffness are also presented.

ABSTRACT: We present a promising method for the investigation of the load-carrying capacity of imperfect shells based on simple analytic approaches. This method is called the reduced-stiffness method. In many cases, it enables one to obtain analytic relations for the estimation of the lower bounds of buckling loads for actual shells. We present the exact lower bounds of the buckling loads for compressed smooth cylindrical shells. For comparison, we also used the classical approach to the analysis of the critical loads for shells.

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ABSTRACT: A reduced stiffness lower bound method for the buckling of laterally pressure loaded sandwich cylindrical shell is proposed. Also, an attempt is made to assess the validity of the proposed reduced stiffness lower bound with FEM numerical examples. In addition, the proposed method is compared with classical and Plantema's approaches of the buckling of the laterally pressure loaded sandwich cylindrical shell. Comparison of the proposed reduced stiffness lower bound with that obtained from non-linear FEM analysis verifies that it indeed provides a safe lower bound to the buckling of laterally pressure loaded sandwich cylindrical shells. The attractive feature of the proposed reduced stiffness method is that it can be readily used in designing laterally pressure loaded sandwich cylindrical shells without being concerned about geometrical imperfections.

DOI: 10.1007/s11071-006-0744-z
ABSTRACT: This paper charts the various ways in which a close working relationship with Michael Thompson, during our early years within the Stability Research Group at UCL, came to have such a profound
influence on the direction of my own research activities. In particular, his fascination with energy and its use in providing a systematic framework for looking at the initial post-buckling of systems was especially contagious, opening up for me new ways of approaching the interpretation of shell buckling. In a sense my own work moved from chaos to stability in shells while Mike's was the reverse.

References listed at the end of the paper:
Mitao Ohga (1), Aruna Sanjeeewa Wijenayaka (1) and James G.A. Croll (2)
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ABSTRACT: Effects of the lateral pressure on the FEM and reduced stiffness lower bound buckling strength of axially loaded sandwich cylindrical shell are examined. Further, a reduced stiffness lower bound buckling strength for the axially loaded sandwich cylindrical shell under lateral pressure is proposed. The effect of the lateral pressure on the FEM and reduced stiffness lower bounds are corresponding; it causes them to reduce slightly. However, reduced stiffness buckling mode shape remains the same. In addition, the proposed reduced stiffness lower bound buckling strength is shown to provide effective and valid for cores having different shear stiffness. It provides comparatively lower bounds to short axially loaded sandwich cylindrical shells under lateral pressure. Further, it provides a safe lower bound that does not depend on precise geometrical imperfection spectra and lateral pressure and it is simple and easy to employ.


ABSTRACT: A direct procedure for the evaluation of imperfection sensitivity in bifurcation problems is presented. The problems arise in the context of the general theory of elastic stability for discrete structural systems, in which the energy criterion of stability of structures and the total potential energy formulation are employed. In cases of bifurcation buckling the sensitivity of the critical load with respect to an imperfection parameter $e$ is singular at the state given by $e = 0$, so that, a regular perturbation expansion of the solution is not possible. In this work we describe a direct procedure to obtain the relations between the critical loads, the generalized coordinates at the critical state, the eigenvector, and the amplitude of the imperfection, using singular perturbation analysis. The expansions are assumed in terms of arbitrary powers of the imperfection parameter, so that both exponents and coefficients of the expansion are unknown. The solution of the series exponents is obtained by searching the least degenerate solution. The formulation is here applied to asymmetric bifurcations, for which explicit expressions of the coefficients are obtained. The use of the method is illustrated by a simple example, which allows consideration of the main features of the formulation.

References listed at the end of the paper:
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ABSTRACT: This paper investigates ways to have a computational implementation of a lower bound approach for the buckling of imperfection-sensitive shells using general purpose finite element codes. This approach was developed by Croll and others, and has been mainly employed by developing special purpose programs or analytical solutions. However, it is felt that this limits the possibilities of the user, and this shortcoming is addressed in the paper. First, the formulation is presented in a way to highlight what computations can be done following a reduced energy approach. Then, a methodology is implemented in conjunction with a general purpose program to compute the lower bound buckling load for cylindrical shells with different geometric configurations under uniform pressure. The accuracy of the procedure and the difficulties in the implementation, depending on the finite element chosen for the discretization are shown. Results demonstrate that the proposed reduced energy model can predict the lower bound load for cylindrical shells under uniform pressure distributions.

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ABSTRACT: This paper reports on the implementation of a lower bound approach to the buckling analysis of cylindrical shells for tanks subjected to wind loads. The formulation is based on a reduced energy model of the shell adapted to a special purpose, semi-analytical, finite element program in which it is possible to separately compute the membrane and bending energy contributions. First, the energy components are investigated, in order to identify stabilizing and destabilizing contributions. Second, an eigenvalue analysis is carried out using a reduced value of the stiffness, in which membrane components are eliminated on the basis that they are...
assumed to be eroded as a result of mode coupling catalyzed by imperfections. The methodology is employed for thin-walled, above ground, tanks under wind pressures. It is shown that the resulting critical loads constitute lower bounds to those obtained using a nonlinear analysis of the shell, including imperfections, and also to those obtained from experiments.


ABSTRACT: In the context of aerospace and marine applications there are considerable incentives for designers to adopt thin shells, whose performances are enhanced by appropriately chosen rib stiffeners or using high-performance composite materials. Imperfection-sensitive buckling in these circumstances is controlled by extremely high numbers of independent material and geometric parameters. As a basis for design, traditional reliance upon scatter of test results is suggested to be untenable and the increasing tendency to replace this approach by use of nonlinear finite elements is argued to bring with it all sorts of other quite considerable practical problems. This paper describes how the long established and very simple “reduced stiffness method” (RSM) is able to provide an alternative design strategy. It shows how a very straightforward extension of classical critical load analysis allows the definition of lower bounds to the potential imperfection sensitivity in each mode and consequently the delineation of the mode and load likely to provide the controlling influence on design. Reliability of its predictions is briefly demonstrated through comparisons with extensive test programmes and confirmation through carefully controlled nonlinear numerical studies. Use of the RSM is shown to offer scope for identifying material and geometric parameters that result in improved and even “optimum” buckling loads. Case studies from past and a current programme of research looking at the buckling of composite shells are used to illustrate this design potential.

Hongtao Wang and James G A Croll (Department of Civil, Environmental, and Geomatic Engineering, University College London, London, WC1E 6BT, UK), “Finite Element Validation of s Lower-Bound Design Method for Optimising Buckling Capacities of FRP Shells”, (cocomat.de, publisher and date not given in the pdf file; most recent reference is 2007)

ABSTRACT: The buckling loads of thin FRP laminated shells are sensitive to initial geometric imperfections. A large number of geometric and material variables prohibit the traditional lower-bound experimental design methodology for isotropic shells from being applied to composite shells. As an alternative, a so-called “reduced stiffness method” (RSM) has been applied to the lower-bound buckling analysis of FRP laminated shells. The RSM analysis has shown that the classical critical mode which gives the lowest reduced stiffness critical load is often different from the mode giving the minimum classical critical load. This paper presents a series of finite element numerical experiments to test the validity of the RSM. By examining the effects of initial imperfections in the form of the recognised classical critical modes, it is shown that the RSM provide a reliable lower-bound method for buckling design of FRP shells.

References listed at the end of the paper:
ABSTRACT: A sequential linear programming method with a simple move-limit strategy is used to investigate the following three important buckling optimization problems of composite shells: (1) optimization of fiber orientations for maximizing buckling resistance of composite shells without cutouts; (2) optimization of fiber orientations for maximizing buckling resistance of composite shells with circular cutouts; and (3) optimization of cutout geometry for maximizing buckling resistance of a composite shell. From the results of optimization study, it has been shown that, given a structural geometry, loading condition and material system, the buckling resistance of a cylindrical composite shell is strongly influenced by fiber orientations, end conditions, the presence of cutout and the geometry of cutout.


ABSTRACT: In an earlier report (TAM Report No. 80), the authors considered the buckling and post-buckling behavior of an ideal elastic cylindrical shell loaded by uniform external pressure on its lateral surface, and by an axial compressive force. Assumptions were introduced which reduced the shell to a system with one degree of freedom. The present investigation is a generalization and a refinement of this theory. The shell is treated as a system with 21 degrees of freedom. By the imposition of constraints on the 21 generalized coordinates, various end conditions can be realized; for example, simply supported ends with flexible end plates (no axial constraint), simply supported ends with rigid end plates, and clamped ends. Also, effects of reinforcing rings have been incorporated in a more general way than in TAM Report No. 80. The restrictive assumption that the centroidal axis of a ring coincides with the middle surface of the shell has been eliminated. A pressure-deflection curve for an ideal cylindrical shell that is loaded by external pressure has the general form shown in Figure 1. The falling part of the curve (dotted in the figure) represents unstable equilibrium configurations. Also, the continuation of line OE (dotted) represents unstable unbuckled configurations. Actually, the shell snaps from some configuration A to another configuration B, as indicated by the dashed line in Figure 1. Theoretically, point A coincides with the maximum point E on the curve, but initial imperfections and accidental disturbances prevent the shell from reaching this point. Point E is the buckling pressure of the classical infinitesimal theory (called the "Euler critical pressure", since Euler applied the infinitesimal theory to columns). To some extent, point A is indeterminate, but it is presumably higher than the minimum point C unless the shell has excessive initial dents or lopsidedness. In TAM Report No. 80, a hypothesis of Tsien was used to locate point A. In the present investigation, point A is not considered. Rather, attention is focused on the development of a theory that will determine the entire load-deflection curve. For short thick shells, such as the inter-ring bays of a submarine hull, the Euler critical pressures, determined by TAM Report No. 80, are too high, presumably because the assumption that the shell buckles without incremental hoop strain is inadmissible in this range. The present report corrects this error. Numerical data on the Euler critical pressures of shells with simply supported ends and flexible end plates have been obtained with the aid of the Illiac, an electronic digital computer. The data are tabulated at the end of this report. For short shells without rings, the buckling pressures are appreciably lower than those determined by von Mises' theory. The numerical data for the Euler buckling pressures of shells with uniformly spaced reinforcing rings are sufficiently extensive to permit interpolation to estimate effects of various ring sizes. Some exploratory numerical investigations of post-buckling behavior have
been conducted with the Illiac. It is not feasible, at the present time, to handle nonlinear equilibrium problems for systems with 18 degrees of freedom. Consequently, for the numerical work, some higher harmonics were discarded so that the system was reduced to 7 degrees of freedom. Even then, the numerical problem is formidable. The calculations were confined principally to the determination of the minimum point C on the post-buckling curve (Figure 1). The pressure at point C is the minimum pressure at which a buckled form can exist. It is found that the ordinate of point C, determined by TAM report No. 80, is somewhat too high. The two theories are compared by a table and curves at the end of this report.


ABSTRACT: (none given)

References listed at the end of the paper:

SUMMARY: High-temperature thin-shell leading-edge buckling test data are analyzed using NASA STRUCTURAL ANALYSIS (NASTRAN) as a finite element tool for predicting thermal buckling characteristics. Etc.
Five references:

ABSTRACT: The thermal snapping and vibration analysis of cylindrical laminated panel subject to thermal load and pressure is performed using layerwise finite elements. To consider large deflections due to thermomechanical loads, von-Kármán nonlinear displacement–strain relationships based on the layerwise theory are applied. Cylindrical arc-length method is used to take into account the snapping phenomena. Thermal snapping and vibration characteristics versus various parameters such as thickness ratio, shallowness, boundary conditions and loading type are investigated. The present results show that thermal snapping changes vibration characteristics as well as static deformations.

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ABSTRACT: The finite element method based on the total Lagrangian description of the motion and the Hellinger–Reissner principle with independent strain is applied to investigate the non-linear static and dynamic
responses of spherical laminated shells under external pressure. The non-linear dynamic problem is solved by employing the implicit time integration method. The critical load of thin spherical laminated panels is investigated by examining the static and dynamic responses. The critical dynamic load is determined by the phase-plane and the Budiansky–Roth criteria. The effect of the artificial coefficient of Rayleigh damping on the dynamic response is considered. The dynamic response with damping included converges to the static response. The damping coefficient greatly affects a highly non-linear dynamic response. For a thin spherical panel with the snapping phenomena, the critical dynamic load is lower than the static one.

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ABSTRACT: The thermal post-buckling responses of shape memory alloy hybrid composite (SMAHC) shell panels are investigated using a finite element method formulated on the basis of the layerwise theory. The von Kármán nonlinear displacement–strain relationships are applied to consider large deflections due to thermal loads. The cylindrical arc-length method is used to take account of the snapping phenomenon which is an unstable behavior observed in the shell panels. A nonlinear finite element procedure based on Brinson's model is developed to investigate the behaviors of shape memory alloy (SMA) wire. The results of numerical analysis show that the recovery stresses of SMA wires can enhance the stiffness of structure and the SMAHC shell panel exhibits superior behaviors of thermal post-buckling compared to the conventional composite panel. It is also shown that embedding SMA wires in a composite structure can prevent the unstable post-buckling behavior.

ABSTRACT: A finite element procedure for the inelastic dynamic analysis of cylindrical structures subjected to lateral dynamic load and axial thrust is given. The plastic strains developed in the structure are treated as fictitious equivalent loads and the neutral axis at each section is determined by using a subsection concept. Equations of motion are then solved numerically by the direction integration method. The finite element procedure is verified by the exact solution using a continuum analysis. Application of the procedure is made to investigate the effects of axial thrust on the inelastic dynamic response of a tall cylindrical structure. The present method may be applied to the analysis of practical designs of cylindrical structures.

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ABSTRACT: The effect of shape memory alloy (SMA) on the buckling behavior of a rectangular composite laminate was investigated by the finite element method. The influence of SMA on buckling of composite
laminates by varying the SMA fiber spacing was studied. The formulation of the location-dependent stiffness matrix due to non-homogeneous material properties and the temperature-dependent recovery stress stiffness matrix were derived. The results show that the Active Strain Energy Tuning method is much better than the Active Property Tuning method in improving the buckling performance of the plate. When the SMA fibers are concentrated in the center area of the plate, the buckling load of the plate will be improved significantly. If the stiffness of the SMA layer is lower than other layers, the influence of the SMA on the buckling load of the plate will become subordinate.

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ABSTRACT: The snap-through dynamics of bi-stable buckled IPMC actuators with double clamped boundary conditions was investigated to generate much larger displacement and periodical stable locomotion based on jumping phenomena with relative low input power. Among square, convex, and concave buckled IPMC actuators, the jumping phenomenon of the concave IPMC actuator was remarkably observed in the harmonic responses of high input voltage and low excitation frequency. Present results show that the end-shortening, the driving voltage and the excitation frequency of the double clamped IPMC actuators strongly affect the large deformation, rapid jumps, and low power consumption due to the snap-through phenomena.

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“Thermal Post-buckling and Vibration Characteristics of Composite Conical Shell Structures”, (publisher and date not given in the pdf file; latest reference is 2006)
ABSTRACT: The vibration and the thermal post-buckling responses of the composite conical shell structures are investigated. The nonlinear finite element formulations of the composite conical shell are derived based on the layerwise displacement theory. The von Karman nonlinear displacement strain relationships are applied to consider large deflections due to thermal loads. The cylindrical arc-length method is used to account for the snapping phenomenon. The effect of structural parameters, such as the semi-cone angle, thickness ratio, and shallowness angle (curvature), on the structural stability of composite conical shell subjected to thermal load is observed.

References listed at the end of the paper:
ABSTRACT: The thermal post-buckling and vibration characteristics of composite conical shells are investigated using a finite element method. Based on the layerwise theory and the von Kármán displacement strain relationships, the nonlinear finite element equations of motion are derived for the thermoelastic response of the composite conical shell structure. The cylindrical arc-length method is used to account for the snapping phenomenon. The influence of the structural parameters, such as the semi-cone angle, thickness ratio, and shallowness angle (curvature), on the structural stability of the composite conical shell subjected to the thermal load is also observed.

References listed at the end of the paper:

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“Helical Buckling of Pipes in Extended Reach and Horizontal Wells—Part 1: Preventing Helical Buckling”,
doi:10.1115/1.2905992
ABSTRACT: This paper studies the helical buckling of pipes (drillstring and tubing) in extended reach and horizontal wells, theoretically and experimentally, resulting in new equations to correctly predict and effectively prevent the helical buckling of pipes in such wells. The theoretical study shows that the so-called helical buckling load that appears in the current literature is only the average axial load in the helical buckling development process. The laboratory experiments confirm the theoretical analysis. The new helical buckling load equations are formalized by combining the theoretical analysis and the experimental results, thereby resolving the existing assumption-and-result inconsistency in the current literature. The new equation predicts the true helical buckling load to be about 1.3 times the so-called helical buckling load in the current literature, and about 1.8 times the critical buckling load that predicts the onset of sinusoidal buckling. Consequently, larger bit weights or packer setting loads can be applied to increase the drilling rate or to ensure a proper seal, before the helical buckling of the pipes can occur.

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ABSTRACT: This paper studies the frictional drag of helically buckled pipes (drillstring and tubing) in extended reach and horizontal wells to correctly predict the actual bit weight or packer load, in cases where helical buckling of pipes may have occurred. Helical buckling of pipes in such wells may occur, since large axial loads are often required. The differential equation of axial force balance with consideration of the axial friction for helically buckled pipes is resolved, and the solution shows that when the pipes are helically buckled, the frictional drag will become very large. The actual bit weight for drilling or packer load for well completion may therefore become much smaller than estimated under the unbuckled pipe conditions. The analytical solution is also shown to agree with the results from laboratory experiments, which simulate the real wellbore-pipe conditions. An example is provided to show the calculation procedure and the importance of the results.

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ABSTRACT: This paper studies sinusoidal and helical buckling of tubulars in inclined wellbores and the “lockup” of tubulars due to buckling. The results show that tubular buckling starts from the tubular bottom in low-inclination wellbores, where the axial compressive load is largest due to tubular weight. In high-inclination wellbores it may start from the top portion of the tubular, where the axial compressive load is largest due to frictional drag. This clarifies the confusion on whether or not the tubular buckles at once on its entire length in inclined wellbores. New sinusoidal and helical buckling load equations are presented to better predict tubular
buckling in inclined wellbores (0–90 deg). The lower the wellbore inclination angle, the smaller the axial compressive load required to initiate tubular buckling. However, a certain nonzero axial compressive load is still needed to buckle the tubulars in vertical wellbores. When tubulars buckle helically, a large wall contact force will be generated, and the “slack-off” weight at the surface will not be fully transmitted to the tubular bottom due to large resultant frictional drag. The “lockup” of tubulars may even occur, where the tubular bottom load cannot be increased by slacking-off weight at the surface.

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ABSTRACT: The buckling of liner shells is a major problem in reactor containment design. In this paper, the local liner shell is considered as the liner plate with special initial imperfection form, based on which, Koiter's asymptotic theory of initial post-buckling is used to obtain expressions for the post-buckling equilibrium paths and post-buckling minimum loads for perfect and imperfect liner shells. The post-buckling behaviors of three liner shell models (four point-supported liner shell, clamped liner shell, and five-point-supported liner shell) are investigated. The influence of the initial imperfection stud spacing and liner thickness on the post-buckling minimum loads is also given.

C.D. Babcock (Department of Aeronautical Engineering, California Institute of Technology), “The Propagating Buckle In Marine Pipelines”, Paper No. 82-M001, Annual Meeting Papers, Division of Production, April 4 - 7, 1982, San Antonio, TX, American Petroleum Institute
ABSTRACT AND INTRODUCTION: An investigation has been carried out in order to understand the dynamics of the propagating buckle and to find a basis for designing efficient and effective arresting devices. The velocity of propagation was measured as a function of diameter to thickness ratio and pressure. These were carried out in different pressure media. It was found that the propagation velocity is affected by the pressurizing medium used as well as the pressure. A methodology for experimentally studying the efficiency of arrestors was established. The so called "Slip-On" arrestor was studied using this method. An empirical formula is derived for the efficiency of this arrestor. It was also found that quasi-static design criteria underestimate the arrestor efficiency under dynamic conditions. Any gap between the arrestor and the pipe greatly reduces the efficiency. Introduction: The propagating buckle is one of the new problems that has appeared as a result of the increased interest in offshore natural resources. The problems can occur during offshore pipelaying operations when the pipe is under combination of loads such as external pressure and bending moment. A local buckling initiated by these loads can propagate down the pipeline if the external pressure is above a critical pressure known as the propagation pressure. A number of investigators (ref. 1, L) have studied the problem. Their studies resulted in empirical relations for the propagation pressure. Tests on some buckle arrestors designs (ref. 3) were also carried out.

ABSTRACT: The response and stability of elastoplastic circular pipes under combined bending and external pressure are investigated both analytically as well as experimentally. A virtual work approach is used to formulate the problem, which results in a set of nonlinear algebraic equations which are solved numerically. The maximum moment and curvature for different pressures are determined as a function of the material and geometric parameters of the problem. For the range of parameters where limit load instability dominates, the results compare very well with experimental results for both steel and aluminium pipes.


ABSTRACT: The paper presents a study of the large deflection collapse of circular rings confined in a rigid cavity under external pressure. The ring is assumed to be inextensional and to have an initial localized imperfection which causes a small section of its circumference to be detached from the confining wall. The cavity formed is pressurized and its growth examined. The formulation is general enough to allow for large deflections of the ring as well as material nonlinearities. The pressure versus change in volume response of the confined ring is found to be characterized by a limit load for both elastic and inelastic material behavior. The limit load is shown to be dependent on both the geometry of the initial imperfection as well as the yield and post yield characteristics of the ring material. The response beyond the limit load is unstable until the crown of the ring touches the opposite side after which it becomes stable again.


ABSTRACT: In many practical engineering applications, relatively stiff, long, circular cavities are lined with more compliant liner shells. Pressure applied through the porous walls of the confining medium can cause buckling of the shells. Such buckling is usually local in nature and occurs at a section with the biggest geometric imperfection. The paper presents experimental evidence which demonstrates that, once such a shell has been locally dented, a buckle which propagates within the confines of the cavity can be initiated. Such a buckle has the potential of completely collapsing the liner. The lowest pressure at which this buckle will propagate is established experimentally through a parametric study of the problem. The phenomenon is found to be physically similar to the propagating buckle problem which can develop in offshore pipelines. A difference is that in the case of the confined shell, the instability is shown to have a strong geometric dependence and, as a result, it can be developed in the case of thin elastic as well as elasto-plastic shells.


ABSTRACT: When inflating long circular tubes made from some rubber compounds it is possible for a localization type of instability to occur. The localization takes the form of a bulge which forms somewhere.
along the length of the tube. Further inflation results in axial enlargement of the bulged section. This occurs at a value of pressure which is substantially lower than the pressure at which the bulge was first initiated. The paper presents experimental and analytical results which show how the initiation and steady state propagation of such bulges in latex rubber tubes is affected by the presence of axial tensile load.


ABSTRACT: Cyclic bending of tubes into the plastic range of the material leads to a progressive accumulation of ovalization of the tube cross-section. Persistent cycling leads to local catastrophic buckling of the tube. This paper presents an experimental study of the problem. The main objective of the study was to establish the effect of the cyclic bending history and of the external pressure on the rate of accumulation of ovalization and on the onset of instability. The cyclic loading histories examined include curvature symmetric bending, bending about a mean value of curvature and moment-controlled bending about a mean value of moment. The rate at which ovalization accumulates in curvature-controlled cyclic bending was found not to be significantly affected by a mean curvature in the cycles. Moment-controlled bending about a mean moment leads to ratcheting in curvature as well as in ovalization. External pressure accelerates the accumulation of ovalization and leads to buckling in fewer cycles than in the corresponding pure bending cases. This was found to be true for all bending histories considered. Significant similarities were observed between the response and onset of instability in the monotonic bending case and all cyclic bending cases. For a group of aluminum tubes instability was found to occur when the ovalization of the cross-section reached a critical value. This critical value was found to be relatively independent of the bending history followed.


ABSTRACT: A thin elastic tube, when inflated, first expands to a cylindrical shape. after some deformation, this is interrupted by the development of a bulge somewhere along the length of the tube. For some rubber materials, the bulge initially grows with decreasing pressure, whereas the rest of the tube unloads. after growing to a certain diameter, the bulge starts spreading axially. This can occur at a well defined value of pressure which is much lower than the pressure required to initiate the bulge. the mechanisms through which the bulge is initiated, its initial growth and its eventual propagation along the length of the tube are studied experimentally and analytically. The results vividly illustrate localization and propagation types of instabilities which govern the mechanical behavior of a variety of solids and structures.

ABSTRACT: Local imperfections induced to long tubes subjected to high external pressures can lead to local collapse from which a propagating buckle can be initiated. This can result in catastrophic collapse of large sections of the structure. The lowest pressure at which such a buckle will propagate, known as the propagation pressure of the tube, is typically half an order of magnitude lower than the collapse pressure of the intact tube. In a number of modern deep water applications, long tubular structures are subject to high axial tension in addition to external pressure. The paper describes the results of an experimental study in which the propagation pressure of long metal tubes was measured in the presence of a constant, axial tensile force. Tension was found to significantly reduce the propagation pressure. A parametric study of the problem, augmented by a simple model of the phenomenon, has yielded approximate expressions for the propagation pressure in the presence of axial tension.


ABSTRACT: Local imperfections induced in long tubes subjected to high external pressures can lead to local collapse, from which a propagating buckle can be initiated. This can result in catastrophic collapse of large sections of the structure. The propagation pressure is the lowest pressure at which such a buckle will propagate. For common structural metal tubes with diameter-to-thickness ratios of less than 100, the propagation pressure is typically half an order of magnitude lower than the collapse pressure of the intact tubes. As a result, the design of several tubular structures with external pressure loading requires that the collapse and propagation pressures be accurately known. This paper deals with the experimental and analytical challenges of establishing the propagation pressure. A special purpose three-dimensional analysis, in combination with experimental observations and results, is used to demonstrate a mechanism of initiation of propagating buckles in long tubes, to study the parametric dependence of the propagation pressure and to illustrate the effect of axial tension on the propagation pressure. Propagation pressures predicted with this analysis are used to evaluate the strengths and weaknesses of simpler models developed in the past.


ABSTRACT: In this paper a combination of experimentation and analysis is used to identify and study the mechanisms that govern the failure of unidirectional fiber composites under compression. The experimental part includes experiments in which the compressive strength and the prevalent failure mechanisms of AS4/PEEK composite are established, tests for establishing the constitutive properties of the composite and its constituents, and an evaluation of the extent of misalignment of fibers in manufactured composites. The failure load of the composite was confirmed to be affected by geometric imperfections in the form of fiber waviness, and failure was found to lead to kink bands with distinct orientations and widths. Motivated by the experimental findings, the composite was idealized as a two-dimensional solid with alternating fiber and matrix layers, each having the measured properties of the two constituents. The compressive responses of microsections of finite width with imperfections of various spatial distributions were established numerically. The calculated responses are characterized by an initially stiff, stable regime terminated by a limit load instability which is associated with
the strength of the composite. Following the limit load, the deformation localized into inclined bands with distinct widths. It has been verified that, as the localization process progresses, the fiber bending stresses at the ends of these bands grow to values comparable to those of the fiber strength. The sensitivity of the calculated response to the geometric characteristics of the imperfections was studied parametrically.


ABSTRACT: It is well known that certain larger structures are susceptible to a type of collapse which starts locally but under favorable conditions can spread and has the potential of affecting the whole structure. The lowest load which can sustain this spreading of collapse propagation load is usually significantly lower than the critical buckling load of the geometrically intact structure. As a result, the option of avoiding the potentiality of propagating collapse by using the propagation load as the design criterion can result in significant penalties in cost and weight. An alternative is to base the design on the critical buckling load of the structure while including periodic stiffeners to arrest potential propagating collapse and keep its effect local. This paper illustrates this new design philosophy through an example involving a long pressure-loaded panel with sparsely spaced circumferential stiffeners cast in the role of buckle arrestors. An analysis is presented which models the process of quasi-static buckle penetration through such a stiffener. A general measure of arresting performance is defined, based on the maximum pressure experienced during the penetration process. A general framework for establishing the dependence of the stiffener arresting efficiency on the problem parameters is developed. Furthermore, fundamental concepts regarding limiting values for stiffener length and thickness are introduced, and results are presented which indicate that in this problem short, thick stiffeners provide the most arresting capacity for a given amount of stiffener material.


ABSTRACT: In this paper the reduction in the collapse pressure of long cylinders which have local dents is evaluated through a combination of experiment and analysis. A number of stainless steel tubes, with diameter-to-thickness ratios of approximately 33, 24 and 19, were indented to various degrees with spherical indentors of two diameters. The geometry of each dent was recorded using an imperfection scanning system and the cylinders were subsequently collapsed under external pressure. Denting reduces the local collapse resistance of the cylinder. For larger dents the collapse pressure was found to approach the propagation pressure of the tube. Collapse was found to be relatively insensitive to the detailed geometry of a dent but to be critically dependent on the maximum ovalization of its most deformed cross section (delta0d). The collapse pressures of tubes with dents produced by indentors of different diameters could be well correlated through this measure of the dent geometry. The denting and collapse processes were simulated numerically using appropriately nonlinear elastoplastic shell analyses. Both steps of such simulations were shown to be in good agreement with experimental results for a broad variation of the parameters of the problem. The key role of the geometric parameter delta0d was exploited in order to generate a Universal Collapse Resistance Curve for dented cylinders. It was possible to show that the post-limit load response (P - delta0d) of a cylinder, with a small but axially uniform initial ovality, provides a very good lower bound to the collapse pressures of the dented
cylinders plotted against the dent parameter \( \Delta_0 d \). The significance of this curve is that it can be used to estimate the reduction in the collapse pressure of a cylinder with any dent geometry from only one relatively simple measurement of the geometry of the dented section.


ABSTRACT: The failure of fiber-reinforced composites in compression is sudden, uncontrolled and results in the dynamic formation of narrow zones of inclined kinked fibers and in a drastic reduction in load bearing capacity. Experimental results are presented which demonstrate that such materials do maintain significant post-failure strength and “ductility.” Following the onset of failure, kink bands which were initiated dynamically could be made to propagate (broaden) in the fiber direction. Under displacement controlled loading, the propagation of the bands takes place in a steady-state manner. In the case of the APC-2/AS4 composite analyzed, quasi-static propagation of this failure took place at a stress level which was 40% of the strength of the intact material. The propagation of the band involved progressive addition of narrow zones of fibers from the adjacent intact material by rotation and breaking. This new characteristic stress of such materials has been called propagation stress. Several requirements and guidelines for establishing the true value of this material property, free of influence from experimental conditions and specimen geometry, are outlined.


ABSTRACT: A common method of limiting the extent of damage induced by a propagating buckle to a deep water pipeline is to periodically install along the line thick rings welded between adjacent strings of the pipe (integral buckle arrestor). The rings locally increase the resistance to collapse and, when properly designed, arrest an incoming buckle. The effectiveness of this type of local reinforcement as a buckle arrestor was studied through a series of full-scale experiments and through a numerical model. The model was first proven to be capable of accurately simulating the quasi-static crossing of such arrestors by a buckle and was then used to study the arresting efficiency of this device as a function of the pipe and arrestor geometric and material parameters. This paper briefly summarizes these results which are subsequently used to establish some bounds for the arrestor thickness and length and to develop empirical design formulae for such devices.


ABSTRACT: In many fiber composites, longitudinal compressive failure leads to the formation of kink bands. It has been found that these kink bands, once formed, can be made to propagate (broaden) in a steady-state manner at a constant stress level called the propagation stress (\( \sigma_P \)). This is a characteristic stress of the material which, for the AS4/PEEK composite used in the study reported here, is approximately 40% of its compressive strength. This phenomenon is investigated experimentally using a special confining set-up that
allows direct observation of the propagation process. For the composite studied, the kink bands have a repeatable inclination (beta) of approximately 15 degrees, and the fibers within the bands are rotated to about 30 degrees in the absence of a load. When loaded to sigmaP, however, they are found to rotate further to 40 degrees, that is, substantially greater than the 2beta reported elsewhere. The mechanism of propagation is found to be a bend-break-rotate sequence undergone by short segments of fibers at the edge of the kink band. It is well known that polymeric matrix composites such as the one used in this study exhibit rate-dependent behavior. Experimental results are presented which show that the kink band propagation stress is also rate dependent.

ABSTRACT: A new micromechanical model is presented to simulate the steady-state axial propagation of kink bands investigated experimentally in the accompanying paper (Part I). The fibers are in a hexagonal array and are assumed to be isotropic and linearly elastic, while the matrix is modeled as an elastic-powerlaw viscoplastic solid. Matrix properties for the model are determined from shear tests on the composite and compression tests on neat PEEK. The model is used to predict the propagation stress (sigmaP) of the AS4/PEEK composite and to investigate the sensitivity of sigmaP to band inclination, matrix properties, and loading rate. A simple model recently reported in the literature is calibrated to the current material system and compared with the present experimental data and model predictions. The micromechanical model is found to predict the propagation stress reasonably well and to capture the rate dependence of the composite. The simple model is found to capture the trends of the behavior.

ABSTRACT: The initiation and growth of a kink band in a uniaxial composite is investigated experimentally. Experiments on unidirectional plates of AS4/PEEK were conducted using a custom biaxial testing device. A relatively stable post-failure response which occurs for displacement controlled shearing under a compressive preload is exploited to observe quasi-static kink band growth. The band initiates from a stress concentration on one of the free edges and grows across the specimen with a constant inclination of about 12°. Detailed in situ measurements show that the fiber rotation and band width at a point increase as the band goes past it. After traversing the specimen, the band propagates (broadens) with constant fiber rotation. The observed kink band characteristics were similar to those of kink bands which grew dynamically in the same composite tested under pure compression. A difference is that the ends of the bands formed under combined compression and shear are highly bent but not broken.

ABSTRACT: Motivated by the experimental findings in Part I, the growth of a kink band in a uniaxial
composite is investigated using two- and three-dimensional micromechanical models. The models include both a local and a global imperfection and were preloaded in compression and then sheared under displacement control. An inclined kink band initiates from the local imperfection and grows across the specimen. Similar results were obtained for pure compression loading. The simulated kink bands are quite similar to those observed experimentally; though, when J2 plasticity is used to model the inelastic matrix, their inclination is lower than in experiments. The calculated band inclination is shown to be insensitive to many model parameters including imperfection characteristics, fiber diameter, volume fraction, and matrix yield stress. However, it is quite sensitive to the dilatancy of the matrix as demonstrated by the use of the Drucker–Prager constitutive model for the matrix. It was found that the ability of the matrix to deform in the direction transverse to the fibers plays an important role in allowing larger, more realistic kink band inclinations to be obtained.

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ABSTRACT: This paper highlights the differences between onshore and offshore pipeline design. It then summarizes the results of combined external pressure, tension, and bending testing on full scale 6 5/8" and 16" pipe, and uses these results to support suggestions for appropriate design formulas for combined external pressure, tension, and bending loads. Finally, purchasing suggestions for pipe subjected to severe deepwater loadings are presented.

ABSTRACT: Progress has been made in the design of buckle arrestors, or more precisely collapse arrestors, for deepwater pipelines. Empirical relationships have been developed for the design of both integral ring and grouted sleeve arrestors, forming the basis of a simple and straightforward design procedure. The good agreement between the latest design formulas and the crossover pressure data obtained from large scale tests by Shell E&P Technology Company and by Professor Kyriakides at U.T. Austin over the past few years, should result in more efficient and reliable buckle arrestors for deepwater pipelines.

ABSTRACT: A design methodology for integral buckle arrestors for deepwater pipelines was presented in a previous study (Park TD, and Kyriakides S., International Journal of Mechanical Sciences 1997;39:643–69). It was based on experiments and analyses in which buckles engaged the arrestors quasi-statically. In this two-part paper series, the performance of the same arrestors is reevaluated under the more realistic dynamic buckle propagation conditions encountered in the sea. The experimental program described in Part I involves tubes with D/t=27.9 and arrestors with La /D=0.5. The quasi-static arresting efficiency of buckle arrestors is first established experimentally as a function of the arrestor thickness. The same arrestor designs are then tested again in constant pressure environments where buckles propagate at velocities of 400–1100 ft/s. Experiments
are conducted using both water and air as pressurizing media. A typical test specimen involves a relatively long upstream section of tube welded to an arrestor and to a downstream tube. The buckle is initiated in the upstream tube, accelerates to steady-state propagation, engages the arrestor and is either arrested or crosses over. For each arrestor design several such tests are required in order to bracket the dynamic crossover pressure. For all cases considered, the dynamic crossover pressure was found to exceed the corresponding quasi-static value. The reasons for this enhancement in performance are discussed in Part II in the light of results from numerical simulations of this process.

ABSTRACT: In the second part of this study we present models for simulating the quasi-static and dynamic propagation and arrest of buckles in pipelines. The models are developed within the framework of the nonlinear finite element ABAQUS and are used to simulate the quasi-static and dynamic arrest experiments in Part I. They are based on finite deformation kinematics and properly treat the contact that develops in the collapsed tube behind the propagating buckle. In the quasi-static model, the tube and arrestor materials are modeled as J2 flow theory solids with isotropic hardening. In the dynamic model, the rate dependence of SS-304 is assumed to exhibit an overstress power-law dependence. The pressurizing medium is assumed to be vacuum. The dynamic model is shown to reproduce accurately the conditions of steady-state buckle propagation as well as the dynamic engagement of a buckle with an arrestor. For buckle velocities of interest, the buckle profile was found to have sharpened considerably compared to the quasi-static one. The numerical results showed the same dynamic enhancement of arrestor performance observed in the experiments. When the much sharper dynamic buckle profile engages an arrestor, it initially induces to it and to the downstream tube significant reverse ovality. This tends to obstruct and delay the flattening of the arrestor and tube which is the cause of the crossing of arrestors with quasi-static efficiencies of less than 0.7. The net result is that a higher pressure is required to cross the arrestors when the buckle is running. As in the experiments, the biggest dynamic enhancement was found to occur for arrestors of efficiencies in the range of 0.35–0.6. Based on the results of this study it is concluded that quasi-static design procedures for integral buckle arrestors proposed previously are conservative.

ABSTRACT: A combined experimental and analytical study of the dynamic propagation of buckles initiated in long pipes under external pressure is presented. The experiments involve measurement of the steady-state velocity of buckles initiated in stainless steel tubes with D/t=27.9. Results from tubes pressurized by air or water are presented for pressure levels ranging from the propagation pressure to the collapse pressure of the tube. The buckle velocity in air was found to be significantly higher than in water at the same pressure. The flip–flop mode of buckle propagation was found to take place for pressure levels 13% below the collapse pressure and higher. A finite element model, capable of simulating the dynamic initiation and propagation of such buckles has been developed. The model accounts for the inertia of the pipe, the nonlinearity introduced by contact between the collapsing walls of the pipe while the material is modeled as a finitely deforming elastic–viscoplastic solid. The buckling and collapse are assumed to take place in vacuum. The model is shown to
reproduce well the dynamic initiation and propagation of buckles in air and the predicted velocities are in good agreement with those measured in this medium. The buckle was found to sharpen significantly with pressure. This sharpening, coupled with higher pressure, causes an increase in the amplitude of reverse ovality in a zone just ahead of the propagating buckle front. At higher pressures, the reverse ovality is shown to be high enough to initiate collapse at a new site. The new collapse is at 90° to the original one. This sequence of events is repeated, resulting in the flip–flop mode of buckle propagation.


ABSTRACT: Pipe-in-pipe systems are extensively used in offshore pipeline applications in which thermal insulation of the pipeline is necessary. Typically, the space between the two pipes is either empty or contains insulation material which provide minimal mechanical support to the system. In deepwater applications, the carrier pipe must be designed to resist collapse due to the ambient external pressure while the design of the inner pipe is usually governed by the pressure of the hydrocarbons it carries. The integrity of the two-pipe system in the event of accidental collapse of the carrier pipe is an issue of concern. In Part I of this two-part report, the results of an extensive experimental study of the problem are presented. The experiments were carried out on two-inch diameter carrier tubes with D/t values of 24.1, 21.1 and 16.7 and inner tubes of several diameters and wall thicknesses. In most cases local collapse of the outer tube led to simultaneous collapse of the inner one. Subsequently, the collapse propagated simultaneously collapsing both pipes. The propagation pressure of the two-pipe system (PP2) has been quantified parametrically. An interesting second mode of collapse propagation was also discovered in which the carrier pipe collapses leaving the inner one intact. Propagation of collapse affecting both pipes is still possible but usually at a higher pressure level. The pressure at which this switch takes place has been found to closely correspond to the propagation pressure of a carrier pipe with a solid rod insert (PPS) of the same diameter as the inner pipe. The parametric dependence of PPS has also been established experimentally. Part I finishes with a discussion of how these new critical pressures of pipe-in-pipe systems should influence the design of such pipelines.


ABSTRACT: In Part II we examine and evaluate the performance of three levels of models for estimating the two new propagation pressures of pipe-in-pipe systems introduced in Part I (PP2 and PPS). The first type of model involves uniform collapse of the system through a kinematically admissible mechanism resulting from the formation of plastic hinges. Closed-form expressions for PP2 and PPS are derived which provide a valuable qualitative view on how they depend on the main parameters of the problem. The predictions, however, significantly underpredict the measured values. The second type of model also involves uniform collapse but is conducted numerically instead. An energy balance between prebuckling and collapsed configurations obtained from a uniform collapse model yields approximate values of PP2 and PPS. It is demonstrated that such predictions are within acceptable engineering accuracy. The third type of model involves fully three-dimensional numerical simulation of the initiation and steady-state propagation of collapse. It is demonstrated that, provided the geometric and material characteristics of the pipes used are accurately represented in such
models, both PP2 and PPS can be predicted to great accuracy. Such models are, however, numerically intensive. Part II finishes with conclusions and design recommendations drawn from both the experimental and analytical parts of the study.


ABSTRACT: A new buckle arrestor concept for pipe-in-pipe systems is introduced and the results of a systematic study of its performance is presented. The concept involves either one single ring or a number of closely packed narrow rings placed in the annulus between the two pipes. Its effectiveness has been studied through a combination of experiments and analyses. The experiments involved two inch carrier tubes of three different D/t values and internal rings of various dimensions. A number of experiments were first conducted using pipe-in-pipe systems. It was found that the inner tube had only a small effect on the crossover pressure of this arrestor and, as a result, in many of the following experiments inner tubes were not included. The crossover pressure of the ring arrestors was studied by varying their length, wall thickness and yield stress. Other parameters varied were the dimensions and properties of the two tubes and the gap between the arrestor and the carrier tube. The process resulted in an empirical design formula for the arresting efficiency expressed as a function of the key nondimensional variables of the problem. Large-scale finite element models which simulate the buckle crossover process have also been developed. They have been shown capable of reproducing experiments accurately. Such models can be used to prove an arrestor design developed through the empirical process described in the report.

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ABSTRACT: Experiments and large scale numerical simulations are used to study the dynamics and the arrest of propagating buckles in pipe-in-pipe systems. In the first set of experiments the velocity of buckles initiated in a constant pressure environment is measured as a function of pressure using first water and then air as pressurizing media. For the outer and inner pipe parameters used, the buckle velocities correlated well with values measured in single pipes. The dynamic propagation experiments in air were then simulated numerically. Calculated buckle velocities followed the same trend as the measured values although they were somewhat higher. In the second set of experiments the effectiveness of internal ring buckle arrestors designed with previously developed quasi-static design procedures is re-evaluated under dynamic buckle propagation. In all cases examined the dynamic arresting efficiency was found to be higher than the quasi-static one. The same behavior was also observed in corresponding numerical simulations. This indicates that design of such devices using quasi-static design criteria should be conservative.

ABSTRACT: It is well known that tubular liners of stiff cavities such as grouted oil-well casing can be collapsed by external pressure. Collapse is initially local but can propagate at a relatively low pressure with catastrophic results. The paper presents a quantitative study of the lowest pressure at which confined collapse can propagate known as confined propagation pressure. Experiments and analysis are used to develop an improved expression relating this critical pressure to the material and geometric parameters of the liner tube. It is shown that these include the yield stress and post-yield characteristics of the material, and the tube D/t. The new empirical relationship developed can provide engineering type estimates of the confined propagation pressure. The quasi-static initiation and propagation of confined collapse was also modeled using three-dimensional finite elements. The model accounts for the finite deformations and addresses the contact nonlinearities which govern the phenomenon. The material is modeled as a finitely deforming elastic–plastic solid. It is demonstrated that the model can predict the confined propagation pressure to a very significant degree of accuracy. It is thus a viable tool for obtaining accurate predictions of this critical pressure.


Francois Claude Bardi, “Plastic buckling and collapse of circular cylinders under axial compression”, Ph.D. dissertation, The University of Texas at Austin, August 2006

ABSTRACT: This study is concerned with the plastic buckling of relatively thick tubes and the ensuing succession of instabilities leading to their failure. The first instability is uniform axisymmetric wrinkling that is treated as a plastic bifurcation. As the wrinkles grow, the axial rigidity of the shell is gradually reduced. This eventually leads to a limit load instability beyond which failure in the form of localized deformation takes place. The problem is studied using experiments and analyses. Stainless steel specimens with D/t of 23-52 were custom-designed to avoid stress concentrations and reproduce long uniform pipe conditions. The specimens were compressed to failure under displacement control. In all cases, a second bifurcation involving non-axisymmetric mode of deformation preceded the limit load. The bifurcation into axisymmetric wrinkling was determined by monitoring the development of wrinkles on the surface of the tubes. This critical state was successfully predicted using an anisotropic deformation theory of plasticity. The anisotropy of the material was established experimentally and modeled using Hill's quadratic anisotropic yield criterion. The problem was first modeled as uniform axisymmetric wrinkling. The model uses Sanders’ shell kinematics assuming small strains and moderately small rotations and includes a modified flow theory of plasticity to accommodate the anisotropy observed in the tubes. Small axisymmetric imperfections based on the critical half-wavelength were integrated into the model. The problem was formulated through the principle of virtual work and solved using Newton’s method. The solution correctly simulates the growth of wrinkles resulting in a limit load instability. The model included second bifurcation calculations from axisymmetric to non-axisymmetric configuration. Second bifurcation instabilities were found to occur before the limit load developed. For this reason, a second model was developed in which non-axisymmetric deformation of the shell was simulated by introducing both axisymmetric and non-axisymmetric imperfections. Non-axisymmetric responses were found to be highly
sensitive to the imperfections. Each experiment was first reproduced accurately by choosing the right combination of imperfections. However, to achieve a satisfactory prediction of the limit state over the whole range of D/t, a thorough parametric study of the imperfection sensitivity was performed. The relative amplitude of the axisymmetric imperfection to the non-axisymmetric imperfection was found to define whether the shell deforms axisymmetrically or not. Furthermore, if one of the imperfections governs the deformation configuration, then the effect of the second onto the response is negligible. Thus, a constant axisymmetric imperfection of 0.05% of the pipe wall thickness and a non-axisymmetric imperfection proportional to (D/t)² / m³ yielded accurate predictions of both mode of deformation and limit load.

References listed at the end of the paper:


The plastic buckling and collapse of long cylinders under combined internal pressure and axial compression was investigated through a combination of experiments and analysis. Stainless-steel cylinders with diameter-to-thickness values of 28.3 and 39.8 were compressed to failure at fixed values of internal pressure up to values 75% of the yield pressure. The first effect of internal pressure is a lowering of the axial stress–strain response. In addition, at some plastic strain level, the cylinder develops uniform axisymmetric wrinkling. Under continued compression, the wrinkles grow stably, gradually reducing the axial rigidity of the structure and eventually lead to a limit load instability. All pressurized cylinders remained axisymmetric until the end of the test past the limit load. The critical stress and wavelength were established using classical plastic bifurcation theory based on the deformation theory of plasticity. The evolution of wrinkling, and the resultant limit state, were established by modeling a periodic domain that is one half of the critical wavelength long. The domain was assigned an initial imperfection corresponding to the axisymmetric buckling mode calculated through the bifurcation check. The inelastic material behavior was modeled through the flow theory of plasticity with isotropic hardening. The variations of the axial response and of the limit strain with pressure observed in the experiments were reproduced well by the model. Inclusion of Hill-type anisotropic yielding in all constitutive models was required for good agreement between predictions and experiments.

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ABSTRACT: Relatively thin-walled tubes bent into the plastic range buckle by axial wrinkling. The wrinkles initially grow stably but eventually localize and cause catastrophic failure in the form of sharp local kinking. The onset of axial wrinkling was previously established by bifurcation analyses that use instantaneous deformation theory moduli. The curvatures at bifurcation were predicted accurately, but the wrinkle wavelengths were consistently longer than measured values. The subject is revisited with the aim of resolving this discrepancy. A set of new bending experiments is conducted on aluminum alloy tubes. The results are
shown to be in line with previous ones. However, the tubes used were found to exhibit plastic anisotropy, which was measured and characterized through Hill’s quadratic anisotropic yield function. The anisotropy was incorporated in the flow theory used for prebuckling and postbuckling calculations as well as in the deformation theory used for bifurcation checks. With the anisotropy accounted for, calculated tube responses are found to be in excellent agreement with the measured ones while the predicted bifurcation curvatures and wrinkle wavelengths fall in line with the measurements also. The postbuckling response is established using a finite element model of a tube assigned an initial axisymmetric imperfection with the calculated wavelength. The response develops a limit moment that is followed by a sharp kink that grows while the overall moment drops. The curvature at the limit moment agrees well with the experimental onset of failure. From parametric studies of the various instabilities it is concluded that, for optimum predictions, anisotropy must be incorporated in both bifurcation buckling as well as in postbuckling calculations.

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ABSTRACT: Integral buckle arrestors are relatively thick wall rings periodically welded in an offshore pipeline at intervals of several hundred meters in order to safeguard the line in case a propagating buckle initiates. They provide additional circumferential rigidity and thus impede downstream propagation of collapse, limiting the damage to the length of pipe separating the two arrestors. The effectiveness of such devices was studied parametrically through experiments and numerical simulations in Park and Kyriakides [On the design of integral buckle arrestors for offshore pipelines. International Journal of Mechanical Sciences 1997;39(6):643–69]. The experiments involved quasi-static propagation of collapse towards an arrestor, engagement of the arrestor, temporary arrest, and the eventual crossing of collapse to the downstream pipe at a higher pressure. The same processes were simulated with finite element models that included finite deformation plasticity and contact. The experimental crossover pressures enriched with numerically generated values were used to develop an empirical design formula for the arresting efficiency of such devices. A recent experimental extension of this work revealed that for some combinations of arrestor and pipe yield stresses, the design formula was overly conservative. Motivated by this finding, a new broader parametric study of the problem was undertaken, which demonstrated that the difference between the pipe and the arrestor yield stress affects significantly the arrestor performance. The original arrestor design formula was then modified to include the new experimental and numerical results producing an expression with a much wider applicability.

ABSTRACT: Circular tubes compressed into the plastic range first buckle into axisymmetric wrinkling modes. Initially the wrinkle amplitude grows with increasing load. The wrinkles gradually induce a reduction in axial rigidity eventually leading to a limit load instability followed by collapse. The two instabilities can be separated by strain levels of a few percent. This work investigates whether a tube that develops small amplitude wrinkles can be subsequently collapsed by persistent cycling. The problem is first investigated experimentally using SAF
2507 super-duplex steel tubes with D/t of 28.5. The tubes are first compressed to strain levels high enough for mild wrinkles to form; they are then cycled axially under stress control about a compressive mean stress. This type of cycling usually results in material ratcheting or accumulation of compressive strain; here it is accompanied by accumulation of structural damage due to the growth of the amplitude of the initial wrinkles. The tube average strain initially grows nearly linearly with the number of cycles, but as a critical value of wrinkle amplitude is approached, wrinkling localizes, the rate of ratcheting grows exponentially and the tube collapses. The rate of ratcheting and the number of cycles to failure depend on the initial compressive pre-strain and on the amplitude of the stress cycles. However, collapse was found to occur when the accumulated average strain reaches the value at which the tube localizes under monotonic compression. A custom shell model of the tube with initial axisymmetric imperfections, coupled to a cyclic plasticity model, are presented and used to simulate the series of experiments performed successfully. A sensitivity study of the formulation to the imperfections and to key constitutive model parameters is then performed.


ABSTRACT: Circular tubes compressed into the plastic range first buckle into axisymmetric wrinkling. Initially, the wrinkle amplitude grows with increasing load, but induces a gradual reduction in axial rigidity that eventually leads to a limit load instability and collapse. For lower D/t tubes, the two instabilities can be separated by strain levels of a few percent. Persistent stress-controlled cycling can cause accumulation of deformation by ratcheting. Here, the interaction of ratcheting and wrinkling is investigated. In particular, it is asked if compressive ratcheting can first initiate wrinkling and then grow it to amplitudes associated with collapse. Experiments on SAF2507 super-duplex steel tubes with D/t of 28.5 have shown that a geometrically intact tube cycled under stress control initially deforms uniformly due to material ratcheting. However, in the neighborhood of the critical wrinkling strain under monotonic loading, small amplitude axisymmetric wrinkles develop. This happens despite the fact that the maximum stress of the cycle can be smaller than the critical stress under monotonic loading. In other words, wrinkling appears to be strain rather than stress driven, as is conventionally understood. Once the wrinkles are formed, their amplitude grows with continued cycling, and as a critical value of amplitude is approached, wrinkling localizes, the rate of ratcheting grows exponentially, and the tube collapses. Interestingly, collapse was also found to occur when the accumulated average strain reaches the value at which the tube localizes under monotonic compression. A custom shell model with small initial axisymmetric imperfections, coupled to a cyclic plasticity model, is used to simulate these cyclic phenomena successfully.


ABSTRACT: The response of long, thin-walled, cross-ply composite tubes subjected to pure bending was studied analytically. The formulation includes three parts: pre-buckling response, material failure and bifurcation buckling. The pre-buckling response is analyzed using nonlinear kinematics to accommodate the ovalization of the cross-section. The formulation is based on the principle of virtual work and is used to generate a numerical solution procedure. The Tsai-Wu failure criterion is used to detect material failure in the pre-buckling response. The maximum stress criterion was also considered for comparison. Finally, the buckling analysis considers the possibility of bifurcation into modes containing periodic displacements along the axis of
the tube. The tubes are assumed to be geometrically perfect and free of residual stress. Three materials-AS3501 graphite-epoxy, Kevlar 49-epoxy, and E-glass-epoxy-and three diameter-to-thickness ratios-50, 100 and 400—are considered. The moment-curvature response of the tubes is non-linear due to the ovalization of the cross-section (Brazier effect) which induces a limit moment instability. Either material failure or bifurcation buckling always occurs prior to the limit moment in the cases considered. Little difference was observed between the failure loads predicted by the Tsai-Wu and the maximum stress criteria. Tubes with plies of circumferentially oriented fibers in the outermost and innermost positions in the wall proved superior in strength compared with the other cases considered.


ABSTRACT: The buckling mode localization of a multiply supported column subjected to fully reversed, displacement-controlled cyclic loading is studied numerically. The results show that localization can take place and lead to limit loads similar to those reported in other structural members in the literature. Analysis of the results reveals the mechanisms by which localization takes place.


OVERVIEW: Long cylindrical tubes and pipes under axial compression will usually bend, behaving as beam columns. Shell-type localized buckling occurs mainly when the structure is restrained from lateral movement. This, for example, is the case for a pipeline buried in a trench (Figure 11.1) or resting on a deformable foundation. Compression can be caused by the passage of hot hydrocarbons carried from the well to a central gathering point by buried flowlines in offshore operations [11.1]. Foundation motion caused by fault movement, landslides, ground subsidence, permafrost melting, or soil liquefaction can also result in severe compression of the lines [11.2 11.6]. Both loading scenarios can impose compressive strains high enough to result in shell-type buckling. In most onshore and offshore pipeline operations, diameter-to-thickness ratios (D/t) and steel grades are such that buckling occurs in the plastic range. In this chapter, the main features of plastic buckling under axial compression are first illustrated experimentally. The formulation for predicting the onset of plastic wrinkling is then developed, followed by a study of how wrinkles grow, localize and lead to collapse.


ABSTRACT: Bending in the presence of external pressure is experienced by pipelines during their installation and also subsequently during their operation. In installation methods such as S-lay (Figure 2.15), J-lay (Figure 2.19), and reeling (Figure 2.4), the pipe is bent under relatively high external pressure in the sagbend [9.1, 9.2]. The pipeline is also bent under external pressure as it conforms to surface undulations on the seafloor. Bending at the sea floor can also be experienced due to snaking resulting from pipe expansion caused by the passage of hot hydrocarbons (in some cases purposely induced, in others accidentally). It is also a condition that can develop in case of upheaval buckling of a section of a buried pipe. Bending ovalizes the pipe cross section, which of course reduces its resistance to external pressure. This interaction through ovalization is aggravated by inelastic material effects, which usually come into play in lower D/t pipes used for offshore applications. This chapter deals with the mechanics of inelastic bending in the presence of external pressure and the associated
limit states. The development of this interaction starts with the behavior under pure bending and pure external pressure. The reader would benefit from exposure to Chapters 4 and 8 before embarking on the following material.


ABSTRACT: Offshore as well as onshore pipelines in operation are under internal pressure. The scenarios for developing axial compression outlined in Chapter 11 also apply to a pressurized pipeline. The general features of plastic buckling under axial compression and internal pressure are similar to those of pure axial loading, presented in Figure 11.2. The cylinder first wrinkles at an increasing load. The wrinkle amplitude grows, leading eventually to a limit load instability. A pipeline will fail by localized collapse at this strain, and as a result this constitutes a limit state. The biaxial state of stress lowers the axial stress levels of the various critical events described in Figure 11.2 but, as will be demonstrated, has a smaller effect on the corresponding strains. In addition, the pressure has a stabilizing effect on the axisymmetric mode, making a switch to non-axisymmetric modes more difficult. These features of the problem are first illustrated experimentally. The formulation for predicting the onset of plastic wrinkling is then developed, followed by a study of how wrinkles grow, localize and lead to collapse.


ABSTRACT: Offshore pipelines are commonly installed empty in order to reduce the installation tension due to the weight of the suspended section (see Chapter 2). In addition, during operation they are periodically depressurized for maintenance. Thus, external pressure is an important load parameter in design; indeed, it is often the prime parameter. This chapter deals with the mechanics of buckling and collapse of long pipes under external pressure. Thinner pipes used in shallower waters buckle elastically, but collapse due to postbuckling inelastic action. The classical elastic buckling pressure is derived in Section 4.1, followed by the derivation of Timoshenko's design formula for the onset of collapse of an initially ovalized pipe. Thicker pipes used in deeper waters buckle and collapse in the plastic range. In Section 4.2, plastic buckling equations are derived. Their relative simplicity makes them useful tools in design. Practical factors that affect collapse include initial imperfections such as ovality and wall thickness variations. Other factors include residual stresses, yield anisotropy, etc. The influence of such factors is best treated numerically. Section 4.3 presents the external pressure part of the formulation and solution procedure of the custom computer code BEPTICO [4.1], capable of including these aspects of the problem. Section 4.4 presents a parametric study of buckling and collapse of elastic-plastic pipe under external pressure. Section 4.5 outlines how actual pipe imperfections can be measured. Examples of typical shape and wall thickness imperfections in seamless pipes are presented and used in collapse calculations.


ABSTRACT: This paper describes an experimental and an analytical and numerical investigation into the buckling behaviour of cylindrical composite tubes under external hydrostatic pressure. The investigations
concentrated on fibre reinforced plastic tube specimens made from a mixture of three carbon and two E-glass fibre layers. The lay-up was $0^\circ/90^\circ/0^\circ/90^\circ/0^\circ$; the carbon fibres were laid lengthwise ($0^\circ$) and the E-glass fibres circumferentially ($90^\circ$). The theoretical investigations were carried out using a simple solution for isotropic materials, namely a well-known formula by “von Mises” and also by finite element analyses using ANSYS. The experimental investigations showed that the composite specimens behaved similarly to isotropic materials tested by various other researchers. The specimens failed by the common modes associated with this study, namely due to elastic buckling, inelastic buckling and axisymmetric yield failure. Furthermore it was discovered that the specimens failed at changes of the composite lay-up due to the manufacturing process of these specimens. These changes seem to be the weak points of the specimens. For the theoretical investigations two different types of material properties were used to analyse the composite. These were calculated properties derived from the properties of the single layers given by the manufacturer and experimentally obtained properties. Two different approaches were chosen for the investigation of the theoretical buckling pressure, a program called “MisesNP”, based on a well-known formula by von Mises for single layer isotropic materials, and two finite element analyses using the famous computer package called “ANSYS”. This latter analyses simulated the composite with a single layer orthotropic element (Shell93) and also with a multi layer element (Shell99). It was found out that the results obtained with ANSYS predicted questionable buckling pressures that could not be reproduced logically. Nevertheless this report provides Design Charts for all approaches and material types. These Design Charts allow the possibility of obtaining a ‘plastic knockdown factor’. The theoretical buckling pressures obtained using MisesNP or ANSYS can then be divided by the plastic knockdown factor, to give predicted buckling pressures. This method can be used for the design of full-scale vessels.

References listed at the end of the paper:


PARTIAL ABSTRACT: The paper reports on the buckling of twelve thin-walled geometrically imperfect tubes, which were tested to destruction under uniform external hydrostatic pressure. The paper also reports on other similar tests to destruction, carried out on a large number of geometrically imperfect tubes. Theoretical studies were also carried out with well-known analytical solutions, together with a numerical solution using a finite element computer package, namely ANSYS. Whereas the theoretical analyses agreed with each other, they did not agree with the experimental data for the shorter tubes; this was because the shorter tubes collapsed by inelastic instability due to initial geometrical imperfections of the tubes. Exact analysis of slightly geometrically imperfect tubes, with random distribution has so far defied reliable theoretical solutions. However, the paper
presents a design chart, which can cater for these geometrical imperfections. The design chart may also be suitable for large vessels such as submarines, off-shore drilling rigs, silos, etc. Circular cylinders under external pressure, often appear in the form of submarine pressure hulls, torpedoes, off-shore drilling rigs, silos, tunnels, immersed tubes, rockets, medical equipment, food cans, etc. Such vessels are good for resisting internal or external pressure, however under uniform external pressure they can collapse at a fraction of the pressure that will cause failure under internal pressure. Failure of these vessels under uniform external pressure is called non-symmetric bifurcation buckling or shell instability [1,2,3]. To improve the resistance of these vessels to the effects of uniform external pressure, the vessels are usually stiffened by ring stiffeners spaced at near equal distances apart. If, however, the ring stiffeners are not strong enough, the entire flank of the vessel can collapse bodily by a mode called general instability. Another mode of failure is known as axisymmetric deformation, where the cylinder implodes axisymmetrically, so that its cross-section keeps its circular form while collapsing. In this study, we will be concerned with elastic and inelastic shell instability; as such vessels can collapse at pressures of a fraction of that which cause the vessels to fail under internal…

Andrew P.F. Little, Carl T.F. Ross, David Flowers, Graham X. Brown and Stefan Arndt, “A theoretical and experimental investigation of externally ring stiffened cylindrical pressure vessels subjected to external pressure”, Proceedings of the International Conference on Computing in Civil and Building Engineering, W. Tizani (Editor), ICCBE2010, 2010 (not sure of date; it is not too legible in the pdf file.)

ABSTRACT: The best shape for withstanding external pressure is a sphere. However, this is not a very efficient shape for payload, and so submarine structures are often based on cylinders. Long cylinders perform worse than short cylinders under external pressure, and so ring-stiffeners are often introduced to reduce the effective length, and increase the resistance to buckling. Under hydrostatic pressure, cylinders fail by lobar buckling. This is where lobes are formed around the circumference, and the number of lobes formed is a characteristic of the vessel. This paper describes an investigation into the buckling of UPVC ring-stiffened pressure vessels subjected to external pressure. Buckling experiments were carried out on five laboratory sized vessels. Two were approximately 50% longer than the other three, but all of them were otherwise identical. Accurate geometric data was obtained from a co-ordinate measuring machine, and this was used to produce finite element models of the vessel. Two finite element packages were used to model the vessel. One was an in-house program CONBUCR which utilises axisymmetric truncated conical elements, with the facility to add nodal stiffness. The second was the commercial code Ansys, where shell elements were used to model the cylinder and beam elements to model the external rings. Reasonable agreement was obtained between the theoretical and experimental results, given the scatter inherent in the determination of experimental buckling pressures. The axisymmetric program was shown to be much quicker to use than Ansys, with little compromise in accuracy. Inhomogeneous material possibly due to the inclusion of impurities can greatly reduce the buckling resistance of a vessel. In addition, cylinders are never perfectly round, and so the practical test results were expected to show buckling resistances less than the theoretical models.

References listed at the end of the paper:

Carl T.F. Ross, Terry Whittaker & Andrew P.F. Little (University of Portsmouth, UK), “Design of submarine
pressure hulls to withstand buckling under external hydrostatic pressure”, Proceedings of the International Conference on Computing in Civil and Building Engineering, W. Tizani (Editor), ICCBE2010, 2010 (not sure of date; it is not too legible in the pdf file.)

ABSTRACT: The paper presents an investigation into various methods of calculating the theoretical collapse loads for a pressure vessel, under uniform external hydrostatic pressure; based on different design codes. The design codes used for the investigation were BS 5500, for vessels under external pressure and also, the design charts of Ross of the University of Portsmouth. It is the opinion of the present authors that the current design methodology, namely BS 5500 was difficult to use and gave inaccurate collapse pressures for some large-scale pressure vessels. Moreover, BS 5500 appeared to be too pessimistic for one mode of failure and too optimistic for another mode of failure. For the present study, a full-scale ‘theoretical’ pressure vessel was used and the aforementioned methodologies applied in its design to see if there were any similarities that each method may have had. From the results obtained, it became apparent that some methodologies were more accurate than others, depending on the mode of collapse. Moreover, it also became apparent that some of the methods themselves were outdated, user-unfriendly and in some cases, may have even been dangerous.

References listed at the end of the paper:


ABSTRACT: This paper reports on theoretical and experimental investigations into the buckling characteristics of a series of six ring-stiffened circular cylinders that experienced general instability when subjected to external hydrostatic pressure. Each study used between 3-5 designs with the same internal and external diameters, but with different numbers and sizes of ring-stiffeners. Four used designs that were machined to a high degree of precision from steel, while the other two were machined from aluminium alloy. The theoretical investigations focused on obtaining critical buckling pressure values, namely $P_{cr}$, for each design from the well-known Kendrick’s Part I and Part III theories, together with an ANSYS finite element prediction. The thinness ratio $\lambda$, which was originally derived by the senior author, was calculated together with a dimensionless quantity called the plastic knockdown factor (PKD), for each model. The plastic knockdown factor was calculated by dividing the theoretical critical buckling pressures $P_{cr}$, by the experimental buckling pressures $P_{exp}$. The thinness ratio was used because vessels such as these, which have small but significant random out-of-circularity, defy “exact” theoretical analysis and it is because of this that the design charts were produced. Three design charts
were constructed by plotting the reciprocal of the thinness ratio \((1/\lambda)\) against the plastic knockdown factor \((P_{cr}/P_{exp})\), using results from Kendrick Part I, Kendrick Part III, and ANSYS. Comparison of the results obtained using Kendrick’s theories and experimentally obtained results was good.

References listed at the end of the paper:


SUMMARY: A number of reinforced concrete (RC) towers constructed in the 1940s to 1970s are still used. In China and India, the construction of towers in power plants has increased and the scale of the tower has also enlarged. Investigations of the collapse accidents in the past and examination of the countermeasures are developing areas of study, and the evaluation of the safety of the existing facilities has become an important topic of research. With respect to the thin RC shells of these towers, much of the research has analysed the buckling-vibration problem and the effect of initial imperfections on structural properties. Several design guidelines have been proposed. To begin with, useful knowledge of the fundamental phenomenon and analysis method was obtained by studying the initial imperfections of a distribution idealized axisymmetrically and asymmetrically. Recommendations for the tolerance limit of the magnitude of the initial imperfections were proposed. According to the results of many leading research studies, the fluctuation in the in-plane stress in the meridian direction caused by the initial imperfections was inversely proportional to the shell thickness due to dead weight and wind load within the elastic stress analysis, and that it largely affects in-plane stress in meridian direction and bending stress in circumferential direction for the circumferential curvature error. In addition, partial initial imperfections with small amplitudes play a major role in meridian and circumferential stresses. In this paper, three-dimensional geometric errors in a collapsed RC cooling tower shell (Ardeer Nylon Works, 1973) were reproduced and analyzed numerically in detail. Further, the effect of the geometric imperfection of the reproduced shape on the elastic stress distribution due to dead weight was examined, and the
The effect on the wind resistance performance was examined using elasto-plastic FE analysis. The results of this study are as follows:

1. The reproduced geometric imperfection widely exists on the shell full face, and it becomes a waveform that recurs in the circumferential and meridian directions.
2. The hoop stress under the action of the dead load can be changed from tension to compression as a result of the imperfection.
3. Due to wind load, the bending cracks develop in the windward direction of the imperfect shell; this leads to the failure of the tower due to the tension that arises because of the bending in the meridian direction.
4. In the model with the imperfection, it is concluded that the turbulence in the remarkable section forces extends further than that in the case of a perfect shell. Moreover, the maximum reduction in the load bearing capacity is predicted to be approximately 18%. The effect of the difference between the wind directions is considered to be a remarkable result (The shape measurement value used in the analysis includes the effect of existing cracks, repetition of wind/thermal stresses and creep).
5. The effect of the comparatively small temperature loading on the lowering of the rigidity and the ultimate strength may be remarkable, and this fact is contrary to the usual behaviour of an RC member. In the case of a thin-shell cooling tower, the temperature crack may become a significant factor in the lowering of the ultimate strength. Therefore, this relationship needs to be examined prudently in the future.
6. In the design and safety assessment of existing towers, an elasto-plastic analysis seems to be necessary.


ABSTRACT: The collapse of steel tubes under external pressure is described using finite element models. The models are validated comparing their predictions against the results of collapse tests performed in our laboratory.

1 INTRODUCTION
The external collapse pressure of very thin steel tubes is governed by classical elastic buckling formulas; however, for thicker tubes more involved elasto-plastic considerations have to be taken into account. There are many factors that have some degree of influence on the external pressure that produce the collapse of a steel tube, among them:

1. The relation (outside diameter/thickness) (D/t ratio).
2. The yield stress of the tube steel (s_y).
3. The work-hardening of the tube steel.
4. The shape of the tube sections (outside diameter shape and thickness distribution).
5. The residual stresses locked in the tube steel.
6. The localized imperfections introduced either...

References listed at the end of the paper:

ABSTRACT: The production of steel OCTG products with guaranteed external collapse pressure (high collapse casing) requires the implementation of an accurate process control. To develop that process control it is necessary to investigate how different parameters affect the external collapse pressure of pipes. Two dimensional finite element models provide an useful tool for performing the “first approach” parametric studies; however a bidimensional representation of the tube geometry (as used in many analytical and semi-empirical formulas) is not enough for determining the external collapse pressure of casings. We use three dimensional models to further investigate the effects of the casing geometry on its external collapse pressure. To acquire the data that describes the geometry of casing samples, we have developed an imperfections measurement system following previous developments by Yeh and Kyriakides. We also present finite element models of OCTG connections which are used as a tool for the evaluation of connections collapse pressure.


ABSTRACT: The production of steel pipes with guaranteed external collapse pressure (e.g. high collapse casings for oil wells) requires the implementation of an accurate process control. To develop that process
control it is necessary to investigate how different parameters affect the external collapse pressure of the pipes. Experimental/numerical techniques implemented to investigate the collapse behavior of steel pipes are presented. The discussion of the experimental techniques includes the description of the facilities for performing external pressure collapse tests and the description of an imperfections measuring system. The numerical techniques include 2D and 3D finite element models. The effects on the value of the pipes’ external collapse pressure of their shape, residual stresses and material properties are discussed.


ABSTRACT: The infinitesimal strain version of the MITC4 shell element (Dvorkin and Bathe [6]) was previously successfully used for the analysis of deep-water applications of steel marine pipelines. The collapse and post collapse responses were modeled and compared with experimental results (Toscano et al. [12]). Even though in those verifications the matching between numerical and experimental results was excellent, it was also noticed that in the post–collapse regime very high strains are developed in the steel shell. In Ref. [12] a version of the MITC4 that uses a posteriori updates of the shell thickness was used to incorporate into the model the finite strain behavior. The results indicated that even though the consideration of finite strains improves the solution, the room for improvement - when the overall equilibrium paths are considered - is so small that it hardly justifies the use of a more expensive numerical model. However, if local strains are sought, the finite strain model produces much better approximations to the actual situation. Hence, the motivation for shell element formulations apt for finite strain elasto-plastic analyses is still open. In previous publications we presented a new shell element formulation, the MITC4-3D that we developed for finite strain analysis (Toscano and Dvorkin [13, 14]) using the MITC4 strains interpolation (Dvorkin and Bathe [6]) and 3D constitutive relations. In this paper we are going to discuss the basic features of the MITC4-3D element and present further verification / validation.

References listed at the end of the paper:


ABSTRACT: In 1970, Ahmad et al. [1] presented a shell element formulation that after many years still constitutes the basis for modern finite element analysis of shell structures. The original formulation was afterwards extended to material and geometric nonlinear analysis under the constraint of the infinitesimal strains assumption [2–4].

References listed at the end of the paper:
INTRODUCTION: The design of High-Pressure/High-Temperature (HP/HT) pipelines on an uneven seabed has become an important issue in the recent years. The need to gain further insight into how expansion, seabed friction and free spans influence on the pipeline behavior through selected load cases is the background for this chapter. The behavior of such pipelines is largely characterized by the tendency to undergo global buckling, either vertically if trenched or covered, or laterally if the pipeline is left fully exposed on the seabed. The main concern in the design of slender pipelines operating under HP/HT conditions is to control global buckling at some critical axial force. The large horizontal and/or vertical displacements induced by global buckling may result in high stresses and strains in the pipe wall that exceed code limits. The simulation of the designed pipeline in a realistic three-dimensional environment obtained by measurements of the seabed topography, allows the engineers to exploit any opportunities that the pipeline behavior may offer to develop both safe and cost-effective solutions. For example, the designer can first analyze the pipeline behavior on the original seabed. If some of the load cases result in unacceptably high stress or strain, seabed modification can be simulated in the finite element model and the analysis re-run to confirm that the modifications have lead to the desired decrease in stress or strain. The finite element model may be a tool for analyzing the in-situ behavior of a pipeline. By the pipeline in-situ behavior it is here meant the...


ABSTRACT: The production of oil and gas from offshore oil fields is, nowadays, more and more important. As a result of the increasing demand of oil, and being the shallow water reserves not enough, the industry is pushed forward to develop and exploit more difficult fields in deeper waters. In this Thesis, a methodology for using the finite element method as a robust engineering tool for analyzing the effect of the manufacturing tolerance on the collapse and post collapse behavior of steel pipes was discussed and illustrated with practical examples. Even though, using a small strain formulation, the matching between numerical and experimental results was excellent, the model results showed high strains in some areas of the collapsed pipes. Therefore, we developed a new shell element, MITC4-3D, incorporating elasto-plastic finite strains, based in the MITC4 formulation. It was implemented for the analyses of elasto-plastic shell structures and the results indicate that it is a very effective element.

References listed at the end of the thesis:


[76] The ADINA System, ADINA R&D, Watertown, MA, U.S.A.
Supplement.


ABSTRACT: A comparison between pipe bends with assumed cross sections, namely elliptic and semi oval to include ovality along with wall thinning, was performed to determine the plastic collapse load under in-plane closing bending moment using finite element limit analysis based on an elastic-perfectly plastic material considering geometric nonlinearity. Twice-elastic-slope method was used to obtain collapse load from the moment-rotation curve drawn for each pipe bend model considered. The effect of ovality on collapse load is significant and higher for elliptic cross sections for almost all cases while the thinning effect is negligible for both the cross sections. The study concludes that the use of elliptic cross section is suitable for analyzing pipe bend with ovality. Therefore, a closed-form solution is proposed to determine collapse load of pipe bend based on the finite element results of elliptic cross sections.

References listed at the end of the paper:

Christian Huehne (1), Raimund Rolfes (1) and Jan Tessmer (2)
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ABSTRACT: Thin-walled shell structures like circular cylindrical shells are prone to buckling. Imperfections which are defined as deviations from perfect shape and perfect loading distributions can reduce the buckling load drastically compared to that of the perfect shell. Design criteria monographs like NASA-SP 8007 recommend that the buckling load of the perfect shell shall be reduced by using a knock-down factor. The existing knock-down factors are very conservative. Furthermore, the structural behaviour of composite material is not considered. A new experimental approach to determine the lower bound of the buckling load of thin-walled cylindrical composite shells is presented. Based on test results the numerical analysis is validated.

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(2) Airbus Deutschland GmbH, ESAS, Kreetslag 10, 21129 Hamburg, Germany
ABSTRACT: A fast semi-analytical model for the post-buckling analysis of stiffened cylindrical panels is presented. The panel is comprised of a skin (shell) and stiffeners in both longitudinal (stringers) and circumferential direction (frames). Local buckling modes are considered where the skin may buckle within a bay and may induce rotation of the stiffeners. Stringers and frames are considered as structural elements and are thus not ‘smeared’ onto the skin. Large out-of-plane deflections and thus non-linear strain–displacement relations of skin and stiffeners are taken into account. The displacements of skin and stiffeners are approximated by trigonometric functions (Fourier series). First, a linear buckling eigenvalue analysis is carried out and some combination of buckling eigenmodes is chosen as imperfection. Then the load history is started and the Fourier coefficients are determined by minimizing the stiffened panel's energy at each load level. A curve-tracing algorithm, the Riks method, is used to solve the equations. The present model can be used to assess the post-buckling behavior of stiffened panels, for example, aircraft fuselage sections.
Development and experimental verification of FE-model for stringer-stiffened fibre composite panels under combined thermal and mechanical loading conditions” (Proceedings European Conference on…, 1998, no publisher given)

ABSTRACT: In this paper a buckling design rule for stringer stiffened curved CFRP panels subjected to combined mechanical and thermal loading is derived by parametric studies with the finite element system ANSYS. At first a finite element model to simulate the buckling behaviour of such panels is established and validated with test results from a former study. Then loading and boundary conditions are adapted to those of the Thermex B testing site at DLR in Braunschweig, and results of linear bifurcation analyses with constant material properties under combined mechanical and thermal load are presented. Additional nonlinear computations with temperature-dependent material properties confirm the results of the linear computations. The results of all computations are summarized as the design rule looked for, and then verified by tests.

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ABSTRACT: Thin-walled stiffened panels tend to buckle under compressive and/or shear loads with resulting redistribution of stresses in the structure. Provided that the stiffeners are capable of sustaining the additional load, such conditions are acceptable in many structures. Since a complete postbuckling analysis for each state of loading is prohibitive, simple approximations are in use. With the appearance of orthotropic panels it is deemed desirable to extend such approximations to panels with orthotropic properties. A short review of available recommendations is given and a one term approach is used to demonstrate the effect of orthotropy. Further, recent panel test results from ETH Zurich are reviewed accordingly, and two different FE-based postbuckling analyses (postbuckling at Zurich and initial postbuckling at Braunschweig) are performed to provide confirmation that the quality of a crude and simplifying formula is acceptable.

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ABSTRACT: The objective of the present paper is to present a simple analytical solution for computing bifurcation buckling loads of thin and moderately thick orthotropic cylindrical shells and panels subjected to axial compression and normal pressure. That solution does not necessarily make use of the simplifying assumptions of shallow shell theory, and takes the flexibility with respect to transverse shear loads into account, which is supposed to be relatively high with laminated composite structures. The analysis is based on the governing nonlinear equations and boundary conditions of deep and shallow shell theory. They are linearised to yield the differential equations for bifurcation buckling. The linearised set admits a single-term analytical solution when the cylinder ends or panel edges are simply supported. It reduces the task to a small size (3*3) algebraic eigenvalue problem that can be solved by standard methods. A computer program BOSCAP
Buckling of Orthotropic Shear-flexible Cylinders And Panels is developed based on the above mentioned formulation which is very quick and easy to use during design trials or in automated optimization. A series of numerical examples is presented to demonstrate effects of transverse shear flexibility and curvature. Good agreement with some test results is shown.


ABSTRACT: A new exact closed-form procedure for free vibration analysis of moderately thick spherical shell panel is presented based on the first-order shear deformation theory. The strain–displacement relations of Donnell and Sanders theories are used to illustrate the procedure. The shell has two opposite edges simply supported (i.e., Lévy-type). Based on the present solution, the governing equations of the vibrated spherical shell panel were exactly solved by introducing the new auxiliary and potential functions as well as using the separation method of variables. The accuracy and superiority of the formulations are validated by comparing the results with those available in the literature and the 3D finite element analysis. The effects of various stretching–bending couplings on the frequency parameters are discussed. Finally, the validity and the range of applicability of the Sanders and Donnell shell theories are investigated.

Christian Huehne, Rolf Zimmermann, Raimund Rolfes, and Bodo Geier, DLR Braunschweig, Institute of Structural Mechanics, Germany, “Sensitivities to geometrical and loading imperfections on buckling of composite cylindrical shells”, (no publisher or date given, but the most recent reference listed at the end of the paper is 2002.)

ABSTRACT: Thin-walled shell structures prone to buckling are sensitive to imperfections. The influence of loading and geometrical imperfections on buckling loads of unstiffened composite cylindrical shells is investigated based on tests and computations. It is shown that their effect depends on laminate set-up. The results show that unification of imperfection sensitivity is allowed; systems sensitive to geometrical imperfections are also sensitive to loading imperfections. The results can be used to define lower limits for knock-down factors of composite shells.

There are 13 references, dated 2002 and earlier. Owner won’t permit copying, so I don’t list them here.)


ABSTRACT: Exploitation of structural reserves in thin-walled composite aerospace structures requires accurate and experimentally validated stability analysis of real structures under realistic loading conditions. For stringer-stiffened panels experimental validation of postbuckling analyses and behavior under dynamic loading is presented. For unstiffened cylindrical shells a robust design method relying on b-factors is suggested.

ABSTRACT: European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Structural weight reduction by exploitation of structural reserves in composite aerospace structures contributes to this aim, however, it requires accurate and experimentally validated stability analysis of real structures under realistic loading conditions. This paper presents different advances from the area of computational stability analysis of composite aerospace structures which contribute to that field. For stringer stiffened panels main results of the finished EU project POSICOSS and the running follow-up EU project COCOMAT are given. Both projects deal with exploitation of reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling and collapse. Next, experimental validation of postbuckling analyses, development of two different fast tools for the postbuckling simulation and findings on the structural behaviour under dynamic loading is presented. Finally, for unstiffened cylindrical shells problems of a robust design method are.

References listed at the end of the paper:
Subject structures are stringer-stiffened CFRP cylindrical panels under axial compression and in-plane shear.


ABSTRACT: The European Commission was funding within its 5th Framework Programme the project POSICOSS, which coped with the demand to design fibre composite fuselage structures for postbuckling under ultimate load. The main objective of the work was the development of improved, fast and reliable procedures for postbuckling analysis and design of fibre composite stiffened panels of future fuselage structures. Another substantial objective was the creation of comprehensive experimental data bases for the purpose of validation. This paper deals with the buckling and postbuckling experiments on axially compressed, stiffened CFRP (carbon fiber reinforced plastics) curved panels, performed by DLR within the POSICOSS project for validation purposes, and it compares experimental results with computations.


ABSTRACT: The European Commission was funding within its fifth Framework Programme the project POSICOSS, which coped with the demand to design fibre composite fuselage structures for postbuckling under ultimate load. The main objective of the work was the development of improved, fast and reliable procedures for postbuckling analysis and design of fibre composite stiffened panels of future fuselage structures. They were essential, because so far postbuckling calculations were extremely time consuming and as such not applicable for design. Another substantial objective was the creation of comprehensive experimental data bases for the purpose of validation. The paper presents an introduction to the POSICOSS project; it derives the main objective of the project from the main general objectives for the design of the next generation of aircraft structures, and it summarizes the work done. The results achieved are only touched, because details of them can be found by consulting the references given.

References listed at the end of the paper:
Anonymous, THE POSICOSS PROJECT
(See: http://www.cocomat.de/Conf-downloads/handout1_POSICOSS.pdf)

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“Buckling and Postbuckling Analysis of a CFRP Stiffened Panel for a Better Material Exploitation”, (no publisher or date given in the pdf file, 2005?; latest reference is dated 2004)
ABSTRACT: This paper will present main results of post-buckling analyses led during the activity of the GARTEUR action group. A CFRP curved stringer stiffened panel under axial compression has been studied. The panel, tested by DLR, has been impacted inducing skin-stringer separation. Partners have carried out several analyses with various in-house and main commercial FE software to identify their abilities and deficiencies. The simulation tools and analysis methods will be compared together with available experimental results.

References listed at the end of the paper:

ABSTRACT: Aerospace industry demands for significantly reduced development and operating costs. Reduction of structural weight at safe design is one avenue to achieve this objective. The running ESA (European Space Agency) study Probabilistic Aspects of Buckling Knock Down Factor acts on this route. It concentrates on thin-walled circular cylindrical CFRP shells subjected to axial compression. It is well known that such structures exhibit not only a high load carrying capacity but also are prone to buckling which is highly imperfection sensitive. Imperfections are defined as deviations from perfect parameters like shape, thickness, material properties and loading distributions, they can reduce the buckling load drastically compared to a perfect shell. In order to account for these imperfections the theoretical buckling load of a perfect cylinder must be multiplied, and therefore reduced, by a knock-down factor (the ratio of buckling loads of imperfect and perfect cylindrical shell). Thus the closer the knock-down factor reflects the effect of imperfections the better is the prediction of the real buckling load. In the still used NASA SP-8007 design guideline from 1968 a lower bound curve for the knock-down factor is proposed. The factor depends on the slenderness (the ratio of radius
and wall thickness) and decreases with increasing slenderness. This factor is rather conservative and the structural behaviour of composite material is not considered adequately. Advanced thin-walled cylindrical shell structures under compression are therefore penalized if the knock-down factor based on this early NASA report must be applied. The current ESA study started in May 2006 and will run for 18 months. Its main objective is to achieve a better buckling knock-down factor for unstiffened CFRP cylindrical shells and to validate the linear and non-linear buckling simulations by test results. The main results will comprise an experimental data base (material properties, measured thicknesses, full scale shape imperfections, load-shortening curves, strains, and deformations) obtained by testing of 10 nominally identical axially compressed CFRP cylindrical shells, sensitivity analyses using Monte-Carlo simulation, validation with tests and a design guideline for that type of structure with a less conservative knock-down factor than taken from NASA SP-8007. All tasks of the ESA study are performed at the Institute of Composite Structures and Adaptive Systems of DLR Braunschweig, which has a rich body of experience in design, manufacturing, testing and analysis of shells prone to buckling. The paper outlines the objectives and expected results of the running ESA study and presents the results achieved so far.

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ABSTRACT: The aircraft and space industry strives for significantly reduced development and operating costs. Reduction of structural weight at safe design is one possibility to reach this objective which is aimed by the following two running research projects: the EC project "COCOMAT" and the ESA study "Probabilistic Aspects of Buckling Knock Down Factors". These projects develop improved concepts and tools for a fast and reliable simulation of the buckling and the postbuckling behavior of thin-walled structures up to collapse, respectively, which allow the exploitation of considerable reserves in primary fibre composite structures in aerospace applications. For the validation of the concepts and tools, a sound database of experiments is needed which is also performed within these projects. This paper focuses on the experimental activities within these projects performed at the buckling test facility of the Institute of Composite Structures and Adaptive Systems (DLR). It presents an overview about the DLR buckling, postbuckling and collapse tests which are already finished and gives an outlook to the results which are expected until the end of the running projects. This paper explains the working of the buckling test facility, the advanced measurement systems, which are running in parallel to the tests, and gives exemplarily two test results. The structures considered are unstiffened cylinders (ESA study) as well as panels, which are understood as sections of cylinders, stiffened by stringers (COCOMAT project). The unstiffened cylinders are more related to space applications (e.g. Ariane busters or parts of the international space station ISS) and the stiffened panels focus more on aircraft structures (e.g. fuselage). The load case considered for all investigations presented in this paper is axial compression under static loading although the test facility is also ready to apply torsion and internal pressure, as well as dynamic axial impact.
ABSTRACT: The European aircraft industry demands reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Contributions to this aim are provided by the completed project POSICOSS (5th FP) and the running follow-up project COCOMAT (6th FP), both supported by the European Commission. As an important contribution to cost reduction a decrease in structural weight can be reached by exploiting considerable reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of post-buckling up to collapse. The POSICOSS team developed fast procedures for the post-buckling analysis of stiffened fibre composite panels, created comprehensive experimental data bases and derived suitable design guidelines. COCOMAT builds up on the POSICOSS results and considers in addition the simulation of collapse by taking degradation into account. The results comprise an extended experimental data base, degradation models, and improved certification and design tools as well as extended design guidelines. One major task of POSICOSS and COCOMAT is the development of improved analysis tools that are validated by experiments performed within the framework of the projects. Because the new tools must comprise a wide range of various aspects a considerable number of different structures had to be tested. These structures were designed under different objectives (e.g. large post-buckling region). For the design process, the consortiums applied state-of-the-art simulation tools and brought in their own design experience. This paper deals with the design process as performed within both projects and with the applied analysis procedures. It is focused on the DLR experience in the design and analysis of stringer-stiffened CFRP panels gained within the scope of these two projects.

ABSTRACT: In the field of aerospace engineering but also in the fields of civil and mechanical engineering the industry demands for significantly reduced costs for development and operating. Reduction of structural weight at safe design is one avenue to achieve this objective. In many cases it results in thin-walled structures, which are prone to buckling if subjected to compression or shear. The presented paper is based on a recent European Space Agency (ESA) study, conducted at DLR Braunschweig, on Probabilistic Aspects of Buckling Knock-Down Factors and contributes to this goal by striving for an improved buckling knock-down factor (the ratio of buckling loads of imperfect and perfect structures) for unstiffened CFRP cylindrical shells. Buckling tests and buckling simulations were performed to investigate the imperfection sensitivity and to validate the applied simulation methodologies. Test results as well as deterministic and probabilistic buckling simulation results are presented and compared. Finally, improved knock-down factors are deduced and discussed.
INTRODUCTION: Currently, imperfection sensitive shell structures prone to buckling are designed according the NASA SP 8007 guideline using the conservative lower bound curve. This guideline dates from 1968, and the structural behaviour of composite material is not appropriately considered, in particular since the imperfection sensitivity and the buckling load of shells made of such materials depend on the lay-up design. This is not considered in the NASA SP 8007, which allows designing only so called "black metal" structures. There is a high need for a new precise and fast design approach for imperfection sensitive composite structures which allows significant reduction of structural weight and design cost. For that purpose a combined methodology from the Single Perturbation Load Approach (SPLA) and a specific stochastic approach is proposed which guarantees an effective and robust design. The SPLA is based on the observation, that a large enough disturbing load leads to the worst imperfection; it deals with the traditional (geometric and loading) imperfections [1]. The stochastic approach considers the non-traditional ones, e.g. variations of wall thickness and stiffness. Thus the combined approach copes with both types of imperfections. A recent investigation demonstrated, that applying this methodology to an axially loaded unstiffened cylinder is leading directly to the design buckling load 45% higher compared with the respective NASA SP 8007 design [2]. This chapter presents in its first part the state-of-the-art in buckling of imperfection sensitive composite shells. The second part describes current investigations as to the SPLA, the stochastic approach and their combination. In a third part an outlook is given on further studies on this topic, which will be performed within the framework of the running 3-year project DESICOS (New Robust DESIgn Guideline for Imperfection Sensitive COmposite Launcher Structures) funded by the European Commission; for most relevant architectures of cylindrical and conical launcher structures (monolithic, sandwich - without and with holes) the new methodology will be further developed, validated by tests and summarized in a handbook for the design of imperfection sensitive composite structures. The potential will be demonstrated within different industrially driven use cases.

Reference cited at the end of the paper:
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PARTIAL INTRODUCTION: Numerous applications of numerical optimization to various structural design problems have been addressed in the literature. A comprehensive survey on this issue was given in [1], presenting a historical review and demonstrating the future needs to assimilate this technology into the practicing design environment. Different approaches were applied successfully by several investigators for treating stress, displacement, buckling and frequency optimization problems. In general, design optimization seeks the best values of a set of n design variables represented by the vector, $X_{nx1}$, to achieve, within certain m constraints, $G_{mx1}(X)$, its goal of optimality defined by a set of k objective functions, $F_{kx1}(X)$, for specified environmental conditions. Mathematically, design optimization may be cast in the following standard form:

Find the design variables $X_{nx1}$ that minimize . . .


INTRODUCTION: The primary goal of the research in constrained elastica is to understand the behavior of a thin elastic strip under end thrust when it is subject to lateral constraints. It finds applications in a variety of practical problems, such as in compliant foil journal bearing, corrugated fiberboard, deep drilling, structural core sandwich panel, sheet forming, non-woven fabrics manufacturing, and stent deployment procedure. By assuming small deformation, Feodosyev (1977) included the problem of a buckled beam constrained by a pair
of parallel walls as an exercise for a university strength and material course. Vaillette and Adams (1983) derived a critical axial compressive force an infinitely long constrained elastica can support. Adams and Benson (1986) studied the post-buckling behavior of an elastic plate in a rigid channel. Chateau and Nguyen (1991) considered the effect of dry friction on the buckling of a constrained elastica. Adan et al. (1994) showed that when a column with initial imperfection positioned at a distance from a plane wall is subject to compression, contact zones may develop leading to buckling mode transition. Domokos et al. (1997), Holms et al. (1999), and Chai (1998, 2002) investigated the planar buckling patterns of an elastica constrained inside a pair of parallel plane walls. It was observed that both point contact and line contact with the constraint walls are possible. Kuru et al. (2000) studied the buckling behavior of drilling pipes in directional wells. Roman and Pocheau (1999, 2002) used an elastica model to investigate the post-buckling response of bilaterally constrained thin plates subject to a prescribed height reduction. Chen and Li (2007) and Lu and Chen (2008) studied the deformation of a planar elastica inside a circular channel with clearance. Denoel and Detournay (2011) proposed an Eulerian formulation of the constrained elastica problem. The emphasis of these studies was placed on the static deformations of the constrained elastica. Very often, multiple equilibria under a specified set of loading conditions are possible. Since only stable equilibrium configurations can exist in practice, there is a need to determine the stability of each of these equilibria in order to predict the behavior of the constrained elastica as the external load varies. For an unconstrained elastica, vibration method is commonly used to determine its stability; see Perkins (1990), Patricio et al. (1998), Santillan, et al. (2006), and Chen and Lin (2008). This conventional method, however, becomes useless in the case of constrained elastica. The difficulty of the conventional vibration method arises from the existence of unilateral constraints. A unilateral constraint is capable of exerting compressive force onto the structure, but not tension. Mathematically, this type of constraints can be represented by a set of inequality equations. This poses challenges in determining the critical states of the loaded structure. In order to overcome this difficulty, the conventional stability analysis needs modification. In this chapter, we introduce a vibration method which is capable of determining the stability of a constrained elastica once the equilibrium configuration is known. The key of solving the vibration problem in constrained elastica is to take into account the sliding between the elastica and the space-fixed unilateral constraint during vibration. In this chapter, we consider the vibration of an elastica constrained by a space-fixed point constraint. This particular constrained elastica problem is used to demonstrate the vibration method which is suitable to analyze the stability of a structure under unilateral constraint. In Section 2, we describe the studied problem in detail. In Section 3, we describe the static load-deflection relation. In Section 4, we introduce the theoretical formulation of the vibration method. In Section 5 an imperfect system when the point constraint is not at the mid-span is analyzed. In Section 6, several conclusions are summarized.


INTRODUCTION: This chapter presents advanced analysis methods for space steel frames which consider both geometric and material nonlinearities. The geometric nonlinearities come from second-order P−Δ and P−δ effects as well as geometric imperfections, while the material nonlinearities are due to gradual yielding associated with residual stresses and flexure. The P−Δ effect results from the axial force acting through the relative displacement of the ends of the member, so it is referred to as a member chord rotation effect. The P−Δ effect is accounted in the second-order analysis by updating the configuration of the structure during the analysis process. The P−δ effect is caused by the axial force acting through the lateral displacement of the member relative to its chord, so it is referred to as a member curvature effect. The P−δ effect can be captured by using stability functions. Since the stability functions are derived from the closed-form solution of a beam-
column subjected to end forces, they can accurately capture the P−δ effect by using only one element per member. Another way to capture the P−δ effect without using stability functions is to divide the member into many elements, and consequently, the P−δ effect is transformed to the P−Δ effect. Geometric imperfections result from unavoidable errors during the fabrication or erection. There are three methods to model the geometric imperfections: (1) the explicit imperfection modeling, (2) the equivalent notional load, and (3) the further reduced tangent modulus. The explicit imperfection modeling for braced and unbraced members is illustrated in... For braced members, out-of-straightness is used instead of out-of-plumbness. This is due to the fact that the P−Δ effect due to the out-of-plumbness is vanished by braces. The limitation of this method is that it requires the determination of the direction of geometric imperfections which is often difficult in a large structural system. In the equivalent notional load method, the geometric imperfections are replaced by equivalent notional lateral loads in proportion to the gravity loads acting on the story as described in ... The drawback of this method is that the gravity loads must be known in advance to determine the notional loads before analysis. Another way to account for the geometric imperfections is to further reduce the tangent modulus. The advantage of this method over the explicit imperfection modeling and equivalent notional load methods is its convenience and simplicity because it eliminates the inconvenience of explicit imperfection modeling and equivalent notional load methods.
formulae/charts given in design specifications are developed for uniform members. Thus, there is a need for a practical tool to analyze buckling behavior of nonuniform members. This study investigates elastic buckling behavior of three-segment symmetric stepped compression members with pinned ends (Fig. 1) using three different approaches: (i) analytical, (ii) numerical and (iii) experimental approaches. As already mentioned, such a member can easily be used to strengthen/rehabilitate an existing steel braced frame or can directly be used in a new construction. Surely, the use of stepped elements is not only limited to the structural engineering applications; they can be used in many other engineering applications, such as in mechanical and aeronautical engineering. In analytical studies, first the governing equations of the studied stability problem are derived. Then, exact solution to the problem is obtained. Since exact solution requires finding the smallest root of a rather complex characteristic equation which highly depends on initial guess, the governing equation is also solved using a recently developed analytical technique by He (1999), which is called Variational Iteration Method (VIM). Many researchers (e.g., Abulwafa et al., 2007; Batiha et al., 2007; Coskun & Atay, 2007, 2008; Ganji & Sadighi, 2007; Miansari et al., 2008; Ozturk, 2009 and Sweilan & Khader, 2007) have shown that complex engineering problems can easily and successfully be solved using VIM. Recently, VIM has also been applied to stability analysis of compression and flexural members. Coskun and Atay (2009), Atay and Coskun (2009), Okay et al. (2010) and Pinarbasi (2011) have shown that it is much easier to solve the resulting characteristic equation derived using VIM. In this paper, by comparing the approximate VIM results with the exact results, the effectiveness of using VIM in determining buckling loads of multi-segment compression members is investigated. The problem is also handled, for some special cases, using widely known structural analysis program SAP2000 (CSI, 2008). After determining the buckling load of a uniform member with a hollow rectangular cross section, the stiffness of the member is increased along its length partially in different length ratios and the effect of such stiffening on buckling load of the member is investigated. By comparing numerical results with analytical results, the effectiveness of using such an analysis program in stability analysis of multi-segment elements is also investigated. Finally, buckling loads of uniform and three-segment stepped steel compression members with hollow rectangular cross section are determined experimentally. In the experiments, the “stiffened” columns are prepared by welding additional steel plates over two sides of the member in such a way that the addition of the plates predominantly increases the smaller flexural rigidity of the cross section, which governs the buckling behavior of the member. By changing the length of the stiffening plates, i.e., by changing the stiffened length ratio, the degree of overall stiffening is investigated in the experimental study. The experimental study also shows in what extent the ideal conditions assumed in analytical and numerical studies can be realized in a laboratory research.

Saullo G. P. Castro, Rolf Zimmermann, Mariano A. Arbelo and Richard Degenhardt, “The single perturbation load approach compared with linear buckling mode-shaped, geometric dimple and measured imperfections for the buckling of cylindrical shells”, to be published in Thin-Walled Structures (2015 or 2016?)

ABSTRACT: The important role of geometric imperfections on the decrease of the buckling load for thin-walled cylinders had been recognized by the first authors investigating the theoretical approaches on this topic. Until nowadays there is no closed solution to take imperfections into account already during the early design phases, forcing the analysts to use empirically based lower-bound methods such as the NASA SP-8007 guideline to calculate the required knock-down factors (KDFs). Since 1970s a considerable number of experimental and numerical observations have been found to support new stochastic and deterministic methods for calculating more realistic KDFs. Among the deterministic approaches the single perturbation load approach (SPLA) originally developed by Hühne will be further investigated. Its capability for predicting KDF is compared with three other methods to create an initial geometric imperfection: linear buckling mode-shaped, geometric dimple and real measurements. The implementation of each method is explained in details and their
limitations are compared. The study is part of the European Union (EU) project DESICOS, whose aim is to combine stochastic and deterministic approaches for developing less conservative design guidelines for imperfection sensitive structures.

Professor Dr.-Ing Richard Degenhardt [German Aerospace Center, Institute of Composite Structures and Adaptive Systems, Structural Mechanics, Braunschweig (DLR)], Words about Professor Degenhardt’s research group concerned with STABILITY (see the website: http://www.dlr.de/fa/en/desktopdefault.aspx/tabid-1462/2063_read-3525/)

**Stability of thin-walled composite structures:**

Light weight structures in the aerospace, mechanical engineering or civil engineering are on the one hand under compression or shear loading susceptible for buckling but on the other hand they have large reserve capacities in the postbuckling region. In order to save weight in these fields the use of materials made of Carbon-Fibre-Reinforced-Plastics (CFRP) is increasing. However, the design and computation of composite structures is more challenging than using classic materials. Stability, non-linear computations and degradation have therefore here an essential relevance. The structural behaviour of stability and deformations is simulated by nonlinear numerical simulations and experiments. Figure 1 illustrates the comparison of an experiment and simulation of a buckled, stringer-stiffened (on the reverse side) CFRP panel. The institute has in the field of stability of thin-walled composite structures competence in the following 4 main topics: Postbuckling behaviour, Imperfection tolerance, Buckling due to dynamic loading, Thermo-mechanical buckling. The objective is to develop fast and reliable software tools in order to simulate the buckling and postbuckling behaviour up to collapse. These software tools can then be incorporated into a design process as well as to deduce simple design rules. To fulfil these tasks numerical and experimental work is essential. The experimental examination is employed to provide a better understanding of the physical behaviour of the structure and to validate the developed software tools.

**Our competence:**
- Postbuckling
- Imperfection tolerance
- Dynamic buckling
- Thermal buckling

**Running projects:**
- COCOMAT (Co-ordinator, Improved Material Exploitation of Safe Design of Composite Structures by Accurate Simulation of Collapse, EC 6th FP)
- ALCAS (Advanced low cost Airframe Structures, EC 6th FP)
- MUSCA (Nonlinear static MULTiSCAle analysis of large aero-structures, EC 6th FP)
- Design of optimal CFRP panels for fuselage structures (DLR - China)
- Advanced Aerospace Structures (Fortschrittliche Flugzeugstrukturen, DLR - EADS)
- Composite Fuselage Demonstrator (DLR-Airbus)
- Probabilistic aspects of buckling knock down factors, Tests and analysis (ESA)
- Buckling Handbook (ESA, ECSS-E-30-24)

**Some finished projects:**
- IBUCK - a fast semi-analytical design tool for stiffened panels (DLR - Airbus Deutschland)
- POSICOSS (Coordinator, Improved Post-buckling Simulation for Design of Fibre Composite Stiffened Fuselage Structures, EC 5th FP)
- Robust Design (DLR - Airbus Germany)
- GARTEUR SM AG 25 (WP-leader, Postbuckling and Collapse Analysis, established recommendations for buckling, postbuckling and collapse analysis of CFRP shells)
- Globales Tragverhalten (Virtual testing of stringer and frame stiffened shells, Airbus Germany)
Multiobjective optimisation of fibre composite structures endangered by buckling (DLR - China)
Identification of the Stiffnesses of Stringer Stiffened Laminated Materials (DLR - China)
Schwarzer Rumpf (Black fuselage, DLR - Airbus Deutschland)
Buckling under dynamic loading (German - Israeli foundation)
FESTIP (Refinement of Buckling Prediction Techniques for Large Thin Shells Under Mechanical and Thermal Load Conditions, ESA)
Fracture Mechanics of Composites (Damage tolerance of CFRP panels and cylinders prone to buckling, ESA)
EDAVCOS (Efficient Design and Verification of Composite Structures, EC 5th FP)
DEVILS (Design and Validation of Imperfection-Tolerant Laminated Shell Structures, EC 4th FP)
GARTEUR SM AG05 (Chairman, Buckling and Postbuckling Behaviour of Composite Panels)
Composite Bulkhead (Stability investigation of an Airbus CFRP bulkhead, A340-500 and A340-600)


ABSTRACT: Currently, imperfection sensitive shell structures prone to buckling are designed according to the NASA SP-8007 guideline, from 1968, using its conservative lower-bound curve. In this guideline the structural behavior of composite materials is not appropriately considered, since the imperfection sensitivity and the buckling load of shells made of such materials depend on the lay-up design. Due to the fact that this approach is outdated for preliminary design purposes, several authors are investigating less conservative methodologies. Some authors propose a new lower-bound curve approach based only on statistical analysis of experimental test on composite cylinders. The problem with this approach is that the range of applicability is limited to the database extension. Finite element models are also used by many researchers to characterize the behavior of cylindrical shell considering different types of material and geometrical imperfections. A representative finite element model allows studying a widespread area of possibilities from the design point of view. In this context a numerical investigation about the different methodologies to characterize the behavior of imperfection sensitive composite structures subjected to compressive loads up to buckling is presented in this paper. A comparative study is addressed between new deterministic methodologies, such as the “Single Perturbation Load Approach” proposed by the European project DESICOS and new statistical approaches based on experimental test on composite cylinders. The aim of this work is to define the range of applicability of these methodologies for unstiffened composite cylinders, advantage and disadvantage to use as a design tool, to provide means to calculate less conservative knock-down factors than the obtained with the NASA SP-8007 guideline.


ABSTRACT: The performance of thin-walled structures, which are endangered by buckling, is often strongly influenced by geometrical imperfections. It is impossible to know in advance the imperfections, which will be present in the real structure. Nevertheless, their influence has to be taken into account already at the design process. Attempts to indentify characteristic imperfections due to specific manufacturing processes overcome this difficulty only partly, as they do not consider imperfections coming into existence after fabrication. The remedy is, to build imperfection tolerant structures. For that purpose, a simple means to measure imperfection
tolerance is defined and a multiobjective optimization formulation is proposed to design fiber composite shell structures, which simultaneously exhibit high imperfection tolerance and high buckling load. By example of axially compressed CFRP cylindrical shells first computational and experimental results are given to demonstrate the feasibility of the concept, and to identify needs for further research.

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ABSTRACT: Thin-walled, unstiffened and stiffened shell structures made of fibre composite materials are frequently applied due to their high stiffness/strength to weight ratios in all fields of lightweight constructions. One major design criterion of these structures is their sensitivity with respect to buckling failure when subjected to inplane compression and shear loads. This paper describes how the structural analysis program BEOS (Buckling of Eccentrically Orthotropic Sandwich shells) is combined with the optimization procedure SAPOP (Structural Analysis Program and Optimization Procedure) to produce a tool for designing optimum CFRP-panels against buckling. Experimental investigations are used to justify the described procedures.

References listed at the end of the paper:


ABSTRACT: Elastic buckling of stiffened plate with local imperfections were presented in this paper. As its difficult to analysis buckling character of the stiffened plate with local imperfections by using elastic plate theory, this paper used finite element method (FEM) to model 30 different cases of local imperfections in stiffened plate, and analysed how the size, depth and direction of local imperfections affect the critical buckling coefficient of the stiffened plate. Results shown that, the size, depth and direction of local imperfections are have significant impact to the buckling behavior of stiffened plate, the largest decrease of critical buckling coefficient due to the local imperfection reaches 30% in this paper, and the critical buckling coefficient of stiffened plate with smaller stiffness ratio is more susceptible to the local imperfections.

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ABSTRACT: We report experimental observations of shell buckling instabilities in free-standing, vertically aligned GaN nanotubes subjected to uniaxial compression. Highly uniform arrays of the GaN nanotubes standing on a GaN template were fabricated and subjected to uniaxial compression using a nanoindenter. The buckling load was found to be of the order of 150 μN for the GaN nanotubes with an outer radius of 40 nm, an inner radius of 20 nm, and heights of 500 and 300 nm. Good agreement was found between the experimental observations, the stress–strain relation equation study findings and the predictions from the cylindrical shell buckling theory.

References listed at the end of the paper:

ABSTRACT: A long, thin, circular, cylindrical shell is subjected to uniform external pressure exerted by a surrounding elastic medium. The stability of equilibrium of the shell is examined by considering possible neighboring equilibrium states. The loading exerted by the elastic medium on the shell in the deformed state is found by solving an associated boundary value problem of the linearized theory of elasticity in the presence of initial stress. Expressions are derived which give the critical pressure for the cases of a bonded and a smooth interface.

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“Buckling And Collapse Of Shell Structures: Sensitivity Analysis”, (publisher and date not given. Latest reference listed at the end of the paper is dated 2007.)

www.cocomat.de/.../45-University_of_Innsbruck_Oberguggenberger.pdf

ABSTRACT: This article addresses the issue of buckling failure of shell structures. We argue that a good understanding of the shell behavior near the limit state can and should be addressed through sensitivity analysis, that is, the assessment of the impact of individual input parameters (loads, material constants, geometry) or sets
of input parameters on the failure of the structure. A major challenge in most applications lies in the fact that high computational costs have to be faced. Methods have to be developed that admit assertions about the sensitivity of the output with as few computations as possible. This articles presents a number of sensitivity indices based on Monte Carlo simulation techniques. We developed these methods in a project from aerospace engineering with light weight shell structures. We believe that the methods will be useful in composite laminated structures, where equally high computational costs are the rule. A thorough understanding of the sensitivities of a structure can ultimately serve as a robust basis for design guidelines.

References listed at the end of the paper:

ABSTRACT: This paper is the second part of the structure study of double cylindrical shell subjected to hydrostatic external pressure. The author makes researches on the relationship between inner and outer shells of pressurized double cylinders using equilibrium conditions of forces and deformation compatibility conditions with ring plate orthogonally connected to inner and outer shells and puts forward the expressions of longitudinal and circumferential forces of double pressurized cylinder. In this paper, equilibrium equations are established for a double cylindrical shell stiffened longitudinally and transversely and subjected to uniform hydrostatic external pressure by using an adjacent equilibrium method and a solution with high accuracy is presented to calculate theoretically critical pressures of panel buckling and interframe shell buckling. The solution can be applied to both the double and single cylindrical shells without longitudinal stiffeners and therefore, it may be applied widely with higher accuracy. Also, some simplified formulae for the engineering application are given to calculate the panel buckling and the interframe shell buckling strength.
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ABSTRACT: The sensitivity of stiffened conical shells to imperfection is considered, via the initial post-buckling analysis. Unlike stiffened cylindrical shells, in the case of generally stiffened conical shells the stiffeners inclination and the distance between the stiffeners vary with the shell coordinates, which complicates the problem considerably. The main objective of the study is to investigate the influence of the stiffeners on the buckling load and on the imperfection sensitivity. Thus, by finding the parameters that influence the shell’s imperfection sensitivity, it is possible to improve the behavior of the whole structure.

References listed at the end of the paper:


ABSTRACT: A hierarchical high-fidelity analysis procedure is adopted for predicting the critical buckling load of filament wound laminated conical shells. This hierarchical procedure includes three levels of fidelity for the analysis. Level-1 assumes that the shell buckling load can be predicted by using simply supported boundary condition with a linear membrane prebuckling solution. Level-2 includes the effects of a nonlinear prebuckling solution and the effects of different boundary conditions. Level-3 includes the nonlinear interaction between pressure. J Mech Eng Sci 1963;5(1):23–7.
nearly simultaneous buckling modes and the effects of boundary imperfections. For the Level-1 analysis a computer code BOLCS had been developed. BOLCS calculates the buckling load of laminated conical shells by a linear bifurcation analysis. The buckling behavior obtained by BOLCS is compared for various load cases with Level-3 solutions calculated by the two-dimensional nonlinear code STAGS-A. The effects of the assumptions and approximations used for the two solutions are discussed. In addition, the influence of the in-plane boundary condition on the buckling behavior of laminated conical shells under axial compression is investigated. It is found that the in-plane boundary condition at the large end of the shell has a major effect on the buckling behavior.


ABSTRACT: Buckling analysis of laminated conical shells under axial compressive load are investigated analytically using high order and Love’s shell theories. Power series are used to solve the developed equations of motion for conical shells with different semi vertex angles, length-to-radius ratio, number of layers and boundary conditions. The validity of the presented procedure is confirmed.

References listed at the end of the paper:

(No conference identified, no abstract, no list of references in this document.)


ABSTRACT: The paper identifies and analyzes the so-called ‘beam’ and ‘shell’ modes of buckling of buried pipelines. Such failures have occurred as a result of compressive loads induced to pipelines by large ground movements in seismically active areas. In the beam mode of buckling, the pipeline tears through the ground and lifts off in a characteristic Ω configuration. The shell mode of buckling is a more localized failure characteristic of shell type structures. The two types of instability are simulated numerically using appropriate nonlinear kinematics, inelastic material behaviour and approximate modelling of the soil-structure interaction mechanisms. Parametric sensitivity studies are presented. It is demonstrated that initial geometric imperfections can strongly influence the critical loads and strains of both types of instability. Conditions under which the two modes of buckling interact are also discussed.
Chiou, Y.J. [National Cheng Kung Univ., Tainan (Taiwan, Province of China). Dept. of Civil Engineering]; Chi, S.Y. [Sinotech Engineering Consultant, Taipei (Taiwan, Province of China). Geotechnical Research Center], “Beam and shell modes of buckling of buried pipes induced by compressive ground failure”, U.S. conference on lifeline earthquake engineering, San Francisco, CA (United States), 10-12 Aug 1995

ABSTRACT: The buckling of buried pipeline induced by compressive ground failure was investigated. Both the beam mode of buckling and local shell mode of buckling, and their interactions were studied. The pipeline response was analyzed numerically. The results agree qualitatively with past researches and possess satisfactory comparisons with actual case histories. The relations of critical buried depth versus ratio of pipe diameter to thickness for buried pipe with different imperfections and various soil foundations were established.


ABSTRACT: This two-part series of papers is concerned with the response and various instabilities which govern the behavior of circular cylindrical shells under pure bending. Part I describes the experimental part of the study and Part II presents the numerical simulation of the various phenomena observed experimentally. Experiments were conducted on long aluminum 6061-T6 shells with II different diameter-to-thickness ratios ranging from 60.5 to 19.5. For such geometries, the structural response and inherent instabilities are strongly influenced by the plastic characteristics of the material. Thinner shells were found to develop short wavelength periodic ripples on the compressed side of the shell. The shells buckled locally and collapsed soon after the appearance of the ripples. Thicker shells were found to exhibit a limit load instability as a direct consequence of the ovalization of the shell cross-section caused by bending. Following the limit load, the ovalization was found to localize, leading to the eventual collapse of the shells. For shells with intermediate D/t values, short wavelength ripples developed at the same time as localization of ovalization was recorded. The shells buckled locally and catastrophically following the development of a limit load.


ABSTRACT: The second part of this study is concerned with the prediction of the response and various instabilities found in Part I to govern the elastic-plastic flexure of circular cylindrical shells. Sanders' shell kinematics and the principle of virtual work were used to formulate the problem. A Rayleigh-Ritz procedure was used to discretize the problem. The resultant non-linear equations were solved iteratively using Newton's method. The three types of behavior involving bifurcation into short wavelength ripples, localization following the attainment of a natural limit load and interaction of the two were studied. In each case the predicted response was found to be in very good agreement with the experimental result.

ABSTRACT: It is well known that long cylindrical shells used in many practical applications involving external pressure loading collapse catastrophically due to a limit load instability. The limit load is due to interaction between geometric nonlinearities and material nonlinearities due to plasticity. This paper addresses the mechanism of collapse triggered by the limit load instability. It is found that following the limit load the collapse quickly localizes to a section of the shell a few diameters long. The deformations and stresses in the region of localization grow with a decreasing overall pressure whereas the rest of the structure remains intact and retains only a small residual effect from the limit load instability as it unloads. However, under favorable conditions the localized collapse triggers an instability which propagates along the length of the shell and has the potential of catastrophically collapsing the whole structure. The characteristics of the localization are studied parametrically through experiment and analysis.


ABSTRACT: Moderately thick circular tubes under compression crush progressively by axisymmetric folding. The paper presents a combined experimental analytical study of the onset of collapse, its localization and the subsequent progressive folding. Results from four displacement control led crushing experiments are presented on tubes of various radius-to-thickness ratios made of different metal alloys. The experimental results include the crushing response, careful measurements of the geometric characteristics of the folds and the mechanical properties of the alloys. A finite element model of the crushing process has been developed and results from simulations are directly compared with the experiments. The model is found to reproduce the crushing response to a significant degree of accuracy. The mean crushing load is essentially the same as in the experiments; the calculated wavelength of the folds are within a few percent from measured values as are other geometric variables considered. Thus, the crushing energy per unit length of tube is predicted to a very good accuracy. In addition, the model was used to demonstrate that changes in the loading cycles which take place as the number of folds increases, are due to small differences between the inner and outer folds which in turn affect the self contact of the fold walls. Three simpler models taken from the literature in which steady-state folding is modeled by kinematically admissible collapse mechanisms are critically reviewed by comparing predictions of key variables to measured values.


ABSTRACT: Elastic buckling of cylindrical shells due to axial compression results in sudden and catastrophic failure. By contrast, for thicker shells that buckle in the plastic range, failure is preceded by a cascade of events, where the first instability and failure can be separated by strains of 1–5%. The first instability is uniform
axisymmetric wrinkling that is typically treated as a plastic bifurcation. The wrinkle amplitude gradually grows and, in the process, reduces the axial rigidity of the shell. This eventually leads to a limit load instability, beyond which the cylinder fails by localized collapse. For some combinations of geometric and material characteristics, this limit load can be preceded by a second bifurcation that involves a non-axisymmetric mode of deformation. Again, this buckling mode localizes resulting in failure. The problem is revisited using a combination of experiments and analysis. In Part I, we present the results of an experimental study involving stainless steel specimens with diameter-to-thickness ratios between 23 and 52. Fifteen specimens were designed and machined to achieve uniform loading conditions in the test section. They were subsequently compressed to failure under displacement control. Along the way, the evolution of wrinkles was monitored using a special surface-scanning device. Bifurcation buckling based on the J2 deformation theory of plasticity was used to establish the onset of wrinkling. Comparison of measured and calculated results revealed that the wrinkle wavelength was significantly overpredicted. The cause of the discrepancy is shown to be anisotropy present in the tubes used. Modeling of the postbuckling response and the prediction of the limit load instability follows in Part II.

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ABSTRACT: In the second part of this study, the evolution of uniform axisymmetric wrinkling in axially compressed cylinders is modeled using the principle of virtual work. A version of this formulation also allows localization of wrinkling. The model domain is assigned an initial axisymmetric imperfection of a chosen amplitude and the wavelength yielded by the first bifurcation check. The solution correctly simulates the growth of wrinkles and results in a limit load instability. The limit strain is influenced by the amplitude of the imperfection. Beyond the limit load, wrinkling tends to localize, eventually leading to local folding. The possibility of bifurcation of the axisymmetric solution to non-axisymmetric buckling modes is examined by using a dedicated bifurcation check. The bifurcation check was found to yield such buckling modes correctly. The evolution of such buckling modes is simulated by a separate non-axisymmetric model assigned imperfections with axisymmetric and nonaxisymmetric components. The domain analyzed is one characteristic wavelength long (2°C). Initially, compression activates mainly axisymmetric deformation. In the neighborhood of the bifurcation point, non-axisymmetric deformation starts to develop, eventually leading to a limit load instability. Experimental responses were simulated with accuracy by assigning appropriate values to the two imperfection amplitudes. Prediction of the limit strains for the whole range of diameter-to-thickness ratios (D/t) considered in the experiments was achieved by making the amplitude of the non-axisymmetric imperfection proportional to (D/t)2/m3 (m is the circumferential wavenumber). Matching all aspects of the experiments required inclusion of the anisotropy measured in the tubes tested through Hill's yield criterion in all models.


ABSTRACT: Long cylindrical tubes and pipes under axial compression will usually bend, behaving as beam columns. Shell-type localized buckling occurs mainly when the structure is restrained from lateral movement.
This, for example, is the case for a pipeline buried in a trench or resting on a deformable foundation. Compression can be caused by the passage of hot hydrocarbons carried from the well to a central gathering point by buried flowlines in offshore operations. Foundation motion caused by fault movement, landslides, ground subsidence, permafrost melting, or soil liquefaction can also result in severe compression of the lines. Both loading scenarios can impose compressive strains high enough to result in shell type buckling…


ABSTRACT: In the present paper the behaviour of cylindrical elastic tubes under pure bending is discussed. This behaviour is characterised by a smooth global maximum on the load-deflection curve which is due to the well-known von Kármán effect, that is to the progressive flattening of the cross section of the tube under bending moment. However, during the loading process another type of failure may also occur before the limit load is reached, that is, at a certain stage the compressed region of the bent tube wrinkles axially and can give origin to a localised instability. Even if these phenomena have been extensively investigated in many classical works, nevertheless the analysis of experimental data shows that there are still some points which seem to be worthy of further considerations, especially from an engineering standpoint and for design purposes. To this aim, a straightforward treatment of the problem is presented which can be employed to give clear reason for several experimental findings by means of plain expressions and with a clear physical meaning. Finally, the results are compared to those obtained by means of a commercially available non-linear finite element code.

V. Reitmann, St. Petersburg State University, Russia, “Estimation of dynamic buckling loads in approximate shell models via frequency-domain methods”, (No publisher or date or abstract are given. Latest reference is dated 2004.)

First sentence in the one-page pdf file available:
“We study the stability and dissipativity of viscoelastic plates with constant thickness under dynamic loads given by the equations ([1, 7])…

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ABSTRACT: The mechanism for bifurcation of elastic-plastic buckling of the semi-infinite cylindrical shell under impacting axial loads is proposed based on the theory of stress wave. Numerical results on three kinds of end supports and step and impulse loads are given.

Xu Xinsheng, Liu Shutian, Liu Kaixin, Li Yunpeng (Institute of Engineering Mechanics, Dalian University of Technology, Dalian, 116023); Non Axisymmetric Buckling Of Elastic Cylindrical Shell Under Axial Stress Wave; Explosion And Shock Waves; 1997-03

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ABSTRACT: This paper discusses the dynamic pre-buckling of finite cylindrical shells in the propagation and reflection of axial stress waves. By introducing the Hamiltonian system into dynamic buckling of structures, the problem can be described mathematically in a symplectic space. The solutions of Hamiltonian dual equations shown in canonical variables are obtained. The problem is reduced to the determination of eigenvalues and eigensolutions, with the former indicating critical buckling loads and the latter buckling modes. Numerical example presented shows phenomena of axisymmetric and non-axisymmetric dynamic buckling subject to impacts of axial load.

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ABSTRACT: This paper investigates the prebuckling dynamics of transversely isotropic thin cylinder shells in the context of propagation and reflection of axial stress waves. By constructing the Hamiltonian system of the governing equation, the symplectic eigenvalues and eigenfunctions are obtained directly and rationally without the need for any trial shape functions, such as the classical semi-inverse method. The critical loads and buckling models are reduced to the problem of eigenvalues and eigensolutions, in which zero-eigenvalue solutions and nonzero-eigenvalue solutions correspond to axisymmetric buckling and nonaxisymmetric buckling, respectively. Numerical results reveal that energy is concentrated at the unconstrained free ends of the shell and the buckling modes have bigger bell-mouthed shapes at these positions.
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ABSTRACT: In this paper, the local and global buckling of cylindrical shells under axial, compressive impact loads is studied. A Hamiltonian system is introduced in the problem. The fundamental problem in the system can be described mathematically by the Hamiltonian dual equations, which are expressed in four pairs of dual variables. The problem is reduced to a problem of eigenvalues and eigensolutions for critical loads and buckling modes, respectively. The buckling modes can be described by their respective orders and they are grouped into two classes, the short-wave or local buckling and the long-wave or global buckling. The solutions are obtained analytically and numerically, and some rules observed are indicated.

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ABSTRACT: The paper deals with the thermal buckling of cylindrical shells in a uniform temperature field based on the Hamiltonian principle in a symplectic space. In the system, the buckling problem is reduced to an eigenvalue problem which corresponds to the critical temperatures and buckling modes. Unlike the classical approach where a predetermined trial shape function satisfying the geometric boundary conditions is required at the outset, the symplectic eigenvalue approach is completely rational where solutions satisfying both geometric and natural boundary conditions are solved with complete reasoning. The results reveal distinct axisymmetric buckling and nonaxisymmetric buckling modes under thermal loads. Besides, the influence for different boundary conditions is discussed.

Symplectic Methods in Dynamic and Thermal Buckling of Elastic Cylindrical Shells
Pubdate:2009-12-28 (no publisher, no author given. Found in “Latest-Science-Articles”)  
ABSTRACT: The stability of structure is an important research subject in modern solid mechanics and much attention has been focused on the problem in industry equipments. Since cylindrical shell is a basic structure, its buckling problems play an important role in the theories of structural stability. Many researches have been carried out and great progress has been made in solving many practical problems. Some phenomena which deal with local buckling of a cylindrical shell in experiments are reported. To explain these, it is necessary to consider basic theories and a new method is needed. It is well known that an object can be impacted or heated. The buckling phenomena of a cylindrical shell subjected to an impact load or a thermal load are not the same because of their different characters. When a shell is impacted, the internal forces caused by the impact will be propagated and reflected in a stress wave form. Because stress waves are affected locally, the shell will be overall bucked and accompanied with local wrinkles, if both loads are applied. High-order partial differential equations often occur when one solves problems which deal with pre-buckling of a cylindrical shell. Sometimes traditional separation of variables is not work anymore if the problem is presented in a Lagrangian system. When this happens, it is necessary to introduce a new system. This paper deals with pre-buckling of a shell
subjected to thermal load, impact load or coupling load. By introducing a Hamiltonian function, the Hamiltonian system for the problem is established. This means that the transformation from a Lagrangian system to a Hamiltonian system is finished. In a symplectic space, eigenvalues and eigenfunctions take the place of the critical buckling loads and buckling modes of the problem. The zero-eigenvalues describe axisymmetric buckling and non-zero eigenvalues mean non-axisymmetric bucking. In pre-buckling problems, small deformation theories are used, while larger deformation theories are applied in solving post-buckling problems. Based on the complete solutions obtained in the pre-buckling problems, a symplectic eigenfunction expansion method is developed and the whole progress from prebuckling to postbuckling are described. A new method for solving such nonlinear problems is presented. Stress waves play an important role in the local buckling of a shell when the waves propagate, reflect and transmit in the shell. After studying these effects, critical loads and buckling modes of a shell subjected to impact loads, thermal loads and coupling loads with different boundary conditions are presented. Numerical results show that when a shell is impacted, local buckling is unavoidable due to the local effects of the stress waves. There will be overall buckling if a shell is heated. When a shell is impacted, a big open is tend to occur at the impact end in the beginning and when the stress waves are reflected, the big open may appear at the reflect end. If a pulse is imposed, a bamboo-node type will come up in the middle of the shell. The pulse usually is produced by the propagation, reflection and transmission of the stress waves in the bullet. In fact, local buckling of a shell is a type of energy concentration in the shell. It can be concluded that local buckling in a shell are mainly caused by the propagation, reflection and transmission of stress waves. Local buckling have something to do with not only the physical properties of the shell but also its geometric feature parameters. The length of a pulse and the wave impedance are of major significance on a bamboo node-type. In post-buckling problems, an initial mode which is in the form of prebuckling solutions is adopted, and the effects of the initial mode to the post-buckling are discussed in three ways, that is, its amplitudes, circular orders and axial branches. It is found that the shell is not sensitive to the initial mode. In post-buckling process, a thinner shell is inclined to a higher circular order and a longer shell tends to a higher axial order. These provide important rules for structure stability design in engineering.

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ABSTRACT: Based on Hamilton's principle, a new accurate solution methodology is developed to study the torsional bifurcation buckling of functionally graded cylindrical shells in a thermal environment. The effective properties of functionally graded materials (FGMs) are assumed to be functions of the ambient temperature as well as the thickness coordinate of the shell. By applying Donnell's shell theory, the lower-order Hamiltonian canonical equations are established, from which the eigenvalues and eigenvectors are solved as the critical loads and buckling modes of the shell of concern, respectively. The effects of various aspects, including the combined in-plane and transverse boundary conditions, dimensionless geometric parameters, FGM parameters and changing thermal surroundings, are discussed in detail. The results reveal that the in-plane axial edge supports do have a certain influence on the buckling loads. On the other hand, the transverse boundary conditions only affect extremely short shells. With increasing thermal loads, the material volume fraction has a different influence on the critical stresses. It is concluded that the optimized FGM mixtures to withstand thermal torsional buckling are Si3N4/SUS304 and Al2O3/SUS304 among the materials studied in this paper.
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ABSTRACT: This article focuses on analytical solutions for bifurcation buckling of FGM cylindrical shells under thermal and compressive loads. A new solution methodology is established based on Hamilton's principle. The fundamental problem is subsequently transformed into the solutions of symplectic eigenvalues and eigenvectors, respectively. Then, by applying a unidirectional Galerkin method, imperfection sensitivity of an imperfect FGM cylindrical shell is discussed in detail. The solutions reveal that boundary conditions, volume fraction exponent, FGM properties, and temperature rise distribution significantly influence the buckling behavior. Critical stresses are reduced greatly due to the existence of initial geometric imperfections.

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ABSTRACT: In this article, the elastic buckling behavior of cylindrical shells under external pressure is studied by using a symplectic method. Based on Donnell’s shell theory, the governing equations which are expressed in stress function and radial displacement are re-arranged into the Hamiltonian canonical equations. The critical loads and buckling modes are reduced to solving for symplectic eigenvalues and eigenvectors. The buckling solutions are mainly grouped into four categories according to the natures of the buckling modes. The effects of geometrical parameters and boundary conditions on the buckling loads and modes are examined in detail.

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ABSTRACT: The effect of two localized axisymmetric initial imperfections on the critical load of elastic cylindrical shells subjected to axial compression is studied through finite element modelling. This was carried out by means of the specialized shell buckling package Stanlax. First, a single defect having a triangular geometry is considered in order to determine the most adverse defect configuration, then two defects having this arrangement and which are symmetrically distributed along the shell length are introduced in the problem in order to assess their global interacting effect on the buckling load reduction. A statistical approach which is based on full factorial design of experiment tables and analysis of variance is used to quantify the relative influence of all the intervening factors. It is shown that two interacting defects yield further reduction of the shell critical load.

ABSTRACT: (none given)
References listed at the end of the paper:
ABSTRACT: The creep buckling behavior of a geometrically imperfect complete spherical shell subjected to a uniform external pressure is examined using Sanders' equilibrium and kinematic equations appropriately modified to include the influence of initial stress-free imperfections in the radius. The Norton-Bailey constitutive equations are used to describe the secondary creep behavior and elastic effects are retained. The initial imperfections have the same shape as the classical axisymmetric elastic buckling mode and the initial elastic response is obtained analytically for external pressures smaller than the corresponding static collapse pressure. Numerical finite-difference procedures are used to obtain the axisymmetrical creep buckling behavior and to determine when a bifurcation or loss of uniqueness into a non-axisymmetric deformation state occurs. The numerical results for the creep buckling behavior of complete spherical shells are similar for hydrostatic and deadweight-type external pressures, at least for the particular parameters examined herein, and demonstrate that initial imperfections exercise an important influence on the critical times. It turns out from a practical viewpoint that axisymmetric creep buckling governs the behavior of the spherical shells examined in this article. It was observed from the present results that the creep buckling times of externally pressurised complete spherical shells are longer than those for “equivalent” axially loaded cylindrical shells.

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ABSTRACT: A perturbation method of analysis has been used to examine the dynamic plastic buckling of a stringer-stiffened cylindrical shell subjected to an axial impact. It transpires that it is more efficient to place stiffeners on the outer shell surface rather than on the inner surface. Various results are presented to demonstrate the influence of the second moment of area, eccentricity, cross-sectional area and number of stiffeners on the dynamic plastic response.

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ABSTRACT: The dynamic elastic buckling behavior of a geometrically imperfect complete spherical shell that is subjected to a uniform external step pressure is examined using Sander's equilibrium and kinematic equations, appropriately modified to include the influence of inertia forces and initial stress-free imperfections.
in the radius. A finite-difference procedure with either the Houbolt or Park methods of time integration is used to predict the axisymmetric dynamic elastic buckling pressures and associated critical mode numbers. The dynamic buckling pressure is significantly smaller than the corresponding static value for small initial imperfections, but is less imperfection.

ABSTRACT: The dynamic axisymmetrical behaviour of a perfect complete spherical shell made from a bilinear or work hardening material and subjected to a uniform external step pressure loading is investigated. A perturbation method of analysis leads to a Mathieu equation which gives the dynamic buckling pressure and associated mode for a complete spherical shell. The influence of the plastic parameter and damping on the dynamic buckling pressure and mode number are also discussed.

(No abstract)

ABSTRACT: Eighty-four dynamic tests on thin-walled square steel tubes having two different cross-sections with c/h = 30.25 and c/h = 32.18 and various lengths were crushed axially on a drop hammer rig. Approximate theoretical predictions were developed for the axial progressive crushing of square box columns using a kinematically admissible method of analysis. This theoretical study predicts four deformation modes which govern the behaviour for different ranges of the parameter c/h. New asymmetric deformation modes were predicted theoretically and confirmed in the experimental tests. These asymmetric modes cause an inclination of a column which could lead to collapse in the sense of Euler even for relatively short columns. The effective crushing distance is considered in the approximate theoretical analysis together with the influence of material strain rate sensitivity, which is important for steel even when the loadings are quasi-static. The simple equations presented herein for the design of axially crushed square box columns give reasonable agreement with the corresponding experimental results.

ABSTRACT: A series of axial crushing tests on steel circular cylindrical shells loaded either statically or dynamically is reported and compared with various theoretical predictions and empirical relations. A modified version of Alexander's theoretical analysis for axisymmetric, or concertina, deformations gives good agreement with the experimental results when the effective crushing distance is considered and provided that the influence of material strain rate sensitivity is retained in the dynamic crushing case.

ABSTRACT: A series of over 120 axial crushing tests were conducted on circular and square steel tubes loaded either statically or dynamically. Approximate theoretical predictions for static and dynamic progressive buckling are developed. Fair agreement with the experimental results is achieved provided the effective crushing distance is taken into account and the influence of material strain rate sensitivity is retained for dynamic loads.


ABSTRACT: The equilibrium equations for elastic circular arches are established using the principle of virtual work. The nonlinear partial differential equations of motion are solved using a finite difference method (Park's method for time difference). The dynamic stability of a hinged and a clamped elastic circular arch with a uniform step load is analysed with finite deformations and initial geometric imperfections. Results show that the buckling mode varies with the value of the arch half angle, theta0. The boundary condition and initial imperfection amplitude also affect the buckling mode. A nearly perfect arch usually buckling with a “direct” buckling form, while an imperfect arch with an “indirect” buckling form. The effect of theta0 on the ratio pd/ps (pd is the dynamic critical load and ps the static critical load) is shown for different initial imperfections and different boundary conditions.


ABSTRACT: The axial impact of cylindrical tubes, which incorporate axial stiffeners, is examined in this paper. For comparison purposes, the effect of static loading is also studied. An examination is made into the influence of stiffener depth (T), number of stiffeners (N) and the effect of placing the stiffeners externally or internally. The experimental results on mild steel specimens show that there are considerable differences between the static and dynamic modes of failure, and that an optimum T/D ratio may exist for a given value of N.


ABSTRACT: The structural members examined in the previous chapters responded in a stable manner when subjected to dynamic loads. However, in practice, dynamic loads may cause an unstable response. This chapter examines the dynamic progressive buckling phenomenon [4.1], which is illustrated in figure 4.1 for a circular tube.
References listed at the end of the paper:

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ABSTRACT: The use of a simple imperfection-sensitive elastic-plastic model for studying the non-linear buckling of short columns and cylindrical shells under dynamic axial compression is discussed in this paper. The axial impact loading of the model by a mass with an initial velocity is considered as a particular example. The critical impact velocities are determined for wholly elastic and elastic-plastic materials with linear strain hardening characteristics. The results show that the maximum initial kinetic energy at the transition between stable and unstable behaviour after impact is sensitive to the magnitude of the material strain hardening
parameter. It is also evident from the results that impact due to larger masses leads to larger lateral displacements at buckling and that the instability of a column is more sensitive to the presence of initial imperfections at higher impact velocities. Some guidance is offered on the choice of the various parameters in the idealized model for the analysis of practical engineering structures.

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ABSTRACT: The present study is concerned with the dynamic anomalous response of an elastic-plastic column struck axially by a mass $m$ with an initial velocity $v_0$. This simple example is considered in order to clarify the influence of the impact characteristics and the material plastic properties on the dynamic buckling phenomenon and particularly on the final vibration amplitudes of the column when it shakes down to a wholly elastic behaviour. The material is assumed to have a linear strain hardening with a plastic reloading allowed. These material properties are the reason a number of elastic-plastic cycles to be realized prior to any wholly elastic stable behaviour, which causes different amounts of energy to be absorbed due to the plastic deformations. The column exhibits two types of behaviour over the range of the impact masses — a quasi-periodic and a chaotic response. The chaotic behaviour is caused by the multiple equilibrium states of the column when any small changes in the loading parameters cause small changes in the plastic strains which result in large changes in the response behaviour. The two types of behaviour are represented by displacement-time and phase-plane diagrams. The sensitivity to the load parameters is illustrated by the calculation of a Lyapunov-like exponent. Poincaré maps are shown for three particular cases.

References listed at the end of the paper:


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“Strain-rate effects in the dynamic buckling of a simple elastic-plastic model”, Journal of Applied Mechanics, 03/1997, Vol. 64, No. 1, DOI: 10.1115/1.2787272

ABSTRACT: The phenomenon of dynamic buckling is examined when the influence of material strain-rate sensitivity is retained in the basic equations for a simple elastic-plastic model with linear strain hardening when subjected to an impact by a mass. Two approaches are proposed for taking into account the material strain-rate effects and both use the Cowper-Symonds constitutive equation. The critical impact velocities depend on the impact mass and are determined for a wholly elastic material, a strain-rate insensitive elastic-plastic material and an elastic-plastic material with a dynamic yield force together with linear or nonlinear hardening due to the strain-rate effects. The results obtained show that both strain-rate sensitive models predict impact velocities which are higher than those predicted by the strain-rate insensitive idealization and that the influence of any initial imperfections is important for the three material models considered.


PARTIAL ABSTRACT: Dynamic axisymmetric buckling of cylindrical shells, loaded dynamically by a Kolsky bar, is studied in order to analyse the influence of stress wave propagation on the initiation of buckling. The considered specimens are made of an aluminium alloy which has linear strain hardening and displays the Bauschinger effect. The acceleration wave speeds are obtained assuming the Tresca yield criterion. The deformation process is analysed by a numerical simulation using a discrete model for the shell and the theoretical predictions are compared with some published experimental data. It is shown that the different modes of...

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ABSTRACT: Dynamic axisymmetric buckling of circular cylindrical shells struck axially by a mass is studied in order to clarify the initiation of buckling and to provide some insight into the buckling mechanism as a transient process. It is assumed that the material is elastic–plastic with linear strain hardening and displaying the Bauschinger effect. The deformation process is analysed by a numerical simulation using a discrete model. Particular attention is paid to the influence of stress wave propagation on the initiation of buckling. It is found that the development of the buckling shape depends strongly on the inertia properties of the striker and on the geometry of the shell. The theoretical method is used to clarify some experimental data and good agreement is obtained with results on aluminium alloy tubes.
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ABSTRACT: The axisymmetric buckling of elastic–plastic cylindrical shells subjected to axial impact are studied using a finite element analysis. This study reveals that shells, subjected to axial impact, are both velocity and mass sensitive, so that larger energies can be absorbed by a shell for high-velocity impacts when decreasing the striking mass. It is shown that the inertia characteristics of the shell, together with the material properties, determine particular patterns of the axial stress wave propagation, thus, causing either dynamic plastic or dynamic progressive buckling to develop during the initial phase of the shell response. Domains of the load parameters, where the different buckling phenomena develop, are obtained for two particular shells. Strain rate effects are also considered when discussing the energy absorbing properties of the shells.

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ABSTRACT: The crushing behaviour of aluminium and steel cylindrical shells, when subjected to an axial impact, is examined using a numerical simulation. The influence of the material properties, shell geometry, boundary conditions and loading techniques on the energy absorbed and the buckling shapes is explored. Various shell response characteristics, such as the peak load, fold lengths, axial compression and energy absorption are studied. An examination is also made of the influence of filtering on the accuracy of data obtained usually in dynamic tests.

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ABSTRACT: A new concept is presented for the dynamic elastic–plastic axisymmetric buckling of circular cylindrical shells under axial impact. The phenomena of dynamic plastic buckling (when the entire length of the shell wrinkles before the development of large radial displacements) and dynamic progressive buckling (when the shell folds form sequentially) are analysed from the viewpoint of stress wave propagation resulting from an axial impact. The conditions for the development of dynamic plastic buckling are obtained. A numerical analysis of the buckling phenomena reveals that the material properties together with the geometrical characteristics of the shell determine the particular type of response for high velocity impacts. It is concluded
that shells made of strain rate insensitive materials can respond either by dynamic plastic buckling or dynamic progressive buckling, depending on the inertia properties of the shell, while those shells made of strain rate sensitive materials respond always by dynamic progressive buckling. It is shown that the prediction for the peak load, which can develop in a shell for a high velocity impact, depends on the particular yield criterion used in the analysis.

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ABSTRACT: Some characteristic features of the dynamic inelastic buckling behaviour of cylindrical shells subjected to axial impact loads are discussed. It is shown that the material properties and their approximations in the plastic range influence the initial instability pattern and the final buckling shape of a shell having a given geometry. The phenomena of dynamic plastic buckling (when the entire length of a cylindrical shell wrinkles before the development of large radial displacements) and dynamic progressive buckling (when the folds in a cylindrical shell form sequentially) are analysed from the viewpoint of stress wave propagation resulting from an axial impact. It is shown that a high velocity impact causes an instantaneously applied load, with a maximum value at t=0 and whether or not this load causes an inelastic collapse depends on the magnitude of the initial kinetic energy.

ABSTRACT: This article discusses the dynamic plastic instability of various basic structural members, subjected to large axial impact loads, which is relevant to the fields of structural impact and structural crashworthiness. In particular, studies on the dynamic axial response of idealised elastic–plastic models, rods, cylindrical shells and square tubes, is discussed in some detail. The analyses for some of the rods, shells and tubes retain the simultaneous influence of elastic and plastic stress waves (axial inertia) and the structural response (lateral inertia). The predictions reveal the profound influence of stress wave propagation phenomena which explain the characteristics of many of the experimental results obtained in laboratories over the years. These more complete analyses are vital for the higher velocity impact scenarios encountered increasingly in designs and for comparing properly the relative merits of different ductile materials in potential energy absorbing systems.

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“Counterintuitive response of long circular tubes to axial impact”, XXI ICTAM, 15-21 August 2004, Warsaw, Poland
Summary: The dynamic transition from progressive buckling to global bending collapse of a long circular tube under an axial impact is studied in order to obtain the energy absorption characteristics. The developed theoretical modes are used to analyse the influence of various parameters on the buckling transition. The analysis reveals a specific impact velocity, which causes a counterintuitive response of a tube. An empirical criterion for the lower and upper bounds to the critical lengths for buckling transition is proposed.

Reference listed at the end:


DTIC Accession Number: ADA221555, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA221555

ABSTRACT: A review of major research activities in North America with respect to the crashworthiness of composite aircraft structures was performed with the goal of identifying potential Canadian contribution to R&D areas where effort would be required to complement the on-going programs in the United States. Recommendations include a study on the effect of aircraft size on crashworthiness design requirements; the implementation of the KRASH code in Canada to establish commonality in analytical methods with major U.S. and European users; an investigation on the energy absorption capabilities of the design features for small aircraft containing composite and/or composite/hybrid structures; and a parametric study on the crashworthiness design of composite-to-composite and composite-to-metal joints.

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11. Wittlin, G., "KRASH Analysis Correlation -- Transport Airplane Controlled Impact Demonstration Test," DOT/FAA/CT-86/13,
35. Pramanik, M. B. and Carnell, B. L., "Landing Gear Performance Simulation by KRASH Program," Proceedings of the American

ABSTRACT: This paper deals with the evaluation of the crashworthiness of thin-walled sandwich box structures for automotive applications. Quasi-static crushing simulations are carried out to estimate the energy absorption of prismatic box columns made from sandwich sheets. The sandwich sheets have perforated cores of different densities with staggered holes perpendicular to the panel faces. It is found that the specific energy absorption of columns made of sandwich sheets is approximately the same as that of conventional columns composed of homogeneous sheets of the same total wall thickness. Furthermore, theoretical analysis indicates that by increasing the core thickness, sandwich structures could be up to 50% lighter while providing the same mean crushing force. However, these gains may not be achieved in practical applications since increasing the core thickness also increases the likelihood of premature face sheet fracture during crushing.

Vivek B. Mariyanna (Department of Mechanical Engineering, College of Engineering, Wichita State University, Wichita, Kansas, USA), “Energy absorption characteristics of stitched corrugated sandwich panels”, Master’s Thesis, December 2005, URI: http://hdl.handle.net/10057/762
ABSTRACT: The tailorable of composite sandwich structure with their strength-to-weight ratio interests in all field of crashworthiness application. An investigation of sandwich structure under static and high speed condition will provide useful information for wide variety of applications. In this present thesis, the characteristics of stitched corrugated sandwich panels as an energy absorption mechanism are evaluated, using
experimental and numerical methods. Edgewise compression tests under static and dynamic loading conditions are performed on unstitched and stitched corrugated sandwich specimens made of glass/epoxy face sheets and polyurethane foam core. Parameters affecting the instability of specimens under compressive edge loads are studied for different ply orientations, corrugation wavelengths, and ply material. The local buckling phenomena are then characterized for a particular corrugation configuration. The parametric studies of this thesis using experimental methods indicate a strong dependence of the different instability modes on the stitch configuration and the test rate on the sandwich panels.

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23. Xingweu DU, Fulin Xue and Zhenlong GU. ”Experimental study of the effect of stitching on the strength of composite laminates”, Harbin Institute of technology, China.

ABSTRACT: Energy absorbers are used to reduce accident induced damages. Thin-walled energy absorbers are widely used in modern industries due to their high efficiency and ease of manufacturing. In this study, thin-walled stainless steel structures in quasi-hemisphere geometry were subjected under quasi-static loading using Santam 150KN apparatus. Experimental results were compared with the results of numerical simulations by LSDYNA and it was shown that there is a good agreement between experimental and numerical results. Two different collapse types in radial and circumferential directions were observed. Also, the multi-cell quasi-hemisphere specimens from 3 to 6 cells were numerically investigated and it is observed that increasing the number of cells increases the absorbed energy. Increasing the thickness of the quasi-hemisphere sample in smaller diameter specimens is more effective. The results showed that Six-cell specimen with the largest diameter and the minimum thickness has the most increase of Specific Absorbed Energy (SAE) with respect to simple section.

References listed at the end of the paper:

11. Alavi Nia, A. and Parsapour, M., "An investigation on the energy absorption characteristics of multi-cell square tubes", Thin-
In this paper, the effects of tapering and introducing axisymmetric indentations on the crash performances of thin-walled tubes are investigated. The crash performances of the tubes are evaluated using two metrics: the crush force efficiency (CFE, the ratio of the average crushing load to the peak load), and the specific energy absorption (SEA, absorbed energy per unit mass). The optimum values of the number of the axisymmetric indentations, the radius of the indentations, the taper angle and the tube thickness are sought for maximum CFE and maximum SEA using surrogate based optimization. In addition, multi-objective optimization of the tubes is performed by maximizing a composite objective function that provides a compromise between CFE and SEA. The CFE and SEA values at the training points of surrogate models (metamodels) are computed using the finite element analysis code LS-DYNA. Polynomial response surfaces, radial basis functions, and Kriging are the different surrogate models used in this study. Surrogate based
optimization of the tubes showed that the tubes with indentations have better crush performance than tubes without indentations. It is found that maximum CFE requires large number of indentations with high radius, small thickness, and medium taper angle, while maximum SEA requires small number of indentations with low radius, large thickness and small taper angle. It is also found that the globally most accurate surrogate model does not necessarily lead to the optimum.

Shujuan Hou, Xu Han, Guangyong Sun, Shuyao Long, Wei Li, Xujing Yang and Qing Li, “Multiobjective optimization for tapered circular tubes”, Thin-Walled Structures, Vol. 49, No 7, pp 855-863, July 2011
ABSTRACT: As more and more new functional requirements are placed, some novel development of sectional configurations of the structural members has been increasingly introduced. This paper presents the optimal design for tapered tubes of three different configurations, namely hollow single, foam-filled single and collinear double tubes. To represent complex crashworthiness objective functions, a surrogate model method, more specifically, response surface method (RSM), was adopted in this study. The design of experiments (DoEs) of the factorial design and Latin Hypercube Sampling techniques is employed to construct the response surface models of specific energy absorption (SEA) and the maximum impact load (MaxL), respectively. In this paper, the linearly weighted average, geometrical average and particle swarm optimization methods are utilized in the multiobjective optimization for these three different tapered tube cases, respectively. A comparison is made among the different tapered profiles with the different optimization algorithms, and the crashworthiness merits of foam-filled tapered tubes are identified

ABSTRACT: Foam-filled thin-wall structures exhibit significant advantages in light weight and high energy absorption. They have been widely applied in automotive, aerospace, transportation and defense industries. Quasi-static tests were done to investigate the crash behavior of the empty and polyurethane foam-filled end-capped conical tubes. Non-linear dynamic finite element analyses were carried out to simulate the quasi-static tests. The predicted numerical crushing force and fold pattern were found to be in good agreement with the experimental results. The energy absorption capacities of the filled tubes were compared with the empty end-capped conical tubes. The results showed that the energy absorption capability of foam-filled tube is somewhat higher than that of the combined effect of the empty tube and the foam alone. Finally, the crash performance of the empty and foam filled conical and cylindrical tubes were compared. Results from this study can assist aerospace industry to design sounding rocket carrier payload based on foam-filled conical tubes.

ABSTRACT: Open cross-section, thin-walled, cold-formed steel columns have at least three competing buckling modes: local, distortional, and Euler (i.e., flexural or flexural-torsional) buckling. Closed-form prediction of the buckling stress in the local mode, including interaction of the connected elements, and the distortional mode, including consideration of the elastic and geometric stiffness at the web/flange juncture, are provided and shown to agree well with numerical methods. Numerical analyses and experiments indicate postbuckling capacity in the distortional mode is lower than in the local mode. Current North American design specifications for cold-formed steel columns ignore local buckling interaction and do not provide an explicit
check for distortional buckling. Existing experiments on cold-formed channel, zed, and rack columns indicate inconsistency and systematic error in current design methods and provide validation for alternative methods. A new method is proposed for design that explicitly incorporates local, distortional and Euler buckling, does not require calculations of effective width and/or effective properties, gives reliable predictions devoid of systematic error, and provides a means to introduce rational analysis for elastic buckling prediction into the design of thin-walled columns.

DOI: 10.1016/j.tws.2012.07.001

ABSTRACT: In this paper, a summary of the available imperfection measurements for cold-formed steel members is presented. Three methods to simulate imperfection fields are introduced: the first is the classical approach employing a superposition of eigenmode imperfections, but scaled to match peaks in the measured physical measurements. The second is a method based on the multi-dimensional spectral representation method, in which imperfections are considered as a two-dimensional random field and simulations are performed taking a spectra-based approach. The third is a novel combination of modal approaches and spectral representation that directly considers the frequency content of the imperfection field, but employs a spectral representation method driven by the cross-sectional eigenmode shapes to generate the imperfection fields. The effect of these different approaches on the simulated strength and collapse behavior of members is investigated using material and geometric nonlinear finite element collapse modeling. The third imperfection generation method, termed the 1D Modal Spectra Method, provides an intriguing new tool in the simulation of thin-walled members.

Nursafarina, A., Hanizah, A.H., Nurbaiah, M.N. and Clotilda, P. (Faculty of Civil Engineering, Universiti Teknologi Mara Malaysia, 40450 Shah Alam, Selangor, Malaysia), “Buckling profile on thin walled steel columns”, International Conference on Business, Engineering and Industrial Applications (ICBEIA), 2011

ABSTRACT: Thin-walled steel sections are usually fabricated with flat plates which are welded along the connection between the plates. Hence, this process of welding can extremely introduce geometric imperfection and residual stresses which can affect the structural behaviour of a loaded thin walled steel structure. This paper presents an experimental study on the buckling profile of thin-walled steel tube columns due to welding. A measuring of buckling profile has been developed with zigzag method using a Web Deflection Transducer Bar on six thin-walled columns. This investigation consists of two different weld patterns. Three of which are with full weld and the remaining are with intermittent weld. The patterns of buckling profile due to welding were measured and the results are presented in this paper.

References listed at the end of the paper:

ABSTRACT: Based on the compression characteristics of the concrete-filled thin-walled square steel tube short columns, the U-shaped tie bars are designed in this paper. The U-shaped tie bars and steel pipe walls are connected with each other in T-shape in order to enhance the local stability of the walls under pressure. According to the concrete strength C30/C35/C40 and the thickness of the steel plates 1.25mm/1.75mm/2.5mm, 42 short-column specimens are made, and the size of all specimens is 200mm×200mm×690mm. The bearing capacity test is done by the 500-ton electro-hydraulic serve testing machine. The strain of U-shaped tie bar and thin-walled steel are tested, and then the whole curve of compression process is obtained. The results show that the U-shaped tie bar has a very good role in bonding, and has good effects on improving buckling mode and the ductility of the components significantly. Concrete-filled thin-walled square steel tube short column fixed U-shaped tie bar has advantages on stronger post-deformability and more applicable to configuration compared with existing research achievements, and can provide a reference for engineering design.

ABSTRACT: This paper investigates the behaviour of axially loaded stiffened concrete-filled steel composite (CFSC) stub columns using the finite element software LUSAS. Modelling accuracy is established by comparing results of the nonlinear analysis and the experimental test. The CFSC stub columns are extensively developed using different special arrangements, number, spacing, and diameters of bar stiffeners with various steel wall thicknesses, concrete compressive strengths, and steel yield stresses. Their effects on the columns behaviour are examined. Failure modes of the columns are also illustrated. It is concluded that the parameters have considerable effects on the behaviour of the columns. An equation is proposed based on the obtained results to predict the ultimate load capacity of the columns. Results are compared with predicted values by the design code EC4, suggested equation of other researchers, and proposed equation of this study which is concluded that the proposed equation can give closer predictions than the others.

L. S. Wang, B. S. Li, "Built-In Spiral Ripe Thin-Walled Square Steel Tube Concrete Column of Nonlinear Finite Element Analysis", Advanced Materials Research, Vols. 690-693, pp. 678-681, 2013, DOI: 10.4028/www.scientific.net/AMR.690-693.678
ABSTRACT: For the problem of square concrete-filled steel tube (CFST) under the action of axial pressure, concrete received local compression and buckling occurred in the application of thin-walled steel pipe. Using built-in spiral reinforcement to strengthen the constraints of thin-walled square steel tube to core concrete. And by using ANSYS program established the built-in spiral reinforcement of thin-walled square steel tube concrete composite column 3 d finite element model, and the results show that spiral reinforcement strengthen the
constraint effect, increase the ultimate bearing capacity of the composite columns of square steel tube by 7.41%; And with stiffening rib and rod measures were compared, built-in spiral ripe construction is convenient, easily applied.


ABSTRACT: The transition between global and progressive buckling is explored in this paper for three different open cross-section shells. The shells were simply supported or clamped at the bottom and were submitted to axial quasi-static loads and to the impact of different drop masses. The experiments were complemented by a detailed finite element analysis, which required a quasi-static material characterisation based on tensile and three point bending tests. It was found that buckling transition from a global to a progressive mode cannot be clearly characterised for these open shells by considering only the overall final bucking shape. Using the finite element analysis, a more meaningful parameter to indicate the collapse mode, the specific energy, was calculated, allowing a better distinction among the most crashworthy profiles.

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“Impact And Crash Modelling Of Composite Structures: A Challenge For Damage Mechanics”, (publisher and date of publication is not given in the pdf file)

ABSTRACT: The paper describes recent progress on the materials modelling and numerical simulation of the impact and crash response of fibre reinforced composite structures. The work is based on the application of explicit finite element (FE) analysis codes to composite aircraft structures under both low velocity crash and high velocity impact conditions. Detailed results are presented for the crash response of helicopter subfloor box structures using a strain based damage and failure criterion for fabric reinforced composites. In order to obtain better agreement with measured impact response, an improved composites damage mechanics model with damage parameters as internal state variables is presented. Improved models for predicting delamination are also considered and a novel approach is presented in which a composite laminate is modelled numerically by stacked shell elements with contact interfaces whose delamination is controlled by fracture mechanics criteria.

References listed at the end of the paper:
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ABSTRACT: The axial crushing and crashing of thin-walled high-strength steel tubes is performed using 3D-shell finite elements and an implicit time integration scheme. The calculated results are compared with published experimental data and results obtained using explicit time integration. The objective is to show that, while for such analyses generally explicit time integration is used, with the current state of the art also an implicit time integration solution should be considered, and such solution approach can provide an effective alternative for a simulation.

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[21] Nia AA, Hamedani JH. Comparative analysis of energy absorption and deformations of thin walled tubes with various section
ABSTRACT: Twenty-five quasi-static and forty-three dynamic axial crushing tests have been performed on square and circular stainless steel type 304 specimens in order to investigate the transitions between dynamic progressive buckling and global bending of thin-walled tubes. The columns consisted of three different circular (mean diameter/ thickness, 2R/H = 7.5, 22, 47) and three different square (mean width/ thickness, C/H = 7.7, 24, 42) cross-sections, which are representative of ‘thick’, ‘intermediate’ and ‘thin’ shells, and have a range of different lengths, L, (3.38 < L/2R < 15.45 and 3.37 s L/C < 20.8) that encompass the two failure modes. Standard collapse modes were identified for the structures and the associated energy absorbing characteristics have been examined and compared with previous studies on mild steel tubes. Empirical formulae for the critical slenderness ratios for the transition between modes are suggested and the material properties of the stainless steels obtained by standard static and dynamic tensile tests are also reported.

References listed at the end of the paper:
(cannot cut and paste)
ABSTRACT: Quasi-static and dynamic axial crushing tests have been performed on circular thin-walled sections made of three materials: 304 stainless steel, aluminium alloy 6063-T6, and mild steel. The tests were arranged to investigate the mode transitions during the impact crushing of thin-walled tubes and the three materials were chosen for their distinctive individual characteristics, such as strain rate sensitive properties, pronounced strain hardening, etc. The stainless steel, aluminium alloy and mild steel shells have moderate diameter-to-thickness ratios, $2R/H$, of 22, 33 and 26, respectively, and were examined over a range of different axial lengths that encompassed both classical progressive buckling and the global bending modes of failure. The tests were conducted at a standardised energy of 9 kJ, approximately, with a few tests repeated at a higher energy of 18 kJ. The shells were impacted at velocities up to 13.4 m/s with masses up to 502 kg. Standard collapse modes developed in the tubes and the associated energy absorbing characteristics have been examined and compared with previous studies on mild steel. Quasi-static and dynamic tensile test results on the materials are also reported and the critical slenderness ratios at the transition between the two principal modes of failure are identified. The effects of strain hardening, strain rate as well as inertia effects due to the individual characteristics of the three materials are explored.

References listed at the end of the paper:

ABSTRACT: An experimental programme is reported which examines the progressive collapse behaviour of some thin-walled closed-section structural sections made from high-strength steels under quasi-static and impact axial loads. A comparison is made with theoretical formulae, which have been used successfully for predicting the behaviour of mild steel thin-walled structures. Ten quasi-static crush tests and 46 impact tests were conducted on spot-welded top-hat and laser-welded square sections. The thin-walled sections were made from two different types of high-strength steel and one mild steel, the mechanical properties of which were determined experimentally from quasi-static and dynamic tensile tests. Although no specific change in the collapse mode was observed, the limited weight-specific energy absorption efficiency of the high-strength steels under dynamic loadings hinders the weight-reduction potential of crashworthy designs. An unexpected difference in the structural effectiveness of spot-welded top-hat sections made from mild steels and high-strength steels was identified, but was not present for similar square sections. This difference further accentuated the loss in the advantage of high-strength steels over mild steels, especially for spot-welded top-hat sections, and led to differences in the agreement between the experimental results and the theoretical predictions.

References listed at the end of the paper:
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ABSTRACT: The common features of the deformation of long circular tubes made from different aluminium alloys and subjected to various axial impact loadings are established and used to develop simplified structural models for global bending collapse and progressive buckling. A two-phase deformation model for axially loaded structural elements is proposed, which retains the characteristic features of the initial compression and subsequent bending/buckling phases. It is shown that the velocity histories in the two principal collapse modes of long tubes play an important role for the formation of the particular deformation pattern. The simplified structural models are verified with some numerical finite-element results and their behaviour is shown to be adequate. A parametric analysis of the models is further performed in order to divulge the major factors, which influence the dynamic buckling transition. The analysis reveals that there is a specific impact velocity associated with the particular geometric and material properties of a circular tube, which causes a counterintuitive response. An empirical criterion for the lower and upper bounds to the critical impact velocity for a
buckling transition is proposed. Further, the upper bound to the impact velocity is used to formulate a criterion for the dynamic buckling transition.

References listed at the end of the paper:

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“Dynamic crushing of thin-walled spheres: An experimental study”, International Journal of Impact
ABSTRACT: Experimental studies on dynamic behavior of thin-walled spheres and sphere arrays in response to different impact velocity are presented. Ping pong balls are selected to study the collapse of thin-walled spheres. The tests were carried out by a modified Split Hopkinson Pressure Bar (SHPB) test system. The experimental results show that the deformation of thin-walled spherical shells depends on the impact velocity. The dynamic force in the range of small elastic deformation is larger than its quasi-static counterpart, but significantly below the latter after snap-through of the shell. The deformation and buckling mode are sensitive to the loading rate. It is noted that the strain rate effect of the materials and the inertia effect of the shell should be considered in the analysis of the shells response to dynamic loading.

ABSTRACT: Plastic crushing behavior of thin-walled spheres under various loading cases is studied using Finite Element Method. The entire plastic deformation process is tracked during the post-buckling process. The results are compared with the experimental results reported in literature [13], and very good agreements between the numerical simulation and the experimental result are achieved.

ABSTRACT: A theoretical analysis of the observed stable collapse mechanism of thin-walled circular frusta and tubes, crushed under axial static and/or dynamic loading, for calculating crushing loads and the energy absorbed during collapse, is reported. The analysis is based on experimental observations regarding the energy-absorbing collapse mechanisms developed during the crushing process. The proposed theoretical model was experimentally verified and proved to be very efficient for theoretically predicting the energy-absorbing capability of the conical shells.

ABSTRACT: The flexural properties, collapse modes and crushing characteristics of various types of composite sandwich panels – that were candidate materials for the manufacture of the front-end bumper of transportation vehicles – were investigated in a series of three-point bending tests that were performed in accordance with the American Society for Testing and Materials International Standard D790. The tested hybrid composites were constructed trying four types of polymer foam core (more specifically polymethacrylimide foam, cross-linked and linear polyvinyl chloride foam and polyurethane foam) and two types of fibreglass reinforced polyester faceplate laminates made of glass fibre reinforcements impregnated in modified acrylic resin, in eight different material combinations. Two modes of collapse were recorded in the series of flexural tests: the first was foam core shear failure and the second was local indentation collapse mode. The influence of the most important material properties of the faceplate laminates and foam core and the sandwich construction geometry on the flexural response and the crushing characteristics of the tested sandwich panels such as the peak load, crash
energy absorption and collapse modes is extensively analysed. Particular attention is paid to the analysis of the mechanics of progressive deformation and crumpling of the sandwich panels in each of the collapse modes emphasising the mechanisms related to the crash energy absorption during the bending of the sandwich panels.


ABSTRACT: Crashworthy structural elements may be subjected to various types of loading, such as axial or lateral compression and bending; consequently, extensive theoretical and experimental research work has been performed exploring the collapse mechanisms occurred under such loading conditions. However, the designer needs theoretical tools ranging from simple analytical calculations to full finite element analysis using non-linear, large deformation codes. The main objective of this paper is to apply the explicit FE code LS-DYNA through a Grid computing platform in order to simulate the crash behaviour of thin-walled cylindrical steel tubes subjected to three-point bending test in various cases of the position and direction of the imposed load. The simulation has been carried out through the GRIA computing platform that advances the computational performance of the executed tests, and additionally enables the remote and collaborative conduction of the experiments. The results taken from the simulation allow in drawing useful concluding remarks pertaining to the design of the crushing process.

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“Finite Element Modeling of Composite Tubular Crash Structures with an Explicit Code”, (no publisher or date given in the pdf file; most recent reference is 2006)

ABSTRACT: As emissions regulations tighten worldwide, automotive manufacturers must look for ways to reduce structural vehicle weight. While employing alloys and exotic metals may provide a degree of weight reduction, a more significant reduction can be achieved through the use of composite materials. Importantly, composites have shown an ability to improve vehicle crashworthiness through higher levels of specific energy absorption and almost ideal crush characteristics. These advantages have not been exploited in mass-produced vehicles, due primarily to the high cost of component manufacture and lack of computational methods for simulation of the crash behavior of such materials. While development of rapid, inexpensive production processes can increase the production volume and reduce cost, manufacturers will still be required to prototype components. The provision of accurate computational models for the failure behavior of composite materials will reduce the demand on manufacturers to prototype designs and ultimately result in structures of higher performance. Herein, a phenomenological Finite Element (FE) modeling methodology is presented, the development of which focused on the accurate consideration of the experimentally observed failure mechanisms typical of the splaying mode of failure. LS-DYNA has been employed to validate a multi-shell model of Continuous Filament Random Mat (CFRM) glass/polyester tubes. This modeling approach utilizes a spotweld approach to modeling delamination with deformable beam elements. Typical constraint-type delamination approaches do not allow shear deformation prior to delamination and result in an inaccurate representation of laminate stiffness. Spotweld validation simulations were performed on 3-point-bend, Double Cantilever Beam (DCB) and End Notch Flexure (ENF) tests with excellent correlation before application in full-tube simulations. Initiation of the splaying mode of failure was accomplished by pre-definition of a debris wedge, the geometry of which was based on micrograph images of the experimental crush zone. Additionally, the methodology was
applied to simulations of plug initiator tube crush experiments and the results are presented. In general, the load-displacement correlation of full-tube simulations is poor demonstrating the difficulty with representing the continuous fracture and delamination processes with discrete elements. Future work will be aimed at improving the simulated delamination behavior to enhance the observed failure mechanisms.

References listed at the end of the paper:

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ABSTRACT: Non-linear finite element software LS-DYNA is used to analyze the axial compression behavior and energy absorption of a high-strength thin-walled member under an impact load. To elucidate the effect of dynamic impact on the strain rate, the Cowper–Symonds equation is applied to analyze the plastic state of stress and the onset of dynamic yielding under different strain rates, such that the modeled deformation behavior of the member is consistent with the actual situation. Results for the thin-walled members made of mild steel and dual phase steel are compared. Assuming two different materials with equal sectional areas, an analysis confirms that the energy absorption of high-strength thin-walled component is better than the mild steel thin-walled component. Hence, thin-walled tubes made of high-strength steel are investigated using a series of analysis. The relationships between displacement and load, average load and energy absorption properties are obtained.

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13. Geier, B. & Singh, G., Some simple solutions for buckling loads of thin and moderately thick cylindrical shells and panels made of
Optimal Design of Filament Wound Grid-stiffened Composite Cylindrical Structures
M Buragohain… - Defence Science Journal, 2010 - publications.drdo.gov.in (cannot find)

... Keywords: Filament winding, grid-stiffened shell, lattice cylinder, smeared stiffeners model, buckling ... Once again, elements of the stiffness matrix of the equivalent shell are used in Ritz buckling analysis procedure by minimising potential energy of the equivalent shell. ...


ABSTRACT: Light weight thin walled cylindrical shells subjected to external loads are prone to buckling rather than strength failure. In this paper, buckling investigation of thin walled cylindrical shells under axial compression is presented. Buckling failure is studied using analytical, numerical and semi empirical models. Analytical model is developed using Classical Shell small deflection theory. A Semi empirical model is obtained by employing experimental correction factors based on the available test data to the theoretical model. A finite elements model is built using ANSYS FEA Code for the same shell. Finally, the different results obtained using the three analysis methods are compared. The comparison reveals that analytical and numerical linear model results match closely with each other but are higher than the empirical values. To investigate this discrepancy, non linear buckling analysis with large deflection effect, is carried out. The effect of geometric imperfection is also studied through a nonlinear model. These nonlinear analyses show that the effects of nonlinearity and geometric imperfections are responsible for the difference between theoretical and experimental results.

References listed at the end of the paper:

ABSTRACT: Lightweight thin-walled cylindrical shells subjected to external loads are prone to buckling rather than strength failure. The buckling of an axially compressed shell is studied using analytical, numerical and semi-empirical models. An analytical model is developed using the classical shell small deflection theory. A semi-empirical model is obtained by employing experimental correction factors based on the available test data in the theoretical model. Numerical model is built using ANSYS finite element analysis code for the same shell. The comparison reveals that the analytical and numerical linear model results match closely with each other but are higher than the empirical values. To investigate this discrepancy, non-linear buckling analyses with large deflection effect and geometric imperfections are carried out. These analyses show that the effects of non-linearity and geometric imperfections are responsible for the mismatch between theoretical and experimental results. The effect of shell thickness, radius and length variation on buckling load and buckling mode has also been studied.

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ABSTRACT: The influence of impact velocity and material characteristics on the dynamic buckling response of circular shells subjected to axial impact loads is studied. It is shown experimentally that the critical buckling length, which marks the transition between progressive and global buckling of aluminium alloy circular tubes, is significantly influenced by the axial impact velocity. A finite element analysis is undertaken to further explore the effects of material yield stress, strain hardening and strain rate sensitivity on the transition phenomenon. It is observed that circular tubes made of ductile alloys with a high yield stress and low strain hardening characteristics have a better performance as energy absorbers than tubes made of alloys with a low yield stress and high strain hardening characteristics. Theoretical analysis of some particular features of the dynamic buckling transition is presented in Part II [International Journal of Solids and Structures (2004)].

ABSTRACT: This is the second paper of a two-part paper investigating the complex phenomenon of the dynamic transition from progressive buckling to global bending collapse of a long circular cylindrical shell subjected to an axial impact. The paper focuses on the theoretical analysis of the phenomenon. The two-phase concept for the deformation of ‘Type II’ structures is employed to explore the influence of the loading parameters and the material and geometrical characteristics of a shell on the critical length that marks the transition between the two collapse modes. Simple models for the initial compressive phase in the case of global bending and for the development of a single axisymmetric wrinkle in a circular shell, are used to analyse some numerical results presented in Part I of this study [International Journal of Solids and Structures 41 (2004) 1565].


ABSTRACT: Two typical buckling patterns of circular cylindrical shells, which can occur due to axial impact loadings, are discussed. The phenomena of “dynamic plastic” buckling (when the entire length of a cylindrical shell wrinkles before the development of large radial displacements) and “dynamic progressive” buckling (when the folds in a cylindrical shell form sequentially) are analyzed from the viewpoint of stress wave propagation resulting from an axial impact. It is shown that the particular impact velocity, which instantaneously causes stresses that exceed the elastic limit of the material at the proximal end of a shell, and therefore can cause the initial instability pattern within a sustained axial plastic flow, depends on the material properties. The present analysis reveals that “dynamic plastic” buckling can develop for relatively low impact velocity, too provided that a shell has certain inertia characteristics. The latter conclusion is in contrast with the established perception that the high impact velocity is a necessary condition for the initial shell instability within a sustained axial plastic flow. A phenomenological approach is used to predict the buckling mode of a circular shell under axial impact with a given initial velocity.

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ABSTRACT: Several experiments were performed with a Kolsky Bar (Split Hopkinson Pressure Bar) device to investigate the dynamic axial buckling of cylindrical shells. The Kolsky Bar is a loading as well as a measuring device which can subject the shells to a fairly good square pulse. An attempt is made to understand the interaction between the stress wave and the dynamic buckling of cylindrical shells. It is suggested that the dynamic axial buckling of the shells, elastic or elasto-plastic, is mainly due to the compressive wave rather than the flexural or bending wave. The experimental results seem to support the two critical velocity theory for plastic buckling, with $V_{c1}$ corresponding to an axisymmetric buckling mode and $V_{c2}$ corresponding to a non-symmetric buckling mode.

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William Taylor Matias Silva,
Programa de Pós-Graduação em Estruturas e Construção Civil – PECC, Universidade de Brasília, Campus Darcy Ribeiro, Dep. Engenharia Civil e Ambiental, Edifício SG12 1o andar, CEP: 70.910-900, Brasília-DF, Brazil.

“A Consistent Nonlinear Shell Element Based On A Corotational Formulation For Hyperelastic Material Models”, 20th International Congress of Mechanical Engineering November 15-20, 2009, Gramado, RS, Brazil

ABSTRACT: The corotational (CR) kinematic description is the most recent of the formulations proposed for geometrically nonlinear structural analysis. Because of this novelty, it has not reached the same level of maturity of the older Lagrangian formulations (Total and Updated). Much work remains to be done, particularly in material nonlinearities. Therefore, the aim of this paper is to develop an efficient shell element for hyperelastic analysis with two important assumptions: (i) strains from a corotated configuration are small while (ii) the magnitude of rotations from a base configuration is not restricted. The assumed natural deviatoric strain (ANDES) three nodes triangular shell element is implemented for hyperelastic material models and its application to different constitutive models is discussed. Results provided by the proposed shell element are compared with the results presented by other authors in the literature in order to show the adequacy of the presented theory and the effectiveness of the numerical procedure and shell element employed in this work.

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Wang Ren, Han Mingbao, Huang Zhuping and Yan Qingchun (Department of Mechanics, Peking University, Beijing, China), “An experimental study on the dynamic axial plastic buckling of cylindrical shells”,


ABSTRACT: This paper deals with an experimental study on the dynamic plastic post-buckling behaviour of a stationary AM_i aluminium alloy cylindrical shell under axial impact. According to current theory, it is believed that within a certain velocity range, the shell will buckle in a uniform axisymmetrical sinusoidal mode. However, we found that when the impact velocity is less than a certain critical value Vc1, the shell will exhibit only uniform plastic deformation in both the axial and radial directions and does not produce the sinusoidal waves. On the other hand, when the impact velocity exceeds another critical value Vc2, the shell will change from the axisymmetric mode into a nonuniform type of large deformation, the number of waves decreases slightly and the shell begins to lose its load-carrying capacity. Experimental results on cylinders with three different thicknesses are presented and discussed. An approximate theoretical formula for estimating Vc2 based on strain rate reversal is also given.

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ABSTRACT: This paper presents a unified theoretical framework for the corotational (CR) formulation of finite elements in geometrically nonlinear structural analysis. The key assumptions behind CR are: (i) strains from a corotated configuration are small while (ii) the magnitude of rotations from a base configuration is not restricted. Following a historical outline the basic steps of the element independent CR formulation are presented. The element internal force and consistent tangent stiffness matrix are derived by taking variations of the internal energy with respect to nodal freedoms. It is shown that this framework permits the derivation of a set of CR variants through selective simplifications. This set includes some previously used by other investigators. The different variants are compared with respect to a set of desirable qualities, including self-equilibrium in the deformed configuration, tangent stiffness consistency, invariance, symmetrizability, and element independence. We discuss the main benefits of the CR formulation as well as its modeling limitations.

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[38] B. Haugen and C. A. Felippa, A unified formulation of small-strain corotational finite elements: II. Applications to shells and mechanisms, in preparation.


ABSTRACT: The variational formulation for thin elastic shells undergoing large deflections is discussed. No restrictions are imposed on the magnitude of the rotational part of the deformation gradient, yet it is assumed that the strains remain small everywhere in the shell. Ten functional and associated variational principles are derived, including the Hu-Washizu, the Hellinger-Reissner, the generalized complementary energy and the stationary potential energy principles. The total Lagrangian description (TLD) is exclusively used.


ABSTRACT: The paper presents a comparatively simple method for assessing the global stability of single- and double-layer reticulated shells, assuming rigid connections between the bars. With knowledge of the rigidities of the reticulated shell, a statically equivalent replacement solid shell is established, the buckling of which is extensively treated in the literature. The critical load of this replacement continuum is determined by taking into account the influences of geometric imperfections (eccentricity), plasticity, (local) bar buckling and – in the case of double-layer reticulated shells – of transverse shear deformation. All these are presented in detail for isotropic shells, but the method can also be used for anisotropic ones. Finally, for dimensioning reticulated shells, a unique safety factor based on the theory of probabilities is recommended, which depends on the uncertainties of the various effects. Numerical values for the safety factor are also given. The method proposed...
provides a transition from shells to plane plates, from surface to bar structures, and from reticulated to solid shells, thus ensuring identical safety levels for all these structures.

A talk by: Emeritus Prof Chris Calladine (CUED), “Understanding The Buckling of Cylindrical Shells”, Friday 19 January 2007, 15:00-16:00, Engineering Department – LR6. This talk is part of the Engineering Department Structures Research Seminars series.

INITIAL REMARKS: The classical theory of buckling of axially-loaded thin cylindrical shells predicts that the buckling stress is directly proportional to the thickness t, other things being equal. But empirical data show clearly that the buckling stress is actually proportional to t^{1.5}, other things being equal. As is well known, there is wide scatter in the buckling-stress data, ranging from one half to twice the mean value. Current theories of shell buckling attribute both the scatter and the low buckling stress – in comparison with the classical – to “imperfection-sensitive”, non-linear structural behaviour. But those theories always take the classical analysis of an ideal, perfect shell as their point of reference. My aim in this talk is to explain directly the observed t^{1.5} law, including the scatter, without the need to invoke the misleading classical theory.

Li Zhi-min (School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, China), “Buckling analysis of three dimensional braided composite cylindrical shells under axial compression”, Structure & Environment Engineering, 2007-04, doi: CNKI:SUN:QDHJ.0.2007-04-003

ABSTRACT: A buckling and postbuckling analysis of clamped supported 3D braided shells of finite length subjected to axial compression is presented. The governing equations are based on Reddy’s higher order shear deformation shell theory with von Kármán-Donnell type of kinematic nonlinearity, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range and initial geometric imperfections of the shell. Asymptotic solutions of a boundary layer theory of shell buckling are analyzed by singular perturbation method. The influence exercised by the fiber volume fraction, and the shell geometric parameter of the cylindrical shell on the buckling behavior of the braided composite shell is investigated. It is concluded that the fiber volume fraction and the shell geometric parameter have a significant effect on the buckling load and postbuckling behavior of braided composite cylindrical shells.

Zeng, Tao (a); Gu, Yu (b); Yan, Shi (a); Jiang, Lili (a); Fang, Daining (b), (a) Department of Engineering Mechanics, Harbin University of Science and Technology, P. R. China, (b) Department of Mechanics and Aerospace Technology, Peking University, “Buckling Analysis of 3D Braided Composite Cylindrical Shells under Axial Loads”, International Journal of Nonlinear Sciences and Numerical Simulation. Vol. 10, No. 10, 2009, pp. 1291–1300, ISSN (Online) 2191-0294, ISSN (Print) 1565-1339, doi: 10.1515/IJNSNS.2009.10.10.1291

ABSTRACT: A simplified theoretical method is presented for analyzing the buckling behavior of a 3D braided composite cylindrical shell. The method is based on the refined anisotropic plate model. The buckling load with different values of geometric parameter is described. In order to verify the proposed model, the finite element package ANSYS is used to calculate the buckling load. Predictions from the proposed model correlate well with the simulation results. The results reveal that geometric parameters and braid angle have a significant effect on the buckling load.

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ABSTRACT: (none given)

ABSTRACT: (none given)

ABSTRACT: (none given)

Z.-M. Li (1) and D.-Q. Yang (2)
(1) School of Mechanical Engineering State Key Laboratory of Mechanical System and Vibration Shanghai Jiao
ABSTRACT: Thermal postbuckling analysis is presented for 3D braided composite cylindrical shell of finite length subjected to a uniform temperature rise. Based on a micro-macro-mechanical model, a 3D braided composite may be as a cell system and the geometry of each cell is deeply dependent on its position in the cross-section of the cylindrical shell. The material properties of epoxy are expressed as a linear function of temperature. The governing equations are based on Reddy's higher order shear deformation shell theory with a von Kármán-Donnell-type of kinematic nonlinearity and including thermal effects. A singular perturbation technique is employed to determine the buckling temperatures and postbuckling behaviors of 3D braided composite cylindrical shells. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, braided composite cylindrical shells with different values of geometric parameter and of fiber volume fraction. The results show that the shell has lower buckling temperatures and postbuckling equilibrium paths when the temperature-dependent properties are taken into account. The results reveal that the fiber volume fraction, braiding angle and the shell geometric parameter have a significant effect on the thermal buckling and postbuckling behavior of braided composite cylindrical shells.

References listed at the end of the paper:


ABSTRACT: Nonlinear buckling and postbuckling behavior for a 3D braided composite cylindrical shell of finite length subjected to lateral pressure, hydrostatic pressure, or external liquid pressure in thermal environments have been presented in this paper. Based on a new micromacromechanical model, a 3D braided composite may be treated as a cell system and the geometry of each cell is deeply dependent on its position in the cross section of the cylindrical shell. The material properties of the epoxy are expressed as a linear function of temperature. The governing equations are based on Reddy’s higher order shear deformation shell theory with a von Kármán–Donnell type of kinematic nonlinearity and including thermal effects. A singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect braided composite cylindrical shells with different values of geometric parameter and of fiber volume fraction in different cases of thermal environmental conditions. The results show that the shell has lower buckling pressures and postbuckling paths when the temperature-dependent properties are taken into account. The results reveal that the temperature changes, the fiber volume fraction, and the shell geometric parameter have a significant effect on the buckling pressure and postbuckling behavior of braided composite cylindrical shells.

References listed at the end of the paper:

Z.-M. Li (1), W. Gu (2), X.-D. Chen (3) and H. Hu (4)
Nonlinear buckling behavior of 3D-braided composite cylindrical shells subjected to internal pressure loads in thermal environments. The nonlinear buckling behavior of a 3D-braided composite cylindrical shell of finite length subjected to internal pressure in thermal environments is considered. According to a new micromacromechanical model, a 3D-braided composite may be treated as a cell system where the geometry of each cell strongly depends on its position in the cross section of the cylindrical shell. The material properties of the epoxy matrix are expressed as linear functions of temperature. The governing equations are based on Reddy’s higher-order shear deformation theory of shells with a von Karman–Donnell-type kinematic nonlinearity and include thermal effects. The singular perturbation technique is employed to determine the buckling pressure and the postbuckling equilibrium paths of the shell.

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ABSTRACT: This paper investigates numerically and experimentally the influence of initial geometric imperfections on the critical loads of initially stretched thick hyperelastic cylindrical shells under increasing uniform internal pressure. Imperfections in shells can have a global or local character. First, two types of local imperfections are considered: (1) a local axially symmetric imperfection in the form of a ring and (2) a small rectangular imperfection. The influence of the imperfection thickness, position and size are analysed in detail. Results show that the critical load decreases as the imperfections increase in size or thickness and as they move from the boundaries to the centre of the shell. The influence of multiple local imperfections is also studied in the present paper. Finally, the influence of global imperfections is considered with the imperfections described as a variation of the shell curvature in the axial direction. The results show that thick hyperelastic shells may be sensitive to local and global imperfections. In all cases the experimental results are in good agreement with the numerical ones, corroborating the conclusions.

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ABSTRACT: A post-buckling analysis is presented for a stiffened braided thin shell subjected to combined loading of external pressure and axial compression. The effects of the nonlinear large deflection and the initial geometrical imperfection are considered in the formulations. The analysis uses perturbation method to determine the interactive buckling loads and the post-buckling equilibrium paths and a three-cell model are used to obtain the elastic constants of braided shell. Some effects such as imperfection parameter, stiffened and Braiding parameters on the post-buckling path are discussed in the article.

ABSTRACT: The nonlinear strain-displacement relations in general cylindrical coordinates are simplified by Sander’s assumptions for the cylindrical shells and substituted into the total potential energy function for thermoelastic loading. … An improvement is observed in the resulting equations as no length limitations are imposed on a thin cylindrical shell…. Based on the improved equilibrium and stability equations, the magnitude of thermoelastic buckling of thin cylindrical shells under deferrent thermal loading is obtained. The results are extended to short and long thin cylindrical shells.

ABSTRACT: In this paper, the elastic axisymmetric buckling of a thin, isotropic and simply supported cylindrical shell with an elastic core under axial compression has been analyzed using energy method. The nonlinear strain-displacement relations in general cylindrical coordinates are simplified using Sanders kinematic relations (Sanders, 1963) for axial compression. Equilibrium equations are obtained by using minimum potential energy together with Euler equations applied for potential energy function in cylindrical shell. To acquire stability equation of cylindrical shell with an elastic core, minimum potential energy theory and Trefftz criteria are implemented. Stability and compatibility equations for an imperfect cylindrical shell with an elastic
core are also obtained by the energy method, and the buckling analysis of shell is carried out using Galerkin method. Critical load curves versus the aspect ratio are obtained and analyzed for a cylindrical shell with an elastic core. It is concluded that the application of an elastic core increases elastic stability and significantly reduces the weight of cylindrical shells.

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doi: 10.1016/j.compositesb.2013.03.017
ABSTRACT: Electro-thermo-torsional buckling response of a double-walled boron nitride nanotube (DWBNNT) has been investigated based on nonlocal elasticity and piezoelectricity theories. The effects of surrounding elastic medium such as the spring constant of the Winkler-type and the shear constant of the Pasternak-type are taken into account. The van der Waals (vdW) forces are considered between inner and outer layers of nanotube. According to the relationship between the piezoelectric coefficient of armchair boron nitride nanotubes (BNNTs) and stresses, the first order shear deformation theory (FSDT) is used. Energy method and Hamilton’s principle are employed to obtain coupled differential equations containing displacements, rotations and electric potential terms. The detailed parameter study is conducted to investigate the effects of nonlocal parameter, elastic foundation modulus, temperature change, piezoelectric and dielectric constants on the critical torsional buckling load. Results indicate that the critical buckling load decreases when piezoelectric effect is considered.

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“Nonlinear vibration and instability analysis of functionally graded-CNT-reinforced cylindrical shells conveying viscous fluid resting on orthotropic Pasternak medium”, Mechanics of Advanced Materials and Structures, in press, Accepted May 2015, DOI: 10.1080/15376494.2015.1029170
ABSTRACT: In this study, nonlinear vibration and instability of embedded temperature-dependent cylindrical shell conveying viscous fluid resting on temperature-dependent orthotropic Pasternak medium are investigated. The equivalent material properties of nanocomposite are estimated using rule of mixture. Both cases of uniform distribution (UD) and functionally graded (FG) distribution patterns of reinforcements are considered. Based on orthotropic Mindlin shell theory, the governing equations are derived. Generalized differential quadrature method (GDQM) is applied for obtaining the frequency and critical fluid velocity of system. The effects of different parameters such as distribution type of SWCNTs, volume fractions of SWCNTs and Pasternak medium are discussed.

K. Magnucki, T. Wegner and W. Szyc (Inst. Of Applied Mechanics, Technical University of Poznan, Poland),
ABSTRACT: A method for the calculation of the critical load for a semi-ellipsoidal shell with a stiffening rib at the edge is presented. The external and internal buckling energy of the shell is described. The Rayleigh quotient
is used as the static buckling criterion, assuming the deflection function to depend on four shape parameters. Some numerical examples are presented showing the influence of the rib stiffness and the shell dimensions on the critical pressure value.

References listed at the end of the paper:

ABSTRACT: The paper is devoted to stability problem of an axially compressed open elastic circular cylindrical shell. Two curvilinear edges of the open cylindrical shell are simply supported while two straight edges are free. Two load cases of the shell are assumed. The first load case - was the invariable axially normal force intensity, and the second load case - the linearly varying axially normal force intensity. Critical loads of the shell for both load cases are determined. These critical loads are compared with a classical load for closed circular cylindrical shell.

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E. Magnucka-Blandzi and K. Magnucki, “Effective design of a sandwich beam with a metal foam core”, Thin-Walled Structures, 04/2007; 45(4):432-438. DOI: 10.1016/j.tws.2007.03.005
ABSTRACT: The subject of the paper is a simply supported sandwich beam with a metal foam core. Mechanical properties of the core vary through its depth. A nonlinear hypothesis of deformation of a plane cross section of the beam is assumed and described. The elastic potential energy and the work of the load are formulated. The system of differential equations of the equilibrium is derived on the basis of the theorem of minimum total potential energy. The system of equations is analytically solved. The stress state and the critical force for the beam are determined. The optimal dimensionless parameters of the beam are calculated. Results of the numerical investigations are presented in figures.

ABSTRACT: The study is devoted to a radial compressed metal foam circular plate. Properties of the plate vary
across its thickness. The middle plane of the plate is its symmetry plane. First of all, a displacement field of any cross-section of the plate was defined. Afterwards, the components of strain and stress states were found. The Hamilton principle allowed one to formulate a system of differential equations of dynamic stability of the plate. This basic system of equations was approximately solved. The forms of unknown functions were assumed and the system of equations was reduced to a single ordinary differential equation of motion. The equation was then numerically processed that allowed one to determine critical loads for a family of metal foam plates. The results of studies are shown in figures. They show the effect of porosity of the plate on the critical loads. The results obtained for porous plates were compared to homogeneous circular plates.

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Ewa Magnucka-Blandz (Institute of Mathematics, Poznan University of Technology, Poznan, Poland), “Lateral buckling of a thin-walled beam under combined load”, Mathematical Methods and Techniques in Engineering and Environmental Science, (vol. & date not given in the pdf file; Most recent reference is 2010)

ABSTRACT: The paper is devoted to a simply supported thin-walled beam. The critical state of the beam under uniformly distributed transverse load, an axial force and two different moments located at its both ends is analytically studied. The elastic potential energy and the work of loads for the beam are described. Basing on the stationary of the total potential energy the general algebraic equation of the critical state for the beam is obtained. The equation describes a convex hyper-surface. Particularly simple load cases are studied. Based on the general equation of the critical state numerical investigations are realized. The results are shown in Figures.

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ABSTRACT: The present paper deals with an influence of the axial extension mode on static and dynamic interactive buckling of a thin-walled channel with imperfections subjected to uniform compression when the shear lag phenomenon and distortional deformations are taken into account. A plate model is adopted for the channel. The structure is assumed to be simply supported at the ends. Equations of motion of component plates were obtained from Hamilton’s principle taking into account all components of inertia forces. In the frame of first order nonlinear approximation, the dynamic problem of modal interactive buckling is solved by the transition matrix using the perturbation method and Godunov’s orthogonalization.

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ABSTRACT: The problem of buckling and initial post-buckling equilibrium paths of thin-walled structures built of plate and/or shell elements subjected to compression and bending has been solved. Plate and shell elements can be made of multi-layer orthotropic materials. A method of the modal solution to the coupled buckling problem within the first-order approximation of Koiter’s asymptotic theory, using the transition matrix method, has been presented. In the solution obtained, the effect of cross-sectional distortions and a shear lag phenomenon is included. The calculations are carried out for a few thin-walled structures.


ABSTRACT: The paper concerns theoretical, numerical and experimental analysis of the stability and ultimate
load of multi-cell thin-walled columns of rectangular and square cross-sections subjected to axial compression (uniform shortening of the column). The theoretical analysis deals with the local and global stability of multi-cell orthotropic columns of a rectangular profile with rectangular cells. It has been shown that for a multi-cell column made of the same material and having the same cross-section area, the value of local buckling stress of the column walls grows rapidly with an increase of the cell number. The experiment conducted for isotropic columns has also proved a significant growth of the ultimate load with the increase of the cell number. The paper gives some conclusions which can be useful in design of thin-walled box columns.

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ABSTRACT: This paper deals with local dynamic buckling of thin-walled girder segments (short beam-columns) subjected to bending. Various shapes of pulse loading (triangle, trapezoid and rectangle) with a duration corresponding to the fundamental period of vibration were taken into account. Assumed boundary conditions correspond to a simple support, this agrees with conditions that exist in the place of the diaphragm in a long spar. The problem was solved by finite element method. In order to determine the critical load pulse amplitudes Volmir, Budiansky–Hutchinson, Ari–Gur and Simonetta criteria were employed.

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ABSTRACT: Thin–walled structure, by its nature, is subjected to loss of stability. In addition, the shell has a cutout, which reduces the critical load. The aim of this study is to determine critical stress of the shell under pure bending. The goal was achieved in two ways: experimentally and analytically. Experimental studies were carried out on a specially designed test bench with the use of a resistive strain gauge. In the analytical solution the form of buckled shell was assumed, and then Bubnov–Galerkin method was applied.

References listed at the end of the paper:


ABSTRACT: The work deals with the problem a straight beam of a rectangular cross-section pivoted at both ends and loaded with a lengthwise compressive force. The beam is made of an isotropic porous material. Its properties vary through thickness of the beam. The modulus of elasticity is minimal on the beam axis and assumes maximum values at its top and bottom surfaces. The principle of stationarity of the total potential energy enables one to define a system of differential equations that govern the beam stability. The system is analytically solved, which leads to an explicit expression for the critical load of the compressed beam. Results of the solution are verified on an example beam by means of the Finite Element Method (COSMOS).

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ABSTRACT: The aim of the paper is to present a procedure for design of a family of shells of revolution of constant mass and, as a next step, of constant volume. As a reference a cylindrical shell is taken into consideration. By decreasing the value of the meridional radius of curvature R1, which for cylindrical shell equals infinity, barrelled shells are created up to the spherical shell for which both meridional and circumferential radii of curvature are equal (R1=R2). A numerical example of using the presented procedure is
considered. Then for the family of shells of revolution of constant mass a buckling analysis using FEM method is carried out. Results of the analysis show the relationship between the radius of curvature of the shell $R_1$ and the critical load $p_{cr}$ in the case of uniform external pressure.


SUMMARY: The present work is devoted to the elastic stability of shells of revolution in the pure bending state. Buckling shapes are presented and the dependency between the shape of a shell and its critical stress is described. The ABAQUUS system based on the finite elements method was used to obtain the results. Examples of works concerning stability of shells under bending can be easily found in the literature. However they are usually limited to cylindrical shells. Brush and Almroth [1] and Volmir [2] present analytical solutions of the problem and a state of the art in this field. In the paper presented here the authors extend the investigation to shells of revolution other than cylindrical ones including a cylinder as a reference point. A family of shells of revolution of the same volume and length is investigated including shells with positive (barrel) and negative Gaussian curvature. The model of a shell is simply supported at both ends. To introduce a pure bending conditions a non-uniform axial load is applied to the edge of the shell. The results obtained from the analyses confirm the advantages of barrelled shells presented for example by Blachut [3]. A barrelled shell can bear about 75% higher load than a cylinder if pure bending conditions are assumed. The gain in buckling strength grows monotonically with decreasing the meridional radius of curvature $R$. The buckling shape is of the form of short wrinkles concentrated near the edge of the shell where the load is applied. Shells with negative Gaussian curvature buckle in a global way and the buckling load decreases with decreasing radius $R$. Since buckling of thin, middle-length bending shells is caused by compressive stresses the buckling analysis under axial compression was also carried out. The results are similar to those obtained for bending load. Critical stresses are slightly higher, up to 5.5%, for bending.

References listed at the end of the paper:


ABSTRACT: The paper is devoted to shells of revolution with positive and negative Gaussian curvature. The meridian of shells is a plane curve in the Cassini oval form. Geometrical properties of the middle surface of the shell of revolution based on this curve are presented. The membrane state of stress of a family of shells with constant capacity and mass under uniform pressure is described analytically and numerically with the use of the FEM (the ANSYS system). The critical pressure, buckling modes and equilibrium paths of analysed shells are calculated numerically. The advantages of a pressure vessel made in the form of Cassini ovaloidal shell, such as the lack of edge effect and a stable post-buckling behaviour, are pointed out. The results of the analytical and numerical investigations are compared and presented in tables and figures.

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2. É.I. Grigolûk, V.V. Kabanov, Stability of Shells, Nauka, Moscow [in Russian].
ABSTRACT: The main goal of this paper is a solution of the problem of buckling and deflection. A circular porous plate with simply supported edge under radial uniform compression and uniformly distributed load (pressure) is considered. Mechanical properties of the isotropic porous material vary across the thickness of the plate. Middle plane of the plate is its symmetry plane. A field of displacements (geometric model of nonlinear hypothesis) is described. The principle of stationarity of the total potential energy allowed to get a system of differential equations that govern the plate stability. A critical load and a deflection are determined. The results obtained for porous plates are compared to homogeneous circular plates.

**ABSTRACT:** This paper considers an isotropic porous shell loaded by axial compression shown in Figure 53.1. The effects of varying porous material and geometric parameters of the cylindrical shell, on the elastic buckling load are studied. The shell is made of an isotropic porous material which varies only across the thickness of the shell wall. Banhart [1] reviewed the possibilities of manufacturing metal foams or other porous metallic structures as well as ways for characterizing the properties of cellular metals. In the present paper the porous shell is a generalization of a sandwich construction.


**ABSTRACT:** The paper is devoted to five different flanges of cold-formed thin-walled beams. Mathematical models of each of the flanges are formulated and solved. The theory of elastic stability of plates and cylindrical shallow shells is applied for this purpose. Critical stress for each flange of the beam is determined. Results of analytical solutions are discussed and compared with numerical (FEM) and experimental investigations. The formulas of critical stresses may be used in practical applications.

References listed at the end of the paper:


ABSTRACT: By the aid of differential geometry analysis on the initial buckling of shell element, a set of new and exact buckling bifurcation equations of the spherical shells is derived. Making use of Galerkin variational method, the general stability of the hinged spherical shells with the circumferential shear loads is studied. Constructing the buckling mode close to the bifurcation point deformations, the critical eigenvalues, critical load intensities and critical stresses of torsional buckling ranging from the shallow shells to the hemispherical shell are obtained for the first time.

References listed at the end of the paper: (cannot cut and paste)

1965 (Chinese version)

ABSTRACT: A thin-walled spherical shell is pivoted at both edges. One of the edges may rotate around the shell axis. Moreover, it is loaded with a torque. The problem of shell stability is considered. The system of equations characterizing the problem consists of a non-linear equation of equilibrium and non-linear compatibility equation. Both equations are solved with Bubnov-Galerkin’s method, assuming beforehand the form of deflection and force-functions. As a result of the solution, an algebraic equation is obtained, with respect to a dimensionless load parameter. The critical load parameter corresponding to the minimal critical load value is determined from this equation. The number m at which the load parameter has the minimum value determines the mode of stability loss. The paper is supplied with a numerical example.
References listed at the end of the paper: (cannot cut and paste. There are 5 references.)

ABSTRACT: A thin-walled spherical shell is pivoted at both ends. The upper edge of the shell, loaded with a torque, may rotate around the shell axis. The problem of the loss of stability of the shell is solved with an energetic method. The change in the total energy of the shell while losing stability is determined. This requires
the forms of the deflection and force functions to be assumed, according to actual boundary conditions. Coefficients of the force function are determined from the solution to the inseparability equation with the Bubnov-Galerkin method. The stability equation of the shell is formulated as a result of application of the Ritz method to the total energy variation. It is an algebraic equation serving for determination of the critical load. It is equal to the minimal value of the load. The work ends with a numerical example.

List of references at the end of the paper: (cannot cut and paste. There are 7 references.)

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ABSTRACT: The subject of the study are open circular cylindrical thin shells with two edges supported and two edges free. The elastic buckling and limit load of these shells in pure bending state are investigated. The study includes simple analytical description, numerical analysis with the use of the Finite Element Method (FEM), and laboratory tests for shells. The results of these three investigation methods are compared and presented in figures. The critical load and limit load for these shells are described in detail. Moreover, an analytical formula of critical stresses for open circular cylindrical thin shells in pure bending state is proposed. The main goal of the paper is comparison of the results of critical load values obtained by analytical, numerical (FEM), and experimental methods.

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ABSTRACT: A limit load analysis of a vessel nozzle with pressure and external force loading was conducted. The limit load was defined by increasing the pressure and the nozzle external loads proportionally until collapse occurred. The evaluation of the limit load analysis was conducted in accordance with ASME BPVC Section VIII Division 2 [1]. The limit load analysis provides insight into the collapse load and failure mode. The results of the limit load analysis and a plastic analysis are compared to the results obtained by linear and nonlinear shell and plate element analyses of the same nozzle. The authors discuss the comparison of the results as there is some variance between the different methodologies.
References listed at the end of the paper:

ABSTRACT: The problem of critical load of an axially compressed open sandwich cylindrical shell with two straightline edges free is presented. Large angle of the shell sector, geometrical and physical symmetry of the facings are assumed. The simply formula for calculation critical stress in the shell is presented.

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ABSTRACT: The problem of elastic buckling of an open sandwich cylindrical thin-walled panel with three edges simply supported and one edge free under axial compression is considered in the paper. The classical broken line hypothesis is replaced by its modified generalized version. On the basis of force and moment equilibrium conditions for the shell element, a set of the fundamental equations is derived. The set is solved with the help of the orthogonalizational Bubnov–Galerkin method. The nonlinear algebraic equation is obtained. Physical and geometrical parameters of the shell, deflection factor and loading are connected in the equation. It is possible, among others, to obtain from here the critical load value.


ABSTRACT: In this paper, the authors consider the influence of axial load on the stability of shells of revolution subjected to external pressure. Shells of different geometry are investigated with emphasis to barrelled shells. The variable quantities are length L and meridional radius of curvature R1 of a shell. The constant parameters are: thickness of the shell h, mass ms and reference radius r0. The material of shells is steel. Numerical calculations were performed in the ABAQUS system. All the shells considered in this paper were subjected to axial compression to determine the force corresponding to the loss of stability in such conditions. A part of this force is then used to preload shell before the buckling analysis in the conditions of external pressure.
is started. The buckling shapes for shells of different geometry are presented with and without the influence of axial load. The ability of controlling the buckling strength and shape is discussed.


ABSTRACT: The paper is devoted to sandwich beams under pure bending. The local buckling problem is analysed. The analytical description of the upper face wrinkling is proposed. From the principle of stationary total potential energy, formulae describing critical stresses in the faces of the beam are derived. The algorithm for determining the critical stresses is shown. Two particular cases of the solution following the core properties are mentioned. The finite element model of the sandwich beam is formulated. The comparison of the results obtained from the proposed analytical model and from FEM analysis is shown for a family of sandwich beams with different thicknesses and core properties.

References listed at the end of the paper:
P. Jasion (1), E. Magnucka-Blandzi (2), W. Szyc (1) and K. Magnucki (1)  
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ABSTRACT: The paper is devoted to the analytical, numerical and experimental studies of the global and local buckling–wrinkling of the face sheets of sandwich beams and sandwich circular plates. A mathematical model of displacements, which includes a shear effect, is presented. The governing differential equations of sandwich plates are derived. The equations are analytically solved and the critical loads are obtained. Finite element models of the plates are formulated and the critical loads and buckling modes are calculated. Moreover, experimental investigations are carried out for the family of sandwich beam-plates. The values of the critical load obtained by the analytical, numerical (FEM), and experimental methods are compared.

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ABSTRACT: The subject of the paper is a sandwich beam with a crosswise or lengthwise corrugated core. The beam is made of an aluminium alloy. The plane faces and the corrugated core are glued together. Geometrical properties and rigidities of the beams are described. The load cases investigated in the work are pure bending and axial compression. The relationship between the applied bending moment and the deflection of the beam under four-point bending is discussed. The analytical and numerical (FEM) calculations as well as experimental results are described and compared. Moreover, for the axial compression, the elastic global buckling problem of the analysed beams is presented. The critical loads for the beams with the crosswise and lengthwise corrugated core are determined. The comparison of the analytical and FEM results is shown.

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ABSTRACT: Cohesive zone model to capture the failure behaviour and strength of CFRP skinned cantilever sandwich beam with delamination is carried out and verified through test. The inputs required to represent the interfacial behaviour between the skin and honeycomb core in cohesive zone model are determined by standard tests. Acoustic emission was monitored during the test. Comparison of the load-displacement response obtained shows a good agreement with the experimental result. Both the test and analysis show a buckling induced delamination resulting earlier buckling failure of the specimen. Prediction of failure load based on nonlinear buckling analysis with CZM and without CZM approach shows a deviation of 6% and 9% respectively with the test. The present study reveals that coupled buckling induced delamination failure of bonded sandwich structures can be accurately predicted by cohesive zone model which incorporates debond growth and buckling simultaneously. Parametric study reveals that the interfacial strength plays a key role in failure load of adhesively bonded sandwich structures in comparison to the delamination fracture toughness.

References listed at the end of the paper:

ABSTRACT: The subject of numerical research is a seven-layer cylindrical shell subjected uniformly distributed external pressure. The shell is thin-walled sandwich structure composed of main corrugated core (made of a thin metal sheet) and two three-layer faces. The cores of the faces are porous and made of isotropic metal foam. The corrugation of the main core is along longitudinal axis of the shell. The shell is simply supported at its all outer edges. Numerical FEM model of the shell is elaborated. Critical pressure for the family of these shells are calculated. Furthermore, developed a model of an equivalent single-layer shell wherein diameter, and weight are the same as the seven-layer shell. It has been shown several times higher resistance to buckling of a seven-layer shell compared to the single-layer shell.

References listed at the end of the paper:


ABSTRACT: We manufactured sandwich-walled cylindrical shells with aluminum pyramidal truss core of constant curvature employing an interlocking fabrication technique for the metallic core. The skins were made of carbon-fiber reinforced composites and co-cured with the metallic truss core. Thereafter, we carried out axial compression tests on some representative samples to investigate the failure modes of these structures and compared with an analytical failure map developed to account for Euler buckling, shell buckling, local buckling between reinforcements and face-crushing. The experimental data closely matched the analytically predicted behavior of the cylinders. In particular, we found that local buckling and face crushing modes can exist together and are the most important modes of failure of the fabricated structure.
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(2) Center for Scientific Computing, P.O. Box 405, FIN-02101 Espoo, Finland  
ABSTRACT: A plate model for analysis and design of laminated composite structures subjected to large deflections is considered. The model is based on a facet approximation of the midsurface and Reissner–Mindlin–Von Kármán type plate equations. The potential energy functional where the linearized strain tensor has been replaced by nonlinear functions, i.e., the Von Kármán model for large deformation is formulated. The nonlinear equations are solved iteratively by Riks’ method with Crisfield’s elliptical constraint for arc length. The linearized equations are discretized by the finite element method. Load–displacement behavior of the structure as well as failure prediction and identification of critical areas of the FE-model are illustrated with a numerical example.

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Mikko Lyly (CSC - Scientific Computing Ltd., P.O. Box 405, FI-02101 Espoo, Finland)  
ABSTRACT: In this paper post-buckling analysis of carbon fibre reinforced plastic cylindrical shells under axial compression is considered. Reissner–Mindlin–Von Kármán type shell facet model is used in the computations. The effect of geometric imperfection shape and amplitude on nonlinear analysis results is discussed. Numerical–experimental correlation is performed using the results of experimental buckling tests found in the literature. Results show that bringing the diamond shape geometric imperfection in the model significantly improves the correlation and gives good accuracy in simulating cylindrical shell post-buckling behaviour.

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ABSTRACT: Design of thin-walled cylindrical shells fabricated from composite materials leads to the requirement of validated simulation procedures for the buckling simulation of realistic, geometrically imperfect shells. In this work, the simulation is performed with a geometrically nonlinear analysis using Reissner-Mindlin-Von Kármán type shell facet model. A diamond shaped geometric imperfection pattern is applied in the computational model. Based on the simulation, limits of buckling loads are estimated for the cylindrical CFRP shells and compared to the test results from the literature.
References listed at the end of the paper:


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ABSTRACT: Postbuckling behaviour of laminated composite structures using Reissner-Mindlin-Von Kármán type plate model is considered. The potential energy functional where the linearized strain tensor has been replaced by nonlinear Von Kármán model for large deformation is formulated. The stabilized MITC-technique is used to discretize the problem by finite elements. Load-displacement behaviour of the structure as well as the failure prediction and the identification of the critical areas of the model are illustrated with numerical examples.

References listed at the end of the paper:


ABSTRACT: In this paper, the static buckling of especially orthotropic stringer-stiffened composite cylindrical shells subjected to combined axial compression and external pressure is investigated, based on geometrical nonlinear analysis with considering pre-buckling deformations. The kinematic relation of shells is based on the Donnell non-linear theory and First Order Shear Deformation (FOSD) is adopted for both shell and stiffeners. Displacements, rotations and interacting forces are expressed in terms of Fourier series expansions as independent approximate solution functions. Unknown coefficients of shell and stringers are related by satisfying continuity conditions of displacements at their contact areas using Lagrange multipliers. The nonlinear equilibrium equations are obtained using the Ritz method. The effects of sensitivity parameters, e.g., shell lay-ups, different numbers of stringers in the circumference, location of stiffeners (outside vs. inside) and the discrete versus smeared approach on interaction buckling curves are considered. Results indicate remarkable differences between outside and inside stringer-stiffened cylinder buckling loads and also illustrate the fundamental role of shell stacking sequences and stiffened shell geometry on the applicability range of the smeared stiffener approach.


ABSTRACT: Optimum laminate configuration for minimum weight of filament wound laminated conical shells subject to buckling load constraint is investigated. In the case of a laminated conical shell, the thickness and the ply orientation (the design variables) are functions of the shell coordinates, influencing both the buckling load
and its weight. These effects complicate the optimization problem considerably. The first level of complexity is attributed to the correlation between the volume and the buckling load and their dependence on the fiber configuration. The second level of complexity is associated with the high computational cost involved in calculation of the buckling load. Thus, the main objective of this study is to solve the optimization problem as well as to reduce the computational cost associated with it. Based on the characteristic buckling behavior of laminated conical shells, the usual penalty function method is used.


ABSTRACT: In this paper a new technique was proposed for the repair of defected metal columns. The finite element method was chosen to find out the adequacy of the proposed method, regarding, the load carrying capacity of two types of thin walled cylindrical columns with L=D = 10 and 20 along with circumferential and longitudinal cracks. The study considers the non linearity behavior in both material as well as geometrical characteristics. Various configurations of the composite patches made from carbon-epoxy were assumed on the cracked region and the influence of a patch on the load carrying capacity of the columns was examined. The obtained results indicate that composite material can not only compensate the effect of damage on column buckling load, but also increase buckling strength to a level even greater than in an intact one.

References listed at the end of the paper:


ABSTRACT: Although, for homogeneous columns, the differences between Engesser’s and Haringx’s formulas for shear buckling have been explained in 1971 by the dependence of shear modulus on the axial stress, for soft-core sandwich columns the choice of the correct formula has baffled engineers for half a century. Recently, Bazˇant explained this difference by a variational analysis which showed that an agreement is achieved if the shear modulus of the light core is considered to depend on the compressive stress in the skins even when small-strain elasticity applies. To clarify this paradoxical dependence, first the variational framework is briefly reviewed. Subsequently, the mathematical results from Bazˇant’s recent study are physically reinterpreted, with the conclusion that only the Engesser-type theory (rather than Haringx-type theory) corresponds to constant shear moduli as obtained, for example, by the torsional test of a tube made from the foam. This is a rather fundamental point for applications because the discrepancy between these two theories can be very large in the case of short columns with thin skins. The implications for standard finite element programs are then explored by computing the critical loads of several sandwich columns with different material and geometric properties. The finite element computations show agreement with the Engesser-type formula predictions, while the Haringx-type prediction can be obtained with the finite element program somewhat artificially—by updating the core modulus as a function of the axial stress in the skins.

References listed at the end of the paper:
Juan C. Virella Crespo, Luis A. Godoy, and Luis E. Suarez (University of Puerto Rico at Mayaguez, Department of Civil Engineering and Surveying), “Buckling and Retrofit of Steel Tanks Subject to Wind and Earthquake Loadings”, talk given in 2002. Some nice photographs of buckled tanks. This citation consists of vu foils (like a PowerPoint presentation). No abstract nor references are given.

ABSTRACT: This paper investigates torsional buckling of an individual multi-walled carbon nanotubes. The multiple shell model is adopted and the effect of van der Waals forces between adjacent nanotubes is taken into account. According to the ratio of radius-to-thickness, multi-walled carbon nanotubes discussed here are classified into three cases: thin, thick, and nearly solid. The critical shear stress and the torsional buckling mode are calculated for various radius-to-thickness ratios. Results carried out show that the buckling mode (m, n) corresponding the critical shear stress is sole, which is obviously different from the axially compressed buckling of an individual multi-walled carbon nanotubes. The investigation on torsional buckling of multi-walled carbon nanotubes in this paper may be used as a useful reference for the designs of nano-oscillators, nano-drive devices and actuators in which multi-walled carbon nanotubes act as basic elements.

ABSTRACT: This paper reports the results of an investigation on combined torsional buckling of an individual multi-walled carbon nanotube (MWNT) under combined torque and axial loading. Here, a multiple shell model is adopted and the effect of van der Waals forces between two adjacent tubes is taken into account. According to the ratio of radius to thickness, MWNTs discussed in this paper are classified into three types: thin, thick and nearly solid. The critical shear stress and the combined buckling mode are calculated for three types of MWNTs under combined torque and axial loading. Results carried out show that the buckling mode (m, n) corresponding to the critical shear stress is unique, which is obviously different from the purely axial compression buckling of an individual MWNT. Numerical results also show that the critical shear stresses and the corresponding buckling modes of MWNTs under combined torque and axial loading are dependent on the axial loading form and the types of MWNTs. The new features and meaningful numerical results in the present work on combined buckling of MWNTs under combined torque and axial loading may be used as a useful reference for the designs of nano-drive devices and rotational actuators in which MWNTs act as basic elements.

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ABSTRACT: This paper describes an investigation into elastic buckling of an embedded multi-walled carbon nanotube under combined torsion and axial loading, which takes account of the radial constraint from the surrounding elastic medium and van der Waals force between two adjacent tube walls. Depending on the ratio of radius to thickness, the multi-walled carbon nanotubes discussed here are classified as thin, thick, and nearly solid. Critical buckling load with the corresponding mode is obtained for multi-walled carbon nanotubes under combined torsion and axial loading, with various values of the radius to thickness ratio and surrounded with different elastic media. The study indicates that the buckling mode \((m, n)\) of an embedded multi-walled carbon nanotube under combined torsion and axial loading is unique and it is different from that with axial compression only. New features for the buckling of an embedded multi-walled carbon nanotube under combined torsion and axial loading and the meaningful numerical results are useful in the design of nanodrive device, nanotorsional oscillator and rotational actuators, where multi-walled carbon nanotubes act as basic elements.


ABSTRACT: This paper investigates the bending stability of a multi-wall carbon nanotube (MWNT) embedded in an elastic medium, based on a multiple shell model. The effects of the surrounding elastic medium and the van der Waals forces between two adjacent tubes are taken into account. The critical bending moment and the corresponding buckling mode for three types of MWNTs with different layer numbers and ratios of radius to thickness are calculated. Results obtained show that the bending buckling mode corresponding to the critical bending moment is unique, which is obviously different from the purely axial compression buckling of an individual MWNT. On the other hand, a simplified method is applied to calculate the bending stability of MWNTs with larger layers, embedded in an elastic medium, by substitution of a multiple shell with fewer layers. The new features of the bending stability of MWNTs embedded in an elastic medium and some meaningful results in this paper are helpful for the application and the design of nanostructures in which MWNTs act as basic elements.


ABSTRACT: This paper investigates torsional buckling of a multi-wall carbon nanotube embedded in an elastic medium. The effects of surrounding elastic medium and van der Waals forces from adjacent nanotubes are taken into account. Using continuum mechanics, an elastic laminated shell model is presented to study the torsional buckling of a multi-wall carbon nanotube embedded in an elastic medium. A laminated cylinder composed of a multi-wall carbon nanotube and a surrounding elastic medium is used to describe the effect of elastic medium on the multi-wall carbon nanotubes. According to the ratio of radius-to-thickness, multi-wall carbon nanotubes discussed here are classified into three cases: thin, thick, and nearly solid. The critical shear stress and the torsional buckling mode are calculated for various radius-to-thickness ratios and elastic medium
effects. Results carried out show that the buckling mode \((m,n)\) corresponding the critical shear stress is sole, which is obviously different from the axially compressed buckling of multi-wall carbon nanotubes. The investigation on torsional buckling of multi-wall carbon nanotubes embedded in an elastic medium in this paper may be used as a useful reference for the designs of nano-oscillators and actuators in which multi-wall carbon nanotubes act as torsional springs.


ABSTRACT: The torsional buckling of an individual multi-walled carbon nanotube under two different loading conditions is studied in this article. The multiple shell model is adopted and the effects of van der Waals forces between adjacent nanotubes are taken into account. An examination with an individual double-walled carbon nanotube shows that the effect of the change of interlayer spacing on the torsional buckling force can be neglected if only the innermost radius is larger than a certain value. Under this condition, single buckling equations are derived and explicit formulas for the critical torsional loads in terms of the buckling modes are obtained. It is found that the critical torsional load of a multi-walled carbon nanotube with torque exerted on the outermost tube is higher than that of the same multi-walled carbon nanotubes under the torques being proportionally applied to each individual layer of the multi-walled carbon nanotubes. For thin multi-walled carbon nanotubes with large radii, the critical shear force (per unit length) of the multi-walled carbon nanotubes uniformly twisted along the cross section does not increase as its layer number (thickness) increases, which is due to the interlayer slips between adjacent nanotubes.


ABSTRACT: Individual multiwalled carbon nanotubes with a range of aspect ratios are subjected to cyclic axial compression to large strains using atomic force microscopy. Distinct elastic buckling and postbuckling phenomena are observed reproducibly and are ascribed to Euler, asymmetric shell buckling (i.e., kinking), and symmetric shell buckling. These show agreement with continuum theories that range from approximate to remarkable. Shell buckling yields reproducible incremental negative stiffness in the initial postbuckled regime. References listed at the end of the paper:

ABSTRACT: Beams made from thin walled elements, while very efficient in terms of the structural strength and stiffness to weight ratios, can be susceptible to highly complex instability phenomena. A nonlinear analytical formulation based on variational principles for the ubiquitous I beam with thin flanges under uniformly bending is presented. The resulting system of differential and integral equations are solved using numerical continuation techniques such that the set of bifurcation points, and the consequent buckling ranges can be portrayed. The interaction between global lateral-torsional buckling of the beam and local buckling of the flange plate is found to oblige the buckling deformation to localize initially at the beam midspan with subsequent cellular buckling (snaking) being predicted. 

References listed at the end of the paper:

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ABSTRACT: An analytical pilot model for interactive buckling in sandwich struts with cores made from a functionally graded material based on total potential energy principles is presented. Using a Timoshenko beam
approach, a system of nonlinear differential and integral equations is derived that predicts critical and secondary instabilities. These are validated against numerical simulations performed within the commercial finite-element package *Abaqus*. Good agreement is found, and this offers encouragement for more elaborate models to be devised that can account for face-core delamination—a feature where functionally graded materials are known to offer distinct advantages.


**ABSTRACT:** An analytical model based on variational principles for a thin-walled stiffened plate subjected to axial compression is presented. A system of nonlinear differential and integral equations is derived and solved using numerical continuation. The results show that the system is susceptible to highly unstable local–global mode interaction after an initial instability is triggered. Moreover, snap-backs in the response showing sequential destabilization and restabilization, known as cellular buckling or snaking, arise. The analytical model is compared to static finite element models for joint conditions between the stiffener and the main plate that have significant rotational restraint. However, it is known from previous studies that the behaviour, where the same joint is insignificantly restrained rotationally, is captured better by an analytical approach than by standard finite element methods; the latter being unable to capture cellular buckling behaviour even though the phenomenon is clearly observed in laboratory experiments.

**References listed at the end of the paper:**


ABSTRACT: Five aluminium blade stiffened panels of three different geometries were tested in compression in a displacement controlled loading apparatus. Panel designs were achieved using VICONOPT, a fast-running optimization package based on linear eigenvalue buckling theory, and include two different design philosophies. The panels were loaded beyond initial buckling to collapse, and the effects of initial overall imperfections were monitored. In all cases the final failure showed evidence of significant interaction between buckling modes. The tests draw particular attention to a violently unstable and unpredictable form of failure, involving a combination of overall and stiffener buckling, which can occur even when initial buckling in the skin has the effect of pushing the panel in the opposite sense.


ABSTRACT: Five aluminium blade stiffened panels of three different geometries were tested in compression in a displacement controlled loading apparatus. Panel designs were achieved using VICONOPT, a fast-running optimization package based on linear eigenvalue buckling theory, and embrace two different design philosophies. The panels were loaded beyond initial buckling to collapse, and the effects of initial overall imperfections were monitored. In all cases the final failure showed evidence of significant interaction between buckling modes. The tests draw particular attention to a violently unstable and unpredictable form of failure, involving a combination of overall and stiffener buckling, which can occur even when initial buckling in the skin has the effect of pushing the panel in the opposite sense.

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ABSTRACT: We investigate the cross-sectional buckling of multi-concentric tubular nanomaterials, which are called multiwalled carbon nanotubes (MWNTs), using an analysis based on thin-shell theory. MWNTs under hydrostatic pressure experience radial buckling. As a result of this, different buckling modes are obtained depending on the inter-tube separation d as well as the number of constituent tubes N and the innermost tube diameter. All of the buckling modes are classified into two deformation phases. In the first phase, which corresponds to an elliptic deformation, the radial stiffness increases rapidly with increasing N. In contrast, the second phase yields wavy, corrugated structures along the circumference for which the radial stiffness declines with increasing N. The hard-to-soft phase transition in radial buckling is a direct consequence of the core-shell structure of MWNTs. Special attention is devoted to how the variation in d affects the critical tube number Nc,
which separates the two deformation phases observed in N -walled nanotubes, i.e., the elliptic phase for N < Nc and the corrugated phase for N > Nc. We demonstrate that a larger d tends to result in a smaller Nc, which is attributed to the primary role of the interatomic forces between concentric tubes in the hard-to-soft transition during the radial buckling of MWNTs.

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Irene Arias and Marino Arroyo (Dept. Applied Mathematics 3, LaCaN, Universitat Politècnica de Catalunya (UPC), Barcelona 08034, Spain), “Size–Dependent Nonlinear Elastic Scaling of Multiwalled Carbon Nanotubes”,
ABSTRACT: We characterize through large-scale simulations the nonlinear elastic response of multiwalled carbon nanotubes (MWCNTs) in torsion and bending. We identify a unified law consisting of two distinct power law regimes in the energy-deformation relation. This law encapsulates the complex mechanics of rippling and is described in terms of elastic constants, a critical length scale, and an anharmonic energy-deformation exponent. The mechanical response of MWCNTs is found to be strongly size dependent, in that the critical strain beyond which they behave nonlinearly scales as the inverse of their diameter. These predictions are consistent with available experimental observations.

References listed at the end of the paper:
Daniel Millan, “Point-set manifold processing for computational mechanics: Thin shells, reduced order modeling, cell motility and molecular conformations”, Ph.D. Dissertation, Departament de Matemàtica Aplicada III (MA3), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, July 2012

ABSTRACT: In many applications, one would like to perform calculations on smooth manifolds of low-dimension $d$ embedded in a high-dimensional space of dimension $D$. Often, a continuous description of such manifold is not known, and instead it is sampled by a set of scattered points in high dimensions. This poses a serious challenge. In this thesis, we approximate the point-set manifold as an overlapping set of smooth parametric descriptions, whose geometric structure is revealed by statistical learning methods, and then parametrized by meshfree methods. This approach avoids any global parameterization, and hence is applicable to manifolds of any genus and complex geometry. It combines four ingredients: (1) partitioning of the point set into subregions of trivial topology, (2) the automatic detection of the geometric structure of the manifold by nonlinear dimensionality reduction techniques, (3) the local parameterization of the manifold using smooth meshfree (here local maximum-entropy) approximants, and (4) patching together the local representations by means of a partition of unity. We show the generality, flexibility, and accuracy of the method in four different problems. First, we exercise it in the context of Kirchhoff-Love thin shells, ($d = 2, D = 3$). We test our methodology against classical linear and non linear benchmarks in thin-shell analysis, and highlight its ability to handle point-set surfaces of complex topology and geometry. We then tackle problems of much higher dimensionality. We perform reduced order modeling in the context of finite deformation elastodynamics, considering a nonlinear reduced configuration space, in contrast with classical linear approaches based on Principal Component Analysis ($d = 2, D = 10, 000$’s). We further quantitatively unveil the geometric structure of the motility strategy of a family of micro-organisms called Euglenids from experimental videos ($d = 1, D \approx 30,000$’s). Finally, in the context of enhanced sampling in molecular dynamics, we automatically construct collective variables, which characterize molecular conformations ($d = 1 \ldots 6, D \approx 30$ to $1,000$’s).

References listed at the end of the paper:


Lorenz, E. (1956, December). Empirical orthogonal functions and statistical weather prediction. Statistical Forecasting Project, Scientific Report 1, MIT, Department of Meteorology, Cambridge, MA, USA.
ABSTRACT: A finite element formulation is presented for modelling geometrically nonlinear thin shells which exploits standard Lagrange finite element basis functions without introducing rotation degrees of freedom. The classical regularity requirements associated with thin bending problems are circumvented by introducing special integrals over inter-element edges. The use of Lagrange finite element basis functions and the absence of rotation degrees of freedom make the formulation relatively simple, and discontinuities in material properties and non-smooth shell geometry can be incorporated trivially. The variational problem can be exactly linearised, leading to an efficient Newton–Raphson solution process. The performance of the approach is demonstrated via a range of numerical benchmarks for both geometrically linear and nonlinear problems. It is shown that cubic elements perform particularly well.

SUMMARY: Calculations on general point-set surfaces are attractive because of their flexibility and simplicity in the preprocessing but present important challenges. The absence of a mesh makes it nontrivial to decide if two neighboring points in the three-dimensional embedding are nearby or rather far apart on the manifold. Furthermore, the topology of surfaces is generally not that of an open two-dimensional set, ruling out global parametrizations. We propose a general and simple numerical method analogous to the mathematical theory of manifolds, in which the point-set surface is described by a set of overlapping charts forming a complete atlas. We proceed in four steps: (1) partitioning of the node set into subregions of trivial topology; (2) automatic detection of the geometric structure of the surface patches by nonlinear dimensionality reduction methods; (3) parametrization of the surface using smooth meshfree (here maximum-entropy) approximants; and (4) gluing together the patch representations by means of a partition of unity. Each patch may be viewed as a meshfree macro-element. We exemplify the generality, flexibility, and accuracy of the proposed approach by numerically approximating the geometrically nonlinear Kirchhoff–Love theory of thin-shells. We analyze standard benchmark tests as well as point-set surfaces of complex geometry and topology.

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DTIC Accession Number: ADA466718, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA466718

ABSTRACT: The study of novel materials produces many challenges in the areas of synthesis, modeling and characterization. For the latter, one would like to be able to determine mechanical, electrical and dynamical properties, and correlate them with structure. In the following chapter, we describe work performed at the University of North Carolina-Chapel Hill (UNC) in the development of microscopy instrument systems, including a natural interface for scanned probe microscopy we call the nanoManipulator. We describe the principle design features of the instrument system including the visual display of data, the haptic (force-feedback) control and display capabilities. Second, we describe the combination of microscopy and manipulation in a joint Scanning Electron Microscopy/Scanning Probe Microscopy system. These systems have been used for studies of nanotube mechanical dynamical and electrical properties and for the study of biological macromolecular structures such as viruses, fibers (pili, fibrin, microtubules, etc.) and molecules (DNA). We describe examples of these studies drawn from our work on nanotubes and viruses.


ABSTRACT: A model, based on the theory of nonlocal continuum mechanics, on the column buckling of multiwalled carbon nanotubes is presented. The present analysis considers that each of the nested concentric tubes is an individual column and that the deflection of all the columns is coupled together through the van der Waals interactions between adjacent tubes. Based on this description, a condition is derived in terms of the parameters that describe the van der Waals forces and the small internal length scale effects. In particular, an explicit expression is derived for the critical axial strain of a double walled carbon nanotube which clearly
demonstrates that small scale effects contribute significantly to the mechanical behavior of multiwalled carbon nanotubes and cannot be ignored.


ABSTRACT: An elastic model is presented for column buckling of a multiwalled carbon nanotube embedded within an elastic medium. The emphasis is placed on the role of interlayer radial displacements between adjacent nanotubes. In contrast to an existing model which treats the entire multiwalled nanotube as a single column, the present model treats each of the nested tubes as an individual column interacting with adjacent nanotubes through the intertube van der Waals forces. Based on this model, a condition is derived in terms of the parameters describing the van der Waals interaction, under which the effect of the noncoincidence of all deflected column axes is so small that it does not virtually affect the critical axial strain. In particular, this condition is met for carbon multiwalled nanotubes provided that the half-wavelength of the buckling mode is much larger than the outermost diameter. In this case, the critical axial strain can be predicted correctly by the existing single-column model. On the other hand, the existing model could overestimate the critical axial strain when the half-wavelength of the buckling mode is close to or smaller than the outermost radius.


ABSTRACT: A multiple-shell model is presented for infinitesimal axially compressed buckling of a multiwalled carbon nanotube embedded within an elastic matrix. In contrast to an existing single-shell model which treats the entire multiwalled nanotube as a singlelayer elastic shell, the present model assumes that each of the nested concentric tubes is an individual elastic shell and the deflections of all shells are coupled through the van der Waals interaction between adjacent nanotubes. By examining a doublewalled carbon nanotube, it is found that the change in interlayer spacing has a negligible effect on the axial buckling strain provided that the innermost radius is at least a few nanometers. Under this condition, a single equation is derived which determines the deflection of the multiwalled carbon nanotube, and it is shown that infinitesimal axial buckling of a N-walled carbon nanotubes is equivalent to that of a single layer elastic shell whose bending stiffness is approximately N times the effective bending stiffness of a single walled carbon nanotube. As a result, the axial buckling strain of a N-walled carbon nanotube is about 5 N times lower than that predicted by the existing single-shell model. The degraded axial buckling strain is attributed to the interlayer slips between adjacent nanotubes, which represents an essential feature of mechanical behavior of multiwalled carbon nanotubes.


ABSTRACT: Motivated by structural heterogeneity and thickness nonuniformity of protein shells (such as microtubules and viral capsids), a refined elastic shell model is suggested to study the effect of transverse shear and effective bending thickness on buckling of an empty spherical viral shell under external pressure. A key feature of the model is that the transverse shear modulus of viral shells is allowed to be much lower than the in-plane shear modulus, in accordance with the weak resistance of two-dimensional protein assemblies to transverse shear. The results show that the transverse shear-induced critical pressure drop could be as big as 50%–70% for smaller-radius viral shells when the transverse shear modulus is about one order of magnitude smaller than the in-plane shear
modulus, although the effect of transverse shear is negligible if the transverse shear modulus is equal to or larger than the in-plane shear modulus. These results suggest that the classical homogeneous shell model widely used in the literature would overestimate the strength of viral shells against buckling under external pressure. The refined model suggested here could extend the applicability of homogeneous elastic shell models from larger-radius viral shells to small-radius ones.


ABSTRACT: This work complements recent developments concerning the buckling of beams lying on a nonlinear (non-convex) elastic foundation, and also reports on some investigations on the role of material nonlinearity. Two structural models are studied using a simple elasto-plastic constitutive relationship, and buckling problems are formulated as reversible fourth-order differential equations. It is demonstrated that modulated responses are possible under certain circumstances. Some numerical simulations are presented supporting the analytical findings.


ABSTRACT: A thin annular plate is subjected to a uniform tensile field at its inner edge which leads to compressive circumferential stresses. When the intensity of the applied field is strong enough, elastic buckling occurs circumferentially, leading to a wrinkling pattern. Using a linear non-homogeneous pre-bifurcation state, the linearised eigenvalue problem describing this instability is cast as a fourth-order linear differential equation with variable coefficients. This problem is investigated numerically and it is shown that the simple application of the Galerkin technique reported in the literature leads to gross errors in the corresponding approximations. Several novel mathematical features of the eigenvalue problem are included as well.

References listed at the end of the paper:


ABSTRACT:

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ABSTRACT: This work addresses a generalization of Dean's classical problem, which sought to explain how an annular thin elastic plate buckles under uniform shearing forces applied around its edges. We adapt the original setting by assuming that the outer edge is radially stretched while the inner rim undergoes in-plane rotation through some small angle. Boundary-layer methods are used to investigate analytically the deformation pattern which is set up and localized around the inner hole when this angle reaches a well-defined critical wrinkling value. Linear stability theory enables us to identify both the critical load and the preferred number of wrinkles appearing in the deformed configuration. Our asymptotic results are compared with a number of direct numerical simulations.
Reference cited at the end of the paper:
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Timoshenko S, 1921 über die Stabilität versteifter Platten”. Der Eisenbau. 12, 147-163.

Ciprian D. Coman (University of Glasgow, Department of Mathematics, University Gardens, Glasgow, G12 8QW, United Kingdom), “Remarks on elastic buckling for sectorial plates”, International Journal of Engineering Science
ABSTRACT: This work investigates the edge-buckling experienced by a sectorial plate in a uniform bi-axial state of stress and subject to in-plane bending. Since the governing differential equations have variable coefficients, it turns out that the neutrally stable eigenfunctions can be qualitatively quite different as the mode number varies. Our interactive boundary-layer analysis succeeds in capturing the most dangerous mode associated with the global minimum of the marginal stability curve, while a complementary WKB route supplies an explanation for the morphological transitions experienced by the eigenmodes. The validity of our analysis is confirmed by direct numerical simulations of the full fourth-order buckling equation, which are in excellent agreement with the theoretical considerations.

ABSTRACT: The problem of inflation for a thick-walled compressible, isotropic, hyperelastic, spherical shell is considered. First we give a new class of strain–energy functions for which analytic solutions to the spherically symmetric problem can be obtained. These solutions are compared with the existing solutions for harmonic materials. Secondly we obtain numerical results for the aspherical bifurcation problem. A number of different strain–energy functions are considered and all show the same qualitative features as those demonstrated by incompressible materials. We show that a decrease in the bulk modulus of the material has a stabilizing effect, in that critical values of the deformation are increased.

SUMMARY: We investigate a pre-stressed annular thin film subjected to a uniform displacement field along its inner boundary. This loading scenario leads to a variable stress distribution characterized by an orthoradial component that may change sign along a concentric circle within the annular domain. When the intensity of the applied field is strong enough, elastic buckling occurs circumferentially, leading to a localized wrinkling pattern near the inner edge. Using a linear non-homogeneous pre-bifurcation state, the eigenvalue problem describing this instability is cast as a singularly-perturbed fourth-order linear differential equation with variable coefficients. The dependence of the lowest eigenvalue on various non-dimensional quantities is numerically investigated using the compound matrix method. These results are complemented by a WKB analysis which suggests that the qualitative and quantitative features of the full model can be described by a simplified second-order eigenvalue problem which takes into account the finite stiffness of the system.

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ABSTRACT: Singular perturbation techniques are used to investigate the linear eigenvalue problem that describes the partial wrinkling of a pre-stressed rectangular thin elastic plate under in-plane bending. The dependence of the critical load and the wavelength of the localised oscillatory pattern on the non-dimensional bending rigidity of the plate is captured with a higher-order boundary-layer analysis. Comparisons with direct
numerical simulations of the original eigenproblem confirm the accuracy and versatility of the asymptotic technique explored in this work.

References listed at the end of the paper:

Xiang Liu and Ciprian Coman (University of Glasgow, Department of Mathematics, University Gardens, Glasgow, G12 8QW, United Kingdom), “The localised wrinkling of a stretched bi-annular thin plate”, World Academy of Science, Engineering and Technology, Vol. 6, No. 11, November 2012, waset.org/publications/12322

ABSTRACT: The wrinkling of a thin elastic bi-annular plate with piecewise-constant mechanical properties, subjected to radial stretching, is considered. The critical wrinkling stretching loading and the corresponding wrinkling patterns are extensively investigated, together with the roles played by both the geometrical and mechanical parameters.

References listed at the end of the paper:

ABSTRACT: This work complements the first author’s recent asymptotic investigations on a class of boundary-eigenvalue problems for tensile buckling of thin elastic plates. In particular, it is shown here that the approximations for the critical buckling load can be improved by using a modified energy method that relies directly on the asymptotic results derived previously. We also explore a number of additional mathematical features that have an intrinsic interest in the context of multi-parameter eigenvalue problems.

References listed at the end of the paper:

ABSTRACT: Analogy between the post-buckling equilibrium form of complete spherical shells with the mandrel inside and the form of living spherical honeycomb structures is investigated. The primary aim of this paper is to describe the typical topological-geometrical properties of the multi-dimple buckling pattern of a complete spherical shell on the basis of this analogy. It was found that, although the sphere itself is the most symmetrical form, the buckling pattern on it (consisting of pentagons, hexagons and heptagons) is asymmetric.

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ABSTRACT: We show that the icosahedral packings of protein capsomeres proposed by Caspar and Klug for spherical viruses become unstable to facetting for sufficiently large virus size, in analogy with the buckling instability of disclinations in two-dimensional crystals. Our model, based on the nonlinear physics of thin elastic shells, produces excellent one-parameter fits in real space to the full three-dimensional shape of large spherical viruses. The faceted shape depends only on the dimensionless Foppl - von Karman number $y=AY^2/\kappa$, where $Y$ is the two-dimensional Young’s modulus of the protein shell, $\kappa$ is its bending rigidity, and $R$ is the mean virus radius. The shape can be parametrized more quantitatively in terms of a spherical harmonic expansion. We also investigate elastic shell theory for extremely large $y$, $10^3< y <10^8$, and find results applicable to icosahedral shapes of large vesicles studied with freeze fracture and electron microscopy.
References listed at the end of the paper:
package DNA against a large internal force”, Nature 413, 748 (2001).
ABSTRACT: The shape and mechanical properties of viral capsids play an important role in several biological processes during the virus life cycle. In particular, to become infective, many viruses require a maturation stage where the capsid undergoes a buckling transition, from an initial spherical procapsid into a final icosahedral faceted shell. Here we study, using a minimal physical model, how the capsid shape and the buckling transition depend on the triangulation number T and the icosahedral class P of the virus structure. We find that, for small shells, capsids with P = 1 are most likely to produce polyhedral shapes that minimize their energy and accumulated stress, whereas viruses with P = 3 prefer to remain spherical. For big capsids, all shells are more stable adopting an icosahedral shape, in agreement with continuum elastic theory. Moreover, spherical viruses show a buckling transition to polyhedral shells under expansion, in consonance with virus maturation. The resulting icosahedral shell is mechanically stiffer, tolerates larger expansions and withstands higher internal pressures before failing, which could explain why some dsDNA viruses, which rely on the pressurization of their genetic material to facilitate the infection, undergo a buckling transition. We emphasize that the results are general and could also be applied to non-biological systems.

Antonio Siber (Institute of Physics, P.O. Box 304, 10001 Zagreb, Croatia), “Buckling transition in icosahedral shells subjected to volume conservation constraint and pressure: Relations to virus maturation”, Phys. Rev. E 73, 061915 (2006) [10 pages], doi: 10.1103/PhysRevE.73.061915

ABSTRACT: Minimal energy shapes of closed, elastic shells with 12 pentagonal disclinations introduced in otherwise hexagonally coordinated crystalline lattice are studied. The geometry and the total energy of shells are studied as a function of the elastic properties of the material they are made of. Particular emphasis is put on the buckling transition of the shells, that is, a strong preference of the shell shapes to “buckle out” in spatial regions close to the pentagonal disclinations for a certain range of the elastic parameters of the problem. The transition effectively increases the mean square aspherity of shapes, making them look more like an icosahedron rather than a sphere, which is a preferred shape prior to the onset of the transition. The properties of the buckling transition are studied in cases when (i) the total volume enclosed by the elastic shell has to be fixed and when (ii) there is an internal pressure acting on the shell. This may be related to the maturation process in nonenveloped dsDNA viruses, where the insertion of the genetic material in a preformed protein shell (viral coating) may effectively impose the fixed volume and/or pressure constraint. Several scenarios that may explain the experimentally observed feature of mature viruses being more aspherical (facetted) from their immature precursors are discussed, and predictions for the elastic properties of viral coatings are obtained on the basis of the presented studies.

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[6] A notable exception are polyoma and the closely related Simian virus 40 (SV-40) which contain 72 pentamers and no hexamers, see e.g. L. Makowski, Biophys. J. 74, 534 (1998).
ABSTRACT: Recent atomic force microscopy (AFM) nanoindentation experiments measuring mechanical response of the protein shells of viruses have provided a quantitative description of their strength and elasticity. To better understand and interpret these measurements, and to elucidate the underlying mechanisms, this paper adopts a course-grained modeling approach within the framework of three-dimensional nonlinear continuum elasticity. Homogeneous, isotropic, elastic, thick-shell models are proposed for two capsids: the spherical cowpea chlorotic mottle virus (CCMV), and the ellipsocylindrical bacteriophage phi29. As analyzed by the finite-element method, these models enable parametric characterization of the effects of AFM tip geometry, capsid dimensions, and capsid constitutive descriptions. The generally nonlinear force response of capsids to indentation is shown to be insensitive to constitutive particulars, and greatly influenced by geometric and kinematic details. Nonlinear stiffening and softening of the force response is dependent on the AFM tip dimensions and shell thickness. Fits of the models capture the roughly linear behavior observed in experimental measurements and result in estimates of Young’s moduli of approximately 280–360 MPa for CCMV and approximately 4.5 GPa for phi29.


ABSTRACT: A series of recent nanoindentation experiments on the protein shells (capsids) of viruses have established atomic force microscopy (AFM) as a useful framework for probing the mechanics of large protein
assemblies. Specifically these experiments provide an opportunity to study the coupling of the global assembly response to local conformational changes. AFM experiments on cowpea chlorotic mottle virus, known to undergo a pH-controlled swelling conformational change, have revealed a pH-dependent mechanical response. Previous theoretical studies have shown that homogeneous changes in shell geometry can play a significant role in the mechanical response. This article develops a method for accurately capturing the heterogeneous geometry of a viral capsid and explores its effect on mechanical response with a nonlinear continuum elasticity model. Models of both native and swollen cowpea chlorotic mottle virus capsids are generated from x-ray crystal structures, and are used in finite element simulations of AFM indentation along two-, three-, and fivefold icosahedral symmetry orientations. The force response of the swollen capsid model is observed to be softer by roughly a factor of two, significantly more nonlinear, and more orientation-dependent than that of a native capsid with equivalent elastic moduli, demonstrating that capsid geometric heterogeneity can have significant effects on the global structural response.


INTRODUCTION: By “spherical shell”, we mean complete spherical configurations, hemispherical heads (such as pressure vessel heads), and shallow spherical caps. In analyses, a spherical cap may be used to model the behavior of a complete spherical vessel with thickness discontinuities, reinforcements, and penetrations. Although the response of a spherical shell to external pressure has received considerable attention from analysts, the calculation of collapse pressure still presents substantial difficulties in the presence of geometrical discontinuities and manufacturing imperfections. The bulk of the theoretical work carried out so far has had a rather limited effect on the method of engineering design, and therefore much experimental support is still needed. At the same time, the application of spherical geometry to the optimum vessel design has continued to be attractive in many branches of industry dealing with submersibles, satellite probes, storage tanks, pressure domes, diaphragms, and similar systems. This chapter deals with the mechanical response and working formulas for spherical shell design in the elastic and plastic ranges of collapse, which could be used for underground and aboveground applications. The material presented is based on state-of-the-art knowledge in pressure vessel design and analysis.

Shahin Nayyeri Amiri (Dept. of Civil Engineering, Kansas State University), “Elastic and plastic buckling of spherical shells under various loading conditions”, Ph.D dissertation, Dept. of Civil Engineering, Kansas State University, Advisor Hayder A. Rasheed, August 2011, URL: http://hdl.handle.net/2097/10855

ABSTRACT: Spherical shells are widely used in aerospace, mechanical, marine, and other industrial applications. Accordingly, the accurate determination of their behavior becomes more and more important. One of the most important problems in spherical shell behavior is the determination of buckling loads either experimentally or theoretically. Therefore, in this study some elastic and plastic buckling problems associated with spherical shells are investigated. The first part of this research study presents the analytical, numerical, and experimental results of moderately thick and thin hemispherical metal shells into the plastic buckling range illustrating the importance of geometry changes on the buckling load. The hemispherical shell is rigidly supported around the base circumference against horizontal translation and the load is vertically applied by a rigid cylindrical boss (Loading actuator) at the apex. Kinematics stages of initial buckling and subsequent propagation of plastic deformation for a rigid-perfectly plastic shell models are formulated on the basis of Drucker-Shield's limited interaction yield condition. The effect of the radius of the boss used to apply the
loading, on the initial and subsequent collapse load is studied. In the numerical model, the material is assumed to be isotropic and linear elastic perfectly plastic without strain hardening obeying the Tresca or Von Mises yield criterion. Finally, the results of the analytical solution are compared and verified with the numerical results using ABAQUS software and experimental findings. Good agreement is observed between the load-deflection curves obtained using three different fundamental approaches. In the second part, the Southwell’s nondestructive method for columns is analytically extended to spherical shells subjected to uniform external pressure acting radially. Subsequently finite element simulation and experimental work shown that the theory is applicable to spherical shells with an arbitrary axi-symmetrical loading too. The results showed that the technique provides a useful estimate of the elastic buckling load provided care is taken in interpreting the results. The usefulness of the method lies in its generality, simplicity and in the fact that, it is non-destructive. Moreover, it does not make any assumption regarding the number of buckling waves or the exact localization of buckling.

References listed at the end of the dissertation:

Computers and Structures Vol.32, No.1, pp.185


ABSTRACT: Axisymmetric buckling analysis is presented for moderately thick laminated shallow annular spherical cap under transverse load. Buckling under central ring load and uniformly distributed transverse load, applied statically or as a step function load is considered. The central circular opening is either free or plugged by a rigid central mass or reinforced by a rigid ring. Annular spherical caps have been analysed for clamped and simple supports with movable and immovable inplane edge conditions. The governing equations of the Marguerre-type, first order shear deformation shallow shell theory (FSDT), formulated in terms of transverse deflection \( w \), the rotation \( \omega \) of the normal to the midsurface and the stress function \( U \), are solved by the orthogonal point collocation method. Typical numerical results for static and dynamic buckling loads for FSDT are compared with the classical lamination theory and the dependence of the effect of the shear deformation on the thickness parameter for various boundary conditions is investigated.

References listed at the end of the paper:
is assumed to be temperature dependent. Governing partial differential equation of motion is solved analytically by using Laplace transform for time domain and power series for spacial domain. The results in Laplace domain is transferred to time domain by employing the fast inverse Laplace transform (FLIT) method. Accuracy of present approach is assessed by comparing the the numerical results with the results of published work in literature. Furtheremore, the effects of non-local parameter and wall thickness on the dynamic characteristics of the nano-sphere are studied.

References listed at the end of the paper:


ABSTRACT: The nonlinear response of multi-layered composite cylindrical shell panels subjected to thermomechanical loads are studied in this article. The structural model is based on the first order shear deformation theory incorporating geometric nonlinearities. The nonlinear equilibrium paths are traced using the arc-length control algorithm within the framework of finite element method. Hashin’s failure criterion has been adopted to predict the first-ply failure of cylindrical laminates. Both temperature independent and temperature dependent elastic properties are considered in the analysis. Specific numerical results are reported to show the effect of radius-to-span ratio, thickness-to-span ratio, laminate stacking sequence, and boundary condition on stability characteristics of laminated cylindrical shell panels subjected to combined thermal and mechanical transverse loads.

References listed at the end of the paper:


ABSTRACT: Stability characteristics of composite skew plates subjected to in-plane compressive load are investigated here using the shear deformable finite element approach. The influences of high prebuckling stresses at the corner regions of isotropic and composite skew plates on their stability characteristics are emphasized for different load direction, boundary condition and laminate stacking sequence. The non-linear governing equations based on von Kármán's assumptions are solved by Newton–Raphson technique to get the hitherto unreported postbuckling equilibrium paths of composite skew plates loaded between two rigid flat platens. The variation of out-of-plane deformation and end-shortening with compressive in-plane load are examined for simply supported and clamped skew plates made of isotropic, symmetric and unsymmetric laminates. Marguerre's shallow shell theory is employed to study the effect of sinusoidal imperfection on the non-linear behavior of composite skew plates.


ABSTRACT: Stability characteristics of isotropic and composite plates subjected to partial or concentrated compressive edge loads are investigated here using a four-noded shear-flexible quadrilateral high-precision plate-bending element. A complete cubic polynomial shape function is used to interpolate the in-plane displacements for better accuracy in capturing the high-stress zone near the locally distributed edge load. The influences of location and distribution of in-plane edge compression on the buckling load of composite plates are studied. The nonlinear governing equations based on von Kármán's assumptions are solved by Newton–Raphson technique to get the hitherto unreported postbuckling equilibrium paths of partially loaded plates made of isotropic, symmetric, and unsymmetric laminates. Marguerre's shallow-shell theory is employed to study the effect of sinusoidal imperfection on the nonlinear behavior of composite plates under partial in-plane load.


ABSTRACT: This paper first compares the writers’ results of static and dynamic analyses of plates, cylindrical and spherical shells employing four-, eight-, and nine-noded elements with different integration rules with those of earlier investigators and including some of the recent composite theories. Thereafter, the nonlinear transient responses of laminated composite cylindrical and spherical shell panels with cutouts are investigated taking up additional examples that are yet to appear in the published literature. For these, the finite-element model is employed using eight-noded C0 continuity, an isoparametric quadrilateral element considering von Karman large deflection assumptions. In the time integration, the Newmark average acceleration method is used in conjunction with a modified Newton–Raphson iteration scheme. Important conclusions with respect to nonlinear transient responses are summarized for cylindrical and spherical shells with and without cutouts.


ABSTRACT: The nonlinear transient response of composite shells with/without cutouts and initial geometric
imperfection is investigated using the finite element method. The present formulation considers doubly curved shells incorporating von Kármán type nonlinear strains into the first order shear deformation theory. The analysis is carried out using quadratic C0 eight-noded isoparametric element. The governing nonlinear equations are solved by using the Newmark average acceleration method in the time integration in conjunction with modified Newton–Raphson iteration scheme. The validity of the model is demonstrated by comparing the present results with those available in the literature. Parametric studies are carried out varying the radius of curvature to width ratio and amplitude of initial geometric imperfection of laminated composite cylindrical, spherical and hyperbolic paraboloid shells with/without cutouts.

ABSTRACT: The concept of functionally graded (FG) materials was first introduced in 1984 by a group of material scientists in Japan, as ultrahigh temperature resistant materials for aircraft, space vehicles and other engineering applications. FG materials are a class of composites that have a continuous variation of material properties from one surface to another and thus eliminate interface problems found in laminated composites. The gradation in properties of the material reduces thermal stresses, residual stresses and stress concentration factors. The gradual variation results in a very efficient material tailored to suit the needs of the structure and, therefore, designated as a FG material. FG materials are typically manufactured from isotropic components such as metals and ceramics since they are used as thermal barrier structures in environments with severe thermal gradients. FG materials have the advantage of heat and corrosion resistance typical of ceramics and mechanical strength and t...
References: (cannot cut and paste)

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ABSTRACT: A C0 finite element formulation using a higher-order shear deformation theory (HSDT) is developed and used to analyse the buckling behaviour of laminated hypar and conoids. Higher order terms in the Taylor's series expansion are used to represent the higher-order transverse cross-sectional deformation modes. The formulation includes Sanders' approximation for doubly curved shells considering the effect of transverse shear. A realistic parabolic distribution of transverse shear strains through the shell thickness is assumed and the use of shear correction factor is avoided. The accuracy of the formulation is validated by carrying out convergence study and comparing the results with those available in the literature.

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ABSTRACT: Nonlinear transient analysis of functionally graded curved panels is carried out employing a higher-order C0 finite element formulation. The element consists of nine degrees-of-freedom per node with higher-order terms in the Taylor’s series expansion which represents the higher-order transverse cross sectional deformation modes. The formulation includes Sanders’ approximation for doubly curved shells considering the effects of rotary inertia, transverse shear and moderately large rotations in the von Kármán sense. A realistic parabolic distribution of transverse shear strains through the shell thickness is assumed and the use of shear correction factor is avoided. The accuracy of the formulation is validated by comparing the results with those available in the literature. The transient dynamic responses of the functionally graded shell panels are investigated by varying the volume fraction index using a simple power law distribution. Material properties are assumed to be temperature-independent and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. Heat conduction between ceramic and metal constituents is neglected. Effects of different panel geometry parameters, boundary conditions and loadings are studied.

References listed at the end of the paper:
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ABSTRACT: This paper investigates the free vibration and buckling behavior of singly and doubly curved shell panels made of functionally graded materials (FGMs). A higher-order shear deformation theory is used for the analysis of five shell panels, namely, cylindrical (CYL), spherical (SPH), hyperbolic paraboloid (HPR), hypar (HYP), and conoid (CON). The shell panels are subjected to a temperature field and in the case of buckling analysis, the shell panels are also subjected to a uniaxial compressive load. The properties of FGMs are considered to be temperature dependent and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The accuracy of the formulation is validated by comparing the results with those available in the literature. The effects of geometric properties, material composition, and boundary conditions on the free vibration and buckling are studied.

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ABSTRACT: This paper reports the dynamic instability behavior of functionally graded (FG) shells subjected to in-plane periodic load and temperature field using a higher-order shear deformation theory in conjunction with the finite-element approach. Properties of FG materials are assumed to be temperature dependent and graded in the thickness direction according to the power-law distribution in terms of volume fraction of the constituents. Five forms of shells considered in this investigation are singly curved cylindrical, doubly curved spherical, and hyperbolic paraboloid having two principal curvatures, doubly curved hypar having twist
curvature only, and doubly curved conoid having one curvature and twist curvature. The boundaries of dynamic instability regions are obtained using Bolotin’s approach. The structural system is considered to be undamped. The correctness of the formulation is established by comparing the writers’ results with those of problems available in the published literature. Effects of material composition and geometrical parameters are studied on the dynamic instability characteristics of the aforementioned five forms of shells having practical applications in many engineering disciplines.


ABSTRACT: In the present paper the postbuckling response of symmetrically and antisymmetrically laminated composite plates subjected to a combination of uniform temperature distribution through the thickness and in-plane compressive edge loading is presented. The structural model is based on a higher-order shear deformation theory incorporating von Karman nonlinear strain displacement relations. Adopting the Galerkin procedure, the governing nonlinear partial differential equations are converted into a set of nonlinear algebraic equations, which are solved using the Newton–Raphson iterative procedure. The critical buckling temperature is obtained from the solution of the linear eigenvalue problem. Postbuckled equilibrium paths are obtained for symmetrically laminated cross-ply, quasi-isotropic and antisymmetric angle-ply composite plates with and without initial geometric imperfections. Modal participation of each mode in the postbuckling deflection is reported using a multi-term Galerkin procedure.


ABSTRACT: The purpose of this paper is to study the nonlinear forced vibration response of delaminated composite shells in hygrothermal environments. Finite element method using an eight-noded C⁰ continuity, isoparametric quadrilateral element is employed. The theoretical formulations are based on the first-order shear deformation theory and von Kármán type nonlinear kinematics. For modeling the delamination, multipoint constraint algorithm is incorporated in the finite element code. The paper finds that the effect of presence of delaminations on the nonlinear transient response of composite shells is dependent not only on the size, but also on the location of the delaminations and the hygrothermal environments. The present study is limited to cylindrical and spherical shells having rectangular planform containing single delamination. Studies on different shell forms having non-rectangular planforms containing multiple delaminations can be taken up for future research. The value in this paper lies in that nonlinear transient response of delaminated shells in hygrothermal environments is studied for the first time. It will assist researchers of nonlinear dynamic behavior of elastic systems.

ABSTRACT: In the present paper the postbuckling and postbuckled vibrations of symmetrically laminated composite plate subjected to a uniform temperature distribution through the thickness is presented. The structural model is based on a higher-order shear deformation theory incorporating von Kármán nonlinear strain–displacement relations and initial geometric imperfections. Adopting a multi-term Galerkin's approximation, the governing nonlinear partial differential equations are converted into a set of nonlinear algebraic equations in the case of postbuckling analysis and nonlinear ordinary differential equations in the case of free vibration analysis. The critical buckling temperatures are obtained from the solution of the corresponding linear eigenvalue problems. Postbuckled equilibrium paths are traced by solving the nonlinear algebraic equations, via the Newton–Raphson iterative procedure. The free vibration frequencies of a thermally postbuckled plate are reported by solving the eigenvalue problem for different postbuckled deflections.

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ABSTRACT: The postbuckling analysis of symmetric and antisymmetric cross-ply laminated cylindrical shell panels subjected to thermomechanical loading is examined in this paper. The formulation is based on an extension of Reissner’s shallow shell simplifications and accounts for parabolic distribution of transverse shear strains. Adopting a multiterm Galerkin’s method, the governing nonlinear partial differential equations are reduced into a set of nonlinear algebraic equations. The nonlinear equilibrium paths through limit points are traced using the Newton–Raphson method in conjunction with Riks approach. Numerical results are presented for symmetric and antisymmetric cross-ply laminated cylindrical shell panels, that illustrate the influence of mechanical edge loads, lateral distributed load, initial imperfection, and temperature field on the limit loads and snap-through behavior.

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ABSTRACT: The nonlinear static response and vibration behavior of cross-ply laminated cylindrical shell panels subjected to axial compression combined with other secondary loading are examined. The shell theory adopted in the present case is based on a higher-order shallow shell theory, includes geometric imperfection and von Kármán-type geometric nonlinearity. The solutions to the governing nonlinear partial differential equations are sought using the multiterm Galerkin technique. The nonlinear equilibrium paths through limit points and bifurcation points are traced using the Newton–Raphson method coupled with the Riks approach. The free vibration frequencies of post-buckled cylindrical panels about the static equilibrium state are reported by solving the associated linear eigenvalue problem. Results are presented for simply supported cross-ply laminated cylindrical shell panels, which illustrates the influence of initial geometric imperfection, temperature field, lateral pressure loads, and mechanical edge loads on the static response and vibration behavior of the shell panel.

ABSTRACT: The present investigation deals with the nonlinear stability behavior of cross-ply laminated composite circular cylindrical shells subjected to partial and complete edge loading along with uniform external pressure. The shell is modeled using Donnell’s shell theory including the first-order shear deformation theory (FSDT). The analysis uses the simply supported boundary condition (at x=0, \( LN_{xx} = 0 \), \( w = M_{xx} = v = \varphi_0 = 0 \)). The equations governing the nonlinear stability behavior of cylindrical shells are derived in terms of displacements (\( u \), \( v \), \( w \)) and rotations (\( \varphi_x \), \( \varphi_\theta \)). The applied partial edge loading is expressed in terms of Fourier series, and stress distributions within the cylindrical shell are determined by prebuckling analysis. The study uses multiterm Galerkin's method along with the Newton-Raphson method to solve the governing partial differential equations of the shell nonlinear stability. With the help of numerical investigations, the authors present the number of modes required for the postbuckling analysis and the influence of initial geometric imperfections on the equilibrium path in the presence of partial edge loading. They have developed a simple algorithm based on potential theory to locate the exact location of bifurcation and limit points on the equilibrium path using the bisection method.


ABSTRACT: Linear and nonlinear dynamic instability behavior of cylindrical sandwich panels subjected to combined static and dynamic nonuniform in-plane loadings is studied in this article. The core compressibility effects are considered in the model by assuming fourth and fifth order expansions for the transverse and tangential displacement of the core. The exact stress distributions within the panel are determined by panel prebuckling analysis for the applied parabolic and partial edge loadings. Galerkin's method is used to reduce the governing partial differential equations of the shell panel into a set of nonlinear ordinary differential equations. Dropping the nonlinear term, dynamic instability regions are obtained by solving the Mathieu-type differential equation by the method of Fourier series. The characteristics feature of the stable and unstable regions are investigated by linear and nonlinear time history responses and phase plots of the shell panel in those regions using Newmark's time integration. Incremental harmonic balance (IHB) method is used to study the nonlinear frequency amplitude responses of the cylindrical sandwich panels.

Tanish Dey and L.S. Ramachandra (Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India), “Static and dynamic instability analysis of composite cylindrical shell panels subject to partial edge loading”, International Journal of Non-Linear Mechanics, Vol. 64, pp 46-56, September 2014, DOI: 10.1016/j.ijnonlinmec.2014.03.014

ABSTRACT: The postbuckling and dynamic instability behavior of simply supported composite cylindrical shell panels subjected to dynamic partial edge loadings and transverse patch loadings is studied in this paper considering von Kármán type of non-linearity. The stress distribution within the panel due to the applied partial edge loadings is evaluated by panel's membrane analysis. Subsequently using these stress distribution and via Hamilton’s variational principle, the equations governing the instability behavior of shell panel are derived. Neglecting inertia terms, governing equations for the postbuckling analysis of panel are obtained. Galerkin’s method is used in the solution procedure. It is observed from the postbuckling analysis that the cylindrical shell panel subjected to partial edge compression behaves as an imperfect shell panel as the partial edge compression
in the $x$-direction induces tensile stress in the $y$-direction which makes the shell panel to deflect out-of-plane. It is also observed that by suitably adjusting the lamina number and lamina layup, the snap through behavior of shells can be altogether avoided. Dynamic instability regions of simply supported composite shell panels are traced by the method suggested by Bolotin. The linear and non-linear dynamic responses of the shell in stable and unstable regions are studied. This brings out various features of the instability problem such as, existence of beats and its dependence on forcing frequency and initial conditions, and effect of non-linearity on the response. It is found that for certain value of dynamic partial edge loading, the panel exhibits chaotic behavior.

K. I. Romanov, Bauman Moscow State Technical University, 2-ya Baumanskaya 5, Moscow, 107005 Russia, Received February 7, 2005. “Plate and Shell Buckling by the Kármán Scheme under Creep Conditions”, doi: 10.3103/S002565440801010X

ABSTRACT: The problem of stability and buckling of plates under creep conditions has been studied in the fundamental papers [1–4]. In the papers [5, 6], the theory of buckling of rods and plates is developed in the framework of the dominating bending model [7], where the forces in the midplane of the plate were determined independently of the solution of the bending problem. In what follows, we use the Kármán scheme [8] to derive two basic differential equations of the coupled theory of the plane stress state and bending. We solve the problem of buckling of a rectilinear plate for linearly viscous (Newtonian) medium and show that the Kármán scheme gives an essential correction to the solution of the bending problem for initial deflections comparable with the plate thickness.

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ABSTRACT: This paper discusses the structural optimization problem of finding the optimal wall thickness of
an axisymmetric cylindrical shell so as to maximize the buckling load when the volume of material is fixed. An optimality condition is derived and then the method of truncated Fourier series is used to find an optimal design which indicates an 83% increase in buckling load over the classical critical buckling load for the case of uniform thickness.

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ABSTRACT: Eigenvalue buckling of cylindrical shells with various boundary conditions under hydrostatic load is examined, using an energy method. Results are compared to known solutions, where these solutions exist. It is found that, for shells of intermediate length, buckling loads for different end conditions may be determined by applying a simple, scalar multiplier to the pin-ended case. This does not apply to long shells, where the circumferential wave number $n\leq 3$. For $n=2$, the ring equation may be applied to all cases, as the boundary conditions no longer influence the solution. It is seen for the case of a shell with one end pinned and the other end free that the buckling solution collapses to the long shell solution, for geometries of practical interest. The effect of radial elastic restraint at the open end is also examined, as an intermediate case between pinned and free ends. The work has application to the design of suction caissons, where cylinder dimensions are usually in the range of intermediate length shells.

References listed at the end of the paper:

R. Pinna (1), C. M. Martin (2), B. F. Ronalds (1),
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(2) University of Oxford, Oxford, UK

ABSTRACT: Suction caissons are a type of foundation which is penetrated into the seabed using net external water pressure rather than more conventional techniques. The geometry of these foundations is such that, structurally, they fall into the category of shell structures. Due to the type of loading experienced by these foundations, which is predominantly hydrostatic, buckling of the caisson shell during suction installation becomes a consideration. This paper examines the factors influencing the buckling load of the caisson, including the boundary conditions of the shell, geometric imperfections, material plasticity, embedment ratio and the amount of lateral restraint offered by the surrounding soil. Results are obtained from three dimensional finite element analyses. (References not available.)


ABSTRACT: Shell eigen buckling behaviour is investigated for combined axial and lateral pressure loading and with various end conditions. In addition to the more common pinned (P) and clamped (C) end conditions, particular emphasis is placed on shells where one or both of the ends are free (F). The physical behaviour in different geometry ranges is used to develop simple, approximate eigenvalue formulae, which are verified against the predictions of linear shell buckling theory using the method of variations. The different end conditions are treated through multipliers to the well-known pin-ended (P–P) case. It is found that, for practical geometries, P–F shells are very much weaker than C–F shells due to the lack of warping restraint. The results have application to the design of suction caisson foundations for offshore platforms.

R. Pinna and B. F. Ronalds (The University of Western Australia, School of Oil & Gas Engineering, 35 Stirling Hwy, Crawley, Western Australia, 6009, Australia), “Buckling and postbuckling of cylindrical shells with one end pinned and the other end free”, Thin-Walled Structures, Vol. 41, No. 6, June 2003, pp. 507-527, doi:10.1016/S0263-8231(03)00006-5

ABSTRACT: Using finite element analysis, this paper examines the linear bifurcation buckling loads, and nonlinear collapse loads, of cylindrical shells with one end pinned and the other end free, under a variety of axial and pressure load combinations. The pinned end is formulated so as to provide no axial restraint. For the bifurcation analysis, loads are related back to the classical solutions for cylinder buckling loads, to explain the very low values found for this set of boundary conditions. The nonlinear analysis includes both imperfections and material plasticity. In this analysis, it is found that cylindrical shells with pinned-free boundary conditions are notably imperfection insensitive, and for a range of geometries are able to reach collapse loads significantly greater than their bifurcation load. For other geometries, collapse loads very close to the bifurcation load are found. This unusual imperfection insensitivity for a cylindrical shell is explained in terms of the large flexibility engendered by the pinned-free boundary conditions and the oval buckling mode.

Rodney Pinna and Beverley F. Ronalds (School of Oil & Gas Engineering, The University of Western Australia, 35 Stirling Hwy, Crawley 6009, Australia), “Buckling and collapse of cylinders with one end open and one end simply supported with varying axial restraint”, International Journal of Mechanical Sciences, Vol. 46, No. 4, April 2004, pp. 541-559, doi:10.1016/j.ijmecsci.2004.05.002

ABSTRACT: This paper examines the buckling and collapse of cylindrical shells under axial load with one end radially and tangentially fixed, with varying axial fixity, and the other end free. The bifurcation loads are found
for elastic cylinders, while collapse loads are found for both elastic and elastic-perfectly plastic cylinders. The varying axial restraint is applied in the form of linear springs. The eigenvalue buckling loads are calculated with conditions matching those of a classical analysis. Bifurcation loads are shown to be a function of the axial restraint; as the axial restraint is increased, the bifurcation load increases dramatically, until it reaches that of a semi-infinite, open ended cylinder. A non-dimensional form of the axial spring stiffness is proposed, and shown to be applicable across a range of geometries. The collapse load and imperfection sensitivity of cylinders with the boundary conditions examined here is also found to be a function of the axial restraint. Cylinders with low axial restraint are shown to be imperfection insensitive, with collapse loads above, or close to, the bifurcation load. As the amount of axial restraint increases, the collapse behaviour displays a degree of imperfection sensitivity associated with more usual boundary conditions.

References listed at the end of the paper:
ABSTRACT: This paper presents the results of physically and geometrically nonlinear analyses of the load-bearing capacity of slender wind-loaded cylindrical shells. These structures do not, even though their geometry is beam-like, behave as beams. The reason for this behaviour deviating from classic beam theory lies in the non-uniform wind pressure along the circumference, which leads to an ovalization of the cross section. There are two global and one local failure modes. The global failure modes are fundamentally different from those of squat shells with h/r<15. The top-stiffened shell in the geometrical transition range of shell-beam does not present the worst case. Additional ring-stiffeners lead to a loss of load baring capacity. Some conclusions are drawn from nonlinear parameter studies for the design practice.
Fourth Int. Colloquium on Computation of Shell & Spatial Structures, Chania-Crete, Greece


ABSTRACT: Despite of the intensive research effort of the last decades there are considerable gaps of knowledge concerning the imperfection sensitivity of steel shell structures, even with regard to the basic buckling cases. It is explained in the presented paper why the most unfavourable imperfection pattern does not exist for shell structures but only different unfavourable patterns depending on the imperfection amplitude. This amplitude-depending pattern cannot be determined with certainty because of the substantial influence of the material non-linearity and because of the numerous post-buckling paths which cross each other. However, the method of quasi-collapse-affine imperfections allows a reasonable approximation to the most unfavourable imperfection pattern. The basic thoughts of this concept are presented. The application of the concept to slender wind-loaded shells illustrates its capability.


ABSTRACT: A geometrically and materially nonlinear analysis with imperfections included (GMNIA) is currently the most sophisticated and perspective the most accurate method of a numerical buckling strength verification. By this way, equivalent geometric imperfections, which have to cover the influence of all deviations from the nominal data of the resistance parameters, are fundamental. The problem of consistent equivalent geometric imperfections includes the problems of their shape and size. It is recommended to start from the failure modes of the perfect structure in order to get imperfection patterns, which are unfavourable with respect to buckling resistance, relevant referring to manufacture and easy to use. The influence of the imperfection length is not sufficiently attended in the present design codes. It is proposed to use the full wave length of the ideal ring buckling mode as the imperfection length of the equivalent geometric imperfection for the basic buckling case of the axially compressed cylindrical shell. Finally, proposals are made for consistent equivalent geometric imperfection amplitudes of this buckling case.
ABSTRACT: The strong load drop in the post buckling area and the huge number of possible buckling modes at almost the same load level cause a considerable imperfection sensitivity of thin-walled shell structures. Thus, the inevitable deviations from the nominal resistance parameters have to be explicitly included in the numerical simulation. Because of the big dimensions of the structures of civil engineering and plant engineering, experiments at original structures are very expensive and are only exceptionally maintainable. Data from buckling experiments are available only for some basic buckling cases of fundamental shell geometries. However in the most cases, only the buckling loads but not the imperfections are documented well.

In order to assess the carrying capacity of buckling cases which are not yet sufficiently investigated, the new shell buckling code EN 1993-1-6:2007 allows numerical buckling strength verifications. Bearing in mind the complexity, diversity and sensitivity of shell buckling phenomena, it is not astonishing, that a number of application problems have not been solved yet [4]. Existing regulation deficiencies may be explored best at the basic buckling cases because of the available comparative experimental data. In the presentation, experiences and research needs are presented which result from performing geometrically and materially nonlinear calculations with imperfections included for the basic buckling case of a circular cylindrical shell subject to hoop compression. The mentioned Eurocode advises the use of equivalent geometric imperfections in order to cover the effect of different accidental imperfections in a safe manner.

In the first part of the presentation, the challenge of equivalent geometric imperfections is discussed. This problem divides up into the questions about the imperfection pattern and the imperfection size. Imperfection modes which have the most detrimental effect should be used according to the Eurocode. It is reasoned in the presentation, that eigenmode-affine imperfections are not appropriate for the buckling case hoop compression. Moreover, the most unfavourable imperfection pattern does not exist for shell structures but only different unfavourable patterns depending on the imperfection amplitude [3]. This amplitude-depending pattern can not be determined with certainty because of the substantial influence of the material non-linearity and because of the numerous postbuckling paths which cross each other. However, the method of quasi-collapse-affine imperfections allows a reasonable approximation to the most unfavourable imperfection pattern [3]. Single longitudinal predeformations resulting from this concept are well suited as equivalent imperfections. Regarding the imperfection amplitude, the question is addressed, what imperfection amplitudes are necessary to gain numerically the experimentally based lower bound buckling resistance of the stress design. Using the imperfection amplitudes recommended in the Eurocode, partly considerable discrepancies result from a numerical analysis of the circular cylindrical shell subject to hoop compression [2]. In order to overcome the knowledge gaps and to relate the accidental imperfections to the buckling resistance, for the first time extensive experimental series of test cylinders with the same nominal data have been performed at the Gdansk University of Technology. The geometric imperfections and the buckling process are well documented.

The numerical simulation of these experiments is dealt with in the second part of the contribution. Using static analyses, only the imperfection parts which initiate the buckling process may be reliably detected. In contrast, this statement is not valid for the buckling pattern. The inert forces must not be neglected performing a numerical simulation of the buckling process, because the collapse takes place with high velocities even though the load is increased very slowly. Therefore, a dynamic analysis is necessary in order to simulate the buckling in a mechanically consistent manner [1]. By means of a dynamic analysis, the arising buckling pattern is closely captured. Dynamic analyses are especially reasonable at the basic buckling case hoop compression, because the buckling process takes place by a sequence of several local buckling phenomena. The succession of stable and
unstable areas of the load-displacement path of a static analysis, which is connected with loading and unloading, does not correspond to mechanical reality. Finally, the minor differences between experiments and numerical simulations, which underline the high imperfection sensitivity of shell buckling, are discussed in detail. Summarising, conclusions are drawn concerning the imperfection parts initiating the buckling process as well as concerning the equivalent imperfection modes and amplitudes which should be used for performing a numerical buckling strength verification.

References:

ABSTRACT: Although edge-wave and centre-buckles in rolled strip are believed to be largely self-equilibrated, the result of residual stress, formation of herringbone and quarter-buckles in hot- or cold-rolled strip is believed to require application of external stress. It is verified here that stress distributions such as those indicated by Roberts are possible causes of quarter-buckling and herringbone buckling. Quarter-buckling is believed to result from stress in the sheet or strip produced by non-parabolic bending of the work rolls. Herringbone buckling is attributed to local regions of axial tension and compression in the transverse stress distribution, caused by misalignment, which effectively produces a shear in the sheet that may manifest itself in diagonal buckling.

ABSTRACT: A personal overview of the buckling process is given, based on more than 30 years research experience. A fundamental distinction is drawn between structures that tend to distribute their pattern of buckling over the entire available length, and those that favour limiting it to a localized portion. Difficulties are compounded by the fact that localized solutions typically are shadowed by distributed counterparts. The difference is found to depend primarily on the stability of the system at the point of buckling. When an unstable localized form shows a tendency to restabilize, a pattern known as cellular buckling can develop, taking place sequentially in both space and time. The paper focuses particularly on the buckling of the axially-compressed cylindrical shell, and shows how the circumferential periodicity coupled with axial localization has special but hidden characteristics. In particular, the circumferential wavenumber is picked at an early stage of buckling and remains locked, while localization in the axial sense permits extensive change to the post-buckling shape.

References listed at the end of the paper:
ABSTRACT: Basic mechanisms for the buckling of a thin cylindrical shell under torsional loading are reviewed from a post-buckling perspective. Deflections are considered so far into the large-deflection range that the shell is allowed to fold to a flat two-dimensional form, in a mechanism reminiscent of a deployable structure. Critical and initial post-buckling effects are explored through concepts of energy minimization and hidden symmetries. For comparisons with the final large-deflection folded shape, a truss element program is employed. It is shown...
that, as buckling develops, the mode shape must change to accommodate both the symmetry-breaking aspects of the predominately inwards deflection, and the rotation of peak and valley lines of the buckle pattern necessary to accommodate the geometry of the final folded shape.

References listed at the end of the paper:

ABSTRACT: This paper focuses on rigid foldability of the cylindrical origami with Kresling pattern. The theory of quaternion representing spatial fixed-point rotation and the rotating vector model were proposed by some researchers to obtain the quaternion rotation sequence method (QRS method) to study the foldability of origami, but the method is limited definitely and not suitable for cylindrical foldable structures. In order to solve the problem, the method was improved in this paper. The single-vertex origami model with six creases was firstly introduced and the motion of this origami pattern was studied. Then the QRS method is improved by taking the geometry relationship into consideration. The results show the cylindrical origami with Kresling pattern is not rigid foldable.

References listed at the end of the paper:

INITIAL WORDS: “For each of us, it is a great pleasure to come together in this tribute to Michael Thompson's remarkable contributions to nonlinear statics and dynamics over the best part of half a century. Although having been friends and colleagues for many years, we have never written anything together, so it is entirely fitting that this should be happening for the first time in this piece. Each of us had Michael as an inspirational research supervisor over a different period in his research career: between us we must span, as close colleagues and collaborators, most of his lifetime of research. . .”

Mark Schenk and Simon D. Guest, “Origami folding: a structural engineering approach”, (publisher and date not given in the pdf file; 2010?)

ABSTRACT: In this paper we present a novel engineering application of Origami, using it for both the flexibility and the rigidity the folding patterns provide. The proposed Folded Textured Sheets have several interesting mechanical properties. The folding patterns are modeled as a pin-jointed framework, which allows the use of established structural engineering methods to gain insight into the kinematics of the folded sheet. The kinematic analysis can be naturally developed into a stiffness matrix approach; by studying its softest eigenmodes, important deformations of a partially folded sheet can be found, which aids in the understanding of Origami sheets for engineering applications.

References listed at the end of the paper:
(cannot cut and paste abstract)

ABSTRACT: This paper presents a theory for predicting the wavelength and amplitude of the wrinkles that form in a membrane in pure shear. Predictions from this theory are compared to experimental measurements and a finite element simulation and are found to be very accurate.
References listed at the end of the paper:
distribution of residual stresses induced by plastic bending. The basic mechanics of the bistability are explained, along with details of the plastic forming. A comprehensive analytical model is developed which predicts the residual stress distribution and bistable configurations of the shell. Good correlation has been found between experimental results and predictions from this model.


ABSTRACT: This is the third and final part of a study of wrinkles in thin membrane structures. High-fidelity, geometrically nonlinear finite element models of membrane structures, based on thin-shell elements, are used to simulate the onset and growth of wrinkles. The simulations are carried out with the ABAQUS finite element package. The accuracy of the results is demonstrated by computing the characteristics of the wrinkles in two specific membrane structures that were investigated experimentally and analytically in the first two papers in this series.

References listed at the end of the paper:

ABSTRACT: Thin-shell deployable reflector structures that are folded elastically in a nearly inextensional mode have been recently realized, exploiting the recent availability of high-modulus, ultrathin composite materials. An inherent and significant limitation of this approach is that these structures remain “floppy” in their deployed configuration. This paper presents a general concept for increasing the deployed stiffness of such structures, through the addition of a collapsible edge stiffener around the rim of a reflector dish. An analytical expression of the frequency/stiffness related to the softest deformation mode of a thin-shell reflector structure is presented, both with and without the stiffener. During folding, the stiffener collapses elastically, and this behavior is facilitated by the introduction of suitable discontinuities within the stiffener, or between the dish and the stiffener. A detailed study of a range of different options is presented, and one particular scheme is selected and optimized. For a specific example, a stiffness increase by a factor of 31 and a fundamental frequency increase by a factor of 4 are achieved, with a mass increase of only 16%.


ABSTRACT: Thin cylindrical shell structures can show interesting bistable behaviour. If made unstressed from
isotropic materials they are only stable in the initial configuration, but if made from fibre-reinforced composites they may also have a second, stable configuration. If the layup of the composite is antisymmetric, this alternative stable configuration forms a tight coil; if the layup is symmetric the alternative stable configuration is helical. A simple two-parameter model for these structure is presented that is able to distinguish between these different behaviours.

References listed at the end of the paper:


ABSTRACT: This paper presents a computational study of the critical buckling pressure of pumpkin balloons, which consist of a thin, compliant membrane constrained by stiff meridional tendons. The n-fold symmetric shape of a pumpkin balloon with n identical lobes is exploited by adopting a symmetry-adapted coordinate system, which leads to the tangent stiffness matrix in an efficient block-diagonal form; the smallest eigenvalue of a particular block leads to the buckling pressure for the balloon. Two different types of balloon design are considered. Extensive results are obtained for the buckling pressures of a set of 10 m diameter experimental balloons and also for an 80 m diameter flight balloon. The key findings are as follows: the same type of buckling mode, forming four circumferential waves is critical for most of the balloons that have been analysed; balloons with flatter lobes are more stable, and the buckling pressure varies with an inverse power-law of the number of lobes; increasing the Young’s modulus, the Poisson’s ratio of the membrane, or the diameter of the end fitting has the effect of increasing the buckling pressure; but increasing the axial stiffness of the tendons has the effect of decreasing the buckling pressure.


ABSTRACT: This thesis presents an experimental, numerical and analytical study of the behavior of thin fiber composites with a silicone matrix. The main difference with respect to traditional composites with epoxy matrix is the fact that the soft matrix allows the fibers to microbuckle without breaking. This process acts as a stress relief mechanism during folding, and allows the material to reach very high curvatures, which makes them
particularly interesting as components of space deployable structures. The goal of this study is to characterize the behavior and understand the mechanics of this type of composite.

Experimental testing of the bending behavior of unidirectional composites with a silicone matrix shows a highly non-linear moment vs. curvature relationship, as well as strain softening under cyclic loading. These effects are not usually observed in composites with an epoxy matrix. In the case of tension in the direction transverse to the fibers, the behavior shows again non-linearity and strain softening, as well as an initial stiffness much higher than what would be expected based on the traditional estimates for fiber composites.

The micro mechanics of the material have been studied with a finite element model. It uses solid elements and a random fiber arrangement produced with a reconstruction process based on micrographs of the material cross section. The simulations capture the macroscopic non-linear response, as well as the fiber microbuckling, and show how microbuckling reduces the strain in the fibers. The model shows good agreement for the bending stiffness of specimens with low fiber volume fraction, but it overestimates the effect of the matrix for more densely packed fibers. This is due to the high matrix strain that derives from the assumption of perfect bonding between fiber and matrix. In the case of tension transverse to the fibers, the model shows a much better agreement with experiments than traditional composite theory, and shows that the reason for the observed high stiffness is the incompressibility of the matrix. In order to capture the strain softening due to fiber debonding, cohesive elements have been introduced between the fibers and the matrix. This allows the model to capture quantitatively the non-linear behavior in the case of loading transverse to the fibers, and the damage due to cyclic loading. A single set of parameters for the cohesive elements produce good agreement with the experimental results for very different values of the fiber volume fraction, and could also be used in the analysis of more complicated loading cases, such as bending or biaxial tension. In addition to the simulations, a homogenized analytical model has also been created. It extends previous analysis of composites with a soft matrix to the case of very thin composites. It provides a good qualitative description of the material behavior, and it helps understand the mechanics that take place within the material, such as the equilibrium of energy terms leading to a finite wave length, as opposed to microbuckling under compression.

References listed at the end of the dissertation:

P.J. Davy and F.J. Guild. The distribution of interparticle distance and its application in finite-element modelling of composite
J. M. Mejia-Ariza, K. Guidanean, T. M. Murphey, and A. Biskner. Mechanical characterization of L’Garde elastomeric resin


Francisco Lopez Jimenez (University of Colorado Boulder) and Sergio Pellegrino (California Institute of Technology), “Folding of thin-walled composite structures with a soft matrix”, AIAA/ASME Structures, Structural Dynamics and Materials Conference, May 2009

ABSTRACT: The paper presents detailed micromechanical finite element simulations of composite materials with soft materials undergoing large macroscopic bending deformation. The simulations allow the study of fibre microbuckling under bending, including the kinematics of the fibres, as well as the strains in the matrix. These simulations lead to a simple analytical model that allows a quite accurate estimation of the buckling wavelength. It also provides the moment-curvature relationship. Finally, the model is also able to predict the maximum strain in the fibres for a given curvature.

References listed at the end of the paper:

M. Pagitz (1) and S. Pellegrino (2)
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ABSTRACT: This paper is concerned with the optimization of the cutting pattern of n-fold symmetric super-
pressure balloons made from identical lobes constrained by stiff meridional tendons. It is shown that the critical buckling pressure of such balloons is maximized if the unstressed surface area of the balloon is minimized under a stress constraint. This approach results in fully stressed balloon designs that in some cases have a smaller unstressed surface area than the corresponding axisymmetric surface that is in equilibrium with zero hoop stress. It is shown that, compared to current designs, the buckling pressures can be increased by up to 300% without increasing the maximum stress in the lobe.

ABSTRACT: This paper presents a simplified simulation technique for orthotropic viscoelastic membranes. Wrinkling is detected by a combined stress-strain criterion and an iterative scheme searches for the wrinkle angle using a pseudo-elastic material stiffness matrix based on a non-linear viscoelastic constitutive model. This simplified model has been implemented in ABAQUS/Explicit and is able to compute the behavior of a membrane structure by superposition of a small number of response increments. The model has been tested against a published solution for a time-independent isotropic membrane under simple shear and also against experimental results on StratoFilm 420 under simple shear.

ABSTRACT: The rapid growth in direct digital manufacturing technologies has opened the challenge of designing optimal micro-structures for high-performance components. Current topology optimization techniques do not work well for this type of problems and hence in this paper we propose a technique based on an implicit representation of the structural topology. The detailed microstructure is designed by a continuous variable, the size distribution field, defined over the design domain by chosen shape functions. We can optimize the structural topology by optimizing only the weights of the size distribution and, for any given size distribution, we use standard meshing software to determine the actual detailed microstructure. We have implemented the optimization loop using commercial CAD and FEA software, running under a genetic algorithm in MATLAB. Application this novel technique to the design of a sandwich beam has produced designs that are superior to any standard solid beam or even optimized truss structure.

ABSTRACT: The buckling of axially compressed cylindrical shells and externally pressurized spherical shells is extremely sensitive to even very small geometric imperfections. In practice this issue is addressed by either using overly conservative knockdown factors, while keeping perfect axial or spherical symmetry, or adding closely and equally spaced stiffeners on shell surface. The influence of imperfection-sensitivity is mitigated, but the shells designed from these approaches are either too heavy or very expensive and are still sensitive to imperfections. Despite their drawbacks, these approaches have been used for more than half a century. This thesis proposes a novel method to design imperfection-insensitive cylindrical shells subject to axial compression. Instead of following the classical paths, focused on axially symmetric or high-order rotationally symmetric cross-sections, the method in this thesis adopts optimal symmetry-breaking wavy cross-sections (wavy shells). The avoidance of imperfection sensitivity is achieved by searching with an evolutionary
algorithm for smooth cross-sectional shapes that maximize the minimum among the buckling loads of geometrically perfect and imperfect wavy shells. It is found that the shells designed through this approach can achieve higher critical stresses and knockdown factors than any previously known monocoque cylindrical shells. It is also found that these shells have superior mass efficiency to almost all previously reported stiffened shells. Experimental studies on a design of composite wavy shell obtained through the proposed method are presented in this thesis. A method of making composite wavy shells and a photogrammetry technique of measuring full-field geometric imperfections have been developed. Numerical predictions based on the measured geometric imperfections match remarkably well with the experiments. Experimental results confirm that the wavy shells are not sensitive to imperfections and can carry axial compression with superior mass efficiency. An efficient computational method for the buckling analysis of corrugated and stiffened cylindrical shells subject to axial compression has been developed in this thesis. This method modifies the traditional Bloch wave method based on the stiffness matrix method of rotationally periodic structures. A highly efficient algorithm has been developed to implement the modified Bloch wave method. This method is applied in buckling analyses of a series of corrugated composite cylindrical shells and a large-scale orthogonally stiffened aluminum cylindrical shell. Numerical examples show that the modified Bloch wave method can achieve very high accuracy and require much less computational time than linear and nonlinear analyses of detailed full finite element models. This thesis presents parametric studies on a series of externally pressurized pseudo-spherical shells, i.e., polyhedral shells, including icosahedron, geodesic shells, and triambic icosahedra. Several optimization methods have been developed to further improve the performance of pseudo-spherical shells under external pressure. It has been shown that the buckling pressures of the shell designs obtained from the optimizations are much higher than the spherical shells and not sensitive to imperfections.

References listed at the end of the paper:


ABSTRACT: This paper presents an efficient computational method for predicting the onset of buckling of axially loaded, corrugated or stiffened cylindrical shells. This method is a modification of the Bloch wave method which builds on the stiffness matrix method. A numerical method and an efficient algorithm have been developed to implement the proposed method in the commercial finite element package Abaqus. Numerical examples have shown that, compared to the nonlinear buckling analyses based on detailed full finite element models, the proposed method can obtain highly accurate buckling loads and buckling modes and can achieve very significant reductions in computational time.

References listed at the end of the paper:


ABSTRACT: Buckling analyses of heavily corrugated cylindrical shells based on detailed full finite element models are usually computationally expensive. To address this issue, we have proposed an efficient computational method of predicting the onset of buckling for corrugated cylindrical shells which builds on the

Xin Ning and Sergio Pellegrino (California Institute of Technology, Pasadena, CA 91125), “Buckling Analysis of Axially Loaded Corrugated Cylindrical Shells”. AIAA 8th Structures, Structural Dynamics and Materials Meeting, (year not given in the pdf file. The most recent reference is 2014.)
Bloch wave method for infinitely periodic structures. We modified the traditional Bloch wave method in order to analyze the buckling of rotationally periodic shell structures. We have developed an efficient algorithm to perform our modified Bloch wave method. The buckling behavior of composite corrugated cylindrical shells with a range of numbers of corrugations was analyzed. Linear and nonlinear buckling analyses of detailed full finite element models were also performed and compared to our method. Comparisons showed that our modified Bloch wave method was able to obtain highly accurate buckling loads and it was able to capture both global and local buckling modes. It was also found that the computational time required by our modified Bloch wave method did not scale up as the number of corrugations increased.

References listed at the end of the paper:

INTRODUCTION:

• Form-finding is a central problem in the design of modern shell structures (Adriaenssens, Block, Veenendaal, Williams 2014).
• Transition from analytically defined “classical” shells to free-form shells initiated by Isler.
• Numerical studies of free-form shells made by Ramm and many others.
• Two form-finding optimization problems:
  1. Find shape with minimal strain energy
  2. Modify shape from optimization 1 for minimal sensitivity to imperfections

Sergio Pellegrino (Graduate Aerospace Laboratories, California Institute of Technology, Pasadena, CA 91125), “Folding and deployment of thin shell structures”. Pellegrino writes: “Last year I gave a series of lectures on the folding and deployment of thin shell structures, as part of a course at CISM (in Udine, Italy) on Extremely Deformable Structures organized by Davide Bigoni. These lectures provided an opportunity to revisit the work that I had done over a period of about 15 years, with many students and collaborators. My write-up of the lectures will appear as a book to be edited by Davide. There is also a downloadable pdf file on my website (http://pellegrino.caltech.edu/publications.html)”

ABSTRACT: Thin shells made of high modulus material are widely used as lightweight deployable space structures. The focus of this chapter is the most basic deployable thin shell structure, namely a straight,
transversely curved strip known as a tape spring. Following a review of the materials used for the construction of deployable thin shell structures, including constitutive models and failure criteria developed specifically for this type of structures, this chapter provides an introduction to the mechanics of tape springs and tape spring hinges. Finite element techniques to model deployable structures containing tape springs are presented and the ability of these models to accurately simulate experimentally observed behavior is demonstrated. These tools can be used to design structures able to achieve specific behaviors. As an example, the design of a two-hinge boom that can be wrapped around a small spacecraft without any damage, and can dynamically deploy and smoothly latch into the deployed configuration is presented.

References listed at the end of the paper:


The MathWorks Inc., Matlab Version R2010a, Natick, MA.

Torayca, Technical Data Sheet No. CFA-001, T300 Data Sheet (http://www.toraycfa.com/pdfs/T300DataSheet.pdf), 2015.


ABSTRACT: This study is concerned with the equilibrium shapes of orthotropic, elliptical plates and shells deforming elastically without initial stresses. The aim is to explore potential bistable configurations and their dependencies on material parameters and initial shape for elucidating novel morphing structures. A strain energy formulation gives way to a compact set of governing equations of deformation, which can be solved in closed form for some isotropic and orthotropic conditions. It is shown that bistability depends on the change in Gaussian curvature of the shell, in particular, for initially untwisted shells, isotropy precludes bistability, where there is negative initial Gaussian curvature, but orthotropic materials yield bistability irrespective of the sign of the initial Gaussian curvature. This improved range of performance stems from increasing the independent shear modulus, which imparts sufficient torsional rigidity to stabilize against perturbations in the deformed state. It is also shown that the range of bistable configurations for initially twisted shells generally diminishes as the degree of twist increases.

References listed at the end of the paper:


(doi:10.1016/j.ijsolstr.2004.02.037)

ABSTRACT: Thin sheet materials of low bending stiffness but high membrane stiffness are often corrugated in order to achieve improvements of several orders of magnitude in bending stiffness with only minimal increases in weight and cost. If these corrugated sheets are initially curved along the corrugations, much of this stiffness gain is lost. In return, the sheets are then capable of significant elastic changes in shape overall, including large changes in overall Gaussian curvature. These shape changes are described here by non-linear and coupled kinematical relationships, which are verified against experiment and finite-element simulations. It is found that gross simplifications can be made about the large displacement behaviour of such shells without a loss of accuracy.


ABSTRACT: This study deals with prestressed shells, which are capable of “morphing” under large deflexions between very different load-free configurations. Prestressing involves plastically curving a flat, thin shell in orthogonal directions either in the opposite or same sense, resulting in two unique types of behavior for isotropic shells. Opposite-sense prestressing produces a bistable, cylindrically curved shell provided the prestress levels are large enough and similar in size: This effect forms the basis of a child's “flick” bracelet and is well known. On the other hand, same-sense prestressing results in a novel, neutrally stable shell provided the levels are also sufficiently large but identical: The shell has to be made precisely, otherwise, it is monostable and is demonstrated here by means of a thin, helically curved strip. The equilibrium states associated with both effects are quantified theoretically and new expressions are determined for the requisite prestress levels. Furthermore, each stability response is revealed in closed form where it is shown that the neutrally stable case occurs only for isotropic materials, otherwise, bistability follows for orthotropic materials, specifically, those, which have a shear modulus different from the isotropic value. Finally, prestressing and initial shape are considered together and, promisingly, it is predicted that some shells can be neutrally stable and bistable simultaneously.

References listed at the end of the paper:

ABSTRACT: Creasing in thin shells admits large deformation by concentrating curvatures while relieving stretching strains over the bulk of the shell: after unloading, the creases remain as narrow ridges and the rest of the shell is flat or simply curved. We present a helically creased unloaded shell that is doubly curved everywhere, which is formed by cylindrically wrapping a flat sheet with embedded fold-lines not axially aligned. The finished shell is in a state of uniform self-stress and this is responsible for maintaining the Gaussian curvature outside of the creases in a controllable and persistent manner. We describe the overall shape of the shell using the familiar geometrical concept of a Mohr’s circle applied to each of its constituent features—the creases, the regions between the creases, and the overall cylindrical form. These Mohr’s circles can be combined in view of geometrical compatibility, which enables the observed shape to be accurately and completely described in terms of the helical pitch angle alone.

References listed at the end of the paper:


ABSTRACT: We consider the axial buckling of a thin-walled cylinder fitted onto a mandrel core with a prescribed annular gap. The buckling pattern develops fully and uniformly to yield a surface texture of regular diamond-shaped buckles, which we propose for novel morphing structures. We describe experiments that operate well into the postbuckling regime, where a classical analysis does not apply; we show that the size of buckles depends on the cylinder radius and the gap width, but not on its thickness, and we formulate simple relationships from kinematics alone for estimating the buckle proportions during loading.
DOI: 10.1007/s00339-006-3632-y

ABSTRACT: This paper presents research on the calculating analysis and experimental observations of shell buckling in individual gallium nitride hollow nanocolumns using nanoindentation. By using the experiment results of critical buckling strain under compression, we investigated the stiffness of hollow nanocolumns which were vertically aligned on a template by using linear elastic shell buckling theory. In addition, more studies of various possible nanomechanical behavior modes of gallium nitride hollow nanocolumns by shall model are provided. Furthermore, there was a comparison between nanocolumns by molecular dynamics simulation (one dimensional structure) and thin film by nanoindentation experiment (two dimensional structures). Finally, the buckling energy of compression for an individual gallium nitride hollow nanocolumn was also discussed.

References listed at the end of the paper:
4 W. Han, S. Fan, Q. Li, Y. Hu, Science 277, 1287 (1997)

ABSTRACT: Buckling considerations arise in the design of steel silos and tanks because the slender shell wall is subjected to compressive stresses, most commonly from the action of wind on the empty structure causing circumferential stresses, and combinations of wall friction forces, roof loads, non-uniform filling and discharge, and non-uniform settlement of the foundation causing meridional stresses. In this paper, recent research work of the author and graduate students relevant to buckling behaviour is briefly reviewed. Problems relevant to buckling behaviour, and which arose in several major tanks and silos with which the author was concerned either at the design stage or arising from operational problems, are discussed. The buckling behaviour and design of slender steel silos and tanks has been reviewed, with particular reference to buckling under wind loading, and under meridional compression. The benefits to be obtained by refined finite element analysis at the design stage have been emphasised, and several examples of buckling phenomena in the design of major structures reviewed. The occurrence of uplift of large empty tanks under severe wind loadings has been detected. A simplified design method for wind buckling has been given, which includes an approximate consideration of the effects of imperfections, meridional end restraints and form of the wind pressure distributions. Situations under which meridional compression can govern the design have been explored. The beneficial effects of a bulk solid content against buckling have been investigated.


PARTIAL INTRODUCTION: In Chapter 5, cylindrical shells under uniform external pressure with particular reference to short, medium-long and long cylinders, boundary conditions, stepped wall thicknesses and ring stiffeners were discussed. This chapter deals with buckling under non-uniform external pressure, examples of which abound in civil/mechanical engineering, marine, ballistic and aerospace structures. Earlier work on the stability of cylinders under external pressure was based on the Donnell stability equations, modified by Batdorf (1947)…. 

Peter Ansourian, “Shell Structures”, Center for Advanced Structural Engineering – CASE, Department of Civil Engineering, The University of Sidney, 2002

ABSTRACT: This project is concerned with the buckling failure of metal structures generally formed of curved plates. These structures are typically used in the liquid and bulk material storage industries, pressure vessels, aerospace vehicles, and in many other contexts. The analysis and design of pressure vessel closures may surprisingly sustain buckling failure under internal pressure. This is followed by a consideration of buckling under external pressure, firstly in the context of the Donnell stability equations which provide solutions of good accuracy in many cases, but secondly using the more rigorous and generally more accurate Flügge equations in coupled form. The latter theory is applied to cases of uniform and non-uniform pressure such as wind and patch loading. A further advantage of the theory is that solutions are possible for non-classical boundary conditions. Solutions are tabulated for uniform, hydrostatic, wind and patch loadings. Buckling under in-plane compressive forces is also briefly considered. Experimental and prototype responses under several loading regimes are examined and the significance to design considered; included are buckling problems associated with corrugated plates. When tank structures are supported on soils of non-uniform stiffness, differential settlement may occur, causing possible overstress or even buckling failure. Analyses based on inextensional theory are valid at low harmonic number in open-top tanks, while finite element analysis is the most general and accurate tool for the linear and non-linear stress and buckling response. The non-linear behaviour and coupled instabilities of steel cylindrical tank shells subjected to meridional edge deformation of harmonic pattern are investigated. The harmonic number n is shown to have a strong influence on the shear and meridional buckling interaction.
Practical applications are related to the design and maintenance of storage tanks and silos. The shear buckling mode is observed at small harmonic number \( n < 5 \) in shells of uniform thickness; with increasing \( n \), the mode is dominated by axial buckling. As the shell deforms in the shear buckling mode, it continues to carry higher load until local buckling occurs near the base. In tapered shells, shear buckling occurs in the upper region of the shell at high \( n \). (No references are given.)

Eiichi Watanabe, Kunitomo Sugiura and Takeshi Yamaguchi (Kyoto University, Japan), “Strength and ductility of thin-walled beam-columns with low yield steel”, Earthquake Engineering. Tenth World Conference, Rotterdam, 1992

ABSTRACT: Discussed herein is the load-deformation relationship of bridge piers considering the local failure characteristics. Firstly, the strength and ductility of thin tubular beam-column segments are investigated by two series of experiments keeping a focus on the cross sectional shape and inelastic characteristics of material. Assuming bridge piers subjected to strong ground motions, monotonic bending tests under the constant axial compressive force are carried out. The effect of the yield ratio and use of round corners on the strength and ductility is evaluated. It is found that the box section with round corners and the use of structural steel with low yield ratio is desirable for the ductility improvement. Secondly, by modeling the plastic hinge behavior considering the local instability based on the experimental observation, the deformation characteristic of steel bridge piers are investigated by numerical simulation. It is concluded that the effect of local instability on the strength deterioration is significant and the P-delta effect accelerates the degradation.


ABSTRACT: This paper presents an estimation of global elastic shear buckling strength of corrugated plates considering the influence of elastically rotational restraint on boundary edges. The corrugated plate possesses higher shear buckling strength compared to a flat one and it has been used to replace concrete web in PC box girder in recent bridge construction in Japan. In this study, the corrugated plate is considered as an orthotropic flat plate. Thick rectangular plate theory is used and Rayleigh-Ritz method is utilized in extracting eigenvalues. Elastically rotational restraint on boundary edges is taken into account in the form of rotational spring in the analysis. Prediction of buckling strengths of corrugated plates is carried out using the Rayleigh-Ritz method, which was proved to be consistent with those as predicted by a proposed formula using a design manual and was found also to cover the more general cases of elastically rotational restraint on the boundary edges showing transition curve of plate buckling strengths from the case of simple support to the case of clamped support. A finite element analysis was also carried out to verify the accuracy of the proposed method. As a result, a discrepancy is found between the buckling strength by the finite element analysis and that by the proposed analysis; however, the formula adopted in the design manual may be thought to be conveniently used because it can lead to the conservative design.

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ABSTRACT: Abstract. Based on both molecular mechanics and computational structural mechanics, a three-dimensional (3D) equivalent beam element is developed to model a C-C covalent bond on carbon nanotubes (CNTs) whereas the van der Waals forces between atoms in the different walls of multi-walled CNTs are described using a rod element. The buckling characteristics of CNTs are conveniently analyzed by using the traditional finite element method (FEM) of a 3D beam and rod model, termed as molecular structural mechanics approach (MSMA). Moreover, to model the CNTs with large length or large diameter, the validity of Euler’s beam buckling theory and a shell model with proper properties defined from the results of MSMA is investigated. The predicted results by this simple continuum mechanics approach agree well with the reported experimental data.

References listed at the end of the paper:


ABSTRACT: In this paper, the buckling of carbon nanotubes, modeled as nonlocal one dimensional continua within the framework of Euler–Bernoulli beams, is considered. Both a stress gradient and a strain gradient approach are considered and a variational approach is adopted to obtain the variationally consistent boundary conditions. The dependence of the buckling load on the nonlocal parameter has been determined using the boundary conditions obtained from the variational analysis. Results indicate significant dependence of nonlocal parameter on buckling load for particular types of boundary conditions. These findings are important in mechanical design considerations of devices that use carbon nanotubes.

References listed at the end of the paper:
3 R. H. Baughman, A. A. Zakhidov, and W. A. de Heer, Science 297, 787, 2002

ABSTRACT: The natural frequencies of isotropic and composite laminates are presented. The forced vibration analysis of laminated composite plates and shells subjected to arbitrary loading is investigated. In order to overcome membrane and shear locking phenomena, the assumed natural strain method is used. To develop a laminated shell element for free and forced vibration analysis, the equivalent constitutive equation that makes the computation of composite structures efficient was applied. The Mindlin-Reissner theory which allows the shear deformation and rotary inertia effect to be considered is adopted for development of nine-node assumed strain shell element. The present shell element offers significant advantages since it consistently uses the natural co-ordinate system. Results of the present theory show good agreement with the 3-D elasticity and analytical solutions. In addition the effect of damping is investigated on the forced vibration analysis of laminated composite plates and shells.

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ABSTRACT: To demonstrate the solutions of linear and geometrically non-linear analysis of laminated composite plates and shells, the co-rotational non-linear formulation of the shell element is presented. The combinations of an enhanced assumed strain (EAS) in the membrane strains and assumed natural strains (ANS) in the shear strains improve the behavior of 4-node shell element. To secure computational efficiency in the incremental non-linear analysis, the present element uses the form of the resultant forces pre-integrated through the thickness. The transverse shear stiffness of the laminates is defined by an equilibrium approach instead of the shear correction factor. Numerical examples of this study show very good agreement with the references.
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ABSTRACT: The formulation of a non-linear composite 4-node co-rotational resultant shell element is presented for the solution of bending, free vibration, critical buckling and postbuckling analysis of composite plates and shells. Using the ANS (assumed natural strain) method the present shell element generates shear locking behavior, and such element performs very well as much as shells get thin. The formulation of the geometrical stiffness presented here is exactly defined on the mid-surface and is efficient for analyzing stability problems of thin and thick laminated plates, and shells by incorporating bending moment and transverse shear resultant forces. The transverse shear stiffness is defined by an equilibrium approach instead of using the shear correction factor. The adoption of a second-order co-rotational formulation makes it computationally efficient compared to the most existing composite shell elements. The proposed formulation is computationally efficient and the test results showed good agreement.

ZHOU, Lingyuan, LI, Tongmei, and LI, Qiao, (School of civil Engineering, Southwest Jiaotong University, Chengdu 610031, China) “Co-rotational formulation-based analysis of shell buckling”, Journal of Southwest Jiaotong University, Vol. 45, No. 6, December 2010, doi: 10.3969/j.issn.0258-2724.2010.06.012
ABSTRACT: In order to solve the nonlinear problem in analyzing the buckling of thin-walled structures, an updated Lagrangian co-rotational method for the nonlinear analysis of shell structures was presented. A program based on this method was developed, and two numerical examples of the buckling analysis of shell structures were given. In this method, an updated Lagrangian formulation is adopted to build the equilibrium equation of shell elements under large displacements, and then the tangent stiffness matrix is obtained with the energy theory. The polar decomposition theory is applied in the computations of the new co-rotational coordinates of elements and the rigid body rotations of nodes, and the finite rotation theory is introduced to separate rigid displacements from total displacements to get deformations of the nodes. As a result, stresses of an element can be calculated based on the deformations by using the small-strain theory to obtain the element state for the current load step. The numerical examples indicate that the nonlinear analysis method based on co-rotational (CR) formulation is efficient and accurate in solving the buckling of shell structures. [15 references, including one by Rankin and Brogan (1986) and one by Rankin (1998)]. (paper is in Chinese.)

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doi: 10.1007/s12206-011-0305-3
ABSTRACT: In this paper, the recently-developed solid-shell element SHB8PS is used for the analysis of a
representative set of popular limit-point buckling benchmark problems. For this purpose, the element has been implemented in Abaqus/Standard finite element software and the modified Riks method was employed as an efficient path-following strategy. For the benchmark problems tested, the new element shows better performance compared to solid elements and often performs as well as state-of-the-art shell elements. In contrast to shell elements, it allows for the accurate prescription of boundary conditions as applied to the actual edges of the structure.

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- Domissy, E. (1997) Formulation et évaluation d’éléments finis volumiques modifiés pour l’analyse linéaire et non linéaire des coques. UT Compiègne, France
- Abed-Meraim, F., Combescure, A. (2001) SHB8PS a new intelligent assumed strain continuum mechanics shell element for impact analysis on a rotating body. First MIT conference on computational fluid and solid mechanics, Cambridge, USA
This paper deals with the convergence acceleration of iterative nonlinear methods. An effective iterative algorithm, named the three–point method, is applied to nonlinear analysis of structures. In terms of computational cost, each iteration of the three–point method requires three evaluations of the function. In this study the effective functions have been proposed to accelerate the convergence process. The proposed method has a convergence order of eight, and it is important to note that its implementation does not require the computation of higher order derivatives compared to most other methods of the same order. To trace the equilibrium path beyond the limit point, a normal flow algorithm is implemented into a computer program. The three–point method is applied as an inner step in the normal flow algorithm. The procedure can be used for structures with complex behavior, including: unloading, snap–through, elastic post–buckling and inelastic post–buckling analyses. Several numerical examples are given to illustrate the efficiency and performance of the new method. Results show that the new method is comparable with the well–known existing methods and gives better results in convergence speed.

References listed at the end of the paper:

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“An accelerated incremental algorithm to trace the nonlinear equilibrium path of structures”, Latin American Journal of Solids and Structures, Vol. 9, No. 4, August 2012

ABSTRACT: This paper deals with the convergence acceleration of iterative nonlinear methods. An effective iterative algorithm, named the three–point method, is applied to nonlinear analysis of structures. In terms of computational cost, each iteration of the three–point method requires three evaluations of the function. In this study the effective functions have been proposed to accelerate the convergence process. The proposed method has a convergence order of eight, and it is important to note that its implementation does not require the computation of higher order derivatives compared to most other methods of the same order. To trace the equilibrium path beyond the limit point, a normal flow algorithm is implemented into a computer program. The three–point method is applied as an inner step in the normal flow algorithm. The procedure can be used for structures with complex behavior, including: unloading, snap–through, elastic post–buckling and inelastic post–buckling analyses. Several numerical examples are given to illustrate the efficiency and performance of the new method. Results show that the new method is comparable with the well–known existing methods and gives better results in convergence speed.

References listed at the end of the paper:

ABSTRACT: The paper presents the inelastic post-buckling analysis of truss structures by the Dynamic Relaxation (DR) method. A simplified inelastic finite element formulation for truss element and new algorithms are proposed for Elastic Post-Buckling (EPB) analysis and Inelastic Post-Buckling (IEPB) analysis using the DR method. The post-buckling paths for elastic, EPB and IEPB analyses are completely traced using the variable-arc-length method. Four numerical examples are presented to illustrate the application of the proposed algorithms.

Glenn A. Hrinda (NASA Langley Research Center, Hampton, Virginia, USA), “Snap-through instability patterns in truss structures”, Presented at one of the AIAA Structures (SDM) meetings; date not given in the pdf file; the most recent reference is 2009)

ABSTRACT: Geometrically nonlinear truss structures with snap-through behavior are demonstrated by using an arc length approach within a finite element analysis. The instability patterns are equilibrium paths that are plotted throughout the snap-through event. Careful observation of these patterns helps to identify weak designs in large space structures, as well as identify desirable snap-through behavior in the miniaturization of electronic devices known as microelectromechanical systems (MEMS). Examples of highly nonlinear trusses that show snap-through behavior are examined by tracing their equilibrium paths.

References listed at the end of the paper:


ABSTRACT: This paper presents a new co-rotational approach for the large displacement analysis of plates employing 4-noded quadrilateral flat shell elements. The proposed approach benefits from (i) a simple local co-
rotational system invariant to the element nodal ordering, (ii) the choice of the two smallest components of the nodal normal vector as global rotational degrees of freedom, and (iii) the use of hierarchic freedoms, that are unaffected by the co-rotational transformations, for higher-order accuracy. Important additional benefits that arise from the aforementioned features include symmetry of the tangent stiffness matrix and complete insensitivity of the large displacement transformations to the size of the incremental step. The applicability of the new approach to moderately thick as well as thin plates is illustrated by considering two alternative local formulations based on the Reissner–Mindlin and discrete Kirchhoff hypotheses. Several examples are finally presented which demonstrate the accuracy, step-insensitivity and computational benefits of the proposed co-rotational approach for large displacement analysis of plate structures.


ABSTRACT: A new 9-node co-rotational curved quadrilateral shell element formulation is presented in this paper. Different from other existing co-rotational element formulations: (1) Additive rotational nodal variables are utilized in the present formulation, they are two well-chosen components of the mid-surface normal vector at each node, and are additive in an incremental solution procedure; (2) the internal force vector and the element tangent stiffness matrix are respectively the first derivative and the second derivative of the element strain energy with respect to the nodal variables, furthermore, all nodal variables are commutative in calculating the second derivatives, resulting in symmetric element tangent stiffness matrices in the local and global coordinate systems; (3) the element tangent stiffness matrix is updated using the total values of the nodal variables in an incremental solution procedure, making it advantageous for solving dynamic problems. Finally, several examples are solved to verify the reliability and computational efficiency of the proposed element formulation. References listed at the end of the paper:

Li, Z. X. (1), Liu, Y. F. (1), Izzuddin, B. A. (2) and Vu-Quoc, L. (3),
(1) Department of Civil Engineering, Zhejiang University, Hangzhou 310058, People's Republic of China
(2) Department of Civil and Environmental Engineering, Imperial College London, London SW7 2BU, U.K.
(3) Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611, U.S.A.
“ A stabilized co-rotational curved quadrilateral composite shell element”, International Journal for Numerical
ABSTRACT: A new curved quadrilateral composite shell element using vectorial rotational variables is presented.
An advanced co-rotational framework defined by the two vectors generated by the four corner nodes is employed to
extract pure element deformation from large displacement/rotation problems, and thus an element-independent
formulation is obtained. The present line of formulation differs from other co-rotational formulations in that (i) all
nodal variables are additive in an incremental solution procedure, (ii) the resulting element tangent stiffness is
symmetric, and (iii) is updated using the total values of the nodal variables, making solving dynamic problems
highly efficient. To overcome locking problems, uniformly reduced integration is used to compute the internal force
vector and the element tangent stiffness matrix. A stabilized assumed strain procedure is employed to avoid spurious
zero-energy modes. Several examples involving composite plates and shells with large displacements and large

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non-linear theory. Comput Methods Appl Mech Eng 79:21–70
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Methods Eng 39:2231–2248
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Struct 71:43–62
rotations are presented to testify to the reliability, computational efficiency, and accuracy of the present formulation.

Shen Hui-shen and Chen Tie-yun (Shanghai Jiaotong University, Shanghai), “A boundary layer theory for the buckling of thin cylindrical shells under external pressure”, Applied Mathematics and Mechanics, Vol. 9, No. 6, pp 557-571, June 1988

ABSTRACT: Based on the boundary layer theory for the buckling of thin elastic shells suggested in ref. [14], the buckling and postbuckling behavior of clamped circular cylindrical shells under lateral or hydrostatic pressure is studied applying singular perturbation method by taking deflection as perturbation parameter. The effects of initial geometric imperfection are also considered. Some numerical results for perfect and imperfect cylindrical shells are given. The analytical results obtained are compared with some experimental data in detail, which shows that both are rather coincident.

References listed at the end of the paper:

Shen Hui-shen and Zhang Jian-wu, Perturbation analyses for the postbuckling of simply supported rectangular
plates under uniaxial compression, Appl. Math. and Mech., 9, 8 (1988), 793–804

ABSTRACT: In this paper, applying perturbation method to von Kármán nonlinear large deflection equations of plates by taking deflection as perturbation parameter, the postbuckling behavior of simply supported rectangular plates under uniaxial compression is investigated. Two types of in-plane boundary conditions are now considered and the effects of initial imperfections are also studied. It is found that the theoretical results are in good agreement with experiments. The method suggested in this paper which has not been found in previous papers is rather simple and easy for the postbuckling analysis of rectangular plates.

References listed at the end of the paper:

Hui-shen Shen (Shanghai Jiaotong University, Shanghai, P.R. China), “Elasto-plastic analysis for the buckling and postbuckling of rectangular plates under uniaxial compression”, Applied Mathematics and Mechanics, Vol. 11, No. 10, October 1990

ABSTRACT: Full-range analysis for the buckling and postbuckling of rectangular plates under inplane compression has been made by perturbation technique which takes deflection as its perturbation parameter. In this paper the effects of initial geometric imperfection on the postbuckling behavior of plates have been discussed. It is seen that the effect of initial imperfection on the inelastic postbuckling of plates is sensitive. By comparison, it is found that the theoretical results of this paper are in good agreement with experiments.

References listed at the end of the paper:

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(2) Department of Naval Architects and Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China

“Buckling and postbuckling behaviour of cylindrical shells under combined external pressure and axial compression”, Thin-Walled Structures, Vol. 12, No. 4, 1991, pp. 321-334,
doi:10.1016/0263-8231(91)90032-E

ABSTRACT: Buckling and postbuckling behaviour of perfect and imperfect cylindrical shells of finite length subject to combined loading of external pressure and axial compression are considered. Based on the boundary layer theory which includes the edge effect in the buckling of shells, a theoretical analysis for the buckling and postbuckling of circular cylindrical shells under combined loading is presented using a singular perturbation technique. Some interaction curves for perfect and imperfect cylindrical shells are given. The analytical results obtained are compared with some experimental data in detail, and it is shown that both agree well. The effects of initial imperfection on the interactive buckling load and postbuckling behaviour of cylindrical shells have also been discussed.

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ABSTRACT: A new approach is extended to investigate the buckling and postbuckling behaviour of perfect and imperfect, stringer and ring stiffened cylindrical shells of finite length subject to combined loading of external pressure and axial compression. The formulations are based on a boundary layer theory which includes the edge effect in the postbuckling analysis of a thin shell. The analysis uses a singular perturbation technique to determine the buckling loads and the postbuckling equilibrium paths. Some interaction curves for perfect and imperfect stiffened cylindrical shells are given and compared well with experimental data. The effects of initial imperfection on the interactive buckling load and postbuckling behaviour of stiffened cylindrical shells have also been discussed.

Hui-Shen Shen (Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, People's
ABSTRACT: A post-buckling analysis is presented for a stiffened laminated cylindrical shell of finite length subject to combined loading of external pressure and axial compression. The formulations are based on a boundary layer theory of shell buckling which includes the effects of the nonlinear pre-buckling deformation, the nonlinear large deflection in the post-buckling range and the initial geometrical imperfection of the shell. The “smeared stiffener” approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine the interactive buckling loads and the post-buckling equilibrium paths. Numerical examples cover the performances of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells. Typical results are presented in dimensionless graphical form.

ABSTRACT: A postbuckling analysis is presented for a circular cylindrical shell of finite length which is subjected to combined loading of external liquid pressure and axial compression. The formulations are based on a boundary layer theory which includes effects of the nonlinear prebuckling deformation, the nonlinear large deflection in the postbuckling range and the initial geometrical imperfection of shells. The analysis uses a singular perturbation technique to determine interactive buckling loads and postbuckling equilibrium paths. Numerical examples are presented that relate to the performances of perfect and imperfect cylindrical shells. Typical results are presented in dimensionless graphical form.

ABSTRACT: A thermal postbuckling analysis is presented for a stiffened laminated cylindrical shell of finite length subjected to a uniform or non-uniform parabolic temperature distribution varying in the circumferential or axial direction. The formulations are based on a boundary layer theory of shell buckling which includes the effects of non-linear prebuckling deformations, non-linear large deflections in the postbuckling range, and initial geometrical imperfections of the shell. The “smeared stiffener” approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine thermal buckling loads and postbuckling equilibrium paths. Numerical examples are presented that relate to the performances of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells. Typical results are presented in dimensionless graphical form and exhibit two different types of thermal postbuckling response.

ABSTRACT: A postbuckling analysis is presented for a stiffened laminated cylindrical shell of finite length subjected to combined axial compression and uniform temperature loading. The two cases of compressive
postbuckling of initially heated shells and of thermal postbuckling of initially compressed shells are considered. The formulations are based on a boundary layer theory of shell buckling, which includes the effects of the nonlinear prebuckling deformation, the nonlinear large deflection in the postbuckling range and the initial geometrical imperfection of the shell. The “smeared-stiffener” approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine buckling loads and postbuckling equilibrium paths. Numerical examples cover the performances of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells with or without initial thermal or compressive stress. Typical results are presented in dimensionless graphical form, and they indicate that the postbuckling response of initially compressed laminated cylindrical shells under thermal load is different from that of mechanically loaded shells with and without initial thermal stress.


ABSTRACT: A postbuckling analysis is presented for a stiffened laminated cylindrical shell of finite length subjected to combined loading of external pressure and a uniform temperature rise. The formulation is based on a boundary layer theory of shell buckling which includes the effects of nonlinear prebuckling deformations, nonlinear large deflections in the postbuckling range and initial geometrical imperfections of the shell. The “smeared stiffener” approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine the interactive buckling loads and the postbuckling equilibrium paths. Numerical examples are presented that relate to the performance of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells. Typical results are presented in dimensionless graphical form for different parameters and loading conditions.


ABSTRACT: A postbuckling analysis is presented for a stiffened, laminated, thin cylindrical shell of finite length subjected to combined loading of external liquid pressure and axial compression. The formulations are based on a boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, nonlinear large deflections in the postbuckling range and initial geometrical imperfections of the shell. The ‘smeared stiffener’ approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine the interactive buckling loads and postbuckling equilibrium paths. Numerical examples cover the performances of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells. Typical results are presented in dimensionless graphical form.
length subjected to combined loading of external liquid pressure and axial compression. The formulations are based on a boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, nonlinear large deflections in the postbuckling range and initial geometrical imperfections of the shell. The ‘smeared stiffener’ approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine the interactive buckling loads and postbuckling equilibrium paths. Numerical examples cover the performances of perfect and imperfect, stiffened and unstiffened cross-ply laminated cylindrical shells. Typical results are presented in dimensionless graphical form.

Hui-Shen Shen (School of Civil Engineering and Mechanics, Shanghai Jiao Tong University, 1954 Hua Shan Road, Shanghai 200030, People's Republic of China), “Hygrothermal effects on the postbuckling of composite laminated cylindrical shells”, Composites Science and Technology, Vol. 60, No. 8, June 2000, pp. 1227-1240, doi:10.1016/S0266-3538(00)00062-2

ABSTRACT: The influence of hygrothermal effects on the buckling and post-buckling of composite laminated cylindrical shells subjected to combined loading of external pressure and axial compression has been investigated by using a micro-to-macro-mechanical analytical model. The material properties of the composite are affected by the variation of temperature and moisture, and are based on a micro-mechanical model of a laminate. The governing equations are based on the classical laminated-shell theory, including hygrothermal effects. The non-linear prebuckling deformations and initial geometric imperfections of the shell were both taken into account. A boundary layer theory of shell buckling is extended to the case of laminated cylindrical shells under hygrothermal environments and a singular perturbation technique is employed to determine the interactive buckling loads and post-buckling equilibrium paths. The numerical illustrations concern the postbuckling behaviour of perfect and imperfect, cross-ply laminated cylindrical shells under different sets of environmental conditions. The results show that the hygrothermal environment has a significant effect on the interactive buckling load as well as post-buckling response of the shell. In contrast, it has a small effect on the imperfection sensitivity.

Hui-Shen Shen (School of Civil Engineering and Mechanics, Shanghai Jiao Tong University, 1954 Hua Shan Road, Shanghai 200030, People's Republic of China), “Buckling and postbuckling of laminated thin cylindrical shells under hygrothermal environments”, Applied Mathematics & Mechanics; Mar2001, Vol. 22 Issue 3, p270

ABSTRACT: The influence of hygrothermal effects on the buckling and postbuckling of composite laminated cylindrical shells subjected to axial compression is investigated using a micro-to-macro-mechanical analytical model. The material properties of the composite are affected by the variation of temperature and moisture, and are based on a micromechanical model of a laminate. The governing equations are based on the classical laminated shell theory, and including hygrothermal effects. The nonlinear prebuckling deformations and initial geometric imperfections of the shell were both taken into account. A boundary layer theory of shell buckling was extended to the case of laminated cylindrical shells under hygrothermal environments, and a singular perturbation technique was employed to determine buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, cross-ply laminated cylindrical shells under different sets of environmental conditions. The influences played by temperature rise, the degree of moisture concentration, fiber volume fraction, shell geometric parameter, total number of plies, stacking sequences and initial geometric imperfections are studied.

References listed at the end of the paper:


ABSTRACT: A postbuckling analysis is presented for a shear deformable cross-ply laminated cylindrical shell of finite length subjected to combined loading of external pressure and axial compression. The governing equations are based on Reddy's higher order shear deformation shell theory with von Kármán–Donnell type of kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of shear deformable laminated cylindrical shells under combined loading cases. A singular perturbation technique is employed to determine interactive buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, unstiffened or stiffened, moderately thick, antisymmetric and symmetric cross-ply laminated cylindrical shells for different values of load-proportional parameters.

ABSTRACT: The effect of hygrothermal conditions on the buckling and postbuckling of shear deformable laminated cylindrical shells subjected to combined loading of axial compression and external pressure is investigated using a micro-to-macro-mechanical analytical model. The material properties of the composite are affected by the variation of temperature and moisture, and are based on a micro-mechanical model of a laminate. The governing equations are based on Reddy's higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity and including hygrothermal effects. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling is extended to the case of shear deformable laminated cylindrical shells under hygrothermal environments and a singular perturbation technique is employed to determine the interactive buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behaviour of perfect and imperfect, moderately thick, cross-ply laminated cylindrical shells under different sets of environmental conditions. The results show that the hygrothermal environment has a significant effect on the interactive buckling load as well as postbuckling response of the shell. In contrast, it has a small effect on the imperfection sensitivity of the shell with a very small geometric imperfection.


ABSTRACT: Thermal postbuckling analysis is presented for a cross-ply laminated cylindrical shell with piezoelectric actuators subjected to the combined action of thermal and electric loads. The temperature field considered is assumed to be a uniform distribution over the shell surface and through the shell thickness and the electric field is assumed to be the transverse component EZ only. The material properties are assumed to be independent of the temperature and the electric field. The governing equations are based on the classical shell theory with von Kármán–Donnell-type of kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of hybrid laminated cylindrical shells. A singular perturbation technique is employed to determine buckling temperatures and postbuckling load-deflection curves. The numerical illustrations concern thermal postbuckling behavior of perfect and imperfect, cross-ply laminated cylindrical thin shells with fully covered or embedded piezoelectric actuators under thermal and electric loads. The results show that the control voltage has a significant effect on the buckling temperature as well as thermal postbuckling response of the shell. In contrast, it has a very small effect on the imperfection sensitivity of (0/90)2S laminated cylindrical shells with piezoelectric actuators.


ABSTRACT: A postbuckling analysis is presented for a cross-ply laminated cylindrical shell with piezoelectric actuators subjected to the combined action of external pressure and heating and under electric loading cases. The temperature rise considered is assumed to be a uniform distribution over the shell surface and through the shell thickness and the electric field is assumed to be the transverse component EZ only. The material properties are assumed to be independent of the temperature and the electric field. The governing equations are
based on the classical shell theory with von Kármán–Donnell type of kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of hybrid laminated cylindrical shells. A singular perturbation technique is employed to determine the interactive buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, cross-ply laminated cylindrical thin shells with fully covered or embedded piezoelectric actuators subjected to combined action of external pressure and heating and under different sets of electric loading cases. The effects played by applied voltage, shell geometric parameter, stacking sequence, as well as initial geometric imperfections are studied.


ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical thin shell of finite length subjected to compressive axial loads and in thermal environments. Material properties are assumed to be temperature-dependent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The governing equations are based on the classical shell theory with von Kármán–Donnell-type of kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of functionally graded cylindrical shells. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of axially loaded, perfect and imperfect, cylindrical thin shells with two constituent materials and under different sets of thermal environments. The effects played by temperature rise, volume fraction distribution, shell geometric parameter, and initial geometric imperfections are studied.


ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical panel of finite length subjected to axial compression in thermal environments. Material properties are assumed to be temperature dependent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The governing equations of a functionally graded cylindrical panel are based on Reddy’s higher order shear deformation shell theory with a von Kármán–Donnell-type of kinematic nonlinearity and including thermal effects. Two cases of the in-plane boundary conditions are considered. The nonlinear prebuckling deformations and initial geometric imperfections of the panel are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of functionally graded cylindrical panels under axial compression. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations
concern the postbuckling behavior of axially loaded, perfect and imperfect, functional graded cylindrical panels with two constituent materials and under different sets of thermal environments. The influences played by temperature rise, volume fraction distributions, the character of in-plane boundary conditions, transverse shear deformation, panel geometric parameters, as well as initial geometric imperfections are studied.

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(2) Department of Building and Construction, City University of, Hong Kong, Kowloon, Hong Kong
ABSTRACT: The effect of local geometric imperfections on the buckling and postbuckling of shear deformable laminated cylindrical shells subjected to combined axial compression and uniform temperature loading is investigated. Two cases of compressive postbuckling of initially heated shells and of thermal postbuckling of initially compressed shells are considered. The governing equations are based on Reddy's higher order shear deformation shell theory with a von Kármán–Donnell-type of kinematic nonlinearity and including thermal effects. The material properties are assumed to be independent of the temperature. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling is extended to the case of shear deformable cross-ply laminated cylindrical shells and a singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the compressive or thermal postbuckling behavior of moderately thick, cross-ply laminated cylindrical shells with local or modal geometric imperfections. The results show that, for the same value of amplitude, the local geometric imperfection has a small effect on the buckling load as well as postbuckling response of the shell than a modal imperfection does.

Hui-Shen Shen (School of Civil Engineering and Mechanics, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China), “Hygrothermal effects on the postbuckling of axially loaded shear deformable laminated cylindrical panels”, Composite Structures, Vol. 56, No. 1, April 2002, pp. 73-85, doi:10.1016/S0263-8223(01)00187-8
ABSTRACT: The effect of hygrothermal conditions on the buckling and postbuckling of shear deformable laminated cylindrical panels subjected to axial compression is investigated using a micro-to-macro-mechanical analytical model. The material properties of the composite are affected by the variation of temperature and moisture, and are based on a micro-mechanical model of a laminate. The governing equations are based on Reddy's higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity and including hygrothermal effects. The nonlinear prebuckling deformations and initial geometric imperfections of the panel are both taken into account. A boundary layer theory of shell buckling is extended to the case of shear deformable laminated cylindrical panels under hygrothermal environments and a singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, moderately thick and thin, cross-ply laminated cylindrical panels under different sets of environmental conditions. The results show that the hygrothermal environment has a significant effect on the buckling load as well as postbuckling response of the panel. In contrast, it has a small effect on the imperfection sensitivity of symmetric cross-ply laminated cylindrical thin panels.
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ABSTRACT: Large deflection and postbuckling responses of functionally graded rectangular plates under transverse and in-plane loads are investigated by using a semi-analytical approach. Material properties are assumed to be temperature-dependent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The plate is assumed to be clamped on two opposite edges and the remaining two edges may be simply supported or clamped or may have elastic rotational edge constraints. The formulations are based on the classical plate theory, accounting for the plate-foundation interaction effects by a two-parameter model (Pasternak-type), from which Winkler elastic foundation can be treated as a limiting case. A perturbation technique in conjunction with one-dimensional differential quadrature approximation and Galerkin procedure are employed in the present analysis. The numerical illustrations concern the large deflection and postbuckling behavior of functionally graded plates with two pairs of constituent materials. Effects played by volume fraction, the character of boundary conditions, plate aspect ratio, foundation stiffness, initial compressive stress as well as initial transverse pressure are studied.

Hui-Shen Shen (School of Civil Engineering and Mechanics, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China), “Postbuckling analysis of pressure-loaded functionally graded cylindrical shells in thermal environments”, Engineering Structures, Vol. 25, No. 4, March 2003, pp. 487-497,
doi:10.1016/S0141-0296(02)00191-8

ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical thin shell of finite length subjected to external pressure and in thermal environments. Material properties are assumed to be temperature-dependent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The governing equations are based on the classical shell theory with von Kármán-Donnell-type of kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of functionally graded cylindrical shells. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of pressure-loaded, perfect and imperfect, cylindrical thin shells with two constituent materials under different sets of thermal environments. The effects played by temperature rise, volume fraction distribution, shell geometric parameter, and initial geometric imperfections are studied. The results reveal that the postbuckling behavior of the FGM shell is stable under external pressure and in thermal environments.

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ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical panel of finite length subjected to lateral pressure in thermal environments. Material properties are assumed to be temperature
dependent, and graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The governing equations of a functionally graded cylindrical panel are based on Reddy’s higher-order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity and include thermal effects. The two straight edges of the panel are assumed to be simply supported and two curved edges are either simply supported or clamped. The nonlinear prebuckling deformations and initial geometric imperfections of the panel are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflection in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of functionally graded cylindrical panels. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of simply supported, pressure-loaded, perfect and imperfect, functionally graded cylindrical panels with two constituent materials under different sets of thermal environments. The influences played by temperature rise, volume fraction distributions, transverse shear deformation, panel geometric parameters, as well as initial geometric imperfections, are studied.


ABSTRACT: An elastic double-shell model is presented for the buckling and postbuckling of a double-walled carbon nanotube subjected to external hydrostatic pressure. The analysis is based on a continuum mechanics model in which each tube of a double-walled carbon nanotube is described as an individual elastic shell and the interlayer friction is negligible between the inner and outer tubes. The governing equations are based on higher order shear deformation shell theory with a von Kármán–Donnell-type of kinematic nonlinearity. The van der Waals interaction between the inner and outer nanotubes and the nonlinear prebuckling deformations of the shell are both taken into account. A boundary layer theory of shell buckling is extended to the case of double-
walled carbon nanotubes under hydrostatic pressure. A singular perturbation technique is employed to
determine the buckling loads and postbuckling equilibrium paths. Numerical results reveal that the single-
walled carbon nanotube has a stable postbuckling path, whereas the double-walled carbon nanotube has an
unstable postbuckling behavior due to the presence of van der Waals interaction forces.

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“Postbuckling of Axially Loaded Functionally Graded Cylindrical Panels with Piezoelectric Actuators in
ABSTRACT: A compressive postbuckling analysis is presented for a functionally graded cylindrical panel with
piezoelectric actuators subjected to the combined action of mechanical, electrical, and thermal loads. The
temperature field considered is assumed to be of uniform distribution over the panel surface and through the
panel thickness and the electric field considers only the transverse component EZ. The material properties of the
presently considered functionally graded materials (FGMs) are assumed to be temperature-dependent, and
graded in the thickness direction according to a simple power law distribution in terms of the volume fractions
of the constituents, whereas the material properties of the piezoelectric layers are assumed to be independent of
the temperature and the electric field. The governing equations are based on a higher-order shear deformation
theory with a von Kármán–Donnell-type of kinematic nonlinearity. A boundary layer theory for shell buckling is
extended to the case of hybrid FGM cylindrical panels of finite length. The nonlinear prebuckling deformations
and initial geometric imperfections of the panel are both taken into account. A singular perturbation technique is
employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations
concern the compressive postbuckling behavior of perfect and imperfect FGM cylindrical panels with fully
covered piezoelectric actuators, under different sets of thermal and electrical loading conditions. The effects due
to temperature rise, volume fraction distribution, applied voltages, panel geometric parameters, in-plane
boundary conditions, as well as initial geometric imperfections are studied.

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“Postbuckling of FGM cylindrical shells under combined axial and radial mechanical loads in thermal
environments”, International Journal of Solids and Structures, Vol. 42, Nos. 16-17, August 2005, pp. 4641-
4662, doi:10.1016/j.ijsolstr.2005.02.005
ABSTRACT: A postbuckling analysis is presented for a shear deformable functionally graded cylindrical shell
of finite length subjected to combined axial and radial loads in thermal environments. Heat conduction and
temperature-dependent material properties are both taken into account. The temperature field considered is
assumed to be a uniform distribution over the shell surface and varied in the thickness direction only. Material
properties are assumed to be temperature-dependent, and graded in the thickness direction according to a simple
power law distribution in terms of the volume fractions of the constituents. The formulations are based on a
higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity. A
boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell, is extended to the case of functionally graded cylindrical shells. A singular perturbation technique is employed to determine the interactive buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect cylindrical shells with two constituent materials subjected to combined axial and radial mechanical loads and under different sets of thermal environments. The results reveal that the temperature field and volume fraction distribution have a significant effect on the postbuckling behavior, but they have a small effect on the imperfection sensitivity of the functionally graded shell.


ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical shell with piezoelectric actuators subjected to axial compression combined with electric loads in thermal environments. Heat conduction and temperature-dependent material properties are both taken into account. The temperature field considered is assumed to be a uniform distribution over the shell surface and varied in the thickness direction and the electric field is assumed to be the transverse component EZ only. The material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents, and the material properties of both FGM and piezoelectric layers are assumed to be temperature dependent. The governing equations are based on a higher order shear deformation theory with a von Kármán-Donnell-type of kinematic nonlinearity. A boundary layer theory of shell buckling is extended to the case of FGM hybrid laminated cylindrical shells of finite length. A singular perturbation technique is employed to determine the buckling load and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of axially loaded, perfect and imperfect, FGM cylindrical shells with fully covered piezoelectric actuators under different sets of thermal and electric loading conditions. The results reveal that temperature dependency, temperature change and volume fraction distribution have a significant effect on the buckling load and postbuckling behavior of FGM hybrid cylindrical shells. In contrast, the control voltage has a very small effect on the buckling load and postbuckling behavior, and it has almost no effect on the imperfection sensitivity of the FGM hybrid cylindrical shells.

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ABSTRACT: A postbuckling analysis is presented for a functionally graded cylindrical shell with piezoelectric actuators subjected to lateral or hydrostatic pressure combined with electric loads in thermal environments. Heat conduction and temperature-dependent material properties are both taken into account. The temperature field considered is assumed to be a uniform distribution over the shell surface and varied in the thickness direction and the electric field considered only has non-zero-valued component EZ. The material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents, and the material properties of both
FGM and piezoelectric layers are assumed to be temperature-dependent. The governing equations are based on a higher order shear deformation theory with a von Kármán–Donnell-type of kinematic nonlinearity. A boundary layer theory of shell buckling is extended to the case of FGM hybrid laminated cylindrical shells of finite length. A singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of pressure-loaded, perfect and imperfect, FGM cylindrical shells with fully covered piezoelectric actuators under different sets of thermal and electric loading conditions. The results reveal that temperature dependency, temperature change and volume fraction distribution have a significant effect on the buckling pressure and postbuckling behavior of FGM hybrid cylindrical shells. In contrast, the control voltage only has a very small effect on the buckling pressure and postbuckling behavior of FGM hybrid cylindrical shells.

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“Postbuckling analysis of axially loaded piezolaminated cylindrical panels with temperature dependent properties”, Composite Structures, Vol. 79, No. 3, July 2007, pp. 390-403,
doi:10.1016/j.compstruct.2006.02.018

ABSTRACT: A postbuckling analysis is presented for a shear deformable laminated cylindrical panel with piezoelectric actuators subjected to the combined action of mechanical, electric and thermal loads. The temperature field considered is assumed to be a uniform distribution over the panel surface and through the panel thickness and the electric field considered only has non-zero-valued component EZ. The material properties are assumed to be dependent of the temperature. The governing equations are based on a higher order shear deformation theory with a von Kármán–Donnell-type of kinematic non-linearity. The non-linear prebuckling deformations and initial geometric imperfections of the panel are both taken into account. A boundary layer theory of shell buckling is extended to the case of hybrid laminated cylindrical panels of finite length. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the compressive postbuckling behavior of perfect and imperfect, cross-ply laminated cylindrical panels with fully covered or embedded piezoelectric actuators under different sets of thermal and electric loading conditions. The results reveal that the temperature dependency and temperature rise have a significant effect on the buckling load and postbuckling behavior of piezolaminated cylindrical panels, but they only have a very small effect on the imperfection sensitivity of the thin panels. In contrast, the control voltage has a small effect on the buckling load, postbuckling behavior and imperfection sensitivity of piezolaminated cylindrical panels.

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ABSTRACT: A boundary layer theory for the buckling and postbuckling of anisotropic laminated thin shells is developed. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-
reinforced. It is also assumed that the well-known von Kármán nonlinear strain–displacement relationships are valid. The governing equations with transverse displacement and stress function as independent variables are deduced to a boundary layer type, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell. A postbuckling analysis is presented for axially loaded, perfect and imperfect, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The joint effects played by anisotropy, nonlinear prebuckling deformations, as well as initial geometric imperfections are studied. The new finding is that there exists a compressive stress along with an associate shear stress and twisting when the anisotropic laminated cylindrical shell is subjected to axial compression, and all the results published previously need to be re-examined.

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ABSTRACT: A boundary layer theory for the buckling and postbuckling of anisotropic laminated thin shells is extended to the loading case of external pressure. A singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of pressure-loaded, perfect and imperfect, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The new finding is that there exists a circumferential stress along with an associate shear stress and twisting when the anisotropic shell is subjected to lateral pressure, and all the results published previously need to be re-examined. The results confirm that the effect of the boundary layer on the solution of a pressurized shell is of the order $\mu^{3/2}$. The postbuckling equilibrium path is stable for the moderately long shell under external pressure and the shell structure is virtually imperfection-insensitive, whereas the postbuckling equilibrium path is unstable for a very short cylindrical shell under the same loading case.

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ABSTRACT: A boundary layer theory for the buckling and postbuckling of anisotropic laminated thin shells is extended to the loading case of torsion. A singular perturbation technique is employed to determine the buckling load and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of twist, perfect and imperfect, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The new finding is that there exists a shear stress along with an associate compressive stress when the anisotropic shell is subjected to torsion, and all the results published previously need to be re-examined. The results confirm that the effect of the boundary layer on the solution of a twist shell is of the order $\mu^{5/4}$. The postbuckling equilibrium path is unstable for the moderately long shell subjected to
torsion and the shell structure is less sensitive to initial imperfections than in the case of axial compression.

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ABSTRACT: A postbuckling analysis is presented for an anisotropic laminated cylindrical shell of finite length subjected to combined loading of axial compression and torsion. The governing equations are based on classical shell theory with von Kármán–Donnell-type of kinematic nonlinearity and including the extension–twist, extension–flexural and flexural–twist couplings. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine interactive buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, anisotropic laminated cylindrical shells for different values of load-proportional parameters. The results show that the postbuckling characteristics depend significantly upon the load-proportional parameter. The results reveal that in combined loading cases the postbuckling equilibrium path is unstable and the shell structure is imperfection-sensitive.


ABSTRACT: Compressive post-buckling under thermal environments and thermal post-buckling due to uniform temperature field or heat conduction are presented for a shear deformable functionally graded cylindrical shell with piezoelectric fiber reinforced composite (PFRC) actuators. The material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents, and the material properties of both FGM and PFRC layers are assumed to be temperature-dependent. The governing equations are based on a higher order shear deformation shell theory that includes thermopiezoelectric effects. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine buckling loads (temperature) and postbuckling equilibrium paths. The numerical illustrations concern the compressive and thermal post-buckling behavior of perfect and imperfect FGM cylindrical shells with fully covered PFRC actuators under different sets of thermal and electric loading conditions, from which results for monolithic piezoelectric actuators are obtained as comparators. The results reveal that, in the compressive buckling case, the control voltage only has a small effect on the postbuckling load-deflection curves of the shell with PFRC actuators, whereas in the thermal buckling case, the effect of control voltage is more pronounced for the shell with PFRC actuators, compared with the results of the same shell with monolithic piezoelectric actuators.

References listed at the end of the paper:
effects. A singular perturbation technique is employed to determine the buckling loads and postbuckling deformation shell theory with a von Kármán expressed as a linear function of temperature. The governing equations are based on a higher order sh

ABSTRACT: A postbuckling analysis is presented for a three-dimensional textile composite cylindrical shell of finite length subjected to axial compression in thermal environments. Based on a micro–macro-mechanical model, a three-dimensional textile composite may be as a cell system and the geometry of each cell is deeply dependent on its position in the cross-section of the cylindrical shell. The material properties of epoxy are expressed as a linear function of temperature. The governing equations are based on a higher order shear deformation shell theory with a von Kármán–Donnell-type of kinematic nonlinearity and including thermal effects. A singular perturbation technique is employed to determine the buckling loads and postbuckling
equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, braided composite cylindrical shells with different values of geometric parameter and of fiber volume fraction in different cases of thermal environmental conditions. The results show that the shell has lower buckling load and postbuckling path when the temperature-dependent properties are taken into account. The results reveal that the temperature changes, the fiber volume fraction, and the shell geometric parameter have a significant effect on the buckling load and postbuckling behavior of textile composite cylindrical shells.

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ABSTRACT: A postbuckling analysis is presented for a shear deformable anisotropic laminated cylindrical shell of finite length subjected to torsion. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The governing equations are based on a higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity and including the extension/twist, extension/flexural and flexural/twist couplings. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The results confirm that there exists a shear stress along with an associate compressive stress when the shell is subjected to torsion. The postbuckling equilibrium path is stable for a moderately thick laminated cylindrical shell under torsion and the shell structure is virtually imperfection-insensitive.

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ABSTRACT: A postbuckling analysis is presented for a 3D braided composite cylindrical shell of finite length subjected to torsion in thermal environments. Based on a micro–macro–mechanical model, a 3D braided composite may be as a cell system and the geometry of each cell is deeply dependent on its position in the cross section of the cylindrical shell. The material properties of epoxy are expressed as a linear function of temperature. The governing equations are based on a higher-order shear deformation shell theory with a von Kármán–Donnell-type of kinematic nonlinearity and including thermal effects. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, braided composite cylindrical shells with different values of geometric parameter and of fiber volume fraction in different cases of thermal environmental conditions. The results show that the shell has lower buckling loads and postbuckling paths when the temperature-dependent properties are taken into account. The results reveal that the temperature changes, the fiber volume fraction, and the shell geometric parameter have a significant effect on the buckling load and postbuckling behavior of braided composite cylindrical shells. They also confirm that the torsional postbuckling
equilibrium path of a moderately thick shell is stable and the shell structure is virtually imperfection–insensitive.

Hui-Shen Shen (School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, People's Republic of China and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, People's Republic of China), “Post-buckling of internal-pressure-loaded laminated cylindrical shells surrounded by an elastic medium”, The Journal of Strain Analysis for Engineering Design August 1, 2009 vol. 44 no. 6 439-458, DOI: 10.1243/03093247JSA505

ABSTRACT: This paper presents a study on the post-buckling response of an anisotropic laminated cylindrical shell of finite length embedded in a large outer elastic medium and subjected to internal pressure in thermal environments. The surrounding elastic medium is modelled as a tensionless Pasternak foundation reacting in compression only. The governing equations are based on higher-order shear deformation shell theory with von Kármán–Donnell kinematic non-linearity and including extension–twist, extension–flexural, and flexural–twist couplings. The thermal effects are also included, and the material properties are assumed to be temperature dependent. Non-linear prebuckling deformations and the initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the post-buckling response of the shells, and an iterative scheme is developed to obtain numerical results without using any assumption concerning the shape of the contact region between the shell and the elastic medium. Numerical illustrations concern the buckling and post-buckling response of cross-ply and symmetric angle-ply laminated shells surrounded by an elastic medium of tensionless foundation of the Pasternak type, from which results for conventional elastic foundations are obtained as comparators. The results reveal that unilateral constraints have a significant effect on the post-buckling response of shells subjected to internal pressure in thermal environments when the foundation stiffness is sufficiently large.


ABSTRACT: A version of nonlocal elasticity theory is employed to develop a nonlocal shear deformable shell model. The governing equations are based on higher order shear deformation shell theory with a von Kármán-type of kinematic nonlinearity and include small scale effects. These equations are then used to solve buckling problems of microtubules (MTs) embedded in an elastic matrix of cytoplasm subjected to bending. The surrounding elastic medium is modeled as a Pasternak foundation. The thermal effects are also included and the material properties are assumed to be temperature-dependent. The small scale parameter $e_0a$ is estimated by matching the buckling curvature of MTs observed from measurements with the numerical results obtained from the nonlocal shear deformable shell model. The numerical results show that buckling loads are decreased with the increasing small scale parameter $e_0a$. The results reveal that the lateral constraint has a significant effect on the buckling moments of a microtubule when the foundation stiffness is sufficiently large.

References listed at the end of the paper:
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ABSTRACT: Based on theory of nonlocal elasticity, a nonlocal double-elastic beam model is developed for the free transverse vibrations of double-walled carbon nanotubes. The effect of small length scale is incorporated in the formulation. With this nonlocal double-elastic beam model, explicit expressions are derived for natural frequencies and associated amplitude ratios of the inner to the outer tubes for the case of simply supported double-walled carbon nanotubes. The effect of small length scale on the properties of vibrations is discussed. It is demonstrated that the natural frequencies and the associated amplitude ratios of the inner to the outer tubes are dependent upon the small length scale. The effect of small length scale is related to the vibrational mode and the aspect ratio.

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ABSTRACT: Elastic buckling of a long double-walled carbon nanotube embedded in an elastic medium and subjected to a far-field hydrostatic pressure is analyzed using the energy method. The study is on the basis of elastic-shell models at nano-scale, and the effect of van der Waals forces on the buckling is considered. The double-walled carbon nanotube is assumed to be thin and the tube is taken to be perfectly bonded to the surrounding medium. Both normal and shear stresses at the outer tube-medium interface are included. The difference between the Poisson's ratio of the tube and that of the elastic medium is taken into account. An expression is derived relating the external pressure to the buckling mode number, from which the critical pressure can be obtained. As a result, the critical pressure is dependent on the inner radius-to-thickness ratio, the material parameters of the elastic medium, and the van der Waals force.

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ABSTRACT: A nonlocal multiple-shell model is developed for the elastic buckling of multi-walled carbon nanotubes under uniform external radial pressure on the basis of theory of nonlocal elasticity. The effect of small length scale is incorporated in the formulation. An explicit expression is derived for the critical buckling pressure for a double-walled carbon nanotube. The influence of the small length scale on the buckling pressure is examined. It is concluded that the critical buckling pressure for a carbon nanotube could be overestimated by the classic (local) shell model due to ignoring the effect of small length scale.


ABSTRACT: Buckling and post-buckling analysis is presented for axially compressed double-walled carbon nanotubes (CNTs) embedded in an elastic matrix in thermal environments. The double-walled carbon nanotube is modeled as a nonlocal shear deformable cylindrical shell, which contains small scale effects and van der Waals interaction forces. The surrounding elastic medium is modeled as a tensionless Pasternak foundation. The post-buckling analysis is based on a higher order shear deformation shell theory with the von Kármán–Donnell-type of kinematic nonlinearity. The thermal effects are also included and the material properties are assumed to be temperature-dependent and are obtained from molecular dynamics (MD) simulations. The nonlinear prebuckling deformations of the shell and the initial local point defect, which is simulated as a dimple on the tube wall, are both taken into account. A singular perturbation technique is employed to determine the post-buckling response of the tubes and an iterative scheme is developed to obtain numerical results without
using any assumption on the shape of the contact region between the tube and the elastic medium. The small scale parameter $e_0a$ is estimated by matching the buckling loads of CNTs observed from the MD simulation results with the numerical results obtained from the nonlocal shear deformable shell model. Numerical solutions are presented to show the post-buckling behavior of CNTs surrounded by an elastic medium of conventional and tensionless Pasternak foundations. The results show that buckling and post-buckling behavior of CNTs is very sensitive to the small scale parameter $e_0a$. The results reveal that the unilateral constraint has a significant effect on the post-buckling response of CNTs when the foundation stiffness is sufficiently large.

References listed at the end of the paper:

ABSTRACT: Buckling and postbuckling analysis is presented for axially compressed microtubules (MTs) embedded in an elastic medium. The governing equations are based on higher order shear deformation shell theory with a von Kármán-Donnell-type of kinematic nonlinearity and include the extension-twist and flexural-twist couplings.
The thermal effects are also included and the material properties are assumed to be temperature-dependent. The small scale parameter $e(0)$ a is estimated by matching the buckling load from their vibrational behavior of MTs with the numerical results obtained from the nonlocal shear deformable shell model. The numerical results show that buckling load and postbuckling behavior of MTs are very sensitive to the small scale parameter $e(0)$ a. The results reveal that the MTs under axial compressive loading condition have an unstable postbuckling path, and the lateral constraint has a significant effect on the postbuckling response of a microtubule when the foundation stiffness is sufficiently large.

References listed at the end of the paper:

Hui-Shen Shen (School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, People’s Republic of China and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200030, People’s Republic of China), “Composite Structures, Vol. 93, No. 10, September 2011, pp.2496-2503, doi:10.1016/j.compstruct.2011.04.005

ABSTRACT: A postbuckling analysis is presented for nanocomposite cylindrical shells reinforced by single-walled carbon nanotubes (SWCNTs) subjected to lateral or hydrostatic pressure in thermal environments. The multi-scale model for functionally graded carbon nanotube-reinforced composite (FG-CNTRC) shells under external pressure is proposed and a singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium path. Numerical results for pressure-loaded, perfect and imperfect, FG-CNTRC cylindrical shells are obtained under different sets of thermal environmental conditions. The results for uniformly distributed CNTRC shell, which is a special case in the present study, are compared with those of the FG-CNTRC shell. The results show that the linear functionally graded reinforcements can increase the buckling pressure as well as postbuckling strength of the shell under external pressure. The results reveal that the carbon nanotube volume fraction has a significant effect on the buckling pressure and postbuckling behavior of CNTRC shells.

ABSTRACT: There has been a growing interest in the active suppression of noise in aircraft interiors in the recent past. While there are already many different technical solutions available in the form of active noise controllers using loudspeakers and structural sources, there is a need for low-profile acoustic sources that could be used for generating large volume velocities with high efficiency and low control effort. This paper presents an investigation into the potential usage of shallow-spherical-shell actuators (also known as RAINBOW actuators), made of piezoelectric materials supported on a flexible foundation along the edge, for such applications. The actuators have been modeled analytically and the effects of curvature, mount stiffness, mass and other parameters on the natural frequencies, linear stroke and volume velocity have been studied. Simulation results are presented and the potential for using the actuator as an efficient acoustic source has been discussed.


ABSTRACT: We probe the local mechanical properties of microtubules at the nanometer scale by radial indentation with a scanning force microscope tip. We find a linear elastic regime that can be described by both thin-shell theory and finite element methods, in which microtubules are modeled as hollow tubes. We also find a nonlinear regime and catastrophic collapse of the microtubules under large loads. The main physics of protein shells at the nanometer scale shows simultaneously aspects of continuum elasticity in their linear response, as well as molecular graininess in their nonlinear behavior.

References listed at the end of the paper:
[11] The role of taxol in the mechanical properties of MT remains unclear, with prior experiments showing both increased and decreased rigidity. B. Mickey and J. Howard, J. Cell Biol. 130, 909 (1995); see also Ref. [3].
A linear response has also been shown to be possible for the indentation of bacteria, due primarily to turgor pressure [M. Arnoldi, M. Fritz, E. Bauerlein, M. Radmacher, E. Sackmann, and A. Boulbitch, Phys. Rev. E 62, 1034 (2000)].


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ABSTRACT: This paper presents an investigation on the buckling and postbuckling of double-walled carbon nanotubes (CNTs) subjected to torsion in thermal environments. The double-walled carbon nanotube is modeled as a nonlocal shear deformable cylindrical shell which contains small scale effects and van der Waals interaction forces. The governing equations are based on higher order shear deformation shell theory with a von Kármán–Donnell-type of kinematic non-linearity and including the extension/twist, extension/flexural and flexural/twist couplings. The thermal effects are also included and the material properties are assumed to be temperature-dependent and are obtained from molecular dynamics (MD) simulations. The small scale parameter e0a is estimated by matching the buckling torque of CNTs observed from the MD simulation results with the numerical results obtained from the nonlocal shear deformable shell model. The results show that buckling torque and postbuckling behavior of CNTs are very sensitive to the small scale parameter e0a. The results reveal that the size-dependent and temperature-dependent material properties have a significant effect on the torsional buckling
and postbuckling behavior of both single-walled and double-walled CNTs.


ABSTRACT: This paper presents an investigation on the buckling and postbuckling of microtubules (MTs) subjected to a uniform external radial pressure in thermal environments. The microtubule is modeled as a nonlocal shear deformable cylindrical shell which contains small scale effects. The governing equations are based on higher order shear deformation shell theory with a von Kármán-Donnell-type of kinematic nonlinearity and include the extension-twist and flexural-twist couplings. The thermal effects are also included and the material properties are assumed to be temperature-dependent. A singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium paths. The small scale parameter \( e(0)a \) is estimated by matching the buckling pressure of MTs measured from the experiments with the numerical results obtained from the nonlocal shear deformable shell model. The numerical results show that buckling pressure and postbuckling behavior of MTs are very sensitive to the small scale parameter \( e(0)a \). The results reveal that the 13_3 microtubule has a stable postbuckling path, whereas the 13_2 microtubule has an unstable postbuckling behavior due to the presence of skew angles.


ABSTRACT: Numerical simulations for local buckling and postbuckling behavior of plant stems are presented under two combined loading cases: (1) axial compression (caused by axial grains) combined with wind pressure; and (2) bending moment (caused by eccentric axial grains) combined with wind pressure. Based on its microstructure, a hollow plant stem is modeled as a stringer stiffened multiwalled shell. The material properties of the stem are assumed to be orthotropic. The nonlinear governing equations for buckling and postbuckling of plant stems are solved through arc-length method along with Newton–Raphson technique. The numerical calculations are carried out using the finite element package ABAQUS. The results show that the postbuckling equilibrium path is unstable for plant stems subjected to axial compression or bending combined with relatively low values of wind pressure. Large reduction in buckling load and in postbuckling strength can be found even if the applied wind pressure is relatively small, which results in the easy occurrence of stem lodging.

D. Dinkler and J. Pontow (Instutüt für Static, Technische Universität, Braunschweig, Germany), “A Model to Evaluate Limit Loads of Imperfection Sensitive Shells”, Computational Mechanics, WCCM VI in conjunction with APCOM'04, Sept 5-10, 2004, Beijing, China, published by Tsinghua Universityhy Press and Springer-Verlag

ABSTRACT: The paper deals with the development and application of stability estimates for structures under time-dependent loads. Applications to bars and shell structures show the variety of the phenomena in dynamic buckling behaviour of elastic structures in case of impulsive loading. The judgement of the stability is based on energy norms, that may be used for investigation of safety against loss of stability by buckling. Static analysis is used to compute the critical strain energy which is necessary to effect the transition from the pre{ to the postbuckling range. Starting from a stable state of equilibrium the presented
procedure allows to decide whether the structure stays for a certain load history within the critical bounds, which separate the motion around the prebuckling state from the motion in a postbuckling region. The stability is proved by comparing the load induced energy and the critical strain energy.

References listed at the end of the paper:


Summary: The paper deals with the stability of perturbation sensitive shells. The perturbation energy concept developed by Dinkler/Kroplin [2] is applied to estimate the static and kinetic limit loads of different perturbation sensitive shells by a single energy value, the perturbation energy. The material behaviour is described by a rate-independent model for elasto-plasticity.

References:


Dieter Dinkler and Oliver Knoke (Institut für Statik, Technische Universität Braunschweig), “Elasto-Plastic Limit Loads of Cylinder-Cone Configurations”, Journal of Theoretical and Applied Mechanics 41, 3, pp. 443-
ABSTRACT: The paper presents a procedure for computation of the limit loads of imperfection-sensitive shells including plastic deformations. On the basis of strain energy of shells, the worst case scenario for critical perturbations at fixed load levels is investigated. Limit loads of cylindrical and conical shells under combined actions are compared to European design rules. The concept is applied to more general buckling cases of combined shell structures.

References listed at the end of the paper:
8. Dinkler D., Spohr I., 1998, Elastic limit loads of cylindrical shells under combined axial and radial compression (in german), Bauingenieur, 73, Springer Verlag


ABSTRACT: The paper deals with the perturbation energy concept and its application to stability of imperfection sensitive structures under time-dependent loads. The evaluation of the stability is based on energy norms, which may be used for investigation of safety against buckling. Starting from a stable state of equilibrium the presented procedure allows to decide whether the structure stays for a certain load history within critical bounds, which separate the motion round the prebuckling state from a motion in the postbuckling region. The stability is proved by comparing the critical energy calculated by a static analysis and the load induced energy. Applications to a truss and a spherical shell illustrate the variety of the phenomena in dynamic buckling behaviour of elastic structures in case of impulsive loading and the accuracy of the proposed method.

Eyassu Woldesenbet, “Buckling analysis of Grid stiffened composite cylinders”, ICCEMCE-03, International

ABSTRACT: Due to their high stiffness to mass ratio, stiffened cylindrical composite shells are major components of Aerospace and Aircraft industries. These structures are employed in fuselage and fuel tank applications, and are usually subjected to combinations of compressive, shear or transverse loads. Usually the failure mode associated with these structures is buckling. This failure mode is further subdivided into ‘local skin and/or stiffener buckling’, and ‘universal buckling’.

References:

Anderson, John Palmer (Georgia Institute of Technology), “Buckling of a spherical sandwich shell under uniform external pressure”, Ph.D. Dissertation, Georgia Tech Library and Information Center, Georgia Institute of Technology, May, 1966


ABSTRACT: This paper discusses the recent experimental and analytical studies related to buckling of fabricated steel cylinders subjected to combinations of axial compression load and external pressure. The effects of initial imperfections and residual stresses are being investigated. A description of the test facilities and model geometries are given. The D/t ratios of the models range from 48 to 1000. The test programs include ring and stringer stiffened as well as ring stiffened cylinders.


ABSTRACT: This paper discusses the recent experimental and analytical studies related to buckling design of fabricated steel shells. The effects of initial imperfections and residual stresses on buckling are under investigation. The test programs include ring and stringer stiffened as well as ring stiffened cylinders subject to combinations of axial compression and external pressure. Proposed modifications to ASME Code Case N-284, “Metal Containment Shell Buckling Design Methods,” as well as the need for additional research, are discussed.
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ABSTRACT: An outline and the status of the NRC research program with the Los Alamos National Laboratory is presented.

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ABSTRACT: Buckling of freestanding nuclear steel containment buildings from dynamic base excitation was investigated in a combined experimental/numerical program. A polycarbonate scale model of a containment building was excited with scaled earthquake transients and single-frequency harmonic transients to determine the peak base acceleration levels required to induce buckling. Buckling was identified using recorded signals from strain gages and accelerometers, with high-speed video records, and by audibility. Experimental results are compared with numerical results obtained by using a freezing-in-time technique. The results are preliminary, since several more tests are to be performed. However, the limited data obtained indicate that the freezing-in-time technique approximates the required acceleration levels reasonably well, although not conservatively. Additional experiments are described that will take containment asymmetries into account, as well as use instrumentation that will provide more accurate measures of the occurrence of buckling.


ABSTRACT: Two aspects of buckling of a free-standing nuclear steel containment building were investigated in a combined experimental and analytical program. In the first part of the study, the response of a scale model of a containment building to dynamic base excitation is investigated. A simple harmonic signal was used for preliminary studies followed by experiments with scaled earthquake signals as the excitation source. The experiments and accompanying analyses indicate that the scale model response to earthquake-type excitations is very complex and that current analytical methods may require that a dynamic capacity reduction factor be incorporated. The second part of the study quantified the effects of framing at large penetrations on the static buckling capacity of scale model containments. Results show little effect from the framing for the scale models constructed from the polycarbonate, Lexan. However, additional studies with a model constructed of the prototypic steel material are recommended.

Funahashi, T.; Naruse, Y. (Toshiba Corp., Yokohama (Japan)); Mieda, T. (Ishikawajima-harima Heavy Industries Co., Ltd., Yokohama (Japan)); Oyamada, O.; Kume, T. (Hitachi Ltd., Hitachi (Japan)); Freiman, M. (Siemens AG, Offenbach am Main (Germany, F.R.)), “Study of spherical steel shell buckling”, Transactions of
ABSTRACT: Buckling test and linear buckling analysis has been performed on the spherical steel shell structure. Measured buckling loads are less than the values obtained by analysis and the knock-down factors are usually defined as the ratios of the experimental buckling load to the analytical values. The knock-down factors derived from the study are: for horizontal direction: 0.47 ~ 0.57 and for vertical direction: 0.40 ~ 0.60. The allowable buckling stress can be evaluated by using a knock-down factor and a safety factor. A simple and practical method for evaluating the allowable buckling stress for spherical shell has been proposed as a result of the study.


ABSTRACT: A simplified method is presented for evaluating the seismic buckling capacity of unstiffened, free-standing steel containment structures. The method is consistent with current US Nuclear Regulatory Commission seismic design standards and with containment buckling interaction equations given in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code which includes the influence of geometrical imperfections of the shell on buckling. Stresses to be considered in the interaction equations are determined from beam theory using standard response spectrum analysis. An empirical correction factor is developed to account for hoop stresses that are not explicitly represented in the beam theory. As the results of these analyses are very sensitive to the damping that is assumed, the extensive three-dimensional finite element analyses that were performed to develop the hoop stress reduction factor were also used to study the sensitivity of containment buckling to the assumed damping. Experiments on model containment structures were then performed to further investigate the damping properties exhibited by these structures. The study in concluded by showing that the simplified method reasonably predicts seismic buckling capacities when compared with independently determined predictions from detailed finite element analyses.


PARTIAL INTRODUCTION: The special feature of pool type fast breeder reactor is the usage of very large sized thin shell structures for its reactor vessels. Due to the large diameter to thickness ratio (around 700 to 900), design of these vessels poses challenging structural mechanics problems particularly under seismic loading. An important threat to structural integrity of reactor vessels is the buckling risk during seismic events…

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ABSTRACT: This paper presents the results of an experimental study on the buckling of scaled-down models of the inner vessel used in nuclear reactor structures. The inner vessel, a shell of composite geometry, consists of two cylindrical shells connected by conical and torus shells. There are six stand-pipes on the conical portion of the vessel carrying heat exchangers and pumps. Scaled-down models of the inner vessel are made by the conventional fabrication methods (rolling, welding) and are tested in the present study. The test setup consists of a loading system for applying concentrated load on the stand-pipes, an air compressor for applying internal pressure and the related instrumentation. Imperfection scans are carried out in a specially fabricated experimental setup using linear variable differential transformers (LVDTs) before and during loading. Using the scanned raw data, the initial geometric imperfections and eccentricity between the LVDTs and the specimen axes at different axial locations are calculated. The results show that the maximum initial imperfections are on the order of 1.75 times the wall thickness; generally, the growth of deformation patterns with loading resembles the shapes of initial imperfections, and the growth is predominant on lower cylinder and torus regions. The general purpose, finite element-based software, ABAQUS, is used to obtain the analytical values. The initial imperfections measured on the experimental models are incorporated into the finite element models. The agreement between experimental and analytical buckling loads is within about 30 percent error.

References listed at the end of the paper:
transmitted appropriately to 3D shell geometries for the buckling analysis. In view of high computational time needed for carrying out buckling analysis at every time increment, the elastoplastic analysis is carried out only at a few critical time steps which are identified based on strain energies that are associated with the shear and compressive stresses developed at the portions of the vessels prone to buckle. The shear buckling of main vessel straight portion and buckling of toroidal portion of inner vessel and thermal baffles are found to be important. The possible randomness of support excitation time histories is accounted for by compressing as well as expanding the nominal time histories by 10%. Buckling strength reduction factors due to the initial geometrical imperfections are adopted from the literature. The inner vessel is found to be the most critical component which buckles under seismic forces induced by a safe shutdown earthquake with a load multiplier of 1.52, which is higher than the minimum factor of safety of 1.3 required as per the design code RCC-MR [RCC-MR: edition, 2002. Design and construction rules for mechanical components for FBR nuclear islands, vol. 1, section I, subsection B. AFCEN, Paris, in press] for service level D conditions.


ABSTRACT: This document is described as the 5th Edition of the ECCS European Recommendations for the Buckling of Steel Shells. It is the successor to the 4th Edition, published in 1988. In the 20 years since the publication of the 4th Edition in 1988, much has changed in the field of metal shell buckling. Extensive research has been undertaken, much new knowledge has been developed, and powerful computational modelling has transformed the field, though much design is still conducted by hand calculation. These changes are reflected in this 5th Edition. The 5th Edition quotes extensively from the Eurocode EN 1993-1-6 (2007) and is completely compatible with that standard. However, the Eurocode has no commentary, so the meaning, limitations and origins of many rules are not always clear. This 5th Edition provides an extensive commentary on the existing rules related to buckling in the Eurocode, but extends far beyond it in giving recommendations, expansions, advice and warnings, explanations and examples, all of which should give the user considerably more insight and confidence in applying the rules of EN 1993-1-6.

P. A. Cooper, C. B Dexter, “Buckling of conical shell with local imperfections”, eBook release: July 2010


ABSTRACT: Plastic zone method of advanced analysis, which uses shell elements to model the entire structure, is the most accurate method available to predict the ultimate strength and behavior of steel frames. The disadvantage of such full shell plastic zone models is that it is computationally expensive and hence its use is limited to small structures. Beam elements in commercial finite element packages can model residual stress and capture spread of plasticity, but cannot model local buckling of plates that the member is made up of, which leads to unloading and failure in steel frames. A hybrid model using shell elements only in the regions vulnerable to elastic or inelastic local buckling and beam elements in other locations could overcome this limitation of full beam element model. The issues in using this hybrid model are, knowing a priori the location and length of the shell element region and connecting the beam and shell regions without any artificial stress concentrations or incompatible displacements. In this study, in addition to addressing these issues, the hybrid model is systematically evaluated by studying its performance in structural elements. It is seen that the hybrid
model strength predictions has an average error of only 0.91% but requires on an average 83% less computational time when compared to the full shell plastic zone models.

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ABSTRACT: The availability of high strength steels and concrete leads to the use of thin steel plates in concrete-filled steel tubular beam–columns. However, the use of thin steel plates in composite beam–columns gives a rise to local buckling that would appreciably reduce the strength and ductility performance of the members. This paper studies the critical local and post-local buckling behavior of steel plates in concrete-filled thin-walled steel tubular beam–columns by using the finite element analysis method. Geometric and material nonlinear analyses are performed to investigate the critical local and post-local buckling strengths of steel plates under compression and in-plane bending. Initial geometric imperfections and residual stresses presented in steel plates, material yielding and strain hardening are taken into account in the nonlinear analysis. Based on the results obtained from the nonlinear finite element analyses, a set of design formulas are proposed for determining the critical local buckling and ultimate strengths of steel plates in concrete-filled steel tubular beam–columns. In addition, effective width formulas are developed for the ultimate strength design of clamped steel plates under non-uniform compression. The accuracy of the proposed design formulas is established by comparisons with available solutions. The proposed design formulas can be used directly in the design of composite beam–columns and adopted in the advanced analysis of concrete-filled thin-walled steel tubular beam–columns to account for local buckling effects.

References listed at the end of the paper:
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“Behaviour and design of high strength steel-concrete filled columns”, The 2013 World Congress on Advances in Structural Engineering and Mechanics (ASEM13), Jeju, Korea, September 8-12, 2013

ABSTRACT: This paper considers the behaviour and design of high strength steel-concrete composite columns used in major infrastructure engineering systems. The paper will highlight the major applications where high strength steel has been used in Australia and internationally. Current codes of practice will then be considered, highlighting the latest developments in Australian and International Standards for the use of high strength steel and high strength concrete in composite structural forms of construction. This paper also presents the results of an experimental study of the use of high strength steel-concrete composite columns which evaluates the in-plane residual stresses. This study uses high strength steel with nominal yield stress of 690 MPa coupled with high strength concrete of characteristic compressive strength of 100 MPa. The concrete used in this study adopts a reduction of 30% of the use of cement content by using high volume fly ash. The use of both of these high strength materials satisfies the Green Building Council of Australia objectives to reduce materials and the impact of construction materials on carbon emissions. This paper focuses on a number of the technical aspects which the combination of these two materials allows. The improved local buckling resistance of the use of steel in contact with concrete is taken into account. Furthermore, the effect of increased confining effect due to the larger elastic range of steel is also considered.

References listed at the end of the paper:

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ABSTRACT: This paper is based on a study that was done by utilising construction and demolition debris that had been effectively recycled, in structural members. The steel tubular columns were filled with different types of waste material, as well as recycled aggregate concrete, instead of normal conventional concrete. The results were subsequently analysed. The behaviour of circular and square concrete-filled steel tubular sections (CFSTs) under axial load, in which coarse aggregate had been partially replaced by recycled aggregates, is presented. The effects of steel tube dimensions, shapes and the confinement of concrete are also examined. Measured column strengths are compared with the values predicted by Eurocode 4, Australian Standards and American Codes. Twelve specimens were tested with 20 MPa concrete and steel sections with diameter-to-thickness ratios of 18.5, 25.3 and 36.0. The columns were of two different shapes - a circular-shaped set with diameters of 76 mm and 89 mm, and a square-shaped set with sizes 72 mm and 91 mm. The circular-shaped columns of 76 mm diameter and the square-shaped columns with 72 mm diameter are 900 mm long. The circular columns with a diameter of 89 mm and the square columns of 91 mm diameter are 350 mm long. Eurocode 4 (EC4) gives the best estimation for both conventional and recycled aggregate concrete. However, the American Concrete Institute (ACI) / Australian Standards (AS) equation predicted lower values than measured during the experiments. Hence the ACI/AS equation has been modified by introducing a multiplying factor ‘k’ to predict good results for columns of L/D < 12. The values of k factor for L/D ratio varying from 4 to 12 are suggested in this study. From the results it has been noted that square columns save 30% of steel when compared with circular columns. It was also observed that the ultimate load of steel tubular columns filled with recycled aggregate concrete is higher than that of conventional concrete and columns filled with recycled aggregate concrete, and can result in a 10% saving in the cost of concrete. This research therefore proposes a solution for effective solid waste management, which will also prove to be cost effective.

References listed at the end of the paper:
ACI Committee 318. 1995. Building code requirements for structural concrete (ACI 318-95). Detroit: American Concrete Institute
ABSTRACT: With the wide application of high-strength concrete and thin-wall steel tube in concrete-filled steel tube, it is essential to study the post-local buckling behavior of rectangle steel plates. Based on large deflection theory of plate, the post-local buckling behavior of steel plates in concrete-filled steel tube is analyzed in this paper. At the same time, the post-local stress of steel plates is obtained. The results indicate that the post-local buckling behavior of steel plates can be effectively utilized in large width-to-thickness ratios of steel plates.

References listed at the end of the paper:


ABSTRACT: Buckling behavior of thin circular cylindrical shells stiffened by one or two rings has been studied in a wind tunnel. Both the prebuckling deflection and the buckling load were measured with a variety of specimens in a smooth flow, and the effects of the stiffeners on them were examined. For comparison purposes, the buckling load of each specimen under hydrostatic pressure was also measured. The results indicate that the prebuckling deflection and ovalling oscillation can be significantly suppressed by relatively light stiffeners. As the flexural rigidity, EsIs, of the ring increases, the axial buckling mode changes from a symmetric one accompanied by ring deflection to another one with the rings acting as nodes, at a critical value of EsIs. This critical value was found to be nearly equal to that for the hydrostatic pressure. On the other hand, contrary to the hydrostatic pressure case, the buckling load gradually increases with an increase in EsIs, even for values of EsIs greater than the critical value.

Portela Gauthier, Genock, Ph.D., University Of Puerto Rico, Mayaguez , 2004, 526 pages; 3141791 (dissertation?), “Wind pressures and buckling of metal cantilever tanks”, Department of Civil Engineering, DAI-B 65/08, p. 4174, Feb 2005

ABSTRACT: This thesis reports work done to evaluate wind pressure distributions on aboveground tanks formed by a cylinder and a roof, and to assess shell buckling due to such pressures. First, wind tunnel experiments were performed to obtain wind pressure distributions developed on the wall and on the roof of circular short steel tanks, including different geometries and group configurations. The geometries considered were selected from typical cylindrical tanks located in the Caribbean Region (including Puerto Rico), with conical, shallow-dome, and deep-dome roofs. The pressure distributions measured on the cylinder of the isolated tanks were similar to pressure values on silos obtained by other authors. However, shielding arrays revealed increments in windward pressures on the cylinder, and group arrays generated changes to the pressure distributions with respect to the isolated tanks. Second, linear bifurcation and nonlinear step-by-step buckling analyses were performed on tanks using the pressure distributions measured from the wind tunnel experiments, in order to obtain buckling loads and their associated modes of deformation. Changes to the initial geometry of tanks using the first mode of deformation obtained from an eigenvalue analysis were investigated to compute the sensitivity due to imperfections. The magnitudes of the imperfections applied varied from 10% to 200% the thickness of the shell. From the results, it seems that bifurcation analyses represent adequately the buckling behavior of isolated tanks with conical roofs, but not of tanks with dome roofs based on the selected dimensions of short tanks. Results also showed that corrosion effects reduce the buckling capacity of steel tanks. On the other hand, ring stiffeners around the cylinder of the tanks provide additional buckling capacity that depends on the elevations at which they are located. About imperfections, it seems that tanks with roofs have higher buckling loads but at the same time are more sensitive to imperfections than open-top tanks.

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“Numerical simulation on buckling of combined multilayered unequal-thickness cylindrical shell”, Journal of Zhejiang University (Engineering Science), 2009 –09

ABSTRACT: The influence of the characteristic factor of unequal-thickness on critical buckling load was
analyzed by numerical simulation method based on geometric features of large vertical combined cylindrical shell. The character of unequal-thickness was considered as geometrical defect, which decreases the critical stress of classical shell buckling to some extent. Finite element analysis (FEA) models of combined multilayered unequal-thickness cylindrical shell were built to analyze the buckling of combined cylindrical shell under different loadings. Critical loads of instability buckling under different loadings were obtained to verify the influence regularity of hoop stress on the buckling of combined cylindrical shell. Results show that the characteristic factor of unequal-thickness can largely decrease the critical load of classical shell buckling. And the number of layers and the thickness difference of adjacent shell courses have the biggest influence on critical buckling load.

ABSTRACT: Experimental and numerical work was conducted to better understand composite shell response to transverse loadings which simulate damage-causing impact events. The quasi-static, centered, transverse loading response of laminated graphite/epoxy shells in a [+/-45(sub n)/O(sub n)](sub s) layup having geometric characteristics of a commercial fuselage are studied. The singly curved composite shell structures are hinged along the straight circumferential edges and are either free or simply supported along the curved axial edges. Key components of the shell response are response instabilities due to limit-point and/or bifurcation buckling. Experimentally, deflection-controlled shell response is characterized via load-deflection data, deformation-shape evolutions, and the resulting damage state. Finite element models are used to study the kinematically nonlinear shell response, including bifurcation, limit-points, and postbuckling. A novel technique is developed for evaluating bifurcation from nonlinear prebuckling states utilizing asymmetric spatial discretization to introduce numerical perturbations. Advantages of the asymmetric meshing technique (AMT) over traditional techniques include efficiency, robustness, ease of application, and solution of the actual (not modified) problems. The AMT is validated by comparison to traditional numerical analysis of a benchmark problem and verified by comparison to experimental data. Applying the technique, bifurcation in a benchmark shell-buckling problem is correctly identified. Excellent agreement between the numerical and experimental results are obtained for a number of composite shells although predictive capability decreases for stiffer (thicker) specimens which is attributed to compliance of the test fixture. Restraining the axial edge (simple support) has the effect of creating a more complex response which involves unstable bifurcation, limit-point buckling, and dynamic collapse. Such shells were noted to bifurcate into asymmetric deformation modes but were undamaged during testing. Shells in this study which were damaged were not observed to bifurcate. Thus, a direct link between bifurcation and atypical damage could not be established although the mechanism (bifurcation) was identified. Recommendations for further work in these related areas are provided and include extensions of the AMT to other shell geometries and structural problems.

ABSTRACT: A benchmark, geometrically nonlinear, shell-buckling problem is reviewed and the correct solution is identified and discussed vis-à-vis the incorrect solution from the open literature. The problem is that of a hinged, thin, isotropic cylindrical shell section, point-loaded transversely at the center, undergoing large deformations (5 x thickness). This benchmark problem and solution were introduced in 1972 and have been reproduced in at least 30 journal articles and books in the more than three decades since that time. The benchmark problem is of interest because it demonstrates many features possible in shell buckling, including a
load-limit point (snap-through buckling) and a deflection-limit point (snap-down, or snap-back). The benchmark problem is typically used to demonstrate the capability of commercial/private finite element codes to traverse such complicated nonlinear load paths. The existing incorrect benchmark solution involves the nonlinear growth of only symmetric deformation modes. The correct solution to this benchmark problem involves bifurcation from the nonlinear load path into a simple asymmetric deformation mode. Experimental data do not exist for verification of the calculated benchmark response, and so a similar problem using a laminated composite shell is suggested as an alternative benchmark problem for shell stability analysis.

ABSTRACT: In this paper, buckling analysis of cylindrical shells with a circumferential crack is presented. The analyses were performed both numerically using FEM and experimentally. The numerical analyses and experiments were conducted for several crack lengths and radius of curvature, and two different boundary conditions were applied, i.e. simply support and clamp in all sides. The results show the effect of the presence of crack to the critical buckling load of the shells. There are good agreements between experimental and numerical results.


ABSTRACT: A long circular cylindrical shell subjected to external pressure may collapse through the development of a propagating buckle. In this work a method has been developed for the theoretical prediction of the smallest propagation pressure in the case of path-dependent material descriptions. The method is illustrated by comparing predictions of the propagation pressure based on J2 flow theory with predictions based on J2 deformation theory for two different radius to thickness ratios. The modelling is based on thin shell theory and small strain approximations, allowing for large deformations. Results for two different non-linear bending strain measures are compared, and the effect of using a finite strain J2 flow theory is investigated.

ABSTRACT: Failure by steady state kink band broadening in uni-directional fibre composites or layered materials is analysed. An incremental scheme for calculation of kink band broadening stresses and lock-up conditions in the band for arbitrary material behaviour is presented. The method is illustrated by material data which are representative for polymer matrix composites for which experimental work exists.

ABSTRACT: Compressive failure of fibre reinforced or layered materials by fibre kinking, matrix splitting and fibre/matrix debonding is analysed. The main focus is on brittle matrix composites, however, the analysis of effects due to debonding is carried out in a general framework allowing for arbitrary time-independent plasticity of the layers. Fibre kinking and matrix splitting are regarded as competing failure modes with the conditions governing the active mode depending on the biaxial stress state in the composite and a combination of micro mechanical parameters. Two criteria for matrix splitting, and two models for the evolution of micro cracks in the matrix have been discussed.


ABSTRACT: An analysis of buckling-driven delamination of a layer in a spherical, layered shell has been carried out. The effects of the substrate having a double curvature compared to previous studies of delamination on cylindrical substrates turn out to be non-trivial in the sense that additional to the effect of the shape of the substrate, a new non-dimensional geometrical parameter enters the conditions for steady-state delamination. It is shown that this additional geometrical parameter in most cases of practical relevance has insignificant influence on the fracture mechanical parameters involved for the problem. The consequence is that solutions need to be mapped as a function of one rather than two dimensionless parameters. Furthermore, the shape of the substrate has profound influence especially on initiation of delamination growth.

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ABSTRACT: The main objective of this work was to investigate and predict the behaviour of damaged structural elements (skin-stringer panels). The study combined characterisation through testing with fractographic analysis, and analysis of delamination using the finite element method. The experimental studies entailed investigation of damage growth from embedded skin defects in panels under compressive load, and the subsequent structural failure. Parameters such as defect size, location with respect to sub-structure and through-thickness position were studied. Local delamination and global panel buckling were modelled, and the resulting delamination growth was simulated using a moving mesh technique. The results illustrated the importance of the location of the 90° plies to the damage evolution, and the criticality of global buckling and stringer detachment in the structural failure. The understanding gained from both the experimental investigations and numerical simulations have led to guidelines for realistic modelling and rules for designing damage tolerant structures.

References listed at the end of the paper:

Leif E. Asp (1) and Karl-Fredrik Nilsson (2)
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PARTIAL ABSTRACT: In this paper a damage tolerance model based on the assumption of delamination criticality in compression-loaded slender composite panels is outlined. In particular, the verification of the model by comparison between numerical predictions and experimental results is reviewed. Growth of shallow delaminations in slender panels is shown to be promoted by the global buckling of the panel. Consequently, care must be taken if structures with delaminations are to be allowed to buckle.…


ABSTRACT: This report describes an in-depth finite element simulation of a spent fuel canister for geological disposal loaded in iso-static pressure until plastic collapse. The canister consists of a copper overpack and a ductile cast iron insert with steel cassettes where the spent fuel is placed. The highly non-linear finite element analysis is based on the explicit formulation and includes large deformations, non-linear material behaviour and
contact between the canister components. The analysis includes comparison between two- and three-dimensional models and assessment of the different geometrical features such as corner radius of the cassette, cassette offset, different bonding/dedonding conditions between insert and steel cassette. The analysis shows that the bonding cassette/insert has a large impact on the collapse load. Two large-scale mock-ups test that had been performed earlier are also simulated by the developed finite element models. There is a very good agreement between measured and computed deformations versus applied load and collapse load.


ABSTRACT: This paper deals with the computational modeling of delamination and the prediction of delamination growth in laminated composites. In the analysis of post-buckled delaminations, an important parameter is the distribution of the local strain-energy release rate along the delamination front. A study using virtual crack closure technique is made for three-dimensional finite-element models of circular delaminations embedded in woven and non-woven composite laminates. The delamination is embedded at different depths along the thickness direction of the laminates. The issue of symmetry boundary conditions is discussed. It is found that fibre orientation of the plies in the delaminated part play an important role in the distribution of the local strain-energy release rate. This implies that the popular use of quarter models in order to save computational effort is unjustified and will lead to erroneous results. Comparison is made with experimental results and growth of the delamination front with fatigue cycling is predicted. A methodology for the prediction of delamination areas and directions using evolution criteria derived from test coupon data is also described. It is found that evolution criteria based on components of the strain-energy release rate predict the rate of delamination growth much better than evolution criteria based on the total strain energy release rate.


ABSTRACT: This paper presents the results of a buckling and postbuckling analysis and modeling of embedded delaminations, and the prediction of delamination growth in laminated composites with consideration for residual thermal stresses. The distribution of the local strain energy release rate along the delamination front is obtained via the virtual crack closure technique applied to three-dimensional (3D) finite element models of circular delaminations embedded in woven and non-woven composite laminates. In each case, the delamination is embedded at a different depth along the thickness direction of the laminates. The fibre orientation of the plies bounding the delamination significantly influences the distribution of the local strain energy release rate. There is general qualitative agreement between the predicted directions of delamination growth and C-scan results of the embedded delaminations. It is found that residual thermal stresses have a significant effect on the onset of buckling of the delaminated sublaminate, but negligible influence on the distribution of the local strain energy release rate in the postbuckled regime. Furthermore, the effect of residual thermal stresses is more pronounced for delaminations that are closer to the surface. A method for the prediction of delamination areas and directions using fatigue growth criteria derived from test coupon data is also presented. It is found that growth criteria based on components of the strain energy release rate predict the rate of delamination growth much better than those based on the total strain energy release rate.
INTRODUCTION: Egg shell quality is of considerable economic significance for commercial egg production. Eggs with shell defects lead to a direct reduction in yield and damage the image of eggs with the end user. Possible causes of these quality reductions are age, housing conditions, feeding, egg handling technology and genetic predisposition. The shell is the outer covering of the egg and performs several important functions and tasks. Each individual egg is unique with its own microstructure which provides a wealth of information about the environment in which it was created. The shell protects the contents of the egg from mechanical impact to some extent and allows a controlled exchange of fluid and gas through the pores. The egg shell also provides protection against microbial entry from the environment and serves as a source of calcium for the development of the embryonal skeleton. Because of its central importance for the egg as a commercial product, breeders and producers are continuously seeking to improve the quality and consistency of the egg shell. In this paper we propose to concentrate on breeding approaches and alternative measuring techniques which have a direct impact on product quality at the producer level and which indicate possibilities for improving shell stability.


ABSTRACT: Dextran-covered PLA nanoparticles have been formulated by two strategies. On one hand, dextran-g-PLA copolymers have been synthesized by click-chemistry between azide-multifunctionalized dextran (DexN3) and alkyne end-functionalized PLA chains (α-alkyne PLA); then nanoprecipitated without any additional surfactants. On the other hand, DexN3 exhibiting surfactant properties have been emulsified with unfunctionalized or α-alkyne PLA, which are dissolved in organic phase with or without CuBr. Depending on the o/w emulsion/evaporation process experimental conditions, dextran-g-PLA copolymers have been produced in situ, by click chemistry at the liquid/liquid interface during the emulsification step. Whatever the process, biodegradable core/shell polymeric nanoparticles have been obtained, then characterized. Colloidal stability of these nanoparticles in the presence of NaCl or SDS has been studied. While the physically adsorbed polysaccharide based shell has been displaced by SDS, the covalently-linked polysaccharide based shell ensures a permanent stability, even in the presence of SDS.


ABSTRACT: (cannot cut and paste the abstract)


ABSTRACT: The similarity in stability characteristics between multiscale circular cylindrical structures is
revealed. Two detailed structures are explored. One is the circular cylindrical shell on an engineering scale, and another is the circular cylindrical lipid bilayer vesicle on a micro- or nanoscale. The critical stability of the vesicle acted on by uniformly distributed radial pressure is analysed. The critical load of the vesicle is derived and compared with that of the thin shell. The astonishing similarity between them is disclosed. The possible applications of such similarity to biophysics, biology and biomedicine are presented.

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“Application and Analysis of Sandwich Elements in the Primary Structure of Large Wind Turbine Blades”,  
Journal of Sandwich Structures and Materials, November 2007, vol. 9, no. 6, pp. 525-552,  
doi: 10.1177/1099636207069071  
ABSTRACT: The present work studies the advantages of applying a sandwich construction as opposed to traditional single skin composites in the flanges of a load carrying spar in a future 180 m wind turbine rotor. A parametric finite element model is used to analyze two basic designs with single skin and sandwich flanges, respectively. Buckling is by far the governing criterion for the single skin design. Introducing a sandwich construction results in a globally more flexible structure making tower clearance the critical criterion. Significant weight reduction up to 22.3% and increased buckling capacity is obtained. Moreover, the study showed that proper choice of core material is important to prevent face wrinkling. Geometric nonlinear analysis showed sensitivity to imperfections. A consistent submodeling technique is presented for verifying the response from the global model in any section of interest.

ABSTRACT: (cannot cut at paste and the small font showing on the screen is too small for an old man to see.)

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“Buckling Optimization of Laminated Hybrid Composite Shell Structures Using Discrete Material Optimization”, 6th World Congress on Structural and Multidisciplinary Optimization Rio de Janeiro, 30 May - 03 June 2005, Brazil  
ABSTRACT: The design problem of maximizing the buckling load factor of laminated hybrid composite shell structures is investigated using the so-called Discrete Material Optimization (DMO) approach. The design optimization method is based on ideas from multi-phase topology optimization where the material stiffness is computed as a weighted sum of candidate materials, thus making it possible to solve discrete optimization problems using gradient based techniques and mathematical programming. The potential of the DMO method to solve the combinatorial problem of proper choice of material, stacking sequence and fiber orientation simultaneously is illustrated for two benchmark plate examples, and ongoing work on buckling optimization of a wind turbine blade test section is outlined.  
References listed at the end of the paper:  


ABSTRACT: The design problem of maximizing the lowest eigenfrequency or the buckling load factor of laminated composite shell structures is investigated using the so-called Discrete Material Optimization (DMO) approach. The design optimization method is based on ideas from multi-phase topology optimization where the material stiffness is computed as a weighted sum of candidate materials, thus making it possible to solve discrete optimization problems using gradient based techniques and mathematical programming. The potential of the DMO method to solve the combinatorial problem of proper choice of material, stacking sequence and fiber orientation simultaneously is illustrated for two multi-layered multi-material plate examples.

References listed at the end of the paper:
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ABSTRACT: The design of composite structures such as wind turbine blades is a challenging problem due to the need for pushing the material utilization to the limit in order to obtain light and cost effective structures. As a consequence of the minimum material design strategy the structures are becoming thin-walled, such that buckling problems must be addressed, and in this work the aim is to obtain buckling optimized multi-material designs of wind turbine blades. The design problem consists of distributing multiple materials within a given design domain, and the candidate materials may be fiber-reinforced materials, oriented at given discrete fiber angles, together with isotropic materials like foam materials used for sandwich structures. The discrete design optimization problem is converted to a continuous problem using the so-called Discrete Material Optimization (DMO) approach based on ideas from multi-phase topology optimization where interpolation functions with penalization are introduced. In this way traditional gradient based optimization techniques including efficient methods for design sensitivity analysis and mathematical programming can be used for solving the multi-material distribution problem. The multi-material topology optimization approach is demonstrated for buckling optimization of a 9 m generic wind turbine blade test section.

ABSTRACT: The design problem of maximizing the buckling load factor of laminated multi-material composite shell structures is investigated using the so-called Discrete Material Optimization (DMO) approach. The design optimization method is based on ideas from multi-phase topology optimization where the material stiffness is computed as a weighted sum of candidate materials, thus making it possible to solve discrete optimization problems using gradient based techniques and mathematical programming. The potential of the DMO method to solve the combinatorial problem of proper choice of material and fiber orientation simultaneously is illustrated for multilayered plate examples and a simplified shell model of a spar cap of a wind turbine blade.

Esben Lindgaard and Erik Lund (Dept. of Mechanical and Manufacturing Engineering, Aalborg University, Denmark), “Optimization formulations for the maximum nonlinear buckling load of composite structures”, Structural and Multidisciplinary Optimization, Vol. 43, No. 5, 2010, pp. 631-646,
doi: 10.1007/s00158-010-0593-8

ABSTRACT: This paper focuses on criterion functions for gradient based optimization of the buckling load of laminated composite structures considering different types of buckling behaviour. A local criterion is developed, and is, together with a range of local and global criterion functions from literature, benchmarked on a number of numerical examples of laminated composite structures for the maximization of the buckling load considering fiber angle design variables. The optimization formulations are based on either linear or geometrically nonlinear analysis and formulated as mathematical programming problems solved using gradient based techniques. The developed local criterion is formulated such it captures nonlinear effects upon loading and proves useful for both analysis purposes and as a criterion for use in nonlinear buckling optimization.

References listed at the end of the paper:


ABSTRACT: The paper presents an approach to nonlinear buckling fiber angle optimization of laminated composite shell structures. The approach accounts for the geometrically nonlinear behaviour of the structure by utilizing response analysis up until the critical point. Sensitivity information is obtained efficiently by an estimated critical load factor at a precritical state. In the optimization formulation, which is formulated as a mathematical programming problem and solved using gradient-based techniques, a number of the lowest buckling factors are included such that the risk of “mode switching” during optimization is avoided. The presented optimization formulation is compared to the traditional linear buckling formulation and two numerical examples, including a large laminated composite wind turbine main spar, to clearly illustrate the pitfalls of the traditional formulation and the advantage and potential of the presented approach.

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(2) School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia
ABSTRACT: Nonlinear buckling optimization is introduced as a method for doing laminate optimization on
generalized composite shell structures exhibiting nonlinear behaviour where the objective is to maximize the
buckling load. The method is based on geometrically nonlinear analyses and uses gradient information of the
nonlinear buckling load in combination with mathematical programming to solve the problem. Thin-walled
optimal laminated structures may have risk of a relatively high sensitivity to geometric imperfections. This is
investigated by the concepts of “worst” imperfections and an optimization method to determine the “worst”
shape imperfections is presented where the objective is to minimize the buckling load subject to imperfection
amplitude constraints. The ability of the nonlinear buckling optimization formulation to solve the laminate
problem and determine the “worst” shape imperfections is illustrated by several numerical examples of
composite laminated structures and the application of both formulations gives useful insight into the interaction
between laminate design and geometric imperfections.

Esben Lindgaard and Erik Lund (Department of Mechanical Engineering, Aalborg University,
Pontoppidanstraede 101, DK-9220 Aalborg East, Denmark), “A unified approach to nonlinear buckling
optimization of composite structures”, Computers & Structures, Vol. 89, Nos. 3-4, February 2011, pp. 357-370,
doi:10.1016/j.compstruc.2010.11.008

ABSTRACT: A unified approach to nonlinear buckling fiber angle optimization of laminated composite shell
structures is presented. The method includes loss of stability due to bifurcation and limiting behaviour. The
optimization formulation is formulated as a mathematical programming problem and solved using gradient-
based techniques. Buckling of a well-known cylindrical shell benchmark problem is studied and the solutions
found in literature are proved to be incorrect. The nonlinear buckling optimization formulation is benchmarked
against the traditional linear buckling optimization formulation through several numerical optimization cases of
a composite cylindrical shell panel which clearly illustrates the advantage and potential of the presented
approach.

Esben Lindgaard and Jonas Dahl (Department of Mechanical and Manufacturing Engineering, Aalborg
University, Fibigerstraede 16, DK-9220, Aalborg East, Denmark), “On compliance and buckling objective
functions in topology optimization of snap-through problems”, Structural and Multidisciplinary Optimization,

ABSTRACT: This paper deals with topology optimization of static geometrically nonlinear structures
experiencing snap-through behaviour. Different compliance and buckling criterion functions are studied and
applied for topology optimization of a point loaded curved beam problem with the aim of maximizing the snap-
through buckling load. The response of the optimized structures obtained using the considered objective
functions are evaluated and compared. Due to the intrinsic nonlinear nature of the problem, the load level at
which the objective function is evaluated has a tremendous effect on the resulting optimized design. A well-
known issue in buckling topology optimization is artificial buckling modes in low density regions. The typical
remedy applied for linear buckling does not have a natural extension to nonlinear problems, and we propose an
alternative approach. Some possible negative implications of using symmetry to reduce the model size are
highlighted and it is demonstrated how an initial symmetric buckling response may change to an asymmetric
buckling response during the optimization process. This problem may partly be avoided by not exploiting
symmetry, however special requirements are needed of the analysis method and optimization formulation. We
apply a nonlinear path tracing algorithm capable of detecting different types of stability points and an
optimization formulation that handles possible mode switching. This is an extension into the topology
optimization realm of a method developed, and used for, fiber angle optimization in laminated composite structures. We finally discuss and pinpoint some of the issues related to buckling topology optimization that remains unsolved and demands further research.

References listed at the end of the paper:

ABSTRACT: Elastic buckling, which occurs in shell structures, is a major design issue because it can cause failures of structures. In particular, the variation in buckling load caused by a decrease in the thickness of the walls of structures is a key issue for safe design. The arc-length method, which is a finite element method, is generally applied to solve this type of problem. However, it has been reported that there are some cases in which the path of the buckling load cannot be solved using this method. We verified the problem by applying the arc-length method to elastic buckling that occurs in a shallow partial spherical shell. To solve the problem, we formulated a novel algorithm used in the explicit finite element method for estimating minimum strength of thin-walled structures. In this algorithm, initial deformation is given by pressing a rigid wall to the vertical direction of buckling mode. We anticipate that the proposed method will prove to be a practical way of calculating the minimum load for partial elastic buckling that occurs in a general shell structure under pressure.

References listed at the end of the paper:


ABSTRACT: The arc-length method has become a widely established solution technique for studying nonlinear structural behavior. By augmenting the set of nonlinear equilibrium equations with a constraint equation, which is a function of both the displacements and load increment, it is capable of traversing limit points. Numerous investigations have shown that highly nonlinear behavior such as sharp “snap-backs” can still lead to numerical difficulties. Two practical examples are presented to assess the effectiveness of this solution technique in capturing secondary instabilities in postbuckling structures, which present themselves as abrupt mode jumps. Although the first example poses no special difficulties, in the second case the nonlinear procedure fails to converge. An improvement to the method’s formulation is suggested, which accounts for the residual forces that are usually neglected, which proceeding to the next increment once convergence is reached on the current increment. The choice of a correct load increment at the first iteration, within a predictor-corrector scheme, is central to the method’s effectiveness. Current strategies for a choice of this load increment are discussed and are shown to be no longer consistent with the modified formulation; therefore, a new approach is proposed.


ABSTRACT: In this article, the buckling and post-buckling behaviours of a laminated composite spherical shallow shell panel embedded with shape memory alloy (SMA) fibres are studied under a thermal environment. System equations for a laminated composite spherical shell panel embedded with SMA fibres are for the first time derived by modelling the geometric non-linearity in the Green–Lagrange sense and the material non-linearity in SMA fibres in the framework of the higher-order shear deformation theory. The shell panel model is discretized by using a non-linear finite-element approach. The governing algebraic equations are then derived by the variational approach and solved using a direct iterative technique. Influences of the thickness ratio, boundary condition, aspect ratio, curvature ratio, lamination scheme, SMA volume fraction, percentage of prestrain, and amplitude ratio on the buckling and post-buckling temperatures of a laminated composite shell panel with and without SMA have been examined in detail. The results are computed using the present model and compared with those available in the literature.

References:

ABSTRACT: A ring-stiffened slightly conical shell is optimized for external pressure according to the design rules of Det Norske Veritas. The whole length and the different two end radii are given. The shell is divided into \( n \) equidistant segments with one stiffener in each segment. Each segment has a different shell thickness determined using a buckling constraint, and each ring-stiffener of welded square box section is designed by means of the required moment of inertia. The optimal number of shell segments (\( n_{opt} \)) is determined by means of costs calculated for a series of \( n \). The cost function includes the material, fabrication and painting costs. The shell normal stresses are determined also by finite element method.

References listed at the end of the paper:


ABSTRACT: In this overview of loaded a longitudinally stiffened welded circular cylindrical steel shell is investigated. The halved rolled I-section stringers are welded outside to the shell. The simply supported belt-conveyor bridge is loaded by bending with a uniformly distributed normal load. The design constraints are related to the shell buckling, panel stiffener buckling and the maximum deflection of the bridge. The optimum shell thickness as well as the dimensions and number of stringers are sought, which minimize the cost function. The cost function includes the material, fabrication and painting costs. For the comparison an unstiffened shell is also optimized. The cost comparison shows that the cost of stiffened version is smaller than that of the unstiffened one only in those cases when the allowable deflection is strict enough.

References:

G.I. Makhasev, “Free and parametric vibrations of cylindrical shells under static and periodic axial loads”, Technische Mechanik, Band 17, Heft 1, 1997, pp. 209-216

ABSTRACT: This study examines free and parametric vibrations of cylindrical shells subjected to axial loads. In the case of free vibrations, the loading is static. Parametric vibrations are excited by a combined load consisting of one static and two periodic load components. The load is assumed to be nonuniform in the circumferential direction, and the shell is noncircular so that vibrations are concentrated near the “weakest” generatrix on the shell surface. By using Tovstik’s asymptotic method in combination with the multiple scale method with respect to time, the solutions of the governing equations are found in the form of functions.
localized near the “weakest” line and growing with time in the case of dynamic instability. The dependence of fundamental frequencies upon the static nonuniform axial force is studied. For the weak parametric excitation, the region of instability of a cylinder is determined directly in terms of its geometry, load intensity, and frequency.

References listed at the end of the paper:
(cannot cut and paste them; 17 references)

ABSTRACT: Low-frequency vibrations of an elastic noncircular cylindrical shell in a nonstationary temperature field is investigated. By using the method of multiple scales, the solutions of the shell equations are constructed in the form of functions localized near “the weakest” generatrix. The equations for definition of the vibration amplitude are derived. The main region of instability of the shell equilibrium is established.

ABSTRACT: Low-frequency parametric vibrations of a viscoelastic cylindrical shell subjected to axial static and additional periodic loads are studied. It is assumed that the shell is noncircular and the load is non-uniform in the circumferential direction. It is supposed that for the weak parametric excitation the shell vibrations are localized near the weakest generatrix on the shell surface. By using Fourier transformations over the circumferential coordinate and the multiple scale method with respect to time, the solutions of the shell equations are constructed in the form of functions that decrease quickly outside a small neighbourhood of the weakest line. The region of instability of the shell is determined with regard to the viscosity.

ABSTRACT: The problem of local buckling of a thin composite laminated cylindrical shell under external pressure is studied. Each layer of the shell is assumed to be isotropic. The special case of the shell being non-circular and/or having no plane edges is considered here. Presupposing that buckling takes place in the neighborhood of some so-called “weakest” generator, the asymptotic Tovstik’s method is applied finding the critical pressure and the eigenmodes. As an example, buckling of a three-layered circular thin cylinder with a sloped edge is investigated. Besides the asymptotic approach the finite element simulation is applied to facilitate the estimation of the range to which the results obtained can be applied. (13 References)

ABSTRACT: The problem of parametric instability is studied for a thin conical shell subjected to nonuniform pulsating pressure. The edges of the shell (not necessary planar curves) are simply supported. The excitation frequency is assumed to be close to the twice the fundamental natural frequency of the shell. By using the WKB method combined with the method of multiple time scales we construct solutions of the governing equations as
functions decreasing away from a certain "most weak" generatrix and slowly increasing in time in the case of parametric resonance. Taking into account the viscous friction, we find the boundaries of the principal domain of local parametric instability.

References listed at the end of the paper:


ABSTRACT: This paper is a continuation of [3-6] and it is devoted to a stability analysis of multilayered vibrating viscoelastic spheres, both in vacuo and in an acoustical fluid. The analysis is done by investigating the effect of viscoelastic damping on the (continuous) Ladyzenskaya-Babùska-Brezzi (LBB) constants for the related boundary-value problems. The sphere is modeled using both 3-D viscoelasticity and the Kirchhoff-Love shell theory.

References listed at the end of the paper:
ABSTRACT: The present work discusses the problem of dynamic stability of a viscoelastic circular cylindrical shell, according to revised Timoshenko theory, with an account of shear deformation and rotatory inertia in the geometrically nonlinear statement. Proceeding by Bubnov-Galerkin method in combination with a numerical method based on the quadrature formula the problem is reduced to a solution of a system of nonlinear integro-differential equations with singular kernel of relaxation. For a wide range of variation of physical mechanical and geometrical parameters, the dynamic behavior of the shell is studied. The influence of viscoelastic properties of the material on the dynamical stability of the circular cylindrical shell is shown. Results obtained using different theories are compared.

References listed at the end of the paper:


ABSTRACT: Approximate elasticity relations are derived for the axially symmetric deformation of a thin shell of revolution made of a nonlinearly elastic material using the three-dimensional equations of the theory of elasticity. The deformations are assumed to be of the order of a small parameter which is proportional to the square root of the dimensionless thickness of the shell. Terms of the second order of smallness with respect to the deformations are retained in the elasticity relations, as a result of which the equations obtained have an error of the order of the dimensionless thickness of the shell, which is customary in the linear theory of shells. The Kirchhoff-Love hypotheses are satisfied only in the first approximation. The axial compression of a shell, assuming that one of the extreme parallels can freely slide along a plane of support, which is perpendicular to the axis of revolution, is considered as an example. A formula is obtained for the limiting load, which physically and geometrically takes account of nonlinear effects in the first approximation.


ABSTRACT: Stability of a complete spherical shell under concentrated load was first considered by D. Bushnell (1967) by means of a finite difference method. In the present paper the effect of the internal pressure on the critical value of a concentrated load is studied by means of a combination of asymptotic and numerical methods.

References listed at the end of the paper:

ABSTRACT: We consider the stability of a thin transversally isotropic circular cylindrical shell under axial compression. We use a local approach according to which the buckling deflection is sought in the form of a doubly periodic function of curvilinear coordinates and the boundary conditions are ignored. We compare the solutions obtained according to the two-dimensional Kirchhoff-Love (KL) and Timoshenko-Reissner (TR) models with the solutions constructed according to the three-dimensional theory. Attention is mainly paid to the case of very small shear stiffness in the transverse direction.

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15. S. A. Ambartsumyan, General Theory of Anisotropic Shells (Nauka, Moscow, 1974) [in Russian].
21. V. V. Bolotin and Yu. N. Novichkov, Mechanics of Multi-Layer Constructions (Mashinostroenie, Moscow, 1980) [in Russian].

ABSTRACT: The buckling modes of a homogeneously compressed elastic plate on a soft elastic substrate are studied. The critical compression is uniquely determined by the bifurcation equation, but this compression is associated with a wide set of buckling modes. It was proved that any solution of the Helmholtz equation satisfies the bifurcation equation. At the same time, in microelectronics, it is required to know which buckling mode is realized. Experimental and theoretical investigations show that the chessboard-like buckling mode should be expected. In what follows, this problem is discussed theoretically. The expected buckling mode can be found by analyzing the energy of the initial postcritical deformation, and the desired mode is determined from the condition of its minimum. The analytic expression of this energy is obtained. Its minimization results in the chessboard-like buckling mode.

References listed at the end of the paper:


and the corresponding behavior of the functions $\lambda(q, g)$ is investigated. The role of the fifth boundary condition in the TR model, which does not exist in the Kirchhoff–Love (KL) model is studied. It is shown that, if the boundary condition $H = 0$ holds and $g \to 0$, then the results based on the TR and KL models coincide. If the restraint $\phi_2 = 0$ is imposed and $g \to 0$, then the TR model produces new results as compared with the KL model.

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18. L. A. Agalovyan, Asymptotic Theory of Anisotropic Plates and Shells (Nauka, Moscow, 1997) [in Russian].
techniques that are used to enable a realistic idealisation of the physical problem and on presenting simulation results for an exemplary structure. Based on this example, the influence of modelling details like mesh density and geometric imperfections on the prediction of the failure load is discussed.

References listed at the end of the paper:

ABSTRACT: We have conducted molecular dynamics simulations on compressing behaviors of single-walled carbon nanotubes (SWCNTs) with a large variaty of aspect ratios. It is found that SWCNTs with large aspect ratios experience column buckling behavior at low strain levels, in contrast to commonly observed shell buckling of short SWCNTs. Further compression leads to a transition to a shell buckling mode, which is distinct from those of short SWCNTs under compression. It originates from the column buckling induced bending loadings. We extract the scaling law with respect to the aspect ratio of SWCNTs based on an analytical model of bending buckling.

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ABSTRACT: Using molecular dynamics simulations, we study axial compressive behavior of single-walled carbon nanotubes (SWCNTs) with a wide range of aspect ratios (length to diameter ratio). It is shown that the difference in aspect ratio leads to distinct buckling modes in SWCNTs. Small-aspect-ratio SWCNTs primarily exhibit shell buckling; they switch to a column buckling mode with increasing aspect ratio. Further compression of the already column buckled large-aspect-ratio SWCNTs results in a shell buckling. This shell buckling mode is distinct from that of small-aspect-ratio SWCNTs in that it originates from the column buckling induced bending deformation. The transition strain from column buckling to shell buckling of large-aspect-ratio SWCNTs is predicted using an analytical expression. The underlying mechanism is discussed by analyzing the variation of C-C bond lengths and angles.
References listed at the end of the paper:

ABSTRACT: Postbuckling and vibration analyses considering large thermopiezoelectric deflections are performed for fully symmetric and partially eccentric piezolaminated composite plates. Non-linear finite element equations based on the layerwise displacement theory are formulated for piezolaminated plates subject to thermal piezoelectric loads. The results demonstrate a methodology for raising the thermal buckling temperature and decreasing the thermal postbuckled deflection. Vibration characteristics under complex thermopiezoelectric loads are investigated in the prebuckling and postbuckling regions. For fully distributed piezolaminates, this study shows that excessive bending moments for the suppression of thermally buckled deflection may cause another type of structural instability. In addition, the effective placement of piezoceramic patches is studied to improve suppression of thermally buckled deflection for the partially segmented piezolaminates.

References listed at the end of the paper:

B. N. Singh; Jibumon B. Babu, (Department of Aerospace Engineering, IIT, Kharagpur, India ),”Thermal buckling of laminated composite conical shell panel with and without piezoelectric layer with random material properties”, International Journal of Crashworthiness, Vol. 14, No. 1, First published 2009, pp. 73 – 81, DOI: 10.1080/13588260802517352
ABSTRACT: In this paper, the sensitivity of randomness in material parameters on the thermal buckling of conical shells embedded with and without piezoelectric layer is examined. A higher order shear deformation theory is used to model the system behaviour of the conical shell. The lamina material properties are modelled as basic random variables. A deterministic finite element method in conjunction with the first-order perturbation technique is employed to handle the randomness in the material properties. Typical numerical results for the second order statistics of the linear thermal buckling load of the composite conical shells/panels with and without piezoelectric layer are obtained. Mean value results are validated with those available in the literature and standard deviation results are also validated with an independent Monte Carlo simulation.

Khuram Shahzad (1), Sagheer Ahmed (2) and Himayat Ullah (1)
(1) NESCOM, Islamabad and (2) MED UET Taxila
“Effect of Geometric Imperfection on Buckling Strength of Cylindrical Shells”, Failure of Engineering Materials & Structures, UET Taxila, Mechanical Engineering Department (no date; most recent reference is 2003)
ABSTRACT: In this research paper, effect of geometric imperfection on buckling of cylindrical shell subjected to different types of loadings has been investigated using Finite element analysis and compared with analytical model by Donnell and semi Empirical model based on experimentation [1,2] of a perfect shell. In finite element analysis Newton Raphson and Arc length methods are used. Based on the presented results conclusions can be
drawn concerning the shell behavior and its sensitivity to different loadings.

References listed at the end of the paper:
9. void
14. NASA SP-8007;“Buckling of thin walled circular cylinder” NASA, Space vehicle design criteria.1968


ABSTRACT: This report constitutes a synthesis of different results of numerical analysis of thin shell problems. The first part involves a general geometric definition of thin shells which is illustrated by different concrete examples. Next, one records the mechanical and the mathematical formulations of the problems and one gives some existence results. The second part presents some results obtained or under study concerning the approximation of these problems by finite element methods. They include conforming methods, flat plate element methods, mixed methods and D.K.T. methods. Finally, the third part contains basic results to solve the optimal design problem of a thin shell (joint work with F. Palma and B. Rousselet).

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(You have to pay for abstract, references)

Related papers:
1. Analysis of optimized plates for buckling
R Levy… - Computers & structures, 1991 - Elsevier

This paper is concerned with the analysis of optimized plates for buckling. The Rayleigh-Ritz
A computer program has been developed, based on both the linear and nonlinear theories of shells, which obtains numerical solutions for the most commonly used types of pressure vessels, namely those with spherical, ellipsoidal or conical heads and also flat-end pressure vessels. A multisegment integration technique has been used to obtain the solutions of the governing equations. The computed solutions are found to be highly accurate when compared with the known results of simple shells, as no nonlinear analysis is reported in the literature on the shell junctions in pressure vessels.

ABSTRACT: The present work is devoted to the investigation of stability of general spherical shells under external pressure with various end-conditions. The governing non-linear differential equations for the axisymmetric deformations of spherical shells, which defines the unique states of lowest potential energy under given pressures, are solved exactly by using the method of multisegment integration, developed by Kalnins and Lestingi [J. appl. Mech. 34, 59 (1967)]. The critical pressure for a particular shell is interpreted from the fact that any further increase in pressure, no matter how small, will cause enormous shell deformation indicating that the state of lowest potential energy for any increase in pressure is far from that at the critical pressure. Numerical results for a few shells, ranging from shallow to hemispherical, are presented here as examples and compared with others, where available.

ABSTRACT: This paper describes the nonlinear analysis of pressure vessels necessary for taking into account the large deformations that take place at the junctions of shells of different geometries. Specifically, a computer program has been developed, based on both the linear and nonlinear theories of shells, which obtains numerical solutions for the most commonly used types of pressure vessels, namely those with spherical, ellipsoidal or conical heads and also flat-end pressure vessels. A multisegment integration technique has been used to obtain the solutions of the governing equations. The computed solutions are found to be highly accurate when compared with the known results of simple shells, as no nonlinear analysis is reported in the literature on the shell junctions in pressure vessels.

ABSTRACT: The present work is devoted to the investigation of stability of general spherical shells under external pressure with various end-conditions. The governing non-linear differential equations for the axisymmetric deformations of spherical shells, which defines the unique states of lowest potential energy under given pressures, are solved exactly by using the method of multisegment integration, developed by Kalnins and Lestingi [J. appl. Mech. 34, 59 (1967)]. The critical pressure for a particular shell is interpreted from the fact that any further increase in pressure, no matter how small, will cause enormous shell deformation indicating that the state of lowest potential energy for any increase in pressure is far from that at the critical pressure. Numerical results for a few shells, ranging from shallow to hemispherical, are presented here as examples and compared with others, where available.
ABSTRACT: This paper deals with the analysis of axisymmetric elastic buckling of semi-ellipsoidal shells under external pressure. Reissner's non-linear equations for the axisymmetric deformations of shells of revolution are specialized here for ellipsoidal shells and used in this analysis. The geometric singularity of these equations at the apex of shells is avoided through further modifications by imposing the conditions of continuity of the shell parameters and other variables across the apex. A multisegment method of integration, as developed by Kalnins and Lestringi, has been used to solve the non-linear equations of ellipsoidal shells. The critical pressure of a shell is interpreted from the fact that the mode of primary deformation along the fundamental equilibrium path of a structure cannot change without a change in its status of stability. The appearance of a secondary deformation on the fundamental equilibrium path is always hinted by a substantial increase in the deformation rate with respect to the load parameter. Specifically, for shells at the critical equilibrium, any further increase in loading, however small, causes the shell enormous deformation indicating that the state of deformation of the shell which corresponds to the lowest potential energy is far from that at critical pressure. Extensive numerical results on the buckling of semi-ellipsoidal shells with completely restrained edges and for varying thickness ratios have been obtained. It is observed that the critical pressure increases with an increase in the ratio of minor to major axes of the ellipsoidal shell and decreases with an increase in its thickness ratio.


ABSTRACT: This paper summarizes the major computer programs in existence for the analysis of shells of revolution by numerical integration and finite difference procedures. The report describes programs for (1) linear and nonlinear analysis of shells subjected to axisymmetric and asymmetric static loads, (2) buckling and vibration behavior including effects of axisymmetric nonlinear prestress, and (3) transient response. Extensions of these programs which are currently underway and some of the primary assets of both the numerical integration and finite difference procedures are discussed. In addition, a summary of the shell theory formulation, the numerical approximation, and the solution techniques of a set of programs denoted SALORS (Structural Analysis of Layered Orthotropic Ring-Stiffened Shells), developed at the NASA Langley Research Center, are described. Stress, vibration, and buckling results from the SALORS program are given for several shell configurations having a variety of structural complexities that illustrate the current capability of shell of revolution programs.


ABSTRACT: Test results and related structural instability analyses are presented for a 10-ft-diam, 37-in. -long cylinder, and a 10-ft-diam, 40-in. -long, 45-deg. conical frustum. Both structures are based upon flanged isogrids and are fabricated in 2024-T851 aluminum. Peak edge load intensities at failure were 1,654 lb/in. for the cylinder and 1,457 lb/in. at the small diam of the frustum. General instability cylindrical-monocoque-structure equivalent knockdown factors for both were in good agreement ( gamma equals 0. 48). Design analysis is also derived for estimating critical cylinder instability edge loads from the performance of two tandem isogrid members. Evaluation is made of effective skin contributing to isogrid load-carrying cross-section.

Walter L. Heard, Jr. (1), Melvin S. Anderson (1), and Paul Slysh (2)
ABSTRACT: An engineering procedure is presented for calculating the compressive buckling strength of isogrid cylinders using shell-of-revolution techniques and accounting for loading beyond the material proportional limit and/or local buckling of the skin prior to general buckling. A general nondimensional chart (based on a nonlinear postbuckling analysis of a typical skin element) is presented which can be used in conjunction with formulas based on simple deformation plasticity theory to calculate postbuckling stiffnesses of the skin. The stiffening grid system is treated as an equivalent isotropic grid layer. Stiffnesses are determined for this grid layer, when loaded beyond the proportional limit, by the same plasticity theory used for the skin and a nonlinear stress-strain curve constructed from simple isogrid-handbook formulas and standard-reference-manual stress-strain curves for the material involved. Comparison of prebuckling strains and buckling results obtained by this procedure with data from a large isogrid-cylinder test is excellent, with the calculated buckling load no more than 4 percent greater than the test value.

ABSTRACT: This paper investigated reliability of a postbuckled composite isogrid stiffened shell structure under a compression load. The outside diameter of the isogrid cylinder was 624.8 mm, the length was 368.3 mm and the total weight of the cylinder was 3.24 kg. A finite element buckling analysis result was compared with the axial compression experimental data. The average critical buckling load of 186.56 kN was obtained by using the Patran finite element analysis (FEA). The isogrid shell was modeled using 3-node triangular elements and the stiffeners were modeled using 4-node quad elements with a total of 504 nodes and 900 elements. The postbuckled isogrid cylinder was compression tested to the failure load of 177.35 kN. The postbuckled cylinder continued to resist compression loading even after one or more stiffeners had fractured. The testing evaluation revealed that the stiffener buckling was the critical failure mode and it has been demonstrated to be tolerant to structural damage due to the multiplicity of load paths. The lower experimental bucking load was due to the small imperfections in the cylinder but this problem can be overcome by advancement in the manufacturing methods.

ABSTRACT: The problem of determining the snap and snap back pressures of thin shallow shells of revolution subject to uniform loading is considered. The deformation is modelled using Marguerre's equations and bifurcation and postbuckling analyses are undertaken. A finite element model of the deformation is given and results for snap and snap back are presented.

ABSTRACT: An efficient substructuring analysis method is presented for predicting the natural frequencies of shells of revolution which may have arbitrary shape of meridian, general type of material property and any kind of boundary condition. This method is developed in the context of first order shear deformation shell theory as well as the classical thin shell theory. The vibrational behaviours of a circular cylinder, an elliptic hyperboloid shell (modelling a cooling tower) and a complete spherical shell are investigated using this method.

Li Jun and Hua Hongzing (Institute of Vibration, Shock & Noise, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, 200240, People’s Republic of China), “Free vibration analyses of axially loaded laminated composite beams based on higher-order shear deformation theory”, Meccanica, Vol. 46, No. 6, pp 1299-1317, December 2011

ABSTRACT: The dynamic stiffness matrix method is introduced to solve exactly the free vibration and buckling problems of axially loaded laminated composite beams with arbitrary lay-ups. The Poisson effect, axial force, extensional deformation, shear deformation and rotary inertia are included in the mathematical formulation. The exact dynamic stiffness matrix is derived from the analytical solutions of the governing differential equations of the composite beams based on third-order shear deformation beam theory. The application of the present method is illustrated by two numerical examples, in which the effects of axial force and boundary condition on the natural frequencies, mode shapes and buckling loads are examined. Comparison of the current results to the existing solutions in the literature demonstrates the accuracy and effectiveness of the present method

References listed at the end of the paper:
doi:10.1016/0956-0521(94)90049-3

ABSTRACT: This paper deals with the development and application of reliable, creative and efficient computational tools for the structural optimisation of variable thickness axisymmetric and prismatic shells and folded plates using computer-aided analysis and design procedure. The problem of finding optimal forms and thickness variations for such structures is solved by integrating computer aided geometry modelling tools, automatic mesh generation, structural analysis, sensitivity evaluation and mathematical programming methods. The shape and thickness variation of the structures are defined using parametric cubic splines and the structural analysis is carried out with either finite element or finite strip methods in which Mindlin-Reissner assumptions are adopted. In static situations, the composition of the strain energy is monitored during the optimisation process to obtain insight into the energy distribution for the optimum structures. This allows us to demonstrate that, in the majority of cases, the optimum shells are membrane energy dominated as might be expected. For the vibrating structures, the mode shapes of the initial and optimum solutions are presented. A set of carefully defined, unambiguous benchmark examples is presented and studied with independent verification to test the various features of the structural optimisation process.
ABSTRACT: In this paper, the problem of optimal design of shells against instability is considered. A thin-walled shell is loaded, in general, by overall bending moment, constant or varying along an axis of a shell, by the appropriate shearing force and by an axial force and a constant torsional moment. We look for the shape of middle surface as well as the thickness of a shell, which ensures the maximum critical value of the loading parameter. The volume of material and the capacity of a shell are considered as equality constraints. The concept of a shell of uniform stability is applied.

References listed at the end of the paper:
M. Barski (1) and J. Kruzelecki (2)

(1) Institute of Machine Design, Cracow University of Technology, al. Jana PawLa II 37, 31-864 Cracow, Poland

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ABSTRACT: In this paper, the problem of optimal design of shells against instability is considered. A thin-walled shell is loaded, in general, by an external pressure and lateral forces causing overall bending moment (which varies along the axis of a shell) and the appropriate shearing force. We look for the shape of meridian as well as the thickness of a shell, which ensure the maximal critical value of the loading parameter. As the equality constraints, the volume of material and the capacity of a shell are considered. The concept of a shell of uniform stability is applied.

M. Barski and J. Kruzelecki, “Optimal design of shells against buckling by means of the simulated annealing method”, Structural and Multidisciplinary Optimization, Vol. 29, No. 1, 61-72,
ABSTRACT: In this paper, the problem of optimal design of shells against instability under combined state of loadings is considered. We look for the shape of a meridian as well as the thickness of a shell, which ensures the maximal critical value of the loading parameter. The equality constraining the volume of material and the capacity of a shell are considered. The concept of a shell of uniform stability is applied.

References listed at the end of the paper:


DOI: 10.1007/s00158-004-0447-3

Related Papers:
1. Optimal design of rotationally symmetric shells for buckling under thermal loadings
ABSTRACT: In the present paper the problem of optimal design of a rotationally symmetric shell with immovable supports loaded by a uniform elevated temperature is investigated. We look for the variable thickness and the shape of the middle surface which lead to the maximal increment of the temperature causing buckling of the wall of this shell. The concept of the shell of uniform stability is applied.

2. Influence of a shearing force on optimal design of shells against buckling under overall bending
ABSTRACT: The present article is devoted to optimization of shells with a double positive curvature against buckling under overall bending moment which varies along an axis of the shell and under an appropriate shearing force which is associated with that variable bending moment. It seeks the shape of the meridian (only the axially symmetrical shape of the middle surface is allowed for here) as well as the thickness of the shell, which ensure the minimal volume of material. As equality constraints the critical value of the loading parameter and the capacity of a shell are considered. The hypothesis of the locality of buckling is utilized and the optimal structure is sought in the class of shells of uniform stability applying the Shirshov local stability condition.

3. Optimization of axially symmetric shells of uniform stability under torsion and axial force

4. Optimal design of shells against buckling under overall bending with shearing force taken into account
M Barski… - Proceedings of the 5th World congress of structural and …, 2003

5. Optimal design of axially symmetrical shells under hydrostatic pressure with respect to their stability
J Kruzelecki & - Structural and Multidisciplinary Optimization, 2000 - Springer

ABSTRACT: Thin-walled shells under compressive loadings can be subjected to loss of stability and then the corresponding constraints should be taken into account in their structural optimization. Instability of shells has very often a local form and buckling does not depend essentially on the ...

6. Optimal design of shells with respect to their stability
M Zyczkowski & - IUTAM Symposiums on Optimization in Structural …, 1973


ABSTRACT: The subject of the present paper is shells of revolution subjected to the external pressure. A family of shells of revolution, with positive and negative Gaussian curvature, were taken into consideration. The volume Vs and length L of the shell were constant. Three different rc/t ratios were investigated: 300, 504 and 700. The goal is to investigate elastic stability of shells of revolution. For that reason two kinds of analyses were performed using ABAQUS system. These are linear eigenvalue buckling prediction and non-linear post-buckling analysis. As a result of the linear analysis the influence of a meridional radius of curvature on the critical load was determined and presented on the graph. Non-linear analysis allowed to create equilibrium paths showing the behaviour of shells in a post-critical state. As can be seen from a number of plots convex barrelled shells are not stable after exceeding the critical load. Some concave barrelled shells on the contrary have stable equilibrium paths in the post-critical range.


The purpose of this report's analysis is to develop a numerical method and computer program for the calculation of the large deflection dynamic response of simply supported shallow spherical shells subjected to a class of spatially asymmetric and timewise step loadings. The program is then used to calculate asymmetric dynamics buckling loads for a few geometries and load durations, which is of importance in the design of spacecraft structures.


ABSTRACT: An investigation of the stability of the roof of an 85-ft diameter cylindrical prestressed concrete wastewater treatment tank is presented. The roof of the tank is a very thick, shallow spherical dome. With a 1/16 rise to span ratio, 2 ft thickness, and an 18 ft diameter central opening at its pole, the dome falls outside the range of parameters for which the thickness design equation for domes in the ACI 350 code applies. The shallowness parameter of the dome is in the range where axisymmetric snap-through buckling can be expected. A finite-element model was used to compute the nonlinear axisymmetric deflection of the dome up to its limit point, the snap-through to its inverted configuration, and the post snap-through load deflection. Bifurcation from the symmetric deformation to a nonsymmetric buckling mode below the limit point was investigated with a different finite-element model than was used for the evaluation of the snap-through. The finite-element results are compared to a form of the design equation for dome thickness in ACI 350. The dome thickness equation in ACI 350 was used to calculate dome load capacity, given the thickness, and was found to be significantly higher
than the capacity computed with the finite-element model.


ABSTRACT: On the basis of nonlinear theory, the axisymmetric dynamic deformations produced in viscoelastic clamped shallow spherical shells by transient pressure loading are analyzed. Two types of loading condition, that is, a step loading and a graded loading, are considered and the three-element model is used to describe the viscoelastic characteristics of the material considered. The governing equations derived by the authors are solved numerically, and the critical loads and the effects of viscoelasticity and loading speed on the dynamic behavior of the shell are discussed. And it is pointed out that Che buckling phenomena have to be analyzed paying an attention to the connection with the time, because the dynamic, static and creep bucklings are related with one another as a function of time. From the results of the present numerical solution, the quasi-static buckling load also is obtained immediately, which differs little from the static buckling load reported so far. The procedure adopted in the present analysis can be applied easily to the problems of elastic shells. The dynamic behavior of elastic shallow spherical shell obtained, by the present procedure is compared with the previous results and an excellent agreement between them is seen.

References listed at the end of the paper:


ABSTRACT: If it is assumed that, during its forced vibrations which lead to dynamic axisymmetric snap-through buckling, a dynamically loaded spherical cap passes through one of its corresponding static, unstable equilibrium configurations, then it is possible to estimate the dynamic axisymmetric snap-through buckling load from a simple static analysis only, without resorting to an elaborate dynamic analysis. It is shown, through numerical analysis of the spherical cap subjected to a timewise step load, that dynamic axisymmetric snap-through buckling loads obtained from the static approach are comparable to those obtained from the dynamic approach.

References listed at the end of the paper:


ABSTRACT: The dynamic axisymmetric behaviour of clamped orthotropic shallow spherical shell subjected to instantaneously applied uniform step-pressure load of infinite duration, is investigated here. The available modal equations, based on an assumed two-term mode shape for the lateral displacement, for the free flexural vibrations of an orthotropic shallow spherical shell is extended now for the forced oscillations. The resulting modal equations, two in number, are numerically integrated using Runge-Kutta method, and hence the load-deflection curves are plotted. The pressure corresponding to a sudden jump in the maximum deflection (at the apex) is considered as the dynamic buckling pressure, and these values are found for various values of geometric parameters and one value of orthotropic parameter. The numerical results are also determined for the isotropic case and they agree very well with the previous available results. It is observed here that the dynamic buckling load increases with the increase in the orthotropic parameter value. The effect of damping on the dynamic buckling load is also studied and this effect is found to increase the dynamic buckling load. It is further observed that this effect is more pronounced with increase in the rise of the shell.

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“Dynamic instability of laminated composite curved panels using finite element method”, Computers &
ABSTRACT: The dynamic instability of laminated composite cylindrical shells due to periodic loads is studied using a C0 shear flexible QUAD-9 shell element. The boundaries of the principal instability region are conveniently represented in the nondimensional excitation frequency-nondimensional load amplitude plane. The effects of various parameters such as ply-angle, number of layers, thickness and radius-to-side ratio on dynamic stability are brought out.

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ABSTRACT: The dynamic axisymmetric behavior of clamped laminated composite spherical caps subjected to suddenly applied loads is investigated using an eight-noded quadrilateral doubly curved shear flexible shell element based on the field-consistency approach. Geometric nonlinearity is considered using von Karman’s strain-displacement relations. The solution is obtained using the Wilson-Π numerical integration scheme. The pressure corresponding to a sudden jump in the maximum average deflection in the time history of the shell structure is taken as dynamic buckling pressure. A detailed parametric study is carried out to bring out the effects of shell geometries and material properties, number of layers, lamination schemes, and type of loading on a dynamic buckling load.


ABSTRACT: The dynamic instability analysis of a joined conical and cylindrical shell subjected to periodic in-plane load is investigated using C0 two-noded shear flexible shell element. The formulation is based on first-order shear deformation theory. The present model accounts for in-plane and rotary inertia effects. The instability regions are determined based on the principle of Bolotin’s method. The boundaries of the principal instability region obtained here are conveniently represented in the non-dimensional excitation frequency - non-dimensional load amplitude plane. The influence of various parameters such as orthotropy, cone angle, lay-up, combinations of different sections, thickness ratio, circumferential wave number, static load, and external pressure on the dynamic stability regions of cross-ply laminates is brought out.

References listed at the end of the paper:

ABSTRACT: Here, the nonlinear axisymmetric dynamic behavior of clamped laminated angle-ply composite spherical caps under suddenly applied loads of infinite duration is studied. The formulation is based on first-order shear deformation theory and it includes the in-plane and rotary inertia effects. Geometric nonlinearity is introduced in the formulation using von Kármán’s strain–displacement relations. The governing equations obtained are solved employing the Newmark’s integration technique coupled with a modified Newton–Raphson iteration scheme. The load corresponding to a sudden jump in the maximum average displacement in the time history of the shell structure is taken as the dynamic buckling pressure. The performance of the present model is validated against the available analytical/three-dimensional finite element solutions. The effect of shell geometrical parameter and ply angle on the axisymmetric dynamic buckling load of shallow spherical shells is brought out.

References listed at the end of the paper:
[14] Dumir PC, Gandhi ML, Nath Y. Axisymmetric static and dynamic buckling of orthotropic shallow spherical caps with


ABSTRACT: Here, free vibrations and transient dynamic response analyses of laminated cross-ply oval cylindrical shells are carried out. The formulation is based on higher order theory that accounts for the transverse shear and the transverse normal deformations, and includes zig-zag variation in the in-plane displacements across the thickness of the multi-layered shells. The contributions of inertia effect due to in-plane and rotary motions, and the higher order function arising from the assumed displacement models are included. The governing equations obtained using Lagrangian equations of motion are solved through finite element approach. A detailed parametric study is conducted to bring out the influence of different shell geometry, ovality parameter, lay-up and loading environment on the vibration characteristics related to different modes of vibrations of oval shell.

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ABSTRACT: Here, linear elastic stability behavior of laminated cross-ply oval cylindrical shells under axial compression is studied through finite element approach. The formulation is based on higher-order theory that accounts for the transverse shear and transverse normal deformations, and incorporates realistic through the thickness approximations of the in-plane displacements. The strain–displacement relations are accurately introduced in the formulation. The contributions of work done by applied loads due to the higher-order function arising from the assumed displacement models are also included. The governing equations are obtained using the principle of minimum potential energy. The combined influence of higher-order shear deformation, shell geometry and ovality, and lay-up on the buckling loads of cylindrical shells is examined.


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ABSTRACT: Here, the free vibration characteristics of functionally graded elliptical cylindrical shells are analyzed using finite element formulated based on the theory with higher-order through the thickness approximations of both in-plane and transverse displacements. The power law variation of properties is assumed in the thickness direction. The finite element employed in the study is based on field-consistency approach and free from shear and membrane locking problems. The strain–displacement relations are accurately introduced in the formulation without making any approximation in the thickness co-ordinate to radius ratio terms. The detailed parametric studies are carried out to study the influences of non-circularity, radius-to-thickness ratio, material composition and material profile index on the free vibration frequencies and mode shape characteristics of functionally graded elliptical shells. The significance of thickness stretch/contraction terms is highlighted through the mode shape study.

ABSTRACT: Interaction of clamped orthotropic shallow spherical shells with nonlinear elastic foundations is studied under transient loads. The effect of softening and hardening foundation nonlinearities on the response behaviour of shallow shells has been investigated. Detailed analysis depicting the influence of hardening type foundation nonlinearity on the maximum response of orthotropic shallow spherical shells has been conducted. The numerical results suggest that for the shell-foundation interaction problems undergoing moderately large deformations, the nonlinear model for the foundation must be considered.
References listed at the end of the paper:

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ABSTRACT: The axisymmetric moderately thick laminated shallow spherical shells undergoing moderately large deflection subjected to dynamic loading are analyzed. Including the effects of transverse shear and rotatory inertia, the equations of dynamic equilibrium are formulated in terms of normal deflection, slope and stress function. Nonlinear governing equations of motion are linearized using quadratic extrapolation technique and the resulting linear differential equations are discretized in space and time domain using fast converging Chebyshev polynomials and the implicit Houbolt time marching scheme, respectively. Considering step function and sinusoidal loadings, both clamped and simply supported immovable laminated spherical shells are analyzed. The effect of control space variables, viz., transverse shear, rotatory inertia, material properties, shell parameter, base radius to thickness ratio, boundary conditions, number of layer and damping on the central response have been studied.


ABSTRACT: The stability and dynamic characteristics of laminated plates (rectangular, sector) and shells (cylindrical/conical/circular/noncircular) are studied using analytical solutions employing chebyshev polynomials and finite element method. The detailed parametric studies are carried out to highlight the effects of geometrical parameters, lamination schemes, loading and boundary conditions on the stability and dynamic response characteristics of plates and shells undergoing large deformation. Few results are presented.

References listed near the end of the paper:
· Nath Y. and Shukla K. K., 2001a, Analytical Solution for Buckling and Post-Buckling of Angle-Ply Laminated Plates Under

ABSTRACT: The stability of postbuckled equilibrium configurations and the nonlinear dynamic characteristics of cross-ply laminated heated cylindrical shells are investigated employing semi-analytical shell finite element. The presence of asymmetric perturbation in the form of small magnitude load spatially proportional to the linear buckling mode shape is considered to initiate the bifurcation of the shell deformation from axisymmetric mode to asymmetric one. The frequencies of small oscillations about equilibrium configuration are obtained by solving the eigenvalue problem formulated using tangent stiffness matrix of the converged equilibrium configuration and mass matrix. The study reveals that the prediction of the postbuckling equilibrium configuration from nonlinear static analysis depends on the nature (longitudinally symmetric/antisymmetric) of initial disturbance. The longitudinally antisymmetric postbuckled equilibrium configuration is stable whereas the longitudinally symmetric one is unstable. The nonlinear dynamic response shows that the shell with longitudinally symmetric disturbance jumps from symmetric mode to antisymmetric mode and the predicted equilibrium configuration is of antisymmetric nature irrespective of the type of initial disturbance. The nonlinear forced dynamic response of the heated shell in the prebuckling region differs significantly from that in the postbuckling region.

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ABSTRACT: Here, the thermo-elastic buckling characteristics of angle-ply laminated elliptical cylindrical shells subjected to uniform temperature rise are studied to highlight the combined influences of non-circularity and ply-angle on the critical temperature parameter and buckling mode shapes. It is brought out that the rate of change of the critical temperature parameter with respect to ply-angle reduces significantly with the increase in the non-circularity parameter. Further the shells in the optimum ply-angle range are found to be highly sensitive to non-circularity whereas their sensitivity is very less away from the optimum ply-angle range.


ABSTRACT: Here, the dynamic stability behavior of a clamped functionally graded materials spherical shell
structural element subjected to external pressure load is studied. The material properties are graded in the thickness direction according to the power-law distribution in terms of volume fractions of the constituents of the material. The effective material properties are evaluated using a homogenization method. The structural model is based on shear deformation theory and geometric non-linearity is considered in the formulation using von Karman’s assumptions. The governing equations obtained are solved employing the Newmark’s integration technique coupled with a modified Newton–Raphson iteration scheme. The load corresponding to a sudden jump in the maximum average displacement in the time history of the shell structure is taken as the dynamic buckling pressure. The present model is validated against the available isotropic cases. A detailed numerical study is carried out to bring out the effects of power-law index of functional graded material on the axisymmetric dynamic stability characteristics of shallow spherical shells.

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ABSTRACT: Here, the dynamic thermal buckling behavior of functionally graded spherical caps is studied considering geometric nonlinearity based on von Kármán's assumptions. The formulation is based on first-order shear deformation theory and it includes the in-plane and rotary inertia effects. The material properties are graded in the thickness direction according to the power-law distribution in terms of volume fractions of the material constituents. The effective material properties are evaluated using homogenization method. The governing equations obtained using finite element approach are solved employing the Newmark's integration technique coupled with a modified Newton–Raphson iteration scheme. The pressure load corresponding to a sudden jump in the maximum average displacement in the time history of the shell structure is taken as the dynamic buckling load. The present model is validated against the available isotropic case. A detailed numerical study is carried out to highlight the influences of shell geometries, power law index of functional graded material and boundary conditions on the dynamic buckling load of shallow spherical shells.

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PARTIAL INTRODUCTION: Recent research works on improved performance materials have addressed new materials, known as functionally graded materials [1] (FGMs), in which the material properties vary smoothly and continuously from one surface of the material to the other surface. These are high-performance, heat-resistant materials that are able to withstand the ultrahigh temperatures and extremely large thermal gradients that are used in fusion reactors and aerospace industries. They maintain their structural integrity and avoid the interface problem that exists in homogeneous composites. Thin-walled structural members of aerospace and defense that are subjected to dynamic load could encounter deflections of the order of the shell thickness. The dynamic response of such shells may lead to the phenomenon of dynamic snapping or dynamic buckling. Hence, the nonlinear behavior of thin structural members, in particular, spherical shells that form an important
class of structural components, has to be understood for their optimum design.

References listed at the end of the paper:


ABSTRACT: Assuming the deformation of the shell has an axial symmetrical form, we transform Marguerre’s equations [1] into difference equations, and use these equations to discuss the buckling of an elastic thin shallow
spherical shell subjected to impact loads. The result shows when impact load acts on the shells, a jump of the shell takes place dependent on the values lambda and the critical buckling load increases with the enlargement of the loading area.

References listed at the end of the paper:


ABSTRACT: The non-linear buckling strength of clamped spherical caps under uniform step loading was investigated. To simplify the finite element formulation of the geometrically non-linear behavior of snap-through buckling, the geometric coordinates of spherical caps are updated at every time step. Thus, a linearized finite element incremental equation based on the principle of virtual work can be derived. A three-dimensional shell element with arbitrary geometry was used in the finite element formulation, and the whole process was accomplished according to the Newmark method as the time integration scheme. Two alternative criteria of critical load, the apex displacement and the average deflection, were utilized to determine the dynamic buckling loads. The results agree well with previously published work.

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ABSTRACT: Random vibrations are considered for the cases of shear-deformable plates with initial curvature and of elastically buckled plates. The nontrivial generalization of the flat plate vibrations is expressed by the fact that “small amplitude” vibrations exist about the curved equilibrium position together with the snap-through and snap-buckling type large amplitude vibrations about the flat position. The problem of snap-buckling in the large deflection random response, i.e., the loss of stability accompanied in simple and regular structures by the change from a symmetric to an antimeric configuration, is studied in detail. The geometrically nonlinear panel vibrations are treated by applying Berger’s approximation to the generalized von Karman-type
plate equations considering hard hinged supports of the straight boundary segments of skew or even more generally shaped polygonal plates. Shear deformation is considered by means of Mindlin’s kinematic hypothesis. A distributed lateral force loading is applied, and additionally, the influence of thermal prestress is taken into account as well as a randomly fluctuating temperature. A multi-mode approach and the Galerkin procedure are applied to the boundary value problem. The result of the projection and of a transformation is a set of nonlinearity coupled ordinary differential equations (ODEs) driven effectively by random forces and with potential restoring forces. For reasons of convergence, a light viscous modal damping is added at this stage. By means of a nondimensional formulation and introducing the eigen-time of the basic mode of the associated linearized problem renders a unifying result with respect to the planform of the panel. With the simplifying approximation of the action of the random environment by effective forces modeled by uncorrelated, zero-mean wide-band noise processes, and by considering the set of modal equations to be finite, the Fokker-Planck-Kolmogorov (F.P.K.) equation for the transition probability density of the generalized coordinates and velocities is derived. The probability of first dynamic snap-through is derived for a single mode approximation with the influence of higher modes taken into account. Using the two-mode expansion, the probability distribution of the asymmetric snap-buckling is also evaluated. All probabilistic results obtained for the complex panel structures to be considered hold independently (in the sense of similitude) of their special planform. They are cast in the form of graphs with a structural parameter varying in a wide range.

References listed at the end of the paper:


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ABSTRACT: A numerical experiment using the finite element method to show that the nondimensional dynamic buckling pressure of deep elastic isotropic clamped perfect spherical caps subjected to suddenly applied uniform pressure is represented by a function of the geometric parameter and the thickness to radius ratio of caps. Three definitions of geometric parameter are considered. The effects of material properties are also taken to consideration.

References listed at the end of the paper:

ABSTRACT: An analytical method for the elasto/visco-plastic dynamic problems of axisymmetrical thin shells subjected to mechanical or thermal loads or both is developed. The equations of motion and the relations between the strains and displacements are derived by extending Sanders' elastic-shell theory. For the constitutive relations, Perzyna's elasto/visco-plastic equations, including the temperature effect, are employed. The derived fundamental equations are numerically solved by the finite-difference method. As numerical examples, simply supported cylindrical shells made of mild steel are treated, and the following two cases are analyzed: a non-uniformly heated cylindrical shell subjected to impulsive internal pressure, and an internally pressurized cylindrical shell subjected to impulsive thermal load. In both cases, the variations of displacements and internal forces with time are discussed.


ABSTRACT: In this paper, by means of combining non probabilistic convex modeling with perturbation theory, an improvement is made on the first order approximate solution in convex models of uncertainties. Convex modeling is extended to largely uncertain and non-convex sets of uncertainties and the combinational convex modeling is developed. The presented method not only extends applications of convex modeling, but also improves its accuracy in uncertain problems and computational efficiency. The numerical example illustrates the efficiency of the proposed method.

References listed at the end of the paper:
Xu Han, Chao Jiang, LiXin Liu, Jie Liu and XiangYun Long (State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China), “Response-surface-based structural reliability analysis with random and interval mixed uncertainties”, Science China Technological Sciences, Vol. 57, No. 7, pp 1322-1334, July 2014

ABSTRACT: Traditional reliability analysis requires probability distributions of all the uncertain parameters. However, in many practical applications, the variation bounds can be only determined for the parameters with limited information. A complex hybrid reliability problem then will be caused when the random and interval variables coexist in a same structure. In this paper, by introducing the response surface technique, we develop a new hybrid reliability method to efficiently compute the interval of the failure probability of the structure due to the probability-interval hybrid uncertainty. The present method consists of a sequence of iterations. At each step, a response surface model is constructed for the limit-state function by using a quadratic polynomial and a modified axial experimental design method. An approximate hybrid reliability problem is created based on the response surface model, which is subsequently solved by an efficient decoupling approach. An updating strategy is suggested to improve the quality of the response surface and whereby ensure the reliability analysis precision. A computational procedure is then summarized for the whole iterations. Four numerical examples and also a practical application are provided to demonstrate the effectiveness of the present method.


ABSTRACT: Functionally graded materials (FGM) are composite materials with microstructure gradation optimized for the functioning of engineering components. For the case of fibrous composites, the fibre density is varied spatially, leading to variable material properties tailored to specific optimization requirements. There is an increasing demand for the use of such intelligent materials in space and aircraft industries. The current preferred methods to study engineering components made of FGM are mainly modelling particularly those that
are finite element (FE) based as experimental methods have not yet sufficiently matured. Hence this thesis reports the development of a new Mindlin-type element and new Reissner-type element for the FE modelling of functionally graded composite (FGC) structures subjected to various loadings such as tensile loading, in-plane bending and out-of-plane bending, buckling and free vibration. The Mindlin-type element formulation is based on averaging of transverse shear distribution over plate thickness using Lagrangian interpolation. Two types of Mindlin-type element were developed in this report. The properties of the first Mindlin-type element (i.e. Average Mindlin-type element) are computed by using an average fibre distribution technique which averages the macro-mechanical properties over each element. The properties of the second Mindlin-type element (i.e. Smooth Mindlin-type element) are computed by using a smooth fibre distribution technique, which directly uses the macro-mechanical properties at Gaussian quadrature points of each element. The Reissner-type element formulation is based on parabolic transverse shear distribution over plate thickness using Lagrangian and Hermitian interpolation. Two types of Reissner-type element were developed in this report, which include the Average and Smooth Reissner-type elements. There were two types of non-linearity considered in the modelling of the composite structures, which include finite strain and material degradation. The composite structures considered in this paper are functionally graded in a single direction only, but the FE code developed is capable of analysing composite structures with multidirectional functional gradation. This study was able to show that the structural integrity enhancement and strength maximisation of composite structures are achievable through functional gradation of material properties over the composite structures.

References listed at the end of the dissertation:


ABSTRACT: Equilibrium and stability equations of a moderately thick rectangular plate made of functionally graded materials under thermal loads are derived based on the first order shear deformation theory. It is assumed that the material properties vary as a power form of thickness coordinate variable z. The derived equilibrium and buckling equations are then solved analytically for a plate with simply supported boundary conditions. Two types of thermal loading, uniform temperature rise and gradient through the thickness are considered, and the buckling temperatures are derived. The influences of the plate aspect ratio, the relative thickness, the gradient index and the transverse shear on buckling temperature difference are all discussed.


ABSTRACT: This investigation deals with the static and dynamic axisymmetric buckling of elastic orthotropic thin shallow spherical shells with elastically restrained edge for inplane and rotational displacements. Governing equations in terms of normal displacementw and stress function psi have been employed. Orthogonal point collocation method is used for spatial discretisation and Newmark-beta scheme is used for time-marching.
The uniformly distributed static and step function conservative loadings normal to the underformed surface are considered. The present results are in good agreement with the available results. The influence of orthotropicity parameter beta and the support stiffness parameters on the static and dynamic buckling loads has been investigated.

References listed at the end of the paper:

under a uniformly distributed step load have been obtained and found to agree closely with the available results.

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ABSTRACT: This paper deals with the moderately large dynamic response of a doubly curved shallow spherical shell of rectangular plan form, supported on a two parameter elastic subgrade and subjected to uniformly distributed step and sinusoidal loadings. Von Kármán-Donnell type non-linear partial differential equations of motion are employed and solved by using finite difference and Houbolt time marching techniques. Two boundary conditions are considered. The influence of stiffnesses and mass of the elastic subgrade on the moderately large amplitude of response of the shell has been investigated.

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ABSTRACT: This paper deals with the static and dynamic buckling of polar orthotropic antisymmetrically laminated, moderately thick shallow spherical shells under uniformly distributed loading. Considering the effects of transverse shear and rotatory inertia, the governing equations of motion for shells undergoing large deformations are derived and expressed in terms of normal deflection W, slope theta and stress function psi. the Chebyshev series technique is used for spatial discretization and the Houbolt scheme is used for temporal discretization. Considering step function loading, both clamped and simply supported immovable laminated spherical shells are analyzed. The effects of transverse shear, rotatory inertia, shell rise, base-radius-to-thickness ratio and material properties on the static and dynamic snap-through buckling of antisymmetrically laminated shells have been studied.

ABSTRACT: The influence of meridional curvature on the postbuckling behaviour of angle-ply laminated cylindrical shells subjected to external pressure, torsional load, axial compression and uniform temperature rise is investigated using the semi-analytical finite element approach. The nonlinear governing equations are solved using Newton–Raphson iterative technique coupled with the adaptive displacement control method. The presence of asymmetric perturbation in the form of a small magnitude load spatially proportional to the linear buckling mode shape is considered to trace the postbuckling path. The variation of ply-angle and ply-thickness along the meridional direction is considered. The results presented reveal that the imperfection sensitivity of the
cylindrical shells having negative Gaussian curvature decreases with the increase in the magnitude of H/r₀ ratio for all the loading cases considered. The imperfection sensitivity of the positive Gaussian curvature shells increases for external pressure, torsional and thermal loading cases, whereas it decreases for axial loading case with the increase in H/r₀ ratio.

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ABSTRACT: Here, the elastic buckling characteristics of laminated cross-ply elliptical cylindrical shells under axial compression is studied through finite element approach. The formulation is based on higher-order theory that accounts for the transverse shear and transverse normal deformations, and incorporates realistic through the thickness approximations of the in-plane displacements. The strain-displacement relations are accurately accounted for in the formulation. The contributions of work done by applied load due to the higher-order function arising from the assumed displacement models are also incorporated. The governing equations obtained using the principle of minimum potential energy are solved through eigenvalue approach. The combined influence of higher-order shear deformation, shell geometry and elliptical cross-sectional parameter, and lay-up on the buckling loads of elliptical cylindrical shells is examined.


ABSTRACT: This paper presents the large deflection elastic curve of buckled bars through perturbation method, and the bifurcation diagrams including the influence of the imperfection at the base by using singular perturbation method of imperfect bifurcation theory. The physical meaning of the bifurcation diagrams is discussed.

References listed at the end of the paper:


ABSTRACT: The present paper deals with an eigenvalue problem for a hemivariational inequality, arising in the study of a mechanical problem: the buckling of a von Kármán plate adhesively connected to a rigid support with delamination effects. For this eigenvalue problem an existence result is obtained by applying a critical point method suitable for nonconvex nonsmooth functions. Further, a result concerning the multiplicity of solutions is proved. The mechanical interpretation of these results is briefly discussed.

References listed at the end of the paper:

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ABSTRACT: Most commercial finite-element programs use the Jaumann (or co-rotational) rate of Cauchy stress in their incremental (Riks) updated Lagrangian loading procedure. This rate was shown long ago not to be work-conjugate with the Hencky (logarithmic) finite strain tensor used in these programs, nor with any other finite strain tensor. The lack of work-conjugacy has been either overlooked or believed to cause only negligible errors. Presented are examples of indentation of a naval-type sandwich plate with a polymeric foam core, in which the error can reach 28.8 per cent in the load and 15.3 per cent in the work of load (relative to uncorrected results). Generally, similar errors must be expected for all highly compressible materials, such as metallic and ceramic foams, honeycomb, loess, silt, organic soils, pumice, tuff, osteoporotic bone, light wood, carton and various biological tissues. It is shown that a previously derived equation relating the tangential moduli tensors associated with the Jaumann rates of Cauchy and Kirchhoff stresses can be used in the user’s material subroutine of a black-box commercial program to cancel the error due to the lack of work-conjugacy and make the program perform exactly as if the Jaumann rate of Kirchhoff stress, which is work-conjugate, were used.

References listed at the end of the paper:
ABSTRACT: Most commercial finite element codes, such as ABAQUS, LS-DYNA, ANSYS and NASTRAN, use as the objective stress rate the Jaumann rate of Cauchy (or true) stress, which has two flaws: It does not conserve energy since it is not work-conjugate to any finite strain tensor and, as previously shown for the case of sandwich columns, does not give a correct expression for the work of in-plane forces during buckling. This causes no appreciable errors when the skins and the core are subdivided by several layers of finite elements. However, in spite of a linear elastic behavior of the core and skins, the errors are found to be large when either the sandwich plate theory with the normals of the core remaining straight or the classical equivalent homogenization as an orthotropic plate with the normals remaining straight is used. Numerical analysis of a plate intended for the cladding of the hull of a light long ship shows errors up to 40%. It is shown that a previously derived stress-dependent transformation of the tangential moduli eliminates the energy error caused by Jaumann rate of Cauchy stress and yields the correct critical buckling load. This load corresponds to the Truesdell objective stress rate, which is work-conjugate to the Green–Lagrangian finite strain tensor. The commercial codes should switch to this rate. The classical differential equations for buckling of elastic soft-core sandwich plates with a constant shear modulus of the core are shown to have a form that corresponds to the Truesdell rate and Green–Lagrangian tensor. The critical in-plane load is solved analytically from these differential equations with typical boundary conditions, and is found to agree perfectly with the finite element solution based on the Truesdell rate. Comparisons of the errors of various approaches are tabulated.
not to be associated by work with any finite strain tensor, and the first has often been combined with tangential moduli not associated by work. The error in energy conservation was thought to be negligible, but recently, several papers presented examples of structures with high volume compressibility or a high degree of orthotropy in which the use of commercial software with the Jaumann rate of Cauchy or Kirchhoff stress leads to major errors in energy conservation, on the order of 25–100%. The present paper focuses on the Green–Naghdi rate, which is used in the explicit nonlinear algorithms of commercial software, e.g., in subroutine VUMAT of ABAQUS. This rate can also lead to major violations of energy conservation (or work conjugacy)—not only because of high compressibility or pronounced orthotropy but also because of large material rotations. This fact is first demonstrated analytically. Then an example of a notched steel cylinder made of steel and undergoing compression with the formation of a plastic shear band is simulated numerically by subroutine VUMAT in ABAQUS. It is found that the energy conservation error of the Green–Naghdi rate exceeds 5% or 30% when the specimen shortens by 26% or 38%, respectively. Revisions in commercial software are needed but, even in their absence, correct results can be obtained with the existing software. To this end, the appropriate transformation of tangential moduli, to be implemented in the user's material subroutine, is derived.


ABSTRACT: A new type of composites structural insulated panels (CSIPs) is presented in this article. These panels are proposed for structural floor and wall applications. The developed composite panels are made of low-cost orthotropic thermoplastic glass/polypropylene laminate as facesheets and expanded polystyrene foam as a core. CSIPs have a considerably high facesheet/core moduli ratio. The common mode of failure of these panels is facesheet/core debonding. Accordingly, this investigation presents models for interfacial tensile stress and critical wrinkling in-plane stress associated with debonding of CSIPs. The facesheet in compression was modeled as a beam on a Winkler foundation. The proposed models were validated using full-scale experimental testing for CSIPs floor and wall panels. Both type of panels failed by facesheet/debonding with natural half-wavelength approximately equal to the core thickness.

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ABSTRACT: This study examined the structural behaviors of foam insulated concrete sandwich panels subjected to uniform pressure. Finite element models were used to simulate the detailed shear resistance of connectors and the nonlinear behaviors of concrete, foam and rebar components. The models were then validated using data from static tests performed at the University of Missouri. Both composite and non-composite action had a significant effect on the response of the foam insulated concrete sandwich panels, indicating that the simulated shear tie resistance should indeed be incorporated in numerical analyses. The modeling approach used here conveniently simulated the structural behaviors during all loading stages (elastic, yielding, ultimate and post-failure) and was compatible with the American Concrete Institute (ACI) Code and existing design practices. The results of this study will therefore provide useful guidelines for the analysis and
design of foam insulated sandwich panels under both static and dynamic loadings.

References listed at the end of the paper:

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ABSTRACT: Buckling analysis of sandwich plate was investigated using layerwise method. The formulation was based on the first-order shear deformation theory, and the Rayleigh-Ritz method was used for approximating and determining the displacement field. The results obtained from layerwise theory was compared with finite element results and showed good agreement. This study demonstrated that layerwise theory could describe buckling behavior of sandwich plates with high accuracy and represents a more realistic and acceptable description of behavior of the plates with much less computational cost.

References listed at the end of the paper:


ABSTRACT: In this paper, for a rectangular sandwich plate with edges simply supported and subjected to a constant compressive thrust A along two opposite edges; the secondary bifurcation points and the secondary buckled states that bifurcate from the primary buckled states are determined by a perturbation method. These results are useful for their numerical calculation and can be used to explain the phenomenon of “mode-jumping”.

References listed at the end of the paper:

ABSTRACT: A method of determining bifurcation directions at a double eigenvalue is presented by combining the finite element method with the perturbation method. By using the present method, the buckled states of rectangular plates at a double eigenvalue are numerically analyzed. The results show that this method is effective.

References listed at the end of the paper:

C. S. Chouchaoui, P. Parks and O. O. Ochoa, (Mechanical Engineering Department, Texas A&M University, College Station, TX 77843, USA), “Similitude study for a laminated cylindrical tube under tensile, torsion, bending, internal and external pressure. Part I: governing equations”, Composite Structures, Vol. 44, No. 4, April 1999, pp. 221-229, doi:10.1016/S0263-8223(98)00068-3

ABSTRACT: A general analytical model is developed for the stresses and displacements of an assembly of several coaxial laminated hollow circular cylinders made of orthotropic layers, and subjected to internal and external pressure, tensile, torsion and bending loads. Slip and friction conditions at the interfaces are not considered in lieu of perfect bonding. The model results are compared to the experimental tensile test of a composite tube. Displacements and stresses are evaluated for different angle-ply layers and radius-to-thickness ratios.

C. S. Chouchaoui, P. Parks and O. O. Ochoa, (Mechanical Engineering Department, Texas A&M University, College Station, TX 77843, USA), “Similitude study for a laminated cylindrical tube under tension, torsion, bending, internal and external pressure Part II: scale models”, Composite Structures, Vol. 44, No. 4, April 1999, pp. 231-236, doi:10.1016/S0263-8223(98)00069-5

ABSTRACT: The aim of this study is to demonstrate the validity of scale model development testing and predict the laminated cylindrical tube behavior under tensile, torsion, bending, internal and external pressure load. Similitude theory is used to develop the necessary similarity conditions. In the amplitude approach, the coefficients of the governing differential equation for the prototype and the model of the prototype are compared to develop scaling laws. For composites, these scaling laws depend not just on geometry, but also on constituent properties and the laminate stacking sequences. The model tubes were loaded under scaled test conditions until catastrophic failure. Data acquired included load, strain measurements and non destructive evaluation of damage mechanisms.

A.A. Jafari, S.M.R. Khalili and R. Azarafza (Department of Mechanical Engineering, K.N.Toosi University of Technology, P.O. Box 16765-3381, Tehran, Iran), “Transient dynamic response of composite circular cylindrical shells under radial impulse load and axial compressive loads”, Thin-Walled Structures, Vol. 43, No.
ABSTRACT: Free and forced vibration of composite circular cylindrical shells are investigated based on the first love's approximation theory using the first-order shear deformation shell theory. The boundary conditions (BCs) are considered as clamped-free edges. The dynamic response of the composite shells is studied under transverse impulse and axial compressive loads. The axial compressive load was less than critical buckling loads. The modal technique is used to develop the analytical solution of the composite cylindrical shell. The solution for the shell under the given loading conditions can be found using the convolution integrals. The effect of fiber orientation, axial load, and some of the geometric parameters on the time response of the shells has been shown. The results show that dynamic responses are governed primarily by natural period of the structure. The accuracy of the analysis has been examined by comparing results with those available in the literature and experiments.

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ABSTRACT: In this paper, the necessary similarity conditions, or scaling laws, for free vibrations of orthogonally stiffened cylindrical shells are developed using the similitude theory. The Donnell-type nonlinear strain–displacement relations along with the smearing theory are used to model the structure. Then the principle of virtual work is used to analyze the free vibration of the stiffened shell. After non-dimensionalizing the derived formulations, the scaling laws are developed, using the similitude theory. Then, different examples are solved to validate the scaling laws numerically and experimentally. The obtained results show the effectiveness of the derived formulations.


ABSTRACT: In this paper, the nonlinear vibration of functionally graded (FGM) cylindrical shells subjected to radial harmonic excitation is investigated. The nonlinear formulation is based on a Donnell’s nonlinear shallow-shell theory, in which the geometric nonlinearity takes the form of von Karman strains. The Lagrange equations of motion were obtained by an energy approach. In order to reduce the system to finite dimensions, the middle surface displacements were expanded by using trial functions. These functions were expressed in terms of Fourier series containing linear mode shapes, which were obtained from free vibration analysis. The large-amplitude response and amplitude frequency curves of shell were computed by using numerical method for both linear and nonlinear analysis.

References listed at the end of the paper:
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ABSTRACT: In this paper, a hybrid atomistic-structural element for studying the mechanical behaviour of carbon nanotubes is introduced. Non-linear formulation for this element is derived based on empirical inter-atomic potentials. This hybrid element is capable of taking into account the non-linear nature of inter-atomic forces as well as the non-linearity arising from large deformations. Using these capabilities, the stability analysis of carbon nanotubes under axial compressive loading is performed and the post-buckling behaviour is predicted. Also, the dependence of axial buckling force on nanotube radius is shown.


ABSTRACT: In this study, the influence of nonuniformity of eccentricity of stringers on the general axial buckling load of stiffened laminated cylindrical shells with simply supported end conditions is investigated. The critical loads are calculated using Love’s First-order Shear Deformation Theory and solved using the Rayleigh-Ritz procedure. The effects of the shell length-to-radius ratio, shell thickness-to-radius ratio, number of stringers, and stringers depth-to-width ratio on the buckling load of nonuniformly eccentric shells, are examined. The research demonstrates that an appropriate nonuniform distribution of eccentricity of stringers leads the buckling load to increase significantly.

References listed at the end of the paper:

ABSTRACT: In this research, the general axial and radial buckling optimization of ring-stiffened cylindrical shells is implemented by the genetic algorithm (GA). The stiffened shell is subjected to four constraints including the fundamental frequency, the structural weight, the axial buckling load, and the radial buckling load. In addition, six design variables including shell thickness, number of stiffeners, stiffeners width and height, stiffeners eccentricity distribution order, and stiffeners spacing distribution order are considered. In analytical solution, the Ritz method is applied and stiffeners are treated as discrete elements. The effect of the weighting coefficients of the objective functions on the optimum solution is studied. The results show that optimized stiffening a cylindrical shell leads to a lower structural weight, higher natural frequencies, and larger axial and radial buckling loads, simultaneously. In addition, the upper and lower bounds of the design variables influence the optimum results considerably. It is also found that the distributions of eccentricity and spacing of the stiffeners influence the magnitudes of the axial and radial buckling loads considerably.

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ABSTRACT: The problem of stability of shells of positive Gaussian curvature subjected to a concentrated load, internal or external pressure and an accumulating ponding fluid in the depression caused by the load is the subject of this paper. Critical values of the load are calculated by a so called “geometrical method”, using variational Lagrangian principles. The shape of the shell is assumed to be nearly isometrical to the initial shape and its bending rigidity is taken into account. Simple relations for the critical load are obtained and the results presented in graphical form. The expressions and diagrams presented facilitate calculation of critical loads and describe the behaviour of the shell undergoing very large deflections.

-----BOOK-----

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ABSTRACT: The present paper gives the results of numerical solutions for non-linear problems concerning transverse bending of flexible shallow hyperbolic paraboloid shells with elastic edge elements and tie-connecting lower corners. Perfect and imperfect shells are analysed. To solve the system of non-linear differential equations, the method of finite differences combined with the method of differentiation with respect to a parameter is used. These methods reduce the boundary value problem to Cauchy's problem which is solved with the use of Runge-Kutta's method. It has been shown that the buckling of a flexible shallow hypar under transverse load occurs in the vicinity of the upper corner zones under the effect of principal compressive membrane forces caused by surface shear. The values of critical loads are given here. They depend significantly on the surface curvature and stiffness of the edge elements and tie. For imperfect shells the position and shape of the initial irregularities influence greatly the value of the critical load.


ABSTRACT: The stability of linearly viscoelastic flexible shallow hyperbolic paraboloid shell is analysed under transverse load. Allowances are made for geometrical nonlinearity and initial imperfections of the surface shape. By application of the method of finite differences with respect to geometrical variables and the method of differentiation with respect to a parameter (time) the solution for the system of equilibrium non-linear integro-differential equations is reduced to Cauchy's problem which can be solved numerically. The critical time was shown to depend on the load, curvature, initial imperfections and edge elements compressibility. Critical loads for an outlying time moment are determined.


ABSTRACT: The stability analysis of stiffened plates by means of the finite strip method is presented. The studies are based on the thin shallow theory, giving nonlinear strain displacement relations, but linear curvature displacement relations. The nonlinear equilibrium equations are obtained by the principle of incremental virtual work, using finite strip discretization. The higher order strip with one internal nodal line is applied. It is shown that considerable improvements can be obtained using this kind of strip. It is especially true for the postbuckling analysis. Numerical examples of the strength of stiffened plates in compression are carried out, covering a range of plate and stiffener slenderness.


ABSTRACT: The purpose of this paper is to examine the two fundamental questions in the finite element analysis of shells; namely, the rates of convergence resulting from different interpolation schemes for the inplane and normal displacements, and the dependence of the condition number of the resulting algebraic
system on the various parameters both of the shell and of the discretization.

ABSTRACT: A cubic-cubic finite element is derived for the thin shell of revolution undergoing large axisymmetrical Kirchhoff deformation. Application is made to the nonlinear elastic distortion of a spherical shell under surface pressure and polar forces.


ABSTRACT: In the present paper the mechanical interpretation of the Berger's hypothesis is considered. Using the geometrical method of Pogorelov and the asymptotic representation of the solutions of the non-linear partial differential equations, the values of the first and second invariants of the strain tensor are evaluated. This method confirms the hypothesis of Berger for the class of non-linear problems of shells under static loading. The result obtained is valid for isotropic and anisotropic shells.

ABSTRACT: The global stability of thin elasto-plastic shells subject to static loading is investigated using the variational principle. With the aid of the assumptions of the geometric method the asymptotic of the energy of deformation on the class of partially-regular surfaces, isometric to the initial ones is obtained. The plastic properties of the material are properly described by the deformation theory of plasticity. The variational principle is applied to cylindrical elasto-plastic shells subject to axial compression. The theoretical results for the minimum critical loading, compared with the experimental ones, show the difference to be not more than 10%

ABSTRACT: This paper presents an attempt to evaluate theoretically the influence of initial geometric imperfections in the shell surface on the value of the upper critical load of a strictly convex shell of revolution which is subjected to uniform pressure. Pogorelov's geometric method for nonlinear stability problems of thin shells is applied to obtain an analytical formula for the upper critical load, dependent on the initial imperfections. A probabilistic solution of the problem is presented. As a result, the stochastic influence of the initial deviations in the shell surface on the probability density function of the critical load and on the shell reliability are estimated and presented graphically. An example is given for an ellipsoidal shell of revolution.

ABSTRACT: A probabilistic method is applied to the problem of stability of a spherical shell with initial imperfections, subjected to uniform external pressure. The distribution law of the normal deflections of the shell is obtained following the Smoluchovsky equation, at a given density of the initial deflections. On this basis the probability for the deflections to be in a given interval is found. A relation for the probability for a jump transition to a new stability form is obtained for a spherical shell with a given probability distribution of the initial imperfections. The relations obtained can be used for solving different kinds of reliability problems, as well as problems for prediction of the shell stability forms together with the probability for their realization.


ABSTRACT: The buckling and post-critical behavior of elastic conservative, shallow shells with very small initial imperfections in the middle-surface shape are investigated for several coincident critical loads. In this case the buckling mode of the shell in the initial post-critical stage is a linear combination of many eigenmodes and a computation of the critical loads is related to the need to solve systems of nonlinear algebraic equations /1,2/. The analysis is on the basis of the Mushtari—Donnell — Vlasov equations /3/ by the Liapunov-Schmidt operator method /4–9/. In the case of shells of arbitrary shape, asymptotic representations are constructed of new equilibria in the initial post-critical stage, a system of bifurcation, equations and formulas to determine its coefficients are obtained, and equations of the critical load surfaces are also derived as functions of the shell imperfection parameters. A complete solution of the problem is given for the non-axisymmetric buckling of the axisymmetric equilibrium of shells of revolution. Computational formulas are written down for the coefficients of the system of bifurcation equations and an algorithm is constructed to determine all its solutions. It is shown that taking account of the connectedness of the eigenmodes yields a substantial reduction in the upper critical pressure. Results of computations are presented for spherical and conical shells in two eigenmodes. According to the computations and experiments, the divergence of the theoretical values of the upper critical loads and the actual snap-through loads of a broad class of elastic shells is related mainly to small initial deviations of their shape from the assumed geometric surface /10–12/. Koiter was the first to investigate the buckling of imperfect shells, and his researches were continued by a number of authors using variational principles (see the surveys /1,2,13–16/, almost all the papers cited in these surveys are limited to a study of buckling in one eigenmode).

Mosch M. Domb (Bombardier Aerospace, Strategic Technology Group, Downsview, Ontario, Canada M3K 1Y5, “Nonlinear buckling predictions of curved panels under combined compression and shear loading”, ICAS2002 Congress, 2002

ABSTRACT: The present work deals with implementation of a nonlinear buckling analysis technique for the prediction of the initial buckling in simply supported curved panels subjected to a combined loading state of compression and shear. Interaction buckling curves are generated for a wide range of curved panels. The curves include the effect of a pre-existing level of imperfection in the panel on the combined buckling characteristics. Good correlation with the parabolic naca interaction curve was obtained for the entire combined loading range
when the model predictions are presented through the buckling stress ratios relative to the nonlinear pure compression and pure shear cases. The results presented in this work show the high sensitivity of curved panel buckling to the degree of initial imperfection in the panel, especially when compression loading is present. The magnitude of imperfection in a given panel would be dependent on the panel configuration parameters and its radius to thickness ratio. Detailed knowledge of this dependency would lead to better prediction of the buckling characteristics of the panel.

ABSTRACT: The load-carrying capability of spherical shells under external pressure has been the subject of a long history and many theoretical and experimental studies have been carried out. However, from a comparative study on the design rules for the minimum thickness of the deep manned spherical shells from various classification societies, significant differences have been found. This indicates that these design rules need to be updated and unified like Common Structural Rules for tankers and bulk carriers. In order to lay a foundation for this target, a systematic study is carried out to develop a consistent calculation method for predicting the ultimate strength of spherical pressure hull under external pressure. This is the first paper of a series of three for reporting this study and in this paper, a critical review on the buckling and ultimate strength of spherical pressure hulls is carried out and further problems to be studied are identified. This could lay a solid foundation for the further study.

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ABSTRACT: On the basis of nonlinear strain component formulations of three-dimensional continuum, this paper has derived the nonlinear strain component formulations of shells with initial geometric imperfections. The derivation is not confined to a special shell, therefore they possess general properties. These formulations provide the theoretical basis of the strain analysis for geometric nonlinear problems of shells with initial geometric imperfections.
References listed at the end of the paper:

ABSTRACT: Shell stability in geometrically nonlinear range is considered. Influence of the temperature change on the value of the critical force is examined. The whole analysis is performed numerically using the Finite Element Method. To solve the problem, nonlinear equilibrium paths for given temperature change and various load values must be calculated. These are cross-sections of the nonlinear equilibrium surface. From such paths the critical value of the load for given temperature change can be determined and stability boundary can be found as the main purpose of the procedure. The detailed numerical analysis was performed in reference to the semi cylindrical shell segment subjected to temperature changes and loaded by the concentrated force.

ABSTRACT: The stability phenomenon of elastic, spherical shells is examined numerically by the finite element method. The attention is focused on spherical caps clamped along the periphery and pressurized externally. The stability phenomenon depends on the cap rise. Very shallow shells do not exhibit instability symptoms. Shells of higher rise exhibit typical snap-through buckling. When the rise is greater the bifurcation phenomenon appears as well. The spherical shell of a particular rise is analysed in detail in the paper. The fundamental path and all bifurcation paths splitting from the fundamental one are calculated. Secondary bifurcations are registered in this particular case as well. The most desired forms of geometrical imperfections are indicated. The ‘worst’ imperfections are determined as well.

J. Marcinowski (Institute of Structural Engineering, University of Zielona Góra, Podgora 50, 65-246 Zielona Góra, Poland), “Stability of relatively deep segments of spherical shells loaded by external pressure”, Thin-
ABSTRACT: The buckling of shells in the form of spherical segment depends strictly on its rise. Determination of full equilibrium paths for shells of higher rise is very laborious and evokes many numerical problems. Spherical caps loaded by the external pressure and clamped along the base circle are the subject of a detailed analysis. The stability analysis for shells of relative slenderness of interval $\lambda = 3.5$ - 12 was performed and is presented in the paper. Three critical points, and namely the primary bifurcation point, the primary higher limit point and the primary lower limit point were basis for the plot of relative critical pressure versus slenderness parameter. This plot has big practical significance. One can read off from it the value of critical pressure being the basis of designing procedure, which takes into account stability criterion. The author's program based on FEM and taking into account all singularities characteristic for nonlinear elastic stability, was used in calculations. The correctness of the approach was verified on the example of spherical segment of slenderness $\lambda = 8$ solved before by other authors.


ABSTRACT: The paper deals with some considerations focused on resistance assessment of slender cylindrical shells subjected to the axial compression. The load carrying capacity of such shells is determined by stability criterion. It is not enough to determine the critical load in order to assess the load carrying capacity. It is necessary to apply the whole procedure recommended by designing codes and other design recommendations. Details of this procedure were presented in the paper. The correctness of the resistance assessment was verified experimentally on segments of cylindrical shells made of stainless steel.

References listed at the end of the paper:
buckling capacity curve for the particular class of spherical caps is the principal goal of this work. The method of determination of the critical pressure and the plastic resistance were described by the authors in [1] whereas the worst imperfection mode for the considered class of spherical shells was found in [2]. The determination of buckling parameters defining the buckling capacity curve for the whole class of shells is more complicated task. For this reason the authors focused their attention on spherical steel caps with the radius to thickness ratio of $R/t = 500$, the semi angle phi $= 30^\circ$ and the boundary condition BC2 (the clamped supporting edge). Taking into account all imperfection forms considered in [2] and different amplitudes expressed by the multiple of the shell thickness, sets of buckling parameters defining the capacity curve were determined. These parameters were determined by the methods proposed by Rotter in [3] and [4] where the method of determination of the exponent $\eta$ by means of additional parameter $k$ was presented. As a result of the performed analyses the standard capacity curves for all considered imperfection modes and amplitudes $0.5t$, $1.0t$, $1.5t$.


ABSTRACT: A thermal buckling analysis of symmetric and antisymmetric angle-ply laminated hybrid composite plates with an inclined crack subjected to a uniform temperature rise is presented in this paper. The first-order shear deformation theory in conjunction with the variational energy method is employed in mathematical formulations. The eight-node Lagrange finite-element technique is used for determining the thermal buckling temperatures of hybrid laminates. The effect of crack size and stacking sequences on the temperatures is investigated.


ABSTRACT: A solution to the problem on the stability according to the flexural buckling mode is given for a cylindrical sandwich shell with a transversely soft core of arbitrary thickness. The shell is under the action of a temperature field inhomogeneous across the thickness, and its end faces are fastened in such a way (in the axial direction, the face sections of the external layer are fixed, but of the internal one are free) that an inhomogeneous subcritical stress-strain state arises in the shell across the thickness of its layers. It is shown that, under such conditions, the buckling mode of the shell is mixed flexural. To reveal and investigate this mode, equations of subcritical equilibrium and stability of a corresponding degree of accuracy are needed. References listed at the end of the paper:


V.Ye. Vyalkov, V.A. Ivanov and V.N. Paimushin (Kazan, USSR), “Modes of loss of stability and critical loads

ABSTRACT: Problems of the modes of loss of stability of a three-layer spherical shell, consisting of thin external layers and a transversely soft filler of arbitrary thickness, which is under conditions of a uniform external pressure, are considered. The two-dimensional equations of the Kirchhoff-Love theory of the moderate flexure of thin shells are used. These equations are set up for the external layers, taking account of the interaction with the filler and, in the case of the filler, using the geometrically non-linear equations of the theory of elasticity, which correspond to the introduction of the assumption that the stretching deformations are small and the shear deformation are finites, which enables the purely shear modes of loss of stability in the filler to be described correctly. An exact analytical solution is found for the problem of an initial centro-symmetric deformation of a shell, which depends linearly on the external pressure. It is shown that the three-dimensional equations for the filler, which have been linearized in the neighbourhood of this solution, can be integrated with respect to the radial coordinate, and reduce to two two-dimensional differential equations, in addition to the six equations by which the neutral equilibrium of the external layers is described. It is established that the system of eight differential equations of stability, constructed for a shell with isotropic layers, when new unknowns in the form of scalar and vortex potentials are introduced, decomposes into two unconnected systems of equations. The first of these systems has two forms of solutions by which the shear modes of loss of stability are described for the same value of the critical load. A mixed flexural mode, the realization of which is possible for certain combinations of the governing parameters of the shell for high values of the external pressure compared with the shear modes, is described by the second system.


ABSTRACT: We consider the problem of static and dynamic buckling modes of thin shells under external hydrostatic pressure. If the statement of the problem uses the linearized equations of motion obtained in the moderately large bending theory of shells according to the classical or refined model, then part of terms related to the external load in these equations are assumed to be conservative, and the other terms are assumed to be nonconservative. In this connection, we study four statements of the elastic stability problem for a cylindrical shell with hinged faces. The first of them is the statement of the static boundary value problem in the sense of Euler, where the action of external pressure is assumed to be conservative. The second statement is used to study small vibrations near the static equilibrium by a dynamic method for the same conservative load. The third and fourth statements of the problem correspond to the action of a nonconservative load and are similar to the first and second statements, respectively. They use the linearized equations of equilibrium and motion constructed earlier in a consistent version on the basis of a Timoshenko type model and allowing one to reveal all classical and nonclassical shell buckling modes.

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10. K. Z. Galimov (Editor), Theory of Shells with Transverse Shear Taken into Account (Kazan Univ., Kazan, 1977) [in Russian].


ABSTRACT: The buckling of thin-walled shell structures under load is still imperfectly understood, in spite of much research over the past 50 years. In this paper the author traces the history of the ideas which have been deployed in order to shed light on what is often referred to as ‘imperfection-sensitive’ buckling behaviour of shells. The ideas, which recur in various combinations, involve interaction of competing buckling modes, nonlinear behaviour, the growth of initial geometric imperfections under load and the alteration of the distribution of membrane stress as imperfections grow. The author claims that there are strong grounds for supposing that ‘locked in’ initial stresses on account of imperfect initial geometry and the static indeterminacy of boundary conditions of real shells have a pronounced effect on the buckling performance. This effect has been ignored in the past, and is the subject of a current experimental study.

Martin Pircher, Prof. Russell Bridge (School of Civic Engineering and Environment University of Western Sydney, Nepean PO Box 10, Kingswood, NSW 2747, Australia), “The Influence of Circumferential Weld-induced Imperfections on the Buckling of Silos and Tanks”, Advances in Steel Structures (ICASS ‘99) Proceedings of The Second International Conference on Advances in Steel Structures 15–17 December 1999, Hong Kong, China, 1999, pp. 639-646, doi:10.1016/B978-008043015-7/50075-0

ABSTRACT: The load carrying behaviour of cylindrical thin-walled shell structures under axial load is strongly dependent on imperfections invariably caused by various manufacturing processes. Axisymmetric imperfections have been recognised to result in particularly severe reductions in strength. Imperfections in the vicinity of circumferential welds in steel silos and tanks fall into this category and therefore deserve special attention. A detailed bifurcation and post-buckling finite elements analysis was performed on imperfect cylindrical shells. Special care was taken to model the weld-induced circumferential imperfection. The geometry was calibrated against data gained from measuring such imperfections on existing silos and residual stresses were taken into account. Interaction between neighbouring weld imperfections and the role of the strake height in this interaction was investigated. Weld-induced residual stresses were found to have a small strengthening influence on the buckling load. Interaction between neighbouring imperfections was found to reduce the buckling strength of the structures. A post-buckling analysis was undertaken to investigate the load-carrying behaviour of the
structure after initial bifurcation.


ABSTRACT: Thin-walled shell structures of a circular cylindrical shape are widely used in structural engineering to serve in applications such as silos, tanks or chimneys. The design of such structures poses some considerable challenges to structural engineers as the load carrying behaviour of cylindrical shells is quite complex, especially for non-axisymmetric load cases. Very often a comprehensive analysis causes considerable expenses and the vast amounts of results which are typically generated make it hard to understand the underlying load-carrying principles of the structure. The introduction of an engineering method to handle two typical non-axisymmetric load cases on circular cylindrical thin-walled shell structures is the goal of this paper. The proposed method offers a quick way to generate critical section forces and displacements. The load cases discussed herein are wind-loading and foundation settlement. Ground support for many cylindrical steel structures is often realised by anchoring the lower shell boundary to a concrete foundation. This is accomplished by steel bolts that can be looked at as spring elements providing elastic support for the shell structure. The influence of this type of support on the section forces and displacements under wind loading can be modelled by combining the two abovementioned load cases via an interaction diagram also given in this paper.

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ABSTRACT: The strength of thin-walled cylindrical shell structures is highly dependent on the nature and magnitude of imperfections. Most importantly, circumferential imperfections have been reported to have an especially detrimental effect on the buckling resistance of these shells under axial load. Due to the manufacturing techniques commonly used during the erection of steel silos and tanks, specific types of imperfections are introduced into these structures, among them circumferential weld-induced imperfections between strakes of steel plates. A study on several factors influencing the buckling of silos and tanks was carried out using the finite-element method. The interaction between neighboring circumferential weld imperfections was investigated, and it was found that the influence on the buckling behavior depended on the strake height in relation to the linear meridional bending half-wavelength and the depth of the imperfection. The shape of localized circumferential weld imperfections was found to influence the buckling behavior of silos and tanks. The influence of a recently developed shape function on the buckling behavior has been examined. The strengthening effect of weld-induced residual stress fields was also studied, and the extent of the increase in buckling strength was derived for a large range of cylinder geometries.

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Axialbelastung.” Der Stahlbau, Berlin, 10, 313–318 (in German).


ABSTRACT: Steel silos and tanks are constructed from plates which are rolled to the correct curvature and welded together to form strakes. Several strakes of curved plates, placed on top of each other then form the completed structure. At each circumferential weld, a slight hourglass depression occurs essentially forming axisymmetric imperfections which are known to be most deleterious. The detrimental influence of this particular type of imperfection on the buckling of axially compressed cylindrical shells such as silos and tanks is well known. Axial compression onto silos or tanks is commonly generated by roof structures, snow loads or, in the case of silos, by friction forces generated by the content. However, very little is known about the post-buckling of thin-walled cylinders with a circumferential weld imperfection. A post-buckling load bearing model was developed and the influence of weld imperfection amplitude, weld-induced residual stress-fields, different boundary-conditions and elastic-plastic material behaviour was studied. Different modelling techniques, taking into account various symmetries of the problem, are also discussed.
ABSTRACT: Steel box sections are usually fabricated from flat plates which are welded at the corners. The welding process can introduce residual stresses and geometric imperfections into the sections which can influence their strength. For some thin-walled sections, large periodic geometric imperfections have been observed in manufactured sections. Subsequent investigations have indicated that the imperfections are in fact buckling deformations i.e. the box section has buckled due to welding residual stresses prior to any application of external load. The welding procedure and the behaviour of the box sections under load has been modelled using a finite element analysis that accounts for both geometric and material non-linearities. Tests have been carried out on box sections with a range of width to thickness ratios for the plate elements. Modelling has been shown to give good correlation with the test results. The conditions for buckling to take place as a result of the welding process have been established. A design method has been proposed.

References listed at the end of the paper:

ABSTRACT: Beams with an I-shaped cross-section (I-sections) are widely used in the building industry throughout Australia and internationally. The Australian Standard AS4100 provides guidelines for the design of such beams. Numerous failure modes are taken into account in these design rules including stability failure modes where such beams buckle out of their plane of loading. Recent failures of beams which have been designed according to the Australian Standard AS4100 have been documented and concerns have been raised that critical out-of-plane failure modes might not be included in the current version of this Australian Standard. A preliminary study on one such I-section was performed at the Centre of Construction Technology and Research (CCTR), University of Western Sydney. This preliminary study revealed that, for short beams, a failure mode exists that is not covered by the current design rules. The current paper documents these findings and proposes a simple failure model which could become the basis for the design against this failure mode.

ABSTRACT: Depending on the geometry of a thin-walled cylindrical structure, three different stability failure modes under wind loading can be observed. In low cylinders, the radial compression at the windward meridian causes a buckling mode similar to cylinders under constant radial compression while very long cylinders display a failure mode characterized by buckling in the lower third of the structure at the side which faces away from the wind. Both of these failure modes have received a certain amount of interest by the research community, and design rules and proposals against both these failure modes exist. The failure of medium-height cylinders is characterized by a number of horizontal ripplelike buckles in an area around the upper half of the windward meridian. Comparatively little attention has been paid to this failure mode in the existing literature. A case study using a finite element model of a cylinder displaying this particular failure mode will be presented in this paper. The governing parameters for this rather unexpected behavior are identified and an explanation for the structural response is given. It is shown that the critical bifurcation mode is strongly dependent on prebuckling deformations. An imperfection sensitivity analysis for various imperfection types is also presented.

ABSTRACT: For particular geometrical constellations of thin-walled cylindrical structures under wind-loading, a peculiar stability failure mode has been observed. This failure mode is characterised by the occurrence of multiple horizontal ripple-like buckles in an area around the upper half of the windward meridian. A recent case
study of a cylinder undergoing this type of buckling revealed the strong influence of localised axi-symmetric imperfections on this particular buckling behaviour. For the present paper a detailed investigation into the nature of this influence of such imperfections on the buckling behaviour under wind loading has been performed using finite elements models. A cylinder with a geometry that displayed the particular buckling pattern in question was considered for this study. The parameters describing the nature of the axi-symmetric weld imperfection were varied and their influence on the buckling of these cylinders was studied in detail. The present study draws from insights gained from similar studies for cylinders under axial loading. Many similarities between the two loading cases can be observed and the influence of weld-induced imperfections on the buckling under the two loading types were compared for this paper.


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ABSTRACT: The linear elastic web bend-buckling behavior of I-section girders with a longitudinal stiffener is investigated by a three-dimensional finite element analysis in which the web, top and bottom flanges, and transverse and longitudinal stiffeners are modeled as thin shell elements. After obtaining the bend-buckling moment for an I-section girder by finite element analysis, the buckling stress and subsequently the buckling coefficient of a rectangular web panel with a longitudinal stiffener are calculated and compared with those obtained by AASHTO LRFD and Eurocode 3. To observe the effect of various parameters on the buckling behavior of an I-section girder under pure bending, the following aspects are considered: the non-symmetry of the cross-section, the location of the longitudinal stiffener, the boundary conditions along the transverse and longitudinal stiffeners and flanges, the flexural rigidity of the longitudinal stiffener, the spacing of the transverse web stiffeners, and the slenderness of the web. Based on the numerical results, new design equations for the bend-buckling coefficient of a longitudinally stiffened I-girder are proposed.

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Dengfeng Wang, Yuanqing Wang, Yongjiu Shi and Pingzhou Cao (Dept. of Civil Eng., Tsinghua University, Beijing, China), “Influence of Multiple Cutouts on the Buckling of Large-Scale Thin-Walled Cylindrical Shells of Desulphurizing Tower under Wind Loading”, International Conference on Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 19-20 February, 2011, DOI: 10.1109/CDCIEM.2011.541
ABSTRACT: The desulphurizing tower used in the power plant is the key environmental protection facility to eliminate the air pollution. Multiple cutouts are opened on the tower wall because of the technology requirement. The presence of multiple cutouts will influence the stability of tower under wind loading. On the project background of the large-scale thin-walled cylindrical shells of a practical desulphurizing tower, the investigations are conducted into the buckling mode and buckling capacity of the large-scale thin-walled cylindrical shells with multiple circular cutouts under wind loading by nonlinear finite element methods. The influences a reinvestigated of the cutout position and the number of cutouts on the buckling behavior of cylindrical shells under wind loading. The comparison is conducted between the buckling response of the cylinder with a single cutout and that of the cylinder with multiple cutouts. On the basis of comparison results, the proposal is produced for the buckling check against wind loading of large-scale thin-walled cylindrical shells structure as desulphurizing tower.

ABSTRACT: In this paper the elastic stability and imperfection sensitivity of axially loaded cylindrical shells on narrow discrete supports is explored. This is done by parametric geometrically nonlinear finite element analyses of the perfect and imperfect cylinders up to the critical load maxima. In addition, classical buckling eigenvalues are computed for reference purposes. The obtained numerical results are plotted in a systematic unified way and related curve-fit expressions are developed for the critical load maxima in dependency of the geometrical parameters of the problem. The support width, the shell slenderness and the type of local support, i.e. flexible versus rigid local support conditions, are varied. The present basic investigation is restricted to shells with linear-elastic material behaviour. The study of the buckling behaviour for narrow local supports, including the limiting case of point supports is of special concern. Strictly speaking, point supports exist only in the mathematical limit, since the stress singularities which occur in this case are mere artefacts and have no direct physical significance. But it turns out that the local buckling behaviour, like shape and evolution of buckles, magnitude of buckling loads etc. tends to an invariant typical limiting scenario, which is surprising but understandable at the same time. This typical local mono-modal buckling scenario, which is also investigated and presented in this paper, may be viewed as the counterpart to the well-known multi-modal characteristic global buckling scenario which occurs under uniform axial compression.
Xiang Rong Chen, Yuan Yuan Jiang, Zhi Yun Zhao (School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an, Shanxi, 710055, China), “Comparison for Different Circumferential Weld-Induced Imperfections on Steel Silos”, Advanced Materials Research (Volumes 250 - 253), May 2011, pp. 3734-3737, doi: 10.4028/www.scientific.net/AMR.250-253.3734

ABSTRACT: As the thin-walled structure, the buckling of steel silos is very sensitive to the initial geometric imperfections. However, these imperfections are uncertain to the shape and amplitude, so the studies of the initial geometric imperfections have important practical significance. Over the years, the circumferential imperfections have been known to result in the most important influence on the buckling of steel silos, which is also the most common defect in practical engineering. Using the existing research results, this paper analyzes three different imperfection shape functions and compare to the result of experiment in order to identify a function for the finite element analysis.


ABSTRACT: This paper represents a brief review of the concepts of the reliability of structures. Some closed form solutions, as well as approximate methods are elucidated. Different attempts to describe probabilistically the so-called “safety factor” are described and some instructive counter-examples are given. High sensitivity exhibited by the reliability of the structure is documented in a model structure. The same structure is also analyzed on the basis of non-probabilistic, convex modelling. The latter is complementary to the probabilistic methods when only limited information is available on uncertain variables and functions.

References listed at the end of the paper:

ABSTRACT: This paper focuses on the buckling of cylindrical shells with small thickness variations. Two important cases of thickness variation pattern are considered. Asymptotic formulas up to the second order of the thickness variation parameter $\mu$ are derived by the combination of the perturbation and weighted residual methods. The expressions obtained in this study reduce to Koiter's formulas, when only the first-order term of the thickness variation parameter is retained in the analysis. Results from the asymptotic formulas are compared with those obtained through the purely numerical techniques of the finite difference method and the shooting method.

ABSTRACT: Thin-walled shell structures are likely to buckle under axial loading way below the classical value. In the presence of granular solids (e.g. sand) in cylindrical shells the stiffness of the contents has a positive influence on the buckling load, similar to internal pressure. In practical silo design this effect is not considered. This is because not much is known about the interaction between the shell and the flexible granular contents and about how to handle this in a computational model. The present study will focus on some simple interaction models. It will be seen that the presence of a granular solid can increase the buckling load remarkably, and also that small modifications in the interaction assumptions have a major influence on the buckling loads.

ABSTRACT: The load carrying behaviour of cylindrical thin-walled shell structures under pressure load is strongly dependent on the nature and magnitude of the imperfections invariably caused by various manufacturing processes. The present paper examines instabilities of long homogeneous and isotropic thin elastic tubes, characterized by geometric imperfections like eccentricity or ovality, on the buckling behaviour in conditions for which, at present, a complete theoretical analysis was not found in literature. Moreover, the additional aspect of the influence of the welded joint geometry and position is investigated over a wide range of diameter to thickness ratio, extending the findings of previous works. The problem of buckling for variable load conditions is relevant in the context of NPP applications as, for instance the optimisation of an integrated and innovative LWR Steam Generator (SG) tubes, according to the updated ASME rules. To the purpose, at Pisa University a rather intense research activity is being carried out on the buckling of thin walled metal specimens in the dimensional range suitable for the above mentioned application. Therefore a test equipment (with the
necessary data acquisition facility), suitable for carrying out test series on this issue, as well as numerical models implemented on the MARC FEM code, were set up. The experiments were conducted on test specimens with different materials, e.g. A-316 ASTM (with and without seam weld) and Inconel 690 TT, as well as different loading conditions (lateral and hydrostatic external pressure). A validation of numerical evaluations by comparison with test results is also performed. A good agreement has been observed between the experimental data and the elasto-plastic finite element analyses results, highlighting also the different influence of the mentioned imperfections on the buckling loads.

ABSTRACT: Buckling tests were performed with four tank structures under vacuum pressure with diameters ranging from 10 to 70 m. After discussion of geometric imperfections tolerated by the standards and methods of measuring geometric imperfections of that size the results of the measurements are reported. Some of these results are far beyond the tolerance criteria of standards for stability design of shells. However, the loads where a buckling failure of the tank occurs is underestimated with the application of these standards. Numerical investigations of the buckling behaviour of the shell with geometric imperfections of eigenmode-shape show that with the size recommended for this purpose by standards the analysis will miss the buckling phenomenon. Different shapes of imperfections are investigated in the numerical analysis with a sector model of the tank shell. Only the numerical investigation with a model of the complete tank shell with the measured imperfections gave results which agreed with the buckling phenomenon observed in the tests as well for the loads as for the location of the buckling loads.

ABSTRACT: This paper highlights the discrepancies found in design codes for very long externally pressurized cylindrical shells subjected to uniform external pressure: although the failure is identical to the column buckling of a ring subjected to an external compressive line load, design codes provide far smaller design values of the buckling load for the cylindrical shell in comparison to the ring. Based on the Eurocode 3 (EN 1993-1-6) on shell buckling this situation is pointed out and validated by numerical studies. The results are interpreted and compared to findings from experimental studies for providing an adopted design proposal for very long cylindrical shells subjected to external pressure. The numerical findings are verified by a set of experimental tests with a series of small cylindrical shells subjected to external pressure. The tests provide the fundamental basis for the proposed improved assessment procedure for cylindrical shells.

ABSTRACT: Sandwich panels are modern pre-fabricated construction components used as cladding elements for different types of buildings. Sandwich panels consist of an insulating core material covered by two faces which are typically made of thin metal sheets. In standard applications, the panels are mounted and fixed on a
load-bearing substructure of beams or purlins. Sandwich panels can reduce the problem of lateral torsional buckling of this substructure of beams or purlins by providing stabilization either by shear stiffness or by torsional restraint. The new edition of the German standard for the design of steel structures DIN 18800 gives formulae for the calculation of the stiffness of the torsional spring for restraint of the substructure under vertical downward loading. These new regulations are based on experimental investigations and parametric finite element analyses. These formulae only apply for sandwich panels with steel facings and polyurethane and mineral wool as core material. The paper explains the load-bearing mechanisms of the stabilisation effect by the sandwich panel. A mechanical model is developed for extending the range of application of the design formulae and to include the effects of creep and elevated ambient temperature. It presents the new regulations of DIN 18800 and explains the tests on which these regulations are based. The spectrum of applications not yet examined is investigated by tests and accompanying numerical calculations within the framework of the EASIE project. As a result of these investigations the torsional restraint of panels with facings made of aluminium and glass fibre reinforced plastics (GFRP) and with cores made of EPS are dealt with. The load case wind suction is discussed in addition. The increase of the torsional restraint obtained by fixing roof panels at the upper flange (which is mainly with saddle washers) is also explained and quantified by these investigations.

References listed at the end of the paper:

ABSTRACT: Experimental investigations and parametric finite element analyses show that the moment-rotation characteristic of sandwich panels providing support against the lateral torsional buckling of beams subjected to gravity loading can be represented as tri-linear. Formulae for calculating the parameters of this characteristic are given for different types of beam combined with sandwich panels for roofs and walls. According to available design codes, the torsional restraint coefficient for rotational stiffness required for design against lateral torsional buckling of beams is governed by the rotational stiffness of the connection, which can be obtained from the characteristic mentioned as the secant stiffness for all common types of sandwich panel and different types of structural arrangement. These values allow the maximum spans of beams to be increased and help to improve the economy of lightweight structures.

ABSTRACT: A method is presented for solving the problem of both prelimit and postlimit point behavior of axially loaded stiffened and unstiffened cylindrical shells. The proposed solution makes it possible to obtain postlimit point equilibrium paths for every desired wave number, \( n \) (number of full waves around the circumference). The governing equations are expressed in terms of normal displacement components and Airy stress functions. Numerical results are presented for an unstiffened cylindrical shell and for a ring and stringer-stiffened cylindrical shell.
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ABSTRACT: The analysis of imperfect, thin, circular, cylindrical shells, subjected to suddenly applied uniform axial compression, is presented. The concept of dynamic stability is discussed and critical conditions for such configurations are obtained. Results are presented for unstiffened configurations. The effects of several parameters on dynamic critical conditions are assessed.

ABSTRACT: The nonlinear analysis of geometrically imperfect, thin, laminated, circular, cylindrical shells subjected to uniform axial compression, and for various in-plane and transverse supports, is presented. Moreover, the solution methodology is described, and results are generated for imperfect laminated (Boron/Epoxy) cylinders with symmetric, antisymmetric and asymmetric stacking of lamina. The applications deal with imperfection sensitivity studies and investigation of the effect of lamina stacking on the critical conditions. Finally, for some of the chosen geometries, experimental data is available and therefore these geometries serve as (partial) benchmarks for the developed solution scheme.

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ABSTRACT: An imperfect, laminated, circular, cylindrical thin shell, simply supported at the boundaries, and subjected to a uniform axial compression and torsion (individually applied and in combination) is analyzed. The analysis is based on nonlinear, Donnell-type, kinematic relations, linearly elastic material behavior, and usual lamination theory. The laminate consists of orthotropic laminae, which typically characterize fiber reinforced composites. Numerical results (critical loads) are generated for several geometries and some of these results are compared to available experimental data. The imperfection sensitivity of the various geometries is studied. It is clearly shown that the laminated shell is more imperfection sensitive under pure axial compression than under pure torsion (same as for the isotropic geometry). The effect of the orientation of the laminae (stacking sequence) on the critical load is also studied.


ABSTRACT: A general analytical and numerical procedure is developed for free and forced vibration of thin-walled shells of revolution made of arbitrarily laminated orthotropic elastic material. The equations of motion are derived with the aid of Hamilton's variational principle. A numerical solution is obtained by expanding the variables in Fourier series in the circumferential direction, and using conical finite elements in the meridional direction. Several examples involving different shell geometries are considered, including the effects of fiber orientation and boundary conditions.

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ABSTRACT: The imperfection sensitivity of thin cylindrical shells, made out of fiber-reinforced composite material and subjected to uniform axial compression, and the effects upon it of certain parameters, are investigated. The methodology is based on linear constitutive relations, nonlinear kinematic shell equations (Donnell-type) and the usual lamination theory. The laminate consists of orthotropic laminae, stacked in a general manner (asymmetric laminate). The uniform axial compression is applied eccentrically, and the geometrically imperfect cylindrical shell can be supported in various ways at the boundaries. In this investigation a number of parametric studies are performed. The scope of these studies is to establish the effect of (a) in-plane and transverse boundary conditions and (b) load eccentricity, on the imperfection sensitivity of typical boron/epoxy laminated cylindrical shells with various stacking sequences of laminate. The sensitivity is established by calculating critical loads for various imperfection amplitudes and shapes.

ABSTRACT: The accuracy of Donnell's equations for the buckling analysis of imperfect (limit point instability), circular, cylindrical, thin orthotropic shells under axial compression is investigated. This is accomplished by comparing critical loads obtained by employing Donnell-type kinematic equations with those based on the more accurate Sanders-type. For this purpose, a solution methodology is developed and described in the body of the paper. This methodology is then employed to generate critical loads for several orthotropic geometries, which cover a wide but practical range of parameters. These include cylinder length to radius ratios, radius to thickness ratios, two positions of the strong direction relative to the cylinder axis (\(\Pi=0\) and \(90\)\(^\circ\)) and two shapes of the initial geometric imperfection, axisymmetric and symmetric. Classical simply supported boundaries are used for all configurations for which results are generated.

ABSTRACT: The buckling of axially-loaded, imperfect, circular, cylindrical, thin shells is studied. A solution
methodology, based on two different shell theory approximations to the kinematic relations, is developed and described. The two approximations are those of Sanders and Donnell. Critical loads (limit point loads) are obtained for two shell geometries, one isotropic and one laminated. Several parametric studies are performed in order to establish the accuracy of the Donnell approximation. This is accomplished by comparison to the results obtained by the Sanders kinematic relations, which are considered to be very accurate for thin shells. The parametric studies include the effect of cylinder to radius ratio on the critical loads, as well as the effect of the radius to thickness ratio. Moreover, the imperfection sensitivity of the two geometries is investigated by both shell theory approximations.

ABSTRACT: The nonlinear equations for a stiffened laminated panel, which modeled by plate and beam elements, are derived by applying the variational principle on the potential energy. The equations include the equation for the panel sections between the stiffeners, the continuity requirements and the boundary conditions. These nonlinear equations by which the post-buckling behavior is characterized are exact in terms of Von Karman's kinematic relations.

ABSTRACT: A geometrical nonlinear theory of composite laminated beams is derived with the effect of transverse shear deformation taken into account. The theory is based on a high-order kinematic model, with the nonlinear differential equations solved by Newton's method and a special finite-difference scheme. A parametric study of the shear effect involving several kinematic approaches was carried out for isotropic and anisotropic beams.

ABSTRACT: An analytical-numerical procedure is applied for composite laminated shells of revolution in investigating the coupling effect between symmetric and antisymmetric modes and its overall influence. The numerical solution is based on separating the variables in Fourier series in the circumferential direction and conical finite elements in the meridional direction. The contribution of the coupling effect is examined by means of parametric analysis.

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ABSTRACT: An analytical-numerical procedure is applied to investigate the post-buckling behavior of a
composite laminated stiffened panel. The panel is modeled by plate elements for which the nonlinear equations are derived (via a variational principle) in terms of the lateral displacement and Airy stress function, and treated by resolving the variables into eigenfunctions in conjunction with a finite-difference scheme.

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ABSTRACT: A general one-dimensional model of a composite delaminated elongated strip (wide beam) under arbitrary axial and transverse loading and boundary conditions is used for predicting the classical buckling load, with the bending-stretching coupling effect as well as the prebuckling geometrical nonlinearity taken into account. The differential equations are solved by Newton's method, using a finite-difference scheme. The contribution of the coupling effect is examined by means of parametric analysis.

ABSTRACT: This paper presents a parametric study of the effect of delamination, and of initial imperfection, on the overall nonlinear behavior of laminated composite beams. The study is based on geometrical nonlinear analysis with the Von-Karman kinematic approach. It is shown that the bifurcation point provides not more than an indication of the buckling behavior, and that the full nonlinear analysis is needed for predicting the load-carrying capacity. It was also found that the delaminated beam is sensitive to initial imperfection.

ABSTRACT: An analytical solution is presented for the postbuckling behavior of composite laminated stiffened curved panels, whether curved in a longitudinal or lateral direction (not both). The nonlinear equations for the model are based on the Von Karman kinematic approach and consist of equilibrium equations for curved plate, continuity requirements, and boundary conditions. These equations are expressed in terms of the out-of-plane displacement and Airy stress functions. The characteristic behavior in the pre- and postlimit positions is exploited by using an eigenfunction series in the longitudinal direction (direction of the stiffeners) and a finite difference scheme in the other direction. A modified Galerkin procedure is used to minimize errors involved in the truncated series and the nonfulfillment of the boundary conditions. The solution obtained through this procedure proved to be very efficient compared to general purpose finite element codes, especially when mode interactions and parametric studies are involved.

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“Nonlinear Analysis of Stiffened Laminated Panels with Various Boundary Conditions”, Journal of Composite
ABSTRACT: A nonlinear analysis of stiffened laminated composite panels under various boundary conditions is presented. The nonlinear differential equations, expressed in terms of the out-of-plane displacement and the Airy stress function, are solved by separating the variables into eigenfunctions in conjunction with a finite-difference scheme. The vibration and buckling eigenfunctions of an isotropic beam are examined as the displacement functions, and a modified Galerkin procedure are used to minimize the error involved in the field equations, the continuity requirements and the boundary conditions. Results are presented for the isotropic and anisotropic cases, with different boundary conditions.


ABSTRACT: An analytical tool for buckling and vibration analysis of laminated shallow curved panels is presented. The equations in terms of transverse displacement and Airy stress function are derived via the Hu-Washizu mixed formulation and solved by the Ritz method, using the eigenfunctions of an isotropic beam. The effect of the prebuckling state and out-of-plane natural boundary conditions is examined. The approximate reduced bending stiffness method is evaluated for cross-ply and angle-ply laminates.


ABSTRACT: An analytical-numerical procedure is applied to investigate the buckling and post-buckling behavior of laminated cylindrical shells with non-circular cross-section of arbitrary closed shape. The buckling and post-buckling analysis are based on Donnell’s nonlinear kinematic relations. The curvature, which is a function of the circumferential coordinate, is expanded in Fourier series. The numerical procedure is based on separation of variables and their expansion into Fourier series. Through the Galerkin procedure, the field and boundary equations, written in terms of the transverse displacement and Airy stress function, are reduced to a system of ordinary differential equations, which are solved by a finite difference scheme. The configuration aspect is investigated parametrically. Unlike the circular cylindrical shells, coupling of the wave number in the circumferential direction is significantly high.


ABSTRACT: The equations, in terms of the normal displacement and Airy stress function, of the Donnell type, are derived via the Hu-Washizu mixed formulation. The curvature, which is a function of the circumferential coordinate, is expanded in Fourier series. The circumferential dependence is eliminated by a combination of Fourier expansion and Galerkin’s method. The resulting ordinary differential equations are then reduced to matrix equations by the use of finite differences. The configurational aspect is investigated parametrically. Unlike the circular cylindrical shells, coupling of the wave number in the circumferential direction is significantly high.

ABSTRACT: The nonlinear analysis of laminated initially imperfect non-circular cylindrical shells is presented. The analytical model is based on Donnell's nonlinear kinematic relations. The equations are derived via the Hu-Washizu mixed formulation, and are expressed in terms of the transverse displacement and the Airy stress function. The curvature of the non-circular cross-section is expanded into a Fourier series, allowing for representation of arbitrary closed cross-sections. The solution procedure is based on expansion of the variables into truncated trigonometric series in the circumferential direction and a finite difference scheme in the longitudinal one. Errors introduced by the truncated series are minimized by the Galerkin procedure and the equations are linearized by the Newton-Raphson method. Solutions beyond the limit point are obtained by Riks' constant arc-length algorithm. Results of both isotropic and laminated, axially loaded oval and elliptic shells are presented. The non-circular configurations are found to be less imperfection sensitive than the circular ones, and for largely eccentric cross-sections the shells are insensitive to initial imperfections.


ABSTRACT: A new simple and efficient algorithm for damage detection and for updating of stiffness and mass matrices is presented, based on minimum static and/or dynamic measured modes and preserving connectivity. A special algorithm was written for grouping uncoupled damage regions, significantly reducing the order of the problem and suitable for any structure size. A mode-scanning procedure is employed for finding the minimum measured modes needed for completing the process. Three illustrative examples are provided.


ABSTRACT: A formulation based on the three-dimensional theory of elasticity is employed to study the buckling of an orthotropic cylindrical shell under combined external pressure and axial compression. A properly defined load interaction parameter expresses the ratio of axial compression and external pressure loading, and critical loads are thus derived for a given load interaction. The results from this elasticity solution are compared with the critical loads predicted by the orthotropic Donnell and Timoshenko nonshallow classical shell formulations. Two cases of orthotropic material are considered with stiffness constants typical of glass/epoxy and graphite/epoxy. Furthermore, two cases of load interaction are considered, representing a relatively high and a relatively low axial load. For both load interaction cases considered and for both materials, the Donnell and the Timoshenko bifurcation points are higher than the elasticity solution, which means that both shell theories are nonconservative. However, the bifurcation points from the Timoshenko formulation is always found to be closer to the elasticity predictions than the one from the Donnell formulation. An additional common observation is that, for a high value of the load interaction parameter (relatively high axial load), the Timoshenko shell theory is performing remarkably well, approaching closely the elasticity solution, especially for thick construction. Finally, a comparison with some available results from higher order shell theories for
pure external pressure indicates that these improved shell theories seem to be adequate for the example cases that were studied.

ABSTRACT: A procedure of total energy release rate and stress intensity factors is developed for general non-homogeneous laminated composite laminates. The total energy release rate is obtained by using the J-integral for a one dimensional model of plane stress, plane strain and cylindrical bending. Decomposition of it into mode I and mode II, by which the mode mixity calculation is carried out, is based on the assumption of equivalent orthotropic properties through the laminate thickness. The process is straightforward and can be used as a criterion for delamination onset and growth of one dimensional structural model under general loading in the pre- and post-buckling states.

ABSTRACT: The delamination growth during the pre- or post-buckling phases in composites with a single delamination (one-dimensional model) is investigated. For that purpose, a general nonlinear analysis, using variational principle, with a new set of relations for the decomposition of the total energy release rate, is used for an arbitrary one-dimensional composite laminate structure. A computer code is developed and used for the parametric study of delamination growth during buckling. The effects of a wide range of parameters, like imperfection, layup, location of delamination, theory type and length-to-thickness ratio, were intensively studied. It is found that a dominant parameter, in terms of the level of energy release rate, is the length-to-thickness ratio.

ABSTRACT: The problem of determining the state of stress in a homogeneous ellipsoidal body (as can be produced by filament winding on a mandrel of elliptical cross-section) is formulated. The material is assumed to possess curvilinear anisotropy, referred to the coordinate system that is inherent to the geometry of the filament wound body. The differential equations that govern the stress functions are derived for the general anisotropy and loading cases. Then the results for the special case of torsion of an orthotropic body are derived.

ABSTRACT: Compression tests on delaminated kevlar/epoxy specimens were conducted in order to determine the buckling and post-buckling behavior of the system and observe the characteristics of the deformation including growth of the delamination. A broad range of geometric configurations, as far as the location of the
delamination through the thickness, was considered. Both the initiation resistance, defined as the applied
displacement per specimen length and the growth resistance, defined as the applied displacement per unit
delamination growth during the postbuckling stage were qualified for each configuration. For the particular
case studied, it was found that the growth resistance is infinite (that is, no growth) for delamination
thickness/total thickness ratio $H/T = 1/15$, becoming 0.52 for $H/T = 2/15$ and dropping to a value of only 0.07
for $H/T = 4/15$. The initiation resistance is also lowered as the delamination is located further away from the
specimen surface and for $H/T = 4/15$ growth initiation occurred before peak load. The experimental program
investigates also the development of the deformation regarding the postbuckled shape, the load-displacement
curve and the corresponding growth of the delamination. Furthermore, a comparison with analytical solutions
for the postbuckling behavior at large applied displacements is performed.

Haiying Huang and George A. Kardomeatas (School of Aerospace Engineering, Georgia Institute of
Technology, Atlanta Georgia, USA), “Buckling of orthotropic beam-plates with multiple central
ABSTRACT: A closed form solution is developed for predicting the critical load of a composite beam-plate
with multiple delaminations. The characteristic equation is derived by using non-linear beam theory, performling
proper linearization and by imposing the appropriate kinematical continuity and equilibrium conditions. The
effects of the dimensions and locations of the delaminations on the critical load are investigated and the results
are compared with previously published data.

R. Li, Y. Frostig, and G. A. Kardomeatas. "Nonlinear High-Order Response of Imperfect Sandwich Beams
doi: 10.2514/2.1509
ABSTRACT: (AIAA format does not permit cutting and pasting)

George A. Kardomeatas and George J. Simitses (Georgia Institute of Technology), “Comparative studies on the
buckling of isotropic, orthotropic, and sandwich columns”, Mechanics of Advanced Materials and Structures,
Vol. 11, pp 309-327, 2004
ABSTRACT: Advanced composite and sandwich construction has raised the issue of accuracy of the column
buckling formulas currently used in structural design. In these advanced material systems, transverse shear
effects are significant and cannot be ignored. The objective of this paper is to answer the question of how
accurate the simple column buckling formulas by Euler or the transverse shear correction formulas by Engesser
and by Haringx or other direct column buckling formulas in the literature are when composite or sandwich
construction and moderate thickness are involved. For this purpose, a three-dimensional elasticity solution
is presented along with finite element results. For the elasticity solution, which is performed for the monolithic
orthotropic material, the column is considered to be in the form of a hollow, circular cylinder and the direct
column buckling formulas are based on the axial modulus. As an example, the cases of an orthotropic material
with stiffness constants typical of glass/epoxy or graphite/epoxy and the reinforcing direction along the
periphery or along the cylinder axis are considered. Finite element results are presented for the sandwich
columns, which are of metallic (aluminum) and laminated (boron/epoxy, graphite/epoxy, and Kevlar/epoxy)
facings and alloy-foam or glass/phenolic honeycomb core. Sandwich columns are especially critical with the
Euler load being, in some cases of typical design, as much as almost five times the critical load from the finite
elements and, therefore, in these cases of sandwich construction, the classical Euler load calculations cannot be
relied upon.


ABSTRACT: The imperfection sensitivity of laminated cylindrical shells is considered—via the initial postbuckling analysis—on the basis of three different shell theories: Donnell in 1933; Sanders in 1963; and Timoshenko in 1961. The procedure involves nonlinear partial differential equations, which are converted into a sequence of three linear sets. The equations are solved with the variables expanded in Fourier series in the circumferential direction and in finite differences in the axial directions. A general code is developed and used in studying the effect of higher exactness of the shell theory on the sensitivity behavior, and in a parametric study of the sensitivity of anisotropic angle-ply cylindrical shells.


ABSTRACT: The sensitivity of isotropic conical shells to imperfection is considered, via the initial postbuckling analysis, on the basis of three different shell theories: Donnell's, Sanders's, and Timoshenko's. The conical shell was chosen as a representative case exhibiting the entire range of imperfection sensitivity. The procedure involves nonlinear partial differential equations, which are converted into a sequence of three linear sets. The latter are solved with the variables expanded in Fourier series in the circumferential direction and in finite differences in the axial directions. A general code is developed and used in studying the effect of higher exactness of the shell theory on the sensitivity behavior and in parametric analyses of the sensitivity of conical shells, especially with respect to the cone semivertex angle.


ABSTRACT: Laminated cylindrical shells are already commonly used in structural engineering, and their buckling and post-buckling behavior is of vital importance in the design of such structures. The validity of linear buckling analysis in this context, has been questioned because of the discrepancy observed between theoretical prediction and test results. The cause of this discrepancy is the fact that the nonlinear behavior of shell-like structures is generally characterized by a limit point rather than by a bifurcation point. For such structures, the load-carrying capacity depends on the level of imperfection (hence the concept “imperfection sensitivity”). The motivation is, therefore, to reduce the sensitivity rather than preventing the imperfection. For that purpose insight into the post-buckling state is called for.

ABSTRACT: A general nonlinear dynamic analysis, based on Donnell's shell-type theory, is developed for an arbitrary imperfect isotropic conical shell. It is used for studying dynamic stability and imperfection sensitivity under dynamic step loading. The nonlinear dynamic time history and the sensitivity behavior are examined in parametric terms over a wide range of aspect ratios. A general symbolic code (using the MAPLE compiler) was programmed to create the differential operators. By this means the Newmark discretization, Galerkin procedure, Newton-Raphson iteration, and finite difference scheme are applied for automatic development of an efficient FORTRAN code for the parametric study, and for examining the correlation of the sensitivity behavior between two different dynamic stability criteria. An extensive parametric study of the effect of the cone semi-vertex angle on the stability and sensitivity to imperfection under dynamic step loading was carried out. It was found that the dynamic buckling can indeed be derived from the nonlinear static solution.

References listed at the end of the paper:

ABSTRACT: A suitable postbuckling analysis, based on geometrically nonlinear behavior, is developed for arbitrary imperfect conical shells. The conical shell was chosen as a representative case exhibiting the entire range of sensitivity to imperfection. A general symbolic code (using the MAPLE compiler) was programmed to create the differential operators of the nonlinear partial differential equations, based on Donnell’s type shell theory. The code then uses the Galerkin procedure, the Newton-Raphson and arc-length procedures, and a finite-differences scheme for automatic development of an efficient FORTRAN code. The code is used for parametric study of the nonlinear behavior and yields the sensitivity characteristic for a wide range of cone semivertex angles. A typical nonlinear behavior of a conical shell is investigated. Comparison with a simpler procedure, based on the initial postbuckling analysis (Koiter’s theory), confirms the need for the present more accurate one, especially for shells with prebuckling nonlinear behavior. The present investigation summarizes the sensitivity behavior with respect to imperfection shapes and amplitudes for the entire range of cone semivertex angles.

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ABSTRACT: A general procedure is developed for stability of stiffened conical shells. It is used for studying the sensitivity behavior with respect to the stiffener configurations. The effect of the pre-buckling nonlinearity on the bifurcation point, as well as the limit-point load level, is examined. The unique algorithm presented by the authors is an extended version of an earlier one, adapted for determination of the limit-point load level of imperfect conical shells. The eigenvalue problem is iteratively solved with respect to the nonlinear equilibrium state up to the bifurcation point or to the limit-point load level. A general symbolic code (using MAPLE) was programmed to create the differential operators based on Donnell’s type shell theory. Then the code uses the Galerkin procedure, the Newton–Raphson procedure, and a finite difference scheme for automatic development of an efficient FORTRAN code which is used for the parametric study.

References listed at the end of the paper:
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ABSTRACT: The problem of snap-through buckling of a clamped, eccentrically stiffened shallow spherical cap is considered under quasi-statically applied uniform pressure and a special case of dynamically applied uniform pressure. This dynamic case is the constant load infinite duration case (step time-function) and it represents an extreme case of blast loading-large decay time, small decay rate. The analysis is based on the nonlinear shallow shell equations under the assumption of axisymmetric deformations and linear stress-strain laws. The eccentric stiffeners are disposed orthogonally along directions of principal curvature in such a way that the smeared mass, and extensional and flexural stiffnesses are constant. The stiffeners are also taken to be one-sided with constant eccentricity, and the stiffener-shell connection is assumed to be monolithic. The method developed in an earlier paper is employed. In this method, critical pressures are associated with characteristics of the total potential surface in the configuration space of the generalized coordinates. In addition, buckling of the complete thin eccentrically stiffened spherical shell under uniform quasi-statically applied pressure is considered, and these results are used to check the numerical answers. The complete spherical shell is stiffened in the same manner as the shallow cap. The results are presented in graphical form as load parameter vs initial rise parameter. Geometric configurations corresponding to isotropic, lightly stiffened, moderately stiffened and heavily stiffened geometries are considered. By lightly stiffened geometry one means that most of the extensional stiffness is provided by the thin shell. A computer program was written to solve for critical pressures. The Georgia Tech Univac 1108 high speed digital computer was used for this purpose.
ABSTRACT: A procedure is outlined for optimizing stiffened, thin, circular, cylindrical shells under uniform axial compression against general instability, in the presence of initial geometric imperfection. The procedure consists of two parts (a) optimization on the basis of a linear buckling analysis and perfect geometry, and (b) parametric studies on a reasonable region in the design space surrounding the optimum point (as obtained from part (a)) to assess the effect of initial geometric imperfections. This procedure is demonstrated through two design examples, for which it is concluded, that the presence of initial geometric imperfections does not alter the optimum weight and the corresponding design variables appreciably.


ABSTRACT: A solution methodology is described for the complete analysis of a geometrically imperfect, thin, circular, cylindrical shell loaded by a uniform axial compression. The analysis includes pre-limit point behavior, the establishment of critical conditions (limit point) and post-limit point behavior. The solution scheme is then utilized to study the effects of various geometrical parameters (radius to thickness and length to radius ratios) on the response characteristics of an imperfect, unstiffened, thin, cylindrical shell. These effects are assessed for a virtually axisymmetric-type of geometric imperfection.

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ABSTRACT: The imperfection sensitivity of thin cylindrical shells, made out of fiberreinforced composite material and subjected to either uniform axial compression or torsion, and the effects upon it of certain parameters, are investigated. The sensitivity is established through plots of critical loads (limit point loads) versus imperfection amplitude. The larger the drop in critical load value with increasing amplitude, the greater the sensitivity. Results are presented for four- and six-ply laminates with simply supported boundaries and various stacking sequences. These sequences lead to symmetric, antisymmetric and asymmetric configurations with respect to the laminate midsurface. The material for all configurations is boron/epoxy. The parametric studies include primarily the effect of lamina stacking and length-to-radius ratio on the critical loads. Among the important findings are that (a) laminated cylindrical shells are more imperfection sensitive under axial compression than under torsion, (b) the imperfection sensitivity decreases as the length-to-radius ratio increases and (c) lamina stacking has a pronounced effect on the imperfection sensitivity of the laminated shell.


ABSTRACT: A model is developed for the study of delamination buckling of axially loaded cylindrical shells. Delamination is assumed to exist before load application, it spans the entire circumference, and it lies on the contact surface of neighboring laminae. The mathematical model employs Donnell-type kinematic relations and linearly elastic material behavior. Furthermore, each lamina is assumed isotropic, and the emphasis is on studying the effect of delamination size and position on the critical load. Two sets of boundary conditions are
used with the model: simply supported and clamped. The study reveals several important conclusions. Among them, one may list the following: (a) the critical load is primarily controlled by the position of the delamination from the reference surface, provided that the delamination is not very close to the boundaries; and (b) for long delaminations (relative to the cylinder length), the critical load is not appreciably affected by the boundary conditions.


ABSTRACT: Delamination buckling of long complete cylindrical shells and curved panels, when acted upon by uniform lateral loading, is being investigated. The geometry is such that it covers a wide range of length to radius ratios, as well as panels of different widths. Results, though, are presented only for very long configurations and a limited number of widths. The boundaries of the panels are either clamped or simply supported, along the straight edges. Finally, the geometry is free of initial geometric imperfections, and all parts of the shell are assumed to be virtually isotropic. The emphasis of the investigation concerns the effect of several factors and parameters on the critical load. These include, load behavior during buckling, width of delamination, position of delamination and panel width.

References listed at the end of the paper:


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ABSTRACT: Delamination is one of the basic defects inherent to laminar materials. The investigation of the buckling characteristics of delaminated cylindrical shells or panels, when subjected to external pressure, is presented herein. The geometry is such that it covers a wide range of length to radius ratios as well as panels of different widths. Results are presented only for very long cylinders and panels. The boundaries are either simply supported or clamped. Furthermore, the material is such that it leads to (quasi) isotropic laminates for all
sections involved, the overall as well as the ones separated by the delamination. Finally, the geometry is free of
initial geometric imperfections. Because of the last two assumptions, a primary membrane state exists and
bifurcational buckling is possible. Buckling loads are calculated for a wide range of parameters. The width and
the through-the-thickness position of delamination greatly affect the bifurcation load.

George J. Simitses and Yeoshua Frostig (Georgia Institute of Technology, Atlanta, Georgia, 30332, USA),
“Radially compressed laminated circular plates”, Composite Structures, Vol. 9, No. 1, 1988, pp. 1-17,
doi:10.1016/0263-8223(88)90028-1
ABSTRACT: The paper deals with buckling of complete and annular circular plates, made of symmetric
laminates with general orientation of the lamina fibers. The plate is subjected to an in-plane, symmetric,
destabilizing load. The load is applied at the outer edge for the complete plate and at the outer and inner edges
for the annular one. The plate is supported in various ways along its boundaries. The paper includes the
derivation of the governing equations and discusses the various methods of solution. Numerical results are
presented for a clamped plate.

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“Analysis of anisotropic laminated cylindrical shells subjected to destabilizing loads. Part I: Theory and
doi:10.1016/0263-8223(91)90021-P
ABSTRACT: The analysis of laminated cylindrical shells of general stacking, but of symmetric construction
(there is no coupling between extension and bending), when acted upon by the destabilizing heads of lateral
pressure, hydrostatic pressure, uniform axial compression and torsion, is presented. Sanders-type equations are
employed in deriving the buckling equations. A solution procedure is developed for computer-generated
numerical results. This procedure is based on the Galenkin method. Extensive parametric studies are performed
and presented in Part II. Justification for the work is provided in the Introduction section of the paper.

George J. Simitses and John S. Anastasiadis (University of Cincinnati, Cincinnati, OH 45221, USA), “Buckling
of axially-loaded, moderately-thick, cylindrical laminated shells”, Composites Engineering, Vol. 1, No. 6, 1991,
pp. 375-391, doi:10.1016/0961-9526(91)90042-Q
ABSTRACT: A higher-order theory is developed (kinematic relations, constitutive relations, equilibrium
equations and boundary conditions), which includes initial geometric imperfections and transverse shear effects,
for a laminated cylindrical configuration, under the actions of lateral pressure, axial compression and torsion.
Through the perturbation technique, buckling equations and boundary conditions are derived for a symmetric
laminated configuration, for a higher-(third) order shear-deformation theory as well as for the cases of first-
order shear-deformation theory and classical theory. Critical axially-compressive loads are computed for finite
length cylinders for several stacking sequences, several radius-to-total-thickness ratios and length-to-radius
ratios and for all the above three theories. The material that was employed in generating results was
boron/epoxy.

ABSTRACT: Models for predicting delamination buckling of laminated complete thin cylindrical shells and cylindrical panels are presented. The load cases are uniform axial compression and uniform pressure, applied individually. The models are different for the two load cases and by design they are kept as simple as possible, to keep the mathematical representation of the model and the associated solution simple enough to permit extensive parametric studies. Through these studies one can identify important structural parameters and fully assess their effect on the critical load. Among the general conclusions are the following: (a) the most influential parameters for a given laminated geometry are the size of the delamination and its through-the-thickness position for both load cases; and (b) the effect of boundary conditions (along the straight edges) is important for the case of pressure, whereas for axial compression the effect of boundary conditions (ends) is small for large delaminations.


ABSTRACT: A general one-dimensional model of a delaminated composite structural element under axial loading is used for predicting the classical buckling load, with the bending-stretching coupling effect. Two cases are examined. In the first case the delamination is such that it does not cause any resistance in the motion of the two detached laminae, due to the applied axial loads. In the second case, the delamination is such that both laminae feel the existence of a spring distribution along the length of the delamination.


ABSTRACT: A higher order theory is developed (kinematic relations, constitutive relations, equilibrium equations, and boundary conditions), which includes initial geometric imperfections and transverse shear effects for a laminated cylindrical configuration under the actions of lateral pressure, axial compression, and eccentrically applied torsion. Equilibrium equations and boundary conditions are presented for the higher order shear deformation theory. The perturbation technique is employed and buckling equations are derived for symmetric laminates under the action of uniform axial compression and lateral pressure. Buckling loads are computed for axially compressed cylindrical laminates of finite length and pressure-loaded very long configurations.


ABSTRACT: The problem of instability of laminated circular cylindrical shells under the action of lateral pressure is investigated. The analysis is based on higher-order shear-deformation theory where the effect of transverse shear is taken into account. The buckling is elastic for moderately thick composite shells and the geometry is assumed to be free of initial imperfections. The equilibrium equations and the related boundary conditions are derived by variational methods. The buckling equations are derived through the perturbation
technique. Critical lateral pressures are computed for finite- and infinite-length cylinders for several stacking sequences and several radius-to-thickness ratios. The numerical results are presented in tabular and in graphical form.

A. Tabiei and G.J. Simitses (Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, U.S.A.), “Buckling of moderately thick, laminated cylindrical shells under torsion”, 34th AIAA SDM Conference, no date given by AIAA; you have to type the abstract (it’s very annoying!)

John S. Anastasiadis (1) and George J. Simitses (2)
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ABSTRACT: A higher-order shell theory was developed (kinematic relations, constitutive relations, equilibrium equations and boundary conditions), which includes initial geometric imperfections and transverse shear effects for a laminated cylindrical shell under the action of pressure, axial compression and in-plane shear. Through the perturbation technique, buckling equations are derived for the corresponding 'perfect geometry' symmetric laminated configuration. Critical pressures are computed for very long cylinders for several stacking sequences, several radius-to-total-thickness ratios, three lamina materials (boron/epoxy, graphite/epoxy, and Kevlar/epoxy), and three shell theories: classical, first-order shear deformable and higher- (third-) order shear deformable. The results provide valuable information concerning the applicability (accurate prediction of buckling pressures) of the various shell theories.

ABSTRACT: The constant demand for lighter and more efficient structural configurations has led the structural engineer to the use of new man-made materials. At the same time, this demand has forced upon him very sophisticated methods of testing, analysis and design, as well as of fabrication and manufacturing. The recent explosive progress in the production and use of composite materials has pointed toward the clear possibility of man creating specific materials for specific applications. At the same time, it has been realized that there arise demands for: a complete understanding of the behaviour of composite materials and the influences on this behaviour; establishment of design criteria upon which proper use of composites can rest; and the training of engineers in the design and use of composite structures. For all three items, it is important to recognize that, with the advent of composite media, certain new material imperfections can be found in composite structures in addition to the better-known imperfections that one finds in metallic structures. Thus, broken fibres, delaminated regions, cracks in the matrix material, as well as holes, foreign inclusions and small voids constitute material and structural imperfections that can exist in composite structures. Imperfections have always existed and their effect on the structural response of a system has been very significant in many cases. References listed at the end of the paper:
1. Naruoka, M. Bibliography on Theory of Plates, Gihodo, Tokyo.
ABSTRACT: The present paper is a review article on the problem of buckling of moderately thick, laminated, composite shells subjected to destabilizing loads. The loads consist of uniform axial compression, uniform lateral pressure and torsion applied individually or in combination. In all the works reported in the literature, the analysis is based on higher-order shear deformation (HOSD) shell theory and/or first-order shear deformation (FOSD) shell theory with or without a shear correction factor. Results obtained by these two shell theories and by employing classical thin shell theory are compared to determine the range of applicability of each in predicting critical conditions. The effect of stacking sequence, radius-to-thickness ratio and length-to-radius ratio is assessed. Typical numerical results are presented in tabular form. Moreover, some limited results, which are based on limit point analysis are also presented (imperfection sensitivity studies).

ABSTRACT: This study investigates problems associated with the design of scaled down models. Such study is important since it provides the necessary scaling laws, and the factors which affect the accuracy of the scale models. For better understanding the applicability of scaled down models in designing laminated composite structures, an analytical investigation was undertaken to assess the feasibility of their use. Employment of similitude theory to establish similarity among structural systems can save considerable expense and time, provided that the proper scaling laws are found and validated. In this study the limitation and acceptable interval of all parameters and corresponding scale factors are investigated. Particular emphasis is placed on the case of buckling of cross-ply cylindrical shells under uniaxial compressive loads. Both complete and partial similarity are discussed. This analytical study indicates that distorted models with a different number of layers and geometries than those of the prototype can predict the behavior of the prototype with good accuracy. However, it is shown that a scaled down model with different material properties than those of the prototype is incapable of predicting the response of the prototype.


ABSTRACT: This work deals primarily with the question of buckling of delaminated curved structural elements subjected to external pressure, and how the presence of the delamination affects the global load carrying capacity of the structure. A review of the effect of the presence of imperfections and defects on buckling in laminated configurations is presented. The emphasis is then placed on delaminations, and the simple mathematical models that have been used for the buckling analysis of delaminated shells. Through these models the parameters that have the largest effect on the buckling load are identified. It is concluded that the two most influencing parameters are the size of delamination and the through-the-thickness position of the delamination. Areas of future research are identified, through the critical review of the reported studies.


ABSTRACT: In order to understand the applicability of scaled down models in designing laminated composite structures, an analytical investigation was undertaken to assess the feasibility of their use. Employment of similitude theory to establish similarity among structural systems can save considerable expense and time, provided the proper scaling laws are found and validated. The developed methodology is demonstrated through application of similitude theory to laminated cylindrical shells. Particular emphasis is placed on the case of free vibration of cross-ply laminated cylindrical shells with double curvature. The results presented herein indicate that, for free vibration responses of laminated cylindrical shells of double curvature, based on structural similitude, a set of scaling laws can be found which are used to develop design rules for designing small scale models. This analytical study indicates that distorted models with a different number of layers, geometries and material properties than those of the prototype can predict the behavior of the prototype with good accuracy. However, it is shown that a scaled down model with distorted curvature is incapable of predicting the response of the prototype.

G.J. Simitses (1), J.H. Starnes, Jr. (2) and J. Rezaeepazhand (3)
ABSTRACT: This paper deals with the development and use of scaled-down models in order to predict the structural behavior of large prototypes. The concept is fully described and examples are presented which demonstrate its applicability to beam-plates, plates and cylindrical shells of laminated construction. The concept is based on the use of field equations, which govern the response behavior of both the small model as well as the large prototype. The conditions under which the experimental data of a small model can be used to predict the behavior of a large prototype are called scaling laws or similarity conditions and the term that best describes the process is structural similitude. Moreover, since the term scaling is used to describe the effect of size on strength characteristics of materials, a discussion is included which should clarify the difference between “scaling law” and “size effect”. Finally, a historical review of all published work in the broad area of structural similitude is presented for completeness.

References listed at the end of the paper:

the static and dynamic critical loads decrease with increasing load duration and converge to those for the load case of infinite duration. The convergence rate is related to the fundamental frequency of the cylinder. In addition, both the static and dynamic critical loads decrease with increasing imperfection amplitude.


ABSTRACT: The dynamic stability of circular metallic and laminated cylindrical shells is investigated. The cylinders are geometrically imperfect and subjected to axial compression or pure bending moment. These loads are suddenly applied with constant magnitude and finite or infinite duration. The finite element method is employed to generate dynamic responses and the equations of motion approach to determine dynamic critical loads. The effects of load duration and imperfection amplitude on critical loads are discussed. It is found that the dynamic critical loads decrease with increasing load duration and converge to those for the load case of infinite duration. The convergence rate is related to the fundamental frequency of the cylinder. In addition, both the static and dynamic critical loads decrease with increasing imperfection amplitude.
ABSTRACT: The problem of instability of imperfect, moderately thick, circular cylindrical shells under the action of uniform lateral pressure is investigated. Two approaches are followed: First, an analysis is done based on nonlinear kinematic relations, where the effect of transverse shear is taken into account and an imperfection function is assumed. The Galerkin procedure is employed to solve the resulting partial differential equations. The second method is based on applying Koiter's general postbuckling theory. To this extent, the objective is the calculation of imperfection sensitivity by relating to the initial post-buckling behavior of the perfect structure. Again, a shear deformation theory which accounts for transverse shear strains and rotations about the normal to the shell mid-surface is employed to formulate the shell equations. The initial postbuckling analysis indicates that the range of imperfection sensitivity depends strongly on the material anisotropy, and also on the shell thickness and whether the end pressure loading is included or not.

References listed at the end of the paper:

PARTIAL INTRODUCTION: Consider a composite boxe

d beam filled with a soft elastic medium such as foam or a sandwich beam consisting of two fiber-reinforced sheets separated by a low-stiffness core. A bending load on these structures is equivalent to a compressive force on one face and a tensile force on the other. Furthermore, a delamination may be present on the compressively loaded composite face. In those cases the composite face rests on an elastic “foundation” which imposes reaction forces on the beam that are proportional to the deflection of the “foundation”. . .

G. A. Kardomateas (School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA), “Asymptotic analysis considerations on the initial postbuckling behavior of delaminated composites”, Acta Mechanica, Vol. 83, No. 3, pp 165-175, September 1990

SUMMARY: An asymptotic analysis for the initial postbuckling behavior of delaminated beam/plates is performed. Under the assumptions of inextensional deformation, the exact expressions that govern the plane elastic deformation of the different parts of the system are expanded in a Taylor series in terms of the distortion variable. Order of magnitude arguments are used to relate the distortion variables and these are subsequently used in an asymptotic solution for the deflections and the load. Finally, a comparison with experiments is performed.

References listed at the end of the paper:


ABSTRACT: The initial post-buckling and growth behavior of delaminations in plates is studied by a perturbation procedure. In this work, no restrictive assumptions regarding the delamination thickness and plate length are made, i.e., the usual thin film assumptions are relaxed. The perturbation procedure is based on an asymptotic expansion of the load and deformation quantities in terms of the distortion parameter of the delaminated layer, the latter being considered a compressive elastica. Closed-form solutions for the load and midpoint delamination deflection versus applied compressive displacement during the initial post-buckling phase are derived. Moreover, closed-form expressions for the energy release rate and the mixity ratio (i.e. Mode II versus Mode I) at the delamination tip are produced. A higher Mode I component is found to be present during the initial post-buckling phase for delaminations of increasing ratio of delamination thickness over plate thickness, h/T (i.e. delaminations further away from the surface). Moreover, the energy release rate corresponding to the same applied strain is larger for a higher h/T ratio. The reduced growth resistance of these
configurations is verified by experimental results on unidirectional composite specimens with internal delaminations.


ABSTRACT: The growth of internal delaminations in composite plates subjected to cyclic compression is investigated. Due to the compressive loading, these structures undergo repeated buckling-unloading of the delaminated layer with a resulting reduction of the interlaver resistance. An important characteristic of the problem is that the state of stress near the delamination tip is of mixed mode, I and II. Equations describing the growth of the delaminations under cyclic loads are obtained on the basis of a combined delamination buckling-post-buckling and fracture mechanics model. The latter is based on a mode-dependent critical fracture energy concept and is expressed in terms of the spread in the energy release rate in the pre- and post-buckling state. It is shown that such a model allows for the accumulation of microdamage at the delamination front. The growth laws developed in this manner are integrated numerically, in order to produce the delamination growth vs number of cycles curves. Furthermore, the investigation includes the possibility of unstable delamination growth. The study does not impose any restrictive assumptions regarding the delamination thickness and plate length (as opposed to the usual thin film assumptions). The results show that for a given value of delamination thickness h the fatigue delamination growth is strongly affected by the relative location of the delamination through the plate thickness T. the fatigue growth being slower for a smaller value of h T (delaminations located closer to the surface). These theoretical predictions are confirmed by experimental results that are obtained for the growth of delaminations in graphite-epoxy unidirectional specimens under cyclic constant amplitude compressive loading. The test data, which were obtained for several different locations of the delamination through the thickness (hence different degrees of mode mixity), and different applied maximum compressive displacement, seem be well correlated with the theory.


ABSTRACT: The buckling of an axially compressed orthotropic column is investigated by using a three-dimensional elasticity formulation. In this manner, an assessment of the thickness and orthotropy effects can be accurately performed. The column is in the form of a hollow circular cylinder. The critical loads from this elasticity solution are compared with the ones from the Euler or Timoshenko transverse shear correction formulas based on the axial modulus. Furthermore, a comparison is made with a recently suggested new formula for column buckling that adds a second term to the Euler value critical load and is supposed to account for thickness effects. As an example, the cases of an orthotropic material with stiffness constants typical of glass/epoxy and the reinforcing direction along the periphery or along the cylinder axis are considered. It is found that the elasticity approach predicts in all cases a lower than the Euler value critical load. Moreover, the degree of non-conservatism of the Euler formula is strongly dependent on the reinforcing direction; the axially reinforced columns show the highest deviation from the elasticity value. The first Timoshenko shear correction formula is in all cases examined conservative. The second Timoshenko shear correction formula is in most cases (but not always) conservative. However, the second estimate is always closer to the elasticity solution than the first one. For the isotropic case both Timoshenko formulas are conservative estimates. The recent new formula for column buckling that adds a second term to the Euler load expression is a non-conservative estimate
but performs very well with very thick sections, being closest to the elasticity solution; for moderate thickness it is in general no better than the Timoshenko formulas.

References listed at the end of the paper:


ABSTRACT: The bifurcation of equilibrium of a compressed transversely isotropic bar is investigated by using a three-dimensional elasticity formulation. In this manner, an assessment of the thickness effects can be accurately performed. For isotropic rods of circular cross-section, the bifurcation value of the compressive force turns out to coincide with the Euler critical load for values of the length-over-radius ratio approximately greater than 5. The elasticity approach predicts always a lower (than the Euler value) critical load for isotropic bodies; the two examples of transversely isotropic bodies considered show also a lower critical load in comparison with the Euler value based on the axial modulus, and the reduction is larger than the one corresponding to isotropic rods with the same length-over-radius ratio. However, for the isotropic material, both Timoshenko’s formulas for transverse shear correction are conservative; i.e., they predict a lower critical load than the elasticity solutions. For a generally transversely isotropic material only the first Timoshenko shear correction formula proved to be a conservative estimate in all cases considered. However, in all cases considered, the second estimate is always closer to the elasticity solution than the first one and therefore, a more precise estimate of the transverse shear effects. Furthermore, by performing a series expansion of the terms of the resulting characteristic equation from the elasticity formulation for the isotropic case, the Euler load is proven to be the solution in the first approximation; consideration of the second approximation gives a direct expression for the correction to the Euler load, therefore defining a new, revised, yet simple formula for column buckling. Finally,
the examination of a rod with different end conditions, namely a pinned-pinned rod, shows that the thickness effects depend also on the end fixity.

G.A. Kardomateas and M.S. Philobos (Georgia Institute of Technology, Atlanta, Georgia, USA), “Buckling of thick orthotropic cylindrical shells under combined external pressure and axial compression”, AIAA Journal, Vol. 33, No. 10, October 1995

ABSTRACT: A formulation based on the three-dimensional theory of elasticity is employed to study the buckling of an orthotropic cylindrical shell under combined external pressure and axial compression. A properly defined load interaction parameter expresses the ratio of axial compression and external pressure loading, and critical loads are thus derived for a given load interaction. The results from this elasticity solution are compared with the critical loads predicted by the orthotropic Donnell and Timoshenko nonshallow classical shell formulations. Two cases of orthotropic material are considered with stiffness constants typical of glass/epoxy and graphite/epoxy. Furthermore, two cases of load interaction are considered, representing a relatively high and a relatively low axial load. For both load interaction cases considered and for both materials, the Donnell and the Timoshenko bifurcation points are higher than the elasticity solution, which means that both shell theories are nonconservative. However, the bifurcation points from the Timoshenko formulation are always found to be closer to the elasticity predictions than the ones from the Donnell formulation. An additional common observation is that, for a high value of the load interaction parameter (relatively high axial load), the Timoshenko shell theory is performing remarkably well, approaching closely the elasticity solution, especially for thick construction. Finally, a comparison with some available results from higher order shell theories for pure external pressure indicates that these improved shell theories seem to be adequate for the example cases that were studied.

References listed at the end of the paper:
ABSTRACT: A three-dimensional elasticity solution to the problem of buckling of orthotropic cylindrical shells under torsion is presented. A mixed form of the Galerkin method with a series of Legendre polynomials in the thickness coordinate has been applied to solve the governing differential equations. The accuracy of existing shell theory solutions has been assessed through a comparison study for both isotropic and orthotropic cylinders. For isotropic cylinders the solutions based on the Donnell shell theory were found to predict nonconservative values for the critical loads. As the circumferential wave numbers increase, shell theory solutions provide more accurate values. For orthotropic cylinders, the classical shell theory predicts much higher critical loads for a relatively short and thick cylinder, while the shear deformation theories provide results reasonably close to the elasticity solutions. Detailed data are also presented for the critical torsional loads over a wide range of length ratios and radius ratios for isotropic, glass/epoxy, and graphite/epoxy cylinders.

ABSTRACT: There exist many formulas for the critical compression of sandwich plates, each based on a specific set of assumptions and a specific plate or beam model. It is not easy to determine the accuracy and range of validity of these rather simple formulas unless an elasticity solution exists. In this paper, we present an elasticity solution to the problem of buckling of sandwich beams or wide sandwich panels subjected to axially compressive loading (along the short side). The emphasis on this study is on the wrinkling (multi-wave) mode. The sandwich section is symmetric and all constituent phases, i.e., the facings and the core, are assumed to be orthotropic. First, the pre-buckling elasticity solution for the compressed sandwich structure is derived. Subsequently, the buckling problem is formulated as an eigen-boundary-value problem for differential equations, with the axial load being the eigenvalue. For a given configuration, two cases, namely symmetric and anti-symmetric buckling, are considered separately, and the one that dominates is accordingly determined. The complication in the sandwich construction arises due to the existence of additional “internal” conditions at the face sheet/core interfaces. Results are produced first for isotropic phases (for which the simple formulas in the literature hold) and for different ratios of face-sheet vs core modulus and face-sheet vs core thickness. The results are compared with the different wrinkling formulas in the literature, as well as with the Euler buckling load and the Euler buckling load with transverse shear correction. Subsequently, results are produced for one or both phases being orthotropic, namely a typical sandwich made of glass/polyester or graphite/epoxy faces and polymeric foam or glass/phenolic honeycomb core. The solution presented herein provides a means of accurately assessing the limitations of simplifying analyses in predicting wrinkling and global buckling in wide sandwich panels/beams.

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ABSTRACT: This article investigates the thermal response of an axially restrained composite column, which is exposed to a heat flux due to fire. The heat damage, the charred layer formation and nonuniform transient temperature distribution in the column exposed to fire from one side are calculated by the thermal model developed by Gibson et al. [1]. For the thermal response analysis, the mechanical properties of the fire-damaged (charred) region are considered negligible, while the degradation of the elastic properties with temperature in the undamaged layer (especially near the glass transition temperature of the matrix) is accounted for using experimental data for the elastic moduli. Due to the nonuniform stiffness distribution through the thickness and the effect of the ensuing thermal moment, the structure behaves like an imperfect column, and responds by bending rather than buckling in the classical Euler (bifurcation) sense. Another important effect of the non-uniform temperature is that the neutral axis moves away from the centroid of the cross-section, resulting in an additional moment due to eccentric mechanical loading, which tends to bend the structure. The compressive behavior of a column subjected to simultaneous high intensity surface heating and axial compressive loading was investigated experimentally to verify the anticipated theoretical response. All specimens exhibited bending and subsequent catastrophic failure, even at compressive stresses well below these corresponding to the Euler load.


ABSTRACT: The elastica behavior of an extensional sandwich panel with a “soft” core when subjected to in-plane compressive loads is presented and it is compared with the response of its extensional equivalent single layer (ESL) with shear deformations model. The field equations along with the appropriate boundary conditions for the sandwich and the ESL panels have been derived through a variational approach following the High-order SAndwich Panel Theory (HSAPT) approach that takes into account the vertical flexibility of the core. The governing equations include the effects of the extension of the mid-surfaces of the face sheets of the sandwich panel or the mid-plane of the ESL model which the classical elastica approach misses. The results of the elastica response of a clamped-simply-supported sandwich panel and its ESL counterpart are presented and compared. They include the response along the panel, deformed shapes and equilibrium curves of in-plane loads versus structural quantities such as displacements and internal stress resultants and stresses. These results reveal that the predicted buckling load of the ESL panel is larger than that of the sandwich panel and that deep in the non-linear range the upper face sheet wrinkles with increasing overall and edge displacements and a release of the load. Hence, the use of an equivalent single layer panel especially when a sandwich panel with a compliant core is considered may lead to unsafe and unreliable predictions when large displacements and large rotations are considered.

References listed at the end of the paper:


ABSTRACT: This paper concerns the dynamic analysis of shell structures, with emphasis on application to
steel and steel-concrete composite blast resistant doors. In view of the short duration and impulsive nature of the blast loading, an explicit integration method is adopted. This approach avoids time-consuming computations of structural stiffness matrix and solving of simultaneous nonlinear equations. Single-point quadrature shell elements are used, with numerical control to suppress spurious hourglass modes. Composite shells are handled by an appropriate integration rule across the thickness. Both material and geometric nonlinearities are accounted for in the formulation. Contact and gap problems are considered using bilinear spring elements in the finite element analysis. Numerical examples are presented for some benchmark problems and application study to blast resistant doors. Good correlation is generally obtained between the numerical results based on the software developed and the results obtained by other means including field blast tests.

References listed at the end of the paper:

ABSTRACT: The present work is concerned with the development of finite element techniques for nonlinear transient dynamic analysis of reinforced concrete plates and shells. Computational models have been developed and coded, which are applied to various engineering problems under static and dynamic loading conditions. The first part of the thesis deals with some aspects of linear-elastic, geometric and material nonlinear finite element formulations of general thin and thick shell analysis under static or quasistatic loading. A generalized displacement method is proposed to overcome the 'shear locking' problem for the degenerated thick shell element when used in the context of thin shell structures. The basic concept and mathematical formulation of the generalized displacement method are detailed and its application is illustrated by numerical examples. The method is also extended to the geometrically nonlinear analysis of thin shells based on both Updated and Total Lagrangian formulation. An elasto-viscoplastic analysis of anisotropic plates and shells is developed by means of the finite element displacement method. A discrete layered approach is adopted to represent different material properties and gradual plastification through the thickness. Viscoplastic yielding is based on the Huber-Mises criterion extended by Hill for anisotropic material and special consideration is given to the evaluation of the viscoplastic strain increment for anisotropic situations. The second part of this thesis is concerned with nonlinear dynamic transient analysis of reinforced concrete shell structures. Direct integration methods are reviewed and discussed. In particular, the general single step explicit, implicit and implicit-explicit algorithms with predictor-corrector forms are presented and corresponding stability conditions are deduced by invoking the energy method. The modelling of reinforced concrete behaviour in shell structures under fast loading conditions is considered. Both a strain rate sensitive elasto-viscoplastic model and a strain rate sensitive elasto-plastic model are presented for describing concrete nonlinearities due to multiaxial compressive or tensile yielding under dynamic loads. The models are used in conjunction with a tensile crack monitoring algorithm to trace concrete crack opening and closing. Various reinforced concrete plates and shells are analyzed and reported in detail, with the results obtained being compared with those from other sources.


ABSTRACT: The aircraft fuselage is a complex structure with relatively low margins of safety, operating in a highly demanding dynamic environment. In the present work, the loading scenario of an on board explosion is investigated. The main scope is to assess the damage induced on an operating fuselage by an explosive charge. Finite element models of a typical commercial fuselage were generated for two material configurations, aluminium and GLARE. The simulation was performed in three stages; initialization phase, where the flight loads are applied on the structure, the blast phase and the final phase where the flight loads are applied on the damaged structure. Simulations were performed for different charge locations for both material configurations. The extent and location of damage allowed the generation of a vulnerability index.

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ABSTRACT: A new one-dimensional high-order theory for orthotropic elastic sandwich beams is formulated. This new theory is an extension of the high-order sandwich panel theory (HSAPT) and includes the in-plane rigidity of the core. In this theory, in which the compressibility of the soft core in the transverse direction is also considered, the displacement field of the core has the same functional structure as in the high-order sandwich panel theory. Hence, the transverse displacement in the core is of second order in the transverse coordinate and the in-plane displacements are of third order in the transverse coordinate. The novelty of this theory is that it allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core and the rotation at the centroid of the core) instead of just one (midpoint transverse displacement) commonly adopted in other available theories. It is proven, by comparison to the elasticity solution, that this approach results in superior accuracy, especially for the cases of stiffer cores, for which cases the other available sandwich computational models cannot predict correctly the stress fields involved. Thus, this theory, referred to as the “extended high-order sandwich panel theory” (EHSAPT), can be used with any combinations of core and face sheets and not only the very “soft” cores that the other theories demand. The theory is derived so that all core/face sheet displacement continuity conditions are fulfilled. The governing equations as well as the boundary conditions are derived via a variational principle. The solution procedure is outlined and numerical results for the simply supported case of transverse distributed loading are produced for several typical sandwich configurations. These results are compared with the corresponding ones from the elasticity solution. Furthermore, the results using the classical sandwich model without shear, the first-order shear, and the earlier HSAPT are also presented for completeness. The comparison among these numerical results shows that the solution from the current theory is very close to that of the elasticity in terms of both the displacements and stress or strains, especially the shear stress distributions in the core for a wide range of cores. Finally, it should be noted that the theory is formulated for sandwich panels with a generally asymmetric geometric layout.

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ABSTRACT: The focus of this paper is the application of the recently introduced extended high-order sandwich panel theory to the global buckling of a sandwich beam/wide panel. Three different solution approaches using the extended high-order sandwich panel theory are presented to investigate the effects of simplifying the loading case by applying loads just on the face sheets and by including or excluding nonlinear axial strains in the core. The results are also compared with results from a benchmark elasticity solution and, furthermore, from the simple sandwich buckling formula by the earlier extended high-order sandwich panel theory. It is found that all three theories are close to the elasticity solution for “soft” cores with E(core)/E(facesheet) < 0.001. However, for “moderate” cores, i.e., with E(core)/E(facesheet) > 0.001, the theories diverge and the extended high-order sandwich panel theory is the most accurate.

Catherine N. Phan (1), George A. Kardomateas (1) and Yeoshua Frostig (2)
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“Blast response of a sandwich beam/wide plate based on the extended high-order sandwich panel theory and comparison with elasticity”, J. Appl. Mech., Vol. 80, No. 6, August 2013

ABSTRACT: This paper presents a one-dimensional analysis for the blast response of a sandwich beam/wide plate with a compressible core. The dynamic version of the recently developed extended high-order sandwich panel theory (EHSAPT) is first formulated. Material, geometric, and loading parameters are taken from blast experiments reported in literature. The novelty of EHSAPT is that it includes axial rigidity of the core and allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core and the rotation at the centroid of the core) instead of just one (shear stress in the core) of the earlier high-order sandwich panel theory (HSAPT). The solution procedure to determine the dynamic response to a general load applied on the top face sheet of a general asymmetric simply supported configuration is outlined. Although the dynamic EHSAPT is formulated in its full nonlinear version, the solution is for the linear problem so the accuracy of EHSAPT, along with the other theories, can be assessed by comparison to an available dynamic elasticity solution. Results show that the EHSAPT is very accurate and can capture the complex dynamic phenomena observed during the initial, transient phase of blast loading.


ABSTRACT: The initiation of failure in composite sandwich beams is heavily dependent on properties of the core material. Several core materials, including PVC foams and balsa wood were characterized. The various failure modes occurring in composite sandwich beams are described and their relationship to the relevant core properties is explained and discussed. Under flexural loading of sandwich beams, plastic yielding or cracking of the core occurs when the critical yield stress or strength (usually shear) of the core is reached. Indentation under localized loading depends principally on the square root of the core yield stress. The critical stress for facesheet wrinkling is related to the core Young’s and shear moduli in the thickness direction. Experimental mechanics methods were used to illustrate the failure modes and verify analytical predictions.

References listed at the end of the paper:


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“Wrinkling of sandwich wide panels/beams based on the extended high-order sandwich panel theory: formulation, comparison with elasticity and experiments”, Archive of Applied Mechanics, Vol. 82, No. 10, pp 1585-1599, October 2012
ABSTRACT: There exist several high-order sandwich panel theories, most notably, the first to be introduced high-order sandwich panel theory (HSAPT) assumes a constant shear stress in the core. Recently, the extended high-order sandwich panel theory (EHSAPT) was introduced, its novelty being that it allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core, and the rotation at the centroid of the core) instead of just one (shear stress in the core) of the earlier theory. In this paper, the EHSAPT formulation for predicting the critical wrinkling load is presented for a simply supported sandwich of general asymmetric construction. The cases of (i) applying the loading just on the face sheets with a linear core assumption and (ii) applying uniform strain loading throughout the thickness of the panel and a nonlinear core assumption are examined. The results are compared with a benchmark elasticity solution. In addition, edgewise compression experiments were conducted on glass face/Nomex honeycomb core and the ensuing wrinkling point is compared with the theoretical predictions. A comparison is also made with earlier edgewise compression experiments on aluminum face/granulated-cork core reported in literature. Other wrinkling formulas that are included in the comparison are: Hoff–Mautner and the HSAPT.

References listed at the end of the paper:

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ABSTRACT: The face/core debond is justifiably considered to be a weak link in the use of sandwich structures. This is because such debonds tend to grow and eventually completely delaminate the face sheet. The most common cause of these defects is poor or missing bonding due to careless manufacturing or a mismatch in the geometry. Similar defects may also arise during service due to thermo-mechanical loads, impact events, or structural fatigue. Debonds or delaminations are susceptible to the phenomenon of “delamination buckling” which occurs when local compressive loading is introduced at the debond site.
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ABSTRACT: The most important issue regarding buckling of sandwich structures is the effect of transverse shear which can significantly reduce the Euler critical load. Simply put, the effect of transverse shear absolutely cannot be neglected. Therefore, all formulas for sandwich buckling are essentially ways to include this effect into the Euler formulas. Two basic ways for including transverse shear in column buckling are the Engesser (1891) and the Haringx (1948, 1949) approaches. Both of these approaches are also outlined by Timoshenko (1936).

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ABSTRACT: Compression loaded faces of sandwich members are sometimes subject to local instability phenomena, the most prominent being the wrinkling or rippling and the intracell buckling or dimpling. This chapter presents the mechanics associated with these phenomena and the classical formulas that predict the conditions for inducing these forms of local instability.
References not given by Springer.

ABSTRACT: There exist several formulas for the global buckling of sandwich plates, each based on a specific set of assumptions and a specific plate or beam model. It is not easy to determine the accuracy and range of validity of these rather simple formulas unless an elasticity solution exists. In this paper, we present an elasticity solution to the problem of global buckling of wide sandwich panels (equivalent to sandwich columns) subjected to axially compressive loading (along the short side). The emphasis on this study is on the global (single-wave) rather than the wrinkling (multi-wave) mode. The sandwich section is symmetric and all constituent phases, i.e., the facings and the core, are assumed to be orthotropic. The buckling problem is formulated as an eigen-boundary-value problem for differential equations, with the axial load being the eigenvalue. The complication in the sandwich construction arises due to the existence of additional “internal” conditions at the face sheet/core interfaces. Results are produced for a range of geometric configurations and these are compared with the different global buckling formulas in the literature.
References listed at the end of the paper:


ABSTRACT: The small internal length scales of nanomaterials/nano-devices may call the direct application of classical continuum models into question. In this research, a nonlocal elastic shell model, which takes the small scale effects into account, is developed to study the thermal buckling behavior of multi-walled carbon nanotubes. The multi-walled carbon nanotubes are considered as concentric thin shells coupled with the van der Waals forces between adjacent nanotubes. Closed form solutions are formulated for two types of thermal buckling of a double-walled carbon nanotube: Radial thermal buckling (as in a shell under external pressure) and axial thermal buckling. The effects of small scale effects are demonstrated, and a significant influence of internal characteristic parameters such as the length of the C-C bond has been found on the thermal buckling critical temperature. The study interestingly shows that the axial buckling is not likely to happen, while the “radial” buckling may often take place when the carbon nanotubes are subjected to thermal loading. Furthermore, a convenient method to determine the material constant, “e0,” and the internal characteristic parameter, “a,” is suggested.


ABSTRACT: In this paper, the vibrational behavior of the multiwalled carbon nanotubes (MWCNTs) embedded in elastic media is investigated by a nonlocal shell model. The nonlocal shell model is formulated by considering the small length scales effects, the interaction of van der Waals forces between two adjacent tubes and the reaction from the surrounding media, and a set of governing equations of motion for the MWCNTs are accordingly derived. In contrast to the beam models in the literature, which would only predict the resonant
frequencies of bending vibrational modes by taking the MWCNT as a whole beam, the current shell model can find the resonant frequencies of three modes being classified as radial, axial, and circumferential for each nanotube of a MWCNT. Big influences from the small length scales and the van der Waal’s forces are observed. Among these, noteworthy is the reduction in the radial frequencies due to the van der Waals’ force interaction between two adjacent nanotubes. The numerical results also show that when the spring constant $k_0$ of the surrounding elastic medium reaches a certain value, the lowest resonant frequency of the double walled carbon nanotube drops dramatically.

Renfu Li and George A. Kardomateas, "Nonlinear High-Order Core Theory for Sandwich Plates with Orthotropic Phases", AIAA Journal, Vol. 46, No. 11 (2008), pp. 2926-2934 (As is usual with AIAA papers one cannot cut and paste the abstract.)


ABSTRACT: There exist several formulas for the global buckling of sandwich plates, each based on a specific set of assumptions and a specific plate or beam model. It is not easy to determine the accuracy and range of validity of these rather simple formulas unless an elasticity solution exists. In this paper, we present an elasticity solution to the problem of global buckling of wide sandwich panels (equivalent to sandwich columns) subjected to axially compressive loading (along the short side). The emphasis on this study is on the global (single-wave) rather than the wrinkling (multiwave) mode. The sandwich section is symmetric, and all constituent phases, i.e., the facings and the core, are assumed to be orthotropic. The buckling problem is formulated as an eigenboundary-value problem for differential equations, with the axial load being the eigenvalue. The complication in the sandwich construction arises due to the existence of additional “internal” conditions at the face-sheet/core interfaces. Results are produced for a range of geometric configurations, and these are compared with the different global buckling formulas in the literature.

References listed at the end of the paper:
ABSTRACT: Sandwich panels have been developed to either produce lighter structures capable of carrying prescribed loads or increase the load-carrying capacity subject to limitations on weight. In these panels, facings carry bending and in-plane loads while the core functions similarly to the web of a beam, mostly resisting transverse shear. Improvements in the load-carrying capacity of sandwich panels can be achieved through modifications in their geometry, boundary conditions, and material distribution. One of the methods recently considered by the authors is based on using facings with a step-wise variable thickness that increases at the critical region of the structure. It was illustrated that the strength of a sandwich panel can be considerably enhanced using such stepped facings, without a detrimental increase of the weight. The present paper expands the study of the feasibility of the stepped-facing sandwich panel concept concentrating on three structural problems, i.e. a possible improvement in stability, changes in the natural frequencies, and forced dynamic response to the explosive blast. It is illustrated that the stepped-facing design can improve stability of the panel and its response to blast loading. However, fundamental frequencies of stepped-facing panels decrease compared to those in their conventional equal-weight counterparts. Such decrease is detrimental in the majority of engineering applications representing a limitation of stepped-facing panels. Nevertheless, the usefulness of the stepped-facing design is proven in the problems of bending, stability, and blast loading. Numerous examples presented in the paper validate our suggestion that the combination of a relatively simple manufacturing process and an improved structural response of sandwich panels with stepped facings may present the designer with an attractive alternative to conventional sandwich structures.

References listed at the end of the paper:
References listed at the end of the paper:


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ABSTRACT: Closed-form algebraic expressions for the energy-release rate and the mode mixity are obtained for a debonded sandwich (trimaterial). The most general case of an “asymmetric” sandwich is considered (i.e., the bottom face sheet not necessarily of the same material or thickness as the top face sheet). The energy-release rate is obtained by use of the J-integral, and the expression is derived in terms of the forces and moments at the debond section. Regarding the mode mixity, a closed-form expression is derived in terms of the geometry, material, and applied loading, and it is proven that, in the trimaterial case, just as in the bimaterial case, the
mode mixity can be obtained in terms of a single scalar quantity $\omega$, which is independent of loading; the $\omega$ value for a particular geometry and material can be extracted from a numerical solution for one loading combination. Thus, this analysis extends the existing formulas in the literature, which are for either a delamination in a homogeneous composite or an interface crack in a bimaterial. These new “trimaterial with a crack” formulas are also proven to yield the formulas for the limits of a bimaterial or for a homogeneous section with a crack.


ABSTRACT: The extended high-order sandwich panel theory was formulated in its one-dimensional version for orthotropic elastic sandwich beams. This theory includes the in-plane rigidity of the core, and the compressibility of the soft core in the transverse direction is also considered. The novelty of this theory is that it allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core, and the rotation at the centroid of the core) instead of just one (midpoint transverse displacement) commonly adopted in other available theories. The theory was derived so that all core/face displacement continuity conditions are fulfilled. It is proven, by comparison to the elasticity solution, that this approach results in superior accuracy, especially for the cases of stiffer cores, for which cases of the other available sandwich computational models cannot correctly predict the stress fields involved. In this paper, a linear finite element is formulated based on the extended high-order sandwich panel theory. The element equations are outlined, and numerical results for the simply supported case of transverse distributed loading are produced for several typical sandwich configurations. These results are compared with the corresponding ones from the elasticity solution. The comparison among these numerical results shows that, with a relatively small number of elements, the results are very close to the elasticity ones in terms of both the displacements and stress or strains. Thus, the finite element version of the extended high-order sandwich panel theory constitutes a very powerful analytical tool for sandwich panels.

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ABSTRACT: The Sanders-type theory of elliptical sandwich shells with different facings is formulated. The governing equations account for transverse shear strains and for rotations about the normal to the middle surface of the shell. The constitutive equations correspond to a sandwich shell where each facing is formed of an even number of regular symmetrically laminated layers. Accordingly, the matrix of extensional, coupling and bending stiffnesses is fully populated, except for the elements A16 and A26 that are equal to zero. In addition, a geometrically nonlinear formulation is presented for an elliptical facing resting on an elastic foundation, based on the Sanders nonlinear shell theory. In this formulation, the rotations about the normal to the middle surface as well as transverse shear strains are disregarded. Both the governing equations for the sandwich shell and the nonlinear solution for a facing are reduced to the corresponding results for a circular cylindrical shell if the radius of curvature of the shell is constant. Numerical examples are presented for the problem of buckling of a
long cylindrical shell subjected to a lateral pressure. This solution, developed by using the energy method, illustrates the penalty involved in using different facings, which may nevertheless be necessary to improve the design by reinforcing the facing exposed to low-velocity impact and other loads.

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ABSTRACT: The paper presents a theoretical formulation for spherical shells reinforced by meridional and circumferential stiffeners. Active damping of the shell is introduced through control action of piezoelectric coupled pairs bonded to the meridional stiffeners. The induced loads can include radial pressure and a thermal field that are independent of the circumferential coordinate. Neglecting local deformations between adjacent meridional stiffeners, the response of the shell will be axisymmetric. The analysis employs the Donnell-Mushtari-Vlasov version of Love's theory of shells together with a smeared stiffeners technique. The paper also considers a particular case of shell mounted piezoelectric coupled pairs without conventional stiffeners. A closed form solution is derived for spherical panels without conventional stiffeners within the range of the meridional coordinate between 75° and 90° using a version of the Geckeler approximation.

References listed at the end of the paper:
ABSTRACT: This paper outlines several issues related to the design of sandwich structures with a truss-reinforced polymeric or hollow core. The first part of the paper employs a simple analytical model that illustrates the contribution of such a core to the structure’s facing stability. While the enhancement of the facing-stability due to truss reinforcement is shown to be considerable, the problems of local strength and truss-element (pin) stability have to be analyzed prior to the acceptance of the design concept discussed in the paper. Accordingly, the second part of the paper presents the results of finite-element analysis used to pinpoint potentially weak elements in the considered design. The paper results in a number of practical conclusions and recommendations that may be useful for the development and implementation of sandwich structures with truss-reinforced cores.

References listed at the end of the paper:


ABSTRACT: A non-linear shallow thin shell element is described. The element is a curved quadrilateral one with corner nodes only. At each node, six degrees of freedom (i.e. three translations and three rotations) make the element easy to connect to space beams, stiffeners or intersecting shells. The curvature is dealt with by Marguerre's theory. Membrane bending coupling is present at the element level and improves the element behaviour, especially in non-linear analysis. The element converges to the deep shell solution. The sixth degree of freedom is a true one, which can be assimilated to the in-plane rotation. The present paper describes how overstiffness due to membrane locking on the one hand and to the sixth degree of freedom on the other hand can be corrected without making use of numerical adjusted factors. The behaviour of this new element is analysed in linear and non-linear static and dynamic tests.
Franc Kosel, Jože Petrisic, Boris Kuselj, Tadej Kosel, Viktor Sajn and Mihael Brojan (Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000, Ljubljana, Slovenia), “Local buckling and debonding problem of a bonded two-layer plate”, Archive of Applied Mechanics, Vol. 74, No. 10, pp 704-726, September 2005

ABSTRACT: The problem of local buckling, debonding initiation and growth process of the debonding of a bonded two-layer plate is treated. In the weaker layer of the plate, compression appears due to the external compressive axial force and bending moment. The conditions for local buckling of the weaker layer have been studied where the possibility that the stress state in the layers could be in elasto-plastic domain has been considered. A mathematical model is developed to determine the bending displacements of laminate layers after the weaker layer buckles locally, and in the state after the plate has been unloaded. The third-order theory introduced by Chwalla has been implemented. Mechanical properties of the layers and adhesive used in the numerical model were measured with experiments. Experimental work comprised the determination of mechanical properties of the chosen materials and experimental verification of the presented mathematical model. Numerically obtained results are compared with those obtained by an experimental approach, and are found to be in good agreement.

References listed at the end of the paper:

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ABSTRACT: The conventional approach to analysis the buckling of rectangular laminates containing an embedded delamination subjected to the in-plane loading is to simplify the laminate as a beam-plate from which
the predicted buckling load decreases as the length of the laminate increases. Two-dimensional analyses are employed in this paper by extending the one-dimensional model to take into consideration of the influence of the delamination width on the buckling performance of the laminates. The laminate is simply supported containing a through width delamination. A new parameter \( \beta \) defined as the ratio of delamination length to delamination width is introduced with an emphasis on the influence of the delamination size. It is found that (i) when the ratio \( \beta \) is greater than one snap-through buckling prevails, the buckling load is determined by the delamination size and depth only; (ii) as the ratio \( \beta \) continues to increase, the buckling load will approach to a constant value. Solutions are verified with the well established results and are found in good agreement with the latter.

References listed at the end of the paper:

ABSTRACT: Delaminated composites under pure bending can undergo snap buckling under certain conditions of applied bending load and geometrical configuration. The phenomenon is demonstrated experimentally and is investigated theoretically by an energy procedure. The geometric non-linearities are included in the formulation. First, a theoretical analysis is performed to model the behavior of the system and define the conditions for snap buckling. The predicted buckling loads are then compared with experimentally obtained data from pure bending loading of Kevlar epoxy specimens with internal delaminations. Good agreement is obtained between the experimental and theoretical results.

References listed at the end of the paper:


Jea-Hyeong Han, George A. Kardomateas, George J. Simites, “Elasticity, shell theory and finite element results for the buckling of long sandwich cylindrical shells under external pressure”, Composites: Part B 35
ABSTRACT: The buckling of a sandwich cylindrical shell under uniform external hydrostatic pressure is studied in three ways. The simplifying assumption of a long shell is made (or, equivalently, ‘ring’ assumption), in which the buckling modes are assumed to be two-dimensional, i.e. no axial component of the displacement field, and no axial dependence of the radial and hoop displacement components. All constituent phases of the sandwich structure, i.e. the facings and the core, are assumed to be orthotropic. First, the structure is considered a three-dimensional (3D) elastic body, the corresponding problem is formulated and the solution is derived by solving a set of two linear homogeneous ordinary differential equations of the second-order in \( r \) (the radial coordinate), i.e. an eigenvalue problem for differential equations, with the external pressure, \( p \) the parameter/eigenvalue. A complication in the sandwich construction is due to the fact that the displacement field is continuous but has a slope discontinuity at the face-sheet/core interfaces, which necessitates imposing ‘internal’ boundary conditions at the face-sheet/core interfaces, as opposed to the traditional two-end-point boundary value problems. Second, the structure is considered a shell and shell theory results are generated with and without accounting for the transverse shear effect. Two transverse shear correction approaches are employed, one based only on the core, and the other based on an effective shear modulus that includes the face-sheets. Third, finite element results are generated by use of the ABAQUS finite element code. In this part, two types of elements are used: a shear deformable shell element and a solid 3D (brick) element. The results from all these three different approaches are compared.

References listed at the end of the paper:

and kevlar/epoxy laminates with 0° deg orientation with respect to the hoop direction, and for alloy-foam core. Shell theory results are generated with and without accounting for the transverse shear effect. Two transverse shear correction approaches are compared, one based only on the core, and the other based on an effective shear modulus that includes the face sheets. The results show that the shell theory predictions without transverse shear can produce highly non-conservative results on the critical pressure, but the shell theory formulas with transverse shear correction produce reasonable results with the shear correction based on the core only being in general conservative (i.e., critical load below the elasticity value). The results are presented for four mean radius over shell thickness ratios, namely 15, 30, 60, and 120 in order to assess the effect of shell thickness (and hence that of transverse shear). For the same thickness, the differences between elasticity and shell theory predictions become larger as the mean radius over thickness ratio is decreased. A comparison is also provided for the same shell with homogeneous composite construction. It is shown that the sandwich construction shows much larger differences between elasticity and shell theory predictions than the homogeneous composite construction. The solution presented herein provides a means of a benchmark for accurately assessing the limitations of shell theories in predicting stability loss in sandwich shells.

References listed at the end of the paper:

G. A. Kardomateas and C. B. Chung (School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332), “Thin Film Modeling of Delamination Buckling in Pressure Loaded Laminated Cylindrical Shells”, AIAA Journal Vol. 30, No. 8, August 1992

ABSTRACT: Delamination is one of the basic defects inherent to laminated shell structures. Under uniform external pressure such delaminations may buckle and subsequently propagate. This phenomenon is modeled here as a first approximation by considering a two-dimensional geometry (ring approximation) and a thin delaminated layer. Growth is studied by a fracture mechanics-based energy release rate criterion. Closed-form expressions for the critical pressure and growth conditions are derived, as well as for the cutoff level of the
delamination range below which local delamination buckling cannot take place. A formulation that accounts for the effects of transverse shearing forces is also presented.

References listed at the end of the paper:

G.A. Kardomateas and C.B. Chung (School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia), “Buckling of a thick orthotropic cylindrical shell under external pressure including hygroscopic effects”, AMD Vol. 162, Mechanics of Thick Composites, ASME 1993

ABSTRACT: The stability of equilibrium of an orthotropic thick cylindrical shell subjected to external pressure in a hygroscopic environment is investigated. In this approach, the structure is considered a three-dimensional elastic body rather than a shell. First, a fundamental analysis that formulates the basic buckling equations with the appropriate boundary conditions in the elasticity context is performed. Subsequently, the critical loads for pure mechanical loading (external pressure) are derived. Following this benchmark analysis, the particular emphasis is placed on examining the effect of the boundary-layer transient hygroscopic stress field on the critical load. Constant moisture concentrations on the inner and outer surfaces are imposed in addition to the external pressure. Since the moisture diffusion process is relatively slow, the hygroscopic stresses are confined for practical time values to a boundary-layer region near the surfaces. The analysis first uses the series expansion for the Bessel functions for small arguments and then the Hankel asymptotic expansions since an increasing number of terms is found to be needed. Compared to the classical shell theory approach, the results of this research show that the shell theory predictions on the critical load can be highly non-conservative when moderately thick construction is involved. However, the hygroscopic boundary-layer has a negligible influence on the critical load.

ABSTRACT: The stability of equilibrium of a transversely isotropic thick cylindrical shell under axial compression is investigated. The problem is treated by making appropriate use of the three-dimensional theory of elasticity. The results are compared with the critical loads furnished by classical shell theories. For the isotropic material cases considered, the elasticity approach predicts a lower critical load than the shell theories, the percentage reduction being larger with increasing thickness. However, both the Flugge and Danielson and Simmonds theories predict critical loads much closer to the elasticity value than the Donnell theory. Moreover, the values of $n$, $m$ (number of circumferential waves and number of axial half-waves, respectively, at the critical point) for both the elasticity, and the Flugge and the Danielson and Simmonds theories, show perfect agreement, unlike the Donnell shell theory.


PARTIAL ABSTRACT: The bifurcation of equilibrium of an orthotropic thick cylindrical shell under axial compression is studied by an appropriate formulation based on the three dimensional theory of elasticity. The results from this elasticity solution are compared with the critical loads predicted by the orthotropic Donnell and Timoshenko non-shallow shell formulations...


ABSTRACT: An elasticity solution to the problem of buckling of orthotropic cylindrical shells subjected to external pressure is presented. In this context, the structure is considered a three-dimensional body. The results show that the shell theory predictions can produce nonconservative results on the critical load of composite shells with moderately thick construction. The solution provides a means of accurately assessing the limitations of shell theories in predicting stability loss.


ABSTRACT: A formulation based on the three dimensional theory of elasticity is employed to study the buckling of an orthotropic cylindrical shell under external pressure. In this paper, a non-zero axial displacement and a full dependence of the buckling modes on the three coordinates is assumed, as opposed to the ring approximation employed in the earlier studies. The results from this elasticity solution are compared with the critical loads predicted by the orthotropic Donnell and Timoshenko non-shallow shell formulations. Two cases
of end conditions are considered; one with both ends of the shell fixed, and the other with both ends capped and under the action of the external pressure. Moreover, two cases of orthotropic material are considered with stiffness constants typical of glass/epoxy and graphite/epoxy. For the isotropic material case, the predictions of the simplified (single expression) Donnell and the Flügge and the Danielson and Simmonds theories are also compared. In all cases, the elasticity approach predicts a lower critical load than the shell theories, the percentage reduction being larger with increasing thickness. The degree of non-conservatism depends strongly on the material properties, being smaller for the isotropic case. Furthermore, although it is a commonly accepted notion that the critical point in loading under external pressure occurs for $n = 2$ and $m = 1$ (number of circumferential waves and number of axial half-waves, respectively), it was found that this is not the case for the strongly orthotropic graphite/epoxy material and the moderately thick construction; for this case, the value of $m$ at the critical point is greater than 1 (yet, in all cases $n = 2$).


ABSTRACT: Benchmark solutions to the problem of buckling of orthotropic cylindrical shells, which are based on the three-dimensional theory of elasticity, are presented in this review article. It is assumed that the shell is under external pressure or axial compression or a combination of these loadings. These solutions provide a means of accurately assessing the limitations of the various shell theories in predicting critical loads. A comparison with some classical shell theories shows that the classical shell theories may produce, in general, highly non-conservative results on the critical load of composite shells with thick construction. One noteworthy exception: the Timoshenko shell buckling equations produce conservative results under pure axial compression.


ABSTRACT: The objective of this paper is to answer the question of how accurately the simple Euler or transverse shear correction Engesser/Haringx/Timoshenko column buckling formulae are, when orthotropic composite material and moderate thickness are involved. The column is in the form of a hollow circular cylinder and the Euler or Timoshenko loads are based on the axial modulus. For this purpose, a three-dimensional elasticity solution is presented. As an example, the cases of an orthotropic material with stiffness constants typical of glass/epoxy or graphite/epoxy and the reinforcing direction along the periphery or along the cylinder axis are considered. First, it is found that the elasticity approach predicts in all cases a lower than the Enter value critical load. Moreover, the degree of non-conservatism of the Euler formula is strongly dependent on the reinforcing direction; the axially reinforced columns show the highest deviation from the elasticity value. The degree of non-conservatism of the Euler load for the circumferentially reinforced columns is much smaller and is comparable to that of isotropic columns. Second, the Engesser or first Timoshenko shear correction formula is in all cases examined conservative, i.e., it predicts a lower critical load than the elasticity solution. The Haringx or second Timoshenko shear correction formula is in most cases (but not always) conservative. However, in all cases considered, the second estimate is always closer to the elasticity solution than the first one. For the isotropic case both Timoshenko formulas are conservative estimates. Examination of a new formula for column buckling that adds a second term to the Euler load expression and is supposed to account
for thickness effects, shows that this estimate is a non-conservative estimate but performs very well with very thick sections, being closest to the elasticity solution, but in general no better than the Timoshenko formulas for moderate thickness.


ABSTRACT: Two important issues associated with structural integrity of composite shells are the prediction of the conditions for the loss of stability and the question of accurately assessing the behavior of the structure in the presence of defects. Since the structures under consideration are subjected to high values of external pressure, which in turn results in both an axial and circumferential local compressive field, buckling/postbuckling of delaminated and pure (without delaminations) shells is an important part of the structural integrity concept. Two other issues that are included in this project are a study of the growth of internal delaminations, and an investigation of the effect of the hygroscopic environment in the context of predicting the combined effects of moisture sorption and external compression with respect to the stress and deformation fields in thick composite shells, and the possibility of local spalling (initiation of internal debonds and interlaminar separation).

References:


ABSTRACT: An improved elasticity solution to the problem of buckling of orthotropic cylindrical shells subjected to external pressure is presented. The 2D axisymmetric cylindrical shell is studied (ring approximation). Specifically, in the development of the governing equations and boundary conditions for the buckling state, the solution includes the terms with the prebuckling normal strains and stresses as coefficients (i.e., the terms $e_{a0}$ and $a_{e0}$ which were neglected in the earlier work as being too small compared to the terms $a_{e0}$ and $a_{k0}$, respectively). The formulation results in a two-point boundary eigenvalue problem for ordinary differential equations in $r$, with the external pressure $p$ as the parameter. The results show that the effect of including the
nonnal strains and stresses is to further decrease the critical load. This decrease (versus the earlier elasticity solution without these terms) depends on the shell thickness and is generally moderate, and in no event comparable with the (quite large) decrease of the elasticity versus the shell theory prediction. This decrease depends also on the degree of orthotropy, and it is smaller for the isotropic case. Finally, a formula is derived for the critical pressure based on a first-order shear deformation formulation, and the comparison shows an improvement versus the classical shell for thick shells, but still the elasticity solution is noticeably lower than the first-order shear deformation prediction.

References listed at the end of the paper:


ABSTRACT: The elasticity solution is constructed for a cylindrical sandwich shell under external and/or internal pressure and for the same shell under axial load. The solution is an extension of the one for a
homogeneous, monolithic shell and is provided in closed form. All three phases, that is, the two face sheets and the core, are assumed to be orthotropic. Moreover, there are no restrictions as far as the individual thicknesses of the face sheets and the sandwich construction may be asymmetric. These solutions can be used as benchmarks for assessing the performance of various sandwich shell theories. Illustrative results are provided in comparison to the sandwich shell theory.

References listed at the end of the paper:


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ABSTRACT: The response of composite columns under axial compressive loading, and in which a non-uniform temperature distribution through the thickness exists, is investigated. This non-uniform temperature distribution can develop when one side of the structures is exposed to heat flux. In this paper, we assume that this distribution is linear, which corresponds to a steady state temperature profile due to heat conduction. The degradation of the elastic properties with temperature (especially near the glass transition temperature of the matrix) is accounted for, by using experimental data for the elastic moduli. Furthermore, the formulation includes transverse shear and it is done first for the general non-linear case and subsequently linearized. Due to the non-uniform stiffness and the effect of the ensuing thermal moment, the structure behaves like an imperfect column, and responds by bending rather than buckling in the classical Euler (bifurcation) sense. Another important effect of the non-uniform temperature is that the neutral axis moves away from the centroid of the cross-section, resulting in another moment due to eccentric loading, which would tend to bend the structure away from the heat source. Simple equations for the response of the column are derived and results are presented for the variation of the deflection with the heat flux, as well as for the combined effects of the applied
load and heat flux. It is found that the thermal moment would tend to bend the structure away from the heat source for small temperatures (small heat fluxes) but towards the heat source for large temperatures. On the contrary, the moment induced due to the eccentric loading would always tend to bend the structure away from the heat source. Results indicate the combined influences of these moments and that of axial constraint.

References listed at the end of the paper:


ABSTRACT: Thick composite and sandwich shells are used in many naval submersible structures and in other applications such as space vehicles. Stability under the prevailing high external pressure in deep ocean environments is of primary concern. In many other applications the loading involves a combination of external pressure and axial compression. It is well known that for these structures the simple classical formulas are in much error, due to both the large thickness and the large extensional over shear modulus ratios of modern composite and sandwich materials. Although there exist several advanced theories, such as first order shear and higher order shear theories, each based on a specific set of assumptions, it is not easy to determine the accuracy and range of validity of these advanced models unless an elasticity solution exists. This paper presents the research performed over the last 15 years on benchmark elasticity solutions to the problem of buckling of (i) orthotropic homogeneous cylindrical shells and (ii) sandwich shells with all constituent phases i.e., facings and core assumed to be orthotropic. The paper focuses on uniform external pressure loading. In this context, the structure is considered a three-dimensional body. The results show that the shell theory predictions can produce in many cases highly non-conservative results on the critical loads. A comparison with the corresponding formulas from shell theory with shear included, is also performed. The present solutions provide a means of accurately assessing the limitations of the various shell theories in predicting stability loss.
References listed at the end of the paper:

ABSTRACT: Ocular rigidity is the change in intraocular pressure produced by an incremental change in intraocular volume. Ocular rigidity was determined in 14 donor eyes by injecting small increments of a balanced salt solution through the limbus, while continually monitoring the intraocular pressure with a transducer. A buckling procedure was then performed in these eyes with the use of various solid silicone or stainless steel encircling elements, and the experiments were repeated. Buckled eyes were significantly less rigid than unbuckled eyes, and eyes with higher buckles were significantly less rigid than those with shallower buckles. The observed changes in rigidity are likely secondary to changes in the shape and stress distribution of the scleral shell and are only to a small degree related to the elasticity of the encircling element. Greater volumes of vitreous substitutes, gases, or antibiotics may be injected into buckled eyes compared with unbuckled eyes before excessive intraocular pressures are reached.


ABSTRACT: Thin-walled shells have wide applications as primary structural elements in simple and complex lightweight structures. In these applications, cylindrical shells contain several imperfections and material discontinuity, namely variously shaped cutout. The understanding of the effects of initial geometric imperfection and cutout on the buckling behavior of such shells is very important. A finite element analysis, using commercial finite element software, is used to study the buckling behavior of cylindrical shells with imperfection or circular cutouts. Particular emphasis is placed on circular cylindrical shells subjected to an axial compression load. Both perfect shells with cutouts and shells with initial geometric imperfection are considered. The main objective of this study is to investigate the buckling behavior of laminated composite shells with circular cutouts and initial geometric imperfection. The effect of cutout geometry and size, material properties, fiber angle, stacking sequences, and initial geometric imperfection are discussed. The results presented herein indicated that, buckling response of laminated composite shells is significantly changed by cutout size, fiber orientation, stacking sequences, and amplitude of initial geometric imperfections.


PARTIAL ABSTRACT: The experimental results from implosion tests of various graphite/epoxy and glass/epoxy cylinders are correlated with predictions from a performance model for thick composite cylinders subjected to external hydrostatic pressure. That performance model consists of a stress module, a stability module, and a material failure module….


ABSTRACT: A parametric study is presented on the accuracy of stability data for axial compression and
torsion by classical and first-order shear deformation theories for laminated composite cylinders. Comparisons
of the data in the forms of curves of critical stress versus L/a (dimensionless wave-length/radius ratio) are made
with those by Biot's theory, which is predicated on three-dimensional elasticity. Two thickness/radius ratios
were considered: H/a = 0.01 and 0.1, typical of thin and thick shell geometries, respectively. First, a comparison
of the data for a homogeneous, isotropic cylinder was given to have a baseline for understanding the role of
material anisotropy. Then, a number of regular symmetric and antisymmetric laminates were considered, all
laminate profiles based on one material system only, that of EL/ET = 25. The data for thin geometries (H/a
greater-or-equal, slanted 0.01) showed that classical theory for laminated composite shells can be trusted to give
accurate results over a reasonably wide range of L/a. For the thick shell geometry, there were regions of
relatively good agreement and regions where classical and first-order shear deformation theories were not
appropriate.

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3, August 1993, pp. 467-472, doi:10.1016/0045-7949(93)90323-6
ABSTRACT: The dynamic stability of an imperfect fiber reinforced composite cylindrical shells under axial
or/torsional impulsive load in the form of a step function is investigated. Donnell-von Kármán type
nonlinear equations are derived for the initially imperfect laminated composite cylinder. Two buckling criteria
are used for comparison. Critical loads are computed for different imperfection parameters. The sensitivity is
established through plots of critical loads versus imperfection amplitude. The larger the drop in critical load
value with increasing amplitude, the greater the sensitivity. Compared with the static case, there is a significant
reduction of the dynamic buckling load subject in axial direction. For the torsional load, no significant reduction
has been found. Comparing dynamic buckling loads obtained by using the Simitses criteria and by using the
Budiansky and Roth criteria, with the Simitse criteria one can get conservative results.

N.S. Rallis and A.N. Kounadis (Civil Engineering Department, National Technical University of Athens,
Greece), “Nonlinear sway-buckling of geometrically imperfect rectangular frames”, Ingenieur-Archiv, Vol. 55,
No. 2, pp 90-97, March 1985
ABSTRACT: By using as model an unbraced rectangular frame, the effect of geometric imperfections due to
right angle deviations is thoroughly discussed. It is found that the value of the angle between the center lines of
the two members is of decisive importance for the response of the frame. There is a critical angle for which the
response of the frame changes from buckling to unbuckled states exhibiting a monotonically rising equilibrium
path. It is shown that this critical angle depends on the column slenderness ratio as well as on the length and
moment of inertia ratio of the two members. Moreover, formulas for direct evaluation of the critical angle as
well as of the load-carrying capacity of the frame are established.
References listed at the end of the paper:
   Ser. E (1977) 701–706

ABSTRACT: A nonlinear stability analysis based on an analytical approach of elastic type is performed for the first time on a simple two-bar frame. In order to obtain an exact determination of its buckling and postbuckling behavior the effect of compressibility of the bar centroidal axis is taken into account. This effect implies very slight increase in the buckling load which can be safely ignored. Moreover, it is found that even in the most extreme cases of geometry and stiffness, the critical buckling displacements are of negligibly small magnitude contrary to existing results obtained by the nonlinear kinematic stability analysis. The two foregoing findings enable us to replace the limit point by a bifurcation point. Such a simplification, being correct in an asymptotic sense, allows the application of a stability analysis of frames by considering their bars as incompressible. A variety of numerical results shows the degree of accuracy and the range of applicability of the aforementioned nonlinear kinematic stability analysis by comparing it with the exact method of stability analysis proposed herein.

References listed at the end of the paper:

4. Kounadis, A. N.: A comparative study of frames by the exact elastica, theory and other approximate analyses. (To be published.)


SUMMARY: A thorough study of the critical and post-critical large displacement response of simple discrete and continuous systems made from a nonlinear elastic material, is presented. Simple material-dependent stability conditions are established, whose application does not require the solution of the intractable nonlinear differential equations of equilibrium. The predominant role of the nonlinear component of the curvature on the buckling mechanism of the foregoing systems, is revealed. Moreover, it is found that elastic systems which were considered as exhibiting post-buckling strength might be imperfection sensitive, if the effect of material nonlinearity is taken into account. An approximate but very efficient analytical approach leading to very reliable results is derived for establishing the large displacement behavior of a nonlinear elastic cantilever bar. The degree of accuracy of this approach is checked by comparing it with the “exact” numerical solution of Runge Kutta. The numerical results presented herein contribute to our understanding of this problem and at the same time show the efficiency, reliability and range of applicability of the proposed approach.

References listed at the end of the paper:
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ABSTRACT: A thorough study of the critical and post-critical large displacement response of simple discrete and continuous systems made from a nonlinear elastic material, is presented. Simple material-dependent stability conditions are established, whose application does not require the solution of the intractable nonlinear differential equations of equilibrium. The predominant role of the nonlinear component of the curvature on the buckling mechanism of the foregoing systems, is revealed. Moreover, it is found that elastic systems which were considered as exhibiting post-buckling strength might be imperfection sensitive, if the effect of material nonlinearity is taken into account. An approximate but very efficient analytical approach leading to very reliable results is derived for establishing the large displacement behavior of a nonlinear elastic cantilever bar. The degree of accuracy of this approach is checked by comparing it with the “exact” numerical solution of Runge Kutta. The numerical results presented herein contribute to our understanding of this problem and at the same time show the efficiency, reliability and range of applicability of the proposed approach.

References listed at the end of the paper:

ABSTRACT: In this investigation the effect of two loadings interaction and right angle deviation on the response of a rectangular two-bar frame is thoroughly discussed. It is found that there is a critical value of the two loadings ratio as well as of the right angle deviation for which the physical equilibrium path and the physically unacceptable complementary path meet each other at an asymmetric bifurcation point. This state constitutes the boundary between stability and instability, since the response of the frame changes from snapthrough buckling to a stable equilibrium path. Moreover, a very efficient and simple to use stability analysis, employed for the first time at a non-rectangular frame, gives reliable results compared to those of the nonlinear kinematic stability analysis.

References listed at the end of the paper:


ABSTRACT: The nonlinear dynamic buckling response of discrete systems under step loading of infinite duration is thoroughly discussed by using one-degree-of-freedom models. The analysis is based on the exact nonlinear differential equations of motions and refers to those systems which when subjected to the same loading applied statically exhibit a limit-point instability. It is found that an unbounded motion may start for the smallest step load which forces the system to pass through an unstable equilibrium state of the postbuckling path with zero total potential energy. This leads to dynamic buckling criteria which allow the determination of exact dynamic buckling loads without solving the corresponding nonlinear differential equations of motion. A comparison of dynamic buckling estimates of previous works with those obtained herein shows that the latter are exact regardless of the magnitude of the initial imperfection. Moreover, some additional results provide a better insight into the actual mechanism of nonlinear dynamic buckling associated with the foregoing type of loading.


ABSTRACT: The large postbuckling response of a uniform cantilever beam subjected to a partial follower
compressive load of constant magnitude is presented. The range of values of the nonconservativeness loading parameter for which a divergence instability occurs is theoretically established. The boundary between divergence and flutter instability corresponds to a double critical point where the first and second buckling loads (eigenvalues) coincide. It was also theoretically established that the critical points corresponding to these loads are stable symmetric. Except of the double critical point, the buckling loads of the first and second eigenmodes are distinct for the entire region of the nonconservativeness loading parameter. However, this is not true for the corresponding postbuckling paths. Indeed using an elastica analysis suitable for rotations up to 360°, it was found that at a certain critical tip rotation depending on the value of the nonconservativeness parameter the first and second postbuckling modes meet each other asymptotically. Numerical results have been obtained using various approximate analytic techniques which are checked by the method of elliptic integrals as well as the numerical schemes of Adams and Runge-Kutta.

References listed at the end of the paper:
8. Kounadis, A. N.: An efficient and simple approximate technique for solving nonlinear boundary and initial-value problems computational Mechanics, 9, 1992

A. N. Kounadis and X. A. Lignos (Civil Engineering Department, National Technical University of Athens, Athens, Greece), “Buckling of tube-like shells filled with other material under uniform axial compression”, Engineering Structures, Vol. 22, No. 8, June 2000, pp. 961-967, doi:10.1016/S0141-0296(99)00047-4

ABSTRACT: Symmetrical buckling of steel tube-like shell structures fully filled with a softer material is considered. Such a compound cross-section, after assuming complete condensation of the contained material, is subjected to uniform axial compression by means of two rigid end plates. We further assume simple boundary conditions on both ends with zero radial displacements. The proposed solution allows establishment of the effect of hoop stresses on the load-carrying capacity of the filled tube.

ABSTRACT: This work deals with dynamic buckling universal solutions of discrete nondissipative systems under step loading of infinite duration. Attention is focused on total potential energy functions associated with universal unfoldings of cuspoid type catastrophes with one active coordinate. The fold, dual cusp and tilted cusp catastrophes under statically applied loading occurring via limit points, asymmetric/symmetric bifurcations and nondegenerate hysteresis points are extended to the case of dynamic loading. Catastrophe manifolds of these types showing imperfection sensitivity under both types of loading are fully assessed. Important findings regarding dynamic buckling of imperfect systems generated by perfect systems associated with ‘imperfect’ bifurcations are explored. The analysis is supplemented by a numerical application of a system exhibiting imperfect bifurcation when it is perfect as well as a hysteresis point associated with a tilted cusp catastrophe, when it becomes imperfect.

References listed at the end of the paper:

A.N. Kounadis (2), J. Mallis (1) and A. Sbarounis (1)
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“Postbuckling analysis of columns resting on an elastic foundation”, Archive of Applied Mechanics, Vol. 75, Nos. 6-7, 2006, pp. 395-404,
doi: 10.1007/s00419-005-0434-1
ABSTRACT: The postbuckling response of perfect and geometrically imperfect elastic columns resting on an
elastic Winkler type foundation is thoroughly discussed. This is established by employing an approximate analytic technique leading to very reliable results in the vicinity of the critical state. It was found that the critical state of perfect columns is a stable symmetric bifurcation point and consequently there is no sensitivity to initial geometrical imperfections. Moreover, a simple but readily analyzed mechanical model is proposed to simulate the salient features of buckling mechanism of the column on elastic foundation with those of the model. The simplicity, reliability and efficiency of the proposed analysis as well as the successful modeling of the buckling mechanism of the column by that of a single mode mechanical model are illustrated with the aid of numerical examples.

References listed at the end of the paper:


ABSTRACT: The lateral postbuckling response of thin-walled structures such as bars and frames with members having steel rolled shapes as well as circular cylindrical shells under axial compression is thoroughly reconsidered. More specifically via a simple and very efficient technique it is found that beams with rolled shapes (symmetric or non symmetric) under uniform bending and axial compression exhibit a stable lateral–torsional secondary path with limited margins of postbuckling strength. New findings for the static and dynamic stability of frames with crooked steel members—due to the presence of residual stresses—are also reported. It is comprehensively established that the coupling effect due to initial crookedness and loading eccentricity may have a beneficial effect on the load-carrying capacity of the frames. Moreover, simple mechanical models are proposed for simulating the buckling mechanism of axially compressed circular cylindrical shells. Very recently Bodner and Rubin proposed an 1-DOF mechanical model whose buckling parameters correlated to those of the
shells by using an empirical formula based on experimentally observed shell buckling loads. In the present analysis a new 2-DOF model for the static and dynamic buckling of axially compressed circular cylindrical shells, which can include mode coupling, is presented.

Ronalds, B.F. and Dowling, P.J., “Buckling of intact and damaged offshore shell structures”, Advances in Marine Structures Conference, Dunfermline, Scotland, May 1986

ABSTRACT: Compression tests are described on longitudinally stiffened cylindrical shells with denting damage. The behavior is compared with that of similar intact shells to ascertain the stiffness and strength reduction in the presence of local damage. Modes of buckling are also discussed. The results suggest a simple analytical procedure which may be used in estimating the consequences of ship collision damage to buoyant offshore platforms.

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ABSTRACT: This article presents results from static and dynamic tests on thick filament wound glass/epoxy tubes. The first part involves the identification of damage initiation and its development. Ultrasonic inspection was employed first to determine projected damage areas. A large number of samples were then sectioned and polished and the true damage area was revealed by a dye penetrant technique. This has made possible detailed descriptions of damage development. The true damage area is roughly 10 times the projected area. The second part of the article is concerned with the evaluation of the influence of this damage on residual strength under hydrostatic pressure loading. The improved understanding of these phenomena and the development of predictive tools is part of an ongoing effort to improve the long-term integrity of composite structures for underwater applications.

S.S. Seleim and J. Roorda (Department of Civil Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada), “Buckling behaviour of ring-stiffened cylinders; experimental study”, Thin-Walled Structures, Vol. 4, No. 3, pp 203-222, 1986

ABSTRACT: The effect of the number and size of rings on the buckling strength of ring-stiffened cylinders is studied experimentally. The results of ten machined ring-stiffened cylinders subjected to lateral pressure are presented. Five of the cylinders failed by the general instability mode and the rest failed by the shell instability mode. A sample of the experimental results which shows longitudinal and circumferential strains as well as the development of the circularity contours till collapse is presented. Buckling pressures obtained from the experiments are shown to be within ±30% of the corresponding value obtained from the theoretical analysis available in the literature.


ABSTRACT: The effect of initial imperfections on the elastic-buckling behaviour of ring-stiffened cylinders
under external pressure is examined using the potential energy approach. Experimental results in the open literature of four ring-stiffened cylinders tested under external pressure were used to compare and verify the theoretical analysis. Both the theoretical and experimental results indicate no apparent influence of initial imperfections on the buckling behaviour within the elastic range. This was so in spite of the presence of an appreciable amount of initial imperfections. The results from this work indicate that less stringent requirements in the manufacturing of ring-stiffened cylinders may be tolerated, leading to possible economy.


ABSTRACT: A numerical study using the finite element method has been carried out to investigate the response of composite shells with cutouts subjected to internal pressure and axial compression. The CAE package ABAQUS, has been employed for the analysis. The buckling and post-buckling responses in a series of shells with different size cutouts are presented. The numerical results show that the buckling load decreases as the size of the cutout is increased and the buckling load increases as the internal pressure is increased. Results also show that for the equivalent cutout areas the cutout with higher width (measurement in the circumferential direction) creates a lower buckling load. The results indicate that the response of a compression loaded cylinder with a cutout is influenced by the internal pressure, cutout area and orientation.

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ABSTRACT: Finite element models were developed to study global, local and mixed mode buckling behaviour of composite plates with embedded delaminations under compression. The global modelling results were compared with corresponding experimental results. It is shown that the numerical results for embedded delaminations agree very well with the experimental results, whereas the difference between the results was high for delaminations located at the edge of the plates. It is also shown that at lower loading levels the interaction of global and local buckling is negligible. At higher loading levels the strain energy release rate distribution and the delamination growth potential at the delamination front strongly depend on the shape of the debonded region and the local buckling mode. It was observed that the local buckling mode was highly influenced by the laminate stacking sequence. In the course of global buckling, a parametric study was carried out to investigate the influence of the delamination size, shape and alignment of a series of composite plates.


ABSTRACT: Composite cylindrical shells and panels are widely used in aerospace structures. These are often
subjected to defects and damage from both in-service and manufacturing events. Delamination is the most important of these defects. This paper deals with the computational modelling of delamination in isotropic and laminated composite cylindrical shells. The use of three-dimensional finite elements for predicting the delamination buckling of these structures is computationally expensive. Here combined double-layer and single-layer of shell elements are employed to study the effect of delamination on the global load-carrying capacity of such systems under axial compressive load. It is shown that through-the-thickness delamination can be modelled and analysed effectively without requiring a great deal of computing time and memory. A parametric study is carried out to study the influence of the delamination size, orientation and through-the-width position of a series of laminated cylinders. The effect of material properties is also investigated. Some of the results are compared with the corresponding analytical results. It is shown that ignoring the contact between the delaminated layers can result in wrong estimations of the critical buckling loads in cylindrical shells under compressive load.


ABSTRACT: Composite cylindrical shells and panels are widely used in aerospace structures. These are often subjected to defects and damage from both in-service and manufacturing events. Delamination is the most important of these defects. This paper deals with the computational modelling of delamination buckling and postbuckling of laminated composite cylindrical shells subjected to external pressure. The use of three-dimensional finite elements for predicting the delamination buckling and postbuckling of these structures is computationally expensive. Here, the combined double-layer and single-layer of shell elements are employed to study the effect of delamination on the global load-carrying capacity of such systems under external pressure. It is shown that through-the-thickness delamination can be modelled and analysed effectively without requiring a great deal of computing time and memory. A parametric study is carried out to investigate the influence of the delamination size, orientation and through-the-thickness position of a series of laminated cylinders. The effects of material properties and stacking sequence are also investigated. Some of the results are compared with the corresponding analytical results. It is shown that ignoring the contact between the delaminated layers can result in wrong estimations of the critical buckling loads in cylindrical shells under external pressure.

Azam Tafreshi (Aerospace Engineering, School of Mechanical, Aerospace and Civil Engineering (MACE), The University of Manchester, P.O. Box 88, Sackville Street, Manchester M60 1QD UK), “ Delamination buckling and postbuckling in composite cylindrical shells under combined axial compression and external pressure”, Composite Structures, Vol. 72, No. 4, April 2006, pp. 401-418, doi:10.1016/j.compstruct.2005.01.009

ABSTRACT: A series of finite element analyses on the delaminated composite cylindrical shells subject to combined axial compression and pressure are carried out varying the delamination thickness and length, material properties and stacking sequence. Based on the FE results, the characteristics of the buckling and postbuckling behaviour of delaminated composite cylindrical shells are investigated. The combined double-layer and single-layer of shell elements are employed which in comparison with the three-dimensional finite elements requires less computing time and space for the same level of accuracy. The effect of contact in the buckling mode has been considered, by employing contact elements between the delaminated layers. The interactive buckling curves and postbuckling response of delaminated cylindrical shells have been obtained. In the analysis of post-buckled delaminations, a study using the virtual crack closure technique has been performed to find the distribution of the local strain energy release rate along the delamination front. The results are compared with the previous results obtained by the author on the buckling and postbuckling of delaminated composite cylindrical shells under the axial compression and external pressure, applied individually.
Azam Tafreshi and Colin G. Bailey (School of Mechanical, Aerospace and Civil Engineering, MACE, The University of Manchester, P.O. Box 88, Sackville Street, Manchester M60 1QD, UK), “Instability of imperfect composite cylindrical shells under combined loading”, Composite Structures, Vol. 80, No. 1, September 2007, pp. 49-64, doi:10.1016/j.compstruct.2006.02.031

ABSTRACT: A numerical study using the non-linear finite element analysis has been carried out to investigate the response of composite cylindrical shells subject to combined loading. The interaction buckling curves of perfect composite cylinders subject to different combinations of axial compression, torsion, bending and lateral pressure are obtained. The postbuckling analysis of composite cylinders with geometric imperfections of eigenmode-shape is carried out to study the effect of imperfection amplitude on the critical buckling load. The initial buckling load of composite shells is substantially reduced by the existence of imperfections. Here it is shown that the effects of imperfections are more apparent when the composite cylindrical shells are subject to combined loadings. The results show that the buckling and non-linear response of geometrically imperfect shell structures subjected to complex loading conditions may not be characterized correctly by an elastic linear bifurcation buckling analysis.

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delaminated layers. The interactive buckling curves and the three method. The combined double shells subject to pure bending and also combined bending and axial compression, using the finite element important of these defects. This paper deals with the instability analysis of delaminated composite cylindrical shells under combined axial compression and bending, AIAA Journal, 1996; 34(11), 2406-2413


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ABSTRACT: Composite cylindrical shells and panels are widely used in aerospace structures. These are often subjected to defects and damage from both in-service and manufacturing events. Delamination is the most important of these defects. This paper deals with the instability analysis of delaminated composite cylindrical shells subject to pure bending and also combined bending and axial compression, using the finite element method. The combined double-layer and single-layer of shell elements are employed, which in comparison with the three-dimensional finite elements requires less computing time and space for the same level of accuracy. The effect of contact in the buckling mode has been considered, by employing contact elements between the delaminated layers. The interactive buckling curves and postbuckling response of delaminated cylindrical shells
have been obtained. In the analysis of post-buckled delaminations, a study using the virtual crack closure technique has been performed to find the distribution of the strain energy release rate along the delamination front. The results show that under pure bending, laminated cylindrical shells are more sensitive to the presence of delamination, than they are under pure axial compression. It was also observed that the effects of delamination are more apparent when the composite cylindrical shells are subjected to combined axial compression and bending. In this case, with a slight increase of the applied bending moment, the strain energy release rate distribution on the compressive side of the cylinder changes drastically.

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ABSTRACT: Improved numerical models have been developed for predicting the compressive strength of impact-damaged sandwich composites comprised of woven-fabric graphite-epoxy facesheets and Nomex honeycomb cores. The proposed methodology contains three key elements: (1) the use of nondestructive inspection estimates of damage, (2) the incorporation of nonlinear through-the-thickness core-crush constitutive response to account for core failure, and importantly (3) the simulation of progressive loss of facesheet structural integrity based upon userspecified ply failure criteria. The finite element predictions of residual strength for panels impacted with relatively blunt objects correlate well with the experimental observations; this is in contrast to a number of estimates from literature that tend to overestimate the strength. The proposed approach may potentially facilitate sandwich design by providing insight into the relationships between material configuration and damage that lead to improved damage tolerance characteristics.

ABSTRACT: Nonlinear vibration and postbuckling behavior of a single layer graphene sheet (SLGS) embedded in a polymer matrix aroused by the nonlinear van der Waals (vdW) forces are investigated using the Kirchhoff plate theory. The interfacial vdW forces are described by a nonlinear function in terms of the graphene deflection. Through harmonic balance method, the nonlinear relation between deflection amplitudes and resonant frequencies of free vibrations of the SLGS and its postbuckling equilibrium path are derived. It is found that variation of resonant frequencies of an embedded SLGS is less dependent on the graphene aspect ratio and mode numbers as compared with a free-standing one. In-plane load effects upon the vibrational behavior of the SLGS and its postbuckling are also discussed. Simulation results have demonstrated the significance of considering the surrounding medium effect and its nonlinearity in the study of the vibration and buckling of the embedded graphene with applications in nanocomposites.
References listed at the end of the paper:
(hard to cut and paste)

ABSTRACT: Recent research studies on the application of the nonlocal continuum theory in modeling of carbon nanotubes and graphene sheets are reviewed, and substantial nonlocal continuum models proposed for static and dynamic analyses of the nano-materials are introduced. The superiority of the nonlocal continuum theory to its local counterpart, and the necessity of calibration of the small-scale parameter as the key parameter revealing small-scale effects are discussed. The nonlocal beam, plate, and shell models are briefly presented and potential areas for future research are recommended. It is intended to provide an introduction to the development of the nonlocal continuum theory in modeling the nano-materials, survey the different nonlocal continuum models, and motivate further applications of the nonlocal continuum theory to nano-material modeling.

References listed at the end of the paper:
ABSTRACT: A systematic parametric study was carried out to investigate the elastic and elastic-plastic buckling behaviors of imperfect steel shell subject to axial compression and internal pressure. Studied parameters include the magnitude of internal pressure, steel strength, and ratio of cylinder radius to shell thickness. Design equations were proposed for calculating the elastic and elastic-plastic buckling strength of imperfect steel shells under combination of axial compression and internal pressure. The buckling strength predicted by proposed equations agrees well with that from the numerical simulation.
References listed at the end of the paper:

ABSTRACT: A hybrid continuum mechanics and molecular mechanics model is developed in this paper to predict the critical strain, stress, and buckling load of the inelastic buckling of carbon nanotubes. With the proposed model, the beamlike and shell-like buckling behavior of carbon nanotubes can be analyzed in a unified approach. The buckling solutions from the hybrid model are verified from molecular dynamics simulations via the MATERIALS STUDIO software package and from available research findings. The existence of the optimum diameter, at which the buckling load reaches its maximum, and the correlation of the diameter with the length of carbon nanotubes, as predicted by Liew (2004, “Nanomechanics of Single and Multiwalled Carbon Nanotubes,” Phys. Rev. B, 69(11), pp. 115429), are uncovered by the hybrid model. The simplicity and effectiveness of the proposed model are not only able to reveal the chiral and size-dependent buckling solutions for carbon nanotubes, but also enable a thorough understanding of the stability behavior of carbon nanotubes in potential applications.

ABSTRACT: Elastic buckling of layered/fibre reinforced composites is investigated. Assuming the existence of both shear and transverse modes of failure, the fibre is analysed as a layer embedded in a matrix. Interacting stresses, acting at the interfaces are determined from an exact derived stress field in the matrix. It is shown that buckling can occur only in the shear buckling mode and that the transverse buckling mode is spurious. As opposed to the well known Rosen shear buckling mode solution (predicated on an infinite buckling wavelength), shear buckling is shown to exist under two regimes: buckling of dilute composites with finite wavelengths and buckling of non-dilute composites with infinite wavelengths. Based on the analysis, a model is constructed which defines the fibre concentration at which the transition between the two regimes occurs. The buckling strains are shown to be (approximately) constant for dilute composites and, in the case of very stiff fibres, to have realistic values compatible with elastic behaviour. For the case of non-dilute composites, the strains are found to be in agreement with those given by the Rosen shear buckling solution. Numerical results for the buckling strains and stresses are presented and compared with the Rosen solution. These reveal that the Rosen solution is valid only for the case of non-dilute composites. The investigation demonstrates that elastic buckling may be a dominant failure mechanism of composites consisting of very stiff fibres fabricated in the framework of nano-technology.

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ABSTRACT: Based on nonlocal theory of thermal elasticity mechanics, an elastic multiple column model is developed for column buckling of MWNTs with large aspect ratios under axial compression coupling with temperature change. The present model treats each of the nested tubes as an individual column interacting with adjacent nanotubes through the intertube van der Waals forces. The thermal effect is incorporated in the formulation. In particular, an explicit expression is derived for the critical axial strain of a double-walled carbon nanotube which clearly demonstrates that small scale effects contribute significantly to the thermo-mechanical behavior of multiwalled carbon nanotubes and cannot be ignored.

References listed at the end of the paper:
ABSTRACT: In this paper, static bending and buckling of a functionally graded (FG) nanobeam are examined based on the nonlocal Timoshenko and Euler-Bernoulli beam theory. This non-classical (nonlocal) nanobeam model incorporates the length scale parameter (nonlocal parameter) which can capture the small scale effect. The material properties of the FG nanobeam are assumed to vary in the thickness direction. The governing equations and the related boundary conditions are derived using the principal of the minimum total potential energy. The Navier-type solution is developed for simply-supported boundary conditions, and exact formulas...
are proposed for the deflections and the buckling load. The effects of nonlocal parameter, aspect ratio, various material compositions on the static and stability responses of the FG nanobeam are discussed. Some illustrative examples are also presented to verify the present formulation and solutions. Good agreement is observed. The results show that the new nonlocal beam model produces larger deflection and smaller buckling load than the classical (local) beam model.

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[67] Słimszeń M. Fundamental frequency analysis of functionally graded beams by using different higher-order beam theories. Nucl Eng Des 2010;240:697–705.
ABSTRACT: Nonlocal elasticity theory is a popular growing technique for the mechanical analyses of MEMS and NEMS structures. The nonlocal parameter accounts for the small-size effects when dealing with nano-size structures such as single-walled carbon nanotubes (SWCNTs). In this article, nonlocal elasticity and Timoshenko beam theory are implemented to investigate the stability response of SWCNT embedded in an elastic medium. For the first time, both Winkler-type and Pasternak-type foundation models are employed to simulate the interaction of the (SWCNT) with the surrounding elastic medium. A differential quadrature approach is utilized and numerical solutions for the critical buckling loads are obtained. Influences of nonlocal effects, Winkler modulus parameter, Pasternak shear modulus parameter and aspect ratio of the SWCNT on the critical buckling loads are analyzed and discussed. The present study illustrates that the critical buckling loads of SWCNT are strongly dependent on the nonlocal small-scale coefficients and on the stiffness of the surrounding medium.

ABSTRACT: In this paper, the thermal buckling behavior of single-walled carbon nanotubes (SWCNTs) embedded in an elastic medium is studied. To this end, the SWCNTs are modeled based on the nonlocal Timoshenko beam theory into which the effect of the elastic medium is incorporated. The generalized differential quadrature (GDQ) method is employed to discretize the governing differential equations and to consider different commonly used boundary conditions (BCs). For simply supported BCs, the results obtained from the present analysis are compared with the ones from the exact solution and an excellent agreement has been achieved. The effects of the aspect ratio, nonlocal parameter and the Winkler parameter on the dimensionless critical buckling temperature are carefully investigated.

ABSTRACT: In this article, a semi-analytical finite element approach based on the nonlocal elastic shell model is proposed to study the thermal buckling of multiwalled carbon nanotubes (MWCNTs). By taking nonlocality into consideration, the small scale effect is incorporated into the model presented herein. Based upon the Eringen nonlocal elasticity, the displacement field equations coupled by the van der Waals interaction force are derived. Comprehensive results for the thermal buckling of multiwalled carbon nanotubes are given. The influences of the small scale parameter and boundary conditions on the thermal instability of MWCNTs are examined. It is indicated that the possibility of the radial buckling mode of deformation due to radially elevated temperature is significantly higher than that of axial buckling mode of deformation due to uniformly reduced temperature when carbon nanotubes experience thermal loads.

R. Ansari and M. Hemmatnezhad (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Nonlinear finite element analysis for vibrations of double-walled carbon nanotubes”,

ABSTRACT: The large-amplitude free vibration analysis of double-walled carbon nanotubes embedded in an elastic medium is investigated by means of a finite element formulation. A double-beam model is utilized in which the governing equations of layers are coupled with each other via the van der Waals interlayer forces. Von-Karman type nonlinear strain-displacement relationships are employed where the ends of the nanotube are constrained to move axially. The amplitude-frequency response curves for large-amplitude free vibrations of single-walled and double-walled carbon nanotubes with arbitrary boundary conditions are graphically illustrated. The effects of material constant of the surrounding elastic medium and the geometric parameters on the vibration characteristics are investigated. For a double-walled carbon nanotube with different boundary conditions between inner and outer tubes, the nonlinear frequencies are obtained apparently for the first time. Comparison of the results with those from the open literature is made for the amplitude free vibration analysis of double walled carbon nanotube ropes. The large amplitude free vibration analysis of double walled carbon nanotube ropes.

References listed at the end of the paper:


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ABSTRACT: Silicon carbide nanotubes possess outstanding properties which enable them to have many applications. The buckling behaviour of silicon carbide nanotubes have been studied here. To do this, a 3D finite element method, known as space frame model has been proposed. Molecular mechanics are linked to density functional theory to derive the properties of this finite element method. It has been shown that the critical buckling force will diminish with increasing aspect ratio. Also, it is represented that increasing the aspect ratio will result in reducing the effect of boundary conditions.


ABSTRACT: A size-dependent finite element (FE) formulation including surface free energy effect is developed in this article to study the post-buckling behavior of nanofilms under the action of thermal loads. The Gurtin-Murdoch surface elasticity theory is utilized to consider the surface effects. Moreover, the principle of virtual work is used so as to derive the equilibrium equations. The proposed FE formulation is based on the first-order shear deformation theory (FSDT). The von Kármán nonlinear relations are also employed to take the geometric nonlinearity into account. After deriving the FE equations, the resulting set of parameterized non-
linear equations is solved using the pseudo arc-length continuation algorithm, and bifurcation diagrams of nanofilms are obtained. Selected numerical results are presented for the influences of surface stress on the thermal post-buckling characteristics of nanofilms subject to different types of boundary conditions.


ABSTRACT: The main goal in this investigation is optimization of two, four, eight and twelve layer shells in order to identify optimized fiber angle in different layers aiming maximizing critical load. In order to identify critical load parameter, a hybrid approach including Finite Element Method (FEM) and Neural Networks (NN) is employed. To achieve the above results, required data for NN is supplied by FEM and the appropriate network is trained. For optimization of obtained function, Genetic Algorithm (GA) is utilized. In this case, GA is also employed over and over in order to obtain the effect of different parameters. Furthermore, existence of several close optimized points and interactions among layers, critical load and fiber angle are discussed.


ABSTRACT: This paper describes an analytical tool for the design of thin-wall tubes for passage through minimal radius of curvature trajectory. The design is based on a model of thin-wall tube buckling under pure bending. An extended analytical solution for general initial cross section is found based on Brazier method by energy theory of elastic stability. The model predicts the critical moment, curvature, flattening, and stress and allows choosing the most suitable cross section shape for a specific purpose. For example, tubes with ocular and rounded-ocular cross sections were found suitable for semiflexible applications such as endoscopy, where they elastically cross a sharp corner.


ABSTRACT: Composite materials thin-walled structures are widely used as skin panel in flight vehicles in recent years. These structures will encounter severe complex loading conditions, which may be a combination of mechanical, aerodynamic, thermal and acoustic loads. Thin-walled structures subjected to this kind of loadings will exhibit nonlinear response; as a result, fatigue failure will occur. High temperature may cause large thermal deflection and stress, for some special conditions, may cause thermal buckling. Once the thermal buckling appears, the stiffness will change correspondingly, it will cause significant influence on the dynamic response and fatigue failure. Accordingly, it is important to research the nonlinear response of this kind of structures under elevated thermal environment. Nonlinear response and thermal pre-buckling/post-buckling behavior of a Graphite-Epoxy composite plate subjected to server thermal loading is numerically investigated in this paper. A composite laminated plate with clamped-clamped boundary conditions is chosen as simulated body, nonlinear finite element model is developed using the first-order shear deformable plate theory, Von Karman strain-displacement relations, and the principle of virtual work. The thermal load is assumed to be a steady-state with different predefined temperature distribution. The thermal strain is stated as an integral quantity of the thermal expansion coefficient with respect to temperature. Then the modes of the plate are analyzed, the nature frequencies and modal shapes are obtained. The critical temperature of buckling is calculated. The static nonlinear equations of motions are solved by the Newton-Raphson iteration technique to
obtain the thermal post-buckling deflection. The Riks method is used to analyze static post-buckling behavior. In the numerical examples, four types of situations are studied, which include i) the buckling behaviors for different initial imperfections, ii) the buckling behaviors for different thickness to width ratios, and iii) The buckling behaviors for different width to length ratios; The critical temperature, the static thermal post-buckling deflection and the load to displacement relation are presented respectively. The influences of different boundary conditions on the buckling behaviors of the plate are achieved as well. The simulation method and results presented in this paper can be valuable references for further analysis of the nonlinear responses of thin-walled structures under complex loading conditions.

ABSTRACT: In this study, a new technique based on Ritz method is developed for damage detection of the circular cylindrical shell structures. Sander's thin shell theory in association with the Ritz method is used to analyze the dynamic behaviour of circular cylindrical shells. By equating the strain and kinetic energy mathematically, the eigenvalue problem is solved which will give the natural frequencies of the circular cylindrical shell. The crack damage on the shell surface is modelled by a line spring along the circumference of the shell. Different damage scenarios are simulated by the changes of the crack locations and spring stiffness. The location and extent of the damage are predicted by the changes of modal parameters. Numerical simulations show that the method is effective and accurate to determine the crack damage in the cylindrical shell structures.

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ABSTRACT: The feasibility of replacing substructure and component testing by analytical "virtual testing" is addressed here for composite structures. The special difficulties in estimating the failure loads of composite structures are described, especially when initiation starts from a local stress concentration. Damage may initiate and then propagate, but final failure can occur at loads significantly higher than that for initiation. The separate modes of in-plane (fibre-dominated) and delamination (matrix dominated) are shown to need different strength and fracture strategies. Several examples are chosen of realistic structures, ranging from notches through to stiffened compression panels, starting with the easiest (in-plane dominated) and finishing with the most difficult mixed in-plane and debonding case.

References listed at the end of the paper:

PARTIAL INTRODUCTION: The problem of impact damage in laminated composite structures, and the
consequent reduction in residual strength, has been a topic of continual research for over two decades. The number of journal papers on the subject now runs into four figures and most have been conscientiously reviewed by Abrate (1991, 1994, 1998). This review is not intended to be in the academic tradition, with emphasis on acknowledging the authorship of all the various research initiatives. Instead we present our opinions so that the reader can appreciate our current understanding of the problem, our capability of predicting by analysis, and the scope of the design tools for avoiding structural damage, or at least designing damage tolerant aerospace structures. There are two types of impact, namely that when a foreign body strikes a structure, or in contrast that when a complete aircraft or helicopter suffers a crash landing of some sort. This latter case is usually discussed as ‘crashworthiness’ and has become a routine feature of automobile design where the energy-absorbing properties of ductile metals are exploited to the full. The objective here is to design a structure which can deform and absorb energy but leave the passenger compartment more or less intact.

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TÜRK, M.H. and HOO FATT, M.S. Localized damage response of composite sandwich plates, Composites Part B, 1999, 30, (2), pp

ABSTRACT: This paper reviews work at the Aeronautical Research Institute of Sweden, and addresses major issues of importance in evaluating the effect of impact on composite structures. Some more extensive reviews of work by other researchers are referenced. The paper addresses impact response and damage formation, damage characterization, and residual strength and stability by combination of experiments and analysis. Studies showing that impact response type depends on impactor-plate mass ratio are presented. Small mass impact is generally more critical at a given configuration and energy. Analytical models for small mass impact and for damage initiation and growth during large mass impact are discussed. Rate dependency of matrix-dominated properties is briefly discussed. Geometric and constitutive characterization of impact damage zones is presented and the influence of degraded properties demonstrated. The use of an FE-based plate model to simulate delamination growth due to sublaminate buckling and panel skin buckling in stiffened panels after impact is described. Skin buckling causes a steep increase in delamination strain energy release rate and should
be prevented.

ABSTRACT: This paper examines the effect of impact damage on local tensile stiffness of multi-directional tape laminates. A finite element model is used for parametric studies of the effect of various patterns of delaminations and cracks across the fibres. Regular and random crack patterns are considered for 8 and 16 ply quasi-isotropic laminates. The effect on local stiffness is evaluated by a recently developed inverse numerical approach. It is found that fibre cracks control the loss of stiffness but that delaminations are instrumental in extending the zone influenced by these cracks. Fractographic observations are finally used to generate a detailed model of the damage in a real laminate. A close agreement was found between the predicted and measured strain fields and the corresponding stiffness distributions obtained with the inverse method.

ABSTRACT: This paper examines the compressive behaviour of plies with fibres previously fractured during impact. The analysis is conducted using finite element (FE) modelling in ABAQUS 6.7. Two- and three-dimensional models are used to consider the possibility of fibre penetration and “brooming” of fractured fibres, or fibre buckling. A parametric study of the influence of the input parameters of the Drucker Prager plasticity model was also conducted, to enable a better understanding of the model. This was used to capture the triaxial stress state in the matrix surrounding the fibres. The results suggest that fibre buckling is more likely to occur due to the geometry of fibres and fibre spacing in carbon fibre composites, but fibre penetration could still occur in regions of low fibre volume fraction.

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ABSTRACT: This paper presents a finite element model of a carbon fibre composite laminate with multiple delaminations of realistic shape and including fibre fracture cracks loaded under compression. The modelling technique is initially applied on circular and elliptical delaminations of single ply sublaminates, which are compared with existing analytical solutions. The techniques are then applied to models with multiple delaminations of realistic shape and their behaviour in buckling and post-buckling is captured. An inverse method is used to determine the stiffness reduction caused by the damage, and shows significant stiffness reduction caused by peanut shaped delaminations. When fibre fracture cracks are added, their contribution to further stiffness reduction is minimal but they have some significant effects on the buckling shapes.

ABSTRACT: The possibility to accurately analyse the buckling and postbuckling behaviour of plates with delaminations of irregular shapes by utilisation of circular or elliptic delaminations was studied. The behaviour of compressed plates with delaminations of irregular and corresponding smallest enclosing circular and elliptic shapes was predicted by computational analyses and compared in terms of buckling loads and maximum values of the energy release rates found along the delamination boundaries. The study indicates that utilisation of circular delaminations could provide highly inaccurate results. Moreover, for truly accurate analyses of the buckling and postbuckling behaviour of delaminated structures it seems to be inevitable to use as precise representation of the shape of delaminations as possible.


ABSTRACT: The issues, problems and techniques concerning the optimization of laminated composites are discussed and specific cases of design optimization are presented. After a general introduction to methods of optimization of composites with emphasis on genetic algorithms, a discussion of design and decision variables is given and problem complexities are highlighted. This is followed by specific examples of composites design under deterministic conditions, and in particular, stiffness and strength optimization, thermal buckling, and optimization with multiple objectives are studied. The design uncertainties are the subject of the separate chapter where design optimization techniques such as convex modeling and anti-optimization are illustrated again by means of specific examples involving uncertain material, load and geometric data. Section 6 provides an overview of the properties and applications of widely used smart materials which is followed by some specific examples of the use of smart materials in vibration control and composite design applications. It is noted that sections 1-5 (except the material on genetic algorithms) are an abridged version of the material in Adali (2003) which is being published in these Lecture Notes with the permission of CRC Press.


ABSTRACT: A variational principle for microtubules subject to a buckling load is derived by semi-inverse method. The microtubule is modeled as an orthotropic shell with the constitutive equations based on nonlocal elastic theory and the effect of filament network taken into account as an elastic surrounding. Microtubules can carry large compressive forces by virtue of the mechanical coupling between the microtubules and the surrounding elastic filament network. The equations governing the buckling of the microtubule are given by a system of three partial differential equations. The problem studied in the present work involves the derivation of the variational formulation for microtubule buckling. The Rayleigh quotient for the buckling load as well as the
natural and geometric boundary conditions of the problem is obtained from this variational formulation. It is observed that the boundary conditions are coupled as a result of nonlocal formulation. It is noted that the analytic solution of the buckling problem for microtubules is usually a difficult task. The variational formulation of the problem provides the basis for a number of approximate and numerical methods of solutions and furthermore variational principles can provide physical insight into the problem.

References listed at the end of the paper:


ABSTRACT: Apparent controversies exist on whether the persistence length of microtubules depends on its contour length. This issue is particularly challenging from a theoretical point of view due to the tubular structure and strongly anisotropic material property of microtubules. Here we adopt a higher order continuum orthotropic thin shell model to study the flexural behavior of microtubules. Our model overcomes some key limitations of a recent study based on a simplified anisotropic shell model and results in a closed-form solution for the contour-length-dependent persistence length of microtubules, with predictions in excellent agreement with experimental measurements. By studying the ratio between their contour and persistence lengths, we find that microtubules with length at ~1.5 μm show the lowest flexural rigidity, whereas those with length at ~15 μm show the highest flexural rigidity. This finding may provide an important theoretical basis for understanding the mechanical structure of mitotic spindles during cell division. Further analysis on the buckling of microtubules indicates that the critical buckling load becomes insensitive to the tube length for relatively short microtubules, in drastic contrast to the classical Euler buckling. These rich flexural behaviors of microtubules are of profound implication for many biological functions and biomimetic molecular devices.


ABSTRACT: The best layup for a hybrid laminated cylindrical shell subject to a buckling load constraint is determined. The objective of the optimisation is the minimum weight design of these structures. The ply angle is taken as the design variable. Various configurations of graphite and boron epoxy layers are considered in order to determine an optimal stacking sequence. The symbolic computational software package MATHEMATICA is used in the implementation and solution of the problem. This approach simplifies the computational procedure as well as the implementation of the analysis/optimisation routine. Results are given illustrating the dependence of the optimal layup on the cylinder length and radius. It is shown that a general
purpose computer algebra system like MATHEMATICA is well suited to solve structural design problems involving composite materials.

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ABSTRACT: The optimal design of a laminated cylindrical shell is obtained with the objectives defined as the maximisation of the axial and torsional buckling loads. The ply angle is taken as the design variable. The symbolic computational software package MATHEMATICA is used in the implementation and solution of the problem. This approach simplifies the computational procedure as well as the implementation of the analysis/optimisation routine. Results are given illustrating the dependence of the optimal fiber angle on the cylinder length and radius. It is shown that a general purpose computer algebra system like MATHEMATICA is well suited to solve small boundary value problems such as structural design optimisation involving composite materials.

P.M.Weaver (Department of Aerospace Engineering, University of Bristol, Queens Building, University Walk, Bristol, BS8 1TR,UK), “Computer-Aided Laminate Selection Using a Graphical Method”, ICCM12, Paris, France, 1999,
ABSTRACT: This paper introduces a methodology for selection of laminates. Software that implements these ideas is also presented. Optimisation of laminate fibre angles is difficult for multiple load cases and objectives—there are many local minima to assess. An alternative approach is presented here that circumvents the need for conventional optimisation strategies that often prove difficult and complicated to implement. The basic idea is to build a database that stores appropriate properties of all permutations of lay-up angles for a laminate. Rather than access these properties by a question and answer, black-box technique, a graphical method is introduced. The designer can select viable laminates by first plotting a succession of 2-D charts containing relevant properties. Then, using simple on-screen techniques, the number of potential laminates is visually reduced by selecting those with desirable properties. The optimisation of a cylindrical shell, subject to axial compression, that undergoes simultaneous Euler-type buckling and local buckling is examined.

References listed at the end of the paper:
11. Weaver, P.M. “Design of Optimal Laminated Composite Cylindrical Shells under Axial Compression”, to be published, 1999
ABSTRACT: Approximate expressions describing shape efficiency are derived and two charts are shown that help with design. The first is a failure chart that shows the complete set of possible designs (and lay-ups) that allow the complexity of the problem to be presented in a simple way. The second is a chart showing optimal lay-ups for a cylindrical shell subject to axial compression. The load-bearing efficiency of cylindrical shells derives from both the properties of the material of which they are made and from the shape itself. Generally, thin-walled or slender shapes are more efficient (meaning lighter and more economical in the use of material) than thick-walled or solid sections. The limit in shape efficiency is either set by manufacturing constraints or, ultimately, by the properties of the material from which it is made. Laminated composite materials are more difficult to analyse than conventional isotropic materials, such as aluminium alloys, because of the additional need to consider the variation of ply orientation through the thickness of the laminate. These ultimate limits are examined and determined by a balance between competitive failure mechanisms.

ABSTRACT: The study of axial compression buckling of isotropic cylinders has received much attention by various researchers over the years. It is commonly acknowledged that the presence of minute imperfections reduces potential buckling loads significantly in comparison with classical linear predictions. This approach has been extended by a significant, yet fewer, number of researchers to composite cylindrical shells. It is shown that imperfections may not be the only major factor for the discrepancy between experimentally obtained buckling loads and those predicted from linear bifurcation theory with orthotropic properties. Flexural/twist anisotropy, present in most balanced, symmetric laminates with angle ply layers is shown to play a significant role in reducing buckling loads from those classically predicted. Indeed, the assumption of deflections in the form of a double sine series appears to be questionable for such laminates. A previously unreported classical linear analysis including the effect of flexural/twist coupling is developed. Backed up by detailed comparison with finite element studies, it is shown that buckling loads can be reduced by up to 30% for a class of quasi-isotropic laminates and is accompanied by a change in mode form from doubly periodic to spiral in nature.

ABSTRACT: This paper addresses two aspects of buckling relevant to design. The first describes the preliminary experimental results that validate the presence of a newly reported spiral buckling mode; whilst the second concerned the effects of extension/twist anisotropy on the buckling loads of cylindrical shells under compression. The influence of designing laminates with antisymmetric lay-ups in comparison with a symmetrical lay-up is also investigated. Antisymmetric quasi-isotropic laminates, based on 0, 90 and ±45° angles produces greater buckling loads than the equivalent symmetric lay-up. Whilst all anisotropic coupling effects appear to lower the buckling loads, a laminate that is 48 plies thick is necessary to eliminate them in thin-walled shells. Such a laminate is at least 6 mm thick. Many designs require thinner laminates, and in so doing, mitigate the need for guidelines on efficient anisotropic lay-ups. Neglecting the effect of prebuckling
deformation, it is found that extension/twist coupling is less deleterious than flexural/twist coupling in this respect. Therefore, antisymmetric laminates appear preferable for initial buckling of quasi-isotropic laminates.


ABSTRACT: It is widely recognised that the optimal lay-up to resist classical local buckling of a laminated cylindrical shell subject to compression loading is one that is quasi-isotropic in nature. This ideal is difficult to achieve in practice due to manufacturing and additional design constraints. The minimum number of unidirectional layers, based on 0°, 90°, ±45° angles, is 48 – an example lay-up is shown. Balanced and symmetric laminates, that exhibit quasi-isotropic properties in-plane, are shown to give reduced buckling capacity depending on two factors. The first concerns the overall homogeneity of the laminate whilst the second is a function of the amount of flexural/torsional coupling. The former is shown to have the greater influence. In the absence of closed-form solutions these effects have been numerically quantified using finite element (FE) analysis techniques. Practical design guidelines are deduced.


ABSTRACT: The use of high-performance composite materials of the sort used in the aerospace and Formula 1 industries is becoming more widespread. On one level they are exciting to work with because they give scope for designing the 'material' in addition to a 'structure' through judicious placement of the ply orientation. Layers are stiff and strong in the fibre direction while weak and compliant in the transverse direction. It is this ability to tailor material properties layer by layer that gives designers huge potential in design. One possible explanation for the prevalent use of quasi-isotropic ('black aluminium') carbon composites in structures is the lack of available design tools. Analysis packages exist that will predict performance, but only for a given choice of fibre orientation. Here a design tool is presented that aids selection of fibre orientations. Optimization of laminate fibre angles is difficult for multiple-load cases and objectives since there are many local minima to assess. The alternative approach that is presented here, for flat plates and cylindrical shells, circumvents the need (in the early stages of design) for conventional optimization strategies that often prove difficult and complicated to implement. The basic idea is to build a database that stores appropriate properties of all permutations of lay-up angles for a laminate. Rather than access these properties by a question and answer, black-box technique, a graphical method is proposed. The designer can select viable laminates by first plotting a succession of two-dimensional charts containing relevant properties. Then, using simple on-screen techniques, the number of potential laminates is visually reduced by selecting those with desirable properties. Two case studies are presented to illustrate the selection method. The first concerns the optimization of a spar web, typically found in an aircraft wing structure, while the second concerns the optimization of a cylindrical shell, subject to axial compression, that undergoes simultaneous Euler-type buckling and local buckling.

P. M. Weaver (Department of Aerospace Engineering, University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK), “On laminate selection and design”, AIAA-2002-1220,
ABSTRACT: Composite materials, at one level, are exciting to work with because they give scope for designing the "material" in addition to a "structure" through judicious placement of the orientation of plies. It is their ability to tailor material properties layer by layer that give designers huge potential in design. One possible explanation for the prevalent use of quasi-isotropic ("black aluminium") carbon composites in structures is the lack of available design tools. Here a design tool is presented that aids selection of fiber orientations.

Optimization of laminate fiber angles is difficult for multiple load cases and objectives—there are many local minima to assess. An alternative approach to complex/numerical optimization methods, is presented here. The basic idea is to build a database that stores appropriate properties of all permutations of lay-up angles for a laminate. The designer can select viable laminates by first plotting a succession of 2-D charts containing relevant properties. Then, using simple on-screen techniques, the number of potential laminates is visually reduced by selecting those with desirable properties. Two case studies are presented. The first concerns the optimization of a spar web, typically found in an aircraft wing structure whilst the second considers the optimization of a cylindrical shell, subject to axial compression, that undergoes simultaneous Euler-type buckling and local buckling.


ABSTRACT: This paper provides an analytical optimization of shell composition with respect to the critical Brazier moment, which will be useful in the design of structures where material failure and local buckling are not likely to occur. The optimum configuration for a tube under bending is independent of Poisson's ratio and largely invariant with $E_{11}$ and $E_{22}$ for common highly directional composite materials. The optimal ply configuration for typical composite tubes is found to be $90-0-90$ deg, with 62 percent 0-deg plies. Such a configuration increases the maximum bending moment in GFRP tubes by 42 percent compared to a quasi-isotropic configuration.


ABSTRACT: The study of axial compression buckling of isotropic cylinders has received much attention by various researchers over the years. It is commonly acknowledged that the presence of minute imperfections significantly reduces potential buckling loads in comparison with classical linear predictions. This approach, of including geometric imperfections, has been extended by a significant, yet fewer, number of researchers to composite cylindrical shells. As the current study shows, imperfections may not be the only major factor for the discrepancy between experimental and linear buckling loads. Flexural/twist anisotropy, present in most balanced, symmetric laminates with angle-ply layers, is shown to play a significant role in reducing buckling loads from those predicted by classical analysis. Indeed, the assumption of deflections in the form of a double sine series appears to be questionable for such laminates. A recently reported classically linear analysis that included the effects of flexural/twist coupling on buckling loads has been further developed to include the effects of extension/twist coupling. It is shown that buckling loads can be improved by making the laminate antisymmetric rather than symmetric, for the class of quasi-isotropic laminates, whilst retaining a spiral mode shape.

ABSTRACT: Work is presented to maximize the resistance of isotropic and orthotropic cylindrical tubes to the non-linear Brazier effect, by filling them with foam cores. Analytical approaches for the mass minimization of such structures, by optimizing shell wall thickness, ply lay-up and foam core density, are presented. The optimum configurations have been shown to have significant mass benefits compared to simple hollow tubes; the sample aluminum shell, aluminum foam core, tubes have been found to be up to 50 pct. lighter (for given Brazier failure bending moment) than their hollow equivalents. The optimization of foam filled orthotropic tubes has found that the increased resistance to the Brazier effect, provided by the foam core, can reduce the necessity for circumferentially oriented plies. The example 20mm radius tubes, CFRP shells with polymeric foam cores, showed theoretical reductions in mass, for given failure bending moments, of the order of 30 pct.. The optimization can readily be modified to accommodate alternative requirements, such as cost, to better reflect actual design criteria for real structures. Whilst it is noted that real structures rarely fail by the Brazier effect (material failure or local buckling generally precede it) this analysis will be of use to those seeking a minimization of non-linearities in the deformation of long hollow structures.


ABSTRACT: Long circular cylindrical shells may locally buckle at lower loads than those predicted by classical linear Donnell solutions due to long range interaction between Euler and local buckling. In fact, Euler buckling may be viewed as a special case of local buckling in which both the longitudinal and circumferential wave numbers are unity. This paper investigates this phenomenon for composite tubes as a function of lay-up. Tubes that are reinforced in predominantly the longitudinal or circumferential directions suffer the least knockdown of approximately 10% for tubes that are designed to buckle concurrently by Euler and local mechanisms. The greatest knockdown of approximately 35% occurs for isotropic laminates. The effect of material lay-up has been taken account of by forming a non-dimensional length parameter that is a function of both tube geometry and material properties. An interaction formula is proposed to help in design situations. References listed at the end of the paper:

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ABSTRACT: An approximate solution is given for the postbuckling of infinitely long and unsymmetrically laminated composite plates. This solution is obtained by superposing a polynomial transverse displacement given by bending due to unsymmetric laminate configurations and a simple functional representation for the buckling mode in conjunction with the Galerkin method. Nondimensional parameters are used to express the approximate solution in a very simple and clear formulation. The results given by this solution for axial compression in the longitudinal direction are compared with the results given by the nonlinear finite element method (FEM) for finite length rectangular long plates. The influence of the boundary conditions on postbuckling response is also studied. For the FEM analysis, two different simply supported boundary conditions on the long edges of the plate are considered. It is found that these two sets of boundary conditions give different results for the buckling and postbuckling finite element analysis. In most cases the FEM analysis overestimate and, respectively, underestimate the approximate closed form solution, depending on the type of simply supported boundary condition considered. Thus, the approximate solution appears useful for design purposes as an averaged quantity between the two FEM analyses. Also, it is found that the reduced bending stiffness method can be successfully used for determining the approximate solution.


ABSTRACT: In this paper an alternative design for variable sweep wings is investigated. It consists of a two-spar, CFRP (carbon fibres reinforced plastics) wing, with truss-like ribs. The spar-web is a shell structure laminated using an unsymmetric stack sequence in order to take advantage of the residual stress field developed during the curing process, resulting in increased transverse curvature of the spar. The effect of this curvature is twofold: to increase the moment of inertia to withstand bending stresses and, under certain loading conditions, to behave like an elastic hinge to allow the sweep angle of the wing to change.

References listed at the end of the paper:


ABSTRACT: A thin shell tube with different length to radius and radius to thickness ratios can buckle locally, globally or with interaction of local and global buckling. The current analysis is to study the dependency of the buckling load of a circular cylindrical shell on these ratios. Different theoretical shell models were used to predict the buckling load and the results were compared with finite element analysis. It was found that the buckling load decreases exponentially when the length to radius ratio increases and increases when the radius to thickness ratio increases. The length to radius ratio is crucial in determining whether the tube is in the local buckling, global buckling or interaction region. The extent of global buckling was predicted analytically using Sanders’ model, and was found to depend on the Poisson’s ratio of the material used. In addition, Loo’s model is found to be the best model in predicting the buckling load in the local buckling and interaction region to within 10% of the finite element results while the Sanders’ model converges to Euler buckling values in the global buckling region.


ABSTRACT: The need for aircraft that possess the ability to adapt themselves to achieve multi-objective mission roles is prompting designers towards the realization of “morphing” aircraft. Conventional designs for multi-role aircraft result in the use of advanced materials and manufacturing techniques. Often the result leads to both significant weight and cost penalties. The properties of bi-stable composite seem to suggest a solution for this problem because of their ability to have more than a single geometric configuration and also for the need to only supply energy to affect the snap-through from one equilibrium state to the other one.
ABSTRACT: An approach to design an aircraft wing with morphing capabilities employing aeroelastic tailoring is presented. Morphing capabilities are achieved by passive actuation, that is the aircraft wing will adapt itself to improve its performance during the designed flight conditions. The approach consists of an aeroelastic steady-state scheme with aero-structure coupling embedded within a global optimisation. The global optimisation is divided into two levels. At the first level, Mathematical Programming (MP) is used to optimise the wing under structural and aerodynamic constraints. Wing-box panels (skins and spars) are modelled using lamination parameters accounting for their anisotropy. Panels are assumed to be symmetric or mid-plane symmetric laminates with 0, 90, 45 or -45 degree ply angles. Each of the wing-box panels is subjected to a combined in-plane loading under strength, buckling and practical design constraints. At the second level, the actual lay-ups of the wing-box panels are obtained using a Genetic Algorithm (GA), accounting for manufacture and design practices.

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41 Magnus, E., and Epton, M. E. “PANAIR - A computer program for predicting subsonic or supersonic linear potential flows about arbitrary configurations using a higher order panel method”. NASA CR 3251, 1980.
M.I. Friswell (School of Engineering, Swansea University, UK), “The prospects for morphing aircraft”, IV ECCOMAS Thematic Conference on Smart Structures and Materials, (publisher and year not given in the pdf file; most recent reference is 2009)

ABSTRACT: Morphing aircraft are flight vehicles that change their shape to effect both a change in the mission of the aircraft and to perform flight control without the use of conventional control surfaces or seams. Aircraft constructed with morphing technology promise the distinct advantages of being able to fly multiple types of missions, to perform radically new manoeuvres not possible with conventional control surfaces, to be more fuel efficient, and to provide a reduced radar signature. The key to morphing aircraft is the full integration of the shape control into the wing structure; a truly smart structure. The design of these vehicles must take full account of the aerodynamic loads and must carefully consider the power requirements for shape control to ensure an overall performance benefit. This paper will overview possible morphing concepts, discuss advantages and disadvantages, and indicate possible future directions for the development of morphing aircraft.

References listed at the end of the paper:


ABSTRACT: A method to optimize long anisotropic laminated fiber composite panels with T-shaped stiffeners is presented. The technique splits the optimization problem into two steps. At the first step, composite optimization is performed using mathematical programming in which the skin and the stiffeners are characterized by lamination parameters accounting for their membrane and flexural anisotropy. Skin and stiffener laminates are assumed to be symmetric or midplane symmetric laminates with 0-, 90-, 45-, or -45- deg ply angles. The stiffened panel consists of a series of skin-stiffener assemblies or superstiffeners. Each superstiffener is further idealized as a group of flat laminated plates that are rigidly connected. The stiffened panel is subjected to a combined loading under strength, buckling, and practical-design constraints. At the second step, the actual skin and stiffener layups are obtained using a genetic algorithm and considering the ease of manufacture. This approach offers the advantage of introducing numerical analysis methods such as the finite element method at the first step, without significant increases in processing time. Furthermore, modeling the laminate anisotropy enables the designer to explore and potentially use elastic tailoring in a beneficial manner.
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ABSTRACT: In this article a novel morphing structure concept is studied using non-linear Finite Element
Analysis (FEA). Bi-stable asymmetrical laminates can be snapped between two geometries through a buckling
mechanism that is activated by an applied load. A piezoelectric Macro-Fibre Composite (MFC) actuator was
chosen to provide this activation load. Bi-stable structures will maintain a given geometrical state without the
need for a constant actuation force. FEA was used to predict the two stable geometries, to understand the
buckling mechanism and to evaluate the feasibility of using MFC actuators for switching between states.
Environmental effects like moisture absorption were also included in the analysis.

Filippo Mattioni, Paul M. Weaver, Kevin D. Potter, Michael I. Friswell (Department of Aerospace Engineering,
Bristol University, Bristol BS8 1TR, UK), “The application of thermally induced multistable composites to
morphing aircraft structures”, in Industrial and Commercial Applications of Smart Structures Technologies

ABSTRACT: One approach to morphing aircraft is to use bistable or multistable structures that have two or
more stable equilibrium configurations to define a discrete set of shapes for the morphing structure. Moving
between these stable states may be achieved using an actuation system or by aerodynamic loads. This paper
considers three concepts for morphing aircraft based on multistable structures, namely a variable sweep wing,
bistable blended winglets and a variable camber trailing edge. The philosophy behind these concepts is outlined,
and simulated and experimental results are given.

References listed at the end of the paper:
Cezar G. Diaconu, Paul M. Weaver and Filippo Mattioni (Department of Aerospace Engineering, University of Bristol, Bristol BS8 1TR, UK), “Concepts for morphing airfoil sections using bi-stable laminated composite structures”, Thin-Walled Structures, Vol. 46, No. 6, June 2008, pp. 689-701, doi:10.1016/j.tws.2007.11.002 ABSTRACT: The present paper investigates the potential of using bi-stable laminated composite structures for morphing an airfoil section. The objective of the paper is to identify geometries and lay-ups of candidate configurations that offer multiple stable shapes for the airfoil section. Carbon-fiber laminated composites with non-symmetric laminate configurations are used for morphing the airfoil section. Thermal curing is used to induce residual stresses into the structure in order to achieve bi-stability. Three concepts that focus on morphing a flap-like structure and the camber and chord of an airfoil section are proposed. Several geometries and laminate configurations are investigated using finite element nonlinear static analysis. The magnitude of loads required to actuate the airfoil section between the stable shapes is evaluated. The impact of manufacturability on producing viable morphing mechanisms within the airfoil section is also discussed.

S. Daynes, K.D. Potter and P.M. Weaver (Department of Aerospace Engineering, University of Bristol, Queen’s Building, University Walk, Bristol), “Bistable prestressed buckled laminates”, Composites Science and Technology, Vol. 68, Nos. 15-16, December 2008, pp. 3431-3437, doi:10.1016/j.compscitech.2008.09.036 ABSTRACT: The bistability of cross-ply [0n/90n]T laminates has already been investigated, both experimentally and analytically, in much detail. Bistability occurs due to geometric non-linearity and the mismatch between the thermal expansion coefficients of the constituent fibre and matrix materials. In this current work a new type of bistable laminate is presented which has a symmetric lay-up. Its bistability derives from careful manipulation of the residual stresses across the width of the laminate. This is done by applying a prestress to selected fibres in [0/90/90/0] FRP prepreg laminates prior to curing. Once cured and cooled down this prestress is released and the resulting laminate then buckles. This buckling creates two bistable bowing geometries with two edges remaining relatively flat. Analytical and finite element modelling is also carried out to better understand this buckling mechanism. Potential applications of these new bistable composites include morphing aircraft skins.

Paul M. Weaver (Advanced Composites Centre for Innovation and Science (ACCIS), Department of Aerospace Engineering, University of Bristol, UK), “Chapter 6: Anisotropic elastic tailoring in laminated composite plates and shells”, in Buckling and postbuckling structures: experimental, analytical and numerical studies, edited by B. G. Falzon and M. H. Aliabadi, Imperial College Press, 2008 ABSTRACT: Significant improvements in structural efficiency are possible using specific, inhomogeneous laminates. These are laminates whose stacking sequence has been optimized against constraints such as buckling, damage tolerance and natural frequencies. Furthermore, there are many design scenarios in which further gains can be made by making use of anisotropy, particularly when buckling or postbuckling is concerned. After a brief introduction to current design practice, buckling and postbuckling formulae are derived for anisotropic plates and shells, subject to different loadings. From these expressions, concepts for anisotropic elastic tailoring are discussed and their implications for design considered.

ABSTRACT: The static and dynamic transitions between stable states for rectangular bi-stable laminated composite plates are considered. The laminated composite plates have nonsymmetric laminate configurations and are subjected to thermal curing in order to introduce residual stresses and to achieve bi-stability. As geometrically nonlinear effects occur, after curing, the plates are able to take multiple stable shapes at service or room temperature. A simple model for dynamic analysis of the snap-through phenomena is proposed based on strain field approximations for the plates. Hamilton's principle is applied in conjunction with the Rayleigh–Ritz method in order to achieve fast results. The model is used to evaluate the initial displacements for the stable states and also to investigate the static and dynamic transitions from one stable state to another. Parametric studies are carried out for various aspect ratios, laminate configurations and actuation loads and the results are compared with those obtained with finite element analysis in order to evaluate the accuracy of the model.


ABSTRACT: A meshless approach is developed and used to predict buckling of discretely assembled multibay composite panels made from skin and stiffeners. The effect of eccentricity is included in the formulation. Particular emphasis is given to stringer run-outs within a stiffened panel, where abrupt eccentricity can trigger very large transverse displacements of the skin in front of the run-out tip. The model is obtained by combining von Karman’s formulation for moderately large deflections in plates with an extended Timoshenko approach for small initial perturbations. Solutions are calculated by means of a Rayleigh–Ritz approach in conjunction with a Galerkin technique. Hilbert’s orthogonal eigenfunctions are employed to obtain a generalized Fourier series expansion of the variables of interest. Limits of applicability, convergence of results and further potential exploitations are discussed. Numerical results obtained are compared with finite element analysis.

References listed at the end of the paper:

Enzo Cosentino (1) and Paul Weaver (2)

ABSTRACT: A novel mixed formulation is derived by means of Reissner's variational approach-based on Castigliano's principle of least work in conjunction with a Lagrange multiplier method for the calculus of variations. The governing equations present an alternative theory for modeling the important three-dimensional structural aspects of plates in a two-dimensional form. By integrating the classical Cauchy's equilibrium equations with respect to the thickness co-ordinate, and enforcing continuity of shear and normal stresses at each ply interface, condenses the effect of the thickness. A reduced system of partial differential equations of sixth-order in one variable, is also proposed, which contains differential correction factors that formally modify the classical constitutive equations for composite laminates. The theory degenerates to classical composite plate analysis for thin configurations. Significant deviations from classical plate theory are observed when the thickness becomes comparable with the in-plane dimensions. A variety of case studies are presented and solutions are compared with other models available in the literature and with finite element analysis.


ABSTRACT: The bistability of unsymmetric cross-ply [0n/90n]T laminates has already been investigated in much detail. In this work a new type of bistable laminate is presented which has a symmetric lay-up. Bistability derives from an unsymmetric fiber prestress applied to the laminate. The experimental procedure used to apply this fiber prestress is presented in detail. Experimental results are compared with analytical and finite element models which have the ability to model fiber prestress accurately. As well as having minimal hygrothermal variability, it is noted that the snap-through loads for a prestressed symmetric laminate can be much higher than its unstressed [0n/90n]T equivalent.


ABSTRACT: The potential of using multistable composite materials for adaptive structures is currently receiving interest from the aerospace community because they possess more than one single equilibrium configuration. Unsymmetric CFRP laminates are studied which have an inner isotropic metallic layer. These hybrid laminates are studied using analytical, finite element and experimental techniques. The thermal contraction of the isotropic layer upon cool down from cure induces large in-plane thermal loads which act remotely from the laminate’s neutral plane, increasing snap-through moments and out-of-plane displacements. The curvatures of the hybrid laminates can be doubled compared to pure unsymmetric CFRP laminates.

A. Pirrera (1), D. Avitabile (2) and P.M. Weaver (1)
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“Bistable plates for morphing structures: A refined analytical approach with high-order polynomials”,
doi:10.1016/j.ijsolstr.2010.08.019
ABSTRACT: The multistability of composite thin structures has shown potential for morphing applications. The present work combines a Ritz model with path-following algorithms to study bistable plates’ behaviour. Classic low-order Ritz models predict stable shapes’ geometry with reasonable accuracy. However, they may fail when modelling other aspects of the elastic structural behaviour. A refined higher-order model is here presented. In order to improve the inherently poor conditioning properties of Ritz approximations of slender structures, a non-dimensional version of Classical Plate Lamination Theory with von Kármán nonlinear strains is developed and presented. In the current approach, we continue numerical solutions in parameter space, that is, we path-follow equilibrium configurations as the control parameter varies, find stable and unstable configurations and identify bifurcations. The numerics are carried out using a set of in-house Matlab® routines for numerical continuation. The increased degrees of freedom within the model are shown to accurately reflect buckling loads and provide useful insight into the relative importance of different aspects of nonlinear behaviour. Finally, the complex, experimentally observed snap-through geometry is captured analytically for the first time. Results are validated against finite elements analysis throughout the course of the paper.

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ABSTRACT: Critical failure was observed in the shear web of a wind turbine blade during a full-scale testing. This failure occurred immediately before the ultimate failure and was partly caused by buckling and non-linear cross-sectional strain. Experimental values had been used to compare and validate both numerical and semi-analytical results in the analysis of the shear webs in the reinforced wind turbine blade. Only elastic material behaviour was analysed, and attention was primarily focused on the Brazier effect. The complex, geometrically non-linear and elastic stress–strain behaviour of the shear webs and the cap in compression were analysed using a balance of experimental, numerical and analytical approaches. It was noted that the non-linear distortion was caused by the crushing pressure derived from the Brazier effect. This Brazier pressure may have a significant impact on the design of new blades, and an optimized box girder had been studied to show the importance of including Brazier pressure in the design process for future wind turbine blades.

Simon C. White, Post-buckling of variable-stiffness shell structures, Ph.D dissertation, Advanced Composites Centre for Innovation and Science, Aerospace Engineering, University of Bristol, UK, 2015
ABSTRACT: The cylindrical shell is one of the most efficient structures for resisting axial compression. They are found in many weight-critical engineering applications due to their low mass and large internal volume. Their structural efficiency is derived from surface curvature which results in large buckling loads. Ultimate
failure is generally due to local buckling (i.e. loss of stability of the shell-wall) which is followed by global collapse. A consequence of this unstable non-linear behaviour is that the structures are sensitive to imperfections and buckle at loads that are a fraction of their linear buckling eigenvalues. In contrast, flat structures (such as plates and stiffened panels) display a relatively well-behaved post-buckling response. In this thesis an investigation into the post-buckling behaviour of variable-stiffness shell structures is presented. Its aim is to determine whether or not cylindrical shells can be designed to have stable post-buckling configurations by adopting non-uniform material properties. In order to create shells with new and novel responses, the design space must be expanded by removing the standard rules for laminate design. Therefore, the present work focuses on laminates in which the reinforcement fibres are not straight but follow curvilinear paths. Such structures are termed variable-stiffness composite structures, due to their smooth variations in anisotropy (i.e. their section stiffnesses and kinematic coupling).

Cylinders, curved panels and flat plates are tailored for improved post-buckling performance using numerical methods. In the case of cylindrical shells, dynamic analyses are performed in order to capture the effects of instability, inertia and path switching. Here, tailoring was performed on cylinders with a circumferential fibre-angle variation in a parametric study. The results show that a wide range of responses can be achieved by varying the shell’s geometry and fibre-angle distribution. New evidence is presented that cylinders with stable post-buckling responses are possible by using variable-stiffness laminates. Tailoring is also performed on curved panels through an optimisation process. Panels are modelled using Koiter’s asymptotic method and a quadrature-based discretisation of the domain. Optimisation is performed using a genetic algorithm with the objective of increasing the structure’s tangent stiffness in the vicinity of the bifurcation. An optimised shell design is presented which is practically unaffected by the increase in radial displacements in terms of axial stiffness.

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ABSTRACT: A concept for a novel folding wing is presented, which, using the Brazier effect, can snap from a stable, extended position to a folded configuration. A wing typical of size used in an unmanned aircraft vehicle (UAV) is examined, including manufacturing aspects as well as an analytical and a finite element model (FEM) of the structure. The wing is simply made of a glass fiber reinforced plastic (GFRP) skin stiffened by ribs at regular intervals. At the mid-span location, a cut-out is made in the leading and trailing edge in order to allow the pressure and suction sides of the wing to collapse inward when folding occurs (due to Brazier effect). The analytical model draws upon work from Brazier to predict the maximum bending moment the folding section can withstand before buckling. A FEM, using a quasi-static analysis and requiring a contact definition to allow the wing surfaces to meet, reproduces with accuracy the folding pattern seen on the prototype. A bending test of the demonstrator confirmed the validity of the models in terms of bending stiffness, bending snap through and folding radius of curvature.

References listed at the end of the paper:
ABSTRACT: The overall objective is a top-down approach to structural instability phenomena in wind turbine blades, which is used to identify the physics governing the ultimate strength of a generic wind turbine blade under a flap-wise static test. The work is concerned with the actual testing and the adoption of a phenomenological approach, and a discussion is conducted to assess and evaluate the wind turbine blade response during loading and after collapse by correlating experimental findings with numerical model predictions. The ultimate strength of the blade studied is governed by instability phenomena in the form of delamination and buckling. Interaction between both instability phenomena occurs causing a progressive collapse of the blade structure.

ABSTRACT: The objective of this paper is to present a geometrical nonlinear and interlaminar progressive failure finite element analysis of a generic wind turbine blade undergoing a static flap-wise load and comparisons with experimental findings. It is found that the predictive numerical models show excellent correlation with the experimental findings and observations in the pre-instability response. Consequently, the ultimate strength of the wind turbine blade studied is governed by a delamination and buckling coupled phenomenon, which results in a chain of events and sudden structural collapse with compressive fibre failure in the delaminated flange material. Finally, a parametric study of the critical load factors with respect to various delamination sizes and positions inside the compressive flange of the wind turbine blade is presented.

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ABSTRACT: The work focuses on the linear buckling analysis of wind turbine blade with different trailing bonding models. Based on finite element model, it has been demonstrated that there are some differences for buckling load factor between different models. Several different models are valid for buckling analysis.

References listed at the end of the paper:

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ABSTRACT: The paper is concerned with the effect of random axisymmetric imperfections on the buckling of circular cylindrical shells under axial compression. The initial imperfections are considered as random functions of the axial coordinate. This is done by expanding them in terms of the buckling modes of the associated perfect structure, and then treating the Fourier coefficients as random variables. Initially the probabilistic properties of the initial imperfections of cylindrical shells, produced by the same manufacturing process, are studied. In contrast to earlier works the probabilistic properties (the mean function and the autocorrelation function or the spectral density) are not assumed. The mean vector and the variance-covariance matrix of the Fourier coefficients are calculated from experimental measurements of the shell profiles. Next the Monte Carlo Method is applied. The Fourier coefficients of the initial imperfection representations are simulated by a special numerical procedure. Thus large number of shells is “created”. For each shell a deterministic analysis of buckling stress evaluation is carried out. Finally, the reliability function representing the probability (i.e. fraction of an ensemble) of the buckling stress exceeding the specified stress is calculated. The reliability function permits to evaluate the design stress for the whole ensemble of shells produced by a given manufacturing process, defined as the stress level for which the desired reliability is achieved. The paper represents an extension of the approach given in Ref. [1] to shell structures.

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ABSTRACT: A new, non-probabilistic method is developed in this study to predict the variability in buckling loads of composite plates and shells stemming from the unavoidable scatter in elastic moduli. The available measurements of elastic moduli are fitted by the four-dimensional uncertainty ‘box’ and appropriate ellipsoid. For the specific cases considered, the maximum buckling load of the composite plate exceeds by 11% the value of the buckling load based on the calculation using the nominal values of elastic moduli. In the case of the cylindrical shell, an appropriate exceedance constitutes 9%.
ABSTRACT: This paper deals with the buckling of the stiffened plate under uni-axial compression. The direct integration of the governing differential equation is performed and the exact solution to the problem is obtained. As examples, a square plate with single stiffener, and a stiffened three-span, continuous plate are investigated, with special attention given to the influence of stiffener misplacement on the buckling load and mode shape of the plate. It is found that a small misplacement of the stiffeners from the nominal configuration may change the buckling mode from a global one to a highly localized one.

ABSTRACT: This study addresses the effect of thickness variation on the stability of the composite cylindrical shells under axial compression. Various lamination configurations and three commonly used composite materials are considered. Numerical results show that certain types of thickness variation patterns can greatly reduce the classical buckling load. Results indicate that the most detrimental effect of the thickness variation occurs when the wave number of the thickness variation is twice that of the classical buckling mode. For this case, an asymptotic formula is established by use of a computer algebra, which relates the buckling load reduction rate to the thickness variation parameter.

ABSTRACT: This study is an extension of a previous investigation of the combined effect of axisymmetric thickness variation and axisymmetric initial geometric imperfection on buckling of isotropic shells under uniform axial compression. Here the anisotropic cylindrical shells are investigated by means of Koiter’s energy criterion. An asymptotic formula is derived which can be used to determine the critical buckling load for composite shells with combined initial geometric imperfection and thickness variation. Results are compared with those obtained by the software packages BOSOR4 and PANDA2.
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ABSTRACT: Hybrid theoretical, experimental and numerical method is proposed for free vibration and buckling of composite shell with unavoidable scatter in elastic moduli. Based on the Goggin’s measurement techniques, the elastic moduli for material T300-QY8911 are measured, and a set of experimental points are obtained. The measurements of elastic moduli are quantified by either (1) the smallest ellipsoid and (2) the smallest four-dimensional uncertainty hyper-rectangle. Then uncertainty propagation in vibration and buckling problems of composite shell by ellipsoidal analysis and interval analysis are, respectively, studied from the theoretical standpoint. Comparison between these analyses is performed numerically.


ABSTRACT: The post-buckling behavior of the thin stiffened plates with uncertain initial deflection under uni-direction compression load is investigated based on Von-Karman large deflection theory. The uncertain initial deflections are considered to be unknown except that they belong to a given set in the interval range. Interval analysis model for computing the bounds of curves of the post-buckling deflection versus load of the plate is presented. Interval analysis model is compared with the stochastic model, which is taken as the benchmarks of accuracy for judgment. The results indicate that the non-probabilistic and stochastic methods will produce similar results for a large deviation of uncertainty. If the probabilistic information is unavailable, one should not propose the probabilistic method based on an arbitrary assumption on the distribution of the deflection coefficients. Rather, one should use the non-probabilistic method to uncertainty.

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ABSTRACT: Non-linear buckling and postbuckling of a moderately thick anisotropic laminated cylindrical shell of finite length subjected to lateral pressure, hydrostatic pressure and external liquid pressure has been presented in the paper. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The governing equations are based on a higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic non-linearity and including the extension/twist, extension/flexural and flexural/twist couplings. The non-linear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the buckling
pressure and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The results confirm that there exists a circumferential stress along with an associate shear stress when the shell is subjected to external pressure.


ABSTRACT: The use of finite element buckling analysis in the stability design of thin shelled structures allows complex geometries and load and boundary conditions to be considered. Two approaches are possible. A linear bifurcation buckling analysis can be carried out to determine the bifurcation load of the perfect structure. Reduction factors can then be applied to account for the geometric imperfections and plasticity. Alternatively a fully non-linear analysis can be performed with deflections, geometric imperfections and plasticity properly modelled. This paper assesses the suitability of each of these methods to predict the buckling loads and post-buckling behaviour of two structures — flat plates and curved panels under combined shear and compression — a load case commonly found in aeroengine structures such as vanes. Experimental data is also presented for comparison.

ABSTRACT: Finite element analysis allows fully non-linear analysis of shells containing geometric imperfections. However, such an analysis requires information on the exact size and shape of the imperfection to be modelled, in order to produce accurate results on which designs can be based. In the absence of such data it is generally recommended that the imperfection be modelled on the first eigenmode with an amplitude selected according to manufacturing procedure. This paper presents the effects of imperfection shape and amplitude on the buckling and postbuckling behaviour of one specific case, to test the accuracy of such recommendations.

ABSTRACT: Projection moiré is frequently used to examine the out-of-plane displacement of thin-walled shells during buckling. One way of implementing this technique is to use double exposure photography to superimpose the initial and deformed images of a grating projected onto the surface of the specimen. This generates a pattern of fringes representative of points of equal displacement, thus presenting a snapshot of the full-field buckling behavior. This paper outlines a technique to extend this method to provide a computer generated real-time fringe pattern throughout the whole buckling and post-buckling process. This is achieved by using a CCD camera and specially developed processing software to continuously superimpose the initial image of the grating (i.e., the first frame of the captured video) onto subsequent frames in which this grating is deformed due to the displacement. This method produces series of fringes in digital format, which are ideal for
ABSTRACT: The initial buckling load of curved panels under compressive loads is substantially reduced by the existence of imperfections, in particular geometric imperfections. It is therefore essential that these imperfections are considered in analysing components which incorporate such panels in order to accurately predict their buckling behaviour. Finite element analysis allows fully non-linear analysis of shells containing geometric imperfections, however, to obtain accurate results information is required on the exact size and shape of the imperfection to be modelled. In most cases this data is not available. It is therefore generally recommended that the imperfections are modelled on the first eigenmode and have an amplitude selected according to the manufacturing procedure. This paper presents the effects of varying imperfection shape and amplitude on the buckling and postbuckling behaviour of one specific case, a curved panel under combined shear and compression, to test the accuracy of such recommendations.

ABSTRACT: The buckling loads and postbuckling behaviour of complex structures can only be determined analytically by simplifying them into a number of component parts and examining these individually using existing design rules. This approach does not consider the effect of geometric imperfections and large deflections or the interaction between overall and local buckling modes. Alternatively, finite element analysis can be used. This approach has the advantage of allowing geometry, boundary and loading conditions to be modelled more accurately. Large-scale deflections and material plasticity can be modelled, the effects of imperfections examined and all possible modes of failure considered. This paper outlines a series of experiments carried out to determine the accuracy of these two alternative techniques in predicting the buckling loads and postbuckling behaviour for the case of a simple aerofoil under combined shear and in-plane bending.

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ABSTRACT: Spars in aircraft wing boxes constitute thin walled shells, providing a load path for vertical shear loading. Well established design rules for the prediction of the initial shear buckling load are extended to cover the cases of compression and in-plane bending, resulting from overall wing bending. A parametric study, performed using an exact strip method and verified by finite element results, for both simply supported and clamped longitudinal edges, shows that the stiffeners effectively provide simple support if their dimensions are made large enough. Using a single plate model for such cases, as simple interaction equation is shown to give accurate and conservative initial buckling predictions for combined loading cases, with some scope for improvement when the stiffener spacing is large.

ABSTRACT: Design rules based on theoretical solutions, which allow the prediction and understanding of the buckling and post-buckling behaviour of homogenous thin plates, exist for only a limited number of simple loading and boundary conditions due to the complexity of the equilibrium equations that describe the problem. When considering fibre composite plates, this issue is exacerbated by the inherent coupling between bending and extensional strains due to unsymmetric lamination, which results in three eighth order coupled partial differential equilibrium equations. This paper details a series of tests carried out to investigate the behaviour of a number of optimised fibre composite plates of differing geometry, simply supported along two edges and built in along the other two, subject to a varying combination of shear and in-plane bending, for which no theoretical solution exists, and assesses the suitability of analytical techniques and finite element analysis to predict this behaviour.
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ABSTRACT: Due to the level of complexity of the governing equations for curved composite panels, few solutions, allowing the critical buckling loads and postbuckling behaviour of such structures to be determined, exist. Those that do are for basic problems based on single load types and simple boundary conditions. For other cases, such behaviour can only be determined by either grossly simplifying both the load and boundary conditions to those which can be predicted using these simplified equations (which may lead to overestimations in buckling load, and thereby premature failure or collapse), or by using alternative tools such as finite strip techniques or finite element analyses. This paper details a series of tests carried out to determine the behaviour of a number of optimised fibre composite panels of differing radii of curvature and aspect ratio, simply supported along two edges and built in along the other two, subject to a varying combination of shear and in-plane bending, for which no theoretical solution exists, and assesses the suitability of finite strip techniques and finite element analysis to predict this behaviour.

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ABSTRACT: Due to their complexity and large numbers of design variables, aerospace structures, such as aircraft wings, are best optimized using a multi-level process. In addition to simplifying the optimization procedure, such an approach allows a combination of different methods to be used, increasing the efficiency of the analysis. This paper presents a technique based on the usage of exact finite strip software, VICONOPT, with the finite element analysis package, ABAQUS. The computer programme VICONOPT is computationally efficient but provides solutions for a restricted range of geometries and loading conditions. Finite element analysis allows accurate models of structures with complex geometries to be created but is computationally expensive. By combining the two, these limitations are minimised, whilst the strengths of each are exploited. The fundamental principles of this multi-level procedure are demonstrated by optimizing a series of curved composite panels under combined shear and in-plane bending subject to buckling constraints.

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ABSTRACT: The paper introduces a discrete model to describe the buckling of a stiffened panel beam under a complex loading environment. The study begins by examining the existing load interaction equation for a continuous panel. Experimental and finite element investigations establish the validity of considering the critical
panel of a more complex structure in isolation. The paper then devises a discrete model for this critical panel, which was validated for a range of boundary conditions using anti-optimisation. The numerical results show that the discrete model exhibits the buckling behaviour of a continuous panel under combined loading. Recent studies established that the truss-lattice configuration has stable post-buckling behaviour and derived fast analysis technique for such a structure. It is therefore concluded that the truss-lattice model introduced in the present paper can offer a fast analysis formulation for buckling (and potentially post-buckling) of multiple-panel beams suitable for optimisation.

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ABSTRACT: This paper examines the effect of imperfections on the behaviour of a series of panels, simply supported along all four edges, and subject to compressive in-plane loading. In each case Digital Image Correlation (DIC) is used to determine the initial profile and set-up of the structure and to monitor its behaviour during test. The data is used to automatically generate a series of meshes representative of each of these
specimens, suitable for analysis using Finite Element Analysis. Comparison of the results obtained from these analyses with those found during the experiments modelled shows an improved correlation when compared with standard techniques for assessing imperfection sensitivity. Set-up is straightforward and models can be obtained quickly based on the data collected.

References listed at the end of the paper:

ABSTRACT: The existence of geometric imperfections, either resulting from the use of manufacturing tolerances or because of damage in situ is known to have a detrimental effect on the buckling and post-buckling behaviour of thin-walled structures, which depending upon factors such as geometry and loading, can be significant. This paper presents an automated technique, based on the use of topography data obtained from optical measurement, for creating finite meshes representative of the geometry of real structures, which can be analysed to obtain accurate predictions of unstable behaviour. The technique incorporates an algorithm to allow mesh density to be varied across the specimen according to level of curvature thus ensuring the meshes generated are not only accurate but also computationally efficient by reducing the number of degrees of freedom where appropriate. The results of applying this technique to a series of curved panels subject to combined shear and in-plane bending (an example of a component of an aero engine blade) are reported.

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ABSTRACT: Thin-walled shell structures like circular cylindrical shells are prone to buckling. Imperfections, which are defined as deviations from perfect shape and perfect loading distributions, can reduce the buckling load drastically compared to that of the perfect shell. Design criteria monographs like NASA-SP 8007 recommend that the buckling load of the perfect shell shall be reduced by using a knock-down factor. The existing knock-down factors are very conservative and do not account for the structural behaviour of composite shells. To determine an improved knock-down factor, several authors consider realistic shapes of shells in
numerical simulations using probabilistic methods. Each manufacturing process causes a specific imperfection pattern; hence for this probabilistic approach a large number of test data is needed, which is often not available. Motivated by this lack of data, a new deterministic approach is presented for determining the lower bound of the buckling load of thin-walled cylindrical composite shells, which is derived from phenomenological test data. For the present test series, a single pre-buckle is induced by a radial perturbation load, before the axial displacement controlled loading starts. The deformations are measured using the prototype of a high-speed optical measurement system with a frequency up to 3680 Hz. The observed structural behaviour leads to a new reasonable lower bound of the buckling load. Based on test results, the numerical model is validated and the shell design is optimized by virtual testing. The results of test and numerical analysis indicate that this new approach has the potential to provide an improved and less conservative shell design in order to reduce weight and cost of thin-walled shell structures made from composite material.


ABSTRACT: This work presents numerical methods of calculation of earthquake resistance of shells of revolution based on the application of the theory of random processes combined with the FEM. Probabilistic character of seismic effect is determined by using artificial accelerograms based on stochastic process. To illustrate the above methods of probabilistic analysis of seismic stability of structures, two real objects and one projected one are considered. Displacements, stresses, forces and moments resulting from the action of seismic load have been determined. Comparison of the results of calculation with those achieved using calculation of prescribed real accelerograms and building design codes have been made. Comparative analysis of the calculation results brings us to the conclusion that the difference between the results obtained using different methods can be quite significant. It means that when designing structures of the types of shells of revolution under consideration it is necessary to do calculations using all methods recommended by design codes as well as probabilistic methods.

References listed at the end of the paper:
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ABSTRACT: A moving load causes the radial displacements of an axi-symmetric shell to be several times higher than that produced by the static application of the same load. The travel velocity of the moving load affects the amplitude of the radial response and a critical velocity above which the shell response becomes unstable can be identified. A finite element model (FEM) is developed to analyze the dynamic response of axi-symmetric shells subjected to axially moving loads. The model accounts for the effect of periodically placing stiffening rings along the shell, on the dynamic response and stability characteristics of the shell. Shape functions obtained from the steady-state solution of the equation of motion for a uniform shell are utilized in the development of the FEM. The model is formulated in a reference frame moving with the load in order to enable studying the shell stability using wave propagation and attenuation criteria. Hence, the critical velocity can be identified as the minimum velocity allowing the propagation of applied perturbations. Such stability boundaries are conveniently identified through a transfer mis formulation. The model is used to determine the critical velocities of the moving load for various arrangements and geometry of the stiffening rings. The obtained results indicate that stiffening the shell generally increases the critical velocity and generates a pattern of alternating stable and unstable regions. The presented analysis provides a viable means for designing a wide variety of stable dynamic systems operating with fast moving loads such as crane booms, robotic arms and gun barrels.

Massimo Ruzzene (School of Aerospace Engineering, Georgia Institute of Technology, 270 Ferst Drive, Atlanta, GA 30332-0150, USA), “Non-axisymmetric buckling of stiffened supercavitating shells: static and dynamic analysis”, Computers & Structures, Vol. 82, Nos. 2-3, January 2004, pp. 257-269

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ABSTRACT: Supercavitating vehicles undergo high longitudinal forces as a result of their high underwater velocity. The drag force compresses axially the body and may cause its buckling. In addition, the time-dependent properties of the cavity generate time-varying longitudinal loads, which are sources of parametric resonances. Static and dynamic buckling need to be considered as limiting factors for the operating speed of this class of vehicles. The stability of supercavitating underwater vehicles is here investigated through a finite element model that predicts the behavior of plain and stiffened shells and is used to obtain stability maps for varying vehicle’s velocity, as well as frequency and amplitude of the force oscillations. Periodically placed circumferential stiffeners are proposed as means to enhance the stability of the considered class of shells. The results indicate the effectiveness of the stiffening rings in extending the range of stable operating conditions, by
increasing the critical static buckling loads, and more importantly by reducing the extension of the regions corresponding to dynamic instability.

ABSTRACT: Supercavitating vehicles undergo high longitudinal forces as result of their high underwater velocity. The drag force compresses axially the body and may cause its buckling. In addition, the unsteady characteristics of the system composed of cavity and vehicle generate time-varying longitudinal loads that are sources of parametric resonances. Supercavitating vehicles are here modeled as thin axisymetric shells acted upon by time-varying axial compressive forces. A finite element model is developed to predict the shells behavior and to perform the buckling analysis. The longitudinal forces are considered to vary periodically in time. Accordingly, the stability analysis is performed using Bolotin’s method and Floquet theory. Stability maps for varying velocity of the vehicle, frequency and amplitude of the force oscillations are obtained. Periodically placed circumferential stiffeners are proposed as means to enhance the stability of the considered class of shells. The presented results indicate how the stiffening rings significantly extend the range of stable operating conditions by reducing the regions of dynamic instability, and suggest that optimal stiffened designs may be identified to achieve stability at given operating speeds and under periodic longitudinal forces.

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ABSTRACT: A laminated cylindrical shell of finite length under combined loads is optimized for minimum sensitivity of buckling load to variations in ply angles subject to a constraint on buckling load. The design variable is taken as the fiber orientation of individual layers. The general theory of laminated plates is employed to determine the buckling loads. The formulation includes the contribution of the shear deformation and the variation of the radius over the thickness of the shell. Numerical results are given for both thin and thick shells. The results are given for various values of the external pressure and different shell aspect ratios. It is shown that the minimum sensitivity design depends on the constraint on buckling load.

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ABSTRACT: Friction stir welding (FSW) is a rapidly emerging joining technology that is finding greater use in aerospace applications due to significant advancements in tooling and process development. However, basic performance and design parameters for aerospace structures incorporating FSW joints have typically been developed on a case by case basis and are not yet available for general applications. Performance and properties
data are needed to advance FSW from coupon level research to direct application. Therefore, the National Institute for Aviation Research (NIAR) initiated an investigation to compare the integrity of typical airframe structure joined using FSW with that of riveted structure. Ultimately, the aim of this investigation is to aid in the development of performance specification data. The structures selected for this research were subscale flat stiffened panels that were based on previously developed designs from generic fuselage applications. The initial stiffened aluminum panels were fabricated with two hat-section stiffeners. Representative of a transport fuselage design, the skin panels were 0.040-in 2024-T3, and the stiffeners were 7075-T6 spaced on 8.0 inch centers. The 2-ft x 2-ft stiffened panels were tested statically in tension, compression, and shear. Finite element models were developed to evaluate the ability of modeling to predict the load carrying capability of FSW structures. In the presentation, test results from riveted panels with identical geometry will be compared with results from both the models and the FSW panels. To date the panels fabricated using FSW have shown an increase in overall performance including an increase in panel strength and axial displacement. The FSW shear panels failed less abruptly and with much less destruction than did the riveted panels, indicating an increase in the ability of the FSW panels to sustain damage.

References listed at the end of the paper:
for the lower load case (400 kN).

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ABSTRACT: Reinforced structures for aircraft fuselages are conventionally composed by base (skin) aluminium plates and reinforcement elements (stringers), joined by riveting operations. During the last decade more effective approaches for reinforced fuselage and wings, such as the Integrally Stiffened Panels (ISP), have appeared. These homogeneous reinforced structures are obtained in an integral form by extrusion, allowing for lower manufacturing costs. During service conditions, these structures can be subjected to extreme compressive loading conditions and, due to their slenderness and low weight, ISP design must account for a reliable determination of buckling loads. However, complexities of the cross-sectional geometrical shapes, together with the occurrence of elastoplastic non-linear effects prior or after buckling, completely impair the use of analytical tools, being the analysis by the Finite Element Method (FEM) imperative in a reliable design process. In the present work, the structural performance of ISP structures is assessed, accounting for buckling in the elastoplastic range, by means of numerical simulation with the Finite Element Method. Also, the buckling load-carrying capacity of multiple sets of reinforced structures, composed by a finite number of ISP and joined by friction stir welding (FSW) operations, is also studied. In doing so, it is possible to numerically infer about the influence of the presence of FSW zones in the overall stiffness and mechanical behaviour of ISP structures with complex cross-section geometries.

References listed at the end of the paper:


ABSTRACT: Stiffened panels are usually the basic structural building blocks of airplanes, vessels and other structures with high requirements of strength-to-weight ratio. They typically consist of a plate with equally spaced longitudinal stiffeners on one side, often with intermediate transverse stiffeners. Large aeronautical and naval parts are primarily designed based on their longitudinal compressive strength. The structural stability of such thin-walled structures, when subjected to compressive loads, is highly dependent on the buckling strength of the structure as a whole and of each structural member. In the present work, a number of modelling and numerical calculations, based on the Finite Element Method (FEM), is carried out in order to predict the ultimate load level when stiffened panels are subjected to compressive solicitations. The simulation models
account not only for the elasto-plastic nonlinear behaviour, but also for the residual stresses, material properties modifications and geometrical distortions that arise from Friction Stir Welding (FSW) operations. To construct the model considering residual stresses, their distribution in FSW butt joints are obtained by means of a numerical-experimental procedure, namely the contour method, which allows for the evaluation of the normal residual stress distribution on a specimen section. FSW samples have been sectioned orthogonally to the welding line by wire electrical discharge machining (WEDM). Displacements of the relaxed surfaces are then recorded using a Coordinate Measuring Machine and processed in a MATLAB environment. Finally, the residual stress distribution is evaluated by means of an elastic FE model of the cut sample, using the measured and digitalized out-of-plane displacements as input nodal boundary conditions. With these considerations, the main goal of the present work will then be related to the evaluation of the effect of FSW operations, in the ultimate load of stiffened panels with complex cross-section shapes, by means of realist numerical simulation models.

ABSTRACT: NASA Lewis Research Center is currently developing probabilistic structural analysis methodology for select Space Shuttle Main Engine (SSME) components. This methodology consists of the following program elements: (1) composite load spectra, (2) probabilistic structural analysis methods, (3) probabilistic finite element theory - new variational principles, and (4) probabilistic structural analysis application. The methodology has led to significant technical progress in several important aspects of probabilistic structural analysis. The program and significant accomplishments to date are summarized in this paper.

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ABSTRACT: The durability of a stiffened composite cylindrical shell panel is investigated under several loading conditions. An integrated computer code is utilized for the simulation of load induced structural degradation. Damage initiation, growth, and accumulation up to the stage of propagation to fracture are included in the computational simulation. Results indicate significant differences in the degradation paths for different loading cases. Effects of combined loading on structural durability and ultimate structural strength of a stiffened shell are assessed.

References listed at the end of the paper:
ABSTRACT: A general computational simulation methodology for an integrated probabilistic assessment of composite structures is discussed and demonstrated using aircraft fuselage (stiffened composite cylindrical shell) structures with rectangular cutouts. The computational simulation was performed for the probabilistic assessment of the structural behavior including buckling loads, vibration frequencies, global displacements, and local stresses. The scatter in the structural response is simulated based on the inherent uncertainties in the primitive (independent random) variables at the fiber matrix constituent, ply, laminate, and structural scales that describe the composite structures. The effect of uncertainties due to fabrication process variables such as fiber volume ratio, void volume ratio, ply orientation, and ply thickness is also included. The methodology has been embedded in the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures). In addition to the simulated scatter, the IPACS code also calculates the sensitivity of the composite structural behavior to all the primitive variables that influence the structural behavior. This information is useful for assessing reliability and providing guidance for improvement. The results from the probabilistic assessment for the composite structure with rectangular cutouts indicate that the uncertainty in the longitudinal ply stress is mainly caused by the uncertainty in the laminate thickness, and the large overlap of the scatter in the first four buckling loads implies that the buckling mode shape for a specific buckling load can be either of the four modes.

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ABSTRACT: The design of composite structures requires an evaluation of their safety and durability under service loads and possible overload conditions. This paper presents a computational tool that has been developed to examine the response of stiffened composite panels via the simulation of damage initiation, growth, accumulation, progression, and propagation to structural fracture or collapse. The structural durability of a composite panel with a discontinuous stiffener is investigated under compressive loading induced by the gradual displacement of an end support. Results indicate damage initiation and progression to have significant effects on structural behavior under loading. Utilization of an integrated computer code for structural durability assessment is demonstrated.

Christos C. Chamis (NASA Lewis Research Center, Cleveland, Ohio), “Probabilistic composite design”, in

ABSTRACT: Probabilistic composite design is described in terms of a computational simulation. This simulation tracks probabilistically the composite design evolution from constituent materials, fabrication process, through composite mechanics and structural components. Comparisons with experimental data are provided to illustrate selection of probabilistic design allowables, test methods/specimen guidelines, and identification of in situ versus pristine strength. For example, results show that: in situ fiber tensile strength is 90 per cent of its pristine strength; flat-wise long-tapered specimens are most suitable for setting ply tension strength allowables; a composite radome can be designed with a reliability of 0.999999; and laminate fatigue exhibits wide-spread scatter at 90 per cent cyclic-stress to static-strength ratios.

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ABSTRACT: A methodology is developed to simulate computationally the uncertain behavior of composite structures. The uncertain behavior includes buckling loads, natural frequencies, displacements, stress/strain, etc., which are the consequences of the random variation (scatter) of the primitive (independent random) variables in the constituent, ply, laminate and structural levels. This methodology is implemented in a computer code IPACS (integrated probabilistic assessment of composite structures). A fuselage-type composite structure is analyzed to demonstrate the code's capability. The probability distribution functions of the buckling loads, natural frequency, displacement, strain and stress are computed. The sensitivity of each primitive (independent random) variable to a given structural response is also identified from the analyses.

C.C. Chamis, R.A. Aiello and P.L.N. Murthy, “Fiber composite sandwich thermostructural behavior: Computational simulation”, (publisher and date not given, ProQuest-CSA)

ABSTRACT: Several computational levels of progressive sophistication/simplification are described to computationally simulate composite sandwich hygral, thermal, and structural behavior. The computational levels of sophistication include: (1) three-dimensional detailed finite element modeling of the honeycomb, the adhesive and the composite faces; (2) three-dimensional finite element modeling of the honeycomb assumed to be an equivalent continuous, homogeneous medium, the adhesive and the composite faces; (3) laminate theory simulation where the honeycomb (metal or composite) is assumed to consist of plies with equivalent properties; and (4) derivations of approximate, simplified equations for thermal and mechanical properties by simulating the honeycomb as an equivalent homogeneous medium. The approximate equations are combined with composite hygrothermomechanical and laminate theories to provide a simple and effective computational procedure for simulating the thermomechanical/thermostructural behavior of fiber composite sandwich structures.

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“Future Experimental Methods Needed to Verify Composite Life-cycle Simulations”, Recent Advances in

ABSTRACT: The future experimental methods needed for composite life-cycle are identified by computationally simulating the fracture of an integrally stiffened composite structure. The simulation describes events occurring during the fracture progression at all composite structure scales, the fracture modes that contribute to those events and the respective local failure mechanisms. The fracture modes in their respective scales provide opportunities to suggest future testing techniques to measure them. For example, energies emitted can be calibrated to identify non-destructive techniques to measure corresponding energies such as acoustic, thermal and even optical. Successful testing methods can then be used to implement monitoring systems for in-service structural life-cycles.

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ABSTRACT: The objective of this report is to summarize the deterministic and probabilistic structural evaluation results of two structures made with advanced ceramic composites (CMC): internally pressurized tube and uniformly loaded flange. The deterministic structural evaluation includes stress, displacement and buckling analyses. It is carried out using the finite element code MHOST1, developed for the 3-D inelastic analysis of structures that are made with advanced materials. The probabilistic evaluation is performed using the integrated probabilistic assessment of composite structures computer code IPACS2. The affects of uncertainties in primitive variables related to the material, fabrication process, and loadings on the material property and structural response behavior are quantified. The primitive variables considered are: thermo-mechanical properties of fiber and matrix, fiber and void volume ratios, use temperature, and pressure. The probabilistic structural analysis and probabilistic strength results are used by IPACS to perform reliability and risk evaluation of the two structures. The results will show that the sensitivity information obtained for the two composite structures from the computational simulation can be used to alter the design process to meet desired service requirements. In addition to detailed probabilistic analysis of the two structures, the following were performed specifically on the CMC tube: (1) predicted the failure load and the buckling load, (2) performed coupled non-deterministic multi-disciplinary structural analysis, and (3) demonstrated that probabilistic sensitivities can be used to select a reduced set of design variables for optimization.

References listed at the end of the report:
ABSTRACT: A computational simulation method is presented to evaluate the deterministic and non-deterministic dynamic buckling of smart composite shells. The combined use of intraply hybrid composite mechanics, finite element computer codes, and probabilistic analysis enable the effective assessment of the dynamic buckling load of smart composite shells. A universal plot is generated to estimate the dynamic buckling load of composite shells at various load rates and probabilities. The shell structure is also evaluated with smart fibers embedded in the plies right next to the outer plies. The results show that, on the average, the use of smart fibers improved the shell buckling resistance by about 10% at different probabilities and delayed the buckling occurrence time. The probabilistic sensitivities results indicate that uncertainties in the fiber volume ratio and ply thickness have major effects on the buckling load while uncertainties in the electric field strength and smart material volume fraction have moderate effects. For the specific shell considered in this evaluation, the use of smart composite material is not recommended because the shell buckling resistance can be improved by simply re-arranging the orientation of the outer plies, as shown in the dynamic buckling analysis results presented in this report.

References listed at the end of the paper:

ABSTRACT: A methodology is developed to computationally assess the probabilistic composite behavior at all composite scales (from micro to structural) due to the uncertainties in the constituent (fiber and matrix) properties, in the fabrication process and in structural variables (primitive variables). The methodology is computationally efficient for simulating the probability distributions of composite behavior, such as material properties, laminate and structural responses. Byproducts of the methodology are probabilistic sensitivities of the composite primitive variables. The methodology has been implemented into the computer codes: Probabilistic Integrated Composite ANalyzer (PICAN) and Integrated Probabilistic Assessment of Composite Structures (IPACS). The accuracy and efficiency of this methodology are demonstrated by simulating the uncertainties in composite typical laminates and comparing the results with the Monte Carlo simulation method.
Available experimental data of composite laminate behavior at all scales fall within the scatters predicted by PICAN. Multi-scaling is extended to simulate probabilistic thermo-mechanical fatigue and to simulate the probabilistic design of a composite redome in order to illustrate its versatility. Results show that probabilistic fatigue can be simulated for different temperature amplitudes and for different cyclic stress magnitudes. Results also show that laminate configurations can be selected to increase the redome reliability by several orders of magnitude without increasing the laminate thickness—a unique feature of structural composites.

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ABSTRACT: A computationally effective method is described to evaluate the nonlinear dynamic buckling of thin composite shells. The method is a judicious combination of available computer codes for finite element, composite mechanics and incremental structural analysis. The solution method is an incrementally updated Lagrangian. It is illustrated by applying it to a thin composite cylindrical shell subjected to dynamic loads. Buckling loads are evaluated to demonstrate the effectiveness of the method. A universal plot is obtained for the specific shell that can be used to approximate buckling loads for different dynamic loading rates. Results from this plot show that the faster the rate, the higher the buckling load and the shorter the time. Results also show that the updated solution can be carried out in the post buckling regime until the shell collapses completely.

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ABSTRACT: A computationally effective method is described to evaluate the probabilistic dynamic buckling of thin composite shells. The method is a judicious combination of available computer codes for finite element, composite mechanics and probabilistic structural analysis. The solution method is an incrementally updated Lagrangian. It is illustrated by applying it to a thin composite cylindrical shell subjected to dynamic loads. Both deterministic and probabilistic buckling loads are evaluated to demonstrate the effectiveness of the method. A universal plot is obtained for the specific shell that can be used to approximate buckling loads for different loading rates and different probability levels. Results from this plot show that the faster the rate, the higher the buckling load and the shorter the time. The lower the probability, the lower the buckling load for a specific time. Probabilistic sensitivity results show that the ply thickness, the fiber volume ratio, the fiber longitudinal modulus, dynamic load and loading rate are the dominant uncertainties in that order.

ABSTRACT: The research and development in composite mechanics are reviewed from 1965 to 2006. The
review covers micromechanics, macromechanics failure theories, impact resistance, structural analysis, plate and panel buckling, shell buckling, progressive fracture, containment, and probabilistic composite simulation. A few remarks are included about aerodynamic loads and a new all composite engine concept. Most of the sample cases are from the author's own research since this research covers all aspects of composites and since this avoids the permissions required by other authors when their results are included. References are cited as appropriate so that the reader can further look in any specific area.

ABSTRACT: We report on a nonlinear equation-based closed-form solution for a spring-loading-enclosed electrothermal post-buckling microbeam that expresses (a) the relation between the compressive loads and its corresponding lateral deflections and (b) the threshold loads required to trigger the buckling phenomenon, under the condition of a variety of transverse loads. Our theoretical research reveals that the post-buckling behavior varies considerably under different transverse load ranges. Three types of double-clamped microbeams connected to microsprings with different dimensions and compliances representing transverse loads were fabricated and measured using microelectromechanical systems (MEMS) technology. Excellent agreement was found between our theoretical analysis and experimental results to confirm our exact solutions. It proves that the influences on thermal post-buckling behavior are dependent on different microbeam dimensions and microspring compliances (i.e., transverse loads). Therefore, an electrothermal buckling/post-buckling beam under external transverse loads can be accurately predicted using our theoretical model, which can be applied to either existing microdevices that are based on similar principles or other potential applications.

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ABSTRACT: MBB-LAGRANGE is a powerful optimization code which allows the optimization of structures. To achieve the optimal design of a structure all special requirements must be fulfilled. That means that constraints e.g. stress, strains or displacements have to be in a feasible range while the objective function e.g. the structural weight reaches a minimum value. The results are strongly dependent on the optimization constraints which must be fulfilled. In this context local and global stability constraints may be essential for the design process. In the continuing development of MBB-LAGRANGE stability constraints are one of the major topics the MBB-LAGRANGE team is busy developing. One topic is the realization of local stability constraints of sandwich structures which will be discussed in this paper. The theoretical background and the integration into the optimization code MBB-LAGRANGE will be shown. An example of a helicopter sandwich structure will demonstrate the influence of this constraint type in the design process while optimal results are found. These results satisfy all requirements: local stability, stress and dynamic constraints.

ABSTRACT: Low-velocity instrumented impact tests were carried out on sandwich panels made of glass fiber-reinforced plastic facesheets and polyurethane foam core. The tests were carried out using a drop weight instrumented impact tester, connected to a data acquisition system. Four different types of sandwich samples using polyester/e-glass and epoxy/e-glass facesheet materials and polyurethane foam were considered for investigation. Two different face sheet materials were chosen to experimentally examine the effect of their elastic modulus on the impact response of the sandwich structures. The data acquisition system records the impact data such as impact force, penetration time and depth of penetration, and plots impact force versus depth of penetration and penetration time versus depth of penetration curves. From the recorded data the impact parameters such as maximum impact force, penetration time and depth of penetration versus impact energy were plotted to study the impact behavior. The results show that higher impact energy is required to break the epoxy/e-glass facesheet and backsheet sandwich specimens than other types of specimens examined. The impact damage caused to the facesheet, the core and the backsheet were thoroughly studied experimentally and the extent of damage caused to the facesheets and the core were also compared by finite element analyses.


ABSTRACT: In the four years since the previous review [Vinson(1)] composite materials and their use in structures have grown and matured considerably. In addition to the continuous & short fibre and particulate composites, there has been much progress in the areas of sheet moulding compounds, woven fabric & three dimensional composites and braided composites employing many of the same fibre materials. New thermoplastic polymers show real promise and progress in metal matrix composites has been made. The analysis of composite material structures subjected to static, vibratory, impact, environmental and long time loading continues to progress. Important effects such as creep, viscoelasticity, damping, postbuckling behaviour and delamination are better understood. However, strength and failure criteria remain areas that need much further investigation and agreement. There has been a rapid increase in simpler-to-use computer codes that are available from the government and universities that ease structural-material analysis and provide more comprehensive descriptions of structural behaviour. In education concerning composite materials, new textbooks have appeared, more universities and organisations are offering courses, and there is a trend of migration of professors to those institutions where composite material research is emphasised. Technology transfer and export controls have had an increasing affect upon the composite materials community, particularly with regard to metal matrix composites. These manifest themselves in sponsored research, both at universities and international meetings. In the aerospace industry, all composite aircraft such as the Sikorsky ACAP helicopter have been developed. The Grumman X-29 Forward swept wing aircraft will fly soon. New turbine engines using more composite materials are under study, as well as increased use of composites in many aircraft and spacecraft vehicles. Composites in the automotive and leisure industries continue on the increase. With increased volume of use and better methods of computer assisted design, analysis and manufacturing, application of composites will extend to other areas such as mass transport.
ABSTRACT: Foam core sandwich cylindrical shells with specially orthotropic composite face materials are treated. Methods by which to analyze and design these shells are presented to prevent overstressing, overall buckling, core shear instability and face wrinkling. In addition, analytic methods to determine the configuration and materials to achieve absolute minimum weight are developed and presented herein. These procedures provide the means to select the face thickness, the core depth, and the optimum foam core shear modulus to attain minimum weight for a given face material. A factor of merit is developed for selecting the composite face material to attain a minimum weight sandwich. The methods clearly define the maximum loads the sandwich shell can withstand without buckling or overstressing of the faces.

ABSTRACT: Sandwich construction offers several advantages over monocoque and various discretely stiffened structures. These include greater load carrying ability, reduced weight, higher buckling loads, and higher fundamental natural frequencies. Equations for the analysis and design of sandwich cylindrical shells subjected to beam-type bending are presented herein. These equations are then manipulated to provide the face thickness, core depth, and core shear modulus to produce a minimum weight structure for a given load index and face material system. A factor of merit to select the best face material is also presented. As examples, carbon/epoxy and E-glass /epoxy cross-ply composite faced sandwich shells are compared, and comparison with a monocoque cross-ply laminated shell is also presented.

ABSTRACT: The study of mechanics of sandwich structures and a development of new and innovative structural concepts have been conducted in the course of the effort. In particular, our research was concerned with a development of Sanders'-type theory of cylindrical sandwich shells with different facing operating in hostile environment. This theory was further extended to elliptical shells. The effects of internal ribs located on the inner surface of thefacings and the woven facing construction on the response of sandwich structures was studied. In particular, rib-reinforced facings were probably first suggested in the course of the present effort. These new structural concepts are important since woven facings can reduce the tendency to delamination, while rib-reinforced facing results in enhanced local strength and stiffness. Also, the effect of damage in the form of matrix cracks in the facings on the response and performance of sandwich panels was investigated. The similarity conditions for sandwich shells were formulated, jointly with Drs. Simitses, Song and Frostig. The study of a new concept of sandwich structures with truss-reinforced core (Z-fiber reinforced core) was undertaken. The latter design may prove attractive in applications where significant shear and off-axis loads are applied to the structures. Other subjects that were investigated include the evaluation of the shear correction coefficient for sandwich structures analyzed by the first-order theory. The latest effort was a development of an analytical model capable of predicting damping of sandwich structures.
ABSTRACT: A non-circular shell cross-section with flat sides and circular arc corners is analyzed using the theorem of minimum potential energy. Two-dimensional, plane strain assumptions are utilized, and the potential energy (PE) expression for the structure is developed, including first-order transverse shear deformation effects. The unknown displacements are represented by power series, and the PE expression is rewritten in terms of the summation convention for the power series. The variation of the PE expression is taken, leading to a linear system of equations that is solved for the unknown power series coefficients. With the displacements determined, stresses are calculated for a composite sandwich construction. Excellent agreement is found with other analytical methods and with finite element analyses.

ABSTRACT: A cylindrical shell with a non-circular cross-section consisting of flat sides and circular arc corners is analyzed using the theorem of minimum potential energy. The three-dimensional analysis builds on previous two-dimensional work. The potential energy expression for the structure is developed, including first-order transverse shear deformation effects. All unknown displacements are represented by power series, and the potential energy expression is rewritten in terms of the summation convention for the power series. The variation of the potential energy expression is taken, leading to a linear system of equations that is solved for the unknown power series coefficients. With the displacements determined, stresses are calculated for a composite sandwich construction. An examination of both short shells (less than twice the boundary layer length) and long shells (more than twice the boundary layer length) is made. The MPE method with power series is found to predict behavior well for short shells, but not for long shells.

ABSTRACT: The use of sandwich structures continues to increase rapidly for applications ranging from satellites, aircraft, ships, automobiles, rail cars, wind energy systems, and bridge construction to mention only a few. The many advantages of sandwich constructions, the development of new materials, and the need for high performance, low-weight structures insure that sandwich construction will continue to be in demand. The equations describing the behavior of sandwich structures are usually compatible with the equations developed for composite material thin-walled structures, simply by employing the appropriate in-plane, flexural, and transverse shear stiffness quantities. Only if a very flexible core is used, is a higher order theory needed.

Jack R. Vinson (Center for Composite Materials and College of Marine Studies, Department of Mechanical Engineering, Spencer Laboratory, University of Delaware, Newark, Delaware, USA), “Elastic instability (Buckling) of composite plates”, Chapter in Plate and Panel Structures of Isotropic, Composite and

ABSTRACT: (none given)

References listed at the end of the paper:


ABSTRACT: An experimental investigation was conducted to study the behavior under biaxial tensile loading of quasiisotropic graphite/epoxy plates with circular holes and to determine the influence of hole diameter on failure. The specimens were 40 cm×40 cm (16 in.×16 in.) laminates of [0/±45/90]s layup. Four hole diameters, 2.54 cm (1.00 in.), 1.91 cm (0.75 in.), 1.27 cm (0.50 in.) and 0.64 cm (0.25 in.), were investigated. Deformations and strains were measured using strain gages and birefringent coatings. Equal biaxial loading was introduced by means of four whiffle-tree grip linkages and controlled with a servohydraulic system. Initially, the circumferential strain is uniform around the boundary of the hole. Subsequently, with increasing load, regions of high strain concentration with nonlinear response develop at eight characteristic locations 22.5 deg off the fiber axes. Failure in the form of cracking and delamination initiates at these points. Maximum strains at failure on the hole boundary reach values up to twice the ultimate strain of the unnotched laminate. The effect of hole diameter on strength was described satisfactorily using an average biaxial-stress criterion. Good correlation was also obtained with theoretical predictions based on a tensor-polynomial failure criterion for the lamina and a progressive degradation model.

ABSTRACT: An experimental investigation was conducted to study the behavior under biaxial-tensile loading of [O2/±45]s graphite/epoxy plates with circular holes and to determine the influence of hole diameter on failure. The specimens were 40-cm×40-cm (16-in.×16-in.) graphite/epoxy plates of [O2/±45]s layup. Four hole diameters, 2.54 cm (1.00 in.), 1.91 cm (0.75 in.), 1.27 cm (0.50 in.) and 0.64 cm (0.25 in.), were investigated. Deformations and strains were measured using strain gages and birefringent coatings. Biaxial tension in a 2ratio1 ratio was applied by means of four whiffle-tree grip linkages and controlled with a servohydraulic system. Stress and strain redistributions occur around the hole at a stress level corresponding to localized failure around the 67.5-deg location and nonlinear strain response at the 0-deg location. Maximum measured strains at failure on the hole boundary are higher (approximately 0.016) than the highest ultimate strain of the unnotched laminate (0.010). Two basic patterns of failure were observed: (a) horizontal cracking initiating at points off the horizontal axis and accompanied by extensive delamination of the subsurface ±45 deg plies, and (b) vertical cracking along vertical tangents to the hole and accompanied by delamination of the outer 0-deg plies. The strength reduction ratios are lower than corresponding values for uniaxial loading by approximately 16 percent, although the stress-concentration factor under biaxial loading is lower.

ABSTRACT: The deformation and failure response of composite sandwich beams and panels under low velocity impact was reviewed and discussed. Sandwich facesheet materials discussed are unidirectional and woven carbon/epoxy, and woven glass/vinylester composite laminates; sandwich core materials investigated include four types of closed cell PVC foams of various densities, aluminum honeycomb, polyurethane foam, foam-filled honeycomb, and balsa wood. These materials were fully characterized under quasi-static loading and, in some cases, under high strain loading conditions as well. Sandwich beams were tested in an instrumented drop tower system under various energy levels, where load and strain histories and failure modes were recorded for the various types of beams. Peak loads predicted by spring-mass and energy balance models were in satisfactory agreement with experimental measurements. Failure patterns depend strongly on the impact energy levels and core properties. Failure modes observed include core indentation/cracking, facesheet buckling, delamination within the facesheet, and debonding between the facesheet and core. Sandwich beams with PVC cores tend to be more stable than beams with different cores. Although sandwich beams with balsa wood cores perform well under static loading, they fail catastrophically under impact loading due to the low fracture toughness along the grain direction. Sandwich beams with honeycomb cores show early catastrophic failure caused by the lack of continuity of the interface between the honeycomb core and the facesheet, resulting in debonding failure. In the case of sandwich panels, it was shown that static and impact loads of the same magnitude produce very similar far-field deformations. The induced damage is localized and is lower for impact loading than for an equivalent static loading. Static testing in general is more conservative regarding strain and damage levels. The load history, predicted by a model based on the sinusoidal shape of the impact load pulse, was in agreement with experimental results. A finite element model was implemented to capture the full response of the panel indentation. The investigation of post-impact behavior of sandwich structures shows that, although impact damage may not be readily visible, its effects on the residual mechanical properties of the structure can be quite detrimental.


ABSTRACT: This study is concerned with the modelling and simulation of delamination prediction of fibrous composite panels under low velocity impact of variable shape impactors. Mathematical formulations were developed and explained for the phenomena and simulations were carried out on ply orientations, stacking sequences, through-the-thickness, and width location of the delaminated areas. The delamination induced strategy was adopted to predict regions of high stress concentration in the vicinity of contact area leading to buckling load factor predictions. An eight, sixteen, and twenty four ply of codes [45/0/-45/90]S, [45/0/-45/90]2S, [45/0/-45/90]3S quasi-isotropic lay-ups, having fabric lamina properties were analyzed using ProEngineer/Mechanica a general purpose finite element method (FEM) software. The software was selected as it is widely distributed, well documented and user-friendly and has as a shell element facilities to generate stack of plies. The delaminated zones are represented by a series of circular area cases with zones for 0, 20, 40, 60, 80 and 100 mm diameters located from the top to the halfway through the thickness resulting in 4, 8, and 12 ply sub-laminates were studied by inducing delamination. Delamination induced models consisting of removing a considerable part from the specimen as well of a very thin and weaker material properties ply were tested. Results were compared against the normalized form of the buckling load for an undamaged virgin laminate. Predicted results were used to calculate and predict buckling load factors for delaminated specimens. Graphics, images and tables were drawn to compare the results. These predictions correlated closely with the results from available literature. The approach has been found to be reliable for the cases considered.
References listed at the end of the paper:


ABSTRACT: A unified analysis method based on two-dimensional elasticity theory is outlined for evaluation of bending, buckling and vibration of multilayer orthotropic sandwich beams and panels. The effects of initial geometric imperfections are included. It is shown that beams or panels deforming under conditions of plain stress or plane strain may be treated as special instances of folded-plate structures using computer programs which are now widely available. Examples are given, including evaluation of stress contours in a sandwich panel under patch load and analysis of overall and local (face-wrinkling) buckling modes in sandwich panels with stiff and soft cores.


ABSTRACT: This paper formulates the stiffness matrix and a procedure for exact solutions of the bending and overall buckling problem of a general class of sandwich beam and frame structures subjected to arbitrary loading and boundary conditions. The solutions for deflections, stresses and buckling load are exact in the sense that they satisfy the governing differential equation, interelement compatibility and all boundary conditions. A preliminary study of the behaviour of sandwich beams using the developed theory shows that the Saint Venant principle may not apply to sandwich beams regarding the effects of applied end moments. Restraint against shear deformations will generally reduce the deflections and shear stresses in the core, and increase stresses in the facings and the buckling load. Quantitative assessment of these and other factors can be easily carried out with the present theory.


ABSTRACT: A predictor–corrector method is presented for the efficient and reliable analysis of structural nonlinear behaviors. The key idea lies on modifying the starting point of iterations of the Newton iterative method. The conventional Newton method starts iterations at the previously converged solution point. However, in the present predictor–corrector method, a point close to the converged solution of the current step is predicted first, and then the Newton method starts iterative procedure at the predicted point. The predictor, the neural network in the present study, recognizes the pattern of the previously converged solutions to predict the starting point of the current step. Then the corrector, the standard Newton method in the present study, is used to obtain the converged solution by iterative computation starting at the predicted point. Numerical tests are conducted to demonstrate the effectiveness and reliability of the present predictor–corrector method. The performance of the present method is compared with the conventional Newton method and Riks' continuation method. The present predictor–corrector method saves computational cost significantly and yields stable results without diverging, for the nonlinear analysis with monotonous deformation path as well as complicated deformation path including buckling and post-buckling behaviors.

ABSTRACT: Laminated composite and sandwich panels are susceptible to mechanical damages in the transverse direction due to their relatively low strength in the transverse direction. For such damages to occur, laminated composite and sandwich panels usually experience geometrically nonlinear deformations. Therefore, analysis taking large deformations into account is required for predicting mechanical damages such as delamination. In the present study, a nonlinear predictor–corrector procedure is adopted for the accurate recovery of stresses in laminated composite and sandwich panels undergoing geometrically nonlinear deformations. It is a post-processing procedure based on the three-dimensional stress equilibrium equations, combined with an 18 node assumed strain solid finite element model based on the Hellinger–Reissner principle tailored for large rotation analysis of laminated composite and sandwich panels. The effectiveness of the proposed approach is demonstrated by means of numerical examples of laminated composite and sandwich panels subjected to mechanical loading and uniform temperature gradient in the thickness direction.


ABSTRACT: Local regions of bond failure between face sheet and core are often observed when sandwich structures are exposed to low energy impacts. Similarly, impact loads frequently result in delaminations within the face sheets. In the absence of any delaminations in the sandwich structure the buckling strain of the debonded region is in this work shown to be the key parameter in assessing the structural integrity of a sandwich component in compression. The objective of this study was to predict the buckling of the debonded region and to investigate the parameters controlling this instability. A large number of analyses of the delamination buckling problem, which in many ways may appear similar to the debond problem, have been carried out in the past. However, the debond-buckling problem has not been addressed before and as shown in this work there are significant differences. The Finite Element method was found able to predict all the experimentally observed phenomena accurately. These calculations were expensive, and a simple one-dimensional closed form solution is proposed for qualitative parametric investigations. Effects of material properties and initial imperfections were examined. Analyses of the buckling of a delamination suggest that the effect of the core can be ignored. In contrast, the results presented in this paper show that the core cannot be ignored in the case of buckling of a debond nor can it be simulated in terms of simple boundary conditions.


ABSTRACT: The use of composite sandwich construction is rapidly increasing in current and future airframe designs especially for general aviation aircraft and rotorcraft. Typically, sandwich constructions for these applications use thin-gage composite facesheets (0.020" to 0.045") which are cocured to honeycomb and foam cores. Due to the nature of these structures, damage tolerance is more complex than conventional laminated structures. Besides typical damage concerns such as through penetration and delamination, additional modes including core crushing and facesheet debonding must also be addressed. This complicates the certification process by introducing undefined Allowable Damage Limits (ADL) and Critical Damage Thresholds (CDT) as related to the ultimate and limit load carrying capability of the structure. This document provides a background review of previous damage tolerance investigations including an overview of traditional metallic damage tolerance methodologies. Illustrative summaries are presented which show the scope of previous investigation.
parameters such as impact energy, facesheet thickness, and core thickness of typical sandwich constructions. Also included is a compilation of damage tolerance certification procedures and regulations taken from FAR Part 23-29 for composite damage tolerance as well as recommendations from associated Advisory Circulars. Past and current airframe industry sandwich constructions which show the scope of current and future sandwich designs were also surveyed. In conclusion, a proposed future research approach and its methodology are presented which should aid in establishing certification guidelines and confidence involving the damage tolerance of sandwich constructions as they apply to general aviation aircraft and rotorcraft.

ABSTRACT: The use of sandwich structures with composite facesheets in commercial aviation is increasing. Such structures provide redundant load paths and high specific bending stiffness. Because of their structural efficiency, light-weight designs result in thin facesheets that are susceptible to impact damage. This study concentrated on the modeling aspects of damage tolerance of thin-gage composite sandwich structures. As such, it is a companion work to the FAA report "Review of Damage Tolerance for Composite Sandwich Airframe Structures," DOT/FAA/AR-99/49, August 1999, which contains a literature review and describes current technical challenges. Current analytical attempts to assess the damage tolerance of composite sandwich structures first characterize the damage state. Based on the type and extent of damage, models are constructed to determine the stress and strain distributions. A failure criterion is then implemented with the calculated stress and strain state. Often components of the damage are neglected to simplify the model of the sandwich structure. Two models to be developed are proposed. The first is a model to determine the extent of load transfer around a damaged area. Localized stiffness reductions will result in a shift in the neutral axis as well as load transfer in the damaged facesheet and to the undamaged facesheet. The amount of load transfer coupled with detailed models of facesheet stability and strength will provide a methodology to determine damage tolerance. The second model is of the specific damage resulting from low-speed impacts. This model will provide a methodology to predict the growth of such damage.

ABSTRACT: The first part of this paper is dedicated to the analytical and numerical characterization of local and global sandwich beam instabilities in a perfect linear framework. Analytical loads are extracted from an original unified model and used to understand in depth, through a parametric study, the role played by each geometrical and material parameter in the development of global as well as local instabilities. Also, the effects of the combinations of these characteristics is used to draw precious design indications. A low CPU time-consuming simplified model is then built and assessed. Critical loads and wavelengths computed from this model are shown to correlate very well with analytical predictions. It is established that this first approach is essential in order to lead to more detailed investigations in a numerical nonlinear framework which is the aim of the second part. The first geometrical nonlinear investigations in which linear elastic materials are considered permit to isolate sandwich configurations developing superior sub-critical post-buckling behaviours. As a
general trend, unstable behaviours are rather related to the occurrence of geometrical localizations along the beam. This is illustrated by the drastic effects of the so-called interactive buckling onto the whole stiffness of the sandwich beam. Moreover, it is shown that sandwiches are very sensitive towards imperfection sizes and forms. Eventually, an elastoplastic constitutive law is introduced for the core. It is demonstrated that plastic flow and strain localization in the core, combined with the occurrence of instabilities, are associated with a drastic drop in the global beam stiffness and with a strong decrease of the maximum limit load for some cases. The phenomenon of shear crimping is also observed which can be assimilated to a post-bifurcated development of the global buckling mode.

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ABSTRACT: Stability analysis of laminated soft core sandwich beam has been studied by a C0 FE model developed by the authors based on higher order zigzag theory (HOZT). The in-plane displacement variation is considered to be cubic for the face sheets and the core, while transverse displacement is quadratic within the core and constant in the faces beyond the core. The proposed model satisfies the condition of stress continuity at the layer interfaces and the zero stress condition at the top and bottom of the beam for transverse shear. Numerical examples are presented to illustrate the accuracy of the present model.

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ABSTRACT: Static analysis of skew composite shells is presented by developing a C_0 finite element (FE) model based on higher order shear deformation theory (HSDT). In this theory the transverse shear stresses are taken as zero at the shell top and bottom. A realistic parabolic variation of transverse shear strains through the shell thickness is assumed and the use of shear correction factor is avoided. Sander’s approximations are considered to include the effect of three curvature terms in the strain components of composite shells. The C_0 finite element formulation has been done quite efficiently to overcome the problem of C_1 continuity associated with the HSDT. The isoparametric FE used in the present model consists of nine nodes with seven nodal unknowns per node. Since there is no result available in the literature on the problem of skew composite shell based on HSDT, present results are validated with few results available on composite plates/shells. Many new results are presented on the static response of laminated composite skew shells considering different geometry, boundary conditions, ply orientation, loadings and skew angles. Shell forms considered in this study include spherical, conical, cylindrical and hyperbolic shells.

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“Buckling of sandwich composites; Effects of core-skin debonding and core density”, Applied Composite Materials, Vol. 12, No. 2, March 2005

ABSTRACT: Foam–core sandwich composites have been fabricated using innovative co-injection resin infusion technique and tested under in-plane compression. The sandwich construction consisted of Klegcell foam as core materials and S2-glass/vinyl ester composites as face sheets. Tests were conducted with various foam densities and also with implanted delamination between the core and the face sheet. The intent was to investigate the effect of core density, and the effect of core–skin debonds on the overall buckling behavior of the sandwich. Analytical and finite element calculations were also performed to augment the experimental observations. It has been observed that core density has direct influence on the global buckling of the sandwich panel, while embedded delamination seem to have minimal effect on both global as well as local buckling. Detailed description of the experimental work, finite element modeling and analytical calculations are presented in this paper.

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ABSTRACT: Thin solar sail membranes of very large span are being envisioned for near-term space missions. One major design issue that is inherent to these very flexible structures is the formation of wrinkling patterns. Structural wrinkles may deteriorate a solar sail’s performance and, in certain cases, structural integrity. A geometrically nonlinear, updated Lagrangian shell formulation is employed using the ABAQUS finite element code to simulate the formation of wrinkled deformations in thin-film membranes. The restrictive assumptions of true membranes as defined by tension field theory are not invoked. Two effective modeling strategies are introduced to facilitate convergent solutions of wrinkled equilibrium states. They include 1) the application of small, pseudorandom, out-of-plane geometric imperfections that ensure initiation of the requisite membrane-to-bending coupling in a geometrically nonlinear analysis and 2) the truncation of corner regions, where concentrated loads are prescribed, to improve load transfer, mesh quality, and kinematics and to reduce severe concentration of membrane stresses. The corner truncation necessitates replacing the concentrated force with a statically equivalent distributed traction. Several numerical studies are carried out, and the results are compared with recent experimental data. Good agreement is observed between the numerical simulations and experimental data.

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“A multi-scale refined zigzag theory for multilayered composite and sandwich plates with improved transverse shear stresses”, V International Conference on Computational Methods for Coupled Problems in Science and Engineering (COUPLED PROBLEMS 2013), S. Idelsohn, M. Papadrakakis and B. chrefler (Editors)
ABSTRACT: The Refined Zigzag Theory (RZT) enables accurate predictions of the in-plane displacements, strains, and stresses. The transverse shear stresses obtained from constitutive equations are layer-wise constant. Although these transverse shear stresses are generally accurate in the average, layer-wise sense, they are
nevertheless discontinuous at layer interfaces, and thus they violate the requisite interlaminar continuity of transverse stresses. Recently, Tessler applied Reissner’s mixed variational theorem and RZT kinematic assumptions to derive an accurate and efficient shear-deformation theory for homogeneous, laminated composite, and sandwich beams, called RZT(m), where “m” stands for “mixed”. Herein, the RZT(m) for beams is extended to plate analysis, where two alternative assumptions for the transverse shear stresses field are examined: the first follows Tessler’s formulation, whereas the second is based on Murakami’s polynomial approach. Results for elasto-static simply supported and cantilever plates demonstrate that Tessler’s formulation results in a powerful and efficient structural theory that is well-suited for the analysis of multilayered composite and sandwich panels.

References listed at the end of the paper:

Tessler, A., Gherlone, M., Versino D. and Di Sciuva, M., “Analytic and computational perspectives of multi-scale theory for homogeneous, laminated composite and sandwich beams and plates”, NASA Technical Report, NASA/TP-2012-217573; L-20141; NF1676L-14627, 2012 (See also possibly AIAA/SDM Conference, 2012) ABSTRACT: This paper reviews the theoretical foundation and computational mechanics aspects of the recently developed shear-deformation theory, called the Refined Zigzag Theory (RZT). The theory is based on a multi-scale formalism in which an equivalent single-layer plate theory is refined with a robust set of zigzag local layer displacements that are free of the usual deficiencies found in common plate theories with zigzag kinematics. In the RZT, first-order shear-deformation plate theory is used as the equivalent single-layer plate theory, which represents the overall response characteristics. Local piecewise-linear zigzag displacements are used to provide corrections to these overall response characteristics that are associated with the plate
heterogeneity and the relative stiffnesses of the layers. The theory does not rely on shear correction factors and is equally accurate for homogeneous, laminated composite, and sandwich beams and plates. Regardless of the number of material layers, the theory maintains only seven kinematic unknowns that describe the membrane, bending, and transverse shear plate-deformation modes. Derived from the virtual work principle, RZT is well-suited for developing computationally efficient, C0-continuous finite elements; formulations of several RZT-based elements are highlighted. The theory and its finite elements provide a unified and reliable computational platform for the analysis and design of high-performance load-bearing aerospace structures.

References listed at the end of the report:
ABSTRACT: This paper reviews multi-scale computational homogenisation frameworks for the non-linear behaviour of heterogeneous thin planar shells. Based on a review of some of the currently available methods, a computational homogenisation scheme for shells is applied on to representative volume elements for plain weave composites. The effect of flexural loading on the potential failure modes of such materials is analysed, focusing on the reinforcement-matrix delamination mechanism. The attention is next shifted toward failure localisation in masonry unit cells. Subsequently, a recently developed computational FE solution scheme accounting for damage localisation at structural scales based on RVE computations is applied.

References listed at the end of the paper:

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(1) Structures and Materials Group, College of Aeronautics, Cranfield University, Bedford, Mk 43 0AL, UK
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ABSTRACT: This paper describes the results of an experimental investigation and a numerical simulation on the impact damage on a range of sandwich panels. The test panels are representative of the composite sandwich structure of the engine nacelle Fan Cowl Doors of a large commercial aircraft. The low-velocity impact response of the composites sandwich panels is studied at five energy levels, ranging from 5 to 20 J, with the intention of investigating damage initiation, damage propagation, and failure mechanisms. These impact energy levels are typically causing barely visible impact damage (BVID) in the impacted composite facesheet. A numerical simulation was performed using LS-DYNA3D transient dynamic finite element analysis code for calculating contact forces during impact along with a failure analysis for predicting the threshold of impact damage and initiation of delaminations. Good agreement was obtained between numerical and experimental results. In particular, the numerical simulation was able to predict the extent of impact damage and impact energy absorbed by the structure. The results of this study is proving that a correct numerical model can yield significant information for the designer to understand the mechanism involved in the low-velocity impact event, prior to conducting tests, and therefore to design a more efficient impact-resistant aircraft structure.

Shokrieh, M.M. and Askari, A. (Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran Univ. of Science and Technology, Narmak, Tehran, Iran), “Similitude Study of Impacted Composite Laminates under Buckling Loading.” ASCE J. Eng. Mech., 139(10), 1334–1340, 2013
ABSTRACT: In this study, critical buckling load of an impacted composite laminate is predicted, using the structural similitude method. Because of impact loading, damaged regions have formed in the laminate. To establish similarity conditions between impacted laminates for buckling loading, the idea of sequential similitude method is introduced. According to the sequential similitude method, similarity conditions can be established for a structure subjected to different loading situations, provided that each loading event is simulated independently. On the basis of this method, to develop similarity conditions for buckling loading of impacted composite laminates, similarity conditions are developed first for impact loading and then for buckling loading separately. Afterward, the obtained conditions are implemented in the commercial finite-element software, ABAQUS, to obtain the critical buckling load. Results show that sequential similitude method can be used as a simple and accurate method for prediction of buckling load of impacted laminates.

ABSTRACT: The bending behavior of a general sandwich beam, delaminated (debonded) at one of the skin-core interfaces, with transversely flexible core, based on variational principles is analytically investigated. The beam construction consists of upper and lower, metallic or composite laminated symmetric skins, and a soft core of a foam or low-strength honeycomb type. The delamination considered is a crack (debond) in which the crack faces may be in contact vertically, but can slip horizontally with respect to one another. The elastic analysis consists of a two-dimensional formulation for the core, in longitudinal and transverse directions, combined with a beam theory formulation for the skins. The effects of the vertical flexibility of the core, in the undelaminated and the delaminated regions, with and without contact, on the behavior are considered. The use of a high-order theory yields a non-linear displacement field in the core, in the undelaminated region, and determines the shear and the peeling (normal) stresses at the skin-core interfaces in the delaminated and the fully bonded regions, as well as at the crack tips. Any type of loading, distributed, localized or concentrated, located either at the upper or the lower skin, or at both, as well as any type of boundary and continuity conditions differing from one skin to the other and to the core at the same section, are allowed. The effect of the delamination length and location on the overall behavior and on the peeling stresses at the skin-core interfaces, are studied.

ABSTRACT: For the determination of debonded sandwich panel residual strength with lateral loading a parametric finite element model is developed. The parametric model allows an arbitrary positioning of the debond within the panel and consists of both solid and shell elements. A fracture mechanical approach using the crack flank displacements obtained from the FEA solution combined with measured mixed-mode fracture toughness values are used to determine the ultimate failure load. Experiments were conducted to compare against the analysis results. The comparison of numerical and experimentally achieved results showed that the used modeling approach predicts the failure load and failure mode well.

ABSTRACT: This thesis highlights research aimed at predicting the compressive failure of sandwich beams with interfacial delaminations. A nonlinear finite element analysis was performed to simulate axial compression of the debonded sandwich beams. The load-deflection diagrams were generated for a variety of specimens used in a previous experimental study. The energy release rate at the crack tip was computed using the J-integral, and plotted as a function of the displacement and load. A detailed stress analysis was performed and the critical stresses in the face sheet and the core were computed. Further, the core was modeled as a elastic, perfectly plastic material and a nonlinear post-buckling analysis was performed. For this model, load-deflection curves, energy release rate plots and von Mises stress plots were generated. By comparing the experimental failure load and the finite element analysis results, the conclusions were reached and the scope of future research in this project was defined.
References listed at the end of the paper:

ABSTRACT: A nonlinear finite element analysis was performed to simulate axial compression of sandwich beams with debonded face sheets. The load-end-shortening diagrams were generated for a variety of specimens used in a previous experimental study. The energy release rate at the crack tip was computed using the J-integral, and plotted as a function of the load. A detailed stress analysis was performed and the critical stresses in the face sheet and the core were computed. The core was also modeled as an isotropic elastic-perfectly plastic material and a nonlinear post buckling analysis was performed. A Graeco-Latin factorial plan was used to study the effects of debond length, face sheet and core thicknesses, and core density on the load-carrying capacity of the sandwich composite. It has been found that a linear buckling analysis is inadequate in determining the maximum load a debonded sandwich beam can carry. A nonlinear post-buckling analysis combined with an elasto-plastic model of the core is required to predict the compression behavior of debonded sandwich beams.

**ABSTRACT:**

Based upon the interfacial spring-layer model, a state-space approach for the energy release rate analysis of stiffened laminates with a planar delamination was presented. The main advantages of the present method are that the same mesh is used for each layer, and only the so-called state variables at the top and bottom surfaces of structure in the final control equation of structures are involved. On the other hand, the oscillatory singular stresses around the delamination front are avoided as a result. Instead, stress resultant jumps are found in the sublaminate across the delamination front. Moreover, the technique accounts for the compatibility of displacements and stresses between layers and the transverse shear deformation in the control equation of structure. To avoid the possibility of material penetration phenomenon of the delaminated region, the unilateral frictionless contact interface is adopted in the interfacial spring layer between sublaminates. With the aid of the virtual crack closure technique, the accuracy of the method was assessed by comparing the results with existing examples. The effects of stiffeners were analyzed by the present method.

Song-Jeng Huang (Department of Mechanical Engineering, National Chung Cheng University, 160 San-Hsing, Ming-Hsiung Chia-Yi, 621, Taiwan, ROC), “An analytical method for calculating the stress and strain in adhesive layers in sandwich beams”, Composite Structures, Vol. 60, No. 1, April 2003, pp. 105-114, doi:10.1016/S0263-8223(02)00288-X

**ABSTRACT:** Various studies on stress–strain modeling of adhesively bonded sandwich beams are briefly described in this paper. An analytical model of sandwich beams taking into account contribution of adhesive layers towards the overall beam stiffness is then proposed. In this model the displacements of each of the five constituent layers of a sandwich beam are computed considering the overall continuity conditions of the sandwich beam. The Euler–Ostrogradskii equations are used to derive the equations of equilibrium, which contain four differential equations with 12 orders. For validation purpose, a case study of a simply supported three-point bending sandwich beam subjected to a load at the mid-span of the beam is carried out using the proposed analytical method, finite element method and a theory proposed by Allen [Analysis and Design of Structural Sandwich Panels, Oxford, UK, 1969]. From the comparison of results obtained from the three methods, there are reasons to suggest improvements in reliability and accuracy of the proposed analytical method, which takes the effect of the adhesive layers into account, over Allen’s theory. The proposed method has clearly shown that the contribution of the adhesive layers to the overall strength of a given sandwich beam cannot be neglected.


**ABSTRACT:** The practical value of the geometrically nonlinear higher-order theory is demonstrated using four-point bend tests carried out on sandwich beam specimens comprised of aluminum face sheets and a PVC foam core. The experimental results were compared with the predictions of classical sandwich theory, and with linear and geometrically nonlinear higher-order sandwich panel theory. The analytical predictions based on the higher-order theory are in excellent agreement with the experimental results. Response parameters show fundamentally distinct behavior with increasing external load, both in the particular section and along the span.
Considering the longitudinal displacements, there is a significant geometrically nonlinear stage of the response that precedes the appearance of the material nonlinearity. The peeling stresses also exhibit significant geometrical nonlinearity in the vicinity of the internal supports. The linear higher-order theory can be used efficiently to estimate the vertical displacements of the soft-core sandwich beams up to high load levels with a great accuracy. Premature failure of sandwich beam specimens with weak adhesive layers is caused by high peeling stresses in the upper interface layer at the ends of the specimen, and the loading capacity decreases by more than 40%.


ABSTRACT: Failure modes for sandwich beams of GFRP laminate skins and Nomex honeycomb core are investigated. Theoretical models using honeycomb mechanics and classical beam theory are described. A failure mode map for loading under 3-point bending is constructed, showing the dependence of failure mode and load on the ratio of skin thickness to span length and honeycomb relative density. Beam specimens are tested in 3-point bending. The experimental data agree satisfactorily with the theoretical predictions. The effect of honeycomb direction is also examined. The concept of a failure mode map is extended to give a useful design tool for sandwich panels manufacturers and their customers.


ABSTRACT: Sandwich construction incorporating a honeycomb cellular core offers the attainment of structures that are very stiff and strong in bending while the weight is kept at a minimum. Generally, an aluminum or Nomex honeycomb core is used in applications requiring sandwich construction with fiber-reinforced composite facesheets. However, the use of a fiber-reinforced composite core offers the potential for even lower weight, increased stiffness and strength, low thermal distortion compatible with that of the facesheets, the absence of galvanic corrosion and the ability to readily modify the core properties to suit specialized needs. Furthermore, the material of the core itself will exhibit anisotropic material properties in this case. In order to design, analyze and optimize these structures, knowledge of the effective mechanical properties of the core is essential. In this paper, the effective three-dimensional mechanical properties of a composite hexagonal cell core are determined using a numerical method based on a finite element analysis of a representative unit cell. In particular, the geometry of the simplest repeating unit of the core as well as the appropriate loading and boundary conditions that must be applied is presented.


ABSTRACT: Sandwich panels can fail in several ways. The faces and core can yield plastically or fracture depending on the nature of the materials from which they are made; the compressive face can buckle locally or “wrinkle”, and the bond between the faces and core can fracture, causing delamination. The critical failure mode, which occurs at the lowest load, depends in part on the properties of the face and core materials and, in part, on the design of the beam. Here, we develop equations describing the load at which failure occurs for each
possible failure mode for a sandwich beam with face and core materials that yield plastically. We then develop a failure mode map, with axes of core relative density and the ratio of face thickness to span length, which, for a given loading configuration and set of face and unfoamed solid core materials, shows the dominant failure mode for every possible beam design. Tests on sandwich beams with aluminum faces and rigid polyurethane foam cores show that the equations and map describe failure well. The map can then be used to design the minimum-weight sandwich beam for a given strength. Similar failure mode maps can be developed for sandwich beams made from face and core materials that fracture and for sandwich plates.

ABSTRACT: In a sandwich beam made of materials that yield plastically, the main modes of failure are yielding and wrinkling of the face and yielding of the core in shear. The minimum weight design of beam is such that the face and core fail simultaneously; otherwise, one component is overdesigned. In this paper, we find the minimum weight design of a foam core sandwich beam or plate of a given strength by constraining the face and core to fail simultaneously using the failure equations developed in the companion paper. We also make use of property-density relationships for foam cores to include the density of the core as one of the beam design parameters to be found in the optimization analysis. The results give the face and core thicknesses and the core density which minimize the weight of a foam core sandwich beam or plate of a given strength.

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ABSTRACT: Sandwich beams with metallic foam cores can fail by several modes: face yielding, face wrinkling, core yielding and indentation. We estimate the initial failure load, corresponding to the first deviation from linearity in the load–deflection curve as well as the peak load for each mode. Failure mode maps are constructed which illustrate the dominant failure mode for practical beam designs. The results of the analysis are compared with experiments on sandwich beams with aluminum foam cores in three-point bending. The peak loads and the failure modes are described well by the analysis.

ABSTRACT: Foams exhibit size effects: if the specimen dimensions are of the same order as the cell size, the moduli and strength depend on specimen size. Metallic foams have particularly large cells (typically 2–20 mm), potentially giving rise to size effects when they are used in sandwich beams. Previous studies have shown that
the shear strength of metallic foams bonded to rigid plates increases by over 50% if the specimen thickness is equal to the cell size. In this study, sandwich beams with aluminum alloy faces and aluminum alloy foam cores were tested in three-point bending to characterize the effect of the beam depth on the limit load. Beams of constant ratio of core thickness to span length but different absolute values of core thickness were tested, and the measured limit loads were compared to analytical values. The analysis gives a good description of the measured limit load when the shear size effect is accounted for.


ABSTRACT: Plastic collapse modes of sandwich beams have been investigated experimentally and theoretically for the case of an aluminium alloy foam with cold-worked aluminium face sheets. Plastic collapse is by three competing mechanisms: face yield, indentation and core shear, with the active mechanism depending upon the choice of geometry and material properties. The collapse loads, as predicted by simple upper bound solutions for a rigid, ideally plastic beam, and by more refined finite element calculations are generally in good agreement with the measured strengths. However, a thickness effect of the foam core on the collapse strength is observed for collapse by core shear: the shear strength of the core increases with diminishing core thickness in relation to the cell size. Limit load solutions are used to construct collapse maps, with the beam geometrical parameters as axes. Upon displaying the collapse load for each collapse mechanism, the regimes of dominance of each mechanism and the associate mass of the beam are determined. The map is then used in optimal design by minimising the beam weight for a given structural load index.

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ABSTRACT: Sandwich panels and beams are used in bending and compression dominated components. The retention of their load capacity in the presence of imperfections is a central consideration. To address this issue, sandwich beams with metallic foam cores have been tested in four-point bending following the introduction of imperfections, created by impressing the face sheets. Limit load expressions for face yielding, core shear, and indentation failure have been developed and used to construct failure mechanism maps. From these maps, specimen designs were determined. Imperfections were introduced by indenting to varying penetrations. The indents were located on both the compressive and tensile side of bending configurations. Experimental measurements of the load/deflection response are obtained and compared with finite element results.

Craig A. Steeves and Norman A. Fleck (Cambridge University Engineering Department, Trumpington Street, Cambridge, CB2 1PZ, UK), “Collapse mechanisms of sandwich beams with composite faces and a foam core, loaded in three-point bending. Part I: analytical models and minimum weight design”, International Journal of
ABSTRACT: Analytical predictions are made for the three-point bending collapse strength of sandwich beams with composite faces and polymer foam cores. Failure is by the competing modes of face sheet microbuckling, plastic shear of the core, and face sheet indentation beneath the loading rollers. Particular attention is paid to the development of an indentation model for elastic faces and an elastic–plastic core. Failure mechanism maps have been constructed to reveal the operative collapse mode as a function of geometry of sandwich beam, and minimum weight designs have been obtained as a function of an appropriate structural load index. It is shown that the optimal designs for composite–polymer foam sandwich beams are of comparable weight to sandwich beams with metallic faces and a metallic foam core.


ABSTRACT: This study focuses on the competing collapse mechanisms for simply supported sandwich beams with composite faces and a PVC foam core subjected to three point bending. The faces comprise Hexcel Fibredux 7781-914G woven glass fibre-epoxy prepreg, while the core comprises closed cell Divinycell PVC foam of relative density 6.6% and 13.3%. The mechanical properties of the face sheets and core are measured independently. Depending upon the geometry of the beam and the relative properties of the constituents, collapse is by core shear, face sheet microbuckling or by indentation beneath the middle loading roller. A systematic series of experiments and finite element simulations have been performed in order to assess the accuracy of simple analytic expressions for the strength. In general, the analytic expressions for peak load are adequate; however, simple beam theory becomes inappropriate and the analytic models are inaccurate for stubby beams with thick faces relative to the core thickness. A failure mechanism map is constructed to reveal the dependence of the dominant collapse mechanism upon the geometry of the beam.


ABSTRACT: Closed-form high-order theory of sandwich panels, including transverse flexibility and shear rigidity of a core, as well as geometrical nonlinearity of unsymmetric faces is generalized for sandwich panels of constant curvature. Variational calculus is used to derive the set of governing equations describing a stress-deformation response of the panel to arbitrary loads. Boundary conditions are presented both in the local and global formulations. The procedure for the numerical solution of the governing nonlinear differential equations is based on the finite-difference method with deferred corrections. The solution technique is illustrated through numerical examples. Influence of the geometrical nonlinearity on the overall behaviour of the sandwich panel and localized effects are demonstrated.

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ABSTRACT: A model for the load-deformation response of a shallow singly-curved sandwich panel is developed on the basis of Reissner plate theory. For arbitrary initial panel geometry and lateral load distribution, the load-deflection relations are derived in the form of two implicit equations. Explicit equations describing the deformation behaviour of symmetric sandwich panels subjected to symmetric loading are also presented. A stability analysis is performed for a simply-supported sandwich panel of constant curvature and loaded by uniform pressure. Structural and buckling parameters which depend on the panel geometry and material properties are introduced. These parameters allow the buckling behaviour of shallow sandwich panels to be predicted. The ideas behind the analysis and the solution technique are illustrated through numerical examples.

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ABSTRACT: Overall behaviour of a simply-supported singly-curved shallow sandwich panel under lateral loading is considered. Three types of linear models — general shell, shallow shell and curved plate theories — are employed to describe a static overall behaviour of such a panel. The shallow panel with a constant curvature loaded by a uniform pressure is used as a trial case to assess the accuracy of the models. A nonlinear model for a panel of arbitrary shape under an arbitrary loading is developed on the basis of the curved plate theory. A closed-form nonlinear analytic solution for the panel of constant curvature under a uniform lateral pressure is obtained, and its accuracy is estimated. An experimental investigation of a sandwich beam under a uniform lateral loading is carried out, and the data obtained are compared with the theoretical calculations.

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ABSTRACT: The overall behaviour of the shallow sandwich panel with an arbitrary initial profile and general boundary conditions under an arbitrary load is discussed. The structural parameters of the panel that allow one to generalize description of the overall behaviour of the panel are introduced. The mathematical model based on the Reissner–Mindlin plate theory is developed, and the set of governing equations is derived. The implicit nonlinear and explicit linear solutions are obtained for the uniformly loaded panel with uniform curvature and similar boundary restraints. An analysis of the global stability is performed for panels that have general configurations. Three stability modes, namely stable deformation, symmetric and asymmetric snap-throughs are found possible. The influence of the structural parameters of the panel on its global behaviour is studied.

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ABSTRACT: The shallow singly curved and rectangular in-plane sandwich panels affected by lateral loads are considered. The set of governing equations on the basis of the Timoshenko–Reissner plate theory is derived for these panels in the case of general boundary conditions. Usage of any real boundary condition is ensured via an introduction of the Airy's function and two potentials including a potential of the vortex-type. The technique of the numerical solution is based on a combination of the solutions by Navier and Levy. Numerical analysis is carried out for the panel that is simply supported along all four edges and for the panel that is simply supported along its curved boundaries and has hinge-like supports along the straight boundaries.


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ABSTRACT: This paper addresses the effect of local indentation/impact damage on the bearing capacity of foam core sandwich beams subjected to edgewise compression. The considered damage is in a form of through-width zone of crushed core accompanied by a residual dent in the face sheet. It is shown that such damage causes a significant reduction of compressive strength and stiffness of sandwich beams. Analytical solutions estimating the Euler’s local buckling load are obtained for two typical modes of damage. These solutions are validated through experimental investigation of three sandwich configurations. The results of the analytical analysis are in agreement with the experimental data.

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ABSTRACT: A failure mode criterion for piece-wise functionally graded sandwich composites is proposed and compared against experimental data. The average peak load for low and high density core configurations at upper region is 138% and 192% higher than the reference group. The proposed failure mode model predicts with accuracy the failure mechanisms. The best performance was obtained by the beam configuration where the core layer with highest density is located right below the upper face-sheet. This case not only leads to the highest value of normal wrinkling stress but it also prevents the core plastic collapse occurrence. However, the core failure by yielding will occur regardless of the core layer stacking sequence.

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ABSTRACT: The paper aims at evaluating the damage resistance of sandwich structure, composed of Nomex® honeycomb core (thickness: 10 mm and 20 mm) and two kinds of facesheets (carbon/epoxy and glass/epoxy laminates) subjected to low velocity impact. The impact tests are performed using the instrumented impact-testing machine and resulting impact damages are inspected by scanning acoustic microscope (SAM). Based on the force and energy histories, six parameters have been introduced as following: load at incipient damage, energy absorbed at incipient load, maximum load, total energy absorbed during impact, plastic energy absorbed by damage, and impact damage area. The impact resistance of the sandwich structure is greatly influenced by the facesheet type and core thickness. And their impact damages are mainly delamination in the facesheets, which is peanut-shaped with major axis along their lower fiber orientation, and their behavior is dependent on the facesheets.


ABSTRACT: In the present paper, the dynamic stability of thin, isotropic cylindrical shells under combined static and periodic axial forces is studied using four common thin shell theories; namely, the Donnell, Love, Sanders and Flugge shell theories. For these four cases, the contribution of the stresses due to the external axial forces are accounted for according to the Donnell theory. In the present analysis, a normal-mode expansion of the equations of motion yields a system of Mathieu–Hill equations, the stability of which is examined. The parametric resonance responses are analyzed based on Bolotin’s method and the effects of the length-to-radius and thickness-to-radius ratios of the cylinder on the instability regions are examined and compared using the four theories. The effects of variation in the magnitude of the axial forces were also examined.

T.Y. Ng and K.Y. Lam (Centre for Computational Mechanics, Department of Mechanical & Production Engineering, National University of Singapore), “Effects of boundary conditions on the parametric resonance of cylindrical shells under axial loading”, Shock and Vibration, Vol. 5, pp 343-354, 1998

ABSTRACT: In this paper, a formulation for the dynamic stability analysis of circular cylindrical shells under axial compression with various boundary conditions is presented. The present study uses Love’s first approximation theory for thin shells and the characteristic beam functions as approximate axial modal functions. Applying the Ritz procedure to the Lagrangian energy expression yields a system of Mathieu–Hill equations the stability of which is analyzed using Bolotin’s method. The present study examines the effects of different boundary conditions on the parametric response of homogeneous isotropic cylindrical shells for various transverse modes and length parameters.

References listed at the end of the paper:


ABSTRACT: This article deals with the transient response of a stiffened composite plate subjected to low velocity impact. An approximate solution for the prediction of plate response to low velocity impact is presented. This solution includes the combined action of the plate and stiffeners as well as the effects of the contact and transverse shear deformation. A finite element (FE) approach is also proposed. In the FE approach, an impact force function based on Hertz contact law is linked into a commercial FE code, which facilitates the study of a more realistic model. Results predicted by the present solution for a simplified stiffened plate are compared with those by the FE approach for a realistic stiffened plate. Effects of the stiffener spacing and thickness, anisotropic material properties, impact mass and contact stiffness on the impact response are also examined.

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“Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches”,
ABSTRACT: The dynamic behavior of composite laminates is very complex because there are many concurrent phenomena during composite laminate failure under impact load. Fiber breakage, delaminations, matrix cracking, plastic deformations due to contact and large displacements are some effects which should be considered when a structure made from composite material is impacted by a foreign object. Thus, an investigation of the low velocity impact on laminated composite thin disks of epoxy resin reinforced by carbon fiber is presented. The influence of stacking sequence and energy impact was investigated using load–time histories, displacement–time histories and energy–time histories as well as images from NDE. Indentation tests results were compared to dynamic results, verifying the inertia effects when thin composite laminate was impacted by foreign object with low velocity. Finite element analysis (FEA) was developed, using Hill’s model and material models implemented by UMAT (User Material Subroutine) into software ABAQUS, in order to simulate the failure mechanisms under indentation tests.

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Hao Wu and Ying Yan (School of Aeronautic Science and Engineering, Beihang University, Beijing, 100083, China), “A Parametric Study for the Design of Stiffened Composite Panel”, COCOMAT (publisher, date, not given in the pdf file, most recent reference is 2008)

ABSTRACT: A parametric study is conducted for the design of stiffened composite panel (SCP). A SCP with two stiffeners, loaded under uniaxial compression load is studied, where effects of stiffener thickness and distance on the critical buckling behaviour of the SCP are investigated. It is illustrated that stiffener has an effect of boundary condition on the skin, and an optimal structural efficiency exists when this effect is significant enough. The boundary condition effect makes the whole SCP buckles as local skin buckling and its critical buckling behaviour is dominated by the local skin buckling with the lowest critical buckling load. The parametric study provides designer with comprehension of the stiffener/skin enhancement in the buckling behaviour of the SCP, serving for the design of SCP in the future.

References listed at the end of the paper:

ABSTRACT: Composite materials are finding increasing use on primary aerostructures to meet demanding performance targets while reducing environmental impact. This paper presents a finite-element-based preliminary optimization methodology for postbuckling stiffened panels, which takes into account damage mechanisms that lead to delamination and subsequent failure by stiffener debonding. A global-local modeling approach is adopted in which the boundary conditions on the local model are extracted directly from the global model. The optimization procedure is based on a genetic algorithm that maximizes damage resistance within the postbuckling regime. For a given loading condition, the procedure optimized the stacking sequence of several areas of the panel, leading to an evolved panel that displayed superior damage resistance in comparison with nonoptimized designs.

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ABSTRACT: This work aims at developing a genetic algorithm (GA) to pursue the optimization of hybrid laminated composite structures. Fiber orientation (predefined ply angles), material (glass-epoxy or carbon-epoxy layer) and total number of plies are considered as design variables. The GA is chosen as an optimization tool because of its ability to deal with non-convex, multimodal and discrete optimization problems, of which the design of laminated composites is an example. First, the developed algorithm is detailed explained and validated by comparing its results to other obtained from the literature. The results of this study show that the developed algorithm converges faster. Then, the maximum stress, Tsai-Wu and Puck (PFC) failure criteria are used as constraint in the optimization process and the results yielded by them are compared and discussed. It was found that each failure criterion yielded a different optimal design.

References listed at the end of the paper:
5. Girard, F., 2006, "Optimisation de Stratifiés en Utilisant un Algorithme Génétique", Master's Dissertation, Faculté des Sciences et Génie, Université Laval, Québec, Canada


ABSTRACT: The paper focuses on modelling uncertainty typical of the aircraft industry. The design problem involves maximizing a safety measure of an isotropic plate for a given weight. Additionally, the dependence of the weight on the level of uncertainty, for a specified allowable possibility of failure, is also studied. It is assumed that the plate will be built from future materials, with little information available on the uncertainty. Fuzzy set theory is used to model the uncertainty. Response surface approximations that are accurate over the entire design space are used throughout the design process, mainly to reduce the computational cost associated with designing for uncertainty. All of the problem parameters are assumed to be uncertain, and both a yield stress and a buckling load constraint are considered. The fuzzy set based design is compared to a traditional deterministic design that uses a factor of safety to account for the uncertainty. It is shown that, for the example problem considered, the fuzzy set based design is superior. Additionally, the use of response surface approximations results in substantial reductions in computational cost, allowing the final results to be presented in the form of design charts.

References listed at the end of the paper:


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ABSTRACT: An integrated step-by-step analysis procedure for the design of axially compressed stiffened composite panels is outlined. The analysis makes use of the effective width concept. A computer code, BUSTCOP, is developed incorporating various aspects of buckling such as skin buckling, stiffener crippling and column buckling. Other salient features of the computer code include capabilities for generation of data based on micromechanics theories and hygrothermal analysis, and for prediction of strength failure. Parametric studies carried out on a hat-stiffened structural element indicate that, for all practical purposes, composite panels exhibit higher structural efficiency. Some hybrid laminates with outer layers made of aluminium alloy also show great promise for flight vehicle structural applications.

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ABSTRACT: A generalized formulation for the doubly curved laminated composite shell is attempted using eight-noded curved quadratic isoparametric finite elements with all three radii of curvature. The formulation is also applied to the isotropic material as a special case. In the present investigation, only the paraboloid of revolution is taken up for computing the deflections and stress resultants. Various parametric studies are carried out and the current results for both isotropic and laminated composite shells are compared with those available in the published literature. The shape functions are obtained from interpolation polynomial and the element stiffness matrices are formed on the basis of macromechanical analysis of laminates using the principle of minimum potential energy.


ABSTRACT: Blade-stiffened composite plates have been analysed for transverse loads using the finite element method. An eight-noded isoparametric quadratic stiffened plate bending element has been employed for the analysis. The element can incorporate transverse shear deformation. First order shear deformation has been considered in the formulation; the stiffener can be placed anywhere within the plate element and need not necessarily follow nodal lines. Therefore, mesh divisions are independent of the stiffener location within the plate. The stiffness matrix of the stiffener element can be appropriately modified to include stiffness properties for all types of open-section stiffeners. The deflections and bending moments have been presented for simply supported square laminated plates with one central stiffener and for stiffened skew plates. The results are compared with those obtained by modeling the stiffened plate by an assemblage of eight-noded isoparametric flat shell elements. The effect of the number of layers of the plate and the stiffener on the flexural response of the stiffened plate is presented. The element is used to show the flexural response of different open-section stiffened plates having the same area of the stiffener cross section. Also, the effect of depth-to-thickness ratio of the stiffener having the same cross section and lamination has been presented.


ABSTRACT: This is a review covering the static and dynamic analysis of stiffened shells which have found widespread applications in a variety of engineering structures. The coverage aims at the analysis including (1) static, (2) free vibration, (3) transient dynamic response and (4) response under stochastic excitation. 214 references (cannot cut and paste them)

Kaustav Bakshi and Dipankar Chakravorty (Civil Engineering Department, Jadavpur University Kolkata-700 032, West Bengal, India), “First ply failure study of thin composite conoidal shells subjected to uniformly distributed load”, Thin-Walled Structures, 03/2014; 76:1–7. DOI: 10.1016/j.tws.2013.10.021

ABSTRACT: The civil engineers often need to cover large column free open spaces with thin shell structures. The doubly curved shells are characteristically stiff and the ruled surfaces are easy to fabricate. The aesthetically pleasing conoidal shells satisfy both these criteria and are preferred by structural engineers. The engineers now look out for strong but lightweight materials and as a result the laminated composites have
evolved. The first ply failure is a very important issue for laminated composites. Such studies for plates are reported but similar work on thin shells is very scanty. This paper is aimed to fulfill this lacuna.

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“Geometrically Linear and Nonlinear First-Ply Failure Loads of Composite Cylindrical Shells”,
doi: http://dx.doi.org/10.1061/(ASCE)EM.1943-7889.0000808
ABSTRACT: Review of the literature on first-ply failure of composite shells shows that research reports on first-ply failure of moderately thin, laminated composite cylindrical shell panels, using a geometrically nonlinear approach, are not available. The present paper aims to fill this deficiency. It uses a finite-element code developed using eight-noded, doubly-curved elements combined with modified Sanders’ first-approximation theory for thin shells and von Kármán-type nonlinear strains. The accuracy of the present geometric nonlinear and first-ply failure formulations are verified separately through solutions of two benchmark problems. Failure loads, failure modes (for individual stress or strain failure) or tendencies (for interactive stress failures), and the locations from where the failures initiate are reported. The results are discussed critically to formulate design guidelines, suggesting practical values for factors of safety applicable to failure loads. Such suggestions also consider the serviceability requirements.

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doi:10.1016/0045-7949(94)00329-2
ABSTRACT: A finite element analysis for studying the free vibration behaviour of generalized doubly curved laminated composite shells is presented using eight-noded curved quadrilateral isoparametric finite elements. The formulation assumes first-order shear deformation theory for thin and shallow shells, and also considers the two principal radii of curvature and the radius of cross-curvature. Some of the results obtained are compared with those present in the existing literature. Several other numerical results are presented by varying fibre orientations, lamination schemes, support spacings, aspect ratio, lower height to higher height ratio (for conoids), the thickness to radius ratio and radii of curvature ratio (for elliptic and hyperbolic paraboloids), which are relevant to the doubly curved shells.

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ABSTRACT: Composite stiffened plates have been analysed for large deflection using the finite element
method. An eight noded isoparametric laminated stiffened plate bending element developed earlier has been used. The element has the capability of including transverse shear deformation for the plate and the stiffener and incorporating one or more stiffeners anywhere within the element. The finite element analysis has been made using Mindlin's formulation and with the assumption of small rotation. The nonlinear equilibrium equations are solved by the Newton-Raphson iteration procedure. Plates and stiffened plates of isotropic and anisotropic material with different boundary conditions have been analysed and results have been compared with those available. Parametric studies have also been carried out.


ABSTRACT: Free vibration analysis of composite stiffened shell panels has been carried out for the first time. As there is no published literature available on the problem, the finite element technique has been applied using two elements, namely the nine-noded Lagrangian element and the heterosis element, for obtaining new results. An improved version of the stiffener modelling is presented here. In this modelling, stiffeners can be placed anywhere inside the element and it need not pass through the nodal lines. Moreover, both elements have the capacity of accommodating curved boundaries and incorporating transverse shear deformation. Results for stiffened composite cylindrical shells and doubly curved shells with different boundary conditions and various laminae orientations have been presented for both concentric and eccentric stiffeners. Parametric studies considering different variables have also been carried out.

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ABSTRACT: This analytical study is concerned with the free vibration, forced vibration, low velocity impact response as well as impact induced first ply failure of delaminated composite shells. It is based on a simple multiple delamination modeling which can take care of any arbitrary number and size of delaminations placed at any location of the laminate. Sander's shallow shell theory is applied for the shell analysis. First order shear deformation theory in conjunction with an eight noded isoparametric quadratic delaminated shell element with five degrees of freedom per node are used to develop the finite element formulation. Newmark's time integration algorithm is employed for solving the time dependent multiple equations of the plate and the impactor. Tsai-Wu failure criterion is used to predict the first ply failure of a laminate due to impact at every time step. Numerical results are generated for different cases by varying the size and location of delaminations as well as the stacking sequences. It is observed that the delaminations reduce the natural frequencies and increase the dynamic displacements. Critical impactor velocity to cause the first ply failure in a laminate is also reduced in the presence of a delamination.

N.V.S. Naidu and P.K. Sinha (Department of Aerospace Engineering, Indian Institute of Technology, Kharagpur 721302, India), “Nonlinear finite element analysis of laminated composite shells in hygrothermal
ABSTRACT: The large deflection bending behaviour of composite cylindrical shell panels subjected to hygrothermal environments is investigated in this paper. The present finite element formulation considers doubly curved thick shells and includes large deformations with Green–Lagrange strains. The analysis is carried out using quadratic eight-noded isoparametric element and the problem is solved using the incremental modified Newton–Raphson scheme. A parametric study is carried out varying the curvature ratios of composite cylindrical shell panels with simply supported and clamped support conditions.

References listed at the end of the paper:


ABSTRACT: The nonlinear transient response of composite shell panels subjected to mechanical load in hygrothermal environments is investigated using finite element method. The present formulation considers doubly curved thick shells and includes large deformations with Green–Lagrange strains. The analysis is carried out using quadratic eight-noded isoparametric element. The nonlinear time dependent equation is solved by using the Newmark average acceleration method in conjunction with an incremental modified Newton–Raphson scheme. The validity of the model is demonstrated by comparing the present results with the solutions available in the literature. A parametric study is carried out varying the curvature ratios and side to thickness ratios of composite cylindrical, spherical and hyperbolic paraboloid shell panels with simply supported boundary conditions.

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ABSTRACT: The nonlinear free vibration behaviour of laminated composite shells subjected to hygrothermal environments is investigated using the finite element method. The present finite element formulation considers doubly curved shells, and the Green–Lagrange type nonlinear strains are incorporated into the first-order shear deformation theory. The analysis is carried out using quadratic eight-noded isoparametric elements. The validity of the model is demonstrated by comparing the present results with the solutions available in the literature. A parametric study is carried out varying the curvature ratios and side to thickness ratios of composite cylindrical shell, spherical shell and hyperbolic paraboloid shell panels with simply supported boundary conditions.

Manoj Kumar Kath, “Dynamic instability of laminated composite curved panels in hygrothermal environment”, Ph.D. dissertation, Dept. of Civil Engineering, National Institute of Technology, Rourkela, India

ABSTRACT: Composite materials are increasingly used in aerospace, naval and high performance civil engineering structures such as aerospace, submarines, automobiles. The structural components, subjected to in-plane harmonic loads may undergo parametric resonance or dynamic stability due to certain combinations of the applied in-plane forcing parameters and natural frequency of transverse vibration. The parametric instability itself requires investigation of vibration and buckling of structures. The present study deals with free vibration, buckling and parametric resonance behavior of laminated composite plates under in-plane periodic loading under varying temperature and moisture. In this analysis, the effects of various parameters such as number of layers, aspect ratios, side-to-thickness ratios, ply orientations, static load factors, lamination angle and the degree of orthotropic are studied. A simple laminated plate model based on the first order shear deformation theory (FSDT) is developed for the free vibration, buckling and parametric instability effects of composite plates subjected to hygrothermal loading. The principal instability regions are obtained using Bolotin’s approach employing finite element method (FEM). An eight-node isoparametric quadratic element is employed in the present analysis with five degree of freedom per node. The element is modified to accommodate the laminated composite plates under hygrothermal environment, considering the effects of transverse shear deformation and rotary inertia. The element stiffness matrix, geometric stiffness matrix due to residual stresses, element mass matrix, geometric stiffness matrix due to applied in-plane loads and nodal load vector of the element are derived using the principle of minimum potential energy. They are evaluated using the Gauss quadrature numerical integration technique. Reduced integration technique is applied to avoid the possible shear locking. A computer program based on FEM in MATLAB environment is developed to perform all necessary computations. The basic vibration and buckling experiments are performed on the industry driven woven fiber Glass/Epoxy specimens subjected to hygrothermal environment. The specimens were hygrothermally conditioned in a humidity cabinet where the conditions were maintained at temperatures of 300K–425K and relative humidity (RH) ranging from 0-1.0% for moisture concentrations. The numerical and experimental results show that there is reduction in natural frequencies and buckling loads with increasing temperature and moisture concentration for laminates both for simply supported and clamped boundary conditions. The dynamic instability study using FEM revealed that, due to the static component of load, the instability regions tend to shift to lower frequencies. The onset of instability occurs earlier and the width of dynamic instability regions increases with rise in temperature and moisture concentration for different parameters. With increase in lamination angle, the width of the instability region becomes smaller. The onset of instability occurs later for square plates than rectangular plates with wider instability region with increase of aspect ratio. The ply orientation significantly affects the onset of instability. It is observed that the excitation frequency increases with introduction of curvatures from flat panel to doubly curved panel in hygrothermal environments. Thus the
instability behaviour of laminated composite panels is influenced by increase in number of layers, aspect ratio, side to thickness ratio, increase in static and dynamic load factor, geometry, material, ply lay-up and its orientation. This can be utilized to tailor the design of laminated composite panels in hygrothermal environment.

References listed at the end of the dissertation:


Sahu, S.K and Datta, P.K. (2001): Parametric resonance characteristics of Laminated composite doubly curved shells subjected to non


ABSTRACT: In this study the geometrically nonlinear transient response of the laminated composite doubly curved shells is investigated using the finite element method. The finite element model includes nonlinearity due to large deflection. A nine-noded isoparametric composite shell element including the first-order shear deformation is developed in curvilinear coordinates for the nonlinear transient analysis. The present formulation is based on the total Lagrangian approach and the material behavior is assumed to be linear and elastic. The governing equations have been solved by the Newton–Raphson iteration technique, wherein the Newmark method has been used for the time integration. The present results are found to compare well with those available in the literature. The nonlinear transient response of the cross-ply and three specially laminated spherical, cylindrical, and hyperbolic paraboloidal shell panels are also analyzed and the results are discussed.


ABSTRACT: In the present investigation, the geometrically nonlinear analysis of laminated doubly curved shells in a hygrothermal environment is presented using the finite element method. The laminated composite shells may be exposed to moisture and temperature during their service life. Hygrothermal effects induce residual stresses and the laminated shell may undergo large bending deformation. The shell geometry used in the formulation is derived using the orthogonal curvilinear coordinate system. Based on the principle of virtual work the nonlinear finite element equations are derived. A total Lagrangian approach associated to the arc-length method is implemented to solve the equilibrium equations. The present results are found to compare well with those available in the open literature and parametric studies are performed to analyze the nonlinear deflections of [0 degrees/45 degrees/90 degrees](s) laminated spherical, cylindrical and conoidal shell panels under hygrothermal condition.

ABSTRACT: In the present investigation the geometrically nonlinear post buckling analysis of laminated composite doubly curved shells is presented using finite element method. The finite element model includes the general geometric nonlinearity due to large deflection. The present nonlinear strain displacement relations are expressed in the curvilinear coordinates. The material behaviour is, however, assumed to be linear and elastic. The principle of virtual work forms the basis to derive the nonlinear finite element equations. To solve the nonlinear finite element equations an incremental iterative technique based on the arc length method is employed. The present results are found to compare well with those available in the literature and are also able to capture both snap through and snap back post buckling behaviour. The nonlinear responses of three specially laminated spherical, cylindrical and conoidal shells are analyzed and the results are discussed.


ABSTRACT: In the present investigation, the geometrically nonlinear post buckling analysis of piezoelectric laminated doubly curved shells is presented using finite element method. The piezoelectric material is used in the form of layers or patches embedded and/or surface bonded on laminated composite shells. The finite element model includes the general geometric nonlinearity due to large deflection. The shell geometry used in the formulation is derived using the orthogonal curvilinear coordinate system. Based on the principle of virtual work the nonlinear finite element equations are derived. A total Lagrangian approach associated to arc-length method is used to solve the equilibrium equations. Smart shells having integrated piezoelectric actuators undergo large displacements resulting snap through phenomenon from one equilibrium state to another. The present results are found to compare well with those available in the open literature and the post buckling responses of $[\pm 45\degree/\text{minus-or-plus sign}45\degree]$s laminated spherical, cylindrical and conoidal shell panels with piezoelectric layer are analyzed and the nonlinear load–deflection curves are presented.

C. K. Kundu and Jae-Hung Han (Department of Aerospace Engineering Korea Advanced Institute of Science and Technology Daejeon, Republic of Korea), “Vibration Characteristics Of Pre And Post Buckled Laminated Composite Spherical Shells”, ICSV15, 15th International Congress on Sound and Vibration, 6-10 July 2008, Daejeon, Korea

ABSTRACT: Laminated composite shell structures may experience large bending deformation resulting in pre-buckling and post-buckling due to higher external loading and the shells may exhibit snap-through and snap-back type post buckling behavior. The vibratory characteristics of post-buckled structures are a problem of primary importance in many engineering fields, including aerospace applications. The vibration characteristics of pre and post buckled laminated composite spherical shells are presented in this paper. The nonlinear finite element method is used for the analysis. The orthogonal curvilinear coordinate system is used for modeling of doubly curved shell geometry. The strain-displacement relations include the general nonlinear terms in the curvilinear coordinate. Based on the principle of virtual work the nonlinear finite element equations are derived. The arc-length method is implemented to capture the snapping response of laminated shells. The vibration characteristics of pre and post buckled shells are performed using tangent stiffness obtained from the converged deflection. The code is first validated and then employed to generate numerical results. Parametric studies are carried out to analyze the snapping and vibration characteristics. It is observed that the frequency in the pre-snapping region decreases with increase in load. But after snap-through, the frequency increases as increase in load, due to the geometric nonlinearity.

References listed at the end of the paper:

ABSTRACT: The vibration characteristics of post-buckled laminated composite doubly curved shells are investigated. The finite element method is used for the analysis of post-buckling and free vibration of post-buckled laminated shells. The geometric non-linear finite element model includes the general non-linear terms in the strain-displacement relationships. The shell geometry used in the present formulation is derived using an orthogonal curvilinear coordinate system. Based on the principle of virtual work the non-linear finite element equations are derived. Arc-length method is implemented to capture the load-displacement equilibrium curve. The vibration characteristics of post-buckled shell are performed using tangent stiffness obtained from the converged deflection. The code is first validated and then employed to generate numerical results. Parametric studies are performed to analyze the snapping and vibration characteristics. The relationship between loads and fundamental frequencies and between loads and the corresponding displacements are determined for various parameters such as thickness ratio and shallowness.


ABSTRACT: Hygrothermal stresses due to the change in environmental condition may induce buckling and dynamic instability in the composite shell structures. In the present investigation, the hygrothermoelastic buckling behavior of laminated composite shells are numerically simulated using geometrically nonlinear finite element method. The orthogonal curvilinear coordinate is used for modeling a general doubly curved deep or shallow shell surface. The geometrically nonlinear finite element formulation is based on general nonlinear strain–displacement relations in the orthogonal curvilinear coordinate system. The present theory can be applicable to thin and moderately thick shells. The mechanical linear and nonlinear stiffnesses, and the nonmechanical nonlinear geometric stiffness matrices and the hygrothermal load vector are presented. It is also observed that during the present numerical solution of nonlinear equilibrium equation, in order to construct the

ABSTRACT: The overall behavior of plates and shells as affected by the presence of a through crack in the elastic range has been studied. Due attention has been paid to finite element modeling aspects of the problem. Forty different cracked plate and shell FE models have been generated and analyzed by a special computer program developed for the purpose of this study. The significance of various parameters such as the order of mesh refining at the crack tip, the effect of boundary conditions, Poisson's ratio, crack length and shell curvature are studied. FE model consisting of isoparametric 4-noded shell elements moderately refined at the crack tip predicted the overall stress and displacement field with acceptable precision.


ABSTRACT: Presence of cracks or similar imperfections can considerably reduce the buckling load of a shell structure. In this paper, the buckling of cylindrical shells with through cracks has been studied. A general finite element model has been proposed, verified and applied to some novel cracked shell buckling problems for which documented results are not available. A special purpose program has been developed for generating finite elements models of cylindrical shells with cracks of varying length and orientation. The buckling behavior of cracked cylinders in tension and compression has been studied. The results of the analysis are presented in parametric form when it seems to be appropriate. Sensitivity of the buckling load to the crack length and orientation has also been investigated.

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ABSTRACT: The presence of cracks in a structure can considerably affect its behaviour. This paper presents a finite element study on the vibration, buckling and dynamic stability behaviour of a cracked cylindrical shell with fixed supports and subject to an in plane compressive/tensile periodic edge load. The effects of crack length and orientation are analysed. Under tension load, the results show that the frequency of the shell initially increases with the load, but then decreases as the load further increases leading to buckling due to tension load.
The size and the orientation of the crack and the loading parameter can all have a significant effect on the dynamic stability behaviour of the shell under both compressive and tensile loading. The effects of these parameters are discussed in detail.

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ABSTRACT: The plastic behavior of an elastoplastic cylindrical shell with circular and rectangular cutouts under bending moment loads was investigated numerically and experimentally. A testing device (pure bending measurement) was designed and made to perform experiments on bending moment tests. The ratio of diameter to thickness of the stainless steel 304 specimens was 40.4 and the ratio of length to diameter was 7.94. The shape of the cutout on the shell was circular or rectangular. The tested specimens were categorized into five dissimilar groups. The effect of size, position and numbers of the cutout on the plastic moment is discussed. In order to investigate the strain distribution around of cutout, nine strain gauges were mounted in the longitudinal and circumferential directions on two specimens with different type of cutout. To investigate the accuracy of analytical and experimental results, numerical analysis considering the behavior of elastoplastic material were performed and good agreement was obtained between them. The strength of bending moment of cylindrical shells was decreased with increasing of sizes of cutout and it was increased with changing the location of the cutout from compression side to tension side. The effect of the number of cutouts (increasing from 1 to 3 (axisymmetrical)) on bending strength of tubes is negligible.

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ABSTRACT: In this paper, the buckling behavior of a composite lattice cylindrical shell is studied and effects of rib defects on the distribution of stress field and buckling response of the shell is investigated. A three dimensional finite element buckling analysis of the lattice shell is carried out using ANSYS suit of program. Geometrical data and material properties of the shell are obtained from the specimens made by filament winding method. Effects of various parameters including the geometrical ratios, defects of ribs on buckling response of the shell are studied. Buckling loads of composite lattice cylindrical shells under axial and shear forces have been obtained experimentally and results are compared with finite element results.

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12. Vasiliev, V. V., Barynin, V. A. and Razin, A. F., "Anisogrid composite lattice structures--development and aerospace
ABSTRACT: The paper investigates the buckling behaviour of anisogrid composite lattice cylindrical shells under axial compression, transverse bending, pure bending, and torsion. The lattice shells are modelled as three-dimensional frame structures composed of curvilinear ribs subjected to the tension/compression, bending in two planes and torsion. The specialised finite-element model generation procedure (model generator/design modeller) is developed to control the orientation of the beam elements allowing the original twisted geometry of the curvilinear ribs to be closely approximated. The effects of varying the length of the shells, the number of helical ribs and the angles of their orientation on the buckling behaviour of lattice structures are examined using parametric analyses. Buckling of the lattice shells with cutouts is also analysed. The results of these studies indicate that the modelling approach presented in this work can be successfully applied to the solution of design problems.

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ABSTRACT: A unified analytical approach is applied for investigating the vibrational behavior of grid-stiffened composite cylindrical shells considering the flexural behavior of the ribs. A smeared method is employed to superimpose the stiffness contribution of the stiffeners with those of the shell in order to obtain the equivalent stiffness parameters of the whole panel. The stiffeners are modeled as a beam and considered to support shear loads and bending moments in addition to the axial loads. Therefore, the corresponding stiffness terms are taken into consideration while obtaining the stiffness matrices due to the stiffeners. Theoretical formulations are based on first-order shear deformation shell theory, which includes the effects of transverse shear deformation and rotary inertia. The modal forms are assumed to have the axial dependency in the form of Fourier series whose derivatives are legitimised using Stokes’ transformation. In order to validate the obtained results, a 3-D finite element model is also built using ABAQUS CAE software. Results obtained from two types of analyses are compared with each other, and good agreement has been achieved. Furthermore, the influence of variations in the shell thickness and changes of the boundary conditions on the shell frequencies is studied. The results obtained are novel and can be used as a benchmark for further studies.

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ABSTRACT: The results of an experimental study on the buckling behavior of thin-walled GFRP cylindrical shells are presented. The specimens were fabricated from continuous glass fiber using a specially-designed filament winding machine. The buckling behaviors of unstiffened shells and stiffened shells with lozenge, triangular and hexagonal grids were then studied under quasi-static axial loading at room temperature. Due to the thin skin of the shells, all specimens first experienced a general buckling mode as well as barreling under the applied loading. Following this general buckling damage, local buckling mode was seen on all specimens. Based on the experimental results, the critical buckling load was higher for the shells with hexagonal and triangular grids while the unstiffened shells and stiffened shells with lozenge grids exhibited much lower critical buckling load. On the other hand, in very small skin thicknesses, when the specific buckling loads for all specimens were compared, the unstiffened shells showed the highest specific buckling load.

References listed at the end of the paper:

ABSTRACT: In this paper, a size-dependent first-order shear deformable shell model is developed based upon the modified strain gradient theory (MSGT) for the axial buckling analysis of functionally graded circular cylindrical microshells based on the modified strain gradient elasticity theory”, Meccanica, Vol. 49, No. 7, pp 1679-1695, July 2014

ABSTRACT: In this paper, a size-dependent first-order shear deformable shell model is developed based upon the modified strain gradient theory (MSGT) for the axial buckling analysis of functionally graded (FG) circular cylindrical microshells. It is assumed that the material properties of FG materials, which obey a simple power-law distribution, vary through the thickness direction. The principle of virtual work is utilized to formulate the governing equations and corresponding boundary conditions. Numerical results are presented for the axial buckling of FG circular cylindrical microshells subject to simply-supported end conditions and the effects of material length scale parameter, material property gradient index, length-to-radius ratio and circumferential mode number on the size-dependent critical buckling load are extensively studied. For comparison purpose, the critical buckling loads predicted by modified couple stress theory (MCST) and classical theory (CT) are also
presented. Results show that the size effect plays an important role for lower values of dimensionless length scale parameter. Moreover, it is observed that the critical buckling loads obtained based on MSGT are greater than those obtained based on MCST and CT.

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36. Donnell LH (1933) The problem of elastic stability, Transactions of the American Society of Mechanical Engineers, Aeronautical Division


ABSTRACT: In this paper, the effects of initial imperfections on the buckling behavior of thick cylindrical shells and curved panels are investigated. It is assumed that the shell has an axisymmetric and periodic initial imperfection in the axial direction. The shell is assumed to have different boundary conditions and subjected to pure external pressure loading. Governing differential equations are developed on the basis of the second Piola-Kirchhoff stress tensor and are reduced to a homogenous linear system of equations using the differential quadrature method. The effects of different boundary conditions, geometric ratios, curvature and imperfection parameter on the buckling behavior of isotropic thick cylindrical shells and curved panels are carefully discussed. The results obtained by the present method are verified with finite element solutions and those reported in the literature.

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R. Akbari Alashti and S. A. Ahmadi (Babol University of Technology, Department of Mechanical Engineering, Babol, Iran), “Buckling Analysis of Functionally Graded Thick Cylindrical Shells with Variable Thickness Using DQM”, Arabian Journal for Science and Engineering, August 2014

ABSTRACT: In this paper, buckling analysis of a functionally graded thick cylindrical shell with variable thickness subjected to combined external pressure and axial compression is carried out. Moreover, the effect of an axisymmetric imperfection on the buckling load of the shell is investigated. It is assumed that material properties of the shell vary smoothly through the thickness according to a power law distribution of the volume fraction of constituent materials, while the Poisson’s ratio is assumed to be constant. The shell is considered to be simply supported at both ends. The governing differential equations are obtained based on the second Piola–Kirchhoff stress tensor and are then reduced to a homogenous linear system of equations using differential quadrature method. Effects of several parameters of the shell including the volume fraction of constituents, geometric ratios, thickness variation amplitude factor, imperfection parameter and loading conditions on the buckling behavior of the functionally graded thick cylindrical shell are investigated. The results obtained by the present method are compared with results reported in the literature.

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ABSTRACT: (cannot cut and paste)

ABSTRACT: The discrepancy between the predictions of flow and deformation theories is investigated. The sensitivity of flow theory analysis to the interaction of multiaxial stresses in the pre-buckling state is reviewed. The predictions of the two theories are further examined based on critical strains at buckling, similar to the sheet metal forming limit curves. The extent to which the material nonlinearity of plastic flow is reflected in critical strains is also discussed for a variety of circumstances.

ABSTRACT: A plastic buckling analysis is presented for infinitely long shear panels in the presence of tensile or compressive loading acting along the principal directions of the plate. Assuming a homogeneous pre-buckling stress state with uniform axial and shear stresses, the critical state at buckling is determined by employing a bifurcation-of-equilibrium approach. The material is assumed elastic-plastic with non-linear strain hardening characteristics. Interaction buckling curves are presented for both flow and deformation theories of plasticity.

ABSTRACT: Porcupine quills are natural structures formed by a thin walled conical shell and an inner foam core. Axial compression tests, differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and Fourier transform infrared spectroscopy (FT-IR) were all used to compare the characteristics and mechanical properties of porcupine quills with and without core. The failure mechanisms that occur during buckling were
analyzed by scanning electron microscopy (SEM), and it was found that delamination buckling is mostly responsible for the decrease in the measured buckling stress of the quills with regard to predicted theoretical values. Our analysis also confirmed that the foam core works as an energy dissipater improving the mechanical response of an empty cylindrical shell, retarding the onset of buckling as well as producing a step wise decrease in force after buckling, instead of an instantaneous decrease in force typical for specimens without core. Cell collapse and cell densification in the inner foam core were identified as the key mechanisms that allow for energy absorption during buckling.

References listed at the end of the paper:


ABSTRACT: Thin walled cylindrical shell structures are widespread in nature; examples include plant stems, porcupine quills and hedgehog spines. All have an outer shell of almost fully dense material supported by a low density, cellular core. In nature, all are loaded in some combination of axial compression and bending; failure is typically by buckling. Natural structures are often optimized. Here we have analysed the elastic buckling of a thin cylindrical shell supported by an elastic core to show that this structural configuration achieves significant weight saving over a hollow cylinder. Biomimicking of natural cylindrical shell structures may offer the
potential to increase the mechanical efficiency of engineering cylindrical shells. The results of the analysis are compared with data in the following, companion paper.


ABSTRACT: The analysis of the previous, companion paper showed that the buckling resistance of a cylindrical shell with a compliant core is greater than that of an equivalent weight shell without a core. Here, we describe uniaxial compression and four point bending tests on silicone rubber shells with and without compliant foam cores. The analysis describes the results of the mechanical tests well.

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ABSTRACT: Thin-walled, cylindrical structures are found extensively in both engineering components and in nature. The weight to load bearing ratio is a critical element of design of such structures in a variety of engineering applications, including space shuttle fuel tanks, aircraft fuselages, and offshore oil platforms. In nature, thin-walled cylindrical structures are often supported by a honeycomb- or foam-like cellular core, as for example, in plant stems, porcupine quills, or hedgehog spines. Previous studies have suggested that a compliant core increases the buckling resistance of a cylindrical shell over that of a hollow cylinder of the same weight. In this paper, we extend the linear-elastic buckling theory by coupling it with basic plasticity theory to provide a more comprehensive analysis of isotropic, cylindrical shells with compliant cores. We examine the optimal design of a thin-walled cylinder with a compliant core, of given radius and specified materials, for a prescribed load bearing capacity in axial compression. The analysis gives the values of the shell thickness, the core thickness, and the core density that maximize the load bearing capacity of the shell with a compliant core over an equivalent weight hollow shell. The analysis also identifies the optimum ratio of the core modulus to the shell modulus and is supported by a Lagrangian optimization technique. The analysis further discusses the selection of materials in the design of a cylinder with a compliant core, identifying the most suitable material combinations. The performance of a cylinder with a compliant core is compared with competing designs (optimized hat-stiffened shell and optimized sandwich-wall shell). Finally, the challenges associated with achieving the optimal design in practice are discussed, and the potential for practical implementation is explored.

References listed at the end of the paper:

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ABSTRACT: Structural analysis of shallow shells is performed and relatively accurate displacements and stresses are obtained. An energy method, which is an extension of the Ritz method, is used in the analysis. Algebraic polynomials are used as displacement functions. The numerical problems which resulted in inaccurate stresses in previous publications are improved by making use of symmetry and performing the computations on the CRAY Y-MP supercomputer which has 29-digit double-precision arithmetics. Curvature effects upon deflections and stress resultants of shallow shells with cantilever and ‘semi-cantilever’ boundaries are studied.

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ABSTRACT: Laminated composite shells are frequently used in various engineering applications in the aerospace, mechanical, marine, and automotive industries. This article follows a previous book and review articles published by the leading author (Qatu, 2004, 2002, 1989, 1992, 1999 [1], [2], [3], [4] and [5]). It reviews most of the research done in recent years (2000–2009) on the dynamic behavior (including vibration) of composite shells. This review is conducted with emphasis on the type of testing or analysis performed (free vibration, impact, transient, shock, etc.), complicating effects in material (damping, piezoelectric, etc.) and structure (stiffened shells, etc.), and the various shell geometries that are subjected to dynamic research (cylindrical, conical, spherical and others). A general discussion of the various theories (classical, shear deformation, 3D, non-linear etc.) is also given. The main aim of this review article is to collate the research performed in the area of dynamic analyses of composite shells during the last 10 years, thereby giving a broad perspective of the state of art in this field. This review article contains close to 200 references. References listed at the end of the paper:
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ABSTRACT: The paper deals with the geometrically non-linear analysis of laminated composite beams, plates and shells in the framework of the first-order transverse shear deformation (FOSD) theory. A central point of the present paper is the discussion of the relevance of five- and six-parameter variants, respectively, of the FOSD hypothesis for large rotation plate and shell problems. In particular, it is shown that the assumption of constant through-thickness distribution of the transverse normal displacements is acceptable only for small and moderate rotation problems. Implications inherent in this assumption that are incompatible with large rotations are discussed from the point of view of the transverse normal strain–displacement relations as well as in the light of an enhanced, accurate large rotation formulation based on the use of Euler angles. The latter one is implemented as an updating process within a Total Lagrangian formulation of the six-parameter FOSD large rotation plate and shell theory. Numerical solutions are obtained by using isoparametric eight-node Serendipity-type shell finite elements with reduced integration. The Riks–Wempner–Ramm arc-length control method is used to trace primary and secondary equilibrium paths in the pre- and post-buckling range of deformation. A number of sample problems of non-linear, large rotation response of composite laminated plate and shell structures are presented including symmetric and asymmetric snap-through and snap-back problems.

ABSTRACT: In recent years, smart structures with piezoelectric sensors and actuators have attracted serious attention for they can sense and alter the mechanical response during in-service operation. On the other hand, light-weight shell type structures may be one of the most popularly used structures in space vehicles. For this reason, shell type smart structures have become the focus of study for many researchers. Tzou and his coworkers [1–3] studied piezoelectric shell type continua using finite element method and analytical analysis method. Chen and Shen[4, 5] performed the study of exact studies of piezoelectric circular cylindrical shells and piezothermoelastic shells, also, they studied the stability of piezoelectric circular cylindrical shells[6].

References listed at the end of the paper:

ABSTRACT: (none given)
References listed at the end of the paper:

ABSTRACT: A mixed-mode method is investigated for the dynamic analysis of partially prismatic structures, such as box girders with intermediate diaphragms and supports, or with variable-depth webs. Thus the prismatic ‘main structure’ is discretised by finite strips, and the non-prismatic ‘sub-structure’ by finite elements. After dynamic reduction of the finite element degrees of freedom, advantage may be taken of the finite strip harmonic expansions in determining mode shapes. The method is tested by a variety of examples. Thus for structures with transverse substructures (e.g. diaphragms), the method is shown to be successful, being up to an order of magnitude faster than finite elements. However, for structures with longitudinal substructures (e.g. variable-depth webs) the method is shown to be unreliable. This is because for such structures, approximations in the dynamic reduction procedure are found to be significant.


ABSTRACT: Thick shells made of composite materials have been analyzed by using a higher order shell theory. In this theory thickness normal strain and two transverse strains are included. A higher order three-noded isoparametric axisymmetric finite element is used to solve the problem. Numerical experiments with the present element indicate that this element yields accurate vibration results with very few elements. In the present study, the suitability of different theories used for vibration studies has been investigated. Three theories are compared, viz. Love's first approximation shell theory, an improved theory with shear deformation and rotatory inertia, and a shell theory with thickness normal strain and shear deformations. It is found that the shear deformations have an appreciable effect on the vibration characteristics of comparatively thick shells, especially composite shells. A parametric study has been conducted to study the effects of various geometric properties of shell on the free vibration characteristics of conical isotropic and composite shells. The effect of mass distribution on the natural frequencies is also studied in the present work.


ABSTRACT: The Leipholz column which is having the Young modulus and mass per unit length as stochastic processes and also the distributed tangential follower load behaving stochastically is considered. The non self-adjoint differential equation and boundary conditions are considered to have random field coefficients. The standard perturbation method is employed. The non self-adjoint operators are used within the regularity domain. Full covariance structure of the free vibration eigenvalues and critical loads is derived in terms of second order properties of input random fields characterizing the system parameter fluctuations. The mean value of critical load is calculated using the averaged problem and the corresponding eigenvalue statistics are sought. Through the frequency equation a transformation is done to yield load parameter statistics. A numerical study incorporating commonly observed correlation models is reported which illustrates the full potentials of the derived expressions.

ABSTRACT: Due to the asymmetry of the material properties about the middle plane, perfect columns made of functionally graded materials (FGMs) may not remain straight when a compressive axial point load is concentrically applied. This article analytically derives the displacement functions and the buckling load of both
perfect and imperfect Euler–Bernoulli functionally graded columns. The method of derivation is based on the translation of the reference plane to the position at which the coupling between the axial and bending deformations is eliminated, i.e. the physical neutral surface position. Then, all the governing equations and their solutions turn out to have the same form as those of homogeneous columns subjected to an eccentric axial load. The effects of geometric imperfection are studied with the main purpose of finding imperfect shapes that make an imperfect column stronger than a perfect one. Further, the governing equations that are used to find those analytical solutions are expanded so that the equations can deal with large deformation and large strain analysis. These new governing equations are solved by finite element (FE) method based on linear exact shape functions. Then, the FE solutions are used to compare and validate the analytical solutions obtained earlier.

K. He, S. V. Hoa and R. Ganesan (Concordia Center for Composites, Department of Mechanical Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, PQ, Canada H3G 1M8), “The study of tapered laminated composite structures: a review”, Composites Science and Technology, Vol. 60, No. 14, November 2000, pp. 2643-2657, doi:10.1016/S0266-3538(00)00138-X

ABSTRACT: Following laminated composite plates and beams, tapered laminated structures, which are formed by dropping off some of the plies at discrete positions over the laminate, have received much attention from researchers because of their structural tailoring capabilities, damage tolerance, and their potential for creating significant weight savings in engineering applications. A review of recent developments in the analysis of tapered laminated composite structures with an emphasis on interlaminar stress analysis, delamination analysis and parametric study is presented. A discussion of various approaches to modelling and analysis of interlaminar response of tapered composites using finite elements and non-finite elements is given. Displacement-based finite elements and hybrid finite elements that are commonly used are also reviewed. A review of various studies on delamination failure mechanisms as a result of drop-off plies in the tapered composites is given next, which mainly encompasses a stress-strength approach and a fracture-mechanics approach. Lastly, a variety of methods that are being used in the parametric studies regarding the structural integrity is presented. Overall remarks drawn from the reviewed works are given in the final section of the paper.


ABSTRACT: (cannot cut and paste the abstract)

Shaikh Akhlaque-E-Rasul and Rajamohan Ganesan (Department of Mechanical and Industrial Engineering, Concordia Center for Composites, Concordia University, 1455 De Maisonneuve W., Montreal, QC, H3G 1M8, Canada), “ Non-linear buckling analysis of tapered curved composite plates”, Science and Engineering of Composite Materials. Vol. 18, No. 3, pp. 157–165, ISSN (Online) 2191-0359, ISSN (Print) 0792-1233, DOI: 10.1515/secm.2011.026, September 2011

ABSTRACT: Linear formulations are insufficient to take into account the effect of large deflections that occur after initial buckling. This effect can only be considered in the non-linear buckling analysis. In the present work, the non-linear analysis is carried out using the finite element method based on first-order shear deformation shell theories. Two non-linear shell theories, Donnell’s and Sanders’ theories, are used in the analysis. Based on the first-ply failure analysis and non-linear buckling analysis, the critical sizes and parameters of the tapered curved plates that will not fail before global buckling are determined. A parametric study that encompasses the
effects of taper angle, critical length-to-height ratio, radius, radius-to-thickness ratio and geometric parameters of the plates is conducted.


ABSTRACT: A new formulation, based on the semi-analytical finite element method, is proposed for elastic shells conveying fluids. The structural equations are based on the shell element proposed by Ramasamy and Ganesan [Comput Struct 70 (1998) 363] while the fluid model is based on velocity potential. Dynamic pressure acting on the walls is derived from Bernoulli's equation. Imposing the requirement that the normal components of velocity of the solid and fluid be equal, introduces fluid–structure coupling. The proposed technique has been validated using results available in the literature. This study shows that instability occurs at a critical fluid velocity corresponding to the shell circumferential mode with the lowest natural frequency and this phenomenon is also independent of the type of structural boundary conditions imposed.


ABSTRACT: Piezoelectric composite cylindrical shells operating in a steady state axisymmetric temperature are analyzed using a semi-analytical finite element method. Numerical studies are conducted on a clamped–clamped composite cylindrical shell for three typical length to radius ratios. The static thermal buckling analysis is carried out for a single layered composite cylindrical shell with different fiber orientation and hence study its influence on thermal buckling temperature. The influence of axisymmetric temperature on the natural frequencies and active damping ratio of the piezoelectric cylindrical shell is also examined. Two configurations of composite laminates: symmetric and antisymmetric with varying the number of plies is also considered to examine the effect on thermal buckling temperature.


ABSTRACT: Thermoelastic buckling and free vibration analysis of geometrically perfect isotropic hemispherical shells subjected to axisymmetric temperature variation are presented. First order shear deformation theory is used to analyze the moderately thick elastic hemispherical shells. The variations of various field variables are assumed in the circumferential direction and the finite element matrices used in the numerical studies are based on the semi-analytical method. The formulation is validated for thermal buckling strains available in the literature. Thermal buckling temperatures are evaluated for deep shells having a cut-out at the apex. Parameters considered in the study include hemispherical shells with a/h ratios of 100 and 500 and each with cut-out angle at apex equal to 7°, 30° and 45°. Boundary conditions considered are clamped–clamped and clamped–free. A study on the distribution of the stress resultants due to thermal loading is examined in order to relate their influence on the buckling temperature of the shells with respect to above-stated geometric
parameters. The effect of temperature on the free vibration natural frequency of the hemispherical shell is also analyzed.


ABSTRACT: Numerical results on the thermal buckling temperature of geometrically perfect HS-Graphite/Epoxy hemispherical shells with cut-out at apex subjected to uniform temperature distribution is presented. The numerical computation is based on the general shell of revolution semi-analytical finite element applicable to moderately thick shells. Studies are presented considering parameters like ratio of base radius to thickness of shell, size of the cut-out at apex and fibre orientation of the lamina and their effects are examined on the magnitude of the buckling temperature. An in-depth study on the magnitude and distribution of the total effective stress resultants and moment resultants is used to explain the role of these quantities on the magnitude of the lowest thermal buckling temperature. It is found that for a given geometry, uniform temperature rise and edge conditions the lowest buckling temperature of a hemispherical shell is mainly due to the large magnitude of the hoop stress resultant close to the edges of the hemispherical shell and also depends on the distribution of hoop stress resultants.


ABSTRACT: This paper presents the buckling and vibration behavior of a viscoelastic sandwich cylinder in a thermal environment analyzed using the semi analytical finite element method. The analysis is carried out using a decoupled thermo mechanical formulation. The temperature field in the shell domain is evaluated using an eight-noded axisymmetric ring element. Buckling and vibration analyses are carried out using a two-noded sandwich shell element in the semi-analytical finite element method. Buckling temperatures are calculated for sandwich shells with two different core materials. The effect of temperature-dependent core shear modulus on buckling temperature and vibration behavior has been investigated for sandwich shells with different mechanical boundary conditions. Variations of natural frequencies and loss factors with temperature have also been examined for sandwich shells with two different core materials.


ABSTRACT: The purpose of the paper is to investigate the linear thermal buckling and vibration analysis of layered and multiphase magneto-electro-elastic (MEE) cylinders made of piezoelectric/piezomagnetic materials using finite element method. The constitutive equations of MEE materials are used to derive the finite element equations involving the coupling between mechanical, electrical, magnetic and thermal fields. The present study is limited to clamped-clamped boundary conditions. The linear thermal buckling is carried out for an axisymmetric cylinder operating in a steady state axisymmetric uniform temperature rise. The influence of
stacking sequences and volume fraction of multiphase MEE materials on critical buckling temperature and vibration behaviour is investigated. The influence of coupling effects on critical buckling temperature and vibration behaviour is also studied. The critical buckling temperature is higher for MEE axisymmetric cylinder as compared to elastic cylinder.

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ABSTRACT: An experimental investigation has been carried out to study the strength and behaviour of Ordinary Portland cement concrete (OPC) and geopolymer concrete (GPC) wall panels. A total of 20 wall panels were tested under uniformly distributed axial load in one-way in-plane action. Out of these, 10 wall panels were made of OPC and the remaining was of GPC. The main variables considered in this study were slenderness ratio (SR) and aspect ratio (AR) of the walls. Also a method was proposed to predict the ultimate load of reinforced GPC wall panels.

ABSTRACT: A new three-node triangular shell element is developed by combining the optimal membrane element and discrete Kirchhoff triangle (DKT) plate bending element, and is modified for laminated composite plates and shells so as to include the membrane-bending coupling effect. Using appropriate shape functions for the bending and membrane modes of the element, the ‘inconsistent’ stress stiffness matrix is formulated and the tangent stiffness matrix is determined. Non-linear analysis of thin-walled structures with geometric non-linearity is conducted using the corotational method. The new element is thoroughly tested by solving few popular benchmark problems. The results of the analysis are compared with those obtained using existing membrane elements.

ABSTRACT: In this study, two optimality criteria are presented for shape optimization of thin-walled structures with geometric nonlinearity modeled by finite elements. The optimization problem considers the thickness and geometry design variables, and aims to maximize the critical load of the structure subject to constant total mass. Results of the optimization with optimality criteria are compared with those found by the gradient-based sequential quadratic programming method. It is shown that the optimum shape can be found using this method without performing the sensitivity analysis, and in less number of iterations compared to the standard gradient-based methods of optimization.

Peyman Khosravi, Rajamohan Ganesan and Ramin Sedaghati (Department of Mechanical and Industrial

ABSTRACT: In the present work, an efficient facet shell element for the geometrically nonlinear analysis of laminated composite structures using the corotational approach is developed. The facet element is developed by combining the discrete Kirchhoff–Mindlin triangular bending element (DKMT), and the optimal membrane triangular element (OPT). The membrane-bending coupling effect of composite laminates is incorporated in the formulation, and inconsistent stress stiffness matrix is formulated. Using corotational formulation and the proposed facet element, some example laminated composite structures with geometric nonlinearity are analyzed, and the results are compared with those found using other facet elements.

S. Akhlaque-E-Rasul and R. Ganesan (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, Canada, H3G 1M8), “Finite element global buckling analysis of tapered curved laminates”, (publisher and date not included in the pdf file; most recent reference is 2009)

ABSTRACT: Due to the variety of configurations of tapered curved composite plates the analysis becomes complex. At present no existing work deals with their response to compressive loading except the other works of present authors. The linear and non-linear buckling analyses of tapered curved composite plates are conducted in the present work using SHELL99 element of ANSYS. The results obtained using ANSYS are compared with that of the Finite Element Analysis using a Lagrange element based on First order Shell Theory (FST), and Ritz solution based on Classical Shell Theory (CST) and FST. The strength characteristics and load carrying ability of the tapered curved plates are investigated considering first-ply failure and delamination failure. Based on these analyses, the critical sizes and parameters of the tapered curved plates that will not fail before global buckling are determined. A parametric study is also carried out.

References listed at the end of the paper:
Shaikh Akhlaque-E-Rasul (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, Canada H3G 1M8), “Compressive response of tapered curved composite plates”, PhD Dissertation, December 2010

ABSTRACT: Tapered laminated structures have considerable potential for creating significant weight savings in engineering applications. In the present thesis, the ply failure and global buckling failure of internally-tapered curved laminates are considered. For the buckling analysis, four different analytical approaches are employed: (1) classical shell theories using Ritz method, (2) first-order shear deformation shell theories using Ritz method, (3) linear finite element analysis based on first-order shear deformation shell theories, and (4) non-linear finite element analysis. Due to the variety of tapered curved composite plates and the complexity of the analysis, no closed-form analytical solution is available at present regarding their response to compressive loading. Therefore, the Ritz method is used for the global buckling analysis considering uniaxial compressive load. Linear buckling analysis of the plates is carried out based on eight classical shell theories and six first-order shear deformation shell theories. To apply the first-order shear deformation shell theories, an appropriate set of shear correction factors has been determined. The buckling loads obtained using Ritz method are compared with the existing experimental and analytical results, and are also compared with the buckling loads obtained using finite element method. The strength characteristics and load carrying capability of the tapered curved plates are investigated considering the first-ply failure and delamination failure. The commercial software ANSYS® is used to analyze these failures. Based on the ply failure and buckling analyses, the critical sizes and parameters of the tapered curved plates that will not fail before global buckling are determined. Linear buckling analysis is insufficient to take into account the effect of large deflections on the buckling loads. This effect can only be considered in the non-linear buckling analysis. However, very large number of load steps is required to determine the buckling load based on the non-linear analysis in which the stability limit load is calculated from the non-linear load-deflection curve. In the present thesis, a simplified methodology is developed to predict the stability limit load that requires the consideration of only two load steps. The stability limit loads calculated using the present simplified methodology are shown to have good agreement with that calculated from the conventional non-linear load-deflection curve. Parametric studies are carried out using the above mentioned four different types of analytical methods. In these studies, the effects of boundary conditions, stacking sequence, taper configurations, radius, and geometric parameters of the plates are investigated.

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the Ritz method based on six well response of tapered shells considering uni 
the present work, approximate analytical solutions are developed using the Ritz method for the global buckling 
closed 
Due to the advanced configurations of tapered composite shells and their complex behavior, 
ABSTRACT: Tapered composite shells provide considerable weight and energy savings in the engineering 
August 2011, pp. 2153 Canada H3G 1M8), “Compressive response of tapered composite shells”, Composite Structures, Vol. 93, No. 9, 
Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, 

Rajamohan Ganesan and Shaikh Akhlaque-E-Rasul (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, Canada H3G 1M8), “Compressive response of tapered composite shells”, Composite Structures, Vol. 93, No. 9, August 2011, pp. 2153-2162, doi:10.1016/j.compstruct.2011.02.010
ABSTRACT: Tapered composite shells provide considerable weight and energy savings in the engineering applications. Due to the advanced configurations of tapered composite shells and their complex behavior, closed-form analytical solutions are not available at present regarding their response to compressive loading. In the present work, approximate analytical solutions are developed using the Ritz method for the global buckling response of tapered shells considering uni-axial compression. Buckling analysis of the shells is carried out using the Ritz method based on six well-established First-order shear deformation Shell Theories (FST). The failure
strength characteristics and load carrying capability of the above mentioned tapered shells are studied considering the first-ply failure. Based on the failure and buckling analyses, the critical values of size and shape parameters of the shells such that they will fail only in global buckling mode are determined. A comprehensive parametric study is carried out and design guidelines for the tapered shells are established based on this study.

ABSTRACT: The paper describes the application of a curved isoparametric shell element to large displacement analyses including instability phenomena. A total Lagrangian formulation has been adopted using the standard incremental/iterative solution procedure. The linear stability analyses usually performed for the initial position were repeated at several advanced fundamental states on the nonlinear prebuckling path. Thus a current estimate of the final failure load is given. The method has been applied to several perfect and imperfect cylindrical shells under uniform pressure or wind load. Finally the example of a cylindrical panel under one concentrated transverse load is discussed.

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ABSTRACT: The stability of a cylindrical shell subjected to wind load is analyzed using numerical solution methods. The multisegment direct integration as well as the finite element method are applied in linear analysis, and a nonlinear finite element algorithm is used to take into account the nonlinear prebuckling effects of the perfect and imperfect structure. The calculated results are compared with measurements, and good agreement is derived with respect to both stability limit and buckling mode.

ABSTRACT: In the paper we are looking at cylindrical shells fixed at the bottom and free at the top. Let us assume that these shells are filled with a viscous, compressible fluid of a mass density, \( p_L \), up to height, \( H \). For definitions see Fig. 1. The shell is accelerated at the bottom, i.e. at position \( x = 0 \), by a horizontal acceleration, \( A(t) \), \( t = \) time.

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7. Welded Steel Tanks for Oil Storage, American Petroleum Institute, API Standard 650, 7th edition, Nov. 80, Appendix E.


ABSTRACT: A finite shell element for layered fibre reinforced composite shells has been developed. The degeneration principle is used in combination with specific kinematic assumptions. The thermo-elastic material is either described by the behaviour of the local components, i.e. fibre and matrix material laws and geometrical configuration in each layer, or by the overall orthotropic layer material laws. Thickness integration for obtaining the different contributions to the shell element's stiffness matrix is performed analytically and prior to the numerical in-plane integration. This leads to a considerable saving in computer time during the incremental-iterative analysis. Geometrical non-linearities in terms of large deformations and material non-linearities in
terms of layer cracking are taken into account. Accompanying eigenvalue analyses allow the determination of the—sometimes rather complicated—buckling behaviour with non-linear prebuckling deformations.

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ABSTRACT: In this chapter formulations of special finite shell elements for the analysis of composite shell structures (layered fiber-composite and sandwich shells) as well as computational considerations of local effects are described. Nonlinearities due to large deformations and progressive damage as well as local and global loss of stability are treated. Finally, some practical applications of the computational procedures are described.

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ABSTRACT: In this section the classical lamination theory is described on the basis of Mindlin-Reissner’s kinematics. Hygrothermal effects are included, and a formulation is achieved which can be simply specified for specific laminates such as symmetric, quasi-orthotropic and quasi-isotropic ones. Furthermore, interlaminar stresses and edge effects as well as some failure criteria and the post-failure behavior with stiffness degradation are considered. Based on antiplane core conditions a sandwich theory is developed, and a procedure is presented for estimating local instability phenomena such as different modes of face layer wrinkling or intracell buckling and failure due to transverse normal stresses.


ABSTRACT: A finite strip (FS) method is presented for the numerical investigation of two design parameters – effective breadth and effective width – of stiffened plates. For the effective breadth, stiffened plates under bending are studied. Due to the transverse bending loads there is shear transmission through the plate from the stiffener which leads to a non-uniform longitudinal stress distribution across the plate width. This phenomenon, termed as shear lag, can be represented by the ‘effective breadth concept’, and has been extensively studied by analytical methods. A linear FS method is presented which utilizes the advantages of decoupling of Fourier terms on the one hand and, on the other hand, allows the treatment of both webs and flanges using a plate model. A definitely different situation exists for estimating the effectiveness of plate breadth (or width) of plates in the postbuckling range. The ‘concept of effective width’ is based on the fact that plates with supported longitudinal edges and/or stiffeners can accept additional load after buckling under longitudinal compression,
and enables the designer to evaluate the postbuckling strength of plate structures simply by using the design parameter ‘effective width’. Several formulae (most of them empirically derived) exist for an approximative calculation of the load dependent value of the effective width. A nonlinear FS method is developed and applied to the investigation of the postcritical strength of locally buckled structures. An incremental successive iterative procedure is introduced for an effective numerical analysis.


ABSTRACT: Introducing beads into thin-walled structures for enhancing bending stiffness is a common practice and has been used for many decades. Typically, forms and patterns of such beads are rather based on experience as well as practical results than on analytical or numerical investigations. Recently computational methods have been developed for designing or optimizing beads. The paper at hand contributes to these attempts. It deals with increasing the buckling resistance as well as the fundamental frequency of thin-walled structures by systematic bead design. The design strategy is based on the idea to disturb the buckling mode and the fundamental vibration mode, respectively, of a structure in an efficient way by laying beads along the direction of the occurring maximum principal curvature of the corresponding mode shape. Since the beads influence this mode shape, an incremental approach is required. Numerical investigations into plate and profile structures are performed by applying this new iterative design procedure in combination with the finite element method.

References listed at the end of the paper:


ABSTRACT: A box-like stringer-stiffened thin-walled CFRP structure was subjected to load cases well beyond the limits of local buckling. The development of the deflection pattern was recorded via optical means and analysed numerically. In addition, the structure was modelled and analysed using the MARC FE program in the nonlinear deflection range. The geometrical imperfections of the test structure were recorded by mechanical
scanning and optical methods and introduced into the mathematical model. For the perfect (‘ideal’) and the geometrically imperfect (‘real’) structural model, the results of the FE analyses were compared and used to judge the effect of geometric imperfections on the postbuckling behaviour of the structure. The effective axial stiffness for the various postbuckling states was evaluated and related to analytical estimates of effective width values for orthotropic sheet-like panels.


ABSTRACT: Computational investigations of the buckling and postbuckling behaviour of a stringer-stiffened composite wing torsion box employing the finite element method are presented. Perfect and imperfect configurations — considering geometrical imperfections as well as initial stresses - are discussed. Two different loadcases are investigated: pure axial loading and axial loading with a superimposed constant torsion moment. The buckling behaviour is determined by tracing the load-deflection curves using Riks' path following method. Additional investigations, such as accompanying eigenvalue analyses and first-ply failure calculations, are performed for the first loadcase. Special attention is put on the modelling of the stiffened regions, where eccentrically placed layers have to be taken into account due to the bonding of the stiffeners to the inner surface of the box. The results show interesting phenomena, such as additional buckling points in the postbuckling region, which, however, can hardly be detected by simply considering the load-axial displacement path.


ABSTRACT: Computational investigations of the buckling and postbuckling behaviour of a stringer-stiffened composite wing torsion box employing the finite element method are presented. Perfect and imperfect configurations considering geometrical imperfections as well as initial stresses are discussed. The determination of load-deflection curves and first-ply-failure calculations for the skin are performed for two different loadcases. In addition, in a global-local approach, the interlaminar stresses, the risk of delamination and first-ply-failure in the stiffener sections in the prebuckled and the postbuckled ranges are examined. This approach combining non-linear global and linear local investigations represents an analysis concept for stiffened composite structures, which considers the stability behaviour of the structure as well as ply failure and onset of delamination in the skin, the stringers and the skin-stringer transitions.

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ABSTRACT: Pushing a conical die into a pipe, a forming process also known as “flaring”, is a way of changing the shape of a thin cylindrical tube into that of a conical shell. Interest in predicting the forming limits for this specific process motivated the present study, in which experiments and Finite Element simulations were employed for the identification of two limiting mechanisms: (a) diffuse necking caused by local loss of material stability at the free, expanding end of the pipe, and (b) loss of global stability due to elasto-plastic “Concertina” buckling of the straight pipe part. The former mechanism leads to the formation of periodic necks and subsequent failure by strain localization and rupture, while the latter mechanism is characterized by a periodic buckling pattern that is similar to the one observed in typical crash elements. Whether collapse or rupture is the limiting factor depends on geometrical parameters and material parameters, such as, for example, the hardening exponent in the Ludwik law. There are some publications of analytical considerations of the flaring process, describing the load displacement behavior of the stamp and the development of plastic deformations in the tube. However, the aspect of material and structural instability requires a deeper insight into the problem, which is provided by the experimental results and the numerical studies presented here. It appears to be important to take the tridimensionality of the stress and strain states into account when reliable predictions of necking and rupture limits are to be made.


ABSTRACT: Pushing a conical die into a tube is a forming process that is suitable for changing the shape of a thin cylindrical tube into that of a conical shell. The degree of expansion that is achievable without destroying the tube is limited by two mechanisms: (a) loss of global stability due to elasto-plastic ´Concertina´ buckling of the straight part of the tube, and (b) diffuse necking caused by local loss of material stability in the conical part of the tube. The former mechanism is characterized by a periodic buckling pattern, that is similar to the one observed in typical crash elements, while the latter mechanism leads to the formation of periodic necks and subsequent failure by strain localization and rupture. In this study experimental evidence for both kinds of instabilities is presented along with corresponding simulation results obtained with the finite element method. For long tube specimens ´Concertina´ buckling was found to be the dominant instability mode while for short tube specimens failure by necking and rupture occurred. The critical circumferential strain for the onset of necking at the expanding tube end was markedly higher than the one expected from uniaxial tension results. This finding is attributed to the supporting effect of the tube sections that are subjected to lower strains.


ABSTRACT: Modern materials and material compounds for application in lightweight structures exhibit, in addition to the use of constituents of high specific stiffness and strength, very special micro- and meso-structures. Typical representatives of such material compounds are sandwiches with thin homogeneous or
composite face layers and structured core materials (for instance honeycombs and closed or open cell foams). The load carrying capacity of lightweight structures made of such materials and material compounds, respectively, is limited by a considerable number of rather different but interconnected instability modes occurring at length scales which are several orders of magnitude smaller than the size of the structural part. These non-global instabilities are the subject of the presented keynote paper.

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ABSTRACT: Corrugated paper is produced in large volumes for packaging purposes, an application which places high demands on the structural stability of the employed corrugated board containers. This is taken into account in the optimization procedure for reducing the area-specific weight of corrugated board which is presented in this paper. For predicting effective properties of corrugated board designs, the geometry of the board is discretized by finite shell elements, and a periodic unit cell model, which contains a minimum of one full wave of the flute, is generated. By application of appropriate periodicity boundary conditions, the effective mechanical behavior of a theoretically infinite board can be predicted within the limits of linear shell theory. Furthermore, local loss of stability can also be calculated. It is possible to embed this model into an optimization procedure which attempts to reduce the area-specific weight of the board by modifying the governing geometrical parameters while enforcing the stiffness and buckling strength constraints. It has to be noted that the calculation of critical loads with respect to local buckling involves a minimization scheme within this optimization loop in order to find the critical buckling wavelength and adjust the unit cell size accordingly. We apply the proposed optimization scheme to a specific kind of corrugated board in order to determine if there is potential for weight-reduction. The optimization scheme gives a set of parameters which describes a new design of corrugated paper with the same buckling strength, but an area-specific weight that is reduced by more than 18% with respect to the original design. The improved corrugated board shows simultaneous buckling of fluting and liners under a compressive membrane load along the generatrix of the flute.

References listed at the end of the paper:
ABSTRACT: Tensile specimens of metal films on compliant substrates are widely used for determining interfacial properties. These properties are identified by the comparison of experimentally observed delamination buckling and a mathematical model which contains the interface properties as parameters. The current two-dimensional models for delamination buckling are not able to capture the complex stress and deformation states arising in the considered uniaxial tension test in a satisfying way. Therefore, three-dimensional models are developed in a multi-scale approach. It is shown that, for the considered uniaxial tension test, the buckling and associated delamination process are initiated and driven by interfacial shear in addition to compressive stresses in the film. The proposed model is able to reproduce all important experimentally observed phenomena, like cracking stress of the film, film strip curvature and formation of triangular buckles. Combined with experimental data, the developed computational model is found to be effective in determining interface strength properties.

References listed at the end of the paper:

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DOI: 10.1016/j.commatsci.2013.07.034
ABSTRACT: The local buckling behavior of perfect/defective and single/multi-walled carbon nanotubes
(CNTs) under axial compressive forces has been investigated by the molecular dynamics approach. Effects of different types of defects including vacancy and Stone–Wales (SW) defects and their configurations on CNTs with different chiralities at room temperature are studied. Results show that defects largely reduce the buckling stress and the ratio of immediate reduction in buckling compressive stress of the defective CNT to the perfect one, but have little influence on their compressive elastic modulus. SW defects usually reduce the mechanical properties more than vacancy defects, and zigzag CNTs are more susceptible to defects than armchairs. In addition, increasing the number of defects leads to higher deterioration in mechanical properties of CNTs. The results of simulations show that in the case of slender single-walled CNTs, the behavior is primarily governed by the Euler buckling law. On the other hand, in the local shell buckling mode, two distinct behaviors are observed, including the primary local shell buckling mode for intermediate CNTs, and the secondary local shell buckling mode for short CNTs. In the local buckling response, CNTs with smaller diameters sustain higher buckling stresses than CNTs with larger diameters.

References listed at the end of the paper:

ABSTRACT: Techniques for the optimization of composite with structures are investigated. The refined optimality criterion technique presented in this paper is an algorithm combining a criterion based on the Kuhn-Tucker conditions and the technique of fully stressed design. The main advantages of this method are the generality of use, the efficiency in computation, and the capability of identifying automatically the set of critical constraints. Sensitivity analysis of constraints is based on the virtual load principle. This method is especially suitable for optimum design of large-scale structures. A modular type computer program, ARS 5 (Automatic Resizing System 5), is developed in accordance with the finite element method, refined optimality criterion, sensitivity analysis and Fortran-77 language for the optimization of composite wing structures subjected to sizes, stresses, displacements, twist and buckling constraints. Numerical results for a triple-spars composite wing structure reveal that the present technique is quite efficient and reliable.


ABSTRACT: This paper presents a two-stage meta-heuristic approach to producing weight-optimised solutions needed prior to the detailed finite element analysis of composite wing. Composite wing covers are assumed to take the form of a group of stiffened sub-panels with varying skin and stiffener geometries according to the wing layout and loads. A population of limited solutions satisfying various design constraints was created using layout (skin and stiffener geometry), selected lay-ups, rule based stacking sequence and various assumed loads. The closed form analytical solutions of flat stiffened orthotropic plates are used for calculating buckling reserve factors and strength margins. For each sub-panel, a meta-heuristic rule was imposed to search for a suitable combination of skin and stiffener geometry. The criterion used was minimum weight satisfying laminate continuity accounting for manufacturability. Later, the optimised solutions for each sub-panel are converted into a format supported by the conventional finite element tool (NASTRAN). The use of meta-heuristic approach and their automation in Visual Basic for Applications resulted in fast convergence and potential time-saving compared to genetic algorithms.


SUMMARY: The paper firstly discusses the fundamental behavior of RC-shells in the ultimate load range which is characterized by a strong interaction of buckling and strength. It reviews current design procedures, few reported structural failures as well as RC model tests and finite element formulations for geometrically and materially nonlinear finite element analyses of RC-shells. Finally a brief description of one specific numerical model is give. It is applied to the ultimate load and stability analyses of conically shaped cooling towers. References listed at the end of the paper: (cannot cut and paste)


ABSTRACT: The paper first classifies various kinds of pressure loads, then linear and nonlinear finite element buckling analyses of cylindrical shells under uniform and nonuniform loads are presented. In particular the influence of displacement dependent loads on the buckling load of cylindrical shells under water and wind loading is discussed. Finally, the paper summarizes the design rules for wind loaded cylindrical tanks recently developed in Austria and Germany. The study has three goals: to clarify the problem and the effect of follower loads, to demonstrate the capability of nonlinear finite element analyses, and to discuss some results for design practice.

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ABSTRACT: The optimal design of structures with distinct geometrically non-linear behavior has attracted a great deal of interest in the last years mainly with respect to sizing for prescribed external loads. In the present contribution a method is proposed to maximize the critical load under certain constraints, e.g. for a given volume, allowing varying shape as well as cross-sections. The combination of direct computation of the critical load and path-following methods is integrated into a general optimization procedure consisting of mathematical programming techniques, sensitivity analysis and computer aided geometric design methods. The formulation includes imperfection sensitivity as an important part within the optimization process.

R. Reitinger and E. Ramm (Institute of Structural Mechanics, University of Stuttgart, Stuttgart, Germany), “Buckling and imperfection sensitivity in the optimization of shell structures”, Thin-Walled Structures, Vol. 23, Nos. 1-4, 1995, pp. 159-177, Special Issue: Buckling Strength of Imperfection-sensitive Shells,
doi:10.1016/0263-8231(95)00010-B

ABSTRACT: The subject of the present study is the optimization of structures with geometrically nonlinear behaviour allowing the inclusion of instability phenomena and imperfection sensitivity in the structural design. The proposed optimization procedure is based on the methods of path following, direct computation of bifurcation and limit points and an accurate and efficient sensitivity analysis. The finite element method is used for the structural analysis. These techniques are used together with mathematical programming schemes and methods of computer-aided geometric, design.
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ABSTRACT: In this paper, we have tried to simulate the buckling processes of shells computationally. The two major tasks needed to be carried out in such a simulation, namely (1) tracing of the time history of structural response, and (2) application of appropriate perturbation in initial condition when a deformed state has become unstable in order to trigger the buckling process, are first clarified. We then proceed to the explanation about the tools, namely (1) path-following scheme, and (2) stability criteria, which are necessary in order to carry out the above two tasks. We have omitted the exposition about the path-following scheme and touched only on the stability criteria based on Liapunov's concept of stability. Finally, we show the results of simulation carried out on three examples of shell structures. From the results, it could be concluded that numerical simulation of buckling processes of shells is possible.

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ABSTRACT: The postbuckling behavior of an axially compressed circular cylindrical shell is exceedingly complicated due to an infinite number of closely spaced postbuckling branches and bifurcation points. The minimum strength existing in the deep bottom of the postbuckling region may serve as a design limit. The primary concern in this present paper is to compute this stable postbuckling equilibrium solution by two different approaches: One is to repeat the procedures of tracing unstable branches, pinpointing bifurcation points and branch-switching in order to carefully approach to the target. The other is to trigger a static jump to the target by two-parametric loading. As a numerical example, a perfect circular cylindrical panel is analyzed to show that a direct jump from the undeformed state to a stable postbuckling solution is possible with a proper choice of the load perturbation.

References listed at the end of the paper:
ABSTRACT: The analysis of large-scale nonlinear shell problems asks for parallel simulation approaches. One crucial part of efficient and well scalable parallel FE-simulations is the solver for the system of equations. Due to the inherent suitability for parallelization one is very much directed towards preconditioned iterative solvers. However thin-walled-structures discretized by finite elements lead to ill-conditioned system matrices and therefore performance of iterative solvers is generally poor. This situation further deteriorates when the thickness change of the shell is taken into account. A preconditioner for this challenging class of problems is presented combining two approaches in a parallel framework. The first approach is a mechanically motivated improvement called ‘scaled director conditioning’ (SDC) and is able to remove the extra-ill conditioning that appears with three-dimensional shell formulations as compared to formulations that neglect thickness change of
the shell. It is introduced at the element level and harmonizes well with the second approach utilizing a multilevel algorithm. Here a hierarchy of coarse grids is generated in a semi-algebraic sense using an aggregation concept. Thereby the complicated and expensive explicit generation of course triangulations can be avoided. The formulation of this combined preconditioning approach is given and the effects on the performance of iterative solvers is demonstrated via numerical examples.

References listed at the end of the paper:


(1999).

ABSTRACT: This paper deals with the numerical computation of buckles and wrinkles appearing in membrane structures by means of the total Lagrangian formulation, using genuine membrane finite elements (with zero bending stiffness) and a prestressed hyperelastic constitutive law. The bifurcation analysis is carried out without assuming any imperfections in the structure. The standard arclength method is modified by means of a specific solution procedure to cope with the occurrence of complex roots when solving the quadratic constraint equation. Applying the proposed formulation to a set of typical numerical examples shows its ability to correctly predict the wrinkling and buckling behaviour in membrane structures.

References listed at the end of the paper:
Raffaele Zinno (University of Calabria, Italy) and Ever J. Barbero (West Virginia University, USA), “A three-dimensional layer-wise constant shear element for general anisotropic shell-type structures”, International Journal for Numerical Methods in Engineering, Vol. 37, pp 2445-2470, 1994

ABSTRACT: This paper deals with the development of a new three-dimensional element with two-dimensional kinematic constraints capable of analysing the mechanical behaviour of the laminated anisotropic shell-type structures. This element, originally developed for the linear analysis of plates, is extended for the linear analysis of laminated composite shells. The element can represent arbitrarily curved shells with variable number of layers and thicknesses, including ply drop-off problems. The element was validated in a previous work by the patch test. All the analytical details necessary to make possible the shell analysis are presented here. Examples are reported to show the capability of the element to predict the behavior of complex structures, and a refined computation of the stresses is carried out by integrating the equilibrium equations.
ABSTRACT: A very simple and practical formulation and procedure to remove the restriction of small rotations between two successive increments for geometrically nonlinear analysis of shells using flat triangular shell elements are presented. The element employed here to implement the present method is the flat triangular element proposed by Bathe and Ho (Comput. Struct. 13, 673–681, 1981). The nonlinear formulation is based on the updated Lagrangian description of motion. The rotation of the coordinate system is assumed to be accomplished by two successive rotations: an out-of-plane rotation followed by an in-plane rotation. The element internal nodal forces are calculated using the total deformational in-plane displacements and nodal rotations. Two methods, referred to as direct method and incremental method, are proposed in this paper to calculate the total deformational rotations. An incremental-iterative method based on the Newton-Raphson method combined with arc length control is adopted. Numerical studies are presented to demonstrate the accuracy and efficiency of the present method.

ABSTRACT: A corotational total Lagrangian (CR-TL) formulation using the Von Kármán assumption is presented for the analysis of nonlinear shell problems. This formulation is applicable for the nonlinear analysis of shell structures with large rotations but moderate deformations. The numerical algorithm used here is an incremental iterative method based on the Newton-Raphson method combined with constant arc length of incremental displacement vector. In order to improve the convergence properties of the equilibrium iterations, special care is taken in the calculation of the geometric stiffness matrix. Numerical examples are presented and compared with the results reported in the literature to demonstrate the accuracy and efficiency of the proposed method.

ABSTRACT: A consistent co-rotational finite element formulation and numerical procedure for the buckling and postbuckling analyses of three-dimensional elastic Euler beam is presented. All coupling among bending, twisting, and stretching deformations for a beam element is considered by consistent second-order linearization of the fully geometrically nonlinear beam theory. However, the third-order terms, which are relevant to the twist rate and curvature of the beam axis, are also considered. An incremental–iterative method based on the
Newton–Raphson method combined with constant arc length of incremental displacement vector is employed for the solution of nonlinear equilibrium equations. The zero value of the tangent stiffness matrix determinant of the structure is used as the criterion of the buckling state. A bisection method of the arc length is proposed to find the buckling load. Numerical examples are presented to demonstrate the accuracy and efficiency of the proposed method and to investigate the effect of third-order terms on the buckling load and postbuckling behavior of three-dimensional beams.

ABSTRACT: A consistent co-rotational total Lagrangian finite element formulation and numerical procedure for the geometric nonlinear buckling and postbuckling analysis of thin-walled beams with monosymmetric open section is presented. The element developed here has two nodes with seven degrees of freedom per node. The element nodes are chosen to be located at the shear centers of the end cross-sections of the beam element and the shear center axis is chosen to be the reference axis. The deformations of the beam element are described in the current element coordinate system, which is constructed at the current configuration of the beam element. In element nodal forces, all coupling among bending, twisting, and stretching deformations of the beam element is considered by consistent second-order linearization of the fully geometrically nonlinear beam theory. However, the third-order term of the twist rate of the beam axis is considered in element nodal forces. An incremental-iterative method based on the Newton–Raphson method combined with constant arc length of incremental displacement vector is employed for the solution of nonlinear equilibrium equations. The zero value of the tangent stiffness matrix determinant of the structure is used as the criterion of the buckling state. A parabolic interpolation method of the arc length is used to find the buckling load. Numerical examples are presented to demonstrate the accuracy and efficiency of the proposed method.

Lei Zhang and Gengshu Tong (Dept. of Civil Engineering, Zhejiang University, Hangzhou 310027, PRC), “Flexural-torsional buckling of thin-walled beam members based on shell buckling theory”, Thin-Walled Structures, Vol. 42, pp 1665-1687, 2004

ABSTRACT: This paper aims at describing the buckling behaviour of transversely loaded composite shell structures. Two distinctive glass fabrics, woven and knitted, embedded in the same thermoplastic matrix, polypropylene, were utilised to produce the composites to be used as subject materials. Curved strips with fixed curvature and span, but with different number of plies and orientations, were compressed between two rigid flat platens. Load–displacement responses and deformed shapes were examined using experiments and numerical simulations based on a general finite element code, LUSAS®. As the nonlinear collapse is the buckling mode evident in the experimental tests, a nonlinear stress analysis technique has been adopted to simulate the buckling responses. Single-ply strips, both for woven and knitted, display limit point symmetrical buckling
failure that shows good agreement with the predictions in terms of critical load and buckling mode. In the cases of multi-ply construction, the modes of failure for woven fabric specimens are by means of delaminations while the multi-ply knitted shells still exhibit similar behaviours to that of the single-ply specimens.


ABSTRACT: Buckling analyses of the laminated plates and shells under axial compression are carried out using the finite element method. The formulation of a geometrically non-linear composite shell element based on the updated Lagrangian method is presented to study the buckling behaviour. The element is capable of small strain and large displacement analysis with finite rotations. It has eight nodes with six degrees of freedom per node. Transverse shear deformation effects are included using a first-order (Mindlin-Reissner) theory which allows modelling of relatively thick plates and shells. Results of buckling behaviour show that the present formulation has very good agreement with existing references.


ABSTRACT: This paper presents results for cylindrical shell configurations using the STAGS computer program. Discontinuities have been imposed upon the shell's skin by incorporating symmetrical cutout openings. In addition, the surface is stiffened with both stringer and ring-stringer arrangements. The cutout problem has been shown to be highly nonlinear for smooth surface shells, but the author has found that bifurcation and collapse loads are close when one is considering stiffened skin configurations. In order to arrive at this conclusion, it was necessary to evaluate the following:

—comparison between smeared and discrete stiffener theory for linear solutions
—numerical finite difference convergence as directed toward buckling determination
—collapse load results with the various skin stiffeners.

This paper also includes a linear bifurcation study relating to stiffening effects around cutout areas present within stringer and ring-stringer shell surfaces. Comparisons have been made between a variety of geometric positions considering cutout frame and thickened skin additions. The investigation points toward an optimum positioning.


ABSTRACT: This paper discusses the fabrication process, test methods and analytical procedures used to evaluate the buckling of composite curved panels. A detailed description is given of the panel fabrication steps and the test fixture used to apply axial loading and to achieve a variety of boundary conditions. Results are presented comparing analytical and experimental buckling loads for three-ply orientations.

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ABSTRACT: The buckling loads of eight-ply graphite-epoxy cylindrical panels with midplane delamination were determined experimentally. The study included two different ply orientations, two different aspect ratios, two different delamination sizes, and one set of boundary conditions; clamped along the top and bottom edges and simply supported along the vertical sides. The experimental test results are compared to the linear bifurcation and nonlinear collapse loads of panels with square cutouts obtained from the STAGSC-1 finite-element computer code.

ABSTRACT: Over the past five years the Air Force Institute of Technology has been carrying out an investigation of small and large unreinforced cutout effects on composite cylindrical panels acting under compressive axial loads. Some of the original findings are reviewed and, in addition, new results are presented relating to different loading conditions. In general, not only does a small cutout reduce the panel's collapse load by at least 50%, but the cutout's position and size have further effect.

ABSTRACT: A finite element method, incorporating a modified Riks technique and full Newton-Raphson method (FNR), is investigated in order to trace a highly nonlinear responses such as snap-through, and single and multiple snap-back phenomena of cylindrical shells. A through the thickness parabolic transverse shear strain is considered. An initial load increment or decrement is automatically determined at the beginning of each load step, then the final load increment or decrement and the corresponding displacements are obtained in several iterations by using the modified Riks technique.

ABSTRACT: A modified Riks technique is applied to the finite element method to trace the nonlinear response from the pre-limit point into the post-limit range for a composite cylindrical shell-like structure. Parabolic transverse shear strain is considered through the thickness of the shell. The results are compared with results which did not consider a parabolic shear strain variation through the thickness of the shell.

ABSTRACT: An analytical study is conducted to determine the fundamental frequencies and critical buckling loads for laminated anisotropic circular cylindrical shell panels, including the effects of transverse shear deformation and rotary inertia, by using the Galerkin technique. A linearized form of Sander's shell strain-displacement relations are derived, which include a parabolic distribution of transverse shear strains. The theory is valid for laminate thickness to radius ratios h/R of up to 1/5. Higher order constitutive relations are derived for the laminate. A set of five coupled partial differential equations of motion and boundary conditions are derived and then solved using the modified Galerkin technique. Simply supported and clamped boundary conditions are investigated. Comparisons are made with the Donnell shell solutions. The effects of transverse shear deformation and rotary inertia are examined by comparing the results with classical solutions, where applicable. The radius of curvature is varied to determine the effects of membrane and bending coupling. The theory compares exactly with the Donnell solutions, which are valid up to h/R = 1/50. As expected, as length to thickness ratios are reduced, shear deformation effects significantly lower the natural frequencies and buckling loads. Analysis also shows that rotary inertia effects are very small. Finally, as h/R is varied from 0 (flat plate) to 1/5 (maximum limit), the frequencies and buckling loads increase due to membrane and bending coupling.

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ABSTRACT: The large-rotation snap-through characteristics of laminated cylindrical panels are investigated using a finite element method incorporating the “constant arc length” technique and Newton-Raphson method based on the assumption of through-the-thickness parabolic transverse shear strains. Comparisons with solutions obtained from the corotational stags code (i.e., a nonlinear finite element code which can follow large displacement/rotation for plate and shell structures without considering through-the-thickness transverse shear deformation) demonstrate the validity, accuracy and advantage of the present development. The nonlinear response for several laminated cylindrical panels are traced using the present method and the effects of anisotropy, fiber orientation, and stacking sequence, on the significance of large-rotation snap-through buckling are studied.

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ABSTRACT: A finite element method, incorporating the modified Riks technique and Newton-Raphson method, is used to trace a highly nonlinear response such as snap-through, single and multiple snap-back phenomenon of cylindrical shells. A through the thickness parabolic transverse shear strain is considered. The
multiple snapping responses of an isotropic panel are investigated, and their results are compared with those not considering the transverse shear deformation. Also comparison differences are noted with respect to a ‘displacement control’ strategy.


PARTIAL INTRODUCTION: The US Air Force Institute of Technology (AFIT) has been carrying out research related to the instability of composite cylindrical panels since 1979. This chapter is a review of the AFIT work and will discuss both its experimental and analytical features. Other organizations have pursued similar research [1,2], and the AFIT work has cited their findings. AFIT is the only organization that has continued to explore many of the intricacies of this interesting area. More than 150 composite graphite/epoxy cylindrical panels have been tested.....


ABSTRACT: Presented here is a new total Lagrangian finite-element formulation for general laminated composite shells undergoing large-displacement, large-rotation, and large-strain motion. The theory fully accounts for geometric nonlinearities (large rotations), large in-plane strains, general initial curvatures, transverse shear deformations, and interlaminar normal stresses by using Jaumann stress and strain measures, an exact coordinate transformation, and a new concept of orthogonal virtual rotations. In addition, with the inclusion of transverse normal and shear stresses, the theory accounts for three-dimensional stress effects and gives accurate effective structural stiffnesses. Because of the inclusion of all possible initial curvatures, the developed strain-displacement expressions can be used for any surface structures and are fully nonlinear, which contain von Kármán strains as a special case. Moreover, the theory accounts for the continuity of interlaminar shear and peeling stresses and the normal and shear stress conditions on the bonding surfaces by using a new layer-wise local displacement field, which results in a higher-order shear theory that contains most shear deformation theories as special cases. In this paper, we develop a fully nonlinear displacement-based finite-element formulation based on the derived shell theory. The verification and accuracy of the theory will be presented in a subsequent paper by comparing obtained numerical results with some exact solutions.

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ABSTRACT: The objective of this research is to determine the physical response including material failure of a thin, curved composite panel designed to resist transverse loading. The cause of the material failure, in the form of fiber, matrix and/or delamination failure, will be determined through failure criterion based on nonlinear movement using a finite element analysis technique. The finite element analysis technique known as the simplified large displacement/rotation (SLR) theory allows for large displacements but assumes small to
moderate rotations (A.N. Palazotto, S.T. Dennis, Nonlinear Analysis of Shell Structures, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 1992). Third-order shell kinematics, defined relative to the shell mid-surface, allow for the characterization of in-plane and transverse shear effects, while neglecting the direct transverse effects. Data generated using the SLR theory both with and without the addition of progressive failure criteria, will be compared with previously published experimental data, noting where the SLR theory diverges from the experimental results. The inclusion of the Hashin failure criterion will provide a more realistic representation of the total physical response of the shell (Z. Hashin, J. Appl. Mech. 47 (1980) 329–334). The criterion will investigate the shell, from initial loading, to further progressive composite failures. As the composite shell fails, the constitutive relations, or shell stiffness will be reduced. Results of the analytic comparison with the experimental data indicate that the SLR theory overpredicts the stiffness of the shell whether considering or not considering failure criteria. Results generated for the case incorporating a progressive failure criterion are closer to the experimental data because of the reduced stiffness due to failure as the deflection increases.


ABSTRACT: The method of multiple scales is used to analyze the non-linear forced response of circular cylindrical shells in the presence of a two-to-one internal (autoparametric) resonance to a harmonic excitation having the frequency OMEGA. If omega_r and a_r denote the frequency and amplitude of a flexural mode and omega_b and a_b denote the frequency and amplitude of the breathing mode, the steady-state response exhibits a saturation phenomenon when omega_b is almost equal to 2omega_r, if the excitation frequency OMEGA is near omega_b. As the amplitude “f” of the excitation increases from zero, a_b increases linearly whereas a_r remains zero until a threshold is reached. This threshold is a function of the damping coefficients and omega_b minus 2omega_r. Beyond this threshold a_b remains constant (i.e. the breathing mode saturates) and the extra energy spills over into the flexural mode. In other words, although the breathing mode is directly excited by the load, it absorbs a small amount of the input energy (responds with a small amplitude) and passes the rest of the input energy into the flexural mode (responds with a large amplitude). For small damping coefficients and depending on the detunings of the internal resonance and the excitation, the response exhibits a Hopf bifurcation and consequently there are no steady state periodic responses. Instead, the responses are amplitude- and phase-modulated motions. When OMEGA is almost equal to omega_b, there is no saturation phenomenon and at close to perfect resonance, the response exhibits a Hopf bifurcation, leading again to amplitude- and phase-modulated or chaotic motions.


ABSTRACT: A general nonlinear theory for the dynamics of elastic anisotropic circular cylindrical shells undergoing small strains and moderate-rotation vibrations is presented. The theory fully accounts for extensionality and geometric nonlinearities by using local stress and strain measures and an exact coordinate
transformation, which result in nonlinear curvatures and strain-displacement expressions that contain the von Karman strains as a special case. Moreover, the linear part of the theory contains, as special cases, most of the classical linear theories when appropriate stress resultants and couples are defined. Parabolic distributions of the transverse shear strains are accounted for by using a third-order theory and hence shear correction factors are not required. Five third-order nonlinear partial differential equations describing the extension, bending, and shear vibrations of shells are obtained using the principle of virtual work and an asymptotic analysis. These equations show that laminated shells display linear elastic and nonlinear geometric couplings among all motions.


ABSTRACT: The objective of this work was to study analytically, numerically, and experimentally the nonlinear dynamic behavior of metallic and composite structural elements to parametric and external excitations. The study was focused on resonance conditions that may produce large and possibly damaging motions. Special attention was given to modal coupling and consequent energy exchanges.

List of Presentations by A.H. Nayfeh, et al given at the end of the report:
ABSTRACT: A general geometrically exact nonlinear theory for the dynamics of laminated plates and shells undergoing large-rotation and small-strain vibrations in three-dimensional space is presented. The theory fully accounts for geometric nonlinearities by using the new concepts of local displacements and local engineering stress and strain measures, a new interpretation and manipulation of the virtual local rotations, an exact coordinate transformation, and the extended Hamilton principle. Moreover, the model accounts for shear coupling effects, continuity of interlaminar shear stresses, free shear-stress conditions on the bonding surfaces, and extensionality. Because the only differences among different plates and shells are the initial curvatures of the coordinates used in the modeling and all possible initial curvatures are included in the formulation, the theory is valid for any plate or shell geometry and contains most of the existing nonlinear and shear-deformable plate and shell theories as special cases. Five fully nonlinear partial-differential equations and corresponding boundary and corner conditions are obtained, which describe the extension-extension-bending-shear-shear vibrations of general laminated two-dimensional structures and display linear elastic and nonlinear geometric coupling among all motions. Moreover, the energy and Newtonian formulations are completely correlated in the theory.

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ABSTRACT: An experimental validation of the suitability of reduction methods for studying nonlinear vibrations of distributed-parameter systems is attempted. Nonlinear planar vibrations of a clamped-clamped buckled beam about its first post-buckling configuration are analyzed. The case of primary resonance of the nth mode of the beam, when no internal resonances involving this mode are active, is investigated. Approximate solutions are obtained by applying the method of multiple scales to a single-mode model discretized via the Galerkin procedure and by directly attacking the governing integro-partial-differential equation and boundary conditions with the method of multiple scales. Frequency-response curves for the case of primary resonance of the first mode are generated using both approaches for several buckling levels and are contrasted with experimentally obtained frequency-response curves for two test beams. For high buckling levels above the first crossover point of the beam, the computed frequency-response curves are qualitatively as well as quantitatively different. The experimentally obtained frequency-response curves for the directly excited first mode are in agreement with those obtained with the direct approach and in disagreement with those obtained with the single-mode discretization approach.
References listed at the end of the paper:


ABSTRACT: (none given on the website Refdoc)


ABSTRACT: Introductory concepts such as those of geometric and material nonlinearities are presented through a rich collection of simple yet illuminating examples shedding light on the phenomenological, theoretical and computational aspects. Most of the basic concepts are elucidated, such as the geometric stiffness, the role of nonlinear constitutive laws, the linearization about a natural or prestressed equilibrium state, the critical conditions/limit states due to the loss of elastic stability and the postcritical behaviors beyond the limit states. A major focus is placed on path following techniques for the construction of equilibrium paths or for continuation of periodic solutions. The illustrative examples range from MEMS systems to flutter control of airfoils.

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ABSTRACT: This paper, which deals with geometrically nonlinear analysis of multilayered shell structures, presents an evaluation of the approximations made when simplified models are introduced. To this purpose, a transverse shear deformable shell finite element formulation including finite rotations and large displacements is employed and von Karman, as well as moderate and small rotation theories, are obtained as particular cases. Classical shear deformation type-results have been improved in moderately thick shell analysis by using modified multilayered shear stiffnesses. These stiffnesses have been calculated through a variational technique which accounts for parabolic interlaminar continuous transverse shear stress fields and zig-zag form of the in-plane displacements along the shell thickness. Stability problems of several flat and cylindrical thin and thick geometries, different multilayered lay-outs (cross-ply, angle-ply symmetrically and unsymmetrically laminated, including sandwich) and loading conditions are considered in the numerical investigations. It has been concluded that geometrical nonlinear effects are problem dependent, furthermore such effects become more significant in thick shell analysis with respect to thin structures.

References listed at the end of the paper:
SUMMARY: This work is an overview of available theories and finite elements that have been developed for multilayered, anisotropic, composite plates and shells. Although a comprehensive description of several techniques and approaches is given, most of this paper has been devoted to the so called axiomatic theories and related finite element implementations. Most of the theories and finite elements that have been proposed over the last thirty years are in fact based on these types of approaches. The paper has been divided into three parts. Part I, has been devoted to the description of possible approaches to plate and shell structures: 3D approaches, continuum based methods, axiomatic and asymptotic two-dimensional theories, classical and mixed formulations, equivalent single layer and layer wise variable descriptions are considered (the number of the unknown variables is considered to be independent of the number of the constitutive layers in the equivalent
single layer case). Complicating effects that have been introduced by anisotropic behavior and layered constructions, such as high transverse deformability, zig-zag effects and interlaminar continuity, have been discussed and summarized by the acronym C*,0. Requirements.

Two-dimensional theories have been dealt with in Part II. Contributions based on axiomatic, asymptotic and continuum based approaches have been overviewed. Classical theories and their refinements are first considered. Both case of equivalent single-layer and layer-wise variables descriptions are discussed. The so-called zig-zag theories are then discussed. A complete and detailed overview has been conducted for this type of theory which relies on an approach that is entirely originated and devoted to layered constructions. Formulas and contributions related to the three possible zig-zag approaches, i.e. Lekhnitskii-Ren, Ambartsumian-Whitney-Rath-Das, Reissner-Murakami-Carrera ones have been presented and overviewed, taking into account the findings of a recent historical note provided by the author.

Finite Element FE implementations are examined in Part III. The possible developments of finite elements for layered plates and shells are first outlined. FEIs based on the theories considered in Part II are discussed along with those approaches which consist of a specific application of finite element techniques, such as hybrid methods and so-called global/local techniques. The extension of finite elements that were originally developed for isotropic one layered structures to multilayered plates and shells are first discussed. Works based on classical and refined theories as well as on equivalent single layer and layer-wise descriptions have been overviewed. Development of available zig-zag finite elements has been considered for the three cases of zig-zag theories. Finite elements based on other approaches are also discussed. Among these, FEIs based on asymptotic theories, degenerate continuum approaches, stress resultant methods, asymptotic methods, hierarchy-p,_,s global/local techniques as well as mixed and hybrid formulations have been overviewed.

References listed at the end of the paper:
SUMMARY: This work is a sequel of a previous author’s article: “Theories and Finite Elements for Multilayered Anisotropic, Composite Plates and Shell”, Archive of Computational Methods in Engineering Vol 9, no 2, 2002; in which a literature overview of available modelings for layered flat and curved structures was given. The two following topics, which were not addressed in the previous work, are detailed in this review: 1. derivation of governing equations and finite element matrices for some of the most relevant plate/shell theories; 2. to present an extensive numerical evaluations of available results, along with assessment and benchmarking.

The article content has been divided into four parts.

An introduction to this review content is given in Part I.

A unified description of several modelings based on displacements and transverse stress assumptions ins given in Part II. The order of the expansion in the thickness directions has been taken as a free parameter. Two-dimensional modelings which include Zig-Zag effects, Interlaminar Continuity as well as Layer-Wise (LW), and Equivalent Single Layer (ESL) description have been addressed.
Part III quotes governing equations and FE matrices which have been written in a unified manner by making an extensive use of arrays notations. Governing differential equations of double curved shells and finite element matrices of multilayered plates are considered. Principle of Virtual Displacement (PVD) and Reissner’s Mixed Variational Theorem (RMVT), have been employed as statements to drive variationally consistent conditions, e.g. $C_\gamma^0$-Requirements, on the assumed displacements and transverse stress fields. The number of the nodes in the element has been taken as a free parameter. As a results both differential governing equations and finite element matrices have been written in terms of a few $3\times3$ fundamental nuclei which have 9 only terms each.

A vast and detailed numerical investigation has been given in Part IV. Performances of available theories and finite elements have been compared by building about 40 tables and 16 figures. More than fifty available theories and finite elements have been compared to those developed in the framework of the unified notation discussed in Parts II and III. Closed form solutions and and finite element results related to bending and vibration of plates and shells have been addressed. Zig-zag effects and interlaminar continuity have been evaluated for a number of problems. Different possibilities to get transverse normal stresses have been compared. LW results have been systematically compared to ESL ones. Detailed evaluations of transverse normal stress effects are given. Exhaustive assessment has been conducted in the Tables 28–39 which compare more than 40 models to evaluate local and global response of layered structures. A final Meyer-Piening problem is used to assess two-dimensional modelings vs local effects description.

References listed at the end of the paper:


SUMMARY: A state-of-the-art in the development of a series of new finite elements by the addition of non-conforming displacement modes is reviewed in this paper. These new plate finite elements are achieved by the combined use of the addition of non-conforming modes, the application of reduced (or selective) integration scheme, and the construction of substitute shear strain fields. The improvement achieved may be attributable to the fact that the merits of these techniques are merged into the new element in a complementary manner. It is shown that the results obtained by the new elements give reliable solutions without any defects for several benchmark problems.

References listed at the end of the paper:


ABSTRACT: In the present paper two main research areas of computational mechanics, namely the finite element development and the design of time integration algorithms are reviewed and discussed with a special emphasis on their combination. The finite element techniques are designed to prevent locking and the time integration schemes to guarantee numerical stability in non-linear elastodynamics. If classical finite element techniques are used, their combination with time integration schemes allow to avoid any modifications on the element or algorithmic level. It is pointed out, that on the other hand Assumed Stress and Enhanced Assumed Strain elements have to be modified if they are combined with energy conserving or decaying time integration schemes, especially the Energy-Momentum Method in its original and generalized form. The paper focusses on the necessary algorithmic formulation of Enhanced Assumed Strain elements which will be developed by the reformulation of the Generalized Energy-Momentum Method based on a classical one-field functional, the extension to a modified Hu-Washizu three-field functional including enhanced strains and a suitable time discretization of the additional strain terms. The proposed method is applied to non-linear shell dynamics using a shell element which allows for shear deformation and thickness change, and in which the Enhanced Assumed Strain Concept is introduced to avoid artificial thickness locking. Selected examples illustrate the locking free and numerically stable analysis.

References listed at the end of the paper:

ABSTRACT: A survey of effective finite element formulations for the analysis of shell structures is presented. First, the basic requirements for shell elements are discussed, in which it is emphasized that generality and reliability are most important items. A general displacement-based formulation is then briefly reviewed. This formulation is not effective, but it is used as a starting point for developing a general and effective approach using the mixed interpolation of the tensorial components. The formulation of various MITC elements (that is, elements based on Mixed Interpolation of Tensorial Components) are presented. Theoretical results (applicable to plate analysis) and various numerical results of analyses of plates and shells are summarized. These illustrate some current capabilities and the potential for further finite element developments.

References listed at the end of the paper:


ABSTRACT: General criteria of instability in time-independent elastic-plastic solids and the related computational approaches are reviewed. The distinction between instability of equilibrium and instability of a deformation process is discussed with reference to instabilities of dynamic, geometric or material type. Comparison is made between the bifurcation, energy and initial imperfection approaches. The effect of incremental nonlinearity of the constitutive law, associated with formation of a yield-surface vertex, on instability predictions is examined. A survey of the methods of post-critical analysis is presented.

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localization”, Swansea.

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ABSTRACT: This paper concerns the theory and implementation of a numerical procedure that is capable of solving the collapse process of a structure when it is loaded past its ultimate carrying strength. The procedure is a combination of two generally available methods: A path following method for the quasi static part of the solutions and a transient method for the dynamic part. The simulation of a compression test on a thin walled cylindrical shell with a local imperfection is provided to demonstrate the effectiveness of the strategy employed.

References listed at the end of the paper:


W.B. Krätzig and P. Nawrotzki, “Computational concepts in structural stability”, Archives of Computational

ABSTRACT: The present essay contains a general structural stability theory for discretized structural systems. Instabilities are essential constituents of nonlinear structural responses, the computational assessment of which in a modern treatment is exclusively based on incremental-iterative (step-wise) numerical techniques, applied to the tangential equation of motion. The paper derives this fundamental equation as first variation of the nonlinear equation of motion in its standard form and its phase projection. Further, it transforms the principle of virtual work for arbitrary nonlinear (Kelvin-Voigt) continua into its incremental variant and finally into the consistent tangential equation of motion. Its various applications then are demonstrated to classes of time-independent and time-dependent, unstable structural responses, for which suitable numerical instruments are outlined. The derived algorithms are based on the concepts of Lyapunow exponents and Poincaré multipliers which are introduced as universal stability measures. Qualitative and quantitative convergence properties of perturbations in the phase space enable the proper establishment of stability definitions. The validity of the received concepts is illustrated by several examples.

References listed at the end of the paper:


References listed at the end of the paper:


ABSTRACT: This paper presents an innovative device to be used as an impact energy absorber. The absorber consists of a central thin trunk surrounded by a number of triangular webs. The entire assembly is enclosed outside a thin square tube that embodies the energy unit. Energy is dissipated by crumpling forces generated at square tube as well as the side walls of the device when the central trunk is displaced axially which characterizes the device as an innovative energy absorber. The results clearly illustrated the effect of absorption capacity of the absorber, and demonstrated the controllability and stability of the absorption rate. It is considered that this promising new energy absorber would be best suited as a structural fender of automobiles and trains’ compartment.

References listed at the end of the paper:
ABSTRACT: The article traces the important steps of the development of the finite element method from its origins in aircraft structural engineering to the present day, where it provides the essential tool for solution of a great variety of problems in engineering and physics. The emphasis and the choice of the “landmarks” stresses the aspects which are general and essentially of mathematical nature applicable to a wide range of situations. For this reason no mention is made of perhaps equally important developments to new application fields such as metal forming, electromagnetics, geomechanics etc.

References listed at the end of the paper:


ABSTRACT: The formulation of general shell elements using the method of mixed interpolation of tensorial components (MITC) is reviewed. In particular three elements that were formulated using the MITC method are examined: the MITC4 and MITC8 that were developed for general nonlinear analysis under the restriction of small strains and the MITC4-TLH that was developed for finite strain elasto-plastic analysis of shells.

References listed at the end of the paper:

ABSTRACT: This article presents a survey of the Core-Congruential Formulation (CCF) for geometrically nonlinear mechanical finite elements based on the Total Lagrangian (TL) kinematic description. Although the key ideas behind the CCF can be traced back to Rajasekaran and Murray in 1973, it has not subsequently received serious attention. The CCF is distinguished by a two-phase development of the finite element stiffness equations. The initial phase develops equations for individual particles. These equations are expressed in terms of displacement gradients as degrees of freedom. The second phase involves congruential-type transformations that eventually bind the element particles of an individual element in terms of its node-displacement degrees of freedom. Two versions of the CCF, labeled Direct and Generalized, are distinguished. The Direct CCF (DCCF) is first described in general form and then applied to the derivation of geometrically nonlinear bar, and plane stress elements using the Green-Lagrange strain measure. The more complex Generalized CCF (GCCF) is described and applied to the derivation of 2D and 3D Timoshenko beam elements. Several advantages of the CCF, notably the physically clean separation of material and geometric stiffnesses, and its independence with respect to the ultimate choice of shape functions and element degrees of freedom, are noted. Application examples involving very large motions solved with the 3D beam element display the range of applicability of this formulation, which transcends the kinematic limitations commonly attributed to the TL description.

References listed at the end of the paper:

experimentally and those obtained by directly attacking the continuous system. Treatment of these models yields results in agreement with those obtained from the Galerkin procedure. Approximate solution procedures based on reduced order models of nonlinear continuous systems obtained via the Galerkin method are developed for producing reduced order models that overcomes the shortcomings of higher order models via the Galerkin method are contrasted with direct application of the method of multiple scales to the governing partial-differential equations and boundary conditions. By means of several examples and an experiment, Nayfeh and co-worker had shown that reduced-order models of nonlinear continuous systems obtained via the Galerkin procedure can lead to erroneous results. A method is developed for producing reduced-order models that overcomes the shortcomings of the Galerkin procedure. Treatment of these models yields results in agreement with those obtained experimentally and those obtained by directly attacking the continuous system.


ABSTRACT: Methods for the study of weakly nonlinear continuous (distributed-parameter) systems are discussed. Approximate solution procedures based on reduced-order models via the Galerkin method are contrasted with direct application of the method of multiple scales to the governing partial-differential equations and boundary conditions. By means of several examples and an experiment, Nayfeh and co-worker had shown that reduced-order models of nonlinear continuous systems obtained via the Galerkin procedure can lead to erroneous results. A method is developed for producing reduced-order models that overcomes the shortcomings of the Galerkin procedure. Treatment of these models yields results in agreement with those obtained experimentally and those obtained by directly attacking the continuous system.

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ABSTRACT: An exact solution for the postbuckling configurations of composite beams is presented. The equations governing the axial and transverse deformations of a composite laminated beam accounting for the midplane stretching are derived. The inplane inertia and damping are neglected, and hence the two equations are reduced to a single nonlinear fourth-order partial–integral–differential equation governing the transverse deformations. We find out that the governing equation for the postbuckling of symmetric or asymmetric composite beams has the same form as that of beams made of an isotropic material. Composite beams with fixed–fixed, fixed–hinged, and hinged–hinged boundary conditions are considered. A closed-form solution for the postbuckling deformation is obtained as a function of the applied axial load, which is beyond the critical buckling load. To study the vibrations that take place in the vicinity of a buckled equilibrium position, we exactly solved the linear vibration problem around the first buckled configuration. Solving the resulting eigenvalue problem results in the natural frequencies and their associated mode shapes. Both the static response represented by the postbuckling analysis and the dynamic response represented by the free vibration analysis in the postbuckling domain strongly depend on the lay-up of the laminate. Variations of the beam’s midspan rise and the fundamental natural frequency of the postbuckling domain vibrations with the applied axial load are presented for a variety of lay-up laminates. The ratio of the axial stiffness to the bending stiffness was found to be a crucial parameter in the analysis. This control parameter, through the selection of the appropriate lay-up, can be manipulated to help design and optimize the static and dynamic behavior of composite beams.


ABSTRACT: This work presents a geometric nonlinear dynamic analysis of plates and shells using eight-node hexahedral isoparametric elements. The main features of the present formulation are: (a) the element matrices are obtained using reduced integrations with hourglass control; (b) an explicit Taylor-Galerkin scheme is used to carry out the dynamic analysis, solving the corresponding equations of motion in terms of velocity components; (c) the Truesdell stress rate tensor is used; (d) the vector processor facilities existing in modern supercomputers were used. The results obtained are comparable with previous solutions in terms of accuracy and computational performance.

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PARTIAL ABSTRACT: This paper presents an improved approach for linear buckling and geometric nonlinear analysis in MSC/NASTRAN. The differential stiffness and the internal forces of the QUAD4 and TRIA3 shell elements have been corrected in MSC/NASTRAN Version 68…


ABSTRACT: An eight-node hexahedral element with uniform reduced integration, which is free of volumetric and shear locking and has no spurious singular modes, is implemented here for geometrically nonlinear static structural analysis. In the element formulation, one-point quadrature is used so that the element tangent stiffness matrix is given explicitly and computational time is substantially reduced in the geometrically nonlinear analysis. In order to avoid shear locking the generalized strain vector is written in a local corotational system and certain non-constant terms in the shear strain components are omitted. The volumetric locking is cured by setting the dilatational part of the normal strain components to be constant. A corotational procedure is employed to obtain the deformation part of the displacement increment in the corotational system and update element stresses and internal force vectors. Numerical examples verify the computational efficiency and the potential of the three-dimensional element in the analysis of shells, plates and beams undergoing large displacements and rotations. Results are compared to those employing classical plate and shell elements.

References listed at the end of the paper:
Liercio Andre Isoldi, Armando Miguel Awruch, Paulo Roberto de F. Teixeira and Inacio B. Morsch [Mechanical Engineering, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil],

ABSTRACT: Geometrically nonlinear static and dynamic behaviour of laminate composite shells are analyzed in this work using the Finite Element Method (FEM). Triangular elements with three nodes and six degrees of freedom per node (three displacement and three rotation components) are used. For static analysis the nonlinear equilibrium equations are solved using the Generalized Displacement Control Method (GDCM) while the dynamic solution is performed using the classical Newmark Method with an Updated Lagrangean Formulation (ULF). The system of equations is solved using the Gradient Conjugate Method (GCM) and in nonlinear cases with finite rotations and displacements an iterative-incremental scheme is employed. Numerical examples are presented and compared with results obtained by other authors with different kind of elements and different schemes.

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Samir A. Emam (Department of Mechanical Engineering, United Arab Emirates University, P.O. Box 17555, Al Ain, United Arab Emirates), “A static and dynamic analysis of the postbuckling of geometrically imperfect composite beams”, Composite Structures, Vol. 90, No. 2, September 2009, pp. 247-253, doi:10.1016/j.compstruct.2009.03.020

ABSTRACT: The static and dynamic response of geometrically imperfect composite beams is presented. The proposed model accounts for the midplane stretching of the beam that follows the classical beam theory and its curvature is assumed to be shallow. The assumption of a small strain, moderate deformation is used. The governing equations are nonlinear integral partial-differential equations. A unified approach is used to handle
the postbuckling response of composite beams with and without imperfection. As a result, an analytical solution for the beam’s static response in terms of the applied axial load, imperfection, and lay up is obtained. Moreover, the free vibrations in the postbuckling domain are investigated. Having the beam’s imperfection as a control parameter, the beam’s static and dynamic response is investigated and presented. Results show that the imperfection has a significant effect on the static and dynamic response of composite beams.


ABSTRACT: Presented here is a new total-Lagrangian displacement-based finite-element formulation for plates and shells undergoing large displacements and rotations. The theory fully accounts for geometric nonlinearities, general initial curvatures, and extensionality by using Jaumann stress and strain measures, an exact coordinate transformation, and orthogonal virtual rotations. Moreover, transverse shear deformations are accounted for by using a first-order shear deformation theory with shear correction factors obtained by matching the shear strain energy and stress resultants with those of a general layerwise higher-order shear deformation theory. Large static deformations of several different plates and shells under different loading and boundary conditions are obtained. Comparison with available results in the literature reveals that the finite-element model is accurate in predicting large deformations of highly flexible two-dimensional structures.

References listed at the end of the paper:

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ABSTRACT: A dynamic finite-element model of a cracked aluminum plate repaired with a composite laminate is presented and the influence of cracks and debond of the repair laminate on the static strength and dynamic characteristics of the repaired structure are investigated. NASTRAN is used to develop a refined two-dimensional finite-element model that accounts for cracks in the aluminum plate, the debond of the repair laminate from the aluminum plate, and transverse shear deformations. The transverse shear effects are accounted for by using an energy-equivalent first-order shear-deformation theory derived from a new layerwise higher-order model of transverse shear deformations. Normal mode analysis shows that debond of the patch significantly reduces natural frequencies and changes the mode shapes of only the higher modes. Frequency response analysis shows that the debond of the patch causes a large change in the magnitudes and shapes of frequency response functions (FRFs) near the patch in the direction of the excitation. Moreover, linear buckling analysis shows that debond reduces the buckling load and may change the buckling mode shape. However, the critical size of debond that reduces the buckling load to a certain percentage of the healthy case is boundary-condition-dependent. Transverse shear deformations also reduce the natural frequencies, move the FRFs to the low-frequency range, and reduce the buckling loads, but they have no significant influence on mode shapes and the shape of the FRFs. This damage characterization study provides information useful for the design of composite repair patches and the development of health-monitoring systems using FRFs.


ABSTRACT: An account is given of the fabrication and proof-testing of a 26 m prototype corrugated GRP hull. In addition to demonstrating the feasibility of corrugated construction and confirming favorable hull cost predictions, a satisfactory outcome was obtained from towing tests to evaluate hull resistance, hull bending tests under hogging and sagging load conditions, and evaluation under a series of underwater explosions. Performance was compared in each case with that of a similar, conventional GRP hull.

ABSTRACT: A nonlinear theoretical analysis for predicting the buckling and postbuckling loads of discretely stiffened composite cylindrical shells is presented in this paper. Geometric and material nonlinearities, the effects of transverse shear and initial imperfection are considered in the analytical model. The composite material formulation is valid with the nonlinear behavior described by the modified Romberg-Osgood relation and Hill's criterion combined in an elastic-plastic model. The prebuckling analysis is obtained using the principle of virtual work, with the postbuckling bifurcation analysis based on Hutchinson's criterion. Some shell examples calculated numerically show that the theoretical analysis is in good agreement with the experimental results and other known solutions. Thus, the nonlinear theory and analysis procedure described herein can be used as an aid in the design process of composite or isotropic cylindrical shells with or without stiffeners and rings.


ABSTRACT: The vibrational response of orthotropic composite cylindrical shells subjected to axial compression is examined, following a refined Love-type theory. Results obtained are compared with those predicted by Donnell-type theory, as found in the literature. Important effects due to shell lay-up, length to radius ratio, radius to thickness ratio and fiber reversal are noted from the calculations performed for a number of double and triple-layered shells.


ABSTRACT: The free vibrations, buckling and the effect of initial prestress upon the frequency spectrum of orthotropic composite cylindrical shells are examined in the context of a theory that includes transverse shear deformation. Results obtained are compared with the predictions of refined Love-type theory and simplified Donnell-type theory that do not consider shear deformation. The calculated examples indicate that transverse shear deformation can be significant not only for short composite shells but even for longer shells possessing low shear moduli.


ABSTRACT: The equations of motion, derived from a Love-type theory, are presented for laminated filament-wound cylindrical shells in which each layer is permitted an arbitrary fixed fiber orientation. A general method of solution is established, based upon the use of a complex finite Fourier transform. The frequency spectra of free natural vibrations are investigated for numerous single, bi- and tri-layered clamped or simply supported generally orthotropic shells. The effect of fiber orientation on the frequency response is found to be quite considerable in certain composite shells; for some shells the frequency is increased by a factor of 3.1 by simply
choosing an optimal combination of the winding angles. Similar important effects are noted due to the combined action of shell heterogeneity and fiber winding angle.


ABSTRACT: The stability of filament-wound composite cylindrical shells under combined torsional/axial loading is considered, for the case in which edge-damage is present at one end of the cylinders. The displacement equilibrium equations, based on Flügge's quasi-linear theory, are solved using a finite complex Fourier transform together with the introduction of a displacement function. The zero of a determinantal equation, arising from nontrivial fulfillment of the boundary conditions, furnishes the value of the critical torque/axial load. The edge-damage is modeled by nonuniform boundary conditions. Results indicated that for isotropic shells the degree of sensitivity to edge-damage decreased the lower the applied axial load, irrespective of the direction of the applied torque. However, for anisotropic shells certain torques can actually enhance the critical axial load sustainable. This effect persists in the presence of edge-damage, and, in addition, can desensitize the shell to edge-damage over a larger section of its circumference.


ABSTRACT: The stability of thin composite layered anisotropic cylindrical shells under axial compression is considered for the case of nonuniform boundary conditions. Such conditions are employed to model the situation where there is edge damage to the shell. The influence of weakening or a crack at an edge on the critical buckling load of a variety of single and multilayered shells is investigated. Results indicate that isotropic shells exhibit a rather sudden steep reduction in the critical buckling load for relatively small edge damage. However, some anisotropic composite shells may not be so sensitive and, in contrast, only a gradual reduction may be brought about by the edge damage. The degree of sensitivity to edge damage appears to be dependent, in some complex fashion, on the various geometric and physical shell parameters.


ABSTRACT: The stability of filament-wound composite cylindrical shells subjected to radial pressure is examined, for the case in which edge-damage is present. The displacement equilibrium equations, based on Flügge's quasi-linear theory, are solved using a finite complex Fourier transform together with the introduction of a displacement function. The zero of a determinantal equation, arising from the nontrivial fulfillment of the boundary conditions, furnishes the value of the critical radial pressure. The edge-damage is modeled by nonuniform boundary conditions. From computed results it is concluded that isotropic shells are capable of withstanding edge-damage up to 50% of their circumference before a reduction in the critical pressure occurs. Anisotropy tends to weaken this sturdiness with all single and bilayered shells considered suffering a fairly sharp drop in the critical pressure sustainable after only up to 20% of the edge is "loosened". This represents a reversal of the roles of isotropy and anisotropy found by the authors for the case when the shells were subjected
to axial compression.

ABSTRACT: The static buckling of orthotropic composite cylindrical shells, under circumferentially non-uniform axial loads is investigated based on Flugge-type field equations. Use of a complex finite Fourier transform provides a simple method for handling any arbitrary non-uniform load but introduces modal coupling between the transformed equations. For simply supported boundaries (conditions SS3) the determination of the critical buckling load reduces to finding the eigenvalues of a finite matrix. Three different non-uniform loads are considered, having forms proportional to (1 + 2costheta), costheta and H(theta* - theta) where H is the Heaviside function, theta is the circumferential coordinate and atheta* is the width of an axially loaded strip of the shell of radius a. Computed results indicate the sensitivity of the critical buckling loads to the type of non-uniform load and the material lay-ups of the cylinders.

ABSTRACT: An experimental investigation to determine the buckling and rupture strength of a fabricated torospherical head under internal pressure loading has recently (1984) been carried out under the sponsorship of several industrial and governmental agencies. Preliminary evaluation of the data indicates a larger than expected factor of safety between initial buckling and failure. An important consideration in the investigation is the elastic stress pattern prior to the initiation of buckling. In this paper, the results of a linear elastic stress analysis are presented in order to demonstrate the resulting stress patterns and to compare several different computer codes. This solution is also thought to be suitable as a benchmark problem for the validation of computer codes for thin shell analysis. The analysis demonstrates several interesting aspects of the significance of bending stresses for a situation where there are neither abrupt geometrical discontinuities nor locally concentrated loads, two classical sources of bending in thin shells.

ABSTRACT: A nonlinear finite element model that is suitable for the static analysis of shells of revolution with local plasticity is developed. Actually, shells of revolution always exhibit local deviations, like a cutout, a junction, and/or an imperfection. The stress concentration caused around a local deviation may make the material plastic in the surrounding region. The analytical model consists of three different types of shell elements: rotational, general, and transitional. The rotational shell elements are used in the region where the shell is axisymmetrical, and the general shell elements are deployed in the region of the deviation. The transitional shell elements are inserted between the two distinctively different types of elements to achieve continuity of displacement fields. Only the general shell element possesses the material nonlinear properties to capture the localized plasticity. A simple description of plastic behavior based on elastic-plastic behavior, the Von Mises criterion, the Prandtl-Reuss flow rule, and a layered structure, developing plastification through the
thickness of the general shell, is used. The stress components at appropriately chosen station points covering the entire volume of the element are stored during the computation. A check is made for initial yielding in the general shell elements at the end of each step of loading. The results of three numerical studies elucidate the localized nonlinear material behavior in a rotational shell structure. In the first example, an axisymmetric junction problem is studied to check the technique against published results. Then, in the last two examples, a cylindrical shell with a circumferential line crack and with a circular cutout are studied. Since the selection of the size of the substructure and the number of harmonics are very important for the localized plasticity problem in the rotational shell, detailed convergence studies are presented. It is shown that the local-global analysis is an attractive alternative to the entirely general element style analysis for axisymmetric shell structures with local imperfections.


ABSTRACT: The mode of collapse in many metallic shells is, oftentimes, one of localized collapse, wherein severe plastic deformation and high displacement gradients are localized within some region. The combined material and geometric non-linearity emanating from this local region is the predominant cause of instability in shells of revolution. In such a situation a local-global strategy is very useful for an efficient analysis. This strategy consists of employing two dimensional degenerated isoparametric shell elements with non-linear capability in a well defined 'local' zone where all the non-linearities are expected to be localized and which also contains some form of local deviation from axisymmetry such as a circumferential imperfection, cutouts, cracks, etc. Linear elastic ring type elements are employed in the remaining axisymmetric zone and the two zones are linked through a transformation between the degrees of freedom involved. The solution of the non-linear problem is achieved by appropriate condensation procedures to reduce the number of active degrees of freedom and the load incrementation is achieved by the well known 'arc length' iterative procedure. Numerical examples are presented to demonstrate that this strategy is very efficient and accurate for problems with well defined non-linear local zones. The capability of this strategy for treating problems with local material discontinuities such as cracks, cutouts, etc. as an efficient alternative to a complete two dimensional discretization is pointed out.

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ABSTRACT: A finite element program is developed as a tool to analyse shells of revolution with local non-linearities. In reality, shells of revolution often exhibit local deviations, like a cut-out, a junction and/or an imperfection. The stress concentration around a local deviation may produce plasticity and/or geometric non-linearities in the surrounding region. The analytical model consists of three different types of elements: rotational, transitional and general. The rotational shell elements are used in the region where the shell is axisymmetrical and linear, while the two-dimensional general shell elements are deployed in the deviation region where non-linearities may occur. Transitional shell elements connect the two distinctively different types of elements to achieve displacement field continuities. The solution using the local-global system with
appropriate condensation and a predicted stress incremental procedure is suggested. It is shown that the technique is a very attractive alternative to the entirely general element style analysis for axisymmetric shell structures with local deviations.

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ABSTRACT: A local–global finite element model suitable for the analysis of column-supported shells of revolution is presented. The model combines, in a single analysis, axisymmetric shell elements, general shell elements, and column elements. Axisymmetric or rotational shell elements which can accommodate geometric nonlinearities are employed in the axisymmetric portion of the shell. In this region, the nonaxisymmetric behavior in loading and deformation is accounted for by including appropriate Fourier harmonics. The column-supported area is modeled using individual column elements. The local zone is identified as the region consisting of the column elements and the physically and geometrically nonlinear general shell elements inserted between the column-support area and the axisymmetric shell portion. In addition, either deviations from the axisymmetric geometry of the shell, such as imperfections or cut-outs, and/or nonlinear materials can be easily included in the local zone. Examples which illustrate the proposed procedure are presented.

ABSTRACT: A local-global finite element technique suitable for the analysis of shells of revolution with localized non-axisymmetric effects such as cracks, cutouts and column supports is presented. Both material and geometrical nonlinearities are considered. The model combines, in a single analysis, rotational shell elements, general shell elements, and column elements. Rotational shell elements are employed in the axisymmetric portion of the shell, where the nonaxisymmetric behavior in loading and deformation is accounted for by including appropriate Fourier harmonics. In the local zone, where deviations from axisymmetry are contained, a general isoparametric shell element is employed. Continuity of displacements between the rotational and general shell elements is achieved either by a layer of transitional elements or by a direct coordinate transformation. If the shell is supported on a discrete system of columns, a standard 3-D beam element with six degrees-of-freedom per node is deployed. This local-global approach has been applied to a wide variety of shell problems.

ABSTRACT: The first part of the paper presents an extensive literature review of the research done on stability of stiffened plates under uniform compression. The methods developed to predict the overall buckling load are
first presented. The common methods and idealization to predict the local buckling load of stiffened plates are also discussed. The philosophies of the various techniques developed to compute the ultimate strength of the structure are then described. Finally, the optimization approaches developed for minimum weight design of the structure are presented. In the second part of the paper, theoretical formulations for the stability analysis of stiffened plates under uniform compression are presented. As a first stage, the governing differential equations for eccentric stiffening are derived. The transition to the orthotropic plate equation is shown through a simplifying assumption. It will be shown that for eccentric stiffening, three coupled differential equations need to be solved, while for concentric stiffening only Huber differential equation need to be considered. Then, an alternative energy-based approach is described for stability analysis of multi-stiffened plates under uniform compression. The structure is idealized as assembled plate and beam elements and rigidity connected at their junctions. The strain energy components for the plate and the stiffener elements are then derived in terms of the out-of- and in-plane displacement functions and sequential quadratic programming is then used to find the buckling load of the structure for given plate/stiffener geometric proportions. Efficiency of the method is compared with the finite element method. Finally, extensive results are presented to investigate the buckling behavior of multi-stiffened plates. The transition from the various buckling modes is shown by changing the plate/stiffener geometric parameters for various concentric and eccentric stiffening configurations. Influence of stiffener spacing, in-plane boundary condition on the buckling load is also highlighted. Using these results guidelines are proposed for efficient design of stiffened plates.

ABSTRACT: This paper describes the interactive buckling behaviour of thin-walled columns by means of a simple engineering analysis. After a brief review of individual column and plate buckling phenomena, the effect of one upon the other is investigated in the presence of initial imperfections. Estimates of the ultimate load capacity of such columns and the effects of material yielding are obtained. The results are compared with published experimental data, yielding good correspondence. The work clearly demonstrates that the interactive presence of Euler buckling, plate buckling, imperfections, and material yielding in thin-walled columns has a serious detrimental effect on their ultimate strength.

ABSTRACT: A comprehensive mode interaction analysis is presented for thin-walled columns having doubly symmetric cross-sections and carrying axial compression. It is shown that as a result of interaction of overall bending with the primary local mode, a “secondary” local mode having the same wavelength as the primary, is triggered. The problem is therefore viewed as one of interaction of three modes: viz. the overall (Euler) buckling mode and the two local modes. The analysis is based on Koiter's theory of mode interaction and employs finite strips to describe local buckling deformation. The column is treated as being loaded by a prescribed end compression at the centroid and a suitably prescribed end rotation to maintain concentricity of load application. Examples are presented to compare the results of the present theory with the currently available analytical results and to examine the behavior of typical cross-sections. Of particular interest is the considerably reduced imperfection-sensitivity of columns with well-separated critical stresses in comparison to that reported earlier in published literature.

ABSTRACT: A new formulation has been developed to study the interactive buckling of thin-walled columns having arbitrary cross-sections. The emphasis in this paper is, however, on columns with a single axis of symmetry. The formulation is designed to take into account the simultaneous interaction of the purely flexural and flexural-torsional overall modes of buckling with local buckling. The local buckling deformations are described in terms of a primary local mode together with two secondary local modes of the same wavelength. The latter are triggered by the interaction of bending in two perpendicular planes with the primary local mode. The three eigenmodes and the six second-order in-plane displacement fields are all computed using a finite-strip technique. The modulation of the amplitudes of the local modes and the overall displacements are described in terms of a one-dimensional finite element model. Thus a new beam element which has embedded in it the local buckling information is developed. It appears that the present analytical model is very versatile being applicable to members of arbitrary cross-section and end conditions. For columns with a single axis of symmetry, it is seen that there exists a non-linear coupling between the purely flexural and the flexural-torsional modes of buckling via local buckling deformation. Typical examples of channel section columns are presented. It is shown that the channel section columns of commonly used proportions are highly imperfection sensitive in the context of combined interaction of the enumerated modes of buckling. This sensitivity remains even for columns with well separated overall and local critical stresses—a feature which is in stark contrast with the behavior of the Tvergaard panel.


ABSTRACT: The paper reviews the theoretical foundations of a new analytical model developed for the study of nonlinear interaction of local and overall instabilities of axially compressed stiffened plates. It is shown that: the mixed second order field contains within itself all the essential secondary local modes liable to be triggered in the interaction; any such mode having an eigenvalue of the same order of magnitude as the primary local critical stress must be treated as a fundamental mode fully participating in the interaction in order that the analytical procedure is not riddled by singularities in the evaluation of the mixed second order field; and the technique of amplitude modulation is an effective substitute for accounting for a set of local modes of the same transverse description but of slightly differing wave lengths. The computational aspects are briefly touched upon and the form of an explicit potential energy function derived is shown. The results obtained using the present model are then compared with the theoretical results obtained by Koiter and Pignataro and Tvergaard for several cases. The question of optimality is examined. The results confirm the earlier finding of Tvergaard that the optimally designed panels would have the local critical stresses higher than the overall buckling ones. A comparison of the present theory against the experimental results obtained by Thompson et al. for panels with “stocky” and “thin” stiffeners is then presented. In all cases, there is found to be very good agreement between the experimental and theoretical results.

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ABSTRACT: A strategy for minimum weight design of axially compressed stiffened panels is presented. It is first noted that the ‘naive’ criterion of simultaneous buckling in the local and overall modes, is not applicable in view of the severe imperfection-sensitivity of such designs. Imperfections are admitted and the required maximum capacity is viewed as the limit point of the nonlinear structure. The interaction of local and overall buckling—the central feature of the behavior of the panels—is accounted for by a well tested analytical model which incorporates amplitude modulation and the influence of secondary local mode(s). The optimization technique employed is based on Powell’s algorithm (VMCON). A systematic approach has been developed for the selection of the trial section. This is based on appropriately ‘beefing up’ and separating the critical stresses of a preliminary section obtained using the ‘naive’ criterion. A reduced model is developed by utilizing the patterns of overall deformation and amplitude modulation obtained from the nonlinear analysis of the trial section. A potential energy expression is developed in terms of the geometric parameters and four degrees of freedom. The algorithm was found to be extremely efficient from the points of view of both computational ease and accuracy. It is found that the configuration of the optimum panel with blade-type stiffeners lies in a transition from ‘thin’ to ‘stocky’ stiffener range. The weight of the optimized panel is sensitive to initial imperfections and can vary over a range of 20% due to moderate level of imperfections commonly assumed in the analyses. The weight of optimal panels with given values of the aspect ratios vary over a wide range and the careful selection of the width of the panel holds the key for successful optimal design.


ABSTRACT: Thick composite-layered shells under hydrostatic pressure are analyzed for buckling and postbuckling response using axisymmetric solid elements. The numerical approach is based on p-version finite elements in conjunction with appropriate trigonometric functions. Particular attention is given to the evaluation of interlaminar stresses in the postbuckling range. The postbuckling response is determined using an asymptotic approach. It is found that layered shells with \( Z \) (the modified Batdorf parameter) < 1000 are imperfection-sensitive with respect to local buckling; shells with relatively small radius to thickness ratios develop significant interlaminar shearing stresses, of the order of 50% of the buckling pressure, for buckling displacements of the order of one-tenth of the shell thickness. Together, the imperfection-sensitivity and the high inter-laminar stresses can precipitate failure before the classical critical pressures are reached. These factors must be considered along with the potential for interaction of local and overall buckling in optimally designed, stiffened shell configurations. Numerical analyses demonstrate the effectiveness of the p-version approach in achieving rapid convergence of the buckling pressures, the imperfection-sensitivity parameter and the magnitude of interlaminar stresses. Wherever possible, comparisons have been made with results available currently in the literature. It is found that for long shells (\( Z > 1000 \)), the Donnell type formulations can seriously underestimate the buckling pressures. The present formulation based on three-dimensional nonlinear elasticity offers an accurate, powerful and yet computationally effective means of analysis of thick shells.

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ABSTRACT: In this paper a local–global analysis technique is presented for the non-linear analysis of shells of revolution with a localized material discontinuity in the form of a crack or a cutout. The local zone is modelled using two-dimensional general shell elements. Axisymmetric shell elements with Fourier description in the circumferential direction are used away from this local zone. In contrast to the earlier work of the authors, the geometric non-linearity is taken into account in the axisymmetric zone as well. The harmonic coupling in the axisymmetric zone is efficiently handled through the pseudo-load approach. A special preconditioned conjugate gradient iterative method is employed in conjunction with the arc length method for achieving improved convergence and negotiating the limit points. The attractive features of this methodology are that the tangential stiffness matrix of the structure is never assembled and factorized and that most of the computations are simple matrix–vector multiplications which are carried out efficiently at the element level. Numerical examples are presented to demonstrate the applicability of this method.

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ABSTRACT: A novel methodology for the analysis of local and overall instabilities in stiffened plates and shells is proposed. The method consists of embedding the local buckling deformation—the buckling mode together with the associated second order fields—in an appropriate shell element. The local buckling deformation is controlled by a relatively small number of degrees of freedom which also allow for amplitude modulation. Examples of stringer-stiffened plates and shells subjected to axial compression are presented. Excellent agreement is found to exist between the results given by the method and those obtained from full blown nonlinear analysis and experiments. It is shown that the proposed technique offers a simple and considerably less expensive approach to mode interaction problems than conventional nonlinear finite element analysis. Imperfection-sensitivity under coincident buckling of axially compressed stringer-stiffened cylindrical shells is explored and it is shown that there can be an erosion of 50% of the load carrying capacity under imperfections of the kind unavoidable in practice.


ABSTRACT: A novel and computationally effective procedure for the study of the overall and local instabilities in composite ring stiffened shells subjected to hydrostatic pressure is presented. The key feature of the formulation employed is a judicious combination of Koiter's amplitude modulation technique and the Bykov-Hutchinson asymptotic procedure for the interactive buckling analysis. A potential energy function is formulated in terms of a comparatively small number of degrees-of-freedom, viz. the degrees-of-freedom depicting the amplitude modulating function and a scaling factor of the overall buckling mode. As a result of the amplitude modulation, there arise in the potential energy function non-vanishing cubic interactive terms which control the process of mode interaction. Imperfection-sensitivity under coincident buckling is examined. It appears that a 50% reduction of the buckling capacity must probably be allowed for as a result of modal
interaction under near-coincident buckling. The optimality under interactive buckling is also examined with the total volume of the material kept constant and the critical stress ratio varied.

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“A structural efficiency study of isogrid-stiffened fiber composite laminate shells: buckling and postbuckling analyses and experiments”, Proceedings of the Tenth International Conference on Composite Materials (ICCM-10), edited by Ken Street, Whistler, B.C., Canada, August 1995

ABSTRACT: Recent advances in fiber composite manufacturing and structural efficiency requirements have led to the consideration of isogrid-stiffened fiber composite laminate shells for various aeronautical and space structural applications. Very little information, if any, on buckling and postbuckling of these grid-stiffened composite shells is currently available in the literature. In this paper, a combined analytical and experimental study is reported on buckling and postbuckling behavior of filament-wound fiber composite laminate cylindrical shells stiffened with isogrid structures made of the same composite. Buckling loads and postbuckling deformation characteristics of isogrid-stiffened composite shells, monocoque shells and pure composite isogrid stiffener structure have been obtained from linear bifurcation and geometric nonlinear postbuckling analyses and experiments.

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ABSTRACT: An analytical study is presented in this paper on the effect of material nonlinearity on buckling and postbuckling of fiber composite laminate plates and shells subjected to general mechanical loading. The material nonlinearity of the composite is modelled by power-law type, nonlinear shear constitutive equations for each lamina. The nonlinear effective composite constitutive equations in an incremental form are incorporated into a geometrically nonlinear analysis for studying buckling and postbuckling deformations of composite laminate structures. A modified Riks' solution scheme with an updated Lagrangian formulation is used to construct the equilibrium path during composite postbuckling. Numerical examples are given to illustrate the effect of material nonlinearity on buckling load, postbuckling stiffness, and associated mode shape change of a composite structure under axial and pressure loading. Influences of lamination parameters, geometric imperfection, and loading mode on the postbuckling equilibrium path and load-bearing strength of the composite structure with the nonlinear material properties are also studied.

References listed at the end of the paper: (cannot cut and paste references)


ABSTRACT: The dynamic instability of interior ring stiffened composite shells under hydrostatic pressure is
investigated. A shell structure such as a submarine vessel can undergo suddenly applied overpressure or successive shocks. In the presence of imperfections, the dynamic instability so triggered leads to a reduction of the load carrying capacity of the shell from that associated with quasi-static loading. Further, the large amplitude vibrations that occur prior to reaching the dynamic limiting pressure can have a damaging effect on the material of the shell. An asymptotic procedure is used in conjunction with p-version finite elements to extract the buckling mode and the associated second-order field. A single differential equation involving cubic nonlinearity is developed to characterize the dynamic behavior of the shell structure. This is solved by the Newmark method for time step integration along with Newton-Raphson iterations. Attention is focused on the reduction of the buckling pressure of the shell under dynamic loading, as well as the shell response at various increasing load levels until the displacements become unbounded.


ABSTRACT: The interaction of local and overall buckling in stiffened plates and cylindrical shells has been analyzed using a novel finite elements in which local buckling deformation has been embedded. Amplitude modulation, a key feature of the interactive buckling has been incorporated in the element formulation. The model has the following additional features: (i) the inclusion of a key secondary local mode where the cross-section has complete or approximate double symmetry; and (ii) the introduction of a simple approach for capturing localization of local buckling; this involves incorporating a single local buckling mode in the analysis, but letting the amplitude modulation function to be different for different elements. Numerical examples of plate and shell structures are presented to throw light on these aspects of the methodology as well as to demonstrate the accuracy and efficiency of the model.

References listed at the end of the paper:
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ABSTRACT: This paper presents a summary of the work carried out at Washington University in recent years on the buckling and associated non-linear response and collapse of moderately thick composite cylindrical shells. Ring elements in conjunction with a three-dimensional elasticity formulation are employed in the analysis. The buckling and postbuckling imperfection sensitivity in individual modes is studied first. The problem of interaction between local and overall instabilities is then investigated in detail. Imperfection sensitivity of typical ring-stiffened shells is established by using a simple and effective approach that combines the asymptotic procedure and the amplitude modulation technique. The influence of dynamic application of the hydrostatic pressure is investigated with the simplified model. The results obtained are compared with those produced by a two-dimensional program package which includes full-fledged non-linear analysis with ring elements, and commercial programs wherever possible. The study has thrown light on several issues regarding the modeling and behavioral aspects of thick composite shells which are summarized at the conclusion of the paper.

Srinivasan Sridharan and Sunjung Kim (Department of Mechanical, Aerospace and Structural Engineering, Campus Box 1130, 1 Brookings Drive, Washington University in St. Louis, St. Louis, MO 63130, USA), "Piezo-electric control of stiffened panels subject to interactive buckling", International Journal of Solids and Structures, Vol. 46, No. 6, March 2009, pp. 1527-1538, doi:10.1016/j.ijsolstr.2008.11.025

ABSTRACT: The paper examines the feasibility of piezo-electric control of stiffened plates carrying axial compression and subject to interaction of local and overall buckling. A simple control strategy involving piezo-electric patches along the tips of the stiffeners carrying equal and opposite electric fields to resist bending of the stiffeners was found to effectively counteract the adverse effects of mode interaction and imperfection-sensitivity. For the dynamic problem, this strategy needed to be supplemented with patches attached to the surfaces of the plate in the middle of the panel to damp out local buckling oscillations. Two panels were considered, these being scaled replicas of each other. This enabled an examination of the scaling laws of response with practical applications in view. The results demonstrate that the structural performance of optimally designed stiffened structures can be enhanced with minimal energy consumption by appropriately designed piezo-electric patch configuration.

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Rabinovitch, 2005 O. Rabinovitch, Geometrically nonlinear behavior of piezo-electric laminated plates, Smart Materials and Structures 14 (2005), pp. 785–798.

S. S. Wang (1), S. Srinivasan (1), K. B. Su (2) and M. G. Dunham (3)
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“A structural efficiency study of isogrid-stiffened fiber composite laminate shells: buckling and postbuckling analyses and experiments”, Proceedings of ICCM-10, Whistler, B.C., Canada, August 1995
ABSTRACT: Recent advances in fiber composite manufacturing and structural efficiency requirements have led to the consideration of isogrid-stiffened fiber composite laminate shells for various aeronautical and space structural applications. Very little information, if any, on buckling and postbuckling of these grid-stiffened composite shells is currently available in the literature. In this paper, a combined analytical and experimental study is reported on buckling and postbuckling behavior of filament-wound fiber composite laminate cylindrical shells stiffened with isogrid structures made of the same composite. Buckling loads and postbuckling deformation characteristics of isogrid-stiffened composite shells, monocoque shells and pure composite isogrid stiffener structure have been obtained from linear bifurcation and geometric nonlinear postbuckling analyses and experiments.

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ABSTRACT: Filament-wound, fiber-reinforced polymer-matrix composite laminate tubes have been used for a wide range of engineering applications, owing to their high specific stiffness, strength and superior corrosion resistance. Leakage failure of composite tubes under multiaxial loading has been an important design concern. Extensive analytical and experimental investigations have recently been reported on leakage failure of composite tubes. These investigations developed deterministic estimates of leakage failure for different combinations of axial load and internal pressure. Effects of uncertainties in material properties and laminate construction on leakage failure need to be studied in detail. In this study; probabilistic analyses are performed to predict first-ply failure of angle-ply composite laminate tubes under combined internal pressure and axial loading. Randomness is considered in (1) elastic moduli along principal lamina directions; (2) uniaxial matrix-dominated strengths of each lamina; and (3) local thickness variation of individual plies. The probabilistic finite element analysis is performed using the ANSYS program and Latin hypercube sampling. Influence of each basic variable on first-ply failure is evaluated. These are compared with experimental results available in the literature.

References listed at the end of the paper:
ANSYS Release 8.0, ANSYS Inc., Canonsburg, PA.

ABSTRACT: The buckling problem of angle-ply laminated long hollow cylinders under axial compression is investigated on the basis of 3D elasticity considerations. The study is based on a recursive and successive approximation method and the introduction of a periodic complex displacement field. By this approach, the composite cylinders may be composed of a number of anisotropic layers, each of which may have different material properties, thicknesses, and laminate profile. The eigenvalue problem, from which the buckling load is
found, always has a dimension of 3 x 3, regardless of the number of the layers. The buckling of either symmetric or antisymmetric angle-ply laminated cylinders under axial compression is investigated through a parametric study. The results are presented in graphic form for cylinders having various thicknesses and layups.

References listed at the end of the paper:

[10-13] (for external pressure). However, the problem of finding the value of the dynamic load for which the limiting state is reached in a shell has been solved only in [16] from among the papers known to the authors, where the bending and stresses in a steel shell were determined in a geometrically linear formulation upon the action of an axial compressive pulse of rectangular shape. The content of a procedure developed by the authors for the solution by the Bubnov-Galerkin method of the geometrically nonlinear equations of average bending under the action of dynamic axial compression or external pressure on an orthotropic cylindrical shell is briefly outlined in this article. Examples are given of the determination of the critical loads for multilayer shells using the strength surfaces for composites under conditions of a plane stress state…


ABSTRACT: A procedure has been shown for calculating the stress-strain state of cylindrical multilayer shells made from composite materials under the combined action of dynamic axial compression and dynamic external pressure, as well as with different variants of combined loading with static and dynamic forces. An investigation has been made of the effect on the mode of the buckled shell surface of the ratio of the application rate of dynamic loads; ranges of loading rates have been established in which stresses predominate caused either by axial compression or external pressure. It has been shown that, as a result of preliminary static loading, a marked change occurs in the initial imperfections of the shell mode which affects subsequent dynamic buckling. To calculate the time when the first defect occurs and its location in the shell body, a procedure has been devised for layer-by-layer strength analysis employing a tensor-polynomial criterion. It was demonstrated that the level of preliminary static loading noticeably affects the time until the first failure of the layer, not only a reduction of this time being possible with an increase in the static loads, but also an increase in it.

References listed at the end of the paper:

PARTIAL ABSTRACT: The main characteristic feature of the process of buckling of cylindrical shells acted on by both static and dynamic axial compressive loads is its high sensitivity to initial imperfections of the shape of the shell. The assumption that, among the factors which reduce the carrying capacity of a shell, deviations from an ideal cylindrical shape of the surface play a dominant role was first advanced in [1]. It subsequently received convincing confirmation in numerous experimental and theoretical investigations. Two trends have developed in the solution of the problem of static stability…


ABSTRACT: (none given)
References listed at the end of the paper:
PARTIAL INTRODUCTION: Problem of the dynamics of stiffened cylindrical shells has attracted the diligent attention of researchers in recent years. Questions concerning the natural and induced vibrations of stiffened cylindrical shells are examined in greater detail in familiar theoretical studies (A review of these investigations is given in [1,2]). Results obtained to date on the problem of the determination of strengthened cylindrical shells under dynamic loads are meager and are clearly inadequate for both a definitive understanding of the effect of strengthening elements on the deformation process, and also their effective use to increase the bearing capacity of designs…

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“Analytical probabilistic modeling of initial failure and reliability of laminated composite structures”,
doi:10.1016/S0020-7683(97)00081-4

ABSTRACT: An analytical approach based on the theory of stochastic processes is developed for the stochastic initial failure analysis and reliability predictions of thin-walled laminated composite structures. The probability of initial failure is calculated using theory of rare passages of the random strain vector field out of the prescribed region of allowable states. The region is limited by the ultimate strain surfaces adopted for each individual layer in the laminate. The surfaces, in their turn, are defined in terms of the scatters in the ultimate strains for the composite layer. Reliability function of a composite layer having random elastic characteristics and loaded with random in-plane tractions is determined through the probability of its initial failure. The reliability function of the laminated composite structure is then calculated through the failure probabilities of individual layers, using the weakest link model. The proposed approach allows one to solve diverse stochastic problems and requires substantially less computational expenses than Monte Carlo simulation technique. The approach may be invaluable for a quick evaluation of various competitive design projects when considering laminated composite structures under the reliability constraint. Applications of the developed approach are illustrated on the examples of reliability predictions of laminated composite cylindrical shells under the effect of random internal pressure and laminated composite plates under random biaxial loading. Numerical results reveal specific probabilistic phenomena related to the effects of ply lay-up, scatters in mechanical and strength characteristics and random loading histories. Results obtained from the developed analytical approach are compared to those calculated with Monte Carlo simulation technique.

V.V. Vendyukov and V.V. Deryushev (Rostov-na-Donu, Russia), “Dynamic short-wave buckling of thin-walled cylindrical shells upon local action of an external pressure pulse”, Scientific and Technical Section,
ABSTRACT: We present the results of experimental investigations of dynamic instability (buckling) of thin-walled cylindrical shells upon local action of an external pressure impulse. In order to create the local short-term loading, we used pulsed radiation from a CO\textsubscript{2} laser. The test pieces were smooth and reinforced shells made from aluminum alloys. The nature of the buckled wave in the treated region and the magnitude of the critical impulse correspond to the short-wave type of buckling in the shell and are determined by the amplitude of the pressure pulse. Axial static compression of the shell leads to a decrease in the critical impulse and an increase in the number of waves in the meridional direction within the treated region.

References listed at the end of the paper:


ABSTRACT: A coupled fluid structure interaction problem is analyzed using semi-analytical finite element method involving composite cylindrical shells conveying hot fluid for free vibration and buckling behavior. The system under study is assumed to have a steady flow of hot fluid and the temperature variation is axisymmetric. First order shear deformation theory is used to model the elastic shells of revolution. Geometric stiffness matrix is evaluated to consider the effects of axisymmetric temperature variation through the shell continuum due to flow of hot fluid. The fluid domain is modeled using the wave equation. Numerical results of the studies on composite cylindrical shells made of HS-Graphite/Epoxy with two different length to radius ratios and clamped–clamped boundary condition conveying hot fluid are presented. The variation of the natural frequency of the coupled system is evaluated with the steady flow of the hot fluid. The influence of the temperature on the mean axial flow velocity through the shell is critically examined. The critical velocity of the hot fluid and cold fluid which leads to shell instability is compared thus establishing the fact that the lowest critical velocity of the hot fluid coincides with the mode corresponding to the lowest critical thermal buckling temperature. Various fibre angles are also considered in the study and its influence is also examined.


ABSTRACT: Linear thermal buckling and free vibration analysis are presented for functionally graded cylindrical shells with clamped–clamped boundary condition based on temperature-dependent material properties. The material properties of functionally graded materials (FGM) shell are assumed to vary smoothly
and continuously across the thickness. With high-temperature specified on the inner surface of the FGM shell and outer surface at ambient temperature, 1D heat conduction equation along the thickness of the shell is applied to determine the temperature distribution; thereby, the material properties based on temperature distribution are made available for thermal buckling and free vibration analysis. First-order shear deformation theory along with Fourier series expansion of the displacement variables in the circumferential direction are used to model the FGM shell. Numerical studies involved the understanding of the influence of the power-law index, r/h and l/r ratios on the critical buckling temperature. Free vibration studies of FGM shells under elevated temperature show that the fall in natural frequency is very drastic for the mode corresponding to the lowest natural frequency when compared to the lowest buckling temperature mode.

ABSTRACT: In this paper, the free vibration analysis of isotropic conical shell panel with all edges clamped carried out by using an integral equation technique is described. Results of a parametric study are presented.

ABSTRACT: The present paper deals with the dynamic response analysis of stiffened conical shell panels using an integral equation method in the space domain. The smearing technique is used for closely spaced stiffeners. The time domain analysis has been done using the mode superposition method. The effect of eccentricity of stiffeners has been studied.

ABSTRACT: In this paper, the application of integral equation technique to dynamic response problem has been illustrated by considering the layered conical shell panel. The method consists of using the integral equation technique in the space domain and direct integration using the Wilson-theta method in the time domain. Since results are not available for layered conical shell panels, the values obtained for the particular case of isotropic cylindrical panel have been compared with the results obtained using a different procedure, viz series solution combined with mode superposition.

ABSTRACT: The theory of nonlinear stability for a truncated shallow conical shell with variable thickness under the action of uniform pressure was presented. The fundamental equations and boundary conditions were derived by means of calculus of variations. An analytic solution for the critical buckling pressure of the shell with a hyperbolically varying thickness is obtained by use of modified iteration method. The results of numerical calculations are presented in diagrams, which show the influence of geometrical and physical parameters on the buckling behavior.
References listed at the end of the paper:
S. Buesing and H.-G. Reimerdes (Department of Aerospace and Lightweight Structures, RWTH Aachen University, 52062 Aachen, Germany), “A strip element with interface layer for the prediction of delamination in buckled composite panels”, The European Commission Project COCOMAT (Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of COllapse), 2006

ABSTRACT: An element for the prediction of delamination is presented, that is based on the combination of two shells with an interface layer. This interface layer enables the calculation of stresses between the shells, which are the input for a failure criterion indicating the onset of delamination between the shells. The element is implemented into a tool for the postbuckling simulation of composite stiffened panels, which is based on the discretisation of the structure by strip elements, while the buckling and postbuckling behaviour are described by trigonometric functions. As less degrees of freedom are necessary compared to a finite element formulation, the computational effort is reduced. Implementing the strip element with interface layer into this tool enables the prediction of the onset of delamination during the postbuckling analysis. In the following, the approach and its validation are presented.

References listed at the end of the paper:

ABSTRACT: A higher-order theory for the analysis of cylindrical and conical sandwich shells with flexible core is presented. The governing differential equations are derived on the basis of a three-layer model and solved by numerical integration. The theory is verified by comparison of achieved results to those published in the literature and to finite element computations.

References listed at the end of the paper:


ABSTRACT: In recent years, structures made up of functionally graded materials (FGMs) have received considerable attention for use in high-temperature applications. In this article, a finite element formulation based on First-Order Shear Deformation Theory (FSDT) is used to study the thermal buckling and vibration behavior of truncated FGM conical shells in a high-temperature environment. A Fourier series expansion for the displacement variable in the circumferential direction is used to model the FGM conical shell. The material properties of the truncated FGM conical shells are functionally graded in the thickness direction according to a volume fraction power law distribution. Temperature-dependent material properties are considered to carry out a linear thermal buckling and free vibration analysis. The conical shell is assumed to be clamped-clamped and has a high temperature specified on the inner surface while the outer surface is at ambient temperature. The one-dimensional heat conduction equation is used across the thickness of the conical shell to determine the temperature distribution and thereby the material properties. In addition, the influence of initial stresses on the frequency behavior of FGM shells has also been investigated. Numerical studies involving the understanding of the role of power law index, r/h ratios, and semi-vertex angle on the thermal buckling temperature as well as on vibration have been carried out.

ABSTRACT: This paper is concerned with the derivation of stiffness matrices for the buckling or vibration analysis of any structure consisting of a series of long, thin, flat plates rigidly connected together at their longitudinal edges. Each plate is assumed to be subjected to a basic state of plane stress which is longitudinally invariant, and it is further assumed that the mode of buckling or vibration varies sinusoidally in the longitudinal direction. During buckling or vibration, the edges of any individual plate are subjected to additional systems of forces and moments which are sinusoidally distributed along the edges, and these give rise to sinusoidally varying edge displacements and rotations. Spatial phase differences between the forces and displacements are accounted for by defining them in terms of complex quantities. The sinusoidal edge forces and displacements are split into two uncoupled systems, corresponding to out-of-plane and in-plane displacements, and two stiffness matrices are defined. The out-of-plane stiffness matrix is shown to be in general complex, and Hermitian in form, but the inplane stiffness matrix is real and symmetrical. Explicit expressions are derived for the elements of the matrices, in which all the essential destabilizing effects of the basic stresses, as well as dynamic effects, are included. Finally, it is shown that buckling and vibration phenomena for any structure of this type are closely interrelated.


ABSTRACT: Many structures consist of a set of thin rectangular flat plates of uniform thickness which are rigidly connected together along their longitudinal edges. Two computer programs which are applicable to such structures are described. They are called gasvip and vipal and they use an exact method of analysis, either to find natural frequencies in the presence of uniform longitudinal stress, or to find the initial buckling stress in uniform longitudinal compression. Gasvip sets up the overall stiffness matrix of the structure, whereas vipal enables substructures to be used. There are some types of problem which cannot be solved by using Vipal, but where it can be used it often takes much less computer time than gasvip. vipal also has the advantage that there is virtually no limit on the number of nodes (i.e., line junctions between component plates) which can be handled within about 4K of core store.


ABSTRACT: This paper describes the underlying theory, and a general-purpose computer program, VIPASA, for determining the critical buckling stresses or natural frequencies of vibration of thin prismatic structures, consisting of a series of plates rigidly connected together along longitudinal edges. Each plate may be either isotropic or anisotropic and may carry a basic stress system consisting of longitudinal and transverse direct stress combined with shear. The structure is assumed to be subjected to a “dead load” system which does not cause buckling; in addition a “live load” system, defined in magnitude by a single load factor, may be applied and the value of the load factor at buckling is determined. Alternatively the natural frequencies of vibration of
the structure when subjected to the dead load system are determined. Any number of critical load factors or natural frequencies can be obtained. The theory is based upon the assumption that all modes are sinusoidal, in the sense that all three components of displacement vary sinusoidally along any longitudinal line, but phase differences are incorporated to allow for the effects of anisotropy and shear. Apart from this assumption no further approximations are made other than those inherent in thin plate theory.

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ABSTRACT: The VIPASA computer program accurately treats buckling and vibration of prismatic plate assemblies with a response that varies sinusoidally in the longitudinal direction. In-plane shear loading of component plates produces skewed mode shapes that do not conform to desired support conditions, and this has placed a limitation on the general applicability of VIPASA. This problem is overcome in the present paper by coupling the VIPASA stiffness matrices for different wavelength responses through the method of Lagrangian Multipliers. Supports at arbitrary locations, including support provided by any elastic structure, are included in the theory. Examples illustrate the accuracy and convergence of the method and some of the principal features of the solution. The complete generality and capability of VIPASA have been retained in a computer program VICON that permits constraints and a supporting structure consisting of any number of transverse beam-columns.

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ABSTRACT: An existing algorithm enables natural frequencies or critical load factors to be found with certainty when “exact” stiffness matrices are used. This algorithm is extended to permit Lagrangian Multipliers to be used to couple the “exact” stiffness matrices of component structures to represent connections between the structures. The new algorithm also permits coupling of the stiffness matrices for different assumed wavelengths of sinusoidal response of a given structure with the stiffness matrices of other structures to satisfy required constraint conditions. The algorithm applies to problems formulated using real or complex arithmetic.

ABSTRACT: The new computer program VISCAN enables exact modal densities to be computed very
economically for any prismatic assembly of isotropic or anisotropic flat plates which are simply supported at their ends and are rigidly connected together along their longitudinal edges, so long as bending and in-plane displacements are uncoupled for the anisotropic plates. A description of how VISCAN was developed from the well established program VIPASA is followed by results for flat, corrugated and stiffened panels and for a cylindrical shell, a corrugated cylinder and a stiffened cylinder. Comparisons are made with existing experimental results for all these structures except the stiffened panel. The method used to change VIPASA into VISCAN could be applied to other existing computer programs to enable exact modal densities to be found for many additional types of structures.

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ABSTRACT: A standard stiffness matrix procedure which permits any combination of rigid, elastic, pinned or sliding connections of the degrees of freedom at the ends of a member to the nodes of its parent structure is described, in order to show how easily it can be extended to allow an existing algorithm to be used to ensure that no eigenvalues of the parent structure can be missed even when “exact” member theory is used. The eigenvalues are the natural frequencies of undamped free vibration analyses or the critical load factors of buckling problems. The method preserves the exactness of the member theory and an efficient method for computer application is indicated. The theory also permits any combination of rigid, elastic, pinned or sliding connections between the freedoms of a substructure and those of its parent structure.

ABSTRACT: This review covers the many applications of the Wittrick-Williams algorithm, which ensures that no critical buckling loads, or natural frequencies of undamped free vibration, are missed even when using the ‘exact’ member equations obtained by solving the appropriate differential equations. The review includes: plane and space frames; prismatic assemblies of isotropic or anisotropic plates, including in-plane plate shear loads; exact multi-level substructuring; design; damping; efficient solution of rotationally or linearly repetitive structures; use of Lagrangian multipliers; programmable pocket calculator methods; program listings for small computers and; references to large computer programs.

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“A parametric study of optimum designs for benchmark stiffened wing panels”, Composites Engineering, Vol. 3, Nos. 7-8, 1993, pp. 619-632, Special Issue: Use of Composites in Aircraft
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ABSTRACT: Results are presented for the most heavily and lightly loaded of eight benchmark stiffened laminated wing panels defined from a Dornier wing by a GARTEUR (Group for Aeronautical Research and Technology in Europe) working party. These benchmark panels had three identical and equally spaced blade
stiffeners. The results were chosen to help designers to understand many important aspects of the choice of design variables, and of the effects of changing the sophistication of modelling and theory used, for a wide range of wing panels. The percentage changes of (global) optimum mass are presented, along with the final values of the design variables. Some examples of mass histories and of (rejected) local optimum masses are also given. The principal design variables are skin and blade ply thicknesses and blade height. Additional factors considered include the effects of adding flanges to the blades whose plies either matched those of the blades or were allowed to vary independently, varying the number of stiffeners, allowing the stiffeners to differ from each other, varying stiffener spacing, varying some ply angles, including the stiffening effect of adjacent spars, including the effects of continuity with laterally adjacent panels, including through thickness shear deformation in the panel analysis and analysing the panel with its true skewed shape rather than approximating it as rectangular in plan.


ABSTRACT: The structural efficiency of a range of panels under uniaxial compression is investigated using the optimum buckling design program VICONOPT. The design uses very efficient VIPASA analysis to guard against all possible modes of failure, together with a tailored sizing strategy. The panels all have nine blades, zed or hat stiffeners and between three and fifteen design variables, covering traditional design using one size of stiffener and more sophisticated design with five sizes of stiffener. Results show that using two stiffener sizes or two stiffener types in alternate positions across the panel width can produce mass savings of up to 30% compared with traditional design. Convergence on an optimum normally occurs within six sizing cycles, but up to twelve sizing cycles are required for sophisticated designs when the initial configuration is poorly chosen. Computational efficiency and material strength constraints are also considered.

References listed at the end of the paper:

ABSTRACT: Optimum design of a blade-stiffened panel of composite/honeycomb sandwich construction and a metal T-stiffened panel is considered using the buckling and strength constraint program VICONOPT. Both panels have practical loadings which produce a nonlinear out-of-plane bending moment, calculated using beam-column expressions. Large deflection finite element analysis of the optima shows that modifications to these expressions are necessary when the panels are shear loaded. The use of integrally machined stiffeners, as opposed to a conventional, built-up panel designed using PANDA2, is shown to permit 20% mass saving when the latter has no postbuckling strength and 3% saving when postbuckling strength is allowed for.

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EXECUTIVE SUMMARY: This effort is funded by the Aging Aircraft Squadron of the Aeronautical Enterprise Program Office (ASC/AAA, Col P.J. Clark). The prime contractor for the Air Vehicle Health Management program, of which this effort is a part, is S&K Technologies, Inc., Dayton, OH (Mr. Kevin Boyd). Twenty-seven Z-stiffened panels, intended to simulate upper wing skin panels of the Boeing 707, were tested to failure in compression to determine buckling strength. Pristine panels and panels with machined grindouts (with various depths up to 62.6% of the panel skin thickness) were tested to failure. Nine panels each of three configurations were fabricated for testing. The results showed a degradation of buckling strength with grindout depth that could be modeled with a modified Johnson-Euler method and a modified Gerard’s method for long and short panels respectively. The panels with the lower slenderness ratio (short panels) were degraded more by a given grindout depth than were their more slender counterparts. However, it was found that span-wise grindouts along the center stiffener—even deep ones—do not have a severe effect on strength. Even at over 60% grindout depth, the worst degradation was less than a 12% reduction in strength. A small number of panels were tested with deep chord-wise grindouts. These tests showed that the strength of the panel was dramatically reduced by these grindouts, which were transverse to the loading direction.

References listed at the end of the report:

ABSTRACT: This paper presents axial compression tests on longitudinally stiffened aluminium panels in alloy AA6082 temper T6. A specially designed test facility is presented. The panels are built up with extruded aluminium profiles connected by longitudinal welds. Two panel types are considered, with open section (L-shaped) stiffeners and closed section stiffeners, respectively. The experimental programme comprises tests on single panels supported along all four edges and as a special case panels supported at two edges only. Tests on panels with lengths 1.0 m and 2.0 m are reported. Two deformation modes were observed in the tests: regular flexural buckling of the entire panel towards either the stiffener side or the plating side, and, for the case of the panels with L-shaped stiffeners, collapse initiated by stiffener tripping. The panel resistance is compared with the design resistance obtained from the European standard for aluminium structures, Eurocode 9. For all panels the experimental capacity exceeded the design value.


ABSTRACT: Existing theory and the associated computer program VICONOPT deal with infinitely wide plate assemblies given that boundary conditions on all sides of each panel form a rectangle. They also deal with cases when the four supports form a parallelogram so that the plate is a skew plate. This is true provided the panel is of finite width, i.e. isolated from any adjacent panels, which is the case commonly modelled in practice. It does not represent what happens in the real structure, however, where normally there is continuity with the adjacent panel. The present paper shows how the theory and the computer program VICONOPT can be modified so that skewed plate assemblies that are infinitely wide and repeat at transverse intervals can now be modelled exactly. The paper also shows that the theory can be used, if a small measure of approximation is accepted, to model this situation by analysing only one of the identical stiffeners with associated panel skin in the common situations where the panel has equally spaced, identical, longitudinal stiffeners between each adjacent pair of longitudinal lines of support. Illustrative results are given.
ABSTRACT: A procedure is presented for the buckling analysis of prismatic skew plate assemblies subject to invariant in-plane stresses. Based on the exact solution of the plate differential equations, the method of Lagrangian multipliers is used to enforce the transverse skew boundaries by a sufficient number of point constraints. Analysis assumes that the plate is infinitely long and that supports repeat at bay length intervals, typifying the continuity found in aircraft wing construction. Following a brief derivation of the formulation adopted, results are presented and comparisons are made with other analyses for an unstiffened isotropic skew plate, subject to pure compression loading with both simply supported and clamped boundary conditions. Results for four benchmark stiffened panels, i.e. plate assemblies, incorporating composite material and combined loading are also given for a range of skew angles.

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ABSTRACT: This paper provides a Koiter-type initial post-buckling analysis for prismatic plate assemblies made of isotropic materials. The structures are assumed to consist of a series of long flat strips rigidly connected together at their edges, subjected to longitudinal in-plane compressive stress. The transcendental eigenvalue problems, which arise when exact solutions to the member equations are used to form the stiffness matrix of the plate assemblies, are first solved to obtain the buckling load and corresponding buckling mode of the structure. The analysis then obtains exact solutions to the post-buckling member equations and the a-coefficient and b-coefficient which characterize the initial post-buckling behavior. The post-buckling characteristics of the stiffened plate are found to be influenced significantly by the height of the stiffener.

ABSTRACT: The use of substructuring in the buckling and vibration analysis of large structures permits very substantial improvements in computational efficiency. The exact multi-level substructuring capability of the widely used computer program VICONOPT for the analysis and optimum design of prismatic plate assemblies has been extended by the inclusion of new theory, presented in this paper, which permits constraints on any of the internal or external nodes of substructures. The computational savings by using substructuring in this way are shown to be typically 50–70% compared with previous VICONOPT solutions. The theory is applicable to any method or computer code for structures whose buckling or vibration modes combine responses of different half-wavelengths, with VICONOPT being used as an example.
ABSTRACT: A comparison of ‘exact’ and approximate methods for the determination of critical buckling loads of prismatic benchmark metal and composite panels is presented. The panels are stiffened by either J-, blade- or hat-stiffeners and are representative of typical aircraft wing panel configurations, with in-plane shear and compression load combinations. Buckling design curves and modes are illustrated, and associated CPU times are given to demonstrate the accuracy and efficiency of the approximations adopted. Initial results for the benchmarks, which are rectangular in plan-form, are compared with rigorous finite element solutions. Thereafter, attention is focused on results for the same panels but with parallelogram plan-form. Two analysis methods based on Classical Plate Theory are used as follows: an existing, ‘exact’ method, incorporating Lagrangian multipliers to constrain the transverse (or skew) boundary conditions; and a recently developed approximate infinite width technique, based on the previous one but analysing only a repeating portion of the plate assembly.

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ABSTRACT: A non-shallow non-linear shell theory is used to analyze the parametric resonance of orthotropic circular cylindrical shells under harmonically varying axial compression. As special cases, post-buckling and non-linear vibration problems are also studied. In the analysis the non-linear terms and the inertias contributed by both normal displacement and circumferential displacement are included. Therefore the final dynamic system includes two equations in w and v. The transverse shear deformation is taken into account by a first order theory. The spatial variables in the governing equations are eliminated by the Galerkin procedure. The final ordinary differential equations are solved by an asymptotic method. Numerical results show the dependence of the post-critical behaviour on the properties of material, geometry and excitation.

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ABSTRACT: Buckling, postbuckling, nonlinear vibration and parametric resonance of thick circular cylindrical
shells under axial compression are analyzed in this paper. The theory developed is based on a nonlinear and non-shallow thick shell theory, with its final equations involving two unknowns, the circumferential displacement \( v \) and the radial displacement \( w \). The shell wall is cross-ply laminated. The plies are specially orthotropic, but the lamination can be unsymmetric. The axial load is assumed to be harmonically time dependent, or constant as a special case. The governing nonlinear partial differential equations are reduced to nonlinear ordinary differential equations in terms of time by the Galerkin procedure. Then, an asymptotic method is used to solve the resulting nonlinear ordinary differential equations. The numerical results for buckling loads are shown to compare very well with those of three-dimensional theories in the literature, even for very thick shells. The effects of lay-up and thickness on postbuckling equilibrium, nonlinear vibration and parametric resonance are demonstrated by examples.

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ABSTRACT: This paper presents a post-buckling analysis for prismatic plate assemblies made of isotropic materials. The structures are assumed to consist of a series of long flat strips rigidly connected together at their edges, subjected to longitudinal in-plane compressive load. The buckling load and corresponding buckling mode of the structure are first obtained as the results of transcendental eigenvalue problems, which arise when exact solutions to the member differential equations are used to form the stiffness matrix of the plate assemblies. The other post-buckling field functions are also obtained analytically as exact solutions to the member differential equations. Results for the load end-shortening and load–deflection relationships for long prismatic plate assembly examples are obtained and compared with results obtained by other authors.

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ABSTRACT: A recently developed reference surface element technique is used to model the behaviour of the buckling and postbuckling of delaminated plates and shells. The technique can be easily incorporated into any finite element analysis programme for which the beam, plate and shell elements etc. satisfy the Reissner–Mindlin assumption. In this paper, the reference surface element formulation of a four-node C0 quadrilateral membrane-shear-bending element (ZQUA24) is presented and numerical investigations are performed for composite plates and shells with various delamination shapes. The numerical results show that the present technique is simple, reliable and able to model delamination buckling and postbuckling behaviour of laminated plates or shells. Observations of practical engineering significance are obtained from the study.

ABSTRACT: An efficient method for the buckling and vibration analysis of plates or stiffened panels with clamped ends is presented. The method uses Lagrangian multipliers to couple sinusoidal modes with appropriate half-wavelengths of response, thereby enforcing the end conditions at discrete point supports. Clamped ends can usually be modelled accurately using only a few point supports, while arguments from symmetry often enable some of the required end conditions to be satisfied without explicitly applying constraints. In such cases few half-wavelengths are needed to obtain excellent accuracy. Solutions obtained for the simple limiting case of single plates are exact or within 1% of the classical or other reported solutions. Solutions obtained for stiffened panels are in close agreement with those obtained using finite element analysis.

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ABSTRACT: The problem of the buckling of finite length externally constrained thin circular cylinders is solved to yield a generalized eigenvalue problem with constraint conditions. The solution is based on an inverse iteration procedure in which the non-linear complementary equation is solved by a non-smooth version of Newton's method that saves computer time and space when compared to a linear complementary algorithm. The numerical results show that the method proposed is effective and that the critical buckling load of the constrained cylinder is almost independent of the length of the cylinder, unlike the critical load of free (unconstrained) thin cylinders. In the direction of its axis, the shell is discretized by finite strips which circumferentially use straight bar and beam displacement functions. It is proved that when the widths of the strips approach zero, the geometrical relationships used in this paper approach those of Koiter–Sanders cylindrical shell theory.


ABSTRACT: The current paper outlines recent developments to algorithms and software for critical buckling and natural vibration analysis and optimum design of prismatic plate assemblies, based on the exact strip approach and the Wittrick—Williams algorithm. The current paper acts as a single source document discussing recent progress and planned future explorations in: initial local postbuckling of stiffened panels; discrete optimization of composite structures to satisfy manufacturing requirements; discontinuous cost functions; constraints on fundamental natural frequencies and frequency-free bands; a feasibility study of response surface optimization; and multi-level optimization of composite aircraft wings. The numerous references provide fuller technical details and illustrative examples.

References listed at the end of the paper:


DERA. Final report of the GARTEUR action group on structural optimisation SM(AG13), vols 1-3, 1997 (DERA, Farnborough).


ABSTRACT: A weighted solution for the critical load of a cylindrical shell is presented. To determine the weights, some special known results are applied. The method can be used to solve generally complicated buckling problems by making use of the solutions of special simple problems. Lastly, some numerical solutions for the same problem are obtained by finite elements. Comparison between the solution method in this paper, the finite element solution and cited results in the literature, shows that the weighted solution has good precision.

ABSTRACT: This paper summarized currently available techniques of setting up flexural–torsional buckling theory of thin-walled members. It is found that all the existing methods introduced a nonlinear load potential in their total potentials, while based on the classical variational principle for stability of a solid structure, no such load potential should be included. This situation has led to an inconsistency between some widely referenced monographs in buckling theories of beams with mono-symmetrical cross-sections. This paper provides a new theory for flexural–torsional buckling of thin-walled members based on the classical variational principle and the theory for thin-walled shells. No nonlinear load potential is included, but a new term: nonlinear strain energy from transverse stresses, which has been neglected in previous theories of thin-walled members, is introduced in. It is found that the nonlinear load potential is not equivalent to the contribution of transverse stresses for beams with mono-symmetrical cross-sections, which causes the inconsistency mentioned above. The comparison shows that the proposed theory and the traditional theory are the same for most cases encountered in practice.
ABSTRACT: The elastic-plastic buckling of cylindrical shells under torsion is analysed with a deep thick-shell model under various boundary conditions. The word ‘deep’ means that in the general equations of equilibrium the three non-linear terms that involve the torsional force are all retained for the buckling analysis. In the Donnell-type shallow-shell theory, however, only one of such terms is retained. The word ‘thick’ means that in calculating strains and stress resultants the factor $(1+z/R)$ is retained. This factor results from the trapezoid-like shape of the cross-section and is usually neglected in the thin-shell theory. For boundary conditions, not only the conventional geometrical boundary conditions, which are in terms of displacements and rotations, but also the mechanical boundary conditions, which are in terms of forces and moments, are considered. The numerical results of examples assess the effect of the additional non-linear terms, the effect of the factor $(1+z/R)$, and the effect of the mechanical boundary conditions.


ABSTRACT: Hoo Fatt’s model was modified to obtain analytical solutions of plastic collapse for 3-D damaged cylindrical shells. To assess the effective wall thickness of a damaged pipeline, we used ASME B31G and its burst test results with Hauch and Bai’s approach. The effective thickness represents the corroded region of a pipe; it helps to transfer the response of the undamaged area near the damaged area. We propose solutions for the buckling of a damaged shell subjected to uniform external pressure. In these solutions, we extended Timoshenko’s solutions for the elastic-plastic buckle of linear elastic in a perfectly plastic cylindrical shell. The plastic collapse of a damaged shell is based on a modification of the interaction formula of the fully plastic membrane forces and bending moments in the nonuniform cylinder.

References listed at the end of the paper:


ABSTRACT: The buckling of initially stressed Mindlin plates is considered using a thick finite strip method. The method is compared with a wide variety of published results and for both thin and moderately thick plates
excellent accuracy is obtained. Some further results are obtained for initially stressed rectangular plates with two opposite edges simply supported and various support conditions on the remaining sides. In general, it is found that for moderately thick plates, Mindlin's plate theory gives lower buckling loads than those obtained using classical thin plate theory.

ABSTRACT: A finite strip method is presented for calculating the linear buckling stresses of structural assemblies of long, thin plate components which, in general, are curved and which are rigidly joined together at their longitudinal edges. It is assumed that on buckling under the action of a biaxial direct stress field the perturbation forces and displacements all vary sinusoidally in the longitudinal direction. A stiffness matrix relating the amplitudes of the perturbation forces and displacements is developed for the curved strip on the further assumption of relatively high-order polynomial variations of the displacement components around the plate width. Numerical results are presented of the application of the curved strip in calculating the buckling stresses of plates, cylinders, panels and formed sections.

ABSTRACT: Four finite strip models are developed for the flexural vibration analysis of rectangular plates based on Mindlin theory which takes account of transverse shear deformation and of rotary inertia. The strips are simply supported at their ends and differ one from another in the order of interpolation employed to represent the variation of each of the plate deflection and the two rotations across the strip. The four models are based in turn on quadratic, cubic, quartic and quintic interpolation. Numerical results are presented of applications of the strip models to the calculation of the natural frequencies of both thin and moderately thick plates. The influence that the assumed value of the shear coefficient has on natural frequencies is considered for two particular moderately thick plates.

ABSTRACT: The Rayleigh-Ritz method is applied to the prediction of the natural frequencies of flexural vibration of square plates having general boundary conditions. The analysis is based on the use of Mindlin plate theory so that the effects of shear deformation and rotary inertia are included. The spatial variations of the plate deflection and the two rotations over the plate middle surface are assumed to be series of products of appropriate Timoshenko beam functions. Results are presented for a number of types of plate and these demonstrate the manner of convergence of the method as the number of terms in the assumed series increases.

ABSTRACT: The elastic buckling of rectangular Mindlin plates is considered using two related methods of
analysis. These methods are the Rayleight-Ritz method and one of its piece-wise forms, the finite strip method. Arbitrary combinations of the standard boundary conditions of clamped, simply-supported and free edges are accommodated by the use in the assumed displacement fields of the normal modes of vibration of Timoshenko beams. The applied membrane stress field leading to buckling can comprise biaxial direct stress plus shear stress. A range of numerical applications is described for isotropic and transversely isotropic plates of thin and moderately thick geometry. The results obtained using the two methods compare closely to one another and to other published results where these are available. A direct relationship between unidirectional buckling stress and frequency of vibration is demonstrated for a category of plates having one pair of opposite edges simply supported.

ABSTRACT: In a previous paper [1] the finite strip method was applied to the prediction of the natural frequencies of vibration of longitudinally invariant, rigidly connected assemblies of circularly curved and flat strips having diaphragm end supports. This work is extended here to include the presence of an initial membrane stress field. An individual curved strip may be subjected to a biaxial direct stress field comprising a uniform stress acting in the circumferential direction and a non-uniform stress acting in the longitudinal direction. The presence of the membrane stress field is accommodated in the analysis by the inclusion of an initial stress or geometric stiffness matrix. A further extension included here is a facility to delete in-surface inertia terms. Results are presented for the application of the strip method in predicting the frequencies of vibration of a circular cylinder subjected to a complicated membrane stress system.

ABSTRACT: A previously developed analysis of the flexural vibration of isotropic rectangular plates is extended to include the presence of a membrane stress system. The method of analysis is the Rayleigh-Ritz method and Mindlin plate theory is used which takes into account effects which are disregarded in the classical plate theory. As in the aforementioned earlier analysis the spatial variations of the deflection and two rotations over the plate middle surface are based on the use of Timoshenko beam functions. The membrane stress system comprises biaxial direct stress plus in-plane shearing stress and is uniform throughout the plate. Numerical results are presented for a number of types of plate and of applied stress which show the manner of variation of the frequencies of vibration as the intensity of stress changes. This manner of variation is similar in form to that demonstrated elsewhere by analyses based on the use of the classical plate theory but the magnitudes of the present calculated frequencies are considerably reduced for moderately thick plates.

ABSTRACT: Description is given of a finite strip method for the analysis of the geometrically non-linear behaviour of laterally loaded, rectangular, laminated composite plates. The analysis is based upon the use of a plate theory which includes the effects of transverse shear deformation. For particular end conditions, two types
of finite strip model are presented, one based on linear crosswise interpolation of each of the five fundamental displacement-type quantities (and employing a reduced integration scheme in evaluating strip properties), the other based on cubic crosswise interpolation. Numerical studies reveal the good convergence properties of the strip models and show the importance of including shear deformation effects in the non-linear analysis.


ABSTRACT: Consideration is given to the twin problems of the elastic buckling of rectangular, symmetrically-laminated composite plates and of the vibration in the presence of applied in-plane stress of such laminates. First-order shear deformation plate theory provides the mathematical model of plate behaviour and the Rayleigh-Ritz and finite strip methods are used to generate numerical results for laminates of thin and moderately thick geometry, with various combinations of standard plate edge conditions. The applied stresses include uniform shear stress as well as direct stresses, and anisotropic material properties can be included. The presented results demonstrate the accuracy of the numerical methods and highlight the very significant influence that transverse shear and related thickness effects can have in the subject problems.

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ABSTRACT: Free vibration of prismatic plate structures of laminated composite material and having diaphragm end supports is considered using the finite strip method. Description is given of the development of stiffness and mass matrices for both out-of-plane and in-plane deformation of a family of strip models. The former deformation is based on first-order shear deformation plate theory, rather than classical plate theory. Frequency calculations are made using full sets of structure equations and using reduced sets obtained from an economisation procedure. Presented results demonstrate the good convergence characteristics of the finite strip approach and reveal the relative efficiency of particular economisation schemes. Comparison made with results based on the use of classical plate theory in deriving out-of-plane strip properties shows that the effects of through-thickness shear and rotary inertia on a natural frequency are heavily dependent upon the nature of the associated mode shape.

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ABSTRACT: A finite strip method is presented for the determination of buckling stresses and natural frequencies of vibration of prismatic plate structures assembled from plate flats, which generally are laminates of fibre-reinforced composite material. The finite strip method is of the single-term type, corresponding to the assumption of sinusoidal longitudinal spatial variation of displacement and force quantities. Anisotropic
material behaviour and applied in-plane shear stress are accommodated by expressing the strip displacement field in terms of complex quantities. The out-of-plane properties of plate flats are based upon the use of first-order shear deformation plate theory. A family of finite strip models is described and a sub-structuring procedure is utilised to reduce the size of the eigenvalue problem. Presented numerical results reveal the high accuracy and good convergence characteristics of the method, as well as indicating the influence of through-thickness shear effects in a range of circumstances.

V. Peshkam, “Linear and geometrically nonlinear analysis of thin rotational shells using the finite element method”, Ph.D. dissertation, Dept. of Civil Engineering and Building, The Polytechnic of Wales, December 1984

SUMMARY: The complete elastic behaviour of rotational shell structures is investigated in the thesis, being presented in two major parts. Energy principles are implemented throughout for the derivation of matrices utilizing the orthotropic strain energy expression developed by Ambartsumyan. Part One concerns the prediction of the small deflection behaviour in seven chapters. Initially it is attempted to analyse various shell structures by examining their deflection patterns, by concentrating on the distribution of stresses and moments in the structure. This is extended further to instability analysis in order to determine the critical load when the structure is subjected to compressive pressures. Economization technique both at the elemental and structural level is deployed based on Irons/Guyan reduction assumption in order to condense the Surplus-Functions and observe their influence on the natural frequencies. The section on dynamic transient response analysis is followed by the latter where the behaviour of structures subjected to forced vibration is studied. Two integration techniques, namely Newmark Beta and Mode Superposition, are used to integrate the second order time dependent differential equations of motion. Finally the linear analysis section is concluded by reformulating the conventional beam element in order to incorporate the Surplus-Functions and to investigate their absolute influence on the convergence of the finite element solution. The performance of the new element has proved to be remarkably superior to its predecessor. The geometrically nonlinear behaviour of shells of revolution subjected to axisymmetric and asymmetric loads are studied in Part Two. Attention is focused on the post-buckling behaviour of structures with particular emphasis given to orthotropic circular plates. The number of numerical examples were restricted due to the limitations of the available literature on the coupled nonlinear behaviour of these structures. However, the problems cited in Part Two with exception of one were found to be in excellent agreement with the other published works.

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ABSTRACT: The prediction of the buckling stresses of prismatic plate structures made of composite laminated material is considered. Recent developments which have provided an extended capability in the finite strip analysis of such structures are brought together and discussed. Different analysis procedures are described, dependent upon whether the plate structure is of finite length, with diaphragm ends, or is ‘long’, and on whether first-order shear deformation plate theory or classical plate theory is used in developing out-of-plane strip properties. Features of the analysis include a very general description of laminate material properties, the
presence of applied shear stress, the accommodation of eccentric connections between plate flats and the use of multi-level substructuring techniques, including the so-called superstrip concept. The associated computer software is used to examine the buckling behaviour of two types of panel, with attention paid to the influence of through-thickness shear deformation and of bending-stretching material coupling in unsymmetric laminates.

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ABSTRACT: Finite strip methods are presented for the prediction of buckling stresses and natural frequencies of vibration of “long” prismatic plate structures which may be formed of fibre-reinforced, composite, laminated material with very general properties. The finite strip methods are of the single-term type with complex algebra employed to accommodate applied in-plane shear stress and anisotropic material behaviour. The developments, described here follow on very directly from an earlier paper in this Journal ([1] Dawe and Craig, Int. J. Mech. Sci.30, 77, 1988) to which frequent reference is made herein. The first development is the introduction of major improvements and extensions on the earlier work [1] which is based upon the use of first-order shear deformation plate theory to represent the out-of-plane properties of plate flats: the chief advance involves the use of multi-level substructuring procedures, including the introduction of so-called superstrips, but eccentric connections of component plates at their junctions is also included. The second development is the introduction of a new finite strip analysis which is based on the use of classical plate theory and which is complementary to the shear deformation analysis, with similar advanced features. Two computer programs, BAVPAS and BAVPAC, are introduced and description is given of some results of the application of these programs.

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ABSTRACT: A description is given of the multi-term, finite strip analysis of the free vibration and buckling, under a system of applied biaxial direct and shear stresses, of thin, prismatic shell structures. The walls of the structure may be composite laminates with a general lay-up. The analysis is based on the use of Koiter-Sanders thin shell theory. Combinations of diaphragm, clamped and free conditions at the two ends of a structure are incorporated. The displacement field of a transversely-curved finite strip utilises Bernoulli-Euler beam functions in the longitudinal direction and quintic polynomial representations in the circumferential direction. The superstrip concept is used in conjunction with the modified Sturm sequence-bisection approach to provide an efficient analysis capability. Several applications involving flat plates, curved plates and complete cylinders are detailed.

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ABSTRACT: The finite strip method is developed for the free vibration analysis of prismatic shell structures having diaphragm end supports. In general, the structure is made up of rigidly-connected, circularly-curved and flat plates which are composite laminates with a broad range of material properties, including bending—stretching coupling and anisotropy. The analysis is developed in two ways, based in turn on the use of first-order shear deformation shell theory and of thin shell theory. The finite strip approach is of the multi-term type and the superstrip concept is employed to produce a powerful and efficient solution capability. Results, in the form of calculated natural frequencies, are presented for a number of problems for which accurate alternative solutions exist, and close comparison of results verifies the present approach.

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ABSTRACT: A finite strip method is described for the analysis of the geometrically non-linear elastic response of composite laminated, orthotropic prismatic plate structures subjected to progressive uniform end shortening. Attention is restricted to local buckling/post-buckling behaviour so that certain simplifying assumptions related to the insignificance of movements of plate junctions can be invoked. Analyses are based on the use of both classical plate theory and first-order shear deformation plate theory and a range of finite strip models is available for use in the contexts of each of these plate theories. A description is given of a number of applications involving the post-local-buckling behaviour of box sections and top-hat-stiffened and blade-stiffened panels. In one application considering a laminated box section, results are generated using a commercial finite element package and these are seen to compare closely with the predictions of the presented finite strip method.


ABSTRACT: A spline finite strip capability is presented for predicting the buckling stresses and natural frequencies of rectangular laminated plates. The plates may have arbitrary lay-ups and general boundary conditions. The spline finite strip method is first developed in the context of first-order shear deformation plate theory and then, by reduction, the method is also developed in the context of classical plate theory. In both approaches the superstrip concept is incorporated into the solution procedure. A considerable range of types of application is described and it is demonstrated that the spline finite strip method is versatile, with good convergence characteristics and accuracy. In these applications, frequent comparison is made with the results of other approaches which comprise a spline Rayleigh-Ritz method, a finite element method, an analytical Rayleigh-Ritz method and a semi-analytical finite strip method.
ABSTRACT: The finite strip method (FSM) is an effective procedure for the numerical analysis of single rectangular plates and of complicated prismatic plate structures. Figure 4.1 shows examples of such plates and plate structures, each modelled by a number of finite strips which run the whole length of the structure. The finite strips are rigidly joined at longitudinal reference lines at which the requisite compatibility conditions should be satisfied. With regard to Figure 4.1 it should be noted, though, that finite strips may well have reference lines (i.e., lines with which degrees of freedom are associated) in their interior, in addition to their exterior longitudinal edges, and that in some types of analysis the length of the strips which is considered for analysis purposes is less than the full length of the structure.

References listed at the end of the paper:
42. Lau, S. C. and Hancock, G. J. (1986) Buckling of thin flat-walled structures by a spline finite strip method. Thin-walled Structures, 4, 265–94
functions. A considerable range of types of applications is described and it is demonstrated that the general spline integrations are carried out analytically by representing the basis general spline functions as a linear combination of cardinal spline functions. A considerable range of types of application is described and it is demonstrated that the general


ABSTRACT: A general spline finite strip capability is presented for predicting the buckling stresses and natural frequencies of composite laminated plates and shells which may have arbitrary lay-ups and any boundary conditions. This method is developed in the context of first-order shear deformation plate and shell theory as well as the classical plate and shell theory and the massive substructuring technique is incorporated into the solution procedure. A notable feature of the present capability is that the general spline integrations are carried out analytically by representing the basis general spline functions as a linear combination of cardinal spline functions. A considerable range of types of application is described and it is demonstrated that the general
spline finite strip method is versatile and has more advantages over the usual equal spline finite strip method is on the buckling and vibration problems that have localized mode shapes.

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ABSTRACT: A description is given of the PASSAS finite strip software package for predicting the buckling stresses and natural frequencies of composite laminated prismatic plate and shell structures of complicated cross-section and general lamination. The basic equations underpinning the development of the properties of a transversely curved finite strip are presented in the context of first-order shear-deformation shell theory and, by reduction, in the context of thin shell theory. The B-spline finite strip method is used and this enables the specification of a wide range of end conditions. The major features of the software package are described, and these include a range of strip models, the use of multi-level substructuring techniques across the structure, including superstrips, and the use of an efficient and reliable solution procedure. Results are presented of the application of PASSAS to the solution of a small number of shell buckling and vibration problems.

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ABSTRACT: A spline finite strip capability is described for predicting the buckling stresses and natural frequencies of vibration of prismatic plate structures which may be of composite laminated construction with arbitrary lay-ups. The plate structures may have general boundary conditions. The capability embraces analyses based on the use of first-order shear deformation plate theory and of classical plate theory, and utilizes substructuring procedures which include the use of superstrips. The theoretical development is not detailed since the present paper reports a very direct extension of a theoretical study developed for the analysis of single plates in an earlier paper in this Journal. A considerable range of buckling and vibration applications is documented and comparison of spline finite strip numerical values of buckling stresses and frequencies is made with results generated using the semi-analytical finite strip method and, in some cases, the finite element method. Buckled and vibrational mode shapes are presented for some applications.

ABSTRACT: A general spline finite strip capability is presented for predicting the buckling stresses and natural frequencies of prismatic plate and shell structures which are composed of composite laminated plate and/or
shell panels that may have arbitrary lay-ups. The prismatic structures may have general cross-sections and boundary conditions. This method is developed in the context of first-order shear deformation plate and shell theory as well as the classical plate and shell theory and a massive substructuring technique is incorporated into the solution procedure. A considerable range of types of application is described and a particularly interesting one shows that the general spline finite strip capability has great flexibility in matching the boundary conditions specified on the entire structures.

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ABSTRACT: The development of an analysis capability for predicting the buckling stresses of composite laminated, prismatic shell structures is described. The basis of the capability is the spline finite strip method, which is presented in the contexts of both first-order shear deformation shell theory and thin shell theory. The structures considered might have arbitrary lamination and general boundary conditions, and the applied stress field in any component flat or curved plate may include shear stress as well as biaxial direct stresses. Multi-level substructuring procedures are used in an efficient solution procedure. The analysis capability is incorporated into a computer software package called PASSAS and selected applications using this package are presented to show the scope and power of the new capability.

ABSTRACT: A description is given of the development of a spline finite strip method for predicting the response of composite laminated, prismatic panels to a progressive uniform end shortening. The response is assumed to be geometrically nonlinear, with the nonlinearity introduced in enhanced strain-displacement equations in a total Lagrangian approach. The set of nonlinear equilibrium equations, obtained by appropriate energy minimization, is solved using the Newton-Raphson method. The development of the properties of a flat finite strip is made in the contexts of both first-order shear deformation plate theory and classical plate theory, and a number of strip models is available corresponding to different displacement fields. Presented applications concern a box section and several longitudinally stiffened panels that include curved panels modeled as faceted shells. Comparison of the finite strip predictions is made, where possible, with results from other sources, and such comparison is shown to be close.

ABSTRACT: Description is given of the development of the spline finite strip method for predicting the critical buckling temperatures of rectangular composite laminated plates. The analysis takes place in two distinct parts, namely an in-plane thermal stress analysis in the pre-buckling stage followed by a buckling analysis using the determined in-plane stress distribution. The buckling analysis takes place in the context of first-order shear
deformation plate theory. The permitted lay-up of the laminates is quite general, within the constraint that the plate remains flat prior to buckling, and the boundary conditions are versatile. The distribution of temperature can be non-uniform in the plane of the plate. A range of applications of the developed procedure is presented and numerous comparisons are made with the results of previous studies. The spline finite strip method is shown to be versatile and accurate, with good convergence characteristics.

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ABSTRACT: The semi-analytical finite strip method is developed for the analysis of the geometrically nonlinear response to dynamic loading of rectangular composite laminated plates. The plates have simply supported ends and their properties are evaluated in the context of first-order shear deformation plate theory. The applied loading acts normal to the plate surface but otherwise may be of a general nature with respect to space and time. Solution to the nonlinear dynamic problem is obtained through use of the Newmark time-stepping scheme in association with Newton–Raphson iteration. Applications are described which relate to isotropic and orthotropic plates, and to laminates. In general a close comparison is demonstrated between the predictions of the developed finite strip approach and those of a finite element method.

ABSTRACT: A description is given of the use of the finite strip method (FSM) in determining the behaviour of composite laminated, prismatic plate and shell structures, with emphasis placed on relatively recent work conducted at The University of Birmingham. Both the semi-analytical and the spline variants of the method are described, and some attention is also paid to "exact" strips. Consideration is given to analyses conducted in the contexts of first-order shear deformation theory and of classical, or thin, theory. The calculation of buckling stresses and natural frequencies of vibration is discussed in detail for single span structures and then, using the spline finite strip approach with variable knot spacings, for multi-span structures and stepped structures. An account is given of the use of the FSM in predicting the post-buckling response of plate structures to progressive end-shortening strain. Brief description is given of the use of the method in predicting the thermal buckling and the transient response to dynamic loading of flat plates. Finally, the calculation of buckling stresses and natural frequencies of sandwich plate structures is considered, based on the adoption of a three-zone plate theory. Numerous examples of the application of the FSM are included in the paper.

ABSTRACT: The thermomechanical postbuckling behaviour of composite laminated plates is studied with the aid of the B-spline finite strip method under the combination of temperature load and applied uniaxial
mechanical stress. To account for through-thickness shear deformation effects, the thermal-elastic, first-order shear deformation (Reissner–Mindlin) plate theory is used in this paper. General boundary conditions and laminate lay-ups can be accommodated in the newly developed finite strip approach. A range of applications is described and the results generated by the finite strip procedure are compared with the results of previous studies. The spline finite strip method is shown to be versatile and accurate with good convergence qualities.

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ABSTRACT: A finite strip procedure has been developed for the post-buckling analysis of composite laminates when subjected to progressive end shortening. The finite strips are developed based on a higher-order shear deformation plate theory and there are nine variables at each nodal line. Initial imperfection expressed in the form of suitable trigonometric function is allowed. Examples including isotropic plates and laminates with arbitrary lay-up arrangement are presented. Numerical results for laminates with and without initial imperfection are used to illustrate the effect of imperfection.


ABSTRACT: Free vibration analysis of shells of revolution using the spline finite element method is presented in this paper. The spline element, which is based on the classical thin shell theory, employs a set of B-spline shape functions for the interpolation of geometry as well as displacements. It has the merits of both the finite element method and splines interpolation. The efficiency and accuracy of the proposed element are illustrated by examples in the paper.

Philemon Sphiwe Simelane (Department of Mechanical Engineering, Cape Peninsula University of Technology, Cape Town, South Africa), “Thermal buckling of laminated composite plates”, Master’s Thesis, 1998

PARTIAL SUMMARY: A thermal buckling analysis of laminated composite plates is studied using plates with rectangular geometry and antisymmetric lamination with respect to the middle plane. A Dubamel-Neumann type constitutive model is used. The effects of transverse shear deformation are accounted for by the use of the Mindlin first-order shear deformation (FSDT) plate theory. An angle-ply laminated construction was used to generalise the formulation. Since buckling is essentially a non-linear behaviour, the intermediate class of deformation was employed. The buckling analysis was carried out in a series of steps; the derivation of the equilibrium equation, nonlinear prebuckling and linearized buckling analysis, and the evaluation of the critical temperature by solving the resulting eigenproblem. The first variation of the total potential energy establishes the equilibrium equation and the second variation analyses the stability of the laminated composite. A displacement-based finite element 'With five degrees of freedom in each node was used. The effects of
lamination angle, modulus ratio, plate aspect ratio, and boundary constrains upon the critical buckling temperature were investigated and found to be quite significant.

References listed at the end of the thesis:

ABSTRACT: In the context of the maturation of finite element methodology this paper reviews solution approaches that combine classical analytical techniques with computer-based numerical methods. Developments in boundary integral equations, asymptotic postbuckling analysis, and limit point analysis are touched upon, as are some aspects of structural modeling. Emphasis is also placed on the importance of understanding both the scope and limitations of a particular structural model. This understanding has implications for the educator as well as for the researcher and the practicing engineer.

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ABSTRACT: The spline finite strip method is applied to the buckling analysis of arbitrarily shaped plates. The plate is first mapped into a rectangular domain in the natural coordinate plane by the subparametric transformation, and the mapped plate is discretised into a number of strips. The displacements of each strip are described by interpolation functions which are given as products of piecewise polynomials and B-3 spline functions. The eigenvalue matrix equation for the buckling analysis is then formulated and solved by the same procedure as that of the standard finite element method. Numerical examples are presented to demonstrate the versatility and accuracy of the method.


ABSTRACT: An important phenomenon is presented which has not been given sufficient attention in the stability of shell structures: the buckling of a circular cylinder subjected to a set of equally distributed discrete axial concentrated loads is studied. It is shown that the critical load of a circular cylinder under axial compression is very sensitive to imperfection of the applied loads as well as to initial geometric imperfections and the boundary conditions.

Long-Yuan Li (Shanghai, China), “The criteria for identifying the type of critical points”, Archive of Applied Mechanics, Vol. 61, No. 4, 991, pp. 231-235, doi: 10.1007/BF00794348

ABSTRACT: It is well known that the buckling of a structure includes two kinds of different physical phenomena. One is called snap-through buckling and the other is called bifurcation. In this paper, the criteria to identify the two different unstable types are developed. The analysis in the present paper shows that the type of
critical points can be directly determined by the incremental equilibrium equations in the general finite element analysis and that it only depends on whether or not the load increment does work through the unstable mode associated with the critical load.

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ABSTRACT: This paper presents a closed-form solution of critical instability stresses for simply supported rectangular plates with an arbitrary number of stiffeners in longitudinal and/or transverse directions. It is shown that there are only two buckling modes that are coupled to each other for single direction stiffened plates and four for double direction stiffened plates. The coupling of buckling modes represents the feature of interactions of global and local buckling modes. It is also shown that stiffeners have twofold effects on the critical instability stress, one is by enhancing the “stiffness”, the other is by changing the buckling mode. Because of the twofold effects it becomes difficult to apply the conventional optimum method to design the stiffeners and the optimum design of stiffeners still remains a difficult problem. This paper discusses the way by which the stiffeners can effectively enhance the buckling resistance of plates.

ABSTRACT: A new finite strip formulation for the nonlinear analysis of stiffened plate structures subjected to transient pressure loadings is presented. The effects of large deflections, and strain rate sensitive yielding material properties are included. An explicit central difference/diagonal mass matrix time stepping method is adopted. Example results are presented for an I-beam, an isotropic plate and a five-bay stiffened panel and compared with other predictions and/or experimental results. It is observed that design level accuracy can be obtained for practical structures for a fraction of the cost of full finite element analyses.

ABSTRACT: A method of buckling analysis of thin flat-walled structures of finite length subjected to longitudinal compression and bending, transverse compression as well as shear is described. The analysis uses the spline finite strip method and allows for boundary conditions other than simply supported ends as required in the semi-analytical finite strip method of buckling analysis. Convergence studies with increasing numbers of section knots are described for plates in compression, bending and shear, and for long columns with different support conditions subjected to compression. A buckling analysis of a stiffened plate subjected to compression and shear is compared with results from a finite element analysis.

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ABSTRACT: This paper describes recent work performed at the University of Sydney to develop buckling and nonlinear analyses of thin-walled structural members undergoing local, distortional and overall buckling. The analyses are based on the finite strip method of structural analysis and include elastic and inelastic buckling and the full nonlinear response with both post-local buckling and plasticity. Two variations of the finite strip method have been used, these being the semi-analytical and spline finite strip methods. A nonlinear beam-column analysis based on the influence coefficient method for including the local buckling behaviour in the overall member response is also described. The analytical methods are compared with tests performed at the University of Sydney on cold-formed rectangular hollow sections, welded I-sections, welded channel sections and cold-formed channel sections. Spatial plastic collapse mechanisms developed for the welded sections described above are also compared with the post-ultimate response of the test sections.


ABSTRACT: The aim of the report is to show that modern methods of verification of steel structures can be used for the structural appraisal of old cast-iron columns. The proposed method of verification takes account of the geometrical imperfections which are typical for cast-iron columns and of the particular behaviour of the material which is distinct from modern structural steel in that the tension strength is significantly lower than the compression strength, the stress-strain curve is non-linear rather than bi-linear and the Young’s modulus is about 2/5 the value for modern steels. The report proposes equations for calculating the strength of cast iron columns by checking failure by yielding in compression and fracture in tension. The proposed strength equations are compared with experimental results obtained by Hodgkinson (1840) and Tetmayer (1901).

References listed at the end of the report:

London County Council (1909). Act 1909, London County Council (General Powers), HMSO.
Ramberg W and Osgood, WR (1943). Description of Stress Strain Curves by Three Parameters. Technical Note No. 902, National Advisory Committee for Aeronautics, Washington, DC.

ABSTRACT: The main objective of this thesis is to investigate the behaviour of Square (SHS) and Rectangular (RHS) Hollow Sections subject to pure concentrated force, pure moment and combined moment and concentrated force, where the concentrated force is applied to tubular sections either by welding a square hollow section branch member or by a bearing plate. The following experimental and theoretical studies have been performed. An extensive test program on a range of cold-formed SHS and RHS subject to pure concentrated force, pure moment and combined moment and concentrated force is described. The concentrated force was applied by either welding a square hollow section branch member (called T-joint tests) or by a bearing plate (called bearing tests). For the T-joint tests, the ratio ($\beta$) of the width of the branch member to the chord member varied from 0.5 to 1.0 in order to observe different failure mechanisms. For the bearing tests, the ratio ($\gamma$) of the bearing length to the width of the bearing plate varied from 0.5 to 1.0 in order to show the effect of the bearing length on the failure load. For both T-joint tests and bearing tests, the span of the simply supported beam was varied in order to determine the interaction relationship between moment and concentrated force. The slenderness of the member section and the shape of the section (SHS or RHS) were varied to cover a wide range of sections. The results of the bearing tests are compared with the T-joint tests on similar sections to demonstrate the significant reduction in failure loads and the more severe interaction between bending moment and concentrated force. Plastic mechanism analysis (yield line method) is adopted in the thesis, since the failure modes of SHS and RHS involve local collapse mechanisms. The final result of a plastic mechanism analysis largely depends on the plastic moment capacity of yield lines and the mechanism model assumed. For the plastic moment capacity of yield lines, existing formulae are reviewed. The lower bound solutions, which are based on the Tresca yield criterion and the von Mises yield criterion, are derived in the theses to determine the reduced plastic moment capacity of an inclined yield line under axial force. A series of experimental tests on plastic hinges under axial force were performed to verify the formulae. Simplified expressions for the verified formulae are given to permit easy application of the theory. The mechanism models developed in the thesis are based on the experimental observations obtained in the thesis. For T-joints in RHS under concentrated force, a modification of the Kato model is proposed for predicting the yield load. A more refined model is developed to predict the post-yield response and the ultimate load, where plastic hinges in the web, the membrane force in the flange and strain hardening of the material are considered. The virtual work principle is used in the derivation. For RHS under bearing force alone, a mechanism model is developed to predict the web yield load. The eccentric loading of the web where the corner radii meet the flange is considered in the model. For T-joints in RHS subject to combined bending and concentrated force, the mechanism model is approximated by the modified Kato model. The reduction of the plastic moment capacity of yield lines is considered in the derivation. The action in the chord (bending moment) rather than the chord normal stress is used for interaction curves. A proposed interaction formula is given, which includes the variation of capacity with $\beta$. For RHS subject to combined moment and bearing force, interaction formulae are
derived based on the test result. Existing design procedures from Australia, America, Britain and Canada, both for cold-formed members and for hot-rolled members, are reviewed and compared with the test results. Improved design procedures are given for SHS and RHS under concentrated force alone and for SHS and RHS subject to combined moment and concentrated force.

Y.B. Kwon, “Post-buckling behavior of thin-walled channel sections”, Ph.D. dissertation, School of Civil and Mining Engineering, University of Sydney, 1991? (supervisor G.J. Hancock)
ABSTRACT: Thin-walled channel sections may undergo a mode of buckling called distortional in which a lip stiffened flange of the section rotates about the flange-web junction. If the sections are composed of high strength steel, then there may be a significant post-buckling reserve of strength beyond the elastic distortional buckling stress in a similar manner to that which normally occurs for local buckling. A nonlinear elastic analysis based on the spline finite strip method has been developed for studying the post-buckling behaviour of thin-walled sections. The method can handle local, distortional and overall buckling modes in the post-buckling range and the interaction between them. It allows for geometric imperfections, arbitrary loading and non-simple boundary conditions. The accuracy is confirmed by studying several plate, section and shell problems for which solutions are known. The results of compression tests of thin-walled channel section columns formed by brake-pressing are described. Two different section geometries, a simple lipped channel and a lipped channel with an intermediate stiffener in the web, were tested between fixed-ended boundary conditions. The geometries and yield strength were chosen to ensure that a substantial post-buckling strength reserve occurred in the distortional mode and that local buckling might occur simultaneously at a shorter wavelength. The nonlinear spline finite strip method is applied to the prediction of the post-buckling behaviour and the influence of the interaction between buckling modes for the test channel columns. Design curves for the maximum strength of different columns undergoing distortional or mixed modes of buckling are proposed. Two basic design methods to account for the local and distortional buckling or mixed local-distortional buckling mode are also proposed. The test results are compared with the proposed methods and are also compared with the Australian Standard, the American Specification and European Recommendations for the design of cold-formed steel structures.

ABSTRACT: A nonlinear elastic analysis based on the spline finite strip method has been developed for studying the post-buckling behaviour of thin-walled sections. The method can handle local, distortional and overall buckling modes in the post-buckling range and the interaction between them. It allows for geometric imperfections, arbitrary loading and non-simple boundary conditions. By comparison, the semi-analytical finite strip method is restricted to simply supported end boundary conditions and a single buckle half-wavelength. The two incremental-iterative strategies adopted in the nonlinear analysis are the arc-length method and the improved iteration method based on displacement control. Switching between load and displacement control can occur automatically as the need arises in an analysis. Numerical examples are presented for comparison with and verification against solutions for the nonlinear behaviour of plates, plate assemblies and cylindrical shells.

Y.B. Kwon and G.J. Hancock (Centre for Advanced Structural Engineering, School of Civil and Mining Engineering, University of Sydney, N.S.W., Australia), “Post-buckling analysis of thin-walled channel sections

ABSTRACT: A theoretical method for predicting the post-buckling behaviour of thin-walled sections is applied to study the influence of the interaction between local and distortional buckling modes for test channel columns described in an earlier paper. The theoretical predictions are based on a nonlinear elastic spline finite strip method for thin-walled sections which has recently been developed. The method can handle sections buckling simultaneously in local and distortional buckles at different half-wavelengths. The investigation includes convergence studies with different convergence criteria, strip subdivision and longitudinal subsections so as to determine reliable convergence criteria and the required discretizations for use in the nonlinear elastic spline finite strip method.


ABSTRACT: The calculation of the stresses and failure modes in thin-walled structural members is a complex procedure. Structural designers will often need help in analysing these types of structures. A vehicle for providing this help is the computer program developed for the microcomputer. In this paper, a computer procedure is described for the cross-section analysis and elastic buckling analysis of thin-walled structural members. The cross-section analysis calculates the section properties, warping displacements, and the longitudinal and shear stresses for thin-walled open and closed cross-sections of any shape. The longitudinal stresses are used to perform an elastic finite strip buckling analysis of thin-walled structural members. The analysis can be done for a number of different buckle half-wavelengths of the member and the load factor and buckled shape are output for each length. The analysis is performed by the user-friendly computer program THIN-WALL, which is also described in the paper.


ABSTRACT: The paper provides a report on the simulation and computational models of structures prone to interaction buckling. The simulation models are divided into perturbation, cell and discrete models, and all major contribution to the research of interaction buckling are classified using this division. The paper also explores current trends in the development of simulation models and likely future research areas.

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ABSTRACT: This paper describes the application of the isoparametric spline finite strip method to the linear elastic analysis of tri-dimensional perforated folded plate structures. The general theory of the isoparametric
spline finite strip method is introduced. Kinematics assumptions and the procedure for combining in-plane (membrane) and bending effects are set out. Particular attention is paid to the procedure for rotating the stiffness matrix and load vector from local to global coordinates. The reliability of the method is demonstrated by comparisons with finely meshed finite element analysis results. Square stiffened perforated plates in compression and bending are analysed.

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ABSTRACT: This paper presents the application of the isoparametric spline finite strip method to the elastic buckling analysis of perforated folded-plate structures. The general theory of the isoparametric spline finite strip method is introduced. The kinematics assumptions, strain–displacement and constitutive relations of the Mindlin plate theory are described and applied to the spline finite strip method. The corresponding matrix formulation is utilised in the equilibrium and stability equations to derive the stiffness and stability matrices. A number of numerical examples of flat and folded perforated plate structures illustrate the applicability and accuracy of the proposed method.

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ABSTRACT: This paper presents the application of the isoparametric spline finite strip method to the geometric nonlinear analysis of perforated folded-plate structures. The general theory of the isoparametric spline finite strip method is introduced. Kinematics, strain–displacements and constitutive assumptions are described and applied to the spline finite strip method. The derivation of the tangential and secant stiffness matrices is presented by applying the equilibrium condition and its incremental form. The reliability of the method is demonstrated by applying the method to classical nonlinear complex plate and shell problems as well as the geometric nonlinear analysis of perforated flat and stiffened plates.

ABSTRACT: In this study, the finite element method is employed to determine the critical in-plane longitudinal load at which elastic local buckling of the web of cellular beam–column elements occurs. To simplify the simulation of the problem, the interaction between the flanges and perforated web is approximated by modelling the web only as a long plate having aspect ratio (L/hw≥10) with multiple circular perforations. The utilized model incorporates restrained out-of-plane displacements along the four edges of the plate. Analyzed plates are
subjected to linearly varying in-plane loads to simulate various combinations of axial and flexural stresses. The effect of different geometrical parameters on the elastic buckling load of perforated web plate is investigated. These geometrical parameters include the plate’s length and width, and the perforations’ diameter and spacing. Comprehensive finite element analyses are conducted to identify the behaviour of wide spectrum of perforated web plates at buckling under various combinations of axial compressive load and bending moment. Outcomes of the study are expected to enhance the understanding of the elastic local buckling of web plates of cellular beam–column elements.


ABSTRACT: A finite element algorithm for analysis of stiffened plates by normal mode approach under stationary random stochastic loading has been presented. The formulations for both spatially homogeneous and nonhomogeneous loads have been indicated. The isoparametric quadratic stiffened plate bending element employed has a unique feature that the stiffeners can be positioned anywhere within the plate element and they need not necessarily be on the nodal lines. The element, being isoparametric quadratic, can readily accommodate curved boundaries, transverse shear deformation, and laminated materials. The formulation is applicable to thin as well as thick plates. A simple lumped load concept has been used for spatially homogeneous loading; for spatially nonhomogeneous loads, however, the isoparametric shape function and the Gaussian integration technique have been employed to form the generalized nodal cross spectral density matrix from the excitation. Displacement and stress response spectra for plates and stiffened plates under white noise and jet noise excitation have been evaluated. The results have been presented along with those of previous investigators. The performance of the element has been found to be very good under all circumstances.


ABSTRACT: The general spline finite strip method has been extended in this paper to the analysis of stiffened plates having arbitrary shape. The main elegance of the formulation lies in the treatment of stiffeners. It has been shown that the stiffener can be placed anywhere within the plate strip which introduces a considerable amount of flexibility in the analysis. Stiffened plates having various shapes, boundary conditions, loadings and also possessing various disposition of stiffeners as available in the literature, have been analysed by the proposed approach. Comparison obtained with existing theoretical and/or experimental values have indicated good accuracy.


ABSTRACT: The spline finite strip method which has long been applied to the vibration analysis of bare plate has been extended in this paper to stiffened plates having arbitrary shapes. Both concentrically and eccentrically
stiffened plate have been analyzed. The main elegance of the formulation lies in the treatment of the stiffeners. The stiffeners can be placed anywhere within the plate strip, and need not be placed on the nodal lines. Stiffened plates having various shapes, boundary conditions and also possessing various disposition of stiffeners, as available in the literature, have been analyzed by the proposed approach. Comparison with published results indicates excellent agreement.

ABSTRACT: Geometric nonlinear analysis of stiffened plates is investigated by the spline finite strip method. von Karman's nonlinear plate theory is adopted and the formulation is made in total Lagrangian coordinate system. The resulting nonlinear equations are solved by the Newton–Raphson iteration technique. To analyse plates having any arbitrary shapes, the whole plate is mapped into a square domain. The mapped domain is discretised into a number of strips. In this method, the displacement interpolation functions used are: the spline functions in the longitudinal direction of the strip and the finite element shape functions in the other direction. The stiffener is elegantly modelled so that it can be placed anywhere within the plate strip. The arbitrary orientation of the stiffener and its eccentricity are incorporated in the formulation. All these aspects have ultimately made the proposed approach a most versatile tool of analysis. Plates and stiffened plates are analysed and the results are presented along with those of other investigators for necessary comparison and discussion.

ABSTRACT: The spline finite strip method has been applied to linear and nonlinear transient vibration analysis of plates and stiffened plates. In this method, spline functions have been used as the displacement interpolation functions in one direction while finite element shape functions have been used for that in the other direction. The von Karman's large deflection plate theory has been used and the formulation has been done in total Lagrangian coordinate system. The governing equations have been solved by the Newton–Raphson iteration technique where Newmark's method has been used for the time integration. The stiffener has been elegantly modelled so that it may lie anywhere within the plate strip, which helps to increase the flexibility in mesh generation. The formulation has been generalised to cater plates having arbitrary shapes and stiffeners having arbitrary orientation and eccentricity. Examples of stiffened and unstiffened plates under different loading history as available in the literature have been solved to study the performance and range of applicability of the proposed method.

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ABSTRACT: Strength of ship plates plays a significant role in the ultimate strength analysis of ship structures. In recent years several authors have proposed simplified analytical methods to calculate the ultimate strength of unstiffened plates. The majority of these investigations deal with plates subjected to longitudinal compression only. For real ship structural plating, the most general loading case is a combination of longitudinal stress, transverse stress, shear stress and lateral pressure. In this paper, the simplified analytical method is generalized to deal with such combined load cases. The obtained results indicate that the simplified analytical method is able to determine the ultimate strength of unstiffened plates with imperfections in the form of welding-induced residual stresses and geometric deflections subjected to combined loads. Comparisons with experimental results show that the procedure has sufficient accuracy for practical applications in design.

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ABSTRACT: In spite of the large number of finite elements developed so far, most of these lack in generality, and are found to be inadequate and inefficient in some way or other, when it comes to analyzing plates of arbitrary geometrical configurations. So far the isoparametric element has been the most successful among available elements because of its ability to model a curved boundary successfully. However, the shear-locking problem inherent in the isoparametric element makes it unsuitable for analyzing thin plates of arbitrary shapes. Though research has been conducted using reduced integration and stabilization to overcome the problem, the formulations either do not converge to the correct solution in the thin-plate limit or they make the stiffness matrix a singular one. In this paper, a four-noded stiffened plate element is developed. This has the advantages and elegance of an isoparametric element in modelling arbitrary shaped plates, but without the disadvantage of shear-locking phenomena. Though this element is a high-order element, only the usual degrees of freedom have been considered, and performance is superior to that of the low-order ones. The stiffened plate element has the feature of accommodating the arbitrary shape of the plate geometry, and the stiffener modelling has been done in a general manner, with the stiffener lying anywhere with arbitrary orientation, and not necessarily following the nodal lines. The new element has been successfully used for the static, free vibration and stability analyses of arbitrary bare and stiffened plates. The results are found to agree quite satisfactorily with those of previous investigators.

ABSTRACT: Analysis of plated structures with rectangular cutouts and internal supports by the finite element method is tedious and time consuming. The spline finite strip method has been developed and applied to solve this problem efficiently.

ABSTRACT: In each of the two case studies described in this paper a vessel containing a pressurised fluid failed by the phenomenon of external-pressure buckling. In the first case study a jacketed reactor vessel developed an inward-facing bulge because the heat-transfer oil in the jacket had expanded during a temperature excursion. The second case study involved the “snap-through” of a spherical-cap partition in an oil storage tank. The partition had been subjected to an unacceptably high external pressure because compressed air had been used to propell a fresh supply of oil into the storage tank. The buckling failures were analysed using standard results for the external-pressure buckling of thin-walled tubes and spherical caps, and the critical collapse pressures were found to be of a suitable magnitude to account for the failures.


ABSTRACT: A finite element formulation is presented for the non-symmetric bifurcation analysis of geometrically nonlinear elastic-plastic shells of revolution. The shell may be branched and segmented. The loads are axisymmetric but may include in-plane shears (non-uniform torsion). In place of the widely used relations of Donnell, Novozhilov and Sanders, a new nonlinear shell theory is adopted which includes nonlinear strains arising from in-plane displacements. For the determination of the non-linear prebuckling load deflection path, the J2 flow theory of plasticity is used. For the non-symmetric bifurcation analysis, three theories are provided: J2 flow theory, J2 deformation theory and J2 flow theory with the shear modulus predicted by J2 deformation theory. A new efficient and automatic solution procedure is described to determine the critical buckling mode, and hence the critical buckling stress. Several example problems are analysed and the predictions of the present analysis are compared with available theoretical and experimental results. Very close agreement is achieved. The effect of using different plasticity theories in the stability analysis is also briefly discussed.

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ABSTRACT: Elevated steel silos and tanks commonly consist of a cylindrical shell, a conical hopper and a skirt. Much of the total weight of the stored material is supported by the hopper, which is in biaxial tension and may fail by forming a plastic collapse mechanism. This paper examines the plastic collapse of hoppers which are sufficiently restrained by a ring at the hopper/cylinder junction for the collapse mode to be entirely confined to the hopper. The hopper joints are assumed to be stronger than the shell plate. An elastic-plastic finite-element program is used to study the plastic collapse behaviour of these hoppers. It is found that the plastic collapse mode is usually a local mechanism near the top of the hopper. Collapse strengths are determined for hoppers of both uniform thickness and varying thickness subject to internal pressure with and without frictional shear. Most of the calculations are performed using elastic-plastic small deflection theory, because this leads to well-defined collapse strengths and relates to classical limit analysis. Calculations made using large deflection theory
show that the non-linear changes of geometry have a significant stiffening and strengthening effect. The parametric study presented in this paper defines a simple lower bound to the strength of the hopper.

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ABSTRACT: Many experiments have been conducted to determine the distribution of pressures and frictional drags on silo walls. Based on this information, design calculations indicate that buckling under vertical compressive stresses is usually the critical consideration for thin-walled steel silos. Many failures of silos in service have occurred by buckling under axial compression and eccentric discharge of the stored solids has been implicated in a number of them. Existing knowledge of the buckling strength of empty, uniformly compressed, cylindrical shells is extensive, and the effects of internal pressurisation are also quite well known. However, little is known about buckling failures in which the wall stresses are directly induced by stored solids, or about the increases in buckling strength which derive from the stiffness of a stored granular solid in contact with the silo wall. This paper describes experiments in which these effects were studied. Model silos were loaded to failure and the wall stresses and consequent buckling failure were caused solely by a stored granular solid. These experiments were designed to explore the buckling strength and behaviour of thin-walled, flat-bottomed silos on initial filling and during discharge. Both concentric and eccentric discharge conditions in funnel flow silos are described. Buckling failures with both stable and unstable characteristics are noted. Finally, conclusions are drawn for the structural design of steel silos.


ABSTRACT: A new finite element formulation for elastic-plastic large deflection analysis of shells of revolution is presented. The new formulation contains most of the best features of nonlinear finite element analyses currently available in the literature, together with some new numerical schemes to improve the capability, accuracy and speed of the computation. It is thoroughly verified using a variety of problems. The doubly curved thin shell finite element used has been widely applied to linear elastic stress analysis and linear stability analysis by the present authors and their co-workers. In place of the widely-used relations of Donnell, Novozhilov or Sanders, more comprehensive nonlinear thin shell strain-displacement relations are used, which account for nonlinear strains caused by in-plane displacements. Unlike most previous nonlinear axisymmetric shell formulations, in-plane shearing is included throughout the treatment. For plastic analysis, a multi-layered approach is adopted, employing the Prandtl-Reuss normal flow rule with isotropic hardening or perfect plasticity. An efficient and accurate state determination algorithm, assuming incremental reversibility for plastic behaviour, is adopted and verified. Implementation of the variable arc-length method provides an efficient iterative procedure for tracing both the pre- and post-critical load-deflection path. Several examples demonstrate the accuracy, efficiency and capability of the present formulation.

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ABSTRACT: Elevated steel bins and tanks typically consist of a cylindrical vessel, a conical hopper and a skirt. The intersection of these three shell segments is termed the transition junction and is subject to a large circumferential compression. A ring is often required at this junction. The high circumferential compression at the intersection may lead to a buckling failure of the ring. Elastic buckling of the ring at the transition junction has been studied recently, but very little is currently known about the plastic buckling of such a ring. This paper presents a theoretical investigation into the plastic buckling of the transition ring using a finite element analysis. Simple annular plate rings are studied first, and the results are compared with the few known predictions from an earlier study. The plastic buckling of T-section rings is then explored.

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PARTIAL ABSTRACT: Elevated silos and tanks are often supported on a number of columns. The discrete supports of the columns induce high stresses adjacent to the column terminations. In particular, very high meridional compressive stresses arise above each column termination and these can lead to buckling of the shell at a load much lower than that for a uniformly supported shell. This paper presents a brief summary of recent theoretical work on the elastic buckling strength of column-supported cylinders. Elastic calculations are relevant provided the shell is of typical practical thickness (500 < R/t < 2000).


ABSTRACT: Large elevated silos and tanks are generally supported on a number of columns. The discrete supports of the columns give rise to high stresses adjacent to the column terminations. In particular, very high meridional compressive stresses arise above each column termination and these can lead to buckling of the shell at a load much lower than that for a uniformly supported shell. This paper presents a study of the linear bifurcation buckling behaviour of column-supported thin elastic perfect cylinders using the finite element method. Cylinders on both rigid and flexible column supports are studied, and the effects of varying several shell parameters are examined. The effects of the top and bottom edge boundary conditions are also investigated. It is well recognised that the linear bifurcation load is only an upper bound on the actual elastic buckling load, because the effects of large deflections and initial imperfections are ignored. Nevertheless, our understanding of the buckling behaviour of these structures is so limited that the results obtained here provide a significant starting point from which more elaborate studies may follow.

J.G. Teng and T. Hong (Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China), “Nonlinear thin shell theories for numerical buckling predictions”, Thin-Walled Structures, Vol. 31, Nos. 1-3, May 1998, pp. 89-115,
ABSTRACT: A basic building block in any numerical (geometrically) nonlinear and buckling analysis is a set of nonlinear strain–displacement relations. A number of such relations have been developed in the past for thin shells. Most of these theories were developed in the pre-computer era for analytical studies when simplicity was emphasized and terms judged to be small relative to other terms were omitted. With the availability of greatly increased computing power in recent years, accuracy rather than simplicity is given more emphasis. Additional complexity in the strain–displacement relations leads to only a small increase in computational effort, but the omission of a term which may be important in only a few complex problems is a major flaw. It is therefore necessary to re-examine classical shell theories in the context of numerical nonlinear and buckling analysis. This paper first describes a set of nonlinear strain–displacement relations for thin shells of general form developed directly from the nonlinear theory of three-dimensional solids. In this new theory, all nonlinear terms, large and small, are retained. When specialized for thin shells of revolution, this theory reduces to that previously derived by Rotter and Jumikis and others. Analytical and numerical comparisons are carried out for thin shells of revolution between Rotter and Jumikis' theory as a special case of the present theory and other commonly used nonlinear theories. The paper concludes with comments on the suitability of the various nonlinear shell theories discussed here for use in numerical buckling analysis of complex branched shells.


ABSTRACT: This paper introduces the NEPAS program which has been developed over a number of years for the nonlinear and buckling analysis of complex branched shells of revolution. Throughout its development, a strong emphasis has been placed on achieving robustness, efficiency, and accuracy. This has led to attempts to identify the best available numerical techniques and the development of new ones for implementation in the program. In this paper, the current capabilities of the NEPAS program are described and the numerical techniques implemented to achieve them are reviewed. A number of numerical examples are included to illustrate these capabilities. Further developments of the program to make it an attractive analysis tool for designers are also discussed.


ABSTRACT: In this paper, the most up-to-date research on the buckling of internally-pressurized cone–cylinder intersections and state-of-the-art finite element analyses are deployed to provide another anatomy of a pressure vessel failure due to mis-operation overpressure recently reported and analyzed by Jones [Jones, DRH. Buckling failures of pressurized vessels: two case studies. Engineering Failure Analysis 1994;1:155–67]. Existing research on these intersections is first outlined, followed by a description of the buckling strength formulae recently developed to approximate finite element buckling loads of the perfect geometry. The validity of these formulae for real vessels with geometric imperfections is next examined through a comparison of theoretical predictions with experimental results, which establishes the limited sensitivity of the buckling load to initial imperfections. The buckling pressure of the cone–cylinder intersection in the failed vessel is then determined using these formulae, while the buckling pressure of the spherical partition in the vessel is evaluated.
using the ECCS rule. These calculations demonstrate that the cone–cylinder intersection buckled first, followed by the buckling of the spherical partition, which also released the vessel from overpressure. The buckling pressure of the spherical partition is therefore also the maximum pressure exerted on the vessel. This proposition is confirmed by postbuckling analyses of the vessel.


ABSTRACT: Cylinders, cones, spheres and tori are some of the common basic shell elements. Steel shell structures such as silos, tanks, pressure vessels, offshore platforms, chimneys and tubular towers generally consist of two or more of these basic shell elements. Axisymmetric intersections featuring meridional slope mismatches between the connected elements are common features in steel shell structures. High bending and circumferential membrane stresses are developed in these intersections, and their buckling and collapse strengths are a key design consideration. This paper presents a summary of recent research on the stress, stability and strength of axisymmetric steel shell intersections. Particular attention is paid to intersections formed from cylindrical and conical segments as these are more common and have been more extensively researched. A simple approximate method for extrapolating the knowledge gained on these intersections to those containing curved shell segments is also suggested.


ABSTRACT: Nonlinear finite-element analysis provides a powerful tool for assessing the buckling strength of shells. Since shells are generally sensitive to initial geometric imperfections, a reliable prediction of their buckling strength is possible only if the effect of geometric imperfections is accurately accounted for. A commonly adopted approach is to assume that the imperfection is in the form of the bifurcation buckling mode (eigenmode-affine imperfection) of a suitable magnitude. For shells of revolution under axisymmetric loads, this approach leads to the analysis of a shell with periodically symmetric imperfections. Consequently, sector models spanning over one or half the circumferential wave of the imperfection may be considered adequate. This paper presents a study which shows that a simple nonlinear analysis of the imperfect shell may not deliver the correct buckling load, due to the tendency of the shell to develop mode changes in the deformation process before reaching the limit point. This inadequacy exists not only with short sector models (half-wave or whole-wave models) but also with more complete models (half-structure or whole-structure models) for different reasons. The paper concludes with recommendations on the proper use of the four different kinds of models mentioned above in determining shell buckling strengths.


ABSTRACT: A new finite element formulation is presented for the non-linear analysis of elastic doubly curved segmented and branched shells of revolution subject to arbitrary loads. The circumferential variations of all quantities are described by truncated Fourier series with an appropriate number of harmonic terms. A coupled
harmonics approach is employed, in which coupling between different harmonics is dealt with directly rather than by the use of pseudo-loads. Key issues in the formulation, such as non-linear coupling and growth of harmonic modes, are carefully and systematically explained. This coupled harmonics approach allows an easy implementation of the arc-length method. As a result, post-buckling load–deflection paths can be traced efficiently and accurately. The formulation also employs a non-linear shell theory more complete than existing classical theories. The results from the present study are independently verified using ABAQUS, while those from other studies are found to be inaccurate in general.

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ABSTRACT: This paper presents a ring element for the static analysis of shells of revolution of arbitrary shape under arbitrarily distributed loads, based on a displacement formulation that includes geometric and physical non-linearity. The trial functions for the displacement field in the circumferential direction of the shell involve harmonic series, so that the dependence in the circumferential direction is removed from the formulation. For this element, the derivation of the internal resisting force vector and of the tangent stiffness matrix is presented. Furthermore, the concept of ring elements is extended to a spring ring element for modelling uplift between a shell of revolution and the supporting ground. After the presentation of element theory, the use of these ring elements is demonstrated with two application studies.

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ABSTRACT: The paper addresses the buckling of an elastic cylinder under non-uniform axial compression applied at one boundary. It presents a systematic numerical investigation of the nonlinear load carrying behavior and imperfection sensitivity of the shell when a non-uniform axial load is applied to one end in the form of two equal-length uniformly loaded zones, diametrically opposite each other. Four imperfection forms are examined: the linear bifurcation mode, the nonlinear buckling mode, several post-buckling deformed shapes for the perfect shell, and a weld depression. Additional aspects, such as the influence of the weld depression position and its wavelength are also investigated. Special attention is given to the mesh convergence study and the sign of the imperfection amplitude. The numerical results demonstrate that the mode of the lowest linear bifurcation load is not always the ‘worst’ imperfection form. It is also shown that the critical position for a weld depression can be approximately located by examining the nonlinear buckling mode of the perfect shell and that the weld depression generally causes the lowest buckling load for this load case.
PARTIAL INTRODUCTION: Thin-shell structures are widely used in many branches of engineering. Examples include aircraft, spacecraft, cooling towers, nuclear reactors, steel silos and tanks for storage of bulk solids and liquids, pressure vessels, pipelines and offshore platforms, though the latter are largely deemed to be outside the scope of this book. The class of shells covered here is very thin, so failure by buckling is often the controlling design criterion. It is therefore essential that the buckling behavior of these shells is properly understood so that suitable design methods can be established.

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ABSTRACT: The design of metal silo structures is dominated by the need to resist shell buckling failures in service. Shell buckling can occur in many different modes, and the strengths are very sensitive to the form and amplitude of very minor deviations of geometry (geometric imperfections) from the ideal shape. Many imperfection forms have been studied in the theoretical literature on shell buckling, but only one study appears to have ever extensively and rigorously measured the imperfections in real full-scale metal silos: this is the study of the 10,000 tonne Port Kembla grain silos in NSW, Australia. The data from this study of three seemingly identical silos are very extensive and cannot be assimilated without considerable processing. In this paper, the first attempt is made to provide a full characterisation of the imperfection set in a manner that permits them to be used in shell buckling analyses of the silo shell that do not rely on simplifying assumptions.

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ABSTRACT: Cylindrical shells in large steel silos and tanks are commonly constructed from a large number of curved panels joined by many circumferential and meridional welds (referred to as the panel method hereafter). The extensive use of welding in these shells is a unique feature not previously studied in laboratory buckling experiments due to the great difficulty in fabricating realistic small-scale model shells. This paper presents an innovative technique for the fabrication of small models of such large steel cylindrical shells constructed from many welded panels. The experimental set-ups to implement this technique in the laboratory are also described. The new technique consists of two stages: (a) production of a high quality model by rolling two sheets (or a single sheet) and welding along the meridional seams; and (b) ‘welding’ in the form of controlled heat input in a
required pattern of circumferential and meridional ‘welds’ on the central portion of the shell surface. The imperfections in an example specimen are also examined to show that they have a realistic pattern. The observed buckling behavior of this specimen is presented and discussed. The specimen buckled at a very low load, confirming that the welding-induced imperfections in such shells are severely detrimental to the buckling strength.

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ABSTRACT: Steel silos and tanks are commonly constructed by welding together a large number of curved steel panels. The panels are first connected with short meridional welds to form circular strakes (or courses), which are then connected by continuous circumferential welds to form the entire shell wall. Associated with the large number of welds are welding-induced shrinkage deformations and residual stresses, both of which may have a significant effect on the buckling strength of the shell wall. In this paper, a simple method for the simulation of the weld depressions and associated residual stresses is first introduced. The results of a series of finite element buckling analyses of a typical steel cylinder with such simulated welding effects are next presented and discussed, leading to a number of significant conclusions. One of these conclusions is that a weld depression pattern produced using the present weld simulation method can offer a suitable equivalent imperfection form for use in the non-linear analysis of shells for stability design, as it leads to buckling loads in close agreement with predictions by the new European code for steel shell structures.

ABSTRACT: The postbuckling response of shells is known to exhibit complex phenomena including mode switching and interaction, particularly in the advanced postbuckling range. The existing literature contains many initial postbuckling analyses as well as advanced postbuckling analyses for a single buckling mode, but little work is available on the advanced postbuckling analysis of shells of revolution considering mode switching and interaction. In this paper, a numerical method for the advanced postbuckling analysis of thin shells of revolution subject to torsionless axisymmetric loads is presented, in which such mode switching and interaction are properly captured. Numerical results obtained using the present method for several typical problems not only demonstrate the capability of the method, but also lead to significant observations concerning the postbuckling behavior of thin shells of revolution. In particular, the results show that strong interaction between different harmonic modes may exist and the transition of deformation mode from one to another is gradual. Consequently, the conventional approach of finding the postbuckling path of a shell as the lower festoon curve of postbuckling paths of individual harmonic modes is not valid and is at best a convenient approximation.
ABSTRACT: This paper is concerned with the application of different types of analysis in the design of civil engineering shell structures which are required to satisfy national or international standards. It outlines the framework of design in the new Eurocode 3 Part 1.6 Strength and Stability of Shell Structures, discusses the power and breadth of this standard and outlines some of its requirements. It also raises several issues that remain difficult to resolve, but which are worthy of careful discussion amongst the leading experts in the shell analysis and stability community.

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ABSTRACT: The imperfection sensitivity of thin shells of revolution has been a topic of great interest to researchers and designers. With the gradual emergence of the new approach of structural design based on advanced numerical simulation, the efficient and accurate prediction of the behaviour of imperfect shells has recently assumed new significance. This paper first presents an efficient semi-analytical finite element formulation for the nonlinear analysis of imperfect shells of revolution subject to general nonsymmetric loads. Both the applied loads and the initial geometric imperfections may take any form and are approximated by Fourier series expansions. Application of the analysis to study the effects of geometric imperfections on the behaviour of shells of revolution is then presented to demonstrate the accuracy and capability of the present method and the imperfection sensitivity of shell structures. As a special case of the present formulation, two different approaches are also presented for the postbuckling analysis of perfect thin shells of revolution under axisymmetric loads. The accuracy and capability of both methods are demonstrated using a number of numerical examples, which also allows some new insight to be gained into the postbuckling behaviour of perfect shells of revolution.


ABSTRACT: The classical buckling problem of the circular cylindrical shell subjected to axial compression is reinvestigated using the intrinsic buckling shell equations. For the purely membrane prebuckling state and relaxed-type boundary conditions complex numerical analysis is performed with the help of Mathematica software. It is found, in particular, that the critical buckling load parameter falls to about half of the classical value following from the simplest Donnell type non-linear shell equations.

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ABSTRACT: We present extensive numerical results of bifurcation buckling analysis of the axially compressed circular cylinder. The analysis is based on the modified displacement version of the non-linear theory of thin elastic shells developed by Opoka and Pietraszkiewicz [Opoka, S., Pietraszkiewicz, W., 2009. On modified displacement version of the non-linear theory of thin shells, International Journal of Solids and Structures, 46, 3103-3110]. To solve the buckling problem we apply the separation of variables and expansion of all fields into Fourier series in circumferential direction, with subsequent accurate calculations of eigenvalues of determinants of corresponding $8 \otimes 8$ complicated matrices. The numerical analysis of the buckling load is performed for the cylinders with length-to-diameter ratio in the range $(0.05, 60)$, with eight sets of incremental work-conjugate boundary conditions analogous to those used in the literature and partly summarized in the book by Yamaki [Yamaki, N., 1984. Elastic Stability of Circular Cylindrical Shells. Elsevier, Amsterdam], and additionally with six sets of boundary conditions not discussed in the literature yet. The results allow us to formulate several important conclusions, such as: (a) omission in the non-linear BVP small terms of the order of error introduced by the error of constitutive equations leads to overestimated buckling loads for long cylinders with clamped boundaries; (b) for some relaxed boundary conditions the buckling load decreases for short cylinders with decrease of the cylinder length; (c) the results for additional six sets of boundary conditions reveal existence of several new cases, in which by relaxing geometric boundary conditions the buckling load falls down to about one half of the classical value in a wide range of the cylinder length-to-diameter ratios.


ABSTRACT: We discuss the non-linear theory of thin shells expressed in terms of displacements of the shell reference surface as the only independent field variables. The formulation is based on the principle of virtual work postulated for the reference surface. In our approach: (1) the vector equilibrium equations are represented through components in the deformed contravariant surface base, and using the compatibility conditions the resulting tangential equilibrium equations are additionally simplified, (2) at the shell boundary the new scalar function of displacement derivatives is defined and new sets of four work-conjugate static and geometric boundary conditions are derived, as well as (3) for prescribed shell geometry all non-linear shell relations are generated automatically by two packages set up in Mathematica. The displacement boundary value problem and the associated homogeneous shell buckling problem are generated exactly without using any additional approximations following from errors of the constitutive equations. Both problems are extremely complex and available only in the computer memory. Such an approach allows us to account also for those a few supposedly small terms which may be critical for finding the correct buckling load of shells sensitive to imperfections. This approach is used in the accompanying paper by Opoka and Pietraszkiewicz [Opoka, S., Pietraszkiewicz, W., 2009. On refined analysis of bifurcation buckling for the axially compressed circular cylinder. International Journal of Solids and Structures, 46, 3111–3123.] to perform the refined numerical analysis of bifurcation buckling for the axially compressed circular cylinder.


ABSTRACT: Equations of equilibrium and appropriate four geometric and static boundary conditions are derived for the general nonlinear theory of thin shells. All shell relations are referred to the undeformed shell
middle surface. A modified tensor of change of curvature is used, which is a third-degree polynomial with respect to displacements. A new independent parameter describing the finite rotation of the shell boundary element is introduced, upon which works the boundary couple. All shell equations are consistently simplified in the case of elastic shells undergoing small strains but finite rotations, and the Hu-Washizu variational principle is constructed.

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“On modeling and non-linear elasto-plastic analysis of thin shells with deformable junctions”, (publisher and date not given in the “pdf” file. The most recent reference is dated 2006.)

ABSTRACT: The undeformed base surface of the irregular thin shell is modelled by the union of a finite number of regular smooth surface elements joined together along spatial curvilinear surface edges. The equilibrium conditions are formulated by postulating an appropriate form of the principle of virtual work, where also deformability of shell junctions is taken into account. The PVW is then discretised by $C^1$ finite elements and the incremental-iterative procedure is applied to solve the highly non-linear BVP. As an example, the axisymmetric deformation state is calculated in the casing of devise measuring the external pressure and having two pairs of circular welded junctions. The problem is solved within the elasto-plastic range of material behaviour with linear combination of isotropic and kinematic hardening, and deformability of the junctions is taken into account.

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Virtual work is derived. Among them are the stiff, entirely simply connected and partly simply supported branch pipes, Int. J. Solids Str. 145 (2011), 2244, doi:10.1016/j.ijsolstr.2011.03.029


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ABSTRACT: We construct the unique two-dimensional (2D) kinematics which is work-conjugate to the exact, resultant local equilibrium conditions of the non-linear theory of branching shells. It is shown that the compatible shell displacements consist of the translation vector and rotation tensor fields defined on the regular parts of the shell base surface as well as independently on the singular surface curve modelling the shell branching. Discussing relations between limits of the translation vector and rotation tensor fields when approaching the singular curve, and analogous fields given only along the singular curve itself, several types of the junctions are described. Among them are the stiff, entirely simply connected and partly simply supported junction as well as the elastically and dissipatively deformable junction, and the non-local elastic junction. For each type of junction the explicit form of the principle of virtual work is derived.
ABSTRACT: We carry out further study of the constitutive laws for Cosserat plates developed by Altenbach and Eremeyev. In particular, we examine the problem of choice of the micropolar material coefficients. Requiring that the constitutive matrix is positive definite, we establish some bounds on values of micropolar constants. The constitutive relations for Cosserat plates have been implemented into formulation of shell finite elements developed within the framework of the statically and kinematically exact, nonlinear six-parameter shell theory. By the linear parametric-sensitivity analysis we study the influence of the micropolar material constants on the response of shell structure with orthogonal intersections of branches. Such structures can naturally be analyzed using the six-parameter shell theory. Having established the most influential coefficients, we show how these values affect the behavior of the structure in the nonlinear range of deformations.


ABSTRACT: Contributions of solid mechanics research to the development of composite materials and structures are reviewed. The main topics include the tensile and compressive strength of fibrous composites; transformation and residual fields in composite and laminated microstructures; plasticity and viscoplasticity of composites during processing, under thermomechanical service loads, and in the presence of evolving fatigue damage; delamination, damage and fracture; and future research needs.

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ABSTRACT: Free vibration analysis of a through-width multidelaminated beam is performed in the present study. Multiple delaminations are assumed to spread from the top through the thickness direction of the beam. The natural frequencies of the multidelaminated beams are obtained from a recurrent single delaminated beam (RSDB) model, which is the subsingle delaminated beam from the top surface of a global beam. Each frequency equation for the RSDB with unknown boundary conditions is obtained through continuity conditions. Then this result is updated to the next one. With these sequential operations, the final frequency equation of the multidelaminated beams is obtained for both end boundary conditions of the global beam. The numerical results
for the beams are compared with those of finite element analysis to give the reliance on the proposed model and to investigate the effects of the shape, number, and size of multidelaminations on the natural frequency. It was shown that the variations in the natural frequency for the multidelaminated beams were significantly affected by the delamination length.

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ABSTRACT: (none given)

References listed at the end of the paper:

ABSTRACT: Certain mechanical systems display transitions between two nominally uniform solution states which have certain features in common with the true phase transitions. Three such examples will be discussed here. In order, they are the bulging of a long cylindrical balloon, neck propagation along bars of certain polymeric materials, and buckle propagation along externally pressurized pipes. Most of the results presented here were taken from two earlier papers by the authors and a colleague.
The two references cited in the abstract:

ABSTRACT: Two examples illustrate the propagation of instability modes under quasi-static, steady-state conditions. The first is the inflation of a long cylindrical party balloon in which a bulge propagates down the length of the balloon. The second is the collapse of a long pipe under external pressure as a result of buckle propagation. In each example, there is a substantial barrier to the initiation of the instability mode. Once initiated, however, the mode will not arrest if the pressure is in excess of the quasi-static, steady-state propagation pressure. It is this critical pressure that is determined in this paper for each of the two examples.

ABSTRACT: Conditions for the onset of wrinkling in doubly-curved sheet metal undergoing forming are obtained from a plastic buckling analysis for short-wavelength, shallow modes. The region of the sheet susceptible to wrinkling is assumed to be unconstrained by the die. When the principal axes of the membrane stress state coincide with the principal axes of the curvatures, simple formulas for the stresses or strains at wrinkling are obtained.

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ABSTRACT: The property profile exhibited by cellular metals identifies several applications, especially in technologies requiring multifunctionality. Their specific property attributes suggest implementation as:
ultralight panels/shells, energy absorbing structures and heat dissipation media as well as for vibration control. Connections between the properties that govern these performance benefits and the cellular architecture, cell morphology and density have been made. Such structural relations facilitate choices of optimum cell characteristics for defined multifunctional applications.

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ABSTRACT: Cellular metals have ranges of thermomechanical properties that suggest their implementation in ultralight structures, as well as for impact/blast amelioration systems, for heat dissipation media and in acoustic isolation. The realization of these applications requires that the properties of cellular metals be understood in terms of their manufacturing constraints and that their thermostructural benefits over competing concepts be firmly established. This overview examines the mechanical and thermal properties of this material class, relative to other cellular and dense materials. It also provides design analyses for prototypical systems which specify implementation opportunities relative to competing concepts.

References listed at the end of the paper:
ABSTRACT: Buckling of cylindrical sandwich shells subject to axial compression is addressed for shells having foamed metal cores. Optimal face sheet thickness, core thickness and core density are obtained which minimize the weight of a geometrically perfect shell with a specified load carrying capacity. Constraints imposed by wrinkling and yielding of the face sheets and yielding of the core are all considered. The range of the structural load index is identified for which the sandwich shells have a competitive weight advantage over stringer stiffened shells. In most of this range, the minimum weight design has elastic buckling simultaneous with face sheet yielding. Imperfection sensitivity of the shells is assessed with special emphasis on the role of plasticity in degrading strength, especially in light of the coincidence of elastic buckling and face sheet yielding in the optimally designed perfect shell. The purpose is to examine the interaction between imperfections and plastic yielding to see if buckling load knockdowns should be larger than those expected for elastic shells.

References listed at the end of the paper:
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“The plastic collapse and energy absorption capacity of egg-box panels”, International Journal of Mechanical

ABSTRACT: The plastic collapse response of aluminium egg-box panels subjected to out-of-plane compression
has been measured and modelled. It is observed that the collapse strength and energy absorption are sensitive to
the level of in-plane constraint, with collapse dictated either by plastic buckling or by a travelling plastic
knuckle mechanism. Drop weight tests have been performed at speeds of up to 6 m s\(^{-1}\), and an elevation in
strength with impact velocity is noted. A 3D finite element shell model is needed in order to reproduce the
observed behaviours. Additional calculations using an axisymmetric finite element model give the correct
collapse modes but are less accurate than the more sophisticated 3D model. The finite element simulations
suggest that the observed velocity dependence of strength is primarily due to strain-rate sensitivity of the
aluminium sheet, with material inertia playing a negligible role. Finally, it is shown that the energy absorption
capacity of the egg-box material is comparable to that of metallic foams.

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ABSTRACT: Sandwich panels offer high stiffness at low weight. Their cores, commonly, are made of balsa-wood, foamed polymers, glue-bonded aluminum or Nomex (paper) honeycombs. These have the drawbacks that they cannot be used much above room temperature, and that their properties are moisture-dependent. The deficiencies can be overcome by using metal foams as cores. This chapter elaborates the potential of metal-foam-cored sandwich structures.

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ABSTRACT: The influence of prototypical imperfections on the nucleation and propagation stages of delamination of compressed thin films has been analyzed. Energy release rates for separations that develop from imperfections have been calculated. These demonstrate two characteristic quantities: a peak that governs nucleation and a minimum that controls propagation and failure. These quantities lead to two separate criteria that both need to be satisfied to cause failure. They involve a critical film thickness for nucleation and a critical imperfection wavelength for buckling. Implications for the avoidance of failure are discussed.


ABSTRACT: Delamination is considered for thin elastic films that are bonded to cylindrical substrates and subject to an equi-biaxial compressive pre-stress. Results for both positive and negative curvatures are obtained. The film buckles or deflects (depending on the sign of the curvature) away from the substrate inducing mixed mode stress intensities at the edge of the delamination. The energy release rate and combination of modal stress intensities at the delamination edges are determined. Steady-state propagation of delamination blisters is analyzed for both axial and circumferential propagation directions. The results depend strongly on the substrate curvature. Circumferential propagation is suppressed when the curvature is negative, but is favored when the curvature is positive. Axial propagation can occur for both positive and negative curvature substrates.
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ABSTRACT: Theoretical studies have indicated that truss core panels with a tetragonal topology support bending and compression loads at lower weight than competing concepts. The goal of this study is to validate this prediction by implementing an experimental protocol that probes the key mechanical characteristics while addressing node eccentricity and structural robustness. For this purpose, panels have been fabricated from a beryllium–copper alloy using a rapid prototyping approach and investment casting. Measurements were performed on these panels in flexure, shear and compression. Numerical simulations were conducted for these same configurations. The measurements reveal complete consistency with the stiffness and limit load predictions, as well as providing a vivid illustration of asymmetric structural responses that arises because the bending behavior of optimized panels is dependent on truss orientation.

References listed at the end of the paper:

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ABSTRACT: A class of planar, pin-jointed truss structures based on the ancient Kagome basket weave pattern with exceptional characteristics for actuation has been identified. Its in-plane stiffness is isotropic and has optimal weight among planar trusses for specified stiffness or strength. The version with welded joints resists
plastic yielding and buckling, while storing minimal energy upon truss bending during actuation. Two plate structures are considered which employ the planar Kagome truss as the actuation plane. It is shown that these plates can be actuated with minimal internal resistance to achieve a wide range of shapes, while also sustaining large loads through their isotropic bending/stretching stiffness, and their excellent resistance to yielding/buckling.

References listed at the end of the paper:


ABSTRACT: Kagome truss plates have properties that suggest they should be uniquely effective as an actuation plane for sandwich plates: a Kagome truss plate has in-plane isotropy, optimal stiffness and strength, and its truss members can be actuated with minimal internal resistance. In this paper, sandwich plates are studied that are comprised of one solid face sheet and one actuated Kagome face sheet joined by a pyramidal truss core. Various aspects of the actuation behavior of these plates are investigated, including internal resistance and strains resulting from actuation and efficiency of actuation. Single and double curvature actuation modes are investigated. Contact is made with analytic results for actuation modes with long wavelength.

References listed at the end of the paper:
ABSTRACT: The performance characteristics of a truss core sandwich panel design based on the 3D Kagomé has been measured and compared with earlier simulations. Panels have been fabricated by investment casting and tested in compression, shear and bending. The isotropic nature of this core design has been confirmed. The superior performance relative to truss designs based on the tetrahedron has been demonstrated and attributed to the greater resistance to plastic buckling at the equivalent core density.


ABSTRACT: The performance of metal sandwich plates under impulsive blast loads is compared to that of solid plates made of the same material and having the same weight. Three core geometries are considered: pyramidal truss, square honeycomb and folded plate. Plates of infinite length and clamped along their sides are subject to uniform impulsive load. The momentum impulse is applied to the face sheet towards the blast in the case of the sandwich plate, while it is distributed uniformly through the thickness of the solid plate. Large impulses are considered that are sufficient to produce lateral plate deflections more than 10% of the plate width. Fracture is not considered; the plates are assumed to have sufficient ductility to be able to sustain the deformations. A limited study of weight optimization is carried out for each of the core types with respect to the respective geometric parameters, including core and face sheet thickness, core member aspect ratios and relative density. A well-designed sandwich plate can sustain significantly larger blast impulses than a solid plate of the same weight. If the blast medium is water, fluid–structure interaction can reduce the momentum imparted to a sandwich plate by almost a factor of two relative to that imparted to a solid plate of the same weight, and, consequently, the relative benefit of the sandwich plate is significantly enhanced over its solid counterpart.

ABSTRACT: Explosive tests were performed in air to study the dynamic mechanical response of square honeycomb core sandwich panels made from a super-austenitic stainless steel alloy. Tests were conducted at three levels of impulse load on the sandwich panels and solid plates with the same areal density. Impulse was varied by changing the charge weight of the explosive at a constant standoff distance. At the lowest intensity load, significant front face bending and progressive cell wall buckling were observed at the center of the panel closest to the explosion source. Cell wall buckling and core densification increased as the impulse increased. An air blast simulation code was used to determine the blast loads at the front surfaces of the test panels, and these were used as inputs to finite element calculations of the dynamic response of the sandwich structure. Very good agreement was observed between the finite element model predictions of the sandwich panel front and back face displacements and the experimental observations. The model also captured many of the phenomenological details of the core deformation behavior. The honeycomb sandwich panels suffered significantly smaller back face deflections than solid plates of identical mass even though their design was far from optimal for such an application.


ABSTRACT: In foregoing study, a new phenomenon of the local dent of upper face sheet occurs in the simulation of dynamic response of sandwich plate subjected to blast loading. The reason and the effect of local dent on energy absorption are not ascertained. In this paper, two kind of square honeycomb plate with the cell wall thickness of 1mm and 0.5mm and with the same mass are modeled. And the dynamic response of both plates subjected to blast loading is simulated using LS-DYNA. For the thicker cell wall (1mm), the local dent is obvious while for the thinner cell wall (0.5mm), the local dent is not obvious and can be ignored. In addition, curves of the ratio of the maximum deflection of lower face sheet of sandwich plate to monolithic solid plate vs the mass of TNT charge as well as the ratio of internal energy are obtained. The results indicate that the local dent has the contribution to the energy absorption of sandwich plate especially in early time and the sandwich plate with the core of thinner cell wall has more effective capacity in blast-resistance than that with the core of thicker cell wall.


ABSTRACT: Structural members and components, such as shells and trusses of different geometries, form the intricate and deep seated parts in the manufacturing of missiles submarines, rockets, airplanes, automobiles etc and find applications in civil structures such as bridges. These members are comprised of components like conical frusta, cylindrical panels and shallow trusses. In many cases, the sole purpose of such shell structures is to absorb the energy generated due to impact which means, that these structures are subjected to heavy loads and can experience failure due to buckling. The objective of this work is to study the buckling and post buckling behavior of such members. The study is carried out using finite element analysis. The widely implemented softwares ANSYS APDL and ANSYS Workbench are used to perform the analysis. The components analyzed consist of shell structures such as conical frusta and cylindrical panels, and other structures like the shallow truss, diagonal truss and the shallow arch. These structures are analyzed for their buckling and post buckling behavior when subject to specific loading conditions and geometric, contact and material non-linearity. The
results compare favorably with known solutions.

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ABSTRACT: Cellular materials with hollow lattice truss topologies exhibit higher compressive strengths than equivalent structures with solid trusses owing to their greater resistance to plastic buckling. Consequently, hollow trusses have attracted interest as the cores for sandwich panels. Finite-element calculations are used to investigate the elastic–plastic compressive collapse of a metallic sandwich core made from vertical or inclined circular tubes, made from annealed AISI 304 stainless steel. First, the dependence of the axial compressive collapse mode upon tube geometry is determined for vertical tubes with built-in ends and is displayed in the form of a collapse mechanism map. Second, the approach is extended to inclined circular hollow tubes arranged as a pyramidal lattice core; the collapse modes are identified and the peak compressive strength is determined as a function of geometry. For a given relative density of hollow pyramidal core, the inclined tube geometry that maximizes peak strength is identified. The predicted collapse modes and loads for the pyramidal core are in excellent agreement with measurements for the limited set of experimentally investigated geometries.

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“Response of metallic pyramidal lattice core sandwich panels to high intensity impulsive loading in air”,

ABSTRACT: Small scale explosive loading of sandwich panels with low relative density pyramidal lattice cores has been used to study the large scale bending and fracture response of a model sandwich panel system in which the core has little stretch resistance. The panels were made from a ductile stainless steel and the practical consequence of reducing the sandwich panel face sheet thickness to induce a recently predicted beneficial fluid–structure interaction (FSI) effect was investigated. The panel responses are compared to those of monolithic solid plates of equivalent areal density. The impulse imparted to the panels was varied from 1.5 to 7.6 kPa s by changing the standoff distance between the center of a spherical explosive charge and the front face of the panels. A decoupled finite element model has been used to computationally investigate the dynamic response of the panels. It predicts panel deformations well and is used to identify the deformation time sequence and the face sheet and core failure mechanisms. The study shows that efforts to use thin face sheets to exploit FSI benefits are constrained by dynamic fracture of the front face and that this failure mode is in part a consequence of the high strength of the inertially stabilized trusses. Even though the pyramidal lattice core offers little in-plane stretch resistance, and the FSI effect is negligible during loading by air, the sandwich panels are found to suffer slightly smaller back face deflections and transmit smaller vertical component forces to the supports compared to equivalent monolithic plates.

References listed at the end of the paper:


ConWep blast simulation software, U.S. Army Corps of Engineers. Vicksburg, MS.


ABSTRACT: This paper presents the results of experimental and numerical work on the response of sandwich panels made of thin-walled tubes and mild steel plates to axial loading. The core of the sandwich panels consists of mild-steel square tubes, 20×20×0.9 mm in cross-section, in three different layouts comprising of four or five or nine tubes, (panels A, B and C respectively). Three tube configurations are investigated, as–received tubes, tubes with circular cut-out on opposite sides, and tubes with dents on opposite sides. The imperfections are located at the mid-section of the tube. The outer skin of the sandwich panel is 150×150×10 mm in cross-section and non-deformable. Quasi-static tests carried out on two and three tubes laid out in parallel between the skin indicate that the axial forces is a multiple of the axial force of a single tube, as expected. Consequently, the sandwich panel with the nine tubes deforms less than the sandwich panels with five and four tubes when subjected to similar impact energy. Triggers in the tubes improve the collapse mode of the sandwich panels. The Finite Element package ABAQUS/Explicit v6.7 is used to construct a ¼ symmetry model using shell elements to simulate the response of the sandwich panels to dynamic axial load. The Finite element simulations, validated using high speed photography footage, show good correlations with experiments.

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ABSTRACT: According to the classical Alexander solution for the axial collapse of bare metal tubes, a theoretical model is presented to predict the effect of thermal environment on the axial crushing load of a sandwich tubes with an arbitrarily fiber-reinforced layer between the two metal walls, based on a ring collapse mode. The mechanical property of metal walls is considered as a linear function of temperature change. A simple comparison, not considering thermal effect with the experiment previously obtained, is used to prove that the derived mean crushing load and length of the local folding mode are reasonable. The effects of wrapping direction of the reinforcing fibers in sandwich tubes and different thermal environments on the axial crushing load are investigated. The results show that the mean crushing load of a sandwich tubes gradually decreases as the temperature change increases, which must be considered in engineering designs.

John W. Hutchinson, “Comments on the Buckling Assessment of the Oyster Creek Drywell Shell with
Emphasis on the Determination of Capacity Reduction Factors”, pbadupws.nrc.gov, October 2009

ABSTRACT: The approach taken in assessing the integrity of the drywell shell against buckling is sound and in accord with the best practices. However, in reviewing the various studies, it appears to this reviewer that the approach set out in ASME Code Case 2286-1 accounting for transverse stress in the capacity reduction factors for spherical shells should be reviewed with eye to modification in the future. The emphasis of this report will focus on what we believe are possible shortcomings and inconsistencies of Code Case 2286-1. In spite of the concerns that will be spelled out about Code Case 2286-1, the capacity reduction factors generated by the alternative approach suggested here are in close agreement with those used in the assessment. Moreover, it will be argued that the alternative approach provides conservative results for the effect of transverse stress on the capacity reduction factor for the baseline case of large spherical shell segments. Thus, it is not our opinion that any possible shortcomings of Code Case 2286-1 should invalidate the conclusions of the buckling assessments.

This report begins with a brief introduction to the use of the capacity reduction factor to account for the effect of imperfections on buckling of thin spherical shells with emphasis on the stabilizing role of transverse stress. It then reviews several prescriptions for reduction factors for spherical shells highlighting what this reviewer believes are the shortcomings of Code Case 2286-1. Finally, capacity reduction factors from the two approaches as applied to the spherical portion of the drywell shell are presented adding confidence to the conclusions of the drywell assessments reported.

References listed at the end of the report:
J. C. Yao, Buckling of a truncated hemispherical under axial tension. AIAA J. 1, 2316 (1963).

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ABSTRACT: We present a basic analysis that establishes the metrics affecting the energy absorbed by multilayer cellular media during irreversible compaction on either a mass or volume basis. The behaviors at low and high impulse levels are distinguished through the energy dissipated in the shock. The overall mass of an energy absorbing system (comprising a cellular medium and a buffer) is minimized by maximizing the non-dimensional dissipation per unit mass parameter for the cellular medium, \( \lambda = \frac{U(m)\rho(s)}{\sigma(y)} \), where \( U(m) \) is the dissipation per unit mass of the cellular medium, ascertained from the area under the quasi-static compressive stress/strain curve, \( \sigma(y) \) is the yield strength of the constituent material and \( \rho(s) \) is the density of the material used in the medium. Plots of \( \lambda \) against the non-dimensional stress transmitted through the medium, \( \sigma(tr)/\sigma(y) \), demonstrate the relative energy absorbing characteristics of foams and prismatic media, such as honeycombs. Comparisons with these benchmark systems are used to demonstrate the superior performance of micro-lattices, especially those with hollow truss members. Numerical calculations demonstrate the relative densities and geometric configurations wherein the lattices offer benefit. Experimental
results obtained for a Ni micro-lattice with hollow members not only affirm the benefits, but also demonstrate energy absorption levels substantially exceeding those predicted by analysis. This assessment highlights the new opportunities that tailored micro-lattices provide for unprecedented levels of energy absorption for protection from impulsive loads.

References listed at the end of the paper:


ABSTRACT: Conical frusta made from leaded gun-metal have been compressed axially. Collapse is either by a travelling plastic hinge or by tearing. An analytical model is developed for the travelling plastic hinge in a rigid, ideally plastic solid; its predictions are compared with the observed response, and with those of an axisymmetric finite element analysis. The travelling hinge mechanism is also observed in the compressive collapse of an egg-box material comprising a square array of conical frusta. Collapse mechanism maps are constructed for the egg-box material, and they show the regimes of dominance of elastic buckling, material tearing and the travelling plastic hinge. The maps are useful for selecting egg-box geometries that maximise the energy absorption per unit mass at any prescribed value of collapse stress. The optimisation indicates that the egg-box material has a similar energy absorption capacity to that of hexagonal honeycombs and is superior to that of metal foams.

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ABSTRACT: Corrugated and diamond lattice materials have been manufactured as the cores of sandwich
panels by slotting together stainless steel sheets and then brazing together the assembly. The out-of-plane compressive, transverse shear and longitudinal shear responses of the corrugated cores have been measured at three relative densities 0.03 < \( \text{rhorb} < 0.10 \) and compared with analytical and finite element (FE) predictions. Finite element models are in good agreement with the experimental measurements while the analytical models over-predict the measured strength due to a neglect of manufacturing imperfections. The out-of-plane compressive and transverse shear responses of the diamond cores have also been measured at three relative densities 0.08 < \( \text{rhorb} < 0.25 \). The compressive strengths are sensitive to the aspect ratio of the specimens for \( L/H < 4 \) and again are below the analytical predictions due to imperfections. The longitudinal shear strength and energy absorption compare favorably with competing core topologies but the prismatic corrugated and diamond cores are weaker than the pyramidal and square-honeycomb under compression and transverse shear.


ABSTRACT: Cylindrical shells under uniaxial compression and spherical shells under equi-biaxial compression display the most extreme buckling sensitivity to imperfections. In engineering practice, the reduction of load carrying capacity due to imperfections is usually addressed by use of a knockdown factor to lower the critical buckling stress estimated or computed without accounting for imperfections. For thin elastic cylindrical shells under uniaxial compression and spherical shells under equi-biaxial compression, the knockdown factor is typically as small as 0.2. This paper explores the alleviation of imperfection-sensitivity for loadings with a reduced circumferential (transverse) membrane stress component. The analysis of Koiter (1963) on the effect of an axisymmetric imperfection on the elastic buckling of a cylindrical shell under uniaxial compression is extended to both cylinders and spheres for loadings that produce general combinations of biaxial membrane stresses. Increases in the knockdown factor due to a reduction of the transverse membrane component are remarkably similar for cylindrical and spherical shells.

References listed at the end of the paper:

12. J. C. Yao, Buckling of a truncated hemispherical under axial tension. AIAA J. 1, 2316-2319 (1963).
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ABSTRACT: Chromium (Cr) films are widely used as interlayers to promote the adhesion of copper or gold to substrates. However, the Cr interlayer usually fractures at lower strains than the ductile metal films. In this paper, the cracking and buckling behavior of Cr films on polyethylene terephthalate (PET) substrates were studied in situ under tensile loading with the Atomic Force Microscope (AFM) and optical microscope imaging. Cr films with three nominal thicknesses of 15, 70 and 140 nm were studied. The depth and width of the cracks, as well as the height and width of the buckles, were measured from AFM images acquired at incremental loading steps. The buckle shapes at different strain levels were carefully examined using AFM line profile. It was found that at large strain levels the measured buckle shapes usually deviated from the elastic buckling mode shapes. Further in situ AFM imaging of the buckles at a smaller scan area revealed that in some cases the buckles were cracked at the apex. These in situ nanoscale measurements provided experimental observations and data for further model development and more accurate measurement of the interfacial fracture energy at the Cr-PET interface.  

References listed at the end of the paper:  
ABSTRACT: We introduce a new methodology to produce aligned, or patterned, surface wrinkles on a soft elastomer sans topography. The surface buckles orient through the manipulation of the local stress distributions, which we control by defining specific regions of local differences in the elastic moduli of the material.

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ABSTRACT: We take a fresh look at diatoms, and find a reasonable visual match of some valve and girdle contours to various kinds of buckling phenomena, describable as corrugations, pleats and folds, and Bessel functions, such as describe the vibrations of a round musical drum. Buckling of raphes and costae, considered as buckling of columns, may account for some of their features. The matches we find will have to be tested by finite element method, computer simulation, time sequence microscopy, micromanipulation, and direct measurement of the physical (constitutive) properties of the materials from which a diatom constructs itself. The genome may set up boundary conditions that lead to mechanical instabilities and buckling, rather than controlling these diatom patterns in any direct way. This investigation also led us to propose that there is an electric potential in the silicalemma that may account for the generally straight course of growth of costae.
References listed at the end of the paper:


ABSTRACT: Thin stiff films on compliant elastic substrates subject to equi-biaxial compressive stress states are observed to buckle into various periodic mode patterns including checkerboard, hexagonal and herringbone. An experimental setting in which these modes are observed and evolve is described. The modes are characterized and ranked by the extent to which they reduce the elastic energy of the film–substrate system relative to that of the unbuckled state over a wide range of overstress. A new mode is identified and analyzed having nodal lines coincident with an equilateral triangular pattern. Two methods are employed to ascertain the energy in the buckled state: an analytical upper-bound method and a full numerical analysis. The upper-bound
is shown to be reasonably accurate to large levels of overstress. For flat films, except at small states of overstress where the checkerboard is preferred, the herringbone mode has the lowest energy, followed by the checkerboard, with the hexagonal, triangular, and one-dimensional modes lowering the energy the least. At low overstress, the hexagonal mode is observed in the experiments not the square mode. It is proposed that a slight initial curvature of the film may play a role in selecting the hexagonal pattern accompanied by a detailed analysis. An intriguing finding is that the hexagonal and triangular modes have the same energy in the buckled state and, moreover, a continuous transition between these modes exists involving a linear combination of the two modes with no change in energy. Experimental observations of various periodic modes are discussed with reference to the energy landscape. Discrepancies between observations and theory are highlighted and open issues are highlighted.

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Von Kármán, T., Tsien, H.S., 1941. The buckling of cylindrical shells under axial compression. J. Aerosci. 8, 303–312.

ABSTRACT: Wrinkles in thin films on soft substrates have been shown to self-organize into topological patterns, providing a possible route towards inexpensive generation of surface microstructure. However, the effect of the magnitude of applied stress in relation to the critical buckling stress, or overstress, on the observed patterns has until this point been neglected experimentally. In this paper, we investigate the effect of overstress using poly(dimethylsiloxane) which has been surface-oxidized with a UV-ozone oxidation technique. Using a swelling-based stress application technique, where the applied swelling stress in the thin film is controlled by changing the concentration of vapor-phase swelling agent (ethanol) in a sealed swelling chamber, we are able to impart swelling stresses below, at, and well above the critical stress. We observe a transition from hexagonally packed dimples at low overstress to ridge-based morphologies (herringbone and labyrinth) at high overstress. The observed dimple structures are remarkably widespread, and the hexagonal arrangement of these dimples is confirmed using Fourier analysis. Although analytical results predict that a square arrangement of dimples is preferred to hexagonal for flat wrinkling surfaces, hexagonal arrays are nonetheless unilaterally observed at low overstress. We attribute this observation to an inherent curvature that develops in the swelling film. The overstress is quantified by measuring the radius of curvature of swelling bilayer beams, both confirming the preferential swelling of the surface oxide layer by ethanol and quantifying the swelling extent. Effects of non-equi-biaxial stress are investigated by inducing a compressive prestress prior to swelling, and “trapped” non-equilibrium morphologies are discussed briefly.


ABSTRACT: The most common solutions for in-situ connections of steel tubular tower segments of onshore wind turbines are ring flange connections. These have certain drawbacks, such as e.g. costly production, long delivery time and rather low fatigue endurance. Friction connections with long open slotted holes have previously been proven to be a competitive alternative. In this work, the new type of connection is investigated in various scales: segment tests, down-scaled experiments and full-scale models. The influence of tower cross-section shape, execution tolerance (horizontal gap between the tower segments) and length of the connection on the bending resistance is thoroughly studied. In addition, buckling behaviour of the shell in the vicinity of the friction connection in towers with circular and polygonal cross-sections is analysed in order to check possible advantages of either cross-section. The influence of two types of the execution tolerances on the connection strength is investigated: inwards bent “fingers”, leading to inclined gaps, and a parallel gap created by different diameters of the tower segments. Based on validated finite element analyses recommendations for execution tolerances are proposed. A closer look is taken at the level of bolt forces under load application for the new friction connections as well as for the ring flange connection. For the former case, the influence of slotted holes on the joint resistance is checked. For both types of connections, comparison is drawn to hand calculation models used in engineering practice. Additionally, the distribution of meridional stresses in the shell in the vicinity of the connection is studied. Based on the findings from the above described investigations, recommendations for the design of friction connections with open slotted holes in steel tubular towers for onshore wind turbines are given.

References listed at the end of the dissertation:


ABSTRACT: An arch structure offers an effective load carrying system for large span structures. Environmental and economical considerations makes glulam a good material of choice for the arch members. However, asymmetric loading of an arch cause bending moment that implies use of deep and narrow arch cross-sections. Such slender section shape increases the risk of instability.

The purpose of this master’s thesis is to gain knowledge of instability phenomena of timber arches. Identification and evaluation of influencing variables by non-linear numerical analysis are compared to the rules for structural design used in EU: Eurocode.

Eurocode considers instability of straight beams and columns with respect to boundary conditions and cross-section properties, while initial imperfections are considered only implicitly. For instability of curved members no analytical approach is provided in the code, thus some numerical method is needed.

In structural design the load carrying capacity of arches is commonly evaluated by finite element (FE) method. Typically used today is linear instability FE analysis. However, this thesis also includes non-linear FE analysis which considers large deformations with redistribution of stresses and a material fail criterion.

Our findings conclude that the linear analysis overestimates the critical load due to instability typically by 20-40% for a parabolic arch. The analysis further indicates that the lateral arch support setup is a fundamental design aspect for the buckling behaviour for which both extrados and intrados lateral support is needed to obtain an effective structure.

The variations in timber material properties and the influence of moisture and long duration of loading are effectively regarded in Eurocode using reduction coefficients. Non-linear FE calculations with respect to influence of moisture and load duration indicated reasonably good agreement with Eurocode. Reduction of material strength due to moisture and load duration effects does not affect the critical load as much as the corresponding reduction of material stiffness. Moisture induced stiffness reduction can give 20% reduction of critical load.

The difficulty in Eurocode is to determine a feasible capacity reduction with respect to the risk of instability for an arch. The authors conclude that structural design of a parabolic arch should be conducted using critical loads from a non-linear FE analysis to be implemented in the Eurocode design calculations.

References listed at the end of the thesis:

ABSTRACT: Recognition of the positive features of elastic instabilities for use in smart and adaptive materials and structures has increased in recent years. Among many unstable events, buckling is one of the oldest and most well-understood types of response and yet this critical condition has been mainly regarded as a failure limit and the afterward response (postbuckling) as a safeguard. However, research on smart/adaptive devices has identified buckling and postbuckling as a favorable behavior. This dissertation explores the potential of cylindrical shells under axial compression, for which mode transitions during the postbuckling response lead to sudden and high-rate deformations from generally smaller changes in the controlling load or displacement input to the system. Such geometric nonlinear responses allow cylindrical shells to be considered as a viable structural prototype for purposes such as energy harvesting, sensing, actuation, etc.

Experimental and numerical studies evaluated three avenues for modifying and controlling the postbuckling response of cylindrical shells: (1) by introducing seeded geometric imperfections (SGI); (2) by introducing non-uniform stiffness distributions (NSD); and (3) by providing lateral constraints and interactions (LCI). An SGI cylinder is obtained by superposing a single mode shape from the eigenvalue analyses on a uniform cylinder to provide a governing role over other initial random imperfections. An NSD cylinder follows a similar concept of introducing artificial imperfections but by strategically placing patterned thickened regions (which alter the stiffness distribution) on the shell surface with the aim of triggering localized buckling events in non-thickened regions. Finally, an LCI cylinder is driven by the desire to gain further control of the postbuckling response through the interaction of multiple cylinders in nested assemblies. The numerical simulations were conducted through extensions on established methods for simulating nonlinear geometric response in slender structures. Prototyped cylinder were fabricated, first by using laminated composite materials and later through 3D printing and tested under cyclic loading. Further extension of these concepts was explored through a design optimization process.

Numerical and experimental results suggest that SGI and NSD cylinders can attain a controllable postbuckling response due to the governing role of artificial imperfections. For both cases, the localized buckling events can be triggered in predefined regions; and careful selection of the geometry and stiffness distribution can lead to elastic postbuckling responses with tailorable features, which implies diverse design opportunities. Further, simulations and test results demonstrated that the elastic postbuckling response of SGI and NSD shells was less sensitive to initial (manufacturing) imperfections as well as loading variations compared to that of uniform cylinders. Studies on LCI cylinders showed that this concept allows the attainment of a higher number of mode transitions in the elastic postbuckling regime and the post-buckling stiffening behavior increases to levels that surpass the initial buckling load. Optimization results showcased that postbuckling response can be tailored into three types (softening, sustaining and stiffening) and design guidelines were developed to achieve a targeted behavior.

The study has led to knowledge on the possibilities, extent and means to control (and thus design) the elastic far postbuckling response of cylindrical shells with the noted variations in geometry, stiffness and boundary conditions. Full characterization and understanding of these variables in the attainment and control of postbuckling response with desirable features can promote the use of the presented cylindrical shell concepts for a variety of purposes of emerging interest and across scales for various applications.

References listed at the end of the dissertation:
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[112] Z. Zhang and T. Li, "Graphene morphology regulated by nanowires patterned in parallel on a substrate surface," Journal of


ABSTRACT: The present thesis addresses some of the problems dealing with the static and dynamic analyses of functionally graded plates and shells subjected to aero-thermo-mechanical loads using field-consistent and high precision plate/shell finite elements. The formulation is based on the first-order shear deformation theory and developed with reference to both the neutral and the mid-surfaces. The material properties vary through the thickness according to a power-law distribution and the locally effective material properties are evaluated using the Voigt rule of mixture or the Mori-Tanaka homogenization method. The geometric nonlinearity is incorporated using von Karman's theory. The solutions are obtained using the Newton-Raphson iterative method/eigenvalue approach for the static problems and using the direct time integration procedure/eigenvalue formulation for the dynamic cases. The methodologies employed here are assessed, wherever possible, by studying the problems for which the solutions are available.

Firstly, as the position of neutral surface for FGM plates/shells varies depending on the material gradation, the effect of in-plane fixity and the approach of neutral/mid-surface based formulation are clearly brought out by investigating the bending behavior of FGM plates. Then, the post-buckling behavior of FGM plates and the appropriate solution procedures to obtain its characteristics depending on the boundary and loading conditions are discussed. The occurrence of secondary instability in the primary post-buckling path of FGM plate at higher load level is also established. Later, the nonlinear free and flutter vibration of FGM plates are examined under aero-thermal loads. The onset of change in equilibrium position, where a sudden drop occurs in the frequency value at higher amplitude of vibration, is also predicted. The flexural vibration of plates changing from limit cycle oscillation to chaotic motion with the increase in aerodynamic load is also examined using a time-response analysis. Here, the aerodynamic force is evaluated based on the third-order piston theory. Finally, the nonlinear axi-symmetric dynamic buckling of shallow spherical caps is analyzed using an axi-symmetric shell element with a semi-analytical approach. Different loading profiles in the form of step load or triangular pulse of various durations are considered. In addition to the above nonlinear studies, the linear asymmetric vibration and buckling of FGM circular plates are also investigated as a special case by deducing the formulation of spherical shells. In all these problems, the parametric studies are performed considering various geometric material parameters, and different types of loading and boundary conditions.
Derek Breid (University of Massachusetts, Amherst), “Controlling morphology in swelling-induced wrinkled surfaces”, Ph.D dissertation, Polymer Science and Engineering, University of Massachusetts – Amherst, February 2012

ABSTRACT: Wrinkles represent a pathway towards the spontaneous generation of ordered surface microstructure for applications in numerous fields. Examples of highly complex ordered wrinkle structures abound in Nature, but the ability to harness this potential for advanced material applications remains limited. This work focuses on understanding the relationship between the patterns on a wrinkled surface and the experimental conditions under which they form. Because wrinkles form in response to applied stresses, particular attention is given to the nature of the stresses in a wrinkling surface. The fundamental insight gained was then utilized to account for observed wrinkle formation phenomena within more complex geometric and kinetic settings. In order to carefully control and measure the applied stresses on a wrinkling film, a swelling-based system was developed using poly(dimethylsiloxane) (PDMS), surface-oxidized with a UV-ozone treatment. The swelling of the oxidized surface upon exposure to an ethanol vapor atmosphere was characterized using beam-bending experiments, allowing quantitative measurements of the applied stress. The wrinkle morphologies were characterized as a function of the overstress, defined as the ratio of the applied swelling stress to the critical buckling stress of the material. A transition in the dominant morphology of the wrinkled surfaces from dimple patterns to ridge patterns was observed at an overstress value of ~2. The pattern dependence of wrinkles on the ratio of the principal stresses was examined by fabricating samples with a gradient prestress. When swollen, these samples exhibited a smooth morphological transition from non-equibiaxial to equibiaxial patterns, with prestrains as low as 2.5% exhibiting non-equibiaxial characteristics. This transition was seen both in samples with low and high overstresses. To explore the impact of these stress states in more complex geometries, wrinkling hemispherical surfaces with radii of curvature ranging from 50-1000 mm were fabricated using the same material system. Upon wrinkling, the hemispheres formed complex hierarchical assemblies reminiscent of naturally occurring structures. The curvature of a surface exhibited a correlation with its critical buckling stress, independent of other factors. This enables the surface curvature to be used as an independent control over the dimple-to-ridge transition which occurs as a function of overstress. As in the flat buckling surfaces, this transition was shown to occur at an overstress value of ~2. Surface curvature was also shown to improve the observed hexagonal ordering of the dimple arrays, resulting in the formation of regular "golf ball" structures. Geometric effects in finite flat plates were also examined. Using circular masks during the oxidation process, plates with radii ranging from 0.4-8.6 mm were created. Upon wrinkling, a dimple-to-ridge transition was observed with increasing plate size, with the morphological switch occurring at a radius of ~2 mm. This observed transition was not found to be due to the inherent mechanics of plates of different sizes, but instead to a reduction in the oxide conversion due to shadowing or stagnation caused by the masking process, which lowered the applied overstress. The shape of the finite plate was found to have little impact on the resulting wrinkle morphologies. Kinetic aspects of wrinkling were qualitatively characterized by observing the wrinkling process over the course of swelling. Wrinkling was observed to frontally propagate across the surface, and the ordering of the patterns which developed showed a qualitative correlation with the degree of uniformity in the advancing wrinkle front. Swelling with different solvents was found to lead to the formation of different patterns, based on the swelling kinetics of the UVO-treated PDMS upon exposure to each solvent.

References listed at the end of the dissertation:

ABSTRACT: Three-dimensional topological insulators host linearly dispersing states with unique properties and a strong potential for applications. An important ingredient in realizing some of the more exotic states in topological insulators is the ability to manipulate local electronic properties. Direct analogy to the Dirac material graphene suggests that a possible avenue for controlling local properties is via a controlled structural deformation such as the formation of ripples. However, the influence of such ripples on topological insulators is yet to be explored. Here we use scanning tunnelling microscopy to determine the effects of one-dimensional buckling on the electronic properties of Bi$_2$Te$_3$. By tracking spatial variations of the interference patterns generated by the Dirac electrons we show that buckling imposes a periodic potential, which locally modulates the surface-state dispersion. This suggests that forming one- and two-dimensional ripples is a viable method for creating nanoscale potential landscapes that can be used to control the properties of Dirac electrons in topological insulators.

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ABSTRACT: Differential growth in elastic materials can produce stress either through incompatibility of growth or by interaction with the surrounding medium. In many situations, this stress can be sufficient to induce shape instability in the growing medium. To gain better insight in growth-induced instabilities, the growth of an elastic shell loaded with hydrostatic pressure or embedded in an elastic medium is studied. The residual stress arising from the incompatibility of growth and the contact stress arising from the interaction with the surrounding medium are computed with respect to growth and geometric parameters and critical values for instability are obtained. Depending on these parameters, different modes of instability can be obtained. References listed at the end of the paper:


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ABSTRACT: The buckling of hyperelastic incompressible cylindrical tubes of arbitrary length and thickness
under compressive axial load is considered within the framework of nonlinear elasticity. Analytical and
numerical methods for bifurcation are developed using the exact solution of Wilkes for the linearized problem
within the Stroh formalism. Using these methods, the range of validity of the Euler buckling formula and its
first nonlinear corrections are obtained for third-order elasticity. The values of the geometric parameters (tube
thickness and slenderness) where a transition between buckling and barrelling is observed are also identified.

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ABSTRACT: In many cylindrical structures in biology, residual stress fields are created through differential growth. In particular, if the outer and inner layers of a cylinder grow differentially, parts of the cylinder will be in a state of axial compression and other parts will be in tension. These tissue tensions change the overall material properties of the structure. Here, we study the role of tissue tension in the overall rigidity and stability of the cylinder. A detailed analysis, based on nonlinear elasticity, of the effect of tissue tension on the mechanical properties of growing cylinders reveal a subtle interplay between geometry, growth, and nonlinear elastic responses that help understand some of the remarkable properties of stems and other biological tissues.

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ABSTRACT: Incremental equilibrium equations and corresponding boundary conditions for an isotropic, hyperelastic and incompressible material are summarized and then specialized to a form suitable for the analysis of a spherical shell subject to an internal or an external pressure. A thick-walled spherical shell during inflation is analyzed using four different material models. Specifically, one and two terms in the Ogden energy formulation, the Gent model and an I1 formulation recently proposed by Lopez-Pamies. We investigate the existence of local pressure maxima and minima and the dependence of the corresponding stretches on the material model and on shell thickness. These results are then used to investigate axisymmetric bifurcations of the inflated shell. The analysis is extended to determine the behavior of a thick-walled spherical shell subject to an external pressure. We find that the results of the two terms Ogden formulation, the Gent and the Lopez-Pamies models are very similar, for the one term Ogden material we identify additional critical stretches, which have not been reported in the literature before.

References listed at the end of the paper:
J.P. Pascom and H.B. Coda (Department of Structural Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, São Paulo, Brazil), “A shell finite element formulation to analyze highly deformable rubber-like materials”, Latin American Journal of Solids and Structures, Vol. 10, No. 6, 2013

ABSTRACT: In this paper, a shell finite element formulation to analyze highly deformable shell structures composed of homogeneous rubber-like materials is presented. The element is a triangular shell of any order with seven nodal parameters. The shell kinematics is based on geometrically exact Lagrangian description and on the Reissner-Mindlin hypothesis. The finite element can represent thickness stretch and, due to the seventh nodal parameter, linear strain through the thickness direction, which avoids Poisson locking. Other types of locking are eliminated via high-order approximations and mesh refinement. To deal with high-order approximations, a numerical strategy is developed to automatically calculate the shape functions. In the present study, the positional version of the Finite Element Method (FEM) is employed. In this case, nodal positions and unconstrained vectors are the current kinematic variables, instead of displacements and rotations. To model near-incompressible materials under finite elastic strains, which is the case of rubber-like materials, three nonlinear and isotropic hyperelastic laws are adopted. In order to validate the proposed finite element formulation, some benchmark problems with materials under large deformations have been numerically analyzed, as the Cook’s membrane, the spherical shell and the pinched cylinder. The results show that the mesh refinement increases the accuracy of solutions, high-order Lagrangian interpolation functions mitigate general locking problems, and the seventh nodal parameter must be used in bending-dominated problems in order to avoid Poisson locking.

References listed at the end of the paper:
ABSTRACT: The nonlinear kinematics of thin shells is developed in full generality according to a duality approach in which kinematics plays the basic role in the definition of the model. The Kirchhoff–Love shell model is the central issue and is discussed in detail but shear deformable and polar models are also considered and critically reviewed. The analysis is developed with a coordinate-free approach which provides a direct geometrical picture of the shell model. The finite and tangent Green strains of the foliated continuum are explicitly expressed in terms of middle surface kinematics. The new expressions contributed here do not require the splitting of the velocity into parallel and normal components to the middle surface, and provide a computationally convenient context. Finite strain measures for the shell and their tangent and secant rates are analyzed and consistency and nonredundancy properties are discussed. The relations between the finite Green strain, its tangent and secant rates and the corresponding shell strains, are provided. The differential and boundary equilibrium equations of the shell are given in variational terms, both in unsplit and split form. A new expression of the boundary equilibrium equations is contributed and its mechanical soundness with respect to the classical one is emphasized. Equilibrium in a reference placement for the shell model is briefly discussed.

References listed at the end of the paper:


ABSTRACT: Based on first-principles calculations, we present various properties of single- and double-layered boron sheets, along with single- and double-walled boron nanotubes. Single-layered boron sheets, made of hexagons and triangles, have buckled ground-state geometries if the ratio of triangles to hexagons is large and stay flat otherwise. We demonstrate that this asymmetric behavior of buckling cannot be explained by a simple chemical picture based on $\sigma-\pi$ mixing. Instead, reduction in the electronic kinetic energy is the driving force for buckling. In addition, we show that double-layered boron sheets can form strong interlayer bonds between two layers only if the precursor single-layered sheet itself prefers a buckled ground-state structure. The optimal double-layered boron sheet in our library is semiconducting and is more stable than any single-layered sheet. Next, we discuss the curvature energies, buckling behavior and soliton structural fluctuations for single-walled boron nanotubes and the implications for the electronic properties of these nanotubes: our main finding is that the semiconducting nature of small-diameter single-walled nanotubes is robust under various perturbations and fluctuations. We end by showing that due to strong bonds forming between walls, the optimal double-walled boron nanotubes have different wall structures from single-walled ones. Such double-walled nanotubes are always more stable than any single-walled nanotube and are furthermore metallic for the likely experimentally relevant diameter range. We conclude with the implications of these results for fabricated nanotube systems.

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“Hyperelastic axial buckling of single wall carbon nanotubes”, Physica E, Bol. 44, pp 525-529, 2011
DOI: 10.1016/j.physe.2011.10.006

ABSTRACT: This paper proposes a hyperelastic finite element-based lattice approach for the description of buckling behaviour in single wall carbon nanotubes (SWCNTs). A one-term incompressible Ogden-type hyperelastic model is adopted to describe the equivalent mechanical response of C–C bonds in SWCNTs under axial compression. The material constants of the model are chosen by matching the linearised response with the elastic constants adopted in the AMBER force field and by establishing equivalence between the Ogden strain energy and the variation of the interatomic strain energy obtained from molecular mechanics simulations. Numerical experiments are carried out and the results are compared to atomistic simulations, demonstrating the predictive capabilities of the present model in capturing initial buckling strain, deformation mechanisms and
post-buckling behaviour under very large compressive deformations.

References listed at the end of the paper:


ABSTRACT: A new structural mechanics model is developed to closely duplicate the atomic configuration and behaviours of single-walled carbon nanotubes (SWCNTs). The SWCNTs are effectively represented by a space frame, where primary and secondary beams are used to bridge the nearest and next-nearest carbon atoms, to mimic energies associated with bond stretching and angle variation, respectively. The elastic properties of the frame components are generalized from molecular dynamics (MD) simulation based on an accurate ab initio force field, and numerical analyses of tension, bending, and torsion are carried out on nine different SWCNTs. The space-frame model also closely duplicates the buckling behaviours of SWCNTs in torsion and bending. In addition, by repeating the same process with continuum shell and beam models, new elastic and section
parameters are fitted from the MD benchmark experiments. As an application, all three models are employed to study the thermal vibration behaviours of SWCNTs, and excellent agreements with MD analyses are found. The present analysis is a systematic structural mechanics attempt to fit SWCNT properties for several basic deformation modes and applicable to a variety of SWCNTs. The continuum models and fitted parameters may be used to effectively simulate the overall deformation behaviours of SWCNTs at much larger length- and timescales than pure MD analysis.


ABSTRACT: A nonlocal continuum mechanics model is developed and applied to study the vibration of both single-walled nanotubes (SWNTs) and double-walled nanotubes (DWNTs) via elastic beam theories. The small-scale effects on vibration characteristics of carbon nanotubes are explicitly derived through a complete mechanics analysis. A qualitative validation study shows that the results based on nonlocal continuum mechanics are in agreement with the published experimental reports in this field. Numerical simulations are conducted to quantitatively show the small-scale effect on vibrations of both SWNTs and DWNTs with different lengths and diameters.

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ABSTRACT: Capsules of micron and sub-micron dimensions are abundant in nature in the form of bacterial or viral capsids and play an increasing role in modern technology for encapsulation and release of agents. The capsules’ mechanical properties are of great importance in this context not only for stability but as well for transport properties in flow, rheology or adhesion. Thus, techniques that allow for single-capsule mechanical characterization have caught much attention recently and we summarize experimental developments in this field as well as theoretical background of capsule deformation with special attention to small deformation measurements. Deformation studies on polyelectrolyte multilayer capsules are introduced as a case study, since they can be tailored in their geometry and composition and are thus well-suited as a model system.

References listed at the end of the paper:
Heireche H., Tounsi A., Benzair A. (Université de Sidi Bel Abbés, BP 89 Cité Ben M’hidi, 22000 Sidi Bel Abbés, Algeria), “Scale effect on wave propagation of double-walled carbon nanotubes with initial axial loading”, Nanotechnology 19, 185703 (2008), https://doi.org/10.1088/0957-4484/19/18/185703

ABSTRACT: This paper studies the vibrational characteristics of double-walled carbon nanotubes (DWNTs) with initial stress using a nonlocal Euler–Bernoulli beam model. Both the effect of initial stress and the effect of small length scale are discussed in detail. The effect of van der Waals forces is incorporated in the formulation. The corresponding resonant vibrational characteristics are presented in detail; they are shown to be very different from those predicted by classical elasticity theory when nonlocal effects are significant. The influence of initial stress in carbon nanotubes on their flexural vibration modes is dependent on the tension or compression form of the initial stress. The investigation of the effects of initial stress on transverse wave propagation in carbon nanotubes may be used as a useful reference for the application and the design of nanoelectronic and nanodrive devices, nano-oscillators, and nanosensors, in which carbon nanotubes act as basic elements.


ABSTRACT: In this paper, we propose a lattice dynamic treatment for the total potential energy of single-walled carbon nanotubes (SWCNTs) which is, apart from a parameter for the nonlinear effects, extracted from the vibrational energy of the planar graphene sheet. The energetics, elasticity and lattice dynamics are treated in terms of the same set of force constants, independently of the tube structures. Based upon this proposal, we have investigated systematically the relaxed lattice configuration for narrow SWCNTs, the strain energy, the Young's modulus and Poisson ratio, and the lattice vibrational properties with respect to the relaxed equilibrium tubule structure. Our calculated results for various physical quantities are nicely in consistency with existing experimental measurements. In particular, we verified that the relaxation effect makes the bond length longer and the frequencies of various optical vibrational modes softer. Our calculation provides evidence that the Young's modulus of an armchair tube exceeds that of the planar graphene sheet, and that the large diameter limits of the Young's modulus and Poisson ratio are in agreement with the experimental values of graphite; the calculated radial breathing modes for ultra-narrow tubes with diameters ranging between 2 and 5 Å coincide with the experimental results and the existing ab initio calculations with satisfaction. For narrow tubes with a diameter of 20 Å, the calculated frequencies of optical modes in the tubule's tangential plane, as well as those of radial breathing modes, are also in good agreement with the experimental measurements. In addition, our calculation shows that various physical quantities of relaxed SWCNTs can actually be expanded in terms of the chiral angle defined for the corresponding ideal SWCNTs.

C.Y. Wang and L.C. Zhang (The School of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney, Sydney 2006, Australia), “A critical assessment of the elastic properties and effective wall thickness of
ABSTRACT: This paper discusses the fundamental issues of the elastic properties and effective wall thickness of single-walled carbon nanotubes (SWCNTs). It provides an in-depth analysis based on the rationale of the nanoscale-to-macroascale deformation relationship of SWCNTs and carries out a critical assessment of the diverse theoretical predictions in the literature. It was found that the in-plane stiffness of SWCNTs is a mechanics quantity that has been consistently reflected by the majority of the existing models. However, a further systematic study is necessary to clarify the dilemma of the wall thickness of SWCNTs.

ABSTRACT: This paper proposes a two-dimensional elastic shell model to characterize the deformation of single-walled carbon nanotubes using the in-plane rigidity, Poisson ratio, bending rigidity and off-plane torsion rigidity as independent elastic constants. It was found that the off-plane torsion rigidity of a single-walled carbon nanotube is not zero due to the off-plane change in the π-orbital electron density on both sides of the nanotube. It was concluded that a three-dimensional elastic shell model of single-walled carbon nanotubes can be established with well-defined effective thickness.

ABSTRACT: This paper is concerned with the use of the nonlocal Timoshenko beam model for free vibration analysis of single-walled carbon nanotubes (CNTs) including the thermal effect. Unlike the Euler beam model, the Timoshenko beam model allows for the effects of transverse shear deformation and rotary inertia. These effects become significant for CNTs with small length-to-diameter ratios that are normally encountered in applications such as nanoprobes. The elastic Timoshenko beam model is reformulated using the nonlocal differential constitutive relations of Eringen (1972 Int. J. Eng. Sci. 10 1–16). The study focuses on the wave dispersion caused not only by the rotary inertia and the shear deformation in the traditional Timoshenko beam model but also by the nonlocal elasticity characterizing the microstructure of CNTs in a wide frequency range up to terahertz. Numerical results are presented using the nonlocal beam theory to bring out the effect of both the nonlocal parameter and the temperature change on the properties of transverse vibrations of CNTs. The exact nonlocal Timoshenko beam solution presented here should be useful to engineers who are designing microelectromechanical and nanoelectromechanical devices.

ABSTRACT: A second-order strain gradient nonlocal shell model is established to study the mode
transformation in single-walled carbon nanotubes (SWCNTs). Nonlocal length is calibrated carefully for SWCNTs in reference to molecular dynamics (MD) simulations through analysis of nonlocal length effects on the frequencies of the radial breathing mode (RBM) and circumferential flexural modes (CFMs) and its effects on mode transformation. All analyses show that only a negative second-order nonlocal shell model is appropriate to SWCNTs. Nonlocal length is evidently related to vibration modes and the radius-to-thickness ratio. It is found that a nonlocal length is approximately 0.1 nm in an average sense when RBM frequency is concerned. A nonlocal length of 0.122–0.259 nm is indicated for the mode transformation in a selected group of armchair SWCNTs. 2:1 and 1:1 internal resonances are found for the same SWCNT based on different models, which implies that the internal resonance mechanism depends on the model employed. Furthermore, it is shown that an effective thickness of approximately 0.1 nm is more appropriate to SWCNTs than 0.066 nm.


ABSTRACT: The unique features of axial, torsional, transverse and radial breathing vibrations are captured for armchair and zigzag singlewalled boron nitride nanotubes (BNNTs) based on molecular mechanics simulations and continuum mechanics theories. Equivalent Young's modulus 1 TPa and shear modulus 0.4 TPa are obtained independent of the chirality of BNNTs. In particular, a distorted optimized structure is observed for the first time for BNNTs with sufficiently large diameter and length. It is found that the deformed structures result in behaviours of BNNTs deviating from those of classical columns/beams. Such symmetry-breaking could also exert significant impacts on the structural instability (buckling) and electronic properties of BNNTs that are sensitive to the structural symmetry.

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ABSTRACT: This paper presents a hyperelastic finite element-based lattice approach for the description of post-buckling response in single wall carbon nanotubes (SWCNTs). A one-term incompressible Ogden-type hyperelastic model is adopted to describe the mechanical response of SWCNTS under axial compression. Numerical experiments are carried out and the results are compared to atomistic simulations, demonstrating the predictive capabilities of the present model in capturing post-buckling behaviour and the main deformation mechanisms under large compressive deformations.

References listed at the end of the paper:
metals. Polymers were the first material to be exploited as matrix materials and the improvement of the available techniques to produce high performance matrix materials, have fostered the way to enhance composite materials and their properties, either mechanical, thermal, electrical or magnetic. CNTs reinforcements have been introduced into polymers, ceramics, cement-based materials and metals. Polymers were the first material to be exploited as matrix material being reinforced by CNTs. Up to

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ABSTRACT: The unceasing upgrading of techniques and processes to fabricate high purity carbon nanotubes (CNTs) and the improvement of the available techniques to produce high performance matrix materials, have fostered the way to enhance composite materials and their properties, either mechanical, thermal, electrical or magnetic. CNTs reinforcements have been introduced into polymers, ceramics, cement-based materials and metals. Polymers were the first material to be exploited as matrix material being reinforced by CNTs. Up to
now other materials have tentatively been investigated for that purpose, including metals. Today, many applications of CNT reinforced composites exist but CNT reinforced metals are still scarce and only found in very specific applications. Several reasons can be identified but the still growing demand for lighter and stronger metals paved the way to more fundamental research on the topic of CNT reinforced metal matrix composites (MMCs). This review describes the state-of-the art in this field and highlights the excellent and promising mechanical, thermal, electrical properties of CNT reinforced MMCs.

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ABSTRACT: This paper is concerned with numerical simulations of three-dimensional finite deformation of a thick-walled circular elastic tube subject to internal or external pressure and zero displacement on its ends. We formulate the system of equations that can accommodate large strain and displacement for the incompressible isotropic neo-Hookean material. The fully non-linear governing equations are solved using the Cþþ based object-oriented finite element library libMesh. A Lagrangian mesh is used to discretize the governing equations, and a weighted residual Galerkin method and Newton iteration solver are used in the numerical scheme. To overcome the sensitivity of the fully non-linear system to small changes in the iterations, the analytical form of the Jacobian matrix is derived, which ensures a fast and better numerical convergence than using a numerically approximated Jacobian matrix. Results are presented for different parameters in terms of wall thickness/radius ratio, and length/ radius ratio, as well as internal/external pressure. Validation of the model is achieved by the excellent agreement with the results obtained using the commercial package Abaqus. Comparison is also made with the previous work on axisymmetric version of the same system (Zhu et al., 2008 [34]; Zhu et al. 2010 [43]), and interesting fully three-dimensional post-buckling deformations are highlighted. The success of the current approach paves the way for fluid–structure interaction studies with potential application to collapsible tube flows and modeling of complex physiological systems.

References listed at the end of the paper:

ABSTRACT: Venous tortuosity is associated with multiple disease states and is often thought to be a consequence of venous hypertension and chronic venous disease. However, the underlying mechanisms of vein tortuosity are unclear. We hypothesized that increased pressure causes vein buckling that leads to a tortuous appearance. The specific aim of this study was to determine the critical buckling pressure of veins. We determined the buckling pressure of porcine jugular veins and measured the mechanical properties of these veins. Our results showed that the veins buckle when the transmural pressure exceeds a critical pressure that is strongly related to the axial stretch ratio in the veins. The critical pressures of the eight veins tested were 14.2 ± 5.4 and 26.4 ± 9.0 mmHg at axial stretch ratio 1.5 and 1.7, respectively. In conclusion, veins buckle into a tortuous shape at high lumen pressures or reduced axial stretch ratios. Our results are useful in understanding the development of venous tortuosity associated with varicose veins, venous valvular insufficiency, diabetic retinopathy, and vein grafts.

References listed at the end of the paper:

ABSTRACT: The stability of blood vessels under lumen blood pressure is essential to the maintenance of normal vascular function. Differential buckling equations have been established recently for linear and nonlinear elastic artery models. However, the strain energy in bent buckling and the corresponding energy method have not been investigated for blood vessels under lumen pressure. The purpose of this study was to establish the energy equation for blood vessel buckling under internal pressure. A buckling equation was established to determine the critical pressure based on the potential energy. The critical pressures of blood vessels with small tapering along their axis were estimated using the energy approach. It was demonstrated that the energy approach yields both the same differential equation and critical pressure for cylindrical blood vessels as obtained previously using the adjacent equilibrium approach. Tapering reduced the critical pressure of blood vessels compared to the cylindrical ones. This energy approach provides a useful tool for studying blood vessel buckling and will be useful in dealing with various imperfections of the vessel wall.

References listed at the end of the paper:
vascular diseases, but the mechanisms are poorly understood. Our recent theoretical analysis suggested that

ABSTRACT: Tortuous arteries are often associated with aging, hypertension, atherosclerosis, and degenerative vascular diseases, but the mechanisms are poorly understood. Our recent theoretical analysis suggested that
mechanical instability (buckling) may lead to tortuous blood vessels. The objectives of this study were to determine the critical pressure of artery buckling and the effects of elastin degradation and surrounding matrix support on the mechanical stability of arteries. The mechanical properties and critical buckling pressures, at which arteries become unstable and deform into tortuous shapes, were determined for a group of five normal arteries using pressurized inflation and buckling tests. Another group of nine porcine arteries were treated with elastase (8 U/ml), and the mechanical stiffness and critical pressure were obtained before and after treatment. The effect of surrounding tissue support was simulated using a gelatin gel. The critical pressures of the five normal arteries were 9.52 kPa (SD 1.53) and 17.10 kPa (SD 5.11) at axial stretch ratios of 1.3 and 1.5, respectively, while model predicted critical pressures were 10.11 kPa (SD 3.12) and 17.86 kPa (SD 5.21), respectively. Elastase treatment significantly reduced the critical buckling pressure ($P < 0.01$). Arteries with surrounding matrix support buckled into multiple waves at a higher critical pressure. We concluded that artery buckling under luminal pressure can be predicted by a buckling equation. Elastin degradation weakens the arterial wall and reduces the critical pressure, which thus leads to tortuous vessels. These results shed light on the mechanisms of the development of tortuous vessels due to elastin deficiency.

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ABSTRACT: Arteries are under significant mechanical loads from blood pressure, flow, tissue tethering, and body movement. It is critical that arteries remain patent and stable under these loads. This review summarizes the common forms of buckling that occur in blood vessels including cross-sectional collapse, longitudinal twist buckling, and bent buckling. The phenomena, model analyses, experimental measurements, effects on blood flow, and clinical relevance are discussed. It is concluded that mechanical buckling is an important issue for vasculature, in addition to wall stiffness and strength, and requires further studies to address the challenges. Studies of vessel buckling not only enrich vascular biomechanics but also have important clinical applications. References listed at the end of the paper:
nonlinear anisotropic structural model.


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“Study on tracheal collapsibility, compliance, and stress by considering nonlinear mechanical property of cartilage”, Annals of Biomedical Engineering, Vol. 37, No. 11, pp 2380-2389, November 2009
DOI: 10.1007/s10439-009-9765-3

ABSTRACT: Tracheal cartilage has been widely regarded as a linear elastic material either in experimental studies or in analytic and numerical models. However, it has been recently demonstrated that, like other fiber-oriented biological tissues, tracheal cartilage is a nonlinear material, which displays higher strength in compression than in extension. Considering the nonlinearity requires a more complex theoretical framework and costs more to simulate. This study aims to quantify the deviation due to the simplified treatment of the tracheal cartilage as a linear material. It also evaluates the improved accuracy gained by considering the nonlinearity. Pig tracheal rings were used to examine the mechanical properties of cartilage and muscular membrane. By taking into account the asymmetric shape of tracheal cartilage, the collapse behavior of complete rings was simulated, and the compliance of airway and stress in the muscular membrane were discussed. The results obtained were compared with those assuming linear mechanical properties. The following results were found: (1) Models based on both types of material properties give a small difference in representing collapse behavior; (2) Regarding compliance, the relative difference is big, ranging from 10 to 40% under negative
pressure conditions; and (3) the difference in determining stress in the muscular membrane is small too: <5%. In conclusion, treating tracheal cartilage as a linear material will not cause big deviations in representing the collapse behavior, and mechanical stress in the muscular part, but it will induce a big deviation in predicting the compliance, particularly when the transmural pressure is lower than −0.5 kPa. The results obtained in this study may be useful in both understanding the collapse behavior of trachea and in evaluating the error induced by the simplification of treating the tracheal cartilage as a linear elastic material.

References listed at the end of the paper:


DOI: 10.1038/srep03630

ABSTRACT: A novel large self-expanding endovascular stent was designed with strut thickness of 70 μm × 70 μm width. The method was developed and investigated to identify a novel simpler technique in aortic aneurysm therapy. Stage 1 analysis was performed after deploying it in a virtual aneurysm model of 6 cm wide × 6 cm long fusiform hyper-elastic anisotropic design. At cell width of 9 mm, there was no buckling or migration of the stent at 180 Hg. Radial force of the stents was estimated after parametric variations. In stage 2 analysis, a prototype 300 μm × 150 μm stent with a cell width of 9 mm was chosen, and it was evaluated similarly after embedding in the aortic wall, and also with a tissue overgrowth of 1 mm over the stent. The 300/150 μm stent reduced the peak wall stress by 70% in the aneurysm and 50% reduction in compliance after embedding. Stage 3 analysis was performed to study the efficacy of stents with struts (thickness/width) 70/70, 180/100 and 300/150 μm after embedding and tissue overgrowth. The adjacent wall stresses were very minimal in stents with 180/100 and 70/70 μm struts after embedding. There is potential for a novel stent method in aortic aneurysm therapy.

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ABSTRACT: (none given)
ABSTRACT: Euler’s celebrated buckling formula gives the critical load $N$ for the buckling of a slender cylindrical column with radius $B$ and length $L$ as

$$N/(\pi^3 B^{-2}) = (E/4)(B/L)^2,$$

where $E$ is Young’s modulus. Its derivation relies on the assumptions that linear elasticity applies to this problem, and that the slenderness $(B/L)$ is an infinitesimal quantity. Here we ask the following question: What is the first nonlinear correction in the right hand-side of this equation when terms up to $(B/L)^4$ are kept? To answer this question, we specialize the exact solution of incremental nonlinear elasticity for the homogeneous compression of a thick compressible cylinder with lubricated ends to the theory of third-order elasticity. In particular, we highlight the way second- and third-order constants —including Poisson’s ratio— all appear in the coefficient of $(B/L)^4$.

References listed at the end of the paper:


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ABSTRACT: Gels are used to design bilayered structures with high residual stresses. The swelling of a thin layer on a compliant substrate leads to compressive stresses. The postbuckling of this layer is investigated experimentally; the wavelengths and amplitudes of the resulting modes are measured. A simplified model with a self-avoiding rod on a Winkler foundation is in semiquantitative agreement with experiments and reproduces the observed cusplike folds.

References listed at the end of the paper:

ABSTRACT: We study the buckling of thin elastic plates caused by residual strains concentrated near a free edge. This is a model for plant leaves and torn plastic sheets morphologies. We derive new governing equations explaining self-similar patterns reported earlier in experiments. We reveal the cascade mechanism, determine the bounds for its wavelengths and predict a similarity factor of 3 in agreement with experiments. This is confirmed by numerical solutions with up to five generations of wrinkles.

References listed at the end of the paper:

ABSTRACT: The patterns arising from the differential swelling of gels are investigated experimentally and theoretically as a model for the differential growth of living tissues. Two geometries are considered: a thin strip of soft gel clamped to a stiff gel, and a thin corona of soft gel clamped to a disk of stiff gel. When the structure is immersed in water, the soft gel swells and bends out of plane leading to a wavy periodic pattern whose wavelength is measured. The linear stability of the flat state is studied in the framework of linear elasticity using the equations for thin plates. The flat state is shown to become unstable to oscillations above a critical swelling rate and the computed wavelengths are in quantitative agreement with the experiment.

References listed at the end of the paper:

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ABSTRACT: The buckling of a thin elastic film bound to a compliant substrate is studied: we analyze the different patterns that arise as a function of the biaxial residual compressive stress in the film. We first clarify the boundary conditions to be used at the interface between film and substrate. We carry out the linear stability analysis of the classical pattern made of straight stripes, and point out secondary instabilities leading to the formation of undulating stripes, varicose, checkerboard or hexagonal patterns. Straight stripes are found to be stable in a narrow window of load parameters only. We present a weakly nonlinear post-buckling analysis of these patterns: for equi-biaxial residual compression, straight wrinkles are never stable and square checkerboard patterns are found to be optimal just above threshold; for anisotropic residual compression, straight wrinkles are present above a primary threshold and soon become unstable with respect to undulating stripes. These results account for many of the previously published experimental or numerical results on this geometry.

References listed at the end of the paper:
ABSTRACT: We study the buckling of a thin compressed elastic film bonded to a compliant substrate. We focus on a family of buckling patterns, such that the film profile is generated by two functions of a single variable. This family includes the unbuckled configuration, the classical primary mode made of straight stripes, as well the pattern with undulating stripes obtained by a secondary instability investigated in the first companion paper, and the herringbone pattern studied in last companion paper. A simplified buckling model relevant for the analysis of these patterns is introduced. It is solved analytically for moderate or for large residual compressive stress in the film. Numerical simulations are presented, based on an efficient implementation. Overall, the analysis provides a global picture for the formation of herringbone patterns under increasing residual stress. The film shape is shown to converge at large load to a developable shape with ridges. The wavelength of the pattern, selected in a first place by the primary buckling bifurcation, is frozen during the subsequent increase of loading.

ABSTRACT: We study the buckling of a compressed thin elastic film bonded to a compliant substrate. An
asymptotic solution of the equations for a plate on an elastic foundation is obtained in the limit of large residual stress in the film. In this limit, the film's shape is given by a popular origami folding, the Miura-ori, and is composed of parallelograms connected by dihedral folds. This asymptotic solution corresponds to the herringbone patterns reported previously in experiments: the crests and valleys of the pattern define a set of parallel, sawtooth-like curves. The kink angle obtained when observing these crests and valleys from above are shown to be right angles under equi-biaxial loading, in agreement with the experiments. The absolute minimum of energy corresponds to a pattern with very slender parallelograms; in the experiments, the wavelength is instead selected by the history of applied load.

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ABSTRACT: We consider the deformation of a thin elastic film bonded to a thick compliant substrate, when the (compressive) misfit is far beyond critical. We take a variational viewpoint – focusing on the total elastic energy, i.e. the membrane and bending energy of the film plus the elastic energy of the substrate – viewing the buckling of the film as a problem of energy-driven pattern formation. We identify the scaling law of the minimum energy with respect to the physical parameters of the problem, and we prove that a herringbone pattern achieves the optimal scaling. These results complement previous numerical studies, which have shown that an optimized herringbone pattern has lower energy than a number of other patterns. Our results are different because (i) we make the scaling law achieved by the herringbone pattern explicit, and (ii) we give an elementary, ansatz-free proof that no pattern can achieve a better law.

References listed at the end of the paper:
ABSTRACT: The wrinkling and delamination of stiff thin films adhered to a polymer substrate have important applications in “flexible electronics.” The resulting periodic structures, when used for circuitry, have remarkable mechanical properties because stretching or twisting of the substrate is mostly accommodated through bending of the film, which minimizes fatigue or fracture. To date, applications in this context have used substrate patterning to create an anisotropic substrate-film adhesion energy, thereby producing a controlled...
array of delamination “blisters.” However, even in the absence of such patterning, blisters appear spontaneously, with a characteristic size. Here, we perform well-controlled experiments at macroscopic scales to study what sets the dimensions of these blisters in terms of the material properties and explain our results by using a combination of scaling and analytical methods. Besides pointing to a method for determining the interfacial toughness, our analysis suggests a number of design guidelines for the thin films used in flexible electronic applications. Crucially, we show that, to avoid the possibility that delamination may cause fatigue damage, the thin film thickness must be greater than a critical value, which we determine.

References listed at the end of the paper:


ABSTRACT: Many ship accidents and casualties are caused by large freak ocean waves. Traditionally, the strength of ships against freak waves is assessed by means of ultimate strength evaluation, assuming quasi-static conditions, but the nonlinear dynamic structural response of ships to freak waves should be considered as well. This paper describes how the strength of a ship can be evaluated in terms of its nonlinear vertical bending moment (VBM). Linear dynamic VBM of a ship, which is derived from hydrodynamics, is calculated using a time-domain strip theory code under freak wave conditions, and the nonlinear dynamic VBM, which is dependent on structural nonlinearity, is calculated using a combination of quasi-static and dynamic nonlinear analyses based on the finite element method (FEM). The nonlinear and linear VBMs are then compared to assess how they differ. Then, the influence of freak wave height and wave speed on the VBMs and deformation is studied.

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ABSTRACT: The topology of the telephone cord buckling of compressed diamond-like carbon films (DLC) on glass substrates has been characterized with atomic force microscopy (AFM) and with the focused ion beam (FIB) imaging system. The profiles of the several buckles have been measured by AFM to establish the symmetry of each repeat unit, revealing similarity with a circular buckle pinned at its center. By making parallel cuts through the buckle in small, defined locations, straight-sided buckles have been created on the identical films, enabling the residual stress in the film to be determined from the profile. It has been shown that the telephone cord topology can be effectively modeled as a series of pinned circular buckles along its length, with an unpinned circular buckle at its front. The unit segment comprises a section of a full circular buckle, pinned to the substrate at its center. The model is validated by comparing radial profiles measured for the telephone cord with those calculated for the pinned buckle, upon using the residual stress in the film, determined as above. Once validated, the model has been used to determine the energy release rate and mode mixity, G(psi). The results for G(psi) indicate that the telephone cord configuration is preferred when the residual stress in the DLC is large, consistent with observations that straight-sided buckles are rarely observed, and, when they occur, are generally narrower than telephone cords. Telephone cords are observed in many systems, and can be regarded as the generic morphology. Nevertheless, they exist subject to a limited set of conditions, residing within the margin between complete adherence and complete delamination, provided that the interface has a mode II
toughness low enough to ensure that the buckle crack does not kink into the substrate.

INTRODUCTION: Residually compressed thin films on thick substrates may buckle. The buckles propagate beneath the film if the induced energy release rate exceeds the interface fracture toughness. The associated mechanics has been documented (Evans and Hutchinson, 1984; Hutchinson et al., 1992; Hutchinson and Suo, 1992; Thouless et al., 1992; Jensen and Thouless, 1995; Evans et al., 1997; Chai, 1998; Hutchinson et al., 2000; Audoly, 2000; Hutchinson, 2001). The buckles exhibit several configurations: ranging from circular, to linear to telephone cord (Fig. 1) (Matuda et al., 1981; Gille and Rau, 1984; Lee et al., 1993; Colín et al., 2000; Moon et al., 2002). Straight buckles propagate with a curved front. The conditions at the stationary side and the circular front have been modeled and rationalized in terms of mode mixity and energy release rate (Hutchinson and Suo, 1992; Hutchinson, 2001; Jensen and Sheinman, 2001). The corresponding mechanics for telephone cord buckles are less well developed. The purpose of this study is to gain some insight by performing measurements on thin films of diamond-like carbon (DLC) deposited onto nominally flat glass substrates and conducting a corresponding mechanics assessment. Such systems are typically subject to high residual compression (1–4 GPa) and modest adhesion, causing them to be susceptible to telephone cord buckles. The profiles of telephone cord buckles are characterized along different chords, by using the atomic force microscope (AFM). To make a direct comparison between telephone cord and (the more completely understood) straight-sided buckles, the focused ion beam (FIB) imaging system has been used to create two parallel (damage free) cuts, converting a section of the former into the latter. Changes in the profile before and after cutting can be used to correlate the two configurations, with all other variables fixed. The ensuing measurements provide a direct assessment of the mechanics of telephone cord buckling.

References listed at the end of the paper:


ABSTRACT: The buckling and wrinkling of thin films has recently seen a surge of interest among physicists, biologists, mathematicians, and engineers. This activity has been triggered by the growing interest in developing technologies at ever-decreasing scales and the resulting necessity to control the mechanics of tiny structures, as well as by the realization that morphogenetic processes, such as the tissue-shaping instabilities occurring in animal epithelia or plant leaves, often emerge from mechanical instabilities of cell sheets. Although the most basic buckling instability of uniaxially compressed plates was understood by Euler more than two centuries ago, recent experiments on nanometrically thin (ultrathin) films have shown significant deviations from predictions of standard buckling theory. Motivated by this puzzle, we introduce here a theoretical model that allows for a systematic analysis of wrinkling in sheets far from their instability threshold. We focus on the simplest extension of Euler buckling that exhibits wrinkles of finite length—a sheet under axisymmetric tensile loads. The first study of this geometry, which is attributed to Lamé, allows us to construct a phase diagram that demonstrates the dramatic variation of wrinkling patterns from near-threshold to far-from-threshold conditions. Theoretical arguments and comparison to experiments show that the thinner the sheet is, the smaller is the compressive load above which the far-from-threshold regime emerges. This observation emphasizes the relevance of our analysis for nanomechanics applications.

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“Multiple-length-scale elastic instability mimics parametric resonance of nonlinear oscillators”, Nature Physics, Vol. 7, pp 56-60, 2011, DOI: 10.1038/nphys1806

ABSTRACT: Spatially confined rigid membranes reorganize their morphology in response to the imposed constraints. A crumpled elastic sheet presents a complex pattern of random folds focusing the deformation energy¹, whereas compressing a membrane resting on a soft foundation creates a regular pattern of sinusoidal wrinkles with a broad distribution of energy²,³,⁴,⁵,⁶,⁷,⁸. Here, we study the energy distribution for highly confined membranes and show the emergence of a new morphological instability triggered by a period-doubling bifurcation. A periodic self-organized focalization of the deformation energy is observed provided that an up-down symmetry breaking, induced by the intrinsic nonlinearity of the elasticity equations, occurs. The physical model, exhibiting an analogy with parametric resonance in a nonlinear oscillator, is a new theoretical toolkit to understand the morphology of various confined systems, such as coated materials or living tissues, for example wrinkled skin¹, internal structure of lungs⁶, internal elastica of an artery¹⁰, brain convolutions¹¹,¹² or formation of fingerprints¹³. Moreover, it opens the way to a new kind of microfabrication design of multiperiodic or chaotic (aperiodic) surface topography through self-organization.

References listed at the end of the paper:
and the elastoplastic sharp herringbone pattern, and their characteristics are compared with the elastic
perfectly plastic. It is found that upon equi-biaxial compression, depending on the competition among the yield strain, critical buckling strain and applied strain, three new types of patterns may emerge: the plastic diamond-like pattern, the elastoplastic square lattice pattern and the elastoplastic sharp herringbone pattern, and their characteristics are compared with the elastic

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ABSTRACT: Most previous studies on spontaneous buckling pattern formations in thin films on compliant substrates were limited to elastic deformation, where the herringbone mode is the most often observed under equi-biaxial compression. In practice, plastic deformation is often encountered in ductile metal and polymer films. The effect of plasticity on buckling patterns is explored in this paper using extensive finite element simulations, where the film is assumed to be elastic—perfectly plastic. It is found that upon equi-biaxial compression, depending on the competition among the yield strain, critical buckling strain and applied strain, three new types of patterns may emerge: the plastic diamond-like pattern, the elastoplastic square lattice pattern and the elastoplastic sharp herringbone pattern, and their characteristics are compared with the elastic
herringbone mode. Moreover, unique features including the asymmetry in crests and troughs, the sharp saw-like undulation profile and varying wavelengths with applied strain are observed for some types of the new patterns. The study may find its potential applications in the design of stretchable electronics, fabrication of micro/nanofluid channels or channel networks, and morphogenesis of tissues and plants, among others.

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ABSTRACT: The static postbuckling of flat and doubly-curved shallow panels under the combined action of a system of uniaxial/biaxial compressive edge loads and a lateral pressure field is investigated, and the effects of transverse shear, initial geometric imperfections and tangential edge constraints upon load carrying capacity of curved panels are emphasized. Comparisons of the classical and shear deformable theories are made and issues related to the sensitivity to the snap-through behaviour are discussed. A variety of loading systems and panel geometries are considered in the numerical illustrations and pertinent conclusions related to the postbuckling response are outlined.


ABSTRACT: An analysis and comparison of several shear deformable bending theories of composite laminated anisotropic plates currently encountered in the field literature are given in this paper. Although apparently different, it is shown in a unitary way, that these theories constitute in fact only different formulations of a single theory, generically designated to as the moderately thick plate theory. Their connection with the first order transverse shear deformation theory is also emphasized and some conclusions concerning its shortcomings and field applicability are presented.


ABSTRACT: This paper deals with the substantiation of a shear deformable theory of cross-ply laminated composite shallow shells. While the developed theory preserves all the advantages of the first order transverse shear deformation theory it succeeds in eliminating some of its basic shortcomings. The theory is further employed in the analysis of the eigenvibration and static buckling problems of doubly curved shallow panels. In this context, the state space concept is used in conjunction with the Lévy method, allowing one to analyze these problems in a unified manner, for a variety of boundary conditions. Numerical results are presented and some pertinent conclusions are formulated.

References listed at the end of the paper:
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ABSTRACT: The static postbuckling of simply-supported single and multilayered composite doublecurved shallow panels subjected to a system of in-plane compressive edge loads is studied. The effects caused by transverse shear deformation, lamination, the character of in-plane boundary conditions and transverse normal stress, are considered and a series of pertinent conclusions are outlined. Comparisons are made of the obtained results with their classical counterparts and conclusions related to their range of applicability arc presented. Moreover, by incorporating the initial geometric imperfections, their influence on the load carrying capacity of curved composite panels is discussed and the peculiarities of their effect as compared to the case of flat panels arc emphasized.


ABSTRACT: This study deals with the postbuckling and vibration behavior of flat and shallow curved panels resting on a Winkler linear/non-linear elastic foundation. The considered plate/shell structural model is based on a higher-order shear deformable theory and encompasses a number of effects such as transverse shear, geometric non-linearities and the initial geometric imperfection. Special emphasis is given to the influence played by Winkler's foundation moduli as well as by the previously mentioned effects upon the postbuckling and vibrational response in the pre/postbuckling ranges and a number of pertinent conclusions are outlined.


ABSTRACT: The postbuckling behavior of flat/curved panels resting on a Winkler linear/nonlinear foundation,
subjected to compressive edge loads and exposed to a nonuniform temperature field is investigated. Effects played by transverse shear, initial geometric imperfections, panel curvature and Winkler's foundation moduli are highlighted and a number of pertinent conclusions are outlined.

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ABSTRACT: A study of the postbuckling behavior of geometrically imperfect anisotropic sandwich doubly-curved and flat panels subjected to a system of compressive edge loads and a lateral pressure is presented. The study is carried out in the context of the weak core sandwich shell model whose superior structural performance as compared to those of the strong core sandwich or standard laminated structures has resulted in its increased use in the design of advanced flight vehicles. A detailed investigation of the influence played by a number of kinematical and physical parameters as well as by the character of tangential boundary conditions on the load carrying capacity of sandwich structures is performed and pertinent conclusions are outlined.

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ABSTRACT: In the present paper, an advanced geometrically nonlinear shell theory of doubly curved structural sandwich panels with transversely compressible core is presented. The model is based on the adoption of the Kirchhoff theory for the face sheets and a second/third order power series expansion for the core displacements. The theory accounts for dynamic effects as well as for initial geometric imperfections. In the v. Kármán sense, large displacement theory is employed with respect to the transverse direction while the displacement gradients with respect to the tangential directions are assumed to be small. The equations of motion are derived by means of Hamilton’s principle and hold valid for all types of elastic and elastic–plastic material models. The theory is illustrated by an analysis of the elastic buckling and postbuckling behavior of flat and curved sandwich panels using an extended Galerkin scheme. Owing to the assumed transverse flexibility of the core, both the global and the local (face wrinkling) instability modes can be addressed.

ABSTRACT: The present study is concerned with the analysis of the transient response of softcore sandwich structures in the postbuckling range using a higher-order geometrically nonlinear shell model including the
transverse core compressibility. The transverse compressibility results in the development of a chaotic vibration with unpredictable wrinkling amplitudes and has significant effects on the eigenfrequency.

References listed at the end of the paper:

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ABSTRACT: In the present study, the effect of the transverse compressibility of the core on the transient dynamic response of structural sandwich panels under rapid loading conditions is investigated. The analysis is based on a higher-order sandwich shell theory in an effective multilayer formulation. The model is based on the standard Kirchhoff–Love hypothesis for the face sheets whereas a first/second order power series expansion is employed for the core. Consistent equations of motion and boundary conditions are derived by means of Hamilton’s principle. An analytical solution is obtained by an extended Galerkin procedure. The theory is applied to the dynamic buckling and postbuckling analyses of plane and curved sandwich panels subjected to rapidly applied tangential and transverse loads. It is observed that the transverse compressibility of the core can have distinct effects on both, the frequency and the amplitudes of the resulting free oscillations. Due to interactions between the overall oscillation and a local oscillation in the presence of a face wrinkling instability mode, the dynamic response can be chaotic, resulting in oscillating face wrinkling instability modes with unpredictable amplitudes.
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ABSTRACT: This paper is devoted to a study of the effects played by transverse core compressibility of sandwich plates and shells on their static and dynamic behavior. The analysis is based on a higher-order structural model using the standard Kirchhoff–Love assumption for the face sheets and a higher order displacement representation for the core layer. The model accounts for the geometrical nonlinearities that are considered in the von Kármán sense and for initial geometric imperfections. Transverse shear effects are included in the soft-core layer. Consistent equations of motion and boundary conditions are derived via the application of Hamilton’s principle. In the cases that are analyzed and presented in this paper, it was revealed that the static and dynamic buckling/response and postbuckling of flat and curved sandwich structures, are strongly affected by transverse compressibility of the core. It is also shown that in the context of this structural model, the wrinkling instability and response are captured directly from the derived governing equations, and not, as customarily, via a post-processing analysis.

ABSTRACT: Buckling loads of sandwich panels obtained by analytical calculations and FE-analysis are compared. Approximate buckling loads for panels with different boundary conditions have been derived using an energy method with deflection functions satisfying the boundary conditions. The comparison shows good agreement for panels with simply supported edges. In other cases the agreement is acceptable for panels with a length/ breadth ratio of 1 or greater. The approximate solutions can thus be used to estimate buckling loads of panels when designing sandwich structures.

ABSTRACT: This paper presents a method for calculating the critical buckling load of sandwich panels. Based on earlier ‘zig-zag’ models for through-thickness displacements, the transverse shear deformation of the faces is included, thus allowing the analysis of thick sandwich plates. Where possible, predictions have been compared with other workers. Also, the influence of face lay-up and plate aspect ratio are investigated.

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ABSTRACT: The wrinkling analysis of anisotropic sandwich panels is found by developing Benson–Mayers unified theory for isotropic sandwich panels into general anisotropic sandwich panels. Both symmetrical and antisymmetrical wrinkling are analyzed and calculated simultaneously. The present method has been applied to orthotropic and antisymmetric cross-ply sandwich plates and the results are in good agreement with the published analytical and experimental results.

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ABSTRACT: Solid unstiffened, sandwich and hat-stiffened rectangular orthotropic fiber reinforced plastic (FRP) plates were tested for buckling by in-plane compression and for stresses and deflections under uniform out-of-plane pressure. The solid unstiffened and hat-stiffened plates were 154 x 77 cm (1 x w) (72 x 36 in), while the sandwich plates were 102 x 77 cm (1 x w) (48 x 36 in). Balsa core was used in the sandwich plates and in the hat-stiffeners. The two short edges of the unstiffened and sandwich plates were clamped, while the two long edges were simply supported. The two long edges of the hat-stiffened plates were free, while the short edges were clamped. The buckling load, as well as stresses and deflections from the tests, were then compared to those from finite element analysis (FEA) and analytic solutions. There was reasonably good agreement between FEA, analytic, and experimental buckling stresses for the unstiffened solid plates. There was reasonable agreement in buckling stresses between FEA and experimental results for the hat-stiffened plate. There was poor agreement between FEA, analytic, and experimental elastic buckling results for the sandwich plates because they failed in local buckling prior to global buckling. Under out-of-plane uniform pressure, FEA and analytic solutions of the stresses and deflections for the unstiffened solid plates agreed well with experimental results. There was poor agreement between FEA and experimental results for stresses and deflections of the hat-stiffened or sandwich plates. Experimental error could be traced, in part, to plate fabrication, the method of applying out-of-plane pressure, edge support, and instrumentation accuracy.

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ABSTRACT: Rectangular orthotropic sandwich fiber reinforced plastic (FRP) panels were tested for buckling
in uniaxial compression. The panels, with either balsa or linear PVC foam cores, were tested in two sizes: 183 cm x 92 cm (72 in. x 36 in.) and 122 cm x 92 cm (48 in. x 36 in.) for aspect ratios of 2.0 and 1.3, respectively. The sandwich panels were fabricated using the vacuum-assisted resin transfer molding (VARTM) technique. The two short edges of the sandwich panels were clamped, while the two long edges were simply supported. The experimental elastic buckling loads of panels with an aspect ratio of 1.3 were 400 kN (90 klb) for balsa core panels and 267 kN (60 klb) for foam core panels. For balsa and foam core panels with an aspect ratio 2.0, the experimental buckling loads were 334 kN (75 klb) and 240 kN (54 klb), respectively. Experimental buckling results for balsa core panels of both sizes differed by 5 _8% from numerical and analytical results. Differences in experimental and predicted buckling loads for foam core panels ranged between 15% and 23%. Post-buckling collapse of balsa and foam core panels with an aspect ratio of 1.3 were 694 kN (156 klb) and 347 kN (78 klb), respectively. For balsa and foam core panels with an aspect ratio of 2.0, post-buckling collapse occurred at 592 kN (133 klb) and 334 kN (75 klb), respectively. A numerical post-buckling analysis qualitatively followed that of the experimental results.

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ABSTRACT: Rectangular orthotropic fiber-reinforced plastic (FRP) sandwich panels were tested for buckling in uni-axial compression. The panels, with 0.32 cm (0.125 in.) face sheets and a 1.27 cm (0.5 in.) core of either balsa or linear poly(vinyl chloride) (PVC) foam, were tested in two sizes: 154x77 cm2 (72x36 in.2) and 102x77 cm2 (48x36 in.2). The sandwich panels were fabricated using the vacuum-assisted resin transfer molding process. The two short edges of the sandwich panels were clamped, while the two long edges were simply supported for testing. The clamped panel ends were potted into a steel frame. The experimental elastic buckling loads were then measured using strain gauges fixed to both sides of the panels. A total of 12 panels were tested under uni-axial compression. Bifurcation in the load versus engineering strain curve was noted in all cases. For all six sandwich panels tested using balsa core, the type of failure was easily identified as face sheet delamination followed by core shear failure. For all six PVC foam core sandwich panels tested, the type of failure consisted of core shear failure with little or no face sheet delamination. In the failed balsa core panels there was little or no evidence of balsa remaining on the FRP face sheet, however, in the PVC foam core panels there were ample amounts of foam left on the FRP face sheet. It was concluded that although the buckling loads for the foam core panels were not as high as those for the balsa core panels, PVC foam core bonding to the FRP face sheets was superior to balsa core bonding.


ABSTRACT: Metallic sandwich panels with textile cores have been analyzed subject to combined bending and shear and then designed for minimum weight. Basic results for the weight benefits relative to solid plates are
presented, with emphasis on restricted optimizations that assure robustness (non-catastrophic failure) and acceptable thinness. Select numerical simulations are used to check the analytical results and to explore the role of strain hardening beyond failure initiation. Comparisons are made with competing concepts, especially honeycomb and truss core systems. It is demonstrated that all three systems have essentially equivalent performance. The influence on the design of a concentrated compressive stress that might crush the core has been explored and found to produce relatively small effect over the stress range of practical interest. “Angle ply” cores with members in the ±45° orientation are found to be near optimal for all combinations of bending, shear and compression.

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ABSTRACT: Metallic sandwich panels with periodic, open-cell cores are important new structures, enabled by novel fabrication and topology design tools. Fabrication protocols based on the sheet forming of trusses and shell elements (egg-boxes) as well as textile assembly have allowed the manufacture of robust structures by inexpensive routes. Topology optimization enables control of failure mechanisms at the truss length scale, leading to superior structural performance. Analysis, testing and optimization have demonstrated that sandwich panels constructed with these cores sustain loads at much lower relative densities than stochastic foams. Moreover, the peak strengths of truss and textile cores are superior to honeycombs at low relative densities, because of their superior buckling resistance. Additional benefits of the truss/textile cores over honeycombs reside in their potentially lower manufacturing cost as well as in their multifunctionality.


ABSTRACT: The buckling behavior of sandwich panels with a core that is flexible in the out-of-plane direction, also denoted as “soft” core including high-order effects, is presented. The buckling analysis consists of the formulation of the linear and the nonlinear governing equations along with the boundary conditions. The sandwich panel construction is general and consists of two skin-panels, metallic or composite laminated symmetric that may be unidentical and a flexible isotropic or orthotropic core made of foam or a low strength honeycomb. The analysis uses a high-order theory formulation, which permits nonlinear distortions of the cross-section plane of the core as well as changes in its height. The analysis determines the bifurcation loads along with the associated mode shapes, local or overall buckling modes, as well as deformations, internal resultants and stresses at skin-core interface layers due to imperfections. Numerical results using closed form solutions for simply-supported panels, with identical and non-identical skin-panels subjected to compressive inplane loads as well as imperfection analysis results, are presented. The results reveal that, under some structural configurations, the local buckling mode is a critical, rather than a global one as a result of the out-of-plane flexibility of the core.
ABSTRACT: The classical and the high-order computational models of unidirectional sandwich panels with incompressible and compressible cores are presented. The significant theoretical and practical differences are discussed and elaborated through some numerical examples of typical sandwich panels. The classical models considered for the incompressible panel consists of two variants of the well-known splitted rigidity approach. The first one, due to Allen and Plantema and many others, assumes that the plane section of the shear substructure takes a specific ‘zigzag’ pattern with no in-plane deformation in the face sheets and a vertical one when the flexural rigidity of the faces is ignored. The second model, due to Frostig, assumes that the plane section of the core in the shear substructure remains vertical and the face sheets are subjected to in-plane deformation as well as flexural ones. They are compared with the accurate incompressible model, denoted as ordinary sandwich panel theory (OSPT) and with the high-order sandwich panel theory (HSAPT) based on a variational approach. In case of a sandwich panel with a compressible core the elastic foundation models based are compared with the high-order one. The governing equations and the appropriate boundary conditions of the classical models have been rederived to clarify the ambiguity involved in the definition of the boundary conditions of the various computational models. The cases of simply supported panel, cantilevered and a two-span panel are used to demonstrate numerically the differences in the overall response of the panel as well as in the near vicinity of the localized loads and supports.

ABSTRACT: When a laminated composite is subjected to compressive loads a delaminated region may buckle. This causes high interlaminar stresses at the delamination front and the delamination may grow. In this study, the effect of multiple delaminations on the postbuckling behavior of laminated rectangular plates is studied experimentally. In the experimental study extensive strain gauging is involved to obtain a thorough investigation of the behavior of the distribution of the surface strains on the plate. Results of the experimental investigation are compared with the theory developed by Chai.

ABSTRACT: The method of reliable solutions alias the worst scenario method is applied to the problem of von Karman equations with uncertain initial deflection. Assuming two-mode initial and total deflections and using Galerkin approximations, the analysis leads to a system of two nonlinear algebraic equations with one or two uncertain parameters-amplitudes of initial deflections. Numerical examples involve (i) minimization of lower buckling loads and (ii) maximization of the maximal mean reduced stress.
References listed at the end of the paper:


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ABSTRACT: Local instability in the form of “intra-cell buckling” or “dimpling” is a well-known failure mode in honeycomb-cored sandwich panels with very thin faces. Most work reported on the subject suggests relatively simple design formulæ for the estimation of the intra-cell buckling load. It is however widely known that these classical design formulæ in some cases considerably underpredict the intra-cell buckling load. In this paper a series of experimental results obtained for different CFRP/honeycomb sandwich panel configurations loaded in compression are presented. The results confirm that the “classical” design formulæ provide overly conservative results. During the tests the intra-cell buckling patterns were monitored carefully, and it was observed that the hitherto assumed buckling patterns did not correspond to the experimental observations. Based on these findings a new simplified design formulæ is suggested, which for the investigated CFRP/honeycomb sandwich panels provides significantly more accurate predictions than the “classical” design formulæ.

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ABSTRACT: The paper presents the results of an investigation of the non-linear behavior of delaminated sandwich panels with a compressible core. The delaminated zone, at one of the face-core interfaces, consists of through-the-width crack, which is free of shear stresses but is capable of accommodating partial contact with compressive stresses only within the debonded zone. The governing non-linear equations along with the appropriate boundary conditions and the continuity conditions are derived through variational principles. The governing equations include moderate deformations type of kinematic relations, and include the high-order effects due to the transverse flexibility of the core. The governing equations along with the stress and displacements fields for the core and the appropriate continuity conditions are presented. The effects of the non-
linear response and the partial contact are described through some numerical cases of three points bending typical sandwich panels with inner delaminations in the vicinity of a concentrated load, in the vicinity of a stiffened core and, finally, far from the load. Numerical results in the form of displacements, bending moments, shear stresses in the core and vertical interfacial normal stresses at the upper and lower face-core interfaces along the panel length and at the delamination crack tips are presented. Buckling curves of load versus various extreme structural parameters are included. The analyses show that a full contact type of delamination transforms into a partial contact area with buckling of the compressed face sheet, as the load is increased and it is associated with extreme large displacements and stresses.

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ABSTRACT: Wind turbine blades are being manufactured using polymer matrix composite materials, in a combination of monolithic (single skin) and sandwich composites. Present day designs are mainly based on glass fiber-reinforced composites (GFRP), but for very large blades carbon fiber-reinforced composites are being used increasingly, in addition to GFRP by several manufacturers to reduce the weight. The size of wind turbines have increased significantly over the last 25 years, and this trend is expected to continue in the future. Thus, it is anticipated that wind turbines with a rated power output in the range of 8—10 MW and a rotor diameter about 170—180 m will be developed and installed within the next 10—15 years. The article presents an overview of current day design principles and materials technology applied for wind turbine blades, and it highlights the limitations and important design issues to be addressed for up-scaling of wind turbine blades from the current maximum length in excess of 61 m to blade lengths in the vicinity of 90 m as envisaged for future very large wind turbines. In particular, the article discusses the potential advantages and challenges of applying sandwich type construction to a larger extent than is currently being practiced for the load-carrying parts of wind turbine blades.

doi: 10.1002/nme.1100

ABSTRACT: A homogenization method is proposed for sandwich structures consisting of two plates interlaced with beams and shells in a periodic, lattice structure. The proposed method is a quasi-continuum approach where the constitutive response is obtained from the generalized forces of the interlacing elements. Buckling is studied as part of this model. Comparison of the homogenized model with fully discrete models show reasonable to very good agreement.

References listed at the end of the paper:

ABSTRACT: Multifunctional sandwich panels with corrugated and prismatic diamond cores have been analyzed and their behavior compared with panels designed using truss and honeycomb cores. Failure mechanism maps have been devised that account for interactions between core and face members during buckling. The optimal dimensions and the minimum weight have been evaluated. The load capacities predicted for near-optimal designs have been validated by conducting selected finite element calculations. Designs that use diamond prismatic cores (with corrugation order 4) are slightly more weight efficient than trusses, when optimized for a specific loading direction. Honeycomb cores, while somewhat more weight efficient, especially at lower load capacities, are not amenable to the fluid flows needed for cooling. We conclude that the diamond prismatic topology is the most weight efficient among designs amenable to simultaneous load bearing and active cooling.

References listed at the end of the paper:

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ABSTRACT: An experimental and computational study of the bending response of steel sandwich panels with corrugated cores in both transverse and longitudinal loading orientations has been performed. Panel designs were chosen on the basis of failure mechanism maps, constructed using analytic models for failure initiation. The assessment affirms that the analytic models provide accurate predictions when failure initiation is controlled by yielding. However, discrepancies arise when failure initiation is governed by other mechanisms. One difficulty is related to the sensitivity of the buckling loads to the rotational constraints of the nodes, as well as to fabrication imperfections. The second relates to the compressive stresses beneath the loading platen. To address these deficiencies, existing models for core failure have been expanded. The new results have been validated by experimental measurements and finite element simulations. Limit loads have also been examined and found to be sensitive to the failure mechanism. When face yielding predominates, appreciable hardening follows the initial non-linearity, rendering robustness. Conversely, for designs controlled by buckling (either elastic or plastic) failure initiation is immediately followed by softening. The implication is that, when robustness is a key requirement, designs within the face failure domain are preferred.

ABSTRACT: A general methodology for the design of strong, lightweight sandwich panels is described and implemented. Several core topologies are considered, including square-section truss members in pyramidal and tetrahedral configurations, square honeycombs, and corrugated sheets. When the number of independent design parameters is restricted to three, closed-form analytical solutions for the optimal design are obtained. Alternatively, when a fourth parameter is added (as needed to fully characterize the panel geometry), numerical routes are required. The results demonstrate that the three parameter optimizations yield design weights that are only slightly heavier than those of the fully optimized panels, provided the value of the fourth parameter is selected judiciously. The weight rankings of the various core topologies change with load capacity, although the differences between them are generally small, particularly upon comparison with the weight of a solid panel.

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“Buckling analysis of Corrugated Core Sandwich Panels”, see
http://www.academia.edu/7028252/Buckling_Analysis_of_Corrugated_Core_Sandwich_Panels
publisher and date not given in the pdf file; most recent reference is 1997.
ABSTRACT: In an effort to improve structural design of corrugated board packages under compression load, buckling analysis of simply-supported corrugated board panels, which constitute the main load-bearing components of a compression-loaded box, has been performed. This paper focuses on prediction of effective
(homogenised) properties of the corrugated core and the critical buckling load of a simply-supported board panel. An improved buckling load prediction has been obtained by incorporation of the additional moments produced by transverse shear deformation in the governing differential equation for equilibrium. The buckling load predictions are compared to previous analytical formulations, finite element analysis and experiments.

References listed at the end of the paper:


ABSTRACT: This study focuses on the mode dependence of delamination growth under cyclic compressive loads in cross-ply composite plates. The model proposed makes use of an initial postbuckling solution derived from a perturbation procedure. A mode-dependent crack growth criterion is introduced. Expressions describing the fatigue crack growth are derived in terms of the distribution of the mode adjusted energy release rate. The resulting crack growth laws are numerically integrated to produce delamination growth versus number of cycles diagrams. The model does not impose any restrictive assumptions on the relative thickness of the delaminated and the base plates, although transverse shear stress effects are not considered. Experimental results are presented for cross-ply graphite/epoxy specimens, and the results are compared with experimental results for unidirectional specimens. The test data are obtained for different delamination locations and for different values of applied compressive strain.

References listed at the end of the paper:
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“Buckling response of sandwich composites: Effect of core density and implanted interface cracks”, Paper ID 1452, (Publisher and date not given in the “pdf” file; the most recent reference is dated 1998.)

ABSTRACT: Buckling response of foam core sandwich composites with various core densities and implanted delaminations have been investigated. Klegcell foams with densities ranging from 75-300 kg/m$^3$ were used in the analysis. Various lengths of delaminations were introduced between the face sheets by implanting non-porous Teflon during the construction of the sandwich. The idea was to determine the influence of $a/L$ (Crack length over the length of specimen) on the critical strain. The study further investigated the effect of interface crack in controlling/accelerating the core shear and local buckling of the face sheet. Buckling tests were carried out with simple support end conditions on a newly designed test fixture. Both in- and out-of-plane displacements were recorded and were utilized in determining the critical buckling loads. Both FEM and analytical calculations were carried out to determine the initial and post-buckling responses. They were later compared with the experimental data. Failure modes with various core densities have also been identified, and their relationship with interface crack propagation has been determined. Details of the experimental, finite element and analytical work are presented in this paper.

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ABSTRACT: A three-dimensional (3D) finite element analysis has been conducted to examine the local buckling behavior of foam-cored composite sandwich panels containing a face-core debond. The influences of core stiffness and debond size and shape are examined. The core stiffness was found to have a profound influence on the local buckling load, especially for low modulus cores and smaller debonds. Panels with square debonds buckled at lower loads than those with circular debonds of the same dimension, and buckling loads for both circular and square debonds decreased with increased debond size. The results of the analysis were compared to local buckling loads determined experimentally. Reasonable agreement was found between the predicted and experimentally measured local buckling loads for both circular and square debonds.

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ABSTRACT: Nonlinear finite element analysis is conducted to predict initiation of debond propagation in compression loaded foam cored sandwich panels containing a circular face/core debond embedded at the panel center. A three-dimensional geometrically nonlinear finite element model of the debonded sandwich panel combined with linear elastic fracture mechanics is used to determine the stress intensity factors $K_I$ and $K_{II}$ and energy release rate at the debond (crack) front parallel and perpendicular to the applied load. A range of core densities and debond sizes are analyzed. The opening mode (mode I) was found to dominate the fracture process. The critical load for crack propagation predicted using fracture mechanics concepts was found to agree with measured collapse loads for smaller debonds, but fell below measured debond propagation loads for larger debonds. In all cases the predicted direction of crack propagation was perpendicular to the loading direction, in agreement with experimental observations.


ABSTRACT: Failure of compression loaded sandwich columns with an implanted through-width face/core debond is examined. Compression tests were conducted on sandwich columns containing implemented face/core debonds. The strains and out-of-plane displacements of the debonded region were monitored using the digital image correlation technique. Finite element analysis and linear elastic fracture mechanics were employed to predict the critical instability load and compression strength of the columns. Energy release rate and mode mixity were determined and compared to fracture toughness data obtained from TSD (tilted sandwich debond) tests, predicting propagation loads. Instability loads of the columns were determined from the out-of-plane displacements using the Southwell method. The finite element estimates of debond propagation and instability loads are in overall agreement with experimental results. The proximity of the debond propagation loads and the instability loads shows the importance of instability in connection with the debond propagation of sandwich columns.

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ABSTRACT: The object of the study was to optimize the shear buckling load of laminated composite plates. The laminates lacked coupling between bending and extension ($B_{ij} = 0$) but had otherwise arbitrary selection of the ply angle variation through the thickness. The plates were rectangular and either simply supported or clamped on all edges. For orthotropic plates, it was seen that there is only one parameter necessary for finding the optimal design for different materials and plate aspect ratios. This parameter can be interpreted as the layup angle $\theta$ in a (+/−$\theta$) orthotropic laminate. When bending-twisting coupling is present, the buckling strength depends on the direction of the applied load. A laminate with non-zero bending-twisting coupling stiffnesses can be described with four lamination parameters. The allowable region of these parameters was investigated, and an optimization of the buckling load within this region was performed. It was seen that even this is a one parameter problem. This parameter can be interpreted as the layup angle $\theta$ in an off-axis unidirectional laminate ($\theta$).

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ABSTRACT: In this paper, the influence of initial imperfection and coupling between bending and extension on vibration, buckling and nonlinear dynamic stability of laminated plates is studied. The governing equation is derived. It is a nonlinear modified Mathieu Equation. Numerical solutions of 5 typical composite materials namely, Glass-epoxy Scotch-1002, Aramid-epoxy Kevlar-49, Boron-epoxy B4-5505, Graphite-epoxy T300-5208 and AS-3501 are computed. Results reveal that the existence of initial imperfection, and also coupling effect, make the plates much more sensitive to entering parametric resonance with amplitude greater than that of perfect plates. Coupling effect for different composite laminates, especially, for that with few layers, is different. If coupling effect is neglected, the design of plate structures for buckling and dynamic stability would unconservatively be for more than 10%.

References listed at the end of the paper:


ABSTRACT: Compression wrinkling of composite sandwich panels with corrugated skins was investigated numerically, analytically and experimentally. Semi-circular and sine-wave shaped corrugations were studied.
The corrugations significantly increased wrinkling strength when compared with equal mass flat panels. Semi-circular corrugations proved to be highly preferable to sine-wave shaped corrugations due to localized buckling in the latter. Over 40 fiberglass and foam core sandwich specimens were manufactured with semi-circular skin corrugations. These specimens were tested to failure, providing confirmation of the numerical and analytical results.


ABSTRACT: The non-classical problem of buckling of a simply-supported rectangular plate due to various types of non-uniform compressive edge loads is analysed here. For each case, the elasticity solution for the internal in-plane stress field is obtained rigorously using a superposition of Airy’s stress functions and also approximately using extended Kantorovich method. Subsequently, the convergent buckling loads are obtained using Galerkin’s method. Results are presented to highlight the dependence of the total buckling load and the corresponding buckled shape on the edge load distribution, as well as to illustrate the applicability of the approximate plane stress solutions.

References listed at the end of the paper:

ABSTRACT: Here, the elastic stability behavior of simply supported anisotropic sandwich flat panels subjected to mechanical in-plane loads is investigated using an analytical approach. The formulation is based on first-order shear deformation theory and the shear correction factors employed are based on energy consideration that depends on the lay-up as well as material properties. The governing equations are obtained using the Raleigh–Ritz method assuming a combination of sine and cosine functions in the form of double Fourier series for the displacement fields. The effectiveness of the integrated formulation is tested for global characteristics considering examples related to multi-layered laminates and sandwich panels for which solutions are available.


ABSTRACT: This study treats the elasto-plastic deformation and buckling behavior of thin cylindrical shell subjected to multi-directional excitations. A steel cylindrical pier is modeled as a thin cylindrical structure with an attached mass on its tip. Numerical simulations are carried out, where the horizontal and the vertical seismic loads are applied simultaneously. The effects of the horizontal and vertical input frequencies and input accelerations on the dynamic behaviors are studied, under both the elastic shell assumption and the elasto-plastic shell assumption. It is found that flattening phenomena will occur for the elastic shell and the buckling phenomena similar to that found in Hyogo Ken Nambu Earthquake occurs for the elasto-plastic shell.


ABSTRACT: When thin cylindrical shells having freely supported end such as heat-shielding shells of after-burners, labyrinth air seals and annular structures in large diameter pipings are subjected to axial annular flow, an unstable vibration and a fatigue failure are apt to be occurred. In this paper, the unstable vibration of thin cylindrical shells is investigated considering the fluid structure interaction between shells and fluid flowing through a narrow passage. The coupled equation of motion between shells and fluid is derived using Flügge's shell theory and Navier-Stokes equation. Especially, focusing on the higher circumferential vibrations, the unstable phenomenon of thin cylindrical shells is clarified by using root locus based on the complex eigenvalue analysis by using the mode functions obtained by the exact solution. The influence of shell-dimensions and so forth on the threshold of the instability of the coupled vibration of shells and flowing fluid are investigated and discussed.

References listed at the end of the paper:

ABSTRACT: Structural pipe-in-pipe cross sections have significant potential for application in offshore oil and gas production systems because they combine thermal insulation performance with structural strength and self weight in an integrated way. Such cross sections comprise inner and outer thin-walled pipes with the annulus between them fully filled by a selectable filler material to impart an appropriate combination of properties. Structural pipe-in-pipe cross sections can exhibit several different collapse mechanisms, and the basis of the preferential occurrence of one over the others is of interest. This article presents an exact analysis for predicting the elastic buckling behaviours of a structural pipe-in-pipe cross section when subjected to external hydrostatic pressure. Simplified approximations are also investigated for elastic buckling pressure and mode when the outer pipe and its contact with the filler material is considered as a pipe on an elastic foundation. Results are presented to show the variation of elastic buckling pressure with the relative elastic modulus of the filler and pipe materials, the filler thickness, and the thicknesses of the inner and outer pipes. Case studies based on realistic application scenarios are used to show that the simplified approximations are sufficiently accurate for practical structural design purposes.

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James M. Hill (Department of Theoretical Mechanics, University of Nottingham, UK), “Critical Pressures for the Buckling of Thick-Walled Spherical Shells under Uniform External Pressure”, The Quarterly Journal of
ABSTRACT: For isotropic incompressible hyperelastic materials the problem of determining the critical pressure at which a thick-walled spherical shell buckles when subjected to a uniform external pressure involves solving a fourth-order system of highly non-homogeneous ordinary differential equations. Closed-form solutions of this system are derived here for a particular hyperelastic material which has not been studied previously. These solutions are used to derive the buckling criterion, and numerical values are obtained for the resulting critical pressures. For thin shells these values are in agreement with classical thin-shell theory while for thicker shells close agreement is obtained with existing results for the neo-Hookean material. However for thin shells the predicted buckling mode is different from that given by previous authors. It can be shown from previously published experimental results on simple extension and simple compression that the new strain-energy function is a valid prototype for vulcanized rubber over a limited range of deformation and moreover that it agrees with the neo-Hookean theory for small strains.


ABSTRACT: General instability is one of the important collapse modes of cylindrical shells reinforced by ring stiffeners under uniform pressure. Few research, however, has appeared in this field because of difficulties and complexity of the problem. Pressure hulls of deep diving submersibles have been designed on the basis of research works which were developed under idealized conditions for boundaries, stress-strain relations, and geometries. Recently, the development of high strength materials and the increase of operating pressure and diameter of pressure hulls have brought a change in proportion of primary structural members of cylindrical ring-reinforced shells, which leads to the review of the design procedure. In order to satisfy the above-mentioned requirements, pressure hulls should be designed on a reasonable basis. In the present paper, the elasto-plastic analysis of the general instability of ring reinforced cylindrical shells is performed on the basis of the finite element method, and results obtained are compared with collapse tests using two machined models and one welded model, which shows good coincidence with the theory. On the basis of a series of calculation, the authors propose a design criteria for the pressure hulls of deep diving submersibles. Furthermore, they investigate the influence of boundary conditions and initial imperfections on the general instability theoretically.

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Anonymous, “Non-deterministic dynamic instability of composite shells”, (publisher and date not given), NASA Technical Reports Server (NTRS)

ABSTRACT: A computationally effective method is described to evaluate the non-deterministic dynamic instability (probabilistic dynamic buckling) of thin composite shells. The method is a judicious combination of available computer codes for finite element, composite mechanics, and probabilistic structural analysis. The solution method is incrementally updated Lagrangian. It is illustrated by applying it to thin composite cylindrical shell subjected to dynamic loads. Both deterministic and probabilistic buckling loads are evaluated to demonstrate the effectiveness of the method. A universal plot is obtained for the specific shell that can be used to approximate buckling loads for different load rates and different probability levels. Results from this plot show that the faster the rate, the higher the buckling load and the shorter the time. The lower the probability, the lower is the buckling load for a specific time. Probabilistic sensitivity results show that the ply thickness, the fiber volume ratio and the fiber longitudinal modulus, dynamic load and loading rate are the dominant uncertainties, in that order.


ABSTRACT: Composite pipe has been used in transporting corrosive fluid in many chemical processes in the petrochemical and pulp and paper industries. It is often subjected to external pressures due to process conditions (vacuum), water hammer, pump suction, and differences in elevation head. Most composite pipe designers are currently using traditional metallic pipe standards which do not take into account the anisotropic nature of composite materials. An analytical model for the buckling of orthotropic composite pipe under external pressure has been developed in this study. In this study, first-order laminated anisotropic plate theory was used to construct models of the kinematic and constitutive behavior of the composite cylinders. The Ritz Method was then applied to determine the buckling load under external pressure. Results obtained from the developed model were compared with the theory derived by Flügge for the case of metallic pipe. Due to the inclusion of shear deformation, the new model gave lower buckling loads than Flügge's results especially for the case of thick-walled pipe. Good agreement was found when comparing the developed model with experimental results provided by Fibercast Company following ASTM D 2924 for centrifugally cast composite pipe.

ABSTRACT: The buckling behavior of $[0/+\theta/-\theta, 90]$$_S$ laminated cylindrical panels under axial compression is investigated by a parametric study on fiber angles and panel widths. The shape of the buckled panel and the buckling mode are influenced by the change of fiber angles. When the fiber angle is not 0 or 90°, panels are deformed into the twisted shape due to the bending-twisting coupling even for symmetric laminates. The fiber angle for the maximum buckling stress of the laminated cylindrical panel depends upon the panel width.

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ABSTRACT: A new technology known as asymmetric sandwich structures is now used for the design of lightweight structures. Static failure tests demonstrate the high performance of this technology and show its original mechanical behavior. Due to this complex mechanical behavior, the use of non-linear finite element models in the pre-project phase is a long, expensive process. This paper presents a specific theory which enables faster design loops. The theory is first validated by comparison to numerical models and is then used to correlate structural tests on asymmetric sandwich plate under combined compression/shear loadings. The tests were conducted on original test equipment designed to investigate the capabilities of this technology.


ABSTRACT: Finite element analysis is conducted to investigate the effect of coupling between the stiff facesheets and the flexible core on the stability of sandwich plates. The facesheets and the core are treated separately as three-dimensional solids. Initially, linear buckling analysis was carried out to determine the buckling loads for a wide range of the facesheet stiffness and core stiffness. Numerical results indicate that, for sandwich plates with a soft core such as PVC foam, the model that smears the facesheets and core overestimates the initial buckling load, demonstrating the importance of treating the facesheets and the core separately. Subsequently, postbuckling analysis was carried out. Numerical results show that, for sandwich plates with a soft core, the postbuckling behavior is unstable in that static equilibrium cannot be maintained once the buckling initiates.

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ABSTRACT: The paper presents a finite element formulation for the geometrically non-linear analysis of shells. The formulation is based on the Hellinger—Reissner approach and uses internal transverse shear stress unknowns to alleviate the problem of shear locking. A ring and a quadrilateral element are presented, together with three examples which demonstrate the accuracy of the elements.
ABSTRACT: The work’s aim has been to verify the suitability of commercial engineering software for geometrically non-linear analysis of shell structures. The paper deals with static, geometrically non-linear analysis of shells made of isotropic materials. The Finite Element Method (FEM) has been chosen to solve the problem. The results of the ROBOBAT Robot Millennium v. 19.0 and MSC.Marc v. 2005r2 commercial software are compared with the literature results.

ABSTRACT: A geometrically nonlinear formulation is presented for the axisymmetric plate and shell structures. The formulation is based on the total Lagrangian approach. The nonlinear equilibrium equations are solved using the Newton-Raphson method. Different numerical examples are performed to obtain the geometrically non-linear behaviour of axisymmetric plates and shells.

References listed at the end of the paper:

ABSTRACT: This paper deals with buckling and vibration analysis of initially stressed damped composite sandwich plates using assumed strain finite elements. A family of plate bending elements containing nine degrees of freedom per node are developed based on a refined higher-order shear deformation theory. The...
higher-order theory contains in-plane displacements that are expanded to include the higher-order terms in the Taylor series expansion as a result of which there is no need for shear correction factors. The popular assumed strain concept is used to ensure that the developed four- and nine-node elements pass the patch test and show no signs of shear locking and spurious zero energy modes in the present finite element formulations. Parametric studies are carried out to study the behavior of length to thickness ratios, boundary conditions, fiber orientations on vibration, and buckling of damped composite sandwich plates.


ABSTRACT: A simple isoparametric assumed strain finite element formulation incorporating a third-order polynomial displacement model for the buckling and vibration analysis of initially stressed composite sandwich laminates is presented. The displacement model involves a nonlinear distribution of in-plane displacements through the plate thickness; the theory does not require shear correction coefficients. A nine-noded quadratic Lagrangian two-dimensional element is used with three displacements, two rotations of the normals about the plate midplane, and two warps of the normals. Full integration is carried out to evaluate various terms in the energy formulation. A consistent mass matrix is employed to preserve the total kinetic energy of the system. The accuracy of the present formulation is verified with the existing results in the literature. Numerical results are presented for the stability and free vibration of initially stressed composite sandwich plates.


ABSTRACT: Top-hat stiffened plates provide an efficient structure for engineering applications. During service debonding between the stiffener and the plate is often observed and parametric studies of open section stiffeners have shown that debond size and location have a significant effect on the damage mode of the panel. However, these studies do not consider the interaction of failure modes and do not assess the ultimate failure of the structure. In this paper top-hat stiffened composite structures are assessed considering debond damage between the stiffener and plate. A non-linear finite element model is used to perform a parametric study on the effect of both damage and the panel’s geometry on the failure modes, ultimate strength and its damage tolerance. Results show that top-hat stiffened panels exhibit a trend between ultimate strength and the debond size with crack initiation not necessarily propagating. Geometric imperfections accelerate buckling but can provide an arrest point for crack propagation.

Yang, N. (1, 2), Das, P.K. (2), Blake, J.I.R. (3), Sobey, A.J. (3) and Shenoi, R.A. (3)
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“The application of reliability methods in the design of tophat stiffened composite panels under in-plane loading”, (publisher and date not given in the pdf file. The latest citation is 2009. Perhaps November 2013?)

ABSTRACT: Composite materials have been widely used in modern engineering fields such as aircraft, space and marine structures due to their high strength-to-weight and stiffness-to-weight ratios. However, structural
efficiency gained through the adoption of composite materials can only be guaranteed by understanding the influence of production upon as-designed performance. In particular, topologies that are challenging to production including panels stiffened with pi or tophat stiffeners dominate many engineering applications and often observe complex loading. The design of stiffened composite panels against buckling is a key point of composite structures. While a growing number of studies are related to the reliability analysis of composites few of these relate to the local analysis of more complicated structures. Furthermore for the assessment of these structures in a design environment it is important to have models that allow the rapid assessment of the reliability of these local structures. This paper explores the use of a stochastic approach to the design of stiffened composite panels for which typical applications can be found in composite ship structures. A parametric study is conducted using Navier grillage theory and First-order Reliability Methods to investigate any detectable trend in the safety index with various design parameters. Finally, recommendations are made to provide guidance on applications.

References listed at the end of the paper:
ABSTRACT: Stiffened composite panels are used within many applications, from aerospace to marine applications. Stiffened panels are utilized for their high strength to weight ratio and flexibility of layups while counteracting the low stiffness exhibited by composites. Complications arise when attempting to utilize the full variability of layups in conjunction with reliability constraints creating a complex design problem when constrained by both buckling and material strength. To aid the process of optimizing the design of composite structures and layups, while ensuring a low mass, this paper presents a bi-level optimization scheme for minimization of the weight of tophat stiffened composite panels with probabilistic deflection constraints. To improve the computational efficiency, an energy based grillage method is formulated and applied for the investigation of buckling problems under bi-directional in-plane loads. The method is validated by comparing the results obtained from FE model calculations. The variables that have a large impact on the structural safety have been identified by both safety index and COV based reliability analysis. A parametric study of plate dimensions and loading ratios is conducted to investigate the coupling effects on critical buckling load. The method presented in this paper, makes it possible for engineers to improve their designs, at an early stage, with an integrated consideration between product performance and design parameters.

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A. Sobey, J.I.R. Blake, R.A. Shenoi, Optimization of FRP structures for marine vessel design and production, OMAE (2009) 337-345


A. Sobey, Concurrent Engineering in the context of the composite leisure boatbuilding industry, Doctor of Philosophy, University of Southampton.


ABSTRACT: Finite element analysis and the optimization problem of sandwich constructions are treated. The thicknesses of the face plates and the core are used as design variables. The hybrid approximation technique in combination with the dual method from mathematical programming is used. Three examples are solved using six-nodal triangular and eight-nodal quadrilateral sandwich shell elements.


ABSTRACT: General buckling analysis of composite sandwich constructions is treated in this paper. Two modes of buckling exist in an elastic structure under certain loading cases, that is, bifurcation point buckling
and extreme point buckling. This paper is concerned with bifurcation point buckling. The energy criterion is used for deriving the theoretical formulae. According to the energy criterion, the positive two-order variation of the general potential energy, $\pi$, for an elastic mechanics system is necessary and sufficient condition to ensure a stable static balance state. The sandwich construction would not support loads and would suffer failure if general instability occurred on it. In the general buckling analysis, the formulae are based on the finite element method of linearity theory. The critical stress control equations corresponding to the bifurcation point buckling can be obtained by commanding two-order variation of the general potential energy, $\pi$, to equal zero. The critical load corresponding to structural general instability can be given by solving the generalized eigenvalue problem. It is shown by four numerical examples that the calculated results and accuracy are satisfied under a set of computation equations derived in this paper.


ABSTRACT: This paper presents buckling of unstiffened/stiffened orthotropic foam sandwich cylindrical shells simply supported at both ends. For the unstiffened cylinders, five equations of equilibrium are derived in terms of the mid-surface displacements and cross-section rotations according to the thick shell theory. Critical buckling loads are obtained by modal expansion under the loading conditions of axial compression, lateral pressure and torsional load with reasonable results. The stiffened cases are investigated by using the principle of minimum potential energy and smear-out technique typical of the fewer discrete and closely spaced small stiffeners. Critical buckling loads and mode shapes are obtained for cylinders with 4 and 20 stiffeners respectively.

References listed at the end of the paper:


ABSTRACT: This paper is concerned with the semi-analytical solution for the axisymmetric buckling for perfect complete thick orthotropic spherical shells and hemispherical shells under various edge conditions,
subjected to uniform full external pressures. The meridional and radial mid-surface displacements and the circumferential cross-sectional rotation are expressed as an expansion in Legendre polynomials respectively in the meridional coordinate. Transverse shear strain effects are included in the energy formulation of small strains. The solutions are achieved directly by use of the Ritz method without considering the force and moment equilibrium and solving the complicated governing equations. Critical buckling loads and the various modes are found from the equations by use of orthogonality and some integral relations.

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ABSTRACT: A three-dimensional vibration study is presented using the three-dimensional theory developed by Chao et al. [34–39] for a variety of simply supported shallow spherical, cylindrical, plate, and saddle (hyperbolic) panels in rectangular planform. A complete survey and comparison of existing literature have been made with excellent lowest frequencies via a 3-D augmented energy variational approach. In all of these shell configurations, natural frequencies are noted to decrease in the above-mentioned order according to minimum total potential energy in the natural state.

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ABSTRACT: A simple C0 isoparametric finite element formulation based on a shear deformable model of higher-order theory using a higher-order facet shell element is presented for the free vibration analysis of isotropic, orthotropic and layered anisotropic composite and sandwich laminates. This theory incorporates a realistic non-linear variation of displacements through the shell thickness, and eliminates the use of shear correction coefficients. The validity and efficiency of the present formulation is established by obtaining solutions to a wide range of problems and comparing them with the available three-dimensional closed-form and finite element solutions. In addition, other plate and shell solutions of different kind and available in the literature are also compiled and tabulated for the sake of completeness. The parametric effects of degree of orthotropy, length-to-thickness ratio, plate aspect ratio, number of layers and fibre orientation upon the frequencies and mode shapes are discussed.

References listed at the end of the paper:
ABSTRACT: This paper begins by presenting a Generalized Beam Theory (GBT) formulation for analyzing the vibration behavior of loaded composite thin-walled members, which accounts for the effects of (i) cross-section in-plane deformation, (ii) shear deformation, (iii) geometric and material coupling, (iv) primary, secondary and non-linear warping, and (v) rotary inertia. This formulation is then used to investigate the local and global vibration behavior of lipped channel columns and beams displaying cross-ply orthotropy, focusing on issues dealing with the variation of the fundamental frequency and vibration mode nature with the member length and applied stress level. For validation purposes, some GBT-based results are also compared with values obtained by means of 4-node shell finite element analyses using ABAQUS. Some relevant conclusions are drawn concerning the dependence of the member vibration mode shape (wave number) on the compression/bending level (applied-to-critical ratio).

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ABSTRACT: On the basis of Flügge's approximations and with account taken of the transverse shear deformation (SDT) and all rotatory inertias, the equations of in-plane buckling and free vibrations of multilayered, anisotropic, doubly curved shells are presented. As a particular case, the equations relative to Love's approximations and Donnell's approximations and as well as of the corresponding classical theories (CLT) are derived. Analytical exact solutions are presented for buckling under axial compression and free vibrations of cross-ply laminated, simply supported, circular cylindrical and spherical composite shells. Depending on geometric parameters of the shell (length to radius ratio a/R, length to thickness ratio a/h and radius to thickness ratio R/h), numerical results (in tables and figures) are quoted to compare the different theories, and some trends are singled out about the effects of both transverse shear deformations and curvatures of the shell. Particular attention is given to the application of Flügge's approximations in which are presented solutions of the equilibrium equations containing terms of the same order in h/R. Finally, the effects of coupled out-of-plane stiffnesses on the theories is investigated.

ABSTRACT: This paper deals with the non-linear analysis of multilayered axially compressed plates in the static elastic conservative cases. A finite element model based on a Reissner-Mindlin theory involving von Kármán nonlinearity is developed. Results related to the classical Kirchhoff plate approximations are obtained via application of a penalty technique to the shear correction factor. The numerical investigations have concerned the large deflections and postbuckling behaviour of symmetrically and non-symmetrically anisotropic flat panels. The main conclusions are: (1) the non-linear effects very much depend on lay-up and boundary conditions, moreover for the asymmetric laminated long plates the snapping-type instability occurs; (2) the shear deformation effects are very much subordinate to both multilayered lay-up and load levels,
furthermore they are greater in the large deflections field; (3) it has been observed that in the neighbourhood of a singularity (of buckling point type) of the tangent stiffness matrix, the use of an arc-length type algorithm could lead to a new buckled path and that happens without employing an appropriate turning bifurcation algorithm with an accompanying eigenvalues calculation, but via a non-convergent iteration in the loadstep.


ABSTRACT: This paper evaluates transverse normal stress effect on vibration of multilayered structures. To this purpose a mixed plate model initially introduced by Toledano and Murakami has been extended to dynamics analysis of double curved shells. These models allow both continuous interlaminar transverse shear and normal stresses as well as the zigzag form of the displacement distribution in the shell thickness directions to be modelled. Governing equations have been derived by employing a Reissner's mixed theorem. Classical models on the basis of standard displacement formulations have been considered for comparison purposes. The evaluations of transverse stress effects have been conducted by comparing constant, linear and higher order distributions of transverse displacement components in the plate thickness directions. Free vibrational response of layered, simply supported plates, cylindrical and spherical shells made of isotropic as well as orthotropic layers has been analyzed. The numerical investigation carried out and comparison with earlier results has concluded that:
1. The possibility of describing interlaminar continuous transverse normal stress makes the mixed theories more attractive with respect to other available modelling.
2. Any refinements of classical models are meaningless, unless the effects of interlaminar continuous transverse shear and normal stresses are both taken into account in a multilayered shell theory.

E. Carrera, L. Mannella, G. Augello, et al, “A two-level optimization feature for the design of aerospace structures”, Proceedings of the…2003 – Prof Eng Publishing (A click on this entry takes us to a journal name, not to the paper. Therefore, more information about the authors and date of publication and abstract are not available for this citation)

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ABSTRACT: Beam models are widely used to investigate the mechanical behavior of slender bodies such as aircraft wings, wind turbines, and slender bridges. Classical beam theories are those by Euler-Bernoulli and Timoshenko [1] which are particularly effective in analyzing the bending of compact slender structure made of isotropic materials. As the structure becomes thin-walled, short, or composite materials are used, classical model validity ceases since a number of non-classical effects has to be taken into account: warping, cross-section distortion, shear effects, etc.. The overcome of these limitations can be obtained by adopting refined beam models. Interesting papers on this topic are those by Kapania and Raciti [2, 3], and Yu and Hodges [4].
References listed at the end of the paper:


ABSTRACT: The present work evaluates the effect of thickness stretching in plate/shell structures made by materials which are functionally graded (FGM) in the thickness directions. That is done by removing or retaining the transverse normal strain in the kinematics assumptions of various refined plate/shell theories. Variable plate/shell models are implemented according to Carrera’s Unified Formulation. Plate/shell theories with constant transverse displacement are compared with the corresponding linear to fourth order of expansion in the thickness direction ones. Single-layered and multilayered FGM structures have been analyzed. A large numerical investigation, encompassing various plate/shell geometries as well as various grading rates for FGMs, has been conducted. It is mainly concluded that a refinements of classical theories that include additional in-plane variables could results meaningless unless transverse normal strain effects are taken into account.


ABSTRACT: The free vibration analysis of thin- and thick-walled layered structures via a refined one-dimensional (1D) approach is addressed in this paper. Carrera unified formulation (CUF) is employed to introduce higher-order 1D models with a variable order of expansion for the displacement unknowns over the cross section. Classical Euler–Bernoulli (EBBM) and Timoshenko (TBM) beam theories are obtained as particular cases. Different kinds of vibrational modes with increasing half-wave numbers are investigated for short and relatively short cylindrical shells with different cross section geometries and laminations. Numerical results of natural frequencies and modal shapes are provided by using the finite element method (FEM), which permits various boundary conditions to be handled with ease. The analyses highlight that the refinement of the displacement field by means of higher-order terms is fundamental especially to capture vibrational modes that require warping and in-plane deformation to be detected. Classical beam models are not able to predict the
realistic dynamic behavior of shells. Comparisons with three-dimensional elasticity solutions and solid finite element solutions prove that CUF provides accuracy in the free vibration analysis of even short, nonhomogeneous thin- and thick-walled shell structures, despite its 1D approach. The results clearly show that bending, radial, axial, and also shell lobe-type modes can be accurately evaluated by variable kinematic 1D CUF models with a remarkably lower computational effort compared to solid FE models.

M. Cinefra, E. Carrera and S. Valvano (Dept. of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy), “Free-vibration analysis of delaminated shells via unified formulation”, (publisher and date not given in the pdf file. The most recent citation is dated 2014.)
ABSTRACT: The present work deals with the free-vibration analysis of multilayered composite shells affected by localised delaminations. The delamination in composite structures may occur either during the manufacturing process or during service period of the structure. Delaminations can be distinguished into two types, one delamination at the free edges caused by high free edge stresses, and the other embedded within the body of the structure which may be due to manufacturing defects or voids, or due to impact loads. To facilitate the understanding of the effect of the delamination on the structures, and to analyze possible algorithms for structural health monitoring of delaminated structures, delamination models are required. Several authors have studied delaminated shells, like Nanda and Sahu have carried out free vibration analysis of delaminated composite shells [1] using different shell theories. Dynamic instability of delaminated skew plates subjected to static and dynamic loads based on higher order shear deformation theory was studied out by Noh and Lee [2]. These works used a single theory or couple of theories to carry out their studies. The proposed investigation tries to comprehensively carry out free vibration analysis of delaminated composite shells using refined and advanced shell models, contained in the Carrera’s Unified Formulation (CUF). One of the most interesting features of the CUF consists in the possibility to keep the order of the expansion of the state variables along the thickness of the plate as a parameter of the model. Finite elements with layer-wise capabilities are employed to ensure an accurate description of the mechanical fields in the layers. It is essential to take into account the discontinuity of the mechanical properties at the layer interfaces. For these reasons, the use of classical plate theories based on Kirchhoff and Reissner-Mindlin hypotheses can lead to inaccurate results. The Mixed Interpolated Tensorial Components (MITC) method is employed to contrast the membrane-shear locking phenomenon that usually affects shell finite elements. This formulation has already shown all its potentiality as a base for finite elements in the mechanical analysis of multilayered shells [3]. Some results from the free-vibration analysis of shells will be provided, in order to show the efficiency of models presented.

References listed at the end of the paper:

ABSTRACT: Linearized buckling analysis of laminated plates subjected to combined bi-axial/shear loading is described in this work. Isotropic, orthotropic and anisotropic plates are referred to. Two-dimensional plate
modelling is considered. The Principle of Virtual Displacement (PVD) is applied. The Finite Element Method (FEM) is adopted in order to approximate the solution. The same cases-study are handled using different kinds of plate Finite Elements (FEs), with the purpose of providing some guidelines/benchmarks useful for identifying the most appropriate modelling for each class of buckling problem. The considered set of FEs is hierarchical in the sense that a variable kinematics approach is employed: both Equivalent Single Layer (ESL) and Layer-Wise (LW) variable descriptions are implemented, keeping the expansion order for thickness variables generic. FE matrices are obtained in compact form by referring to Carrera’s Unified Formulation (CUF). When available, exact solutions are referred to in order to assess the FEM results.

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ABSTRACT: Buckling is one of the characteristic failure modes of slender laminated and sandwich structures like plates and shells. It is well known that a rational design of composite structures demands dedicated models in order to cope with their complex behavior due to the heterogeneous multilayered cross-section, the characteristic transverse shear deformability and the coupled membrane-bending-twisting response. These peculiarities increase the complexity of the buckling behavior of composite shells [1]. This paper presents a rigorous assessment of various 2D approximations against buckling of laminated and sandwich plate/shell models. For this, the established variable kinematics modeling technique known as Carrera’s Unified Formulation (CUF) is employed. CUF permits a systematic assessment of a large number of plate/shell models, whose accuracy has been demonstrated to range from classical 2D models to quasi-3D descriptions [2]. By referring to the closed-form solution of Navier, the attention is restricted to simply-supported, orthotropic laminates and sandwich plates and cylindrical shells under axial load. Two different pre-buckling states are addressed, i.e., a uniform initial stress and a uniform initial strain load.
References listed at the end of the paper:

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ABSTRACT: The buckling of thin-walled structures is presented using the 1D finite element based refined beam theory formulation that permits us to obtain N-order expansions for the three displacement fields over the section domain. These higher-order models are obtained in the framework of the Carrera unified formulation (CUF). CUF is a hierarchical formulation in which the refined models are obtained with no need for ad hoc
formulations. Beam theories are obtained on the basis of Taylor-type and Lagrange polynomial expansions. Assessments of these theories have been carried out by their applications to studies related to the buckling of various beam structures, like the beams with square cross section, I-section, thin rectangular cross section, and annular beams. The results obtained match very well with those from commercial finite element softwares with a significantly less computational cost. Further, various types of modes like the bending modes, axial modes, torsional modes, and circumferential shell-type modes are observed.

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De Xie and Sherrill B. Biggers, Jr. (Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, USA), “Postbuckling analysis with progressive damage modeling in tailored laminated plates and shells with a cutout”, Composite Structures, Vol. 59, No. 2, February 2003, pp. 199-216, doi:10.1016/S0263-8223(02)00233-7

ABSTRACT: An approach to modeling inplane damage progression in postbuckled laminated composite panels is shown to be accurate by comparison to experimental test data from other sources. A simple tailoring concept is shown to be very effective in increasing compressive buckling loads and ultimate loads for flat plates and curved panels with a central cutout. Effects of cutout size, the degree of tailoring, and inplane restraint on the unloaded edges are investigated. Optimal tailoring produces relative improvements in the flat plates ranging from 40% to 175% in buckling load and 190–240% in ultimate load capacity when compared to uniform plates with the same cutout sizes. In the curved panels, tailoring lowers the imperfection sensitivity and in some cases produces ultimate loads greater than the theoretical undamaged buckling loads. To the contrary, the ultimate load for the uniform curved panel is much lower than the undamaged buckling load. Relative improvements in ultimate loads range from a low of about 40% to a high of about 155% compared to uniform curved panels. Large differences in the damage initiation locations and damage progression patterns are shown between the flat and the curved panels. In summary, the tailoring concept investigated here can provide excellent improvements in ultimate load capacity in flat and curved panels with the largest benefits occurring in thin flat panels that are loaded far into the compressive postbuckling regime.

References listed at the end of the paper:

ABSTRACT: This paper discusses the development and application of two alternative strategies, in the form of global and sequential local response surface (RS) techniques, for the solution of reliability-based optimization (RBO) problems. The problem of a thin-walled composite circular cylinder under axial buckling instability is used as a demonstrative example. In this case, the global technique uses a single second-order RS model to estimate the axial buckling load over the entire feasible design space (FDS), whereas the local technique uses multiple first-order RS models, with each applied to a small subregion of the FDS. Alternative methods for the calculation of unknown coefficients in each RS model are explored prior to the solution of the optimization problem. The example RBO problem is formulated as a function of 23 uncorrelated random variables that include material properties, the thickness and orientation angle of each ply, the diameter and length of the cylinder, as well as the applied load. The mean values of the 8 ply thicknesses are treated as independent design variables. While the coefficients of variation of all random variables are held fixed, the standard deviations of the ply thicknesses can vary during the optimization process as a result of changes in the design variables. The structural reliability analysis is based on the first-order reliability method with the reliability index treated as the design constraint. In addition to the probabilistic sensitivity analysis of the reliability index, the results of the RBO problem are presented for different combinations of cylinder length and diameter and laminate ply patterns. The two strategies are found to produce similar results in terms of accuracy, with the sequential local RS technique having a considerably better computational efficiency.


ABSTRACT: Postbuckling analysis of composite laminates representative of wind turbine blade substructures, utilizing the commercial finite element software ANSYS, is presented in this paper. The procedure was validated against an existing postbuckling analysis. Three shell element formulations, SHELL91, SHELL99,
and SHELL181, were examined. It was found that the SHELL181 element with reduced integration should be used to avoid shear locking. The validated procedure was used to examine the variation of the buckling behavior, including postbuckling, with lamination schedule of a laminate representative of a wind turbine blade shear web. This analysis was correlated with data from a static test. A 100% postbuckling reserve in a composite structure representative of a shear web was quantified through test and analysis. The buckling behavior of the shear web was improved by modifying the lamination schedule to increase the web bending stiffness. Modifications that improved the buckling load of the structure did not always equate to improvements in the postbuckling reserve.


ABSTRACT: This paper deals with development of triangular finite element for buckling and vibration analysis of laminated composite stiffened shells. For the laminated shell, an equivalent layer shell theory is employed. The first-order shear deformation theory including extension of the normal line is used. In order to take into account a non-homogeneous distribution of the transverse shear stresses a correction of transverse shear stiffness is employed. Based on the equivalent layer theory with six degrees of freedom (three displacements and three rotations), a finite element that ensures C0 continuity of the displacement and rotation fields across inter-element boundaries has been developed. Numerical examples are presented to show the accuracy and convergence characteristics of the element. Results of vibration and buckling analysis of stiffened plates and shells are discussed.

R. Rikards, K. Kalnins & O. Ozolinsh (Institute of Materials and Structures, Riga Technical University, Riga 1658, Latvia), “Skin-Stringer Debonding and Delamination Analysis in Composite Stiffened Shells”, (no publisher or date given in the pdf file; most recent reference is 2002)

ABSTRACT: In the present paper the skin-stringer delamination problem for composite stiffened shells is solved. The skin-stringer delamination is analyzed employing linear fracture mechanics approach. Energy release rates (ERR) are calculated by Modified Virtual Crack Closure Integral (MVCCI) method. The problem is solved not using the 3D solid finite elements, but employing the 2D shell elements. Employment of the 2D shell elements instead of 3D elements significantly reduces computational efforts in the case when whole composite stiffened structure is analyzed for post-buckling. Mode I, mode II and mixed mode I/II fracture properties are obtained for the fracture criterion of the carbon/epoxy composite laminate. The fracture criterion is used for prediction of debonding at the skin-stringer interface.

References listed at the end of the paper:
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ABSTRACT: The development of an optimization design procedure for stiffened composite shells has emerged as an essential component in overcoming the challenge of deriving design guidelines with a reasonable amount of tested structures. The optimization procedure is based on the building of surrogate models employing the experimental design and response surface methodology. Surrogate models are built using continuous and discrete quantitative parameters and approximated with global and local nonparametric approximations. The numerical data obtained from finite element simulations of composite stiffened shells subjected to buckling and post-buckling is used for the building of surrogate models. Additionally a data set of natural experiments has been implemented into surrogate models showing high efficiency in the estimation of the post-buckling behavior of the stiffened composite shells (panels). The resulting design procedure provides an effective optimal design tool for the preliminary study of composite stiffened shells.

ABSTRACT: The intense interest coming from the aerospace industry indicates the need of safe exploitation of composite materials within post-buckling region. Since stiffened curved panels are by far the most consumed...
structural component, it is important to study the behavior of structural degradation to evaluate the safe design guidelines. An assessment of structural degradation in terms of stiffness reduction in the skin stringer zone is carried out to estimate the degradation influence on the postbuckling stiffness of the axially loaded stiffened panels. The presented procedure is based on the building of metamodels employing experimental design and response surface methodology. Metamodels are built using stiffened shell geometrical variables adding structural degradation variables such as degradation region length ratio and material elastic property reduction coefficient. The numerical responses, obtained from explicit FEM simulations of composite stiffened shells subjected to buckling and post-buckling, are used for the building of metamodels. The resulting design procedure provides an effective analysis tool for the safe exploitation of composite stiffened panels under axial compression.

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“Overview of Slow Computational and Fast Simulation Tools”, (COCOMAT project, publisher and date not given in the pdf file; most recent reference is September 2008)

ABSTRACT: The paper overviews the progress achieved by the European Commission funded project COCOMAT [1] work package devoted to the development of improved simulation procedures for collapse of composite airframe structures, which take degradation into account. It has been identified by industrial applications that very accurate, but necessarily slow tools are required for the final certification, whereas reliable fast tools reducing design and analysis time by an order of magnitude, will allow for an economic design process. Twelve industrial and academic partners have been involved in the extension of commercial analysis software such as SAMCEF, B2000, ABAQUS, MSC.MARC, MSC.NASTRAN and improvement of in-house tools. In general, structural degradation has been implemented as growth of skin-stringer separation and delamination in the stiffened composite structures. Interlaminar fracture growth criteria have been implemented by means of Virtual Crack Closure Technique (VCCT) and Virtual Crack Extension (VCE) Method. Furthermore stress/strain based failure criteria such as Hashin, Puck and Maximum Stress have been introduced to model initiation and progression of the ply damage. Finally, all developed tools have been validated by means of the experimental results obtained from the other work packages within the COOCMAT project. Among the validation experiments were: double cantilever beam, end-notched flexure and mixed mode stiffener specimens together with stiffened panel and box structures with pre-existing and industrially pre-selected damage.

Acknowledgment: This work was supported by the European Commission, Competitive and Sustainable Growth Programme, Contract No. AST3-CT-2003-502723, project COCOMAT

References listed at the end of the paper:
ABSTRACT: The structural behaviour of composite stiffened flat panels under axial compression is here investigated up to collapse. The panel configuration is designed to buckle once the limit load is reached and to work in post-buckling until the ultimate load. The design phase is based on the use of four different kinds of finite element analyses: eigenvalue, non-linear static with modified Riks’ method and both implicit and explicit dynamic analyses. Once the final configuration is identified, two specimens are manufactured. The initial geometrical imperfections are measured and analyzed, then axial compression tests are performed until collapse. As foreseen by the numerical analyses, experimental results prove the ability of the panels designed to work in the post-buckling field until collapse which takes place due to the failure of the stiffener blades. Finally, the measured initial imperfections are included in the model significantly increasing the numerical–experimental correlation

ABSTRACT: A multi-objective optimization procedure for the design of composite stiffened panels capable to operate in post-buckling is presented. The procedure is based on Genetic Algorithms and three different methods of global optimization: Neural Networks, Radial Basis Functions and Kriging approximation. Response surfaces are used to approximate the post-buckling behaviour of the panels using a limited number of sample points. Optimization results underline the significance of non-dominated solutions, as the best panel configurations inside the domain of interest. Finally, one of the non-dominated solutions is selected, manufactured and tested up to collapse. The analyses, performed a priori without considering any kind of imperfection, are closed and in good agreement with the tests in terms of pre-buckling and post-buckling stiffness, as well as in terms of collapse loads. The introduction of imperfections reduced the percentage errors between computations and tests within 5% in so far as buckling and collapse loads are concerned. The obtained results prove the influence of the initial imperfections not only on the first-buckling load but also in the post-buckling range up to collapse.

Carlos A. Coello Coello (Laboratorio Nacional de Informática Avanzada, Rébsamen 80, Xalapa, Veracruz 91090, México), “Constraint-handling using an evolutionary multiobjective optimization technique”, (publisher and date not given in the pdf file)

ABSTRACT: In this paper we introduce the concept of non-dominance (commonly used in multiobjective optimization) as a way to incorporate constraints into the fitness function of a genetic algorithm. Each individual is assigned a rank based on its degree of dominance over the rest of the population. Feasible individuals are always ranked higher than infeasible ones, and the degree of constraint violation determines the rank among infeasible individuals. The proposed technique does not require fine tuning of factors like the traditional penalty function and uses a self-adaptation mechanism that avoids the traditional empirical adjustment of the main genetic operators (e.g., crossover and mutation).


ABSTRACT: In order to improve confidence in composite structure design, a better description of the failure of laminates is necessary. In this paper the buckling and postbuckling behaviour of axially compressed layered composite panels is studied by means of Finite Element Method (FEM). A series of experiments was conducted to verify the FEA-results, but also to address the stability and strength of the composite structure. Combining a geometric nonlinear finite element analysis (FEA) based on the von Kármán theory and High Order Shear Deformation Theory (HOST) are used to study the first-ply failure behavior as well as the postbuckling behavior of laminated type composite structures. For this purpose and for the investigation of the failure responses, the improved 4-node layered shell finite elements are used. The finite element formulation is based on the third order shear deformation theory with four-node shell finite elements having eight degrees of freedom per node. A simple method is proposed to predict buckling loads and the post-buckling behaviour. The comparisons between the numerical and the experimental results show quite a good agreement.

References listed at the end of the paper:

ABSTRACT: This paper deals with the formulation of beam elements for the numerical analysis of instability phenomena in frame-type structures. Total versus co-rotational approaches are discussed comparatively, for both two-dimensional and three-dimensional problems, and the similarities between the two types are outlined.

In the context of 3D beam elements, special attention is given to the parameterisation of the orthogonal transformation used to define the rotational field of the beam. The technique advocated in the paper is based on the so-called rotational vector. This leads to symmetric stiffness matrices and avoids the need for special updating procedures for the rotational variables. A set of test problems, for which the critical behaviour is governed by fold, cusp and butterfly catastrophes, is used to assess the performances of the considered element types. It is shown that analytically verified identities in element formulation, also hold in numerical application. The examples also show how complex instability behaviour can be reproduced by all elements, where sufficient accuracy is introduced into the kinematic expressions. The analytical derivation of element expressions, with symbolic manipulations from stated basic assumptions, is consistently used in the paper.

ABSTRACT: This paper investigates the formulation of co-rotational flat facet triangular elements for the numerical analysis of instability phenomena in shell structures. The elements have three nodes with six degrees of freedom at each node. The term ‘co-rotational’ relates here to the provision of a local system that continuously rotates and translates with the element. Following mainly Nour-Omid and Rankin [B. Nour-Omid and C.C. Rankin, Finite rotation analysis and consistent linearization using projectors, Comput. Methods Appl. Mech. Engrg. 93 (1991) 353–384], the definition of an element resorts to a change of variables from the local frame to the global one. This is done through the use of a projector matrix which relates the variations of the local displacements to the variations of the global ones, by extracting the rigid body modes from the latter. The main difference from the original formulation lies in the parameterization of 3D finite rotations. In contrast to the paper by Nour-Omid and Rankin, a parameterization based on the rotational vector is here adopted and thus, an additional change of variables has to be performed. As a result, the rotational variables become additive and the necessity of a special updating procedure is avoided. The main feature of the adopted formulation is its independence of the local assumptions used to derive the internal forces and tangent stiffness in local coordinates. For a certain class of elements (i.e. elements with the same number of nodes and degrees of freedom) the main co-rotational framework is the same. Using this property, three types of local formulations are considered. A set of carefully chosen test problems is used in order to assess the performances of the three element types.

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ABSTRACT: The paper describes how quasi-static, conservative instability problems can be analysed in a multi-parametric space, using generalised path-following procedures for augmented equilibrium problems. The general formulation of such augmented equilibrium problems is discussed in some detail. The focus is set on two classes of generalised 1D paths: basic equilibrium paths and fold lines, i.e. critical subset paths. The solution methods are seen as extensions to common incremental-iterative strategies, allowing the computation of subsets of equilibrium states which also fulfil some auxiliary conditions, e.g. criticality. In this context, some emphasis is also given to the evaluation of the properties of the problem, at a certain state; the tangential stiffness is here used to evaluate – possibly multidimensional – tangent spaces, and in the isolation of special states, i.e. vanishing variables, turning points and exchanges of stability, being important aspects of instability analyses. A set of carefully chosen numerical examples demonstrate on one hand the ability of the numerical procedures to deal with complex instability phenomena, including coincident or near coincident buckling modes, modal interaction, secondary bifurcations, and, on the other hand, their versatility in performing parameter sensitivity analyses. Finally, comparisons with alternative techniques, based on asymptotic strategies, are also put forth.

ABSTRACT: This paper discusses some aspects of FEM based shell instability analyses. The primary focus is on the properties of different element formulations. A co-rotational setting is used for the large-displacement, small-strain form. Three core elements are briefly described. Numerical examples show that, although the elements show very similar behaviours in the linear regime, the differences in results for non-linear and instability problems may be considerably larger.

References cited at the end of the paper:
ABSTRACT: We show that mode jumping in the buckling of a rectangular plate may be explained by a secondary bifurcation — as suggested by Bauer et al. [1] — when “clamped” boundary conditions on the vertical displacement function are assumed. In our analysis we use the singularity theory of mappings in the presence of a symmetry group to analyse the bifurcation equation obtained by the Lyapunov-Schmidt reduction applied to the Von Kármán equations. Noteworthy is the fact that this explanation fails when the assumed boundary conditions are “simply supported”. Mode jumping in the presence of “clamped” boundary conditions was observed experimentally by Stein [9]; “simply supported” boundary conditions are frequently studied but are difficult — if not impossible — to realize physically. Thus, it is important to observe that the qualitative post-buckling behavior depends on which idealization for the boundary conditions one chooses.

References listed at the end of the paper:
ABSTRACT: The buckling of thin elastic rectangular plates due to two arrays of edge dislocations symmetrically placed with respect to the longitudinal axis of the plate is studied for two different dislocation orientations. The analysis is based on the governing equation of plate buckling. Through a standard eigenvalue analysis the buckling criterion is analytically-numerically computed and numerical results are presented pertaining to cases of practical engineering interest such as welding.

References listed at the end of the paper:


ABSTRACT: This work is concerned with the numerical study of unsymmetrical buckling of clamped orthotropic plates under uniform pressure. The effect of material heterogeneity on the buckling load is examined. The refined 2D shell theory is employed to obtain the governing equations for buckling of a clamped circular shell. The unsymmetric part of the solution is sought in terms of multiples of the harmonics of the angular coordinate. A numerical method is employed to obtain the lowest load value, which leads to the appearance of waves in the circumferential direction. It is shown that if the elasticity modulus decreases away from the center of a plate, the critical pressure for unsymmetric buckling is sufficiently lower than for a plate with constant mechanical properties.

References listed at the end of the paper:
ABSTRACT: The qualitative behavior of buckled states of two different models of elastic beams is studied. It is assumed that random imperfections affect the governing nonlinear equations. It is shown that near the first critical value of the buckling load the stochastic bifurcation is described asymptotically by an algebraic equation whose coefficients are Gaussian random variables. The corresponding asymptotic expansion for the displacement is to lowest order a Gaussian stochastic process.

References listed at the end of the paper:
third beam model based on the second-order approximation of finite rotations is also discussed along with its application to constructing a consistent formulation of the linear eigenvalue problem for computing an estimate of the critical load. Exact linearized forms, which are crucial for facilitating the buckling load computation and assuring a robust performance of a Newton-method-based continuation strategy, are presented for all three beam models. An elaborate set of numerical simulations of buckling and post-buckling analysis of beam structures is given in order to illustrate the performance of each of the presented models. Finally, some conclusions are drawn.


**ABSTRACT:** The paper deals with the formulation of plate and shell elements based on the discrete Kirchhoff technique. In the first part we review the flat facet shell elements which have been formulated during the last 30 years. In the second part, we present the formulation of a new family of discrete Kirchhoff plate/shell elements based on the free formulation. The triangular, quadrilateral, pentagonal and hexagonal elements belong also to the family of semi-Loof elements having only displacements at the corner nodes and one tangential rotation along each side.


**ABSTRACT:** The mixed degenerate shell finite element DDSE, incorporating drilling degrees of freedom, is dedicated to solve some engineering applications directly and without any numerical tricks. This finite element has shown good performances in the linear and nonlinear, isotropic and anisotropic, static problems. Thanks to the application of shear and membrane substituted strain fields; it is also free from any locking. The very satisfactory results obtained by its previous application to the nonlinear dynamic regime have suggested the present work. The formulation of the problem, the derivation of the time integration scheme and the mass matrix were conducted in the most appropriate way to deal with the dynamic buckling load prediction. Both geometrical and material nonlinearities are considered in this study. The general stability criterion of Budiansky-Ruth is used, together with the phase plane control to detect the critical dynamic buckling load. In order to evaluate the accuracy of the element and the effect of the plasticity on the critical dynamic buckling value, two selected and documented examples of the critical dynamic buckling load determination were treated.


**ABSTRACT:** An improved arc-length method based on the nonlinear finite element approach is applied to the postbuckling analysis of composite laminated cylindrical panels under axial compression. In the non-linear finite element analysis, the updated Lagrangian formulation and the eight-node degenerated shell element are used. The composite cylindrical panels considered as numerical examples are unidirectional, cross-ply, angle-ply, and quasi-isotropic laminates. Experiments are conducted to verify the validity of the present analysis for a cross-ply laminate. Present finite element results show good agreement with experiments on buckling and
postbuckling behaviour. There exist some differences between the initial buckling loads and the postbuckling load-carrying capacities of composite cylindrical panels.


ABSTRACT: Based on the conventional arc-length method, an improved arc-length method with high-efficiency is proposed. The weighted modifications with respect to the variation of structural stiffness and extra-interpolation modification by using the information of known equilibrium points are introduced to improve the incremental arc-length. An approximate expansion method for the accumulated and expected arc-length is used to ensure the convergence at given load levels in large range of applications. Numerical results show that the improved arc-length method has well adaptability and higher efficiency in the post-buckling analysis of plates and shells structures for tracing whole load-deflection path and obtaining the convergence values at any specified load levels.

References listed at the end of the paper:

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ABSTRACT: A combined experimental and analytical study of a hat-stiffened carbon-fibre composite panel loaded in uniaxial compression was investigated. A buckling mode transition was observed in the panel’s skin bay which was not captured using non-linear finite-element analysis. Good correlation between experimental and numerical strain and displacement results was achieved in the prebuckling and initial postbuckling region of the loading history. A Marguerre-type Rayleigh-Ritz energy method was applied to the skin bay using representative displacement functions of permissible mode shapes to explain the mode transition phenomenon. The central criterion of this method was based on the assumption that a change in mode shape occurred such that the total potential energy of the structure was maintained at a minimum. The ultimate strength of the panel was limited by the column buckling strength of the hat-stiffeners.

ABSTRACT: The postbuckling behaviour of a panel with blade-stiffeners incorporating tapered flanges was experimentally investigated. A new failure mechanism was identified for this particular type of stiffener. Failure was initiated by mid-plane delamination at the free edge of the postbuckled stiffener web at a node-line. This was consistent with an interlaminar shear stress failure and was calculated from strain gauge measurements using an approximate analysis based on lamination theory and incorporating edge effects. The critical shear stress was found to agree well with the shear strength obtained from a three-point bending test of the web laminate.


ABSTRACT: Damage tolerant hat-stiffened thin-skinned composite panels with and without a centrally located circular cutout, under uniaxial compression loading, were investigated experimentally and analytically. These panels incorporated a highly postbuckling design characterised by two integral stiffeners separated by a large skin bay with a high width to skin-thickness ratio. In both configurations, the skin initially buckled into three half-wavelengths and underwent two mode-shape changes; the first a gradual mode change characterised by a central deformation with double curvature and the second a dynamic snap to five half-wavelengths. The use of standard path-following non-linear finite element analysis did not consistently capture the dynamic mode change and an approximate solution for the prediction of mode-changes using a Marguerre-type Rayleigh-Ritz energy method is presented. Shortcomings with both methods of analysis are discussed and improvements suggested. The panels failed catastrophically and their strength was limited by the local buckling strength of the hat stiffeners.


ABSTRACT: A postbuckling blade-stiffened composite panel was loaded in uniaxial compression, until failure. During loading beyond initial buckling, this panel was observed to undergo a secondary instability characterised by a dynamic mode shape change. These abrupt changes cause considerable numerical difficulties using standard path-following quasi-static solution procedures in finite element analysis. Improved methods such as the arc-length-related procedures do better at traversing certain critical points along an equilibrium path but these procedures may also encounter difficulties in highly non-linear problems. This paper presents a robust, modified explicit dynamic analysis for the modelling of postbuckling structures. This method was shown to predict the mode-switch with good accuracy and is more efficient than standard explicit dynamic analysis.

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References listed at the end of the paper:
[5] Cecchini LS, Weaver PM. The Brazier effect in multi-bay aerofoil sections, University of Bristol, UK.


ABSTRACT: In this report the strength of a wind turbine blade is found and compared with a full-scale test, made in the same project. Especially the postbuckling behaviour of the compression flange is studied. Different compressive failure mechanisms are discussed and the limitations in using the Finite Element Method. A suggestion to the further work is made.

References listed at the end of the report:
[1] Risø-R-1390(EN) "Fundamentals for improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report" Bent F. Sørensen, AFMISBN 87-550-3176-5; ISBN 87-550-3177-3(Internet) ISSN 0106-2840
[4] Risø-R-1394(EN) "A general mixed mode fracture mechanics test specimen for characterising adhesive joints" Bent F. Sørensen, AFMISBN 87-550-3186-2; ISBN 87-550-3187-0(Internet) ISSN 0106-2840

ABSTRACT: This paper presents a robust finite element procedure for modelling the behaviour of postbuckling structures undergoing mode-jumping. Current non-linear implicit finite element solution schemes, found in most finite element codes, are discussed and their shortcomings highlighted. A more effective strategy is presented which combines a quasi-static and a pseudo-transient routine for modelling this behaviour. The switching between these two schemes is fully automated and therefore eliminates the need for user intervention during the solution process. The quasi-static response is modelled using the arc-length constraint while the pseudo-transient routine uses a modified explicit dynamic routine, which is more computationally efficient than standard implicit and explicit dynamic schemes. The strategies for switching between the quasi-static and pseudo-transient routines are presented.


ABSTRACT: The phenomenon of secondary instabilities in stiffened composite panels loaded in uniaxial compression is studied through a number of experimental investigations. This behavior is shown to manifest itself as a ‘mode-jump’ – a sudden change in the out-of-plane deformation of a buckled panel. Use of high-speed digital speckle photogrammetry is made to gain further insight into an I-stiffened panel’s response during the transient phase associated with mode-jumping. At high loading, this sudden dissipation of energy will be shown to be able to cause failure in vulnerable structures. Predicting this structural response reliably, using the finite element method, poses considerable numerical challenges and the shortcomings of current non-linear solution schemes are discussed. A robust and efficient strategy, which utilizes an automated quasi-static/pseudo-transient hybrid scheme, is presented and validated using a number of experimental tests. This approach is shown to be able to predict mode-jumping with good accuracy.


ABSTRACT: A theoretical analysis is presented for determining the free vibrational characteristics of thin-walled, circular cylindrical shells with layers of anisotropic elastic material arbitrarily laminated either symmetrically or unsymmetrically about the shell middle surface. An arbitrarily laminated, anisotropic version of Love's first-approximation shell theory is used to formulate the coupled equations of motion. An exact solution with a classical checkerboard nodal pattern is found for the case of a shell with specially orthotropic layers arbitrarily laminated and with freely supported ends. For a boron/epoxy composite cylinder, the significant effect of omitting bending-stretching coupling is demonstrated and various lamination arrangements are investigated. Also, a general solution is presented for the axisymmetric modes of an arbitrarily laminated anisotropic shell. Finally, an approximate solution, using a combination of two helical-nodal-pattern modes, is obtained for the unsymmetric modes of the same general class of shell with a supported boundary condition.

ABSTRACT: The plate theory recently developed by Levinson is extended to laminates. Closed-form solutions of this theory, as well as those of Reissner-Mindlin plate theory with appropriate shear correction, Seide's discrete-layer plate theory, and the higher-order theory of Lo et al. are all compared with Pagano's elasticity-theory solution for the cases of cylindrical bending of a single orthotropic layer and a symmetric cross-ply (0°/90°/0°) laminate consisting of three equal-thickness layers. Quantities compared are maximum plate deflection, bending stress distribution and transverse shear stress distribution.


ABSTRACT: The dynamic instability of simply supported, finite-length, circular cylindrical shells subjected to parametric excitation by axial loading, is investigated analytically. The shell is taken to be orthotropic, due to closely spaced longitudinal and/or circumferential stiffeners or to many layers of fiber-reinforced composite material either oriented at angles of 0° and 90° (cross-ply) or at +theta and –theta (angle-ply) with respect to the shell axis. The theory used is a general first-order shear deformable shell theory introduced by Hsu, Reddy, and Bert; it can be considered to be the thick-shell version of the popular Sanders-Koiter thin-shell theory. By means of tracers, this theory can be reduced to thick-shell versions of the theories of Love (and Loo) and of Donnell (and Morley). Quantitative results are presented to show the effects of shell geometry, materials, and fiber orientation on the stability boundaries.

References listed at the end of the paper:


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ABSTRACT: Initial buckling of an elastic coating perfectly bonded to a circular-section prismatic bar subjected to axial extension is investigated analytically. The phenomenon is associated with the substrate Poisson contraction. Two different models of the coating are used: the first is based on classical thin-shell theory and the other is based on first-order shear-deformation shell theory. The results for typical examples are compared and used to explain cracking of the coating previously observed experimentally.

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ABSTRACT: The dynamic stability of thin, multi-layered composite shells reinforced by axial and ring stiffeners and subjected to pulsating loads acting in the axial direction is considered. The presence of a thermal field is shown to affect the location of dynamic instability regions in the load amplitude-frequency plane. The boundaries of these regions can be evaluated as functions of static critical loads, natural frequencies, and thermal terms; the latter can be easily calculated. This permits straightforward conclusions to be drawn regarding dynamic stability of shells for which the buckling and free vibration problems have already been solved.
References listed at the end of the paper:


ABSTRACT: Effects of temperature on buckling and post-buckling behavior of reinforced and unstiffened composite plates or cylindrical shells are considered. First, equilibrium equations are formulated for a shell subjected to the simultaneous action of a thermal field and an axial loading. These equations are used to predict a general form of the algebraic equations describing the post-buckling response of a shell. Conditions for the snap-through of a shell subjected to thermomechanical loading are formulated. As an example, the theory is applied to prediction of post-buckling response of flat large-aspect-ratio panels reinforced in the direction of their short edges.


ABSTRACT: A new approach to apply the differential quadrature method to the deflection, buckling, and free vibration analysis of beams and plates with various boundary conditions is presented. A different method for application of the beam boundary conditions, proposed earlier by Wang and Bert, is extended to clamped-fixed, simply supported-fixed, and fixed-fixed beams and excellent results are obtained. It is found that the differential quadrature method gives less accurate results for the buckling load when the plate aspect ratio a/b exceeds 2.45
for the cases considered and possible reasons for this are discussed.


ABSTRACT: Laminated composite, circular cylindrical hollow shafts are used extensively as primary load-carrying structures in many applications under various loading configurations. Advanced composite materials also seem ideally suited for long, power drive-shaft applications. At the same time, from a design point of view, local and general instability arising from the action of torsional loads often represents the limiting load condition. In the present study, a theoretical analysis is presented for determining the buckling torque of a circular cylindrical hollow shaft with layers of arbitrarily laminated composite materials by means of various thin-shell theories. Comparisons with previous investigations are listed for isotropic and arbitrarily laminated composite material drive shafts. Consideration is also given to the various shell theories, such as those of Flügge, Sanders, Love (first approximation), Loo, Morley, and Donnell. The effect of the off-axis stiffnesses and the bending moment on buckling torque is considered.


PARTIAL ABSTRACT: Classical plate theory (CPT) is generally credited to Kirchhoff over 125 years ago. . . References listed at the end of the paper:


ABSTRACT: This paper investigates analytically certain refinements in the nonlinear analysis of tubes undergoing axial bending, with emphasis on thick-walled effects, axial moment of inertia, circumferential bending and membrane action, and higher-order terms in angular position.

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ABSTRACT: Modeling the complex deformations of cylindrical tubes under external pressure is of interest in engineering and physiological applications. The highly nonlinear post buckling behavior of cross section of the tube during collapse attracted researchers for years. Major efforts were concentrated on studying the behavior of thin wall tubes. Unfortunately, the knowledge on post buckling of thick wall tubes is still incomplete, although many experimental and several theoretical studies have been performed. In this study we systematically studied the effect of the wall thickness on post buckling behavior of the tube. For this purpose, we utilized a computational model for evaluation of the real geometry of the deformed cross sectional area due to negative transmural (internal minus external) pressure. We also developed an experimental method to validate the
computational results. Based on the computed cross sections of tubes with different wall thicknesses, we developed a general tube law that accounts for thin or thick wall tubes and fits the numerical data of computed cross sectional areas versus transmural pressures.

References listed at the end of the paper:


ABSTRACT: In this research the torsional stability of a composite drive shaft torsion is studied. Composite materials are considered as the suitable choice for manufacturing long drive shafts. The applications of this kind of drive shafts are developed in various products such as cars, helicopters, cooling towers, etc. From the design point of view, local and global torsional instability of drive shafts limits the capability for them to transfer torque. After reviewing the closed form solution methods to calculate the buckling torque of composite drive shafts, a finite element analysis is performed to study their behavior. Furthermore, to evaluate the results obtained by the finite element method, a comparison with experimental and analytical results is presented. A case study of the effects of boundary conditions, fiber orientation and stacking sequence on the mechanical behavior of composite drive shafts is also performed. Finally, the reduction of the torsional natural frequency of a composite drive shaft due to an increase of applied torque is studied.

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ABSTRACT: One interesting application of composite materials is the composite drive shafts as power transmission tubing which are used in many mechanical and structural systems; such as automobiles, marine and flight vehicles, gas and wind turbines...etc. In this paper, a composite drive shaft for an automotive application is optimized for maximizing the torsional buckling torque under mass constraint. Other constraints include bending natural frequency as well as interlaminar shear failure criterion. The selected design variables are the fiber volume fraction, fiber orientation angle and thickness of each composite layer. A case study for a simply supported drive shaft made of carbon/epoxy composite material is considered through the work of this paper. The attained optimum solutions are compared with a known baseline design having the same length, same cross section and same material properties. The optimization problem is built in a nondimensional form; and Global Optimization Toolbox in MATLAB program has been implemented for modeling the optimization problem. It was found that the cross-ply layup gives the best results for maximum buckling torque and bending natural frequency without mass penalty.

ABSTRACT: One of the challenges facing the designers of aeroengine drive shafts is to transmit higher torques while at the same time reducing the overall diameter of the engine in order to reduce drag. The resulting high performance drive shafts are smaller, lighter and have thinner walls, and it is essential that the factors affecting instability are known and understood. Torque is the principal load carried by these shafts, and most of the analytical methods for predicting torsional stability are either analytical or semi-empirical and tend not to cover the relevant range of geometries of interest here in terms of shaft geometry. Also, they give only limited information about the failure mode involved. A finite element analysis (FEA) approach has been developed to
address this need, and this paper presents results for plain shaft sections subjected to torque loading. Geometries leading to elastic buckling and plastic collapse are identified, along with appropriate formulae for calculating the torque capacity.


ABSTRACT: The measured torsional buckling load of Graphite/Epoxy shafts is found in good agreement with theoretical predictions based on a general shell theory that includes elastic coupling effects and transverse shearing deformations. The direction of the applied torque and the lay-up stacking sequence drastically affects the buckling load (up to 80%). Transverse shearing deformations are found significant when the number of circumferential waves in the buckling pattern is larger than 3. The residual strength of shafts with holes is also measured, and the dominant failure mode remains torsional buckling. The buckling mode patterns are seemingly unaffected by damage but buckling loads are lower compared to undamaged specimens. Material failure concentrated around the hole does not occur until the hole size is approximately one-third of the shaft's diameter. Teflon disks inserted between plies to simulate delaminations decrease the buckling load, but not significantly. In conclusion, stiffness characteristics, rather than strength characteristics dominate the behavior of thin-walled, undamaged shafts under torsional load, and this appears to remain true for shafts with sizable damage (up to about one-third of the shaft's diameter).

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ABSTRACT: Optimization is one of the important stages in the design process. In this paper the genetic algorithms method is applied for weight and transient dynamic response and two constraints including critical buckling loads and principle strains optimization of laminated composite cylindrical shells. The multi-objective function seeks the minimum structural weight and transient dynamic response. Nine design variables including material properties (fibre and matrix), volume fraction of fibre, fibre orientation and thickness of each layer are considered. In analytical solution, vibration of composite circular cylindrical shells are investigated based on the first-order shear deformation shell theory. The boundary conditions are assumed to be fully simply support. The dynamic response of the composite shells is studied under transverse impulse and axial compressive loads. The modal technique is used to develop the analytical solution of the composite cylindrical shell. The solution for the shell under the given loading conditions can be found using the convolution integrals. An example of simply supported laminated composite cylindrical shells is given to demonstrate the optimality of the solution obtained by the genetic algorithms technique. Results are shown that the weight coefficient of multi-objective function and the type of the constraints have considerable effect on the optimum weight and dynamic response.

ABSTRACT: In this paper, a refined model of interlocked composite grid stiffened structure and an equivalent model based on simplified ICG panel are built. Buckling and dynamic response of the composite panel are then analyzed using the models. The result is the accuracy of buckling and mode analysis of refined model is greatly improved compared with the equivalent model. Simulation for impact response under different impactors is considered. The coefficients such as material properties and structure dimension of the slot are discussed.

Faruk Elaldi (University of Baskent, Faculty of Engineering, Mechanical Engineering Department, 06530 Ankara, Turkey), “Buckling, Post-Buckling And Failure Analysis Of Hat Stiffened Composite Panel”, Proceedings of 8th International Fracture Conference 7 – 9 November 2007 Istanbul/TURKEY

ABSTRACT: Current use of advanced composites in aircraft structures has demonstrated the potential for decreasing structural weight. But, the inherent complexities associated with the design and analysis of carbonfiber composite structures has restricted its use in post-buckling designs. In conventional aircraft application, it is common practice to design stiffened metallic plate and shell structures to buckle below design ultimate limit. The buckling and failure characteristics of a thin composite skin reinforced by stiffeners, such as fuselage shell or wing components, have to be determined explicitly. Post-buckled design allows buckling before design limit is reached and the buckled structure can carry design ultimate load. Closed-sectioned hat stiffened panels were studied by several researchers in order to show significant post-buckling strength. Usually, the post-buckled design also results in significant weight savings when compared to buckling-resistant design. In the present study, the aim was to explore technologies for manufacturing integral composite structures to evaluate the manufacturing concepts by determining the structural behavior of hat-stiffened composite panels under compression loading. The experimental results of hat-stiffened panels for initial buckling and post-buckled response under compression loading were compared with numerical results obtained using linear and non-linear finite element analysis.

References at the end of the paper:

Faruk Elaldi and Levent Colak (Department of Mechanical Engineering, University of Baskent Ankara 06530, Turkey), “Buckling and Post-buckling Behavior of Compression Loaded Composite Panels with Hat
ABSTRACT: The aim of this study was to explore post-buckling behaviors of hat-stiffened composite panels under compression loading. A shadow Moiré technique was used to monitor the out-of-plane displacement of the skin panel. The experimental results of hat-stiffened panels for initial buckling and post-buckled response of the panels were compared with numerical results obtained from linear and non-linear finite element methods. It was found to be in reasonably good agreement with each other. The panels showed good post-buckling strength and total failure began with the local buckling of the hat stiffeners.

References listed at the end of the paper:


ABSTRACT: The aim of this study was to explore post-buckling strength potential of two different stiffener types and evaluate structural efficiencies of those by making a comparison. This has been done by first determining the buckling and post-buckling behavior of J- and hat-stiffened composite panels under compression loading. By making a structural efficiency definition, the experimental results of J- and hat-stiffened panels for initial buckling and post-buckled responses of the panels were compared with predicted and analytical results.

References listed at the end of the paper:


ABSTRACT: Donnel type stability equations for buckling of stringer stiffened cylindrical panels under combined axial compression and hydrostatic pressure are solved by the displacement approach of [6]. The solution is employed for a parametric study over a wide range of panel and stringer geometries to evaluate the combined influence of panel configurations and boundary conditions along the straight edges on the buckling behavior of the panel relative to a complete “counter” cylinder (i.e. a cylinder with identical skin and stiffener parameters). The parametric studies reveal a “sensitivity” to the “weak in shear”, Nx = Nxphi= 0, along the straight edges, SS1 boundary conditions type where the panel buckling loads are always smaller than those predicted for a complete “counter” cylinder. In the case of “classical”, SS3 B.Cs., there always exist values of panel width, 2phi0, for which rho = 1, i.e. the panel buckling load equals that of the complete “counter” cylinder. For SS2 and SS4 B.Cs. types, the nature by which the panel critical load approaches that of the complete cylinder appears to be panel configuration dependent. Utilization of panels for the experimental determination of a complete cylinder buckling load is found to be satisfactory for relatively very lightly and heavily stiffened panels, as well as for short panels, (L/R) = 0.2 and 0.5. Panels of moderate length and stiffening have to be debarred, since they lead to nonconservative buckling load predictions.

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ABSTRACT: Results are presented for impact tests conducted on postbuckled, thin, orthotropic carbon/epoxy laminates manufactured by the RTM process from preforms of uniweave fabric, some of which were stitched with Kevlar sewing thread. They were impacted by a 13 mm diameter 8.9 g steel projectile at velocities ranging to 90 m/s on their convex and concave faces. For impact velocities above a critical value, either penetration occurred or the specimens failed catastrophically. Their corresponding critical velocity boundaries were established. Their projected impact damage area increased with increased impact velocity, however, it was independent of preload. Their postimpact properties remained largely unchanged. Stitching reduced significantly the projected damage area, however none of their other impact damage resistance and tolerance characteristics were effected, including their critical velocities for penetration and catastrophic damage. Impacting on the concave face, compared to impacting on the convex face, reduced the projected damage area and the penetration critical velocity boundary. No catastrophic damage was observed for these specimens.

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ABSTRACT: Damage tolerance of stitched stiffened composite panels with clearly visible impact damage to a stiffener was investigated. Two-blade stiffened composites panels were fabricated using resin film infiltration technique. The effects of stitching are assessed using unstitched, selectively stitched and fully stitched panels. Impact damage was induced using a drop weight impact of 30 J from the skin side over the stiffener. The experimental results indicate that selectively stitched panels showed 14.4% improvement in compression after impact strength compared to both the unstitched and fully stitched panels. Post-buckling finite element analysis was performed to predict the buckling and failure strengths of these stiffened panels.

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ABSTRACT: Delamination as a result of low-velocity impact loading is a major cause of fibre-reinforced composite failure. Through-thickness reinforcement in the form of transverse stitching is an effective way to suppress delamination in these composite laminates. In this paper, the effect of stitching on Mode II delamination toughness is analysed by using two specimen geometries, namely, the end-notch flexure (ENF) specimen geometry and the end-notch cantilever (ENC) specimen geometry. The ENC specimen geometry allows larger crack propagation lengths which may be necessary to develop fully the stitch-thread bridging zone in the case of compliant stitch threads. Initially the energy release rate, $G_{II(\Delta a)}$, is determined by the contour
integral method and then the use and equivalence of the stress intensity factor approach is demonstrated. The effect of stitching on both specimen geometries is found to be the same, and identical closed-form analytical expressions are obtained for the potential energy release rate, GIIR(_ia), required for crack propagation. The effect of stitching is expressed in terms of the stitching parameters _± and _≤. The influence of friction between the crack surfaces is also included in the analysis. A simple design study for sizing the ENF and ENC specimens to minimise geometric non-linear response is presented. The effects of the stitching parameters and various geometric and material properties are examined.


ABSTRACT: We analyze the steady-state response of a functionally graded thick cylindrical shell subjected to thermal and mechanical loads. The functionally graded shell is simply supported at the edges and it is assumed to have an arbitrary variation of material properties in the radial direction. The three-dimensional steady-state heat conduction and thermoelasticity equations, simplified to the case of generalized plane strain deformations in the axial direction, are solved analytically. Suitable temperature and displacement functions that identically satisfy the boundary conditions at the simply supported edges are used to reduce the thermoelastic equilibrium equations to a set of coupled ordinary differential equations with variable coefficients, which are then solved by the power series method. In the present formulation, the cylindrical shell is assumed to be made of an orthotropic material, although the analytical solution is also valid for isotropic materials. Results are presented for two-constituent isotropic and fiber-reinforced functionally graded shells that have a smooth variation of material volume fractions, and/or in-plane fiber orientations, through the radial direction. The cylindrical shells are also analyzed using the Flügge and the Donnell shell theories. Displacements and stresses from the shell theories are compared with the three-dimensional exact solution to delineate the effects of transverse shear deformation, shell thickness and angular span.

References listed at the end of the paper:

Jacob L. Pelletier and Senthil S. Vel (Mechanical Engineering Department, University of Maine, 5711 Boardman Hall, Orono, ME 04469, USA), “Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass”, Computers & Structures, Vol. 84, Nos. 29-30, November 2006, pp. 2065-2080, doi:10.1016/j.compstruc.2006.06.001

ABSTRACT: We present a methodology for the multi-objective optimization of laminated composite materials that is based on an integer-coded genetic algorithm. The fiber orientations and fiber volume fractions of the laminae are chosen as the primary optimization variables. Simplified micromechanics equations are used to estimate the stiffnesses and strength of each lamina using the fiber volume fraction and material properties of the matrix and fibers. The lamina stresses for thin composite coupons subjected to force and/or moment resultants are determined using the classical lamination theory and the first-ply failure strength is computed using the Tsai–Wu failure criterion. A multi-objective genetic algorithm is used to obtain Pareto-optimal designs for two model problems having multiple, conflicting, objectives. The objectives of the first model problem are to maximize the load carrying capacity and minimize the mass of a graphite/epoxy laminate that is subjected to biaxial moments. In the second model problem, the objectives are to maximize the axial and hoop rigidities and minimize the mass of a graphite/epoxy cylindrical pressure vessel subject to the constraint that the failure pressure be greater than a prescribed value.

References listed at the end of the paper:


ABSTRACT: In this paper, optimization of a spherical shell under various dynamic loads is investigated. The aim of this optimization problem is to minimize the volume of the shell. Design variables are corner thicknesses of each finite element. Constraints are stresses obtained from von Mises stress criterion not to exceed the yield stress in corner nodal points of each finite element at the top and bottom surfaces of shell and thicknesses are restricted not to be less than 2.5 mm. In addition to shell's own weight, the vertical loads with equal intensity are applied at the nodal points on the upper edge of spherical shell, varying with respect to time function P(t). Time varying load vector is considered three different cases such as step, step after ramp and impulse functions. A program is coded with MapleV for optimization of spherical shell and finite element package program ANSYS is used for structural analysis. Obtained results are presented in graphical and tabular form. Finally, concluded remarks are given.

ABSTRACT: A C0 (penalty) finite element is developed for the equations governing the heterogeneous laminated plate theory of Yang, Norris and Stavsky. The YNS theory is a generalization of Mindlin's theory for homogeneous, isotropic plates to arbitrarily laminated anisotropic plates and includes shear deformation and rotary inertia effects. The present element can also be used in the analysis of thin plates by appropriately specifying the penalty parameter. A variety of problems are solved, including those for which solutions are not available in the literature, to show the material effects and the parametric effects of plate aspect ratio, length-to-thickness ratio, lamination scheme, number of layers and lamination angle on the deflections, stresses, and vibration frequencies. Despite its simplicity, the present element gives very accurate results.


ABSTRACT: Closed-form and finite-element solutions are presented for the free vibration of axially compressed, thick, circular cylindrical shells laminated of bimodulus composite materials, which have different elastic properties depending upon whether the fiber-direction normal strain is tensile or compressive. The theory used is a dynamic, shear deformable theory, which is the moderately-thick-shell analog of the Sanders 'best' first-approximation thin-shell theory. By means of certain tracers introduced in the paper, the analysis can be reduced to the thick-shell analog of simpler shell theories, namely Love's first-approximation and Donnell's shallow-shell theory. The buckling load is found by determining the lowest value of axial compressive load for which the lowest natural frequency vanishes. To validate the analysis, numerical results obtained by the two solutions are compared with each other and with existing results (for ordinary, not bimodulus, materials) for special cases. The effects of shell theory, secondary buckling effects, aspect ratio, and bending-stretching coupling are investigated parametrically.


ABSTRACT: A special three-dimensional element based on the total Lagrangian description of the motion of a layered anisotropic composite medium is developed, validated and employed to analyse laminated anisotropic composite shells. The element contains the following features: geometric nonlinearity, dynamic (transient) behaviour and arbitrary lamination scheme and lamina properties. Numerical results of nonlinear bending, natural vibration and transient response are presented to illustrate the capabilities of the element.


ABSTRACT: An extension of the Sanders shell theory for doubly curved shells to a shear deformation theory of laminated shells is presented. The theory accounts for transverse shear strains and rotation about the normal to the shell midsurface. Exact solutions of the equations are presented for simply supported, doubly curved, cross-ply laminated shells under sinusoidal, uniformly distributed, and concentrated point load at the center. Fundamental frequencies of cross-ply laminated shells are also presented. The exact solutions presented herein for laminated composite shells should serve as benchmark solutions for future comparisons.
ABSTRACT: A dynamic, shear deformation theory of a doubly curved shell is used to develop a finite element for geometrically non-linear (in the von Karman sense) transient analysis of laminated composite shells. The element is employed to determine the transient response of spherical and cylindrical shells with various boundary conditions and loading. The effect of shear deformation and geometric non-linearity on the transient response is investigated. The numerical results presented here for transient analysis of laminated composite shells should serve as references for future investigations.

ABSTRACT: A finite-element computational procedure is developed for the first-ply failure analysis of laminated composite plates. The procedure is based on the first-order shear deformation theory and a tensor polynomial failure criterion that contains the maximum stress, maximum strain, the Hill, Tsai-Wu and Hoffman failure criteria as special cases. By specifying the desired criterion, a first-ply failure analysis of composite laminates subjected to in-plane and/or bending loads can be achieved. A number of problems are presented to evaluate these failure criteria when applied to laminates subjected to in-plane and or bending loads.

ABSTRACT: A review of two-dimensional (e.g., equivalent single-layer) kinematic models of laminated composite plates and constitutive models of fiber-reinforced composites for failure is presented. The recent research work of the author in the formulation of refined theories of laminated composite plates is also included.

ABSTRACT: The present paper deals with a novel approach to the derivation of constrained geometrically nonlinear shell theories which has been given in recent years by Pietraszkiewicz [1–4]. This approach has a distinct advantage over others in that it is theoretically well founded on exact polar decomposition of the shell deformation into rigid-body translation, pure stretch along the principal directions of strain and rigid-body rotation. Pietraszkiewicz [1–4] developed an exact theory of finite rotations in shells which allows for the derivation of appropriate kinematic shell relations for restricted strains and rotations of clearly defined order of magnitude. This approach has led already to a significant number of related publications [5–36] which cover various aspects of nonlinear shell theory: the derivation of first approximation theories for shells and beams undergoing small strains accompanied by moderate, large, or unrestricted rotations, associated variational
principles, stability and post-buckling equations, and finite element computations. Furthermore, a similar approach to the derivation of a moderate rotation shell theory via the polar decomposition theorem has been given just recently by Naghdi and Vongsarnpiboon [37] in terms of Cosserat surface theory. Therefore, it seems to be justified to term these recent advances [1–37] based on exact polar decomposition of shell deformation with subsequent restriction of strains and rotations a new, current trend in shell theory. First, the present paper reviews briefly the progress obtained in Refs. [1–36]. Then, we present some foundations of large rotation shell theory, especially some new results which allow for the construction of variationally derivable theories. The general large rotation shell theory is simplified for problems in which the in-surface rotations remain moderate or even small. The latter variant is compared with two theories given recently by Nolte and Stumpf [9] and Pietraszkiewicz [14]. Then, for all these variants a set of basic variational principles is derived in a unified operator notation. Finally, as contribution towards the numerical justification of the present approach we present solutions for a spherical shell stability problem obtained together with ChróImage cielewski [63] by three-dimensional finite element analysis and compare this reference solution with those obtained by Nolte [8] on the basis of large rotation shell theories.

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ABSTRACT: A general refined shell theory that accounts for the transverse deformation, small strains, and moderate rotations is presented. The theory can be reduced to various existing shell theories including: the classical (i.e., linear Kirchhoff-Love) shell theory, the Donnell-Mushtari-Vlasov shell theory, the Leonard-Koiter-Sanders moderate rotations shell theory, the von Kármán type shear-deformation shell theory and the moderate-rotation shear-deformation plate theory developed by Reddy. The present theory is developed from an assumed displacement field, nonlinear strain-displacement equations that contain small strain and moderate rotation terms, and the principle of virtual displacements. The governing equations exhibit strong coupling between the membrane and bending deformations, which should alter the bending, stability, and post-buckling behavior of certain shell structures predicted using the presently available theories.

ABSTRACT: A general two-dimensional shear deformation theory of laminated composite plates is presented. The theory account for a desired degree of approximation of the displacements through the laminate thickness. As special cases, the classical, first-order (Reissner–Mindlin) and other shear deformation theories available in the literature can be deduced from the present theory.

ABSTRACT: An exact mathematical tool to analyze the free vibration and buckling of symmetric cross-ply laminated plates is developed. The procedure, based on a generalized Lévy type solution considered in conjunction with the state space concept, enables one to solve exactly the equations governing the laminated anisotropic plate theory as considered by Reddy [3,4]. Combinations of simply supported, clamped and free boundary conditions are considered. Comparisons with other higher order, first order and classical plate theories are made.


ABSTRACT: Analytical solutions for displacements, natural frequencies and buckling loads of cross-ply circular cylindrical shells under various boundary conditions are developed using the classical, first-order and third-order shell theories and the state-space technique. The third-order theory of shells of Reddy accounts for cubic variation of surface displacements through the thickness of the laminate and there is no need for shear correction factors. Analytical solutions are developed for simply-supported, clamped and free boundary conditions, and the effect of boundary conditions, lamination schemes and shear deformation on the deflections, stresses, natural frequencies and buckling loads is investigated.


ABSTRACT: Analytical and finite-element solutions of the classical, first-order, and third-order laminate theories are developed to study the buckling and free-vibration behavior of cross-ply rectangular composite laminates under various boundary conditions. The effects of side-to-thickness ratio, aspect ratio, and lamination schemes on the fundamental frequencies and critical buckling loads are investigated. The study concludes that shear deformation laminate theories accurately predict the behavior of composite laminates, whereas the classical laminate theory overpredicts natural frequencies and buckling loads.


ABSTRACT: Thermal deformations and stresses in cross-ply laminated circular cylindrical shells are investigated. The state space approach is used to solve exactly the thermoelastic governing equations of the third-order, first-order and classical theories for arbitrary boundary conditions. To illustrate the thermoelastic behavior, exact analytical solutions for deflections and stresses are obtained for laminated circular cylindrical shells undergoing uniform and linearly varying temperature fields through the thickness while having sinusoidal distribution of thermal loading.

A.M. Zenkour (Department of Mathematics, Faculty of Science, Kafir El-Sheikh University, Kafir El-Sheikh, 33516, Egypt and Department of Mathematics, Faculty of Science, King Abdul Aziz University, P.O. Box 80203, Jeddah, 21589, Saudi Arabia), “Stresses in cross-ply laminated circular cylinders of axially variable thickness”, Acta Mechanica, Vol. 187, No. 1, pp 85-102, November 2006
ABSTRACT: This paper presents the results from an analytical investigation of the behavior of composite circular cylinders subjected to internal and external surface loading. The present cylinder consists of a number of homogeneous ply groups of axially variable thickness. Each ply group forming a layer is treated as an individual thin elastic cylinder of generally orthotropic material with interfacial stresses on the inner and outer surfaces of the layer as boundary loading. The deformation and stresses in each layer can be expressed in terms of interfacial stresses along the exterior surfaces of each layer. All displacement and stresses throughout the composite cylinder can be determined subsequently after satisfying boundary conditions at the inside and outside surfaces of the cylinder in conjunction with the recurrence relationship among interfacial stresses. Numerical results are presented for different values of the inner-to-outer ratio, number of layers, stacking sequence, axially-variable-thickness parameter, and load factor. Based on the presented results, conclusions can be drawn concerning the cylinder behavior and its sensitivity to different parameter variations.

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ABSTRACT: Finite element models of the continuum-based theories and two-dimensional plate/shell theories used in the analysis of composite laminates are reviewed. The classical and shear deformation theories up to the third-order are presented in a single theory. Results of linear and non-linear bending, natural vibration and stability of composite laminates are presented for various boundary conditions and lamination schemes. Computational modelling issues related to composite laminates, such as locking, symmetry considerations, boundary conditions, and geometric non-linearity effects on displacements, buckling loads and frequencies are discussed. It is shown that the use of quarter plate models can introduce significant errors into the solution of certain laminates, the non-linear effects are important even at small ratio of the transverse deflection to the thickness of antisymmetric laminates with pinned edges, and that the conventional eigenvalue approach for the determination of buckling loads of composite laminates can be overly conservative.

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ABSTRACT: The instability of composite laminated plates under uniaxial, harmonically-varying, in-plane loads is investigated. Both symmetric cross-ply laminates and antisymmetric angle-ply laminates are analyzed. The first-order shear deformation plate theory is used to model composite laminates. The resulting linear equations of motion are transformed into small, uncoupled sets of equations, and instability regions in the plane of load amplitude versus load frequency are determined using the finite element method. The effects of damping, ratio of edge length to thickness of the plate, orthotropy, boundary conditions, number of layers and lamination angles on instability regions are examined.


ABSTRACT: The incremental equations of motion based on the principle of virtual displacements of a continuous medium are formulated using the total Lagrangian description. A degenerate shell element with a degenerate curved beam element as a stiffener is developed for the geometric nonlinear analysis of laminated, anisotropic, stiffened shells. Compatibility and completeness requirements are stressed in modeling the general shell-type structures in order to assure the convergence of the finite-element solution. An iterative solution procedure, either Newton-Raphson method or modified Riks method, is employed to trace the nonlinear equilibrium path. A variety of numerical examples are presented to demonstrate the validity and efficiency of the stiffened shell element. The effects of boundary conditions, lamination scheme and geometric nonlinearity on deflections are also investigated.

ABSTRACT: The dynamic and static behavior of cross-ply laminated shells are investigated using the third-order shear deformation shell theory of Reddy. The theory is a modification of the Sanders shell theory and accounts for parabolic distribution of the transverse shear strains through the thickness of the shell and does not require shear correction coefficients. The Lévy-type exact solutions for bending, buckling and natural vibration are presented for doubly curved, cylindrical and spherical shells under various boundary conditions.


ABSTRACT: Transient response of simply-supported circular cylindrical shells is investigated using a higher-order shear deformation theory (HSDT). The theory is a modification of the Sanders' shell theory and accounts for parabolic distribution of the transverse shear strains through thickness of the shell and tangential stress-free boundary conditions on the bounding surfaces of the shell. The results obtained using the classical shell theory (CST) and the first-order shear deformation theory (FSDT) are compared with those obtained using the higher-order theory. The state-space approach is used to develop the analytical solutions to the equations of motion of the three theories.


ABSTRACT: A moderate rotation theory of laminated anisotropic shells, proposed by Schmidt and Reddy [J. appl. Mech. 55, 611–617.1988], is developed and its application is presented. All aspects of the derivations are explicitly developed and specific forms of the equations are derived in this part. The finite-element formulation and its applications are presented in Part 2 of the paper.


ABSTRACT: The finite element model of the moderate rotation theory (MRT) is developed and its application to composite plates and shells is presented. Comparison of results obtained by the moderate rotation theory with the von Kármán non-linear theory and continuum 2D theory is made.


ABSTRACT: Analytical solutions of the Reddy layer-wise laminate theory for buckling of composite cylindrical shells are presented. The layer-wise shell theory accounts for varying degrees of displacement expansion through the thickness of the shell. The Navier solution procedure is used to obtain exact buckling loads of cross-ply laminated cylindrical shells.
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ABSTRACT: The static response of cross-ply laminated shallow shells subjected to thermal loadings is investigated. An exact analytical solution using the state space approach is presented in conjunction with the Lévy method, for doubly curved, cylindrical and spherical shells under various boundary conditions. Numerical results of the higher-order theory of Reddy and Liu (1985, 1987) for center deflection of cross-ply laminated shallow shells are compared with those obtained using classical and first-order shell theories.

A. A. Khdeir (Department of Civil Engineering, Division of Structural Mechanics, Middle East Technical University, 06531, Ankara, Turkey), “A remark on the state-space concept applied to bending, buckling and free vibration of composite laminates”, Computers & Structures, Vol. 59, No. 5, June 1996, pp. 813-817, doi:10.1016/0045-7949(95)00330-4
ABSTRACT: The present study shows that the state-space concept used to generate exact solutions for various boundary conditions for bending, buckling and free vibration of composite laminates, can be modified easily and exactly and has no drawback when the laminate thickness is reduced. Numerical results for central deflections, axial stresses, transverse shear stresses, critical buckling loads and natural frequencies of cross-ply laminated plates are obtained using the classical, first- and third-order theories for large side to thickness ratios.

ABSTRACT: Generalized Levy-type solutions are obtained for the problems of linear vibration and stability of cross-ply laminated plates. The governing equations, which are derived by using the principle of virtual displacement and a third-order shear-deformation plate theory, are transformed into a set of first-order linear ordinary differential equations with constant coefficients. The general solution of these equations can be obtained by using the state-space concept. Then, application of the boundary conditions yields equations for the natural frequencies and buckling loads. Unfortunately, a straightforward application of the state-space concept yields numerically ill-conditioned problems as the plate thickness is reduced. Various methods for overcoming this problem are discussed. A combination of an initial-value method and the modified Gram-Schmidt orthonormalization procedure is used to overcome this problem. It is shown that this method not only yields results that are in excellent agreement with the results in the literature, but also it converges fast and gives all the frequencies and buckling loads regardless of the plate thickness.

ABSTRACT: The layer-wise shell theory of Reddy is used to study the postbuckling response of circular
cylindrical shells. The Rayleigh-Ritz method is used to solve the equations by assuming a double Fourier expansion of the displacements with trigonometric coordinate functions.


ABSTRACT: An improved analytical procedure is introduced in the context of free vibration and stability problems of cross-ply laminated circular cylindrical shells. The Donnell shear-deformation type theory and Donnell's classical theory are used to illustrate the procedure. Numerical results are presented for shells with a variety of boundary conditions. Special attention is given to the axisymmetric problems and new results, not yet found in the literature, for stability and vibration are reported. It is recommended that the new technique be used for generating the Lévy-type solutions in vibration and stability problems of laminated shell panels and plates when the number and order of equations are higher than those of the classical theories.


ABSTRACT: Plate finite elements based on the generalized third-order theory of Reddy and the first-order shear deformation theory are analysed and compared on the basis of thick and thin plate modelling behaviour, distortion sensitivity, overall accuracy, reliability and efficiency. In particular, several four-noded Reddy-type elements and the nine-noded Lagrangian and heterosis (Mindlin-type) plate elements are analysed to assess their behaviour in bending, vibration and stability of isotropic and laminated composite plates. A four-noded Reddy-type element is identified which is free of all spurious stiffness and zero energy modes, computationally efficient, and suitable for use in any general-purpose finite element program.


ABSTRACT: The nonlinear response of laminated composite structures subjected to thermal loads is investigated. Analysis is performed using a refined theory and an associated finite element model for geometrically nonlinear analysis of laminated composite shell structures. The model is based on a third-order displacement field which accounts for both transverse shear and transverse normal deformations. Numerical studies of simply-supported plates and cylindrical panels indicate that when the panels are free to expand or contract in the transverse direction, the predicted critical buckling temperatures do not depend significantly upon whether or not transverse normal deformations are explicitly accounted for in the analysis model. However, the critical buckling temperatures are strongly dependent upon whether or not the transverse normal deformations are restrained along the boundaries of the panels.

ABSTRACT: The buckling and postbuckling of stiffened laminated cylinders under uniform axial compression is investigated to determine the effects of shell lamination scheme and stiffeners on the reduced load-carrying capacity. The effect of geometric imperfection is also included. The analysis is based on the layerwise shell theory of Reddy for simply-supported, cross-ply laminated circular cylinders, and the smeared stiffener technique is used to account for the stiffener stiffness. The Rayleigh-Ritz method is used to reduce the continuum problem to a set of nonlinear algebraic equations, which are then solved using the Riks-Wempner iterative technique. Numerical results for stiffened and unstiffened, cross-ply laminated, simply-supported graphite-epoxy cylinders are to the number of nearly simultaneous buckling modes.


ABSTRACT: A new displacement-based two-dimensional theory for the analysis of multilayered plates is presented. The theory is based on the only kinematic constraint of transverse inextensibility, whereas no restrictions are imposed on the representation of the in-plane displacement components. A governing system of integral-differential equations is obtained which can be given a closed-form solution for a number of problems where no boundary layer are present. It is also shown that most of the 2-D plate models can be directly derived from the presented theory. The possibility of developing asymptotic solutions in the boundary layers is discussed with reference to the problem of a plate in cylindrical bending. Finally some numerical solutions are compared with those given by the plate model by Lo et al. (1977) and with F.E.M. solutions.

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ABSTRACT: Analytical solutions for buckling loads of composite cylindrical shells with axial and circumferential stiffeners are presented using a layerwise shell theory. The layerwise shell theory accounts for displacement variations through the thickness of the shell. The effect of stiffeners is averaged over the domain of the shell, and the effect of stiffener eccentricity is taken into account. The Navier solution procedure is used to develop analytical solutions for buckling of stiffened cylindrical shells. Numerical results are presented to illustrate the accuracy of the layerwise shell theory in comparison to single-layer shell theories.

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ABSTRACT: The post-buckling of stiffened, cross-ply laminated, circular determine the effects of shell lamination scheme and stiffeners on the reduced load-carrying capacity. The effect of geometric imperfection is also included. The analysis is based on the layerwise shell theory of Reddy, and the “smeared stiffener”
technique is used to account for the stiffener stiffness. Nu cylinders under uniform axial compression is investigated to numerical results for stiffened and unstiffened cylinders are presented, showing that imperfection-sensitivity is strictly related to the number of nearly simultaneous buckling modes.

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ABSTRACT: The first-order shear deformation moderate rotation shell theory of Schmidt and Reddy [R. Schmidt and J. N. Reddy, J. Appl. Mech. 55, 611–617 (1988)] is used as a basis for the development of finite element models for the analysis of the static, geometrically non-linear response of anisotropic and laminated structures. The incremental, total Lagrangian formulation of the theory is developed, and numerical solutions are obtained by using the isoparametric Lagrangian 9-node and Serendipity 8-node shell finite elements. Various integration schemes (full, selective reduced, and uniformly reduced integration) are applied in order to detect and to overcome the effects of shear and membrane locking on the predicted structural response. A number of sample problems of isotropic, orthotropic, and multi-layered structures are presented to show the accuracy of the present theory. The von Kármán-type first-order shear deformation shell theory and continuum 2D theory are used for comparative analyses.


ABSTRACT: The response of functionally graded ceramic metal plates is investigated using a plate finite element that accounts for the transverse shear strains, rotary inertia and moderately large rotations in the von Kármán sense. The static and dynamic response of the functionally graded material (fgm) plates are investigated by varying the volume fraction of the ceramic and metallic constituents using a simple power law distribution. Numerical results for the deflection and stresses are presented. The effect of the imposed temperature field on the response of the fgm plate is discussed. It is found that in general, the response of the plates with material properties between those of the ceramic and metal is not intermediate to the responses of the ceramic and metal plates.

Ireneusz Kreja (Gdansk University of Technology, Gabriela Narutowicza 11/12, 80-952 Gdansk, Poland), “Stability analysis of cylindrical composite shells in MSC/Nastran”, Archives of Civil and Mechanical Engineering, Vol. V, No. 3, 2005, pp. 31-41

ABSTRACT: In the paper, the capabilities of the MSC/NASTRAN system in the field of stability analysis of composite laminated shells are critically tested. Two selected benchmark examples of laminated cylindrical panels under axial compression are examined. The MSC/NASTRAN results obtained either in buckling analysis or in nonlinear incremental calculations are compared with the solutions available in the literature.

References listed at the end of the paper:


PARTIAL ABSTRACT: The Layerwise Shell Theory is used to model discretely stiffened laminated composite cylindrical shells for stress, vibration, pre-buckling and post-buckling analysis. The layerwise theory reduces a three-dimensional problem to a two-dimensional problem by expanding the three-dimensional displacement field as a function of a surface-wise two dimensional displacement field and a one-dimensional interpolation through the shell thickness. Any required degree of accuracy can be obtained by an appropriate, independent selection of the one-dimensional interpolation functions through the thickness and the two-dimensional interpolation of the variable on the surface…

(cannot cut and paste the references)
ABSTRACT: The layerwise shell theory is used to model discretely stiffened laminated composite plates and cylindrical shells for stress, vibration, pre-buckling and post-buckling analyses. The layerwise theory reduces a three-dimensional (3-D) problem to a two-dimensional (2-D) problem by expanding the 3-D displacement field as a function of a surface-wise 2-D displacement field and a one-dimensional (1-D) interpolation polynomial through the shell thickness. Using a layerwise format, discrete axial and circumferential stiffeners are modeled as 2-D beam elements. Similar displacement fields are prescribed for both the stiffener and shell elements. The contribution of the stiffeners to the membrane stretching, bending and twisting stiffnesses of the laminated shell or plate, is accounted by forcing compatibility of strains and equilibrium of forces between the stiffeners and the skin.

ABSTRACT: Fiber-reinforced composite materials continue to experience increased adoption in aerospace, marine, automobile, and civil structures due to their high specific strength, high stiffness, and light weight. This increased use has been accompanied by applications involving non-traditional configurations such as compression members with elliptical cross-sections. To model such shapes, we develop and report an improved generalized shell element called 4EAS-FS through a combination of enhanced assumed strain and the substitute shear strain fields. A flat shell element has been developed by combining a membrane element with drilling degree-of-freedom and a plate bending element. We use the element developed to determine specifically buckling loads and mode shapes of composite laminates with elliptical cross-section including transverse shear deformations. The combined influence of shell geometry and elliptical cross-sectional parameters, fiber angle, and lay-up on the buckling loads of an elliptical cylinder is examined. It is hoped that the critical buckling loads and mode shapes presented here will serve as a benchmark for future investigations.

References listed at the end of the paper:
Chun KS, Son BJ, Chang SY (2002) A study on behavior of anisotropic circular cylindrical shell including large deformation effects. J...

ABSTRACT: The dynamic stability of thin, laminated cylindrical shells under combined static and periodic axial forces is studied using Love’s classical theory of thin shells. A normal-mode expansion of the equations of motion yields a system of Mathieu–Hill equations. Bolotin’s method is then employed to obtain the dynamic instability regions. The present study examines the dynamic stability of antisymmetric cross-ply circular, cylindrical shells of different lamination schemes. The effect of the magnitude of the axial load on the instability regions is also examined.

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ABSTRACT: In this paper, a formulation for the dynamic stability analysis of functionally graded shells under
harmonic axial loading is presented. A profile for the volume fraction is assumed and a normal-mode expansion of the equations of motion yields a system of Mathieu–Hill equations the stability of which is analyzed by the Bolotin’s method. The present study examines the effects of the volume fraction of the material constituents and their distribution on the parametric response, in particular the positions and sizes of the instability regions.

T. Y. Ng, X. Q. He and K. M. Liew, “Finite element modeling of active control of functionally graded shells in frequency domain via piezoelectric sensors and actuators”, Computational Mechanics, Vol. 28, No. 1, pp 1-9, February 2002,

ABSTRACT: A flat-shell element is presented for the active control of functionally graded material (FGM) shells through integrated piezoelectric sensor/actuator layers. The finite element formulation based on first-order shear deformation theory (FSDT) can be applied to shells ranging from relatively thin to moderately thick dimensions. A constant gain displacement and velocity feedback control algorithm coupling the direct and inverse piezoelectric effects is applied to provide active control of the integrated FGM shell in a self-monitoring and self-controlling system. Frequency response characteristics of the FGM shell containing the piezoelectric sensors/actuators are analyzed in the frequency domain. The effects of constituent volume fraction and the influence of feedback control gain values on the dynamic responses of the FGM shell system are examined in detail.


ABSTRACT: An exact solution is obtained for three-dimensional deformations of a simply supported functionally graded rectangular plate subjected to mechanical and thermal loads on its top and/or bottom surfaces. Suitable temperature and displacement functions that identically satisfy boundary conditions at the edges are used to reduce the partial differential equations governing the thermomechanical deformations to a set of coupled ordinary differential equations in the thickness coordinate, which are then solved by employing the power series method. The exact solution is applicable to both thick and thin plates. Results are presented for two-constituent metal–ceramic functionally graded rectangular plates that have a power law through-the-thickness variation of the volume fractions of the constituents. The effective material properties at a point are estimated by either the Mori–Tanaka or the self-consistent schemes. Exact displacements and stresses at several locations for mechanical and thermal loads are used to assess the accuracy of the classical plate theory, the first-order shear deformation theory, and a third-order shear deformation theory for functionally graded plates. Results are also computed for a functionally graded plate with material properties derived by the Mori–Tanaka method, the self-consistent scheme, and a combination of these two methods.

References listed at the end of the paper:
34 Pagano, N. J., “Influence of Shear Coupling in Cylindrical Bending of Anisotropic Laminates,” Journal of Composite Materials,

ABSTRACT: The nonlinear response of functionally graded ceramic–metal shell panels under mechanical and thermal loading is studied. The nonlinear formulation is based on a modified version of Sander's nonlinear shell theory, in which the geometric nonlinearity takes the form of von Kármán strains. It is assumed that the material properties vary through the thickness according to a power-law distribution of the volume fraction of the constituents. The displacement field is expressed in terms of a set of mesh-free kernel particle functions. The bending stiffness is evaluated using a stabilized conforming nodal integration technique, and the shear and membrane terms are computed using a direct nodal integration to eliminate shear and membrane locking. The arc-length method, combined with the modified Newton–Raphson approach, is employed to trace the full load–displacement path. The characteristic of the displacement and the axial stress in panels under thermal and mechanical loading is investigated, and the effects of the volume fraction exponent, boundary conditions, and material properties on the nonlinear response of shell panels are also examined.

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“Dynamic stability analysis of functionally graded cylindrical shells under periodic axial loading”, International
ABSTRACT: In this paper, a formulation for the dynamic stability analysis of functionally graded shells under harmonic axial loading is presented. A profile for the volume fraction is assumed and a normal-mode expansion of the equations of motion yields a system of Mathieu–Hill equations the stability of which is analyzed by the Bolotin’s method. The present study examines the effects of the volume fraction of the material constituents and their distribution on the parametric response, in particular the positions and sizes of the instability regions.

ABSTRACT: Three-dimensional thermomechanical deformations of simply supported, functionally graded rectangular plates are studied by using an asymptotic method. The locally effective material properties are estimated by the Mori–Tanaka scheme. The temperature, displacements and stresses of the plate are computed for different volume fractions of the ceramic and metallic constituents, and they could serve as benchmark results to assess two-dimensional approximate plate theories.

J. N. Reddy and Zhen-Qiang Cheng (Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843-3123, USA), “Frequency correspondence between membranes and functionally graded spherical shallow shells of polygonal planform”, International Journal of Mechanical Sciences, Vo. 44, No. 5, May 2002, pp. 967-985, doi:10.1016/S0020-7403(02)00023-1
ABSTRACT: The present work presents further development of the linking relationships between vibration frequencies predicted by different theories, and they are extended from a flat plate to a spherical shallow shell. In analogy with the membrane vibration problem, exact correspondences are found for vibration frequencies of a functionally graded spherical shallow shell using the classical theory and the first-order and third-order shear deformation theories. Only the predominantly stretching and thickness-shear vibration of dilatational type and predominantly flexural vibration are considered in this work. They are decoupled from the predominantly stretching and thickness-shear vibration of rotational type. These results apply to a simply supported functionally graded spherical shallow shell of polygonal planform with arbitrarily varying material properties in the thickness direction. A Winkler–Pasternak elastic foundation and rotary inertias are incorporated. It is proved that the mathematical analogy warrants positive free vibration frequencies for the shallow shell. Mori–Tanaka's scheme is used to estimate the material properties in the numerical results.

ABSTRACT: In this paper, a review of the shear deformation plate and shell theories is presented and a consistent third-order theory for composite shells is proposed. The discussion of plate and shell theories from Stavsky to the present is largely a review of various theories for modeling laminated shells, including shear effects and some analytical studies. Following this discussion, a finite element formulation of the proposed theory is developed. The formulation has seven displacement functions satisfying the tangential traction-free conditions on the inner and outer surfaces of the shell. Exact computations of stress resultants are carried out
through numerical integration of material stiffness coefficients of the laminate. Numerical examples are presented for typical benchmark problems involving isotropic and composite plates, and cylindrical and spherical shells.

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ABSTRACT: In the present work the buckling and postbuckling behavior of laminated cylindrical shells under axial compression and lateral pressure loading are investigated. A nonlinear theory for thin cylinders incorporating the effects of transverse shear deformation is employed. A modal solution based on the Koiter theory is utilized to derive the nonlinear equilibrium equations for the postcritical behavior of the shell. The Rayleigh–Ritz method is used to obtain analytical solutions for the critical load through algebraic routines written in Maple. Prebuckling and postbuckling equations are also solved by using symbolic computation. The influence played by geometrical parameters of the cylinder and physical parameters of the laminate (i.e. fiber orientation of each lamina, material properties and number of layers) on the critical and postcritical behavior of the shell is examined. It is noticed that the stability of shells is highly dependent on laminate characteristics and, from these observations, it is concluded that specific configurations of laminates should be designed for each kind of application.

ABSTRACT: A geometrically nonlinear analysis of functionally graded shells is presented. The two-constituent functionally graded shell consists of ceramic and metal that are graded through the thickness, from one surface of the shell to the other. A tensor-based finite element formulation with curvilinear coordinates and first-order shear deformation theory are used to develop the functionally graded shell finite element. The first-order shell theory consists of seven parameters and exact nonlinear deformations and under the framework of the Lagrangian description. High-order Lagrangian interpolation functions are used to approximate the field variables to avoid membrane, shear, and thickness locking. Numerical results obtained using the present shell element for typical benchmark problem geometries with functionally graded material compositions are presented.

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ABSTRACT: Various available beam theories, including the Euler–Bernoulli, Timoshenko, Reddy, and
Levinson beam theories are reformulated using the nonlocal differential constitutive relations of Eringen. The equations of motion of the nonlocal theories are derived, and variational statements in terms of the generalized displacements are presented. Analytical solutions of bending, vibration, and buckling are presented using the nonlocal theories to bring out the effect of the nonlocal behavior on deflections, buckling loads, and natural frequencies. The theoretical development as well as numerical solutions presented herein should serve as references for nonlocal theories of beams, plates, and shells.

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ABSTRACT: The equations of motion of the Euler–Bernoulli and Timoshenko beam theories are reformulated using the nonlocal differential constitutive relations of Eringen [International Journal of Engineering Science 10, 1–16 (1972)]. The equations of motion are then used to evaluate the static bending, vibration, and buckling responses of beams with various boundary conditions. Numerical results are presented using the nonlocal theories to bring out the effect of the nonlocal behavior on deflections, buckling loads, and natural frequencies of carbon nanotubes.

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ABSTRACT: The accuracy of widely employed classical shell-theory-based formulae to calculate the buckling strain of single- and double-walled carbon nanotubes is assessed here. It is noted that some simplifications have been made in deriving these widely employed formulae. As a result critical buckling strains calculated from these formulae are independent of aspect ratio (length/diameter). However, molecular dynamics simulation results in the literature show an aspect ratio dependence of buckling strain. Therefore, analytical expressions are derived in this paper to calculate buckling strains of single- and double-walled carbon nanotubes based on classical shell theory without simplifications. Applicability of these expressions is further verified through molecular dynamics simulations based on the COMPASS force field. In addition, improvement in results achieved through a refinement of classical shell theory is assessed by calculating buckling strains based on first-order shell theory. Results show that simplified formulae introduce a significant error at higher aspect ratios and smaller diameters. The formulae derived here show reasonable agreement with the molecular dynamics results at all aspect ratios and diameters. First-order shell theory is found to produce a slight improvement in results for CNTs with smaller diameters and lower aspect ratios.

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ABSTRACT: Owing to their remarkable mechanical properties, carbon nanotubes have been employed in many diverse areas of applications. However, similar to any of the many man-made materials used today, carbon nanotubes (CNTs) are also susceptible to various kinds of defects. Understanding the effect of defects on the mechanical properties and behavior of CNTs is essential in the design of nanotube-based devices and composites. It has been found in various past studies that these defects can considerably affect the tensile strength and fracture of CNTs. Comprehensive studies on the effect of defects on the buckling and vibration of nanotubes is however lacking in the literature. In this paper, the effects of various configurations of atomic vacancy defects, on axial buckling of single-walled carbon nanotubes (SWCNTs), in different thermal environments, is investigated using molecular dynamics simulations (MDS), based on a COMPASS force field. Our findings revealed that even a single missing atom can cause a significant reduction in the critical buckling strain and load of SWCNTs. In general, increasing the number of missing atoms, asymmetry of vacancy configurations and asymmetric distribution of vacancy clusters seemed to lead to higher deterioration in buckling properties. Further, SWCNTs with a single vacancy cluster, compared to SWCNTs with two or more vacancy clusters having the same number of missing atoms, appeared to cause higher deterioration of buckling properties. However, exceptions from the above mentioned trends could be expected due to chemical instabilities of defects. Temperature appeared to have less effect on defective CNTs compared to pristine CNTs.

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ABSTRACT: Postbuckling analysis of functionally graded ceramic–metal plates under edge compression and temperature field conditions is presented using the element-free kp-Ritz method. The first-order shear deformation plate theory is employed to account for the transverse shear strains, and the von Kármán-type nonlinear strain–displacement relationship is adopted. The effective material properties of the functionally graded plates are assumed to vary through their thickness direction according to the power-law distribution of the volume fractions of the constituents. The displacement fields are approximated in terms of a set of mesh-free kernel particle functions. Bending stiffness is estimated using a stabilised conforming nodal integration approach, and, to eliminate the membrane and shear locking effects for thin plates, the shear and membrane terms are evaluated using a direct nodal integration technique. The solutions are obtained using the arc–length iterative algorithm in combination with the modified Newton–Raphson method. The effects of the volume fraction exponent, boundary conditions and temperature distribution on postbuckling behaviour are examined.


ABSTRACT: A three-dimensional degenerated isoparametric multilayer finite element is described in conjunction with an automatic incremental/iterative method to find the complete non-linear response of arbitrarily laminated composite panels under destabilizing loads. In the prebuckling range of the structural
response, incremental bifurcation analyses are combined with an arclength algorithm to control the step size; for the postbuckling path, the increment size is determined automatically by a new recurrence formula. The good behaviour of this proposed procedure is illustrated on two structural applications, namely a thick hinged multilayer cylindrical shell subjected to a transverse load and a highly curved cylindrical composite panel under in-plane compression.

ABSTRACT: This paper describes some of the current global/local testing and analysis approaches to evaluating the design of composite structure. A case study for the local, fracture mechanics analysis of failure in a 4-stringer compression panel is described in detail. The analysis investigates the variation of strain energy release rate G with debond length using a 2-D plane strain finite element analysis (FEA) of one of the stringers. The boundary conditions on the local model were determined from a global shell element model of the panel. Delamination was also modelled in the cap of the stringer using FEA and a closed form solution. The values of G for these two damage modes were compared with the material's fracture toughness. Using this analysis, the load to initiate the stringer debond and to cause edge delamination of the cap may be determined.

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ABSTRACT: A finite element methodology for postbuckling failure analysis of composite stringer/skin panels is presented. The methodology employs a global two-dimensional plate finite element model for representing overall panel deformation and a local three-dimensional solid finite element model for representing stress within a critical panel region. Global and local models are connected with a two-dimensional/three-dimensional coupling methodology that is based on multipoint constraints. Analyses are carried out for two different panel designs utilizing both linear and nonlinear material models. Computational results for failure load, failure location, and failure mode compare favorably with results from earlier experimental test programs. The findings suggest that failure initiation in postbuckled composite stringer//skin panels can be effectively modeled with the developed finite element methodology.

ABSTRACT: This paper presents experimental and numerical investigations on the performance of repaired thin-skinned, blade-stiffened composite panels in the post-buckling range. The results show that under the present repair scheme the strength of the panel can be recovered satisfactorily. Further, the repair scheme is seen capable of restoring the general load path in the panels as well as the general post-buckling behaviour.

K. Swaminathan and Govind R. Sangwai (National Institute of Technology Karnataka, Surathkal, Mangalore –
ABSTRACT: In the present work two higher order computational models with 9 and 12 DOF already available in the literature for which analytical formulations and solutions for the stress analysis not yet reported are considered. In addition to these models, few higher order models and the first order model developed by other investigators are also considered for the evaluation. A simply supported plate subjected to sinusoidal transverse load with SS-2 boundary conditions is considered for the analysis. Solutions are obtained using Navier's technique. Transverse stresses are computed by post processing technique and the accuracy of models in predicting the stresses is evaluated.

Nemi Sharan (Master’s Thesis, Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha-769008), “Vibration and stability of laminated composite doubly curved shells by a higher order shear deformation theory”, May 2011

ABSTRACT: The present study deals with a higher order shear deformation theory of laminated shells as suggested by Reddy and Liu. The theory is based on a displacement field in which the displacements of the middle surface are expanded as cubic functions of the thickness coordinate, and the transverse displacement is assumed to be constant through the thickness. This displacement field leads to the parabolic distribution of the transverse shear stresses (and zero transverse normal strain) and therefore no shear correction factors are used. The theory is also based on the assumption that the thickness to radius ratio of shell is small compared to unity and hence negligible. The governing equations are derived in orthogonal curvilinear coordinates. These equations are then reduced to those of doubly curved shell. All the quantities are suitably non-dimensionalised. The Navier solution has been used which gives rise to a generalized eigenvalue problem in matrix formulation. The natural frequencies for vibration and buckling loads of laminated orthotropic doubly curved shells and panels with simply supported ends are obtained. The eigenvalues, and hence the frequency parameters are calculated by using a standard computer program. To check the derivation and computer program, the frequencies in HZ for different layer are compared with earlier results. The lowest value of frequency parameter and buckling load are computed for the laminated composite doubly curved shell. The effects of various parameters such as number of layers, aspect ratio, modular ratio, etc on the above are studied. Frequency also increases as number of layers of the shell increases for symmetric cross-ply layout. But when there is unsymmetrical cross-ply layout, then frequency decreases. With the increasing of modular ratio, non-dimensional frequency is also increasing.

References listed at the end of the thesis:

ABSTRACT: The present study discusses buckling of multilayered composite plates from the standpoint of a natural shear deformation theory (NSDT) which is developed and shaped by means of matrix language on a model facet three-node triangular finite element. Isotropic, sandwich, and hybrid plates can also be treated. It is
shown that by invoking a physical decomposition and lumping concept, evolved through the adoption of a natural coordinate system in harmony with the given element geometry, an assembly of three edge-beams is created and is solely responsible for the carrying of the transverse shear forces. Thus, three correction factors can directly adjust the element's transverse shear stiffness for thicker plates while retaining a direct linear strain distribution across the element thickness. Subsequently, the geometric stiffness, which arises mostly from the rigid body movements of the element is derived, and the corresponding buckling eigenvalue problem is stated. The complete derivation of the geometrical stiffness matrix is in principle reduced to a simple transformation of the nodal freedoms. The matrix formulation, as well as convergence of the triangular element are completely natural, and numerical experiments for simply supported plates reveal that the obtained buckling loads conform very well at the thin limit with results from classical plate theory, and for moderately thick plates from a higher order shear deformation theory, as well as from theory of elasticity.


ABSTRACT: In the present study, the behaviour of laminated composite plates under thermally induced loads is examined. A natural thermoelastic theory is developed, based on a linear through-the-thickness temperature variation. The material properties are assumed independent of temperature, but this assumption in no way restricts the generality of the formulation and the developed computer program. The theory is implemented on a model three-node triangular facet finite element which accounts for transverse shear deformation. The underlying principles of the developed methodology lie in the Natural Mode method which is a physically inspired and mathematically consistent method which was conceived with the intention of analyzing large and complex structures. The triangular element necessitates the computation of a $12 \times 12$ natural stiffness matrix, and a $12 \times 1$ thermal (initial) load vector, which makes it probably one of the most inexpensive shell elements available. The effects of large displacements are included in our theory through the geometrical stiffness. In this regard, an Eulerian scheme conceived for the solution of geometrically nonlinear thermoelastic deformation is discussed. The methodology is validated with numerical examples which show the response of multilayered composite plates on thermally or thermomechanically induced bending, buckling, and postbuckling. All composite plates examined have shown remarkable resistance against high-temperature.


ABSTRACT: The evolution of the Natural Mode Method (NMM) for finite element analysis of complex composite structures continues in the present study by applying its principles and formulating the kinematically consistent matrix of a model three-node multilayered triangular element. Both translational and rotational inertia are included in the mass matrix which is conceived using kinematical and geometrical arguments consistent with the assumed natural rigid-body and straining modes of the element. Linear eigenfrequencies are validated with experimental and finite element solutions. Subsequently the large-amplitude nonlinear undamped free vibration of composite plates is investigated. A computational scheme is conceived, whereby the structure is initially displaced by conducting a full geometrically nonlinear static analysis, and subsequently set to transient nonlinear free oscillations by removing the static loading. In this regard, we discuss the two structured Eulerian (convective) computational schemes employed namely, the ARIBAN scheme (accumulation of rigid-body and
natural modes) for static nonlinear analysis, and the cubic Hermitian scheme (CUHERM) for large-displacement transient deformation. Numerical examples demonstrate the efficiency of the formulation and the potential of the Natural Mode Method to deal vigorously with intricate nonlinear time-dependent phenomena, as well as its potential to provide answers for larger and more complex structures. The study also indicates the efficiency and tailoring flexibility offered by advanced composite structural systems.

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ABSTRACT: A novel approach to the art of optimal design of modern flying vehicles including the application of multiple objective functions and constraints is presented and should hopefully advance the art of modern aircraft design. First, the concept of system identification is used to characterize non-linear systems in terms of generalized state space coordinates. Next, modern optimal control theory is applied to design concurrently, the functional elements of an aircraft system. Furthermore, modal coordinates are used to formulate the equations of motion of the total system so that the computational effort is minimized. The proposed analytical concept is validated using simple test cases.

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ABSTRACT: Here we study the thermo-mechanical postbuckling response of fibrous composite laminates. This study is based on the Natural Mode Method and invokes rigid-body and straining modes of deformation that are assigned to the edges of flat and shallow shell laminated triangular finite elements. Some new ideas on the subject are introduced and implemented in the conceived nonlinear algorithm, most notably the incorporation of temperature-dependent material properties (cubic variation), the decomposition of the total strain energy into its invariant natural components, assessing also their effect on failure initiation, the combined effect of load and temperature and the influence of initial imperfections on the overall behaviour, and finally comments on some of the intricate differences revealed for some problems by using the flat and shallow shell triangular elements. Comparisons with reported analytical and experimental results is attempted where available. Overall, the computational experiments substantiate the developed methodology and show its potential to treat larger and more complex panels and also contribute to their design.

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ABSTRACT: We present the computational performance and the achieved accuracy of the TRIC flat triangular shell element for nonlinear postbuckling analysis of arbitrary isotropic and composite shells. The element is based on the natural mode finite element method, which allows a convenient description of the current position of the structure. These natural modes are assigned to a convective coordinate system which follows the element during deformation within the framework of an Eulerian motion. With respect to this coordinate system the natural modes are additive. Numerical examples verify the accuracy, computational efficiency and the potential of the TRIC element in predicting the postbuckling behaviour of shells. Natural energy measures inform us about the energy allocation during nonlinear deformation and the interplay of the separate energy components.

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ABSTRACT: TRIC is a facet triangular shell element, which is based on the natural mode method. It has been shown that the TRIC shell element satisfies the individual element test and in the framework of the nonconsistent formulation the convergence requirements are fulfilled, while it has been proved to be very efficient in linear and nonlinear static problems. Moreover, another major advantage in the formulation of this element is the incorporation of the transverse shear deformations in a way that defies the shear-locking phenomenon. In this work the derivation of the consistent and lumped mass matrices of the TRIC element is presented so that it can be used in linear and nonlinear dynamic problems. Both translational and rotational inertia are included in the consistent mass matrix, which is conceived, using kinematical and geometrical arguments consistent with the assumed natural rigid body and straining modes of the element. All the kinematical and geometrical arguments that are invoked for the derivation of the consistent mass matrix are briefly presented. Moreover, two formulations of the lumped mass matrix of TRIC are derived. The first formulation is based entirely on geometrical considerations whereas the second is based on lumping the consistent mass matrix of TRIC. Finally, the element’s robustness and accuracy will be shown by applying it to properly selected benchmark examples of nonlinear shell dynamics, while its computational efficiency will be demonstrated by comparing the CPU performance of the element with the other available shell elements.

References listed at the end of the paper:


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ABSTRACT: In the present study, a generalization of the Energy–Momentum Method, denoted by Generalized Energy–Momentum Method, applied to the non-linear dynamics of shells will be developed within the framework of the Generalized-α Method. This algorithmic environment contains the unconditionally stable Energy–Momentum Method and its numerically damped version as well as the classical Newmark and α-methods as special cases. In order to control the size of the time steps of the integration scheme with respect to accuracy and efficiency, an adaptive time stepping procedure based on local a posteriori error estimation will be improved for non-linear dynamical systems and applied to the proposed class of algorithms. The spatial discretization is realized by an eight noded finite shell element of Reissner/Mindlin type including an extensible shell director field permitting the application of three-dimensional material laws. The original formulation of this finite element will be developed for non-linear dynamic analysis and adapted for the employment within the introduced energy conserving/decaying time integration scheme.

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ABSTRACT: A novel integration scheme for nonlinear dynamics of geometrically exact shells is developed based on the inextensible director assumption. The new algorithm is designed so as to imply the strict decay of the system total mechanical energy at each time step, and consequently unconditional stability is achieved in the nonlinear regime. Furthermore, the scheme features tunable high frequency numerical damping and it is therefore stiffly accurate. The method is tested for a finite element spatial formulation of shells based on mixed interpolations of strain tensorial components and on a two-parameter representation of director rotations. The robustness of the scheme is illustrated with the help of numerical examples.

References listed at the end of the paper:
ABSTRACT: A modified time-integration method is developed for non-linear structural dynamics combining controllable algorithmic dissipation of higher modes and, at the same time, conservation of energy as well as linear and angular momentum. Although these features seem to be actually inconsistent, numerical stability with...
large time steps for dynamic buckling and snap-through problems as well as for dynamical systems with smooth solutions is guaranteed. Arbitrary implicit, one-step time-integration schemes with Newmark approximations are suitable for use as basic algorithms for the proposed method. The desired conservation attributes are obtained if the basic algorithm is augmented by energy and momentum constraints. The potential of the suggested algorithm is demonstrated by selected applications to non-linear dynamics of shell structures.


ABSTRACT: The present study is concerned with the application of two vector iteration methods in the investigation of the large deflection behavior of spatial structures. The dynamic relaxation and the first order conjugate gradient belong to this category of methods which do not require the computation or formulation of any tangent stiffness matrix. The convergence to the solution is achieved by using only vectorial quantities and no stiffness matrix is required in its overall assembled form. In an effort to evaluate the merits of the methods, extensive numerical studies were carried out on a number of selected structural systems. The advantages of using these vector iteration methods, in tracing the post-buckling behavior of spatial structures, are demonstrated.


ABSTRACT: A review of conventional testing methods for applying external hydrostatic pressure to buckling-critical shells is presented. A new “volume-control” pressure testing method, aimed at preventing catastrophic specimen failures and improving control of specimen deformation near the critical load, is also introduced. The implementation of conventional and volume-control systems in an experimental program involving the destructive pressure testing of ring-stiffened cylinders is described. The volume control method was found to improve control of the specimen deformations, especially near the critical load, and catastrophic failures observed while using a conventional setup were avoided. The quasi-static tracking of post-collapse load-deformation relationships for snap-through buckling behaviour was possible while using a volume-control system, but precise control of dynamic shell deformations during buckling was not achieved for specimens failing with large buckling lobes. Expressions for estimating the available control over specimen deformations for pressure testing systems are presented.

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1. BSI (1980) BS 5500 British standard specification for unfired fusion welded pressure vessels, Issue 5, United Kingdom: British Standards Institution (BSI)
9. Weingarten VI, Seide P (1965) Elastic stability of thin-walled cylindrical and conical shells under combined external pressure and


ABSTRACT: In this study, the buckling behavior of optimum laminated composite cylindrical shells subjected to axial compression and external pressure are studied. The cylindrical shells are composed of multi orthotropic layers that the principal axis gets along with the shell axis (x). The number of layers and the fiber orientation of layers are selected as optimization design variables with the aim to find the optimal laminated composite cylindrical shells. The optimization procedure was formulated with the objective of finding the highest buckling pressure. The Genetic Algorithm (GA) and Imperialist Competitive Algorithm (ICA) are two optimization algorithms that are used in this optimization procedure and the results were compared. Also, the effect of materials properties on buckling behavior was analyzed and studied.

References listed at the end of the paper:


ABSTRACT: Thin walled cylinders under external pressure may be affected by instability phenomena particularly dangerous when taking place in the elastic domain. Geometric imperfections caused by fabrication processes heavily influence the critical pressure. In order to investigate the relationship between the collapse mechanism and the various types of imperfections affecting this kind of structures a series of experimental tests on scale models has been carried out. The dimensional parameters of the specimens have been selected in order to keep the instability phenomenon in the elastic range. At the same time numerical calculations simulating the experimental tests have been performed by finite element method. The geometrical defects measured on the specimens were introduced in the correspondent numerical models. A good agreement was found in the comparison between experimental and numerical results.


ABSTRACT: Theoretical and experimental research on the ultimate strength of rigid pipelines for deepwater applications conducted at the Laboratory for Submarine Technology—COPPE has been reviewed. Small scale laboratory tests included intact pipes under external pressure combined with longitudinal bending as well as damaged pipes under external pressure. Results obtained from specialist computer programmes and analytical formulations have been correlated with experimental results in order to propose ultimate strength equations to be used in the design procedures. Aspects related to the pipeline installation by reeling method are considered.


ABSTRACT: A theoretical explicit formulation for numerical simulation of the buckle propagation in deepwater pipelines is proposed. It is based on thin shell theory incorporating large rotations and material elastic–plastic behavior for infinitesimal strains. The equilibrium equations are solved numerically through a computer program using the finite difference method associated to the dynamic relaxation technique. The pipe post-buckling behavior is determined by the arc-length method used in convolute regions of the load–displacement curve. The numerical results are correlated with experimental data from small scale laboratory tests.


ABSTRACT: The Hobbs equations have been used for years to evaluate the susceptibility of flowlines to lateral buckling. However these equations are sometimes used without a clear understanding of the driving mechanism and for some flowlines configurations care shall be taken for a direct application of these formulas. In particular, the infinite mode buckle shape, although widely considered in the industry, does not reflect the lateral buckling mechanism. Through a thorough review of the assumptions and validity of the Hobbs equations, this paper presents adequate formulations to evaluate the susceptibility to lateral buckling for specific flowlines configurations. The cases of short flowlines, medium flowlines and unbounded pipe in pipe systems...
are presented. The methodology described in Hobbs paper is analyzed in detail and the bases of the equations are rewritten for short and medium flowlines. The pipe length in the feed-in zone before and after buckle is calculated based on the strain profiles in the pipes. Then the critical buckling force is deduced by the application of an equation of continuity of displacements. For unbounded pipe in pipe the same principle is used with the addition of an uncoupled behaviour between the axial and lateral components and the share of axial force at the bulkhead location. The contribution of the centralizers is also incorporated in the formulation. Eventually, the criteria presented in the paper are compared with a more realistic probabilistic approach to evaluate their degree of conservatism.

W. Fricke and R. Bronsart (Editors), Proceedings of the 18th International Ship and Offshore Structures Congress (ISSC 2012), 9-13 September 2012, Rostock, Germany, Volume 2, “Committee V.5 Naval Vessels”.

ABSTRACT: Concern for structural design methods for naval ships and submarines including uncertainties in modeling techniques. Particular attention shall be given to those aspects that characterise naval ship and submarine design such as blast loading, vulnerability analysis and others, as appropriate.

IN PARTICULAR WE ARE INTERESTED IN SECTION 6.2: Ring-Stiffened Cylinder Subject to Hydrostatic Pressure Load: This case study consisted of a round robin whereby the participants generated collapse predictions for two experimental models (Mackay and Pegg, 2010). Those models were tested under a joint project of Defence Research and Development Canada and the Netherlands Ministry of Defence that examined the effect of corrosion thinning on pressure hull strength and stability (Mackay, Smith et al., In Press). The test models are small-scale aluminium ring-stiffened cylinders, their nominal dimensions are shown in Figure 8. The two models chosen for the case study are nominally identical, except for a patch of artificial corrosion on one of the specimens that was introduced by machining away some of the shell material (Figure 9). The participants were allowed to use any method to predict the strength of the cylinders, including analytical, empirical or numerical methods, or some combination thereof. Each participant reported the predicted collapse pressure and yield pressure of each specimen, as well as predicted pressure-strain histories. The experimental results were withheld until after the participants submitted their results.

CONTENTS OF THE ENTIRE VOLUME 2:

1 General Discussion – Similarities and Differences Between Naval and Commercial Structural Design
   1.1 Introduction
   1.2 Some Historic Notes on Naval Structural Design
   1.3 Which Differences
   1.4 Similarities
   1.5 Differences
   1.6 Military Loads
   1.7 Submarines
   1.8 Relation to Rules and Regulations
   1.9 Concluding Remarks

2 Optimization of Naval Structures Using Lightweight Materials
   2.1 Why Consider Lightweight Materials?
   2.2 Requirements and Decision Criteria for Naval Vessels
   2.3 Lightweight Materials as Means for Optimization
   2.4 Further Challenges for Mitigation of Weight in Naval Vessels
      2.4.1 Structural Fire Protection
2.4.2 Capital Costs vs. Lifecycle Savings

2.5 Hull Monitoring

2.6 Conclusion

3 Submarine Pressure Hull Structural Design
   3.1 Introduction
   3.2 Materials
   3.3 Geometric Imperfections
   3.4 Effect of Residual Stresses on Pressure Hull Strength
   3.5 Pressure Hull Design Methodology
   3.6 Application of Numerical Methods to Pressure Hull Structural Design

4 Military Loads
   4.1 Under Water Weapons Effects
   4.2 Asymmetric Threats

5 Residual Strength After Damage

6 Benchmark Studies
   6.1 Square Plate Subject to a Blast Load
   6.2 Ring-Stiffened Cylinder Subject to Hydrostatic Pressure Load
      6.2.1 Measured Specimen Geometry
      6.2.2 Measured Material Properties
      6.2.3 Round-robin Results

7 Discussion and Conclusions

8 Recommendations

9 References
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56. RINA Rules for Naval Ships (2011)

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ABSTRACT: The ultimate longitudinal bending strength of thin plated steel structures such as box girder bridges and ship hulls can be determined using an incremental-iterative procedure known as the Smith progressive collapse method. The Smith method first calculates the response of stiffened panel sub-structures in the girder and then integrates over the cross section of interest to calculate a moment–curvature response curve. A suitable technique to determine the strength behaviour of stiffened panels within the Smith method is therefore of critical importance. A fundamental assumption of the established progressive collapse method is that the buckling and collapse behaviour of the compressed panels within the girder occurs between adjacent transverse frames. However, interframe buckling may not always be the dominant collapse mode, especially for lightweight stiffened panels such as are found in naval ships and aluminium high speed craft. In these cases overall failure modes, where the buckling mode extends over several frame spaces, may dominate the buckling and collapse response. To account for this possibility, an adaptation to large deflection orthotropic plate theory
is presented. The adapted orthotropic method is able to calculate panel stress-strain response curves accounting for both interframe and overall collapse. The method is validated with equivalent nonlinear finite element analyses for a range of regular stiffened panel geometries. It is shown how the adapted orthotropic method is implemented into an extended progressive collapse method, which enhances the capability for determining the ultimate strength of a lightweight stiffened box girder.

References listed at the end of the paper:

ABSTRACT: Results are described of a numerical study of the initial compressive buckling and post-buckling behaviour of GRP panels reinforced by longitudinal hat-section stiffeners. Particular reference is made to the effects of interaction between local buckling of the panel laminate and overall column-like buckling involving bending of the stiffeners. Conclusions are reached regarding the influence of interactive effects on collapse strength and recommendations are made on allowance for these effects in design.

References listed at the end of the paper:

DOI: 10.1016/j.marstruc.2009.09.001

ABSTRACT: This paper presents extensive non-linear finite element (FE) analysis and formulation development work carried out on the ultimate compressive strength of plates and stiffened panels of ship structures. A review of contemporary designs for large ships was carried out. The existing formulae for plate ultimate compressive strength were reviewed and compared with non-linear FE analysis results. A semi-analytical formula for ultimate compressive strength assessments of stiffened panels was proposed and is described. The developed formula was verified against results using ABAQUS non-linear FE software for a series of 61 stiffened panels and a good agreement between the proposed formula and FE results were achieved. The method was verified against a large number of published FE results and was also compared with 58 experimental results. The developed method was also applied to the deck and bottom structures for a range of various sizes oil tankers and bulk carriers.

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ABSTRACT: An overview of current design practices for submarine pressure hulls is presented, along with the results of a survey of the literature that was conducted to determine standard nonlinear numerical modelling practices for those structures. The accuracies of the conventional submarine design formulae (SDF) and nonlinear numerical analyses for predicting pressure hull collapse are estimated by comparing predicted and experimental collapse loads from the literature. The conventional SDF are found to be accurate within approximately 20%, with 95% confidence, for intact pressure hulls. The accuracy of a wide range of nonlinear numerical methods, including axisymmetric finite difference and general shell finite element (FE) models, is found to be within approximately 16% with 95% confidence. The accuracy is found to be within 9% when only higher fidelity general shell FE models are considered. It is shown how the observations taken from the survey could serve as a starting point for establishing modelling guidelines, quantifying the accuracy of nonlinear FE analysis in pressure hull collapse calculations, and introducing this method into a design procedure by way of a partial safety factor.

ABSTRACT: Pressure hulls are the main load bearing structures of naval submarines, commercial and research submersibles, and autonomous underwater vehicles (AUVs). The many similarities between pressure hull, offshore, aerospace and some civil engineering structures mean that advances in one group are often applicable to the others, and thus this document is sometimes concerned with the entire collection of thin-walled curved structures designed for instability, referred to hereafter as “buckling-critical shells.” The state-of-the-art of pressure hull structural analysis and design is established in this document by: 1) explaining the nature of structural strength, and associated weaknesses, in pressure hulls; 2) summarizing traditional and contemporary structural analysis and design methods for pressure hulls; 3) identifying trends with respect to numerical modeling of buckling-critical shell structures; and 4) reviewing novel design procedures for buckling-critical shell structures. It is suggested that the layered conservatism of the traditional design approach could be improved by the use of nonlinear numerical methods for strength predictions, and a way forward is suggested that would allow pressure hull design procedures to incorporate these methods.

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ABSTRACT: An energy method is developed for analyzing the flexural-torsional and lateral-torsional buckling (“tripping”) behavior of flanged stiffeners subjected to axial force, end moment, lateral pressure and any combination of these. A strain distribution is assumed and the total potential energy functional is then derived. The strain assumptions coincide with van der Neut’s assumption. However, unlike the somewhat obscure differential equation approach given by van der Neut, this study provides a simple, clear, energy approach. Both the rigid web case and the flexible web case are studied. The study explores the effect of plate rotational restraint, and a previously unresolved question regarding plate mode shape is answered. The method requires only four degrees of freedom and therefore the solution process is rapid. A number of sample stiffened panels are analyzed using the ABAQUS finite-element program; the results are in quite good agreement. The method has also been extended to inelastic tripping, and this generalized form shows excellent agreement with experimental tests on typical steel panels. This work will be presented in a second paper, to avoid an overly long publication.


ABSTRACT: A previous paper [1] proposed an elastic tripping model using a Rayleigh-Ritz approach with 4 d.f. This paper extends the elastic model into the inelastic range, using deformation theory and an iterative and incremental formulation. Nonetheless, because of the efficiency of the Rayleigh-Ritz formulation, the solution is very rapid, even for ordinary PCs. The method can be used for analyzing the flexural-torsional and lateral-torsional buckling (“tripping”) behavior of flanged stiffeners subjected to axial compression, end moment, uniform lateral pressure and any combination of these. The effects of cross-sectional distortion, postbuckling behavior of the plate (incorporated by considering the plate effective width) and plasticity are included. Results obtained using the method are shown to be in good agreement with experimental results, and to be more accurate than other methods.

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ABSTRACT: A non-linear finite element (FE) package has been used to investigate the torsional behaviour of flat-bar stiffeners in longitudinally stiffened panels subject to axial loading. The effects of plate slenderness, stiffener slenderness and boundary conditions have been studied including the modelling of the outstand both as part of a stiffened panel and in isolation. A simple analytical approach is proposed by using a theoretical mechanism model developed by Murray combined with a simple elastic loading line to give an upper bound to the tripping failure load. The results are compared with existing design guidance.

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“Tripping of thin-walled stiffeners in the axially compressed stiffened panel with lateral pressure”, Thin-Walled Structures, Vol. 37, No. 1, pp 1-26, May 2000, DOI: 10.1016/S0263-8231(00)00010-0

ABSTRACT: Tripping of stiffeners in stiffened panels under combined loads of axial force and lateral pressure is studied. Firstly, on the basis of the Vlasov's differential equation for torsional buckling of thin-walled bars, a generalized eigenvalue problem for tripping of stiffeners is derived by using the Galerkin's Method. Then the effect of the lateral pressure (dead load) to the critical axial stress (live load) upon tripping is investigated by solving the eigenvalue problem. The rotational restraint provided by the plate is taken into account. The effects of the compressive stress in the plate and the plate buckling mode are also discussed. Finally, an approximate equation to estimate the critical tripping stress with the effect of the lateral pressure is proposed. After some modifications, it can be applied in design rules for the purpose of checking the tripping strength of the stiffeners.


ABSTRACT: Tripping of stiffeners under combined loads of axial force, lateral pressure and end moment is studied. First, the neutral balance differential equation under the three combined loads is deduced. The equation is solved with Galerkin's method and a general eigenvalue problem is got. Second, the rotational restraint provided by the plate is studied. Based on the result of FEM, existing formula is modified and comparison of results according to different spring stiffness shows that the modified formula is more reasonable. A program based on the method is developed and its result has a very good coincidence with the result of FEM program MARC. Last, a series of calculation is conducted with above program to study the relation of the three kinds of loads. Regression of the results of the calculation gives out a correlativity formula of the three kinds of loads.


ABSTRACT: The subject of this research is the buckling behavior of a rectangular plate, with a bulb flat stiffener attached to one side of the plate. The stiffener cross section has a thin web and a bulb flat flange that extends to one side of the web. The stiffened plate structure is subjected to axial compression that increases to
the buckling load. Results of the investigation include planar property formulas for the asymmetric flange geometry, an analytic expression for the Saint-Venant torsional constant of the flange cross section, and an analytic expression for the buckling stress corresponding to a tripping mode of the structure. The torsional constant for the bulb flat stiffener is 15–23% higher than understood previously. The analytic expression for the buckling stress of a bulb flat stiffened plate differs by less than 4% from finite element and experimental results.

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ABSTRACT: An increasingly popular approximate method for assessing ship hull girder ultimate strength is to combine the individual elasto-plastic load-carrying characteristics of each single stiffened-plate unit comprising the ship hull cross section. In order to evaluate methods (numerical and experimental) for developing the load-carrying characteristics (load–shortening curves), a full-scale testing system was designed and constructed to provide data for stiffened steel plate units under combined axial and lateral loads. The system included an assembly of discrete plate edge restraints that were developed to represent symmetric boundary conditions within a grillage system. Twelve full-scale panels including ‘as-built’, ‘deformed’ and ‘damaged’ specimens were tested in this set-up. The specimens failed by combined plate and flexural buckling, stiffener tripping or local collapse, depending on the magnitude of lateral loads and local damage. Load-shortening curves associated with different failure modes were found to be distinctly different and it was found that a small lateral load could change the failure mode from flexural buckling to tripping. Current design criteria should directly consider effects of the lateral loads on the failure modes and the collapse loads of stiffened plates.

ABSTRACT: A series of elastoplastic large deflection analyses are performed on stiffened plates with flat-bar and angle-bar stiffeners subjected to thrust, and the influences of sectional geometries of stiffeners on the buckling/plastic collapse behaviours are investigated. It has been found that: (1) Local panel buckling strength among stiffeners, post-buckling inplane rigidity and ultimate strength is increased owing to the stiffener; (2) stiffened plates undergo elastoelastic secondary buckling after local panel buckling; (3) higher ultimate strength is attained by stiffeners with lower depth-to-thickness ratio of a web, but, the reduction in capacity after the ultimate strength is more rapid for stiffened plates with such stiffeners; (4) when stiffeners with relatively high depth-to-thickness ratio are provided, the ultimate strength is lower than with a lower depth-to-thickness ratio, but the capacity reduction after the ultimate strength is rather moderate.

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ABSTRACT: An analytical formula for estimating elastic local buckling strength of a continuous stiffened plate subjected to biaxial thrust is derived considering the influence of plate/stiffener interaction and welding residual stresses. Through a comparison of calculated results with those by FEM eigenvalue analysis, high accuracy of the proposed formula is demonstrated. A series of buckling strength analyses is performed on the deck and bottom plating of actual ships.

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ABSTRACT: A new simplified model for collapse analysis of stiffened plates is developed in the framework of the idealized structural unit method (ISUM). By idealizing material and geometrical nonlinearities, larger structural units are defined as an element in ISUM than in conventional finite element analysis (FEA). The proposed stiffened plate model consists of ISUM plate elements and beam-column elements. The formulation of the plate element is performed by introducing accurate shape functions to simulate the buckling/plastic collapse behaviour of plate panels. Combining plate and beam-column elements allows for both local buckling of the plate panel and overall buckling of the stiffener. Fundamental collapse modes of plate panels and stiffened plates are investigated by conventional FEA. According to the observed characteristics, the new simplified model is formulated. Comparisons with FEA demonstrate the accuracy of the simplified model and its high applicability to typical stiffened plates in marine structures.

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ABSTRACT: This paper shows that the application of pre-determined failure equations, derived from nonlinear finite element analyses, is effective in determining failure of structural components in a simpler linear finite element analysis. An analysis method is presented which is called simplified failure analysis. The first step of this method is the nonlinear determination of a component's failure limit. Next, a linear coarse-meshed finite element model of the component is analyzed under the failure load determined in the previous step. The resulting linear stress distribution is a ’representative failure stress’ for the component because it is in equilibrium with the applied failure load. This ‘failure stress’ is then used in simpler linear analysis to provide a representative failure limit. This method is verified by an analysis of a structural grillage.


ABSTRACT: In this paper, simplified formulas to calculate the ultimate strength of corrugated bulkheads are derived using the beam–column theory. The formulas can take account of the influences of shear force and
adjoining structures. By comparing the results from present formulas with those of other numerical analyses, it is shown that the formulas derived in this paper are accurate and reliable for engineering purposes. Thus, a more powerful design tool is provided. Finally the effects of the shear force and rigidities of adjoining structures on the ultimate strength of corrugated bulkheads are also studied.

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ABSTRACT: The ultimate longitudinal strength of a typical bulk carrier is analyzed by using a simplified method. The moment–curvature curve, the ultimate bending moment and the location of the instantaneous neutral axis at ultimate state are calculated for both hogging and sagging conditions of the ship under vertical bending. The stress distribution over the hull cross-section at ultimate state is also obtained. The ultimate strength of the ship hull under combined vertical and horizontal bending moments is further investigated. An interaction curve is obtained according to the results of a series of calculation for the hull subjected to bending conditions with different angles of curvature. It is found that the interaction curve is asymmetrical because the hull cross-section is not symmetrical about the horizontal axis and the behavior of the structural members under compression is different from that under tension due to the non-linearity caused by buckling. The angle of the resultant bending moment vector and that of the curvature vector are different in general cases. An interaction equation suitable for bulk carriers is proposed based on the results of the analyzed ship.

Yufeng Zha and Torgeir Moan (Department of Marine Structures, Faculty of Marine Technology, Norwegian University of Science and Technology, N-7491 Trondheim, Norway), “Ultimate strength of stiffened aluminium panels with predominantly torsional failure modes”, Thin-Walled Structures, Vol. 39, No. 8, pp 631-648, August 2001, DOI: 10.1016/S0263-8231(01)00027-1

ABSTRACT: The aim of this paper is to investigate the ultimate strength of aluminium plates with flatbar stiffeners with a torsional buckling or tripping failure mode. The formulations for torsional buckling of stiffeners in steel plating are still debated. Compared with steel structures, the ultimate strength of aluminium structures is sensitive not only to residual stresses and initial deformations, but also to the deterioration of mechanical strength in heat-affected zones (HAZ). In the present paper, the ultimate strength of stiffened aluminium panels with predominantly torsional failure modes is investigated by experimental and theoretical analysis. Stiffened panels made of the aluminium alloy AA5083-H116 and AA6082-T6 are considered. Various height of flatbar and various thickness of plate and stiffener were studied. The test results are compared with numerical predictions by using the finite element code ABAQUS (ABAQUS Version 5.7 (1997)), considering the influence of initial deflections, welding residual stresses and HAZ. The influence of HAZ and residual stresses on the ultimate strength of stiffened aluminium panels with the actual failure mode is discussed in detail. The numerical predictions are also compared with strength of material formulations used in DNV Rules for Classification of High Speed and Light Craft (Rules for classification of high speed and light craft, Hull structural design (1996)), NORSOK (Design of steel structures (1998)) all for steel, using the relevant values of the modulus elasticity and yield strength of aluminium, as well as EUROCODE 9 (Eurocode 9, Part 1-1: General rules (1998)).
ABSTRACT: This is the first of two companion papers dealing with nonlinear finite element modelling and analysis of the ultimate strength of a bulk carrier hull girder under alternate hold loading condition (AHL) condition. The purpose is to contribute to establishing rational ultimate longitudinal strength criteria for the hull girder under combined loading. The focus is on the hogging condition. An important issue is the significant double bottom bending in empty holds in AHL due to combined global hull girder bending moment and local loads. The local loads may substantially reduce the strength of the hull girder. Different AHL conditions, i.e. fully loaded cargo and (partially) heavy cargo are considered. A critical review of external and internal design pressures for different AHL conditions is accomplished using both CSR-BC rules and DNV rules. A methodology for nonlinear finite element modelling of hold tanks of a bulk carrier under AHL is presented by use of ABAQUS. A mesh convergence study is carried out in order to find the appropriate mesh for the model. The implication of using different design pressures on the hull girder strength is assessed. The FE results can be used as a basis for establishing simplified methods applicable to practical design of ship hulls under combined loadings. This issue is discussed in the companion paper.

ABSTRACT: This is the second of two companion papers dealing with nonlinear finite element modelling and ultimate strength analysis of the hull girder of a bulk carrier under Alternate Hold Loading (AHL) condition. The methodology for nonlinear finite element modelling as well as the ultimate strength results from the nonlinear FE analyses was discussed in the companion paper (Part 1). The purpose of the present paper is to use the FE results to contribute towards developing simplified methods applicable to practical design of ship hulls under combined global and local loads. An important issue is the significant double bottom bending in the empty hold in AHL due to combined global hull girder bending moment and local loads. Therefore, the stress distributions in the double bottom area at different load levels i.e. rule load level and ultimate failure load level are presented in detail. The implication of different design pressures obtained by different rules (CSR-BC rules and DNV rules) on the stress distribution is investigated. Both (partially) heavy cargo AHL and fully loaded cargo AHL are considered. Factors of influence of double bottom bending such as initial imperfections, local loads, stress distribution and failure modes on the hull girder strength are discussed. Simplified procedures for determination of the hull girder strength for bulk carriers under AHL conditions are also discussed in light of
the FE analyses.

Lars Brubak and Jostein Hellesland (Mechanics Division, Department of Mathematics, University of Oslo, P.O. Box 1053, NO-0316 Oslo, Norway), “Strength criteria in semi-analytical, large deflection analysis of stiffened plates in local and global bending”, Thin-Walled Structures, Vol. 46, No. 12, pp 1382-1390, December 2008 DOI: 10.1016/j.tws.2008.03.013

ABSTRACT: Various strength criteria that may be used in semi-analytical methods for ultimate strength prediction of arbitrarily stiffened plates are studied. The main objective is to evaluate the applicability of the criteria in ultimate strength predictions of in-plane loaded plates, both in local and global bending. The equilibrium path is traced using large deflection theory and the Rayleigh–Ritz approach on an incremental form. The approach is able to account for the reserve strength of slender plates in the postbuckling region. Results are compared with fully nonlinear finite element analyses for a variety of plate dimensions and stiffeners with regular and irregular arrangements. Good agreement is obtained with a combination of a plate and a stiffener criterion. With the considered criteria included, the method is computationally very efficient and gives rather high numerical accuracy.

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ABSTRACT: In this paper, the optimal stiffener design of moderately thick plates under uniaxial and biaxial compression is investigated on the premise that the plate thickness and the required ultimate strength are given. As the theoretical basis of stiffener design, the ultimate strength formulations of weak stiffened thick panels under in-plane biaxial compression are first developed on the basis of large deflection orthotropic plate theory, in which the post-weld initial deflection is taken into account. The von Mises yield criterion is employed to determine the limit state of the panel, and the Nelder–Mead simplex algorithm is used to obtain the efficient solution of nonlinear differential equations. The optimization method presented is based on the stiffener design principles of the overall instability stress and of the working stress. In the optimization formulation, the numbers and geometric sizes of the stiffeners are defined as design variables; the weight ratio of stiffeners to plate is taken as a single objective function; requirements against overall buckling of the panel, local buckling of the plates between the stiffeners and local buckling of the stiffeners themselves are set as constraint functions. Results of both design examples and parameter studies show that, for moderately thick plates, the stiffener weight given by the proposed optimization method is much lower than the weight determined by the current stiffener design method on the premise of the same requirement of structural safety. Using the present optimization method to obtain the lightest and the most effective stiffener layout for moderately thick plates is proposed.

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ABSTRACT: In order to perform a detailed analysis of large deflection behavior of a rectangular plate or stiffened plate, an efficient semi-analytical method is developed. First, incremental forms of the governing differential equations of plates and stiffened plates with initial deflection are derived. These equations are linearized and may be easily solved. Secondly, these equations are solved for each load increment by the Galerkin method with a special consideration of simply supported boundaries. A procedure of equilibrium correction at intermediate load steps is presented such that good accuracy of the solution may be maintained with larger load steps. This method is successfully applied to plates with initial deflection subjected to in-plane as well as out-of-plane loads to obtain the whole histories of the behavior of these plates. Application of this method to stiffened plates with initial deflection is also presented. Comparisons of results obtained by this method with those obtained by other methods are made and the validity of the method is demonstrated. This incremental version of the Galerkin method is found to be extremely advantageous in certain types of plate and stiffened plate problems. These types are identified and the efficiency of the method is demonstrated.

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ABSTRACT: A method for analysis of the structural damage due to ship collisions is developed. The method is based on the idealized structural unit method (ISUM). Longitudinal/transverse webs which connect the outer and the inner hulls are modelled by rectangular plate units. The responses are determined by taking into account yielding, crushing, and rupture. Some plates of the outer and the inner shell subjected to large membrane tensions are modelled by membrane tension triangular/rectangular plate units, while the remaining shell panels are modelled by the usual plate units. The effect of stiffeners on the stiffness and the strength is considered as well. In order to include the coupling effects between local and global failure of the structure, the usual nonlinear finite-element technique is applied. In order to deal with the gap and contact conditions between the striking and the struck ships, gap/contact elements are employed. Dynamic effects are considered by inclusion of the influence of strain-rate sensitivity in the material model. On the basis of the theory a computer program has been written. The procedure is verified by a comparison of experimental results obtained from test models of double-skin plated structures in collision/grounding situations with the present solutions. As an illustrative example the procedure has been used for analyses of a side collision of a double-hull tanker. Several factors affecting ship collision response, namely the collision speed and the scantlings/arrangements of strength members, are discussed.

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“A numerical investigation of tripping”, Marine Structures, Vol. 11, Nos 4-5, pp 159-183, May 1998
DOI: 10.1016/S0951-8339(98)00010-0
ABSTRACT: The twin aims of the present study are to investigate numerically the characteristics of tripping failure of flat-bar stiffened panels subject to uniaxial compressive loads and also to study the accuracy of two available design formulations. A special-purpose nonlinear finite element method capable of efficiently analyzing the elasto-plastic large deflection behavior of stiffened panels is developed and used in the study. A benefit of the application of the nonlinear finite element method is that it makes possible a rigorous accounting of the interacting effects of stiffener tripping and plating collapse and also the inclusion of the influence of elasto-plastic rotational restraint at the plate-stiffener intersection prior to and during failure. A parametric series of elasto-plastic large deflection analyses for stiffened panels with flat-bar type of stiffeners under uniaxial compressive loads are carried out varying member proportions and structural parameters. Based on the computed results, a basic investigation of tripping behavior of flat-bars is made, and the accuracy of design formulations is studied. The calculations and comparisons of this paper are for flat-bar stiffened panels under uniaxial compression, but the special-purpose finite element method implemented is considerably more general.

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ABSTRACT: Aluminum sandwich construction has been recognized as a promising concept for structural design of lightweight transportation systems such as aircraft, high-speed trains and fast ships. The aim of the present study is to investigate the strength characteristics of aluminum sandwich panels with aluminum honeycomb core theoretically and experimentally. A series of strength tests are carried out on aluminum honeycomb-cored sandwich panel specimen in three point bending, axial compression and lateral crushing loads. Simplified theories are applied to analyze bending deformation, buckling/ultimate strength and crushing strength of honeycomb sandwich panels subject to the corresponding load component. The structural failure characteristics of aluminum sandwich panels are discussed. The test data developed are documented.

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“Large deflection orthotropic plate approach to develop ultimate strength formulations for stiffened panels under combined biaxial compression / tension and lateral pressure”, Thin-Walled Structures, Vol.39, No.3, pp.215-246, 2001, DOI: 10.1016/S0263-8231(00)00059-8
ABSTRACT: This paper uses the large deflection orthotropic plate approach to develop the ultimate strength formulations for steel stiffened panels under combined biaxial compression/tension and lateral pressure loads, considering the overall (grillage) buckling collapse mode. The object panel has a number of one-sided small stiffeners in either one or both orthogonal directions. The stiffened panel is then modeled as an equivalent orthotropic plate, for which the various elastic constants characterizing structural orthotropy are determined in a consistent systematic manner using classical theory of elasticity. The panel edges are considered to be simply supported. The influence of initial deflections is taken into account. The membrane stress distribution inside the panel under combined uniaxial loading (in either longitudinal or transverse direction) and lateral pressure is
analyzed by solving the nonlinear governing differential equations of large deflection orthotropic plate theory. It is presumed that the panel collapses when the most highly stressed boundary location yields, resulting in closed-form expressions for the ultimate strength of the stiffened panel. Based on the insights previously developed through numerical studies, the panel ultimate strength interaction formulation between biaxial loads, with lateral pressure regarded as a secondary load component is then proposed as a relevant combination of the two sets of panel ultimate strength formulations, i.e. one for combined longitudinal axial load and lateral pressure and the other for combined transverse axial load and lateral pressure. The validity of the proposed ultimate strength formulations is verified by a comparison with nonlinear finite element and other numerical solutions.

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“Ultimate strength of ship hulls under torsion”, Ocean Engineering, Vol. 28, No. 8, pp 1097-1133, August 2001
DOI: 10.1016/S0029-8018(01)00015-4

ABSTRACT: For a ship hull with large deck openings such as container vessels and some large bulk carriers, the analysis of warping stresses and hatch opening deformations is an essential part of ship structural analyses. It is thus of importance to better understand the ultimate torsional strength characteristics of ships with large hatch openings. The primary aim of the present study is to investigate the ultimate strength characteristics of ship hulls with large hatch openings under torsion. Axial (warping) as well as shear stresses are normally developed for thin-walled beams with open cross sections subjected to torsion. A procedure for calculating these stresses is briefly described. As an illustrative example, the distribution and magnitude of warping and shear stresses for a typical container vessel hull cross section under unit torsion is calculated by the procedure. By theoretical and numerical analyses, it is shown that the influence of torsion induced warping stresses on the ultimate hull girder bending strength is small for ductile hull materials while torsion induced shear stresses will of course reduce the ship hull ultimate bending moment.

DOI: 10.1016/S0263-8231(01)00043-X

ABSTRACT: This paper develops advanced, yet design-oriented ultimate strength expressions for stiffened panels subject to combined axial load, in-plane bending and lateral pressure. The collapse patterns of a stiffened panel are classified into six groups. It is considered that the collapse of the stiffened panel occurs at the lowest value among the various ultimate loads calculated for each of the collapse patterns. The panel ultimate strengths for all potential collapse modes are calculated separately, and are then compared to find the minimum value which is then taken to correspond to the real panel ultimate strength. The post-weld initial imperfections (initial deflection and residual stress) are included in the developed panel ultimate strength formulations as parameters of influence. The validity of the developed formula is confirmed by comparing with the mechanical collapse tests and nonlinear FEA. A comparison of the present method is also made with theoretical solutions from the Det Norske Veritas classification society design guideline. Important insights developed are summarized.
References listed at the end of the paper:
References:


ABSTRACT: In this paper the ultimate strength characteristics of dented steel plates under axial compressive loads are investigated using the ANSYS nonlinear finite element code. The effects of shape, size (depth, diameter), and location of the dent on the ultimate strength behavior of simply supported steel plates under axial thrust are studied. A closed-form formula for predicting the ultimate compressive strength of dented steel plates are empirically derived by curve fitting based on the computed results. The results and insights developed in the present study will be useful for damage tolerant design of steel plated structures with local denting.

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“A concise introduction to the idealized structural unit method for nonlinear analysis of large plated structures and its application”, Thin-Walled Structures, Vol. 41, No. 4, pp 329-355, April 2003

DOI: 10.1016/S0263-8231(02)00113-1

ABSTRACT: The idealized structural unit method (ISUM) has now been widely recognized by researchers as an efficient and accurate methodology to perform nonlinear analysis of large plated structures such as ships, offshore platforms, box girder bridges or other steel structures. This paper presents a summary of pertinent ISUM theory and its application to nonlinear analysis of steel plated structures. Important concepts for development of various ISUM units which are needed to analyze nonlinear behavior of steel plated structures are described. Some application examples are shown, wherein comparisons of ISUM analysis predictions are made with numerical or experimental results for progressive collapse analysis of general types of steel plated structures and ship hulls, to illustrate the possible accuracy and versatility of the ISUM method. The use of ISUM for the analysis of internal collision/grounding mechanics of ships is also illustrated. This paper is in part an attempt to demystify ISUM and its applications for the benefit of a designer of steel plates structures (Paik and Thayambali, Ultimate limit state design of steel plated structures; 2002).
ABSTRACT: The aim of the present study is to obtain experimental data on the ultimate strength of steel plates under dynamically applied axial compressive loads. A series of dynamic collapse tests were carried out on steel plate models under axial compressive loads, varying the loading speed. Based on the test results, the effect of loading speed (or strain rate) on the ultimate strength of steel plates is investigated. Relevant useful formulations for assessing the dynamic ultimate compressive strength of steel plates are also derived as a function of the strain rate by curve fitting. The test data developed are documented.

ABSTRACT: The present paper deals with the estimation of buckling loads of plates with cracking damages. The hierarchical trigonometric functions are used to define the displacement function of the cracked plate. Selective choosing of the trigonometric functions satisfies the various boundary conditions of a plate bounded by support members in a continuous plated structure. Moreover, the analysis of the cracked plate can be carried out with a minimum number of equations accurately. In the present paper, the buckling loads of plates with various types of cracks, such as edge crack and central crack, are estimated under uniaxial compressive load, biaxial compressive load and in-plane shear load. The results are found to correlate well with those obtained using a finite element method.

ABSTRACT: The present study was undertaken by the support from Ship Structure Committee (http://www.shipstructure.org), a North American-based interagency research and development committee, in association with SR-1446 project, and also from Alcan Marine, France. Empirical expressions are developed for predicting the ultimate compressive strength of welded aluminum stiffened panels used for marine applications. Existing data of the ultimate compressive strength for aluminum stiffened panels experimentally and numerically obtained by the SR-1446 project is used for deriving the formulations which are expressed as functions of two parameters, namely the plate slenderness ratio and the column (stiffener) slenderness ratio. The formulae implicitly include the effects of weld induced initial imperfections, and softening in the heat affected zone.

ABSTRACT: The aim of the present study is to investigate the ultimate strength characteristics of perforated steel plates under edge shear loading, which is a primary action type arising from cargo weight and water pressure in ships and ship-shaped offshore structures. The plates are considered to be simply supported along all (four) edges and kept straight. The cutout is circular and located at the center of the plate. A series of ANSYS nonlinear finite element analyses (FEA) are undertaken with varying the cutout size (diameter) as well as plate dimensions (plate aspect ratio and thickness). By the regression analysis of the FEA results obtained, a closed-form empirical formula for predicting the ultimate shear strength of perforated plates, which can be useful for first-cut strength estimations in reliability analyses or code calibrations, is derived. The accuracy of the ultimate strength formula developed is verified by a comparison with more refined nonlinear FEA results.


ABSTRACT: The present paper is a sequel to the author’s papers [Paik JK, Ultimate strength of perforated steel plates under edge shear loading. Thin-Walled Structures 2007; 45: 301–6, Paik JK Ultimate strength of perforated steel plates under axial compressive loading along short edges. Ships Offshore Struct, 2007; 2(3): (in press)]. In contrast to the previous papers with the focus on edge shear or uniaxial compressive loads, the aim of the present study is to investigate the ultimate strength characteristics of perforated steel plates under combined biaxial compression and edge shear loads, which is a typical action pattern of steel plates arising from cargo weight and water pressure together with hull girder motions in ships and ship-shaped offshore structures. The plates are considered to be simply supported along all (four) edges, keeping them straight. The cutout is circular and located at the center of the plate. A series of ANSYS nonlinear finite element analyses (FEA) are undertaken with varying the plate dimension (thickness). Based on the FEA results obtained, closed-form empirical formulae of the ultimate strength interaction relationships of perforated plates between combined loads, which can be useful for first-cut estimations of the ultimate strength in reliability analyses or code calibrations, are derived.


ABSTRACT: It is well known that welding-induced initial deflections, among other factors, significantly affect the ultimate strength behavior of welded plate structures. This means that it is of vital importance to identify the features of plate initial deflections prior to the plate ultimate strength computations. The aim of the present paper is to investigate the characteristics of initial deflections that occur during welding fabrication of aluminum plates used for marine applications. A total of 78 single and multi-bay stiffened plate prototype aluminum structures which are full scale equivalent to sub-structures of an 80 m long all aluminum high speed vessel are constructed by metal inert gas (MIG) welding. Initial deflections of plating between stiffeners are then measured. A statistical analysis of the measured database is performed to determine mean and coefficient of variation (COV) of the plate initial deflection. The insights developed from the present study will be very useful for reliability analyses and code calibrations of ultimate limit state strength and fabrication quality control for welded aluminum plate structures.

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ABSTRACT: The present paper is Part I of a series of three papers prepared by the authors on the methods useful for ultimate limit state assessment of marine structures, that have been developed in the literature during the last few decades. It is considered that such methods are now mature enough to enter day-by-day design and strength assessment practice. The aims of the three papers are to conduct some benchmark studies of such methods on ultimate limit state assessment of (unstiffened) plates, stiffened panels, and hull girders of ships and ship-shaped offshore structures, using some candidate methods such as ANSYS nonlinear finite element analysis (FEA), DNV PULS, ALPS/ULSAP, ALPS/HULL, and IACS common structural rules (CSR) methods. As an illustrative example, an AFRAMAX-class hypothetical double hull oil tanker structure designed by CSR method is studied. In the present paper (Part I), the ultimate limit state assessment of unstiffened plates under combined biaxial compression and lateral pressure loads is emphasized using ANSYS, DNV PULS, and ALPS/ULSAP methods, and their resulting computations are compared. Part II will deal with methods for the ultimate limit state assessment of stiffened panels under combined biaxial compression and lateral pressure using ANSYS, DNV PULS, and ALPS/ULSAP methods, and Part III will treat methods for the progressive collapse analysis of the hull structure using ANSYS, ALPS/HULL, and IACS CSR methods.

ABSTRACT: The present paper is Part II of a series of three papers on methods useful for the ultimate limit state assessment of ships and ship-shaped offshore structures. In contrast to Part I [Paik et al., 2007a. Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part I unstiffened plates, Ocean Engineering, doi:10.1016/j.oceaneng.2007.08.004] that deals with unstiffened plates, the present paper (Part II) is focused on methods for the ultimate limit state assessment of stiffened plate structures under combined biaxial compression and lateral pressure actions. The object structure is the bottom part of an AFRAMAX-class hypothetical double-hull oil tanker structure designed by IACS common structural rules (CSR) method, that is the same ship studied in Part I. Three candidate methods, namely ANSYS nonlinear finite element method, DNV PULS method, and ALPS/ULSAP method, are employed for the present study. The results and insights developed from the present study are summarized in terms of ultimate strength characteristics of bottom-stiffened plate structures.

ABSTRACT: Box columns are often used as main strength members of various types of thin-walled structures such as ships, ship-shaped offshore structures, and aerospace structures. Until and after the ultimate limit state is reached, box columns exhibit highly nonlinear structural behavior in terms of geometrical and material aspects. In particular, the effects of local buckling, global buckling, and their interaction play a significant role in the resulting consequences of box columns under extreme actions. In order to calculate the maximum load-carrying capacity of box columns, it is thus highly required to perform the progressive collapse analysis to take into
account progressive failures of individual components and their interacting effects. The aim of the present study is to demonstrate a method that is useful for the progressive collapse analysis of thin-walled box columns in terms of computational efficiency and accuracy. Theoretical outline of the method is addressed. Short, medium and long box columns in length are studied in terms of interacting effects between local component failure modes and global system failure modes. The effect of unloaded edge conditions of individual plate elements is also studied. A comparison of the method with more refined nonlinear finite element method computations is made.

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“Numerical method for predicting the elastic lateral distortional buckling moment of a mono-symmetric beam with web openings”, Thin-Walled Structures, Vol. 49, No. 6, pp 713-723, June 2011
DOI: 10.1016/j.tws.2011.01.003

ABSTRACT: When used as floor joists, the new mono-symmetric LiteSteel beam (LSB) sections require web openings to provide access for inspections and various services. The LSBs consist of two rectangular hollow flanges connected by a slender web, and are subjected to lateral distortional buckling effects in the intermediate span range. Their member capacity design formulae developed to date are based on their elastic lateral buckling moments, and only limited research has been undertaken to predict the elastic lateral buckling moments of LSBs with web openings. This paper addresses this research gap by reporting the development of web opening modelling techniques based on an equivalent reduced web thickness concept and a numerical method for predicting the elastic buckling moments of LSBs with circular web openings. The proposed numerical method was based on a formulation of the total potential energy of LSBs with circular web openings. The accuracy of the proposed method's use with the aforementioned modelling techniques was verified through comparison of its results with those of finite strip and finite element analyses of various LSBs.

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ABSTRACT: The primary objective of the present paper is to experimentally examine the buckling collapse characteristics of fusion welded aluminum-stiffened plate structures under axial compression until and after the ultimate limit state is reached. The secondary objective of the paper is to study a nonlinear finite element method modeling technique for computing the ultimate strength behavior of welded aluminum structures. A set of aluminum-stiffened plate structures fabricated via gas metal arc welding is studied. The test structure is equivalent to a full scale deck structure of an 80 m long high speed vessel. The plate part of the structures is made of 5383-H116 aluminum alloy, and extruded stiffeners are made of 5083-H112 aluminum alloy. Welding induced initial imperfections such as plate initial deflection, column type global initial deflection of stiffeners,
sideways initial distortion of stiffeners, welding residual stresses, and softening in the heat-affected zone are measured. The ANSYS nonlinear finite element method is employed for the numerical computations of the test structure’s ultimate strength behavior by means of a comparison with experimental data. Insights and conclusions developed from the present study are documented.


ABSTRACT: The formulation of a nonlinear composite shell element is presented for the solution of stability problems of composite plates and shells. The formulation of the geometrical stiffness presented here is exactly defined on the midsurface and is efficient for analyzing stability problems of thin and thick laminated plates and shells by incorporating bending moment and transverse shear resultant forces. The composite element is free of both membrane and shear locking behavior by using the assumed natural strain method such that the element performs very well as thin shells. The transverse shear stiffness is defined by an equilibrium approach instead of using the shear correction factor. The proposed formulation is computationally efficient and the test results showed good agreement. In addition the effect of the viscoelastic material is investigated on the postbuckling behaviour of laminated composite shells.

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ABSTRACT: A co-rotational, quasi-conforming formulation of a 4-node stress resultant shell element is presented for non-linear analysis of plate and shell structures. The tangent stiffness matrix in this quasi-conforming formulation is explicitly integrated. This makes the element computationally efficient in incremental, non-linear analysis. It includes drilling degrees of freedom, which improves membrane behavior and allows the modeling of stiffened plates and shells. It is also free of shear locking behavior. The formulation of the geometrical stiffness is derived using the full definition of Green strain tensor. The inclusion of the bending moment and transverse shear resultant forces in the geometric stiffness allows effective analysis of stability problems of moderately thick plates and shells. The stresses are accurately taken at the nodal points without extrapolation. The plasticity is traced by applying the von Mises yield condition and Prandtl–Reuss flow rule to discrete points through the thickness. The multi-layered approach is based on equally spaced stations, including extreme fibers. A modified trapezoidal rule is used for the numerical integration of the constitutive relation in the plasticity part. Numerous tests are carried out for the non-linear validation of present 4-node shell element and the results are in good agreement with references.

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ABSTRACT: In this paper, we investigate the natural frequencies and buckling loads of functionally graded material (FGM) plates and shells, using a quasi-conforming shell element that accounts for the transverse shear strains and rotary inertia. The eigenvalues of the FGM plates and shells are calculated by varying the volume fraction of the ceramic and metallic constituents using a sigmoid function, but the Poisson ratios of the FGM plates and shells are assumed to be constant. The expressions for the membrane, bending and shear stiffness of FGM shell elements are more a complicated combination of material properties than a homogeneous element. In order to validate the finite element numerical solutions, the Navier solutions for rectangular plates based on the first order shear deformation theory are also presented. The present numerical solutions for composite and sigmoid FGM (S-FGM) plates and shells are verified by the Navier solutions and various examples of composite and FGM structures. The present results are in good agreement with the Navier theoretical solutions.

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ABSTRACT: The quasi-conforming technique was introduced in the 1980’s to meet the challenge of inter-elements conforming problems and give a unified treatment of both conforming and nonconforming elements. While the linear formulation is well established, the nonlinear formulation based on the quasi-conforming technique that includes geometric and material nonlinearity is presented in this paper. The formulation is derived in the framework of an updated Lagrangian stress resultant, co-rotational approach. The geometric nonlinear formulation provides solutions to buckling and postbuckling behaviour while the material nonlinear formulation considers the spread of plasticity within the element while maintaining an explicit construction of element matrices. Aside from the elasto-plastic constitutive relation, formulations on laminate composites and reinforced concrete are also presented.
The formulations of laminate composite and reinforced concrete material are present based on the layer concept, the material properties can vary throughout the thickness and across the surface of a shell element. The various failure criteria for laminate composite are included in the formulation which makes it possible to analyses the progressive failure of fibre and matrix. For the reinforced concrete material, the nonlinearities as a result of tensile cracking, tension stiffening between cracks, the nonlinear response of concrete in compression, and the yielding of the reinforcement are considered. The steel reinforcement is modeled as a bilinear material with strain hardening.

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ABSTRACT: In this paper the ability of the basic shell triangular (BST) element to perform linearized buckling analysis is evaluated. The results have been compared with analytical solutions and other finite elements in the literature, such as ANDES3, ANDES4, QSEL, FFQC and BCIZ. This type of analysis is applied to the design of steel structures to obtain the collapse load of panels using the effective width of the plate. In this approach, which is currently recommended by most of the design standards, a semi-empirical/analytical method is used to take into account the nonlinear geometric and material behavior, geometric imperfections and residual stresses. To obtain the critical loads two methods have been mainly applied: the finite strip method and the finite element method, which is more appropriate to deal with any boundary condition and loading pattern. In practice, to obtain the local and distortional buckling, some assumptions related to the interaction between plates are made in order to obtain practical formulae that can be applied; these simplifications can lead to unsafe results, so the linearized buckling analysis must be carried out in a proper way, taking into account the interactions. It is concluded that the BST element presents an excellent behavior to predict the critical loads in compression and shear, and therefore this element must be utilized in future codes when this type of analysis turns out to be mandatory.


ABSTRACT: A nonlinear resultant shell element is developed for the solution of problems of composite plates and shells undergoing nonlinear static and nonlinear dynamic behavior with progressive layer failure. The formulation of the tangent stiffness is defined on the mid-surface and is efficient for analyzing thick laminated plates and shells by incorporating bending moments and transverse shear resultant forces in the geometric stiffness. The composite element is free of both membrane and shear locking behavior by using the assumed natural strain method, such that the element also performs very well as thin laminate shells. An equilibrium approach is used to derive the improved transverse shear stiffness, instead of using a shear correction factor. The proposed formulation is computationally efficient and the test results show good agreement with references. The composite shell element is extended to determine ply failures in laminated composite structures undergoing nonlinear static or dynamic behavior. The failure analysis is done by first, computing for the inter-laminar stresses at each gauss point in an element. Having obtained the stresses in each layer, checking for failure is performed based on a chosen failure criterion. Four failure criteria are available to enable the user to adopt the appropriate criterion for the type of problem parameters present.


ABSTRACT: In computing eigenvalues for a large finite element system it has been observed that the eigenvalue extractors produce eigenvectors that are in some sense more accurate than their corresponding eigenvalues. From this observation the paper uses a patch type technique based on the eigenvector for one mesh quality to provide an eigenvalue error indicator. Tests show this indicator to be both accurate and reliable. This technique was first observed by the authors for an error estimation for the buckling and natural frequency of beams and for two-dimensional in plane structures. This paper produces an error indicator for the more complex problem of out-of-plane plate buckling analysis.
ABSTRACT: The main objective of this article is to present an overview of the modelling that has been proposed by various workers in the field of smart or intelligent structures. Before the main discussion on the various models, some background information will be presented in relation to intelligent structures and the types of adaptive materials that are available. Although there are several categories of materials that can be implemented in intelligent structures, this article will focus on models that use piezoelectric materials as sensors and/or actuators (S/A). The modelling of the intelligent structures can be categorized in terms of the structural configuration (e.g., rod composites, fibre composites, monolithic structures, etc.) and also according to the type of modelling whether by finite element modelling or by analytical exact solutions. Models in this field of work had incorporated concepts from different background including three-dimensional linear elastic theory and dielectric theory to give rise to the linear piezoelectric model. Rules of Mixture and methods for calculating effective properties of fibre composites were extended to include piezoelectric fibre composite models. Classical Laminated Plate Theory was also adopted in laminated composite models where some laminae were piezoelectric materials. Exact solutions were applied to simple models and illustrated the potential of using piezoelectrics. Finite element techniques were used for more complicated problems that included complex geometries, nonlinear behaviour and dynamic control of the structure. The difference between induced strain and actuation strain is usually not addressed when using FE techniques, instead the piezoelectric strain can be regarded as an equivalent external force/moment or incorporated into the strain energy. In regard to control algorithms, the most common form applied by investigators in this field seems to be the negative velocity feedback control with single input and single output and some included linear quadratic control. More advanced control algorithms such as using multiple input and multiple output or even neural networks are less established.


ABSTRACT: The nonlinear mechanics for piezoelectric laminates and plates is presented, including nonlinear effects due to large displacements and rotations. The mechanics is incorporated into the piezoelectric mixed-field laminate theory. Using this mechanics, a nonlinear finite-element method and an incremental solution are formulated for the nonlinear analysis of adaptive plate structures. An eight-node-plate finite element is developed. The mechanics is applied to predict the buckling of piezoelectric plates induced by combined electromechanical loading. Application cases quantify the mechanical buckling of composite beams and plates with piezoelectric sensors, the piezoelectric buckling of active beams and plates, and the feasibility of active buckling compensation.

ABSTRACT: A theoretical framework for analyzing the pre- and postbuckling response of composite laminates and plates with piezoactuators and sensors is presented. The mechanics include nonlinear effects due to large rotations and stress stiffening, and are incorporated into a coupled mixed-field piezoelectric laminate theory. Using the previous mechanics, a nonlinear finite element method and an incremental-iterative solution are formulated for the analysis of nonlinear adaptive plate structures subject to in-plane electromechanical loading. A novel eight-node nonlinear plate finite element is also developed. Evaluation cases predict the buckling and postbuckling response of adaptive composite beams and plates with piezoelectric actuators and sensors. The case of piezoelectric buckling and postbuckling induced by the actuators is addressed and quantified. Finally, the possibility to actively mitigate the mechanical buckling and postbuckling response of adaptive piezocomposite plates is illustrated.

Ishikawa, Takashi; Matsushima, Masamichi; Hayashi, Yoichi (Composite Structure Section, Airframe Division, National Aerospace Laboratory, 6-13-1 Ohsawa, Mitaka-shi, Tokyo 181, Japan), “Improved correlation of predicted and experimental initial buckling stresses of composite stiffened panels”, Composite Structures, Vol. 26, Nos. 1-2, 1993, pp. 25-38, doi:10.1016/0263-8223(93)90041-N

ABSTRACT: Experimental and numerical investigations are conducted for rigorous correlation of initial buckling properties of stiffened panels made of carbon fiber/poly-ether-ether-ketone (CF/PEEK) and CF/epoxy. Decreasing longitudinal elastic modulus of unidirectional CF composites lamina in compression plays a key role for better numerical predictions. A consideration of end fixtures in finite element modeling plays another key role in correlation and both initial buckling stress and mode for the short panels used here. A quarter finite element model with an end fixture by hypothetical symmetry is considered as the irreducible minimum in the modeling. A careful setting of lamina thickness is also important for better predictions. Initial imperfection close to the real shape of CF/PEEK panels is taken into account and an improvement in correlation of predicted and experimental results is reached. A conventional Rayleigh-Ritz approach considering only a local buckling mode of skin is developed. This analytical prediction compares fairly well with the numerical and experimental results in the preceding work in which their stringers are stiff enough.

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ABSTRACT: Numerical predictions of linear buckling and post-buckling behavior of CFRP T-stiffeners are conducted by Finite Element Analysis. Such behavior is crucially important in aircraft structural design. Comparison between numerical predictions and experimental behavior is executed in detail. Width-to-thickness ratio in flange or web mainly governs linear buckling stresses. Inserted filler along the intersection line between flange and web also considerably affects the linear buckling behavior. By taking realistic initial imperfection into account, geometrical nonlinear analysis provides fairly descriptive post-buckling deflection behavior in flange and web. It is also possible to predict the final failure stress by assuming simple failure criteria and non-progressive failure.
ABSTRACT: This paper investigates the sensitivity of the buckling and post-buckling behaviour of imperfect steel plates used in ship and related marine structures when subject to variations in their initial conditions. The different aspects analysed comprise of variation in aspect ratio, boundary conditions, initial out-of-plane imperfection and material elastic and plastic properties such as strain hardening. The analyses were carried out using the non-linear finite element program ABAQUS. The results obtained for the several plate models show that the three most relevant parameters affecting the buckling and post-buckling of uniaxially loaded plates are aspect ratio, unloaded edges boundary conditions and initial out-of-plane imperfection amplitude.

ABSTRACT: Equations are derived to assess the strength of plates subjected to biaxial compressive loads, including the effect of initial distortions and residual stresses. These equations are then extended to the case of simultaneous lateral pressure loads. In calibrating the proposed methods and in assessing their model uncertainty published results of experiments and of numerical calculations have been used. The proposed methods were shown to be unbiased as regards plate slenderness and aspect ratio. The model uncertainty of each method was quantified and thus can be used to derive design formulations with the desired level of safety.

ABSTRACT: This paper presents the results of a parametric study to quantify the effect of lateral pressure on the collapse of square and rectangular steel plates under a predominantly compressive load. The load-shortening behaviour of square and rectangular plates under the combined effect of longitudinal compression and lateral pressure were obtained using a general-purpose non-linear finite element code for different breadth to thickness ratios. Finally design curves are proposed to predict the collapse strength of the compressed plates under lateral pressure.

ABSTRACT: This paper presents the results of an experimental investigation to determine the torsional ultimate strength of a ship-type hull girder with a large deck opening. A comparison between nonlinear finite element calculations and the experimental results for the two models is presented. The effect of different assumptions and of the variation of different parameters is studied.

ABSTRACT: A method for reliability assessment of the post-buckling compressive strength of laminated composite plates and stiffened panels under axial compression is presented in the paper. The prediction of the post-buckling compressive strength is performed by a progressive failure analysis which was developed based on a progressive stiffness degradation model and a nonlinear finite element analysis with a new explicit through-thickness integration scheme. A method coupled with the finite element analysis is proposed for reliability assessment where a finite difference method combined with an improved first-order reliability algorithm that omits the non-important random variables but retains sufficient accuracy was developed for reliability estimation. Two numerical examples are described demonstrating the capabilities of the method developed.


ABSTRACT: Test results are presented of eight stiffened panels subjected to axial compression until collapse and beyond. The specimens are three-bay stiffened panels with associated plate made of very high tensile steel S690. The use of this very high strength steel led to the unconventional solution of using U stiffeners and this paper aims at understanding the difference of performance of this stiffener type as compared with the conventional ones. Four different configurations are considered for the stiffeners, which are made of mild or high tensile steel for bar stiffeners and mild steel for ‘L’ and ‘U’ stiffeners. The influence of the stiffener's geometry on the ultimate strength of the stiffened panels under compression is analyzed.


ABSTRACT: Results of eight tests on long stiffened panels under axial compression until collapse are presented. The specimens are three-bay panels with associated plates made of very high tensile steel S690. Four different configurations are considered for the stiffeners, which are made of mild or high tensile steel for bar stiffeners and mild steel for L and U shape stiffeners. The influence of the stiffener’s geometry on the ultimate strength of the stiffened panels under compression is analyzed. This series of experiments belongs to an extended series of tests that include short and intermediate panels, which allows analyzing the effect of space framing on the strength of stiffened panels.

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ABSTRACT: A system reliability analysis of an oil tanker bottom component which consists of a stiffened panel under combined uniaxial compression and lateral sea pressure loads is presented in this paper. The stiffened panel is idealized as a structural system composed by several stiffeners with attached plating in parallel. The structural capacity of each stiffener with attached plating or system component is described by a nonlinear finite element model, considering as failure criterion the buckling collapse under the combined uniaxial compression and lateral sea pressure loads. These load components are defined considering a typical seagoing operational condition of the oil tanker in ballast load. The uncertainty in the relevant design basic variables is quantified using stochastic models proposed in the literature. To efficiently solve the structural system reliability problem a Monte Carlo based reliability estimation method recently proposed is combined with a response surface method. The combination of these two methods has been shown to be an efficient technique to solve structural system reliability problems that involve computationally demanding numerical models to describe the structural capacity of the system components. Annual probabilities of buckling collapse failure of the stiffened panel are estimated using this solution technique. The effect of corrosion on the stiffened panel reliability is quantified. The importance of considering the lateral sea pressure and correlation between the local and global wave-induced loads in the reliability problem are evaluated.

DOI: 10.1016/j.marstruct.2012.10.003
ABSTRACT: Five specimens are tested under axial compression until collapse to investigate the ultimate strength of wide stiffened panels with four stiffeners. To avoid the side bays collapse and reduce the influence of the clamped boundary condition on the collapse behaviour, the tests are made on panels with two half bays plus one full bay in the longitudinal direction with simply supported condition at the end edge of loading. Initial loading cycles are used to release the residual stresses of the stiffened panels and the gap between the stiffened panels and the supported steel block. Strain gauges are installed on the plates and the stiffeners to record the distribution of strain. This series of experiments is compared to a series of tests with narrow panels (two stiffeners), which allows analysing the effect of the width on the strength of stiffened panels.

ABSTRACT: The results of five tests on narrow stiffened panels under axial compression until collapse and beyond are presented to investigate the collapse behaviors of stiffened panels. Tension tests were used to evaluate the material properties of the stiffened panels. The tests were made on panels with two half bays plus one full bay in the longitudinal direction. Initial loading cycles were used to eliminate the residual stresses of the stiffener panels. The strain gauges were set on the plates and the stiffeners to record the strain histories. The
displacement load relationship was established. The collapse behavior, modes of failure and load-carrying capacity of the stiffened panels are investigated with the experiment.

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ABSTRACT: The aim of this paper is to determine an appropriate configuration of the boundary conditions and geometric model to calculate the ultimate strength of a continuous stiffened panel under compressive loading in the finite element (FE) analysis. The $1 + 1$ spans model with periodical symmetric boundary conditions is proposed to be used in the FE analysis, whose results are compared with the $1/2 + 1 + 1/2$ span model with periodical symmetric and symmetric boundary condition, and the $1/2 + 1 + 1 + 1/2$ span model with symmetric boundary conditions. The effects of the continuity of the stiffened panel with different geometric models and boundary conditions on its collapse mode are investigated. A beam tension test has been used to define the true stress-strain relationship in the FE analysis. The two-span model, either $1 + 1$ or $1/2 + 1 + 1/2$, with periodical symmetric conditions give a reasonable FE modeling, which can consider both odd and even number half waves and, thus, have the smallest model uncertainty.


DOI: 10.1016/j.marstruc.2013.09.002

ABSTRACT: A series of finite element analyses are conducted to investigate the influence of boundary conditions and geometry of the model on the predicted collapse behaviour of stiffened panels. Periodic and symmetric boundary conditions in the longitudinal direction are used to calculate the ultimate strength of stiffened panels under combined biaxial thrust and lateral pressure. The calculated ultimate strength of stiffened panels are compared with those by different FEM (finite element method) code and are assessed. The periodic boundary condition in the longitudinal direction for two spans or bays model provides an appropriate modelling to a continuous stiffened panel and can consider both odd and even number of half waves and thus, is considered to introduce the smaller model uncertainty for the analysis of a continuous stiffened panel.


ABSTRACT: This work deals with the evaluation of the ultimate bending moment of a severely corroded box girder subjected to uniform vertical bending moment through a series of nonlinear finite element analysis. Two models of corrosion degradation have been adopted, one is an average general corrosion thickness reduction,
and the other is the real thickness of the corroded plates. New stress–strain relations have been developed to account for the effect of corrosion on the flexural rigidity. To validate the new developed stress–strain relationships, a comparison between the finite element analysis results using the existing stress–strain models, the newly developed ones and the experimental test results of a severely corroded box girder have been conducted. The comparison showed a good agreement and supported the choice of the newly developed stress–strain relationships of corroded structures.


ABSTRACT: Recent developments in the aircraft industry towards substantially improving fuel economy and extending flight range have accelerated interest in the use of advanced composites as primary structural materials. The airframes of next-generation airliners will have substantial parts made of light-weight composites. This means that the engineering demands on the performance of fiber-reinforced composites will become greater. There is therefore a need to better understand and predict the multiple complex failure mechanisms in composite structures, and to devise more reliable failure theories and damage progression models. There is a large body of literature on progressive damage analysis in composites, much of which employs damage mechanics and material stiffness degradation methods. This article reviews some of the more recent work in this area and describes the issues pertinent to application in composite structures. The authors' ongoing research efforts in modeling and prediction of progressive damage through the relatively novel element-failure method (EFM), which has been coded into a user-defined UEL code in Abaqus, are discussed. In particular, results for notched composite laminates and pin-loaded (PL) analyses are shown and compared to experimental data. Although EFM is the computational platform on which the damage is advanced in the structure, the results are dependent on the choice of the failure criterion. Various failure criteria are used throughout the cases discussed herein, from the more traditional Tsai—Wu (TW) criterion to the very recently proposed micromechanics-based failure (MMF) criterion. The EFM may also be used with cohesive elements, with the former intended for modeling in-plane damage progression, while the latter for delamination onset and propagation. This hybrid EFM-cohesive element approach is illustrated with an analysis of double-notched composite laminate. The computational models are relatively robust up to and including ultimate load, and enable the mapping of extensive damage patterns in composite structures. They represent a suite of computational tools that extend the capability to model damage and failure propagation beyond initial failure prediction.

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ABSTRACT: The object of this paper is to develop a finite displacement theory of naturally curved and twisted rods undergoing finite rotations. Particular attention is paid to investigate the coupling of finite rotations in space under the Bernoulli-Euler hypothesis. A finite rotation vector is employed to derive the displacement field available for finite rotations. A new variable is introduced as a fourth parameter associated with rotations of cross sections. Then the twist and curvatures after the deformation are expressed in terms of four parameters without using small-strain assumptions. The equilibrium equations and the associated boundary conditions, in
which second order terms with respect to displacement components are fully taken into account, are derived from the principle of virtual work. The accuracy of the present equilibrium equations is confirmed through comparisons with those obtained by the equilibrium method.


ABSTRACT: This paper deals with finite rotations, and finite strains of three-dimensional space-curved elastic beams, under the action of conservative as well as nonconservative type external distributed forces and moments. The plausible deformation hypothesis of “plane sections remaining plane” is invoked. Exact expressions for the curvature, twist, and transverse shear strains are given; as is a consistent set of boundary conditions. General mixed variational principles, corresponding to the stationarity of a functional with respect to the displacement vector, rotation tensor, stress-resultants, stress-couples, and their conjugate strain-measures, are stated for the case when conservative-type external moments act on the beam. The momentum-balance conditions arising out of these functionals, either coincide exactly with, or are equivalent to, those from the “static method”. The incremental variational functionals, governing both the Total and Updated Lagrangian incremental finite element formulations, are given. An example of the case of the buckling of a beam subject to axial compression and non-conservative type axial twisting couple, is presented and discussed.

T. Yoda and S.N. Atluri (Computational Modeling and Infrastructure Rehabilitation Center, Georgia Institute of Technology, 30332-0356, Atlanta, GA, USA), “Postbuckling analysis of stiffened laminated composite panels, using a higher-order shear deformation theory”, Computational Mechanics, Vol. 9, No. 6, pp 390-404, 1992

ABSTRACT: The investigation aims at: (i) constructing a modified higher-order shear deformation theory in which Kirchhoff’s hypotheses are relaxed, to allow for shear deformations; (ii) validating the present 5-parameter-smeared-laminate theory by comparing the results with exact solutions; and (iii) applying the theory to a specific problem of the postbuckling behavior of a flat stiffened fiber-reinforced laminated composite plate under compression. The first part of this paper is devoted mainly to the derivation of the pertinent displacement field which obviates the need for shear correction factors. The present displacement field compares satisfactorily with the exact solutions for three layered cross-ply laminates. The distinctive feature of the present smeared laminate theory is that the through-the-thickness transverse shear stresses are calculated directly from the constitutive equations without involving any integration of the equilibrium equations. The second part of this paper demonstrates the applicability of the present modified higher-order shear deformation theory to the post-buckling analysis of stiffened laminated panels under compression. To accomplish this, the finite strip method is employed. A C²-continuity requirement in the displacement field necessitates a modification of the conventional finite strip element technique by introducing higher-order polynomials in the direction normal to that of the stiffener axes. The finite strip formulation is validated by comparing the numerical solutions for buckling problems of the stiffened panels with some typical experimental results.

References listed at the end of the paper:

ABSTRACT: An analytical investigation is conducted to predict the post-buckling strength of laminated composite stiffened panels under compressive loads. When a stiffened composite panel buckles, the skin would deform into a sinusoidal mode shape, and hence induces additional moments and forces near the skin-stiffener interface region. These induced loads would cause the existing small edge delamination cracks to propagate along the skin-stiffener interface, and this in turn would lead to the global failure of the stiffened panel. To reduce the cost of the analytical investigation, the failure of the stiffened panel under post-buckling loads is modeled in two stages: a global analysis to model the post-buckling behavior of the stiffened panel; and a local analysis to model the onset of propagation of the edge delamination crack at the skin-stiffener interface. The results from this study are compared with an experimental investigation conducted by Starnes, Knight, and Rouse (1987). It is found that for the eight different specimens that are considered in this study, the calculated critical energy release rate for the propagation of the edge delamination crack in each specimen differs substantially from those for the others; hence it may be concluded that the total energy release rate would not be a suitable fracture parameter for predicting the post-buckling strength of the stiffened panels. On the other hand, using the fracture criterion based on the critical mixed-mode stress intensity factors, the predicted post-buckling strength of the stiffened panels compares quite favorably with the experimental results and the standard deviation of the error of prediction is less than 10%. Furthermore, by applying the criterion of critical mixed-mode stress intensity factors on a simple damage model, the present analysis is able to predict the significant reduction in the post-buckling strength of stiffened panels with a damage due to a low-speed impact at the skin-stiffener interface region.

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ABSTRACT: An efficient formulation for dynamic analysis of planar Timoshenko’s beam with finite rotations is presented. Both an inertial frame and a rotating frame are introduced to simplify computational manipulation. The kinetic energy of the system is obtained by using the inertial frame so that it takes a quadratic uncoupled form. The rotating frame together with the small strain assumption is employed to derive the strain energy of the system. Since the exact solutions for linear static theory of Timoshenko’s beam are used to obtain the strain energy, the present stiffness operator is free from the locking problem without using any special technique. The resulting equations of motion of the system are defined in terms of a fixed global coordinates system. Nonlinear effects appear only in the transformation of displacement components between global and local coordinates. This results in a drastic simplification of nonlinear dynamic analysis of flexible beams. Numerical examples demonstrate the accuracy and efficiency of the present formulation.


ABSTRACT: A simple method to follow the postbuckling paths in the finite element analysis is presented. During a standard path-following by means of arc-length method, the signs of diagonal elements in the triangularized tangent stiffness matrix are monitored to determine the existence of singular points between two adjacent solution points on paths. A simple approach to identify limit or bifurcation points is developed using the definition of limit points and the idea of generalized deflections. Instead of the exact bifurcation points, the approximate bifurcation points on the secants of the solution paths are solved. In order to follow the required
postbuckling branches at bifurcation points, the asymptotic postbuckling solution at the approximate bifurcation points, and the initial postbuckling behaviour based on Koiter's theory are given and used for the branch-switching. Some numerical examples of postbuckling behaviour of metallic as well as laminated composite structures are computed using a “quasi-conforming” triangular shell element to demonstrate the proposed method.

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ABSTRACT: In this paper, a unified method is presented: (i) to model delaminated stiffened laminated composite shells; (ii) for synthesising accurate multiple post-buckling solution paths under compressive loading; and (iii) for predicting delamination growth. A multi-domain modelling technique is used for modelling the delaminated stiffened shell structures. Error-free geometrically nonlinear element formulations — a 2-noded curved stiffener element (BEAM2) and a 3-noded shell element (SHELL3) — are used for the finite element analysis. An accurate and simple automated solution strategy based on Newton type iterations is used for predicting the general geometrically nonlinear and postbuckling behaviour of structures. A simple method derived from the 3-dimensional J-integral is used for computing the pointwise energy release rate at the delamination front in the plate/shell models. Finally, the influence of post-buckling structural behaviour and the delamination growth on each other has been demonstrated.

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ABSTRACT: In this paper, a unified method is presented: (i) to model delaminated stiffened laminated composite shells; (ii) for synthesising accurate multiple post-buckling solution paths under compressive loading; and (iii) for predicting delamination growth. A multi-domain modelling technique is used for modelling the delaminated stiffened shell structures. Error-free geometrically nonlinear element formulations — a 2-noded curved stiffener element (BEAM2) and a 3-noded shell element (SHELL3) — are used for the finite element analysis. An accurate and simple automated solution strategy based on Newton type iterations is used for predicting the general geometrically nonlinear and postbuckling behaviour of structures. A simple method derived from the 3-dimensional J-integral is used for computing the pointwise energy release rate at the delamination front in the plate/shell models. Finally, the influence of post-buckling structural behaviour and the delamination growth on each other has been demonstrated.

References listed at the end of the paper:
ABSTRACT: Results from an experimental and analytical study of a curved stiffened aluminum panel subjected to combined mechanical and internal pressure loads are presented. The panel loading conditions were simulated using a D-box test fixture. Analytical buckling load results calculated from a finite element analysis are presented and compared to experimental results. Buckling results presented indicate that the buckling load of the fuselage panel is significantly influenced by internal pressure loading. The experimental results suggest that the stress distribution is uniform in the panel prior to buckling. Nonlinear finite element analysis results
correlates well with experimental results up to buckling.

References listed at the end of the paper:


ABSTRACT: An initial experimental and analytical investigation was conducted to examine the effects of the inherent mechanical couplings exhibited in fully anisotropic (i.e. unsymmetric) graphite/epoxy laminates on the buckling loads and mode shapes. Experimental techniques were devised to test 254 mm square plates of AS1/3501-6 graphite/epoxy under uniaxial compressive load with free, simply-supported and clamped edges. The results indicate that the mechanical couplings, especially those which relate stretching and bending behavior, cause out-of-plane deflections prior to buckling and reduce the buckling load significantly, i.e. the load at which out-of-plane deflections become large. The analytical results also show that the buckled mode shapes exhibit twisting due to the mechanical couplings. Suggestions are offered for improvements in the experimental and analytical techniques to better understand these phenomena.

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ABSTRACT: A study was conducted to evaluate the reliability of a sandwich column specimen for uniaxial compressive tests. Both stress-strain and failure behavior were observed, and comparisons were made with predictions from existing techniques. The properties of the aluminum honeycomb core were also measured and included in the analysis to show its limited effects on the overall behavior of the specimen. Control tests were performed on specimens with aluminum facesheets to further quantifiy the effect of the honeycomb core on the overall behavior of the structure. The main battery of tests was conducted with graphite/epoxy facesheets of [theta12], [+theta/-theta/0]s, and [0/+theta/-theta]s configurations. The general excellent correlations between
the observed moduli and Poisson’s ratios and predicted values indicate that the specimen provides true stress-strain behavior. Moreover, consistent failure modes within the test section including both in-plane failure and ply buckling or delamination failure followed by in-plane failure indicate that the specimen is valid for failure behavior data.


ABSTRACT: The response of laminated cylindrical composite shell structures to transverse loading was studied through impact and quasi-static testing. A highly nonlinear structural instability phenomenon, closely resembling a snap-through instability, was found to have a strong influence on the loading/impact response including the resulting damage. Because of this structural instability, the behavior of convex shells under static or dynamic (i.e., impact) transverse loading is found to be much different than that for plates. These differences include trends displayed in the response parameters as well as damage extent and distribution. Convex shells with a response instability are found to have increased impact damage resistance compared with plates. A concept is proposed wherein the instability provides a mechanism, not available in plates, by which shell structures dissipate impact energy through structural deformation and thus exhibit improved impact damage resistance. Conversely, convex shells with no response instability have decreased impact damage resistance compared with plates. The differences in composite shell and plate behavior, particularly damage resistance, have important ramifications to the design of damage tolerant aerospace components and are discussed.


ABSTRACT: The damage resistance of thin composite structures was investigated experimentally. Specifically, surface damage in the form of dent-depth measurements are compared with internal damage states obtained by the X-radiography technique to better understand the implications of "barely visible impact damage" (BVID). Impact and quasi-static tests were conducted on plate and shell graphite/epoxy specimens between 0.804 mm and 2.412 mm thick in a [45n/10n], layup configuration. Damage was measured via visual, transducer, and X-ray methodologies. No correlation was found between internal (nonvisible) damage from the X-ray data and measured characteristics of the surface damage, specifically the depth of the dent. The results indicate that the use of dent depth as a metric can be misleading, particularly in that no dent depth can be found in some cases where substantial subsurface damage exists. Other examples are given wherein substantial (relative to other specimens) dent depths are measured with no corresponding internal damage. In previous work, peak force was found to correlate the resulting internal damage for both shell and plate specimens. However, dent depth shows no such general trend or correlation with peak force. This, coupled with previous damage tolerance work, places into question the use of dent-depth for thin (less than 2.4 mm, or 0.10") composite plate and shell structures in current damage tolerance methodologies.

ABSTRACT: The transverse-loading response of laminated composite shell structures is studied experimentally and numerically. Monolithic graphite-epoxy shell structures having layups of $[\pm 45\theta_n/0\theta_n]$ ($n = 1, 2, \text{and} 3$) closely represent commercial fuselage structures in both geometry and boundary conditions. A combined experimental and numerical approach is used to assess shell response to centered transverse loading. Experimentally, load-deflection response and mode-shape evolutions are measured and damage resistance characterized via dye-penetrant enhanced x radiography and sectioning. Nonlinear finite element analyses including buckling and dynamic collapse are conducted for comparison to the experimental data. Modeling results allow a more refined interpretation of observed bifurcation phenomena, particularly premature transition to a secondary equilibrium path attributed to geometric imperfections. A novel finite element technique introduced in previous work is found to be superior to traditional methods for identifying and traversing bifurcation points in this work. A simply supported axial boundary condition is found to give a much more complex buckling response (bifurcation and limit-point buckling, as well as dynamic collapse) than specimens with a free axial edge (bifurcation or limit-point buckling). Experimental and numerical comparisons for the range of thicknesses considered indicate that elasticity of the in-plane boundary condition and transverse shear effects need further consideration. Observed shell damage is typical of that observed for composite plates. Results of this work give new insight into the response of composite fuselage panels to damaging transverse events, particularly in regard to instability/buckling behavior.

References listed at the end of the paper:
ABSTRACT: The transverse loading response of convex composite shell structures typical of aircraft fuselage sections was investigated, and the experimental work is reported. Important mechanisms in the response, particularly instabilities (buckling), were studied by investigation of the force-deflection response and the evolution of full-field deformation shapes. Quasi-static tests were conducted to simulate impact of convex shells. The specimens were laminated, cylindrical shell sections in [±45n/0n]s configurations, where n takes on values of 1, 2, and 3. The three structural parameters of radius, span, and thickness were varied according to a scaling relation and were chosen to represent approximate fuselage dimensions of general aviation and commercial transport aircraft. All specimens were evaluated for damage with dye-penetrant enhanced x-ray radiography and sectioning after mechanical testing. The structural response changes both quantitatively and qualitatively for the different shell geometries and was categorized into three types based on the existence of the instability transition characteristics such as deformation shapes. The presence of the instability becomes more likely for deeper, thinner specimens where the ratio of membrane stiffness to bending stiffness is higher. This can be characterized by a structural parameter involving geometric and material factors. The majority of the specimens showed no damage, but the limited experimental evidence did show plate-like damage occurring in the shell specimens before any instability. Suggestions for further work to extend these findings are made.
Laminated shells are in excellent agreement with measured load-deflection and mode-shape evolutions as previously reported. Two cases of extraordinarily good agreement between the data and model, particularly large-deflection asymmetric deformations modes through a bifurcation point and far into the postbuckling regime, clearly establish validated new benchmarks. Asymmetries in both directions of the shell plane, relative to the centrally applied point load, are discussed with regard to bifurcation and material couplings in the composite laminate. Asymmetric stress distributions are discussed in the context of composite damage resistance and previous experimental findings on atypical shell damage mode and extent. The influence of test fixture compliance is evaluated and briefly discussed.


ABSTRACT: The structural response, including the mechanisms associated with snap-through buckling, of cylindrical composite shell panels subjected to transverse loading was investigated via experiments and numerical analysis. Specimens of Hercules AS4/3501-6 graphite/epoxy in [±45n/On]s (n=1,2,3) configurations and with a planar aspect ratio of 1 were tested in static indentation with pinned-free boundary conditions. Structural parameters (radius, span, and thickness) were varied to encompass values utilized in the structural configurations of transport aircraft fuselages. Force-deflection response and panel deformation-shapes were determined during the tests and the damage from the tests was evaluated using x-ray photography and sectioning techniques. A range of experimental force-deflection responses was observed including smooth-stable, smooth with an instability region and nonsmooth responses with an instability region. Deformation-shapes were generally three-dimensional and exhibited both symmetry and unsymmetry. A switching between symmetric and unsymmetric deformation-shapes occurred in some specimens corresponding with load-drops or the panel snapping away from the indentor. The geometric ratio of specimen height to thickness characterizes the structural response as specimens with larger values of this parameter were more likely to exhibit an instability in the force-deflection response, unsymmetric deformation-shapes, and panel snap-away. Force-deflection and deformation-shape behavior for pinned-free and simply-supported-free boundary conditions were determined using a finite element analysis and the predicted results for the two boundary conditions either bounded the experimental response or matched the experimental response well for one of the two boundary conditions. The existence of nonzero in-plane compliance in the test fixture accounts for the variation of the experimental response with respect to the predicted results as the relative magnitudes of the in-plane stiffnesses of the shell and of the boundary conditions is a key consideration in determining the structural response of shell panels. An experimental comparison of different boundary conditions along the axial edges showed that increased rotational restraint increases the critical snapping load, decreases the magnitude of the load reduction within the instability region of the force-deflection response, and prevents the formation of unsymmetric spanwise deformation-shapes. Damage in the form of matrix cracking and delaminations in the specimen backside was detected in only the deepest, thickest specimen geometry. Such damage forms near the critical snapping load and may be similar to that found in plates due to the localized concave configuration which develops beneath the loading point resulting in tensile bending stresses. Further work based on these results is recommended to investigate the effects of unsymmetric deformations, in-plane compliance, and various boundary conditions on the structural response and damage characteristics of similar shells. Further experimental work to pinpoint the transition in damage behavior due to the formation of localized concavity is also suggested.

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1. Tsai, S. W., Theory of Composites Design, Think Composites, Dayton, 1992.

ABSTRACT: This project demonstrated the implementation of embedded optical fibers as sensors for detecting the onset of shell buckling instabilities and compressive failure in composite cylinders. In the present work, five 6-inch diameter cylinders (four filament-wound and one prepreg tape) with integrated optical fiber strain sensors were fabricated and tested in compression. The cylinders were instrumented with an axial strain gage for local strain measurements and a helically wound 633 nm optical fiber for integrated strain measurement. The integrated strains along the optical fiber path were obtained by using a modified Mach-Zehnder interferometer with feedback electronics controlling PZTs in the reference arm. This distributed sensing technique provides a more reliable and sensitive means of detecting critical strains and the onset of pre-buckling deformations than the conventional local strain gage.


ABSTRACT: The local and global compressive buckling behavior of stability-critical, high-aspect ratio, cantilevered composite IsoTruss grid structure columns was examined. The influence of local bay length and number of carbon fiber tows in the longitudinal and helical members on the compressive strength of IsoTruss columns was examined. Four 3-m (118.0 in.) long IsoTruss specimens were fabricated and tested in axial compression with fixed-free boundary conditions. The test results exhibit the same trend as the finite element predictions, although the error is higher for shorter bay lengths. Local buckling depends on bay length, with higher buckling loads observed for shorter bay lengths. Global buckling, on the other hand, is independent of bay length; although increasing the bay length reduces the weight and thus increases the overall efficiency of an IsoTruss structure. The Euler column buckling prediction only considers the overall diameter and the axial stiffness of the longitudinal members; therefore, Euler buckling predictions are accurate only for IsoTruss configurations that fail in global buckling.

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ABSTRACT: Simulating the mechanical behavior of a cloth is a very challenging and important problem in computer animation. The models of bending in most existing cloth simulation approaches are taking the assumption that the cloth is little deformed from a plate shape. Therefore, based on the thin-plate theory, these bending models do not consider the condition that the current shape of the cloth under large deformations cannot be regarded as the approximation to that before deformation, which leads to an unreal static bending. [This paper introduces a dynamic bending model which is appropriate to describe large out-plane deformations such as cloth buckling and bending, and develops a compact implementation of the new model on spring-mass systems. Experimental results show that wrinkles and folds generated using this technique in cloth simulation, can appear and vanish in a more natural way than other approaches.]

References listed at the end of the paper:
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ABSTRACT: A facet shell element based on an anisoparametric plate bending element and a quadratic plane-stress element with vertex rotations is formulated for geometrically nonlinear analysis of shells. The updated Lagrangian formulation which proves to be effective for three-node elements is employed. The restriction of small rotation between the increments is removed by using Hsiao's finite rotation method in which the rigid body motion is eliminated from the total displacement. The displacement control is used to alleviate the singularity of the tangential stiffness matrix in the limit point type problems. Numerical solutions are presented for beams, plates and shells to evaluate the performance of the element.


ABSTRACT: Analytical predictions of the postbuckling response of curved composite panels are difficult, especially under in-plane compression, because of the presence of snap-back with a steep negative slope beyond the bifurcation point. In this study, the pre- and postbuckling response of curved laminated panels with cutouts is investigated by developing a new finite element based on the free formulation. This triangular, flat, shell element, in conjunction with the updated Lagrangian form of the co-rotational approach, accounts for the coupling terms arising from general material anisotropy, as well as large displacements and rotations. The analysis predictions correlate well with the corresponding experimental data available in the literature. Review of the studies in this subject area reveal that none of the available methods, including the STAGS-C1 finite element program, is capable of providing the full description of the postbuckling phenomenon beyond bifurcation for curved composite panels with small cutouts.


ABSTRACT: A flat shell element based on the free-formulation finite element concept is developed for analysing geometrically non-linear thin composite shells. A corotational form of the updated Lagrangian formulation is utilized. Numerical results for typical validation problems are presented in order to demonstrate the accuracy and validity of this element. These results are obtained by solving the incremental equilibrium equations through the cylindrical arc-length method.

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ABSTRACT: This study presents a nonlinear analysis with application to a doubly curved shallow shell element free of ‘locking’. The ‘locking’ phenomenon is eliminated by explicitly determining the shear and membrane correction factors. The element formulation utilizes the Reissner-Mindlin and Marguerre theories. The analysis of thin and moderately thick composite shells undergoing large displacements and rotations is achieved by using the corotational form of an updated Lagrangian formulation. The validity of the analysis is established by correlating present results with various benchmark cases that involve large displacements and rotations, as well as elastic stability.

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ABSTRACT: A new stiffened shell element combining shallow beam and shallow shell elements is developed for geometrically nonlinear analysis of stiffened composite laminates under mechanical loading. The formulation of this element is based on the principle of virtual displacements in conjunction with the corotational form of the total Lagrangian description of motion. In the finite element formulation, both the shell and the beam (stiffener) elements account for transverse shear deformations and material anisotropy. The cross section of the stiffener (beam) can be arbitrary in geometry and lamination. In order to combine the stiffener with the shell element, constraint conditions are applied to the displacement and rotation fields of the stiffener. These constraint conditions ensure that the cross section of the stiffener remains co-planar with the shell section after deformation. The resulting expressions for the displacement and rotation fields of the stiffener involve only the nodal unknowns of the shell element, thus reducing the total number of degrees-of-freedom. Also, the discretization of the entire stiffened shell structure becomes more flexible. The robustness of the stiffened shell element has been proven by comparison against other shell elements considered previously.

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ABSTRACT: The response of moderately thick laminated panels experiencing large displacements and rotations under non-uniform thermal loading is investigated through a nonlinear finite element analysis. The present nonlinear thermoelastic analysis incorporates an anisoparametric, doubly curved, shallow shell element that is free of the 'locking' phenomenon. The effects of large displacements and rotations, transverse shear deformations, the coupling between stretching and bending due to shallow geometry, and Duhamel–Neumann-type thermoelastic material anisotropy are included in the element formulation. The equations of equilibrium are derived from the virtual work principle, along with the co-rotational form of the total Lagrangian formulation. A non-uniform temperature field across the shell surface is approximated by piecewise-uniform temperature distributions over individual elements. In the thickness direction, the temperature distribution is approximated linearly. Accuracy of the present analysis is established by comparison with benchmark solutions. The numerical results are presented for various configurations, including cutouts under uniform and non-uniform temperatures. The numerical results demonstrate that the present finite element analysis is computationally robust and efficient.


ABSTRACT: A semi-analytical method is developed for pre-buckling and buckling analyses of thin, symmetrically laminated composite panels with an elliptical cutout at an arbitrary location and orientation under general thermo-mechanical loading conditions. Both the pre-buckling and buckling analyses are based on the principle of stationary potential energy utilizing complex potential functions and complete polynomials. The complex potential functions capture the steep stress gradients and local deformations around the cutout, and the “complete” polynomials improve the global buckling response of the laminate. The complex potential functions in the pre-buckling state automatically satisfy the in-plane equilibrium equations, thus reducing the first variation of the total potential energy in terms of line integrals only. Because the complex potential functions for out-of-plane displacements are augmented by the “complete” polynomials, the area integral terms in the second variation of the total potential energy, referred to as the Trefftz criterion, are retained in the buckling analysis. The kinematic boundary conditions are idealized by employing extensional and rotational springs (elastic restraints) with appropriate stiffness values. Based on the numerous validation problems, this analysis is proven credible for predicting the buckling load of rectangular and non-rectangular panels with a cutout.

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ABSTRACT: A semianalytical solution method to predict stress field and structural bifurcation in laminates having a cutout by employing a simple \{3,0\}-plate theory is presented. The stress analysis includes both in-plane and bending stress fields. In this theory, the in-plane and out-of-plane displacement fields are respectively assumed in the forms of cubic and uniform through-the-thickness expansions. The cubic expansion ensures the correct behavior of transverse shear deformations while satisfying the condition of zero transverse shear stresses at the laminate faces. The equations of equilibrium for the stress and buckling analysis are derived based on the principle of stationary potential energy. Comparison against the classical laminate and \{1,2\}-plate theories proves this semianalytical method credible.


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ABSTRACT: A finite element analysis is carried out for the bending and buckling of unstiffened, sandwich and hat-stiffened orthotropic, rectangular plates. Systematic calculations are performed for deflection, stress and critical buckling load of the plate using first order shell elements, and first and second order three-dimensional solid elements. The calculated results are compared with available analytical solutions for unstiffened plates. First-order shell and second-order three-dimensional solid elements are found to model accurately bending and buckling of the plate structures, but first-order three-dimensional solid elements give very inaccurate, inconsistent results even when the mesh density is high. For thin, unstiffened plates, one layer of second-order three-dimensional solid elements through-the-thickness is found to give sufficient accuracy. The same is found to be true for thin sandwich plates using one layer of second-order three-dimensional elements for each of the skins and one layer for the core. For a hat-stiffened plate clamped along the short edges and simply supported along the long edges, the first buckling mode occurs in the region between the stiffeners. Different approaches for joining the stiffeners to the plate are discussed.

“Weight Optimization of a Composite Shell in Type 4 Pressure Vessels Using Genetic Algorithm”, from sid.irA Khani, A Vafaesefat… - Mechanical And Aerospace …. 2007 - sid.ir
Finally, the composite shell with minimum number of layers whose Tsai-Wu failure criterion is below one is selected as the laminate with minimum weight. .. (in Arabic?)

ABSTRACT: The buckling characteristics of a typical free-standing welded steel containment vessel are considered. The results of analyses utilizing computer codes are compared for a variety of load combinations. Practical conclusions of the vulnerability of such a containment vessel to buckling for a variety of load inputs and combinations are drawn.


ABSTRACT: A review of the relationship between the theory of shell stability and design is presented. The classic problem of buckling of a spherical shell is used to illustrate the lack of correspondence between theory and experiment. The influence of theory on current design codes and its application to a practical problem are discussed.


ABSTRACT: In this paper the effect of random geometric imperfections on the critical load of isotropic, thin-walled, cylindrical shells under axial compression with rectangular cutouts is presented. Second moment characteristics of geometric imperfections are estimated by data of available measurements, a simulation procedure based on the Karhunen-Loeve expansion is applied for generating realizations of geometric imperfections. Nonlinear static Finite Element analyses are carried out for the calculation of the response statistics of the critical load of the cylindrical shells. Histograms of the critical load as obtained by direct Monte Carlo simulation are presented.

Reference listed at the end of the paper:
ABSTRACT: In this paper the effect of random geometric imperfections on the limit loads of isotropic, thin-walled, cylindrical shells under deterministic axial compression is presented. Therefore, a concept for the numerical prediction of the large scatter in the limit load observed in experiments using direct Monte Carlo simulation technique in context with the Finite Element method is introduced. Geometric imperfections are modeled as a two dimensional, Gaussian stochastic process with prescribed second moment characteristics based on a data bank of measured imperfections. (The initial imperfection data bank at the Delft University of Technology, Part 1. Technical Report LR-290, Department of Aerospace Engineering, Delft University of Technology). In order to generate realizations of geometric imperfections, the estimated covariance kernel is decomposed into an orthogonal series in terms of eigenfunctions with corresponding uncorrelated Gaussian random variables, known as the Karhunen–Loève expansion. For the determination of the limit load a geometrically non-linear static analysis is carried out using the general purpose code STAGS (STructural Analysis of General Shells, user manual, LMSC P032594, version 3.0, Lockheed Martin Missiles and Space Co., Inc., Palo Alto, CA, USA). As a result of the direct Monte Carlo simulation, second moment characteristics of the limit load are presented. The numerically predicted statistics of the limit load coincide reasonably well with the actual observations, particularly in view of the limited data available, which is reflected in the statistical estimators.

References listed at the end of the paper:

maximum of the load

distinct non

collapse or snap

fundamental problems have to be distinguished in the field of structural stability: the buckling problem and the

solution of equilibrium equations under variation of a number of parameters such as load level, imperfection

areas such as asymptotic analysis \[69\] and general

ABSTRACT: The state of the art in the capability to predict the stability behavior of shell structures refers to

Lecture Notes in

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“Non-Linear Static Analysis”, Chapter 5 in Uncertainty Assessment of Large Finite Element Systems


ABSTRACT: The state of the art in the capability to predict the stability behavior of shell structures refers to

areas such as asymptotic analysis \[69\] and general nonlinear analysis (see e.g. \[16, 30\]). In both approaches, the

solution of equilibrium equations under variation of a number of parameters such as load level, imperfection

magnitude etc., is necessary. Of paramount interest is the determination of the so-called critical points. Two

fundamental problems have to be distinguished in the field of structural stability: the buckling problem and the

collapse or snap-through problem, respectively. The corresponding critical points are denoted as bifurcation

points and limit points. By definition a bifurcation point describes the equilibrium state of a structure where

distinct non-interacting solutions are possible. The limit point on the other hand characterizes the local

maximum of the load-deflection curve. Contrary to perfect structures, imperfect structures do not show a clear
separation of response modes. Instead, the response is a combination of all excited modes. Depending on the magnitude of the imperfection, it is possible that bifurcation points may vanish.


Abstract: The treatment of uncertainties in the analysis of engineering structures remains one of the premium challenges in modern structural mechanics. It is only in recent years that the developments in stochastic and deterministic computational mechanics began to be synchronized. To foster these developments, novel computational procedures for the uncertainty assessment of large finite element systems are presented in this monograph. The stochastic input is modeled by the so-called Karhunen-Loeve expansion, which is formulated in this context both for scalar and vector stochastic processes as well as for random fields. Particularly for strongly non-linear structures and systems the direct Monte Carlo simulation technique has proven to be most advantageous as method of solution. The capabilities of the developed procedures are demonstrated by showing some practical applications.
parameters have an insignificant influence on the response, all parameters of the INTEGRAL FE model have been included in the analysis. More than 1300 independent random variables have been used to model uncertainties of the material and geometric data. A similar approach has been applied to the Ariane 5 FE model, i.e. all uncertain parameters of the model have been included in the analysis. Within the study an efficient procedure for calculating non-exceedance probabilities of the structural response has been developed. A novel sampling procedure has been introduced, which allows a significant reduction of the variance of the estimator of the probability of failure when compared to that of direct Monte Carlo simulation. This is particularly important in view of the large computational effort associated with a single analysis, especially with the coupled load analysis where a single run could take up to 30 minutes. The only prerequisite for the application of this sampling procedure is an estimate of the gradient of the performance function of the structure. The calculation of the gradient is carried out efficiently benefiting from the correlation between a randomly chosen input and the corresponding output of the system.

References listed at the end of the paper:

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ABSTRACT: In this paper, the effect of random geometric imperfections on the critical load of isotropic, thin-walled, cylindrical shells under axial compression with rectangular cutouts is presented. Second moment characteristics of geometric imperfections are estimated by data of available measurements, a simulation procedure based on the Karhunen–Loève expansion is applied for generating realizations of geometric imperfections. Nonlinear static finite-element analyses are carried out for the calculation of the response statistics of the critical load of the cylindrical shells. Cumulative distribution functions of the critical load as obtained by direct Monte Carlo simulation are presented. Furthermore, the individual and combined effects of random boundary and geometric imperfections on the limit loads of isotropic, thin-walled, cylindrical shells under axial compression are also treated. Again, second moment characteristics of these imperfections are estimated by data of available measurements of imperfections, a simulation procedure also based on the Karhunen–Loève expansion is applied for generating realizations of both boundary and geometric

ABSTRACT: A simple four-noded geometrically nonlinear shell element, which handles arbitrarily large displacements and rotations, is presented in this paper. Based on the assumption of small incremental strain in each load step, a corotational procedure is employed to extract the pure deformational displacements and rotations and update element stresses and internal force vectors through a piece-wise linearized strain-displacement relation. To derive the tangent stiffness matrix, a three-dimensional degenerate, isoparametric shell model is employed. The ‘locking’ problem is alleviated by using mixed interpolation of tensorial transverse shear strain components. The approach described in this paper is ideally suited for implementation in existing linear finite element programs. A number of numerical examples are also presented.

ABSTRACT: A stiffened shell element is presented for geometrically non-linear analysis of eccentrically stiffened shell structures. Modelling with this element is more accurate than with the traditional equivalent orthotropic plate element or with lumping stiffeners. In addition, mesh generation is easier than with the conventional finite element approach where the shell and beam elements are combined explicitly to represent stiffened structures. In the present non-linear finite element procedure, the tangent stiffness matrix is derived using the updated Lagrangian formulation and the element strains, stresses, and internal force vectors are updated employing a corotational approach. The non-vectorial characteristic of large rotations is taken into account. This stiffened shell element formulation is ideally suited for implementation into existing linear finite element programs and its accuracy and effectiveness have been demonstrated in several numerical examples.

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ABSTRACT: A co-rotational, updated Lagrangian formulation for geometrically nonlinear analysis of shells is presented. In this finite element procedure, a standard updated Lagrangian formulation is employed to generate the tangent stiffness matrix, and a co-rotational theory is used for updating element strain, stress and internal force vectors during the Newton-Raphson iterations. Large rotation theory has been accommodated to take into account the non-vectorial characteristic of the rotational degrees-of-freedom. The present procedure is ideally suited for implementation in existing linear finite element programs and its effectiveness have been demonstrated.
by a number of numerical examples.

ABSTRACT: An improved method is presented for solving nonlinear problems with multiple limit points and snap-back points. It is formulate in N + 1 dimensional space that includes one load parameter and N displacements as the unknowns. To solve these unknowns, a constraint equation is needed in addition to the N equations of equilibrium. Whether the constraint equation is proper can be justified from the bounded nature of the load parameter. The method presented herein may be referred to as the “generalized displacement control method.” With the introduction of a general stiffness parameter, the method has been demonstrated to be numerically stable at the critical points, effective in adjusting the step sizes, and self-adaptive in changing the loading directions. Two examples with curves of the looping type have been solved by the present method for illustration.

ABSTRACT: Buckling of arches is studied using a corotational finite element model in conjunction with a modified Riks-Wempner technique. The corotational formulation allows for separation of rigid body displacements from deformation displacements of the element. The program can equally be applied to rigid or prestressed arches, as it takes into account the sequential fabrication of stressed (i.e. prebuckled) arches. Looping paths tracing nonlinear response of arches have been successfully obtained for several cases, including rigid and prestressed elastica arches with both symmetric and asymmetric modes of buckling. Comparisons are made with the results for prestressed arches using shooting method, and with the benchmark results for various rigid arches using discrete element method. When compared to a discrete element technique, the present method appears to be more cost-effective, as a finite element mesh with 60% fewer elements can result in virtually the same degree of accuracy.

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ABSTRACT: Structural components are prone to corrosion damage, especially when exposed to a sea environment. This article describes an investigation on the effects of local corrosion applied to plates and stiffened panels typically found in ship structures. Finite element investigations of initial buckling, ultimate collapse and post-ultimate responses are presented and described through the use of load-shortening collapse curves. Geometric imperfections and residual stresses were included in the model and results are compared to analytical calculations and available experimental measurements. This improved knowledge of the structural integrity of a damaged ship structure can be used to develop more efficient maintenance practices.
ABSTRACT: Sandwich pipes can be a potentially optimal system for use in deep-water applications. In recent years, there has been considerable interest in understanding the stability characteristics of these pipes under the governing loading conditions, with the aim of generating optimal design. External hydrostatic pressure is a critical loading condition that a submerged pipeline experiences during its installation and operational period. This article presents an analytical approach for estimating the buckling capacity of sandwich pipes with various structural configurations and core materials, subject to external hydrostatic pressure. The influence of adhesion between the core layer and inner or outer pipes is also a focus of this study. Beside the exact solution, two simplified equations are developed for estimating the buckling capacity of two configurations commonly used in practice. Details of both the exact and simplified analytical formulations are presented and the required parameters are defined. The efficiency and integrity of the proposed simplified solutions are compared with a solution developed by other researchers. A comprehensive series of finite element eigenvalue buckling analyses was also conducted to evaluate the accuracy and applicability of the proposed solutions.

References listed at the end of the paper:


ABSTRACT: Sandwich Pipes (SP) can be considered as an enhanced design configuration for Pipe in Pipe (PIP) systems. By improving the structural properties of the core layer and the components’ interface adhesion, SP systems can be an effective design alternative for deepwater applications. However, designing such a hybrid structure demands more knowledge of the response of the system under the governing loading and environmental conditions. A SP system would be a suitable design alternative for offshore pipelines that are subjected to very large hydrostatic pressure in deepwater. Therefore, full understanding of the behavior of such systems under the external hydrostatic pressure is a prerequisite for designing optimum SPs. In this paper a set of parametric models are generated based on practical design configurations. The Finite Element (FE) software package, ABAQUS, is used to create the models and analyze them. The FE models are analyzed through eigenvalue buckling and post-buckling analyses with the assumptions of linear and nonlinear buckling. Appropriate initial imperfections and FE parameters are administered. Moreover, the integrity of FE models is investigated through a mesh convergence study and also by considering various types of element locking mechanism. The results of these three methods of analysis are compared and the discrepancy between the results obtained through the linear analysis in comparison to the nonlinear post-buckling analysis is highlighted. Moreover, the influence of using various material plasticity models on the buckling and post-buckling responses is also investigated. Different models describing the materials stress-strain curves in the form of the elastic perfectly plastic, elastic followed by plastic exponential hardening, as well as the existence of the Lüder’s bands are also considered. Furthermore, the effect of core material’s stiffness on the buckling and post-buckling response of the system is also examined. Based on the equivalent plastic strain, it will be shown that in order to ensure system’s effective composite sandwich action, the core must have a certain minimal stiffness. Finally, the influence of the enhancement in the steel grade used to form either the internal or external pipe on the stability response of both PIP and SP systems will be illustrated.


ABSTRACT: This paper presents a model for optimum design of three panel forms, namely tee stiffened, flat-bar stiffened and corrugated panels to be used in ship structures. Scantlings of the three forms have been modelled as free design variables. Limit values against different possible failure modes in conjunction with safety factors and load effects have formed the sets of design constraints. Some production restrictions are also incorporated in the model. An optimization algorithm based on sequential linear programming has been used for optimum design of the three forms. Some special features are incorporated in the optimization algorithm to avoid numerical instability problems and to handle integer variables and more than one design criterion. The capability of the model is demonstrated in a series of practical applications against a wide range of design parameters such as loads, variation of span, price ratio index (labour rate to material price ratio) and design criteria (minimum cost, minimum weight and equal priority). Appropriate presentation and analysis of results have produced a practical guide to strive for improvement in the overall ship structure even satisfying
conflicting design demands. Moreover, the designer's capability to reflect his preference level to particular criteria has been demonstrated through the investigation of a wide range of Pareto-optimal designs.

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ABSTRACT: This paper is concerned with the numerical solution of large deflection structural problems involving finite strains, subject to contact constraints and unilateral boundary conditions, and exhibiting inelastic constitutive response. First, a three-dimensional finite strain beam model is summarized, and its numerical implementation in the two-dimensional case is discussed. Next, a penalty formulation for the solution of contact problems is presented and the correct expression for consistent tangent matrix is developed. Finally, basic strategies for tracing limit points are reviewed and a modification of the arc-length method is proposed. The good performance of the procedures discussed is illustrated by means of numerical examples.
PARTIAL INTRODUCTION: It is our belief that a thorough understanding of the mathematical underpinnings of elasticity is crucial to its analytical and numerical implementation. For example, in the analysis of rotating structures, the coupling of the equations for geometrically inexact models obtained by linearization or other approximations with those for rotating rigid bodies can easily lead to misleading artificial “softening” effects that can significantly alter numerical results. … In this paper we consider fully nonlinear geometrically exact models for rods, plates (and shells) which take into account shear and torsion as well as the usual bending effects in traditional rod and plate models. These models can be obtained either from the three-dimensional theory by a systematic use of projection methods … or by a direct approach within the context of Cosserat continuum…

References listed at the end of the paper:


ABSTRACT: (no abstract given)


ABSTRACT: Computational aspects of a linear stress resultant (classical) shell theory, obtained by systematic linearization of the geometrically exact nonlinear theory, considered in Part I of this work, are examined in detail. In particular, finite element interpolations for the reference director field and the linearized rotation field are constructed such that the underlying geometric structure of the continuum theory is preserved exactly by the discrete approximation. A discrete canonical, singularity-free mapping between the five and the six degree of freedom formulation is constructed by exploiting the geometric connection between the orthogonal group (SO(3)) and the unit sphere (S2). The proposed numerical treatment of the membrane and bending fields, based on a mixed Hellinger-Reissner formulation, provides excellent results for the 4-node bilinear isoparametric element. As an example, convergent results are obtained for rather coarse meshes in fairly demanding, singularity-dominated, problems such as the classical rhombic plate test. The proposed theory and finite element implementation are evaluated through an extensive set of benchmark problems. The results obtained with the present approach exactly match previous solutions obtained with state-of-the-art implementations based on the so-called degenerated solid approach.

ABSTRACT: Computational aspects of a geometrically exact stress resultant model presented in Part I of this work are considered in detail. In particular, by exploiting the underlying geometric structure of the model, a configuration update procedure for the director (rotation) field is developed which is singularity free and exact regardless the magnitude of the director (rotation) increment. Our mixed finite element interpolation for the membrane, shear and bending fields presented in Part II of this work are extended to the finite deformation case. The exact linearization of the discrete form of the equilibrium equations is derived in closed form. The formulation is then illustrated by a comprehensive set of numerical experiments which include bifurcation and post-buckling response, as well as comparisons with closed form solutions and experimental results.


ABSTRACT: This paper is concerned with the extension of the shell theory and numerical analysis presented in Part I, II and III to include finite thickness stretch and initial variable thickness. These effects play a significant role in problems involving finite membrane strains, contact, concentrated surface loads and delamination (in composite shells). We show that a direct numerical implementation of the standard single extensible director shell model circumvents the need for rotational updates, but exhibits numerical ill-conditioning in the thin shell limit. A modified formulation obtained via a multiplicative split of the director field into an extensible and inextensible part is presented, which involves only a trivial modification of the weak form of the equilibrium equations considered in Part III, and leads to a perfectly well-conditioned formulation in the thin-shell limit. In sharp contrast with previous attempts in the context of the degenerated solid approach, the thickness stretch is an independent field, not a dependent variable updated iteratively via the plane stress condition. With regard to numerical implementation, an exact update procedure which automatically ensures that the thickness stretch remains positive is presented. For the present theory, standard displacement models would exhibit ‘locking’ in the incompressible limit as a result of the essentially three-dimensional character of the constitutive equations. A mixed formulation is described which circumvents this difficulty. Numerical examples are presented that illustrate the effects of the thickness stretch, the performance of the proposed mixed interpolation, and the well-conditioned response exhibited by the present approach in the thin-shell (inextensible director) limit.


ABSTRACT: This paper considers the formulation and numerical implementation of a geometrically exact resultant based shell model for the analysis of large deformations of thin and moderately thick shells. The model is essentially a single extensible director Cosserat surface. Variable thickness and thickness stretch effects are properly modeled via the extensibility condition on the director field. A simple linear elastic constitutive model is given which possesses the correct asymptotic limits as the thickness tends to zero and recovers the plane stress constitutive relations in the thin shell limit. On the computational side, a configuration update procedure for the director field is presented which is singularity free and exact regardless of the magnitude of the director (rotation and thickness stretch) increment. The performance of the shell model is assessed through an extensive set of numerical examples.

References listed at the end of the paper:


ABSTRACT: The continuum basis and numerical implementation of a finite deformation plasticity model formulated within the framework of the geometrically exact shell model presented in Parts I and III of this work, is discussed in detail. The model is formulated entirely in stress resultants, and hence the expensive integration through the thickness associated with the traditional degenerated solid approach is entirely by-passed. In particular, the classical Ilyushin-Shapiro plasticity model for shells is extended to accommodate kinematic and isotropic hardening, and consistently formulated to accommodate finite deformation. The corresponding closest-point-projection return mapping algorithm is shown to reduce to the solution of a system of two nonlinear scalar equations, and proved to be amenable to exact linearization leading to a closed form expression of the consistent elastoplastic tangent moduli. Numerical simulations are presented and comparisons with exact and approximate solutions are made which demonstrate the excellent performance of the proposed methodology.


ABSTRACT: If the mid-surface of a shell is smooth, the classical theory describes the orientation of the director field attached to the mid-surface by two independent (rotational) degrees of freedom. At a shell intersection, where this smoothness assumption no longer holds, it is shown that the director field in the full nonlinear continuum shell equations must be necessarily described by three degrees of freedom. This added degree of freedom, however, is totally unrelated to the so-called drill rotation, widely used as a means of tackling the shell intersection problem. A computational procedure involving a trivial modification of the global singularity-free update procedure described in Part III of this work is described, which completely resolves the shell intersection problem without introducing ‘drill springs’ or related ad-hoc devices. The proposed approach leaves unchanged standard finite element formulations in terms of 5 DOF/node, affects only the global update formulae and exhibits excellent performance, as illustrated by representative numerical simulations.

ABSTRACT: The accurate prediction of the buckling load of thin shell structures is an important yet elusive goal. It is particularly important in the aerospace industry where thin shell members are commonly used as structural elements. Due to a lack of adequate analytical results, current practices in industry put heavy reliance on experimental testing and empirical data to supplement theoretical analysis (see D. Bushnell, Computerized Buckling Analysis of Shells, Martinus Nijhoff, Dordrecht, 1985). This paper focuses on recent results of the group theoretic approach to a numerical, global postbuckling analysis of a perfect, axially compressed cylindrical shell with “built-in” end conditions. The “built-in” end conditions obviate the existence of a “trivial” membrane solution branch. The example of an axially compressed cylindrical shell was chosen because it is well known that for thin shells, the primary axisymmetric solution branch is riddled with closely spaced, symmetry-breaking bifurcation points. In a numerical arc-length continuation scheme, the close proximity of the bifurcation points on the primary path manifests itself in severe ill-conditioning of the tangent stiffness matrix. Group theory helps one systematically find an “optimal” set of basis vectors, or symmetry modes, which reflect the symmetry of a given solution path. The immediate payoff in using these symmetry modes as basis vectors is that the tangent stiffness matrix block-diagonalizes and the numerical ill-conditioning is avoided. Thus, an efficient and accurate technique for computing solution branches of a specific type and a subsequent diagnosis for symmetry-breaking bifurcations is made relatively simple. Understanding the global behavior of the perfect structure is crucial in identifying critical imperfections and will ultimately diminish the heavy reliance on expensive experimental verification.

References listed at the end of this paper:


PARTIAL ABSTRACT: Over the past ten years there has been a growing interest within the mechanics community towards the application of group theoretic methods to aid in the global buckling analysis of symmetric imperfection-free structures. Within the context of a numerical arc-length continuation procedure, group theory helps one systematically find an “optimal” set of basic vectors which reflect the symmetry of a given problem. The immediate payoff in formulating the numerical procedure with respect to the symmetry-adapted basis is a global de-coupling of the equilibrium equations which in turn leads to: (1) a dimensional reduction in the problem size; (2) improved numerical conditioning while computing solutions in the vicinity of singular points; (3) a systematic method for detecting and diagnosing for symmetry-breaking bifurcations.
ABSTRACT: Progress in the application of group theoretic methods to the nonlinear bifurcation analysis of symmetric structures has provided new hope in understanding the global postbuckling behavior of symmetric thin shell structures. However, what is still lacking in the computational mechanics community is a general purpose FE code with a group theoretic capability designed to take ‘optimal’ advantage of existing symmetry. This paper addresses some of the important issues associated with developing such a code—the long term goal being to provide structural analysts with new numerical tools for doing careful global analyses of imperfection sensitive structures which may eventually lead to more accurate predictions of the maximum load-carrying capacity of thin imperfection sensitive shell structures.

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ABSTRACT: Due to the very nonlinear behavior of thin shells under collapse, numerical simulations are subject to challenges. Shell finite elements are attractive in these simulations. Rotational degrees of freedom do, however, complicate the solution. In the present study a co-rotated formulation is employed. The deformation of the shell is decomposed into a contribution from large rigid body rotation and a strain-producing term. A triangular assumed strain shell finite element is used. Hence, a high performance elastic element is combined with the co-rotated formulation. In the co-rotated co-ordinate system the plasticity is accounted for by a simplified Ilyushin stress resultant yield surface. The stress update is determined from the backward Euler difference, and a consistent geometrical and material tangent stiffness is derived. Comparison with other published analysis results show that the present formulation gives acceptable accuracy. (27 references’ cannot cut and paste from this pdf file.)

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ABSTRACT: The geometrically nonlinear constant stress triangle of Morley is implemented and extended to include material nonlinearity. The facet element was designed in a total Lagrangian approach and is valid for moderate rotations. In a search for a simple plasticity formulation, stress resultants plasticity (involving a solution of single scalar yield function) is employed. A modification is introduced in the Ilyushin yield surface such that it is rendered a hyperellipse to avoid corner discontinuities. Explicit plasticity equations are derived so as to avoid the most involving matrix operations and attain faster computations. In this work it is aimed to study the performance of the element and assess its application to practical problems such as plate buckling in offshore structures. The formulation appears to work well.

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ABSTRACT: In this study we present a new approach to analyse cracked shell structures subjected to large geometric changes. It is based on a combination of a rectangular assumed natural deviatoric strain thin shell finite element and an improved linespring finite element. Plasticity is accounted for using stress resultants. A power law hardening model is used for shell and linespring material. A co-rotational formulation is employed to represent nonlinear geometry effects. With this, one can carry out nonlinear fracture mechanics assessments in structures that show instabilities due buckling (local/global), ovalisation and large rigid body motion. By numerical examples it is shown how geometric instabilities and fracture compete as governing failure mode.

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ABSTRACT: The dynamic stiffness method is introduced to analyze thin-walled structures including thin-walled straight beams and spatial twisted helix beam. A dynamic stiffness matrix is formed by using frequency dependent shape functions which are exact solutions of the governing differential equations. With the obtained thin-walled beam dynamic stiffness matrices, the thin-walled frame dynamic stiffness matrix can also be
formulated by satisfying the required displacements compatibility and forces equilibrium, a method which is
similar to the finite element method (FEM). Then the thin-walled structure natural frequencies can be found by
equating the determinant of the system dynamic stiffness matrix to zero. By this way, just one element and
several elements can exactly predict many modes of a thin-walled beam and a spatial thin-walled frame,
respectively. Several cases are studied and the results are compared with the existing solutions of other
methods. The natural frequencies and buckling loads of these thin-walled structures are computed.

References listed at the end of the paper:


ABSTRACT: In standard stability investigations of structures applying the finite element method usually bifurcation and snap-through loads – so-called singular or stability points – are detected, see e.g. [4],[6],[7]. It is well-known that for complex structures like cylindrical shells these loads depend strongly on the geometrical and other imperfections, see [8],[9],[10]. It has been shown in [1] that the singular points and the corresponding modes vary significantly for small deviations of the approximated geometry using different ansatz-functions. Furthermore investigations in [1] have shown that the converging behavior for imperfect structures is non-monotonic. Particular limitations exist for the stability analysis of shell structures which involve contact between parts or with surrounding objects. In the end it could be followed that stability points and the corresponding loading determined numerically by static stability analysis are often of limited use for design purposes. In contrast to the loading obtained for singular points the so-called post-buckling loads, which are the stable equilibrium states in the post-buckling region, are rather independent of geometrical imperfections and of approximation order, see [1]. Therefore it is advantageous to use post-buckling loads for design purposes instead of loads obtained for singular points. Since the applicability of static analyses in the computation of
post-buckling paths like proposed e.g. in [5] is rather limited, it is favorable to model the complete loading and deformation behavior by a time dependent process, see [3], [2], [11], [12]. The major advantage of a purely transient analysis is the complete simulation of the buckling process as it happens in reality. This is possible with moderate numerical effort, since the matrices used in the solution are usually better conditioned compared to pure static analysis. In addition, this allows to take the changing boundary conditions as found in contact situations properly into account. For practical design purposes not only the equilibrium state itself is significant but also the “robustness” of such states against finite perturbations in contrast to infinitesimal perturbations. In the case of systems with many equilibrium states at a defined load level finite perturbations can transfer the mechanical system from a stable equilibrium state to another equilibrium state or in some cases even to an unbounded motion initiating buckling. Then a sensitivity measure can be defined as the reciprocal value of the minimum perturbation energy, necessary for this transfer S = 1/Wper,min, see [2]. In the present paper stability and sensitivity studies are performed for simple stability problems (beams) and finally for rather general shell structures involving geometrical imperfections and in particular contact.

References listed at the end of the paper:


possibilities to treat the stability considerations in an accompanying way. Furthermore we discuss modern concepts to calculate singular points directly using so called extended systems. Remarks on branch-switching procedures terminate the theoretical considerations. At the end of the paper some numerical examples are given to illustrate the derived methods and algorithms.

References listed at the end of the paper:
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ABSTRACT: A numerical model for layered composite structures based on a geometrical nonlinear shell theory is presented. The kinematic is based on a multi-director theory, thus the in-plane displacements of each layer are described by independent director vectors. Using the isoparametric approach a finite element formulation for quadrilaterals is developed. Continuity of the interlaminar shear stresses is obtained within the nonlinear solution process. Several examples are presented to illustrate the performance of the developed numerical model.


ABSTRACT: A numerical model for the nonlinear analysis of thick laminates is presented. Using a multiplicative decomposition of the displacement vector in shell space, the 3D problem is reduced to a 2D problem. Although the total number of degrees of freedom is comparable to 3D brick elements this approach provides several advantages, e.g. a simplified mesh generation due to a 2D-type data structure and a better bending behavior. The developed isoparametric quadrilateral finite element is capable of predicting interlaminar stresses and local effects. Several linear and nonlinear examples are presented to illustrate the performance of the developed numerical model.


ABSTRACT: A numerical model for the non-linear analysis of laminates is presented. The developed element
is based on piecewise polynomial interpolation in thickness direction. Although the total number of degrees of freedom is comparable to a discretization with 3D brick elements this approach provides several advantages, e.g. a simple mesh generation due to a 2D-type data structure and a better bending behavior. The developed isoparametric quadrilateral finite element allows prediction of the complete stress state. Furthermore, a transition element is presented which is used to couple the developed element with 5-parameter shell elements. Several linear and non-linear examples are presented to illustrate the performance of the developed numerical model.


ABSTRACT: Moderate and finite rotation theories [7] [4] [6] are available including the finite element analysis, especially the treatment of shear locking problems. The five parameter shell model used in this paper is based on geometrically non-linear Reissner-Mindlin kinematics where the finite element formulation may be derived using the Biot—or 2. Piola—Kirchhoff stress resultants, alternatively. The description of finite rotations of the shell normal is expressed in terms of a skew-symmetric tensor.

References listed at the end of the paper:


ABSTRACT: In this paper a finite shell element for large deformations is presented based on extensible director kinematics. The essential feature is an interface to arbitrary three-dimensional material laws. The non-linear
The Lagrangian formulation is based on the three-field variational principle, parametrized with the displacement vector, enhanced Green-Lagrangian strain tensor and second Piola Kirchhoff stress tensor. The developed quadrilateral shell element is characterized by a course mesh accuracy and distortion insensitivity compared with bilinear displacement approaches. Furthermore, plane stress response is approximately recovered in the asymptotic case of vanishing thickness. A number of example problems investigating large deformation as well as finite strain applications are presented. Compressible and incompressible hyperelastic materials of the St. Venant-Kirchhoff, Neo-Hookean and Mooney-Rivlin type are particularly used.

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“Finite element formulations for geometrical and material nonlinear shells based on a Hu-Washizu functional”, VIII International Conference on Computational Plasticity (COMPLAS VIII), E. Enate and D.R.J. Owen, Editors, CIMNE, Barcelona, 2005

ABSTRACT: The paper deals with the nonlinear finite element analysis of thin shells. Numerical tests show the advantages of the developed mixed hybrid quadrilateral element. The essential feature of the element formulation is the robustness in nonlinear computations with large rigid body motions. It allows very large load steps in comparison to standard displacement models or enhanced strain models.

References listed at the end of the paper:


ABSTRACT: In this paper we consider compressed flat thin films on rigid substrates. Residual compressive stresses arising e.g. from temperature loading are the driving quantities of the irreversible delamination process. A Reissner–Mindlin shell formulation is used as a model for the thin film, since small geometrical imperfections are considered to initiate buckling. For the interface we postulate the existence of a cohesive free energy as a function of the opening displacement vector and internal variables. The irreversible delamination process is described using a cohesive law of exponential type, where the parameters depend on the combination of the modes I, II and III. In order to analyse the delamination process exactly we use the energy criterion of the steady-state growth.

References listed at the end of the paper:

ABSTRACT: The delamination process of thin films on rigid substrates is investigated. Such systems are typically subject to high residual compression and modest adhesion causing them to buckle driven blisters. In certain cases buckles with the shape of telephone cords are observed. A finite element model for quasi-static delamination growth is developed. Applying a Reissner-Mindlin shell kinematic for the film allows continuous shape functions. The traction vector at the film-substrate interface is obtained from the derivative of a cohesive free energy. Incorporation of loading and unloading conditions is considered for the irreversible process. The equilibrium state is computed iteratively in dependence of the compressive residual stresses. The computed telephone cord delaminations are stable asymmetric configurations whereas the symmetric configurations are unstable.

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Friedrich Gruttmann, “Nonlinear finite element shell formulation accounting for large strain material models”, Chapter in Recent Developments and Innovative Applications in Computational Mechanics, pp 87-95, 2011, DOI: 10.1007/978-3-642-17484-1_11

ABSTRACT: Based on the kinematic assumptions of Mindlin-Reissner a three-field variational formulation with independent displacements, stress resultants and shell strains is presented. Within the finite element formulation the interpolation of the independent shell strains consists of two parts. The first part corresponds to the interpolation of the stress resultants. Within the second part thickness strains are incorporated, which allows direct implementation of nonlinear three-dimensional constitutive equations. A mixed hybrid quadrilateral shell element is formulated. The essential feature of the element is the remarkable robustness in nonlinear applications.

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Nicholas Keage, Christopher Maiolo, Rebecca Pierotti and Xing Ma (School of Natural and Built Environments, University of South Australia, Adelaide, Australia), “Experimental study and numerical simulation on compressive buckling behavior of thin steel skins in unilateral contact with rigid constraints”, Frontiers of Architecture and Civil Engineering in China, Vol. 5, No. 3, pp 335-343, September 2011

ABSTRACT: In this paper, a practical test and finite element analysis has been undertaken to further investigate the effects of contact buckling. A test rig was designed and constructed to record vertical and transverse deflections of compressively loaded steel skin plates. The boundary conditions were modeled as fully fixed. A finite element analysis was also undertaken using the software package Strand7. Results from both analyses have been examined and compared to data established from previous studies on contact buckling. Both the finite element analysis and practical results correlate well with this data. The result of the investigation has confirmed contact buckling theories and has foreshadowed the onset of the newly observed phenomenon of secondary contact buckling.

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9. Ma X, Butterworth J W, Clifton C G. Practical analysis procedure for compressive local buckling of skin sheets in composite

ABSTRACT: On the basis of Kirchhoff–Love-hypothesis and small elastic strains a geometrically nonlinear theory of thin shells is derived in symbolic tensor notation. Furthermore, an incremental version for finite increments of the displacements is formulated and the corresponding incremental principle of virtual work. This is the starting point of FEM with curved triangular elements, each containing 63 kinematical DoFs. Different levels of geometrical nonlinearity are implemented in the developed computer programs for nonlinear, critical and postcritical calculations. As examples quadrilateral sections of circular cylindrical shells with different boundary conditions are investigated for normal pressure, normal point loads, axial loads and combined loads, considering additionally imperfections. Comparisons with published results are made as far as possible. The results show the validity of Donnell’s approximation in a wide range.

References listed at the end of the paper:


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“An Efficient Algorithm For The Computation Of Stability Points Of Dynamical Systems Under Step Load”,
Engineering Computations, Vol. 9 No. 6, 1983, pp. 669 – 679,
doi: 10.1108/eb023890
ABSTRACT: Many engineering structures exhibit loss of stability under static and dynamic loading. Due to the significance of these phenomena in engineering design this topic has attracted considerable attention during the last decades. In recent years much effort has been made to devise algorithms within finite element analysis to investigate the static stability behaviour of structures. With these methods stable and unstable paths can be traced, and limit or bifurcation points can be computed efficiently. The associated arc-length or branch-switching procedures are today standard tools in existing finite element codes.

ABSTRACT: In this paper a class of non-linear problems is discussed where stability as well as post-buckling behaviour is coupled with contact constraints. The contact conditions are introduced via a perturbed Lagrangian formulation. From this formulation the penalty and Lagrangian multiplier method are derived. Both algorithms are investigated together with an algorithm based on an augmented Lagrangian method. The resulting finite element formulation is applied to structural problems of beams and shells undergoing finite elastic deflections and rotations. For the examination of the post-buckling behaviour the arc-length method is used. The performance of the element formulation and a comparison of the different contact algorithms are demonstrated by numerical examples.

References listed at the end of the paper:

ABSTRACT: The practical behaviour of problems exhibiting bifurcation with secondary branches cannot be studied in general by using standard path-following methods such as arc-length schemes. Special algorithms have to be employed for the detection of bifurcation and limit points and furthermore for branch-switching. Simple methods for this purpose are given by inspection of the determinant of the tangent stiffness matrix or the calculation of the current stiffness parameter. Near stability points, the associated eigenvalue problem has to be solved in order to calculate the number of existing branches. The associated eigenvectors are used for a perturbation of the solution at bifurcation points. This perturbation is performed by adding the scaled eigenvector to the deformed configuration in an appropriate way. Several examples of beam and shell problems show the performance of the method.


ABSTRACT: In the analysis of nonlinear elastic shells often the stability and postbuckling behaviour governs the response. Here we discuss problems which also include contact constraints. A nonlinear cylindrical shell element is derived directly from the associated shell theory using one point integration and a stabilization technique. Within a general solution algorithm a simple but effective branch-switching procedure is presented. Additional considerations allow the treatment of bifurcation problems with contact constraints. Several examples of beam and shell problems show the performance of the developed algorithms and elements.

References listed at the end of the paper:


ABSTRACT: In this paper we discuss theoretical and numerical aspects of the formulation of a cylindrical shell element for composite materials. The element is based on a direct introduction of the finite element approach into the shell equations, especially for the base vectors, see Simo, J. C. et al. (1989–1992) |Comp. Meth. Appl.
Mech. Engng (Part I) 72, 267–304, (Part II) 73, 53–92, (Part III) 79, 21–70, (Part IV) 81, 91–126, (Part V) 96, 133–171 and Gruttmann et al. (1989) [Ing. Arch. 59, 54–67]. Introducing the special geometry of cylinders we end up with a simple but highly accurate element which can be formulated in an easy way and which shows excellent convergence behavior in linear and nonlinear problems.


ABSTRACT: The investigation of the non-linear response of shell-like structures requires insight into stability behaviour. In the paper we compare two strategies to compute singular points based on different eigenvalue problems. We show a simple algorithm to calculate critical load factors $A$ used in engineering buckling analysis from the eigenvalues of the standard eigenvalue problem…Some numerical examples illustrate the derived results and algorithms.


ABSTRACT: This paper is concerned with a geometrically non-linear solid shell element to analyse piezoelectric structures. The finite element formulation is based on a variational principle of the Hu–Washizu type and includes six independent fields: displacements, electric potential, strains, electric field, mechanical stresses and dielectric displacements. The element has eight nodes with four nodal degrees of freedoms, three displacements and the electric potential. A bilinear distribution through the thickness of the independent electric field is assumed to fulfill the electric charge conservation law in bending dominated situations exactly. The presented finite shell element is able to model arbitrary curved shell structures and incorporates a 3D-material law. A geometrically non-linear theory allows large deformations and includes stability problems. Linear and non-linear numerical examples demonstrate the ability of the proposed model to analyse piezoelectric devices.


ABSTRACT: Buckling of trapezoidally corrugated panels under in-plane loading is analyzed by a spline finite strip method. The influence on the elastic buckling load of various parameters, such as geometry, loading forms and boundary conditions, etc., is studied. It is found that: (1) for longitudinal compression the buckling load increases with the corrugation angle $\alpha$, and for a given $\alpha$ the highest buckling load is achieved when the “proportion parameter” $y = 1$; (2) for shear loading the buckling load increases as $\alpha$ increases, and for a given $\alpha$ the highest buckling load is obtained when $y = 2$; and (3) for a combined loading of compression and shear, interactive curves can be approximated by unit circles when $\alpha = 15, 30, 45, 60$ and $90$ degrees. However, when $\alpha = 75$ degrees a parabola seems to be a better approximation. Based on the numerical experiments, simplified formulae and interactive curves are suggested for practical design.

Bo L. O. Edlund (Chalmers University of Technology, Göteborg, Sweden), “Buckling of metallic shells:
Buckling and postbuckling behaviour of isotropic shells, especially cylinders” (a review paper), Structural Control and Health Monitoring, Vol. 14, No. 4, pp. 693-713, June 2007, doi: 10.1002/stc.202

ABSTRACT: The large discrepancies between observed buckling loads for thin shells and the predictions of the classical theory have been a great challenge to many researchers since the 1920s. In this paper, the basic behaviour and characteristics are described and recent research, mainly from the last 10 years, is reviewed. The focus is on cylindrical shells and on the influence of initial imperfections on the buckling behaviour.


ABSTRACT: Local buckling of web plates having a longitudinal stiffener in different positions under simultaneous shear and in-plane bending is investigated. The interaction study is carried out by both numerical simulation of the problem utilizing finite element method, and by an analytical procedure based on energy method using trigonometric functions. Interaction curves show that the existence of small amounts of in-plane bending may increase the shear buckling capacity, and that the introduction of a longitudinal stiffener significantly increases the critical stress of web plates. Also a very good correlation between the proposed energy method and the finite element method is obtained.


ABSTRACT: In [1], nonlinear large deflection finite element analysis was implemented to depict the characteristics of the shear failure mechanism of steel plate girders. That paper aimed at clarifying how–when–why and where plastic hinges form in flanges. The present paper extends those results to the state of stresses in web plates. It is shown that although the principal compressive stresses in the center of the web plates remain constant after an elastic buckling, they do increase considerably in other regions. In addition, the angles at which tension fields form; and the ultimate strength of plate girders is discussed and compared to those obtained by different theoretical and experimental hypotheses.

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“Buckling and postbuckling behavior of unstiffened slender curved plates under uniform shear”, Thin-Walled Structures, Vol. 49, No. 8, April 2011, pp. 1017-1031, doi:10.1016/j.tws.2011.03.007

ABSTRACT: Buckling and postbuckling behavior of curved plates under in-plane shear are investigated. After revisiting classic elastic buckling results, the elastoplastic postbuckling behavior and the effects of curvature parameter and aspect ratio are simulated via geometrical and material nonlinear analyses. Imperfection sensitivity is studied for various imperfection shapes and magnitudes. An increase in curvature parameter raises the elastic buckling load, produces unstable buckling and reduces postbuckling reserves. The buckling load and shear capacity are higher in shorter plates. Small initial imperfections are found to have severe effects on the initial buckling load of plates with large curvature parameter, but little effect on ultimate postbuckling capacity.

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ABSTRACT: Two principal possibilities for analyzing the structural response of quasi-statically loaded steel shell structures to different actions are available: the commonly used static path tracing and the dynamic analysis with slowly changing loads, i.e. quasi-static loading. However, the failure process of thin-walled shells can often not be traced into the deep post-buckling area with static methods. The current research is focused on a thin-walled circular cylindrical steel shell collapse analysis under constant shear loading. It is shown that it is possible to overcome the difficulties and inconsistencies of the static analysis by using quasi-static analysis. This method allows to distinguish local and global instability points and to determine too the experimentally observed post-buckling strength.

M.R. Eslami and M. Shariyat (Mechanical Engineering Department, Amirkabir University of Technology, (Tehran Polytechnic), 424 Hafez Avenue, Tehran 15914, Iran), “A high-order theory for dynamic buckling and

ABSTRACT: Using a high-order Reissner-Mindlin-type shear deformation theory in a power series form, the general large deformation form of the Green strain tensor for imperfect cylindrical shells is introduced. Then, based on Hamilton’s principle, the equations of motion are derived for laminated composite shells. Related constitutive equations are also proposed. In this formulation, temperature dependency of material properties is considered, too. No simplifications are made in solving the coupled nonlinear equations of motion. Finally, few examples of the well-known references are reconsidered for comparison purposes.

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ABSTRACT: Buckling behavior of rectangular functionally graded plates with geometrical imperfections is studied in this paper. The equilibrium, stability, and compatibility equations of an imperfect functionally graded plate are derived using the classical plate theory. It is assumed that the nonhomogeneous mechanical properties of the plate, graded through thickness, are described by a power function of the thickness variable. The plate is assumed to be under in-plane compressive loading. Simultaneous solving of the stability and compatibility equations in conjunction with the equilibrium equations leads to the buckling relation of the plate. The critical buckling load of a sample plate is obtained and compared for different geometrical ratios. The results are reduced and compared with the results of perfect functionally graded and imperfect isotropic plates.

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ABSTRACT: Thermal buckling analysis of rectangular functionally graded plates (FGPs) with geometrical imperfections is presented in this paper. The equilibrium, stability, and compatibility equations of an imperfect functionally graded plate are derived using the classical plate theory. It is assumed that the nonhomogeneous mechanical properties of the plate, graded through thickness, are described by a power function of the thickness variable. The plate is assumed to be under three types of thermal loading as uniform temperature rise, nonlinear temperature rise through the thickness, and axial temperature rise. Resulting equations are employed to obtain the closed-form solutions for the critical buckling temperature change of an imperfect FGP. The results are reduced and compared with the results of perfect functionally graded and imperfect isotropic plates.

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ABSTRACT: Buckling analysis of rectangular thick functionally graded plates under mechanical and thermal loads is presented in this paper. It is assumed that the non-homogeneous mechanical properties vary linearly
through the thickness of the plate. The plate is assumed to be under three types of mechanical loadings, namely; uniaxial compression, biaxial compression, and biaxial compression and tension and two types of thermal loadings, namely; uniform temperature rise and non-linear temperature rise through the thickness. The equilibrium and stability equations are derived using the third order shear deformation plate theory. Resulting equations are employed to obtain the closed-form solution for the critical buckling load for each loading case. The results are verified with the known data in the literature.


ABSTRACT: Composite materials are formed by the combination of two or more materials that retain their respective characteristics when combined together to achieve desired properties (physical, chemical, etc.) that are superior to those of individual constituents. The main components of composites are reinforcing agents and matrix. Composites have high strength-to-weight ratio and high stiffness-to-weight ratio as compared to conventional materials. Composite are used in many sectors like civil, aerospace, automobiles, marine, medical and power transmission etc., but in this paper more emphasis is given on structural applications. This seminar presents the literature review of application and behaviour of laminated composite material in structural members. Being a thin walled structure, their behaviour is governed by stability criteria. Here a brief review of stability behaviour of laminated composite stiffened panels is presented along with addition the knowledge are also identified into which more comprehensive analysis is needed.

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Mana Behnamasl, “Comparison of the behaviour of curved and straight types of steel shell roof structures”,
Master’s thesis, Dept. of Civil Engineering, Eastern Mediterranean University, Cazimagusa, North Cyprus, 2010
ABSTRACT: In this research, the straight and curved models of the steel shell roof with different plates were
analysed, designed and the results were compared with one another. Through this exercise it is aimed at
achieving an ideal shell roof structure which could cover a larger surface. Therefore, three types of shell roofs
were considered duopitch, cylindrical and dome and the main objective was to compare the straight and curved
model of the shells. According to the findings of the literature review, this is the first time for such comparison
to be carried out among the basic types (duopitch, cylindrical, dome) of shell roof structure. In addition to the
advantage of covering large openings the shell roof structures also use the least materials to do this. Most of its
resistance against the forces imposed on it is due to its curved surface. It is this particular characteristic of the
shell structures that has been attracting architects and civil engineers more in the recent years. This research
shows how effective the curved surfaced shell roof can be with different angles in helping the structure to
resistance its self weight and applied loads. Moreover, it also indicates under which conditions a particular
structure can be more reliable. This kind of shell roof is not common in all shapes and each model needs special
characteristics. When all the comparisons were made, an optimal structure with the largest span of shell roof
and resistance to loads was obtained. In this research, three different angles were used in three shell roof models
in simple and general conditions and the results were compared in order that a structure with ideal condition can
be obtained in future while basic conditions also need to be understood. For each shell roof type, three plates
were considered for analyses and designed. A metal box with either 5cm or 7cm I-section edges, each box has
0.5m length and breadth and I-section edges with either 0.05m or 0.07m height and 0.003m thickness. A metal
box with L-section edges, each box has 0.5m length and breadth and L section edge with 0.05m height and
0.02m edge and 0.03m thicknesses. The comparison between these plates indicates the load carrying capacity
and span capability of the structures. When all different shell roof types are able to cover the same opening,
then it is these plates which determine the weight and the amount of stresses in the structure. The research
showed that it is necessary and important to consider the maximum possible loads these structures could carry
and also to find out the maximum span and the loads that these types of structures can tolerate. This kind of
design is very economic in shell structures and has the capability of replacement and frequent usage in different
areas while the other structures do not have this ability.
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Mahmoud Shariati and Masoud Mahdizadeh Rokhi (Department of Mechanical Engineering, Shahrood University of Technology, Daneshgah Boulevard, Shahrood, Iran), “Numerical and experimental investigations on buckling of steel cylindrical shells with elliptical cutout subject to axial compression”, Thin-Walled Structures, Vol. 46, No. 11, November 2008, pp. 1251-1261, doi:10.1016/j.tws.2008.02.005

ABSTRACT: The effect of cutouts on load-bearing capacity and buckling behavior of cylindrical shells is an essential consideration in their design. In this paper, simulation and analysis of thin steel cylindrical shells of various lengths and diameters with elliptical cutouts have been studied using the finite element method and the effect of cutout position and the length-to-diameter (L/D) and diameter-to-thickness (D/t) ratios on the buckling and post-buckling behavior of cylindrical shells has been investigated. For several specimens, buckling test was performed using an INSTRON 8802 servo hydraulic machine and the results of experimental tests were compared to numerical results. A very good correlation was observed between numerical simulation and experimental results. Finally, based on the experimental and numerical results, formulas are presented for finding the buckling load of these structures.

References listed at the end of the paper:


ABSTRACT: Shell structures have been widely used in pipelines, aerospace and marine structures, large dams, shell roofs, liquid-retaining structures and cooling towers [1]. Buckling is one of the main failure considerations when designing these structures [2]. At first, researchers focused on the determination of the buckling load in the linear elastic zone, but experimental studies showed that the buckling capacity of thin cylindrical shells is much lower than the amount determined in the classic theories [3, 4]. Shell structures, like other types of structures, are usually susceptible to various types of defects and damages such as initiation and propagation of cracks, corrosion, chemical attack and time-dependent material degradation, which impair their structural soundness. The presence of cracks in a shell structure can play the role of geometrical imperfection and thus reduce the load carrying capacity of the shell structure [5-7]….

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Shariati M. and Rokhi M.M. (Dept. of Mechanical Engineering, Shahroud University of Technology, Shahrood, Iran), “Buckling of Steel Cylindrical Shells with an Elliptical Cutout”. International Journal of Steel Structures, 10(2), 193-205 (2010)
ABSTRACT: Numerical simulation and analysis of steel cylindrical shells with various diameter and length having an elliptical cutout, subjected to axial compression were systematically carried out in this paper. The investigation examined the influence of the cutout size, cutout angle and the shell aspect ratios L/D and D/t on the pre-buckling, buckling, and post-buckling responses of the cylindrical shells. For several specimens, an experimental investigation was also carried out via an INSTRON 8802 servo hydraulic machine and the results obtained from the experiments were compared with numerical results. A very good accordance was observed between the results obtained from the finite element simulation and the experiments. Furthermore, some equations in the form of a buckling load reduction factor were developed.

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Rasmussen, K. J. R., Burns, T., Bezkorovainy, P., and Bambach, M. R. (Department of Civil Engineering, University of Sydney). “Recent Research on the Local Buckling of Cold-formed Stainless Steel Sections.” International Journal of Steel Structures, 5(1), pp. 87–100, 2003

ABSTRACT: Research at the University of Sydney in the stainless steel area has for the last three years concentrated on the local buckling strength of stainless steel plates with application to cold-formed sections. The research has encompassed tests on single stainless steel plates, and the finite element modelling of stainless steel plates. Research was also carried out to determine the stress-strain curves for stainless steel materials over the full strain range solely in terms of the Ramberg-Osgood parameters (n, s0, E0). Advanced finite element models have been used to derive direct expressions for the plate strength in terms of the Ramberg-Osgood parameters using a modified Winter curve. The explicit plate strength equations showed that as a result of gradual yielding, the strength of stainless steel plates is reduced below the strength of carbon steel plates, as predicted by the standard Winter equation, by up to 13% depending on the alloy and cold-working history. Most recently, the explicit strength equations were applied to cold-formed sections and design models were proposed for determining the strength of such sections. It was shown that the corners of cold-formed sections play a more important role for stainless steel sections than for carbon steel sections because the corner areas can be cold-worked to much higher strengths than in the case of carbon steel sections. Because of the enhanced mechanical properties of the corners, the standard Winter equation can in many cases be used safely for the design of cold-formed stainless steel sections. There are however a number of exceptions, which have been identified. The present paper summarises the research on the local buckling strength conducted at the University of Sydney over the last three years.

References listed at the end of the paper:

reliability analysis shows the method to be suitable for design. The theoretical elastic buckling stress of the composite steel sections delays local buckling and subsequently results in significant increases in elastic buckling stress, axial capacity and strength-to-weight ratio of the compression members. The experiments are an extension of a previous study [Bambach MR, Elchalakani M. Plastic mechanism analysis of steel SHS strengthened with CFRP under large axial deformation. Thin-Walled Structures 2007;45(2):159–70] in which 25 commercially produced SHS with plate slenderness values between 0.3 and 1.6 were strengthened with CFRP in the same manner. A design method is developed whereby the theoretical elastic buckling stress of the composite steel–CFRP sections is used to determine the axial capacity, and is shown to compare well with the 45 test results. A reliability analysis shows the method to be suitable for design.
References listed at the end of the paper:


ABSTRACT: In this paper, the buckling and post-buckling of steel thin-walled semi-spherical shells are investigated under different loadings, both experimentally and numerically. Various vertical compression
loadings are applied to specimens using the following methods: a rigid flat plate and some rigid bars with circular, square and spherical cross sections, a rigid tube, a plate with a hole, and an indented tube. The effects of geometrical parameters of specimens on the buckling load, such as the diameter and thickness, are studied. The numerical analysis is carried out by ABAQUS software and the experimental tests are performed using an Instron 8802 servo-hydraulic machine. The numerical and experimental results are similar to one another. Therefore, the numerical results are valid.


ABSTRACT: The effects of the length, sector angle, and different boundary conditions on the buckling load and post buckling behavior of cylindrical panels have been investigated using experimental and numerical methods. The experimental tests have been performed using a servo-hydraulic machine, Instron 8808, and for numerical analysis, Abaqus finite element package has been used. The numerical results are in good agreement with the experimental tests.


ABSTRACT: The effects of the length, sector angle and different boundary conditions on the buckling load and post buckling behavior of cylindrical panels have been investigated using experimental and numerical methods. The experimental tests have been performed using a servo hydraulic machine and for numerical analysis, Abaqus finite element package has been used. The numerical results are in good agreement with the experimental tests.


ABSTRACT: A series of finite element analysis on the cracked composite cylindrical shells under combined loading is carried out to study the effect of loading condition, crack size and orientation on the buckling behavior of laminated composite cylindrical shells. The interaction buckling curves of cracked laminated composite cylinders subject to different combinations of axial compression, bending, internal pressure and external pressure are obtained, using the finite element method. Results show that the internal pressure increases the critical buckling load of the CFRP cylindrical shells and bending and external pressure decrease it. Numerical analysis show that axial crack has the most detrimental effect on the buckling load of a cylindrical shell and results show that for lower values of the axial compressive load and higher values of the external pressure, the buckling is usually in the global mode and for higher values of axial compressive load and lower levels of external pressure the buckling mode is mostly in the local mode.

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ABSTRACT: Within this contribution, buckling of tubular steel shells with circular cutout will be analyzed. The experimental results will be compared by FEM simulation results within circular cutouts of the specimen. The experimental buckling tests have been conducted using a Servo-hydraulic machine (Instron 8802). Considering the broad application range of tubular thin-walled shells, prediction of the behavior of these elements in combined loading case (especially for buckling behavior) has gained a great level of importance. In this study, the influence of shell length, shell diameter, shell angle and diameter of circular cutouts on the predicted buckling values for the tubular shell has been explored. Numerical simulations of tubular shell subjected to combined loading were conducted. The analytical solutions show excellent agreement with the numerical results predicted by FEM.

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DOI: 10.1016/j.ijpvp.2012.07.012
ABSTRACT: This study deals with free vibrations and buckling analysis of nanocomposite Timoshenko beams reinforced by single-walled carbon nanotubes (SWCNTs) resting on an elastic foundation. The SWCNTs are assumed to be aligned and straight with a uniform layout. Four different carbon nanotubes (CNTs) distributions including uniform and three types of functionally graded distributions of CNTs through the thickness are considered. The rule of mixture is used to describe the effective material properties of the nanocomposite beams. The governing equations are derived through using Hamilton's principle and then solved by using the generalized differential quadrature method (GDQM). Natural frequencies and critical buckling load are obtained for nanocomposite beams with different boundary conditions. Effects of several parameters, such as nanotube volume fraction, foundation stiffness parameters, slenderness ratios, CNTs distribution and boundary conditions on both natural frequency and critical buckling load are investigated. The results indicate that the above-mentioned parameters play a very important role on the free vibrations and buckling characteristics of the beam.

ABSTRACT: A structural mechanics model is employed for the investigation of the bending buckling behavior of perfect and defective single-walled carbon nanotubes (SWCNTs). The effects of different types of defects (vacancies and Stone-Wales defects) at various locations on the critical bending buckling moments and curvatures are also studied for zigzag and armchair nanotubes with various aspect ratios (length/diameter). The locations of defects are along the length of the nanotube and around the circumference. Moreover, the results of this structural mechanics model are compared with a finite element model. The simple continuum model, especially, could be adopted to predict the critical buckling moments and curvatures of SWCNTs with large aspect ratio. Finally, the results of the present structural model are compared with those from molecular dynamics (MD) simulation, and there is good agreement between our model and the MD model.

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“Buckling behavior of perfect and defective DWCNTs under axial, bending and torsional loadings via a structural mechanics approach”, Meccanica, Vol. 48, No. 8, pp 1959-1974, October 2013
ABSTRACT: The buckling behavior of perfect and defective double-walled carbon nanotubes (DWCNTs) under axial compressive, torsional and bending loadings is investigated using a structural mechanics model. The effects of van der Waals (vdW) forces are further modeled using a nonlinear spring element. Critical buckling loads, critical buckling moments and the effects of vacancy defects were studied for armchair nanotubes with various aspect ratios. The results show that vacancy defects greatly reduce the critical buckling load of DWCNTs. The density of defects plays an important role in buckling of DWCNTs. The results of this numerical model are in good agreement with their comparable existing works.

References listed at the end of the paper:
Mahmoud Shariati (1), Abdolhosein Fereidoon (2) and Amin Akbarpour (3)
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“Buckling Load Analysis of Oblique Loaded Stainless Steel 316ti Cylindrical Shells with Elliptical Cutout”,
Research Journal of Recent Sciences, Vol. 1, No. 8, pp. 53-63, August 2012

ABSTRACT: This paper concerns with experimental and numerical studies on buckling of thin-walled cylindrical shells under oblique loading. The buckling loads are obtained from finite element models. Experiments are conducted on several Specimens made of stainless steel 316ti by using an INSTRON 8802 servo-hydraulic machine. Then results are compared. A very good correlation was observed between numerical simulation and experimental results. Investigations on buckling and post-buckling behavior of cylindrical shells with cutout were carried out for shell length (L), shell diameter (D) and cutout position (CP/L ratio). The specimens were constrained by fixtures that design for this result and inserted at both ends, which mimics the fixed boundary condition used in the finite element simulations.

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ABSTRACT: The interactive mechanisms between internal blast loading and dynamic elastic response of spherical containment vessels are studied in this paper. The blast loading history in containment vessels can be divided into three periods, i.e. the primary-shock period, the shock-reflection period and the pressure-oscillation period. It is shown that the initial response of the containment vessel depends on both the impulse and the shape of the primary-shock depending on the ratio of the loading period to the breathing mode period. However, during the shock-reflection period, the response of the containment vessel can be coupled with the reflected shock waves in the vessel, especially when the dominant frequency of reflected shock waves is close to the breathing mode frequency of the vessel. During the pressure-oscillation period, the dynamic loading is mainly the oscillation of the internal pressure due to the oscillatory volume change of the vessel, which couples dissipatedly with the vibration of the vessel leading to reduced vibration amplitudes. The effects of the influential non-dimensional parameters on the resonant interaction in shock-reflection period are discussed, based on which guidelines are recommended for avoiding the strain growth in the shock-reflection period in the design of spherical containment vessels.

References listed at the end of the paper:

ABSTRACT: This paper treats the dynamic response and energy absorption of aluminum semi-spherical shells under axial loading using non-linear finite element techniques. Aluminum and steel spherical shells of various radii and thicknesses were made by spinning. The influence of geometrical, material and loading parameters on the impact and quasi-static response is investigated using validated numerical models. Also the axial inward inversions of semi-spherical shells are investigated. The research information generated will be useful in developing guidance towards the design of these devices in impact applications.

References listed at the end of the paper:
PARTIAL INTRODUCTION: Thin-walled members are the elements of many engineering structures. They become unstable and start to buckle if they subjected under a compressive loads greater than their ultimate buckling load. Moreover, some of these members usually have cut outs due to their applications and these discontinuities can affect on their stability. The stability analysis of thin-walled structures under axial compression has been investigated by some researchers. Obviously, the stability of these structures is dependent on the type of support and loading. The buckling and the geometrically nonlinear elasto-plastic collapse of perforated plates were investigated using finite element solutions. Elasto-plastic postbuckling of damaged orthotropic plates based on the elasto-plastic mechanics and continuum damage theory have been studied. El-Sawy et al. employed the FEM to determine the elasto-plastic buckling stress of uniaxially loaded square and rectangular plates with circular cutouts. Plates with simply supported edges in the out-of-plane direction and subjected to uniaxial end compression in their longitudinal direction were considered.

References listed at the end of the paper:
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“Buckling of cracked laminated cylindrical shells subjected to combined loading”, Appl Compos Mater, 2012, DOI: 10.1007/s10443-012-9300-9

ABSTRACT: A series of finite element analyses on the cracked composite cylindrical shells under combined loading is carried out to study the effect of loading condition, crack size and orientation on the buckling behavior of laminated composite cylindrical shells. The interaction buckling curves of cracked laminated composite cylinders subjected to different combinations of axial compression, bending, internal pressure and external pressure are obtained, using the finite element method. Results show that the internal pressure increases the critical buckling load of the CFRP cylindrical shells and bending and external pressure decrease it. Numerical analyses show that axial crack as the most detrimental effect on the buckling load of a cylindrical shell, and results show that for lower values of the axial compressive load and higher values of the external pressure, the buckling is usually in the global mode, and for higher values of axial compressive load and lower levels of external pressure the buckling model is mostly in the local mode.

References listed at the end of the paper:
REFERENCES LISTED AT THE END OF THE PAPER:


ABSTRACT: In this research, softening and ratcheting behaviors of Ck20 alloy steel cylindrical shells were studied under displacement-control and force-control cyclic axial loading and the behavior of hysteresis curves of specimens was also investigated. Experimental tests were performed by a servo-hydraulic INSTRON 8802 machine. The mechanical properties of specimens were determined according to ASTM E8 standard. Under force-control loading with non-zero mean force, ratcheting behavior occurred on cylindrical shell and plastic strain accumulation continued up to the collapse point of cylindrical shell. The rate of ratcheting strain became higher using the higher force amplitude. Softening behavior was observed under displacement control loading and, due to the occurred buckling in compression zone, this behavior became more extreme. The behavior of hysteresis curves of this alloy was not symmetrical under tensile and compressive loads. Moreover, the influence of loading history was studied on the behavior of hysteresis curves of the specimens under various types of loadings.


ABSTRACT: This research was an experimental and numerical investigation of the cylindrical expanded Sheets under impact loading. Two types of absorbers with different cell angles were examined (i.e. α = 0 and α = 90). The experiments were performed using the drop hammer setup, and the numerical simulations were conducted by ABAQUS. In this study, the type of collapse, force-displacement diagrams, the crushing length, and the absorbed energy were investigated. The experimental and numerical results were compared, and it was observed that they were in good agreement. Results showed that the absorbers with the cell angle of α = 0 had a symmetric collapse and a high energy absorption capacity. Also, various heights of fall were considered for the impact mass to examine the type of collapse in the models. The crushing amounts of the models were also compared in different heights. Multi-walled expanded metal tubes were studied, and the effect of being multi-walled in collapse was examined.

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“Buckling analysis of carbon nanotube bundles under axial compressive, bending and torsional loadings via a
ABSTRACT: A structural mechanics model is employed for the investigation of the buckling behavior of carbon nanotube bundles of three single-walled carbon nanotubes (SWCNTs) under axial compressive, bending and torsional loadings. The effects of van der Waals (vdW) forces are further modeled using a nonlinear spring element. The effects of different types of boundary conditions are studied for nanotubes with various aspect ratios. The results reveal that bundles comprising longer SWCNTs exhibit lower critical buckling load. Moreover, for the fixed-free boundary condition the rate of critical buckling load reduction is highest, while the lowest critical buckling load occurs. Simulations show good agreement between our model and molecular dynamics results.

References listed at the end of the paper:

ABSTRACT: Buckling of steel thin-walled semi-spherical shells with square cutout due to axial compressive loads has been studied by numerical simulations, and results were compared with those from the experiments. Three vertical compression loadings were applied to specimens using the following methods: a rigid flat plate and a rigid bar with circular and spherical cross sections. The main aim of this study is to determine the influence of the cut-out size-to-location (a/H) and the thickness-to-diameter (t/D) on the mean collapse load of the semi-spherical shells. The finite element models were analyzed using ABAQUS nonlinear buckling analysis and the experimental tests were performed using an INSTRON 8802 servo-hydraulic machine. Finally, the different results obtained using the two analysis methods were compared. The comparison reveals that experimental and numerical nonlinear model results match closely with each other.

ABSTRACT: Numerical analysis of cracked composite cylindrical shells under combined loading is carried out to study the effect of crack size and orientation on the buckling behavior of laminated composite cylindrical
The interaction buckling curves of cracked laminated composite cylinders subject to different combinations of axial compression, torsion, internal pressure and external pressure are obtained, using the finite element method. In general, the internal pressure increases the critical buckling load of the CFRP cylindrical shells while torsion and external pressure decrease it. Numerical analyses show that axial crack has the most detrimental effect on the buckling load of a cylindrical shell while for cylindrical shells under combined external pressure and axial load, the global buckling shape is insensitive to the crack length and crack orientation.

Hamidreza Allahbakhsh and Ali Dadraei (Mechanical Department, Islamic Azad University, Shahrood Branch, Shahrood, Iran), “Buckling Analysis of Laminated Composite Panel with Elliptical Cutout Subject to Axial Compression”, Modelling and Simulation in Engineering, Vol. 2012 (2012), Article ID 171953, 10 pages, doi:10.1155/2012/171953

ABSTRACT: A buckling analysis has been carried out to investigate the response of laminated composite cylindrical panel with an elliptical cutout subject to axial loading. The numerical analysis was performed using the ABAQUS finite-element software. The effect of the location and size of the cutout and also the composite ply angle on the buckling load of laminated composite cylindrical panel is investigated. Finally, simple equations, in the form of a buckling load reduction factor, were presented by using the least square regression method. The results give useful information into designing a laminated composite cylindrical panel, which can be used to improve the load capacity of cylindrical panels.

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15. H. T. Hu and J. S. Yang, _Buckling optimization of laminated cylindrical panels subjected to axial compressive load_, Composite

ABSTRACT: This thesis reports on a series of experimental and finite element modeling studies of sandwich panels typical of wind turbine blade construction. Buckling is a common failure mode in composite structures such as fiberglass wind turbine blades and sandwich construction is often employed in sensitive areas to increase buckling resistance with minimum weight and cost. The panels were flat or curved with fiberglass facesheets and balsa cores. The primary objective of the study was to investigate the accuracy of linear and nonlinear finite element buckling predictions for panels of this type. Modeling procedures used for composite structures like blades often utilize linear eigenbuckling and geometrically nonlinear incremental buckling analyses. Often, the nonlinear model used the linear mode shape to perturb the model and to produce a buckling shape on the perfect geometry. The present study uses the random nodal displacement perturbation method for the nonlinear analysis which is entirely independent of the linear mode shape. The random perturbation method can be used for complicated structures and does not impose a mode shape on the model which may or may not be correct. Both methods, linear and nonlinear, were validated with buckling experiments on idealized blade substructures: curved and flat fiberglass/balsa sandwich shells. Five different series of panels were tested incorporating changes to four parameters: support conditions (simple-free-simple-free and four sided simply supported), radius of curvature (flat, shallow and deep), facesheet lay-up, and core thickness. Good correlation between tests and shell element FE modeling was found for both the linear and nonlinear cases for the critical buckling loads for most models. Good correlation was also found for the early postbuckling response, with late postbuckling strains becoming invalid and deflections being rough approximations after some response shift (mode shift or mesh rippling). Certain combinations of numerical and/or structural parameters were found to present problems to some of the analysis techniques. The combination of curvature and free side edges caused problems for predicting the correct critical buckling mode for both the linear and nonlinear analyses. Deep curvatures and high mesh densities also caused problems predicting the correct mode shape for four sided simply supported panels. Complex boundary conditions tended to compound these problems. Proper modeling of the boundary conditions was found to be critical for accurate results, especially for the curved panels. In this study, this required modeling the load supports of the test fixture. Finally, closed form solutions found in the literature had poor correlation for both critical buckling loads and mode shapes. The random nodal displacement perturbation method was found to have several general characteristics. First, it tended to give conservative
results as compared to the linear models. A statistical study demonstrated relatively consistent results with a standard deviation of 3.7% (down to 2.2% for smooth responses). The random method also tended to exacerbate any problems encountered with all nonlinear models, such as snap-through critical buckling responses, mode shifts to non-symmetric shapes and mesh rippling behavior. Additionally, a model would occasionally pass the critical buckling mode and continue loading until finally buckling into a higher mode shape. These last two problems were a function of the average size of the perturbations (slight for the mode shifts, significant for snap-through and higher buckling modes). Finally, large perturbations would sometimes violate curvature requirements for sandwich modeling due to high local curvatures caused by the random displacements.

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Masuto Tanaka, Development of incompressible hyper-elastic shell elements using assumed strains and their application to buckling analysis of thin-walled tube under bending, Ph.D. dissertation, Science for Open and Environmental Systems, University not given, year not given (2007?)

ABSTRACT: The numerical implementation of nonlinear finite element procedures for flexible thin-walled structures using incompressible hyper-elastic shells is indispensable in the application of practical engineering and medical fields to predict and evaluate the behaviors of rubber-like shell structures and biological soft tissues. The investigation of a flexible thin-walled tube under bending is especially important in various branches of modern technology such as the forming limit of bent pipe, manufacturing of medical tubes, elastomer seals and numerical model for blood vessels. When a long thin-walled tube, such as a hydraulic hose, is subjected to a bending moment, its cross-section becomes distorted. Due to the reduction of the geometrical moment of inertia as its cross-section flattens, the stiffness of the tube decreases with the increase of load. With further moment, the tube collapses with a local kink in its longitudinal direction. The ovalization phenomenon of the cross-section in bending thin-walled tubes was first investigated by Brazier. However, since this work was based on the assumption of infinitesimal strain, his theory could not cope with the kink phenomenon which is shown physically. The pre/post buckling analysis of this kink instability of thin-walled tubes under bending is still an open issue due to its strong nonlinearity. In order to conduct finite element analysis of the above flexible thin-walled tube, not solid elements but shell structure elements which can treat the constitutive law for rubber-like materials allowing large elastic strains are required in view of computational efficiency, modeling effort and accuracy. In recent years, these finite strain shell elements accounting for thickness change have been presented. The elements use additional degrees of freedom for thickness change and three dimensional constitutive relations. However, these additional degrees violate computational efficiency and simplicity of modeling which are primary advantages of shell structure elements, and then derive the complicated formulations. In order to overcome this difficulty, a lot of formulations for the large strain shell elements are still being developed. The objective in this study is to present a new formulation for robust and efficient finite shell elements to investigate the instability problem which shows strong nonlinearity such as buckling analysis of flexible thin-walled tube under bending. Firstly, a high-accurate incompressible hyper-elastic shell element using two dimensional constitutive relations is developed. Then, the performance of the presented shell element is illustrated by its applications to several numerical examples including bending analysis of a thin-walled tube. Finally, the nonlinear mechanism of kink phenomenon of flexible thin-walled tube under bending is clarified.

The composition of this thesis and the contents in each chapter are shown as follows. In chapter 1, the
background and the purpose of the present study are described. In chapter 2, definition of hyper-elasticity and derivation of the constitutive law are summarized as the fundamental review of this study. In chapter 3, a finite strain shell element with its material restricted to hyper-elasticity is developed. This shell element is based on the MITC shell element developed by Bathe to perform locking-free behavior using assumed transverse shear strains. In addition to this MITC formulation, an assumed transverse normal strain is introduced to treat thickness change. In this formulation, the transverse normal strain is assumed to be uniform throughout the element, and evaluated at the middle surface using the incompressibility condition. Indeterminate pressure, which occurs in incompressible materials, is eliminated at the element level using the plane stress condition. The advantage of this technique is that well-conditioned tangent stiffness for a large strain shell element can be obtained without any additional variables. In chapter 4, a numerical implementation of the solid element and shell element with the Ogden material model is presented. This formulation derives the efficient constitutive law of Ogden material using invariants of the right Cauchy-Green tensor in the extension form of the Mooney-Rivlin’s law, without solving eigenvalue problems or coordinate system transformations. This chapter also validates the relationship between the present expression of the constitutive law and numerical stability. In chapter 5, buckling analysis of thin-walled tube under bending is investigated using the present hyper-elastic shell elements. Firstly, in order to compare with Brazier’s solution, the numerical analysis of a Hookean cylindrical tube is conducted using MITC4 shell elements that neglect thickness changes. From the numerical analyses, it is revealed that there are two critical points, a bifurcation point and a limit or turning point that causes the snap-back phenomenon before the limit point that Brazier estimated. The critical point where the bifurcation point coincides with the limit point is called the "hilltop branching point". Symmetrical kinks are observed along the primary path in the final, largely deformed, configuration, while only one kink is observed along the bifurcation path. Then, by using the developed large strain shell elements in which the Ogden material model is utilized, the pre/post buckling behavior of a rubber tube under bending with thickness changes is thoroughly investigated. It is revealed that there is hilltop branching point consisting of one turning point that causes the snap-back phenomenon and two bifurcation points. The results of Ogden material model also shows two symmetrical kinks in the final deformed configuration, which are located on the inside of the tube relative to the results of the Hookean model. In chapter 6, the concluding remarks of this thesis and the future works are given.


ABSTRACT: This thesis presents a series of analytical models, based on the Generalized Beam Theory (GBT), to describe the buckling and post-buckling behaviour of thin-walled prismatic cold-formed steel structural members under compression and/or bending. GBT has a unique feature of enabling an theoretical significance to the structural analysis of these members, which can not be achieved by any other known method. Initially, a review of the current state of the art in GBT is carried out, together with a review on the most recent bibliography of alternative methods for post-buckling analysis of thin-walled structures, allowing to define the specific goal of the present work – the setting up of a consistent GBT-based methodology for post-buckling analysis. Next, a consistent formulation based on the concept of Total Potential Energy in the framework of the classical GBT theory, for post-buckling analysis, was created, enabling the rigorous study of open non-branched and closed mono-cellular sections. Subsequently, a series of refinements in the GBT theory and in the adopted numerical strategies, namely in the Rayleigh-Ritz method and in the bifurcational calculus techniques, were made in order to analyze the perfect structural member, without making resource to imperfections, made by plane plates rigidly connected along the folding lines with a general cross section. Finally, the developments
were illustrated and validated by the resolution of several examples, which were compared to other methods of analysis for the critical behaviour and for the post-buckling equilibrium paths, like the Finite Strip and the Finite Elements Method.

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ABSTRACT: A numerical stability analysis of an axially compressed multilayered composite shell is presented. The authors examine how the stability performance of a panel can be influenced by a centrally located square cut-out. The computations are performed within FEM computer program NX-Nastran (ver. 6.0). The stability is investigated by means of a linearized buckling analysis as well as of a non-linear large deformations incremental analysis. To get more insight into the performance of the layered structure, the failure index according to Tsai–Wu criterion is monitored in the study.

References listed at the end of the paper:
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ABSTRACT: A numerical study of the local buckling and fracture response of a thin composite plate with an inclined crack and subjected to tension is presented. Local buckling of the unsupported edges of the crack occurs due to compressive stresses caused by a Poisson effect in the neighborhood of the crack. The relationship between fracture of a plate with a crack and the local buckling and postbuckling responses of the plate is established through a geometrically nonlinear finite-element analysis in conjunction with concepts from fracture mechanics. The analysis is based on a co-rotational form of the updated Lagrangian formulation that is implemented with a triangular shell element that includes transverse shear deformation effects. The potential energy release rate results are computed for a predetermined radial crack propagation direction that coincides with the location of the maximum stationary strain energy density near the crack tip. The results indicate that the local buckling load increases and the potential energy release rate decreases as the crack orientation changes from a transverse crack to a longitudinal crack aligned with the direction of the applied tension load. The effect of stacking sequence on the local buckling load and on the energy release rate for specific crack orientations is also discussed.


ABSTRACT: A nonlinear boundary-value problem for shells is formulated. The problem statement permits us to analyze the behavior of the postbuckling solutions in a finite-dimensional space with the dimension independent of the discretization technique. A branching pattern is established for the solutions of the problem in the case of a uniform external pressure. Four characteristic types of solution are recognized in the case of an arbitrary external pressure. The associated buckling loads are determined. It is found out that five significant parameters are sufficient for a qualitative analysis of a cylindrical shell.


ABSTRACT: Buckling loads and postbuckling behavior of cylindrical shells subjected to localized external pressure are considered. The modified extended Kantorovich method with path-tracing technique is applied to
determine the buckling loads of the cylindrical shells. It is found that the load is dependent nonmonotonically on geometrical parameters of the area subjected to external pressure. Respective postbuckling shapes show correlation with the shapes corresponding to secondary bifurcation paths for the cases of a cylindrical shell under uniform external pressure and a cylindrical shell under uniform axial load.

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DOI: 10.1016/j.tws.2010.05.004

ABSTRACT: In this article, the buckling of cylindrical shells with longitudinal joint has been investigated through the experimental and numerical analysis. It was clarified that the buckling behavior of cylindrical shells with longitudinal joints under lateral external pressure is not only related to its dimension, but also longitudinal joint and an imperfection. The buckling of cylindrical shells with rigid joint buckles only once and in multi-lobed buckling, whereas one with flexible joints buckles twice and firstly in single-lobed buckling in the vicinity of the joint, secondly in multi-lobed buckling in remaining undeformed area. And the more flexible the longitudinal joint, the lower the critical pressure, with respect to the same dimension of jointed cylindrical shells and
imperfection condition. Moreover the numerical analysis approaches were also presented and verified, by which the imperfection can greatly enlarge the effect of joint on buckling has been demonstrated.

References listed at the end of the paper:


ABSTRACT: The major problems due to welding effects are the residual stresses and distortions of which the levels affect more or less the resistance and lifetime of welded structure. In steel industry and particularly in shipbuilding, during these last few decades, thin plates are used more and more in ship construction in order to lighten the structure weight. Unfortunately, excessive distortions occurred on these thin stiffened panels and straightening works must be executed in respecting the limit tolerance fixed by the Quality Standard of Ship Construction. These futile works reduce Productivity and Quality, increase Construction Cost and get longer Fabrication Delay. Thus, it is necessary to evaluate, control and minimize the distortion and stress levels of thin welded panels before welding assembly operations. In this paper, a short presentation of the Methodology and its industrial applications in shipbuilding are presented for two panels of a Chemical Parcel Tanker (1996) and a large “Testing” Panel in full scale of a Passengers Ship (2002). The numerical results due to welding effects so obtained within short computer-time (three hours and half for a 3D FE model of more than two million of degrees of freedom) on a linear FEM software were verified with measured stress values and identified with the buckling state of the “Testing” Panel before and after welding operations by photographs.

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ABSTRACT: A simplified method to estimate the ultimate strength of a continuous plate, typical in ship bottom plating, subjected to combined transverse thrust and lateral pressure is developed. A series of elastic/elastoplastic large deflection finite element analysis (FEA) of a continuous plate supported along the lines of longitudinal stiffeners and transverse frames is performed. Attention is focused on the effect of a continuity of plating on its buckling and ultimate strengths, while the previous studies are mainly concerned with an isolated plate. Based on the FEA results, a set of formulae has been derived for the estimation of the ultimate strength of a continuous plate under combined transverse thrust and lateral pressure. An increase of elastic buckling strength and a change in the collapse mode from a simply supported mode to a clamped mode
are considered as an effect of a continuity of plating. It has been proven from a comparison with FEA that the proposed formulae give very accurate predictions of the ultimate strength.

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ABSTRACT: A set of design formulae to estimate the ultimate strength of a continuous stiffened panel subjected to combined transverse thrust and lateral pressure is presented, extending the basic idea proposed for a continuous plate in Part-1 study. The effect of plate/stiffener interaction on the elastic buckling strength of local plate panel is introduced in the formulation as well as the effect of continuity of plating. The overall collapse of stiffeners under lateral pressure is included in the possible failure modes. It has been proven from a comparison with FEA results that the proposed formulae give a good prediction of the ultimate strength of a continuous stiffened panel.

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ABSTRACT: The main objective of this paper is to present the results of the finite element method for non-linear analysis of stiffened plates subjected to axial compression load considering post-buckling behaviour up to collapse. For this purpose two series of well executed experimental data on longitudinally stiffened steel plates with and without transversal stiffeners subjected to uniform axial in-plane load carried out to study the buckling and post-buckling up to final failure have been chosen. The first series are those of Ghavami where the influences of stiffener cross-section of the type rectangular (R), L and T, their spacing and the presence of rigid transversal stiffeners have been studied. The second series of Tanaka & Endo, where the behaviour of stiffened plates having three and two flat bars for longitudinal and transversal stiffeners respectively were analysed. For the purpose a well-established commercially available Finite Element program ANSYS has been chosen. The selected element was SHELL43, which can trace the full-range, elastic-plastic behaviour of the stiffened plates. It is seen that the simulated results of FEM are in good consistency with the test results.

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“Ultimate strength and ductility characteristics of intermittently welded stiffened plates under in-plane axial
ABSTRACT: The ultimate strength and ductility characteristics of the intermittently welded stiffened plates under the action of in-plane axial compression are investigated in this paper. A series of detailed numerical analyses of longitudinally stiffened steel plates subjected to in-plane compressive load is performed using the ADINA commercial finite element code. Complete equilibrium paths are traced up to collapse for a nonlinear elastic-plastic response of stiffened plates. Analyzed stiffened plates are imperfect and their aspect ratio, plate slenderness, and column slenderness are changed in a systematic manner. Different types of stiffener are chosen for stiffened plate models. Three different stiffener-to-plate welding procedures are considered: continuous, chain intermittent, and staggered intermittent fillet welding.

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“A comparative study on three different construction methods of stiffened plates—strength behaviour and ductility characteristics”, Revista Escola de Minas, Vol. 60, No. 2, April/June 2007

ABSTRACT: Strength and ductility characteristics of non–continuously welded stiffened plates under in plane axial compression are the main focus of this research. A series of detailed numerical analyses of stiffened steel plates subjected to in plane compressive load is performed. Complete equilibrium paths are traced up to collapse for non–linear elastoplastic response of stiffened plates. Stiffened plates are selected from the deck structure of real sea–going ships and inland waterway vessels. Three different stiffener–to–plate welding procedures are considered: continuous, chain intermittent and staggered intermittent fillet welding. Special attention is paid to the finite element modeling of the fillet welds in either of welding practices. Some available tests are simulated applying finite element method.

References listed at the end of the paper:
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ABSTRACT: Intermittent fillet welding of stiffeners to plates and its influence on the collapse behaviour of stiffened plates is investigated applying the finite element method. Special attention is paid to the modelling of the fillet welds at the plate-to-stiffener junction. Some available experimental results are simulated in order to obtain reliable numerical results. A series of numerical analyses of stiffened steel plates subjected to an in plane axial compressive load has been performed. Stiffened plates are selected from the deck structure of real seagoing ships and inland waterway vessels. Complete equilibrium paths are traced up to collapse for the nonlinear elastoplastic response of stiffened plates. Finally a proposal is presented for the permissible gap of welds in intermittent fillet welding of stiffened plates.

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ABSTRACT: Cracks of any size may occur at various locations and orientations throughout thin-walled structures. The presence of cracks in such structures can considerably affect their load bearing behaviour. This paper addresses a finite element study on the buckling strength of a cracked plate with simple supports subjected to an axial compressive edge load. The effects of crack location, crack orientation, crack length and plate aspect ratio are analysed. The size of the crack as well as its location and orientation are shown to have significant effects on the buckling behaviour of the plate under compressive loading. Some new results are also discussed in detail.

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ABSTRACT: In this paper, the results of an investigation into the post-buckling behaviour of high-strength aluminium alloy stiffened plates subjected to combined axial compression load and different magnitudes of lateral pressure using non-linear finite element approach is presented. Both material and geometric non-linearities have been taken into account. The principal variables studied are the plate thickness, boundary conditions and the stiffener geometries beside the geometrical imperfection, the width of the welding heat-affected zone (HAZ) and welding residual stresses. The influence of these variables on the post-buckling behaviour and ultimate strength of such stiffened plates has been investigated in details.

References listed at the end of the paper:
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ABSTRACT: The main target of this research is to identify the merits and disadvantages of the application of a newly proposed design of stiffened aluminium plates incorporating transverse floating frames, from buckling/ultimate strength points of view. In order to achieve this, an extensive investigation into the buckling and ultimate strength of orthogonally stiffened aluminium plates with different structural arrangements of transverse frames is presented in this paper. The transverse frames are assumed to be either in fixed or floating position. Other combined placements of the transverse frames are also proposed and included in the comparative study. Nonlinear finite element analyses are performed on the models. Average stress–average strain relationships and also stress and deflection contours are obtained from the analyses. Buckling and ultimate strength characteristics of all models are identified and compared to each other. The key findings show that the model with transverse floating frames does not necessarily has the highest buckling strength as is believed in common practice. Also, the mixed or complex pattern of the installation of the transverse frames may lead to the highest ultimate strength.

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ABSTRACT: The present research was undertaken based on the results obtained by the same authors in a sensitivity study on the buckling and ultimate strength of continuous stiffened aluminium plates. Empirical expressions are developed for predicting ultimate compressive strength of welded stiffened aluminium plates used in marine applications under combined in-plane axial compression and different levels of lateral pressure. Existing data of the ultimate compressive strength for stiffened aluminium plates numerically obtained by the authors through the previously performed sensitivity analysis are used for deriving formulations that are expressed as functions of two parameters, namely the plate slenderness ratio and the column (stiffener) slenderness ratio. Regression analysis is used in order to derive the empirical formulations. The formulae implicitly include effects of the weld on initial imperfections, and the heat-affected zone.

ABSTRACT: The paper addresses the problem of the influence of randomly distributed corrosion wastage on the collapse strength and behaviour of unstiffened/stiffened steel plates in longitudinal compression. A series of elastic-plastic large deflection finite element analyses is performed on both-sides randomly corroded steel plates and stiffened plates. The effects of general corrosion are introduced into the finite element models using a novel random thickness surface model. Buckling strength, post-buckling behaviour, ultimate strength and post-ultimate behaviour of the models are investigated as results of both-sides random corrosion.

References listed at the end of the paper:
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ABSTRACT: The main targets of this research are mainly divided in to two parts: (1) identifying the effects of parabolic curvature on the buckling strength and behaviour of stiffened plates under in-plane compression, (2) generating practical graphs for extracting eigenvalue buckling stress of parabolic curved stiffened plate to dimensionless parameters. A parametric model for study of the problem is created. The model includes different parameters related to plate, stiffeners and also parabolic curvature. Three distinct sensitivity cases are assumed. In each sensitivity case, many different models are analysed and their buckling strengths are obtained using a finite element commercial program (ANSYS). Buckling strength and behaviour of all models with different ratios of parabolic curvature are compared to each other.

References listed at the end of the paper:

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“Nonlinear large deflection analysis of stiffened plates”, Chapter 4 in Finite Element Analysis – Applications in Mechanical Engineering, edited by Farzad Ebrahimi, October 2012, DOI: 10.5772/48368

PARTIAL INTRODUCTION: Stiffened plates are basic structural members in marine structures as shown in Figure 1, and include also aeronautic and space shuttles among other structures. Due to the simplicity in their fabrication and high strength-to-weight ratio, stiffened plates are also widely used for construction of land based structures such as box girder and plate girder bridges. The stiffened plate has a number of one-sided stiffeners in either one or both directions, the latter configuration being also called a grillage (Figure 2). Ultimate limit state design of Stiffened plates’ structures requires accurate knowledge about their behaviour when subjected to extreme loading conditions. One of the most important loads applied on stiffened plates is the longitudinal in plane axial compression arising for instance from longitudinal bending of the ship hull girder as presented in Figure 3. The need to improve our knowledge of the buckling modes of such plates was emphasised after the collapse of several offshore structures and some ships in Brazil as well as the failure of several box girder bridges in the seventies of the twentieth century, Merrison Committee [1], Crisfield [2], Murray [3], Frieze, et.al. [4]. Stiffened plates are efficient structures, as a large increment of the strength is created by a small addition of weight in the form of stiffeners. However the collapse mechanisms of stiffened plates under predominantly compressive load present a complex engineering problem due to the large number of possible combinations of plate and stiffener geometry, materials, boundary conditions and loading. The design of such structure has to meet several requirements such as minimization of the weight and maximization of the buckling load. Thus, the designer of this structure is confronted with the problem of satisfying two conflicting objectives; such problems are called multi-objective or vector optimisation problems. In general, the objective-functions do not attain their optimum in a common point of the feasible points, Brosowski & Ghavami [5, 6].

References listed at the end of the paper:

ABSTRACT: The main target of this research is to identify the effects of camber parabolic curvature on the ultimate strength and behavior of stiffened plates under in-plane compression. A parametric model for the study of the problem is created. The model includes different parameters related to plate, stiffeners, and also parabolic camber curvature. Three distinct sensitivity cases are assumed. In each sensitivity case, many different models are analyzed and their ultimate strengths are obtained using an in-house finite element program. Ultimate strength and behavior of the models with different ratios of parabolic curvature are compared to each other and interpreted.


ABSTRACT: The post-buckling behavior of composite ships' stiffened plate panels has been studied. In this study, the average strain-average stress curves for these panels are derived using progressive failure method as well as nonlinear finite element method. The boundary conditions are appropriate for the continuous plate panels used in shipbuilding. The effects of the aspect ratio, initial geometrical imperfection and stiffener size on the post-buckling of these stiffened panels are evaluated.

References listed at the end of the paper:

DOI: 10.1007/978-3-642-48013-3_3
ABSTRACT: Within the last years, a wide variety of complicated geometrically and physically nonlinear shell problems was approximately solved using mainly the Finite Element Method (FEM). Complex engineering structures need large systems of nonlinear equations for incremental load paths. Own investigations, using the SHEBA-element with 63 DOF's /4/, /8/, have shown that the limit capacity even of large and fast scalar computers (in our case a Cyber 76/73 configuration) may be exceeded in the case of critical and postcritical calculations.

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ABSTRACT: The present paper couples the geometrically nonlinear shear deformation theory of thin shell structures [finite rotations; small strains; Başar (1987)] with the Hermitian-method (Collatz 1966; Almannai 1976). It presents a brief review of a nonlinear theory considering shear deformations by means of an operator formulation and the transformation of partial differential equations into algebraic equations by means of appropriate two-dimensional finite-difference operators. The nonlinearity can be treated by an incremental-iterative procedure. Finally the efficiency of the developed numerical method will be demonstrated by selected examples. Special attention is focussed on the convergence behaviour and the reliability of geometrically interpretable forces with respect to engineering applications.

References listed at the end of the paper:


ABSTRACT: This contribution shows the effectiveness and versatility of the corotational formulation in the development of shell finite elements for geometric and material nonlinear analysis of thin structures. In particular, flat triangular elements especially suited to shell structures made of shape memory alloys (SMA) or soft biological tissues are dealt with.
References listed at the end of the paper:
(Cannot easily cut and paste)

Carlos M. Tiago (1) and Paulo M. Pimenta (2)
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“On the nonlinear analysis of thin shells by the generalized moving-least squares approximation”, 8th. World Congress on Computational Mechanics (WCCM8); 5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008); June 30 –July 5, 2008 Venice, Italy
ABSTRACT: In the present contribution a geometrically exact thin shells formulation is presented. An analysis procedure based on a meshfree approximation is outlined. As no restrictions are imposed on the rotational fields, the present formulation falls on the category of the geometrically exact structural theories. The derivation is made by imposing the kinematic hypothesis on the three-dimensional continuum. Contrary to previously presented works [1,2], where shear deformation was accounted, here only the bending deformation is included. We define energetically conjugated cross sectional stresses and strains based on the first Piola-Kirchhoff stress tensor and the deformation gradient, respectively. The complete linearization of the weak form is presented. For hyperelastic materials and conservative loadings the tangent bilinear form, i. e., the generalized stiffness matrix, is always symmetric even in points far from the generalized equilibrium positions. Initially curved shells are regarded as a stress-free deformed state from a chosen plane reference configuration [3]. The mapping between both configurations allows the exact consideration of the initial configuration. As the variational basis of the formulation requires the use of C1 approximations, the generation of compatible of finite elements is not trivial in the present case. In order to circumvent this inconvenience, meshless approximations are used. The first-order Generalized Moving-Least Squares Approximation has been successfully used in the solution of thin plate bending problems [4,5,6]. Although it increases the number of degrees-of-freedom per node, its performance is clearly superior to the conventional Moving-Least Squares Approximation in this specific class of problems. As
the approximation does not possess the Kronecker-delta property, the imposition of the essential boundary conditions is not immediate. These are enforced using a hybrid-displacement version of the shell formulation. To this end, the steps indicated in [7] are followed. This thin shell formulation has the basic advantage over their shear-deformable counterpart: no special devices have to be taking into account in order to avoid shear-locking.

References listed at the end of the paper:


ABSTRACT: This work presents a fully nonlinear Kirchhoff-Love shell model. In contrast with shear flexible models, our approach is based on the Kirchhoff-Love theory for thin shells, so that transversal shear deformation is not accounted for. We define energetically conjugated cross-sectional generalized stresses and strains. The fact that both the first Piola-Kirchhoff stress tensor and the deformation gradient appear as primary variables is also appealing. The weak form of the equilibrium equations and their boundary conditions of the model are consistently derived. Elastic constitutive equations are obtained from fully three-dimensional finite strain constitutive models in a consistent way. A genuine plane-stress condition is enforced by the vanishing of the mid-surface normal nominal stress (first Piola-Kirchhoff stress), yet rendering a symmetric linearized weak form. A plane reference configuration is assumed for the shell mid-surface, but, initially curved shells can be accomplished, if one regards the initial configuration as a stress-free deformed state from the plane position. As a consequence, the use of convective non-Cartesian coordinate systems is not necessary and only components on orthogonal frames are employed.

References listed at the end of the paper:
- P.M. Pimenta. Geometrically-Exact Analysis of Initially Curved Rods. In Advances in Computational Techniques for Structural
ABSTRACT: The current work discusses the application of the TUBA finite elements [1,2], initially developed for thin plates problems, to geometrically exact thin shell analysis. The proposed geometrically exact shell model is derived from the 3D continuum mechanics. The shell kinematics is based on the Kirchhoff-Love assumption and is characterized by the deformation gradient, which yielded the generalized cross-section strain measures — stretches and curvatures, written in terms of first- and second-order derivatives of displacements [3]. As the energetically conjugate quantity, the first Piola-Kirchhoff stress tensor is chosen. The shell’s initial geometry is exactly represented using a mapping from a reference configuration. A neo-Hookean material functional, supplemented by the plane stress condition, is incorporated in the constitutive level of the model. The theory is derived independently from the specific numerical method to be used, thus allowing any available approximation of C1 type to be used for the implementation. Special attention is given to the treatment of the natural and essential boundary conditions. The TUBA family of plate finite elements is considered for the discretization of the displacement vector field. These triangular elements, with necessarily straight sides in the reference configuration, provide C1 continuous approximations, mandatory for the proper implementation of the Kirchhoff-Love model. The family contains 3 pairs of elements (primary and reduced), which provide polynomial approximants of degrees k = 5, 6 and 7 respectively. The reduced elements have a simpler structure and a smaller number of nodes, but still guaranty C1 continuity [4]. The boundary normal derivative of the approximation in these elements is constrained, such that its order is reduced by one unit, from (k − 1), as for the primary elements, to (k − 2). Due to complexity of the elements degrees of freedom (which are the function value, its first- and second-order derivatives), the imposition of the essential boundary conditions is not trivial and needs some preliminary analysis of the boundary behavior. The proposed model is assessed by means of numerical nonlinear shells problems examples.

References listed at the end of the paper:
Paulo M. Pimenta, “Fully nonlinear Kirchhoff-Love shells: Theory and numeric with C1 finite elements”, April 2014 seminar given at Gottfried Wilhelm Leibniz Universität Hannover, Germany

ABSTRACT: The current work discusses the application of the TUBA finite elements, initially developed for linear thin plates problems, to geometrically exact thin shell analysis. The proposed geometrically exact shell model is derived from the 3D continuum mechanics. The shell kinematics is based on the Kirchhoff-Love assumption and is characterized by the deformation gradient, which yielded the generalized cross-section strain measures — stretches and curvatures, written in terms of first- and second-order derivatives of displacements. As the energetically conjugate quantity, the first Piola-Kirchhoff stress tensor is chosen. The shell’s initial geometry is exactly represented using a mapping from a reference configuration. A neo-Hookean material functional, supplemented by the plane stress condition, is incorporated in the constitutive level of the model. The theory is derived independently from the specific numerical method to be used, thus allowing any available approximation of C1 type to be used for the implementation. Special attention is given to the treatment of the natural and essential boundary conditions. The TUBA family of plate finite elements is considered for the discretization of the displacement vector field. These triangular elements, with necessarily straight sides in the reference configuration, provide C1 continuous approximations, mandatory for the proper implementation of the Kirchhoff-Love model. The family contains 3 pairs of elements (primary and reduced), which provide polynomial approximants of degrees k = 5, 6 and 7 respectively. The reduced elements have a simpler structure and a smaller number of nodes, but still keep C1 continuity. The boundary normal derivative of the approximation in these elements is constrained, such that its order is reduced by one unit, from (k − 1) to (k − 2). Due to complexity of the elements degrees of freedom (which are the function value, its first- and second-order derivatives), the imposition of the essential boundary conditions is not trivial and needs some preliminary analysis of the boundary behavior. The proposed model is assessed by means of numerical nonlinear shells problems examples.

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ABSTRACT: Nowadays aluminum stiffened plates are one of the major constituents of the marine structures, especially high-speed vessels. On one hand, these structures are subject to various forms of loading in the harsh sea environment, like hydrostatic lateral pressures and in-plane compression. On the other hand, fusion welding is often used to assemble those panels. The common marine aluminum alloys in the both 5,000 and 6,000 series, however, lose a remarkable portion of their load carrying capacity due to welding. This paper presents the results of sophisticated finite-element investigations considering both geometrical and mechanical imperfections. The tested models were those proposed by the ultimate strength committee of 15th ISSC. The presented data illuminates the effects of welding on the strength of aluminum plates under above-mentioned load conditions.

References listed at the end of the paper:
39(10), pp.861-885.


ABSTRACT: This paper presents the results of an extensive sensitivity analysis carried out by the Committee III.1 “Ultimate Strength” of ISSC’2003 in the framework of a benchmark on the ultimate strength of aluminium stiffened panels.

Previously, different benchmarks were presented by ISSC committees on ultimate strength. The goal has typically been to give guidance to the designer on how to predict the ultimate strength and to indicate what level of accuracy would be expected. This time, the target of this benchmark is to present reliable finite element models to study the behaviour of axially compressed stiffened aluminium panels (including extruded profiles). Main objectives are to compare codes/models and to perform quantitative sensitivity analysis of the ultimate strength of a welded aluminium panel on various parameters (typically the heat-affected zone). Two phases were planned. In Phase A, all members analysed the same structure with a defined set of parameters and using different codes. It was expected that all the codes/models predict the same results. In Phase B, to boost the scope of the analysis, the different members (using their own model) performed FE analyses for a range of variation of different parameters (sensitivity analysis).
ABSTRACT: Results are presented of compression tests on two large-scale longitudinally stiffened GRP panels representing ships’ deck structures. Two distinct types of collapse are demonstrated, one involving debonding of stiffeners precipitated by local, interframe buckling of the laminate and the other resulting from outer-fibre failure of the stiffeners caused by overall column-like buckling. Test results are correlated with theoretical analysis, including estimates of initial buckling stress using accurate folded plate analysis together with evaluation of large-displacement postbuckling behaviour using non-linear finite element analysis. Recommendations are made regarding design procedure and safety factors.

References listed at the end of the paper:


ABSTRACT: Recent advancement in manufacturing technology has initiated a new phase of buckling structures analysis and structural design research development. As the ability to manufacture stiffeners in complex shapes has become increasingly more sophisticated, researchers are able to further enhance the design of thin-walled stiffeners. This paper presents an attempt to discover a structural design which employs the use of sub-stiffeners and the ability to retain maximal buckling load. FEM analysis was performed on compression loaded rectangular stiffened panels clamped on all sides to determine optimal attributes of two panel concepts: (1) stiffeners height changes according to sinusoidal law across the panel width, (2) stiffeners area changes according to sinusoidal law across the panel width. In both cases, total volume of the material was held constant. Non-dimensional parameters of the optimal panels were obtained. It was found that there was a positive correlation between the amount of change in buckling patterns caused by a sub-stiffener, and the amount of initial buckling load which could be obtained.

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ABSTRACT: This work describes the theoretical modal analysis model for the stiffened bottom plate of a tank that is filled with fluid having an undisturbed free surface. In the analysis model, the effects of bending, transverse shear and rotary inertia in both the plate and the stiffener are considered. Analytical results concerning the natural frequencies of the stiffened plate correlate well with experimental modal testing (EMT) results for above the second mode. To overcome the complexities in the modal analysis of the fluid–structure interaction, the Mindlin plate theory and the potential flow theory are applied; the velocity potential is also expressed using double finite Fourier transforms. Additionally, a parametric study was also performed for eigenfrequencies of the plate with a stiffener, in terms of the ratio of the depth of the stiffener to the thickness of the plate and that of the width of the stiffener to the thickness of the plate. Analysis results revealed the phenomenon of “mode reversal”, i.e. the first and second mode shapes of the plate with a deep stiffener in contact with air and water, respectively, are reversed. An occurring condition of “mode reversal” is derived and verified by both finite element analysis and EMT.

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ABSTRACT: An investigation of the deformation and buckling characteristics of a composite, oblate bulkhead that has an inverted geometry and is subjected to pressure-only loading is presented for three bulkhead geometries and thicknesses. The effects of a stiffening support ring at the bulkhead to cylinder interface are also evaluated. Buckling analyses conducted using the axisymmetric shell code BOSOR4 are discussed for several bulkhead configurations. These results are analytically verified using results from the Structural Analysis of General Shells (STAGS) code for a selected bulkhead configuration. The buckling characterization of an inverted, oblate bulkhead requires careful attention as small changes in bulkhead parameters can have a significant effect on the critical buckling load. Comparison of BOSOR4 and STAGS results provided a very good correlation between the two analysis methods. In addition, the analysis code BOSOR4 was found to be an efficient sizing tool that is useful during the preliminary design stage of a practical shell structure. Together, these two aspects should give the design engineer confidence in sizing these stability critical structures. Additional characterization is warranted, especially for a composite tank structure, since only one bulkhead configuration was examined closely.

References listed at the end of the paper:

ABSTRACT: A great deal of attention has been focused on plates subjected to shear loading over the past decades. One main fact in design of such elements, which fall in the category of thin-walled structures, is their buckling behavior. Plate girders and recently shear walls are being widely used by structural engineers, as well as ship and aircraft designers. The role of stiffeners is proved to be vital in design of such structures to minimize their weight and cost. In this work, by using ANSYS finite element method of analysis, some 1200 plates are analyzed in order to study the role of stiffeners and to come up with some limits for an optimized design procedure. This eigenvalue method of analysis is first validated with the theoretical calculations and known cases for a wide range of typical panel geometries. The results show that the number of panels produced by
intermediate transverse stiffeners should not be less than the value of plate's aspect ratio. In other words, the transverse stiffeners should divide the length of the plate to portions equal or less than its width. It is also shown that the optimum geometric properties of the stiffeners correspond to the point when the buckling shape of a plate changes from the overall mode to local mode. Furthermore, all stiffened plates, with a similar aspect ratio and number of stiffeners, have a specific value of EI/aD, for which the critical shear stress is optimal. In addition, some expressions to predict these properties are presented.

ABSTRACT: It is generally accepted that cracks degrade the load bearing capacity of thin plates. The aim of the present paper is to investigate the influence of central cracks on the residual strength and stiffness degradation of shear panels using numerical finite element analysis. Various geometrical and mechanical characteristics of cracked panels such as the crack length, crack angle of inclination, panel aspect ratio, slenderness of panel, boundary conditions, Poisson's ratio, and Young's modulus are considered in the analyses. It is shown that the length and the angle of cracks may change the buckling behaviour of shear panels, and their combinational effects can result in substantial degradation.

ABSTRACT: Utilizing shear panels is a common practice in civil, naval and aerospace engineering structures and the performance of the one with thin steel plate shear walls is an interesting issue of ongoing related researches. It is a well-recognized phenomenon that the behaviour, and consequently the design procedure, of shear panels are mostly dominated by pre-yield buckling occurrence. However the existence of crack defects due to corrosion, fatigue, welding or mishandling may shed more complexities to such panels in terms of bearing capacity degradation. In this paper, a procedure for modelling and analysis of shear panels containing central or edge cracks, using the finite element method, is presented. Results can be incorporated to recognize the required mesh refinements around the crack tips and edges. In addition, the effect of relative crack length on buckling capacity of shear panels is investigated.

ABSTRACT: A perturbation method for determining the buckling strength of imperfection-sensitive structures is presented. The method is based on an extended system which was first used by Seydel in computation of limit points of nonlinear systems. The effects of various possible sources of structural imperfections on perfect structures with simple buckling loads are investigated by the method. The derivations and results of the present exposition are equally applicable to discrete and continuous systems. In the finite element implementation of the
new formulation, the perturbation expansions are determined by solving numerically several linear problems with a single positive-definite sub-stiffness matrix. The method is illustrated with its application to the analyses of imperfection-sensitivity of a simply supported column on a linear-elastic foundation subjected to axial compression.


ABSTRACT: A finite element asymptotic analysis for determining the lower bound dynamic buckling estimates of imperfection-sensitive structures under step load of infinite duration is presented. The lower bound dynamic buckling loads and the corresponding displacements are sought in the form of asymptotic expansions based on the static stability criterion and they can be determined by solving numerically (FEM) several linear problems with a single nonsingular sub-stiffness matrix.

References listed at the end of the paper:


ABSTRACT: This paper is concerned with the direct calculation of buckling strength of an imperfect structure. The main assumptions are that, for the perfect structure, there is a symmetric or a linear fundamental path and the corresponding first critical point is a simple symmetry-breaking or a simple bifurcation point. An extended system of limit points is proposed for which the newly introduced scaling parameters are regular solution and thus standard methods can be used to compute them. Using the extended system, one can directly obtain the exact buckling loads without tracing the postbuckling paths. An efficient implementation of Newton’s method solving the extended system is presented and numerical examples are given.

Baisheng Wu, Yongping Yu and Zhengguang Li (Department of Mechanics and Engineering Science, School of Mathematics, Jilin University, Changchun 130012, PR China), “Analytical approximations to large post-buckling deformation of elastic rings under uniform hydrostatic pressure”, International Journal of Mechanical
ABSTRACT: This paper presents analytical approximations to large post-buckling deformation of a circular, elastic, and inextensional ring under uniform hydrostatic pressure. By combining the Newton's method with the method of harmonic balance, we establish analytical approximations to large deformation of the ring. Unlike the classical method of harmonic balance, the linearization is performed prior to proceeding with harmonic balancing thus resulting in a set of linear algebraic equations instead of one of non-linear algebraic equations. We are hence able to establish analytical approximate solutions. These approximate solutions show excellent agreement with the exact solution, and are valid for small as well as large difference of the curvatures of the undeformed and the deformed ring.

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ABSTRACT: Many structural applications require nonlinear finite element analyses in order to assess response and capacity. Plastic deformations may be accounted for by means of thickness integration or stress resultants. The stress resultant model employed herein is based on Ilyushin’s linear yield criterion for thin shells. The corners present with this criterion are circumvented by means of a simplification, hence, there is no need for multi-surface stress resultant updates. A backward Euler difference is employed in the stress resultant update, and a consistent tangent is used in the Newton–Raphson iterations on the global equilibrium. Limit points are traversed by means of an orthogonal trajectory method. The response of compression dominated shells with imperfections typically corresponds to limit point behaviour. For stress resultant plasticity, the nonlinear transition from initial yield to full plasticity in shell bending is missed. Hence, the efficiency obtained by eliminating thickness integration is countered by some inaccuracy in the response simulation. This is investigated by means of comparison with finite element simulations employing integration through thickness (with linear or nonlinear hardening). Both steel and aluminium alloys are considered. In collapse response of slender structures, the straining of the material may be moderate, but the motion may be governed by large rigid body translations and rotations. A way of accounting for this by means of the co-rotated approach is presented. Triangular high-performance facet shell elements are employed. By example computations, the importance of nonlinear geometry contributions is illustrated.


(cannot cut and past the abstract)


PARTIAL INTRODUCTION: In the designing of plates and shells, especially in calculations of their stability, it is of particular importance to take into account their geometrically nonlinear behavior. The most widely used
Method of stress analysis of structures is the finite element method. However, the literature has not dealt adequately with shells of anisotropic composite materials in geometrically nonlinear statements: the finite elements are usually constructed by proceeding from an actual theory of shells [1,2], and this does not provide the possibility of endowing them with a universally valid nature. This problem can be solved with the so-called degenerate finite elements of shells: finite element discretization is applied to three-dimensional equations of equilibrium in which the magnitudes are expressed in accordance with the adopted hypotheses through the magnitudes on the surface of the reference shells corresponding to them. In the present work we generalize the above-mentioned type of element [3,4] in relation to the calculation of anisotropic composite shells in geometrically nonlinear statement…

(abstract not given)

References listed at the end of the paper:

ABSTRACT: The post-buckling behaviour of composite cylindrical panels in axial compression is investigated using the nonlinear finite element theory. A branch-switching algorithm with an ‘eigenmode injection’ is discussed. The effect of the reinforcement angle on the buckling load, as well as the post-buckling behaviour of the panels, are analysed. Examples are considered for separated and closely spaced bifurcation points. By varying the reinforcement angle of the panels from 0 to 90°, two kinds of buckling modes are discovered for asymmetric and unstable symmetric lowest points of bifurcation. Local minima for the secondary branches of geometrically perfect panels are no less than 15% of their buckling loads, while values of the buckling loads alter more than twice in this region. A 16-node degenerated shell element with full integration scheme is used.

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ABSTRACT: In this paper, we explore the capabilities of some nonlinear strategies based on domain decomposition for nonlinear analyses, and more particularly for post-buckling analyses of large slender structures. After having recalled the classical Newton–Krylov–Schur methods, chosen here to serve as a reference, we propose two versions specifically developed to treat nonlinear phenomena at the most relevant scale through nonlinear localizations per substructure. All these different strategies lead to solving similar condensed problems on which we apply classical Domain Decomposition Methods. Performances are discussed and comparative results in terms of convergence are presented in the case of beam frames with large rotations and local buckling.

ABSTRACT: This paper investigates a computational strategy for studying the interactions between multiple through-the-width delaminations and global or local buckling in composite laminates taking into account possible contact between the delaminated surfaces. To achieve an accurate prediction of the quasi-static response, a very refined discretization of the structure is required, leading to the resolution of very large and highly nonlinear numerical problems. In this paper, a nonlinear finite element formulation along with a parallel iterative scheme based on a multiscale domain decomposition is used for the computation of three-dimensional mesoscale models. Previous works by the authors already dealt with the simulation of multiscale delamination assuming small perturbations. This paper presents the formulation used to include geometric nonlinearities into this existing multiscale framework and discusses the adaptations that need to be made to the iterative process to
ensure the rapid convergence and the scalability of the method in the presence of buckling and delamination. These various adaptations are illustrated by simulations involving large numbers of DOFs.


ABSTRACT: Buckling failure is quite a common occurrence in plates under compression, in particular when the plate’s thickness is sufficiently small with respect to others plates’ sizes; such a mode of crisis can often precede strength failure. Buckling failure under tension loading can also be a practical occurrence, especially in cracked plates in which it often takes place as a local buckling phenomenon, due to compression stresses transverse to the loading direction which develop around such imperfections. The aim of the present paper is to analyse the buckling phenomena of variously cracked rectangular elastic thin plates under tension or compression, by considering the effects of various geometrical, mechanical and boundary characteristics of the problem. A short explanation of the buckling phenomena in plates is recalled and several numerical parametric analyses are performed, employing the finite element method, in order to determine the critical load multiplier, in compression or in tension, by varying some of the problem’s geometrical and mechanical parameters. In particular, the buckling critical load multiplier is determined for different crack lengths, crack orientations and material Poisson coefficients and by varying the plate’s boundary conditions. Furthermore, some cracked configurations are analysed by means of a fully geometrical non-linear analysis, with contact between crack faces taken into account, in an effort to understand the effective whole structural behaviour also beyond the critical load. The results obtained are summarised graphically in figures and some interesting and useful conclusions are drawn on the sensitivity to the above-mentioned parameters to the buckling failure of variously restrained cracked compressed or tensioned plates.

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ABSTRACT: In this paper, a general theory on the asymptotic field near the crack tip for plates and shells with and without shear deformation effect is established. It is found that four stress intensity factors, two for symmetrical and antisymmetrical stretching and two for symmetrical and antisymmetrical bending, are required to describe arbitrary asymptotic fields near the crack tip for plates without shear deformation. An additional stress intensity factor is required for the transverse shearing force induced by antisymmetrical bending when the shear deformation is included in the analysis. It is also proven by means of the complex variable technique that for problems of plates with shear deformation, there exist similarities in the asymptotic expressions of moments and membrane forces and also in the asymptotic expressions of in-plane displacements and rotations of the mid-surface. The energy release rate associated with crack growth in the direction of the crack line can be expressed in terms of stress intensity factors by means of Irwin's method of work and energy associated with a virtual crack extension. A combined stress intensity factor can be defined through the total energy release rate. The
theory of the fracture of plates is generalized and applied to the study of problems in the fracture of shells. An example of an infinitely long cylindrical shell with a circumferential crack subjected to remote axial tension is given to demonstrate the application of the theory and to test the accuracy of the numerical analysis used for the problem.

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ABSTRACT: In this paper, the problem of the fracture of a fuselage stiffened by longitudinal longerons and circumferential frames is analyzed by means of the finite element method. Our research is motivated by the fail-safety design concept of fuselage for civil aircraft. In this study, the total energy release rate are evaluated for five types of basic loading, namely, axial extension, pure bending, twisting, transverse shearing, and radial expansion due to internal pressure. The crack is located either at the mid-point or near the end of the fuselage. It extends in two bays with the stiffener at its center. The stiffener which bisects the crack is assumed to be broken at the location of the crack. Computational results indicate that the total energy release rate $G_t$ increases with the increasing crack length. However, when the crack tip approaches the stiffener, the value of $G_t$ decreases as a result of the reinforcement from the stiffener. For a crack near the end of the fuselage, as a result of boundary effect, the value of $G_t$ is larger in comparison with the case of the crack at the mid-point of the fuselage. We also find that the effect of geometrical nonlinearity can reduce the value of $G_t$ for the fuselage under axial tension or pure bending. For the fractured fuselage under pure bending, shell buckling can occur at the concave side of the fuselage prior to crack growth. The maximum tensile stress in the stiffener in front of the crack tip is also investigated.


ABSTRACT: The present paper investigates the formulation of 3D co-rotational beam elements for the buckling and post-buckling analysis of frame structures. Following Pacoste and Eriksson [Comput. Methods Appl. Mech. Engrg. 144 (1997) 163], the term co-rotational relates here to the provision of a local reference frame that continuously rotates and translates with the element. Within this context, several issues are emphasised. The first one refers to the parameterisation of finite 3D rotations. The alternative put forth in the paper is based on the spatial form of the incremental rotational vector. The second issue concerns warping effects which are introduced by adding a seventh degree of freedom at each node. Different types of local formulations are considered and it is shown that at least some degree of non-linearity must be introduced in the local strain definition in order to obtain correct results for certain classes of problems. Within the present approach the centroid and shear center of the cross-section are not necessarily coincident. Finally, in the context of instability problems, a method for the direct computation of critical points is also briefly discussed. This is based on a minimal augmentation procedure as developed by Eriksson [Comput. Methods Appl. Mech. Engrg.
Ten examples, including large displacement and stability problems, are used in order to assess the performances of the elements.

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doi: 10.1002/cnm.710  
ABSTRACT: In the context of corotational triangular shell elements, the objective of this paper is to show that for certain stability problems it is interesting to choose a local element frame invariant to the element node ordering. Two methods of obtaining such a local frame are presented. These two methods, already proposed by other authors, are reformulated. For the first one, based on the minimisation of local nodal displacements, it is shown that the iterative process can be avoided.

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doi:10.1016/j.cma.2006.01.007  
ABSTRACT: The corotational formulation for triangular thin shell elements presented in [A. Eriksson, C. Pacoste, Element formulation and numerical techniques for stability problems in shells, Comput. Methods Appl. Mech. Engrg. 191 (2002) 3775–3810] is further developed in order to incorporate elasto-plastic deformations. Several local formulations are implemented and tested. These local elements are geometrically linear and are obtained by the by superposition of a membrane and a plate part. Eleven elastic and elasto-plastic examples are presented. Both the incremental and deformation theories of plasticity are considered. The first objective is to assess the performance of the present formulation in modelling elasto-plastic instability problems. The second objective is to compare the different linear local formulations: it is shown that some of them give better results in instability problems.

doi:10.1016/j.cma.2006.10.006  
ABSTRACT: The corotational framework for triangular shell elements has been presented by different authors (see the Introduction). The purpose of this paper is to introduce three modifications in this approach. The first one is a simplified definition of the local rotations. The second one is a reduction of the number of local degrees of freedom from 18 to 15. The third and principal one concerns the parameterisation of the global finite rotations. A new approach based on Euler parameters (quaternion) is proposed. In particular, it is shown that only three parameters are required. The purpose of these three modifications is to obtain a formulation which gives the same numerical results but which is computationally more efficient than the original one. This aspect
is illustrated in several numerical examples.

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ABSTRACT: The present work deals with a numerical–experimental investigation into the post-buckling behavior of two demonstrators representative of the bottom skin panel of an unpressurized aircraft fuselage: one represents an undamaged reference structure, the other includes debonding and impact damage. Tests have been developed for static compression loading up to the ultimate load. The recorded data from five transducers and one strain gauge have been utilized to obtain numerical–experimental correlation. Numerical analyses have been developed using two available commercial codes and by different modeling approaches and analytical procedures. Further results have been obtained and compared with each other and with experimental evidence in order to assess the capability and feasibility of numerical predictions in the post-buckling field.

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ABSTRACT: A non-linear 9-node stress resultant shell finite element with six degrees of freedom per node is formulated. The material non-linearity is based on an implicit integration scheme using the von Mises yield criterion and linear isotropic hardening. The small strain geometric non-linearity is formulated using the polar decomposition theorem of continuum mechanics via a corotational updated Lagrangian method, which represents finite rotations with accuracy. Reduced integration is used to remove locking and calculate the stresses at their optimal stress accuracy points. A practical procedure is employed to stabilize the troublesome spurious zero energy modes. A number of tests covering the non-linear material and geometry ranges and buckling show the good performance of the new element.

ABSTRACT: In this paper, the stability of carbon fiber reinforced plastics (CFRP) cylinders under axial compression was studied by the finite element analysis method. According to the Riks method, compressive capacity of the composite structures was investigated by nonlinear analysis, in which the eigen buckling modes were considered in the form of initial defects. And the post-buckling performances of different structures were also compared.

A. Murphy (1), M. Price (1), C. Lynch (2) and A. Gibson (1)
ABSTRACT: Fuselage panels are commonly fabricated as skin-stringer constructions, which are permitted to locally buckle under normal flight loads. The current analysis methodologies used to determine the post-buckling response behaviour of stiffened panels relies on applying simplifying assumptions with semi-empirical/empirical data. Using the Finite Element method and employing non-linear material and geometric analysis procedures it is possible to model the post-buckling behaviour of stiffened panels without having to place the same emphases on simplifying assumptions or empirical data. Previous work has demonstrated that using a commercial implicit code, the Finite Element method can be used successfully to model the post-buckling behaviour of flat riveted panels subjected to uniform axial compression. This paper expands the compression modelling procedures to flat riveted panels subjected to uniform shear loading, investigating element, mesh, idealisation and material modelling selection, with results validated against mechanical tests. The work has generated a series of guidelines for the non-linear computational analysis of flat riveted panels subjected to uniform shear loading, highlighting subtle but important differences between shear and compression modelling requirements.

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Reliability Based Buckling Analysis of Composite Panels22 April 2004, Palm Springs, California

ABSTRACT: New skin alloys are being developed that are both damage tolerant and strong in compression. At the same time, stiffener alloys are still getting stronger. Stiffened panel designs need to be optimized in new ways to fully benefit from these new material properties. FEA has shown that, provided the joint between skin and stiffeners is good and stringers are strong enough, the overall efficiency of a stiffened panel with large attach flanges is greater than that of a panel which has very high quadratic section moment. Stringer pitches can thus be kept at economic levels while panel buckling performance is increased by the use of new higher strength, high damage tolerance skin and the next generation of high strength stiffeners. The tangent modulus curves of the new materials mentioned are generally steeper than those of current materials. The present analyses have demonstrated that because the strain in a post-buckled stiffened panel is far from uniform, this does not present any particular risks with respect to sudden loss of stiffness of the panel.

References listed at the end of the paper:

Mustafa Özakça (1), Adrian Murphy (2), Sjoerd van der Veen (3)
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“Buckling And Post-Buckling Of Sub-Stiffened Or Locally Tailored Aluminium Panels”, ICAS 2006, 25th
International Congress Of The Aeronautical Sciences

ABSTRACT: Today's high-strength and damage tolerant materials permit significant increases in working- and limit stresses. In order to fully exploit these stress increases as weight savings on aircraft, it is important to improve the buckling stability of stiffened panels. The (post-)buckling performance of panels with sub-stiffening or local tailoring of the skin thickness (“skin sculpting”) was investigated using linear variable thickness finite strip analysis, (non-linear) finite element analysis and experiments on stiffened panels. Four different slender, high post-buckling ratio aluminium panels were crushed, revealing gains in post-buckling collapse loads of more than 10%. Gains in initial skin buckling were over 15%, accompanied by a gain in post-buckling stiffness. Non-linear FEA helped to understand the behaviour of these panels and select the most promising designs. Linear finite strip analysis allowed optimisation of one of these, revealing a potential for further improvement of the initial buckling load by over 10%. Design rules for sub-stiffened panels were derived. Using these design rules, the concept of sub-stiffening was successfully transposed to more optimised, stockier sections, and non-linear FEA was used to predict the associated gains in post-buckling performance. In spite of extensive plasticity, the gain was still of the order of 10% on the post-buckling collapse load, with good post-buckling stiffness. The better understanding of the behaviour of locally tailored structures led to the evaluation of two other new concepts for stiffened panels: one with gradually increasing skin thickness toward the pad-ups under stiffeners (“sculpted skins”) and one with curved sub-stiffening patterns, resulting in skins with varying stiffness in both of the in-plane directions. For the sculpted skins, variable thickness finite strip optimisation was used to obtain insight into the importance of different design variables, and derive a method for sizing. Non-linear FEA of an application of this concept to realistic, optimised aircraft panels loaded in slight bi-compression confirmed initial buckling gains of up to 30% and predicted post-buckling performance gains of the order of 10%. For the variable stiffness sub-stiffening, a numerical experiment was designed in order to study linear eigenmodes of various configurations. The potential improvement in buckling performance over unstiffened plates of equal weight was as high as 450%. More relevantly, the effect of variable stiffness sub-stiffening was estimated over two times higher than that of orthogonal sub-stiffening.

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Engineering Sciences Data Unit (ESDU) Structures series
Koiter W.T., Pignataro M., 1976, A general theory for the interaction between local and overall buckling of stiffened panels, Delft University report 556 WTHD 83

P. Coudor (1), S. Van der Veen (2) and A. Beakou (1)
ABSTRACT: Recent advances in aeronautics and material science allow for a significant increase in load capacity; consequently, structural parts are more stressed than in the past. In most cases, stresses and strains cannot be determined accurately enough using conventional closed form engineering formulae. Therefore, even if much more time-consuming, finite element analysis is used. Because of a high ratio between panel length and adhesive thickness, models need a large number of elements. Thus, computing time can be very long. The aim of this paper is to present a global-local approach to reduce this time. First, a global shell elements model is developed. Second, a local solid elements model is generated from the displacement obtained in the global model. Finally, global-local FEA enables greater precision.

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[3] Sjoerd van der Veen, Adrian Murphy, Rinze Benedictus. Post-buckling failure of welded aluminium panels.

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ABSTRACT: To increase the structural efficiency of integrally machined aluminium alloy stiffened panels, it is plausible to introduce plate sub-stiffening to increase the local stability and thus panel static strength performance. Reported herein is the experimental validation of prismatic sub-stiffening, and the computational verification of such concepts within larger recurring structure. The experimental work demonstrates the potential to ‘control’ plate buckling modes. For the tested sub-stiffening design, an initial plate buckling performance gain of +89% over an equivalent mass design was measured. The numerical simulations, modelling the tested sub-stiffening design, demonstrate equivalent behaviour and performance gains (+66%) within larger structures consisting of recurring panels.

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ABSTRACT: Previous work has demonstrated the potential to introduce plate element sub-stiffening to increase the local stability and thus static strength performance of integrally machined aluminium alloy stiffened panels. The introduction of plate element prismatic sub-stiffening modifies local plate buckling behaviour and within realistic design constraints, may produce sizable performance gains with equivalent mass designs. This article examines through experimental and computational analysis the potential of non-prismatic sub-stiffening for tailoring local plate stability performance. Using non-prismatic sub-stiffening, the experimental work demonstrates potential initial buckling performance gains with equivalent mass designs (+185%), and computationally, potential mass savings with equivalent static strength performance designs (–9.4%).


ABSTRACT: This paper was to verify the STAGS (general shell, geometric and material nonlinear) code and the critical crack-tip-opening angle (CTOA) fracture criterion for predicting stable tearing in cracked panels that fail with severe out-of-plane buckling. Materials considered ranged from brittle to ductile behavior. Test data used in this study are reported elsewhere. The STAGS code was used to model stable tearing using a critical CTOA value that was determined from a cracked panel that was “restrained” from buckling. The analysis methodology was then used to predict the influence of buckling on stable tearing and failure loads. Parameters like crack-length to-specimen-width ratio, crack configuration, thickness, and material tensile properties had a significant influence on the buckling behavior of cracked thin-sheet materials. Experimental and predicted results showed a varied buckling response for different crack-length-to-sheet-thickness ratios because different buckling modes were activated. Effects of material tensile properties and fracture toughness on buckling response were presented. The STAGS code and the CTOA fracture criterion were able to predict the influence of buckling on stable tearing behavior and failure loads on a variety of materials and crack configurations.

References listed at the end of the report:
ABSTRACT:
This paper presents the fracture analyses conducted on the FAA/NASA stiffened and unstiffened panels using the STAGS (STructural Analysis of General Shells) code with the critical crack-tip-opening angle (CTOA) fracture criterion. The STAGS code with the “plane-strain” core option was used in all analyses. Previous analyses of wide, flat panels have shown that the high-constraint conditions around a crack front, like plane strain, has to be modeled in order for the critical CTOA fracture criterion to predict wide panel failures from small laboratory tests. In the present study, the critical CTOA value was determined from a wide(unstiffened)panelwithanti-bucklingguides. Theplane-straincoresizewasestimatedfromprevious fracture analyses and was equal to about the sheet thickness. Rivet flexibility and stiffener failure was based on methods and criteria, like that currently used in industry. STAGS and the CTOA criterion were used to predict load-against-crack extension for the wide panels with a single crack and multiple-site damage cracking at many adjacent rivet holes. Analyses were able to predict stable crack growth and residual strength within a few...
percent (5%) of stiffened panel tests results but over predicted the buckling failure load on an unstiffened panel with a single crack by 10%.

References listed at the end of the paper:
fracture criterion to characterize the fracture behavior and a material and a geometric nonlinear finite element shell analysis code to perform the structural analyses. The present paper presents the results of a study to evaluate the fracture behavior of 2024-T3 aluminum alloys with thickness of 0.04 inches to 0.09 inches. The critical CTOA and the corresponding plane strain core height necessary to simulate through-the-thickness effects at the crack tip in an otherwise plane stress analysis, were determined from small laboratory specimens. Using these parameters, the CTOA fracture criterion was used to predict the behavior of middle crack tension specimens that were up to 40 inches wide, flat panels with riveted stiffeners and multiple-site damage cracks, 18-inch-diameter pressurized cylinders, and full scale curved stiffened panels subjected to internal pressure and mechanical loads.

References listed at the end of the paper:

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ABSTRACT: This paper presents the results of residual strength analyses on stiffened and unstiffened panels using the STStrucural Analysis of General Shells (STAGS) finite-element shell code and the critical crack-tip-
opening angle (CTOA) fracture criterion. Previous analyses of wide, flat panels have shown that high-constraint conditions around a crack front must be modeled in order for the critical CTOA fracture criterion to predict wide panel failures from small laboratory tests. Thus, the STAGS code with the _plane-strain _core option was used in all analyses. In the present study, the critical CTOA (\_c\_c) value and the plane-strain core height were determined from a fit to the experimental load-against-crack-extension results from a series of middle-crack tension specimens (76 _1016 mm wide) tested with anti-buckling guides. In the residual strength analyses of the 305-mm wide stiffened panels with a single crack, modeling of the sheet, stiffeners, rivet flexibility and buckling were based on methods and criteria, like that currently used in industry. STAGS and the CTOA criterion were used to predict load-against-crack extension for the single stiffened panels for both intact and cut stiffeners. Analyses were able to predict stable crack growth and residual strength of the single stiffened panels within about ±5% of the test failure loads.

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ABSTRACT: This paper highlights the results from fracture analyses conducted on the FAA/NASA wide panels (with and without stiffeners) using structural analysis of general shells code and the critical crack-tip-opening angle (CTOA) fracture criterion. The critical CTOA and plane-strain core height values, calibrated from a fit to the experimental load-against-crack-extension results from a series of unstiffened panels (76–1016 mm wide) tests with anti-buckling guides (Part I of this paper), were used in the analyses of wide stiffened and unstiffened panels. As discussed in Part I of this paper, high constraint around the crack front like plane strain has been accounted for by using the “plane-strain core” option in all analyses. By accounting for high constraint around crack front, it was possible for the critical CTOA fracture criterion to predict wide panel failures from small laboratory tests. As followed in Part I of this paper, rivet flexibility and stiffener failures in the analyses of wide panels were based on methods and criteria like that currently used in the industry. Analyses were able to predict stable crack growth and residual strength of both stiffened and unstiffened panels with various amounts of multiple-site damage within ±10% of the test results. Finally, it has been demonstrated that, it is possible to predict the residual strength of wide stiffened and unstiffened panels with critical CTOA calibrated from small laboratory coupons.


ABSTRACT: The results of residual strength pressure tests and nonlinear analyses of stringer- and frame-stiffened aluminum fuselage panels with longitudinal cracks are presented. Two types of damage are considered: a longitudinal crack located midway between stringers, and a longitudinal crack adjacent to a stringer and along a row of fasteners in a lap joint that has multiple-site damage (MSD). In both cases, the longitudinal crack is centered on a severed frame. The panels are subjected to internal pressure plus axial tension loads. The axial tension loads are equivalent to a bulkhead pressure load. Nonlinear elastic-plastic residual strength analyses of the fuselage panels are conducted using a finite element program and the crack-tip-opening-angle (CTOA) fracture criterion. Predicted crack growth and residual strength results from nonlinear
analyses of the stiffened fuselage panels are compared with experimental measurements and observations. Both the test and analysis results indicate that the presence of MSD affects crack growth stability and reduces the residual strength of stiffened fuselage shells with long cracks.

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References listed at the end of the paper: numerical examples are given to illustrate performance of the decomposition of the strains and the other an additive decomposition of the deformation gradient. Several possibilities for implementing this model within the framework of the finite element method are examined: one stretching, which allows for large deformations and direct use of 3d constitutive equations. Three different possibilities for implementing this model within the framework of the finite element method are examined: one leading to 7 nodal parameters and the remaining two to 6 nodal parameters. The 7-parameter shell model with no simplification of kinematic terms is compared to the 7-parameter shell model which exploits usual simplifications of the Green–Lagrange strains. Two different ways of implementing the incompatible mode method for reducing the number of parameters to 6 are presented. One implementation uses an additive decomposition of the strains and the other an additive decomposition of the deformation gradient. Several numerical examples are given to illustrate performance of the shell elements developed herein.

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ABSTRACT: We discuss a theoretical formulation of shell model accounting for through-the-thickness stretching, which allows for large deformations and direct use of 3d constitutive equations. Three different possibilities for implementing this model within the framework of the finite element method are examined: one leading to 7 nodal parameters and the remaining two to 6 nodal parameters. The 7-parameter shell model with no simplification of kinematic terms is compared to the 7-parameter shell model which exploits usual simplifications of the Green–Lagrange strains. Two different ways of implementing the incompatible mode method for reducing the number of parameters to 6 are presented. One implementation uses an additive decomposition of the strains and the other an additive decomposition of the deformation gradient. Several numerical examples are given to illustrate performance of the shell elements developed herein.

References listed at the end of the paper:
ABSTRACT: In this work we study the time-stepping schemes for shell models, which describe the shell-director vector motion by the finite rotations. Different possibilities for choosing director rotations are examined and their relationships are cast in terms of the commutative diagram. The Newmark time-stepping schemes, making use of different rotation parameters, are then developed. The mid-point scheme modified to either conserve or dissipate the total energy is further examined. Several numerical simulations are presented to illustrate the performance of each developed scheme.

References listed at the end of the paper:


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Brian: Hello, how can I assist you today?
ABSTRACT: In the context of the geometrically nonlinear analysis of structures by continuation methods, a technique for the determination of the imperfection sensitivity is carried out. The technique is based on Galerkin's reduction of equilibrium equations in the subspace of extrapolation branches emanating from the bifurcation points. The pre- and post-critical behaviour in the neighbourhood of bifurcation points, however, is well approximated provided that extrapolations have a large convergence domain. To this end an efficient asymptotic representation of the primary and secondary equilibrium paths and procedures that overcome the ill-conditioning of the systems defined in the critical points is used here.


ABSTRACT: A finite element method is presented for the transient analysis of large-displacement, small-strain problems with material non-linearities. The method employs a convected coordinate technique and a direct nodal force computational scheme of considerable efficiency. Detailed formulations are given for a plane, constant strain triangular element and a Euler-Bernoulli beam element. Results are presented for several example problems and compared with experimental data and other numerical solutions.

S. Lopez and K. Russo (Dipartimento di Modellistica per l’Ingegneria Universit`a della Calabria 87030 Rende, Cosenza, Italy), “Statical and dynamical structural analysis by a kinematical description of the small strains involving finite rotations”, Laboratorio di Meccanica Computazionale Rapporto Interno, Report n. 52, November 2008

ABSTRACT: A geometrically nonlinear formulation to analyse structures in the hypotheses of large displacements and rotations and small strains is presented. In this formulation, applied to low-order elements and based on the total Lagrangian kinematics, the use of the rotation matrices is bypassed. A selective based definition of the strain tensor, used in order to avoid shear-locking problems, is effected by the linear definition of deformations because it is element reference system independent. In addition, complex manipulations required to obtain conservative descriptions and well-posed transformation matrices are avoided. Numerical tests have been carried out to evaluate the validity of the developed technique both in the statical and in the dynamical context.

References listed at the end of the report:

1973; 7; 255-271.


ABSTRACT: A geometrically nonlinear formulation to analyse structures in the hypotheses of large displacements and rotations and small strains is presented. In this formulation, applied to low-order elements and based on the total Lagrangian kinematics, the use of the rotation matrices is bypassed. A selective based definition of the strain tensor, used in order to avoid shear-locking problems, is effected by the linear definition of deformations because it is element reference system independent. In addition, complex manipulations required to obtain conservative descriptions and well-posed transformation matrices are avoided. Numerical tests have been carried out to validate the developed technique both in the statical and in the dynamical context.

ABSTRACT: Both analytical and finite element investigations are performed for the various static and dynamic aspects of the mode jumping phenomenon of a simply-supported rectangular plate heated deeply into the post-buckling regime. For the analytical method, the von Kármán plate equation is reduced to a system of non-linear ODEs by expressing the transverse deflection as a series of linear buckling modes. The ODEs, combined with the non-linear algebraic constraint equations obtained from in-plane boundary conditions, are then solved numerically under the parametric variation of the temperature. The results are checked by the finite element method, where a hybrid static–dynamic scheme is implemented. The contribution of each assumed (buckling) mode component is studied systematically. Characterized by the strong geometrical non-linearity, the secondary bifurcation point of the thermally loaded plate with fixed in-plane boundary conditions occurs far beyond the primary buckling point, and the jump behavior cannot be predicted correctly without sufficient assumed modes. Stationary bifurcation analysis indicates that while the post-buckling deflection before mode jumping is composed of pure symmetric modes, additional pure antisymmetric modes will appear after the occurrence of the snapping and they play the role of destabilizing the equilibrium. Furthermore, by monitoring natural frequencies and modal shapes, we find that a mode shifting phenomenon (the exchanging of vibration modes) exists in the primary post-buckling regime. Breaking of the symmetry of the dynamic modes is also found. By introducing a linear temperature sweeping scheme, transient analysis is performed to capture the snapping phenomenon dynamically, which occurs with moderate heating ratio. Comparison between the analytic and finite element results shows good agreement.


ABSTRACT: Various static and dynamic aspects of post-buckled thin plates, including the transition of buckled patterns, post-buckling dynamics, secondary bifurcation, and dynamic snapping (mode jumping phenomenon), are investigated systematically using asymptotical and non-stationary finite element methods. In part I, the secondary dynamic instability and the local post-secondary buckling behavior of thin rectangular plates under generalized (mechanical and thermal) loading is investigated using an asymptotic numerical method which combines Koiter’s nonlinear instability theory with the finite element technique. A dynamic multi-mode reduction method—similar to its static single-mode counterpart: Liapunov–Schmidt reduction—is developed in this perturbation approach. Post-secondary buckling equilibrium branches are obtained by solving the reduced low-dimensional parametric equations and their stability properties are determined directly by checking the eigenvalues of the resulting Jacobian matrix. Typical post-secondary buckling forms—transcritical, supercritical and subcritical bifurcations are observed according to different combinations of boundary conditions and load types. Geometric imperfection analysis shows that not only the secondary bifurcation load but also changes in the fundamental post-secondary buckling behavior are affected. The post-buckling dynamics and the global analysis of mode jumping of the plates are addressed in part II.

Hui Chen and Lawrence N. Virgin (Department of Mechanical Engineering, Pratt School of Engineering, Duke University, Durham, NC 27708-0300, USA), “Finite element analysis of post-buckling dynamics in plates. Part

ABSTRACT: With the secondary bifurcation and the local post-secondary buckling behavior being analyzed in Part I, Part II of this study consists of developing an adaptive non-stationary load sweeping algorithm to investigate post-buckling dynamics and mode jumping phenomena of generally (mechanically and thermally) loaded thin plates in a global context. The non-stationary sweeping procedure has the merits of adapting large load steps to capture static characteristics of stable equilibrium paths both before and after mode jumping and reduce automatically the step size to ensure a dynamic transition between the two stable branches. Thus, it is computationally effective. Furthermore, by adopting the non-stationary sweeping scheme, this procedure can avoid spurious convergence of the transient response to an unstable equilibrium. Corresponding to different post-secondary bifurcation forms, which are determined using asymptotical finite element analysis developed in Part I, subsequent buckling patterns of various complexity occurring after mode jumping are obtained using the method developed in this article. Qualitative changes in post-buckled patterns are observed after the occurrence of the secondary bifurcation or the mode jumping. Free vibration analysis using the tangent stiffness matrix obtained from the converged static or dynamic solutions shows a vibration modal shifting phenomena occurs during the process of the load sweep. The spurious convergence phenomenon caused by the application of the traditional hybrid static–dynamic method is found and explained.


ABSTRACT: An analytic method is presented in this paper to study the postbuckling and mode jumping behavior of bi-axially compressed composite laminates. The governing partial differential equations (PDEs) are derived rigorously from an asymptotically correct, geometrically non-linear theory. A novel and relatively simpler solution approach is developed to solve the two coupled fourth-order PDEs, namely, the compatibility equation and the dynamic governing equation. The generalized Galerkin method is used to solve boundary value problems corresponding to antisymmetric angle-ply and cross-ply composite plates, respectively. The variety of possible modal interactions is expressed in an explicit and concise form by transforming the coupled non-linear governing equations into a system of non-linear ordinary differential equations (ODEs). The comparison between the present method and the finite element analysis (FEA) shows a pretty good match in their numerical results in the primary postbuckling region. While the FEA may lose its convergence when solution comes close to the secondary bifurcation point, the analytic approach has the capability of exploring deeply into the post-secondary buckling realm and capture the mode jumping phenomenon for various combinations of plate configurations and in-plane boundary conditions. Free vibration along the stable primary postbuckling and the jumped equilibrium paths are also studied.


ABSTRACT: In this chapter the optimal design of laminated composite structures is considered. A review of the literature is proposed. It aims at giving a general overview of the problems that a designer must face when he works with laminated composite structures and the specific solutions that have been derived. Based on it and
on the industrial needs an optimization method specially devoted to composite structures is developed and presented. The related solution procedure is general and reliable. It is based on fiber orientations and ply thicknesses as design variables. It is used daily in a European industrial context for the design of composite aircraft box structures located in the wings, the center wing box, and the vertical and horizontal tail planes. This approach is based on sequential convex programming and consists in replacing the original optimization problem by a sequence of approximated sub problems. A very general and self adaptive approximation scheme is used. It can consider the particular structure of the mechanical responses of composites, which can be of a different nature when both fiber orientations and ply thicknesses are design variables. Several numerical applications illustrate the efficiency of the proposed approach.

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“Buckling optimization of composite stiffened panels: some important issues”, 2nd International Conference on Engineering Optimization, September 6 - 9, 2010, Lisbon, Portugal

ABSTRACT: In this paper, the buckling optimization of thin-walled stiffened composite panels is studied. Some important issues are recalled, and an efficient solution procedure is discussed. It is shown how to properly represent the buckling behavior with the finite element method. Several approximations of the Sequential Convex Programming method (SCP) are compared on an industrial test case consisting in the optimization of a curved stiffened composite panel submitted to compression and shear.

References listed at the end of the paper:


Fernanda Mariana Nunes Ravetti and Sérgio Frascino Müller de Almeida, “Post buckling of composite panels subjected to thermal residual stresses”, MSC Software Presentation Number 2007-21, 2007

ABSTRACT: Composite material structures are completely stress free during curing or consolidating process, under high temperatures that vary between 120 deg. C and 400 deg. C. After this process, temperature decreases and material starts to get stiffer. As material physical properties are different in transverse and longitudinal direction, thermal residual stresses appear due to this difference, mainly because of thermal expansion coefficient. Thermal residual stresses effects can be null if the structure is a uniform (not stiffened) square plan panel symmetrically laminated, without external constraints. However, if the panel is reinforced or not symmetrically laminated, the resultant stresses can be not null and affect the panel mechanical behavior. This research studies post-buckling behavior of graphite-epoxy reinforced panels under compression in the presence of thermal residual stresses, considering two different stringer types and three different stringer widths. According to the results found, thermal residual stresses can affect the panel mechanical behavior - depending
on type and width of the stringers - increasing stiffness and changing buckling modes, mainly for smaller loads and wider stringers.


ABSTRACT: A fully 3D failure model to predict damage in composite structures subjected to multiaxial loading is presented in this paper. The formulation incorporates shear nonlinearities effects, irreversible strains, damage and strain rate effects by using a viscoplastic damageable constitutive law. The proposed formulation enables the prediction of failure initiation and failure propagation by combining stress-based, damage mechanics and fracture mechanics approaches within an unified energy based context. An objectivity algorithm has been embedded into the formulation to avoid problems associated with strain localization and mesh dependence. The proposed model has been implemented into ABAQUS/Explicit FE code within brick elements as a userdefined material model. Numerical predictions for standard uniaxial tests at element and coupon levels are presented and discussed.

References listed at the end of the paper:

ABSTRACT: A technique for enhancement of buckling loads of composite plates is proposed. The technique relies on using stress stiffening to create a non-zero tensile force acting along the plate plane which ultimately permits the application of higher external compressive forces that lead to traditional buckling instabilities. The idea is to completely restrain the plate movements in its plane direction, at all edges, and to apply voltages to pairs of symmetrically bonded piezoelectric patches. This voltage is applied such that the piezoelectric patches contract resulting in a uniform tensile force over the plate plane.

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M. Shariyat. Dynamic buckling of imperfect laminated plates with piezoelectric sensors and actuators subjected to thermo-electro-mechanical loadings, considering the temperature-dependency of the material properties. Composite Structures, 88(2):228-239, 2009


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ABSTRACT: An axisymmetric finite element that can model rubber-like hyper-elastic material has been employed to study post-critical response in the inflation of axisymmetric membranes. An extensive parametric study has been performed to investigate the non-linear response of a tube under internal pressure. The issue of combined proportional and non-proportional loading in the context of incremental-iterative solution is discussed. Further, a robust bracketing procedure, useful to compute clustered bifurcation points, is proposed. Finally, the eigen-mode injection method is used to branch into the post-critical paths. Contrary to previous findings, the Newton-Raphson method worked satisfactorily in all the cases tested.

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PARTIAL ABSTRACT: A non-conforming three-node triangular finite element with 18 degrees of freedom is used in conjunction with the Kirchhoff theory for the non-linear analysis of thin composite plate-shell structures. The formulation of the geometrically non-linear analysis is based on an updated Lagrangian formulation associated with the Newton-Raphson iterative technique, which incorporates an automatic arc-length control procedure….

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ABSTRACT: This paper deals with buckling and free vibrations of multilaminated structures of arbitrary geometry and lay-up using a single layer higher order shear deformation theory discrete model. This model is based on an eight-node C0 serendipity finite element with 10 degrees of freedom per node to contemplate general applications. The present model is tested on the evaluation of buckling loads and free vibrations of multilaminated plates and shells. The effects of different number of layers, lamination angles, material anisotropy, and length or radius to thickness ratios are studied.


ABSTRACT: This paper presents a discrete model for the design sensitivity analysis of thin laminated angle-
ply composite structures using a plate shell element based on a Kirchhoff discrete theory for the bending effects. To overcome the nondifferentiability of multiple eigenvalues, which may occur during a structural optimization involving free vibrations or buckling design situations, a nonsmooth eigenvalue based criterion is implemented. Angle-ply design variables and vectorial distances from the laminated middle surface to the upper surface of each layer are considered as design variables. The design sensitivities and the directional derivatives are evaluated analytically. The efficiency and accuracy of the model developed is discussed with two illustrative cases which show the need to compute sensitivities of multiple eigenvalues as directional derivatives for laminated composite structures.

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ABSTRACT: This paper presents a discrete model for the buckling sensitivity analysis of thin multi-layered angle-ply composite structures. The model is based on a simple and efficient plate-shell element with 18 d.f. using the discrete Kirchhoff theory for the bending effects. Angle-ply design variables and vectorial distances from the middle surface to the upper surface of each layer, indirectly the thickness of each layer, are considered as design variables. The objective of the design is the maximization of the constrained or unconstrained buckling load parameter. The optimization process can be carried out using a two-level approach. The design sensitivities are evaluated analytically, quasi-analytically and by global finite difference. The efficiency and accuracy of the model developed is discussed with reference to several applications.

ABSTRACT: Shell buckling under circumferential strain loading appears often in many biomedical problems, such as collapse of asthmatic airways, esophagus etc. Currently there is no analytic solution from which the critical buckling load can be calculated from the geometrical and material properties of the shell layers. The theoretical analysis leads to the numerical solution of a generalized eigenvalue problem. The purpose of the present paper is to present a method with which the sensitivity of the buckling load (minimum positive eigenvalue) to uncertainties of the geometrical and material parameters can be calculated. It is shown that the sensitivity can be evaluated with the aid of the left (adjoint) eigenvectors. The proposed method is validated against separate global computations using the finite difference method. Finally, we employ the information on sensitivity to optimize the thickness of the outer shell layer in order to maximize the buckling load.

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ABSTRACT: A high order shear deformation theory is used to develop a discrete model for the sensitivity
analysis and optimization of laminated plate and shell structures in non-linear response. The geometrically non-linear analysis is based on an updated Lagrangian formulation associated with the Newton–Raphson iterative technique, which incorporates an automatic arc-length procedure. Fiber orientation angles and vectorial distances from middle surface to the upper surface of each layer are considered as the design variables. Different objectives, such as generalized displacements at specified nodes, volume of structural material, and limit load, and constraints of displacement and stress failure criterion are considered. The design sensitivities are evaluated analytically and are compared with sensitivities evaluated by the global finite difference. Numerical examples are given to show the accuracy of the proposed model in the non-linear response and the corresponding design sensitivity analysis, and to show the applicability in the optimal design.

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ABSTRACT: In this paper is presented a numerical method for the structural analysis of laminated conical shell panels using a quadrilateral isoparametric finite element based on the higher order shear deformation theory. The displacement expressions used for the longitudinal and circumferential components of the displacement field are given by power series of the transversal coordinate and the condition of zero stresses in the top and bottom surfaces of the shell is imposed. The shape functions used for the transversal displacement are C1 conforming and the finite element is a conical/cylindrical panel with 8 nodes and 40 degrees of freedom. The model presented performs static analysis with arbitrary boundary conditions and loads, as well eigenvalue problems (free vibration and buckling). Illustrative examples are presented and discussed.

References listed at the end of the paper:

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ABSTRACT: A general semi-analytical finite element model is developed for bending, free vibration and buckling analysis of shells of revolution made of laminated orthotropic elastic material. The 3D elasticity theory is used and the equations of motion are obtained by expanding the displacement field and load in the Fourier series in terms of the circumferential coordinate, \( \Pi \). The coefficients of the expansion are functions of \((r,z)\), and are approximated using the finite element method. This leads to a semi-analytical finite element in the \((r, z)\) plane. The element is validated by comparing the present results with the analytical and numerical solutions available in the literature.

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ABSTRACT: This paper presents the development of a semi-analytical axisymmetric shell finite element model with piezoelectric layers using the 3D linear elasticity theory. The piezoelectric effect of the material could be used as sensors and/or actuators in way to control shell deformation. In the present 3D axisymmetric model, the equations of motion are expressed by expanding the displacement field using Fourier series in the circumferential direction. Thus, the 3D elasticity equations of motion are reduced to 2D equations involving circumferential harmonics. In the finite element formulation the dependent variables, electric potential and loading are expanded in truncated Fourier series. Special emphasis is given to the coupling between symmetric and anti-symmetric terms for laminated materials with piezoelectric rings. Numerical results obtained with the present model are found to be in good agreement with other finite element solutions.

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ABSTRACT: This paper addresses the bending and free vibrations of multilayered cylindrical shells with piezoelectric properties using a semi-analytical axisymmetric shell finite element model with piezoelectric layers using the 3D linear elasticity theory. In the present 3D axisymmetric model, the equations of motion are expressed by expanding the displacement field using Fourier series in the circumferential direction. Thus, the 3D elasticity equations of motion are reduced to 2D equations involving circumferential harmonics. In the finite element formulation the dependent variables, electric potential and loading are expanded in truncated Fourier series. Special emphasis is given to the coupling between symmetric and anti-symmetric terms for laminated materials with piezoelectric rings. Numerical results obtained with the present model are found to be in good agreement with other finite element solutions.

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ABSTRACT: In the present work, a study of thermoelastic analysis of functionally graded cylindrical shells subjected to transient thermal shock loading is carried out. A semi-analytical axisymmetric finite element model using the three-dimensional linear elasticity theory is developed. The three-dimensional equations of motion are reduced to two-dimensional ones by expanding the displacement field in Fourier series in the circumferential direction involving circumferential harmonics. The material properties are graded in the thickness direction according to a power law. The model has been verified with the results of simple analytical isotropic cylindrical shells subjected to a transient thermal loading. Additional FGM results for stresses and displacements are presented.

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ABSTRACT: In the present work, a study of free vibrations of functionally graded cylindrical shells made up of isotropic properties is carried out. A semi-analytical axisymmetric finite element model using the 3D linear elastic theory is developed. The 3D equations of motion are reduced to 2D by expanding the displacement field in Fourier series in the circumferential direction involving circumferential harmonics. The material properties are graded in the thickness direction according to a power law. The model has been verified with simple benchmark problems and the results show that the frequency characteristics are found to be close to published results of isotropic cylindrical shells. New results are included for FGM shells.
**ABSTRACT:** This paper focuses on the development of the partitioned solution method (PSM) for analyzing the stability behavior of doubly-curved shallow orthotropic panels under external pressure, covering both the buckling and postbuckling responses. Adjacent equilibrium method (AEM) is used to verify the developed PSM method and the associated stability results. The equilibrium and compatibility equations are derived using Donnell-type thin shell theory, with the Airy stress function and the out-of-plane displacement as unknowns. Based on AEM and PSM, both an eigenvalue problem and non-linear algebraic equations are obtained which are used as the basis for the stability criteria, respectively. Results obtained from those two methods are presented and compared with each other for a few arbitrary sets of system parameters, wherein no postbuckling solutions are presented with AEM. The influence of the boundary conditions on the stability behavior is also investigated using the PSM.

**ABSTRACT:** The focus of this paper is on the investigation of the mathematical nature of buckling from the point of view of bifurcation theory. For the doubly curved orthotropic panels subjected to quasi-static uniform load and with hinged boundary conditions, the solution to the non-linear partial differential equation is partitioned into two parts and projected onto the complete space spanned by the eigenfunctions of the linear operator of the governing equation. Furthermore, the fundamental branch, from which a new solution will emanate, is approximated by the first single mode pair which is close to the real membrane state. Whereas the ensuing bifurcated branch is approximated by the other single mode pair, under the assumption that the coupling between modes can be neglected. The present analysis could give a deep insight into the mechanism of the instability of panel structures, and show that there exists a mode transition at the critical point and the snap-through, then results from saddle-node bifurcation on the bifurcated branch. As a conclusion, the buckling of the system studied can be stated as: a bifurcated branch emanates from the fundamental branch at a critical point, and a saddle-node bifurcation, behaving as jumping, then occurs on the ensuing bifurcated branch.

**ABSTRACT:** In the frame of the geometrically nonlinear theory of thin elastic shells with moderate rotations a
set of consistent equations for the nonlinear stability analysis is derived by application of energy criteria. Some methods of functional analysis are used which enable to prove the symmetry of the stability equations and to calculate bifurcation buckling from linear and nonlinear equilibrium branches and also snap-through buckling loads by variational approximating procedures.

References listed at the end of the paper:


ABSTRACT: In this paper the non-linear stability and post-buckling analysis of elastic structures is considered in the frame of a geometrically non-linear shell theory with moderate rotations. Using a total Lagrangian description variational statements as well as associated sets of shell equations including boundary conditions are derived to determine the fundamental equilibrium path, critical points of snap-through or bifurcation buckling and also the post-buckling deformations. To present these equations in a compact form a unified operator description is introduced. It also allows one to prove some important properties, which are needed to construct appropriate approximation procedures like finite element methods. A shell example is calculated numerically by using a simple Rayleigh-Ritz approximation. It is shown that for a two-parameter loading the collection of critical snap-through buckling points is a catastrophe of the ‘cusp’ type.


ABSTRACT: In the first part of this paper a Lagrangean nonlinear theory of thin elastic shells for unrestricted rotations is considered, where the boundary conditions are non-rational functions of the shell deformations. Using energy considerations the equations of critical equilibrium are derived, which define the general eigenvalue problem of shell buckling. Furthermore post-buckling equations are obtained by application of the static perturbation technique. If the rotations of the shell elements can be restricted to be moderate, essential simplifications in the prebuckling, buckling and post-buckling equations are achieved, which is shown in the second part.

References listed at the end of the paper:


ABSTRACT: A nonlinear shell theory is derived for large strain—large bending deformations of shells composed of highly nonlinear materials. Expressions for the stress resultants and stress couples are presented. The equilibrium equations are obtained as weak solution of the stationary principle of total potential energy. A modified Kirchhoff hypothesis is used which accounts for thickness changes as well as for a shift in the location of the original midsurface of the shell. As example the eversion of a spherical shell is calculated numerically.

References listed at the end of the paper:

ABSTRACT: For the geometrically nonlinear first approximation theory of elastic shells three energy-consistent large rotation shell variants are constructed. The governing shell equations are derived as Euler-Lagrange equations of an associated variational principle of stationary total potential energy. The numerical applicability is considered for a highly nonlinear shell problem. To incorporate the presented theories into the frame of shell models published in the literature a comparative analysis is carried out for a large number of shell equations.

References listed at the end of the paper:

ABSTRACT: A new theory is presented for shells of revolution undergoing axisymmetric arbitrarily large strain deformations. The material of the shell is assumed to be hyperelastic incompressible. The formulated theory is applied to analyse the flexural buckling of circular plates under uniform radial loads.

References listed at the end of the paper:


ABSTRACT: A rigorous theory of small deformation superimposed on finite deformation is developed within a fully general theory of elastic shells. The mathematical structure of the configuration space and its associated tangent space is examined for the underlying shell model. Essential features of the theory are examined in the context of applications to the buckling analysis of specific problems.

ABSTRACT: The paper is concerned with the nonlinear theory and finite element analysis of shell structures with an arbitrary geometry, loading and boundary conditions. A complete set of shell field equations and side conditions (boundary and jump conditions) is derived from the basic laws of continuum mechanics. The developed shell theory includes the so-called drilling couples as well as the drilling rotation. It is shown that this property is crucial in the analysis of irregular shell structures, such as those containing folds, branches, column supports, stiffeners, etc. The relevant variational principles with relaxed regularity requirements are also presented. These principles provide the mathematical basis for the formulation of various classes of shell finite elements. The developed finite elements include a displacement/rotation based Lagrange family, a stress resultant based mixed and a semi-mixed family as well as so-called assumed strain elements. All elements have six degrees of freedom at each node, three translational and three rotational ones, including the drilling rotation formulated on the foundation of an exact (in defined sense) shell theory. As such, they are equally applicable to smooth as well as to irregular shell structures. The general applicability of the developed elements is illustrated through an extensive numerical analysis of the representative test examples. In order to obtain a still deeper insight into the problem a Lagrange family of standard degenerated shell elements with five degrees of freedom per node and an element with six degrees of freedom per node based on the von Kármán plate theory are considered as well. The presented numerical results include complex plate and doubly-curved shell structures. Linear and non-linear solutions with a pre- and post-buckling analysis are discussed.

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ABSTRACT: The effect of buckling on stress distribution in the crack tip vicinity is explored. The computed stress state reveals that the buckling leads to a weaker crack tip singularity than the one of linear elastic fracture mechanics. The change of the singularity has been studied in this work by post-buckling analysis using FE method. The weaker singularity has been taken into account in a modified fracture mechanical theory. The implications for fracture mechanical predictions are discussed.

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ABSTRACT: his paper discusses different types of implicit time integration algorithms for the dynamics of spatial beams. The algorithms are based on a form of co-rotational technique which is external to the element.
Both end-point and mid-point formulations are presented. The latter can be considered as an `approximately energy conserving algorithm'. A new method is described for introducing numerical damping. Finally some numerical examples are presented in order to illustrate the differences in performance of the different integration schemes.


ABSTRACT: The simplest facet-shell formulation involves the combination of the constant-strain membrane triangle with a constant-curvature bending triangle. The paper describes a technique whereby this facet-formulation is extended to handle geometric non-linearity by means of a co-rotational procedure. Emphasis is placed on the derivation of a technique that is increment-independent with both the internal force vector and tangent stiffness matrix being derived from the 'total strain measures' in a 'consistent manner'. Numerical examples are presented which demonstrate an excellent numerical performance.


ABSTRACT: The main theme of the paper is the development of a simple but efficient facet element for the non-linear analysis of shells. A sub-theme involves the development of an efficient ‘resultant approach’ for dealing with plasticity. Finally, the paper considers some recent developments in relation to path-following for problems involving instabilities or ‘near instabilities’.

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ABSTRACT: The paper describes a unified framework for applying the co-rotational method to the analysis of solids, shells and beams. The general method stems from an unusual application of the technique which involves solid elements. The proposed framework allows a formulation that is simpler than many of the earlier procedures and, in addition, gives a direct indication of the terms in the tangent stiffness which may be ignored.

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ABSTRACT: A new procedure is proposed for implicit dynamic analysis using the finite element method. The main aim is to give stable solutions with large time-steps in the presence of significant rigid body motions, in particular rotations. In contrast to most conventional approaches, the time integration strategy is closely linked
to the “element technology” with the latter involving a form of co-rotational procedure. For the undamped situation, the solution procedure leads to an algorithm that exactly conserves energy when constant external forces are applied (i.e. with gravity loading).


ABSTRACT: The paper discusses four separate aspects of the non-linear finite element method: (i) An alternative formulation for the static co-rotational technique in conjunction with a simple faceted shell idealisation. (ii) Solution procedures for non-linear dynamics with emphasis on energy conserving techniques (iii) The use of interface elements and fracture energy related softening “stress-strain” curves for modelling mixed mode delamination in “composites” (iv) Hybrid static/dynamic solution procedures. While the topics are separate, there are links and these are explored.


ABSTRACT: The simplest facet-shell formulation involves the combination of the constant-strain membrane triangle with a constant-curvature bending triangle. The paper first describes an alternative co-rotational procedure to the one initially proposed by Peng and Crisfield in 1992. This new formulation introduces a spin matrix which allows a simpler formulation for the consistent tangent stiffness matrix. The paper then moves to the dynamics of the element. To obtain stable solutions, an energy-conserving mid-point time-integration scheme is developed. This scheme exactly conserves the total energy when external forces are constant and when the physical system does not present any damping. The performance of this scheme is compared with other more conventional implicit schemes through a set of numerical examples involving large-scale rotations.


ABSTRACT: The paper describes a simple corotational formulation applied to one-dimensional interface elements which embed a fracturing procedure for mixed-mode delaminations. Having thereby introduced geometric non-linearity, the technique can be applied to situations involving a combination of buckling and delamination. Detailed comparisons are made with experimental results for such a problem.


ABSTRACT: This paper deals with the computation of buckling behaviour and with the prediction of
delamination growth in a compressively loaded delaminated laminate. The laminate is modelled as an assembly of three plates with account for geometric non-linearities. Both local and global bucklings are investigated. We propose analytical formulae for computing the energy release rate along the delamination front. Our approach consists in adapting the J-integral method of 2D elasticity to our plate model, dealing with discontinuities instead of singularities. Numerical results are discussed and compared to experiments.

Sébastien Baguet and Bruno Cochelin (Laboratory of Mechanics and Acoustics, Marseille, France), “Stability of thin-shell structures and imperfection sensitivity analysis with the asymptotic numerical method”, Revue Européenne des Eléments Finis, Hermès, 2002, 11/2-3-4, pp.493-509. <10.3166/reef.11.493-509>

ABSTRACT: This paper is concerned with stability behaviour and imperfection sensitivity of thin elastic shells. The aim is to determine the reduction of the critical buckling load as a function of the imperfection amplitude. For this purpose, the direct calculation of the so-called fold line connecting all the limit points of the equilibrium branches when the imperfection varies is performed. This fold line is the solution of an extended system demanding the criticality of the equilibrium. The Asymptotic Numerical Method is used as an alternative to Newton-like incremental-iterative procedures for solving this extended system. It results in a very robust and efficient path-following algorithm that takes the singularity of the tangent stiffness matrix into account. Two specific types of imperfections are detailed and several numerical examples are discussed.

References listed at the end of the paper:


PARTIAL ABSTRACT: This paper concerns the computation of non-linear modes of elastic structures under large displacements. We present as numerical method that we have implemented in a general purpose finite element code. Bifurcation of modes will be also addressed.


ABSTRACT: A path-following technique is presented for the numerical solution of a class of elastic structural problems. The principle is to follow a non-linear solution branch by applying a perturbation technique in a stepwise manner. The solution is represented by a succession of local polynomial approximations. The perturbation technique used here is the asymptotic-numerical method proposed by Damil and Potier-Ferry. It is a combination of asymptotic expansions and finite element calculations which permits one to determine a large part of a non-linear branch by inverting only one stiffness matrix. The present continuation technique requires less computing time than the classical predictor-corrector schemes. Moreover, it is very robust and completely automatic, thanks to the analytical representation of the branch within each step. Various numerical examples are presented to evaluate the performance of the method.
ABSTRACT:
This special publication contains the papers presented at the special sessions honoring Dr. Manuel Stein during the 38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference held in Kissimmee, Florida, April 7-10, 1997. This volume, and the SDM special sessions, are dedicated to the memory of Dr. Manuel Stein, a major pioneer in structural mechanics, plate and shell buckling, and composite structures. Many of the papers presented are the work of Manny's colleagues and co-workers and are a result, directly or indirectly, of his influence. Dr. Stein earned his Ph.D. in Engineering Mechanics from Virginia Polytechnic Institute and State University in 1958. He worked in the Structural Mechanics Branch at the NASA Langley Research Center from 1943 until 1989. Following his retirement, Dr. Stein continued his involvement with NASA as a Distinguished Research Associate.

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ABSTRACT: A wide column test of a composite isogrid panel subjected to quasi-static, axial compression is modeled with a hybrid-static dynamic computational method. The data from the test panel exhibited discontinuous responses in the compressive load for slowly increased end-shortening. The computational model was developed to corroborate these discontinuities with the phenomenon of mode jumping. Mode jumping refers to the transient response of the panel from an unstable bifurcation point on a postbuckled equilibrium path to a second stable equilibrium state on a new equilibrium path. On the new equilibrium path, both the analysis and test show that the panel can resist increased end-shortening beyond that of the unstable critical point. Fair agreement is achieved between the analysis and test.

References listed at the end of the paper:


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ABSTRACT: Bifurcation of an initially longitudinal through crack in an internally pressurized cylindrical shell at a circumferential stiffener is investigated using a finite element analysis. The finite element model is developed from a fracture test of an aluminum shell having a 22.9 cm radius, a 1.02 mm wall thickness, and stiffened by two externally bonded circumferential straps spaced 40.6 cm apart. After initial stable crack growth in the longitudinal direction with increasing pressure, the crack propagated dynamically toward the strap, bifurcated near the strap into circumferential branches running parallel to the straps. Stable and unstable crack growth curves of pressure versus half-crack length are determined from the nonlinear analysis using a critical value of the crack tip opening angle as the criterion to predict crack growth. Although the crack growth curves are determined from a static analysis, they corroborate the test results for the location of crack path bifurcation. Also, the principal stress criterion for predicting crack turning is consistent with the test.


ABSTRACT: A numerical method is presented for the initial post-buckling analysis of folded plate structures. The method combines Koiter's initial post-buckling theory with the spline finite-strip method. Splines replace the often used Fourier series, in order to facilitate the description of both local non-periodic buckles which may
occur under concentrated transverse loading, and of oblique buckling modes pertaining to shear. Because determination of the shape of the buckle in axial direction requires more unknowns than in the classical finite-strip method, this method can be placed mid-way between the semi-analytical finite-strip method and a full finite element method. A numerical example pertaining to a thin-walled beam loaded by a concentrated transverse force, demonstrates the interactions between two distortional buckling modes.

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ABSTRACT: This paper is a contribution to the understanding of the interaction between overall lateral-torsional buckling and local buckling of a beam under transverse loading. It concentrates on the case where the critical load for local buckling is smallest. Three approaches have been used: numerical analysis using the asymptotic theory; a qualitative analysis using an a priori simple discrete model; and experiments. The study suggests that just three modes in the asymptotic analysis are adequate to describe the interactive behaviour. The resulting reduced potential energy expression is quite similar to that of the a priori simple discrete model and provides insight into the destabilizing phenomenon. The experiments confirm these results.

References listed at the end of the paper:


ABSTRACT: Second-order post-buckling fields emanate from the solutions of a constrained minimization
problem. Two iterative solution algorithms for this specific type of constrained problem are described. A classical augmented Lagrangian algorithm is compared with a simpler one utilizing the specific feature of the initial post-buckling analysis. Numerical examples of prismatic plate-type structures are presented.

David Camenish Gelder, “Buckling and crippling of square steel thin-walled tubes fabricated with symmetrically-overlapping U-channels and foam”, Master’s thesis, Dept. of Civil and Environmental Engineering, Brigham Young University, Provo, Utah, August 2012

ABSTRACT: Testing and analysis has been performed on square steel thin-walled tubes fabricated using symmetrically-overlapping U-channels and foam. This research analyzes flange-to-flange attachment, effect of foam in the columns, effect of adhesive stiffness, and influence of steel thickness, as related to the local buckling loads, global buckling loads, and crippling loads. Four 14-foot (4.27 m) foam-filled, thin-walled, galvanized steel columns were manufactured by Novatek, Inc. and tested in axial compression with pinned boundary conditions. For three of the four configurations, the two-piece 4-in. (10.2-cm) square shell surrounded prefabricated polystyrene foam inserts; the fourth column had no foam insert. The column outer shells were composed of two 16-gauge galvanized steel channels with overlapping flanges and the webs on opposite sides of the column. The two adjacent flanges on each side of the columns were adhesively bonded together in all cases. In addition to the adhesive, two columns had either periodic screws or short welds spaced evenly along the length of the columns to delay the onset of flange buckling of the outer channel, and potentially increase the compression strength. The other two columns had adhesive only bonding the flanges, one of which had no foam filler. The various configurations all exhibited similar compression strengths. Failure for all columns initiated with local buckling, followed by global buckling and local crippling, which occurred simultaneously. The method of flange attachment, the effect of the foam in the columns, and flange thicknesses were isolated and analyzed using mechanics-based analysis, parametric studies, and finite element analysis. The results show the ideal spacing of screws or short-welds, if used, is less than or equal to 5 in (12.7 cm) for the given column length. This increases the local buckling load to the Euler buckling load and preserves the original shape of the cross-section. The adhesive needs only a tensile strength of approximately 1 ksi (6.4 kPa) to prevent local buckling for any spacing of screws or short-welds, but needs to be applied uniformly (much of the adhesive in the column tests had been scraped off of the flanges during assembly). The results also show that foam core does not increase the Euler buckling load, but does increase the crippling load by delaying inward buckling of the column webs and flanges. Using foam with the given stiffness and a yield strength of 50 psi (345 kPa), uniform foam-to-steel bonding could increase the crippling strength up to 21% even without adhesive between the flanges. Using adhesive with the given stiffness between the flanges could increase the crippling strength by up to 63% without foam. The crippling strength could increase up to 72% if both adhesive between the flanges and a foam insert are used.

References listed at the end of the thesis:
CE 523 (2011). "Design and Analysis of Aircraft Structures." Class Notes, Brigham Young University, Provo, UT.

SUMMARY: Aluminium extrusions applied in daily practice are often thin-walled with complex cross-
sectional shapes. These shapes are based on a variety of demands that are in general non-structural. As a result, several types of instability may occur, including overall and cross-sectional instability modes as well as mode interactions. Research on overall buckling is usually based on simple and symmetrical cross-sections, whereas cross-sectional instability is simplified to buckling of individual plates. It is therefore highly unlikely that these design rules provide an accurate description of the actual buckling behaviour of arbitrary cross-sections. As predicted failure modes not necessarily agree with actual ones, the outcome of the results may be overly conservative but could be unsafe as well. In order to investigate the actual cross-sectional stability behaviour of aluminium extrusions, a large experimental program is executed at Eindhoven University of Technology. This program consists of aluminium extrusions under uniform axial compression. Test specimens with rectangular hollows (SHS), U-sections (US), as well as very complex cross-sectional shapes (CS) have been tested. A detailed investigation is made into the influence of the test set-up, initial imperfections, as well as the material characteristic. This results in is a large set of test data on the actual buckling behaviour of aluminium extrusions, including local, distortional, flexural and flexural-torsional buckling, as well as mode interaction. To support the findings of the experiments, a numerical program using the finite element (FE) method is executed. Most experiments are simulated using the actual geometry, material, and imperfections. Comparison of the experimental and numerical results shows that an accurate prediction is achieved. Furthermore, the FE-analyses allow a detailed investigation of specific aspects like the bifurcation load, the influence of imperfections and materials, the test set-up, and mode interaction. The FE-results enable the development of a new and general prediction model for the local buckling behaviour of aluminium extrusions. Based on the actual local buckling behaviour of cross-sections, it is derived for uniformly compressed aluminium extrusions with arbitrary cross-sections consisting of flat plates. As such, it allows an accurate and conservative prediction of the strength and stiffness of a large range of commercial extrusions. The promising results of this model may result in design rules that enable more economical designs and are able to include distortional buckling and mode interaction. This combination of experimental, numerical (FE), and analytical work results in a thorough investigation on the actual local buckling behaviour of aluminium extrusions with arbitrary and complex cross-sections.

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ABSTRACT: A Kirchhoff–Love type curved triangular finite element is proposed for geometrically nonlinear analysis of elastic isotropic shells undergoing small strains but large displacements. The finite-element formulation is based on the expression of the strain energy in terms of invariants of the strain and curvature-change tensors of the shell middle surface. The element sides are chosen as three independent directions for determining the strains and curvature changes. The emphasis is put on improvement of the bending behavior of the element so that the element is able to undergo finite curvature changes. Recursive relations are obtained for exactly calculating the coefficients of the first- and second-order variations of the strain energy of the finite element which are necessary to formulate the equilibrium and stability conditions of the discrete model of a shell. A shell finite element with 15 degrees of freedom is developed and tested. Numerical examples are presented to demonstrate the accuracy and mesh convergence of the finite-element solutions.

ABSTRACT: An engineering approach for constructing a curved triangular finite element of a thin shell is considered. The approach is based on the assumption that the triangle sides are planar nearly circular curves before and after deformation. A geometrically nonlinear formulation of a triangular finite element of a thin Kirchhoff–Love shell is given. The predictive capabilities of the element are tested using benchmark problems of nonlinear deformation of elastic plates and shells.

ABSTRACT: This paper describes the improvements in the B2000 system in order to simulate the behaviour of composite stiffened panels. For improved non-linear numerical behaviour, use was made of shell elements following the theory from Bathe with a total Lagrangian formulation. The non-linear Newton-Raphson processor required modification to jump past the initial buckling point into the post-buckling domain. Examples are presented to demonstrate the new capabilities.

References listed at the end of the paper:

ABSTRACT: A finite element based hybrid subspace analysis procedure to predict the non-linear behaviour of statically loaded structures is presented. The basic idea is to reduce the total number of degrees of freedom significantly, utilizing global shape functions like buckling modes and path derivatives in a so-called Rayleigh–Ritz approach. The transformation from the full into the reduced system and vice versa as well as the calculation of the global shape functions is detailed. The presented flow-chart of the computational procedure has been implemented in a finite element environment. Numerical examples provide an insight into the potential of the approach to solve accurately and efficiently non-linear problems within the design phase.


ABSTRACT: European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Structural weight reduction by exploitation of structural reserves in composite aerospace structures contributes to this aim, however, it requires accurate and experimentally validated stability analysis of real structures under realistic loading conditions. This paper presents new achievements from the area of computational and experimental stability research of composite aerospace structures which contribute to that field. The first four topics focus on stringer stiffened panels and the last one on imperfection sensitive unstiffened cylinders.
Section 1 presents new results achieved so far in the running EU (European) project COCOMAT, which deals with an accurate and reliable simulation of collapse. The main objective of COCOMAT is a future design scenario which exploits considerable reserves in fibre composite fuselage structures by accurate simulation of collapse. The project results comprise an experimental data base, improved slow and fast computational tools as well as design guidelines.

Section 2 deals with validated postbuckling simulation of stiffened CFRP-panels by experiments. The validation procedure to ensure reliable numerical simulations requires extensive experimental data, especially in the case of nonlinear calculations with the possibility of several bifurcation and limit points in the postbuckling region. Therefore, the experiments have to be planned carefully, to ensure a reliable and goal-oriented validation with respect to the numerical analysis.

Section 3 presents the fast tool IBuck for the simulation of the postbuckling behaviour. It is a semi-analytical tool for the simulation of axially loaded panels that are stiffened in both axial and circumferential direction. In today’s design process dynamic loading, e.g. due to gusts or landing impact, is assumed to be uncritical, since the dynamic process increases buckling stability. Section 4 shows that rapidly applied loading of stiffened panels can yield critical dynamic behavior in the postbuckling regime. When applying the new design philosophy it has either to be assured that these critical interactions do not occur under the loading velocities to be expected, or they have to be taken into consideration.

Section 5 presents a recently developed approach for unstiffened shells which are usually susceptible to imperfections. This robust design approach is based on a single buckle as the worst imperfection mode leading directly to the load carrying capacity of a cylinder. It also promises to improve the knock-down factors which are according the current guidelines very conservative.

Future work should facilitate full applicability of the analysis methods in preliminary design. For that purpose speed of the collapse analysis of stiffened panels needs to be increased and for collapse simulation degradation must be taken into account. The application field of the robust design method should be widened towards imperfection sensitive stiffened shells (skin-dominant designs).

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[2] www.cocomat.de (The running project COCOMAT is supported by the European Commission, Priority Aeronautics and Space, Contract AST3-CT-2003-502723.)
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ABSTRACT: A fibre–metal laminate is a composite of metal and fibre-reinforced prepreg layers. An example of such a material is Glare. It consists of alternating layers of aluminium and glass-fibre-reinforced prepreg. The material can be sensitive to delamination buckling, which occurs when a partially delaminated panel is subjected to a compressive force. The interaction of local buckling and extension of the delaminated zone typically results in a decrease of the residual strength and, eventually, in a collapse of the structure. This phenomenon can be observed in experimental tests, but numerical analyses are needed to obtain a better understanding of the mechanisms and the critical parameters. In this paper, some experimental observations are discussed regarding delamination buckling in Glare and, on the basis of these observations, a numerical model is constructed at a meso-mechanical level. In this approach, solid-like shell elements are used to model the individual layers. They are connected by interface elements, which are capable of modelling delamination between the layers.

References listed at the end of the paper:

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M. -W. Moon (1), K. -R. Lee (2), K. H. Oh (1) and J. W. Hutchinson (3)
(1) School of Materials Science and Engineering, Seoul National University, Seoul 151-742, Republic of Korea
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doi:10.1016/j.actamat.2004.03.014
ABSTRACT: Lithographic techniques applied to a substrate prior to film deposition can create areas of low
interface adhesion surrounded by regions of high adhesion. If the film is under compression and if buckle
delamination is nucleated, conditions can be controlled such that delaminations are confined to the patterned
areas of low adhesion. When the area of low adhesion is a strip, the width of the strip controls the buckle
morphology: smooth Euler buckles for narrow strips, asymmetric telephone cord buckles for wider strips, and
symmetric varicose buckles under a very limited range of conditions. Results for the elastic energy in the
buckled state show that above a critical stress the telephone cord morphology is the preferred morphology.
Energy release rates for propagating delaminations are determined for each of the three morphologies. Tapered
strips provide an accurate means of measuring interface adhesion based on the width of the strip where the
delamination arrests.

References listed at the end of the paper:

ABSTRACT: It is shown that unless the substrate is at least as stiff as the film, the energy stored in the substrate contributes significantly to the energy release rate of film delamination under compression either with or without cracking. For very compliant substrates, such as polyethylene terephthalate (PET) with a indium tin oxide (ITO) film, the energy release rate allowing for the deformation of the substrate can be more than an order of magnitude greater than the value obtained neglecting the substrate's deformation. The argument that buckling delaminations tunnel at the tip rather than spread sideways because of increase in mode-mixity may need modification; it is still true for stiff substrates, but for compliant substrates the average energy release rate decreases with delamination width and the limitation in buckled width may be due to this stability as much as the increase in mode-mixity.

References listed at the end of the paper:

M. Ahmer Wadee (Department of Civil and Environmental Engineering, Imperial College of Science, Technology & Medicine, London, SW7 2AZ, UK), “Nonlinear buckling in sandwich structs: mode interaction

ABSTRACT: Recent developments in the variational modeling of nonlinear interactive buckling phenomena found in compression sandwich panels are presented. Strong interactions between local and global modes are found to lead to localized buckling in the more compressed face-plate after the global instability. Important features such as the effect of using orthotropic core materials and face-plates of differing thicknesses, the potential for face-core delamination, panels under combined bending and compression, and the sensitivity to imperfections are discussed. The combination of modal interactions and the introduction of initial geometric imperfections in the struts shows that the critical buckling loads from linear analysis can significantly overestimate their true elastic strength.

ABSTRACT: A geometrically nonlinear model is developed to investigate the buckling behaviour of plates with a pre-existing delamination under uniaxial compression. The Rayleigh–Ritz procedure, based on trigonometric out-of-plane displacement functions, is used in conjunction with potential energy principles to describe the buckling and postbuckling response. The formulation is enhanced with the introduction of a discrete cohesive zone model to allow the delamination to grow under further loading. Different cases are investigated with residual capacities of the plates being evaluated in the neighbourhood of a transitional depth of delamination, where the postbuckling behaviour changes from thin film to mixed mode to global buckling. The model is validated with the commercial finite-element code Abaqus and criteria are proposed such that the component may be exploited beyond the critical loads.


ABSTRACT: A finite-difference method was proposed and used for analysis of critical loads of shells that have initial imperfections of different types, both regular and local. Ribbed shells were analyzed with allowance for the discreteness in the arrangement of the ribs.

References listed at the end of the paper:

Recent papers by G. D. Gavrilenko, et al:

Effect of localized imperfections on the critical loads of ribbed shells
G. D. Gavrilenko and V. I. Matsner
International Applied Mechanics, 2010, Volume 46, Number 7, Pages 771-775

Stability of compressed cylindrical shells with localized asymmetric deflections
G. D. Gavrilenko
International Applied Mechanics, 2010, Volume 46, Number 1, Pages 54-59
ABSTRACT: The paper proposes a new approach to the problem of stability of imperfect shells, which is used to assess their quality. Numerical results for ribbed shells with initial deflections of two types are presented. Comparing them allows assessing the quality of shells. The approach is used to determine the minimum critical load of a smooth shell, which was experimentally examined before

Critical loads of shells with high-modulus reinforcement
G. D. Gavrilenko and V. I. Matsner
International Applied Mechanics, 2009, Volume 45, Number 6, Pages 654-659

Free vibration of shells with axisymmetric dimples and bulges under axial compression
G. D. Gavrilenko, V. I. Matsner and O. A. Kutenkova
Strength of Materials, 2009, Volume 41, Number 2, Pages 209-218

Free vibrations of ribbed cylindrical shells with local axisymmetric deflections
G. D. Gavrilenko, V. I. Matsner and O. A. Kutenkova
International Applied Mechanics, 2008, Volume 44, Number 9, Pages 1006-1014
Stability of imperfect cylindrical shells, 2008 Springer Science+Business Media / 0039-2316
G. D. Gavrilenko (Timoshenko Institute of Mechanics, National Academy of Sciences of Ukraine, Kiev, Ukraine)

ABSTRACT: A procedure of approximate evaluation of the critical loads of shells proposed earlier on the basis of the nonlinear theory of shells is used to analyze the influence of initial imperfections of any shape on the parameters of the critical loads. The numerical results are compared with the available experimental and theoretical data corresponding to the complete loss of stability of shells and exhaustion of their load-carrying capacity.

References listed at the end of the paper:

Strength of Materials, 2008, Volume 40, Number 4, Pages 463-468

Influence of axisymmetric dents in ribbed shells on minimum critical loads
G. D. Gavrilenko and V. I. Matsner
International Applied Mechanics, 2007, Volume 43, Number 5, Pages 534-538

On lower-bound estimates of critical loads for cylindrical shells
G. D. Gavrilenko, A. S. Sitnik and V. I. Matsner
International Applied Mechanics, 2006, Volume 42, Number 10, Pages 1145-1150

ABSTRACT: The paper proposes a new approach to estimate the lower bounds of critical loads for circular cylindrical shells. These bounds are compared with the ordinary lower bound of critical load under which a shell with initial deflections loses stability. The lower bound produced by the approach is higher than the ordinary bound and can be used in design.

Experimental justification of the analytical method for determining the upper and lower bounds of the critical loads in ribbed shells
G. D. Gavrilenko and V. I. Matsner

ABSTRACT: The method developed for determining the upper and lower bounds of the critical load parameters in elastic ribbed shells is described. The critical parameters for cylindrical shells with three types of stiffening, namely, by cross ribs, by stringers and by rings only, are justified experimentally. It is shown that the lower bounds of the critical loads agree with the minimum experimental parameters much better than the upper bounds of the critical loads determined from the linear momentless theory.

References listed at the end of the paper:

Some features of the buckling of stringer shells
G. D. Gavrilenko and V. I. Matsner
International Applied Mechanics, 2006, Volume 42, Number 2, Pages 176-180
ABSTRACT: A technique for stability analysis of stringer shells is proposed. It is used to analyze the minimum critical stresses. The dependence of the dimensionless parameters $\sigma_{cr}/\sigma_{el}$ on the number of stringers is plotted. The linear and nonlinear theories of ribbed shells are used to examine the features of how stringer shells lose stability. It is shown that the minimum critical stresses determined using the theory of ribbed shells and a structurally orthotropic model are close within the range of stiffness parameters considered

Analytic upper-bound estimates for the critical loads of perfect ribbed shells
G. D. Gavrilenko and V. I. Matsner
International Applied Mechanics, 2005, Volume 41, Number 12, Pages 1391-1398

Stability and Load-Carrying Capacity of Elastic Reinforced Cylindrical Shells
G. D. Gavrilenko and V. I. Matsner
Strength of Materials, 2005, Volume 37, Number 6, Pages 624-632

Stability and load-bearing capacity of smooth and ribbed shells with local dents
ABSTRACT: A method for analysis of the stability and load-bearing capacity of imperfect smooth and ribbed shells is developed. This method is based on the finite-difference method and is implemented as an algorithm for fast calculation of critical forces, as opposed to the finite-element method. The theoretical results discussed include both early and recent results. The emphasis is on shells with local dents. The numerical results are successively corrected and compared with available experimental data for shells with a single dent and with other data. The method enables us to discover new features in the behavior of thin-walled structures under loading: development of precritical state, change in the dent shape, and exhaustion of load-bearing capacity. The lower local critical loads and upper stresses are determined. They correspond to general buckling and agree well with available experimental data.

Calculation of Load-Carrying Capacity of Elastic Shells with Periodic Dents (Theory and Experiment)

G. D. Gavrilenko and V. L. Krasovskii
Strength of Materials, 2004, Volume 36, Number 5, Pages 511-517
ABSTRACT: The phenomenon of the local loss of stability (buckling) earlier discovered by the authors experimentally was simulated theoretically. An approach to assessing the load-carrying capacity of circular cylindrical shells with periodic dents is presented. The authors show that application of the linear theory or solution of the problem in the nonlinear formulation with few iterations (when calculating the subcritical state) results in large quantitative errors. To get more accurate and reliable numerical data, one needs to solve the problem of the nonuniform subcritical state in the nonlinear formulation with many iterations. The local buckling loads determined numerically are lower than the experimental values, i.e., the errors are on the safe side. The loads characterizing the overall buckling are either close to the experimental values or also lower.

Reduced-Stiffness Method in the Theory of Shells

G. D. Gavrilenko and J. G. A. Croll
International Applied Mechanics, 2004, Volume 40, Number 7, Pages 715-743
ABSTRACT: The fundamentals of the reduced-stiffness method, which is used in buckling analysis of reinforced and perfect and imperfect nonreinforced shells, are set out. The method is validated analytically and experimentally. The lower bound determined by this method is very close to the experimental lower bound. Some aspects of the current state and prospects for development and generalization of the method are discussed.

References listed at the end of the paper:
Effect of the Stress State on the Critical Load and Load-Carrying Capacity of Shells with Axisymmetrical Dents
G. D. Gavrilenko and V. I. Matsner
Strength of Materials, 2004, Volume 36, Number 2, Pages 171-177

Stability of Circular Cylindrical Shells with a Single Local Dent
G. D. Gavrilenko and V. L. Krasovskii
ABSTRACT: The theoretical-and-experimental investigation has been performed on the stability of smooth cylindrical shells of steel with a single local dent. All the shells manufactured using the same process were tested with the fulfillment of identical conditions for observations and measurements. Theoretical calculations were carried out by the mesh method with the use of the nonlinear theory of shells. A comparison of the experimental and theoretical values of the critical loads has been made. The theoretical-and-experimental approach proposed enables one to evaluate the quality of shells by studying local dents and other specific imperfections.

ABSTRACT: We propose a nonlinear approach to the stability analysis of imperfect cylindrical shells under axial compression. The approach takes into account the initial deflections (imperfections) of the shell shape from cylindrical. A series of typical initial deflections is analyzed: local and longitudinal bulges (dents) and unilateral annular corrugations. A nonlinear stability problem is solved. The results are represented as plots of the nondimensional stress versus the nondimensional amplitude of initial deflections. It is shown that the capabilities of the nonlinear theory for estimating the critical stresses for thin shells have not been exhausted yet and that it could be used in future to explain some phenomena experimentally observed in shells

References listed at the end of the paper:
11. A. V. Karmishin, V. A. Lyaskovets, V. I. Myachenkov et al., Statics and Dynamics of Thin-Walled Shell Structures [in Russian], Mashinostroenie, Moscow (1975).


ABSTRACT: Two new approaches are proposed for the numerical and analytical stability analyses of imperfect shells. One approach is based on the generalized mesh method, whereas the other employs a modified reduced-stiffness method. Both approaches apply to shells with initial geometrical imperfections. Numerical results are compared with experimental data for shells with a single dent. Analytical results are also presented and compared.

References listed at the end of the paper:
ABSTRACT: A small number of studies (Gavrylenko, 1989, 1999) are devoted to the evaluation of the critical loading of incomplete ribbed shells. There are only a few calculations (Singer et al., 1971) for ribbed shells.
New approaches are given in Arbocz et al., (2001), and Gavrylenko & Croll, (2001).

References listed at the end of the paper:


ABSTRACT: The FETI algorithms are a family of numerically scalable domain decomposition methods. They have been designed in the early 1990s for solving iteratively and on parallel machines, large-scale systems of equations arising from the finite element discretization of solid mechanics, structural engineering, structural dynamics, and acoustic scattering problems, and for analyzing complex structures obtained from the assembly of substructures with incompatible discrete interfaces. In this paper, we present the second generation of these methods that operate more efficiently on large numbers of subdomains, offer greater robustness, better performance, and more flexibility for implementation on a wider variety of computational platforms. We also
report on the application and performance of these methods for the solution of geometrically non-linear structural analysis problems. We discuss key aspects of their implementation on shared and distributed memory parallel processors, benchmark them against optimized direct sparse solvers, and highlight their potential with the solution of large-scale structural mechanics problems with several million degrees of freedom.

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ABSTRACT: Sandwich plate systems (SPS) are advanced materials that have begun to receive extensive attention in naval architecture and ocean engineering. At present, according to the rules of classification societies, a mixture of shell and solid elements are required to simulate an SPS. Based on the principle of stiffness decomposition, a new numerical simulation method for shell elements was proposed. In accordance with the principle of stiffness decomposition, the total stiffness can be decomposed into the bending stiffness and shear stiffness. Displacement and stress response related to bending stiffness was calculated with the laminate shell element. Displacement and stress response due to shear was calculated by use of a computational code write by FORTRAN language. Then the total displacement and stress response for the SPS was obtained by adding together these two parts of total displacement and stress. Finally, a rectangular SPS plate and a double-bottom structure were used for a simulation. The results show that the deflection simulated by the elements proposed in the paper is larger than the same simulated by solid elements and the analytical solution according to Hoff theory and approximate to the same simulated by the mixture of shell-solid elements, and the stress simulated by the elements proposed in the paper is approximate to the other simulating methods. So compared with calculations based on a mixture of shell and solid elements, the numerical simulation method given in the paper is more efficient and easier to do.

ABSTRACT: A non-linear shallow thin shell element is described. The element is a curved quadrilateral one with corner nodes only. At each node, six degrees of freedom (i.e. three translations and three rotations) make the element easy to connect to space beams, stiffeners or intersecting shells. The curvature is dealt with by Marguerre's theory. Membrane bending coupling is present at the element level and improves the element behaviour, especially in non-linear analysis. The element converges to the deep shell solution. The sixth degree of freedom is a true one, which can be assimilated to the in-plane rotation. The present paper describes how overstiffness due to membrane locking on the one hand and to the sixth degree of freedom on the other hand can be corrected without making use of numerical adjusted factors. The behaviour of this new element is analysed in linear and non-linear static and dynamic tests.

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“Composite panel optimization with nonlinear finite-element analysis and semi-analytical sensitivities”, NAFEMS Seminar: November 6 - 7, 2007 “Simulating Composite Materials and Structures”, Bad Kissingen, Germany

ABSTRACT: This paper describes some recent developments of software tools for the optimization of fuselage composite stiffened panels. The two most innovative features of the underlying work are related to the evaluation of buckling and collapse reserve factors and the associated sensitivities, the latter being computed in the framework of both linear and nonlinear finite element analyses. Results obtained with an industrial test case are also presented to confirm the successful integration of these tools in a powerful software environment.

References listed at the end of the paper:
[1] VIVACE Website: http://www.vivaceproject.com


ABSTRACT: Advanced nonlinear analyses developed for estimating structural responses for recent applications for the aerospace industry lead to expensive computational times. However optimization procedures are necessary to quickly provide optimal designs. Several possible optimization methods are available in the literature, based on either local or global approximations, which may or may not include sensitivities (gradient computations), and which may or may not be able to resort to parallelism facilities. In this paper Sequential Convex Programming (SCP), Derivative Free Optimization techniques (DFO), Surrogate Based Optimization (SBO) and Genetic Algorithm (GA) approaches are compared in the design of stiffened aircraft panels with respect to local and global instabilities (buckling and collapse). The computations are carried out with software developed for the European aeronautical industry. The specificities of each optimization method, the results obtained, computational time considerations and their adequacy to the studied problems are discussed.

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“Design of fiber metal laminate shear panels for ultra-high capacity aircraft”, Aircraft Design, Vol. 4, Nos. 2-3,
ABSTRACT: Due to their excellent fatigue characteristics and relatively low density, fiber metal laminates (FML) are considered as candidates for fuselage materials in future generation ultra-high capacity aircraft (UHCA). To exploit the postbuckling behavior, as is the practice in conventional aluminum alloy fuselage structures, an existing engineering design method for postbuckled shear panels was adapted for applications with FML materials. To verify the adapted design methodology, two stiffened FML shear panels were designed and tested until failure. The dimensions of the panels were taken to be representative of an UHCA fuselage structure. In addition, detailed finite element analyses were performed with STAGS to predict panel response during testing. The finite element results showed very good agreement with experimental data, giving confidence in replacing very costly actual panel tests with computer simulations. It was found that the test panel dimensions were outside the region where the current engineering design method for postbuckled panels is valid. To account for this phenomenon, an extension to the current design method is proposed.


ABSTRACT: Multiple delamination causes severe degradation of the stiffness and strength of composites. Interactions between multiple delamination, and buckling and postbuckling under compressive loads add the complexity of mechanical properties of composites. In this paper, the buckling, postbuckling and through-the-width multiple delamination of symmetric and unsymmetric composite laminates are studied using 3D FEA, and the virtual crack closure technique with two delamination failure criteria: B-K law and power law is used to predict the delamination growth and to calculate the mixed-mode energy release rate. The compressive load-strain curves, load-central deflection curves and multiple delamination process for eight composite specimens with different initial delamination sizes and their distributions as well as two angle-ply configurations $0^\circ$//$(\pm \theta)$//$0^\circ$ ($\theta$ = 0° and 45°, and “/’” denotes the delaminated interface) are comparatively studied. From numerical results, the unsymmetry decreases the local buckling load and initial delamination load, but does not affect the global buckling load compared with the symmetric laminates. Besides, the unsymmetry affects the unstable delamination and buckling behaviors of composite laminates largely when the initial multiple delamination sizes are relatively small.

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8. Whitcomb, J.D.: Analysis of a laminate with a postbuckled embedded delamination, including contact effects. J. Compos. Mater. 26(10), 1523–1535 (1992)
ABSTRACT: A sandwich panel with initial through-the-width debonds is analyzed to study the buckling of its faceskin when subject to an in-plane compressive load. The debonded faceskin is modeled as a beam on a Winkler elastic foundation in which the springs of the elastic foundation represent the sandwich foam. The Rayleigh-Ritz and finite-difference methods are used to predict the critical buckling load for various debond lengths and stiffnesses of the sandwich foam. The accuracy of the methods is assessed with a plane-strain finite-element analysis. Results indicate that the elastic foundation approach underpredicts buckling loads for sandwich panels with isotropic foam cores.

References listed at the end of the report:

ABSTRACT: A progressive failure analysis method has been developed for predicting the failure of laminated composite structures under geometrically nonlinear deformations. The progressive failure analysis uses C1 shell elements based on classical lamination theory to calculate the in-plane stresses. Several failure criteria, including the maximum strain criterion, Hashin’s criterion, and Christensen’s criterion, are used to predict the failure mechanisms and several options are available to degrade the material properties after failures. The progressive failure analysis method is implemented in the COMET finite element analysis code and can predict the damage and response of laminated composite structures from initial loading to final failure. The different failure criteria and material degradation methods are compared and assessed by performing analyses of several laminated composite structures. Results from the progressive failure method indicate good correlation with the existing test data except in structural applications where interlaminar stresses are important which may cause failure mechanisms such as debonding or delaminations.

References listed at the end of the report:

ABSTRACT: This study applies the crack growth resistance curve (R-curve) method to predict the residual strength of a composite fuselage panel with discrete source damage. The R-curve is constructed from the energy release rates computed from cracked tensile plate test specimens at their failure loads. To predict the residual strength of a curved fuselage panel with discrete source damage using the R-curve method, G-curves of the energy release rate of the damaged fuselage panel need to be established. These G-curves are generated for various fuselage pressures over a range of crack lengths. Since this study found that the membrane stiffening effect could significantly reduce the energy release rate at the crack tip of a pressurized fuselage, geometrically nonlinear behavior was considered in the calculations. The residual strength of the damaged fuselage panel was determined by comparing the energy release rates with the “allowable-like” R-curve. The correlation between the crack growth predictions and the damage progression results obtained from experiments is very good. Therefore, the R-curve method has the potential to be a practical engineering method for predicting the residual strength of damaged fuselage panels.

ABSTRACT: In this paper, we derive weakly nonlinear equations for the dynamics of a thin elastic plate of large extent under conditions of heavy fluid loading. Two situations are then considered. First, we consider the case in which transverse motion of the plate generates a weaker in-plane motion, which is in turn coupled back to the evolution of the transverse motion. This results in the familiar nonlinear Schrödinger equation for the amplitude of a transverse plane wave, and we show that solitary-wave solutions are possible over the range of (non-dimensional) frequencies $\omega > \omega_c$, which depends on the material properties. Dimensional values of $\omega_c$ are physically realizable for a typical composite material underwater. Second, we consider the case in which the amplitudes of the transverse and in-plane motion are of the same order of magnitude, possible at a single resonant frequency, which leads to an evolution equation of rather novel type. We find a range of travelling-wave solutions, including cases in which incident in-plane waves can generate localized regions of transverse displacement.


ABSTRACT: A methodology for simulating the growth of long through cracks in the skin of pressurized aircraft fuselage structures is described. Crack trajectories are allowed to be arbitrary and are computed as part of the simulation. The interaction between the mechanical loads acting on the superstructure and the local structural response near the crack tips is accounted for by employing a hierarchical modelling strategy. The structural response for each cracked configuration is obtained using a geometrically non-linear shell finite element analysis procedure. Four stress intensity factors, two for membrane behaviour and two for bending using Kirchhoff plate theory, are computed using an extension of the modified crack closure integral method. Crack trajectories are determined by applying the maximum tangential stress criterion. Crack growth results in localized mesh deletion, and the deletion regions are remeshed automatically using a newly developed all-quadrilateral meshing algorithm. The effectiveness of the methodology, and its applicability to performing practical analyses of realistic structures, is demonstrated by simulating curvilinear crack growth in a fuselage panel that is representative of a typical narrow-body aircraft. The predicted crack trajectory and fatigue life compare well with measurements of these same quantities from a full-scale pressurized panel test.


ABSTRACT: …The primary objective of the project was to create a capability to simulate curvilinear fatigue crack growth and ductile tearing in aircraft fuselages subjected to widespread fatigue damage. The second objective was to validate the capability by way of comparisons to experimental results. Both objectives have been achieved. … The document is derived primarily from the PhD thesis of Dr. Chen.)

(cannot cut and paste abstract)
Andrea A. Faggiani and Brian G. Falzon (Department of Aeronautics, Imperial College London, London, SW7 2AZ, United Kingdom), “Optimizing Postbuckling Composite Panels For Damage Resistance”, 16th International Conference On Composite Materials (year and publisher not given. Most recent reference is dated 2006)

ABSTRACT: The design of current composite primary aerostructures, such as fuselage or wing stiffened panels, tends to be conservative due to the susceptibility of the relatively weak skin-stiffener interface. This weakness is due to through-thickness stresses which are exacerbated by deformations due to buckling. This paper presents a finite-element-based optimization strategy, utilizing a global-local modelling approach, for postbuckling stiffened panels which takes into account damage mechanisms which may lead to delamination and subsequent failure of the panel due to stiffener debonding. A genetic algorithm was linked to a finite element package to automate the iterative procedure and maximize the damage resistance of the panel in postbuckling. For a given loading condition, the procedure optimized the panel’s skin layup leading to a design displaying superior damage resistance compared to non-optimized designs.

References listed at the end of the paper:
[19] Bushnell, D. "Optimization of composite, stiffened, imperfect panels under combined loads for service in the postbuckling

ABSTRACT: The behavior of blade-stiffened graphite-epoxy panels with impact damage is examined to determine the effect of adding through-the-thickness stitches in the stiffener flange-to-skin interface. The influence of stitches is evaluated by examining buckling and failure for panels with failure loads up to 3.5 times greater than buckling loads. Analytical and experimental results from four configurations of panel specimens are presented. For each configuration, two panels were manufactured with skin and flanges held together with through-the-thickness stitches introduced prior to resin infusion and curing and one panel was manufactured with no stitches holding the flange to the skin. No mechanical fasteners were used for the assembly of any of these panels. Panels with and without low-speed impact damage were loaded to failure in compression. Buckling and failure modes are discussed. Stitching had little effect on buckling loads but increased the failure loads of impact-damaged panels by up to 30%.

Dawn C. Jegley (NASA Langley Research Center, Hampton, VA 23681, USA), “Study of compression-loaded and impact-damaged structurally efficient graphite-thermoplastic trapezoidal-corrugation sandwich and semisandwich panels” (publisher and date not given, ProQuest-CSA)
ABSTRACT: The structural efficiency of compression-loaded trapezoidal-corrugation sandwich and semisandwich composite panels is studied to determine their weight savings potential. Sandwich panels with two identical face sheets and a trapezoidal corrugated core between them and semisandwich panels with a corrugation attached to a single skin are considered. An optimization code is used to find the minimum weight designs for critical compressive load levels ranging from 3000 to 24,000 lb/in. Graphite-thermoplastic panels based on the optimal minimum weight designs were fabricated and tested. A finite element analysis of several test specimens was also conducted. The results of the optimization study, the finite element analysis, and the experiments are presented. The results of testing impact damage panels are also discussed.

ABSTRACT: The results of an analytical and experimental investigation of 4-ply Kevlar-49-epoxy panels loaded by in-plane shear are presented. Approximately one-half of the panels are thin-core sandwich panels and the other panels are solid-laminate panels. Selected panels were impacted with an aluminum sphere at a velocity of either 150 or 220 ft/sec. The strength of panels impacted at 150 ft/sec was not reduced when compared to the strength of the undamaged panels, but the strength of panels impacted at 220 ft/sec was reduced by 27 to 40 percent. Results are presented for panels that were cyclically loaded from a load less than the buckling load to a load in the postbuckling load range. The thin-core sandwich panels had a lower fatigue life than the solid panels. The residual strength of the solid and sandwich panels cycled more than one million cycles exceeded the baseline undamaged panel strengths. The effect of hysteresis in the response of the sandwich panels is not significant. Results of a nonlinear finite element analysis conducted for each panel design are presented.

References listed at the end of the paper:

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ABSTRACT: A composite isogrid panel design for application to a rotorcraft fuselage is presented. An optimum panel design for the lower fuselage of the rotorcraft that is subjected to combined in-plane compression and shear loads was generated using a design tool that utilizes a smeared-stiffener theory in conjunction with a genetic algorithm. A design feature was introduced along the edges of the panel that facilitates introduction of loads into the isogrid panel without producing undesirable local bending gradients. A low-cost manufacturing method for the isogrid panel that incorporates these design details is also presented. Axial compression tests were conducted on the undamaged and low-speed impact damaged panels to demonstrate the damage tolerance of this isogrid panel. A combined loading test fixture was designed and utilized that allowed simultaneous application of compression and shear loads to the test specimen. Results from finite element analyses are presented for the isogrid panel designs and these results are compared with experimental results. This study illustrates the isogrid concept to be a viable candidate for application to the helicopter lower fuselage structure.

References listed at the end of the paper:

ABSTRACT: An approximate method based on strut approach to predict the ultimate strength of simply-supported stiffened panels with initial imperfections and square cutouts, subjected to uniaxial compression is presented. The reduction in stiffness of the plate between stiffeners is considered by using an ‘effective width concept’. Tests are reported on welded stiffened steel panels with varying plate slenderness ratio and column slenderness ratio. Based on the experimental investigations and the proposed method, the influence of square openings, extending the full width between stiffeners, on the ultimate strength of stiffened panels is evaluated.


ABSTRACT: Experimental investigations are carried out up to collapse on eighteen stiffened steel plates having initial imperfections under uniaxial compression with simply supported boundary conditions on both loading and unloading edges. The thickness of the flange plates is varied as 4 mm and 5 mm respectively. Three types of commercially available open section rectangular flats are used as stiffeners. Six panels without cutout, six panels with square cutout which extends the full width in between stiffeners (d/b=1.0), four panels with rectangular cutout (d/b=1.5) and two panels with reinforced rectangular cutout are fabricated. The initial geometric imperfections such as plate imperfection deltax, overall imperfection of the whole panel deltasx and torsional imperfection in stiffener deltasy are measured for all panels fabricated. The axial deformation of the whole panel, out-of-plane deflections and strains along the midsection of the panels measured during the tests is discussed. The reduction in strength of the panels due to the presence of square cutout, rectangular cutout and increase in strength due to reinforcement around rectangular cutout are calculated based on the experimental observations.

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ABSTRACT: The high strength to weight ratio and high stiffness to weight ratio of stiffened plates find wide application in aircraft structures, ship structures, offshore oil platforms and lock gates. The strength and stability of stiffened plates is highly influenced by openings and initial imperfections. The main objective is to study the behaviour of stiffened steel plates with openings up to collapse and to trace the post-peak behaviour under axial and out-of-plane loads. Four stiffened steel plates with a square opening were fabricated for testing. Angle sections were used as stiffeners. Imperfections in the plate, stiffener and overall imperfection of the whole panel were measured. All fabricated panels were tested to failure. A finite element (FE) model was developed for the
analysis of stiffened plates with initial imperfections and validated with the test results. Parametric studies were conducted using the developed FE model, and interaction curves and equations were developed for the design of stiffened plates with initial imperfections and openings. The interactive effect for stiffened panels with a square opening was found to be linear, with proportional reduction of the ultimate axial load carrying capacity due to the constant out-of-plane load.


ABSTRACT: A simple energy-based approach to calculate stresses at skin-stiffener interfaces of composite stiffened panels under shear loads is presented. Solutions to the governing partial differential equations are sought that satisfy boundary conditions and traction continuity. The stress functional forms are determined by minimizing the energy using a variational approach. The resulting closed form stress expressions are compared to finite element solutions and are shown to be in very good agreement.

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ABSTRACT: In the present paper the topological optimal design of isotropic/orthotropic thin structures performed via genetic algorithms is shown. Examples involving structural weight minimization under compressive load or buckling load maximization are presented. A modified finite strip method was developed and used to analyze parametric structures arranged in form of plates or stiffened panels with almost arbitrary cross-section shapes. Specific design variables were defined to assure a robust control over geometrical and topological features. In particular, a semi-analytical formulation for the determination of eigenvalues and eigenvectors was adopted in order to reduce computational efforts requested by the optimization task. A mesh-independent solver, involving a reduced number of degrees of freedom, was implemented and interfaced with a genetic optimizer for the purpose. The optimization procedure was based on a specific bit-masking oriented genetic algorithm, able to handle in parallel different genetic operators expressly conceived to process with proper metrics discrete and continuous design variables. As preliminary example, the buckling load maximization of a metallic plate with an arbitrary grid-shaped cross-section is described first. Then a topological optimization concerning the weight minimization of a composite stiffened panel subject to constraint about buckling load is illustrated and discussed in detail about parametric model definition and genetic procedure.


ABSTRACT: State-of-the-art nonlinear finite element analysis techniques are evaluated by applying them to a
realistic aircraft structural component. A wing panel from the V-22 tiltrotor aircraft is chosen because it is a typical modern aircraft structural component for which there is experimental data for comparison of results. A novel solution strategy which accounts for geometric nonlinearity through the use of corotating element reference frames and nonlinear strain displacement relations is used to analyze this detailed model. Results from linear analyses using the same finite element model are presented in order to illustrate the advantages and costs of the nonlinear analysis as compared with the more traditional linear analysis. Strain predictions from both the linear and nonlinear stress analyses are shown to compare well with experimental data up through the Design Ultimate Load (DUL) of the panel. However, due to the extreme nonlinear response of the panel, the linear analysis was not accurate at loads above the DUL. The nonlinear analysis more accurately predicted the strain at high values of applied load, and even predicted complicated nonlinear response characteristics, such as load reversals, near the observed failure load of the test panel. In order to understand the failure mechanism of the panel, buckling and first-ply failure analysis were performed. The predicted buckling load was 17% above the observed failure load while first-ply failure analyses indicated significant material damage at and below the observed failure load.

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ABSTRACT: This paper presents a multilayered/multidirector and shear-deformable finite-element formulation of shells for the analysis of composite laminates. The displacement field is assumed continuous across the finite-element layers through the composite thickness. The rotation field is, however, layerwise continuous and is assumed discontinuous across these layers. This kinematic hypothesis results in independent shear deformation of the director associated with each individual layer and thus allows the warping of the composite cross section. The resulting through-thickness strain field is therefore discontinuous across the different material sets. Numerical results are presented to show the performance of the method.

References listed at the end of the paper:
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ABSTRACT: This paper presents a continuum-based shear-deformable finite element formulation for geometrically nonlinear analysis of thick layered composite shells. The proposed variational formulation is based on an assumed strain method. From a kinematical viewpoint displacements and rotations are assumed finite while strains are infinitesimal. The model is then cast in a co-rotational framework which is derived consistently from the updated Lagrangian method. Close relationship between the co-rotational procedure and the underlying updated Lagrangian procedure is presented to highlight the efficiency of the method for application to composite shell analysis. Numerical examples are presented to demonstrate the accuracy and the range of applicability of the proposed formulation.

ABSTRACT: A continuum based layerwise shear-deformable finite element formulation is presented for elasto–plastic analysis of layered composites shells. The proposed formulation is cast in a corotational configuration for finite deformation analysis. The elasto-plastic constitutive equations that are based on rate-independent deviatoric plasticity are also written in the corotational kinematic framework. Issues of covariance
and spatial invariance are addressed, and an appropriate stress updating strategy is proposed. Numerical examples are presented to demonstrate the range of applicability of the proposed framework for bending-dominated response of elasto-plastic layered composite shells.

References listed at the end of the paper:

ABSTRACT: An implementation of solution strategies for controlling the analysis of the non-linear equilibrium behavior of elastic structures is presented. The automated procedure guides the solution-stepping process in the vicinity of critical stability points, including limit points, and bifurcation points of multiplicity one or two. The procedure was developed for use with analysis methods in which the total potential energy of a structure is expressed as a power series of finite order in an arbitrary number of generalized coordinates. Aspects of both the Riks-Wempner arc-length control method and the equivalence-transformation method of Thurston are incorporated. The procedure is applied to several plate and stiffened-panel problems in order to demonstrate key features, and to illuminate difficulties that arise in some situations.


ABSTRACT: Stability analysis is a crucial aspect of structural design, particularly for beam, plate and shell type structures. The stability of a structure is often governed by singular points in its equilibrium path. These points usually pose serious problems to ordinary finite element solution methods and require special treatment. In this paper, the state-of-the-art of finite element path-following techniques is critically reviewed with special attention to bracketing procedures for the singular points and branch switching algorithms. Some practical aspects involved will be explained in detail and demonstrated through numerical examples at the end.


ABSTRACT: The paper presents results of comparative experimental examinations and numerical analyses of rectangular plates subjected to shear treated as a skin of half–monocoque aircraft structure. There were considered: the plate without stiffeners 2 mm thick and structure with 1 mm thickness, stiffened by 15 integral ribs. Results of nonlinear numerical FEM analyses and experimental investigations with use of 3D DIC method were compared to ones conducted for smooth plate with equivalent mass. It was documented that introduction of sub–stiffening significant influence on both the form of deformation and distribution of stress in the structure. For smooth plate low cycle fatigue test was conducted.

References listed at the end of the paper:
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ABSTRACT: A three-segment ten-member thin-shell structure with flat walls is considered made of material with instantaneous characteristic approximated by means of an ideally elastic-plastic material model. The structure material (polycarbonate) demonstrates the temporary double refraction effect in polarized light. The system is subject to twisting resulting in state of local post-critical deformation of skin segments within the structure area that is interpreted, in first approximation, as a field of drawing forces. As a result of non-linear numerical analysis in the course of which conformance of equilibrium paths obtained numerically and by means of the experiment is assured, the stress field is determined taking into account the structure’s flexural and membrane state.

References listed at the end of the paper:


Tomasz Kopecki (Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Rzeszów, Poland, “Numerical And Experimental Analysis Of Post-Critical Deformation States In A Tensioned Plate Weakened By A Crack”, Journal of Theoretical And Applied Mechanics 48, 1, pp. 45-70, Warsaw 2010  

ABSTRACT: The paper presents the methodology of determination of the stress distribution in post-critical state of deformation of the rectangular plate weakened with the crack subjected to tension. The problem was formulated as physically and geometrically non-linear. Using the finite elements method, numerical analyses were performed. While solving the nonlinear issue, the progressive change of geometry of the structure in successive incremental steps were compared with results of experimental studies, performed simultaneously.
The obtained results made the base for the assessment of reliability of effects of nonlinear numerical analysis, conditioned by the presence of imperfections of the plate in the neutral state. Two kinds of imperfections were considered: geometric-based on the assumption of the preliminary deflection of the plate in the zone of weakness and the second one – in form of load perturbation, normal to the middle surface of the plate.

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PARTIAL INTRODUCTION: Rational approach to design of load-carrying structures seems to suggest the necessity of focusing special attention on crucial areas of these structures, which are decisive for durability and reliability of the structure. The presence of such crucial areas in a designed solution, resulting usually from its practical functions, should be given careful consideration in view of opportunity to introduce appropriate changes in the design solutions possibly before costly and time-consuming workshop realization of a prototype. The intent of the author is to draw attention to gravity of the factor integrating nonlinear numerical analysis with an experiment – in a broad sense of this word. Then, this chapter presents a methodology that can be used for assessment and current improvement of numerical models thus ensuring correct interpretation of results obtained from nonlinear numerical analyses of a structure. The proposed methodology is based on carrying out experimental examination of selected crucial elements of load-carrying structures parallel with their nonlinear numerical analysis. Special attention is paid to factors determining proper realization of adequate experiments with emphasis placed on the role…
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INTRODUCTION: Modern aviation structures are characterised by widespread application of thin-shell load-bearing systems. The strict requirements with regard to the levels of transferred loads and the need to minimise a structure mass often become causes for accepting physical phenomena that in case of other structures are considered as inadmissible. An example of such a phenomenon is the loss of stability of shells that are parts of load-bearing structures, within the range of admissible loads.

Thus, an important stage in design work on an aircraft load-bearing structure is to determine stress distribution in the post-critical deformation state. One of the tools used to achieve this aim is nonlinear finite elements method analysis. The assessment of the reliability of the results thus obtained is based on the solution uniqueness rule, according to which a specific deformation form can correspond to one and only one stress state. In order to apply this rule it is required to obtain numerical model’s displacements distribution fully corresponding to actual deformations of the analysed structure.

An element deciding about a structure’s deformation state is the effect of a rapid change of the structure’s shape occurring when the critical load levels are crossed. From the numerical point of view, this phenomenon is interpreted as a change of the relation between state parameters corresponding to particular degrees of freedom of the system and the control parameter related to the load. This relation, defined as the equilibrium path, in case of an occurrence of mentioned phenomenon, has an alternative character, defined as bifurcation. Therefore, the fact of taking a new deformation form by the structure corresponds to a sudden change to the alternative branch of the equilibrium path [1-4].

Therefore, a prerequisite condition for obtaining a proper form of the numerical model deformation is to retain the conformity between numerical bifurcations and bifurcations in the actual structure. In order to
determine such conformity it is required to verify the results obtained by an appropriate model experiment or by using the data obtained during the tests of the actual object. It is often troublesome to obtain reliable results of nonlinear numerical analyses and it requires an appropriate choice of numerical methods dependent upon the type of the analysed structure and precise determination of parameters controlling the course of procedures.

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Tomasz Kopecki and Przemyslaw Mazurek (RzeszÓw University of Technology, Faculty of Mechanical Engineering and Aeronautics, RzeszÓw, Poland), “Problems of numerical bifurcation reproducing in post-critical deformation states of aircraft structures”, Journal of Theoretical and Applied Mechanics, Vol. 51, No. 4, pp 969-977, Warsaw 2013

ABSTRACT: The study presents results of research on the problem of obtaining credible results of nonlinear FEM analyses of thin-walled load-bearing structures subjected to post-critical loads. The similarity of numerical simulation results and actual stress distribution states depends on the correct numerical reproduction of bifurcations that occur during an advanced deformation process.

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PARTIAL INTRODUCTION: The design work on aircraft constructions, with applicable standards and requirements imposed by regulations applicable to aircraft design taken into account, represents a discipline significantly different than other fields of modern engineering. In fact, as opposed to rules commonly applicable to design of technical structures, in view of the need to limit the mass, in the case of airframe structures there is a necessity to allow phenomena involving loss of stability with respect to some of their components under the in-flight conditions. From the historical point of view, the issue of the loss of stability was a factor significantly slowing down the progress in aviation at early stage of its development. In aspiration to ensure safety, a large group of designers adhered to the lattice structure concepts for many years. The first attempts to develop some more advanced solutions were based on the use of corrugated sheet metal as the skin material for wings and fuselages. Such solution was adopted in numerous constructions manufactured on a mass scale, e.g. Ford Trimotor or Junkers 52...

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“Buckling and ultimate strength interaction in plates and stiffened panels under combined inplane biaxial and shearing forces”, Marine Structures, Vol. 8, No. 1, pp 1-36, 1995, DOI: 10.1016/0951-8339(95)90663-F

ABSTRACT: The main portion of a ship's structure is usually composed of stiffened plates. Between girders and floors, stiffeners are furnished to plates usually in the longitudinal direction. Under various loads applied to a ship, such as those due to cargo, buoyancy and waves, these stiffened plates are subjected to combined inplane and lateral loads. Imperfections due to fabrication exist mainly in the form of initial deflection and residual stresses. The behaviour of perfectly flat plates is, however, an important reference in design. In this paper, buckling, ultimate and fully plastic strength interaction relationships for rectangular perfectly flat plates and uniaxially stiffened plates subjected to inplane biaxial and shearing forces are derived and expressed in explicit forms based on the results of theoretical investigations of the non-linear behaviour of plates and stiffened plates.
The accuracy of these interaction relationships is confirmed through comparison with the results of other analysis methods. With the aid of these interaction relationships, buckling load, ultimate strength and/or fully plastic strength of such perfectly fat plates and uniaxially stiffened plates subjected to inplane loads may be predicted by hand calculation.

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“Buckling strength of steel plating with elastically restrained edges”, Thin-Walled Structures, Vol. 37, No. 1, pp 27-55, May 2000, DOI: 10.1016/S0263-8231(00)00009-4

ABSTRACT: The twin aims of the present study are to investigate the buckling strength characteristics of steel plating elastically restrained at their edges and also to develop simple design formulations for buckling strength as a function of the torsional rigidity of support members that provide the rotational restraints along either one set of edges or all (four) edges. The characteristic equation for the buckling strength of steel plating that is elastically restrained along either long or short edges while the other edges are simply supported was derived by an analytical method. Using the computed results obtained by directly solving the buckling characteristic equation, closed-form expressions of the buckling strength of the plating with one set of edges elastically restrained while the other set of edges is simply supported are derived empirically by curve fitting. Based on the insights developed in the present study, approximate equations for the buckling strength for plating with all edges elastically restrained are proposed as a function of a relevant combination of the three simpler edge condition cases (i.e., long edges elastically restrained/short edges simply supported, long edges simply supported/short edges elastically restrained, and all edges simply supported). The effect of distortion of support members before the plating buckles is also approximately accounted for. The validity of the proposed closed-form buckling strength design formulations is studied by a comparison with theoretical and numerical solutions.

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“A semi-analytical method for the elastic-plastic large deflection analysis of welded steel or aluminum plating under combined in-plane and lateral pressure loads”, Thin-Walled Structures, Vol. 39, No. 2, pp 125-152, February 2001, DOI: 10.1016/S0263-8231(00)00058-6

ABSTRACT: The aim of the present paper is to develop a semi-analytical method which can quickly and accurately compute the elastic–plastic large deflection response of welded steel or aluminum plating under a combination of biaxial compression/tension, biaxial in-plane bending, edge shear and lateral pressure loads, until the ultimate limit state is reached. The post-weld initial imperfections (i.e. initial deflection and residual stresses) are included in the method as parameters of influence. It is assumed that the plating is simply supported at all (four) edges which are kept straight. A unique feature of the developed method is that geometric nonlinearity associated with large deflection response of plating under combined loads is treated by analytically solving the nonlinear governing differential equations of the elastic large deflection plate theory, while material nonlinearity due to plasticity is dealt with implicitly by a numerical procedure. This approach reduces the magnitude of numerical computations, resulting in a saving of modeling effort and computing time. As another
contribution, this paper investigates and discusses the ultimate strength characteristics of plating, by varying the plate properties and load combinations, based on elastic–plastic large deflection analysis using the developed method.

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(2) Plant Engineering and Construction Division, POSCO Engineering and Construction Co., Ltd., Pohang 790-704, South Korea
ABSTRACT: In the earlier publications [Paik JK, Thayamballi AK, Lee SK, Kang SJ. A semi-analytical method for the elastic–plastic large deflection analysis of unstiffened plates under biaxial loads, edge shear, biaxial in-plane bending and out-of-plane (lateral) pressure loads until the ultimate strength is reached. The effect of initial imperfections in the form of initial deflection and welding residual stresses is accounted for in the calculations. The validity of the developed method is demonstrated by comparing with existing theoretical and numerical results where relevant. The present theory can be useful for ultimate strength analysis of plates and stiffened panels made of steel or aluminium alloys.

ABSTRACT: In addition to corrosion, fatigue cracking is another important factor of age related structural degradation, which has been a primary source of costly repair work of aging steel structures. Cracking damage has been found in welded joints and local areas of stress concentrations such as at the weld intersections of longitudinals, frames and girders. Fatigue cracking has usually been dealt with as a matter under cyclic loading, but it is also important for residual strength assessment under monotonic extreme loading, because fatigue cracking reduces the ultimate strength significantly under certain circumstances. In this paper, an experimental and numerical study on the ultimate strength of cracked steel plate elements subjected to axial compressive or tensile loads is carried out. The ultimate strength reduction characteristics of plate elements due to cracking damage are investigated with varying size and location of the cracking damage, both experimentally and numerically. Ultimate strength tests on cracked steel plates under axial tension and cracked box type steel structure models under axial compression are undertaken. A series of ANSYS nonlinear finite element analyses for cracked plate elements are performed. Based on the experimental and numerical results obtained from the present study, theoretical models for predicting the ultimate strength of cracked plate elements under axial compression or tension are developed. The results of the experiments and numerical computations obtained are documented. The insights developed will be very useful for the ultimate limit state based risk or reliability assessment of aging steel plated structures with cracking damage.
References listed at the end of the paper:


ABSTRACT: The main objective of the present study is to examine the residual ultimate strength characteristics of steel plates with cracking damages under axial compressive actions through experimental investigations. The present study is a sequel of the author's previous paper (Paik, J.K., Satish Kumar, Y.V., Lee, J.M., 2005. Ultimate strength of cracked plate elements under axial compression or tension. Thin-Walled Structures, 43, 237–272). In contrast to the previous paper which dealt with transverse cracks located in the direction normal to the axial loading direction, the present paper is concerned with longitudinal cracks which are located in parallel to the axial loading direction. Similar to the previous paper, the orientation/location and size of cracks inside the plates are varied for the present experimental investigations. The details of experimental results are documented. The database and insights developed from the present work will be useful for cracking damage-tolerant design of steel-plated structures and also for condition assessment or health monitoring of aging steel-plated structures.


ABSTRACT: The main objective of the present paper is to numerically examine the residual ultimate strength
characteristics of steel plates with longitudinal cracks under axial compressive actions. The present paper is a sequel to the author's previous paper [Paik, J.K., 2008. Residual ultimate strength of steel plates with longitudinal cracks under axial compression—Experiments. Ocean Engineering 35, 1775–1783]. In contrast to the previous paper, the present paper deals with nonlinear finite element method investigations. Because the test programme is usually limited to a few test models in number for many reasons, the application of nonlinear finite element methods is often more beneficial to handle a more variety of parameters of influence. In the present paper, the insights developed from a series of ANSYS nonlinear finite element method computations are documented, where the effects of the crack orientation, the crack location, the crack size, the plate thickness, and the plate aspect ratio on the residual ultimate strength of steel plates with longitudinal cracks under axial compression are discussed. The insights developed from the present work will be useful for cracking damage-tolerant design of steel-plated structures and also for health monitoring or condition assessment of aging steel-plated structures with cracking damages.

Jeom Kee Paik and Jung Kwan Seo (Department of Naval Architecture and Ocean Engineering, Pusan National University, 30 Jangjeon-Dong, Gumjeong-Gu, Busan 609-735, South Korea), “Nonlinear finite element method models for ultimate strength analysis of steel stiffened-plate structures under combined biaxial compression and lateral pressure actions – Part II: Stiffened panels”, Thin-Walled Structures, Vol. 47, Nos 8-9, pp 998-1007 DOI: 10.1016/j.tws.2008.08.006
ABSTRACT: The present paper (Part II) is a sequel to the previous paper (Part I) [Paik JK, Seo JK. Nonlinear finite element method models for ultimate strength analysis of steel stiffened-plate structures under combined biaxial compression and lateral pressure actions—Part I: Plate elements. Thin-Walled Struct 2008, this issue, doi:10.1016/j.tws.2008.08.005.] on the application of nonlinear finite element methods for ultimate strength analysis of steel stiffened-plate structures under combined biaxial compression and lateral pressure actions. In contrast to Part I dealing with plate elements, the present paper (Part II) treats stiffened panels surrounded by strong support members such as longitudinal girders and transverse frames. In similar to Part I, some important factors of influence such as structural dimensions, initial imperfections, loading types and computational techniques in association with ultimate limit states are studied. Some useful insights in terms of nonlinear finite element method modeling are developed using ANSYS code together with the ALPS/ULSAP semi-analytical method, the latter being for the purpose of a comparison.


I. Shufrin, O. Rabinovitch and M. Eisenberger (Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Technion City, Haifa 32000, Israel), “Buckling of symmetrically laminated rectangular plates with general boundary conditions – A semi analytical approach”, Composite Structures, Vol.82, No. 4, February 2008, pp. 521-531, doi:10.1016/j.compstruct.2007.02.003
ABSTRACT: A semi-analytical extended Kantorovich approach for the buckling analysis of symmetrically laminated rectangular plates with general boundary conditions is presented. The solution is derived as a multi-function expansion that allows the analysis of laminated plates characterized by a non-separable solution. Among these, the cases of buckling of angle-ply laminates under inplane compression and shear buckling of any type of plate are the most common ones. The formulation is based on the variational principal of total energy minimization and the iterative extended Kantorovich method. The exact element method is adopted for
the solution of the resulting differential eigenvalue problem. The capabilities of the proposed approach and its applicability to buckling analysis of composite laminated plates that cannot be analyzed using the classical single-term extended Kantorovich method are demonstrated numerically. The results are compared with exact solutions (where available), and with approximate results from other numerical methods. The accuracy and convergence of the proposed approach are also discussed.

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“Buckling of laminated plates with general boundary conditions under combined compression, tension, and shear—A semi-analytical solution”, Thin-Walled Structures, Vol. 46, Nos. 7-9, July-September 2008, pp. 925-938, Special Issue: to mark the Retiral of Professor Jim Rhodes, Founding Editor, doi:10.1016/j.tws.2008.01.040

ABSTRACT: A semi-analytical approach to the buckling analysis of generally supported laminated plates subjected to a general combination of inplane shear, compression, and tension loads is presented. Arbitrary out of plane and inplane boundary conditions at the edges of the plate are considered. The formulation is based on the variational principle of virtual work and the multi-term extended Kantorovich method. The semi-analytical method is used for the pre-buckling and buckling (stability) analyses of laminated rectangular plates with inplane restraints under arbitrary inplane loads. The accuracy and convergence are examined through a comparison with exact solutions (where available) and with finite element analyses. The applicability of the method is demonstrated through various numerical examples that focus on the buckling of rectangular composite plates with a variety of boundary conditions and various combinations of the inplane shear, compressive, and tensile loads.

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ABSTRACT: A semi-analytical approach to the elastic nonlinear stability analysis of rectangular plates is developed. Arbitrary boundary conditions and general out-of-plane and in-plane loads are considered. The geometrically nonlinear formulation for the elastic rectangular plate is derived using the thin plate theory with the nonlinear von Kármán strains and the variational multi-term extended Kantorovich method. Emphasis is placed on the effect of destabilizing loads and on the derivation of the solution methodologies required for tracking a highly nonlinear equilibrium path, namely: parameter continuation and arc-length continuation procedures. These procedures, which are commonly used for the solution of discretized structural systems governed by nonlinear algebraic equations, are augmented and generalized for the direct application to the PDE. The boundary value problem that results from the arc-length continuation scheme and consists of coupled differential, integral, and algebraic equations is re-formulated in a form that allows the use of standard
numerical BVP solvers. The performance of the continuation procedures and the convergence of the multi-term extended Kantorovich method are examined through the solution of the two-dimensional Bratu–Gelfand benchmark problem. The applicability of the proposed approach to the tracking of the nonlinear equilibrium path in the post-buckling range is demonstrated through numerical examples of rectangular plates with various boundary conditions.

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Shukla, K.K., Nath, Y., Kreuzer, E., Sateesh Kumar, K.V., 2005. Buckling of laminated composite rectangular plates. Journal of
ABSTRACT: The initiation, growth, and stability of buckling driven debonding in structural assemblies of stiff blocks, compliant joints, and adhesively bonded composite layers are analytically investigated. The model is developed with focus on masonry walls externally strengthened with composite materials where static and, mainly, dynamic loads may induce compression in the strengthening layers triggering a buckling driven debonding near the joints. The model introduces the interfacial nonlinearity (debonding) through a cohesive interface approach. The geometrical nonlinearity is introduced through the kinematics of intermediate class of deformation (large deflections, moderate rotations, small strains), and the material nonlinearity of the masonry construction is introduced through the constitutive law for the mortar joints. A numerical study of the debonding process in strengthened masonry walls is presented. The study uses the periodicity of the wall for sub-structuring and examines configurations that include composite strips or sheets, strengthening on one face of the wall or on both faces, and compliant mortar materials. Emphasis is placed on the localized debonding near the joint, its stability characteristics, and the possibility to detect the debonding process before it reaches the point of instability.

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Geometric non-formulation also considers cross-functions are derived special longitudinal functions to the Timoshenko beam functions used in standard finite strips. These special all degrees of freedom at clamped and pinned boundaries. The support movements are introduced by adding


ABSTRACT: This paper presents a Mindlin finite strip formulation which considers support displacements in all degrees of freedom at clamped and pinned boundaries. The support movements are introduced by adding special longitudinal functions to the Timoshenko beam functions used in standard finite strips. These special functions are derived from the deflection patterns of a Timoshenko beam under support displacements. The formulation also considers cross-ply composite plates. The material is linearly elastic and orthotropic. Geometric non-linearities are also considered. The proposed finite strip formulation makes it possible to analyse


ABSTRACT: This paper presents a Mindlin finite strip formulation which considers support displacements in all degrees of freedom at clamped and pinned boundaries. The support movements are introduced by adding special longitudinal functions to the Timoshenko beam functions used in standard finite strips. These special functions are derived from the deflection patterns of a Timoshenko beam under support displacements. The formulation also considers cross-ply composite plates. The material is linearly elastic and orthotropic. Geometric non-linearities are also considered. The proposed finite strip formulation makes it possible to analyse
problems that hitherto could not be handled by the standard finite strips. Three examples are used to demonstrate the applicability of the new finite strips.

ABSTRACT: The finite strip method based on the higher-order plate theory is developed for determining the natural frequencies of laminated plates. This method can accurately predict the through thickness effect of transverse shear deformation. Furthermore, only a few degrees of freedom are required in the finite strip method. Some numerical results for various span-to-thickness ratios, material properties and stack sequences are presented for illustrative purposes. The present model provides a better way to obtain more accurate natural frequency results.

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ABSTRACT: A layerwise B-spline finite strip method is developed for free vibration analysis of truly thick and thin composite laminated plates within the context of a layerwise plate theory proposed by Reddy [Commun. Appl. Numer. Methods 3 (1987) 173]. The development is the extension of an earlier work [Int. J. Mech. Sci. 37 (1995) 645] in which a Bk,k"_1-spline finite strip method was developed based on the first-order shear deformable plate theory and B-splines of order k and k"_1 were used to avoid shear-locking. In this new method the composite laminated plates are divided into a number of numerical layers in the thickness direction. A linear variation of in-plane displacements are assumed within each numerical layer to represent the through thickness shear warping which can be significant for thick composite laminated plates due to their relatively low through thickness shear moduli. Numerical tests show that the method has the capability to produce accurate predictions for natural frequencies of truly thick and thin composite laminated plates.

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ABSTRACT: A finite strip method for non-linear static analysis based on the tangential stiffness matrix has been developed using the new concept of polynomial finite strip elements, with Mindlin (first-order shear deformable element) plate-bending theory for composite plates. A progressive failure algorithm for composite laminates has been successfully developed for the new finite strip methods using a stress-based failure criterion, Tsai–Wu. A finite strip analysis programming package which is capable of performing non-linear progressive damage analysis for composite stiffened plates and shells has also been developed with Mindlin plate-bending
element. Good agreement with the finite element results has been observed through various test cases, confirming the accuracy and reliability of the new developed method.

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ABSTRACT: The finite strip method has been employed for the analysis of shear-deformable composite laminates since 1976. A number of works have shown the high accuracy, efficiency and convenience of this method. In the present study, a new shear-deformable finite strip is developed to analyse the static and vibration behaviour of composite laminates. By selecting the proper displacement functions, the new strip includes all the effects of material anisotropy and suits arbitrary inplane boundary conditions at the ends. Thus, the present method is applicable not only to cross-ply laminates and symmetrical angle-ply laminates, but also to arbitrary angle-ply laminates, e.g. antisymmetrical angle-ply laminates and (0/45/–45/90 degree) laminates.

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ABSTRACT: The finite strip method has been applied to the stability analysis of rectangular shear-deformable composite laminates. However, for the plates with two opposite simply supported sides, the existing analysis was restricted to the symmetrical cross-ply laminates under compression loading. In the present study, by selecting proper displacement functions and including the coupling between different series terms, the finite strip method is extended to the stability analysis of any anisotropic laminated plates under arbitrary in-plane loading. Furthermore, a number of numerical results are presented to show the effects of thickness, fibre orientation and stacking sequence on the buckling loads.

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ABSTRACT: In the present study, a finite strip method for the elastic analysis of anisotropic laminated composite plates is developed according to higher-order shear deformation theory. This theory accounts for the parabolic distribution of the transverse shear strains through the thickness of the plate and for zero transverse shear stresses on the plate surfaces. In comparison with the finite strip method based on first-order shear deformation theory, the present method gives improved results while using approximately the same number of degrees of freedom. It also eliminates the need for shear correction factors in calculating the transverse shear stiffness.
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“Progressive failure analysis of composite plates by the finite strip method”, Computer Methods in Applied
Mechanics and Engineering, Vol. 124, Nos. 1-2, 15 June 1995, pp. 49-61,
doi:10.1016/0045-7825(95)00788-3
ABSTRACT: In the present study, a finite strip method for the progressive failure of anisotropic composite
laminates is developed based on the higher-order shear deformation theory and Lee's strength criterion. This
method produces results in a good agreement with existing analytical and numerical solutions. The effects of
fibre orientation and the number of plies on the load-carrying capacity are also investigated in numerical
examples.

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“Three-dimensional finite strip analysis of laminated panels”, Computers & Structures, Vol. 85, Nos. 23-24,
ABSTRACT: In this paper, a combined finite strip and state space approach is introduced to obtain three-
dimensional solutions of laminated composite plates with simply supported ends. The finite strip method is used
to present in-plane displacement and stress components, while the through-thickness components are obtained
by using the method of state equation. The method can replace the traditional three-dimensional finite element
solutions for structures that have regular geometric plans and simple boundary conditions, where a full three-
dimensional finite element analysis is very often both extravagant and unnecessary. The new method provides
results that show good agreement with available benchmark problems having different material compositions,
thickness and boundary conditions. The new method provides a three-dimensional solution for laminated plates,
while the advantages of using the traditional finite strip method are fully taken. This solution also yields a
continuous transverse stress field across material interfaces that normally is not achievable by other numerical
modelling of laminates, such as the traditional finite element method.

Y.-P. Tseng and W.J. Wang (Department of Civil Engineering, Tamkang University, Taiwan 25137, R.O.C.),
“A refined finite strip method using higher-order plate theory”, International Journal of Solids and Structures,
ABSTRACT: The higher-order plate theory is adopted in the finite strip method to analyse orthotropic
laminated plates in this paper. Several examples with the existing elasticity solutions are illustrated to validate
the accuracy and efficiency of the present formulation. Although fewer degrees of freedom are required, the
present model yields the same or even better displacement and flexural stress results than the higher-order plate
element. The through-thickness distribution of transverse shear stress is also properly predicted through the
stress equilibrium equation.

Jacob Avrashi (Computational Mechanics and Material Mechanics Laboratories, Faculty of Mechanical
Engineering, Technion - Israel Institute of Technology, Haifa 32000, Israel), “Accuracy and numerical stability
of the non-uniform finite strip method”, Finite Elements in Analysis and Design, Vol. 17, No. 1, June 1994,
pp.75-88, doi:10.1016/0168-874X(94)90021-3
ABSTRACT: Two most significant aspects of the use of the non-uniform finite strip (NUFS) method for composite laminated plates are discussed in the present paper: The accuracy of the displacement and generalized forces and the numerical stability of the scheme. Numerical results for symmetric and asymmetric highly orthotropic plates are presented to show the strips' behavior characteristics regarding the spectral accuracy, finite element convergence, accuracy of displacement and generalized forces and the consumed CPU time. A comparison of the classical laminated plate strip and Mindlin strip shows some significant differences, especially for highly orthotropic plates.

ABSTRACT: The postbuckling behavior of circular cylindrical shells of finite length under uniform external pressure is analysed using the spline finite strip method. A Total Lagrangian formulation on the displacement dependent pressure load in the orthogonal curvilinear reference frame is derived. An improvement for the arc-length iteration method is presented. The postbuckling equilibrium path and the contour map of equal radial deflection computed are in good agreement with the experimental and analytical results reported in Esslinger, M. and Geier, B., Postbuckling Behaviour of Structures, Springer-Verlag, Wien, New York, 1975.

ABSTRACT: The postbuckling analysis of shells is studied by the spline finite strip method. The selection of higher order terms in the incremental variational principle is discussed. An improvement on the arc-length iteration method is presented. The examples all demonstrated the versatility and accuracy of the present method. The computed results for a circular cylindrical shell under axial compression correlate very well with the experiment results.

ABSTRACT: A spline finite strip is proposed to analyse thick isotropic or laminated composite plates. The formulation is based upon the principle of virtual work and the third-order plate theory developed by Reddy. The variational functional requires the satisfaction of C1-continuity of the assumed vertical deflection variable which can be easily fulfilled by the present method. The proposed spline finite strip is a conforming element with a smaller number of unknowns at each node compared to other existing elements based on the third-order theory. For the analysis of thin isotropic or laminated plates, the present element shows no sign of shear locking. A number of computational examples are given to demonstrate the efficiency and the accuracy of the present method.

ABSTRACT: The stability of shear-deformable plates under constant initial stresses is studied by the spline finite strip method. Third-order plate theory is used as the basis for developing the strip element. The classical B3-spline function is modified in such a way that the resulting spline finite strip element incorporates the merits of spline interpolation and the versatility of the finite element method. A set of demonstration analyses are presented to show the validity of the modified spline finite strip method.


ABSTRACT: A global-local approach is proposed to analyse thick laminated plates. This approach treats a thick laminated plate as a three-dimensional inhomogeneous anisotropic elastic body. The cross-section of a laminated plate is first discretized into conventional eight-node elements. The interpolation function along the span of the plate is defined by the cubic B3-spline function. The displacement functions can be expressed as the product of the usual isoparametric shape functions and the spline function. A set of global polynomials of an appropriate order is selected to transform the nodal variables of the cross-section to a much smaller set of generalized parameters associated with the polynomials. These parameters can be obtained by means of the standard Rayleigh-Ritz technique. The total number of unknowns involved is drastically reduced with a minor sacrifice of accuracy. The six components of stresses, the fundamental natural frequencies and the critical buckling loads can be determined with acceptable accuracy. Numerical examples are given to demonstrate the accuracy and effectiveness of the global-local procedures.


ABSTRACT: In this paper, the original spline finite strip, which is based upon the thin-plate theory, is modified and generalized in the sense that the formulation is based upon a third-order plate theory and is applicable to thin plates and shear-deformable plates (e.g. thick isotropic plates and laminated composite plates). To extend its application to nonlinear analysis, displacement formulation is employed with geometric nonlinearity and small initial imperfection taken into account. To demonstrate the performance of the present finite strip in the analysis of plates, a number of numerical examples are given.


ABSTRACT: The isoparametric spline finite strip method has been applied to the free vibration and stability analysis of shells. The convergence of the method is reviewed critically. Additional numerical examples on shells of different geometry are also employed to demonstrate the efficiency, accuracy and versatility of the method.

ABSTRACT: This paper deals with the development of a family of higher order B-spline finite strip models applied to the static and free vibration analysis of laminated plates, with arbitrary shape and lay-ups, loading and boundary conditions. The lamination scheme can be such that the embedded and/or surface bonded piezoelectric actuating and sensing layers are included. The structure is discretised in a specified number of strips, and the geometry and displacement components of each strip are represented by interpolating functions that are products of linear or cubic B-spline, and linear or quadratic Lagrange functions along the y and x orthonormal directions. The accuracy and relative performance of the proposed discrete models are compared and discussed among the developed and alternative models.


ABSTRACT: Description is given of both spline and semi-analytical finite strip method for predicting the post-buckling response of rectangular composite laminated plates with initial imperfections, when subjected to progressive end shortening. The initial imperfections are all assumed to be of the sinusoidal shape in the longitudinal direction, and of different shapes in the transverse direction. The laminates are simply supported out of their plane at the loaded ends as well as unloaded edges. The in-plane lateral expansion is allowed all around the plates. The plates are assumed to be thin so that the analysis can be carried out based on the classical plate theory. Geometric non-linearity is introduced in the strain-displacement equations in the manner of the von Karman assumptions. The formulations of the finite strip methods are based on the concept of the principle of the minimum potential energy. The Newton-Raphson method is used to solve the non-linear equilibrium equations. A number of applications involving plates with different shapes of initial imperfections are described to investigate the capability of both versions of finite strip method.


ABSTRACT: A geometrically non-linear finite strip for the post-buckling analysis of geometrically perfect thin symmetric cross-ply laminated plates under uniform end shortening is presented in this paper. The formulation of the aforementioned finite strip is based on the concept of the semi-energy approach. In this method, the out-of-plane displacement of the finite strip is the only displacement which is postulated by a deflected form. The postulated deflected form is substituted into von Kármán’s compatibility equation which is solved exactly to obtain the corresponding forms of the mid-plane stresses and displacements. The solution of von Kármán’s compatibility equation and the postulated out-of-plane deflected form are then used to evaluate the potential
Energy of the related finite strip. Finally, by invoking the Principle of Minimum Potential Energy, the equilibrium equations of the finite strip are derived. The developed finite strip is then applied to analyze the post-local-buckling behavior of thin flat laminates. The results are discussed in detail and compared with those obtained from finite element method (FEM) of analysis. It should be mentioned that the FEM analysis was carried out employing the general purpose ANSYS package. The study of the results has provided confidence in the validity and capability of the developed finite strip in handling the post-buckling problem of symmetric cross-ply laminated plates.


ABSTRACT: Description is given of semi-analytical finite strip method for predicting the geometrically non-linear response of rectangular composite laminated plates with initial imperfections, when subjected to progressive end shortening and pressure loading. In the finite strip formulations, the initial imperfections are all assumed to be of the sinusoidal shape in both of the longitudinal and transverse direction. The laminates are simply supported out of their plane at the loaded ends as well as unloaded edges. The plates are assumed to be thin so that the analysis can be carried out based on the classical plate theory. Geometric non-linearity is introduced in the strain–displacement equations in the manner of the von Karman assumptions. The formulations of the finite strip methods are based on the concept of the principle of the minimum potential energy. The Newton–Raphson method is used to solve the non-linear equilibrium equations. A number of applications involving plates with both initial imperfection and pressure load are described and discussed.


ABSTRACT: Two different versions of finite strip method, namely spline and semi-analytical methods, are developed for analyzing the geometrically non-linear response of rectangular composite laminated plates of arbitrary lay-up to progressive end-shortening in their plane and to pressure loading. The plates are assumed to be thin so that the analysis can be carried out based on the classical plate theory. The in-plane lateral deflection is allowed at the loaded ends of the plate, whilst the lateral expansion of the unloaded edges is either free or completely prevented. Geometric non-linearity is introduced in the strain–displacement equations in the manner of the von Karman assumptions. The formulations of the finite strip methods are based on the concept of the principle of the minimum potential energy. A number of applications involving isotropic plates, symmetric and unsymmetric cross-ply laminates are described to investigate the effects of pressure loading. The comparison between the two sets of results obtained by different finite strip methods is very good. The study of the results revealed that the response of the laminates is significantly influenced by the application of the normal pressure loading. Particularly, the response of unsymmetric laminates is strongly affected by the sign of the normal pressure loading.

ABSTRACT: In composite laminated plates various mechanical properties may be attained by changing the lay-up arrangement. The bend–twist coupling is one of the significant properties which dominate the mechanical performance of a laminated plate structure in large out-of-plane deformations. The effects of bend–twist coupling on the post-buckling behavior of composite laminated plates have been studied in this paper by implementing a finite strip approach based on the concept of a rigorous post-buckling solution for composite plates and plate structures, namely the semi-energy approach. All the plates are assumed to be symmetrically balanced laminates having uniform in-plane stiffness properties. As far as the out-of-plane stiffness properties are concerned, all the properties, except for the bend–twist coupling terms which are assumed to change from one laminate to another, are the same among different laminates. The orthotropic solutions have also been determined by precluding the bend–twist coupling terms. A comprehensive set of parametric studies have been carried out to investigate the effects of bend–twist coupling terms on the post-buckling load–displacement path, post-buckling deformations and stress distribution. The comparison between the results revealed markedly different behaviors among different laminates due to the bend–twist coupling effects. The outcome of the paper can help structural designers to have a better understanding of the effects of bend–twist coupling terms on the post-buckling behavior of laminated composite plates at the design stage.


ABSTRACT: This paper presents the theoretical developments of an exact finite strip for the buckling and initial post-buckling analyses of I-section struts. The so-called exact strip is developed based on the concept that it is effectively a plate. The presented method, which is designated by the name Full-analytical Finite Strip Method, provides an efficient and extremely accurate buckling solution. In the development process, the Von-Karman's equilibrium equation is solved exactly to obtain the buckling loads and mode shapes for the I-section struts. The investigation of buckling behavior is then extended to an initial post-buckling study with the assumption that the deflected form immediately after the buckling is the same as that obtained for the buckling. The current post-buckling study is effectively a single-term analysis, which is attempted by utilizing the so-called semi-energy method. Through the solution of the Von-Karman's compatibility equation, the in-plane displacement functions which are themselves related to the Airy stress function are developed in terms of the unknown coefficient in the assumed out-of-plane deflection function. All the displacement functions are then substituted in the total strain energy expressions. The theorem of minimum total potential energy is subsequently applied to solve for the unknown coefficient. Finally, the developed method is subsequently applied to analyze the initial post-buckling behavior of some representative I-sections for which the results were also obtained through the application of a Semi-energy Finite Strip Method [Ovesy HR. The development and application of a semi-energy post-local buckling finite strip. PhD dissertation, Cranfield University, UK, 1998]. Through the comparison of the results and the appropriate discussion, the knowledge of the level of capability of the developed method is significantly promoted.

H.R. Ovesy and H. Assaee (Aerospace Engineering Department, Center of Excellence in Computational
ABSTRACT: In composite laminated plates, the mechanical coupling is one of the significant properties that dominate the performance of a laminated plate structure in large out-of-plane deformations. Some effects of mechanical coupling on the post-buckling behavior of composite laminated plates have been studied in this paper by implementing a finite strip approach based on the concept of a rigorous post-buckling solution for composite plates and plate structures, namely the semi-energy approach, which has been originally developed by the authors of this paper. Moreover, to check the validity and soundness of the presented semi-energy FSM the results obtained from the developed approach are compared with those obtained from a fairly conventional and well-exploited finite strip technique, namely the full-energy finite strip method as well as the results obtained from ANSYS (i.e., the general purpose finite element method software). In this paper, the post-buckling behavior of an anti-symmetric angle-ply square plate with the stacking sequence configuration as \([\pm 45]^2\) has been studied. Moreover, according to the anti-symmetric nature of lamination in the mentioned plate, there exists a mechanical coupling between in-plane membrane and out-of-plane twisting curvature; therefore, the results of this analysis have been referred as coupled solutions in this paper. In order to evaluate the effects of mechanical coupling on the post-buckling performance of mentioned plates, the uncoupled solution has also been determined by precluding the coupling terms (i.e., B16, B26). The post-buckling load–end shortening and load–maximum out-of-plane deflection paths have been obtained for coupled as well as uncoupled solutions. The comparison between the obtained results by coupled and uncoupled solutions revealed markedly different behaviors due to the presence of mechanical coupling in the anti-symmetric angle-ply laminates. The outcome of this paper can help structural designers have a better understanding of the effects of mechanical coupling on the post-buckling behavior of laminated composite plates at the design stage.


ABSTRACT: This paper presents theoretical developments of an exact finite strip for the buckling analysis of symmetrically laminated composite plates and plate structures. The so-called exact finite strip is developed based on the concept that it is effectively a plate and the von-Kármán’s equilibrium equation is solved exactly to obtain the general form of out-of-plane buckling deflection mode for the corresponding strip. This shape function is used to obtain a transcendental stiffness matrix for the strip through the minimization of the potential energy technique. The overall stiffness matrix for the whole section is obtained by assembling the individual strip stiffness matrices. Within the overall stiffness matrix, due to the special characteristics of the developed exact strip, it is not possible to identify a separate geometric stiffness matrix, which is independent of the buckling load parameter in the case of conventional FEM or FSM methods. In this paper, two secure methods (i.e., bisection method and recursive Newton’s method) for finding the buckling load and the corresponding buckling mode of the plate structures are used. The calculated buckling loads and the corresponding modes are exact in the sense that in their calculation, the usual approximations which are made in the conventional finite element or finite strip methods are avoided.

H.R. Ovesy and J. Fazilati, (Aerospace Engineering Department and Center of Excellence in Computational...

ABSTRACT: In the present paper, the linear eigen buckling analysis and the non-linear post-buckling equilibrium path of composite laminated plates and cylindrical shell structures are investigated. The method of analysis is the semi-analytical finite strip approach which has been developed originally on the basis of full energy methods. The strip established here is the one with the radius of curvature “R” in the transverse direction, whilst in the longitudinal direction the strip has no curvature. In the longitudinal direction, shape functions of trigonometric type are applied due to their continuous characteristics. The application of the latter shape functions has allowed the energy integrations to be performed analytically in the longitudinal direction. The method is generally known as “Semi-Analytical”. It is noted that the use of trigonometric functions has limited the boundary conditions at the loaded ends of the strip to the simple supported one. In the transverse direction, the first-order Lagrange shape functions are used for the in-plane displacements, and the third-order Hermite functions are utilized to estimate the out-of-plane displacements. In the linear buckling analysis, the strain–displacement relationships are based on the Koiter– Sanders theory of shells, whilst in the non-linear post-buckling developments Donnell’s type of shell theory (Donnell’s strain–displacement relationships) is applied. It is noted that to the authors’ knowledge the incorporation of Donnell’s shell theory into the formulations of the semi-analytical finite strip method for the post-buckling non-linear analysis of the structures has not been attempted elsewhere. To check the validity and soundness of the results, some case studies are performed by implementing the finite strip method as well as the finite element method. For further validation, the obtained results are also compared with those available in the literature.


ABSTRACT: Two versions of finite strip method (FSM) namely semi-analytical and spline methods are developed to calculate the stability and instability regions in the case of flat and curved thin-walled composite laminated structures under harmonic axial in-plane loads in the context of so-called parametric loading. The strain terms are expressed in terms of the Koiter–Sanders theory of shallow shells. In order to demonstrate the capabilities of the developed methods in predicting parametric behavior of the subject structures, some representing results are obtained and compared with those in the literature. Good accuracy in the results is achieved.

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ABSTRACT: The application of the semi-energy CLPT-FSM for the non-linear analysis of symmetric laminates is extended to include the effects of normal pressure loading in addition to the end-shortening.
Moreover, a new semi-energy FSM is developed based on the concept of FSDT theory in order to attempt the large deflection solution for relatively thick laminates. It is noted that for a given level of accuracy, the developed semi-energy FSM requires a markedly lower number of degrees of freedom compared to those of FEM analysis. Hence, the semi-energy FSM is more computationally efficient than the conventional energy based schemes.

ABSTRACT: A Reddy type, third order shear deformation theory of shells is applied to the development of two versions of finite strip method (FSM), namely semi-analytical and spline methods, to predict the parametric stability and instability regions in the case of cylindrical moderately thick composite laminated panels. The structures are assumed to be under harmonic in-plane loads in the context of the so-called parametric loading. The linear strain terms are expressed in terms of the Koiter-Sanders theory of shallow shells. In order to demonstrate the capabilities of the developed methods in predicting parametric behavior of the subject structures, some representative results are obtained and compared with those in the literature wherever available.

H.R. Ovesy and J. Fazilati (Aerospace Engineering, Amirkabir University of Technology, Tehran, Iran), “Buckling and free vibration finite strip analysis of composite plates with cutout based on two different modeling approaches”, 16th International Conference on Composite Structures (ICCS 16), Porto, 2011, A.J.M. Ferreira (Editor)
SUMMARY: The static stability and dynamic behavior of moderately thick laminated plates are studied by using the developed higher order finite strip method (FSM). The effects of internal cutouts are modeled applying two different modeling approaches. Some results are presented and the methods are compared.

SUMMARY: The dynamic instability of cylindrical shell panels having internal cutouts is studied by using the developed finite strip method (FSM). The effects of perforations are investigated using a negative stiffness modeling approach. Good accuracy in the results is achieved.

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This paper is concerned with buckling analyses of rectangular functionally graded plates (FGPs) under uniaxial compression, biaxial compression and combined compression and tension loads. It is assumed that the plate is a mixture of metal and ceramic that its properties changes as a function according to the simple power law distribution through the plate thickness. The fundamental eigen-buckling equations for rectangular plates of functionally graded material (FGM) are obtained by discretizing the plate into some finite strips, which are developed on the basis of the higher order plate theory (HOPT). The solution is obtained by the minimization of the total potential energy. Numerical results for a variety of FGPs are given, and compared with the available results, wherever possible. The effects of thickness ratio, variation of the volume fraction of the ceramic phase through the thickness, aspect ratio, boundary conditions and also load distribution on the buckling load capacity of FGM plates are determined and discussed. It is found that the buckling behavior of FGM plates is particularly influenced by application of HOPT, especially when the plates are thick.


This paper is concerned with the parameter sensitivity analysis of structures undergoing large displacements. The authors introduce the analytical sensitivity expressions for an element independent co-rotational formulation of a geometrically nonlinear finite element method. An extension of this formulation to treat follower forces is presented. The co-rotational framework uses a pre-existing linear finite element library and does not require the development and implementation of kinematically nonlinear element formulations. This feature along with the element independence makes the co-rotational framework an attractive option for the implementation of geometrically nonlinear analysis and sensitivity analysis capabilities. The sensitivity formulations with respect to shape and material parameters are presented and their numerical treatment is discussed. The importance of a consistent tangent stiffness, including unsymmetric terms, on the accuracy of computed sensitivities is addressed. The framework is applied to shape and topology optimization examples, verifying the methodology and highlighting the importance of accounting for large displacement effects in design optimization problems.

N. El-Abbasi and S. A. Meguid (Engineering Mechanics and Design Laboratory, Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, ON, M5S 3G8, Canada), “Finite element modeling of the thermoelastic behavior of functionally graded plates and shells”, International Journal of Computational Engineering Science, Vol. 1, Issue 1, June 2000

A new thick shell element is used to study the thermoelastic behavior of functionally graded structures made from shells and plates. The element accounts for the varying elastic and thermal properties across its thickness. It also accounts for the thickness change, normal stresses and strains. The nonlinear heat transfer equations governing the through-thickness thermal distribution are treated using the Rayleigh-Ritz method. Prescribed temperatures as well as convection conditions are imposed on both faces of the shell. Three examples involving functionally graded beams, circular plates and spherical shells are examined. The effect of the volume fraction of the constituent materials and the through-thickness integration order are also investigated.

J. Woo and S. A. Meguid (Engineering Mechanics and Design Laboratory, Department of Mechanical and
ABSTRACT: In this paper, an analytic solution is provided for the coupled large deflection of plates and shallow shells made of functionally graded materials (FGMs) under transverse mechanical loads and a temperature field. The material properties of the functionally graded shells are assumed to vary continuously through the thickness of the shell, according to a power law distribution of the volume fraction of the constituents. The fundamental equations for thin rectangular shallow shells of FGM are obtained using the von Karman theory for large transverse deflection, and the solution is obtained in terms of Fourier series. The effect of material properties, shell geometry and thermomechanical loading on the stress field are determined and discussed. The results reveal that thermomechanical coupling effects play a major role in dictating the response of the functionally graded shell.

References listed at the end of the paper:

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ABSTRACT: In this paper, an analytical solution is provided for the postbuckling behaviour of moderately thick plates and shallow shells made of functionally graded materials (FGMs) under edge compressive loads and a temperature field. The material properties of the functionally graded shells are assumed to vary continuously through the thickness of the shell, according to a power law distribution of the volume fraction of the constituents. The fundamental equations for moderately thick rectangular shallow shells of FGM are obtained using the von Karman theory for large transverse deflection and high-order shear deformation theory.
for moderately thick plates. The solution is obtained in terms of mixed Fourier series and the obtained results are compared with those of the Reissner–Mindlin's theory for moderately thick plates and the classical theory ignoring transverse shear deformation. The effect of material properties, boundary conditions and thermomechanical loading on the buckling behaviour and the associated stress field are determined and discussed. The results reveal that thermomechanical coupling effects and the boundary conditions play a major role in dictating the response of the functionally graded plates and shells under the action of edge compressive loads.

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“Accurate modeling of the crush behaviour of thin tubular columns using material point method”, Science China Physics, Mechanics and Astronomy, Vol. 56, No. 6, pp 1209-1219, June 2013

DOI: 10.1007/s11433-013-5073-x

ABSTRACT: In this paper, we apply the material point method (MPM), also known as a meshfree method, to examine the crush behaviour of thin tubular columns. Unlike the finite element method, randomly-distributed-weak-particle triggers were used to account for the deformation behaviour of collapse modes. Both symmetric and asymmetric modes of deformation and their associated mean collapse loads are determined for an elastoplastic constitutive law describing the tubular columns. Attention was devoted to the accuracy and the convergence of the MPM simulation, which is determined by the number of the particles and the size of the background cells used in our explicit solver. Furthermore, a novel contact approach was adopted to establish the crush behaviour of the tubular columns. Two aspects of the work were accordingly examined, including three different crush velocities (5, 10 and 15 m/s) and varied geometrical features of the tube (t/d and l/d) based on the deformation history. The results of our model, which were compared with existing analytical predictions and experimental findings, identify the critical geometric features of the tubular columns that would dictate the deformation mode as being either progressive collapse or following Euler’s buckling mode.

References listed at the end of the paper:
1. Mallock A. Note on the instability of tubes subjected to end pressure and on the folds in a flexible material. Proc R Soc Ser A, 1908, 81: 388–393

ABSTRACT: (none given)

ABSTRACT: Interface technology for geometrically nonlinear analysis is presented and demonstrated. This technology is based on an interface element which makes use of a hybrid variational formulation to provide for compatibility between independently modeled connected sub-domains. The interface element developed herein extends previous work to include geometric nonlinearity and to use standard linear and nonlinear solution procedures. Several benchmark nonlinear applications of the interface technology are presented and aspects of the implementation are discussed.
References listed at the end of the paper:


G. W. Housner and M. A. Haroun (California Institute of Technology, Pasadena, Californial 91125), “Dynamic analyses of liquid storage tanks”, (no publisher or date given in the pdf file. Most recent reference is 1980.) ABSTRACT: Theoretical and experimental investigations of the dynamic behavior of ground-supported, deformable, cylindrical liquid storage tanks were conducted. The study was carried out in three phases: A) a detailed theoretical treatment of the coupled liquid-shell system, B) an experimental investigation of the dynamic characteristics of full-scale tanks, and C) a development of an improved design procedure based on an

ABSTRACT: The nonlinear analysis of elastic-plastic shells of revolution is performed by combining an efficient one-dimensional transfer-matrix approach on the element level with the usual finite element assemblage of the system. It is based on a Fourier-representation of the loading, the shell variables and initial imperfections in the circumferential direction. This semi-analytical procedure is formulated for geometrically and physically nonlinear problems. It is applied to the detailed investigation of the buckling behavior and imperfection sensitivity of various dished end closures under external pressure.

References listed at the end of the paper:
ABSTRACT: The paper deals with the results of systematic numerical studies on the nonlinear load-carrying and buckling behavior of ring-stiffened circular cylindrical shells under external pressure. In particular it focuses attention on the conditions under which stiffeners with rectangular cross-sections lead to either global or local (interstiffener) buckling and on the influence of elastic-plastic material behavior. The numerical results are presented in the form of nondimensional diagrams in which the buckling loads of stiffened shells are given directly as functions of a global stiffening parameter containing all relevant information on both the shell’s geometry and the type and arrangement of the stiffeners. They indicate the buckling mode as well as the amount by which the load-carrying capacity of a stiffened shell is larger than that of the corresponding unstiffened one. This makes them particularly useful for practical design purposes.

ABSTRACT: The dynamic behaviour of liquid-filled shells of revolution is investigated considering the soil–structure interaction and the fluid–structure interaction, respectively. In the circumferential direction the loads and variables are approximated by Fourier series. The shell is modelled through shell ring elements including non-linear behaviour, coupled with isoparametric continuum ring elements and special infinite elements for the soil and isoparametric pressure ring elements for the fluid. Transient loadings like earthquake excitation and the non-linearities of the shell and the soil require an analysis in the time domain. To reduce the size of the problem, linear parts of the system are condensed by the substructure technique. The soil region is divided into
two parts, a near field permitting non-linearities like plastification or uplifting of the shell, and a far field for the treatment of radiation of energy. The boundary conditions for the shell footing have a strong influence on the distribution of the axial membrane forces and, hence, on the stability limit, which is mostly governed by plastic collapse and caused by the dynamically activated pressure acting on the tank wall. It is shown how the soil properties influence the dynamic stability of the shell under harmonic excitation and under realistic earthquake motion.


ABSTRACT: For the evaluation of the imperfection-sensitivity of elastic and elastic-plastic shells a fully nonlinear finite-element-method has been developed that directly gives the ‘worst’ imperfection shape connected to the ultimate limit load. The approach uses no approximations such as asymptotical theories or computations in the deep postcritical range. The key point of the method is the description of imperfections as nodal degrees of freedom at the element level. These unknown quantities are implemented by isoparametric shape functions in a finite shell element including finite rotations and thickness stretch. The ultimate buckling load and the corresponding ‘worst’ imperfection shape is defined by two different criteria and numerically determined by an extended system of nonlinear equations. In the computation of the structurally stable collapse the deflections, the imperfection shape, the eigenvector and the lowest possible load-level are obtained. The method is illustrated by several numerical examples.


ABSTRACT: This paper deals with the numerical evaluation of the limit loads and of the imperfection sensitivity of shells. A semi-analytic treatment of the field equations governing the nonlinear static behaviour of shells of revolution as well as a novel approach for general shells to construct the relationship between the limit load and amplitudes and shapes of the ”worst” imperfections in a direct way are covered. Applying these methods a large number of results for thin shells are analyzed investigating the influence of the material behaviour, the geometry and the boundary conditions. Included are also combinations of shells and high imperfection sensitive shells. For several types of shells the load carrying behaviour and their imperfection sensitivity is discussed.

References listed at the end of the paper:

ABSTRACT: Liquid-filled storage tanks under earthquake excitation are loaded by hydrodynamic pressure due to the interactive motion with the containing fluid. The dynamic response and the buckling of these tanks have been studied by many authors both experimentally and theoretically, but a unified design procedure is still lacking. To gain insight more easily into the load carrying behavior and failure mechanism of anchored tanks, a quasistatic approach is presented in this paper instead of solving the coupled problem in the time domain. For these purposes, a nonlinear finite element procedure is applied using pressure eigenforms as equivalent loads. The numerical model used for the investigations is discretized by mixed ring shell elements taking geometric and physical nonlinearities into account. Different superpositions of the pressure eigenforms which are calculated by a special interactive model lead to different behavior of the tank-fluid system depending on the intensity of the horizontal and the vertical earthquake component. The results obtained are compared with classical values and with simplified design procedures provided in Eurocode 8, Part 4.


ABSTRACT: This paper deals with the dynamic behavior of flexibly supported liquid-filled storage tanks under earthquake excitation. A simplified mechanical model is proposed to simulate the characteristics of the surrounding soil with its energy absorbing properties. In addition, a quasistatic approach is presented to analyse certain types of instability phenomena. Some examples which are verified by more detailed investigations in the time domain give insight into the particular dynamic behavior of these tanks. The results are also compared to
those obtained by the current design procedure provided in the current draft of EC8, part 4.

References listed at the end of the paper:


ABSTRACT: For the design of spherical shells under external pressure relatively few information can be found in corresponding codes and recommendations, e.g. not at all in the new draft of Eurocode 3 ENV 1993-1-6. Under this aspect, new design rules for these shells were developed, which take into account relevant details like boundary conditions, material properties, and imperfections. They are usually based on a large number of systematic numerical simulations to obtain results describing the load carrying behaviour and imperfection sensitivity of thin spherical shells. In addition, previous theoretical and experimental results are discussed. Based on the results, diagrams and design rules have been developed which might be used for new recommendations in the design concept of the Eurocode.

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ABSTRACT: Based on rigorous parametric non-linear elastic buckling analyses, the present work underlines the developments towards theoretical lower bounds of existing experimental buckling loads for some of the
most practical shell geometries and loading cases, namely circular cylindrical shells under external pressure and/or axial loads and spherical caps under external pressure. Simple equations and formulae are presented and their predictions for buckling loads are compared with available test results and values prescribed by some of the existing design codes. These explicit lower bounds are close and non-conservative estimates of buckling loads of imperfect shells and as such are proposed as a consistent and rational basis for design of these shell structures.


ABSTRACT: Elevated silos and tanks in steel usually consist of a cylindrical vessel and a conical hopper. One of the main areas of interest in design is the junction of the cylindrical and the conical structure where large circumferential compressive stresses may cause failure by instability. This paper describes the buckling behavior of the cylindrical and the conical wall in the junction area and the overall stability of a stiffening ring located at the junction.


ABSTRACT: Cylindrical steel containments, like silos and tanks, frequently rest on column-supports, which induce high local axial forces into the shell. This causes pronounced stress concentrations, which might impair the shell by local yielding or buckling failure above the support. The load-carrying behaviour of such axially loaded cylindrical shells has been investigated in recent years resulting in proposals for design rules. However, in many practical cases the axial loading acts in combination with internal pressure caused by the filling medium of the containment, which induces circumferential (hoop) stresses in the shell. The effect of these stresses on the load-carrying capacity is the objective of this paper. The study was carried out on the basis of numerical investigations, which were verified by experimental results of steel models. The calculations, based on geometrically nonlinear analyses, include the effects of geometrically imperfections as well as material plasticity. The scope of the paper covers unstiffened cylinders with a radius/thickness ratio of 500 and the steel grade Fe 360 resting on four local supports.

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ABSTRACT: Many metal silos and tanks are locally supported on columns or other discrete supports to permit easy access beneath the vessel. The discrete supports introduce local forces into the cylindrical shell, which in turn produces zones of local high axial compression. The strength of compressed cylindrical shells has long been known to be governed by buckling considerations, but the buckling strength of discretely supported cylinders has only been investigated in recent years. Design rules which pre-date this study were empirical in nature and not based on rigorous buckling calculations or tests. In the present study, the theoretical buckling
behaviour in the elastic–plastic range has been found to be so complicated that much work is needed to define the buckling strength for the purposes of structural design. This paper presents a description of the linear and nonlinear behaviour of isotropic unstiffened cylinders which are discretely supported at the lower edge. Much of the information given here is vital to the development of a more reliable design rule for shells under these loading conditions.


ABSTRACT: This chapter comprises all cases of external pressure uniformly distributed around the circumference. Due to the uniform stress field in the prebuckling state, the theoretical buckling behaviour may consistently and directly be derived from the differential equations. Accordingly, a great number of solutions for different cases are available for shells of constant wall thickness. For variable, that is, stepped wall thickness and for cylinders restrained by stiffening rings, the solutions have been derived numerically on the basis of the linear buckling equations…


ABSTRACT: The impulsive collapse of cylindrical steel shells filled with air or water is investigated experimentally. It is established that this process has distinctive characteristics associated with the existence of water compression waves, which inhibit collapse of the walls to the point of complete closure of the interior duct of the shell.

References listed at the end of the paper:


ABSTRACT: The paper reports the results of an experimental investigation of impulsive collapse of steel pipelines (filled with water or air) by an impact from two opposite sides by two massive plates accelerated simultaneously towards each other by an explosive charge. The experimental results confirmed that the proposed method of closing the walls of various standard-size pipelines filled with a liquid or gas is promising. The numerical results of a three-dimensional modeling of the dynamic collapse of tubes impacted by accelerated plates are presented. Some features of the Euler calculation technique for elastoplastic flows as applied to the description of processes occurring in devices for emergency shut-down of liquid-filled steel pipelines are considered.

References listed at the end of the paper:


ABSTRACT: This paper deals with practical problems encountered in the design of seismically loaded liquid-filled vertical tanks. Global stability, buckling under combined action of axial compression and internal pressure and the effect of flexible boundaries on axial buckling are studied. The question of the mutual interaction of global and local failure modes is considered. Numerical studies on the basis of finite element-discretized-shell models are carried out which show the typical features of the different failure modes. Both the effect of internal pressure on axial buckling (elephant foot failure) as well as the flexibility of the base ring results in noteworthy reductions of the axial buckling resistance. Global stability effects turned out to play no major role in the present tank design.


ABSTRACT: A comprehensive nonlinear finite element elastic stability analysis was performed with the aim of explaining the effect of a deep single longitudinal initial dent on the load-carrying behaviour of an externally pressurized cylindrical shell. The numerical results are compared with available test results and agree well, at least qualitatively. Imperfection sensitivity studies were carried out comparing the effect of the single dent with the effect of evenly distributed periodic initial imperfections. Imperfection sensitivity tends to vanish for increasing amplitudes of the idealized case of a single dent.


ABSTRACT: Upright cylindrical thin-walled steel containment structures, like silos and tanks, are commonly supported on discrete supports or columns to permit access beneath the hopper for the gravity withdrawal of the contents. In practical silo structures a variety of different support designs are used…. 

ABSTRACT: The buckling of laminated plates with elliptic delamination under compressive loading was studied experimentally and analytically. In the experiment, a tensile test machine was used to determine the load-displacement behavior of the delaminated plates under uniaxial loading and the buckling strength was extracted therefrom. In analysis, a nonlinear finite element program based on the updated Lagrangian formulation was developed to analyze the response of the laminated plates. The formulation includes large displacements and large rotations. The plates were divided into finite elements and the degenerated shell elements were used. The Newton-Raphson method was used to solve the resulting equation for the nonlinear system and a displacement-controlled scheme was used in the solution procedure near the buckling load. This process was repeated until a desired accuracy was achieved. The buckling behavior of mixed and global types of the delaminated composite plates were examined. Four parameters, including the size of the delaminated region, the orientation of the fiber direction, the position of the delaminated region in the thickness direction and the orientation of the major axis of the elliptic region with the loading axis, were varied to assess their influence on the buckling behavior of the plates. Good agreement was obtained between the analytical and experimental results.

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ABSTRACT: The buckling behavior of an elastoplastic cylindrical shell with a cutout under pure bending was investigated analytically and experimentally. For analysis, a finite element code based on an updated Lagrangian formulation was established to analyze the problem of bending buckling by considering nonlinear geometric and material properties. An iterative displacement-controlled scheme was adopted in the solution procedure to ensure the pure bending state and to avoid numerical instability near the limiting buckling moment. A testing device was used to perform experiments on bending buckling. The ratio of diameter to thickness of the aluminum specimens was 50; the ratio of length to diameter was 7.9. The shape of the cutout on the shell was circular or rectangular. The influence of the size and location of the cutout on the limiting buckling moment is discussed. Antisymmetric deformation around the cutout in the shells was observed after bending buckling of the shell.


ABSTRACT: Slender cylinders of intermediate length subjected to external pressure normally buckle into sinusoidal waves in the circumferential and meridional directions; the wave numbers are a function of the edge restraints, aspect ratio L/R and wall slenderness R/t. The influence of edge restraints diminishes with increasing L/R, and disappears in very long cylinders. All instability formulae purporting to evaluate the lowest eigenvalue require minimisation with respect to the circumferential wave number n; any ‘exact’ formulation requires the a
priori evaluation of \( n \). Therefore, in any investigation of the effect of boundary conditions on the buckling pressure \( q_{cr} \), the evaluation of \( n \) is crucial. The effects of imperfections and consequent non-linear response are significant in this context, and shall form the subject of a future publication. The classical solution for the estimation of \( n \) involves ‘standard’ end conditions which consist only of radial restraints, and is derived from a minimisation, for example, of the Southwell equation with respect to \( n \). For other sets of boundary conditions, the governing equations become almost intractable unless reduced theories, such as long wavelength theory, are used, and resort must be made to numerical methods such as Rayleigh-Ritz, finite differences or finite elements. To the authors' knowledge, a comprehensive theoretical or numerical study of the effect of boundary conditions on the buckling wavenumber and the critical pressure is not available in the literature.

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ABSTRACT: In the present paper, numerical and experimental investigation have been undertaken into the buckling and post-buckling behavior of thin-walled cylindrical steel shells with varying thickness subjected to uniform external pressure. For the experimental study, four different cylindrical steel shell specimens with varying thickness were tested to collapse. For the post-buckling analysis of these structures, material and geometric nonlinear collapse analysis are carried out. To trace the equilibrium paths through limit points into the post-critical range, the ‘Arc-Length-Type Method’ has been used. In order to verify the accuracy and validity of the finite element modeling, the numerical results, obtained from nonlinear finite element collapse analyses, have been compared with the results of the experimental study. The study shows that the theoretical behavior predicted by the nonlinear finite element collapse analyses followed closely the experimental behavior. Consequently, it has been found that the finite element model is reliable enough to be used to undertake nonlinear analyses for investigation into the buckling and post-buckling behavior of thin-walled cylindrical steel shells with varying thickness. Also it has been found that the buckling mode can be generated in whole length of the shell if the thickness variation is low. However, in the case of high variation of thickness, the buckling mode is formed in thinner part only. Also, the considerable effects of circumferential and vertical weld line on the buckling strength and mode shapes are verified.

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“Experimental study on the buckling and post-buckling behavior of thin-walled cylindrical shells with varying thickness under hydrostatic pressure”, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, edited by Alberto Domingo and Carlos Lazaro, Valencia, Universidad Politecnica de Valencia, Spain, pp 2511-2522
ABSTRACT: The application of thin-walled cylindrical shells, as the essential structural members, has been known for engineers and functional duty of them is basic necessities of modern industries. These structures are prone to fail by buckling under external pressure which could be happened during discharging or wind load. Although the buckling capacity of the shells depends principally on two geometric ratios of "length to radius" (L/R) and "radius to thickness" (R/t), but the effect of thickness variation on the behavior of the shells is
complicated to be studied. On the other hand, the buckling strength of thin cylindrical shells is sensitive to the magnitude and shape of geometric imperfections. The effect of thickness variation and geometric imperfections on the buckling and postbuckling behavior of cylindrical shells is experimentally investigated in this paper. Top end of the specimens has conical roof and the bottom end has simply supported conditions. The measured data and obtained results are reported for the specimens under the effect of hydrostatic external pressure. Each specimen has different variation in thickness along its length. The slender parameters of tested shells are $L/R = 2, 1, 0.5$ and $R/t = 500, 600$. In addition, the considerable effect of circumferential and vertical weld line on the buckling strength and mode shapes is verified.

References listed at the end of the paper:
[3] Aghajari, S., Abedi, K., Showkati, H., Buckling and post-buckling behavior of thin-walled cylindrical steel shells with varying thickness subjected to uniform external pressure, Thin-Walled Structures, 2006; 44; 904–909.


ABSTRACT: The buckling capacity of the cylindrical shells depends on two geometric ratios of $L/R$ and $R/t$. However the effect of thickness variation on the behavior of the shells is more complicated and the buckling strength of them is sensitive to the magnitude and shape of geometric imperfections. In this paper the effects of thickness variation and geometric imperfections on the buckling and postbuckling behavior of cylindrical shells are experimentally investigated. The obtained results are presented under the effect of uniform lateral pressure. It is found in this investigation that the buckling mode can be generated in the whole length of the shell, if the thickness variation is low.

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ABSTRACT: Submarine pipelines are deemed as thin-walled structures in which relative external pressure may be created in some cases of fluid transmission. The certain effect of this type of loading is local buckling and its propagation along the considerable length of the line. In this study, an experimental program has been performed, in which the influence of ring stiffeners on the buckling strength of pipelines is investigated. In the tests, only hydrostatic pressure is considered as the major loading case, and the effect of further loads is neglected. The modes of initial buckling, buckling propagation, postbuckling, and development of yield lines and the final collapse of the pipeline have been closely appraised. It is verified that the buckling threshold highly hikes up by attaching some light ring stiffeners. By decreasing the ring spacing, the difference between buckling and failure loads is diminished and torsion-type yield lines at failure mode occur on the pipe skin.

References listed at the end of the paper:
ABSTRACT: Cylindrical shell structures are highly susceptible to buckling phenomena when they experience compressive stress. In fact, there are few experimental researches that give the real behavior of a cylindrical shell submitted to pure bending, especially thin shells. This is due to the difficulty of pure bending applying to such thin shells and that such structures behavior under bending is frequently considered rather similar to pure compression. This chapter describes an experimental investigation of a procedure including a system for applying pure bending to cylindrical shells with radius to thickness ratio equals 155. The instrumentation consists of a new loading system in which the pure bending is applied using concentrated loads at the ends of the test model. Ultimately, the critical values for moments as well as buckling modes were compared with finite element (FE) results.

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“Experimental investigation on the effect of geometric imperfections on the buckling and post-buckling behavior of steel tanks under hydrostatic pressure”, Thin-Walled Structures, 01/2014; 74:59–69.
DOI: 10.1016/j.tws.2013.09.005

ABSTRACT: Weld-induced geometric imperfections have been reported to have especially detrimental effects on the buckling resistance of shells under hydrostatic pressure. The effect of circumferential imperfections caused by continuous welding on the joined areas between the curved panel edges of the cylindrical and conical shells of steel storage tanks with fixed conical roofs is the most important case in this context. The present paper discusses 12 laboratory specimens in three groups, labeled SP200 (S=Specimen, P=Perfect, 200=height (mm) and radius of Cylinder), SP250 (S=Specimen, P=Perfect, 250=height (mm) and radius of Cylinder) and SP300 (S=Specimen, P=Perfect, 300=height (mm) and radius of Cylinder) loaded under uniform hydrostatic pressure. The samples were modified to include circumferential imperfections at the junctions between the curved edges of the panels of the cylindrical and conical shells, with amplitudes of 2t, 4t and 8t in depth (where t is the thickness of the conical or cylindrical shell). The results of testing under different codes are compared. This study shows that geometrical imperfections at different ratios of t/R (where R the radius of the tanks) may have decreasing, neutral or increasing effects on buckling resistance and can result in softening or stiffening behaviors of the shells.

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ABSTRACT: The load acting on a cylindrical shell, with added periodic stiffeners, under a transient pressure pulse propelling a pullet (gun case) has been experimentally studied. This study is based on two modes of velocities, the first is subcritical mode and the second is supercritical mode. The stiffeners are added to the gun tube of an experimental gun facility, of 14mm bore diameter. The radial strains are measured by using high-
frequency strain gage system in phase with a laser beam detection system. Time-resolved strain measurement of the wall response is obtained and both precursor and transverse hoop strains have been resolved. The time domain analysis has been done using “wavelet transform package” in order to determine the frequency domain modes of vibrations and detect the critical frequency mode. A complete comparison of the dynamic behavior of the shell tube before and after adding periodic stiffeners has been done, which indicated that a significant damping effect reaches values between 61.5 and 38% for subcritical and critical modes. The critical frequency of the stiffened shell is increased, so the supercritical mode is changed to subcritical mode. The amplification and dispersion factors are determined and constructed; there is a reduction in the corresponding speed frequencies by about 10%. Also the radial-bending vibrations and tube muzzle motions are detected at muzzle velocity ratio of 0.99%, the results indicated that there is a significant improvement in increasing the number of rounds per second by about 36% and increasing the pointing precision by about 47%.

References listed at the end of the paper:

ABSTRACT: Using complex series representations, a quasi-analytical finite element procedure is developed which can analyze the static and dynamic mechanical fields of anisotropic axisymmetric shells and bodies. Due to its generality the procedure can handle arbitrary laminate construction with possible meridional and radial variations in locally or globally mechanically anisotropic materials. In this respect, in contrast to traditional quasi-analytical procedures which are limited to the ‘specially’ orthotropic case, the present treatment reveals several important effects of material and/or structural anisotropy. To illustrate the procedure as well as the significant effects of material anisotropy, several numerical examples are given along with comparisons with known analytical treatments.


ABSTRACT: A numerical integration procedure is developed which can obtain the frequency and buckling eigenvalues and associated eigenfunctions of prestressed rotating anisotropic shells of revolution. The axisymmetric prestress state incorporated in the analysis can consist of torque as well as anisotropy induced circumferential effects. Apart from the usual centripetal load, the rotation effects treated by the analysis also consist of Coriolis acceleration forces. The material and/or structural anisotropy included in the analysis is of the most general linear Hookean form. Hence, the stiffness matrix of the governing shell constitutive relation can be fully populated. To illustrate the numerical procedure as well as the significant effects of general axisymmetric prestress states (including torsion), Coriolis acceleration forces and material and/or structural anisotropy, several numerical experiments are given along with comparisons with analytical treatments.


ABSTRACT: A quasi-analytical finite element procedure is developed which can obtain the frequency and buckling eigenvalues of prestressed rotating anisotropic shells of revolution. In addition to the usual centrifugal forces, the rotation effects treated also include the contribution of Coriolis forces. Furthermore, since a nonlinear version of Novozhilov's shell theory is employed to develop the element formulation, the effects of moderately large prestress deflection states can be handled. Due to the generality of solution procedure developed, the axisymmetric prestress states treated can also consist of torque loads. In order to illustrate the procedures capabilities, as well as the significant effects of Coriolis forces, torque prestress and material anisotropy, several numerical experiments are presented.


ABSTRACT: Based on the finite element and perturbation procedures, an analytical-numerical approach to non-linear vibrations is developed. In particular, the overall solution employs the finite element method to handle spatial dependencies while the constrained version of the perturbation procedure is used to treat the temporal behavior. Due to the generality of the method developed, any combination of structure and boundary restraints can be treated as well as the possibility of conservative and non-conservative situations wherein the
system can have any number of frequency branches. Furthermore, the procedure is not restricted to excitations in the neighborhood of specific frequencies, but rather applies to the full range. To demonstrate the capabilities of the solution approach, the results of several numerical studies are included along with experimental verification.

ABSTRACT: Through the use of a family of generalized Rayleigh quotients, this paper considers the influence of nonstationary time dependent loads/disturbances on the spectral characteristics of structure modeled by 3-D nonpolar elasticity theory wherein the fields are treated as small excursions superposed on large. To generalize the results, the influence of nonconservatism and generalized inertia fields are admitted. The main emphasis of the work is given to determining the various properties of the eigenvalue problem arising out of such nonstationary loading situations. This includes ascertaining the occurrence of various types of spectral/critical speed shifts/bifurcations induced by moving disturbances. As a further extension of the work, the results are specialized to the eigenvalue problem arising from nonconservative gyroscopic FE simulations of moving load problems.

ABSTRACT: This paper considers the pre and post buckling behavior of general structures exposed to high temperature fields for long durations wherein creep effects become significant. The solution to this problem is made possible through the use of closed upper bounding constraint surfaces which enable the development of a new time stepping algorithm. This permits the stable and efficient solution of structural problems which exhibit indefinite tangent properties. Due to the manner of constraining/bounding successive iterates, the algorithm developed herein is largely self adaptive, inherently stable, sufficiently flexible to handle geometric material and boundary induced nonlinearity, and can be incorporated into either finite element or difference simulations. To illustrate the capability of the procedure, as well as, the physics of creep induced pre and post buckling behavior, the results of several numerical experiments are included.

ABSTRACT: This paper develops a multi phase self-adaptive predictor corrector type algorithm to enable the solution of highly nonlinear structural responses including kinematic, kinetic and material effects as well as potential pre/postbuckling behavior. The hierarchy of the strategy is such that three main phases are involved. The first features the use of a warpable hyperelliptic constraint surface which serves to upperbound dependent iterate excursions during successive INR type iterations. The second corrector phase uses an energy constraint to scale the generation of successive iterates so as to maintain the appropriate form of local convergence behavior. The third involves the use of quality of convergence checks which enable various self-adaptive modifications of the algorithmic structure when necessary. Such restructuring is achieved by tightening various conditioning parameters as well as switch to different algorithmic levels so as to improve the convergence
process. Included in the paper are several numerical experiments which illustrate the capabilities of the procedure to handle varying types of nonlinear structural behavior.

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ABSTRACT: By introducing a moving updated Lagrangian observer, this paper develops traveling finite elements with the capacity to handle the global response resulting from steadily moving contact fields. The generality of the results is such that large deformation kinematics and kinetics as well as the full compliment of inertial fields can be handled. To streamline the handling of nonlinear behavior, an elliptically constrained solution algorithm is also developed. Employing this algorithm, the results of several numerical benchmarking studies are presented which illustrate the capacity of the moving updated Lagrangian formulation as well as the potential effects of nonlinearity.

ABSTRACT: This paper overviews the current state of solution schemes used to solve pre- and postbuckling problems. Main emphasis will be given to (i) defining the generic features of buckling, (ii) outline the shortcomings associated with classical incremental Newton-Raphson type schemes, (iii) introducing the constrained incremental Newton-Raphson methodology, (iv) review capacities of various currently available general purpose codes, and (v) point out several areas of further investigation.

ABSTRACT: This paper develops strategies which enable the automatic adjustment of the constraint surfaces recently used to extend the range and numerical stability/efficiency of nonlinear finite-element equation solvers. In addition to handling kinematic and material induced nonlinearity, both pre- and postbuckling behavior can be treated. The scheme developed employs localized bounds on various hierarchial partitions of the field variables. These are used to resize, shape, and orient the global constraint surface, thereby enabling essentially automatic load/deflection incrementation. Due to the generality of the approach taken, it can be implemented in conjunction with constraints of arbitrary functional type. To benchmark the method, several numerical experiments are presented. These include problems involving kinematic and material nonlinearity, as well as pre- and postbuckling characteristics.

ABSTRACT: In a three-part series of papers, a generalized finite element analysis scheme is developed to
handle the steady and transient response of moving/rolling nonlinear viscoelastic structure. This paper considers the development of the moving/rolling element strategy, including the effects of large deformation kinematics and viscoelasticity modeled by fractional integrodifferential operators. To improve the solution strategy, a special hierarchical constraint procedure is developed for the case of steady rolling/ translating as well as a transient scheme involving the use of a Grunwaldian representation of the fractional operator. In the second and third papers [R. Kennedy and J. Padovan, Comput. Struct. 27, 259–273 (1987) and Y. Nakajima and J. Padovan, Comput. Struct. 27, 275–286 (1987)], 3-D extensions are developed along with transient contact strategies enabling the handling of impacts with obstructions. Overall the various developments are benchmarked via comprehensive 2- and 3-D simulations. These are correlated with experimental data to define modeling capabilities.


ABSTRACT: In a three-part series of papers, a generalized finite element solution strategy is developed to handle traveling load problems in rolling, moving and rotating structure. The main thrust of this section consists of the development of 3-D and shell type moving elements. In conjunction with this work, a compatible 3-D contact strategy is also developed. Based on these modeling capabilities, extensive analytical and experimental benchmarking is presented. Such testing includes traveling loads in rotating structure as well as low- and high-speed rolling contact involving standing wave-type response behavior. These point to the excellent modeling capabilities of moving element strategies.


ABSTRACT: In a three-part series of papers, a generalized finite element methodology is formulated to handle traveling load problems involving large deformation fields in structure composed of viscoelastic media. The main thrust of this paper is to develop an overall finite element methodology and associated solution algorithms to handle the transient aspects of moving problems involving contact impact type loading fields. Based on the methodology and algorithms formulated, several numerical experiments are considered. These include the rolling/sliding impact of tires with road obstructions.


ABSTRACT: Employing an instantly centered moving Lagrangian observer (ICMLO), this two part series of papers develops a finite element (FE) modeling methodology which can handle multibody problems involving several rotating components each with its own distinct rotational history. The overall thrust of the work is to enable the modeling of mechanical systems as opposed to purely structural problems. This includes the ability to simulate rotating equipment, transportation systems, aircraft frame-engine interactions, i.e. complete machinery responses. In this part, emphasis is given to (i) establishing the ICMLO, (ii) developing the FE
formulation, and (iii) deriving the associated steady and transient solution algorithms. In Part II, extensive modifications are introduced to handle automotive type vehicular models. To demonstrate the scheme, simulations involving vehicular-obstruction rollover events are presented.

ABSTRACT: Employing an instantly centered moving Lagrangian observer (ICMLO), this two part series develops a finite element scheme and associated solution algorithms which can handle the modeling of machinery involving a variety of rotating components each with its own distinct rotational history. In this part, the methodology is extended to handle the steady and transient response of ground based automotive type vehicular systems. This includes the modeling of roadway-multiple tire-suspension-vehicular structural interactions during (i) steady rolling; (ii) obstacle envelopment, as well as; (iii) motion on generalized trajectories. In particular, the simulation accounts for such aspects as (i) contact impact; (ii) rolling friction; (ii) potential liftoff, free motion and recontact during obstacle envelopment. To illustrate the scheme, a full vehicular simulation is presented.

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ABSTRACT: This paper develops a parallelizable multilevel multiple constrained nonlinear equation solver. The substructuring process is automated to yield appropriately balanced partitioning of each succeeding level. Due to the generality of the procedure, both sequential, partially and fully parallel environments can be handled. This includes both single and multiprocessor assignment per individual partition. Several benchmark examples are presented. These illustrate the robustness of the procedure as well as its capacity to yield significant reductions in memory utilization and calculational effort due both to updating and inversion.

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ABSTRACT: By considering the characteristics of deformation of rotationally periodic structures subjected to rotationally periodic loads, the periodic structure is divided into several identical substructures in this paper. If the structure is really periodic but not axisymmetric, the number of the substructures can be defined accordingly. If the structure is axisymmetric (special in the case of the periodic), the structure can be divided into any number of substructures. It means, in this case, the number of substructures is independent of the
number of buckling waves. The degrees of freedom (DOFs) of joint nodes between the neighbouring substructures are classified as master and slave ones. The stress and strain conditions of the whole structure are obtained by solving the elastic static equations for only one substructure by introducing the displacement constraints between master and slave DOFs. The complex constraint method is used to get the bifurcation buckling load and mode for the whole rotationally periodic structure by solving the eigenvalue problem for only one substructure without introducing any additional approximation. Finite element (FE) formulation of shell element of relative degrees of freedom (SERDF) in the buckling analysis is then derived. Different measures of tackling internal degrees of freedom for different kinds of buckling problems and different stages of numerical analysis are presented. Some numerical examples are given to illustrate the high efficiency and validity of this method.

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ABSTRACT: Shell element of relative degrees of freedom (SERDF) is a special transformation of solid element. It can be used in finite element (FE) analysis of both thin and thick shell structures and the formulation is simpler than normal shell elements. Introduction of additional internal degrees of freedom will improve the calculation precision. FE formulation of SERDF in the buckling analysis is derived in this article. Different measures of tackling additional internal degrees of freedom for different kinds of buckling problems and different stages of numerical analysis are presented. Some numerical examples are given to illustrate the validity of this element and the method.


ABSTRACT: In this paper a new finite element (FE) with relative degrees-of-freedom (DOF) is developed for modeling composite shells with arbitrary number of layers. With this shell element, satisfactory resolution can be ensured even if a relatively coarse FE mesh is employed. Moreover, this element can be easily connected with other solid type elements. All of these features enable its promising application in the simulation of modern composite structures, for example the buckling analysis of rotationally periodic laminated composite shells. For this kind of problem, a computational strategy that consists of the rotationally periodic FE method and this new shell element is adopted in this paper. The efficiency and accuracy of this proposed computational strategy are illustrated by two benchmarks as well as an implementation to a large scale practical structure.


ABSTRACT: This paper presents a finite element scheme to analyze the buckling behavior of composite shells subjected to thermal and mechanical loads. Firstly, a kind of multi-layered composite shell element with relative degrees-of-freedom is adopted to model laminated composite shells. Then the corresponding temperature
A new criterion of critical heat flux is proposed in place of the traditional criterion of critical temperature. Finally, the advantage of the proposed scheme is illustrated by calculating the stable region of thermal-mechanical loads for a honeycomb sandwich composite cylinder.

References listed at the end of the paper:


ABSTRACT: A finite element (FE) buckling analysis of rotationally periodic laminated composite shells is performed in this paper. Because the buckling mode of such structures is characterized as rotationally periodic, a corresponding FE buckling analysis scheme is proposed to reduce the computational expenses. Moreover, a new kind of relative degrees-of-freedom element is developed, which can be connected to other solid elements with ease and can yield satisfactory results with a relatively coarse FE mesh. Numerical results of two laminated cylindrical shells subjected to lateral pressure are compared with theoretical ones. The good agreement of them shows the validity of this new computational strategy. Finally, a practical structure is analysed to demonstrate the advantage of this method.


ABSTRACT: Buckling design of cylinders under axial compression is sensitive to the assumptions made in the modeling of initial imperfections. Normally, imperfection modes are selected solely on the basis of buckling mode considerations and their amplitudes determined using existing tolerance specifications. Whilst this approach may be used for metal cylinders, it cannot be readily applied to the design of fibre-reinforced composite cyoloinders where the effects of manufacturing on imperfection characteristics have not yet been studied in any detail. This paper presents results from a statistical analysis of imperfections on two groups of composite cylinders manufactured by lay-up. Dominant features are quantified and the effect of fibre orientation on imperfeclitons is examined. Simple models describing the random variability of imperfection modal amplitudes are presented in order to be used in buckling strength studies.
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ABSTRACT: This paper presents a detailed statistical analysis on geometric imperfections recorded on two series of nominally identical composite cylinders. These defects can be classified in two categories, both due to the particular manufacturing method used: out-of-roundness and change of thickness due to the overlapping of various layers. The statistical analysis is developed for various purposes: to evaluate the common properties of cylinders with different laminations, to build up a characteristic model for the geometric imperfections suitable for probabilistic simulations in buckling analysis and to identify the parameters for quality control processes. The analysis of the change in thickness due to overlapping layers allows evaluation of the stiffening effects of the manufacturing process that, in some cases, could affect the buckling behaviour of composite cylinders. A standard procedure for the characterization and qualification of manufacturing processes for composite shells, with particular attention to the factors that influence their buckling behaviour, is proposed.

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ABSTRACT: In most shell buckling codes, guidance on the design of conical shells is restricted to unstiffened cones and even in this case the clauses are based on the procedures for cylindrical shells. Virtually no guidance is offered on stiffened cones and the particular characteristics of conical shells are not treated in detail. In this paper, use is made of finite element analysis to quantify critical elastic response and imperfection sensitivity through numerical models, whose adequacy has been quantified through comparisons with test data. The finite element results obtained were aimed at validating existing design recommendations for unstiffened cones and at developing a design approach for stringer-stiffened cones under compression, with a philosophy and format compatible with the European Shell Buckling Recommendations (ECCS).

ABSTRACT: This article deals with the experimental buckling behaviour of glass fibre-reinforced plastic (GFRP) cylinders under concentric and eccentric compression. The laminates are of type ‘Rovimat 1200’ consisting of woven glass-fibre roving within a polyester resin matrix. Two-ply cylinders, for which the nominal radius-to-thickness ratio is about 108, with anti-symmetric lay-up of different orientation and overlapping procedure, are examined. In particular, the comparative response of cross-ply and angle-ply configurations is investigated and discussed. The results of experiments on eight models are presented including
thickness and imperfection mapping, load and strain measurements as well as salient observations regarding the behaviour of each model. Systematic and automated data acquisition techniques using a laser scanning system and computer-controlled loading procedures were used in order to provide the experimental measurements in a form that can be readily used for further analytical and design studies. The results demonstrate the significant influence of laminate orientation and loading eccentricity on the buckling strength of anti-symmetric cross-ply and angle-ply GFRP cylinders.

References listed at the end of the paper:

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ABSTRACT: In thin-walled shells of revolution with widely-spaced meridional stiffeners loaded in compression, a local panel buckling may develop. For the particular case of cylindrical panels, the buckling and postbuckling behaviour has been investigated in detail, whereas limited research is available for the more general case of conical panels. In this paper, the linear and non-linear elastic buckling response of the conical panel is studied for a wide range of shell and stiffening parameters by means of an appropriate finite element model. The classical buckling load is determined on the basis of linear analysis. The imperfection sensitivity is studied through non-linear analysis of imperfect conical panels with imperfections affine to the critical mode. Different aspects of the behaviour are quantified through suitably defined curvature parameters.

ABSTRACT: Different modes of instability might occur in thin-walled stiffened shells. In particular, local shell and stringer buckling modes and global buckling mode might develop in axially stiffened cones. In this paper, such modes are studied in conical shells under axial compression through a linear eigenvalue finite element analysis. In order to examine buckling modes in isolation (in line with typical simplified formulae) as well as competing modes together, use is made of different finite element models, including discrete and smeared models. Changes of buckling modes are captured by varying stiffener slenderness, number of stiffeners and tapering angle, treated as design parameters. Some evidence of mode interaction is recorded by the clustering of eigenvalues/eigenmodes.

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ABSTRACT: The paper presents the results obtained during a test programme involving unstiffened steel cones in compression. Due to the relatively low slenderness of the specimens, the failure was in all cases significantly influenced by plasticity effects. A plastic mechanism approach, including second order effects, is shown to be a simple and effective tool for predicting the collapse load and also for simulating the load-shortening response. The derivation of the theoretical expressions pertaining the mechanism are summarised and some aspects regarding the solution procedures are presented. Comparisons between the proposed mechanism approach and the experiments are reported. Finally, some design considerations and comments with regard to existing shell buckling codes are presented.


ABSTRACT: The design of some steel shells, like energy absorbers or bumpers, requires the knowledge of their behavior in large deformations. In this paper, the method of sequential limit analysis is presented and applied to axisymmetric shells in order to study their post-collapse response. Although the material behavior is assumed as rigid-plastic, results compare favorably with those produced by elastic-plastic incremental analyses and the procedure appears to be more efficient and numerically stable. Large displacement effects, both of stable and unstable nature, are implicitly accounted for by mesh updating.


ABSTRACT: The torsional buckling characteristic of an elastic cylinder with a hard surface coating layer is addressed in this paper. Deformations of the core and surface layer are obtained analytically through the Navier’s equation and thin shell model, respectively. Both infinitely and finitely long cylinders are studied and
the effects of the surface layer’s stiffness, thickness, residual stresses, as well as the cylinder lengths on the critical torsional angle and buckling morphologies, are discussed. It is found that either the surface rippling or global buckling mode may occur when there exist residual stresses within the surface layer. The critical torsional angle increases when the surface layer becomes stiffer and thinner. In addition, higher-order rippling modes frequently occur for a finite-length cylinder with stiffer and thinner surface layer.

References listed at the end of the paper:


ABSTRACT: Experimental and numerical simulation researches were presented on dynamic buckling behaviors of cylindrical shell subjected to explosion loading. An account is given of some principal observations made from a series of experiments in which steel cylindrical shells were subjected to central impact by 200g cylindrical TNT dynamite with different distances. By means of an finite element computer code LS-DYNA, the nonlinear dynamic response process of the cylindrical shells subjected to explosion
loading were numerically simulated with Lagrangian-Eulerian coupling method. The numerical simulation results were in good agreement with experimental data. The results provide a reference for the design of explosion-resisting structures.


ABSTRACT: In this work, surface effects including surface elasticity and residual surface stress on the buckling of nanowires are theoretically investigated. Based on modified core-shell (MC-S) model, the effective elasticity incorporating surface elasticity effect of the nanowire is derived, and by using the generalized Young-Laplace equation the residual surface stress is accounted for. The ratio of critical load with and without surface effects are obtained for a nanowire loaded in uniaxial compression. Taking silver (Ag) nanowires as an example, the analyzed results demonstrate that the influence of surface effects on the critical load of buckling becomes more and more significant as the nanowire diameter decreases. Moreover, it is shown that the influence of residual surface stress on the critical load is more prominent than that of surface elasticity.

References listed at the end of the paper:


ABSTRACT: A perturbation analysis for the impact torsional buckling of imperfective elastic cylindrical shells subjected to a step torque is given. The imperfection is supposed to be small and has arbitrary form. It is shown that only the imperfection which has the shape of static torsional buckling mode could influence the critical step torque. Finally a formula is presented for the critical step torque.

References listed at the end of the paper:
212–233.

ABSTRACT: By using the energy criterion in [3], the impact torsional buckling for the rigid plastic cylindrical shell is studied. The linear dynamic torsional buckling equations for the rigid plastic shell is drived, and the critical impact velocity is given.

References listed at the end of the paper:

PARTIAL INTRODUCTION: Glass fibre-reinforced plastic (GFRP) shells could be an attractive structural form for a number of applications in construction due to their good strength-to-weight ratio, inherent corrosion resistance, and relatively low cost compared to other composite systems. However, their efficient use is restricted by the limited availability of design criteria and by fairly scant test data on which any such criteria can be validated.…

ABSTRACT: Nowadays building design can not prescind from high requirements both for structural and physic-energetic performances. It is well known that the behaviour of light-weight structures is even better than those built with traditional materials (concrete and steel), with respect to static and dynamic loads, due to the reduced impact of horizontal and vertical forces on the structure. FRPs, despite being a fragile material, have a
good structural behavior because of their low weight and, similarly to wood, for the high level of ductility that is achieved through the use of mechanical connections among elements. Present research involves the design and optimization of a GFRP load bearing panel that maximizes the structural response with respect to concentrated and distributed loads, even of great intensity. In particular, the panel should maximize the response to compression, that is problematic because of buckling in presence of axial forces. The structural analysis is carried on using FEA software and the panel is modeled as a pultruded – monoaxial – element. The study takes into account not only the structural issues and the panel is designed as an integrated element, for facades and floors, that responds to highest Italian standards for thermal performance. Panels can be assembled together, to create modular buildings. Moreover, the weight of the panel is optimized to reach significant advantages on the construction site and reduce the need for workforce. Starting from the design stage, is given emphasis to the life-cycle of the panel and particular attention is paid to the possibilities of reuse.

References listed at the end of the paper:

ABSTRACT: Externally pressurized thin-walled GFRP composite cylindrical shell strength was studied against failure. Fiber breakage, matrix breakage, interlamine shear deformation, delamination shear deformation and micro buckling failure were investigated employing maximum failure criteria as volumetric fiber fraction factor varied. One-ply cylindrical shell with fiber angle orientation of 0 degree was modeled in ABAQUS finite element simulation and the result was varied using analytical approaches. Moreover, the pressure fluctuations for various volumetric fiber fraction factors were quadratic according to plotted graphs obtained. Meanwhile, MATLAB software was used for theoretical analysis. The comparison of two approaches was proved to be accurate. Subsequently, failure strength of various laminated GFRP cylindrical shell with different fiber angle orientations at each ply was studied for diverse volumetric fiber fraction factors. Stacking sequence, fiber angle orientations were mainly effective on failure strength.

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ABSTRACT: A study on a Circular cylindrical thin-walled shell failure made of GRP composite subjected to static internal and external pressure was carried out. The results were acquired using analytical and FEM simulation approaches for various volumetric fiber fractions. Fiber breakage, matrix breakage, interlaminar shear deformation, delamination shear deformation and micro buckling failure were investigated employing maximum failure criteria against internal and external pressure. One-ply cylindrical shell with fiber angle orientation of 0 degree was modeled in ABAQUS finite element simulation and the result was varied using analytical approaches. Moreover, the pressure fluctuations for various volumetric fiber fraction were quadratic according to plotted graphs. Meanwhile, MATLAB software was used for theoretical analysis. The comparison of two approaches was proved to be accurate. Subsequently, failure strength of various laminated GFRP cylindrical shell with different fiber angle orientations at each ply was studied for diverse volumetric fiber fraction factors. Stacking sequence, fiber angle orientations were mainly effective on failure strength.

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ABSTRACT: The buckling of an axially compressed truncated conical shell with rigid bulkheads is reinvestigated. Two improvements are made. First, the condition that the total horizontal displacement must vanish because of the rigid buckhead and axisymmetry is treated as a constraint. This constraint is brought into the system by use of the Lagrange multiplier; then a complete set of boundary conditions for conical shells is
derived by the variational method. Second, the stability is evaluated at the deformed state which is determined by the asymptotic solutions of the pair of Donnell-type equations for axisymmetric configuration. It is found that when the angle rotation at the smaller end during the loading process is taken into consideration the buckling strength is lowered to an extent comparable with the existing experimental results.


ABSTRACT: As is well known, the elastic stability of shell structures under certain loading conditions is characterised by a severely unstable postbuckling behaviour. The presence of simultaneous buckling modes (‘competing’ modes corresponding to the same critical buckling load) is deemed to be largely responsible for such a behaviour. In the present paper, within the framework of the so-called classical theory (linear bifurcation eigenvalue analysis), the buckling behaviour of axially compressed cylindrical shells is firstly reviewed. Accordingly, doubly periodic eigenvectors (buckling modes) corresponding to the same eigenvalue (critical buckling load) can be determined, and their locus in a dimensionless meridional and circumferential buckling wavenumber space is described by a circle (known as the Koiter circle). In the case of axially compressed conical shells, no clear evidence of the existence of simultaneous buckling modes can be found in the literature. Then, such a problem is studied here via linear eigenvalue finite element analyses, showing that simultaneous doubly periodic modes do also occur for cones, and that their locus in a specifically defined dimensionless wavenumber space can be described by an ellipse (hereafter termed as the Koiter ellipse) whose aspect ratio is dependent on the tapering angle of the cone.


ABSTRACT: This paper considers the dynamic stability of a nonhomogeneous orthotropic elastic cylindrical shell, the properties of which vary continuously with the coordinates in the longitudinal and thickness directions, under the effect of an external pressure varying with a power function of time. At first, the fundamental relations and the dynamic stability equations of a nonhomogeneous orthotropic elastic cylindrical shell, under the effect of an external pressure, are derived. Then, the general formulas for the critical load and the dynamic factor are obtained by using Bubnov-Galerkin and Sachenkov’s methods [1,2] and an asymptotic analysis. The respective formulas for homogeneous orthotropic and isotropic elastic cylindrical shells are found as special cases. Finally, carrying out some computations, the effect of the nonhomogeneity on the critical load and the dynamic factor are studied. The results obtained are compared with the experimental and theoretical results of other authors.


ABSTRACT: In this study, the dynamic stability of a laminated orthotropic truncated conical shell, subjected to an external pressure which is a power function of time, was considered. First, the modified Donnell-type dynamic stability and compatibility equations of a laminated orthotropic truncated conical shell, subjected to an
external pressure, were obtained. Applying the Galerkin and Sachenkov and Baktieva (1978) methods one after the other, the static and dynamic critical external pressures, the pertinent wave numbers and the dynamic factor were found explicitly. Finally, carrying out some computations for cross-ply laminated truncated conical shells, the effects of the variation of the number and orientation of the layers and the power function of time in the external pressure expression on the critical parameter were studied.

ABSTRACT: The subject of this investigation is to study the buckling of cross-ply laminated orthotropic cylindrical thin shells with variable elasticity moduli and densities in the thickness direction, under external pressure, which is a power function of time. The dynamic stability and compatibility equations are obtained first. These equations are subsequently reduced to a system of time dependent differential equations with variable coefficients by using Galerkin's method. Finally, the critical dynamic and static loads, the corresponding wave numbers, the dynamic factors, critical time and critical impulse are found analytically by applying a modified form of the Ritz type variational method. The dynamic behavior of cross-ply laminated cylindrical shells is investigated with: a) lamina that present variations in the elasticity moduli and densities, b) different numbers and ordering of layers, and c) external pressures which vary with different powers of time. It is concluded that all these factors contribute to appreciable effects on the critical parameters of the problem in question.

Abdullah H. Sofiyev and Orhan Askogan, “Dynamic buckling of an elastic orthotropic conical shell whose thickness varies as a power function”, Digest, pp 797-812, December 2002
ABSTRACT: (cannot cut and paste)

Abdullah H. Sofiyev (Department of Civil Engineering, Suleyman Demirel University, Isparta, Turkey), “The buckling of an orthotropic composite truncated conical shell with continuously varying thickness subject to a time dependent external pressure”, Composites Part B: Engineering, Vol. 34, No. 3, April 2003, pp. 227-233, doi:10.1016/S1359-8368(02)00105-1
ABSTRACT: In this study, the buckling of an orthotropic composite truncated conical shell with continuously varying thickness, subject to a uniform external pressure which is a power function of time, has been considered. At first, the fundamental relations and the Donnell type stability equations of an orthotropic composite truncated conical shell, subject to an external pressure, have been obtained. Then, employing Galerkin method, those equations have been reduced of time dependent differential equation with variable coefficients. Finally, applying the variational method of Ritz method type, the critical static and dynamic loads, the corresponding wave numbers and the dynamic factor have been found analytically. Using those results, the effects of the variations of the power in the thickness expression, the semi-vertex angle, the power of time in the external pressure expression and the ratio of the Young's moduli on the critical parameters are studied numerically, for the case when the thickness of the conical shell varies as a power and exponential function. It is observed, from the computations carried out, that these factors have appreciable effects on the critical parameters of the problem in the heading.
ABSTRACT: The subject of this investigation is to study the buckling of cross-ply laminated orthotropic truncated circular conical thin shells with variable Young's moduli and densities in the thickness direction, subjected to a uniform external pressure which is a power function of time. After obtaining the dynamic stability and compatibility equations we reduce both of them to a time dependent ordinary differential equation with variable coefficient by using Galerkin's method. The critical dynamic and static loading, the corresponding wave numbers, the dynamic factors, critical time and critical impulse are found analytically by applying the Ritz type variational method. The dynamic behavior of cross-ply laminated truncated conical shells is investigated with: (a) lamina that present variations in the Young's moduli and densities, (b) different numbers and ordering of layers, (c) variable semi-vertex angles, and (d) external pressures which vary with different powers of time. It is concluded that all these factors contribute to appreciable effects on the critical parameters of the problem in question.

ABSTRACT: The buckling of an orthotropic composite cylindrical shell with variable thickness, subjected to a dynamic loading, is reported here. At first, the fundamental relations and Donnell type dynamic buckling equation of an orthotropic cylindrical shell with variable thickness have been obtained. Then, employing Galerkin's method, these equations have been reduced to a time dependent differential equation with variable coefficients. Finally, for different initial conditions and approximation functions, applying the Ritz type variational method, analytical expression has been found for the dynamic factor. Using these results, the effect of the variations of the power of time in the external pressure expression, the loading parameter and the ratios of the Young's moduli on the dynamic factor are studied numerically for the case when the thickness of the cylindrical shell varies as a power and exponential functions. It has been observed that these effects change the dynamic factor of the problem in the heading appreciably.

ABSTRACT: This study considers torsional buckling of cross-ply laminated orthotropic composite cylindrical thin shells under loads, which is a power function of time. The modified Donnell type dynamic stability and compatibility equations are obtained first. These equations are subsequently reduced to a time dependent differential equation with variable coefficients by using Galerkin's method. The critical parameters are found analytically by applying the Ritz type variational method. According to theoretical solutions, numerical analyses are done.

Zihn Zerin (Department of Civil Engineering, Ondokuz Mayis University, Samsun, Turkey), “On the vibration of laminated nonhomogeneous orthotropic shells”, Meccanica, Vol. 48, No. 7, pp 1557-1572, September 2013
ABSTRACT: In this paper, an analytical procedure is given to study the free vibration of the laminated
homogeneous and non-homogeneous orthotropic conical shells with freely supported edges. The basic relations, the modified Donnell type motion and compatibility equations have been derived for laminated orthotropic truncated conical shells with variable Young’s moduli and densities in the thickness direction of the layers. By applying the Galerkin method, to the basic equations, the expressions for the dimensionless frequency parameter of the laminated homogeneous and non-homogeneous orthotropic truncated conical shells are obtained. The appropriate formulas for the single-layer and laminated complete conical and cylindrical shells made of homogeneous and non-homogeneous, orthotropic and isotropic materials are found as a special case. Finally, the influences of the non-homogeneity, the number and ordering of layers and the variations of the conical shell characteristics on the dimensionless frequency parameter are investigated. The results obtained for homogeneous cases are compared with their counterparts in the literature.

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“The Buckling of Laminated Cylindrical Thin Shells under Torsion Varying as a Linear Function of Time”,


ABSTRACT: The buckling of laminated orthotropic cylindrical thin shells under torsion, which is a linear function of time, has been investigated. First, fundamental relations and the modified Donnell type stability equations of the laminated cylindrical thin shells are derived. Applying Galerkin’s method, a differential equation having a variable coefficient depending on time is obtained and by applying the Ritz-type variational method to these equations, general formulas for static and dynamic critical loads, corresponding wave numbers and the dynamic factor are obtained. Finally after performing the computations, the effects of the variations of the numbers and ordering of layers, loading speed, and the ratio of radius to thickness on the critical parameters are investigated.

References listed at the end of the paper:
ABSTRACT: This study considers the buckling of an elastic truncated conical shell having a meridional thickness expressed by an arbitrary function, subject to a uniform external pressure, which is a power function of time. At first, the fundamental relations and Donnell type dynamic buckling equation of an elastic conical shell with variable thickness have been obtained. Then, employing Galerkin's method, those equations have been reduced to a time-dependent differential equation with variable coefficients. Finally, applying the Ritz type variational method, the critical static and dynamic loads, the corresponding wave numbers, dynamic factor and critical stress impulse have been found analytically. Using the results, thus obtained, the effects of the thickness variations with a power or an exponential function, the variation of the semi-vertex angle and the variation of the power of time in the external pressure expression are studied through pertinent computations. It is observed that these factors have appreciable effects on the critical parameters of the problem in the heading.

ABSTRACT: In this work, the stability of conical shells made of functionally graded materials (FGMs) subject to a uniform external pressure, which is a power function of time, has been studied. The material properties of functionally graded shells are assumed to vary continuously through his thickness of the shell, according to a power law distribution of the volume fractions of the constituents. The fundamental relations, the dynamic stability and compatibility equations of functionally graded truncated conical shells are obtained first. Applying Galerkin's method, these equations have been transformed to a pair of time dependent differential equation with variable coefficient. This differential equation is solved for different initial conditions by variational method by using Lagrange–Hamilton type principle. Thus, general formulas have been obtained for the critical parameters. The results show that the critical parameters are affected by the configurations of the constituent materials, loading parameters variations, the variation of the semi-vertex angle and the power of time in the external pressure expression variations. Comparing results with those in the literature validates the present analysis.
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“The stability of functionally graded cylindrical shells under linearly increasing dynamic torsional loading”,

ABSTRACT: In this study, a formulation for the stability of cylindrical thin shells made of functionally graded material (FGM) subjected to torsional loading varying as a linear function of time is presented. The properties are graded in the thickness direction according to a volume fraction power law distribution. The modified Donnell type dynamic stability and compatibility equations are obtained. Applying Galerkin’s method then applying Lagrange–Hamilton type principle to these equations taking the large values of loading speed into consideration, analytic solutions are obtained for critical torsional parameters values. The results show that the critical torsional parameters are affected by the configurations of the constituent materials variations. Comparing results with those in the literature validates the present analysis.


ABSTRACT: In this study, an analytic solution is provided for the stability and vibration behavior of truncated conical shells composed of Si3N4 and SUS304 under the axial compressive load. The material properties of the FG conical shells are assumed to vary continuously through the thickness of the shell according to quadratic and inverse quadratic distribution of the volume fraction of the constituents. The fundamental relations and governing equations for thin conical shells composed of Si3N4 and SUS304 is obtained by using Love’s shell theory and a solution is obtained by applying Galerkin’s method. The effects of the constituent volume fractions on the critical axial load and frequency parameter of the truncated conical shell are also elucidated.

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Tani, J., Yamaki, Y. (1970) Buckling of truncated conical shells under axial compression, AIAA Journal 8 568–570


ABSTRACT: In this study, the response of a FG (Functionally Graded) coated truncated conical shell subjected to an axial load is investigated by means of non-linear equations governing the finite deformations of the shell. In the solution of non-linear basic equations in the finite deflection the Superposition and Galerkin methods have been used. The effects of material property of FG composite coatings and geometrical parameters on the non-linear critical axial load are discussed in detail through a parametric study. The results are verified by comparing the obtained values with those in the existing literature.
ABSTRACT: In this study, the stability problem of a circular orthotropic cylindrical shell under the effect of an axial compression varying with a power function of time is considered. At first, the modified Donnell type dynamic stability and compatibility equations are obtained using Love’s shell theory. Applying the Galerkin and Rayleigh-Ritz variational techniques to these equations and taking the large values of loading parameters into consideration, analytics are obtained for critical parameter values. The results show that critical parameters are affected by loading parameters variations, ratio of the Young’s moduli variations, radius to thickness variations and the power of time in the axial compression expression variations. Comparing results with those in the literature validates the present analysis.

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ABSTRACT: The dynamic stability of orthotropic cylindrical thin shells of exponentially variable geometric and mechanical parameters is studied by using Galerkin and Ritz type variational methods. The qualitative and quantitative effects of the external geometry, material properties, and design features on the critical loads, corresponding wave numbers, and the dynamic factor are evaluated. Comparing results with those in the literature validates the present analysis.

ABSTRACT: In this paper, the vibration and stability of a three-layered conical shell containing a functionally
graded material (FGM) layer subjected to axial compressive load are studied. The material properties of the functionally graded layer are assumed to vary continuously through the thickness of the shell. The variation of properties follows an arbitrary distribution in terms of the volume fractions of the constituents. The fundamental relations, the dynamic stability and compatibility equations of three-layered truncated conical shells containing an FGM layer are obtained first. Applying Galerkin’s method, these equations are transformed to a pair of time dependent differential equations, and critical axial load and frequency parameter are obtained. The results show that the critical parameters are affected by the configurations of the constituent materials and the variation of the shell geometry. Comparing results with those in the literature validates the present analysis.

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ABSTRACT: The dynamic buckling of a cylindrical shell subject to a uniform axial compression, which is a linear function of time, is examined within the framework of small strain elasto-plasticity. The material of the shell is incompressible and the effect of the elastic unloading is not taken into consideration. Initially, employing the deformation theory, the fundamental relations and Donnell type stability equations have been obtained. Finally, by using the Galerkin’s methods the closed form solutions are presented. Comparing the results with those in the literature validates the present analysis.

References listed at the end of the paper:

ABSTRACT: The dynamic buckling of truncated conical shells made of functionally graded materials (FGMs) subject to a uniform axial compressive load, which is a linear function of time, has been studied. The material properties of functionally graded shells are assumed to vary continuously through the thickness of the shell. The variation of properties followed an arbitrary distribution in terms of the volume fractions of the constituents. The fundamental relations, the dynamic stability and compatibility equations of functionally graded truncated conical shells are obtained first. Applying Galerkin’s method, these equations have been transformed to a pair of time dependent differential equation with variable coefficient and critical parameters obtained using the Runge–Kutta method. The results show that the critical parameters are affected by the configurations of the constituent materials, compositional profile variations, loading speed variations and the variation of the shell geometry. Comparing the results of this study with those in the literature validates the present analysis.


ABSTRACT: The vibration and stability analysis is investigated for composite cylindrical shells that composed of ceramic, FGM, and metal layers subjected to various loads. Material properties of FG layer are varied continuously in thickness direction according to a simple power distribution in terms of the ceramic and metal volume fractions. The modified Donnell type stability and compatibility equations are obtained. Applying Galerkin’s method analytic solutions are obtained for the critical parameters. The detailed parametric studies are carried out to study the influences of thickness variations of the FG layer, radius-to-thickness ratio, lengths-to-radius ratio, material composition and material profile index on the critical parameters of three-layered cylindrical shells. Comparing results with those in the literature validates the present analysis.


ABSTRACT: In this study, the thermal buckling loads of truncated conical shells of functionally graded material are considered. The material properties of functionally graded shells are assumed to vary continuously through his thickness of the shell, according to a power law distribution of the volume fractions of the constituents. The fundamental relations, the modified Donnell type stability and compatibility equations of functionally graded truncated conical shells are obtained first. Then applying Galerkin’s method, the closed form solutions are presented for the truncated conical shell with simply supported boundary conditions subjected to three types of thermal loading. Using the obtained results, the effects of the variations of the
gradient index of materials, the semi-vertex angle and the ratio radius to thickness in the critical buckling temperature expression are studied through pertinent computations. Comparing results with those in the literature validates the present analysis.


ABSTRACT: In this study, the stability of a generic three-layered truncated conical shell containing a functionally graded (FG) layer subjected to uniform external pressure is investigated. The material properties of the functionally graded layer are assumed to vary continuously through the thickness of the shell. The variation of the properties follows an arbitrary distribution in terms of the volume fractions of the constituents. The fundamental relations, the stability and compatibility equations of three-layered truncated conical shells containing a FG layer are obtained, first. Then, applying Galerkin's method, the closed form solution for critical external pressure is obtained. The results show that the critical parameters are affected by the configurations of the constituent materials, the variations of the thickness of the FG layer and the variation of the shell geometry. Comparing the results with those in the literature validates the present analysis.

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ABSTRACT: In this paper, the buckling of non-homogeneous isotropic truncated conical shells under uniform lateral pressure and resting on a Winkler foundation is investigated. The basic relations and governing equations have been obtained for non-homogeneous truncated conical shells. The critical uniform lateral pressures of non-homogeneous isotropic truncated conical shells with or without a Winkler foundation are obtained. Finally, carrying out some computations, effects of the variations of truncated conical shell characteristics the non-homogeneity and the Winkler foundation on the critical uniform lateral pressures have been studied. The results are compared with other works in the open literature.

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ABSTRACT: In this study, the buckling of thin truncated conical shells made of functionally graded materials (FGMs) subjected to hydrostatic pressure is investigated. The material properties of functionally graded truncated conical shell are assumed to vary continuously through the thickness. The variation of properties followed an arbitrary distribution in terms of the volume fractions of the constituents. The fundamental relations, the stability and compatibility equations of FGM hybrid truncated conical shells are obtained. Using Galerkin's method, these equations were transformed to pairs of time-dependent differential equations and then hydrostatic buckling pressure expression was obtained. Numerical calculations have been made for fully metal, fully ceramic, Si3N4/Ni and ZrO2/Ti–6Al–4V truncated conical shells. The results reveal that the volume
fraction distributions have a significant effect on the buckling pressure of FGM hybrid truncated conical shells. Finally, results are validated through comparison of obtained values with those in the literature.

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ABSTRACT: In this paper, the vibration and stability of orthotropic conical shells with non-homogeneous material properties under a hydrostatic pressure are studied. At first, the basic relations have been obtained for orthotropic truncated conical shells, Young's moduli and density of which vary continuously in the thickness direction. By applying the Galerkin method to the foregoing equations, the buckling pressure and frequency parameter of truncated conical shells are obtained from these equations. Finally, carrying out some computations, the effects of the variations of conical shell characteristics, the effects of the non-homogeneity and the orthotropy on the critical dimensionless hydrostatic pressure and lowest dimensionless frequency parameter have been studied, when Young's moduli and density vary together and separately. The results are presented in tables, figures and compared with other works.

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ABSTRACT: In this paper, the free vibration and buckling of laminated homogeneous and non-homogeneous orthotropic truncated conical shells under lateral and hydrostatic pressures are studied. At first, the basic relations, the modified Donnell type dynamic stability and compatibility equations have been obtained for laminated orthotropic truncated conical shells, the Young's moduli and density of which vary piecewise continuously in the thickness direction. Applying superposition and Galerkin methods to the foregoing equations, the buckling pressures and dimensionless frequency parameter of laminated homogeneous and non-homogeneous orthotropic conical shells are obtained. The appropriate formulas for single-layer and laminated cylindrical shells made of homogeneous and non-homogeneous, orthotropic and isotropic materials are found as a special case. Finally, the effects of the number and ordering of layers, the variations of conical shell characteristics, together and separately variations of the Young's moduli and densities of the materials of layers on the critical lateral and hydrostatic pressures, and frequency parameter are found for different mode numbers. The results are compared with other works.


ABSTRACT: The purpose of this paper is to investigate the elastic buckling of FGM truncated thin conical
shells under combined axial tension and hydrostatic pressure. Here axial tensions are separately applied to small and large bases of the truncated conical shell, respectively. It is assumed that the cone is a mixture of metal and ceramic, and that its properties change as the power and exponential functions of the shell thickness. After giving the fundamental relations, the stability and compatibility equations of an FGM truncated conical shell, subject to combined axial tension and hydrostatic pressure, have been derived. Applying Galerkin’s method general formulas have been obtained for the critical combined and separate loads of FGM conical shells. The appropriate formulas for homogenous and FGM cylindrical shells are found as a special case. Effects of changing shell characteristics, material composition and volume fraction of constituent materials on the critical combined and separate loads of FGM shells with simply supported edges are also investigated. The results obtained for homogeneous cases are compared with their counterparts in the literature.

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ABSTRACT: This article presents a method to study the free vibration and stability of laminated homogeneous and non-homogeneous orthotropic cylindrical, truncated and complete conical shells of general staking with clamped edges under a hydrostatic pressure. Based on the Love first approximation theory, the basic relations, the modified Donnell-type stability and compatibility equations have been obtained for laminated orthotropic truncated conical shells, the material properties of which vary piecewise continuously in the thickness direction. To solve this problem an unknown parameter $\lambda$ was included in the approximation functions. Applying Galerkin methods, the buckling pressures and fundamental natural frequencies of laminated homogeneous and non-homogeneous orthotropic conical shells are obtained. The parameter $\lambda$ which is included in the obtained formulas is obtained from the minimum conditions of critical stresses and frequencies. The different generalized values are obtained for the parameter $\lambda$ for buckling pressures and frequencies of cylindrical shells, truncated and complete conical shells. The appropriate formulas for single-layer and laminated cylindrical shells made of homogeneous and non-homogeneous, orthotropic and isotropic materials are found as a special case. Finally, the influences of the degree of non-homogeneity, the number and ordering of layers and the variations of conical shell characteristics on the critical hydrostatic pressure and natural frequencies are investigated. The results obtained for homogeneous cases are compared with their counterparts in the literature.

References listed at the end of the paper:
This paper presents an analytical study on the dynamic behavior of the infinitely-long, FGM cylindrical shell subjected to combined action of the axial tension, internal compressive load and ring-shaped compressive pressure with constant velocity. It is assumed that the cylindrical shell is a mixture of metal and ceramic that its properties changes as a function of the shell thickness. The problem is studied on the basis of the theory of vibrations of cylindrical shells. Derived formulas for the maximum static and dynamic displacements, dynamic factors and critical velocity for the FGM cylindrical shell subjected to moving loads. Numerical calculations have been made for fully metal, fully ceramic and FGM (Si3N4/SUS304) cylindrical shells. A parametric study is conducted to demonstrate the effects of the material property gradient, the radius to thickness ratio and the velocity of the moving load on the dynamic displacements and dynamic factors of the inner and ring-shaped pressures for FGM cylindrical shells.
ABSTRACT: In this study, the stability of cylindrical shells that composed of ceramic, FGM, and metal layers subjected to axial load and resting on Winkler-Pasternak foundations is investigated. Material properties of FGM layer are varied continuously in thickness direction according to a simple power distribution in terms of the ceramic and metal volume fractions. The modified Donnell type stability and compatibility equations on the Pasternak foundation are obtained. Applying Galerkin’s method analytic solutions are obtained for the critical axial load of three-layered cylindrical shells containing an FGM layer with and without elastic foundation. The detailed parametric studies are carried out to study the influences of thickness variations of the FGM layer, radius-to-thickness ratio, material composition and material profile index, Winkler and Pasternak foundations on the critical axial load of three-layered cylindrical shells. Comparing results with those in the literature validates the present analysis.

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ABSTRACT: In this paper an analytical procedure is given to study the free vibration and stability characteristics of homogeneous and non-homogeneous orthotropic truncated and complete conical shells with clamped edges under uniform external pressures. The non-homogeneous orthotropic material properties of conical shells vary continuously in the thickness direction. The governing equations according to the Donnell’s theory are solved by Galerkin’s method and critical hydrostatic and lateral pressures and fundamental natural frequencies have been found analytically. The appropriate formulas for homogeneous orthotropic and isotropic conical shells and for cylindrical shells made of homogeneous and non-homogeneous, orthotropic and isotropic materials are found as a special case. Several examples are presented to show the accuracy and efficiency of the formulation. The closed-form solutions are verified by accurate different solutions. Finally, the influences of the non-homogeneity, orthotropy and the variations of conical shells characteristics on the critical lateral and hydrostatic pressures and natural frequencies are investigated, when Young’s moduli and density vary together and separately. The results obtained for homogeneous cases are compared with their counterparts in the literature.

Abdullah Heydaroglu Sofiyev and Mehmet Avcar (Department of Civil Engineering of Suleyman Demirel University, Isparta, Turkey), “The stability of cylindrical shells containing an FGM layer subjected to axial load on the Pasternak Foundation”, Engineering, Vol. 2, pp 228-236, 2010

ABSTRACT: In this study, the stability of cylindrical shells that composed of ceramic, FGM, and metal layers subjected to axial load and resting on Winkler-Pasternak foundations is investigated. Material properties of FGM layer are varied continuously in thickness direction according to a simple power distribution in terms of the ceramic and metal volume fractions. The modified Donnell type stability and compatibility equations on the Pasternak foundation are obtained. Applying Galerkin’s method analytic solutions are obtained for the critical axial load of three-layered cylindrical shells containing an FGM layer with and without elastic foundation. The detailed parametric studies are carried out to study the influences of thickness variations of the FGM layer, radius-to-thickness ratio, material composition and material profile index, Winkler and Pasternak foundations on the critical axial load of three-layered cylindrical shells. Comparing results with those in the literature validates the present analysis.
A.H. Sofiyev (Department of Civil Engineering, Suleyman Demirel University, 32260 Isparta, Turkey), “Influences of elastic foundations and boundary conditions on the buckling of laminated shell structures subjected to combined loads”, Composite Structures, Vol. 93, No. 8, July 2011, pp. 2126-2134, doi:10.1016/j.compstruct.2011.01.023

ABSTRACT: This article presents to study the stability of laminated orthotropic cylindrical and truncated conical shells resting on elastic foundations and subjected to combined loads with the clamped and simply supported boundary conditions. Here, axial tensile loads separately applied to the small and large bases of a laminated truncated conical shell, respectively. The basic relations, the modified Donnell type stability and compatibility equations have been obtained for laminated orthotropic truncated conical shells on the Pasternak type elastic foundation. Applying Galerkin method, the critical combined loads of laminated orthotropic conical shells on the Pasternak type elastic foundation with different boundary conditions are obtained. The appropriate formulas for single-layer and laminated cylindrical shells on the Pasternak type elastic foundation made of orthotropic and isotropic materials are found as special cases. Finally, influences of the boundary conditions, the elastic foundation, the number and ordering of the layers and variations of the shell characteristics on the critical combined loads are investigated. The results are compared with their counterparts in the literature.


ABSTRACT: Non-linear buckling analyses of imperfect functionally graded truncated conical shells with simply supported boundary conditions and subjected to an axial compressive load have been presented in this work. The material properties of functionally graded shells are assumed to vary continuously through the thickness of the shell. The non-linear prebuckling deformations and initial geometric imperfections of an FGM truncated conical shell are both taken into account. The fundamental relations, modified Donnell type non-linear stability and compatibility equations of an imperfect FGM truncated conical shell are obtained and are solved by superposition and Galerkin methods, and the upper and lower critical axial loads has been found analytically. The numerical illustrations concern the non-linear buckling response of FGM truncated conical shells with different values of truncated conical shell parameters, initial imperfections and compositional profiles. Comparing the results of this study with those in the literature validates the present analysis.


ABSTRACT: In this study, the torsional stability analysis is presented for thin cylindrical with the functionally graded (FG) middle layer resting on the Winker elastic foundation. The mechanical properties of functionally graded material (FGM) are assumed to be graded in the thickness direction according to a simple power law and exponential distributions in terms of volume fractions of the constituents. The fundamental relations and basic equations of three-layered cylindrical shells with a FG middle layer resting on the Winker elastic foundation under torsional load are derived. Governing equations are solved by using the Galerkin method. The numerical results reveal that variations of the shell thickness-to-FG layer thickness ratio, radius-to-shell thickness ratio, lengths-to-radius ratio, foundation stiffness and compositional profiles have significant effects on the critical torsional load of three-layered cylindrical shells with a FG middle layer. The results are verified by comparing the obtained values with those in the existing literature.

ABSTRACT: In this study, the non-linear buckling behavior of truncated conical shells made of functionally graded materials (FGMs), subject to a uniform axial compressive load, has been investigated using the large deformation theory with von the Karman–Donnell-type of kinematic non-linearity. The material properties of functionally graded shells are assumed to vary continuously through the thickness of the shell. The variation of properties followed an arbitrary distribution in terms of the volume fractions of the constituents. The fundamental relations, the modified Donnell type non-linear stability and compatibility equations of functionally graded truncated conical shells are obtained and are solved by superposition and Galerkin methods and the upper and lower critical axial loads have been found analytically. Finally, the influences of the compositional profile variations and the variation of the shell geometry on the upper and lower critical axial loads are investigated. Comparing the results of this study with those in the literature validates the present analysis.

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ABSTRACT: The vibration and stability analyses are presented for axially compressed three-layered truncated conical shells with a functionally graded (FG) middle layer surrounded by elastic media. The material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction according to simple power law and exponential distributions in terms of the volume fractions of the constituents. Five sets of the material mixture are considered. The Pasternak model is used to describe the reaction of the elastic medium on the truncated conical shell. The fundamental relations, the modified Donnell-type dynamic stability and compatibility equations for the three-layered truncated conical shell with an FGM middle layer are derived. The governing equations are solved by using the Galerkin method and obtained expressions for dimensionless frequency parameters and dimensionless critical axial loads for three-layered truncated conical shells with the FG middle layer with and without an elastic foundation. The numerical results reveal that variations of the shell thickness-to-FGM thickness ratio, lengths-to-radius ratio, Winkler foundation stiffness, shear subgrade modulus of the foundation, material mixture and compositional profiles of the FG middle layer have significant effects on the values of dimensionless critical axial load and dimensionless frequency parameter. The results are verified by comparing the obtained values with those in the existing literature.

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ABSTRACT: In this study, the buckling analysis of layered cylindrical shells with functionally graded material face sheets subjected to an axial compressive load is investigated. The dimensionless axial buckling load of layered cylindrical shells with functionally graded material face sheets is obtained. Effects of volume fractions of functionally graded material face sheets and cylindrical shell characteristics on the dimensionless axial buckling load have been studied.

References listed at the end of the paper:

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ABSTRACT: In this study, the torsional vibration and stability problems of functionally graded (FG) orthotropic cylindrical shells in the elastic medium, using the Galerkin method was investigated. Pasternak model is used to describe the reaction of the elastic medium on the cylindrical shell. Mixed boundary conditions are considered. The material properties and density of the orthotropic cylindrical shell are assumed to vary exponentially in the thickness direction. The basic equations of the FG orthotropic cylindrical shell under the torsional load resting on the Pasternak-type elastic foundation are derived. The expressions for the critical torsional load and dimensionless torsional frequency parameter of the FG orthotropic cylindrical shell resting on elastic foundations are obtained. The effects of variations of shell parameters, the exponential factor characterizing the degree of material gradient, orthotropy, foundation stiffness and shear subgrade modulus of the foundation on the critical torsional load and dimensionless torsional frequency parameter are examined.

References listed at the end of the paper:

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“Buckling and vibration of shear deformable functionally graded orthotropic cylindrical shells under external pressures”, Thin-Walled Structures Vol. 78, pp 121-130, May 2014, DOI: 10.1016/j.tws.2014.01.009
ABSTRACT: In this study, the vibration and buckling of functionally graded (FG) orthotropic cylindrical shells under external pressures is investigated using the shear deformation shell theory (SDST). The basic equations of shear deformable FG orthotropic cylindrical shells are derived using Donnell shell theory and solved using the Galerkin method. Parametric studies are made to investigate effects of shear deformation, orthotropy, compositional profiles and shell characteristics on the dimensionless frequency parameter and critical external pressures. Some comparisons among various theories have been performed in order to show the differences between the parabolic shear deformation theory (PSDT) and several higher-order shear deformation theories (HSDTs).

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“Buckling of non-homogeneous orthotropic conical shells subjected to combined load”, Steel Composite Structures, 2015, DOI: http://dx.doi.org/10.12989/scs.2015.19.1.001
ABSTRACT: The buckling analysis is presented for non-homogeneous (NH) orthotropic truncated conical shells subjected to combined loading of axial compression and external pressure. The governing equations have been obtained for the non-homogeneous orthotropic truncated conical shell, the material properties of which vary continuously in the thickness direction. By applying Superposition and Galerkin methods to the governing equations, the expressions for critical loads (axial, lateral, hydrostatic and combined) of non-homogeneous orthotropic truncated conical shells with simply supported boundary conditions are obtained. The results are verified by comparing the obtained values with those in the existing literature. Finally, the effects of non-homogeneity, material orthotropy, cone semi-vertex angle and other geometrical parameters on the values of the critical combined load have been studied.

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ABSTRACT: This article is the result of an investigation on the influence of a Pasternak elastic foundation on the stability of exponentially graded (EG) cylindrical shells under hydrostatic pressure, based on the first-order shear deformation theory (FOSDT) considering the shear stresses. The shear stresses shape function is distributed parabolic manner through the shell thickness. The governing equations of EG orthotropic cylindrical shells resting on the Pasternak elastic foundation on the basis of FOSDT are derived in the framework of Donnell-type shell theory. The novelty of present work is to achieve closed-form solutions for critical hydrostatic pressures of EG orthotropic cylindrical shells resting on Pasternak elastic foundation based on FOSDT. The expressions for critical hydrostatic pressures of EG orthotropic cylindrical shells with and without an elastic foundation based on CST are obtained, in special cases. Finally, the effects of Pasternak foundation, shear stresses, orthotropy and heterogeneity on critical hydrostatic pressures, based on FOSDT are investigated.

References listed at the end of the paper:

Ambartsumian, S.A. (1964), Theory of Anisotropic Plates; Strength, Stability, Vibration, Technomic, Stamford, USA.


ABSTRACT: In this study, the non-linear stability of three-layered conical shells with functionally graded core have not been investigated previously. The purpose of this paper is to study this problem. The large de cition theory with von Karman -Donnell-type of kinematic non-linearity is used to deduce the basic equations. The basic equations are solved analytically by using Superposition and Galerkin methods. The influences of several parameters on the dimensionless non-linear critical axial loads are discussed.


ABSTRACT: The prime aim of the present study is to present analytical formulations and solutions for the stability analysis of heterogeneous orthotropic truncated conical shell subjected to external (lateral and hydrostatic) pressures with mixed boundary conditions using the Donnell shell theory. The mixed boundary conditions are as follows: at one end of FGM truncated conical shell is a sleeve that prevents its longitudinal displacement and rotation, and the other end is a freely support. The basic equations of heterogeneous
orthotropic truncated conical shells are derived and solved applying the Galerkin’s method for the two cases of mixed boundary conditions using new approximation functions. Then the expressions for dimensionless critical external pressures are obtained. The results are compared and validated with the results available in the literature. Finally, a detailed parametric study is conducted to study the effect of heterogeneity, material orthotropy and mixed boundary conditions on the critical external pressures.

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ABSTRACT: This paper is concerned with the elastic buckling of vertical cylindrical shells under combined end pressure and body force. Such buckling problems are encountered when cylindrical shells are used in a high-g environment such as the launching of rockets and missiles under high-propulsive power. The vertical shells may have any combination of free, simply supported, and clamped ends. Based on the Goldenveizer-Novozhilov thin shell theory, the total potential energy functional is presented and the buckling problem is solved using the Ritz method. Highlight in the formulation is the importance of the correct potential energy functional which includes the shell shortening due to the circumferential displacement. The omission of this contributing term leads to erroneous buckling solutions when the cylindrical shell is not of moderate length (length-to-radius ratio smaller than 0.7 or larger than 3). New solutions for body-force buckling parameters are presented for stubby cylindrical shells to long tube-like shells that approach the behavior of columns. The effects of the shell thickness and length on buckling parameter are also investigated.

ABSTRACT: This paper is concerned with the development of a global p-element method for the analysis of self-weight buckling of thin cylindrical shells. Such buckling problems occur when cylindrical shells are subject to high-g acceleration, for instance the launching of rockets and missiles under high propulsive power. The cylindrical shells may have any combination of free, simply supported and clamped ends. A p-element computational method has been developed based on various thin shell theories including Donnell, Sanders and Goldenveizer-Novozhilov models. The strain energy for the global element during buckling is formulated and
an eigenvalue equation is derived. Unlike the conventional buckling problem where the eigenvalue is directly solved, a pre-determined buckling parameter is fixed at the outset for a geometric-dependent stiffness and a recursive numerical procedure is developed to compute the effect of critical buckling length. The critical buckling length is found to be proportional to thickness to a power of approximately 0.9. The effects of shell thickness and length on buckling parameter are also investigated. Comparison of results from various shell theories indicates solutions of the Sanders and Goldeneveizer-Novozhilov shell theories are in excellent agreement while the Donnel shell theory is good for buckling of short cylindrical shells.


ABSTRACT: Small submersibles, which permit man to observe and work as part of the three-dimensional undersea environment, are among the most promising tools for achieving effective exploitation of the oceans. An important element of any submersible is the pressure hull, frequently contributing one-fourth to one-half and more of the total vehicle weight. The Naval Ship Research and Development Center has played a major role in developing pressure hull structures for undersea vehicles. This paper describes some of the principal structural features of existing and envisioned small submersibles and summarizes recent advances in design and analysis methods. Particular emphasis is given to computer programs developed and/or used at the Center. Specifically, it describes advances in stress, stability, and vibration analyses as well as early stage developments in structural fatigue and reliability analyses. It also discusses computer programs and automated procedures designed for rapid response in feasibility studies and preliminary and final design cycles; these provide for both the generation of input data and the graphical display of computed results.


ABSTRACT: The correct formulations for solving nonlinear structural problems by the finite element method have now been established. Numerous investigators have given the derivation for the solution of problems by the incremental tangent stiffness method and total formulation methods. These derivations have been applied to many problems and the results have been shown to be quite accurate for the problems that have been selected. However there is one area of application that has received practically no attention. This is in the investigation of the buckling strength of pressure loaded rings and shells. The effect of pressure loading where the loading changes direction as the structure deforms has been included in several previous derivations, by what is known as the load stiffness matrix, but to the author's knowledge no one has investigated problems where this effect has been included in the solution procedure. For rings and some buckling modes of shells, the results can be in error by as much as 50%. This paper will describe an iterative process for solving the nonlinear equilibrium equations and correcting the loads to include the effect of changing geometry at each load level. This approach is different from the classical eigenvalue or bifurcation method. Several case studies will be described which were performed on ring and shell problems. The geometry of these example problems were axisymmetric and in order to apply a nonlinear collapse analysis, the structure had to be perturbed out of its axisymmetric pattern into a buckling pattern. Imperfect geometry and very small concentrated loads were used to cause this perturbation and this will be described in the paper. The sensitivity of the computed collapse pressure to the finite element mesh gradation will be discussed. A comparison will be made between results obtained by
including the effect of following pressure load and those obtained by not including this effect.

ABSTRACT: In this study cylindrical boundary conditions for finite element analysis are formulated that allow torsional displacement and buckling of a sector of a cylinder of half axial height, and of a circumferential arc angle that will divide into 360°. Finite element tests are carried out on unstiffened elastic cylinders to verify the method of analysis against classical elastic torsional buckling theory. Elastic–plastic limit point finite element tests are carried out on ring and stringer stiffened and stringer stiffened cylinders to investigate the effects of stiffeners on post-buckling behaviour in torsion. A stringer stiffened cylinder is subjected to many combinations of axial force and surface pressure in the elastic range of response and then tested to failure in torsion to investigate the effects of axial and surface pressure loads on the resistance to plastic collapse in torsion.

ABSTRACT: The buckling resistance of orthogonally stiffened cylinders is investigated for elastic critical buckling and non-linear elasto-plastic buckling tests. The effects of residual stresses arising from cold forming the cylinder and welding frame components are considered in the analysis of two stiffened cylinder models with similar material weights and different geometric spacings. A static axial load is applied to the models to represent loading from the supported structure followed by a non-linear elasto-plastic buckling step representing a wave loading combined with hydrostatic pressure, producing large displacement compartment buckling. Residual stress is shown to cause a reduction in buckling resistance of approximately 25% in the stiffened cylinder segments.

G.H. Nie, R. Shi and R.J. Zhang (Key Laboratory of Solid Mechanics of MOE, Dept. of Engineering Mechanics, Tongji University, Shanghai, P.R. China), “Plastic and buckling behaviors of tubular beams under combined bending and torsion”, (publisher/date not given in the pdf file. Identifying number: ICF100322OR, Most recent date of the 5 references cited is 1994. Cannot cut and past anything from the pdf file.)

ABSTRACT: The buckle and collapse of offshore pipeline subjected to combined actions of tension, bending, and external pressure during deepwater installation has drawn a great deal of attention. Extended from the model initially proposed by Kyriakides and his co-workers, a 2D theoretical model which can successfully account for the case of simultaneous tension, bending, and external pressure is further developed. To confirm the accuracy of this theoretical method, numerical simulations are conducted using a 3D finite element model within the framework of ABAQUS. Excellent agreement between the results validates the effectiveness of this theoretical method. The model is then used to study the effects of several important factors such as load path,
material properties, and diameter-to-thickness ratio, etc., on buckling behaviors of the pipes. Based upon parametric studies, a few significant conclusions are drawn, which aims to provide the design guidelines for deepwater pipeline with solid theoretical basis.

References listed at the end of the paper:


ABSTRACT: By considering the characteristics of deformation of rotationally periodic structures under rotationally periodic loads, the periodic structure is divided into some identical substructures in this study. The degrees-of-freedom (DOFs) of joint nodes between the neighboring substructures are classified as master and slave ones. The stress and strain conditions of the whole structure are obtained by solving the elastic static equations for only one substructure by introducing the displacement constraints between master and slave DOFs. The complex constraint method is used to get the bifurcation buckling load and mode for the whole rotationally periodic structure by solving the eigenvalue problem for only one substructure without introducing any additional approximation. The finite element (FE) formulation of shell element of relative degrees of freedom (SERDF) in the buckling analysis is derived. Different measures of tackling internal degrees of freedom for different kinds of buckling problems and different stages of numerical analysis are presented. Some numerical examples are given to illustrate the high efficiency and validity of this method.

References listed at the end of the paper:
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ABSTRACT: In case of buckling of spherical shells, most of experiments have been performed with the use of a spherical cap clamped along the circular boundary, and the buckling pressure obtained shows complicated trends which cannot be predicted by the conventional theory; in some cases, experimental buckling pressure raises beyond its theoretical prediction. This difficulty is settled in the present paper with the aid of the finite element calculations by introducing not only geometrical imperfections but also displacements of the clamped boundary of the spherical cap.

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INTRODUCTION: The technical assessment studies of pool-type LMFBR have been made for the purpose of the costdown and the high reliability of power plants by Central Research Institute of Electric Power Industry and nuclear power plant makers (Hitachi, Toshiba and Mitsubishi Ltd.) in Japan. Since earthquakes take place frequently in Japan, one of the important subjects is the seismic analysis of the reactor vessels that may be subjected to various dynamic loads and may buckle in seismic excitations. It is known that shear type buckling modes take place for short cylindrical shells under lateral loads. Although there is much experimental and analytical data on the buckling of cylindrical shells under axial compression, not so many studies have been done on shear buckling problems which are necessary for the seismic analysis of nuclear reactor vessels, and there are many points to be clarified taking into account the various parameters affecting shear buckling. In this study the shear type buckling of cylindrical shells is investigated by experiments and nonlinear finite element analysis taking various parameters into account.
ABSTRACT: Buckling tests for nearly perfect cylinders and cylinders with intentional imperfection made by press-working technique were carried out subjected to transverse shearing loads. The radius-to-thickness ratios were 50-200 and bending-to-shear stress ratios were 1.2-5.0, where both types of buckling in shear and in bending might occur. The purposes of these tests were to evaluate the interaction relation between elastic-plastic buckling strength in bending and in shear and to clarify the imperfection effect on these two types of buckling. From test results, we proposed a weak interaction between buckling in shear and in bending and correction factors of buckling loads for larger imperfection in the interim buckling design guide of LMFBR.

ABSTRACT: A geometrically nonlinear stability analysis of a torispherical shell subjected to internal pressure was performed, using doubly curved finite elements which provide an exact description of the middle surface. The critical pressure and the corresponding buckling mode were calculated. Internal pressure-nodal displacement curves were obtained for the pre- and postbuckling regions for the computation model. The buckling modes in bifurcation points were calculated and the changes of the deflection shape on the postbuckling paths analyzed. The effect of geometric imperfections on the critical pressure was studied. Imperfection shapes affine to buckling modes in bifurcation points were investigated and critical pressure-imperfection amplitude curves obtained.

ABSTRACT: The elastic stability of an imperfect torispherical shell subjected to internal pressure was analyzed numerically using the finite element method. Imperfection patterns affine to the buckling mode in the bifurcation points of the perfect structure were studied and internal pressure-nodal displacement curves obtained for the pre- and postbuckling regions of the computation model. The effect of the imperfection pattern amplitude on the critical pressure and the postbuckling minimum was analyzed. The imperfection sensitivity was presented graphically.

References listed at the end of the paper:


ASBSRACT: The imperfection sensitivity of torispherical shells subjected to internal pressure was investigated numerically, using the finite element displacement method. Imperfection patterns affine to the first buckling mode at the bifurcation points of the perfect structure were considered. Load-normal displacement curves were obtained for the pre- and postbuckling regions of the perfect computation model and also for imperfect computation models with different imperfection amplitudes. The dependence of the critical pressure and the postbuckling minimum on the imperfection amplitudes was presented graphically. Torispherical shells subjected to internal pressure failed to demonstrate any significant imperfection sensitivity for the imperfection
patterns analysed.

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ABSTRACT: The constitutive equation for an elastic-plastic material model was derived using the von Mises yield criterion and assuming isotropic strain hardening. A layered finite element permitting geometrically linear and geometrically nonlinear elastic-plastic analysis of thin shell structures is presented. The effect of linear strain hardening on the size of plastic regions and the distribution of internal forces in an internally pressurized torispherical shell was analyzed. At sufficiently high pressures a significant difference in the distribution of internal forces was observed between elastic, perfectly plastic and strain hardening material. The effect of the size of plastic regions on the difference in the magnitude of internal forces obtained by geometrically linear and geometrically nonlinear computations of the torispherical shell was studied. An increase in the size of the plastic region was found to produce greater differences in the computation of meridional bending moments than in the computation of hoop stress resultants.

P.M. Baiz and M.H. Aliabadi (Imperial College London, South Kensington, SW7 2AZ, London, UK),

ABSTRACT: In this work a boundary element (BE) formulation for buckling problem of shear deformable shallow shells is presented. A set of five boundary integral equations are obtained by coupling two-dimensional plane stress elasticity with shear deformable plate bending (Reissner). The domain integrals appearing in the formulation (due to the curvature and due to the domain load) are transferred into equivalent boundary integrals. The BE formulation is presented as an eigenvalue problem, to provide direct evaluation of critical load factors and buckling modes. Several examples are presented. The BE results for a cylindrical shallow shell with different curvatures are compared with other numerical solutions and good agreements are obtained.

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ABSTRACT: This paper presents applications where the DBEM formulations presented by Dirgantara and Aliabadi [3, 4] is combined with the multi region BEM presented recently by Baiz and Aliabadi [2], for the analysis of cracked shear deformable plates and shallow shell assemblies. Stress intensity factors are obtained using the CTOD technique. Several examples are solved to demonstrate the capabilities of the proposed technique. Comparing DBEM with FEM, it was clear that good accuracy and efficiency can be achieved with the present multi region DBEM.
ABSTRACT: Boundary element only formulations for the stability analysis of isotropic and anisotropic plates are presented. Domain integrals which arise in the formulation are transformed into boundary integrals by the radial integration method and the dual reciprocity method. Plate buckling equations are formulated as standard eigenvalue problem. The accuracy of the proposed formulations including buckling coefficients and buckling modes is assessed by comparison with results from literature.

ABSTRACT: This paper presents four boundary element formulations for post buckling analysis of shear deformable shallow shells. The main differences between the formulations rely on the way non-linear terms are treated and on the number of degrees of freedom in the domain. Boundary integral equations are obtained by coupling boundary element formulation of shear deformable plate and two-dimensional plane stress elasticity. Four different sets of non-linear integral equations are presented. Some domain integrals are treated directly with domain discretization whereas others are dealt indirectly with the dual reciprocity method. Each set of non-linear boundary integral equations are solved using an incremental approach, where loads and prescribed boundary conditions are applied in small but finite increments. The resulting systems of equations are solved using a purely incremental technique and the Newton–Raphson technique with the Arc length method. Finally, the effect of imperfections (obtained from a linear buckling analysis) on the post-buckling behaviour of axially compressed shallow shells is investigated. Results of several benchmark examples are compared with the published work and good agreement is obtained.

ABSTRACT: This chapter describes recent developments on the buckling and postbuckling analysis of thin walled structures by the Boundary Elements Method (BEM). Boundary integral equations are obtained by coupling two dimensional plane stress elasticity with boundary element formulation of Reissner plate bending. The linear buckling problem is formulated as a standard eigenvalue problem, in order to obtain directly critical loads and buckling modes as part of the solution. A multi-region BEM formulation is also introduced for the analysis of local buckling in thin walled assemblies. Nonlinear equations for large deflection and postbuckling analysis are also investigated. Nonlinear system of equations is solved using an incremental solution strategy, where displacements and tractions are applied in small but finite increments. Several examples of flat and curved plates (shallow shells) with different dimensions and boundary conditions are analyzed, including plate assemblies. Results are compared with other numerical and analytical solutions, and good agreement is obtained.
ABSTRACT: Multilevel optimization including progressive failure analysis and robust design optimization for composite stiffened panels, in which the ultimate load that a post-buckled panel can bear is maximized for a chosen weight, is presented for the first time. This method is a novel robust multiobjective approach for structural sizing of composite stiffened panels at different design stages. The approach is integrated at two design stages labelled as preliminary design and detailed design. The robust multilevel design methodology integrates the structural sizing to minimize the variance of the structural response. This method improves the product quality by minimizing variability of the output performance function. This innovative approach simulates the sequence of actions taken during design and structural sizing in industry where the manufacture of the final product uses an industrial organization that goes from the material characterization up to trade constraints, through preliminary analysis and detailed design. The developed methodology is validated with an example in which the initial architecture is conceived at the preliminary design stage by generating a Pareto front for competing objectives that is used to choose a design with a required weight. Then a robust solution is sought in the neighbourhood of this solution to finally find the layup for the panel capable of bearing the highest load for the given geometry and boundary conditions.

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K.A. Stevens, R. Ricci and G.A.O. Davies (Department of Aeronautics, Imperial College of Science,
Technology and Medicine, Prince Consort Road, London SW7 2BY, UK), “Buckling and postbuckling of composite structures”, Composites, Vol. 26, No. 3, pp 189-199, March 1995
DOI: 10.1016/0010-4361(95)91382-F
ABSTRACT: The postbuckling behaviour of a flat, stiffened, carbon fibre composite compression panel has been studied, theoretically and experimentally. The panel had a collapse load in excess of three times the buckling load. An initial failure mechanism leading to eventual explosive collapse of the panel is identified and the damaging stress resultant is measured in the panel and predicted from a finite element analysis.

ABSTRACT: In this paper, a finite element analysis is performed for buckling of the pressure vessels with ellipsoidal head subjected to uniform pressure. According to the characteristic of deformation of the pressure vessel, it is divided into some identical substructures. The degrees of freedom (DOFs) of joint nodes between the neighboring substructures are classified as master and slave ones. The stress and strain distributions of the whole structure are obtained by solving the static equations for only one substructure by introducing the displacement constraints between master and slave DOFs. The complex constraint method has been used to get the buckling load and mode for the whole structure by solving the eigenvalue problem for only one substructure without introducing any additional approximation. Some numerical examples have been given to illustrate the high efficiency and validity of this method.

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ABSTRACT: For the accurate prediction of the collapse behaviour of thin cylindrical shells, it is accepted that geometrical and other imperfections in material properties and loading have to be accounted for in the simulation. There are different methods of incorporating imperfections, depending on the availability of accurate imperfection data. The current paper uses a spectral decomposition of geometrical uncertainty (Karhunen–Loève expansions). To specify the covariance of the required random field, two methods are used. First, available experimentally measured imperfection fields are used as input for a principal component analysis based on pattern recognition literature, thereby reducing the cost of the eigenanalysis. Second, the covariance function is specified analytically and the resulting Friedholm integral equation of the second kind is solved using a wavelet-Galerkin approach. Experimentally determined correlation lengths are used as input for the analytical covariance functions. The above procedure enables the generation of imperfection fields for applications where the geometry is slightly modified from the original measured geometry. For example, 100 shells are perturbed with the resulting random fields obtained from both methods, and the results in the form of temporal normal forces during buckling, as simulated using LS-DYNA, as well as the statistics of a Monte Carlo analysis of the 100 shells in each case are presented. Although numerically determined mean values of the limit load of the current and another numerical study differ from the experimental results due to the omission of
imperfections other than geometrical, the coefficients of variation are shown to be in close agreement.

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ABSTRACT: The optimization of shell buckling is performed considering peak normal force and absorbed internal energy in the presence of geometrical imperfections implemented through Karhunen-Loève expansions. Initially, the mass of a shell is minimized in the presence of random initial imperfections by allowing cutouts in the material, subject to constraints on the average peak force and average internal energy. Then, robustness is considered by minimizing the coefficient of variation of the normal peak force while constraining the average peak force and average internal energy. LS-OPT is used both to generate an experimental design and to perform a Monte Carlo simulation (96 runs) using LS-DYNA at each of the experimental design points. The effect of imperfections when minimizing the mass is not large, but when considering robustness, however, the optimal design has a substantially increased hole size and increased shell thickness, resulting in a heavier design with maximal robustness within the constraints.

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ABSTRACT: The buckling stresses of model grain bins with varying radius to wall thickness (r/t) ratios and levels of internal pressure were determined. No available analytical model effectively predicted the observed results. A best fit model with lower bounds is presented that relates the buckling stress to the level of lateral grain pressure and the r/t ratio of the bin wall.

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ABSTRACT: In this paper we show the existence of global minimizers for the geometrically non-linear equations of elastic plates, in the framework of the general 6-parameter shell theory. A characteristic feature of this model for shells is the appearance of two independent kinematic fields: the translation vector field and the rotation tensor field (representing in total 6 independent scalar kinematic variables). For isotropic plates, we prove the existence theorem by applying the direct methods of the calculus of variations. Then, we generalize our existence result to the case of anisotropic plates.

References listed at the end of the paper:
ABSTRACT: The optimum design of stiffened shell structures is investigated using a robust and efficient optimization algorithm where the total weight of the structure is to be minimized subject to behavioral constraints imposed by structural design codes. Evolutionary algorithms and more specifically the evolution strategies (ES) method, specially tailored for this type of problems, are implemented for the solution of the structural optimization problem. The discretization of the stiffened shell is performed by means of cost-effective and reliable shell and beam elements that incorporate the natural mode concept. Three types of design variables are considered: sizing, shape, and topology. A benchmark test example is examined where the efficiency and robustness of ES over other optimization methods is investigated. Two case studies of stiffened shells are subsequently presented, where a parametric study is undertaken to obtain the most efficient design compatible with the regulations suggested by design codes such as Eurocode. The important role of the stiffeners and how they can be optimally chosen to improve the performance of shell structures in terms of carrying capacity and economy is demonstrated.

References listed at the end of the paper:


ABSTRACT: Stochastic finite-element analysis of shells is performed using the spectral representation method for the description of the random fields in conjunction with the local average method for the formulation of the stochastic stiffness matrix of the elements. A stochastic formulation of the nonlinear triangular composites facet triangular shell element is implemented for the stability analysis of cylindrical panels with random initial imperfections. The imperfections are described as a two-dimensional univariate homogeneous stochastic field. The elastic modulus and the shell thickness are also described as two-dimensional univariate homogeneous stochastic fields. The variability of the limit load of the cylindrical panel is then computed using the Monte Carlo simulation. Useful conclusions for the buckling behavior of cylindrical panels with random initial imperfections are derived from the numerical tests presented in this paper. These tests also demonstrate the applicability of the proposed methodology in realistic problems.


ABSTRACT: The effect of material and thickness imperfections on the buckling load of isotropic shells is investigated in this paper. For this purpose, the concept of an initial ‘imperfect’ structure is introduced involving not only geometric deviations of the shell structure from its perfect geometry but also a spatial variability of the modulus of elasticity as well as the thickness of the shell. The initial geometric imperfections are described as a two-dimensional uni-variate (2D-1V) stochastic field with statistical properties that are either based on an available data bank of measured initial imperfections or assumed, in cases where no experimental data is available. In order to describe the non-homogeneous characteristics of the initial imperfections, the spectral
representation method is used in conjunction with an autoregressive moving average model with evolutionary power spectra based on a statistical analysis of the experimentally measured imperfections. In cases where no experimental results is available, the initial imperfections are assumed to be homogeneous and their impact on the buckling load is investigated on the basis of ‘worst’-case scenarios with respect to the correlation length parameters of the stochastic fields. The elastic modulus and the shell thickness are described as 2D-1V non-correlated homogeneous stochastic fields, while the stochastic stiffness matrix of the shell elements is formulated using the local average method. The Monte Carlo Simulation method is used to calculate the variability of the buckling load, while for the determination of the limit load of the shell, a stochastic formulation of the elastoplastic and geometrically non-linear TRIC facet triangular shell element is implemented.

References listed at the end of the paper:
ABSTRACT: The optimum design of isotropic shell structures with random initial geometric, material and thickness imperfections is investigated in this paper and a robust and efficient methodology is presented for treating such problems. For this purpose, the concept of an initial “imperfect” structure is introduced involving not only geometric deviations of the shell structure from its perfect geometry but also a spatial variability of the modulus of elasticity as well as of the thickness of the shell. An efficient reliability-based design optimization (RBDO) formulation is proposed. The objective function is considered to be the weight of the structure while both deterministic and probabilistic constraints are taken into account. The overall probability of failure is taken as the global probabilistic constraint for the optimization procedure. Numerical results are presented for a cylindrical panel, demonstrating the efficiency as well as the applicability of the proposed methodology in obtaining rational optimum designs of imperfect shell-type structures.

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ABSTRACT: The investigator and his colleagues focus on the efficient numerical computation of global solutions of problems of nonlinear elastostatics in a high-performance computational environment. Particular attention is paid to the global post-critical behavior of symmetric imperfection-free elastic shell structures --- the analysis of which has great significance in understanding the large deformation response and ultimate collapse scenario of realistic engineering structures. A major theme of the work is to exploit the natural parallelism, via group theoretic techniques, in an important class of engineering problems characterized by underlying symmetries. They also investigate the use of automatic differentiation software in the context of those problems. Finally, they study the effectiveness of symmetry-motivated preconditioners, within the context of Krylov iterative subspace methods, for a class of “almost-symmetric” problems in structural mechanics. Due to their high strength-to-weight ratios, thin shell structures have been used extensively in aerospace, civil, mechanical and nuclear engineering applications, e.g., dome roofs, aerospace vehicles, pressure vessels,
containment vessels, etc. Yet the ability of engineers to predict the ultimate failure of such systems has heretofore been more of an art than a science (relying heavily upon costly experimental verification -- see "Computerized Buckling Analysis of Shells", by D. Bushnell, Martinus Nijhoff 1985). The investigators combine new mathematical ideas of symmetry and nonlinear analysis with high-performance computing methodology to analyze such systems efficiently and systematically. A long-term goal is to provide engineers with useful tools for the systematic analysis (and ultimately better design) for this important class of structures. Funding for the project is provided by the Computational Mathematics program and the Office of Multidisciplinary Activities in MPS and by the New Technologies program in CISE.


ABSTRACT: Discrepancies observed in experimental buckling loads of thin shells are often due to the random nature of initial shape imperfections, material properties and non-perfect boundary conditions. The work presented in this paper aims at finding the optimal dimensions of a single bay of a ring-stiffened cylinder representative of a submarine pressure hull under external hydrostatic pressure. It accounts for uncertainties of material properties and amplitudes of imperfections, supposed distributed over the two most critical buckling modes in a first simplified approach (overall and interframe buckling modes). The Reliability-Based Design Optimization problem considered here consists in finding an optimal deterministic design minimizing the weight of the structure while meeting a prescribed safety level. The present work hinges on closed-form / semi-numerical solutions for the buckling problems in a first approach. FORM reliability results based on a 3D shell finite element model are presented in a second part, in an effort to base such a design optimization on a more accurate mechanical model and to provide a sound basis for the optimal design of structures prone to buckling.

References listed at the end of the paper:

ABSTRACT: In the present paper, the effect of random non-uniform axial loading on the buckling behaviour of isotropic thin-walled imperfect cylindrical shells is investigated. Random initial (out-of-plane) geometric imperfections, thickness and material property variability, together with a non-uniform stochastic axial loading are incorporated into a cost-effective non-linear stochastic finite element analysis using the non-linear TRIC shell element. For this purpose, the concept of an initial ‘imperfect’ structure is introduced involving not only deviations of the shell structure from its perfect geometry but also a spatial variability of the modulus of elasticity as well as of the thickness of the shell. The initial imperfections as well as the axial loading are modeled as stochastic fields with statistical properties that are either based on an available data bank of measured initial imperfections or assumed, in cases where no experimental data is available. Based on these simulation features, a simple and realistic approach is proposed for the estimation of the variability (scatter) of the limit loads by means of a brute-force Monte Carlo Simulation procedure. In addition, ‘worst case’ buckling scenarios are identified by means of a sensitivity analysis with respect to assumed parameters used for the description of stochastic fields that are not supported by corresponding experimental measurements. In addition it is shown that in the context of such sensitivity analysis, modeling of the non-uniformity of the axial loading is, from a computational point of view, fully equivalent to modeling the geometric boundary imperfections. The numerical tests performed demonstrate the significant role that the random varying axial loading plays on the buckling behaviour of imperfection sensitive structures like the axially compressed thin-walled cylinder considered in this study.

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“A computationally efficient method for the buckling analysis of shells with stochastic imperfections”,

ABSTRACT: A computationally efficient method is presented for the buckling analysis of shells with random imperfections, based on a linearized buckling approximation of the limit load of the shell. A Stochastic Finite Element Method approach is used for the analysis of the “imperfect” shell structure involving random geometric deviations from its perfect geometry, as well as spatial variability of the modulus of elasticity and thickness of the shell, modeled as random fields. A corresponding eigenproblem for the prediction of the buckling load is solved at each MCS using a Rayleigh quotient-based formulation of the Preconditioned Conjugate Gradient method. It is shown that the use of the proposed method reduces drastically the computational effort involved in each MCS, making the implementation of such stochastic analyses in real-world structures affordable.

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ABSTRACT: In this paper, the effect of material and thickness spatial variation on the buckling load of isotropic shells with random initial geometric imperfections is investigated. To this purpose, a random spatial variability of the elastic modulus as well as of the thickness of the shell is introduced in addition to the random initial geometric deviations of the shell structure from its perfect geometry. The main novelty of this paper compared to previous works is that a non-Gaussian assumption is made for the distribution of the two aforementioned uncertain parameters i.e. the modulus of elasticity and the shell thickness which are described by two-dimensional univariate (2D-1V) homogeneous non-Gaussian stochastic fields. The initial geometric imperfections are described as a 2D-1V Gaussian non-homogeneous stochastic field with properties derived from corresponding experimental measurements. Numerical examples are presented focusing on the influence of the non-Gaussian assumption on the variability of the buckling load, which is calculated by means of the Monte Carlo Simulation method. It is shown that the choice of the marginal probability distribution for the description of the material and thickness variability is crucial since it affects significantly the statistics of the buckling load of imperfection sensitive shell-type structures.

References listed at the end of the paper:

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ABSTRACT: Buckling loads of thin-walled I-section beam-columns exhibit a wide stochastic scattering due to the uncertainty of imperfections. The present paper proposes a finite element based methodology for the stochastic buckling simulation of I-sections, which uses random fields to accurately describe the fluctuating size and spatial correlation of imperfections. The stochastic buckling behaviour is evaluated by crude Monte-Carlo simulation, based on a large number of I-section samples, which are generated by spectral representation and subsequently analyzed by non-linear shell finite elements. The application to an example I-section beam-column demonstrates that the simulated buckling response is in good agreement with experiments and follows key concepts of imperfection triggered buckling. The derivation of the buckling load variability and the stochastic interaction curve for combined compression and major axis bending as well as stochastic sensitivity studies for thickness and geometric imperfections illustrate potential benefits of the proposed methodology in buckling related research and applications.

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ABSTRACT: An asymptotic spectral stochastic approach is presented for computing the statistics of the equilibrium path in the post-bifurcation regime for structural systems with random material properties. The approach combines numerical implementation of Koiter’s asymptotic theory with a stochastic Galerkin scheme and collocation in stochastic space to quantify uncertainties in the parametric representation of the load–displacement relationship, specifically in the form of uncertain post-buckling slope, post-buckling curvature, and a family of stochastic displacement fields. Using the proposed method, post-buckling response statistics for two plane frames are obtained and shown to be in close agreement with those obtained from Monte Carlo simulation, provided a fine enough spectral representation is used to model the variability in the random dimension.


ABSTRACT: The present paper addresses the problem of the response variability of structures, which experience bifurcation buckling. The buckling strength of such structures may be very sensitive to the small structural imperfections, which are practically inevitable in all real structures. A new general method is presented, which is particularly suitable for the treatment of the stochastic nature of the structural imperfections. The new method is exemplified with two well known buckling problems. The first problem is the buckling of a column on a linear elastic foundation. The shape imperfections of the column are treated as a weakly stationary random process with a pre-specified auto-correlation function. The second problem is the buckling of a thin cylindrical shell under axial compression. The shape imperfections of the shell are treated as a broad-band random Gaussian process with an arbitrarily specified power spectral density function. In both cases, representative numerical results are presented for the purpose of improving our understanding of the response variability of these structures.

References listed at the end of the paper:

ABSTRACT: In this paper, the effect of random initial geometric, material and thickness imperfections on the buckling load of isotropic cylindrical shells is investigated. To this purpose, a stochastic spatial variability of the elastic modulus as well as of the thickness of the shell is introduced in addition to the random initial geometric deviations of the shell structure from its perfect geometry. The modulus of elasticity and the shell thickness are described by two-dimensional univariate (2D-1V) homogeneous non-Gaussian translation stochastic fields. The initial geometric imperfections are described as a 2D-1V homogeneous Gaussian stochastic field. A numerical example is presented examining the influence of the non-Gaussian assumption on the variability of the buckling load. In addition, useful conclusions are derived concerning the effect of the various marginal probability density functions as well as of the spectral densities of the involved stochastic fields on the buckling behaviour of shells, as a result of a detailed sensitivity analysis.


OBJECTIVES: 1. To determine the worst imperfection shape for axially loaded cylinders, and 2. To develop an equivalent deterministic imperfection that brings the finite element solution into acceptable agreement with the lower bound of test results and can be used in the numerical analysis and design of cylindrical shells.

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56, 1936, pp 795-806.
ABSTRACT: A simple general method for the evaluation of the effect of shape imperfections on the buckling strength of thin shells is briefly presented. This method is applied to the axially compressed thin cylindrical shell resulting in an efficient numerical procedure for the computation of its buckling strength. The procedure is applicable to any sufficiently smooth imperfection pattern and has given results in good agreement with the available experimental data.
ABSTRACT: It is well known that the response of structures subjected to bifurcation buckling may be affected radically, both quantitatively and qualitatively, by small structural imperfections. A new analytical method is presented for the determination of the buckling strength of such structures. The method results in the numerical solution of an ordinary matrix eigenvalue problem in a simple closed-form formula that is particularly suitable for the study of the response variability of these structures. The method is exemplified with the investigation of the well-known problem of the buckling of the axially compressed thin cylindrical shell. The structural imperfections of the shell are treated as a broadband random Gaussian process with an arbitrarily specified power spectral density function. Numerical results are obtained that demonstrate the inadequacy of Koiter’s analysis for such problems, the simplicity and efficiency of the present method, and the significant effect of the power spectral density function of the imperfection pattern on the variability of the buckling strength of the shell.


ABSTRACT: The present chapter addresses a sixty-year-old problem, namely the buckling analysis and design of imperfection-sensitive structures. The problem has been the focus of increased research interest recently because such structures are particularly common in advanced engineering applications. The chapter starts with an introductory-level overview of the problem and concentrates on the presentation of a new method which is particularly suitable and efficient for the problem. The new method has become feasible by modern advances in computer-aided algebra and calculus and has been tentatively named Critical Imperfection Magnitude Method or CIM Method, in short. It is based on three well-established pillars, namely the classical stability theory of structures, the perturbation methods of applied mathematics, and the reliability methods for the design of structures. As compared to previous methods in the field, the new method is much more general in scope, conceptually much simpler, and numerically much more efficient. A major result of the method is the clear identification of the significant imperfection sources and components from the very large number of possible sources and components. Furthermore, the new method can be easily combined with the finite element method in order to provide the design engineer with a readily available means for the rational design of imperfection-sensitive structures in buckling.


ABSTRACT: Buckling is a critical issue for structural stability in structural design. In most of the buckling analyses, applied loads, structural and material properties are considered certain. However, in reality, these parameters are uncertain. Therefore, a prognostic solution is necessary and uncertainties have to be considered. Fuzzy logic algorithms can be a solution to generate more dependable results. This study investigates the material uncertainties on column design and proposes an uncertainty model for critical column buckling reinforced concrete buildings. Fuzzy logic algorithm was employed in the study. Lower and upper bounds of elastic modulus representing material properties were defined to take uncertainties into account. The results show that uncertainties play an important role in stability analyses and should be considered in the design. The proposed approach is applicable to both future numerical and experimental researches. According to the study
results, it is seen that, calculated buckling load values are stayed in lower and upper bounds while the load values are different for same concrete strength values by using different code formula.

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“Stochastic imperfection modelling in shell buckling studies”, Thin-Walled Structures, Vol. 23, Nos. 1-4, 1995, pp. 179-200, Special Issue: Buckling Strength of Imperfection-sensitive Shells
doi:10.1016/0263-8231(95)00011-2

ABSTRACT: One possible avenue that may improve design against buckling is to recognise and account for the random nature of initial geometric imperfections introduced by manufacturing. This paper presents the application of a probabilistic methodology to the design and analysis of cylindrical shells under axial compression. Results from two cases are presented and compared: the first involves stringer-stiffened steel cylinders failing elastoplastically, whereas the second examines unstiffened composite cylinders buckling elastically. In both cases, the method is underpinned by statistical analysis of imperfections measured on nominally identical specimens. Nonlinear FE analysis is used for strength assessment and the results of the statistical analysis are introduced in the imperfection modelling. It is demonstrated that the method has advantages over code design based on ‘lower bound’ curves, in terms of the calculated buckling loads but also in offering a systematic and rational way by which randomness in imperfections can be assessed.


ABSTRACT: This paper describes a measurement system that was developed for an experimental study on buckling of glass reinforced composite cylinders. An automated non-contact laser device operating inside the test specimen provided a three dimensional scanning system for measuring the deformation of the shell wall. The measurement system was used to obtain the initial geometric imperfections, as well as the deformation under varying control axial displacement. All loading and data acquisition operations were carried out using
advanced computer controlled techniques. Due to the large number of measurements undertaken in each test, data collection was followed by processing and reduction techniques, thus delivering the data in a form suitable for finite element analysis and comparative studies. Typical results are presented in order to demonstrate the reliability, accuracy and versatility of the system.


ABSTRACT: This paper presents the results of buckling tests on laminated composite cylinders made from glass fibre reinforced plastic (GFRP). The laminates used are of type ‘DF1400’ consisting of woven glass fibre roving within a polyester resin matrix. In total, six cylinders constructed from two-ply laminates, in which the main variable is the laminate orientation, were tested under axial compression. The specimen details, experimental set-up and loading arrangements are described, and a detailed account of the test results is given. The results include thickness and imperfection mapping, and displacement, load and strain measurements. Use was made of an automated laser scanning system, which was developed for measuring the initial geometric imperfections as well as buckling deformations during various stages of loading. The results of this experimental study demonstrate the influence of laminate orientation on the buckling strength of composite cylinders, and provide detailed information necessary for analytical and design investigations.

References listed at the end of the paper:

ABSTRACT: The experimental behaviour of laminated glass fibre-reinforced plastic (GFRP) cylinders under compression and bending is examined in this paper. The laminates are of type ‘Rovimat 1200’ consisting of woven glass fibre roving, with a chopped mat on one side, within a polyester resin matrix. Two and three-ply cylinders with various orthogonal orientations were considered, for which the nominal radius-to-thickness ratio was about 108 and 72, respectively. Use was made of an automated laser scanning system for measuring geometric imperfections and progressive buckling deformations of the models. Following a description of the specimen and loading details, the results of experiments on ten models are presented. The results include thickness and imperfection mapping, displacement and load measurements as well as important observations regarding the failure mode and overall behaviour of each model. The findings highlight the effects of laminate construction and loading eccentricity on the buckling strength of cylinders within the range examined. Both elastic buckling and material-dominated failure modes were observed, depending on the slenderness and load type considered. The tests also provide detailed experimental data, which are necessary for further analytical and design studies.


ABSTRACT: This paper gives the details of a numerical finite element validation study for laminated GFRP cylinders subjected to concentric and eccentric compression. The laminates are of type ‘Rovimat 1200’ consisting of woven glass fibre roving, with a chopped mat on one side, within a polyester resin matrix. Two and three-ply cylinders with various orthogonal orientations are considered, for which the nominal radius-to-thickness ratio is about 108 and 72, respectively. The numerical results are compared to findings from a previous experimental investigation in which detailed measurements were obtained. Following a brief description of the experimental work, details of the development of suitable finite element models are presented and associated limitations are highlighted. Careful attention is given to thickness idealisation as well as the introduction of geometric imperfections into the numerical models. Both linear eigenvalue analysis and geometrically nonlinear simulations are undertaken using a general purpose finite element program. The correlation between numerical and experimental results is discussed in terms of buckling strength, axial stiffness, buckling deformations and surface strains. The analysis is shown to give a good representation of the buckling behaviour of GFRP cylinders of the type examined. It is also concluded that whereas the cylinders appear to be less sensitive to the effects of initial geometric imperfections than their isotropic counterparts, including such imperfections in a geometrically nonlinear analysis does improve the comparison between tests and finite element results, and is considered essential for the derivation of numerical ‘knockdown’ factors.

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ABSTRACT: The results of a numerical simulation study for the buckling behaviour of laminated composite cylinders are presented in this paper. The laminates are made from glass-reinforced plastic (GFRP) of type ‘DF 1400’ consisting of woven glass fibre roving within a polyester resin matrix. Two-ply cylinders with various laminate orientations, subjected to axial compression, are considered. The numerical simulations are compared to the results of a previous experimental investigation which is briefly described. The finite element model, used to carry out the numerical simulations, is presented and associated limitations are discussed. Linear eigenvalue analysis as well as geometrically non-linear simulations are undertaken using a general purpose finite element program. Detailed measurements of thickness variations and geometric imperfections, carried out within the experimental study, are directly introduced in the analysis. Several thickness representations are considered and their influence on the results is assessed. The correlation between numerical and experimental results is also discussed in terms of buckling strength, axial stiffness, buckling modes and surface strains. In addition to demonstrating the influence of various modelling idealisations on the results, this numerical study highlights the effect of the specific material and laminate construction detail on the buckling behaviour of composite cylinders.


PARTIAL INTRODUCTION: Glass fibre-reinforced plastic (GFRP) shells could be an attractive structural form for a number of applications in construction due to their good strength-to-weight ratio, inherent corrosion resistance, and relatively low cost compared to other composite systems. However, their efficient use is restricted by the limited availability of design criteria and by fairly scant test data on which any such criteria can be validated…


ABSTRACT: Observations of failure mechanisms in monotonic loading are reported for graphite/epoxy composites containing three-dimensional (3D) interlock weave reinforcement. The key phenomena are delamination and kink band formation in compression, tow rupture and pullout in tension, and combinations of these in bending. The materials exhibit great potential for damage tolerance and notch insensitivity. This is partly due to the presence of geometrical flaws that are broadly distributed in strength and space; and partly to the coarseness of the reinforcing tows, which leads to extensive debonding and reduced stress intensification around sites of failure. Rules of mixture corrected for the effects of tow irregularity suffice to estimate elastic moduli. Rough estimates of the stress at which the first failure events occur in compression or tension can be made from existing micromechanical models. Ultimate tensile failure might be modeled by regarding failed tows that are being pulled out of the composite as a cohesive zone. The characteristic length estimated for this zone, which is a direct measure of damage tolerance and notch insensitivity, has very large values of order of magnitude 0.1–0.5 m.

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ABSTRACT: The paper is concerned with the structural response of a composite shell structure intended as a model of an under-water vehicle for service in sea environment. The main objective of the research is the prediction of the collapse pressure using both analytical expressions and linear or non-linear numerical analysis and the following comparison with the experimental pressure obtained in off-shore tests. The structure is composed of three basic parts with regular geometry: a cylindrical part (with the following geometrical properties: R/t=30.5, L/R=2 being the internal radius 305 mm, the length 610 mm and the thickness 10 mm) and two conical and spherical end-closures with the same thickness. The cylindrical shell was made up of 7 plies of E-glass woven roving with polyester resin. Various structural analyses were conducted before performing the experiment in the sea to verify the reliability of the analytical and numerical tools. Firstly the entire model was analysed to predict the nature of the collapse (material failure or elastic buckling) and it was stated that the collapse was due to elastic buckling of the cylindrical part. Consequently, the attention was focused on this component and approximation formulae for the evaluation of the linear buckling pressure of isotropic and composite cylindrical shells were used together with finite element models. Afterward the study was enlarged to consider the effects of the recorded geometric imperfections into a non-linear buckling analysis. The collapse pressures were compared to the design values derived from the available recommendations and to the experimental result obtained in an off-shore test (1.3 MPa).


ABSTRACT: The thermal buckling of uniformly heated, clamped, truncated conical shells with axisymmetric initial deflections is theoretically studied. The axisymmetric initial deflections are represented by a cosine function. The Donnell-type basic equations governing the finite deformation of conical shells are solved by means of a finite difference procedure. It is found that the effect of axisymmetric initial deflections on the thermal buckling of truncated conical shells is quite significant for the axially constrained case, but negligible for the axially free one except very shallow cones. The thermal buckling of a clamped annular plate with the axisymmetric initial deflection is also examined.


ABSTRACT: Dimensional analysis is applied to a simple model of stiffened laminated cylindrical shells to determine the dimensionless parameters that characterize the buckling of these structures. Donnell shell theory is used to describe the kinematic deformation of the shells. The axial and ring stiffeners are modeled using the smeared technique. A nondimensional load is defined as a function of nine nondimensional parameters, which are a combination of the material and geometric properties of the shell. Additional assumptions regarding the construction of the shell walls can be used to reduce the number of nondimensional parameters. Some simply supported shells subjected to hydrostatic pressure are examined to demonstrate the use of the dimensionless parameters. Estimates of the imperfection sensitivity of these shells are made using Koiter's asymptotic theory. The dimensional analysis provides a framework for the systematic investigation of the relationship between material, geometry and the buckling loads of stiffened composite shells. The results of this analysis are intended to provide information that can be used in the preliminary stages of a shell design.
ABSTRACT: Three different methods are employed to estimate the buckling loads of several ring stiffened and orthotropic cylindrical shells using finite elements. The methods used are a nonlinear bifurcation analysis and two linearized buckling analyses, one that ignores the initial displacement stiffness matrix, and one that includes it. Large differences are observed between the predictions made by the two linearized buckling analyses for a range of shell geometries. Detailed studies of a shell with six stiffeners demonstrate that these differences are caused by different versions of the linearized eigenvalue problem, rather than by the use of different numerical formulations.…
ocean structures by finite element method”, Ocean Engineering, Vol. 28, No. 6, 1 June 2001, pp. 621-638, doi:10.1016/S0029-8018(00)00021-4

ABSTRACT: Static analysis of stiffened shells has been carried out using an eight-noded isoparametric element for the shell and a three-noded curved beam element for the stiffener. A same displacement function is used for the shell and the stiffener elements. A modified technique has been followed to analyse the shell, which is an improvement over the degenerated shell concept. The stiffness matrix of the curved beam element is generated irrespective of its position and orientation within the shell element. The stiffness matrix of the stiffener is then transferred to all the nodes of the shell element. Numerical examples of stiffened shells with concentric and eccentric stiffeners have been analysed and the results presented together with those available in published literature.

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ABSTRACT: A new approach for the large deflection analysis of isotropic and composite arbitrary orientated stiffened plates is presented. Non-linear equilibrium equations are derived using the principle of virtual work applied to a continuum with a total Lagrangian description of motion. Eight node isoparametric plate elements are combined with three node beam elements, using the concept of equal displacements at the plate–stiffener interface, to represent the stiffened plate. The stiffness of the beam element is computed first irrespective of its position within the plate element and then transferred to the plate nodes depending on its orientation and position within the plate element. The Newton–Raphson incremental-iterative solution technique is used to obtain the non-linear response path. Results obtained by the present approach are compared with those available in the open literature to demonstrate the validity and efficiency of the proposed approach and good agreement is found in all the investigated cases.


ABSTRACT: (same as above)

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ABSTRACT: A finite element method for the buckling loads on a longitudinally square stiffened plate with square cutouts is investigated under various combinations of biaxial loading at the plate boundary. The forces are assumed to act in the plane of the undeformed middle surface of the plate. The characteristic equations for the natural frequencies, buckling loads and their corresponding mode shapes are obtained from the equation of motion. The buckling load parameter for various modes of the stiffened plate with square cutouts subjected to in-plane biaxial loads, has been determined for various edge conditions. Numerical results are presented for a range of hole to plate size from 0 to 0.8. In the structural modeling, the plate and the stiffeners are treated as separate elements where the compatibility between these two types of elements is maintained. The present approach is more flexible than any other finite element modeling in that the mesh division is independent of the location of the stiffeners.
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ABSTRACT: The paper presents finite element free vibration and buckling analysis of laminated hat-stiffened shallow and deep shells using arbitrarily oriented stiffener formulation. Modified approach for modelling the curved stiffener is implemented using necessary transformations. A simplified stiffener formulation is presented to accommodate various shapes of stiffener shapes in developing the rigidity matrix for the finite element formulation. Investigation has been carried out on free vibration and buckling analyses of laminated composite stiffened shell structures with laminated open section (rectangular or ‘T’ shaped) and closed section (‘hat’ shaped) stiffeners. Parametric study on the hat-stiffened panels for the free vibration and buckling analyses confirms that the closed section stiffener being torsionally rigid is found to show better performance over open section stiffeners.

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ABSTRACT: Fracture mechanics-based predictive methodologies are commonly employed to estimate onset of interlaminar damage growth in composite structures. Full implementation of interlaminar fracture mechanics in design requires the continuing development of codes to calculate energy release rates and advancements in
delamination growth criteria under mixed mode conditions. In this research, an analytical crack tip element (CTE) methodology was evaluated and applied to predict skin-to-stiffener separation, which is a typical failure mode in aerospace structures. The methodology was correlated against empirical data obtained from structural testing of a single blade stiffened panel with an embedded artificial debond. Failure initiation occurred at the location predicted by the CTE and the predicted load for initiation agreed with the average of a set of experimental results.


ABSTRACT: Significance of using higher-order shear deformation theory (HSDT) over the first-order shear deformation theory (FSDT) for analyzing laminated composite stiffened plates is brought out using the finite element method (FEM). For this purpose, a C0 HSDT, is extended for application to stiffened configurations, for linearly elastic static and natural vibration analysis. The spatial displacement fields of both the plate and the stiffener are derived as functions of reference plane variables using Taylor series expansion. The developed computational tool is employed for analyzing systems having varying configurations using the FSDT and two different HSDTs, and their comparative effects are systematically studied, demonstrating the need for using HSDT instead of FSDT, for obtaining accurate structural response of such stiffened configurations.

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ABSTRACT: The behaviour of Steel I-Beams exhibiting lateral-torsional buckling at elevated temperature has been studied by means of experimental and numerical analysis. The authors in an earlier paper have presented an analytical formula for the buckling resistance moment in the fire design situation. This new proposal, different from the actual proposal of the Eurocode 3 Part 1.2 has been validated in this work by comparison with the results from a set of 120 experimental and numerical tests performed on IPE 100 beams, submitted to temperatures varying from room temperature to 600 °C. The numerical simulations have been based on the measured geometrical dimensions of the cross-sections, the longitudinal imperfections, i.e. the out of straightness of the beams, the residual stresses and the yield strength. The Eurocode simple model promotes ultimate loads that depend mainly on the non-dimensional slenderness of the beams. The analytical results provided by the Eurocode 3, for a certain range of the slenderness, appear to be unsafe when compared with the numerical and experimental results. It is shown that the new proposal is safer than the Eurocode 3 formulas.

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“New proposals for the design of steel beam-columns in case of fire, including a new approach for the lateral-torsional buckling”, Computers and Structures, Vol. 82, pp 1463-1472, 2004
DOI: 10.1016/j.compstruc.2004.03.042

ABSTRACT: The possibility of having, in parts 1-1 and 1-2 of Eurocode 3, the same approach for the design of beam-columns and for lateral–torsional buckling, was investigated by the authors in previous papers using a numerical approach, where it was concluded that those assumptions could be made. In the present paper, a new approach for lateral–torsional buckling has been used with the formulae for the design of beam-columns at elevated temperature based on prEN 1993-1-1 combined with the formulae from prEN 1993-1-2. In both cases the results obtained are much better than the current design expressions, when compared with those obtained in the numerical calculations.

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ABSTRACT: An updated Lagrangian formulation of a quadratic degenerated isoparametric shell element is presented for geometrically nonlinear elasto-plastic shell problems. A finite rotation effect is included in the formulation by adopting a co-rotational scheme. The load stiffness matrix has been derived for the treatment of a pressure load. For elasto-plastic behavior, the layered element model is used. The Newton-Raphson iteration method is employed to solve incremental nonlinear equations. For tracking of post-buckling behavior, the work control method is taken into account. Verification of the present technique is obtained by analyzing the available reference problems. Good correlations between the computed results and referenced data can be drawn.

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ABSTRACT: In this work, the search for the optimal form for torispherical dome ends under external pressure load is conducted. Based on the fabrication and strength requirements, a group of ‘compromised’ contours are considered. With the adoption of both the BS5500 and ASME Section VIII Pressure Vessel codes, a reasonable buckling pressure range is proposed. The geometry of the dome end is described by the four-centered ellipse method which is commonly used in engineering drawing. A minimum weight optimization problem is studied by the discrete backtrack programming method; the optimal forms are obtained under buckling constraints. The elastic buckling analysis of the dome end is carried out by the finite element method using doubly-curved truncated shell elements. Two different sized dome end examples are studied. The developed optimal search procedure is found to be very efficient and easy-to-use for the applications, such as torispherical dome and subjected to externally pressurized loading.
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ABSTRACT: In this study, we proposed a minimum weight design of a submarine pressure hull under hydrostatic pressure with constraints on factors such as general instability, buckling of shell between frames, plate yielding, and frame yielding. A typical submarine pressure hull is also adopted for a prototype model. This design problem is not only formulated as a discrete nonlinear, nondifferentiable, multimodal constrained minimization problem, but also solved by using the backtrack programming method. Results in this study indicate that the solution for the optimal model's weight reduces an average 6.65% more than the prototype model. The process in this study is favorable for the submersible pressure hull design process.

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ABSTRACT: In order to increase the flight range of aerospace vehicles and the efficiency of solid rocket motors, designers attempt to reduce the weight of solid rocket motors. A skirt is a potential element for weight reduction in rocket motors as it leads to reduction of the total weight of solid rocket motor. Due to its significance for solid rocket motors, the objective of this paper is to investigate the optimal design of a fiber-reinforced composite cylindrical skirt subjected to a buckling strength constraint and an overstressing strength constraint under aerodynamic torque and axial thrust. The present optimal design problem involve in determining the best laminate configuration to minimize the weight of the cylindrical skirt. To find the optimal solution accurately and quickly, the hybrid genetic algorithm (HGA) is employed in this work. Buckling strength and overstressing strength of the fiber-reinforced composite cylindrical skirt are analyzed using classical laminate theory and elastic stability theory of thin shells. The Tsai-Wu failure criterion is employed to assess the first ply failure, and an overstressing load level factor is introduced to describe the failure strength. In addition, a buckling load factor is introduced to describe the buckling strength. Due to the critical issue of buckling strength, the effects of the design parameters on the buckling strength are investigated in this work. Finally, a practical design example of the proposed fiber-reinforced composite cylindrical skirt is investigated using the present analysis procedure. Results reveal that the fiber-reinforced composite cylindrical skirt laminated symmetrically with both cross-ply layers [0/90∞] and angle-ply layers [+45/−45∞] can sustain a great buckling load. Furthermore, the buckling strength of the skirt shell laminated with equal-hybrid between the angle-ply layers and the cross-ply layers is greater than that of the skirt shell laminated with over-weighted hybrid between the angle-ply layers and the cross-ply layers. Results provide a valuable reference for designers of aerospace vehicles.
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ABSTRACT: The multiple intersecting spheres (MIS) pressure hull is a logical derivative of the single unstiffened sphere, which is frequently used for deep operating, small submersibles because of its attractive low buoyancy factor. This paper investigates the optimum design of an MIS deep-submerged pressure hull subjected to hydrostatic pressure, using a powerful optimization procedure combined the extended interior penalty function method (EIPF) with the Davidon-Fletcher-Powell (DFP) method. In this study, the thickness of the shell, the width of the rib-ring, the inner radius of the rib-ring and the angle of intersection of the spherical shell are selected as design variables, and structural failure and human requirements are considered to minimize the buoyancy factor. Additionally, a sensitivity analysis is performed to study the influence of the design variables on the optimal structural strength design. The results reveal that the shell thickness is most important to lobar buckling strength, and that rib-ring width, rib-ring inner radius and spherical shell intersection angle are most important to rib-ring hoop strength. Optimization results may provide a valuable reference for designers.

ABSTRACT: A method is developed for the static stress and deformation analysis of axisymmetric shells under axisymmetric loading by reduction of the shell to ring sections. In particular, the wall thickness of the shell may vary and the method is applicable to the analysis of shells with irregular meridional geometry. Explicit expressions for the influence coefficients for each ring element are derived. In the development of these expressions, exact evaluation of stresses in the circumferential direction of the ring is used. The distribution of stresses in the meridional direction of the ring element is assumed to be linear with each element. By using the derived influence coefficients, the unknown forces at the junctures of the ring elements are found by the standard flexibility method of indeterminate structural analysis. Subsequently, the displacements and internal stresses are determined. Example solutions for a flat circular plate under transverse loading and for a cylindrical shell under a boundary edge loading show excellent agreement with solutions found by solving the governing differential equations.

ABSTRACT: The critical states of cylindrical shells with initial imperfections having plastic and creep deformations are investigated. These states are defined as the load values at which the shell deflections rise
The method of successive loading for which the reaction of the shell to small loading steps is studied and the process of deformation is considered is used. Some experimental results for shells with irregular imperfections are given.

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Yu. M. Voichkov (Lavrent’ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk, 630090, Russia and Novosibirsk State University, Novosibirsk, 630090, Russia), “Rabotnov’s two-layer model of a shell and critical time of shell buckling during creep”, Journal of Applied Mechanics and Technical Physics, Vol. 51, No. 4, pp 615-622, July 2010

ABSTRACT: The main propositions of Rabotnov’s two-layer model of a shell are given. It is shown that the Rabotnov’s functional can be obtained from the mixed variational principle of creep theory. The notion of critical time is introduced and a procedure for obtaining an explicit formula for it using a variational equation is described.

References listed at the end of the paper:

ABSTRACT: This paper intends to present an effective analysis of the buckling phenomenon in wind loaded cylindrical storage tanks in the form of a program package based on general purpose finite element codes. This program, namely TK-INDUSTRIAL, written in ANSYS Parametric Design Language (APDL), aims to evaluate the buckling response of storage tanks under wind or hurricane. As a major result, the critical buckling wind speed and the influence of using ring stiffeners to increase this critical speed were assessed. The proposed program was shown to provide appropriate results and can be used as a strong tool to simulate the buckling of wind loaded cylindrical storage tanks.

References listed at the end of the paper:
ABSTRACT: This paper is concerned with estimating the elastic buckling pressures of large liquid natural gas (LNG) storage tanks which are used by the British Gas Corporation for seasonal demand peak shaving. They consist of two concentric ring stiffened cylindrical shells separated by substantial thermal insulation which maintains the LNG within the inner shell at \( _{\sim}165^\circ\)C with minimal boil off. There is natural gas vapour above the LNG and throughout the tank interior which is normally at just above atmospheric pressure. The shell walls increase in thickness from the top to the bottom and are fabricated from very thin steel or aluminium alloy plates (diameter to thickness ratio \(\sim4000\) at the top) since they are usually in hoop tension, but under certain conditions this can become compressive making elastic buckling a possible mode of failure. The individual buckling pressures for the two shells can be estimated using standard procedures but in these LNG tanks the annular insulation transfers loads between the shells enhancing their individual strengths. A numerical method using the finite difference code BOSOR4 and a simple analytical method have been used to estimate these pressures.

ABSTRACT: In order to provide some insight into the effect of an impulsive disturbing load on the stability of a structure which is already subjected to major static loads near its critical state, the response of an imperfection sensitive idealized model with one degree of freedom was examined using the analytical approximation method. Conclusions regarding the response and the stability under the arbitrary form of the impulse are presented.
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ABSTRACT: In Part I of this article (November 1987 Experimental Techniques) the manufacture of thin shells by electro-plating has been described. The testing techniques and some typical results are now presented. The buckling strength of thin-walled shells is known to depend on manufacturing imperfections and is difficult to assess by mathematical modeling alone. An experimental procedure, using accurate electro-deposited models is described in this paper.

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ABSTRACT: Numerical, analytical and experimental techniques have been combined to find the strength of thin-wall cylindrical shells under blast loading. Two types of load are considered: rotationally symmetrical and sideways. The first type can be modelled analytically and the theoretical results are compared with those obtained from electro-formed copper shells loaded in a pressure chamber. The second type can be treated only by numerical analysis, backed by experiments using similar models loaded in an open shock tube apparatus.


ABSTRACT: A simple analytical method has been developed to estimate the response of cylindrical storage tanks to axisymmetric external blast loads. Included in this is the response of an inner vessel and annular insulation of the type used for storing large quantities (about 20,000 te) of liquid natural gas (LNG). Although complex, the response has simplifying features which have been fully exploited. In particular existing elastic shell solutions have been modified to model the initial response which is dominated by non-axisymmetric elastic buckling of the thin-walled shells. Then limit analysis has been used to model the final collapse which is dominated by the formation of axial plastic hinges in the shells. The method has been verified using physical tests on 1/150th scale models of the prototype tanks. These have been loaded with external axisymmetric blasts in a shock chamber. Special techniques were used to generate accurate model shells with very thin walls (about 50 _°m thick) by electro-deposition of copper onto removable wax cores.


ABSTRACT: A simple plastic damage analysis of a spherical shell under the impact of a flat-nosed missile is
presented in this paper. Based on the conservation of energy, a relationship between the permanent central deflection of a shell and the initial missile kinetic energy is established and shown to agree with other more complex theoretical methods. The present analysis is shown to agree with some available experimental results and can thus be used to predict the degree of damage of missile impacted spherical shells.


ABSTRACT: The present study is concerned with nonlinear analysis of toroidal shells and storage tanks. The study serves to demonstrate the usefulness of the differential quadrature method in this area of computational mechanics. The problem of the response of axisymmetric toroidal shells to uniform external pressure forms the first part of this study. Nonlinear thin shell theory, accounting for large displacements, is employed. The new differential quadrature method is used to obtain numerical results. For validation a bifurcation solution is found using the finite element method. The commercial code ADINA is used for this purpose. Finally the two methods are used to provide results for eight cases of toroidal shells. An axisymmetric analysis of a liquid storage tank with a circular base plate resting on an elastic foundation forms the second part of this study. Nonlinear shell theory is used for the tank wall and base plate, while a linear model is used for the foundation. A convergence study is carried out to determine the appropriate analysis parameters for the method. Partial validation is obtained by comparison with previously published results. These results are compared with finite element method results. Additional results are presented covering a wide range of tank geometric parameters.


ABSTRACT: In this paper, a finite element formulation is given in detail for the creep buckling of an axisymmetric shell. A special emphasis is placed on the bifurcation mode of creep buckling. A bifurcation point is determined by examining the shape of the potential energy in the vicinity of an axisymmetric equilibrium state obtained from a creep deformation analysis in the prebuckling stage. To illustrate the capability of the finite element formulation, a numerical example is presented for the creep buckling of a shallow spherical shell subjected to a uniform external pressure. In this analysis, not only the axisymmetric snap-through type but also the asymmetric bifurcation one are considered as buckling modes.


ABSTRACT: The finite element method is applied to the creep buckling of circular cylindrical shells under axial compression. Not only the axisymmetric mode but also the bifurcation mode of the creep buckling are considered in the analysis. The critical time for creep buckling is defined as either the time when a slope of a displacement versus time curve becomes infinite or the time when the bifurcation buckling occurs. The creep buckling analyses are carried out for an infinitely long and axially compressed circular cylindrical shell with an axisymmetric initial imperfection and for a finitely long and axially compressed circular cylindrical shell. The numerical results are compared with available analytical ones and experimental data.

ABSTRACT: Creep buckling analyses under stepwise varying loads are performed on a circular cylindrical shell with initial imperfection subjected to axial compression and a partial spherical shell under uniform external pressure. The finite element method is applied to a creep deformation analysis to obtain the critical time when creep buckling occurs. The results show that a linear cumulative damage rule for creep buckling can be well applied to the creep buckling of the circular cylindrical shell, but cannot to that of the partial spherical shell.

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ABSTRACT: In this paper the bifurcation buckling pressure for the torispherical head of the Mark II type BWR containment vessel subjected to dynamically applied internal pressure is calculated, using a finite element program for a dynamic analysis. Three kinds of dynamic loadings, that is, step loading, ramp loading and pulse loading are considered in the present analysis. The minimum bifurcation buckling pressure is predicted for the respective loadings. The minimum bifurcation buckling pressure for dynamic loading is much lower than the bifurcation buckling pressure for static loading.

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ABSTRACT: In the present work, analytical and experimental investigations were performed on creep buckling. Special attention was focussed on bifurcation behavior during creep deformation. The finite element method was used to analyze creep buckling of circular cylindrical shells without initial imperfection. The number of circumferential waves obtained from the analyses agrees well with those of the experiments. The present experimental investigation shows that the circumferential waves are suddenly caused near a bulge. It is also found that there is no correlation between the wavelength of the circumferential waves observed at creep buckling and that of the circumferential initial imperfection. Deformation patterns at the bifurcation creep buckling obtained from the analyses are analogous to those of the experiments. It is concluded from the analyses and the experiments that the circumferential waves observed in creep buckling experiments are due to bifurcation buckling during creep deformation.
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ABSTRACT: Cylindrical tanks with conical roof shells are utilized as oil storage tanks and for some containment vessels. It is known that conical roof shells and torispherical shells subjected to static internal pressure buckle into a displaced shape with circumferential waves caused by an instability condition commonly called bifurcation buckling. It can be important to obtain the dynamic bifurcation buckling load in designing conical roof shells. In this paper, the bifurcation buckling pressure is calculated for dynamic pressure during accident conditions as characterized by step pressure loading, ramp pressure loading and pulse pressure loading. The minimum bifurcation buckling pressure is shown to be a linear function of radius-to-thickness ratio $R/h$ of the shell in a linear fashion on a logarithmic scale. The minimum bifurcation buckling pressure is minimum for conical roof shells subjected to the step loading. The minimum dynamic bifurcation buckling pressure for step loading is about half of the static bifurcation buckling pressure.

ABSTRACT: The pressure-radius relation of spherical rubber balloons has been derived and its stability behavior analyzed. Here we show that those features are practically unchanged for thick spherical shells of Mooney-Rivlin materials. In addition, we also show that eversion of a spherical shell is possible for any incompressible isotropic materials if the shell is not too thick.

List of references at the end of the paper:

ABSTRACT: This paper presents a numerical study of the dynamic contact instability of shallow spherical shells. The problem considered is that of a spherical shell loaded through a massless rigid circular plate by a sudden step load acting in the direction normal to the loading plate and along the axis of symmetry of the shell. Thus, the spherical shell is subjected to a dynamic contact loading. The interaction characteristic of the circular plate and the spherical shell is described and the snap-through instability of the spherical shell due to the dynamic contact loading is discussed in detail. The numerical analysis demonstrates that the system may be dynamically stable even if local snap-through buckling occurs in the central area of the spherical shell. Dynamic instability occurs only in the case where the spherical shell exhibits an overall snap-through buckling.
ABSTRACT: This paper presents a numerical study which is concerned with the prediction of the response and instabilities in long circular cylindrical shells under dynamic pure bending. Of particular interest is the response of such shells, bent into the plastic range of the material, and the various instability characteristics of the shells under dynamic bending (sudden step load). It was found that the major deformation characteristic of the shells is essentially similar to that observed in the static bending when the applied moment is much smaller than the critical dynamic moment. However, when the applied moment is close to the critical dynamic moment, the ovalization of the shell cross-section was found to be localized over a length of several shell diameters in the central region, even though the response of the shell curvature was shown to be still stable in this case. When the applied moment reaches the critical dynamic moment, the response of the shell curvature was shown significantly increasing with time and the shell buckled catastrophically. For thicker shells, it was found that the development of localized ovalization of the shell cross-section is the major factor that causes shell dynamic instability. For thinner shells, however, besides the localized ovalization, the bifurcation induced by short wavelength ripples on the compressed side of the shell was also observed in the initial buckling patterns. After the bifurcation, the initial buckling pattern was replaced by the final postbuckling mode characterized by a localized sharp cupping in the centre of the shell.


ABSTRACT: This paper presents a numerical study of the dynamic snap-through instability of cylindrical panels subjected to the combined loading of uniform pressure and a central concentrated load. All static and dynamic (sudden step load) combinations of the concentrated load and the uniform pressure are considered. The characteristics of the dynamic instability of the panel are described for the two cases of static pressure with dynamic concentrated load and dynamic pressure with static concentrated load. The critical load curves for both cases are presented. To explain the effects of the initial static loads on the critical dynamic loads, the static and dynamic critical loads corresponding to both static loads or both dynamic loads are also calculated. The Budiansky-Roth criterion is employed in all these studies to determine the critical dynamic loads. The numerical results show that the static critical load curve gives an upper-bound whereas the dynamic critical load curve offers a lower-bound. Both the compound critical load curves lie between the static and dynamic critical load curves.


ABSTRACT: (cannot cut and paste)
ABSTRACT: In this paper we investigate the dynamic instability problems of long circular cylindrical shells subjected to sudden step bending moments. The expressions to predict the critical dynamic moments are derived. The dynamic instability model is established on two basic assumptions. One is the Brazier’s deformed kinematic assumption. The other is the dynamic characteristic assumption in which we assume the longitudinal curvature and ovalisation vibrations reach their extreme values simultaneously when the dynamic instability occurs. Thus, the dynamic instability problem is reduced to the solution of two static equilibrium equations and an energy balance equation. The present results show that the dynamic instability of the long circular cylindrical shells occurs at a moment about 80% of the corresponding critical static moment.

ABSTRACT: In this paper, the nonlinear bending response of finite length cylindrical shells with stiffening rings is investigated by using a modified Brazier approach. The basic assumptions for the present study are that the deformation of a shell subjected to pure bending can be simplified into a two-stage process. One is that the shell ovalizes but its axis remains straight; the other is that the bending of the shell is regarded as a beam with nonuniform ovalization. The nonlinear bending response is derived by applying the minimum potential energy principle and the corresponding critical moment, associated with local buckling, is determined by employing the Seide–Weingarten approximation. Numerical results are shown and compared with those obtained from other methods, which demonstrates that the assumptions used in the present study are reasonable.

ABSTRACT: External pressure buckling, free vibration, and external pressure-vibration interaction data were obtained on a sixth scale Lexan model of the Titan IV (Prototype) nose cone fairing. The objectives of these experiments were to validate analytical models used in the prototype design and also to provide experimental data on the effects of discontinuous circumferential rings, flexible ring to shell attachment, separation rails, and skin splices. In addition a nondestructive buckling load predictive test technique based on natural frequencies was evaluated using the Lexan model. The advantage of a Lexan model is that it can be buckled without sustaining damage, thus allowing repeated buckling experiments to be performed. Correlation studies were carried out using NASTRAN finite element and BOSOR finite difference models. Buckling and frequency data showed good agreement between analysis and experiment. Pressure-vibration interaction data were obtained to investigate an experimental procedure for extrapolating the interaction curve to predict the critical buckling load. While it was found that extrapolation of these data always overpredicted the buckling pressure, the data were used to develop a procedure that was successfully applied as stop-test criteria in the prototype test.
ABSTRACT: A combined analytical and experimental programme on the buckling of cylinders under axial compression, external pressure, and combined loading was conducted to develop a methodology for predicting the buckling of shell structures with manufacturing induced imperfections. A unique method of fabricating test cylinders from Lexan without longitudinal seams was developed. Cylindrical blanks formed by blow moulding were thermoformed and machined to the correct wall thickness to form perfect cylinders. The co-ordinates were measured and the cylinders tested. After testing, the cylinders were thermoformed on a second mandrel containing the desired imperfection shape and amplitude, remeasured, and tested. Excellent correlation to predictions from the BOSOR4 and ABAQUS computer codes was achieved.


ABSTRACT: Starting out from recent experimental results according to which thin-walled spherical shells subjected to a uniform external pressure deform in an axisymmetric mode at the beginning of the buckling process, the buckling and the postbuckling behavior of complete spherical shells were investigated under the assumption that both the unintentional, random initial deviations from the exact shape, and the following elastic deformations are symmetric to some radius of the shell. The shell was imagined to be decomposed into a cap which shows large deformations, and into a remainder in which the displacements are so small that in their analysis a linear theory can be used satisfactorily. The total potential energy of the system was minimized numerically and in the minimization process the conditions at the boundary between cap and remainder were enforced rigorously. Complete and continuous postbuckling curves were obtained in a number of cases and the maximal value of the pressure parameter was determined in a sufficiently broad range of the geometric parameter to draw conclusions regarding the practical behavior of spherical shells under external pressure. Comparison with earlier theoretical and experimental work yielded satisfactory agreement.


ABSTRACT: An experimental investigation into the plastic buckling of cylindrical tubes subjected to bending moments at the ends is reported on. Suitable parameters by means of which the buckling moment may be represented are first discussed, and after a description of the apparatus and the testing procedure, the results of tests on stainless steel and aluminium alloy tubes are given. These results are compared with analytical results for the collapse of cylinders under pure bending, and uniform axial compression. The mode of deformation of the cylinders is discussed and the experimental strains are compared with those of others for tests on axially compressed cylinders as well as cylinders in pure bending. The strains lie within ± 30% of those predicted by J2 deformation theory for cylinders in axial compression: the corresponding range of stresses is about ± 5%.

ABSTRACT: An approximate analysis is presented of the bifurcation of an elastic-plastic circular cylindrical shell subjected to pure bending. The method of analysis is an extension into the plastic range of an earlier analysis[8]; a relatively simple solution is obtained by making various approximating assumptions, and by a judicious choice of the eigenmode. The results show that the critical outer fibre stress is up to about 35% greater than the critical stress of an axially compressed cylinder, using J2 flow theory, in contrast to the elastic or elastic-plastic (deformation theory) cases, where these two stresses are practically equal.


ABSTRACT: Bifurcation under axial compression of discretely stringer-stiffened cylinders in the elastic and plastic ranges is studied. The stiffeners are treated as long plates. Small-strain J2 flow and deformation theories of plasticity are used. The effect of stiffener size on the critical stress is investigated; this is discussed with reference to the critical stresses of an equivalent simply-supported panel, and of a long plate simply-supported on three edges and free along one longitudinal edge. The effects of stiffener eccentricity, and of the number of stiffeners, is also discussed.

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ABSTRACT: The behavior in the plastic range of axially compressed stringer-stiffened cylinders is investigated. The shell under consideration is assumed to have an initial imperfection in the form of sinusoidal deviation both axially and circumferentially. The constitutive relation employed here is J2 deformation theory of plasticity. This relation, as well as kinematic assumptions regarding the behavior of the panels and stiffeners that constitute the stiffened shell, is used in the principle of virtual work to obtain a set of nonlinear algebraic equations whose solution provides complete information about the prebuckling equilibrium path. Bifurcation from the primary path is examined by making use of a functional whose first variation is zero when two solutions to the problem are possible. This leads to an eigenvalue problem, the eigenvalue being the critical compressive load and the eigenfunction being the corresponding buckling mode. Results are presented for shells of different geometries and material properties, and a comparison of results is made with results obtained by others. The imperfect shells analyzed all exhibit stable behavior, with sufficiently large imperfections having a beneficial effect. Results for bifurcation from these paths are also discussed.

ABSTRACT: The paper deals with buckling of antisymmetric angle- and cross-ply, simply supported rectangular flat plates under shear and compressive loads. The Rayleigh-Ritz energy method is used to find the buckling load, by assuming a double series form of trial functions for the buckled displacement field. Both the symmetric and antisymmetric buckling modes are considered. The effect of the number of layers, the aspect ratio and the lamination angle on the buckling load is studied. Results are presented for plates subjected to (i) shear loads only and (ii) both shear and uniaxial compressive loads; for the latter case, the results are presented in the form of interaction curves.

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ABSTRACT: This paper is aimed at the development of an analytical method to handle thermal buckling of laminated composite circular cylindrical shells. An eighth-order governing differential system for predicting this response is formulated from an energy approach. With the focus on simply-supported, antisymmetric angle-ply laminated composite cylinders subjected to circumferentially-varying temperatures, Galerkin's method is employed, where the corresponding numerical results provide insight into the response of the critical buckling temperature to such factors as lamination angles, number of layers, stacking sequence, geometric aspect ratios and various temperature functions. For example, in the case of antisymmetric laminates, the coupling effect between bending and compression vanishes as the number of layers increases. This phenomenon is confirmed for common composite materials such as Graphite/Epoxy and Boron/Epoxy.


ABSTRACT: Thermal buckling of a laminated cylindrical plate subjected to a temperature change is studied. The governing differential equations for Donnell-type laminated cylindrical shells are used and Galerkin's method is employed to determine the critical buckling temperature. Clamped and simply supported boundary conditions are both considered. The effects of various parameters on thermal buckling are examined.


ABSTRACT: By adopting the energy method, a method of calculating the stability of the rotational composite shell is presented that takes into account the influence of nonlinear prebuckling deformations and stresses on the buckling of the shell. The relationships between the prebuckling deformations and strains are calculated by nonlinear Kármán equations. The numerical method is used to calculate the energy of the whole system. The
nonlinear equation is solved by combining the gradient method and the amended Newton iterative method. A computer program is also developed. Examples are given to demonstrate the accuracy of the method presented in this paper.

ABSTRACT: The instability of a cylindrical shell under three point bending is considered. The problem has application to the industrial pipe ram bending process. The loading is idealized as a set of pads of uniform radial pressure in the regions of die-shell contact. A theoretical solution for the smallest buckling load is developed, using the Donnell and Sanders linearized stability equations. A finite element solution is also presented. The paper concludes with a discussion of results, from the two methods.

ABSTRACT: The elastic instability of a thin curved pipe under three-point bending is considered. The problem has application to the industrial ram pipe bending process. The loading is idealized as a set of pads of uniform pressure applied radially on discrete regions of the pipe surface. A shell-theory solution for the lowest buckling load is developed, using the Donnell-type linearized stability equations in toroidal coordinates. Sample results are presented for a specific pipe and these results are compared with ones for a geometrically similar straight pipe.


ABSTRACT: A study is conducted of the linear elastic buckling of circular cylindrical shells by the new Differential Quadrature Method (DQM). To date this numerical method in the area of buckling analysis has been applied only to rectangular plates. The Fluegge shell stability equations serve as the basis of the analysis. By assuming the form of the buckling modes in the circumferential direction the stability equations are transformed into ones dependent only on the axial coordinate of the shell. The resulting ordinary differential equations are then solved using the one-dimensional DQM approach. Results are first given for shells with simple or clamped boundary conditions, and these are compared with previously published results. Finally, new results are presented for shells with clamped-free boundary conditions, which have relevance to the buckling analysis of liquid storage tanks.


ABSTRACT: The free vibration characteristics of linear elastic toroidal shell panels are determined. A solution based on the Mushtari–Vlasov–Donnell shell equations is developed using the Differential Quadrature Method. The work represents the first application of this method to problems in shell theory with variable coefficients in the governing equations. Numerical results are calculated using the method, and these are compared with results found using a Fourier series and a finite element solution.


H.S. Shin and D. Redekop, “Nonlinear analysis of axisymmetric toroidal shells using the DQM”, Proc. CSME Forum, Montreal, Canada, May 2000, 10 pages


ABSTRACT: A method is developed to predict the buckling characteristics of an orthotropic shell of revolution of arbitrary meridian subjected to a normal pressure. The solution is given within the context of the linearized Sanders–Budiansky shell buckling theory and makes use of the differential quadrature method. Numerical results for buckling pressures and mode shapes are given for complete toroidal shells. Both completely free shells and shells with circumferential line restraints are covered. The loadings considered consist either of uniform pressure or circumferential bands of constant pressure. It is demonstrated that the differential quadrature method is numerically stable and converges. For isotropic toroidal shells, good agreement is observed with previously published analytical and finite element results. New results for buckling pressures and mode numbers are given for orthotropic shells and for band loaded shells.


ABSTRACT: The linearized buckling problem is considered for an isotropic clamped-clamped cylindrical shell with an oblique end. A theoretical solution based on the Budiansky shell theory is developed, and numerical results are determined using the differential quadrature method. In formulating the solutions, the surface of the shell is developed onto a plane, and the resulting irregular domain is then mapped, using blending functions, onto a square parent domain. The analysis is carried out in the parent domain. Convergence, validation, and parametric studies are conducted for a uniform external pressure loading. Results determined are compared with finite element results. The paper ends with an appropriate set of conclusions.

ABSTRACT: The finite element method (FEM) is used to predict free vibration and buckling characteristics of complete circular toroidal shells with meridional ring stiffeners. New vibration results are presented in the paper which indicate the effect on the natural frequencies of ‘rigid’ meridional ring stiffeners, and of equatorial lines of support. New buckling results are presented which indicate the effect on the buckling pressure of meridional ring stiffeners, and of equatorial lines of support. Results for the natural frequencies and the critical buckling pressure are given for shells covering a wide range of the geometric parameters. Close agreement of results is observed in comparisons with previously published results.

DTIC Accession Number: ADA187801

ABSTRACT: The specific impetus for this work was a conceptual design of a submarine using the toroid as the pressure hull. The designers could not find a ready body of knowledge to obtain scantlings for their pressure hull. This work began with a review of efforts to solve complete toroidal structures. Several works were found which addressed general shells and extended into partial toroids, but the solution of a complete toroid was not found to be a common exercise. Some of the these works are briefly reviewed. An attempt was then made to solve for the displacements in a thin walled circular toroid using the energy method. Several problems were identified associated with the structure geometry which make the solution for the complete toroid difficult. In addition, the functional used for the energy method needs to be more complex than the simple trigonometric or power series functionals used in this work. These two areas, geometry and functionals, are fertile areas for further study.

DTIC Assessment Number: ADA200586

ABSTRACT: The specific impetus for this work was a conceptual design of a submarine using the toroid as the pressure hull. This work is a continuation of the work started by Bowen (1987). As such, it is hoped that a better understanding of the behavior of a toroid under hydrostatic pressure can be realized. This work began with a review of efforts to solve complete toroidal structures. A specific toroid was then modeled in the BOSOR4 computer program to obtain displacements of the meridian under hydrostatic pressure. Functions were then derived that described the general form of these displacements. Using these functions as the assumed solution for the energy method an energy balance was made and a program was written to solve the displacements of a generic toroid under hydrostatic loading.


ABSTRACT: In this paper, the free vibrations of elastic in vacuo circular toroidal shells under different boundary conditions are studied using the linear Sanders thin shell theory. Beam functions are used to describe the motion along the meridional direction whilst trigonometric functions are used to represent the deformation
of the cross section. It is shown that both the natural frequencies and the mode shapes can be accurately predicted as long as the employed beam functions satisfy the boundary conditions at the ends of the shells. The dependence of the free vibration characteristics of an elastic toroidal shell upon boundary conditions and toroidal to cross-sectional radius ratio is also illustrated and explained in this paper.


ABSTRACT: Cylindrically curved unstiffened and stiffened plates are often used in ship structures. For example, they can be found at deck with a camber, side shell at fore and aft parts and bilge circle part of ship structures. It has been believed that such cylindrically curved plates can be modelled fundamentally by a part of a circular cylinder. From the estimations using cylindrically curved plate models, it is known that, in general, curvature increases the buckling strength compared to a flat plate under axial compression. Existence of the curvature is also expected to increase the ultimate strength as well as buckling strength. In the present paper, series of Finite Element analyses are performed on stiffened curved plates varying several parameters such as curvature, panel slenderness ratio as well as web height and type of stiffener. The results of numerical calculations on stiffened and unstiffened curved plates are examined to clarify the influences of these parameters on characteristics of their buckling/plastic collapse behaviour and strength under axial compression.


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ABSTRACT: In the present paper, to clarify and examine the fundamental buckling behaviours of cylindrically curved plates subjected to axial loading, a series of elastic and elasto-plastic large deflection analyses as well as elastic eigen buckling analysis are performed together with the comparisons with the buckling behaviours of circular cylinder. On the basis of the numerical results, the effects of curvature, magnitude of initial imperfection, slenderness ratio and aspect ratio on the characteristics of the buckling and post buckling collapse behavior of cylindrically curved plates and circular cylinders under axial compression are discussed. The buckling strength and ultimate strength formulae of the cylindrically curved plate are empirically derived based on the FEM series analysis by curve fitting using least square method. The validity of the ultimate strength formulations developed in this study has to some extent been verified through comparison with nonlinear numerical solutions.


ABSTRACT: Geometrically nonlinear free vibrations of closed isotropic cylindrical shells are investigated through an analytical–numerical model. The method developed is a combination of Sanders–Koiter nonlinear shell theory and the finite element method. The cylindrical shell is subdivided into cylindrical finite elements
and the displacement functions are derived from exact solutions of Sander's equations for thin cylindrical shells. Expressions for the mass, linear and nonlinear stiffness matrices are determined by exact analytical integration. Various boundary conditions of shell and in-plane effects are considered. Nonlinear responses are analyzed using the Runge–Kutta numerical method. The nonlinear frequency ratio is determined with respect to the amplitude thickness ratio of the motion for different study cases. Detailed numerical results are presented for various parameters for a closed isotropic shell, indicating either hardening or softening types of nonlinear behaviors, depending on the structure data. The present results show good agreement with the published ones for several cases of shells. This research clarifies the current disagreement about various types of cylindrical shells with geometric nonlinearities.


ABSTRACT: Based on the First-order Shear Deformation Theory (FSDT) this paper focuses on the dynamic behavior of moderately thick functionally graded conical, cylindrical shells and annular plates. The last two structures are obtained as special cases of the conical shell formulation. The treatment is developed within the theory of linear elasticity, when materials are assumed to be isotropic and inhomogeneous through the thickness direction. The two-constituent functionally graded shell consists of ceramic and metal. These constituents are graded through the thickness, from one surface of the shell to the other. A generalization of the power-law distribution presented in literature is proposed. Two different four-parameter power-law distributions are considered for the ceramic volume fraction. Some material profiles through the functionally graded shell thickness are illustrated by varying the four parameters of power-law distributions. For the first power-law distribution, the bottom surface of the structure is ceramic rich, whereas the top surface can be metal rich, ceramic rich or made of a mixture of the two constituents and on the contrary for the second one. Symmetric and asymmetric volume fraction profiles are presented in this paper. The homogeneous isotropic material can be inferred as a special case of functionally graded materials (FGM). The governing equations of motion are expressed as functions of five kinematic parameters, by using the constitutive and kinematic relationships. The solution is given in terms of generalized displacement components of the points lying on the middle surface of the shell. The discretization of the system equations by means of the Generalized Differential Quadrature (GDQ) method leads to a standard linear eigenvalue problem, where two independent variables are involved without using the Fourier modal expansion methodology. Numerical results concerning six types of shell structures illustrate the influence of the power-law exponent, of the power-law distribution and of the choice of the four parameters on the mechanical behaviour of shell structures considered.

References listed at the end of the paper:


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“2-D differential quadrature solution for vibration analysis of functionally graded conical, cylindrical shell and

ABSTRACT: This paper focuses on the dynamic behavior of functionally graded conical, cylindrical shells and annular plates. The last two structures are obtained as special cases of the conical shell formulation. The first-order shear deformation theory (FSDT) is used to analyze the above moderately thick structural elements. The treatment is developed within the theory of linear elasticity, when materials are assumed to be isotropic and inhomogeneous through the thickness direction. The two-constituent functionally graded shell consists of ceramic and metal that are graded through the thickness, from one surface of the shell to the other. Two different power-law distributions are considered for the ceramic volume fraction. The homogeneous isotropic material is inferred as a special case of functionally graded materials (FGM). The governing equations of motion, expressed as functions of five kinematic parameters, are discretized by means of the generalized differential quadrature (GDQ) method. The discretization of the system leads to a standard linear eigenvalue problem, where two independent variables are involved without using the Fourier modal expansion methodology. For the homogeneous isotropic special case, numerical solutions are compared with the ones obtained using commercial programs such as Abaqus, Ansys, Nastran, Straus, Pro/Mechanica. Very good agreement is observed. Furthermore, the convergence rate of natural frequencies is shown to be very fast and the stability of the numerical methodology is very good. Different typologies of non-uniform grid point distributions are considered. Finally, for the functionally graded material case numerical results illustrate the influence of the power-law exponent and of the power-law distribution choice on the mechanical behavior of shell structures.


ABSTRACT: In this paper, the Generalized Differential Quadrature (GDQ) method is applied to study the dynamic behaviour of laminated composite doubly-curved shells of revolution. The First-order Shear Deformation Theory (FSDT) is used to analyze the above mentioned moderately thick structural elements. The governing equations of motion, written in terms of stress resultants, are expressed as functions of five kinematic parameters, by using the constitutive and kinematic relationships. The solution is given in terms of generalized displacement components of points lying on the middle surface of the shell. The discretization of the system by means of the Differential Quadrature (DQ) technique leads to a standard linear eigenvalue problem, where two independent variables are involved. Results are obtained taking the meridional and circumferential co-ordinates into account, without using the Fourier modal expansion methodology. Examples of hyperbolic, catenary, cycloid, parabolic, elliptic and circular shell and panel structures are presented to illustrate the validity and the accuracy of the GDQ method. Furthermore, GDQ results are compared with those presented in literature and the ones obtained by using commercial programs such as Abaqus, Ansys, Nastran, Straus and Pro/Mechanica. Very good agreement is observed.


ABSTRACT: In this paper, the Generalized Differential Quadrature (GDQ) method is applied to study the dynamic behaviour of laminated composite doubly-curved shells of revolution. The First-order Shear
Deformation Theory (FSDT) is used to analyse the above mentioned moderately thick structural elements. In order to include the effect of the initial curvature a generalization of the Reissner–Mindlin theory, proposed by Toorani and Lakis, is adopted. The governing equations of motion, written in terms of stress resultants, are expressed as functions of five kinematic parameters, by using the constitutive and kinematic relationships. The solution is given in terms of generalized displacement components of points lying on the middle surface of the shell. The discretization of the system by means of the Differential Quadrature (DQ) technique leads to a standard linear eigenvalue problem, where two independent variables are involved. Results are obtained taking the meridional and circumferential co-ordinates into account, without using the Fourier modal expansion methodology. Comparisons between the Reissner–Mindlin and Toorani–Lakis theory are presented. Furthermore, GDQ results are compared with those presented in literature and the ones obtained by using commercial programs such as Abaqus, Ansys, Nastran, Straus and Pro/Mechanica. Very good agreement is observed.


ABSTRACT: This work presents the static and dynamic analyses of laminated doubly-curved shells and panels of revolution resting on Winkler-Pasternak elastic foundations using the Generalized Differential Quadrature (GDQ) method. The analyses are worked out considering the First-order Shear Deformation Theory (FSDT) for the above mentioned moderately thick structural elements. The effect of the shell curvatures is included from the beginning of the theory formulation in the kinematic model. The solutions are given in terms of generalized displacement components of points lying on the middle surface of the shell. Simple Rational Bézier curves are used to define the meridian curve of the revolution structures. The discretization of the system by means of the GDQ technique leads to a standard linear problem for the static analysis and to a standard linear eigenvalue problem for the dynamic analysis. Comparisons between the present formulation and the Reissner-Mindlin theory are presented. Furthermore, GDQ results are compared with those obtained by using commercial programs. Very good agreement is observed. Finally, new results are presented in order to investigate the effects of the Winkler modulus, the Pasternak modulus and the inertia of the elastic foundation on the behavior of laminated shells of revolution.

References listed at the end of the paper:


[61] X. Wang, X. Wang and X. Shi, “Accurate Buckling Loads of Thin Rectangular Plates under Parabolic Edge Compressions by


ABSTRACT: The pure complete toroidal shell and the compartment of toroidal shell with ring stiffener, with circular meridian cross-section, have been investigated respectively by the numerical analysis method in this paper because of the difficulty of the theoretically solution. The thin shell element was adopted to obtain elastic analysis of a closed toroidal shell due to external pressure, which confirms the conclusion of membrane theory. Based on the nonlinear finite element method (FEM), the structural characteristics of the ring-stiffened toroidal shell have been carried out. In presented analyzing, adopting the elastic-plasticity stress-strain relations, the influences between material nonlinearity and geometry nonlinearity of the stability of structure hull are also considered. Comparing with the traditional cylindrical pressure hull, the ring-stiffened toroidal pressure hull is superior in resisting influences of the initial deflection to a certain extent and having larger reserve buoyancy. It means that the ring-stiffened toroidal shell could be used to realize better performance in the general structural form with its specific shape in underwater engineering.

ABSTRACT: A plastic buckling analysis for axially compressed square tubes is described in this paper. Deformation theory is used together with the realistic edge conditions for the panels of the tube introduced in our previous paper (Li and Reid, 1990), referred to hereafter as LR. The results obtained further our understanding of a number of problems related to the plastic buckling of axially compressed square tubes and simply supported rectangular plates, which have remained unsolved hitherto and seem rather puzzling. One of these is the discrepancy between experimental results and the results of plastic buckling analysis performed using the incremental theory of plasticity and the unexpected agreement between the results of calculations based on deformation theory for plates and experimental data obtained from tests conducted on tubes. The non-negligible difference between plates and tubes obtained in the present paper suggests that new experiments should be carried out to provide a more accurate assessment of the predictions of the two theories. Discussion of the results herein also advances our understanding of the compact crushing behavior of square tubes beyond that given in LR. An important conclusion reached is that strain hardening cannot be neglected for the plastic buckling analysis of square tubes even if the degree of hardening is small since doing so leads to an unrealistic buckling mode.

References listed at the end of the paper:

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ABSTRACT: This paper is concerned with the membrane shell analysis of filament overwound toroidal pressure vessels and optimum design of such pressure vessels using the results of the analysis by means of mathematical nonlinear programming. The nature of the coupling between overwind and liner has been considered based on two extreme idealizations. In the first, the overwind is rigidly coupled with the liner, so that the two deform together in the meridional direction as the vessel dilates. In the second, the overwind is free to slide relative to the liner, but the overall elongations of the two around a meridian are identical. Optimized designs with the two idealizations show only minor differences, and it is concluded that either approximation is satisfactory for the purposes of vessel design. Aspects taken into account are the intrinsic overwind thickness variation arising from the winding process and the effects of fiber pre-tension. Pre-tension can be used not only to defer the onset of yielding, but also to achieve a favorable in-plane stress ratio which minimizes the von Mises equivalent stress in the metal liner. Aramid fibers are the most appropriate fibers to be used for the overwind in this type of application. The quantity of fiber required is determined by both its short-term strength and its long-term stress rupture characteristics. An optimization procedure for the design of such vessels, taking
all these factors into account, has been established. The stress distributions in the vessels designed in this way have been examined and discussed through the examples. A design which gives due consideration of possible mechanical damage to the surface of the overwind has also been addressed.

References listed at the end of the paper:
Theisken, J.C., Private communication of results from experiments at NASA Glenn Research Center, 2007.

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ABSTRACT: We analyze the potential for liner buckling in a 40-in Kevlar49/epoxy overwrapped spherical pressure vessel (COPV) due to long, local depressions or ‘valleys’ in the titanium liner, which evidently appeared after proof testing (autofrettage). We begin by presenting the geometric characteristics of approximately 20 mil (0.02 in.) deep depressions measured by laser profilometry in several vessels. While such depths were more typical, depths of more than 40 mils (0.02 in.) were seen near the equator in one particular vessel. Such depressions are largely the result of overlap of the edges of crossing overwrap bands (with rectangular cross-section prepreg tows) from the first or second wrap patterns particularly where they begin and end. We then discuss the physical mechanisms of formation of the depressions during the autofrettage process in terms of uneven void compaction in the overwrap particularly around lines of tow overlap, and the resulting 10-fold increase in through-thickness stiffness of the overwrap. We consider the effects of liner plastic yielding mechanisms on residual bending moments and interface pressures between the liner and overwrap, both at the peak proof pressure (~6500 psi) and subsequently when reducing the pressure back to 0 psi. During depressurization, the Bauschinger effect becomes very important wherein extensive prior yielding in tension reduces the magnitude of the yield threshold in compression by 30 to 40% compared to the virgin annealed state of the titanium. In the absence of a depression, the liner is elastically stable in compression even at overwrap-liner interface pressures up to 6 times the ~ 1000 psi interface pressure that exists at 0 psi following proof. Using a mechanics model based on a plate on an elastic foundation, we develop an extensive analysis of the possible destabilizing effects of a frozen-in liner depression. The analysis treats the perturbing effects of the residual bending moments and interface pressures remaining after the proof hold as well as the Bauschinger effect on the compressive yield threshold when depressurizing to 0 psi. The key result is that depression depths of up to 40 mils can be tolerated by the liner, but above 40 mils, the Bauschinger effect drives destabilization, and buckling becomes increasingly likely depending on the details of depression formation during autofrettage. It is almost certain that destabilization leading to buckling will occur for depression depths beyond 55 mils.


ABSTRACT: The process of filament winding has gained broad support among a wide range of applications from rocket propellant tanks and automobile natural gas storages tanks to SCUBA and firefighting equipment. The high stiffness-to-weight characteristic of these pressures vessels makes them ideal for such applications. Many failure criteria have to be considered when designing composite pressure vessels. These include, but are not limited to, fiber rupture, liner fatigue, liner buckling, overwrap leakage, and composite crack propagation
resulting in burst. In order to simulate a number of these failure mechanisms, the debonding between the liner a composite overwrap must be modeled. In this paper, the use of surface based cohesive behavior in Abaqus to model the debonding between a metallic liner and a carbon fiber composite overwrap will be investigated. The deformation behavior across the bond will be examined along with the effects of bond failure. A procedure will be developed to systematically set up a simulation of the debonding of a liner from a composite overwrapped pressure vessel due to phenomenon such as cylinder buckling and surface defects which effect the liner-to-composite bond.


ABSTRACT: Since the recognition that local buckling of plate elements can significantly reduce the column buckling load of thin walled beams and columns, significant research has established a firm basis for understanding the interplay between buckling modes in classical built-up structures. Recent work on a modal projection procedure for representing the results of both static and dynamic nonlinear collapse computations has demonstrated that for structures whose collapse process includes a predominantly linear prebuckling domain, the failure process can be well understood by tracking the growth of the bifurcation eigenvectors in the solution. It has recently been observed that for structures which exhibit mode coupling characteristics, the bifurcation eigenvectors by themselves do not form a set of orthogonal functions when their inner product is evaluated. For complex structures or structures exhibiting complex multi-modal postbuckling behavior, this procedure provides an approach to evaluate the design basis for buckling mode interactions. Examples are shown illustrating this for collapse analyses involving both the classical case of geometric imperfections and material imperfections such as delaminations in composite structures.


ABSTRACT: A method for determining the resistance of an imperfect isotropic steel shell is proposed in this paper. The following hypotheses are supported: hypothesis on dominant characteristics of the usual initial geometric imperfection; hypothesis on the equivalent axisymmetric calculation model; and hypothesis on the general rules that govern the relationship between the mean value of the amplitude on the critical cross-section and the wall thickness, for different r/t relations. The correctness of the above hypotheses is proven by numerically simulated experiments using the computer program BOSOR5, for characteristic r/t relations.

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ABSTRACT: This paper reports the results of a numerical study undertaken on the buckling behaviour of lightly stiffened elliptic paraboloidal steel panels intended for use as long-span shuttering for lightweight concrete bridge decks, walkways and floors. Steel panel shutters of double curvature may allow the casting of concrete over relatively large spans while avoiding the use of supporting scaffolding and other intermediate props. Such long-span shutters are desirable when the ground below the deck cannot adequately support scaffolding, or the space below the deck carries traffic carriageways which should not be obstructed by scaffolding. In this study, the effect of the wet concrete is simulated as a uniform pressure normal to the shell surface (limiting case), while the dead weight of the hardening concrete is simulated as a uniformly distributed loading on the horizontal projection of the shell surface. The results show that panel rise and aspect ratio have a considerable influence on the buckling strength of the shutter. Tentative viability limits are established.


ABSTRACT: A postbuckling analysis is presented for a stiffened cylindrical shell of finite length subjected to combined loading of external pressure and a uniform temperature rise. The formulations are based on a boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, nonlinear large deflections in the postbuckling range and initial geometrical imperfections of the shell. The “smeared stiffener” approach is adopted for the stiffeners. The analysis uses a singular perturbation technique to determine the interactive buckling loads and the postbuckling equilibrium paths. Numerical examples cover the performances of perfect and imperfect, stringer and ring stiffened cylindrical shells. Typical results are presented in dimensionless graphical form.

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ABSTRACT: Stability equations for toroidal shells under hydrostatic pressure are derived from Sanders'1 non-linear equations of equilibrium and kinematic relations of the middle surface for general shells. The stability equations are solved by use of the asymptotic method. Theoretically predicted buckling pressures are in good agreement with experimental results obtained by Fishlowitz.2 The influence of prebuckling deflection on the critical load is investigated.


ABSTRACT: In the present investigation on the dynamic plastic buckling of cylindrical shells under axial compression waves, the critical axial stress and the exponential parameter of inertia terms in stability equations are treated as a couple of characteristic parameters. The criterion of transformation and conservation of energy in the process of buckling initiation is used to derive the supplementary restraint equation of buckling
deformation at the fronts of axial elastic and plastic compression waves. The supplementary restraint equation, stability equations, boundary conditions and continuity conditions constitute the necessary and sufficient conditions of determining the two characteristic parameters. Two characteristic equations are derived for the two characteristic parameters. The critical axial stress or the critical buckling time, the exponential parameter of inertia terms and the initial modes of buckling deformation are calculated quantitatively from the solution of the characteristic equations.


ABSTRACT: The relations of the critical stress and transverse inertia effect to the loading duration are investigated for the dynamic buckling of thin cylindrical shells under axial step loading. The critical stress and the inertial exponent are treated as the two characteristic parameters. The criterion of energy conservation is used to derive the supplementary restraint condition for buckling deformations at compression wave front. By use of the Galerkin method, an algebraic eigenvalue problem for the two characteristic parameters is derived from the governing equations and boundary conditions. The solution of the eigenvalue problem, which satisfies the supplementary restraint condition, gives the values of the critical stress and the inertial exponent for the dynamic buckling. The relation of critical stress to loading duration, predicted by the theoretical analysis, is in reasonable agreement with the experimental results.

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ABSTRACT: Buckling behavior of cross-ply cylinders under hydrostatic pressure is investigated using a semi-analytical finite element based on a consistent first order shear deformable shell theory. Potential loss due to external pressure, also called pressure stiffness (PS) is taken into account by making use of Koiter's related energy expression. A number of verification problems are solved and the numerical results are compared with the analytical results available in the literature and excellent agreement is observed. New numerical results are presented to assess the effect of PS on buckling due to hydrostatic pressure. It is shown that PS causes a decrease in the buckling load and this decrease depends on the size of the cylinder and the material. Also, issues related to thickness optimization are examined and optimal lamina thicknesses are determined for a number of cases with and without PS taken into account.


ABSTRACT: A curved axisymmetric shell finite element based on a consistent first-order shear deformable shell theory is developed for the linear stability analysis of cross-ply laminated shells of revolution under compressive loads. Finite element analysis results are presented for isotropic, orthotropic and cross-ply
laminated shells of revolution in comparison with the analytical and numerical results found in the literature. These comparisons demonstrate the applicability and the high performance of the element in stability analysis of thin and moderately thick cross-ply laminated composite shells of revolution under compressive loads.

ABSTRACT: The elastic buckling and initial post-buckling behavior of clamped shallow spherical shells under concentrated load is considered. It is found that bifurcation into an asymmetric deflection pattern will occur before axisymmetric snap-buckling unless the ratio of the shell rise to the thickness lies within a narrow range corresponding to relatively thick shells. The initial post-buckling analysis indicates that the shell retains its load carrying capacity as it makes the transition to asymmetric behavior. These results are in qualitative agreement with available experimental data.

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ABSTRACT: This work presents an analysis and numerical results for the buckling of longitudinally stiffened prismatic structures that consist of an assemblage of flat plate and cylindrical panel components. The applied loading is assumed to induce uniform in-plane biaxial stresses, and all types of buckling modes (general, local, and coupled) are automatically accounted for in the analysis. Previous analyses of such problems by the exact (Wittrick) and approximate (Cheung) finite strip methods are based on the assumption that the structure is simply supported on the transverse ends by diaphragms (SS3 classical simple supports). The present work extends these analyses to include the case of completely clamped transverse ends (CC4), as well as simply supported ends. A one term Galerkin method is used to replace the governing partial differential equations of equilibrium for each component by ordinary differential equations in terms of the transverse coordinate, and the ordinary equations are solved exactly. The principle of virtual work is employed to obtain the stiffness matrix for each component. Numerical results are presented for a wide variety of CC4 and SS3 prismatic structures. These results compare favorably with available solutions.

H.A. Ashour (Faculty of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar), “Creep buckling of cylindrical panels under multiaxial loading”, Computers & Structures, Vol. 52, No. 1, July 1994, pp. 139-148, doi:10.1016/0045-7949(94)90265-8
ABSTRACT: This work presents an analysis of the creep buckling problem of geometrically imperfect circular cylindrical panels under multiaxial loading with simple support boundary conditions. The analysis is based on a nondimensional form of Donnell-type equations for a slightly imperfect cylindrical panel. The elastic constitutive equations for a thin panel are employed. The basic elastic equilibrium equations in the middle surface displacement components are derived through the employment of the principle of virtual displacements. For creep deformations, Odqvist's constitutive equations for steady creep are employed. In the present analysis, creep buckling is characterized by either reaching a maximum deflection limit or experiencing a bifurcational buckling state. Based on the present analysis, a computer program has been developed for the creep buckling
analysis of cylindrical panels. The panel ends are assumed to be simply supported. The applied loading is assumed to be axial compression and lateral pressure. Numerical results are presented for imperfect isotropic panels under both uniaxial and multiaxial loading. For the case of uniaxially compressed plates, the present results are generally in good agreement with previous experimental and analytical results. These results suggest that each of the level of the axial compressive load, the level of the lateral pressure, the amplitude and direction of the initial imperfection, and the panel curvature greatly affect the creep buckling times of cylindrical panels. The results presented indicate that avoiding negative (toward the centre of curvature) initial imperfections would help to suppress the creep buckling process for cylindrical panels under multiaxial loading conditions. It would also help to eliminate the possibility of a bifurcational buckling state to exist. This can be achieved by intentionally introducing a small positive initial imperfection in the form of a simple out of roundness.


ABSTRACT: An infinitely long, axially compressed, circular cylindrical shell with an imperfection in the shape of the axisymmetric classical buckling mode, undergoing steady or nonsteady creep, is analyzed. The axisymmetric problem is solved incrementally using nonlinear shell equations The ratio of the applied stress to the classical buckling stress determines if the shell will collapse axisymmetrically or if it will bifurcate into a nonaxisymmetric mode, and whether or not bifurcation will result in instantaneous collapse. The bifurcation problem is formulated exactly and the initial postbuckling behavior is investigated via an asymptotic elastic analysis, based on Koiter's general theory. Numerical results are compared with available experimental data.


ABSTRACT: A problem-oriented method for the nonlinear elastic-plastic analysis of nonsymmetrically loaded shells of revolution is described. It is based on an approximation of the circumferential distribution of the loads and variables by Fourier series. Ring finite elements are used in the axial direction. Their stiffness matrices are obtained by accurate numerical integration rather than by trial functions. To be able to take full advantage of the Fourier decomposition and the one-dimensional discretization, all nonlinearities are treated iteratively in the form of pseudo-load vectors. Thus, the various Fourier harmonics are governed by uncoupled algebraic equations and no explicit knowledge of the nonlinear global tangent stiffness matrix is required. Convergence problems of the iterative procedure are avoided by employing a sort of conjugate gradient method with a special preconditioning within each increment. Numerical examples involving strongly nonlinear behavior and highly nonsymmetric states of stress and deformation are given which demonstrate the effectiveness of the method.


ABSTRACT: This paper addresses the nonlinear dynamic analysis of shells of revolution. Starting from a discretization procedure which is tailored to the particular geometry of these shells, a direct time integration
procedure is discussed. It employs the Newmark temporal operator, and a modified preconditioned conjugate-direction method is used to solve the resulting algebraic equations. Subsequently, a closely related reduced basis technique is presented which combines some of the features of the direct integration procedure with those of the standard reduction methods.


ABSTRACT: An analysis of the elastic–plastic load-carrying behaviour of thin-walled spatial beam structures is presented. It is based on a beam theory valid for large displacements and rotations, which admits arbitrary cross-sections, curved axes, initial imperfections, a general material description, and which fully accounts for the influence of warping constraints as well as the stress-history dependence of the elastic–plastic shear moduli. An incremental updated Lagrangian viewpoint is adopted in the derivation of the basic beam equations from a generalized variational principle, and in the numerical solution procedure the displacement–finite element approach is followed. The associated tangential stiffness matrices are obtained by direct numerical integration of the governing incremental differential equations rather than through the use of shape functions in connection with a virtual work principle. Applications of the theory are given in which the influence of the loading configuration, material parameters, geometric nonlinearities and warping constraints on the load-carrying behaviour and on the bifurcation and ultimate loads of thin-walled beam structures is explored.

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ABSTRACT: The paper deals with the results of a systematic numerical investigation of the nonlinear elastic and elastic plastic load-carrying behaviour and imperfection sensitivity of torispherical pressure vessel heads under uniform external pressure. In particular, the presentation focuses on the qualitative and quantitative influence of the radius-to-thickness ratio R/t, the yield stress σ0 and the magnitude of initial geometric imperfections (in the shape of the elastic bifurcation mode) on the elastic-plastic load-carrying behaviour. It is found that thinner shells are more sensitive to the value of the yield stress and the magnitude of initial geometric imperfections, but their load-carrying capacity, relative to the elastic bifurcation pressure, may also be significantly higher than that of thicker shells.

H. Obrecht, B. Rosenthal, P. Fuchs (Baumechanik-Statik, Universitaet Dortmund, D-44221 Dortmund, Germany), “Buckling And Imperfection-Sensitivity Of Axially Compressed Cylindrical Shells With Compliant Cores”, (no date or publisher given, latest reference is 2001, fluid.ippt.gov.pl)

ABSTRACT: The extent to which the mechanical properties and dimensions of compliant cores influence the load-carrying capacity and imperfection-sensitivity of axially compressed cylindrical shells is analyzed numerically for a wide range of configuration parameters. It is found that a comparatively thin layer of core material is sufficient to achieve substantial increases in the buckling loads while at the same time the
imperfection-sensitivity is significantly smaller than for the unfilled shell.

References listed at the end of the paper:


ABSTRACT: From the point-of-view of economy and safety it is desirable to employ structural configurations with a favorable strength-to-weight ratio and a sufficiently small imperfection-sensitivity. The presentation focuses on two examples falling into this category: The axially compressed cylindrical shell filled with – and/or surrounded by - a compliant core, and auxetic structures. Both exhibit unexpected aspects in their load-carrying behavior and have a significant weight-savings potential.

H. Obrecht, P. Fuchs, U. Reinicke, B. Rosenthal and M. Walkowiak (Lehrstuhl für Baumechanik-Statik, Technische Universität Dortmund, August-Schmidt-Strasse 6, D-44221 Dortmund, Germany), “Influence of wall constructions on the load-carrying capability of light-weight structures” (Dedicated to Professor Choon Fong Shih, President of the National University of Singapore on the occasion of this 60th birthday.), International Journal of Solids and Structures, Vol. 45, No. 6, March 2008, pp. 1513-1535, doi:10.1016/j.ijsolstr.2007.10.017
ABSTRACT: Results of systematic numerical studies are presented which suggest that suitable alternative wall constructions may lead to elastic load-carrying capacities of light-weight structures which significantly exceed those of conventional monocoque constructions, and that in certain cases this improvement may also be accompanied by a decrease in imperfection-sensitivity. Two kinds of wall modifications are considered: a hybrid wall construction where the skin of a light-weight structure is coated with a low-density material, and nonhomogeneous – in particular lattice and biaxially corrugated – wall constructions. The paper focuses on the elastic load-carrying behavior of shell- and plate-like structures, and structural efficiency is assessed on the basis of their bifurcation buckling resistance while other design criteria, such as e.g. stiffness and plasticity, are not taken into account.

Hailan Xu, “Buckling, postbuckling and imperfection sensitivity analysis of different type of cylindrical shells by Hui’s postbuckling method”, 2013 Ph.D. dissertation, University of New Orleans
ABSTRACT: Buckling and postbuckling has been critical design parameters for many engineering structures. In recent years, this topic has continued to be of major concern due to (1) the discovery of new materials with amazingly superior properties, (2) increasingly more stringent safety requirements, (3) lighter, and more durable
requirements. Such applications can be routinely found in aerospace, naval, civil, and electrical, and nuclear engineering structures and especially in the vehicle industries. Koiter is the first one to show that the imperfection-sensitivity of a structure is determined by its initial postbuckling behavior. In Koiter’s 1945 general postbuckling theory, it defines the initial postbuckling behavior and imperfection sensitivity behavior by the postbuckling b coefficient. Hui and Chen (1986) were the first to show that the well-known Koiter’s General Theory of Elastic Stability of 1945 can be significantly improved by evaluating the postbuckling b coefficient at the actual applied load, rather than at the classical buckling load. The reason for such significant improvement in predicting the imperfection sensitivity is due to the fact that for an imperfection-sensitive structure, the slope of the buckling load versus imperfection amplitude curve approaches negative “infinity” as the imperfection amplitude approaches to zero. Thus for “finite” amplitude of the geometric imperfection, the applied load is significantly lower than the classical buckling load, leading to significant overestimate of imperfection using Koiter’s General theory of 1945. Such improvement method was demonstrated to be (1) very simple to apply with no tedious algebra, (2) significant reduction in imperfection sensitivity and (3) although it is still asymptotically valid, there exists a significant extension of validity involving larger imperfection amplitudes. Strictly speaking, Koiter’s theory of 1945 is valid only for vanishingly small imperfection amplitudes. Hence such improved method is termed Hui’s Postbuckling method. This study deals with the Postbuckling and imperfection sensitivity of different kinds of cylinders by using the Hui’s postbuckling method. For unstiffened cylinder and laminate cylinder, the solution of Hui’s postbuckling method is compared with ABAQUS simulation result. A parameter variation of stringer/ring stiffened cylinder is also evaluated. A positive shift of the postbuckling b coefficient has been observed, which indicates a significant overestimate of the imperfection sensitivity by Koiter's general stability theory. More importantly, the valid region is significantly increased by using Hui's postbuckling method compared with the Koiter's general stability theory.

References listed at the end of the dissertation:

[18] D. M. A. Leggert and R. P. N. Jones, "The behavior of a cylindrical shell under axial compression when the buckling load has been exceeded," ARC rep and mem no 2190, 1942.
[47] V. L. Krasovsky, "Pre-buckling deformation and buckling of isotropic and reinforced thin-walled cylinders under axial..."

ABSTRACT: An axisymmetric shell optimization procedure is developed which is a fast, user-friendly and practical tool for design use in disciplines including aerospace, mechanical and civil engineering. The shape and thickness of a shell can be optimized to minimize shell mass, mass/volume ratio or stress with constraints imposed on von Mises stress and local buckling. The procedure was created with the aid of the GENOPT optimization development system (Dr. D. Bushnell, Lockheed Missiles and Space Co) and uses the FAST1 shell analysis program (Prof. C. R. Steele, Stanford University) to perform the constraint analysis. The optimization method used is the modified method of feasible directions. The procedure is fast because exact analysis methods allow complex shells to be modelled with only a few large shell elements and still retain a sufficiently accurate solution. This is of particular advantage near shell boundaries and intersections which can have small regions of very detailed variation in the solution. Finite element methods would require many small elements to capture accurately this detail with a resulting increase in computation time and model complexity. Reducing the complexity of the model also reduces the size of the required input and contributes to the simplicity of the procedure. Optimization design variables are the radial and axial coordinates of nodes and the shape parameters and thicknesses of the elements. Thickness distribution within an element can be optimized by specifying the thickness at evenly spaced control points. Spline interpolation is used to provide a smooth thickness variation between the control points. An effective method is developed for reducing the number of required stress constraint equations. Various shells have been optimized and include models for comparison with published results. Shape, thickness and shape/thickness optimization has been performed on examples including a simple aerobrake, sphere-nozzle intersections, ring reinforced cylinder and elliptical and torispherical tank heads. Convergence of different initial designs to one final design is demonstrated for a shape, thickness and shape/thickness optimization problem. The sphere-nozzle intersection is investigated in detail and the equal area replacement rule for reinforcement is verified for most intersection geometries.


ABSTRACT: With the stability analysis of hyperbolic cooling tower shells with ring-stiffeners, our paper proposes the linear pre-buckling consistent theory. The numerical result shows that this linear analysis method is very effective and practical in engineering, for its precision of computation is up to the level of the nonlinear analysis when it is used for the study of critical loads of the hyperbolic cooling tower which is mainly governed by wind pressure and for the study of the effect of some other factors concerned in design on the buckling of shells. Based on that, we have obtained a series of conclusions which will greatly benefits the engineering design when discussing the effect on the critical wind loading of the shell which is caused by the following factors such as the position of rings, the number of rings and the dead weight.

References listed at the end of the paper:


ABSTRACT: Design and construction of efficient and economic Reinforced Concrete (R.C.) Hyperbolic Cooling Towers have driven the engineers toward the design of tall and thin-shell towers which have considerable high slenderness aspect ratio. Consequently, the shell of R.C. Cooling Towers with relative high slenderness aspect ratio is extremely prone to buckling instability due to wind loading. To increase the structural stability or buckling safety factor, one economic approach is to design and construct stiffening rings for the R.C. Hyperbolic Cooling Towers. Despite the research previously performed to determine the effect of stiffening rings on the buckling behavior of the R.C. Hyperbolic Cooling Towers, information resulting in maximum buckling stability is absent considering the optimized utilization of the quantity and dimension as well as the location of this type of stiffeners. In this paper, not only the effect of the stiffening rings on the buckling stability of the R.C. Cooling Tower is studied but also the optimized location, quantity and dimension of the stiffening rings are carried out for a sample RC Cooling Tower. The dimensions of the selected sample cooling tower are in average typical dimensions which are used in the current practice. In this study, finite element (F. E.) analyses has been carried out to define the buckling modes and resistance of this tower due to wind loading for different number of stiffening ring configurations. Based on the conducted buckling analysis, the optimized number, location and dimension of the stiffening rings that maximizes the tower.s buckling stability are defined and the methodology to achieve this information is discussed in this paper.


ABSTRACT: This paper is concerned with a numerical solution of hyperbolic cooling tower shell, a class of full nonlinear problems in solid mechanics of considerable interest in engineering applications. In this analysis, the post-buckling analysis of cooling tower shell with discrete fixed support and under the action of wind loads and dead load is studied. The influences of ring-stiffener on instability load are also discussed. In addition, a new solution procedure for nonlinear problems which is the combination of load increment iteration with modified R-C are-length method is suggested. Finally, some conclusions having important significance for
practice engineering are given.

References listed at the end of the paper:


ABSTRACT: Optimum design considerations for an underwater storage vessel to contain liquid gases and oils led to the assessment of an axisymmetric shell of revolution—the Echinodome or drop shape. Analytical treatment of the various types of loading to which the shell could be subjected indicated that buckling was the more critical design criteria. A small GRP spherical shell under hydrostatic pressure was investigated for its buckling behavior both experimentally and theoretically. In the experimental approach surface strains were measured using electric resistance strain-gage rosettes on the inner and outer surfaces. Predictions of critical buckling pressure were made from the experimental results using a Southwell technique and numerically by the finite-element method. The influence of the results on design procedures is discussed.

References listed at the end of the paper:

ABSTRACT: The paper examines theoretically the buckling behaviour of an echinodome—an optimum form of axisymmetric shell of revolution. The types of loading considered are of a concentrated nature applied axisymmetrically and symmetrically. Firstly static buckling behaviour is studied followed by dynamic buckling. Both bifurcation and non-linear collapse buckling are taken into account for static loading and only the non-linear collapse approach is pursued for the dynamic case. Comparisons are made between the corresponding dynamic and static buckling loads and the relative significance of the dynamic situation is discussed.


ABSTRACT: The buckling behavior of an underwater shell of revolution structure of optimum form—an echinodome—is examined under axisymmetric and symmetric point loads both experimentally and theoretically. For the concentrated loadings, experimental predictions of critical buckling are based on the Southwell technique and a possible alternative method is suggested. Bifurcation and nonlinear collapse buckling analyses are described theoretically. Within the bifurcation investigation both linear and nonlinear approaches are included. The effects of base fixity on the instability of the structure are considered. Comparisons are made with earlier external-pressure loading effects and the relative significance of the two forms of loading are discussed.

References listed at the end of the paper:

ABSTRACT: A two-dimensional finite-difference technique for irregular meshes is formulated for derivatives up to the second order. The domain in the vicinity of a given central point is broken into eight 45 degree pie shaped segments and the closest finite-difference point in each segment to the center point is noted. By utilizing Taylor series expansions about a central point with a unique averaging process for the points in the four diagonal segments, good approximations to all derivatives up to the second order and including the mixed derivatives are obtained. For square meshes the general derivative expressions for arbitrary meshes which were determined reduce to the usual finite difference formulae. In one example problem the Poisson equation is solved for an irregular mesh. In a second example for the first time a problem with a geometric nonlinearity, namely large deflection response of a flat membrane, is solved with an irregular mesh. The solutions compare very favorably with results obtained previously. Some discussion is given on possible approaches for determination of finite difference derivatives higher than the second.

ABSTRACT: Large deformation elastic-plastic buckling loads are obtained for axisymmetric spherical caps with initial imperfections. The problem formulation is based on equilibrium equations in which the plastic deformation is taken as an effective plastic load. Both perfectly plastic and strain hardening behavior are considered. Strain hardening is represented by the Prager-Ziegler kinematic hardening theory, so that the Bauschinger effect is accounted for. Solutions of elastic-plastic circular plates and spherical caps are in good agreement with previous results. For the spherical cap it was determined that both initial imperfection and
plastic deformation have the same effect of reducing buckling capacity; as the magnitude of the imperfection increases, the influence of plastic deformation becomes less important. It is also found that the geometric parameter $\alpha$, which is used as an important factor in elastic response, becomes meaningless for the elastic-plastic buckling analysis of spherical caps.

ABSTRACT: Dynamic buckling loads are obtained for axisymmetric spherical caps with initial imperfections. Two types of loading are considered, namely, step loading with infinite duration and right triangular pulse. Solutions of perfect spherical caps under step loading are in excellent agreement with previous findings. Results show that initial imperfections do indeed have the effect of reducing the buckling capacity for both dynamic and static responses, although they are affected in a different manner. From the solutions obtained for triangular pulse situations, it is revealed that pulse duration has a very significant impact on the magnitude of the dynamic buckling load. When comparing these solutions with those of step loading, it is concluded that the step loading with infinite duration is the limiting case of a triangular pulse, and that the step loading provides the most severe loading situation for dynamic analysis.

ABSTRACT: A finite difference method is developed for the large deformation elastic-plastic dynamic buckling analysis of axisymmetric spherical caps with initial imperfections. The problem formulation is based on governing differential equations of motion, treating the plastic deformation as an effective plastic load. Both perfectly plastic and strain hardening behavior are implemented in the program. Strain hardening is incorporated through use of the Prager-Ziegler kinematic hardening rule, so that the Bauschinger effect is accounted for. The solution for the large deformation elastic-plastic dynamic response of a spherical cap is compared very favorably with other findings. Two spherical cap models are selected to study the title problem. Results obtained indicate that both plastic yielding and initial imperfection play significant roles in reducing the load carrying capacity of these shell structures. Both increase their influence as the thickness to radius ratio and the imperfection magnitude increase, respectively. It is also found that dynamic effect has the influence of lowering load carrying capacity of perfect spherical caps; however, its influence on imperfect spherical caps depends on the magnitude of initial imperfections.

ABSTRACT: The present study investigates the effect of Winkler-Pasternak elastic foundation parameters on the nonlinear dynamic response of shallow spherical shells. The values of foundation parameters $k$ and $\beta$ have been determined for the minimaximum central response of the shallow shells for both the clamped as well as simply supported immovable edge conditions. Donnell type partial differential equations governing the moderately large amplitude behaviour of shallow spherical shells resting on Winkler-Pasternak elastic foundations under step pressure loading, have been analysed. The space and time-wise integrations of governing equations have been carried out using Chebyshev series and Houbolt techniques, respectively. It is also shown
that the present analysis can be extended to study the dynamic buckling of shallow shells resting on elastic foundations.

SUMMARY: Time dependent pressure loads may cause dynamic buckling instabilities in the response of thin-walled structures. A typical example is the dynamic snap-through of a spherical shell under sudden external pressure. Usually, the critical load is obtained performing several time step analyses under different load magnitudes to localize the critical step load. In this paper a more efficient alternative is described allowing to determine the critical load directly or with at least considerably less time history analyses. The dynamic stability is evaluated in the sense of Liapunov’s first method. The geometrically and materially nonlinear finite element method is applied. In the above mentioned simplified procedure stability criteria are evaluated parallel to one nonlinear time response analysis. Starting with the eigenproblem of the system matrix the applicability of the kinetic stability criterion is shown. The procedure can be extended to the eigenproblem for the load parameter in order to approximate the critical step load to some extent directly. Numerical examples demonstrate the quality of the proposed method.

ABSTRACT: Elastic-plastic deformation of a thin-walled sandwich toroidal shell (a curved tube) is considered. A geometrically nonlinear theory of finite displacements but small strains is applied. Deformation of the whole torus is assumed to be rotationally symmetric and, moreover, deformation of a meridional section of the tube is symmetric with respect to the symmetry plane of the initial torus. The torus is subject to simultaneous uniform normal pressure, internal or external, and in-plane bending. The process is controlled by the two independent parameters: the pressure and the change of unit toroidal angle. Depending on the choice of loading trajectory, a process of elastic-plastic deformation can be terminated in various ways. The first possible termination of a continuous process of deformation is due to the onset of local kinematic discontinuity (strain localization or onset of a plastic hinge), regarded as inadmissible. The second termination (limit point) corresponds to a maximal value of the load factor and it limits the stable precritical period of deformation. The interaction curves corresponding to different termination modes intersect at corners; some parts of these curves are concave.

ABSTRACT: Optimum laminate configurations for laminated rectangular plates under uniaxial or biaxial compression are investigated and are obtained under buckling constraints. Complete freedom is permitted in the selection of the ply angle variation through the thickness; however, it is proved that the maximum buckling load occurs when the orientation angle in each of the layers is the same. Three types of optimal angle (directions) are obtained in terms of the material properties, the geometrical properties and the type of buckling mode. They are expressed in closed analytical form.
ABSTRACT: The paper deals with the buckling analysis of axisymmetric fully clamped composite shells of revolution such as spherical caps, torispheres and hemispheres. Its first part is devoted to linear buckling analysis in order to determine the appropriate divisors for buckling pressures. Then, the effects of fibre orientation on buckling pressure calculated with the use of the BOSOR4 program are discussed for single-layered (angle-ply), two-layered and quasiisotropic composite shells made of unidirectional glass and carbon/epoxy resin. It is shown that the maximal buckling pressures occur for quasi-isotropic composite shells. The upper and lower bounds of buckling loads for arbitrary fibre orientations of composite torispheres and hemispheres are also proposed.


ABSTRACT: The paper deals with the investigations of failure modes of laminated shells of revolution subjected to external pressure. These are analysed for two typical shell forms such as fully clamped hemispheres and torispheres made of unidirectional or woven roving glass/epoxy and carbon/epoxy. The buckling pressures of composite shells are compared with the failure pressures obtained from the various failure criteria in the stress space. The effects of fibre orientation and initial geometric imperfections are also discussed. The imperfections considered are in the form of increased-radius polar imperfections and Legendre polynomial imperfections. For CFRP perfect torispherical shells the numerical results are verified by experimental tests.

References listed at the end of the paper:

ABSTRACT: The present paper deals with the static buckling and post-buckling behaviour of clamped elastic laminated shallow spherical shells subjected to a uniform external pressure. Applying the Rayleigh-Ritz procedure to Marguerre's equations combined with precise pre-buckling numerical analysis, reasonably accurate solutions are obtained for buckling upper and lower pressures. The effects of fibre orientations on pre- and post-buckling behaviour, buckling loads and modes are considered. The results for composite shells are compared with those calculated for quasi-isotropic ones.


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ABSTRACT: Presents a finite element formulation of the layout optimization and design sensitivity applied to doubly-curved shells of revolution. The objectives of the optimization are to maximize buckling pressures and first-ply-failure pressures. The problem is formulated and solved with the use of geometrically non-linear transverse shear shell theory. However, the optimization method proposed limits the sensitivity analysis to a geometrically linear problem. Focuses special attention on the formulation of the optimization problem taking into account various factors, such as the form of geometrical and physical relations, types of design variables and the finite element discretization. Demonstrates several numerical examples to illustrate the capability of the proposed optimization procedures.


ABSTRACT: This paper presents optimization problems of cylindrical shells subjected to buckling and ply failure constraints. The objective is to maximize failure load. The layers are assumed to be oriented at 0 °, 90 ° and ± 45 °, so that the locations of plies in the laminate (3N variables) are design variables. The aim of the present work is to discuss the influence of various formulations of governing equations on optimal solutions including the effects of transverse shear deformations and to present the use of different variants of genetic algorithms, i.e. different selection, mutation and crossing. A series of numerical examples illustrates the discussed problem.


ABSTRACT: A thin-walled sandwich plate having laminated composite faces and subject to axial compression is studied. The first part of the work is devoted to the discussion of the 2-D geometrically nonlinear formulation of governing equations with the use of the Hamilton and the Lagrange variational principles. It allows us to compare and verify values of buckling loads and natural frequencies obtained with the use of different variants of sandwich plate theory. The analytical results are also confronted with the FE computations conducted with the use of the NISA II package. Then, we consider also the problems of local failure damage of sandwiches basing on the 3-D FE analysis. The aim of those investigations is to point out the effects of the normal stresses and their influence on the sandwich behaviour.


ABSTRACT: The first part of the paper is devoted to the presentation and discussion of various problems encountered in theoretical and numerical modelling of fatigue phenomena and failure modes in the 2-D description of composite structures. Then, a numerical FE model is proposed based on the progressive pure deterministic evaluation of the stiffness degradation of structures. Using the proposed formulation logarithmic fatigue life contours have been estimated for composite plates subjected to shear loads or tension.


ABSTRACT: A new optimization problem for laminated multilayered structures having surface bounded piezoelectric (PZT) patches have been formulated and solved. The present formulation introduces boundaries of PZT patches as new class of design variables. In addition, classical design variables in the form of ply orientation angles of orthotropic layers are also taken into account. The design objective is the minimization of normal maximal deflections. The standard Rayleigh–Ritz method is used; however, the accuracy of optimal design are verified with the aid of the FE package ABAQUUS. Examples are presented to illustrate the performance of the proposed model. For the actuator/actuator configuration, it was shown that the PZT actuators can significantly reduce deformations of the composite plate. Those effects were dependent on the value of the applied voltage. It was demonstrated that the proper choice of the actuator form is more efficient in reducing deflections. The influence of the fiber orientation and their material properties on the optimal design is also presented and discussed. The growth of the plate geometrical ratio \(a/b\) results in the increase of the effectiveness of the optimization procedure based on the appropriate choice of the boundary curve of the PZT patch.


ABSTRACT: In this paper the problem of the optimal design of thin-walled tubular columns under axial compression and torsion controlled by displacements is investigated. A radius of cross-sectional circular profile varying along the axis of the shell-column as well as a wall thickness, which lead to the maximal displacements caused by loadings before the structure buckles are sought. both global (buckling of a column) and local (wall
buckling of a shell) stability of a structure are taken into account. the geometry of the structure is approximated by the convex Bézier polynomial. the results are obtained using the simulated annealing method.

References listed at the end of the paper:

ABSTRACT: In this study, effective computational procedures are introduced and used to characterize the dynamic behavior of cylindrical panels with circular cross-section having the single delamination between laminate layers. Based on the computed results it is possible to determine the effect of delamination on the overall structural dynamic behavior. Those results are used to quantify the difference between the results of the relevant parameters in the cases of perfect and defected structures. Usually, the wave propagation can be observed with the use of piezoelectric sensors. Therefore, in the next step of our analysis we modeled delaminated structures with a finite number of PZT sensors to consider also their influence on the structural dynamic response. The numerical analysis have been conducted with the use of 3D finite elements. A lot of numerical results allow us to understand better the influence of various parameters on the form of wave propagation in cylindrical multilayered shells.

INTRODUCTION: Many laminated composite structures are assembled from parts that are thin. These assembled structures, loaded e.g. in compression, can buckle overall. For isotropic stiffened structures a variety of buckling interactions can occur involving local and overall deformations of both plate or shell sheet and stiffeners. In the case of laminated multilayered structures, being more complex built-up than isotropic ones, plated or shell structures can buckle in more complex and subtle ways. In addition, buckling modes can be preceded or associated with other failure modes, such as e.g. the First-Ply-Failure, delaminations or local buckling of sublaminates. For sandwich structures having faces made of multilayered laminates the number of possible failure modes even increases due to the existence of face wrinkling and/or core shear instability. It is necessary to emphasize also that the effects of local geometrical imperfections have been to cause discrepancies between experimental tests and theoretical predictions. Other uncertainties dealing with geometrical properties (e.g. length or shell ovalisation) and material properties will not be studied herein. The designer of any structure susceptible to buckling must have a certain knowledge/intuition about buckling behavior. With enhanced intuitive knowledge about shell buckling, the designer should have an improved ability to foresee situations in which buckling might occur and thus modify a design to avoid it. In this way they will be able to set up more appropriate models for experimental test and for analytical predictions. The general objective of this paper is to convey to the designer a “feel” for multilayered laminated plate and shell buckling. An understanding of instability can be developed by study of large number of examples involving a variety of plated and shell structures. The experimental results are based mainly on the tests conducted by Muc [1, 2, 3] and on the review of the most representative examples presented in the literature. Emphasis is given here to nonlinear behavior of structures caused by both large pre-buckling deflections and/or large deformations (strains), understood in the sense of 2D approach to the analysis of plated and shell structures. The present paper deals with the presentation of experimental tests for various composite structures, i.e. rectangular and square plates, cylindrical shells, cylindrical sandwich panels and various types of domed heads (spherical, ellipsoidal and torispherical) having different geometrical ratios. A number of examples involves practical shell structures (especially for pressure

ABSTRACT: The present effort focuses on the development of finite element models to implement in the bifurcation and post buckling nonlinear analysis of laminated shells. This paper deals with the two aspects of the numerical simulation of the buckling and post buckling response of layered composite structures. The first aspect is the formulation and evaluation of an efficient shell finite element valid for geometrical nonlinear analysis of laminated shells. The formulation of the element is based on the third order shear deformation theory with the assumption of moderately large deflections but small rotations. The theory allows parabolic description of the transverse shear stresses, and therefore the shear correction factors of the usual shear deformation theory are not required in the present theory. Since the formulation is based on the third order theory, applicability is extended to moderately thick to thin situations using a discrete Kirchhoff technique. The second aspect pertains to the prediction of the onset of local delamination in the post buckling range and accurate determination of transverse shear stresses in the lamina ted structures. The accuracy and effectiveness of the finite element and the strategies developed are demonstrated by means of detailed numerical and experimental examples.

References listed at the end of the paper:


ABSTRACT: The paper presents general design criteria for designing pressure vessels to withstand external pressure. Combinations of dome ends, cones and cylinders are considered. The criteria reduce to those given in BS 5500 for simple geometries. General criteria are given for the design of ring stiffening including the choice of stiffener proportions. The use of sophisticated analytical techniques to assist in meeting those criteria is demonstrated by means of numerical examples.


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“Marguerre shell type secant matrices for the postbuckling analysis of thin, shallow composite shells”, Structural Engineering and Mechanics (an international journal), Vol. 18, No. 1, pp 41-58, July 2004

ABSTRACT: The postbuckling behaviour of thin shells has fascinated researchers because the theoretical prediction and their experimental verification are often different. In reality, shell panels possess small imperfections and these can cause large reduction in static buckling strength. This is more relevant in thin laminated composite shells. To study the postbuckling behaviour of thin, imperfect laminated composite shells using finite elements, explicit incremental or secant matrices have been presented in this paper. These incremental matrices which are derived using Marguerre.


ABSTRACT: Even a weak disturbance caused by an asymmetric mesh is enough to break structural symmetry, which triggers the bifurcation buckling and post-buckling behavior of composite laminated cylindrical shells under compression loading by ABAQUS. The mesh perturbation is more objective and authentic; it will not destroy the original model structure in Finite Element Analysis, comparing with the traditional perturbation method by introducing the initial imperfections into the model. A series of numerical experiments are performed to investigate the influence of different types of asymmetric mesh on the predicted secondary buckling load. The predicted secondary buckling load agrees better with analytical solution than predicted
primary buckling load and the results from the traditional perturbation method respectively. Therefore, secondary buckling load provides the key design criterion for composite laminated cylindrical shells. Primary and secondary post-buckling patterns of different complexity are explored, which agrees well with experimental buckling modes. Our major conclusions can be summarized briefly: different types of asymmetric mesh have little influence on the predicted secondary buckling load; Care must be exercised regarding the mesh density in order to produce the secondary buckling mode as well as the reliable secondary buckling load.

References listed at the end of the paper:


ABSTRACT: This paper gives the perturbation formulation of continuation method for nonlinear equations. Emphasis is laid on the discussion of searching for the singular points on the equilibrium path and of tracing the paths over the limit or bifurcation points. The method is applied to buckling analysis of thin shells. The pre-and post-buckling equilibrium paths and deflections can be obtained, which are illustrated in examples of buckling analysis of cylindrical and toroidal shells.

References listed at the end of the paper:

ABSTRACT: Flat shell strips are combined with flat shell elements in the buckling analysis of ring-stiffened cylindrical shells with cutouts. The influence of the ring-stiffeners is smeared over the whole shell and the stiffened shell is treated as an orthotropic shell. The region of the shell without cutouts is analysed by the finite strip method and the region with cutouts by the finite element method. On the interfaces of the two regions, finite strips and finite elements are connected together by specially developed transition elements. Numerical examples are given to verify the accuracy and efficiency of this method. Buckling loads of an axially compressed ring-stiffened cylindrical shell with one cutout under various cutout radiuses are calculated by the present method. The curve predicting the relationship between buckling loads and the dimension of the cutout is drawn.


ABSTRACT: Numerical aspects of initial stability analysis of a cylindrical shell of non-constant parameters along the generator and under non-symmetrical loads are considered. A variational approach based on Sanders’ and Donnell’s non-linear equations of thin, elastic shells is applied. The problem is decomposed to determine: the stability vectors in the axial direction in the first step, and the critical load and the stability vector in the circumferential direction in the second step. The discretization is based on finite Fourier representations and the finite difference method. To find the approximate stability vector in the axial direction an auxiliary problem for axisymmetric loads is solved. The error of the method is defined and the effectiveness of the method is estimated. The decomposition leads to small and fast algorithms suitable for personal computers. Shells with constant and stepped thicknesses under wind loads are calculated as examples. Tested algorithms show considerable effectiveness and good accuracy of results.


ABSTRACT: A finite element formulation applicable to the general shell of revolution is presented for the stress and stability analysis of toroidal pressure vessels under hydrostatic pressure. Considering the follower force effect of the external pressure, linear bifurcation buckling loads and corresponding mode shapes have been obtained in both axially and equatorially symmetric as well as antisymmetric buckling modes. Calculated critical values are compared with results of other investigations.
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ABSTRACT: The subject of this paper is the buckling behavior of thin-walled beams with an enforced axis of rotation subjected to longitudinal compressive loadings. The stiffeners are mathematically modeled by a refined nonlinear beam theory recently derived. An analytical solution is obtained to the beam buckling equations. This solution is expressed in terms of a simple formula which yields the tripping loads of T, angle, I, Z, and other open cross-sections. These predictions are shown to agree with those of other authors and with a finite element code.

ABSTRACT: The subject of this paper is the buckling behavior of a rectangular plate, with parallel thin-walled stiffeners attached to one side, subjected to a combination of axial compression and lateral pressure. The plate is modeled by the Von Kármán plate equations and the stiffeners by a nonlinear beam theory recently derived. An analytical solution is obtained for the buckling load corresponding to a torsional tripping mode of the stiffeners. This solution is compared with the experiments and theories of other researchers.

ABSTRACT: The subject of this paper is the buckling behavior of a rectangular plate, with parallel thin-walled stiffeners attached to one side, subjected to a combination of axial compression, lateral pressure and bending moment. The plate is modeled by the Von Kármán plate equations and the stiffeners by a nonlinear beam theory recently derived. An analytical solution is obtained for the buckling load corresponding to a torsional tripping mode of the stiffeners. The effects of various boundary conditions, imperfections and residual stress are included.

ABSTRACT: A geometrically nonlinear shear deformation theory has been developed for elastic shells to accommodate a constitutive model suitable for composite shells when modeled as a two-dimensional continuum. A complete set of kinematical and intrinsic equilibrium equations are derived for shells undergoing large displacements and rotations but with small, two-dimensional, generalized strains. The large rotation is represented by the general finite rotation of a frame embedded in the undeformed configuration, of which one axis is along the normal line. The unit vector along the normal line of the undeformed reference surface is not in
general normal to the deformed reference surface because of transverse shear. It is shown that the rotation of the frame about the normal line is not zero and that it can be expressed in terms of other global deformation variables. Based on a generalized constitutive model obtained from an asymptotic dimensional reduction from the three-dimensional energy, and in the form of a Reissner-Mindlin type theory, a set of intrinsic equilibrium equations and boundary conditions follow. It is shown that only five equilibrium equations can be derived in this manner because the component of virtual rotation about the normal is not independent. It is shown, however, that these equilibrium equations contain terms that cannot be obtained without the use of all three components of the finite rotation vector.

References listed at the end of the paper:

ABSTRACT: A new, simplified version of Reissner's equations for the torsionless, axisymmetric deformation of elastically isotropic shells of revolution suffering small strains but large angles of rotation is specialized to clamped spherical caps under uniform outward pressure. The non-dimensional equations contain a thickness parameter, a shallowness parameter, and a load parameter. The latter two are written as powers of the former and the dependent variables scaled so that as the thickness parameter goes to zero, meaningful limit equations emerge. Seventeen distinct sets of simplified equations are found. In thirteen cases these are linear and the solutions are listed. These results should provide a useful set of benchmarks for testing the efficacy of numerical codes which often have difficulties with very thin shells.

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ABSTRACT: Motivated by applications to seed germination, we consider the transverse deflection that results from the axisymmetric indentation of an elastic membrane by a rigid body. The elastic membrane is fixed around its boundary, with or without an initial pre-stretch, and may be initially curved prior to indentation.
General indenter shapes are considered, and the load–indentation curves that result for a range of spheroidal tips are obtained for both flat and curved membranes. Wrinkling may occur when the membrane is initially curved, and a relaxed strain–energy function is used to calculate the deformed profile in this case. Applications to experiments designed to measure the mechanical properties of seed endosperms are discussed.


ABSTRACT: The unwrinkled transition zone between the rigid boundaries and the wrinkled portion of a spherical membrane subjected to a pulling force is analyzed. The strains are first assumed to be small, and two cases are considered: (a) a spherical membrane barrel pulled into a wrinkled cylinder and (b) a hemispherical membrane pulled into a wrinkled cone. It is shown that in both cases the angular size of the transition zone is $O(\epsilon)$, where $\epsilon$ is the prevailing strain, rather then $O(\sqrt{\epsilon})$ as in the usual nonlinear membrane edge effect problem. Large rotations and substantial variations in the circumferential stresses and strains take place in this narrow zone. The extension to the case of “moderate” strains is then made for the spherical barrel, using a power series approach. It follows from the results that the size of the transition zone becomes $O(\sqrt{\epsilon})$ as the wrinkled region shrinks to zero. Finally, a complete large strain analysis of a partly wrinkled spherical barrel membrane is made. Included are both the transition zone and the interior wrinkled region. The analysis establishes the ranges of validity of the previous solutions and demonstrates the deterioration of the “edge effect”. A formula for the “wrinkle strain” in the interior is included. Interestingly, the deviation of the slope of the deformed membrane from the wrinkled direction is shown to be always small, so that the problem can be assumed to be geometrically linear in $\cot(slope)$, but materially nonlinear.

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ABSTRACT: A procedure is presented for obtaining mixed, nonlinear variational principles for elastic shells based on the intrinsic formulation of the shell equations. The applicability of the procedure is demonstrated by developing specific principles for shells of weak curvatures and for circular cylindrical shells in regular and extended forms. Other cases are also discussed. The principles are developed within the scope of small-strain, large-rotation theory for shells under the Kirchhoff-Love hypothesis and require the availability of curvature functions for the given classes of shells. No other restrictions need be placed, except for those related to the geometries of the shells under investigation. Specifically, subject to the limitation of small extensional strains, the displacements and rotations may be large and no particular mode of shell behavior is postulated. The variational functional basically contain the strain energy of bending and the complementary energy of the membrane force resultants. These functionals are formulated in terms of curvature and stress functions and their Euler-Lagrange equations are those of normal equilibrium, Gauss compatibility and associated boundary conditions. All may be nonlinear. Using the extended principle as a starting point, approximate principles and equations are developed in Part II for the nonlinear, nonuniform bending of orthotropic circular cylindrical tubes of finite length (extended Brazier effort). The semi-membrane approximation, with membrane-type shear
deformation retained, is used in the analysis, plus some added restrictions of the Rayleigh-Ritz type on the curvature and stress fields. The results can be used for problems involving tubes subjected to various beam and shell type boundary conditions. The specific example of a clamped tube subjected to pure beam bending is calculated, using solutions of the equations for weak nonlinearity and a Rayleigh method for strong nonlinearity. Application of some of the results to the nonlinear “local buckling” analysis of a finite-length tube subjected to bending compare favorably with published results. Besides the interest in the specific problem, this demonstrates the applicability of the mixed principle for obtaining direct, approximate nonlinear solutions to useful ongoing problems, as a complement to more exact, but cumbersome, finite element or series solutions.

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ABSTRACT: A procedure for deriving mixed variational principles for nonlinear shell analysis was presented in Part I and formulated in more detail for shells of weak curvatures and for circular cylindrical shells. The cylindrical shell principle is extended here to accommodate those special cases in which the retention of mixed terms in the compatibility equations is of significance. Emphasis is put on the interaction of longitudinal extensional strains with large circumferential changes of curvature. As a simple first example, it is applied to the orthotropic Brazier process, for which an Euler-Lagrange equation and perturbation solution are also derived. Variational principles have important uses for providing direct, approximate “engineering solutions” to highly nonlinear problems. Such solutions complement the more exact but cumbersome finite element or double series techniques. In the present case, reasonable simplifying assumptions are introduced in the extended principle to construct approximate principles and equations for the problem of strong, nonlinear, nonuniform bending of finite-length orthotropic tubes. As a specific example, the pure bending of a clamped, finite-length tube is studied. Approximate analysis is carried to collapse (or local buckling). Some of the local buckling results are compared with numerical results from the literature.


ABSTRACT: Starting from the equations of general elastic nonlinear membrane theory in intrinsic form, the equations governing the incremental state of stress in an orthotropic circular membrane tube are derived and discussed. The tube is initially subjected to uniform internal pressure and to longitudinal extension, which lead to large homogeneous deformation. Then some changes in loading and/or geometry are considered, e.g. an additional load is applied, the shape of the boundary is changed or a slit is formed in the membrane. These changes are regarded as small perturbations on the initial homogeneous state of stress. The general form as well as some simplified forms of the equations are presented, leading finally to a set of two equations in terms of two scalar potential functions. Two different variational formulations for the problem are also presented, each of which may serve as a basis for numerical treatment.

ABSTRACT: In Part I of this article (1995, Int. J. Solids Structures 32, 1907–1925) a simplified theory for the incremental state of stress in an orthotropic circular membrane tube was presented. In this second part, a numerical method is devised to solve the resulting elliptic sixth-order system of equations, for tubes which contain no slits or holes. In this method, Fourier decomposition is used in the circumferential direction and finite element discretization is used in the longitudinal direction. Special finite elements with six degrees-of-freedom are employed. Using this numerical method, the solutions of several specific problems of membrane tubes are obtained, presented and discussed. These include two problems concerning the decay of boundary disturbances. The theoretical treatment of such decay is also discussed.

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ABSTRACT: The nonlinear behavior of an axisymmetric hyperelastic membrane subjected to pulling forces is analyzed. The membrane is considered to be ideal in the sense that it cannot carry compressive stress resultants. If the membrane has a positive initial Gaussian curvature, the pulling gives rise to wrinkles which form over parts of the surface. The full nonlinear equations governing the membrane behavior in the doubly tense and in the wrinkled regions are formulated, and then solved using a numerical integration procedure. Solutions for various examples are presented, with Hookean and neo-Hookean constitutive behavior. These include a few examples of wrinkled membranes with positive initial Gaussian curvatures, and one example of a membrane with a negative initial Gaussian curvature, where no wrinkles are formed.


ABSTRACT: This paper investigates the effects of the bending-stretching coupling on the imperfection sensitivity of axially compressed laminated, thin, rectangular flat plates. In particular, it is found that under certain circumstances this coupling phenomenon results in a nonzero cubic term of the potential energy, so that the structure may be imperfection sensitive depending on the sign of the imperfection. The analysis considers a nonlinear prebuckling state due to bending-stretching coupling of the structure. The buckling and initial postbuckling problem is solved using Koiter's theory of elastic stability.

ABSTRACT: This paper deals with the effects of initial geometric uni-directional imperfections on vibrations of a pressurized spherical shell or spherical cap. The analysis is based upon shallow shell theory. Frequency vs applied pressure interaction curves are plotted for various values of the imperfection amplitude. Imperfections are shown to have a severe effect in reducing the natural frequencies similar to that demonstrated in the buckling behavior of spherical shells.


ABSTRACT: This paper aims to review Koiter’s theory of amplitude modulation of the local mode and present it in a form suitable for general application. Various features of this theory are compared with Koiter’s general theory of 1945. The amplitude modulation theory is applied to two-mode buckling of stringer stiffened cylindrical shells under axial compression. New mode interaction results are reported involving the simultaneous local and overall buckling in which the local mode is postbuckling unstable.

References listed at the end of the paper:

ABSTRACT: This paper deals with the effects of initial geometric imperfections and in-plane boundary conditions on the large-amplitude vibration behavior of angle- and cross-ply rectangular thin plates. It is found that the presence of imperfection amplitudes of the order of only half the total laminated-plate thickness may significantly raise the vibration frequencies and change the large-amplitude vibration behavior from the well-known hard-spring to soft-spring behavior. The effects of fibre angles and bending-stretching coupling for angle-ply plates and Young's moduli ratios and number of layers for antisymmetric cross-ply plates are examined.

David Hui (The Ohio State University, Department of Engineering Mechanics, Boyd Laboratory, 155 W. Woodruff Ave., Columbus, Ohio 43210, USA), “Asymmetric postbuckling of symmetrically laminated cross ply, short cylindrical panels under compression”, Composite Structures, Vol. 3, No. 1, 1985, pp. 81-95, doi:10.1016/0263-8223(85)90029-7
ABSTRACT: Buckling and initial postbuckling behavior of symmetrically laminated, thin cross ply cylindrical panels under axial compression are investigated. The panels are simply supported at all four edges. Closed form solutions are obtained for the buckling loads. The initial asymmetric postbuckling behavior is demonstrated by computing the postbuckling coefficients within the context of Koiter's theory of elastic stability. Parameter studies involving the flatness parameter, the length-to-width ratio, number of layers and Young's moduli ratio are presented for typical cross ply cylindrical panels likely to be encountered in practice.

ABSTRACT: This paper deals with the two-mode initial postbuckling analysis of geometrically imperfect beams on elastic foundation under compression. By adjusting the beam length to the characteristic length ratio, it is found that the resulting two-mode stability problem may be classified as the double-cusp model in catastrophe theory. The appropriate postbuckling coefficients are computed with the use of Koiter's theory of elastic stability. The equilibrium paths and the critical sets are plotted and analysed. Eight independent control parameters are suggested. The paper is the first in the open literature to apply the double-cusp model to a two-mode stability problem which displays imperfection-sensitivity.

ABSTRACT: This paper deals with the use of Koiter's improved postbuckling theory in axial buckling of integrally stiffened cylindrical panels. According to Koiter's improved theory, the postbuckling coefficients are evaluated at the actual applied load rather than at the classical buckling load. Substantial positive shift of the postbuckling is found which indicates that the imperfection sensitivity predicted by Koiter's 1945 general theory may significantly overestimate the degrading effects of these imperfections. Such a positive shift is especially crucial in studying mode interactions such as local and overall buckling mode interactions of stringer-reinforced cylindrical shells.


ABSTRACT: This study deals with the postbuckling behavior of infinite beams on non-linear elastic foundations subjected to axial compression. The analysis utilizes an improved Koiter's postbuckling theory such that the postbuckling coefficients are evaluated at the actual applied load rather than at the classical buckling load. The improved postbuckling paths are found to agree well with the non-linear large deflection solution using the Ritz procedure. This paper substantiates Koiter's conjecture that the general theory of elastic stability may be improved. The implications of various lower-bound buckling loads are examined.


ABSTRACT: This work deals with the effects of shear loads on the vibration and buckling of typical antisymmetric cross-ply thin cylindrical panels, subjected to combined loads. Changes in the buckling loads due to geometric and material parameter variations are investigated with particular emphasis on distinguishing the symmetric and antisymmetric modes. The paper presents the first known results on shear buckling of cross-ply cylindrical panels as well as vibrations of these structures under shear loads. The resulting interaction curves will allow one to formulate effectively a preliminary design of these panels which will withstand shear loads.


ABSTRACT: A theoretical and experimental study of the buckling and postbuckling behavior of unidirectionally laminated graphite/epoxy plates was conducted under combined thermal cooling and compressive loading. The rectangular plates were simply supported at the loaded edges and free in the remaining edges. The plates were found to bend during cooling even without mechanical loads because of the negative thermal expansion coefficient of the material in the loading direction and the in-plane end constraints at the two-loaded edges. Such bending from thermal load was treated as an initial geometric imperfection, and
the analysis was based on Koiter's theory of elastic stability. The experimental postbuckling curves agreed well with the theoretical values.

References listed at the end of the report:


ABSTRACT: Domes are efficient structural systems for long clear-span buildings. The introduction of laminated timber highlighted the economic advantages of this material and led to the use of timber domes even for very large spans. In this paper, reticulated timber domes of triangular network shape with decking and bottom tension ring are considered. These types of domes have high stiffness in all directions along the surface and are kinematically stable. The dome is subjected to uniformly distributed load over the entire structure. The dome model is generated with a preprocessor program called DOME-IN and analysed with ABAQUS. The focus of this paper is to evaluate the behaviour of reticulated timber domes with respect to different stiffnesses of the bottom ring beam, here defined as a non-dimensional ring beam area parameter Ar*, which is shown to be a very well adapted design parameter for the ring beam. As far as global buckling is concerned, the critical pressure is sensitive to the bottom ring beam stiffness only if the latter is within a certain range. In terms of design, the stiffness of the ring beam should exceed Ar* > 2 in order to utilise the full buckling load capacity of the dome system itself. The maximum deflection, normal forces and bending moments versus the ring beam area parameter are also evaluated. The maximum values of the deflection and the internal actions next to the bottom ring are very sensitive to the bottom ring beam stiffness only if the latter is less than about Ar* < 10. A
recommended value for the design of the bottom ring beam is $A_* > 20$.


ABSTRACT: The use of fibre-reinforced polymer (FRP) composites in the pressure hulls of submersible vehicles is examined with reference to material and fabrication options, alternative structural configurations, evaluation of stresses, deformations and buckling behaviour and other aspects of design. The performance of FRP is contrasted with that of steel and light alloy construction. Reference is made to two illustrative trial designs, one corresponding to a manned submersible for shallow-water operation and the other to a deep-water autonomous underwater vehicle.


ABSTRACT: DRA Dunfermline has had a continuing involvement in the development of deep diving composite pressure hulls through the NERC Autosub project and as part of the MAST II programme which culminated recently in the testing of a relatively large scale model pressure hull. This paper describes analytical models which were developed in conjunction with a series of model tests and used in the design of the large scale hull model. Comparisons between theoretical predictions and experimental data are also given. In keeping with the topic of the workshop the emphasis is on buckling with stress and failure analysis being reported more fully elsewhere.


ABSTRACT: This paper describes the application of finite element (FE) analysis to the prediction of the non-linear elasto-plastic collapse of ring-stiffened cylinders under hydrostatic loading. A range of legacy experimental test models have been analysed using FE idealisations generated using measured as-built shape data including out-of-circularity (OOC), frame alignment and tilt and other scantlings. The FE models also explicitly included the residual stresses caused by cold bending. Short and long ring-stiffened cylinders, which were designed to isolate interframe and overall collapse modes, respectively, were considered as were some intermediate length cylinders where the possibility of interactive collapse was also present. In general, the collapse pressures were predicted to within 6%. However, for some of the interframe collapse models, it was necessary to use the minimum measured plate thickness to achieve this. This was largely attributable to the limited measured plate thickness data.


ABSTRACT: The paper outlines the fundamentals of the method of solving static problems of geometrically nonlinear deformation, buckling, and postbuckling behavior of thin thermoelastic inhomogeneous shells with
complex-shaped midsurface, geometrical features throughout the thickness, or multilayer structure under complex thermomechanical loading. The method is based on the geometrically nonlinear equations of three-dimensional thermoelasticity and the moment finite-element scheme. The method is justified numerically. Results of practical importance are obtained in analyzing poorly studied classes of inhomogeneous shells. These results provide an insight into the nonlinear deformation and buckling of shells under various combinations of thermomechanical loads.

References listed at the end of the paper:
64. S. G. Lekhbitskii, Anisotropic Plates [in Russian], Gostekhizdat, Moscow (1957).
74. V. V. Novozhilov, Theory of Thin Shells [in Russian], Sudpromgiz, Leningrad (1962).

ABSTRACT: The article is devoted to the geometrically and physically linear and nonlinear formulations of the problems regarding the dynamic loading of shells of revolution. Analytical and numerical methods of solving the problems of impact buckling and supercritical behavior of elastic and elastic-plastic shells of revolution following axisymmetric and non-axisymmetric forms are considered. The role of boundary, wave, geometrically and physically nonlinear effects is assessed, as well as the effect of the bound nature of axisymmetric and non-axisymmetric forms in the process of buckling with multistage loss of stability. The non-axisymmetric forms of the loss of stability of cylindrical shells in the elastic-plastic region are realized according to the second and third forms both for static and dynamic loading, and, hence, the theory of shallow shells is not applicable for analyzing these processes.


ABSTRACT: A method for analyzing the elephant-foot buckle failure of ground-supported, broad cylindrical liquid storage tanks under horizontal excitation is presented. The method is based on Sanders' nonlinear thin shell theory and an idealized fluid model. Following the ring finite element discretization in the shell and the boundary solution technique in the fluid region, the matrix equations of motion are derived. An iterative formulation for the solution of the equations is proposed in terms of pseudo-loads. The dynamic response of the tank at each iterative step can be obtained by means of the mode-superposition procedure and direct time integration method. Numerical results show that the effects of cos ntheta modes due to the geometrical nonlinearity of the shell are of great significance on the axial and hoop membrane forces near the elephant-foot buckle region of the broad liquid storage tanks.

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ABSTRACT: A study of plastic buckling of a circular cylindrical shell subject to axial, torsional and circumferential loading stresses is presented. In the deformation model, the transverse shear is taken into account by a first-order theory with a correction factor. For the buckled equilibrium, the contributions of both v (circumferential displacement) and w (normal displacement) to the buckling are included so that a better accuracy can be achieved. J2 deformation theory and J2 flow theory of plasticity are used for the establishment of the constitutive relations for buckling analysis. With the existence of torsional load, the equation of radial equilibrium includes the term of mixed second-order derivative ∂²w/∂x∂y and the plastic in-plane stress–strain relations are anisotropic, and therefore a handy form of solution in terms of trigonometric functions is no longer possible. Consequently, the finite difference method is used. To improve the accuracy, a five-point finite difference scheme is employed instead of the conventional central difference. Numerical results of examples show the interactive roles of the in-plane loads in the plastic buckling.
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ABSTRACT: In this paper, a shell finite element is designed within the total Lagrangian formulation framework to deal with the plastic buckling and post-buckling of thin structures, such as cylindrical shells. First, the numerical formulation is validated using available analytical results. Then it is shown to be able to provide the bifurcation modes—possibly the secondary ones—and describe the complex advanced post-critical state of a cylinder under axial compression, where the theory is no longer operative.

ABSTRACT: The present study deals with the severity of cracks in pressure equipments, where such defects are often involved. Our work is particularly concerned with the problem of cylindrical shells and also the little well-known problem of spherical shells, including all sorts of practical defects, namely axisymmetric or semi-elliptic, both internal and external cracks. The stress intensity factor in the linear elastic domain and the J integral in the elastoplastic range are performed using the finite element method and compared to the results provided by the application of the semi-analytical A16 or R6 simplified criteria, depending on a limit load calculation. The nocivity of the defects depends on the crack shape and size and other structural geometrical parameters. Use is made of a polynomial decomposition of the stress field in the vicinity of the crack in order to cover all industrial loadings. All the numerical results, for a wide range of shell and crack geometries, are depicted using appropriate tables and curves in order to check the fracture criteria more easily.

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“Elastoplastic collapse of cylindrical tubes under external pressure”, 7th EUROMECH Solid Mechanics Conference J. Ambrosio et.al. (eds.) Lisbon, Portugal, 7–11 September 2009
ABSTRACT: The buckling problem of a circular cylindrical shell has long been widely investigated due to its great importance in the design of aerospace and marine structures. But very little attention has been paid until now on the influence of residual stresses on the critical and often unstable response of such structures. In this paper, a shell finite element is designed within the total Lagrangian formulation framework to deal with the elastoplastic buckling and post-buckling of thin cylindrical tubes under external pressure and axial compression. A specific experimental process will be introduced in order to measure residual stresses in the shell very
accurately, so as to include them in the numerical calculations. The present formulation will enable us to describe the complete non-linear solution, namely the critical load, the bifurcation mode and the bifurcated equilibrium branch up to an advanced post-critical state corresponding to collapse. Comparisons will be made between numerical results and the experimental critical value and deformation patterns of a new generation profiler. Furthermore, the combined effects of geometric imperfections, residual stresses and plasticity will be analyzed.

References listed at the end of the paper:

ABSTRACT (Note: This abstract is very similar to that in the previous entry. Is this a different paper?): The buckling problem of a circular cylindrical shell has long been widely investigated due to its great importance in the design of aerospace and marine structures. Geometric imperfections and residual stresses are inevitable in practice and have been so far frequently considered in analytical and numerical predictions. But little attention has been paid until now on the combined influence of such initial defects on the critical and often unstable response of such elastoplastic structures. In this paper, a shell finite element is designed within the total Lagrangian formulation framework to deal with the elastoplastic buckling and post-buckling of thin cylindrical tubes under external pressure and axial compression. A specific experimental process will be introduced in order to measure residual stresses in the shell very accurately, so as to include them in the numerical calculations. The present formulation will enable us to describe the complete non-linear solutions, namely the critical pressures (bifurcation and limit (collapse) loads), the bifurcation modes and the bifurcated equilibrium branches up to advanced post-critical states. Comparisons will be made between numerical results and the experimental critical value and deformation patterns of a new generation profiler. Furthermore, the combined effects of geometric imperfections, residual stresses and plasticity will be analyzed.

Kahina Sad Saoud and Philippe Le Grognec (Mines Douai, Polymers and Composites Technology & Mechanical Engineering Department, 941 rue Charles Bourseul - CS 10838, 59508 Douai Cedex, France), “A unified formulation for the biaxial local and global buckling analysis of sandwich panels”, Thin-Walled Structures, Vol. 82, pp 13-23, September 2014, DOI: 10.1016/j.tws.2014.03.009

ABSTRACT: Sandwich structures are increasingly employed in many practical applications thanks to their interesting compromise between lightweight and high mechanical properties. However, due to some specific geometric and material features, such structures are subject to global as well as local buckling phenomena, which lead to collapse in most cases. The buckling analysis of sandwich panels is therefore an important issue for their mechanical design. In this respect, this paper is devoted to the theoretical study of the elastic local/global buckling of rectangular sandwich plates under uniaxial or biaxial compression(-tension). Only classical sandwich materials are considered with homogeneous and isotropic core/skin layers. In the present formulation, a Love–Kirchhoff plate model is used to represent the thin skins, whereas the relatively thick core is modeled as a 3D continuous solid. Furthermore, the proposed approach is based on the elastic bifurcation theory in a general 3D framework, and leads to closed-form analytical expressions of the critical loadings and the corresponding bifurcation modes. The accuracy of the derived formulae is checked for both local and global modes by comparison with the results of finite element computations. Parametric analyses are finally performed, investigating primarily the influence of the aspect ratio of the plate and the ratio of the compressive (or tensile) loadings between both directions on the first buckling mode type and the associated minimum critical value.


ABSTRACT: A collection of all available literature data upon experiments of composite cylinders under axial
compression is performed. Theoretical estimation of bifurcation load for all the tested cylinders is achieved solving stability differential equations with the use of a combined “bi-modal and torsion” solution and Galerkin approximation. Experimental knockdown factors with respect to theoretical predictions are derived and they are used to tune the imperfection amplitude of an in-house code, which computes collapse load of imperfect cylindrical composite shells using an axy-symmetric sine-shaped imperfection. “Equivalent imperfection amplitudes” are statistically analysed and with the help of imperfections sensitivity curves, Monte Carlo simulations are performed in order to obtain new reliability-based knockdown factor for cylinders with different stacking sequences. The values obtained directly by statistical analysis of the tests results and the ones derived by the statistical analysis of the calibrated imperfection amplitudes represent an improvement with respect to old design values extrapolated from isotropic shells.

ABSTRACT: Local force introduction in cylinders has received relatively little attention in the past and the designer often finds himself lost by the lack of design regulations or experimental evidence. This research activity, starting at the Ghent University, examines this stability problem and its purpose is to develop simple recommendations in order to assist designers in the steel industry. A short overview of the available literature on this particular topic is brought into the present contribution, together with our preliminary experimental observations and theoretical analyses with respect to unstiffened cylindrical shells subjected to local forces.

ABSTRACT: Cylinders on discrete supports are prone to local instability. This failure phenomenon can be avoided by reinforcing the cylindrical wall by means of stringer stiffeners in combination with ring stiffeners. The goal of our research is to find design rules for this kind of shell structures. For this purpose, a numerical model was developed. In this contribution, the numerical model is validated by verifying the correspondence with the results of experiments on scale models. Two experiments are here discussed. The corresponding failure patterns are examples of the two possible patterns that were found in all the experiments. For the numerical simulations of these experiments, the measured geometrical imperfections and the real stress-strain relationship of the steel were incorporated into the numerical model. The results of the simulations show that the correspondence between experiments and simulations is sufficient.

ABSTRACT: Frequently the governing failure mode of liquid-filled conical tanks is associated with buckling near the lower rim due to compression of the shell wall in meridional direction notwithstanding the stabilizing tension in circumferential direction. But important axisymmetric imperfections may increase the circumferential tensile stresses in such a way that local yielding precipitates a buckling failure. This failure mode is of the same
kind as the “elephant’s foot” buckling at the support of axially compressed thin steel cylinders with internal pressure. This paper gives numerical results for a series of imperfect conical tanks. The collapse is in some cases of the type “elephant’s foot” buckling. The paper explains why the imperfections can cause large circumferential tensile stresses leading to plastic collapse of the tank.

References listed at the end of the paper:

[6] ABAQUS, Hibbitt, Karlsson & Sorenson, Inc. E-mail: info@abaqus.com, support@abaqus.com, http://www.abaqus.com.


ABSTRACT: The influence of interactive buckling on the postbuckling behaviour of thin-walled elastic beams with imperfections is studied. The investigation is concerned with thin-walled closed and open cross-section beam-columns under axial compression and a constant bending moment. The beams are assumed to be simply supported at the ends. The asymptotic expansion established by Byskov and Hutchinson is employed in the numerical calculations in the form of the transition matrix method. The paper's aim is to achieve the improved study of the equilibrium path in the postbuckling behaviour of imperfect structures with regard to the second-order approximation. The calculations are carried out for several types of beams.


ABSTRACT: The influence of modification of boundary conditions at both ends of the structures regarding interactive buckling on the postbuckling behaviour of thin-walled elastic columns with imperfections is studied. The investigation concerns thin-walled closed and open cross-section columns under axial compression. The columns are assumed to be simply supported at the ends. The asymptotic expansion established by Byskov and Hutchinson is employed in the numerical calculations in the form of the transition matrix method. The aim of the paper is to improve the study of the equilibrium path in the postbuckling behaviour of imperfect structures regarding the second order approximation.
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ABSTRACT: The design of thin-walled beam-columns must take into account the overall instability and the instability of component plates in the form of local buckling. This investigation is concerned with interactive buckling of thin-walled closed cross-section beam-columns with central intermediate stiffeners under axial compression and constant bending moment. The beams are assumed to be simply supported at the ends. The asymptotic expansion established by Byskov and Hutchinson is employed in the numerical calculations performed using the transition matrix method. The paper's aim is to contribute to the study of the equilibrium path in the post-buckling behaviour of imperfect structures using the first order approximation. The calculations are carried out for a few closed beam-columns.

ABSTRACT: For anisotropic materials, Tsai-Wu [1] proposed the failure criterion that takes into account the difference in strength due to positive and negative stresses. Hashin [2] pointed to some internal incoherencies of the function of material effort with respect to stress parameters. The minimum of the External Function does not coincide with the unstressed state. Therefore, the criterion presented by Tsai-Wu [1] has limited possibilities of application for optimization purposes. A modification of the Tsai-Wu criterion, needed in the case of the multicriterion optimal design of thin-walled composite structures, has been presented. A proposal of the evaluation of the load carrying capacity of multi-layered composites with respect to their failure mode has been put forward.

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ABSTRACT: The design of thin-walled beam–columns must take into account the overall instability and the instability of component plates in the form of local buckling. This investigation is concerned with interactive buckling of thin-walled beam–columns with central intermediate stiffeners under axial compression and a constant bending moment. The columns are assumed to be simply supported at their ends. The asymptotic expansion established by Byskov and Hutchinson (AIAA J. 15 (1977) 941) is employed in the numerical calculations performed by means of the transition matrix method and Godunov’s orthogonalisation. Instead of the finite strip method, the exact transition matrix method is used in this case. The most important advantage of
this method is that it enables us to describe a complete range of behaviour of thin-walled structures from all global (flexural, flexural-torsional, lateral, distortional and their combinations) to local stability. In the presented method for lower bound estimation of the load carrying capacity of structures, it is postulated that the reduced local critical load should be determined taking into account the global pre-critical bending within the first order non-linear approximation to the theory of the interactive buckling of the structure. The paper’s aim is to expand the study of the equilibrium path in the post-buckling behaviour of imperfect structures with regard to the second order non-linear approximation. In the solution obtained, the transformation of buckling modes with an increase of the load up to the ultimate load, the effect of cross-sectional distortions and the shear lag phenomenon are included. The calculations are carried out for a few beam–columns. The results are compared to those obtained from the design code and to the data reported by other authors. The results discussed in the present study represent the most important results obtained by the authors in earlier investigations devoted to central intermediate stiffeners (Int. J. Solid Struct. 32 (1995) 1501; Eng. Trans. 43 (1995) 383; Int. J. Solid Struct. 37 (2000) 3323; Int. J. Solid Struct. 33 (1996) 315; Thin Wall. Struct. 39 (2001) 649; Arch. Mech. Eng. XLVIII (2001) 29).


ABSTRACT: The influence of modal interactive elastic buckling on the post-buckling behaviour of thin-walled composite beam-columns with imperfections is studied when the distortional deformations are taken into account. The investigation is concerned with open cross-section columns under an axial compression or/and a constant bending moment. The beam-columns are assumed to be simply supported at the ends. The asymptotic expansion established by Byskov and Hutchinson [Mode interaction in axially stiffened cylindrical shells, AIAAJ, 15(7) (1977) 941–948] is employed in the form of the numerical transition matrix method. The paper’s aim is to improve the study of the equilibrium path in the post-buckling behaviour of imperfect structures with regarding the second order non-linear approximation and the effect of cross-sectional distortions. The principal goal of numerical analysis is to investigate the influence of the wall orthotropy factor of columns upon the all buckling modes from global (flexural, flexural–torsional, lateral, distortional and their combinations) to local and upon the coupled post-buckling state. In the solution obtained the transformation of buckling modes with the increase of load up to the ultimate load and shear lag phenomenon is included.

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“Interactive buckling of thin-walled beam-columns with intermediate stiffeners or/and variable thickness”, International Journal of Solids and Structures, Vol. 37, No. 24, pp 3323-3344, June 2000

DOI: 10.1016/S0020-7683(99)00044-X

ABSTRACT: The design of thin-walled beam-columns must take into account the overall instability and the instability of component plates in the form of local buckling. This investigation is concerned with interactive buckling of thin-walled beam-columns with central intermediate stiffeners or/and variable thickness under axial compression and a constant bending moment. The columns are assumed to be simply supported at the ends. The asymptotic expansion established by Byskov and Hutchinson (1977: Byskov, E. and Hutchinson, J. W. (1977).


ABSTRACT: In the paper the influence of following factors: initial imperfections, shape and duration of pulse loading on the dynamic response of plate structures is presented. The effect of material properties in the plastic range and the estimation of structure capacity to sustain dynamic pulse loadings based on different dynamic stability criteria is discussed as well.

References listed at the end of the paper:


ABSTRACT: In the paper, the buckling phenomenon for static and dynamic loading (pulse of finite duration) of functionally graded plates subjected to uniform temperature increment is presented. The work deals with thin rectangular plates with unmovable edges, simply supported or clamped along all edges. The material properties varying smoothly across the thickness are assumed to be temperature-independent. The investigations are conducted for different values of volume fraction index and uniform temperature rise in form of rectangular pulse of finite duration.

References listed at the end of the paper:


ABSTRACT: In the paper some basic ideas in approach to stability, post buckling behaviour and load carrying capacity of thin-walled composite structures are presented. Authors do not present equations that could only
make the understanding of this issue “harder”. Thin walled composite beam-columns with open and closed cross-section (channel and square cross-section) are calculated as an example. In order to analyse the stability and the structure performance after its loss, the ANSYS 5.7 package and authors' software has been used. Results obtained from both applied methods are compared. Presented examples show that the sole application of the FEM does not guarantee to obtain correct results of load carrying capacity and postbuckling path.

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ABSTRACT: The interactive buckling of prismatic, thin-walled composite columns with open sections, reinforced with intermediate stiffeners and with edge reinforcements, has been considered. The columns are assumed to be simply supported. The nonlinear problem has been solved with the Koiter’s asymptotic theory within the first order approximation. The asymptotic theory of the first order nonlinear approximation allows for simultaneous evaluation of the effect of imperfections and interactions of various modes of buckling on the behaviour of thin-walled structures. This evaluation can be only the lower bound estimation of the load carrying capacity. Detailed calculations have been made for several cases of columns.


ABSTRACT: The problem of buckling and initial post-buckling equilibrium paths of thin-walled structures built of plate and/or shell elements subjected to compression and bending has been solved. Plate and shell elements can be made of multi-layer orthotropic materials. A method of the modal solution to the coupled buckling problem within the first-order approximation of Koiter’s asymptotic theory, using the transition matrix method, has been presented. In the solution obtained, the effect of cross-sectional distortions and a shear lag phenomenon is included. The calculations are carried out for a few thin-walled structures.


ABSTRACT: The static and dynamic problem of interaction of global buckling modes in compressed columns with complex open and closed cross-sections was considered in the paper. The columns made of laminate composites were assumed to be simply supported at both loaded ends. A plate model was adopted in the analysis. The equations of motion of individual plates (Schokker et al., 1996; Sridharan and Benito, 1984) were obtained from Hamilton’s Principle, taking into account all components of inertia forces (Teter and Kolakowski, 2005). Within the frame of the first order nonlinear approximation, the dynamic problem of modal interactive buckling was solved by the transition matrix using a perturbation method. Distortions of cross-sections and the shear-lag phenomenon were taken into consideration in the problem solution. A modification of the quasi-bifurcation dynamic Kleiber-Kotula-Saran criterion (Kleiber et al., 1987) was proposed. A
comparison of the proposed modification to the Budiansky-Hutchinson criterion (Budiansky and Hutchinson, 1966; Hutchinson and Budiansky, 1966) was presented for a rectangular pulse loading.


ABSTRACT: The paper deals with dynamic buckling of thin-walled structures (plates and beam-columns with open cross-section) subjected to compressive rectangular pulse loading. The local, global and interactive dynamic buckling was analysed. Author proposes the new criterion for critical amplitude of pulse loading leading to stability loss. The proposed criterion is a modification of quasi-bifurcation criterion formulated by Kleiber, Kotula and Saran. Results obtained using proposed criterion were compared with other well-known criteria (Volmir (V) and Budiansky–Hutchinson (B–H) criterion).


ABSTRACT: The study is concerned with the finite element analysis of complex axisymmetric structures subjected to arbitrary static or dynamic loadings. The structures are assumed to be made of elastic or elasto-plastic material. For large deformation analysis the total Lagrangian description is utilized. Five types of axisymmetric finite elements are employed: triangular and quadrilateral solid rings, a conical thin shell element and two transition elements. A combination of a two-dimensional finite element process and a Fourier series in the circumferential direction, well known in linear applications, is shown to be effective also in the fully nonlinear range of structural behaviour. Some numerical illustrations are given.


ABSTRACT: The results of the stability analysis of simply supported layered isosceles trapezoidal plate subjected to axial in-plane compression are presented. The layup configuration is confined to symmetric laminates. The solution has been obtained by means of the Galerkin orthogonalisation method combined with the proposed method of the coordinate system transformation. The results of the analytical solution are compared with the verifying FEM calculation. The computed results in the form of graphs of the buckling force as a function of material and geometrical parameters of the panel are included.

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ABSTRACT: A theoretical analysis is presented for the behaviour after buckling of intermediately stiffened plates loaded in compression. The loaded and unloaded edges are simply supported but the unloaded edges are free to wave in the plane of the plates. A semi-energy method of analysis, based on the von Kármán's compatibility equation and the principle of minimum total potential energy, is used. The results are presented graphically for a range of plate aspect ratios and stiffener sizes and comparison is made with experimental results.


ABSTRACT: The buckling behaviour of thin-walled structural sections made from specially orthotropic material is studied using a semi-analytical, seminumerical approach. The approach used combines plate and beam theory in dealing with the out-of-plane and in-plane deformations of the walls of a cross-section, and has common features to both the finite strip approach and the generalised beam theory approach. The particular problems examined here concern the effects of directionality of the material, and for all cases considered material with stiff direction set longitudinally along the section is compared with the same material set with the stiff direction across the section. It is found that the buckling behaviour in either case can be found directly from an examination of the other case.


ABSTRACT: A brief examination of some of the research on the post-buckling elastic and plastic behaviour of plates and plate structures is outlined. This field is so wide ranging that only a very superficial examination of the early research has been carried out, and the writer has concentrated on some specific aspects of the general field of study. A very limited examination of some of the early research on rectangular cross-section tubes is also given.

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ABSTRACT: (none given)

ABSTRACT: A brief examination of some of the research on the post-buckling analysis of plates and plate structures is outlined. Only a very superficial examination has been carried out. The behaviour of plates and sections under eccentric load or eccentric compression is considered, and the application of plate analysis to strut, beam and column design is discussed.

ABSTRACT: A method is introduced for determining the critical initial imperfection of discretized structures that decreases the load-bearing capacity most rapidly. The effects of imperfections on simple critical points, such as limit points of loads and simple bifurcation points, are theoretically investigated based on the idea of the Lyapunov-Schmidt decomposition developed in bifurcation theory. Imperfection sensitivity varies with the types of points. Nonetheless critical imperfection pattern is expressed in the same formula regardless of the types. Among various imperfections, the most influential can be found in a quantitative manner. The validity and the usability of the proposed method are illustrated through its application to simple example structures.

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ABSTRACT: This paper is a theoretical study on random initial imperfections of structures. The explicit form of probability density function of the load-bearing capacity (critical load) of structures is derived for random initial imperfections based on a decomposition of the space of imperfection vectors into two orthogonal subspaces: the subspace that asymptotically affects the load-bearing capacity and the other that does not. Tight bounds on the range of load-bearing capacity are presented for various types of simple critical points. By means of the asymptotic theory of statistics, we show the inefficiency of a conventional random method that approximates the minimum loadbearing capacity by the minimum load for a number of random initial imperfections. The theoretical and empirical probability distribution functions for simple truss structures are compared to show the validity and effectiveness of the present method.
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ABSTRACT: This paper offers a theoretical study on the probabilistic nature of critical loads (buckling loads) of structures subject to normally distributed initial imperfections. Explicit form of probability density function of critical loads are derived for various types of critical points. Double bifurcation points of structures with regular-polygonal symmetry are dealt with by means of the group-theoretic bifurcation theory. The distribution of minimum values of the critical loads is investigated to present a statistical design index. The theoretical and empirical probability density functions for simple structures are compared to show the validity and effectiveness of this method. The method is quite efficient when it is directly applicable; otherwise, the explicit forms, at least, can greatly supplement the inefficiency of the conventional random method.


ABSTRACT: The author’s method of design sensitivity analysis of nonlinear coincident buckling load factors and corresponding optimization method of finite dimensional elastic structures are shown to be applicable to a structure with moderately large number of degrees of freedom. The sensitivity formulations are written in general form for coincident buckling load factors including limit points and bifurcation points. Optimum designs are found for a spherical latticed dome subjected to a concentrated load and distributed loads, respectively. The results are compared with those by linear eigenvalue formulation. An approximate optimal solution against nonlinear buckling can be obtained by only scaling the solution under linear eigenvalue formulation even for the case where the effect of prebuckling deformation is very large. It is shown that the proposed method is practically applicable to optimum design with coincident critical points especially for the case of hill-top branching where bifurcation points are located at the limit point. In this case, imperfection sensitivity is not enhanced as a result of optimization. The reduction of maximum load factor due to a minor imperfection is shown to be in the same order as that to a major imperfection. Therefore symmetric imperfection as well as asymmetric imperfection should be considered in estimating the maximum loads.

References listed at the end of the paper:

ABSTRACT: The imperfection sensitivity law by Koiter played a pivotal role in the early stage of research on initial post-buckling behaviors of structures, but seems somewhat overshadowed by numerical approaches in the computer age. In this paper, to make this law consistent with practical application, the law is extended to implement the influence of a number of imperfections, and the second-order (minor) imperfections are considered, in addition to the first-order (major) imperfections considered in the Koiter law. Explicit formulas are presented to be readily applicable to the numerical evaluation of imperfection sensitivity. A procedure to describe the probabilistic variation of critical loads is presented for the case where initial imperfections of structures are subject to a multivariate normal distribution; the formula for the probability density function of critical loads is derived by considering up to the second-order imperfections. The validity and usefulness of the present procedure are demonstrated through the application to truss structures.

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ABSTRACT: The mechanism of imperfection sensitivity of elastic–plastic plates under compression is complex as they undergo elastic and/or plastic buckling, dependent on their width–thickness ratio. For elastic buckling, the Koiter power law is an established means to describe the imperfection sensitivity. Yet, for plastic buckling, there is no such an established way to describe it. In this paper, the quadratic power law is advanced to describe imperfection-insensitive plastic buckling behavior. The Koiter power law is extended by implementing the quadratic law so as to describe the elastic and plastic buckling in a synthetic manner. The finite-displacement, elastic–plastic analysis was conducted on simply-supported square plates under compression by varying the plate thickness and the initial deflection of a sinusoidal form. In association with an increase of the plate slenderness parameter (decrease of plate thickness), the predominant buckling is shown to change from (1) plastic buckling to (2) unstable elastic–plastic buckling and to (3) elastic stable bifurcation followed by a maximum point of load. In accordance with the change of the mechanism of buckling, the power law is changed pertinently to describe the complex imperfection sensitivity of the compression plates in a synthetic manner. The extended imperfection sensitivity law is thus advanced as a simple and strong tool to describe the ultimate buckling strength of elastic–plastic plates.

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“Asymptotic and probabilistic approach to buckling of structures and materials”, Applied Mechanics Reviews, Vol. 61, No. 4, 16 pages, June 2008, DOI: 10.1115/1.2939583

ABSTRACT: The general theory of elastic stability invented by Koiter (1945, “On the Stability of Elastic Equilibrium,” Ph.D. thesis, Delft, Holland) motivated the development of a series of asymptotic approaches to deal with the initial postbuckling behavior of structures. These approaches, which played a pivotal role in the precomputer age, are somewhat overshadowed by the progress of computational environment. Recently, the importance of the asymptotic approaches has been revived through the extension of their theoretical background and the combination with the framework of finite element method and with group-theoretic bifurcation theory in nonlinear mathematics. The approaches serve as an efficient and insightful strategy to tackle probabilistic scatter of critical loads. We review, through the perspective of theoretical engineers, the historical development and recent revival of the asymptotic approaches for buckling of imperfection-sensitive structures and materials.


ABSTRACT: Sensitivity coefficients of a critical load factor corresponding to a degenerate critical point is shown to be unbounded even for a minor imperfection excluding very restricted case where the imperfection does not have direct effect on the lowest eigenvalue of the stability matrix. This fact leads to serious difficulty in obtaining optimum design under nonlinear stability constraints. The optimum design problem is alternatively formulated with constraint on the lowest eigenvalue of the stability matrix, and the sensitivity formula for the lowest eigenvalue is presented. The existence of a degenerate critical point and accuracy of the sensitivity coefficient are discussed through the example of a four-bar truss.

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ABSTRACT: The purpose of this review paper is to summarize the existing methods of design sensitivity analysis and optimization of elastic conservative finite-dimensional systems with respect to nonlinear buckling behavior. Difficulties related to geometrical nonlinear singular behaviors are discussed in detail. Characteristics of optimized structures are demonstrated in reference to snapthrough behavior, hill-top branching, and degenerate critical points. A new optimization result of a flexible truss that fully utilizes the snapthrough behavior is also presented.


ABSTRACT: Imperfection sensitivity characteristics of the non-linear buckling load factors of non-optimal and optimal symmetric frames are investigated. The frames are subjected to symmetric proportional vertical loads. The optimization problem is formulated under constraints on linear buckling load factors. Although the buckling load factors corresponding to sway and non-sway modes coincide at the optimum design, the non-sway-type asymmetric bifurcation point disappears as a result of geometrically non-linear analysis. Therefore, the maximum allowable load factors of perfect and imperfect systems should be determined by assigning displacement constraints. It is shown that quantitative evaluation is possible for imperfection sensitivity and mode interaction based on the higher order differential coefficients of the total potential energy even for frames of which the critical points should be numerically obtained. Numerical examples are presented to show that the properties of the non-sway bifurcation point are similar to those of a symmetric bifurcation point, and the interaction between sway and non-sway modes does not always lead to enhancement of imperfection sensitivity.

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ABSTRACT: Imperfection sensitivity properties are derived for finite dimensional elastic conservative systems exhibiting hill-top branching at which arbitrary many bifurcation points coincide with a limit point. The critical load at a hill-top branching point is demonstrated to be insensitive to initial imperfections when all the bifurcation points are individually symmetric. Therefore, it is not dangerous to design a frame or truss so that many members buckle simultaneously at the limit point, although the notion of the danger of optimization by compound bifurcation is widespread.

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ABSTRACT: We investigate the reliability of realistic structural models with stochastic initial imperfections. The models considered here include: a column on a nonlinear elastic foundation with normally distributed imperfections with given mean and variance-covariance, and cylindrical shells possessing the realistic imperfections which are chosen, based on the available experimental measurements for shell profiles. The explicit forms of the theoretical probability density of buckling loads and the reliability functions evaluated as functions of applied loads of these structures are obtained by means of the bifurcation theory, based on the assumption that the imperfections are small and represent normally distributed random fields. The parameters for these forms are to be determined based on the analysis on a large number of structures with different initial imperfections. The former functions accurately simulate the empirical histogram of buckling loads, while the latter are compatible with the pre-existing results of the number of failed structures in the ensemble. The analytical forms, which demand minimal computational costs, are of great assistance in evaluating the reliability of structures, and appear to constitute a potential design alternative in the future.

ABSTRACT: In this paper, the nonlinear bending and stability of thin spherical shallow shell with variable thickness under uniformly distributed loads are investigated by a new modified iteration method proposed by Prof. Yeh Kai-yuan and the author [1]. Deflections and critical loads have been calculated and the numerical results obtained have been given in figures and tabular forms. It is shown that the final equation determining the central deflection and the load obtained coincides with the cusp catastrophe manifold.

ABSTRACT: In this paper, two simple models which complement one another in mirroring the plastic buckling properties of structures are analysed in detail to introduce a scheme for postbuckling and imperfection sensitivity analysis that is suitable for tackling real structures. The variation of the size of the unloading area is used as the perturbation parameter and a special perturbation scheme is designed to deal with the moving boundary problems caused by plastic unloading, so that the extension of Koiter's theory of initial elastic postbuckling to the plastic range becomes possible.

ABSTRACT: This is the sequel to the author's paper on model analysis, in the current volume. The scheme
developed there to tackle the problem of the postbuckling and imperfection sensitivity analysis of structures in the plastic range is extended to shallow shells. A parameter characterizing the extension of the unloading area is used as the perturbation parameter, and the systematic perturbation method designed in the previous paper is modified to solve moving boundary problems in two variables. Relevant formulations are presented and discussed.


ABSTRACT: Plate and shell structures are widely used in civil engineering. Their static, dynamic behavior and the stability are the most interested topics since long. Advances in several aspects are reviewed in this paper.

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ABSTRACT: The objective of this investigation is to study the random vibration of a nonlinear geometrically shell structure by using the finite element method in conjunction with the equivalent linearization approach. When the shell structure is subjected to excessive loadings, the large deformations of the shell structure must be considered. In that sense, the stiffness of the governing equation of the shell structure is related to deflection; therefore, it is nonlinear and difficult to solve. In this study, the applied loadings to the shell structure are assumed to be a nonstationary random excitation to characterize many physical loadings such as earthquake, wind, aerodynamic and acoustic loadings. The equivalent linearization and the finite element method are adopted to perform the nonlinear random vibration analysis of the shell structures, which can be quite nonuniform and complex in geometry or nonhomogeneous in material. These obtained statistical dynamics responses are very useful for estimating the structure safety and reliability. Meanwhile, some statistical responses obtained by the present approach are checked by the Monte Carlo simulation technique.

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ABSTRACT: The statistical dynamic responses of geometrically nonlinear shell structures with stochastic Young's modulus of elasticity are investigated in this study. In general, large deformation of the shell structures must be considered when shell structures are under excessive loading, and then the governing equations of the shell structures become nonlinear since the stiffness matrix of the system is related to the deflection. In this
paper, the stochastic finite element method along with the perturbation technique is used to deal with statistical responses of shell structures with structural randomness; in particular, the Newton–Raphson iteration procedure in conjunction with Newmark scheme is adopted to solve the nonlinearity of the dynamic governing equation of shell structures. Some results obtained by the perturbation technique and those from the Monte Carlo simulation approach show a good agreement. Finally, it should be emphasized that these statistically dynamic responses are very useful for estimating the reliability of structures.

ABSTRACT: This paper presents a multiobjective optimization methodology for composite stiffened panels. The purpose is to improve the performances of an existing design of stiffened composite panels in terms of both its first buckling load and ultimate collapse or failure loads. The design variables are the stacking sequences of the skin and of the stiffeners of the panel. The optimization is performed using a multiobjective evolutionary algorithm specifically developed for the design of laminated parts. The algorithm takes into account the industrial design guidelines for stacking sequence design. An original method is proposed for the initialization of the optimization that significantly accelerates the search for the Pareto front. In order to reduce the calculation time, Radial Basis Functions under Tension are used to approximate the objective functions. Special attention is paid to generalization errors around the optimum. The multiobjective optimization results in a wide set of trade-offs, offering important improvements for both considered objectives, among which the designer can make a choice.

ABSTRACT: A novel optimization methodology for stiffened panel is proposed in this paper. The purpose of the optimization methodology is to improve the first buckling load of the panel which is obtained by finite element method. The stacking sequence of the stiffeners is taken as design variables. In order to ensure the manufacturability of design, the design guidelines of stacking sequence are taken into account. A DOE based on Halton Sequence makes the initial points of genetic algorithm spread more evenly in the design space of laminate parameters and consequently accelerates the search to convergence. The numerical example verifies the efficiency of this method.

ABSTRACT: Cone–cylinder intersections are used commonly in pressure vessels and piping. In the case of a cone large end-to-cylinder intersection under internal pressure, the intersection is subject to a large circumferential compressive force. While both the cone and the cylinder may be locally thickened to strengthen the intersection, it is often desirable and convenient to provide an annular plate ring at the cone-to-cylinder joint to supplement local thickening or as an alternative strengthening measure, leading to a ring-stiffened cone–
cylinder intersection. Only limited work has been carried out specifically on ring-stiffened cone–cylinder intersections under internal pressure. This paper presents the first experimental study on such intersections. In addition to the presentation of test results including geometric imperfections, failure behaviour and the determination of buckling mode and load based on displacement measurements, results from nonlinear bifurcation analysis using the perfect shape and nonlinear analysis using the measured imperfect shape are presented and compared with the experimental results.

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ABSTRACT: Buckling analysis of cylinders under axial compression is sensitive to the assumptions made in the modelling of initial imperfections. Normally, imperfection modes are selected solely on the basis of buckling mode considerations and their amplitudes are determined using tolerance specifications in codes or experimentally recorded values. Whilst this approach may be used for metal cylinders with some confidence, due to the many test results available for validation purposes, it is not appropriate for the analysis and design of fibre-reinforced composite cylinders where the test results are limited and the effects of manufacturing on the imperfection characteristics have not yet been studied in detail. This paper presents a methodology for probabilistic buckling strength assessment based on the results of a statistical analysis on imperfections on two groups of composite cylinders manufactured by lay-up. The dominant features are quantified and the effect of fibre orientation on imperfections is examined. Simple models describing the random variability of imperfection modal amplitudes are presented. Using these probabilistic models, characteristic imperfection shapes are developed for fibre-reinforced cylinders and their use in buckling strength prediction and tolerance specification is demonstrated.


ABSTRACT: (not given)


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PARTIAL ABSTRACT: The problem of the postbuckling behavior and sensitivity to initial geometrical imperfections of multilayered composite cylindrical shells is solved with allowance for the interaction of different buckling modes. The solution is based on the Byskov-Hutchinson asymptotic method and nonlinear equations of a Timoshenko-type shell theory…

References listed at the end of the paper:
PARTIAL ABSTRACT: Methods for calculating the buckling loads of shells with geometrical imperfections have been developed by many authors [2, 13-15]. A detailed survey of this activity and a relevant bibliography can be found in several review articles and books [2, 3, 7, 8]. In the present article we are concerned primarily with methods pioneered by Koiter [14,15]. A “special theory” is proposed in [14] for determining the maximum loads or bifurcation loads of axially compressed cylindrical shells in the presence of initial axisymmetric bending deflections. Koiter has also developed a general theory of buckling and initial postbuckling behavior [15] for investigating the influence of nonaxisymmetric initial imperfections on buckling loads...In addition to comparing the results of the calculations with Koiter’s special theory [14] and the Byskov-Hutchinson procedure [11], we propose to analyze certain details of the interaction of axisymmetric and nonaxisymmetric imperfections and the influence of the mechanical properties of composite materials on the sensitivity of shells to imperfections.
ABSTRACT: The equations for integral instantaneous characteristics of composite materials consisting of elastoplastic fibers and matrix are derived based on the known hypotheses of uniform strain or stress fields. The constitutive relations for a layered shell are obtained. The numerical algorithm elaborated is used to solve the stability problem for conical boron-aluminum shells under external pressure and axial compression. It is shown that the shells of medium thickness lose their stability under loads whose magnitude depends on the plasticity of the binder. The plasticity has a decisive influence on the choice of the optimum directions of reinforcement. If the parameters of a shell are such that the buckling occurs beyond the elastic limit, the shell must be reinforced in the direction of precritical stresses. However, this is possible only upon separate action of loads.

References listed at the end of the paper:


ABSTRACT: Three design techniques for stability analysis of longitudinally corrugated cylindrical shells are examined. The first two account for the true geometry of the shell and the third one replaces the corrugated shell with an equivalent orthotropic shell using reduction formulas. The exact formulations employ classical and Timoshenko-type theories. The techniques are analyzed by an example of sinusoidally corrugated shells. It is shown that the exact formulation permits finding practically important relations for corrugation parameters, which raises considerably the specific critical loads.


ABSTRACT: The stability problem is solved for an axially compressed cylindrical shell. Its cross section is formed by circular arcs of radius r with ends supported on a closed circle of radius R. The solution is based on the Flügge equations of the classic theory of deep cylindrical shells. It is shown that the critical axial load for shells of medium length and appropriately chosen cross-sectional profile can be increased by a factor of R/r approximately, compared with the circular shell. The shells length affects considerably the efficiency of noncircular shells of this type. This design model allows us to find out how the local properties of the shell and its stiffness are related.

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7. V. V. Novozhilov, Theory of Thin Shells [in Russian], Sudpromgiz, Leningrad (1962).


ABSTRACT: The problem of buckling instability of cylindrical shells under axial compression is considered. The shells consist of cylindrical sections of smaller radius. The geometrical parameters of the shells are approximated by Fourier series on a discrete point set. A Timoshenko-type shell theory is used. The solution is obtained in the form of trigonometric series. It is shown that shells consisting of cylindrical sections have considerable advantages over circular ones. At a constant shell weight, the choice of suitable parameters of shell sections leads to a significant increase in the critical load. The composite shells considered possess higher efficiency indices in comparison with isotropic ones.

References listed at the end of the paper:
5. V. V. Novozhilov, Theory of Thin Shells [in Russian], Sudpromgiz (1962).

DOI: 10.1007/s10778-006-0023-1

ABSTRACT: The stability of fiber-reinforced cylindrical shells under torsion is analyzed in the case where the principal directions of elasticity in the layers do not coincide with the coordinate directions. The solution to the linearized equations of the technical theory of anisotropic shells is obtained in the form of trigonometric series. It is shown that for some reinforcement configurations the critical loads may depend on the direction of the torsional moment. It is also established that the minimum (in absolute value) eigenvalue does not always
correspond to the critical load. This fact should be taken into account not only in the case of torsion but also in more complicated cases of loading.

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ABSTRACT: A method for determining the natural frequencies and modes of corrugated noncircular cylindrical shells is presented. The influence of the length and amplitude of corrugations on the fundamental frequency of unloaded and axially compressed shells is examined. The difference between the dependences of frequencies and critical loads on shell geometry is shown. The possibility of optimizing shells in frequencies and critical loads is established.

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ABSTRACT: A method for calculating the buckling stability of layered cylindrical shells made of composite materials with one plane of symmetry of mechanical characteristics is worked out. As a special case, shells made of fibrous materials by winding in directions not coinciding with coordinate axes are considered. An analysis of stability of shells under an axial compression, external pressure, and torsion is carried out. It is shown that, at a great number of layers and appropriate reinforcing angles, the shells can be considered orthotropic. The solution to the problem of the initial postbuckling behavior of shells made of composites with one plane of symmetry is also obtained. It is found that shells of this type can be less sensitive to geometrical imperfections. This fact is important from the practical point of view.

References listed at the end of the paper:

ABSTRACT: A solution is obtained to describe the stability and initial postbuckling behavior of cylindrical shells made of composites with one plane of symmetry. The solution is based on the Donnell-Mushtari-Vlasov nonlinear theory of anisotropic shells and Koiter’s theory of buckling and postbuckling behavior. Calculated results are presented for boron plastic shells with reinforcement of different types under external pressure. It is shown that the conventional model of a composite as an orthotropic material is erroneous for many types of reinforcement.

ABSTRACT: Cylindrical shells consisting of cylindrical panels of smaller radius and subjected to uniform external pressure are analyzed for stability. The geometrical parameters of the shells are approximated by Fourier series on a discrete set of points. The Timoshenko theory of shells is used. The solution is represented in the form of trigonometric series. It is shown that short-and medium-length shells with cylindrical panels are advantageous over circular shells. By selecting appropriate parameters of the panels, keeping the mass of the shell constant, it is possible to achieve a significant gain in critical loads. The shells under consideration are less effective than isotropic shells. Shells with sinusoidal corrugation under external pressure are of no practical interest.

References listed at the end of the paper:

ABSTRACT: The paper presents an analytical solution describing the stability and postbuckling behavior of a cylindrical shell made of an anisotropic material with one plane of symmetry and subjected to torques at the ends. The solution is found using Koiter's buckling theory and the Donnell-Mushtari-Vlasov theory of anisotropic shells. The force and deflection functions are approximated by trigonometric series that satisfy hinged boundary conditions. The system of algebraic equations to which the problem is reduced at the main stage of solution is analyzed. Specific results on stability and sensitivity to imperfections of boron-plastic shells consisting of layers with different reinforcement directions are obtained.

References listed at the end of the paper:
ABSTRACT: The paper proposes a method of incremental loading for solving nonlinear problems of shell theory. A feature of this method is that the same algorithm is used before buckling, at the limit point, and after buckling. The method is based on the assumption that all the unknowns, including the load parameter, are on an equal footing. It is shown that the method can be used to solve algebraic equations with Cramer's rule involved to avoid numerical instability in the neighborhood of the limit point. Test problems confirm the validity of the approach.

References listed at the end of the paper:


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ABSTRACT: A method of solving problems of nonlinear deformation of anisotropic spherical shells with consideration of critical points and postcritical behavior is outlined. The method employs the method of incremental loading in which the load increment is specified with an unknown coefficient determined as an unknown function equivalent to the other ones. The algorithm is based on the numerical discrete-orthogonalization method, which allows analyzing the deformation path for a number of shells with different anisotropy parameters.

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ABSTRACT: The paper outlines a method of analyzing layered anisotropic shells of revolution for stability using complex Fourier series. This simplifies the derivation of the basic equations compared with complete trigonometric Fourier series. Anisotropic shells in the form of a torus segment are analyzed for stability. This method allows optimizing the structure of the material and the geometry of the shell.

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ABSTRACT: The problem of determining the deformation of a longitudinally corrugated, long cylindrical shell under external pressure is considered. The topics that are covered can be summarized as follows: the formulation of a boundary value problem for the incremental approach as a normal system of differential
equations under appropriate boundary conditions, the determination of postbuckling behavior characteristics for cylindrical shells using the discrete orthogonalization method, and an analysis of deformation for both closed and open cylindrical shells. In particular, we consider the stability and postbuckling behavior of both isotropic and composite shells. The solution is based on the relationships for the cubic version of nonlinear Timoshenko-type shell theory. A comparison is made with the well-established quadratic version, as well as analytical solutions where applicable. The necessity for using more precise equations to examine the postbuckling behavior of shells is shown. Using this higher-order approach, it is possible to determine the postbuckling behavior with much greater accuracy.


ABSTRACT: We study coupled extensional and flexural cylindrical vibrations of a corrugated cylindrical shell piezoelectric transducer consisting of multiple pieces of circular cylindrical surfaces smoothly connected along their generatrices. Using the classical shell theory, a theoretical solution is obtained. Based on the solution, basic vibration characteristics of resonant frequencies, mode shapes, and internal forces are calculated and examined for the corrugated transducers, consisting of a few circular pieces each about 50 mum thick, with radius of 5 mm and span angle of 120 degrees. For these transducers the first resonance is of the order of 10-100 Hz.

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ABSTRACT: Shells are for the most part the deep-seated structures in manufacturing submarines, missiles, tanks and their roofs, and fluid reservoirs; therefore it is a matter of concern to bring about some basic regulations associated with the existing codes. Above all, truncated conical shells (frusta) and shallow conical caps (SCC) subjected to external uniform pressure when discharging liquids or wind loads are discussed closely in this paper concerning and thrashing out their empirical nonlinear responses along with envisaging numerical methods in contrast. The buckling aptitude of shells is contingent upon two leading geometric ratios of “slant-length to radius” (L/R) and “radius to thickness” (R/t). In this paper, developing six frusta and four shallow cap specimens and their relevant FE models, use is made of laboratory modus operandi to enumerate buckling elastic and plastic responses and asymmetric imperfection sensitivity, whose adequacy has been reckoned through comparisons with arithmetical and numerical data correspondingly. These obtained upshots were aimed at validating and generalizing the data for unstiffened truncated cones and SCC in full scale.

References listed at the end of the paper:

ABSTRACT: Large elevated steel silos generally consist of a cylindrical vessel, a conical discharge hopper and a skirt which may either be supported on the ground or by a number of columns. The cone–cylinder–skirt junction is subject to a large circumferential compressive force due to the radial component of the meridional tension in the hopper, so either a ring is provided or the shell walls are locally thickened to strengthen the junction. Many theoretical studies have examined the buckling and collapse strengths of these junctions, but no previous experimental study has been reported. This has been due to the great difficulties associated with testing these thin-shell junctions at model scale. This paper first describes the development of an experimental facility for testing model steel silo transition junctions. Issues covered include the fabrication of quality model junctions using thin steel sheets, the loading method and the precise three-dimensional measurement of geometric imperfections and deformed shapes using a laser-displacement meter. Typical experimental results of a cone–cylinder–skirt–ring junction are next presented to demonstrate the capability of the developed facility. Procedures for processing the test results to determine both the buckling load and the number of buckling waves are also presented.

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INTRODUCTION: Buckling loads of elastic-plastic shells can be determined by means of two approaches. In the first one, called the constant load approach, it is assumed that the external load does not change in post-buckling state this is accompanied by arising local unloading regions (passive processes). In the second one, the so called Shanley approach is assumed [2, 3], i.e. that the load increases in the post-buckling state, and the passive processes develop only as a result of post-critical deflections. In paper [4] the Shanley approach has been used for calculating bifurcation loads of conical shells. The presented procedure account for the stability analysis of elastic-plastic shells basing on the two fundamental plasticity theories, i.e.: the incremental (plastic flow) theory, and the total strain (deformation) theory. It is also possible to use the results of paper [4] for analyzing elastic shells. The problem is quite complicated when including the effects of unloading. This leads to nonlinear differential equations; although geometrical linearity is assumed. It is the purpose of this paper to linearize these equations for a simply supported conical shell, with the assumption of a two-parametrical external load and a linear stress-deformation material hardening relation.
ABSTRACT: A method of determination of critical loads for thin-walled conical shells loaded by shear forces developed by moment of twist is presented. The three governing equations of neutral equilibrium with respect to basic displacement vector components \( u, v, \) and \( w \) are used. It is assumed that effective stress in the prebuckling state of stress in the shell can exceed the yield limit of the shell material. The use is made both of physical relations of Nadai–Hencky small elastic–plastic deformation theory of plasticity, and Prandtl–Reuss J2 incremental plastic flow theory. Also, a bilinear stress–strain material model, material compressibility and Shanley approach will be accepted in the analysis. Galerkin method is applied to solve the problem equations and iterative techniques are accepted in numerical algorithm to determine critical loads for elastic–plastic shells.

ABSTRACT: Theoretical fundamentals are presented for large deformation stability of a conical shell under assumptions of elastic-plastic properties following the Prandtl-Reuss incremental plastic flow theory and initial shape imperfections of the order of the shell thickness. The problem is reduced to a set of two nonlinear partial differential equations of the fourth order with two unknowns, i.e. the deflection function \( w \) and the stress function \( \psi \). Solution is obtained as a nonlinear relation between the load and deflection parameter. Numerical results are presented in diagrams.

ABSTRACT: The paper deals with the derivation of the basic stability equations of bi-layered elastic-plastic conical shells and a approximate solution to these equations, both theoretically and by numerical procedures. The subject of the analysis is a bilayered open conical shell under a combined load comprising longitudinal forces and external pressure. Kirchhoff-Love’s hypotheses hold for the layers, and use is made of constitutive relations in the form of generalized Hooke’s law for the elastic stability analysis, and the Prandtl-Reuss incremental plasticity theory for the stability analysis in the elastic-plastic range. The stability equations are derived using the virtual work principle, and Ritz’s method is applied to solve the equations. An iterative computer algorithm has been developed which made it possible to analyse the shells in the elastic, elastic-plastic or totally plastic prebuckling state of stress. The numerical results are presented in diagrams.

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5. Zielnica J., 1999, Large deformations and stability of bilayered elastic-plastic open conical shells, Archives of Civil Engineering, 45, 3, 521-536
ABSTRACT: The paper presents stability analysis of an elastic-plastic sandwich open conical shell of a circular cross section under combined external load in the form of lateral pressure, longitudinal forces, and shear. The shell consists of two load-carrying faces made of an isotropic, compressible work-hardening material, and they are of different thicknesses and made of different material properties; the core material is of a soft type and it resists transversal forces only. It is also assumed that the shell can be deformed into plastic range before buckling. The flexural stiffness of the faces is taken into account, the Kirchhoff-Love hypotheses hold for the faces, and the active deformation processes are considered. The constitutive relations used in the analysis are those of the incremental Prandtl-Reuss plastic flow theory associated with the Huber-Mises yield condition. The virtual work principle is the basis to obtain the governing stability equations and the Ritz method is used to derive differential equations of the considered problem. An iterative computer algorithm was elaborated to analyse the shells both in the elastic or elastic-plastic prebuckling state of stress.

References listed at the end of the paper:


ABSTRACT: The paper presents a derivation of the stability equation and the solution method of the problem.
for an orthotropic elastic–plastic open conical shell. The use is made of the constitutive relations of incremental plastic flow theory, elastic compressibility of the material, and Shanley concept of increasing load are taken into account in the consideration. A variation, strain energy method is used to derive the stability equation for bilayered open conical shell with nonuniform pre-critical stress distribution. The shell is free supported at the edges and the load acting the shell, in the form of longitudinal force and lateral pressure, is active one, i.e. unloading is not considered.


ABSTRACT: The objective of this work is the stability analysis of an open sandwich cylindrical shell with unsymmetrical faces under combined load basing on moderately large deflections (geometrically nonlinear theory), and elastic-plastic properties of the material of the faces are taken into considerations. The shell consists of two load-carrying faces made of isotropic, compressible, work hardening material and they are of different thickness and made of different materials. Kirchhoff-Love (K-L) hypotheses hold for the faces, and the active deformation processes are considered. The core is assumed to be elastic, incompressible in the normal z direction and it resists transverse shear only. The elastic constants Ec and Gc of the core are taken to be variable, and the strength capacity of the shell is substantially influenced by these constants. Prebuckling stress state is taken to be membrane one and the virtual work principle is the basis to derive the strain energy expression. The resulting nonlinear stability equation is solved by Ritz method. An iterative algorithm of elastic-plastic analysis was elaborated to solve the stability equations and the final objective of the work is numerical analysis of the influence of geometrical and material parameters on critical loads and equilibrium paths.

References listed at the end of the paper:

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ABSTRACT: The paper presents stability analysis of elastic–plastic, free supported sandwich cylindrical shell with unsymmetrical faces, loaded by longitudinal forces, transversal pressure, and shear. The J2 incremental Prandtl–Reuss plastic flow theory constitutive relations were used in the analysis and it was assumed that
geometrical strain-displacement relations are nonlinear ones. It was also assumed that the shell faces have different thicknesses and these are made of different isotropic compressible materials with linear stress-hardening. Active loading processes are accepted in the analysis, the stability equations are derived using strain energy formulation. Ritz method is used to solve the equations and an iterative computational algorithm was elaborated to get numerical results.

ABSTRACT: Shell structures are very interesting from the design point of view and these are well recognized in the scientific literature. In this paper the analysis of the buckling loads and stability paths of a sandwich conical shell with unsymmetrical faces under combined load based on the assumptions of moderately large deflections (geometrically nonlinear theory) is considered and elastic-plastic properties of the material of the faces are taken into considerations. External load is assumed to be two-parametrical one and it is assumed that the shell deforms into the plastic range before buckling. Constitutive relations in the analysis are those of the Nadai-Hencky deformation theory of plasticity and Prandtl-Reuss plastic flow theory with the H-M-H (Huber-Mises-Hencky) yield condition. The governing stability equations are obtained by strain energy approach and Ritz method is used to solve the equations with the help of analytical-numerical methods using computer.

ABSTRACT: This paper presents the theoretical background for elastic-plastic stability problem of a conical shell with the assumption that the shell has initial shape imperfections of the order of shell thickness. Physical relations follow Prandtl-Reuss incremental plastic flow theory of plasticity associated with Huber-Mises yield condition. The stability problem is reduced to a set of two nonlinear partial differential equations of the fourth order with the two unknown functions: deflection function and stress function. As a result of solution the nonlinear relation between the external load and deflection function parameter is obtained. The equations are solved by Galerkin method and with the help of a numerical algorithm. The approximate functions satisfy the boundary conditions of free-supported shell edges. An iterative software code was elaborated to get numerical results for elastic-plastic shells.

ABSTRACT: A nonlinear axisymmetric bending theory for a circular, planform, shallow, spherical, sandwich shell with a soft core under the action of uniform edge moments is constructed by means of calculus of variations. An analytical solution for the critical buckling edge moment is obtained by use of a modified iteration method.

Guowei Cao, Zhiping Chen, Licai Yang, Haigui Fan and Fan Zhou (Dept. of Chemical and Biological Engineering, Zhejiang University, China), “Analytical study on the buckling of cylindrical shells with arbitrary thickness imperfections under axial compression”, Journal of Pressure Vessel Technology, Vol. 137, No. 1,
ABSTRACT: This paper presents an analytical study on the buckling of axially compressed cylindrical shells with arbitrary thickness imperfections (nonaxisymmetric and axisymmetric). First, the basic governing partial differential equations, which consider thickness imperfections, are obtained. Second, a unified method that combines the perturbation method and Fourier series expansion is developed to derive buckling load, radial displacement and stress function, that are expressed by triple series in terms of thickness imperfection parameter and buckling modes up to arbitrary order. Third, two patterns of nonaxisymmetric thickness imperfections, which are modal and exponential, are, respectively, investigated. These results are absolutely new to literature. When modal thickness imperfection becomes axisymmetric, the buckling loads degenerate to the known results. In addition to the analytical investigation, analyses and comparisons are also carried out.

E. Tertel (University of Zielona Gora, Faculty of Mechanical Engineering, Poland), “Stability of elastic-plastic sandwich conical shells with a change in the thickness of face-layers”, Journal of Vibroengineering, Vol. 15, No. 2, June 2013
ABSTRACT: The paper presents an analysis of elastic-plastic stability of sandwich conical shells with a change in the thickness of face-layers. The shells under consideration consist of two load-carrying face-layers and a lightweight core layer. The thickness of those faces may vary, just as their material properties. The load-carrying faces are made of isotropic, compressible, work-hardening materials. The core layer is assumed to be elastic, incompressible in the normal z direction and it resists transverse shear only. External load is assumed to be in the form of longitudinal force and lateral pressure. Deformation of the shells within the plastic range is possible before buckling. With respect to the presented research, constitutive relations of the Nadai-Hencky deformation theory, alongside the H-M-H (Huber-Mises-Hencky) yield condition constitutive relations, are accepted in the analysis. To derive the stability equations a variation, strain energy method is accepted and the Ritz method has been used to solve the stability equations.

ABSTRACT: Three theories are presented for the analysis of ring-stiffened or monocoque cylindrical shells under hydrostatic pressure. The theories compute the stress state and the axisymmetric collapse, interbay buckling, and general instability pressures from external hydrostatic pressure loading. The theories were derived for the case of specially orthotropic material with theoretically uniform properties through the thickness; the theories apply equally to shells made of isotropic materials. A computer program, DAPS4 (Design and Analysis of Plastic Shells, Version 4), was written that incorporates these theories that can be used as an initial sizing tool or analysis of a shell's hydrostatic pressure capability. The program includes a "pseudo-plastic" method to account for the reduction of computed collapse pressures when the stress state is above the proportional limit of the material's stress-strain curve. The purpose of this report is to document the theories and the code. Correlation with numerous pressure tests is shown. A user manual with example problems is included. The theories reported herein were developed as part of the author’s independent research in the area of shell buckling over the past 22 years offering a number of improvements to the prior theories and the DAPS3 computer program. Navy projects that have benefited over the years from the application of the DAPS3 and DAPS4 codes include the CVLWT, Long Pulse, Metal Matrix Composites, MK 46 Torpedo, and MK 48 Torpedo.
References listed at the end of the report:

ABSTRACT: A new finite element formulation for predicting the buckling pressure of axisymmetric shells is presented. The finite element proposed is double curved and has constant meridional curvature. Cubic polynomials are used for describing all the displacements. The linear part of the thin shell strain-displacement relations is adopted from Novozhilov's theory and the nonlinear part from Stricklin. Linear prebuckling stress resultants are used in this bifurcation instability analysis. Numerical examples of hemi-ellipsoidal dome heads and Echinodome tanks are satisfactorily solved.

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ABSTRACT: The analysis of submarine pressure hull assumes great importance among structural engineers due to the complexity involved in the collapse mechanism of stiffened shell structures. In most of the cases, the failure of stiffened shell structures occurs due to elastic buckling. But for some combinations of shell-stiffener geometry and material characteristics, the structure can fail by inelastic buckling, for which the methods of analysis are meagre. In this paper, the analysis of submarine pressure hull structure in which the failure gets governed by inelastic buckling is demonstrated. Three different approaches have been employed to investigate the ultimate strength of the ring stiffened submarine pressure hull structure with inelastic buckling modes of failure. The methods used are ‘Johnson–Ostenfeld inelastic correction’, ‘imperfection method’ and ‘finite element approach’. A typical submarine shell structure has been analysed for the inelastic buckling failure using these three approaches and the results are discussed.

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ABSTRACT: The results of stability analysis of ribbed shells performed on the basis of the techniques developed by I. Ya. Amiro and his followers are reviewed. Attention is focused on the features of their buckling due to the discrete arrangement of ribs.

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ABSTRACT: The results of stability analysis of ribbed shells performed on the basis of the techniques developed by I. Ya. Amiro and his followers are reviewed. Attention is focused on the features of their buckling due to the discrete arrangement of ribs.
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ABSTRACT: The results of experimental studies into the stability and vibration of structurally inhomogeneous shells are generalized. The necessity for subsequent integrated investigations is substantiated.

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ABSTRACT: The paper presents a technique for stability analysis of cylindrical shells reinforced with longitudinal elements in the form of a plate or a flanged plate. The effect of the widths of the plate and flange on the critical stress and buckling modes is analyzed.

References listed at the end of the paper:


ABSTRACT: The paper presents a method for stability analysis of an elastic system consisting of a ribbed cylindrical shell and noncrossing plates. The influence of the width and thickness of the plate on the buckling stresses and modes is analyzed.

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ABSTRACT: The paper presents a technique for stability analysis of cylindrical shells reinforced with longitudinal elements in the form of a plate or a flanged plate. The effect of the widths of the plate and flange on the critical stress and buckling modes is analyzed.

References listed at the end of the paper:


ABSTRACT: Elliptical shell structures will increasingly be used as construction elements in future aerospace concepts. The static and the stability behavior of such non-axisymmetric shells is analyzed in this paper. To describe the behavior of the shell structures a complete tensor formulated shell bending theory considering the Kirchoff-Love hypothesis is used. Examples are presented showing the mechanical behavior under thermal loads, surface loads, and a combination of these loads. The achieved results demonstrate the capability of the introduced calculation method.


ABSTRACT: Pressurized propellant tanks might become dynamically unstable with detrimental dynamic responses if a dynamic excitation leads to a coupling of pressure oscillations (especially due to the response of axisymmetric modes) with very low damped ovalizing modes. This phenomenon can be described and identified as the so-called parametric instability. During the dynamic qualification test campaign of the new Ariane 5 Cryogenic Upper Stage ESC-A, a parametric instability was observed for sinusoidal tests under certain test conditions with low static pressure in the propellant tank. The parametric instability was identified and an analytical simulation was performed that confirmed the instability. During flight, harmonic excitations might occur due to pressure oscillations within the solid rocket booster. However, the application of the analytical model on flight conditions indicates that the flight behaviour will be stable. This was confirmed by results from additional tests. This paper describes the phenomenon of the parametric instability of pressurized propellant tanks and presents an analytical methodology to assess the risk of the occurrence of a parametric instability.


PARTIAL INTRODUCTION: …The partial differential equation system of an axisymmetric shell with arbitrary meridian has been developed based on a complete and consistent second order theory using the normal hypothesis. Provided that the displacements are small and the material linear elastic, the second order theory is in many cases a good tool for stability analysis. By developing the physical states in the circumferential direction in a Fourier-series it is possible to eliminate the circumferential coordinate. This way the partial differential equations are transformed into an ordinary differential equation system of first order in meridional direction. In the case of axisymmetric prestress the equations of each wave-number can be evaluated separately…. 
ABSTRACT: Autonomous underwater vehicle (AUV) is a robot which travels underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles. They are controlled and powered by a remote control operator. In military applications AUVs are more often referred to simply as unmanned undersea vehicles. Applications of AUV are specifically used for different applications like, oil and gas industry uses AUVs to make detailed maps of the seafloor before they start building subsea infrastructure pipelines and sub-sea completions. Whereas defense department uses for under water surveillance. Since these vehicles travel underwater the structure need to be designed to withstand the pressure of water concealing them. In the present paper, the analysis is made on a battery composite shell (Epoxy/E-glass) (Fig.1) of AUV. Initially researchers focused on the buckling strength of filament wound cylinders by experimentally deriving composite moduli for shells of different diameter to thickness ratios [1]. A composite cylinder contains of various layers of filament layers hence layup (orientation of fiber) has significance effect on buckling of the cylinder [2]. Further the analytically characterization of cylinder buckling is explained by analyzing computation models of cracked cylinder [3], [4]. Numerical modeling of analyzing stresses in the cylinder under buckling loads is referred from H. Kanou [5]. The main objective of the paper is to reduce the weight of AUV without compromising on strength by using CFRP (Carbon fiber reinforced plastic) material in place of Epoxy/E-glass which has comparatively less density. Further modification in the shell geometry is made by adding stiffeners in an attempt to reduce more weight. The mechanical behavior of Epoxy, CFRP, shells with and without stiffeners is compared under buckling loads. For this a shell model of battery compartment with stiffeners is created in Ansys 12 software which is subjected to pressure both in circumferential and axial directions to see the buckling effect of the shells with stiffeners.

References listed at the end of the paper:

recent than that, possibly presented at one of the conferences held in Braunschweig, Germany, such as one of the “International Conference on Buckling and Postbuckling Behavior of Composite Laminated Shell Structures”

ABSTRACT: The dimensioning of an orthotropic stiffened cylindrical CFRP shell subjected to load introduction of concentrated axial loads using rapid analytical methods is presented. The dimensioning considers required constraints in the force flux distribution, strength of the laminate, general instability, panel instability (from ring frame to ring frame) and local instability. The rapid analytical methods allow for mass optimization. The final design is confirmed by detailed FE analysis. A comparison of the FE analysis with the analytical results is shown.

INTRODUCTION: Primary structures in launcher rockets consist of orthotropic stiffened shells. In order to meet lightweight targets more and more CFRP shell designs are used. For example, in the upper composite of the Ariane 5 (upper stage and payload area) all primary structures, except the propellant tanks, are built of CFRP. The Ariane 5 design of these orthotropic stiffened shells is buckling and stiffness driven. High concentrated loads due to the load introduction of the booster propulsive loads must be carried and distributed into the structure.

The solid booster loads of Ariane 5 are introduced in a cylindrical shell, the so called JAVE (Front Skirt), which is an orthotropic stiffened metallic shell (aluminium). The JAVE is connected with a 5.4 m diameter CFRP made cylindrical sandwich shell, called ISS (Inter Stage Skirt), which carries axial force fluxes due to the load introduction of more than 1000 N/mm.

For the study of a future launcher based on Ariane 5 elements, called WOTAN, the axial force fluxes introduced in the 5.4 m diameter cylindrical shell are up to 5300 N/mm. The high force fluxes have to be attenuated on an acceptable level within an axial length of only 4.5 m until entering the propellant tank structure.

Different CFRP designs are possible for the cylindrical shell: Sandwich design (CFRP face sheets with metallic honeycomb core), stringer and ring stiffened skin (all in CFRP) or a corrugated CFRP shell stiffened by CFRP rings. The design choice and the mass optimization have to consider a huge set of variable parameter and design criteria such as: 1. Axial force flux distribution (which depends on the design or stiffness, respectively), 2. Strength of the laminate, 3. General instability of the cylindrical shell, 4. Panel instability (from ring frame to ring frame), 5. Local instability.

The presentation describes the approach for dimensioning and optimization. For the parametric investigation rapid tools have been used which base on the analytical solution of shell differential equation. The rapid tools allow the dimensioning and mass optimization with an affordable effort and in a systematic manner. The final chosen design has been investigated in detail with a complex Finite Element Model. The FE model confirmed the results of the simplified tool. Comparisons of results achieved with the simplified method and with the detailed FE model are presented.

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A. Rittweger, Th. Schermann, H. -G. Reimerdes and H. Öry (Institut für Leichtbau, Technical University

ABSTRACT: A stiffness matrix for an element of a shell of revolution has been derived, considering arbitrary load distributions and initial geometric imperfections. This element-stiffness matrix is based on the transfer-matrix method and describes the whole section of a shell of revolution between two rings in modal coordinates (a so-called super-element). The modal coordinates here are circumferential Fourier members, thus reducing the partial differential equations to ordinary ones. Several stability analyses investigating the sensitivity of composite shells to different geometric imperfection shapes were carried out. The influence of the load distribution and boundary conditions in combination with geometric imperfections was analysed by different modellings of a hypothetical Jupe Avant shell of the ARIANE 5 rocket.


ABSTRACT: This review highlights some practical aspects of the design of thin-walled shells for aerospace applications. This type of shell must comply with the mission profile. It is therefore necessary to find an optimum structural concept with low weight, high strength, high buckling load and a low imperfection sensitivity. In an optimum design, structural instability occurs slightly below the material strength or yield strength. In general, and by contrast with other structural elements such as beam and plates, a thin-walled cylindrical shell shows a high imperfection sensitivity. Hence, recommendations are given concerning the design of shells and approximate stability analyses are presented for different mechanical loading conditions.


ABSTRACT: (cannot cut and paste abstract)


ABSTRACT: The buckling and postbuckling behaviour of stiffened composite panels is investigated in this paper. For the analysis a procedure is applied that is based on the discretisation of the structure by strip elements. This procedure enables the determination of element stiffness matrices representing analytical solutions of the governing differential equations. Next to the presentation of the underlying theory, numerical results are given for a curved stiffened panel configuration. In order to verify the applicability of the approach, a comparison to experimental results is included.

ABSTRACT: In the first part of this paper, rib-stiffened thin-walled spherical shells under external hydrostatic pressure are optimized using classical approximate methods and empirical knock-down-factors. In the second part of the paper, the influence of known imperfections is investigated. The thin-walled spherical shells under external pressure are very sensitive to geometrical imperfections. Hoff recognized that for entire isotropic spherical shells the more likely imperfection will be a local circular dent, which for such shells, can always be considered as an axisymmetric one. Hoff's idea has been further investigated by Koga–Hoff, Galletly et al. These results showed that for a given depth of an imperfection a critical size of the corresponding circular dent exists, giving the minimum for the actual load carrying capacity of the shell. This paper suggests to extend Hoff's theory to isogrid and waffle-grid stiffened spherical shells. The issue of these investigations is a set of knock-down-factors plotted versus imperfection amplitude related to the total thickness of the rib-stiffened (isogrid or waffle-grid) shell. These curves fit reasonably with those established for isotropic shells by Hoff et al. or by Koiter, and enable to estimate the jeopardy of measured actual dents.


ABSTRACT: The postbuckling compressive strength and collapse phenomena of composite laminated cylindrical panels with various fiber angles and width-to-length ratios are characterized by the nonlinear finite element method. For the iteration and load increment along the postbuckling equilibrium path, a modified arc-length method in which the effect of stress unloading due to failure can be considered is introduced. In the progressive failure analysis, the maximum stress criterion and complete unloading model are used. Validity of present finite element results are verified by experiment for [0(3)/90](S) cylindrical panel and [0/90/+/-45](S) plate. The postbuckling compressive strength of composite laminated cylindrical panels is independent of the initial buckling stress but high in the panel with large value of the bending stiffness in axial direction. In several of the cylindrical panels, it is observed that the prebuckling compressive failures occur and directly result in collapse before buckling.


ABSTRACT: The postbuckling behavior of graphite-epoxy laminated stiffened panels has been studied analytically and experimentally herein. In this research, the stiffened panels were analyzed using the nonlinear finite element method. The progressive failure analysis adopted the maximum stress criterion and the complete unloading failure model. In the failure analysis, the considered failure modes were matrix failure, shear failure and fiber failure. The stiffeners were formed by the continuous lay-up of the skin to improve the integrity of the
stiffened composite panels. A shadow moiré technique was used to monitor the out-of-plane deformation of the skin panel. Piezoelectric film sensors were used to detect the failure events during experiments. The analytical results on the buckling load, postbuckling behavior, and postbuckling compressive strength showed good agreement with the experimental results. Parametric studies were conducted to show the effects of stacking sequences and stiffener shapes on the buckling load and postbuckling compressive strength of stiffened composite panels.


ABSTRACT: To estimate the overall performance of composites, it is necessary to identify the influence of the buckling and delamination failure. For that reason, a fiber optic sensor was applied to the delaminated composite beams to detect the buckling occurrence and delamination growth. The delaminated composite beams subjected to the compressive load were tested to identify the signal characteristics of the fiber optic sensor. The signals of the fiber optic sensor from buckling or delamination growth were quantitatively evaluated by short time Fourier transform and wavelet transform.


ABSTRACT: (cannot cut and paste)

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ABSTRACT: At present, the compressive strength of composite laminates containing an open-hole can be predicted theoretically by using fracture mechanics based models such as the linear softening cohesive zone model. In this approach, the inelastic deformation associated with fibre microbuckling that develops near the hole edge is replaced with an equivalent crack loaded on its faces by a bridging traction which is linearly reduced with the crack closing displacement. By making use of this model, and by establishing an equivalent hole diameter from X-radiographs and/or ultrasonic C-scan images, the residual compressive strength after impact can be predicted. This paper outlines how the ‘equivalent hole’ is determined and gives tabulated results of experimental and theoretical data. It is also shown that these data are in good agreement with each other for plain compression, open-hole compression and compression after impact strengths.

Y. Zhuk, I. Guz and C. Soutis (Department of Aeronautics, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BY, UK), “Compressive behaviour of thin-skin stiffened

ABSTRACT: The in-plane compressive behaviour of thin-skin stiffened composite panels with a stress concentrator in the form of an open hole or low velocity impact damage is examined analytically. Drop weight impact in laminated polymer composites causes matrix cracking, delaminations and fibre breakage, which together can seriously degrade the laminate compressive strength. Experimental studies, using ultrasonic C-scan images and X-ray shadow radiography, indicated that the overall damage resembles a hole. Under uniaxial compression loading, 0° fibre microbuckling surrounded by delamination grows laterally (like a crack) from the impact site as the applied load is increased. These local buckled regions continued to propagate, first in discrete increments and then rapidly at failure load. The damage pattern is very similar to that observed in laminated plates with open holes loaded in compression. Because of this resemblance, a fracture mechanics model, developed initially to predict notched compressive strength, was applied to estimate the compression-after-impact (CAI) strength of a stiffened panel; in the analysis the impact damage is replaced with an equivalent open hole. Also, the maximum stress failure criterion is employed to estimate the residual compressive strength of the panel. The unnotched compressive strength of the composite laminate required in the analysis is obtained from a three-dimensional stability theory of deformable bodies. The influence of the stiffener on the compressive strength of the thin-skin panel is examined and included in the analysis. A good agreement between experimental measurements and predicted values for the critical failure load is obtained.

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ABSTRACT: The in-plane compressive strength of a stiffened thin-skinned composite panel with a stress concentrator is examined. Two possible in-plane failure mechanisms are investigated. The first one is near-surface instability at the edge of the cutout, where high stress gradients are expected because of the stress concentration and the thickness heterogeneity of the laminated skin. Analytical 3D formulas allowing simple parametrical investigation of the phenomenon under consideration are derived. The second failure mechanism is fiber microbuckling in 0°-plies. An equivalent crack model is used to predict the compressive strength of a multidirectional composite laminate. How a stiffener affects the compressive strength of the thin-skinned panel with a hole is studied for both mechanisms. Experimental and predicted values of the critical load are in good agreement.

References listed at the end of the paper:


ABSTRACT: In this study, the effect of laminate thickness on the compressive behaviour of composite laminates was investigated through systematic experimental work using the stacking sequences, [04]ns, [45/0/-45/90]ns and [45n/0n/-45n/90n]s (n=2 - 8) with a 3 mm diameter open hole at the centre. Parameters such as fibre volume fraction, void content, fibre waviness and interlaminar stresses, influencing compressive strength with increasing laminate thickness were also studied experimentally and theoretically. Furthermore the stacking sequence effects on failure strength of multidirectional laminates were examined. For this, two different scaling techniques were used: (1) ply-level technique [45n/0n/-45n/90n]s and (2) sublaminate level technique [45/0/-45/90]ns. An apparent thickness effect existed in the lay-up with blocked plies, i.e. unidirectional specimens ([04]ns) and ply-level scaled multidirectional specimens ([45/0/-45/90]ns). Fibre waviness and void content were found to be main parameters contributing to the thickness effect on the compressive failure strength. However, the compressive strength of the sublaminate level scaled specimens ([45/0/-45/90]ns) was almost unaffected regardless of the specimen thickness (since ply thickness remains constant). From the investigation of the stacking sequence effect, the strength values obtained from the sublaminate level scaled specimens were slightly higher than those obtained from the ply level scaled specimens. This applied to all specimen thicknesses regardless of the presence of an open hole. The reason for this effect was explained by the fibre waviness, void content, free edge effect and stress redistribution in blocked 0∞ plies and unblocked 0∞ plies. Finally the
average strengths of open hole specimens obtained from both stacking sequences increased with increasing specimen thickness. The measured failure strengths were compared with the predicted values.


ABSTRACT: A closed-form solution for the buckling loads of compressively loaded composite plates longitudinally stiffened by blade stringers is developed. The approach is based on adequate formulations for the buckling shapes for both the plate and the stringers in the form of rather simple functional representations. As a by-product, a closed-form solution for a clamped stringer plate is derived. Furthermore, a full series expansion is developed for comparison purposes. The method works with satisfying accuracy and requires negligible computational expenses when compared to accompanying finite element calculations.


ABSTRACT: The present contribution deals with the onset of local buckling of compressively loaded thin-walled beams with open I, C, Z, T and L-cross-sections made of laminated composite materials. The method employs a discrete plate analysis approach in the course of which each structural subelement of interest—which presently is the flange—of the thin-walled cross-section is considered as a separate composite plate with elastic rotational restraints at those edges where an adjacent substructural element is located. While in many investigations the laminate schemes of webs and flanges are considered to be purely orthotropic, in the present paper the laminate layups are allowed to be of an arbitrary non-orthotropic nature, which also allows for the analysis of laminates with inherent bending–torsion coupling. The analysis of the buckling loads of the flanges of thin-walled composite beams is performed using the Ritz-method for which some especially adjusted displacement shape functions are employed. For the case of pure orthotropy, a novel closed-form solution is described. The accuracy of the employed approaches is established by comparison with accompanying finite element simulations of thin-walled composite beams. It is revealed that the presented methodology is highly efficient in terms of computational effort and yet performs with satisfying accuracy, which makes it very attractive for actual practical applications whenever the local stability behaviour of wide-flange thin-walled composite beams is to be considered.

References listed at the end of the paper:
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ABSTRACT: This paper discusses the buckling behaviour of orthotropic composite plates under uniform uniaxial compression with one free reinforced unloaded edge. A typical application example for use of such a mechanical model is the web of stiffeners and frames attached to the fuselage skin of an aircraft. The considered plates are rectangular and simply supported at the loaded transverse edges. One of the longitudinal unloaded edges is also simply supported, while the second unloaded edge is not supported at all but is reinforced by a flange of arbitrary cross-section. At first, an exact solution for the elastic buckling problem is derived from the governing differential equation by imposing the underlying boundary conditions. Thereafter, two approximate closed-form solutions for the buckling load are derived, which can be conveniently used for practical application purposes. Generic buckling curves using characteristic non-dimensional quantities are also presented. Finally, the question of the required bending stiffness $EI_{\text{min}}$ of the flange is treated, to ensure that the flange withstands buckling and provides simply supported boundary conditions to the free reinforced plate edge.


ABSTRACT: In this paper, the postbuckling behavior of rectangular orthotropic laminated composite plates with initial imperfections under inplane shear load is investigated in a closed-form analytical manner. The plates under consideration are assumed to be infinitely long in the longitudinal direction. At the longitudinal edges, two different sets of boundary conditions are considered, specifically 1) simply supported edges and 2) fully clamped edges. Using Timoshenko-type shape functions for both the initial bifurcational buckling analysis and the subsequent Marguerre-type postbuckling studies, closed-form analytical solutions for the buckling loads and for the postbuckling state variables are derived. A comparison with geometrically non-linear finite element computations shows that the derived analysis approaches are suitable for postbuckling studies in load ranges not too far beyond bifurcational buckling as they are currently relevant for e.g., composite airframe structural analysis and design. Due to their strictly closed-form analytical nature, the presented analysis methods can be used conveniently in engineering practice for all application purposes where computational time is a crucial factor, especially for preliminary analysis and design or optimization procedures.

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ABSTRACT: In this paper, a closed-form method for the analysis of the local postbuckling behaviour of aircraft panels that are braced by hat-stringers is presented. The stiffened panels are loaded by transverse compression which is a load case that has been treated only scarcely in the open literature, and the corresponding buckling and postbuckling behaviour that eventually leads to failure of the panel is quite different to what is observed when a panel under longitudinal compression is considered. This contribution clarifies that the ultimate load bearing capacity of a stiffened panel with closed-profile stringers under transverse compression is governed by several consecutive stability cases. Firstly a closed-form approximate analysis method for the linear buckling analysis of the skin between two stringers taking the torsional stiffness of the hat-stringers into account is derived (stability case 1). Secondly, a simple Marguerre-type postbuckling
analysis method is presented that accounts for the geometrically nonlinear behaviour of the panel skin after buckling (stability case 2) and enables a closed-form analysis of its effective width. Thirdly, the linear buckling analysis is adapted to the analysis of the panel skin under a stringer (stability case 3). It will be shown that stability cases 2 and 3 cannot be treated independently, but have to be considered interactively which necessitates an iterative procedure. The accuracy of the proposed analysis method, relying on the simplifying assumption of a perfectly flat plate rather than considering a cylindrically curved panel is established by comparison with results of accompanying geometrically nonlinear finite element calculations.

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ABSTRACT: The current paper deals with a closed-form approximate solution for the postbuckling behavior of an unstiffened, singly-curved, orthotropic shell. As loading condition the case of uniform axial compression is treated. Concerning the boundary conditions all edges are supposed to be simply supported. Additionally, geometrical imperfections in form of an initial deflection of the shell can be accounted for. Choosing rather simple shape functions for the deflection a closed-form expression for the Airy stress function is obtained from the compatibility condition. As the equilibrium condition cannot be satisfied exactly the solution procedures of Galerkin as well as Ritz are employed to obtain an approximate solution. The resulting expressions from these procedures again allow for a closed-form solution of the load-deflection-relationship. After the force and the amplitude are known all other state variables such as stresses and displacements can be evaluated in a closed-form manner. Due to the rather simple formulation of the deflection shape the algorithm is limited to cases where the qualitative shape of the deflection does not change significantly. On the other hand the very high computational efficiency of the described solution procedure makes it ideally suited for use in the field of optimization and preliminary design, if the applied load does not exceed the linear buckling load too much.

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ABSTRACT: Liquid metal fast breeder nuclear reactors demand the usage of large sized thin shells for their reactor vessel components due to low operating pressure and high thermal load. Buckling is a very important aspect in the design of these vessels. In this article, analysis of the inner vessel of a typical 500 MWe fast breeder reactor is presented. Here, two different geometric configurations of the inner vessel are considered. One configuration is with the conical step joining the upper and the lower cylindrical portions, and the other is with the toroidal bottom joining the upper cylindrical part. The buckling strength of the vessel for both configurations are calculated and compared. Also, the effects of thermal load, initial geometric imperfection, geometric nonlinearity, etc. are investigated. The finite element method is used for analysis.
ABSTRACT: Thin shells are prone to fail by buckling due to compressive membrane stress. Although shells develop primarily membrane stresses, in most practical situations, they have some bending stresses as well as a result of supports, loading condition and discontinuity. In such case, the response of a shell to external loads becomes nonlinear. Linearization of the nonlinear equilibrium equations gives rise to an eigen value problem solving which buckling load is obtained. Eigen value buckling analysis is computationally faster than the nonlinear analysis involving tracing the load-deflection path and finding the corresponding collapse load. However, the buckling load estimated using the eigenvalue buckling analysis is approximate and usually overestimated. For the systems with large prebuckling rotations this approach may give highly unconservative results. Attempts have been made for better prediction of actual buckling load of shells of revolutions by combining eigenvalue buckling analysis and geometric nonlinear analysis. Such methods are computationally more efficient than the nonlinear buckling analysis but more reliable than the linear buckling analysis. This study presents an overview of the stability analysis of shells of revolution using a conical frustum shell element incorporating the linear and simplified nonlinear buckling analysis including the treatment of initial geometric imperfection.

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ABSTRACT: The geometric nonlinear responses of laminated composite cylindrical panels subjected to (i) axial compression and (ii) central concentrated load are investigated in this work. The parameters considered are: number of layers, symmetric/antisymmetric laminate constructions, cross-ply/angle-ply fibre orientation, boundary conditions and central angle of panel. An eight-node degenerated layered shell element with an efficient explicit through-thickness integration scheme is employed. It has been observed that the cylindrical panels under axial compression exhibit stable post-buckling paths and the number of layers in the laminate for a given total thickness has considerable influence on the load–deflection behaviour. The strength of shallow panels with longitudinal edges hinged, curved edges free and subjected to a central concentrated load is controlled by the limit point load, whereas for deep panels with other parameters remaining the same, the strength is controlled by the bifurcation load. The boundary conditions have significant influence on the load-carrying capacity. The panels with longitudinal edges hinged and curved edges free should be avoided in construction, as they undergo either limit point or bifurcation failure at very low load levels compared with other edge conditions.

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“Experimental Stuudies on LMFBR Inner Vessel Models”, Paper #1109, Transactions.. (publisher, date not given)
PARTIAL ABSTRACT: This paper presents the results of an experimental study on the buckling of scale models of Liquid Metal Fast Breeder Reactor (LMFBR) inner vessel. The inner vessel consists of two cylindrical shells. The upper and the lower shells are connected by conical and torus shells. Six identical models are tested under three loading conditions. Imperfection scans are carried out using contact type probes, before loading and during loading. Scanning is carried out simultaneously for upper cylinder, conical, torus and lower cylinder using separate LVDTs and the data scanned are stored in a PC-based data acquisition system. Strain gages are mounted at strategic locations and strains are recorder during…

ABSTRACT: In this paper we will first give a short introduction to stability phenomena and stability theory. Further we will discuss a linear buckling safety concept according to DIN 1045 (DIN 1045 1988) and VGB-BTR (VGB-BTR 1997). In this context we will present a practical procedure for determining the lower bound of the limit load of a shell structure with the concept of reduced membrane buckling. Also we will give an application of this method to find the ideal wall thickness distribution of a cooling tower shell in the first design studies. Special attention is given to the material nonlinearities with respect to buckling. The phenomena of perfect and imperfect cooling tower shells are analyzed, and the nonlinear buckling behavior will be discussed for ideal and imperfect cooling tower shells.

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ABSTRACT: Natural draught cooling tower shells are loaded mainly by their dead weight and by the wind, which may both cause buckling failure. The present paper compares various numerical procedures to investigate the stability behaviour of cooling tower shells. These are a complete nonlinear analysis, a linear eigenvalue analysis for a stationary non-axisymmetric wind load, and a linear eigenvalue analysis for a wind load, approximated to be axisymmetric. The aim is to evaluate whether a geometrically nonlinear analysis can be replaced by a time-saving classical buckling analysis, probably even for an axisymmetric state of stress. The third procedure, as the most conservative, but a very effective one, will be applied to investigate the mechanical influence of ring stiffeners on the buckling behaviour of cooling tower shells. Kinetic instability phenomena will also be examined. The structural improvement resulting from ring stiffeners will be quantified and summarized in design recommendations.

W.B. Krätzig (Institute for Statics and Dynamics, Ruhr-University, W-4630 Bochum, Germany), “‘Best’ transverse shearing and stretching shell theory for nonlinear finite element simulations”, Computer Methods in Applied Mechanics and Engineering, Vol. 103, Nos. 1-2, March 1993, pp. 135-160,
doi:10.1016/0045-7825(93)90043-W

ABSTRACT: Convinced of the powerful capability of modern computational techniques the question of ‘best’ physical shell models is re-raised. In the present paper, ‘best’ interior shell equations are derived by mapping a 3-dimensional body, described as a multi-director-continuum, on a Cosserat-surface kinematics. The derived shell equations hold for arbitrarily large deformations and material laws in rate-description, incorporating shear distortions and thickness changes. The optimal character of the developed model — proven by tensor norm bounding techniques — is finally demonstrated by results of numerical simulations of nonlinear shell responses.
ABSTRACT: The present essay contains a general structural stability theory for discretized structural systems. Instabilities are essential constituents of nonlinear structural responses, the computational assessment of which in a modern treatment is exclusively based on incremental-iterative (step-wise) numerical techniques, applied to the tangential equation of motion. The paper derives this fundamental equation as first variation of the nonlinear equation of motion in its standard form and its phase projection. Further, it transforms the principle of virtual work for arbitrary nonlinear (Kelvin-Voigt) continua into its incremental variant and finally into the consistent tangential equation of motion. Its various applications then are demonstrated to classes of time-independent and time-dependent, unstable structural responses, for which suitable numerical instruments are outlined. The derived algorithms are based on the concepts of Lyapunow exponents and Poincaré multipliers which are introduced as universal stability measures. Qualitative and quantitative convergence properties of perturbations in the phase space enable the proper establishment of stability definitions. The validity of the received concepts is illustrated by several examples.

References listed at the end of the paper:

ABSTRACT: The paper designs a general stability theory for discretized shell structures based on stepwise numerical solution techniques. To this purpose the nonlinear principle of virtual work is transformed into its l subprinciple and finally discretized. The resulting equation for Kelvin–Voigt material, usually denoted as tangential equation of motion, turns out to be a sufficient and suitable basis for the numerical evaluation of arbitrary nonlinear responses including their instability phenomena.

References listed at the end of the paper:

ABSTRACT: A geometrically and physically nonlinear finite element model for thin reinforced concrete shells is presented which allows simulation of the deformation history of imperfect structures up to their numerical failure. Application to the assessment of existing natural draught cooling tower shells subjected to dead weight and wind loading demonstrates the usefulness of the numerical procedure. Results showed that failure was due to a nonlinear stress problem, rather than elastic buckling. For worst-case imperfections relating to the physically nonlinear failure mode, the shells exhibited only a moderate imperfection sensitivity. Further work will concentrate on more realistic imperfection patterns, since worst-case imperfections give a rather too conservative lower bound for the collapse loads.

ABSTRACT: The present contribution is concerned with dynamic stability investigations of arbitrary structural responses, in particular shell responses. In order to trace such nonlinear fundamental processes, incremental/iterative path-following algorithms are employed to the tangential equation of motion which is derived under special regard of finite rotation shell theories, elasto-plastic material behaviour, and motion-dependent loading. Occurring instabilities can be detected with the help of Lyapunow exponents as generalized concept for the detection of quantitative stability properties. Well known investigation procedures are recognized as special cases of the Lyapunow-exponent-concept for stationary, transient, periodic, and arbitrary solution curves in the phase space. A new numerical procedure for the determination of one-dimensional Lyapunow exponents is introduced to identify critical directions in the solution space for large discretized structures by reduction to relevant manifolds

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ABSTRACT: Shell structures are extremely efficient, thin walled load-carrying components, in the elastic as well as in the inelastic regime. Realistic and efficient computational strategies lately are in rapid development. Such computational strategy for modelling of nonisothermal, highly nonlinear hardening responses in elastoplastic shell analysis has been proposed in this article. Therein, the closest point projection algorithm employing the Reissner-Mindlin type kinematic model, completely formulated in tensor notation, is applied. A consistent elastoplastic tangent modulus ensures high convergence rates in the global iteration approach. The integration algorithm has been implemented into a layered assumed strain isoparametric finite shell element, which is capable of geometrical nonlinearities including finite rotations. Under the assumption of an adiabatic process, the increase of the temperature is analysed during elastoplastic deformation. Finally, numerical
examples illustrate robustness and efficiency of the proposed algorithms.

W.B. Kratzig, Reinhard Harte, Ulrich Montag and Ralf Woermann, “From large natural draft cooling tower shells to chimneys of solar upwind power plants”,
https://www.researchgate.net/publication/50838736_From_large_natural_draft_cooling_tower_shells_to_chimneys_of_solar_upwind_power_plants, Publisher and date not given.

ABSTRACT: Natural draft cooling towers (NDCTs) presently form the world-largest RC shell structures, solar updraft power plants (SUPPs) will do this in future. The paper starts with explanations of the working principles of NDCTs and SUPPs. In industrialized countries with strong legal emphasis on sustainable power production technologies, NDCTs are widely spread, while SUPPs represent future solar power generation concepts in the world’s tropical areas, using solar irradiation as power plant fuel. Consequently, the paper elaborates on recent German NDCTs, under them the world-highest tower shell. The design of such high-efficient RC tower shells will be explained including their critical response characteristics. The paper then changes to future SUPPs, describing the structural components of their solar chimneys, followed by a sketch of some of their critical response characteristics. The aim of this presentation is to draw the readers’ attention to extremely large shell structures (Mega-shells), present and in future, and to demonstrate their close structural mechanics relationship to each other.

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ABSTRACT: After demonstrating how to improve simply the BS 5500 strength formulation for hydrostatically loaded fabricated ring-stiffened cylinders, a simple yet consistent strength formulation is derived for determining their strength when subjected to combined axial loading including tension and radial pressure. The quadratic Merchant-Rankine formula in generalised form as suggested by Odland is adopted as the basis of the proposed formulation. This involves knockdown factors which are derived to provide a good fit with experimental data. Its accuracy is compared with that of the DnV Rules and BS 5500. The effects of boundary conditions and residual stresses are investigated using unstiffened and stress-relieved test data respectively.

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ABSTRACT: The development of a numerical model describing the large-deflection elasto-plastic behaviour of flat plates and attached flatbar stiffeners including the effects of interaction is described in this paper. The Marguerre large deflection thin plate equations are used to represent both the plate and the stiffener so enabling the lateral-torsional behaviour to be accurately modelled. Complete interaction is achieved by satisfying the full set of equilibrium and kinematic conditions acting along the intersection.
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ABSTRACT: Having described, in Part 1, the theoretical basis of the method used to study the lateral-torsional behaviour of stiffeners attached to flat plating, detailed comparisons with a series of tests and other theoretical formulations are presented in this paper.

ABSTRACT: A numerical study of the effect of aspect ratio on the buckling and collapse behaviour of flatbar-stiffened plates in compression is described. The plate equations are expressed in finite difference form and the solution is obtained using a dynamic relaxation algorithm. Initial imperfections and residual stresses are also introduced in the study. It was found that, for aspect ratios between 2 and 3.5, buckling occurs in the elastic regime, with the panels exhibiting significant post-buckling strength prior to collapse. For aspect ratios between 1 and 2 buckling occurs as the plastic zone increases, followed by rapid unloading as the panel collapses suddenly. The ultimate strength of the panel reduces with increasing aspect ratio, remaining practically constant at higher aspect ratios. The latter is attributed to the initial single half-wave distortion profile that prohibits the formation of the preferred buckling mode.

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ABSTRACT: Shell-like structures are prevalent in nature. However, because of their slenderness they are prone to buckling, and to such an extent that this is often the dominant consideration in their design. Early attempts to determine buckling pressures were unsatisfactory. Although initial geometric distortions are now recognised as the cause of this, little comprehensive work has been conducted on doubly-curved shells, particularly hemispheres, subjected to external pressure and having asymmetric initial shapes. This paper presents the results of such a study, in two parts. In Part I, the background research on doubly-curved shells is briefly reviewed. The kinematic, equilibrium and constitutive equations used in the work are stated. The adopted numerical procedure which can generate static or dynamic solutions is described along with the results of convergence studies. In Part II, the effect of various initial shapes and their location will be described; the critical combination will be identified. The parameters selected to nondimensionalise the results will be
indicated, followed by those of the study which primarily involve initial deformation magnitude and shell slenderness. Two strength formulations which conveniently represent the results of the study will be presented.

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ABSTRACT: Shell-like structures are prevalent in nature. However, because of their slenderness they are prone to buckling, and to such an extent that this is often the dominant consideration in their design. Early attempts to determine buckling pressures were unsatisfactory. Although initial geometric distortions are now recognised as the cause of this, little comprehensive work has been conducted on doubly-curved shells, particularly hemispheres, subjected to external pressure and having asymmetric initial shapes. This paper presents the results of such a study, in two parts. In Part I, which was presented in the previous issue of Thin-Walled Structures, the background research on doubly-curved shells was briefly reviewed. The kinematic, equilibrium and constitutive equations used in the work were stated. The adopted numerical procedure which can generate static or dynamic solutions was described along with the results of convergence studies. In this Part, the effect of various initial shapes and their location is described: the critical combination is identified. The parameters selected to nondimensionalise the results are indicated, followed by those of the study which primarily involve initial deformation magnitude and shell slenderness. Two strength formulations which conveniently represent the results of the study are presented.


ABSTRACT: Results from a series of studies on stiffened plates under axial compression are presented in this paper. The large-deflection elasto-plastic behaviour of each panel component is described by the von Karman equations, thus enabling the lateral-torsional buckling of the stiffener to be modelled in a rigorous manner. Material nonlinearity is represented using the von Mises yield criterion in conjunction with the Prandtl-Reuss flow rule. Results are presented in the form of average stress-strain curves which are used to generate maximum strength curves for the stiffener and plate.


ABSTRACT: The total potential energy of buckling of a plate with variable stiffness has been discretized by the method of finite differences. According to the principle of minimum potential energy, by equating the partial derivative of total potential energy with respect to each grid point displacement to zero in succession, a set of linear homogeneous equations is obtained. This reduces to a standard characteristic value problem, the eigenvalues of which yield the buckling loads. Test problems of plates with uniform stiffness, gradually varying stiffness and abrupt variation of stiffness with different boundary conditions and a stepped column as a
degnerate case of plate have been considered. Results are compared with those of analytical and numerical methods available. Good agreement has been observed in all cases. The proposed method has the advantage that the total number of equations is far less than in finite element method and application of boundary conditions is simple.

ABSTRACT: A procedure is developed for the design of a stiffened cylinder under a given uniform axial compression with minimum weight. The approach allows the consideration of various shapes of stiffening members. The effective stiffness of the skin in its post-buckled state is taken into account in the basic analysis. The buckling analyses are accomplished as a minimum problem in the buckling mode shape parameters space using the variable metric method. A mixed procedure which combines the exterior penalty function concept and random search is used to minimize the weight of the stiffened cylinders. The design examples demonstrate the validity of the present approach.

ABSTRACT: Cylindrical shells exhibit buckling under axial loads at stresses much less than the respective theoretical critical stresses. This is due primarily to the presence of geometrical imperfections even through such imperfections could be very small (e.g., comparable to thickness). Under internal pressure, the shell regains some of its buckling strength. For a relatively large radius-to-thickness ratio and low internal pressure, the effect can be reasonably estimated by an elastic analysis. However, for low radius-to-thickness ratios and greater pressures, the elastic-plastic collapse controls the failure load. In order to quantify the elastic-plastic buckling capacity of cylindrical shells, an analysis program was carried out by use of the computer code BOSOR5 developed by Bushnell of Lockheed Missiles and Space company. The analysis was performed for various radius-to-thickness ratios and imperfection amplitudes. The analysis results are presented in this paper.

K. Bandyopadhyay, J. Xu and S. Shteyngart, “Cylindrical shell buckling through strain hardening”, Brookhaven National Laboratory Report BNL-61540, no date given (the most recent reference is dated 1994)
ABSTRACT: Recently, the authors published results of plastic buckling analysis of cylindrical shells. Ideal elastic-plastic material behavior was used for the analysis. Subsequently, the buckling analysis program was continued with the realistic stress-strain relationship of a stainless steel alloy which does not exhibit a clear yield point. The plastic buckling analysis was carried out through the initial stages of strain hardening for various internal pressure values. The computer program BOSOR5 was used for this purpose. The results were compared with those obtained from the idealized elastic-plastic relationship using the offset stress level at 0.2% strain as the yield stress. For moderate hoop stress values, the realistic stress-strain case shows a slight reduction of the buckling strength. But, a substantial gain in the buckling strength is observed as the hoop stress approaches the yield strength. Most importantly, the shell retains a residual strength to carry a small amount of axial compressive load even when the hoop stress has exceeded the offset yield strength.
ABSTRACT: Loadings to cause severe accidents on containment buildings can include combinations of uniform internal pressure, dynamic pressure, and seismic. Most studies that have been conducted to predict containment building capacity have focused on the effect of overpressurization on containment performance. A simple methodology that permits rapid and reasonably accurate analysis for assessing the capacity of steel containment buildings due to global or local uniform or spatially varying dynamic loading was developed. An axisymmetric model was used and the circumferential variation of the pressure, displacements, and stress resultants were represented by Fourier series. Shell vibration and buckling analysis were performed using modified versions of BOSOR4 and BOSOR5 finite difference codes. The modified version of BOSOR5 allows the input of pressures that vary along the meridianal direction. These pressures were increased until failure of the containment occurred. Failure was defined to occur when membrane strains reached twice the yield strain or the bifurcation point was introduced. The applicability of this analysis method was verified by analyzing several problems as well as a simplified containment building. The axisymmetric analysis demonstrated a powerful tool to access the capacity of steel containment buildings.

ABSTRACT: The high stresses at intersections are caused by discontinuity shear stresses and moments which exist to maintain compatibility at the junction. The finite element method was used to determine the stress field at the intersection of a radial nozzle attached to a torispherical crown of a cylindrical vessel. The mechanical loads acting on the structure consisted of nozzle thrust, bending moment, torsion and internal pressure. A comparison between predicted and measured readings gave acceptable results for internal pressure loading but fair for other loadings. A computer program was written to calculate interaction between any two combining loads. The results, presented graphically, could be used to predict first yield for vessels of this configuration.

ABSTRACT: In this paper, the finite element analysis is used to investigate the effect of shape of dome ends on the buckling of pressure vessel heads under external pressure. The Finite Element Analysis (FEA) with the use of elastic buckling analysis was applied to predict the critical buckling pressure. The influence of geometrical parameters such as thickness, knuckle radius, and the ratio of minor axis to the major axis of dome ends, on the weight and the critical buckling pressure of hemispherical, ellipsoidal, and torispherical dome ends, was studied. The four-centered ellipse method was used to describe the geometry of the dome end.

ABSTRACT: In this study, the elastic buckling behavior of clamped laminated composite cylindrical shells under external pressure was studied. The Finite Element Method (FEM) was used to predict the critical elastic buckling pressure behavior when composite cylindrical shells were subjected to external pressure. The edges of the cylindrical shell ends were completely constrained to simulate clamped end conditions. The influences of parameters such as wall thickness, fiber angle, number of layers and L/R ratio of laminated composite cylindrical shells on critical buckling pressure were studied. It has been found that the under external pressure, the thickness and the fiber angle of the layers have the most significant effect on the critical buckling pressure.

References listed at the end of the paper:


ABSTRACT: This paper is concerned the analysis of functionally graded cylindrical shell under impulse loads by using the Rayleigh-Ritz method. The mass density and modulus of elasticity of the FG cylindrical shell is assumed to vary according to a power law distribution in terms of the volume fractions of the constituents. Hamilton’s principle with Rayleigh-Ritz method is used to derive the equation of motion of the FG cylindrical shell. The steady responses of forced vibration can be obtained by solving the equation of motion. The considered impulse load types are step pulse, sine pulse, triangular pulse and exponential pulse. The analytical results in special case are compared and validated using finite element method.

References listed at the end of the paper:


ABSTRACT: A buckling criterion for shells with an axisymmetric middle surface and subjected to edge loads and hydrostatic surface pressure loading is formulated starting from Hill's three-dimensional continuum theory for uniqueness of deformation of inelastic solids. It turns out that a physically consistent two-dimensional set of equations may be derived for a quite general class of strain-hardening elastic-plastic solids, the only essential restriction being that of a smooth yield function. The intrinsic errors inherent in the derived rate equations, being an integral part of an eigenvalue problem, are discussed in relation to a circular cylinder under axial compression. Analytical results are given which illustrate the influence of the constitutive properties and the boundary constraints on the magnitude of the critical load.


PARTIAL ABSTRACT: Accuracies of the Southwell method and the force/stiffness (F/S) method were
examined when the methods were used in the predictions of buckling loads of hypersonic aircraft wing tubular panels, based on nondestructive buckling test data. Various factors affecting the accuracies of the two methods were discussed. Effects of load cutoff point in the nondestructive buckling tests on the accuracies of the two methods were discussed in great detail…

ABSTRACT: Buckling analysis was performed on a hat-stiffened panel subjected to uniaxial compression. Both local buckling and global buckling were analyzed. It was found that the global buckling load was several times higher than the local buckling load. The predicted local buckling loads compared favorably with both experimental data and finite element analysis.

ABSTRACT: A buckling analysis was performed on a hat-stiffened panel subjected to shear loading. Both local buckling and global buckling were analyzed. The global shear buckling load was found to be several times higher than the local shear buckling load. The classical shear buckling theory for a flat plate was found to be useful in predicting the local shear buckling load of the hat-stiffened panel, and the predicted local shear buckling loads thus obtained compare favorably with the results of finite element analysis.

References listed at the end of the paper:

PARTIAL ABSTRACT: Thermocryogenic buckling and stress analyses were conducted on a horizontally

ABSTRACT: In the present review we considered several problems of nonlinear shell theory, their deformation and stability. Specialists in many areas have devoted much attention recently to problems of the nonlinear behavior of evolutionary systems. New scientific trends related to the study of stability problems have been generated. They can be called the Hopf bifurcation theory; or, the theory of attractors, referring to the study of unstable trajectory behavior in phase spaces; or, catastrophe theory, applied in solving multiparametric stability problems; or, the theory of phase transitions and critical phenomena, developed in special areas of physics; or, a theory considering nonequilibrium phase transitions and self-organization complex spatial and temporal ordered structures (synergetics). The use of methods developed by these scientific trends in shell theory enables deep understanding of effects of stability loss, in both equilibrium and motion, and helps to create investigation methods. (184 references)

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141. Theory of Flexible Plates [Russian translation], IL, Moscow (1957).
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ABSTRACT: A refined Timoshenko-type model based on the straight-line hypothesis is used to develop an approach to analyzing the stress state of longitudinally corrugated cylindrical shells with elliptic cross-section. The approach is to reduce the two-dimensional boundary-value problem that describes the stress–strain state of the shell to a one-dimensional one and to solve it with the stable numerical discrete-orthogonalization method. The solutions obtained using the straight-line hypothesis and the equations of three-dimensional elasticity are compared. The dependence of the stress–strain state of the shell on the number and amplitude of corrugations and the aspect ratio of the cross-section is analyzed.


ABSTRACT: A simple, but efficient procedure for the investigation of the geometrically non-linear dynamic behaviour of thin elastic shells which can be described sufficiently accurate by the Donnell-Marguerre-Mushtari-Vlasov theory is proposed and tested. It is based on a mixed variational formulation generalizing D'Alembert's principle. The discretization with respect to the space is performed by Euler's method and that with respect to the time by means of the central difference quotient. Due to the regular and simple structure of the governing algebraic equations wave propagation phenomena can be studied adequately. The introduction of an (artificial) damping allows the approximation of pure static problems and includes as well the branching of equilibrium. Some illustrative examples are presented.


ABSTRACT: The longitudinal compressive buckling loads of thin-walled cylinders in the yield region were analyzed by using both the incremental and the finite forms of a non-classical constitutive relation of plasticity (NCP). The relations of the critical stress sigma(cr) vs the ratio between R (the radius) and h (the thickness of the wall) were derived. The critical stresses of the thin-walled cylinders made of aluminum alloys AM__ and _1T were analyzed and compared with the experimental results. Comparison shows that for the cylinders made of _1T both forms of NCP can provide reasonable prediction; but for those made of AM__, the result given by the finite form of NCP is satisfactory, while the critical stress predicted by the incremental form of NCP is about 25% higher than the experimental data. The capability of the NCP in the description of the material instability, the response of material under an abrupt strain disturbance and its easy application indicate that it may be of potential in the analysis of structural buckling.


ABSTRACT: (cannot cut and paste abstract)

ABSTRACT: Numerical solutions are used as the basis for a comparative analysis of the qualitative and quantitative effect of small initial curvatures of the generatrices of conical and cylindrical shells on the critical axial pressures of the shells

References listed at the end of the paper:


ABSTRACT: The bifurcation stability and natural vibrations of shells of revolution with variable geometric and mechanical parameters are studied by using refined models and the variational–difference method. The qualitative and quantitative effects of the external geometry, material properties, and design features on the critical load and natural frequency are evaluated.

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which increases as the load increases. The inhomogeneous material being damaged inhomogeneous form of a system of elliptic chaotically distributed microcracks throughout its volume, the concentration of curvature is proposed, taking into account the microdamageability of an isotropic material in the form of the formation of a system of elliptic chaotically distributed microcracks throughout its volume, the concentration of which increases as the load increases. The inhomogeneous material being damaged is simulated by a


ABSTRACT: An approach to the study of the bifurcational stability of convex shells of revolution of double curvature is proposed, taking into account the microdamageability of an isotropic material in the form of the formation of a system of elliptic chaotically distributed microcracks throughout its volume, the concentration of which increases as the load increases. The inhomogeneous material being damaged is simulated by a
continuum, the elastic symmetry and mechanism of deformation of which are associated with the character of the distribution of microstrength and the form of the interaction of the edges of the microcracks, which depends on the stressed state induced in the body. The problem of bifurcational stability in the case of shells of revolution is formulated using the concept of continued loading within the framework of the Kirchoff-Love hypothesis. As an example, problems of the stability of ellipsoidal shells in the case of an internal and external pressure are solved.


ABSTRACT: Shells of revolution made of a granular composite material with microdamageable components are studied. Microdamages are simulated by spheroidal pores filled with a damaged material. The concentration of pores increases with increasing load. The problem is formulated using the concept of continuous load and the Kirchhoff-Love hypotheses. Solutions are presented for shells of positive and zero Gaussian curvature.

References listed at the end of the paper:


ABSTRACT: The bifurcation-stability problem for shells of revolution made of fibrous composite with damageable matrix is formulated and solved. Increase in the damage of the matrix under loading is taken into account.

References listed at the end of the paper:
ABSTRACT: The problem of bifurcation instability of cylindrical shells made of transversely isotropic laminate materials with progressively damaged reinforcement is formulated and solved.

ABSTRACT: The problem of bifurcation instability of shells of revolution made of particulate composites with components subject to long-term damage is formulated and solved.

Donald Mackenzie, Duncan Camilleri and Robert Hamilton (Department of Mechanical Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow G1 1XJ, Scotland, UK), Thin-Walled Structures, Vol. 46, Nos. 7-9, July-September 2008, pp. 963-974, A special issue to mark the Retiral of Professor Jim Rhodes, Founding Editor, doi:10.1016/j.tws.2008.01.033
ABSTRACT: Thin shell torispherical pressure vessel heads are known to exhibit complex elastic–plastic deformation and buckling behaviour under static pressure. In pressure vessel Design by Analysis, the designer is required to assess both of these behaviour modes when specifying the allowable static load. The EN and ASME boiler and pressure vessel codes permit the use of inelastic analysis in design by analysis, known as the direct route in the EN Code. In this paper, plastic collapse or gross plastic deformation loads are evaluated for two sample torispherical heads by 2D and 3D FEA based on an elastic-perfectly plastic material model. Small and large deformation effects are considered in the 2D analyses and the effect of geometry and load perturbation are considered in the 3D analysis. The plastic load is determined by applying the ASME twice elastic slope criterion of plastic collapse and an alternative plastic criterion, the Plastic Work Curvature criterion. The formation of the gross plastic deformation mechanism in the models is considered in relation to the elastic–plastic buckling response of the vessels. It is concluded that in both cases, design is limited by formation of an axisymmetric gross plastic deformation in the knuckle of the vessels prior to formation of non-axisymmetric buckling modes.

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“Experimental and numerical studies on the behavior of cylindrical and conical shells with varying thickness along the length subjected to axial compression”, Global Journal of Researches in Engineering, Vol. 10, No. 4, September 2010, pp. 92-
ABSTRACT: The behavior of aluminum cylindrical and conical shells of thickness variation along their lengths subjected to quasi-static axial compression was examined. The study was conducted using experimental and FE simulation approaches. The cylinders had mean radius of 25 mm, while the cones had smaller and larger radii of 15 mm and 35 mm respectively. Their thicknesses were increased linearly from top end to bottom end with the
thickness ratio (TR) of 0.0, 0.1 and 0.2. The mean thicknesses of specimens were 1.0 mm, 1.5 mm and 2.0 mm. The numerical simulations on those experiments were also conducted using the finite element code, ABAQUS. The results from experiment and FEA simulation were compared and good agreement was achieved. It was found that the energy absorption capacity of cylinder with thickness varying along the length is increasing as the value of TR increases. In contrast, the cone with thickness varying along the length seems to lose its energy absorption capacity as the value of TR increases. In addition, their deformation histories and load-displacement curves were presented and discussed.

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Maria Esslinger and Bodo Geier (Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Braunschweig, Germany), “Calculated postbuckling loads as lower limits for the buckling loads of thin-walled circular cylinders”, Chapter in Buckling of Structures, part of the series International Union of Theoretical and Applied Mechanics, Edited by Bernard Budiansky, Springer, 1976, pp 274-290

ABSTRACT: It is well known that the experimental buckling loads of thin-walled circular cylinders are lower than the bifurcation loads, since thin-walled cylinders are sensitive to initial imperfections. This imperfection sensitivity depends on the radius, the wall thickness and the length of the cylinders as well as on the shape and arrangement of stiffeners. Therefore in searching for the most effective stiffening, it is not sufficient to compare bifurcation loads; one has to take into account the imperfection sensitivity too.

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Maria Esslinger and Gert Poblotzki, “Two different methods for shell buckling calculation in the elastic-plastic region”, Forschungsbericht - Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt. 1988 (from ProQuest-CSA)

ABSTRACT: A shell buckling calculation procedure that transfers the criterion for loading or unloading from the buckling, rather than from the prebuckling mode of the ideal shell, is presented. Application is demonstrated by numerical examples.


(no abstract given)

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“Flat bar steel ring stiffeners on cylinders subjected to external pressure”, Thin-Walled Structures, Vol. 15, No.4, 1993, pp. 249-269, doi:10.1016/0263-8231(93)90032-6

ABSTRACT: It is known that plates are not sensitive to initial imperfections, since, after buckling, their load
The deformation curve is upwards. Flat rings on circular cylinders are circular ring plates. Therefore, their postbuckling behavior is the same. This is proved theoretically in this paper. Hence, it follows that the slenderness of flat rings is not restricted by stability considerations, in contrast to the ECCS and BS 5500 recommendations.


Table of Contents:
Comportement en Post-Flambement de Panneaux en Materiau Composite Carbone (Postbuckling Behaviour of Panels made from Carbon Fibre Composite Material), J. Locatelli, C. Czekajski, J.C. Sourisseau, Aérospatiale .......................................................... 1

The Compression Buckling Behaviour of Cylindrically Curved Unstiffened CFRP Panels Including the Effect of Imperfections. M. B. Snell (RAE), N. T. Morley (BAe) ................................................................. 35

Flambage et post-flambage des panneaux composites galbés.-Comparaison calculs-essais (Buckling and Post Buckling of Curved Composite Panels.- Comparison of Computations and Test Results), C. Cornuault, Dassault ................................................................. 49

Computational Results for Cylindrically Curved Compression Panels as Obtained with the Computer Program COMBUC, J. H. van der Sloat, Fokker ................................................................................................................ 111

A Note on "Buckling" of Unbalanced Composite Plates, J. H. van der Sloat, Fokker ................................................................................................................ 123

Analytical Investigation of the Buckling Behaviour of Laminated Anisotropic Plates and Shells, B. Geier, K. Rohwer. DLR .................................................................................................................. 131

Postbuckling of Thin Walled Composite Structures. Design, Analysis and Experimental Verification J.F.M. Wiggenraad, NLR ... 159

Quick Design of Stiffened CFRP Panels, H. Fluh. MBB .................................................................................................................. 167

Theoretical Evaluation of the Out-of-Plane Forces Exhibited by CFC-Structures Loaded into the Post Buckled Region, R. W. West, M. Major. BAe .................................................................................................................. 183

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ABSTRACT: With the aid of calculated examples it is demonstrated how computer programs can be verified by checking whether the prebuckling deflections and deformations as well as the buckling modes fit together convincingly. The examples discussed are a long cylinder loaded by pure axial load and pure bending and a short cylinder with a shrunk ring.

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ABSTRACT: The buckling loads of laminated cylinders can strongly depend on the position of the differently oriented layers within the shell. This paper deals with two different laminated orthotropic cylinders with opposite stacking sequence of the laminate layers. Cylinders of this construction had been thoroughly tested within a BRITE EURAM project. Analytical and semi-analytical methods have been used to predict the buckling loads, and the results are reported in this paper as well as test results for comparison. An explanation of the striking influence of stacking sequence is given. With some more examples the findings are verified. It is suggested that the presented results can be used for benchmarking purpose.


ABSTRACT: The analysis of an axially compressed circular tube deforming in progressive axisymmetric folds carried out by Wierzbicki et al. [(1992) Int. J. Solids Structures Vol. 29, 3269–3288] assumes an eccentricity factor relating the inward and outward parts of the folds. This factor was arbitrary and was not derived from the analysis. The present work re-examines the problem and produces a value for the eccentricity factor which conforms with the experimental findings. Values of the critical angles required for the formation of the inward and outward folds obtained from the analysis were substantiated by those obtained from experiments.

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ABSTRACT: The energy absorption characteristics of corrugated tubes are experimentally studied. The corrugations are introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube generator. The aims are to improve the uniformity of the load—displacement behaviour of axially crushed tubes, predict and control the mode of collapse in each corrugation in order to optimize the energy absorption capacity of the tube. Effect of heat treatment and foam filling of these tubes are also considered. Metal tubes are mostly used throughout this study, however, PVC tubes are also considered for comparison purposes. The experimental results of crushing of the corrugated tubes make these tubes a good candidate for a controllable energy absorption element.

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ABSTRACT: Motivated by complex multi-fluid geometries currently being explored in fibre-device manufacturing, we study capillary instabilities in concentric cylindrical flows of N fluids with arbitrary viscosities, thicknesses, densities, and surface tensions in both the Stokes regime and for the full Navier–Stokes problem. Generalizing previous work by Tomotika (N = 2), Stone & Brenner (N = 3, equal viscosities) and others, we present a full linear stability analysis of the growth modes and rates, reducing the system to a linear generalized eigenproblem in the Stokes case. Furthermore, we demonstrate by Plateau-style geometrical arguments that only axisymmetric instabilities need be considered. We show that the N = 3 case is already sufficient to obtain several interesting phenomena: limiting cases of thin shells or low shell viscosity that reduce to N = 2 problems, and a system with competing breakup processes at very different length scales. The latter is demonstrated with full 3-dimensional Stokes-flow simulations. Many N > 3 cases remain to be explored, and as a first step we discuss two illustrative N → ∞ cases, an alternating-layer structure and a geometry with a continuously varying viscosity.


ABSTRACT: We use a fully coupled, three-dimensional, finite-element method to study the evolution of the surface-tension-driven instabilities of a liquid layer that lines an elastic tube, a simple model for pulmonary airway closure. The equations of large-displacement shell theory are used to describe the deformations of the tube and are coupled to the Navier–Stokes equations, describing the motion of the liquid. The liquid layer is susceptible to a capillary instability, whereby an initially uniform layer can develop a series of axisymmetric peaks and troughs, analogous to the classical instability that causes liquid jets to break up into droplets. For sufficiently high values of the liquid's surface tension, relative to the bending stiffness of the tube, the additional compressive load induced by the development of the axisymmetric instability can induce non-axisymmetric
buckling of the tube wall. Once the tube has buckled, a strong destabilizing feedback between the fluid and solid mechanics leads to an extremely rapid further collapse and occlusion of the gas-conveying core of the tube by the liquid. We find that such occlusion is possible even when the volume of the liquid is too small to form an occluding liquid bridge in the axisymmetric tube.

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- Plateau J, vol. 2 1873 Paris:Gauthier-Villars
ABSTRACT: Dynamic buckling of antisymmetrically laminated angle-ply rectangular plates due to axial loads proportional to time and axial step loads is considered. The nonlinear response of initially imperfect plates is determined from the numerical solution of the governing differential equation. In the case of the step loading this equation can be solved analytically. In the particular case of a perfect plate the solution of the linear problem yields the condition of dynamic buckling. Another problem considered in the paper is the behavior of an imperfect plate initially loaded by axial static stresses. The static response is determined first and the motion of the plate is superimposed on the static displacements in the second phase of the solution.

References listed at the end of the paper:
(cannot cut and paste them)

ABSTRACT: Divergence instability of a simply supported orthotropic composite shell reinforced in both axial and circumferential directions is considered. The shell is subject to an axial static load and to the action of an external supersonic gas flow in the direction parallel to the shell axis. Two variants of the solution considered in the paper include discrete widely spaced stiffeners and closely spaced stiffeners; the latter case can be treated using a smeared stiffeners technique.

ABSTRACT: In this paper, motions of composite cylindrical panels in a gas flow are considered. It is shown that the main factor contributing to large static deformations is a nonuniform aerodynamic heating, while aerodynamic pressure is of secondary importance, at high Mach number. It was found that the main factor
resulting in the increase of deformations is the nonuniform distribution of temperature along the curved edges. Deformations decrease rapidly in shallower panels. Nonuniformly heated panels become unstable at the values of axial compressive load, which are much smaller than the static buckling value calculated in the absence of heating. The condition of panel flutter of nonuniformly heated composite panels in a gas flow is also formulated.


ABSTRACT: This paper deals with some questions arising in dealing with engineering eigenvalue problems. The emphasis is placed on the coincident or closely spaced natural frequencies from the standpoint of the normal mode method applied for determining the structural response; it concentrates on the degree of refinement in the determination theories which should be introduced, in order to obtain accurate predictions of the response of structures subjected to high-frequency excitation. Nonsymmetric eigenvalue problems arising in composite plates are considered. Some pertinent questions associated with the eigenvalue problems arising for small vibrations superimposed on the basic nonlinear state, as well as those for nonprobabilistic treatment of uncertainty are posed. Special considerations associated with interval arithmetic and convex models of uncertainty are elucidated. Each section is concluded with open problems, awaiting for their resolution by the combined efforts of mathematicians and engineers.

References listed at the end of the paper:


ABSTRACT: Bending of shear-deformable orthotropic cylindrical shells, reinforced by ring stiffeners, manufactured from a cylindrically-orthotropic material, in a steady-state thermal field, is considered. The difference between the temperatures outside and inside the shell remains constant. The material properties of the shell and the stiffeners can depend on the temperature. Closed-form solutions are obtained in a number of important particular cases. Numerical examples illustrate that even moderate differences between the external and internal temperatures can result in significant stresses and deformations of the shell.

Birman V and Simitses GJ. Dynamic stability of long cylindrical sandwich shells and panels subject to

ABSTRACT: The paper presents an analysis of dynamic stability of long cylindrical sandwich shells and shallow panels subject to a uniform periodic lateral pressure. The solution is obtained using the Sanders shell theory by assumption that the shell or panel remains in the state of plane strain during both steady-state and perturbed motion. The steady-state motion of a shell is axisymmetric, while perturbed vibrations superimposed on the steady response are asymmetric. The analysis of perturbed motion is reduced to specifying the conditions of stability of the Mathieu equation. Subsequently, the criteria of dynamic stability and the boundaries of the regions of unstable motion in the pressure amplitude–pressure frequency plane are immediately available. A shallow panel subjected to hydrodynamic pressure experiences forced vibrations. However, these vibrations can become unstable. Dynamic stability of such vibrations is investigated through the solution of the linearized equations for perturbed motion. It is shown that these equations can be reduced to a system of Mathieu equations.

References listed at the end of the paper


ABSTRACT: This paper presents a review of the principal developments in functionally graded materials (FGMs) with an emphasis on the recent work published since 2000. Diverse areas relevant to various aspects of theory and applications of FGM are reflected in this paper. They include homogenization of particulate FGM, heat transfer issues, stress, stability and dynamic analyses, testing, manufacturing and design, applications, and fracture. The critical areas where further research is needed for a successful implementation of FGM in design are outlined in the conclusions.
ABSTRACT: The paper presents an analysis of stability and free vibrations of rectangular functionally graded panels reinforced by a system of parallel stringers. The exact solution of the problem is illustrated for large aspect ratio panels with simply supported long edges and arbitrary boundary conditions along the short edges (hereafter the reference to an “exact solution” implies a closed-form solution in the content of the theory of plates). The spacing between the stringers and the cross sections of individual stringers can be arbitrary. In the particular case where identical stringers are equally spaced, the solution is simplified using the smeared stiffeners technique. The optimization problem concerned with the choice of stringers and their spacing in the situations where the buckling loads or fundamental frequencies are prescribed is also considered. The closed-form solution of the optimization problem is shown in the case of blade stringers.

ABSTRACT: The chapter outlines the foundations of the theory of plates and shells. The general approach employed in all versions of the relevant theories leads to particular cases including the classical (technical) theory of isotropic and composite plates and shells. Examples of solutions of linear bending and buckling problems are illustrated. The effect of large nonlinear deformations on the response of plates and shells is reviewed. The analysis of stiffened plates and shells is discussed, including the method modeling discrete reinforcements and the smeared stiffeners technique applicable to closely spaced identical stringers. It is shown that openings and cut-outs influence the behavior and strength of plates and shells, both locally through the stress concentration as well as globally through their effect on the stiffness. The concepts of composite and sandwich plates and shells are elucidated, providing insight on the peculiarities of mechanics of these structures.

ABSTRACT: The torsional buckling of a plastically deforming cruciform column under compressive load is investigated. The problem is solved analytically based on the von Kármán shallow shell theory and the virtual work principle. Solutions found in the literature are extended for path-dependent incremental behaviour as typically found in the presence of the vertex effect that is present in metallic polycrystals. At the critical load for buckling the direction of straining changes by an additional shear component. It is shown that the incremental elastic–plastic moduli are spatially nonuniform for such situations, contrary to the classical J2 flow and deformation theories. The critical shear modulus that governs the buckling equation is obtained as a weighted
average of the incremental elastic–plastic moduli over the cross-section of the cruciform. Using a plasticity model proposed by the authors, that includes the vertex effect, the buckling-critical load is computed for an aluminium column both with the analytical model and a FEM-based eigenvalue buckling analysis. The stable post-buckling path is determined by the energy criterion of path-stability. A comparison with the experimentally obtained classical results by Gerard and Becker (1957) shows good agreement without relying on artificial imperfections as necessary in the classical J2 flow theory.

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Schurig, M., Bertram, A., submitted for publication. A material model for the vertex effect in polycrystal plasticity based on a modified plastic potential. IJSS, submitted for publication.


ABSTRACT: A method is proposed for the determination of plastic bifurcation buckling load of metal matrix composite plates. The metallic matrix behavior is described by an elastic-viscoplastic constitutive law, while the fibers are assumed to be either elastic or elastic-viscoplastic material. The approach is based on the load level and history dependent instantaneous effective properties of the inelastic plate, which are established by a micromechanical analysis. An incremental procedure is developed in which a buckling condition has to be established and its fulfilment must be checked at each increment. The method is applied for the prediction of the plastic buckling of boron/aluminum composite plates in various situations, by employing the classical and higher order shear deformation plate theories.


ABSTRACT: The postbuckling behavior of viscoelastic composite laminated plates is considered. The viscoelastic behavior of the single ply is characterized by a micro-mechanical theory, in conjunction with the properties of the fibers and viscoelastic resin matrix. Higher-order shear-deformation theory is employed to study the post-buckling phenomenon. The resulting viscoelastic effects are shown, and comparison with lower order theories is presented.


ABSTRACT: The plastic bifurcation buckling loads of ARALL (aramid aluminum laminate) plates are predicted. The plastic behavior of the plate is caused by the significant plasticity effects of the aluminum strips. The critical load level at which the ARALL plate loses its stability is determined from the material properties of the elastoplastic aluminum alloy strips and the elastic unidirectional aramid/epoxy composite layers, in conjunction with their geometric characteristics.
Esther Feldman and Jacob Aboudi (Department of Solid Mechanics, Materials and Structures, Fleishman Faculty of Engineering, Tel Aviv University, Ramat Aviv 69978, Israel), “Postbuckling analysis and imperfection sensitivity of viscoplastic plates and cylindrical panels”, Thin-Walled Structures, Vol. 17, No. 4, 1993, pp. 273-290, doi:10.1016/0263-8231(93)90007-W

ABSTRACT: The postbuckling behaviour of elastic-viscoplastic rectangular plates and cylindrical panels is analysed. The rate-dependent inelastic material behaviour is modelled by a unified theory of viscoplasticity. Initial geometrical imperfections of the inelastic structure are included and their effect on the postbuckling behaviour is investigated. The analysis relies on an incremental approach in which at each loading increment the Galerkin method is employed. Results are presented for a plate made of an elastic-viscoplastic material and subjected to a uniaxial compression, applied at a constant strain rate on both edges. The results display the applied loading against the out-of-plane displacement, and the effects of loading rate and imperfection sensitivity. It turns out that there is a significant difference between the postbuckling behaviour of a plate in the two cases: (1) when the bifurcation buckling of a geometrically perfect plate occurs in the elastic region, and (2) when it occurs after a plastic flow takes place.


ABSTRACT: The postbuckling behaviour of metal matrix composite (MMC) laminated cylindrical panels under quasistatic in-plane loading is investigated. A micro-to-macro analysis is used to obtain the response of the composite structure. The micromechanical analysis allows us to establish the overall instantaneous elastic-viscoplastic behaviour of the MMC composite at each load increment. The macromechanical analysis provides the response of the geometrically imperfect cylindrical panel to the applied external loading. Results are presented for unidirectional and antisymmetric angle-ply SiC/Ti composite panels, subjected to uniaxial compressive loadings. The effects of the panel curvature, initial imperfections and rate of loading on the postbuckling response are illustrated. Comparisons with the response of the corresponding perfectly elastic panels are shown.


ABSTRACT: A micromechanical approach is combined with a structural analysis in order to investigate the time-dependent response and dynamic buckling of structures composed of nonlinear polymeric matrices (e.g. epoxy) reinforced by elastic fibres. The composite structures considered herein are either plates or cylindrical shells both of which are under cylindrical bending conditions. Results are given which illustrate the effect of nonlinear behaviour on the dynamic response of the composite structure.

ABSTRACT: Deformation theories are known to give solutions similar to flow theory for proportional loading where the components of the stress tensor at all points grow proportionally. However, if buckling is involved, deformation theories generally give better agreement with experiments. In this study, a deformation theory has been successfully employed for the elastic-plastic buckling analysis of plates under nonproportional external loading and nonproportional stresses. Loading, unloading, and reloading situations have been conveniently considered via conducting multistage analysis after casting the constitutive relations of a deformation theory in an incremental form. In order to achieve an economical solution the modified Newton-Raphson method has been generally used when the structure is loading (or reloading) everywhere while the initial stress method has been employed if unloading due to changes in the external loads takes place. The procedure has been applied in several cases and displayed accuracy and reliability. Three comparisons with experiments are shown to demonstrate the applicability of the integrated procedure.


ABSTRACT: Optimization of the axial buckling load of composite, cylindrical shells through a judicious choice of laminate configuration is often associated with increased imperfection sensitivity. Current approaches of combining postbuckling theory with an optimization program demand highly sophisticated analytical and computational methods, yet are insufficient to provide a rational theme that can be used to derive general design guidelines. The present paper is an attempt to explore the subject matter via a different avenue, such that various nonlinear effects may be understood in physical terms which require relatively little in the way of advanced mathematics and computation. The paper proposes to study the problem using a simple, but intuitively appealing, reduced stiffness analysis of cylinder buckling which recognizes the physical characteristics present in advanced postbuckling and uses them in an equivalent linear, eigenvalue analysis. This investigation highlights the specific relationship between laminate stiffness parameters, efficiency of buckling resistance and imperfection sensitivity in postbuckling deformation. It is observed that the criteria for optimality and reduced imperfection sensitivity are often opposed to each other. The reduced buckling load appears to be a useful indicator for evaluating qualitatively the relative imperfection sensitivity of various nearly optimal laminated shell designs which would be of great interest to designers. Another interesting feature is the analytical study in terms of bounded generic orthotropic constants which furnishes a general theme on the issue. A comprehensive discussion on the theoretical foundation of the reduced stiffness approach and other similar approximate methods is provided. It has been shown throughout this paper that the proposed physical approach successfully and consistently explains most of the observations reported in the literature which were based on nonlinear postbuckling analyses.


ABSTRACT: In the literature, the linear buckling load of rectangular plate elements is maximized by optimizing fibre orientation and thickness in a preselected lamination sequence. The paper considers the effects of laminate optimization on the postbuckling behaviour of biaxially compressed, specially orthotropic laminates and suggests modifications of the lamination parameters to improve postbuckling performance. Postbuckling studies, in general, involve the formal derivation of nonlinear equilibrium paths using, say, the methods of
Galerkin, finite element, etc. In contrast, a simpler but effective method is proposed whereby the initial postbuckling stiffness, defined by the slope of the postbuckling load-end shortening relation at bifurcation, is adopted as a qualitative index characterizing postcritical behaviour. An explicit solution is described for simply supported plates. It is established that the postbuckling stiffness and linear buckling load are governed by completely different functions: the former depends exclusively on inplane (membrane) stiffness while the latter is a function of bending stiffness only. It has been suggested that unfavourable postbuckling performance usually follows optimization of the buckling load. A detailed parametric study substantiates this proposition by illustrating that laminates, optimal in linear buckling, do exhibit inferior postbuckling characteristics due to reduced stiffness. Improved laminate designs are suggested that exhibit superior performance in both pre- and postbuckling.


ABSTRACT: In this paper, a description of how the curvilinear finite difference (CFD) energy method can be applied to the geometrically nonlinear analysis of general thin shells of arbitrary geometry will be given. The main features of the present finite difference formulation are its ability to implement the most general nonlinear strain-displacement relationship that is valid for any arbitrarily large finite deformation and out-of-plane rotation, its ability to model any kind of shell geometry and its capability to work on irregular computational meshes. A series of numerical examples are also included to verify the computer programming work developed here in this work.


ABSTRACT: Damage to the thin-walled cylindrical shells is addressed in this dissertation with reference to the possible collision of supply ships with the main legs of fixed or floating types of offshore platforms. Towards this end experimental and analytical investigation are carried out to give insight to the mechanics of the cylinder to withstand the impact force induced during the collision. The subsequent residual load carrying strength and the fatigue integrity of the damaged shell when subjected to external loading are also considered. The research investigation presented is divided into three phases. Firstly, localized damage are introduced to some of the test models, mostly through a knife edge indenter representing an idealized side-edge impact of a ship. A theoretical formulation based on a rigid plastic mechanism approach has been developed which provide a close correlation with the observed relationship between the residual dent depth and the corresponding impact load, from the tests on the unstiffened models. The application of this method to ring-stiffened models is also examined. Numerical simulation of the denting test, by using finite element method, are also carried out by using a commercial finite element programme.

Some of the dented models are subsequently tested under combinations of axial loading and external pressure for the investigation of the collapse behavior of the damaged shells. Undamaged shells are also tested in order to complement the experimental observations by providing a basis of comparison for the damage induced strength reduction. Numerical analysis of the intact model are performed with the incorporation of the initial imperfection in the test models. For the damaged shells, the effect of residual stresses due to denting is also examined. Together with the experimental observations, the effect of the localized damage in the load carrying capacity of cylindrical shells has been examined.

The final phase of the investigation examines the likelihood of fatigue cracking when the damaged cylinders are...
subjected to cyclic loading. Experiments are carried out on damaged shells, retrieved from the denting tests. Based on the correlation of strain-gauge data obtained during the test and the results from numerical analysis, the major factors responsible for the fatigue crackings on the test models have been identified. 157 References are listed at the end of the dissertation. Unfortunately, these cannot be cut and pasted.


ABSTRACT: The geometric nonlinear buckling problem of a thin doubly curved shallow shell with all edges hinged is complicated and difficult to obtain an exact analytical solution. Thus, differential equations are solved incrementally by using the differential quadrature method in this paper. Detailed formulations are worked out. Convergence study is performed. Several examples with various material properties, curvatures and dimensions are investigated. Comparisons are made with existing semi-analytical data or finite element data. It is shown that the critical loads are lower than the data obtained by either so-called Adjacent Equilibrium Method or Partitioned Solution Method. The possible reasons to cause the difference are discussed.


ABSTRACT: An analytical study of nonlinear flexural vibrations of cylindrical shells to random excitation is presented. Donnell's thin-shell theory is used to develop the governing equations of motion. Thermal effects for a uniform temperature rise through the shell thickness are included in the formulation. A Monte Carlo simulation technique of stationary random processes, multi-mode Galerkin-like approach and numerical integration procedures are used to develop nonlinear response solutions of simply-supported cylindrical shells. Numerical results include time domain response histories, root-mean-square values and histograms of probability density. Comparison of Monte Carlo results is made to those obtained by statistical linearization and the Fokker–Planck equation.

References listed at the end of the paper:
The paper presents the creep-stability analysis of viscoelastic cylindrical shells under axial compression. The mechanical properties of the material are described by the constitutive equations of the linear viscoelastic theory in terms of convolution integral operators. The approximate analytical solution to the problem is obtained by means of a modification of the quasi-elastic method. As a result, the instability condition for the shell is formulated. It is shown that for viscoelastic materials with limited creep, there is a safe load limit below which the structure is asymptotically stable. Any load above the safe load limit leads to buckling at the
corresponding critical time.


ABSTRACT: Stresses and deformations in composite cylindrical tubes as a result of combined loading (internal and external pressure, axial load, applied torque) and a temperature gradient through the wall thickness are studied. The composite tubes studied are, in general, long thick-walled cylinders made of arbitrarily oriented— with respect to the tube axis—orthotropic plies. A displacement-based linear elasticity solution is used in the analysis. Classical Laminated Plate Theory (CLPT), which assumes the composite laminate to be in a state of plane stress, does not predict any stresses in the thickness direction; however, in thick-walled tubes, through-the-thickness stresses may not always be negligible. The elasticity solution has shown that, under internal pressure only, in angle-ply and single-ply tubes, the resulting radial stress is virtually independent of the ply fiber orientation. In cross-ply tubes, these stresses show significant differences. In the case of a uniform temperature change only, the nonlinear distribution of the radial stress changes substantially depending on the ply fiber orientation. Another difference between the CLPT and Elasticity Theory for the analysis of cylindrical tubes is found in predicting the maximum twist rate of the cylinder with unbalanced wall laminate. Elasticity Theory has shown that for thick-walled, single-ply cylinders subjected to a uniform temperature change, the maximum twist rate occurs at the ply orientation angle greater than 45°, depending on the wall thickness and the mean radius of the cylinder, as opposed to 45° as predicted by the CLPT. The twist rate in thin-walled tubes subjected to internal pressure only is found to be much greater than in thick-walled tubes, due to the presence of large radial and hoop stresses in thick walls. In multi-layer cylinders, jumps in hoop and axial stresses have been observed at ply interfaces. Their magnitudes are shown to depend on the angles of fiber orientation.

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ABSTRACT: The literature pertaining to the collapse of thick wall pipes in deep water is evaluated. The subject matter is categorized by type of loading: (1) pure external pressure, (2) pressure plus tension, and (3) pressure plus bending. The study focuses on the buckling or yield type of failure rather than fracture; and with well casing as well as conventional high strength line pipe. The failure theories are discussed and summarized; and the data and theories are compared. It is found that elastic stability should be based on mean diameter. Although not sensitive to elastic imperfections, plasticity effects especially prevalent in thick wall pipe are recognized as a cause of substantial imperfection sensitivity with respect to initial ovality. The abundance of data for oil well casing is found to contrast sharply with the lack of data for line pipe. Tension plus pressure appears to be amenable to a tangent modulus approach. Bending plus pressure is found to be the least well documented both in terms of theory and testing.
ABSTRACT: Finite element analyses of the collapse behaviour for long, relatively thick-walled metal tubes are presented under combined external pressure, tension and bending loads. The effects of initial ovality, residual stress, strain-hardening, yield anisotropy and load paths have been accounted for in the analyses. The analysis procedure has been validated using experimental results. Collapse envelopes for thick tubes under combined external pressure, tension and bending loads are presented in the form of pressure-moment-tension interaction, pressure-tension-curvature interaction and pressure-axial strain-curvature interaction. Factors affecting collapse envelopes are identified by means of parametric studies. Interaction equations to predict collapse envelopes are proposed based on the present finite element analyses considering major factors. The interaction equations are verified against finite element results and good agreement has been achieved for tubes with various geometric and material parameters and initial imperfections.

PARTIAL INTRODUCTION: This study originated from a specific problem that arose in conjunction with the IRIS (International Reactor Innovative and Secure) project (Carelli et al., 2004; Carelli, 2009). IRIS adopts an integrated primary system reactor (IPSR) configuration with all the primary loop components of a classical Pressurized Water Reactor (PWR) contained inside the vessel (Fig. 1). Among the reactor core internals are the steam generator (SG) units (Cinotti et al., 2002) with the primary fluid flowing outside the tube bundles and subjecting them to significant external pressure. In this situation buckling affects the tube collapse modality and codes become extremely conservative, to the point that up to five years ago design procedures based on the ASME Boiler & Pressure Vessel code (Section III) required an external diameter to thickness ratio ($D/t$) less than 8.5, leading to an increased thermal resistance in the heat exchange process between primary and secondary fluids, with detrimental consequences on the dimensioning of the heat transfer surface. A reduction in the tube thickness would allow the reduction of the overall heat transfer surface needed to exchange the same amount of power, with consequent saving on tube lengths and/or number of tubes. On the other hand, if the design of the steam generator units is not modified, an increase in the exchanged thermal power and a consequent up rating of the reactor can be obtained. Besides IRIS, other recent proposals for next generation power plants based on PWR technology consider an IPSR design (Ingersoll, 2009; Karahan, 2010; Ninokata, 2006). Such integrated design is particularly suitable for small sized units, i.e., reactors with a power less than 300 MWe following the IAEA’s definition (IAEA, 2007). A significant number of small sized PWR IPSRs is currently under development (e.g., RITM-200, ABV, CAREM, SMART, MRX, NHR-200, Westinghouse SMR, mPower, NuScale, see http://www.world-nuclear.org/info/inf33.html). Packing all the PWR primary components into the reactor pressure vessel (RPV) (Fig. 2) offers several advantages (Ingersoll, 2009): (i) all large coolant pipes are eliminated (only small feed water and steam outlet pipes penetrate the vessel wall); (ii) the total inventory of primary coolant is much larger than for an external loop PWR (this feature increases the heat capacity and thermal inertia of the system and hence yields a much slower response to core heat-up transients); (iii) typically the heat exchangers are placed above the core creating a relatively tall system that facilitates more effective natural circulation of the primary coolant in the case of a coolant pump failure; (iv) the vessel accommodates a relatively large pressurizer volume that provides better control . . .
References listed at the end of the paper:


Arve Bjorset (Department of Structural Engineering, Faculty of Civil and Environmental Engineering, The Norwegian University of Science and Technology, N-7491 Trondheim, Norway), “Capacity assessment of titanium pipes subjected to bending and external pressure”, (no publisher given), March 2000 (dissertation?) ABSTRACT: Exploration for oil and gas is moving towards deeper waters. Steel has been the most common riser material. Related to deep water concepts titanium has become an alternative to steel for these applications. Several codes exist today for predicting collapse loads for marine pipes. However, the capacity formulas are developed for steel. If the formulas are applied directly to titanium several parameter uncertainties will be
unknown. Ideally, extensive model testing of titanium pipes is required. This thesis discusses and investigates utilisation of experimental material test data and a supplementary numerical approach based on finite element analysis. The relationship between material model parameters as input to the analysis and the collapse capacity is investigated by performing a series of nonlinear FEM analyses. Statistical models for the input material model parameters are established based on tests on small specimens cut from titanium pipes. These models are subsequently combined with results from the FEM analyses by application of response surface methods. As output from the analysis, the probability distributions of the pipe capacity with respect to local buckling/collapse are obtained. Finally, the data from the nonlinear finite element analyses are compared to a relevant design code. Suggestions for a possible basis for design formulas to check for the local collapse capacity of deep water titanium risers are provided.

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ABSTRACT: It has been observed in experiments that the localization of plastic buckling patterns has a large influence on the strength deterioration of steel structures under cyclic loading. In this study the theoretical aspects of this cyclic localization phenomenon were investigated. The localization behavior is caused by a plastic bifurcation on the decreasing equilibrium path subsequent to the maximum load point. Thus, we first show a precise numerical method based on the finite element method for analysis of the plastic bifurcation. Then, using this method, we examine the localization behavior of cylindrical shells and plates under cyclic loading. Specifically, we investigate the effect of structural parameters and that of constitutive models on the strength deterioration.

ABSTRACT: The study of the seismic response of broad, anchored, cylindrical liquid-storage tanks has large practical significance because these structures are used in many critical engineering applications (petroleum industries, nuclear power stations, municipal water supply systems, wine industries ...). The performance of such tanks during recent earthquakes and in experiments has indicated that the existing codes for designing tanks are in need of improvement. Due to the complexity of the dynamic analysis, several researchers have used a static approach to predict the dynamic buckling load. It has been demonstrated that such a static analysis yields useful information. On the basis of this finding, an approximate analytical method is developed to study the buckling of broad, anchored, cylindrical liquid-storage tanks subjected to horizontal ground motion. The solution is based on the linearized Donnell's shell stability equations and Galerkin's approach. The smallest buckling load (or the critical load factor) is calculated using the inverse iteration method. Theoretical results are then determined for two cases of broad tanks presented as examples. The validity of the findings of the present work is checked through comparison with results obtained by the numerical Finite Element Method (FEM).

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ABSTRACT: Stress analysis of a water storage structure has been carried out for static and seismic loading. Based on the stress analyses results, assessment of most likely failure modes for the structure caused by seismic event has been carried out. An attempt has been made to quantify the initial leakage rate and average emptying time for the structure during seismic event after evaluating the various crack parameters, viz., crack-width and crack-spacing at the locations of interest. Finally, the seismic fragility of the structure is developed as families of conditional probability curves plotted against peak ground acceleration (PGA) parameter at the location of interest considering the randomness and uncertainty associated with various parameters that could affect the seismic structural response.


ABSTRACT: If the parameter epsiv2, which measures the thickness-to-rise of the shell, is small, the axisymmetric polar dimpling of shallow spherical shell due to quadratic pressure distribution is dynamic instability, i.e., a small perturbation can change it to an asymmetric polar dimple mode. In two cases, the problem can be reduced to an eigenvalue problem Twn=cn wn, where T can approximately be reduced to a Sturm-Liouville operator if epsiv2Lt1. The existence of at least one real eigenvalue of T, which means that the axisymmetric polar dimpling is dynamically unstable, is proved by spectral theorem or Hilbert theorem. Furthermore, an eigenfunction, which represents one of the asymmetric modes of the unstable dimple shell, belonging to an eigenvalue of T is found.

References listed at the end of the paper:

ABSTRACT: Stiffened composite panels are often used as structural components in aircraft in order to avoid buckling. It is well known that stacking sequence optimizations are indispensable for laminated composite structures. Stiffened composite panels usually have more than two stacking sequences because they consist of a panel skin laminate and stiffener laminates. This means that the stacking sequences need to be jointly optimized to achieve structural optimization of the stiffened composite panel. The authors have proposed a new stacking sequence optimization method, called the fractal branch and bound method, for optimizing a single laminate. In the present study, the fractal branch and bound method is extended to optimizing multiple stacking sequences. The extended method is applied for obtaining two optimal stacking sequences for the maximization of the buckling load of a hat-stiffened composite panel. The improved method successfully provides two optimal stacking sequences determined in a short period of time.

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ABSTRACT: The fractal branch-and-bound method has been developed by the authors for stacking-sequence optimizations of symmetric and balanced composite laminates comprise of two in-plane and two out-of-plane lamination parameters. Cylindrical structures such as tanks or pipes, however, are usually made from balanced laminates. In the present study, therefore, we focus on the stacking-sequence optimizations of unsymmetrical composite laminates. In the unsymmetrical laminates, nine lamination parameters including three coupling-lamination parameters exist, and its feasible design region of fractal pattern is unrevealed. The paper clarifies the feasible region in which the in-plane, out-of-plane and coupling lamination parameters create fractal patterns of tetrahedrons or tetradecahedrons. Using the fractal patterns of lamination parameters, the improved fractal branch-and-bound method is proposed for unsymmetrical laminates including coupling lamination.
parameters. This new method is applied to stacking-sequence optimization problems of maximization of buckling load of cylindrical laminated shells. As a result, the method is successfully applied, and a practical optimal stacking sequence is obtained with low computational cost.


ABSTRACT: Laminated carbon fiber reinforced polymer (CFRP) composites have widespread applications in aerospace structures, and thus optimization of the stacking sequences in these composites is indispensable. Here, a fractal branch and bound method (FBB) is proposed for optimizing the stacking sequences. This method requires only low computational costs, and an optimal result can be obtained rapidly by means of the deterministic process. For practical stacking sequence optimizations, more than two laminates have to be optimized, because a practical aerospace structural component usually comprises a panel and stiffeners made from composite laminates. Since the stacking sequences of the skin panel and stiffeners affect the buckling load of the stiffened panel, the optimization of both laminates must be performed simultaneously. In the present study, a new method to implement a strength constraint for the FBB method is proposed for the simultaneous optimization of more than two laminates (such as a panel and stiffeners). Moreover, a quadratic polynomial objective function, which includes lamination parameter variables of the two laminates: the stiffeners and the panel, is adopted. The strength constraint is implemented by means of a response surface. The new method is applied to the buckling load maximization of a blade-stiffened composite panel, in which the strength constraint is demonstrated as a feasibility study. The method successfully obtained optimal stacking sequences with the strength constraint at low computational cost.


ABSTRACT: The optimization method for composite structural components described herein uses modified efficient global optimization with a multi-objective genetic algorithm and a kriging response surface. For efficient global optimization using kriging, the kriging response surface is used as a representative of the function value. The stochastic distribution of the kriging is used to improve the estimation error of the kriging surrogate model. Using efficient global optimization, a hat-stiffened composite panel was optimized to reduce the weight with the buckling load constraint. The expected improvement was used as a single objective function of a particle swarm optimization. Nevertheless, it is difficult to obtain a feasible solution that satisfies buckling load constraints with the progress of optimization. Using a multi-objective genetic algorithm, we obtain the feasible optimal structure satisfying the constraints. The expected improvement objective function is divided into two objective functions: weight reduction and the uncertainty of satisfaction of the buckling load constraint. Kriging approximation, which is improved with the selected Pareto optimal frontier, reduces the computational cost. Also, a genetic algorithm is used to optimize the stiffened panel configuration. The fractal branch-and-bound method is used for stacking sequence optimizations. This method obtained a feasible optimal structure at a low computational cost.

References listed at the end of the paper::


ABSTRACT: For cylindrical shell, because of its structure characteristic (i.e. long and thin-walled), it has low stiffness, bad fabrication procedure. And it’s very easy to cause vibration in the cutting process, especially the type of regenerative vibration. So, it’s vital for the surface quality of work-piece and cutting stability to select cutting parameter reasonably. The paper proposed a dynamic optimization method, which aimed at maximization of material removal rate. This method could guarantee the maximum material removal rate under the condition of cutting stability based on Particle Swarm Algorithm (PSA). In the end, it verified the optimization results by the experiments.


ABSTRACT: This study focuses on the improvement of the axial buckling capacity of elliptical composite cylinders through the use of a circumferentially-varying lamination sequence. The concept of varying the lamination sequence around the circumference is considered as a viable approach for off-setting the disadvantages of having the cylinder radius of curvature vary with circumferential position, the source of the reduced buckling capacity when compared to a circular cylinder with the same circumference. Post-buckling collapse behavior and material failure characteristics are also of interest. Two approaches to implementing a circumferential variation of lamination are examined. For the first approach the lamination sequence is varied in a stepwise fashion around the circumference. Specifically, each quadrant of the cylinder circumference is divided into three equal-length regions denoted as the crown, middle, and side regions. Eight different cylinders designs, whereby each region is constructed of either a quasi-isotropic or an axially-stiff laminate of equal thickness, are studied. Results are compared to the baseline case of an elliptical cylinder constructed entirely of a quasi-isotropic laminate. Since the thickness of the quasi-isotropic and axially-stiff laminates are the same, all cylinders weight the same and thus comparisons are meaningful. Improvements upwards of 18% in axial buckling capacity can be achieved with one particular stepwise design. The second approach considers laminations that vary circumferentially in a continuous fashion to mitigate the effects of the continuously-varying radius of curvature. The methodology for determining how to tailor the lamination sequence circumferentially is based on the analytical predictions of a simple buckling analysis for simply-supported circular cylinders. With this approach, axial buckling load improvements upwards of 30% are realized. Of all the cylinders considered, very few do not exhibit material failure upon collapse in the post-buckled state. Of those that do not, there is little, if any, improvement in bucking capacity. Results for the pre-buckling, buckling, post-buckling, and material failure are obtained from the finite-element code ABAQUS using both static and dynamic analyses. Studies with the code demonstrate that the results obtained are converged.

ABSTRACT: The results of optimization of thin-walled sandwich cylindrical shells under the combined loads of axial compression and external pressure are presented. The face layers of the shell are made of aluminium alloy, and the core is made of foamed plastic. The thicknesses of layers are taken as design variables. The weight of the shell is taken as the objective function, and stability condition and strength conditions are taken as the main constraints. The system of stability equations is obtained based on the condition of the minimum of shell potential energy. The problem of general stability is solved in an approximate manner by means of the Bubnov-Galerkin method. The initial imperfections are treated with the knockdown factors. For the the optimization, a method of systematic search is used. The results are discussed.

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ABSTRACT: Thin-walled sandwich structures have become extremely useful because of their high strength-to-mass and stiffness-to-mass ratios. The results of the bicriteria optimization of thin-walled sandwich cylindrical panels under combined loads are presented in this article. Panel mass and panel deformability are two objective functions, where panel deformability is defined with the help of bending rigidity. A set of constraints includes stability and stress conditions, a constraint connected with the importance of applied theoretical models, and technological and constructional requirements. The optimization problem was solved using the Pareto concept of optimality and application of the OPTIKON computer program, which implements elements of an expert system. The OPTIKON program was designed to solve multicriteria optimization problems for non-linear engineering models with discrete and continuous sets of design variables. The results of numerical calculations are presented as tables and diagrams.

ABSTRACT: Evidence is presented and arguments advanced to support the proposition that vibration induced by turbulence in the air stream plays a significant role in initiating the collapse of open-topped oil storage tanks in high winds. On this basis a new criterion is suggested for calculating the size of the circumferential strengthening members of tanks (wind girders). It is pointed out that a new criterion for calculating the wind speed at which tanks fail can only be couched in probabilistic terms and while it is not yet possible to derive such a criterion, the necessary steps and research to do so are discussed. Some interesting results on flow-induced vibrations in circular cylindrical structures are derived and discussed in the light of other relevant research to gain a clearer understanding of such phenomena.

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ABSTRACT: The paper addresses a computational model for elasto-plastic large deformation analysis of thin
shells. The large displacement, large rotation but small strain shell theory is developed from the three dimensional continuum theory via standard assumptions on the displacement field (see for example [1] for details). A model for thin shells is obtained by approximating the terms describing the shell geometry. The resulting strain measures are identical to those that may be obtained by a Cosserat surface approach [2].

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ABSTRACT: The theory of structural stability is both an important and a difficult subject, whose main field of application is found in the design of thin wall lightweight structures and shells. It is unavoidable to employ nonlinear model and to use finite element numerical method in order to obtain the critical load under the action of which the instability of structures will occur. Thus, it becomes very important how to simplify such a nonlinear problem that appears in instability analysis. In this paper, an improvement on previous nonlinear buckling analysis is proposed, in which the emphasis is on the shortcut of calculation of pre-buckling fundamental path. The nonlinear equation used to solve the displacement vector is translated into the linear one to solve the load factor by means of the concept of energy conservation. The detailed procedure to calculate the nonlinear buckling load is presented and two simple examples are also shown as the application of suggested method. The theoretical analysing and numerical examples show that the suggested method is valid for predicting the nonlinear critical loads of structures.

References listed at the end of the paper:

ABSTRACT: A 64-dof isoparametric quadrilateral finite element is presented for the analysis of generally laminated shells of revolution. The effects of shear deformation and rotary inertia are accounted for by using shear deformation theory that employs the parabolic shear strain variation across the thickness. The classical thin shell theory is the special case of shear deformation theory used in the present study. Thus, the thin shell element also can be obtained from the present thick shell element by simply having the displacement parameters (u1 and v1,) associated with the shear rotations as zeros. The numerical results presented illustrate the performance of the element and the effects of shear deformation.


ABSTRACT: The paper presents a theoretical and an experimental analysis of the buckling of 4 thin-walled circular cylinders, which were tested to destruction under uniform external hydrostatic pressure. The mode of failure of the vessels was lobar buckling or shell instability, where the vessel imploded inwards with evenly spaced waves spaced around its circumference. The theoretical analysis adopted the finite element method, where the commercial computer package, namely ANSYS was used. The theoretical work involved the inclusion of both material and geometrical non-linearity, using an incremental step-by-step method. About 50 steps were used per model. Comparison between theory and experiment was good and this appeared to indicate that the method could be applied to full-scale vessels.

References listed at the end of the paper:


ABSTRACT: The article reports on two theoretical investigations and an experimental investigation into the collapse of six circular conical shells under uniform external pressure. Four of the vessels collapsed through plastic non-symmetric bifurcation buckling and one vessel collapsed through plastic axisymmetric buckling. A sixth vessel failed in a mixed mode of plastic non-symmetric bifurcation buckling, combined with plastic axisymmetric buckling. The theoretical and experimental investigations appeared to indicate that there was a link between plastic non-symmetric bifurcation buckling and plastic axisymmetric buckling. The theoretical investigations were via the finite element method and were used to provide a design chart for these vessels.

Carl T.F. Ross and J.R. Sadler (Department of Mechanical and Manufacturing Engineering, University of Portsmouth, Portsmouth, PO1 3DJ, UK), “Inelastic shell instability of thin-walled circular cylinders under

ABSTRACT: The paper describes experimental tests carried out on three ring-stiffened circular conical shells that suffered plastic general instability under uniform external pressure. The cones were carefully machined from EN1A mild steel to a very high degree of precision. The end diameters of the cones, together with their thicknesses were the same, but the size of their ring stiffeners was different for each of the three vessels. In the general instability mode of collapse, the entire ring-shell combination buckles bodily in its flank. The paper also provides three design charts using the results obtained from these three vessels, together with the results obtained for twelve other vessels from other tests. All 15 vessels failed by general instability. One of these design charts was based on conical shell theory and two of the design charts were based on the general instability of ring-stiffened circular cylindrical shells, using Kendrick’s theory, which were made equivalent to ring-stiffened circular conical shells suffering from general instability under uniform external pressure. The design charts allowed the possibility of obtaining plastic knockdown factors, so that the theoretical elastic buckling pressures, for perfect vessels, could be divided by the appropriate plastic knockdown factor, to give the predicted buckling pressure. The theoretical work is based on the solutions of Kendrick, together with the finite element program of Ross, namely RCONEBUR and the commercial finite element package ANSYS. This method can also be used for the design of full-scale vessels.

References listed at the end of the paper:


ABSTRACT: The paper presents new experimental results on the collapse of unstiffened aluminum alloy
circular cylinders suffering elastic and plastic nonsymmetric bifurcation buckling under external hydrostatic pressure. These results complement the results given in two previous Marine Technology papers written by the senior author, which were intended for the structural design of near-perfect unstiffened and ring-stiffened circular conical shells under external hydrostatic pressure. The present paper presents a structural design chart for geometrically imperfect circular cylinders under uniform external pressure, which is more likely to be used than the design charts for the previous near-perfect vessels because it represents the more "usual" case. In addition to an experimental analysis, theoretical analyses were also carried out. An analytical solution by von Mises was used, together with a finite element analysis solution, using the Shell 93 element of the ANSYS computer package. Comparison between ANSYS and the analytical solution was reasonable. A design chart is provided, which looks like it could be quite useful for practical purposes.


ABSTRACT: The paper presents the experimental results for 15 ring-stiffened circular steel conical shells, which failed by non-linear general instability. The results of these investigations were compared with various theoretical analyses, including an ANSYS eigen buckling analysis and another ANSYS analysis; which involved a step-by-step method until collapse; where both material & geometrical nonlinearity were considered. The investigation also involved an analysis using BS5500 (PD 5500), together with the method of Ross of the University of Portsmouth. The ANSYS eigen buckling analysis tended to overestimate the predicted buckling pressures; whereas the ANSYS nonlinear results compared favourably with the experimental results. The PD5500 analysis was very time consuming and tended to grossly underestimate the experimental buckling pressures and in some cases, overestimate them. In contrast to PD5500 & ANSYS, the design charts of Ross of the University of Portsmouth were the easiest of all these methods to use and generally only slightly underestimated the experimental collapse pressures. The ANSYS analyses gave some excellent graphical displays.

References listed at the end of the paper:

Alexander Yu. Evkin (Department of Mathematics, King Fahd University of Petroleum and Minerals, Hail

ABSTRACT: Nonlinear behavior of deep orthotropic spherical shells under inward radial concentrated load is studied. The singular perturbation method is developed and applied to Reissner’s equations describing axially symmetric large deflections of thin shells of revolution. A small parameter proportional to the ratio of shell thickness to the sphere radius is used. The simple asymptotic formulas describing load–deflection diagrams, maximum bending and membrane stresses of the structure are derived. The influence of boundary conditions on the behavior of the shell by large deflections is considered. Obtained asymptotic solution is in close agreement with the experimental and numerical results and has the same accuracy (in the asymptotic meaning) as the given equations of nonlinear theory of thin shells.


ABSTRACT: The system of differential equations governing the analysis of rotationally symmetric shells under time-dependent or static surface loadings is formulated with the transverse, meridional, and circumferential displacements as the dependent variables. The thickness of the shell may vary, and four homogeneous boundary conditions may be prescribed at each boundary edge of the shell. The governing differential equations for each Fourier harmonic are obtained by use of Fourier series in the circumferential direction of the shell. Influence coefficients at each of the node points along the shell meridian are obtained for each Fourier component by employing ordinary finite difference representations for the meridional co-ordinate derivatives. With these influence coefficients, a set of homogeneous flexibility equations governing the free vibration characteristics of the shell is obtained and solved for the frequencies and mode shapes for each Fourier component. The solutions under time-dependent or static surface loadings and due to initial displacements and velocities are then obtained by expanding the solutions in terms of the modes of free vibration of the shell for each Fourier component. The solution for the total shell response is obtained by Fourier series summation. Solutions for typical shells have been found to be in excellent agreement with solutions by the method of temporal and spatial finite differences. Solutions for a parabolic shell are presented as an example. The solution is also presented for a published cylindrical shell example and is seen to be in excellent agreement with the published finite element method results.

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“Optimal weight design of laminated composite panels with different stiffeners under buckling loads”, ICAS 2010, 27th International Congress Of The Aeronautical Sciences, 2010

ABSTRACT: The present investigation is devoted to development of new optimal design concepts that exploit the full potential of advanced composite materials in aircraft lateral wing upper covers. Three rib bays laminated composite panels with T, I and HAT-stiffeners are modelled with ANSYS and NASTRAN finite element codes to investigate their buckling behaviour in dependence on skin and stiffener lay-ups, stiffener height, stiffener top and root width. Due to the large dimension of numerical problems to be solved, an optimisation methodology is developed employing the method of experimental design and response surface
technique. Weight optimisation problems are solved for laminated composite panels with three types of stiffeners, two stiffener pitches and four load levels taking into account manufacturing, repairability and damage tolerance requirements. Optimal results are verified using ANSYS shared-node and NASTRAN rigid-linked models.

References listed at the end of the paper:


ABSTRACT: The superior performance of the consistent shell element in the small deflection range has encouraged the authors to extend the formulation to large displacement static and dynamic analyses. The nonlinear extension is based on a total Lagrangian approach. A detailed derivation of the non-linear extension is based on a total Lagrangian approach. A detailed derivation of the non-linear stiffness matrix and the unbalanced load vector for the consistent shell element is presented in this study. Meanwhile, a simplified method for coding the nonlinear formulation is provided by relating the components for the nonlinear B-matrices to those of the linear B-matrix. The consistent mass matrix for the shell element is also derived and
then incorporated with the stiffness matrix to perform large displacement dynamic and free vibration analyses of shell structures. Newmark's method is used for time integration and the Newton-Raphson method is employed for iterating within each increment until equilibrium is achieved. Numerical testing of the nonlinear model through static and dynamic analyses of different plate and shell problems indicates excellent performance of the consistent shell element in the nonlinear range.

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ABSTRACT: The aim of this investigation is to study the effect of different imperfection shapes on the inelastic stability of liquid-filled conical tanks and to determine the critical imperfection shape that would lead to the minimum inelastic limit load. The study is carried out numerically using a self-developed shell element used to simulate a number of conical tanks having an imperfection shape in the form of Fourier series of equal coefficients. The Fourier analysis of the buckling modes indicates that the existence of axisymmetric imperfection will lead to the critical inelastic limit load for conical tanks.

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ABSTRACT: In the current study an optimum design technique of stiffened liquid-filled steel conical tanks subjected to global and local buckling constraints is developed using a numerical tool that couples a non-linear finite element model developed in-house and a genetic algorithm optimization technique. This numerical tool is an extended version of an earlier one, adapted for the optimum design of unstiffened conical tanks. The design variables considered in the current study are the shell thicknesses, the geometry of the steel vessel as well as the dimensions and number of stiffeners. The developed numerical tool is capable of selecting the set of design variables that leads to optimum safe design. The analysis is conducted twice; first, case of stiffeners free at their bottom edge, which represents the case of retrofitting an existing tank. In the second case the stiffeners are assumed to be anchored to the bottom slab of the tank, which represents the situation of a newly designed tank. Finally, the optimum design of the stiffened tanks is compared to the optimum design of unstiffened tanks computed in a previous study.

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ABSTRACT: Empty and water filled cylindrical Tin (Sn) coated steel cans were loaded under axial compression at varying loading rates to study their resistance to withstand accidental loads. Compared to empty cans the water filled cans exhibit greater resistance to axially applied compression loads before a complete collapse. The time and load or stroke and load plots showed three significant load peaks related to three stages during loading until the cylinder collapse. First peak corresponds to the initial structural buckling of can. Second peak occurs when cylindrical can walls gradually come into full contact with water. The third peak shows the maximum load carrying capability of the structure where pressurized water deforms the can walls into curved shape until can walls fail under peak pressure. The collapse process of water filled cylindrical shell was further studied using Smooth Particle Hydrodynamics (SPH) technique in LSDYNA. Load peaks observed in the experimental work were successfully simulated which substantiated the experimental work.

References listed at the end of the paper:

ABSTRACT: The aim of this paper is to design an optimum Y-stiffener plate combination using multi-objective optimization with real-coded genetic algorithms under the action of uniaxial compressive loads, because the most important loads applied on stiffened plates in ship hull is longitudinal in-plane axial compression arising for instance due to longitudinal bending because the cargo is not distributed equally in holds or due to grounding, stranding or collision. Five of the Y-stiffened panel dimensions were selected to be the independent design variables of the optimization problem. The objective functions are the ultimate buckling load and the volume per unit area of the Y-stiffener plate combination. Nonlinear finite element analysis was used to calculate the ultimate buckling load of 35 different sets of the design variables, with certain range for each of the design variables. The effects of independent design variables on the ultimate buckling load and the volume per unit area for Y-stiffener plate combination were studied and discussed. A new surrogate function to predict the ultimate buckling load of Y-stiffener plate combination is created and validated using the values of the ultimate buckling loads calculated using nonlinear finite element analysis. The proposed surrogate function is valid only in the specific ranges of the design variables. The Pareto optimal sets were calculated using multi-objective optimization with real-coded genetic algorithms and the optimum set of the independent design variables which is associated with the optimal geometric dimensions of the Y-stiffened panel was selected as the set which has the maximum ultimate buckling load to volume per unit area ratio. The optimum set was tested and validated using sensitivity analysis technique.

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ABSTRACT: Wrinkling criteria are proposed for an elastic isotropic and plastic anisotropic shell with compound curvatures in the noncontact region of a sheet subjected to internal forming stresses. A quasi-shallow shell is modeled by Donnell-Mushtari-Vlasov (DMV) shell theory. A bifurcation functional from Hill's general theory of uniqueness and bifurcation in elastic-plastic solids is used to model the local wrinkling phenomenon. Both strain hardening and transverse anisotropy are taken into consideration. This wrinkling criterion is especially useful as a failure criterion in three dimensional finite element modeling (FEM) of sheet forming. Given the principal stresses or strains and the geometry provided at each incremental deformation step, the criterion can be used to predict wrinkles in the elements in the unsupported region.

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ABSTRACT: A numerical method for predicting the onset of flange wrinkles of small wavelength during deep drawing process is presented. The method is based on the approach developed by Cao and Boyce (1997) for predicting the buckling behavior of sheet metal under lateral constraint using a combination of energy conservation and finite element method. Continuum elements are used in a simple Finite Element Analysis model to study wrinkles with a maximum wavelength of ten times the sheet thickness. The analysis provides the critical buckling stress and the resulting buckling wavelength as functions of normal pressure. Such relationships are then implemented in a Finite Element Method (FEM) package that uses membrane elements to simulate the workpiece deformation during a forming process. The use of membrane elements significantly reduces the amount of computation time required in comparison to using structural shell elements with multiple integration points through the thickness. The stress histories calculated from the FEM membrane analysis are used to predict the onset of buckling during the forming process. The application of the forming of a rectangular pan is examined. The comparison between numerical simulation and the experimental results is presented. Our approach predicts the onset of buckling in excellent agreement with the experimental observations.


ABSTRACT: An experimental investigation was conducted on the initiation and growth of wrinkling due to nonuniform tension using the Yoshida buckling test. The initiation of wrinkling was detected by strain gages mounted on both surfaces of the samples in the loading and transverse directions. The bifurcation of aluminum auto body sheets appeared to be smooth and much less abrupt than that observed in a steel sheet. A special fixture was designed to, perhaps for the first time, continuously measure the in situ growth of the buckle heights so that the rates of buckle growth were monitored as functions of strain and stress in the loading direction. In contrast to what is commonly believed, it was found that the buckle height is not predominantly determined by the material yield strength, and lower average r value does not increase the rate of buckle growth. Crystallographic texture components and pole figures of the test materials were also measured, and the relationship of plastic anisotropy with wrinkling behavior was investigated by experiments with specimens aligned in the rolling direction, the transverse direction and 45-deg to the rolling direction of the sheet materials.


ABSTRACT: This study presents a numerical investigation on the deformation of the circular blanket against a male die under impulsive loading to form a torispherical head shape. A finite element model was developed and verified with experimental tests for the explosive forming of torispherical heads made of AA5083 aluminum alloy in the framework of LS-DYNA crash simulator software. The nature of the deformation was turned from the stretching to the buckling and compression of the specimen by using a male die, which is a novel concept in the high speed forming processes. Johnson-Cook (JC) and Modified Zerilli-Armstrong (MZA) constitutive equations were used to describe the behavior of the specimen in a high strain rate forming process with different stress status. Most of the experimentally observed material behaviors simulated well in pure tension or compression tests, while the transient zone was not adequately described. The predicted width for the transient rim is considerably smaller than experimental measurements. The blast loading process including the underwater detonation and the interaction with the specimen simulated using Arbitrary Lagrangian-Eulerian
formulation as well as cavitations and reloading effect. The simulation results for blast loading verified base on Cole’s relation for the underwater detonation of small charges, show a good agreement of 95% accuracy.

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ABSTRACT: The initiation and growth of wrinkles in sheet metal forming processes are influenced by many factors such as the stress state, the mechanical properties of the sheet material, the geometry of the body, and the contact conditions. It is difficult to analyze wrinkling initiation and growth considering these factors, because the effects of the factors are very complex and the wrinkling behavior may show a wide variation for small deviation of the factors. In this study, bifurcation theory is introduced for the finite element analysis of wrinkling initiation and growth. All the above mentioned factors are conveniently considered by the finite element method. The wrinkling initiation is determined by checking the determinant of the stiffness matrix at each iteration and the wrinkling behavior is analyzed by successive iteration with the perturbed guess along the eigenvector. The finite element formulation is based on the incremental deformation theory and elastic–plastic material modeling. The finite element analysis is carried out using continuum-based resultant shell elements. The initiation and growth of wrinkling in the elliptical cup deep drawing process are analyzed by the proposed algorithm. The effect of the aspect ratio of a punch on the wrinkling behavior in the elliptical cup deep drawing process is investigated.


ABSTRACT: This paper deals with two-dimensional plane stress wrinkling model of elastic/plastic annular plate. Based on energy method and nonlinearity of strain-displacement law, a bifurcation functional in polar coordinate is derived analytically. This technique leads to the critical conditions for the onset of the elastic/plastic wrinkling of the flange during the deep-drawing process. Tresca yield criterion along with deformation theory of plasticity are utilized and the material of the plate is assumed to behave perfectly plastic. Moreover, the influence of the blankholder upon wrinkling and on the number of the generated waves is quantitatively predicted by the suggested scheme. The main advantage of the proposed solution is its better agreement with the experimental and analytical results found by the other researchers.

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ABSTRACT: Tube Hydroforming Process (THF) is heavily affected by the pressure-displacement diagram, and adjustment of the raw tube. Three common defects of the process are bursting, buckling and wrinkling. In this work, the leading conditions to wrinkling defect have bee


ABSTRACT: The general wrinkling theory based on the rate formulation of the principle of virtual work has been applied in a number of studies on wrinkling during sheet metal forming. No contact with the die was allowed. In this study it is shown that with the right choice of wrinkling modes, the theory can also be used for contact situations. Furthermore, loads normal to the sheet can be taken into account. Therefore, the wrinkling theory has a larger area of application then it was previously considered.

Marisa P. Henriques, Ricardo J. Alves de Sousa, Robertt A. F. Valente (Department of Mechanical Engineering, University of Aveiro Campus Universitário de Santiago, Aveiro, Portugal), “Numerical Simulation Of Wrinkling Deformation In Sheet Metal Forming”, 7th EUROMECH Solid Mechanics Conference J. Ambrosio et.al. (eds.) Lisbon, Portugal, 7–11 September 2009

ABSTRACT: The main goal of the present paper is to perform an initial analysis of distinct numerical simulation strategies, based on the Finite Element Method (FEM), in the description of wrinkling initiation and propagation during sheet metal forming operations. Wrinkling defects in plastically formed parts can be characterized as compression instabilities, and from this fundamental point of view can then be seen as localized buckling, within the general theory of plastic bifurcation and lost of uniqueness. Seeking for a higher generality in the analysis, numerical simulation procedures – such as the FEM – allow for a strong contribution on the study of wrinkling effects in realistic sheet metal forming problems. For these cases, complexities in contact, loading, geometry and process parameters can completely impair the use of analytical tools, being numerical simulation strategies the most appropriate ones. From the FEM standpoint, the authors will focus the present study in two particular aspects: a) the influence of a given finite element formulation choice and b) the influence of the chosen anisotropic constitutive model in the prediction of the onset and propagation of wrinkling deformation modes during forming. Starting from the latter, this work intends to analyze the influence of accounting (or not) for planar anisotropy behaviours within finite element numerical simulation procedures. Free-forming examples will be taken into consideration, being analyzed with isotropic and anisotropic material models included in the FEM commercial package Abaqus. Additionally, the influence on
wrinkling onset and propagation as coming from the chosen finite element formulation will also be taken into account. To do so, different shell and tridimensional continuum finite elements will be used along with implicit numerical solution procedures, the later option allowing for the attenuation of numerical instabilities in triggering wrinkling effects. Following these guidelines, the present work intends to provide some preliminary insights into how numerical simulation parameters and modelling decisions can influence the results coming from finite element procedures, regarding wrinkling defects in sheet metal formed parts.

References listed at the end of the paper:


ABSTRACT: Wrinkling is one of the major defects in sheet metal products and may be also attributable to the wear of the tool. The initiation and growth of wrinkles are influenced by many factors such as stress ratios, mechanical properties of the sheet material, geometry of the workpiece, contact condition, etc. In the study, the bifurcation theory is introduced for the finite element analysis of wrinkling initiation and growth. All the above mentioned factors are conveniently considered by the finite element method. The wrinkling initiation is found by checking the determinant of the stiffness matrix at each iteration and the wrinkling behavior is analyzed by successive iteration with the perturbed guess along the eigenvector. The effect of magnitude of perturbation on the wrinkling behavior can be avoided by the Newton-type iteration method. The finite element formulation is based on the incremental deformation theory and elastic-plastic material modeling. The finite element analysis is carried out using the continuum-based resultant shell elements considering the planar anisotropy of the sheet metal. In order to investigate the effects of geometry and stress state on the wrinkling initiation and growth, a modified Yoshida buckling test is proposed as an effective buckling test. The finite element analysis are carried out for the modified Yoshida buckling test. The buckling behavior of the sheet is analyzed for various modified dimensions.

References listed at the end of the paper:


INTRODUCTION: Surface distortions in the form of localised buckles and wrinkles are often observed in sheet metals during stamping and other forming operations. In fact, wrinkling is becoming one of the most troublesome modes of failure in sheet forming mainly because of the trend towards thinner, high-strength sheet metals. Therefore, the critical conditions which promote the initiation of wrinkling are of fundamental significance to the design of deep drawn components and may be incorporated in a predictive model for FE simulation. The methods used in the past to predict wrinkling failures in sheet metals have been mostly empirical (e.g. Yoshida Buckling Test which consists of subjecting a square flat specimen to diagonal tension. Buckling eventually develops in the central region of the specimen and attempts are made to correlate buckle heights and buckling loads with various material properties). The Yoshida buckling test and other similar
empirical methods have, unfortunately, proved to be inadequate for predicting observed trends. A more recent approach for the analysis of local wrinkling has been presented by Hutchinson and Neale (1985). It consists of formulating the problem within the context of plastic bifurcation theory for thin shell elements. In this work the analysis of Hutchinson and Neale (1985) and its extension by Neale (1989) to account for more general constitutive models (e.g. anisotropy) is used.

References listed at the end of the paper:

A. Selman, Notes on error estimation and adaptive mesh refinement in thin sheet metal forming processes Internal Report, University of Twente, Faculty of Mechanical Engineering, WB.99 / NIMR-0154 (1999).

ABSTRACT: An adaptive mesh refinement procedure for wrinkling prediction analyses is presented. First the critical values are determined using Hutchinson’s bifurcation functional. A wrinkling risk factor is then defined and used to determined areas of potential wrinkling risk. Finally, a mesh refinement is operated.

References listed at the end of the paper:

[3] (there is no Ref. no. 3 in the original)

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“On adaptive mesh refinement in wrinkling prediction analysis”, In: fifth ESAFORM conference on Material Forming, April 14-17, 2002, Krakow, Poland

ABSTRACT: Hutchinson approach has been successfully used by a number of researchers in thin sheet metal forming processes for wrinkling prediction. However, Hutchinson approach is limited to regions of the sheet that are free of any contact. Therefore, a new wrinkling indicator that can be used in the contact areas is proposed. Discretisation error indicators are also used to present a comprehensive approach to wrinkling prediction analysis.

References listed at the end of the paper:


ABSTRACT: Discretisation errors indicator, contact free wrinkling and wrinkling with contact indicators are, in a challenging task, brought together and used in a comprehensive approach to wrinkling prediction analysis in thin sheet metal forming processes.

References listed at the end of the paper:

Meinders, Timo (1), Selman, Sid (2), Atzema, Eisso H. (3) and Huetink, Han (1)
ABSTRACT: In this work, the analysis of Hutchinson and Neale is used for wrinkling prediction. Under a number of assumptions, limitations and simplifications a wrinkling criterion with some restrictive applicability, is obtained. Unfortunately, Hutchinson analysis is limited to regions of the sheet that are free of any contact. When contact is taken into account the problem is further complicated. Consequently, a local indicator based on the change of curvatures under compressive stresses is developed. Both wrinkling indicators are used to drive the adaptive mesh refinement in order to be able to accurately spot wrinkling. The numerical results will be compared to those obtained through experimental testing. A number of hemispherical product samples have been used with various blank holder forces and drawn to different depths to capture the onset of wrinkling, its mode and location.

References listed at the end of the paper:
References listed at the end of the paper:


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ABSTRACT: An analysis for the prediction of wrinkling in curved sheets during metal forming is presented. Using a local approach, similar to that employed for conventional forming limit diagram representations, we construct “wrinkling limit curves” (WLCs) which represent the combinations of the critical principal stresses for wrinkling in curved sheet elements. Wrinkling limit curves are first determined using a bifurcation analysis for plastic buckling in short-wavelength shallow modes. A study of the effects of material properties and sheet...
geometry on the critical conditions for wrinkling is carried out. We then analyse the effects of geometric imperfections on wrinkling. This analysis is based on the implementation of a finite element scheme. The influence of nonproportional loading is also investigated. In our analysis the material is assumed to be isotropic, elastic-plastic with the plastic part modelled using both J2 deformation theory and J2 flow theory of plasticity.

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ABSTRACT: Excessive wavy surfaces formed by a cold- or hot-rolling process in a thin plate degrades the value of the plate significantly, which is called the flatness problem in the industry. It is a result of post-buckling due to the residual stress caused by the rolling process. Because the buckling occurs in a very long, continuous plate, a unique difficulty of the problem as a buckling problem is that the buckling length is not given but has to be found. In many previous works, the length that gives the lowest critical load of the plate for the given load profile was taken as the buckling length. In this work, it is shown that this approach is flawed, and a new approach is developed to solve the flatness problem by extending a classic post-buckling analysis method based on the energy principle. The approach determines the buckling length and amplitude without using any unfounded assumptions or hypothesis. Using simple displacement functions, approximate solutions are obtained in closed forms for the plate subjected to a linearly distributed residual stress. The new solution approach can be used to determine the condition for the maximum rolling production that does not cause the flatness problem.

ABSTRACT: In this study, static and free vibration characteristics of anisotropic laminated cylindrical shell with various end conditions are considered by making the use of differential quadrature method (DQM). Equations of motion are derived based on three-dimensional theory of elasticity. Applying the state space in conjunction with DQM to the governing differential equations and to the edges boundary conditions in term of displacements, new state equations at discrete points are derived. By solving the obtained state equations, static and frequency behavior of laminated shell are evaluated. To ensure the accuracy of the present approach, comparisons are made with those for the shell with simply supported edges which can be solved analytically. Finally, the effect of edges condition on the static and vibration behaviour of shell is investigated.

ABSTRACT: The differential quadrature method (DQM) is used to analyze the one-dimensional buckling of a laminated composite beam plate having an across-the-width delamination located at an arbitrary depth and an arbitrary location along its span. A beam theory with shear deformation is used in formulating the problem.
Several case studies are conducted to examine the buckling response of laminates hosting such a delamination. Using DQM, the system of equilibrium equations and the boundary conditions are transformed into a system of linear algebraic eigenvalue equations that are solved by a standard eigensolver. The influences of several parameters that affect the buckling strength of such laminates are investigated. The investigated parameters are the shear deformation factor, the length of the delamination, and the through-the-thickness and longitudinal positions of the delamination. The results verify the accuracy and efficiency of DQM.

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ABSTRACT: The application of differential quadrature method (DQM), as an effective and robust numerical method, for the analysis of buckling of delaminated composite plates is introduced. The analysis investigated the response of laminated composite plates hosting a circular or an elliptical delamination. The delaminations were assumed to be fairly thinner than the plate hosting them, and thus, they could be treated as plates with clamped edges. Several case studies were used to verify the integrity of DQM in predicting the buckling strain of the plates. The investigation included the examination of several parameters influencing the buckling strength. The results obtained from DQM were compared with those obtained by the Rayleigh–Ritz and finite element solutions of other workers.


ABSTRACT: Optimization of the buckling load of a filamentary laminated circular cylindrical shell subjected to axial compression and/or external pressure has been undertaken. The shell is made up of a group of N orthotropic plies whose principal axis coincides with the shell axis. The optimization procedure adopted involves a two-step approach; a random search is employed to determine an initial guess for a systematic search based on Powell's method. The efficiency of this procedure is demonstrated for four-ply laminated cylindrical shells of various length-to-radius ratios involving three typical material systems.

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ABSTRACT: The paper proposes a procedure of optimization of reinforced structures of aerospace employment. Such procedure, denominated NAPAO, uses the sizing code PANDA2 for the shell structures while the global optimization is realized through MSC.Nastran. NAPAO has been applied to structural modules of the International Space Station Alpha, of which Alenia Spazio S.p.A. has responsibility. The applications have shown that the procedure of proposed optimization represents a versatile and efficient tool which allows a reduction of mass in relatively brief times if compared with those of a structural optimization developed completely in a FEM code.
References listed at the end of the paper:

PARTIAL ABSTRACT: This paper presents an evaluation of ultimate strength of imperfect cylindrical steel shells under axial compression. The ultimate strength is evaluated analytically using finite displacement method on the basis of the degenerated shell element…

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ABSTRACT: The development of a new four node degenerated shell element is presented for the analysis of the shell structures undergoing large deformations. In the formulation of the new element, the assumed covariant transverse shear strains are used to avoid the shear locking problem, and the assumed covariant membrane strains which are separated from the covariant inplane strains by mid-surface interpolation, are applied to eliminate the membrane locking problem and also to improve the membrane bending performance. This element is free of serious shear and membrane locking problems and undesired spurious kinematic deformation modes. An incremental total Lagrangian formulation is presented which allows the calculation of arbitrarily large displacements and rotations. The resulting nonlinear equilibrium equations are solved by the Newton-Raphson method combined with load or arc-length control. The versatility and accuracy of this new degenerated shell element is demonstrated by solving several numerical examples.

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ABSTRACT: Active piezoelectric thin-walled structures, especially those with a notably higher membrane than bending stiffness, are susceptible to large rotations and transverse deflections. Recent investigations conducted by a number of researchers have shown that the predicted behavior of piezoelectric structures can be significantly influenced by the assumption of large displacements and rotations of the structure, thus demanding a geometrically nonlinear formulation in order to investigate it. This paper offers a degenerated shell element
and a simplified formulation that relies on small incremental steps for the geometrically nonlinear analysis of piezoelectric composite structures. A set of purely mechanical static cases is followed by a set of piezoelectric coupled static cases, both demonstrating the applicability of the proposed formulation.

References listed at the end of the paper:


ABSTRACT: The progressive introduction of advanced fibre composite materials into aerospace structures has enabled significant performance improvements to be achieved. Structures using these materials are generally designed so that their behaviour is essentially linearly elastic through to failure. The realisation of further significant weight reductions in light-weight aerospace structures is highly dependent on design technologies which will enable postbuckling stiffened panels to be utilised in primary structures. The capabilities of the finite element code, MSC/NASTRAN, to predict the onset of buckling and subsequent postbuckling behaviour of a blade-stiffened fibre composite panel have been investigated. The panel consists of T300/914 carbon/epoxy unidirectional tape and is reinforced by integral stiffeners. Basic modelling techniques for the efficient analysis of such postbuckling assemblies are presented. It is concluded that the prediction of their performance requires specialist modelling skills and a sound understanding of the behaviour of the composite materials used in the structure.

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ABSTRACT: In stiffened panels with defects, such as skin delaminations or stringer debonding, buckling may occur prior to the designed critical buckling load. Depending on the damage parameters, such defects may also affect the post-buckling behaviour and consequently the structural performance. An automated finite element (FE) modelling tool has been developed to predict the post-buckling behaviour of panels. It was coupled with a linear elastic fracture mechanics approach to determine damage criticality, based on the “no-growth” principle. The structural behaviour in the post-buckling range and its interaction with the damage parameters were analysed. Local buckling occurred as a result of localised stiffness reduction in the damage region. Global buckling occurred when sufficient in-plane strain was reached. The onset of local buckling was an important factor on stringer debonding criticality as the local buckling mode had an effect on the corresponding global buckling. In comparison, the onset of local buckling for the skin delamination was lower due to the thin sub-laminate separation. However, it was less influential on the damage criticality because the local buckling slowly dissipated in the far post-buckling range. It was found that the initiation of local buckling, and the interaction between the local and global buckling mode, would determine the damage criticality.

ABSTRACT: In order to promote the efficient use of composite materials in civil engineering infrastructure, effort is being directed at the development of design criteria for composite structures. Insofar as design with regard to buckling of composite shells is concerned, it is well known that a key step is to investigate the influence of initial geometric imperfection on the non-linear behaviour of the composite shells. One possible approach is to use the validated numerical model based on the non-linear finite element analysis. Thus, the objective of this article is to present the formulation used in developing a composite shell element and to validate the element from the composite panels. The finite element used in the current study is an eight-noded shell element with six degrees of freedom per node. The non-linear formulation of the shell element is based on the updated Lagrangian method. The shell element is capable of small strain and large displacement analysis with finite rotations. In order to remove the rigid body rotation, a co-rotational method is used. The transverse shear deformation effects using the Reissner–Mindlin theory are included in formulating the linear and geometric stiffness matrix. Thus, the present composite shell element allows modeling of relatively thick composite plates and shells for both the linear and non-linear analyses. The validation of the composite shell element shows that the present results have very good agreement with existing references. Subsequently the postbuckling analyses for the modeling of the curved panel with initial imperfections are performed in order to investigate the effect of the initial geometric imperfection shape and amplitude. The results are used to estimate imperfection sensitivity for such panels.


ABSTRACT: The presence of in-plane loading may cause buckling of stiffened panels. An accurate knowledge of critical buckling load and mode shapes are essential for reliable and lightweight structural design. This paper presents some parametric studies on simply supported laminated composite blade-stiffened panels subjected to in-plane shear loading. A total of 450 models were analyzed using ANSYS 7.1 and a database is prepared for different plate and stiffener combinations. Studies are carried out by changing the panel orthotropy ratio, stiffener depth, pitch length (number of stiffeners), smeared extensional stiffness ratio of stiffener to that of the plate and extensional stiffness to shear stiffness ratio of the plate. Based on the studies, few important parameters influencing the buckling behaviour are identified and guidelines for better stiffener proportioning are developed, which will be helpful for the designer.


ABSTRACT: This article presents parametric studies on simply supported laminated composite stiffened panels subjected to in-plane shear loading. A number of models were analyzed using ANSYS and a database is prepared for blade-, angle-, T-, and hat-stiffened laminated composite panels. Studies are carried out by changing the type of stiffeners, the panel orthotropy ratio, smeared extensional stiffness ratio of stiffener to that of the plate, and extensional stiffness to shear stiffness ratio of the plate. The difference in buckling behavior of
different types of stiffened panels is presented. Based on key parameters influencing the buckling behavior, guidelines for better stiffener proportioning are developed, which will be helpful to the designers.

ABSTRACT: A generalized stochastic buckling analysis of laminated composite plates, with and without centrally located circular cutouts having random material properties, is presented under uniaxial compressive loading. In this analysis, the layerwise plate model is used to solve both prebuckling and buckling problems. The stochastic analysis is done based on mean centered first-order perturbation technique. The mean buckling strength of composite plates is validated with results available in the literature. It has been observed that the present analysis can predict buckling load accurately even for plates with large cutouts. Micromechanics based approach is used to study the effect of variation in microlevel constituents on the effective macrolevel properties like elastic moduli. Consequently, the effect of uncertainty in these material properties on the buckling strength of the laminated plates is studied. Parametric studies are carried out to see the effect of hole size, layups, and boundary conditions on the mean and variance of plate buckling strength.

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ABSTRACT: Optimal design of laminated composite stiffened panels of symmetric and balanced layup with different number of T-shape stiffeners is investigated and presented. The stiffened panels are simply supported and subjected to uniform biaxial compressive load. In the optimization for the maximum buckling load without weight penalty, the panel skin and the stiffened laminate stacking sequence, thickness and the height of the stiffeners are chosen as design variables. The optimization is carried out by applying an ant colony algorithm (ACA) with the ply contiguous constraint taken into account. The finite strip method is employed in the buckling analysis of the stiffened panels. The results shows that the buckling load increases dramatically with the number of stiffeners at first, and then has only a small improvement after the number of stiffeners reaches a certain value. An optimal layup of the skin and stiffener laminate has also been obtained by using the ACA. The methods presented in this paper should be applicable to the design of stiffened composite panels in similar loading conditions.

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ABSTRACT: This article presents a methodology and process for a combined wing configuration partial topology and structure size optimization. It is aimed at achieving a minimum structural weight by optimizing
the structure layout and structural component size simultaneously. This design optimization process contains two types of design variables and hence was divided into two sub-problems. One is structure layout topology to obtain an optimal number and location of spars with discrete integer design variables. Another is component size optimization with continuous design variables in the structure FE model. A multi city-layer ant colony optimization (MCLACO) method is proposed and applied to the topology sub-problem. A gradient based optimization method (GBOM) built in the MSC.NASTRAN SOL-200 module was employed in the component size optimization sub-problem. For each selected layout of the wing structure, a size optimization process is performed to obtain the optimum result and feedback to the layout topology process. The numerical example shows that the proposed MCLACO method and a combination with the GBOM are effective for solving such a wing structure optimization problem. The results also indicate that significant structural weight saving can be achieved.

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ABSTRACT: This paper presents a theoretical study on the elastic-plastic interaction buckling of imperfect longitudinally stiffened panels under axial loads. A material and geometric nonlinear spline finite strip method is developed to analyse such interaction problems. The initial geometric imperfections and residual stresses due to welding are involved in the analysis. An iterative numerical procedure combining a modified arc-length method and Newton-Raphson iteration is employed for the solution of the nonlinear incremental equilibrium equations and a full range load deflection path is obtained. Numerical results are presented which show that the authors' method is not only an efficient tool but is also accurate in the analysis of large deflection elastic-plastic behaviour of folded plate structures.


ABSTRACT: The theoretical background and details of a computer program for the optimum design of multi-layered fibre composite stiffened plates (STIPSY) subjected to in-plane compression and secondary out-of-plane loading, are presented. The blade, angle and hat section stiffeners are considered in the program. The widths of the elements, the thickness of the three layers having commonly used fibre orientations (0°, ±45° and 90°) in each of the number of layers in each element are the design variables. Any desired set of constraints from the various serviceability, material strength, stability and side constraints available in the program may be invoked by the user along with the corresponding factor of safety. The Gradient Projection Method (GPM) and Sequential Unconstrained Minimization Technique (SUMT) are the alternate procedures available in the program to solve the resulting non-linear optimization problem. A few sample results are presented at the end.

ABSTRACT: An investigation into the buckling of stringer- or ring-stiffened laminated-composite circular-cylindrical shells subjected to axial compression or hydrostatic pressure has been undertaken. The stiffeners were made up of unidirectional fibre-reinforced epoxy while the shell laminate contained N orthotropic plies with equal amounts of fibres in the + theta-i and –theta-i directions in ith ply. Based on Koiter’s general theory of elastic stability, the stiffener eccentricity effect and the initial postbuckling behaviour were examined. It was found that, in every case studied, external stiffening was more efficient than internal stiffening, the buckling and initial postbuckling behaviour of stiffened laminated cylinders were significantly influenced by the laminate configuration. Consequently, taking the fibre orientations of lamina as optimizing parameters, a two-step optimization procedure was employed to maximize the buckling load of stiffened composite cylinders. The lamina fibre orientations of optimal shells were found to be strongly dependent on the reduced Batdorf parameter, Z.


ABSTRACT: A large number of internal resonances, sensitivity to small imperfections and to a small external non-conservative action are characteristic for a number of elastic shells subjected to conservative forces. It is shown that, in combination, these three features result in dynamic instability of a system, that manifests itself in the existence of a solution of the explosive instability type when the deviation from the equilibrium state becomes infinitely large in a finite time. A simple method is proposed to calculate the ultimately allowable load by which one should be guided in designing structures containing thin shells. This load calculated by a linear model corresponds to the appearance of the first internal resonance in the system. The results are illustrated by well-known experimental facts.


ABSTRACT: Within the framework of finite element analysis, an asymptotic method is presented for the study of geometrically nonlinear static behavior of thin structures under one-parameter conservative loading. The method can be applied when the prebuckling behavior is moderately non-linear so that the bifurcation analysis is no longer accurate enough. An iterative process makes it possible to find suitable deformation modes which enable a good approximation of the structural behavior around the buckling point. As in the Rayleigh-Ritz approach, a reduced energy can be formulated with only a small number of generalized degrees of freedom. The influence of small initial imperfections on the buckling load can easily be analyzed as in Koiter's asymptotic method. A comprehensive treatment and several improvements of this asymptotic iterative method are given and selected examples illustrate the basic features of the method.


ABSTRACT: The paper presents theoretical and experimental investigations on three varying-thickness circular cylinders, which were tested to destruction under external hydrostatic pressure. The five buckling theories that were presented were based on inelastic shell instability. Three of these inelastic buckling theories adopted the FEM
and the other two theories were based on a modified version of the much simpler von Mises theory. Comparison between experiment and theory showed that one of the inelastic buckling theories that was based on the von Mises buckling pressure gave very good results while the two finite element solutions, obtained by dividing the theoretical elastic instability pressures by experimentally determined plastic knockdown factors, gave poor results. The third finite element solution, which was based on material and geometrical nonlinearity, gave excellent results. Electrical resistance strain gauges were used to monitor the collapse mechanisms, and these revealed that collapse occurred in the regions of the highest values of hoop stress, where considerable deformation took place.

ABSTRACT: Flexible shells, designed to sustain elastic displacements, have a “semimembrane” type of deformation, described by simplified equations. In what follows, flexible shell equations are derived and used to analyse bending of curved tubes and buckling of tubes and toroidal shells under external pressure, as interdependent problems. Design formulas and curves are presented.

References listed at the end of the paper:

ABSTRACT: Flexure of cylinders and slightly curved pressurized tubes is investigated for given conditions on the edges, in particular for end flanges. The large precritical deformation is determined with the help of the Flexible-Shell-Theory. The stability analysis of the deformed shell is carried out with the aid of the hypothesis of local buckling. The critical bending moments which determine the collapse load are presented for various tube lengths, initial curvatures and external-pressure values by graphs.
References listed at the end of the paper:


ABSTRACT: A class of problems is considered where the buckling initially starts only in a part of the shell—locally. The stability analysis is focused on the zone of initial buckling. This leads to radical simplification. First the basic hypothesis and stability equations are formulated. Closed-form stability criteria asymptotically exact for very thin shells are discussed. This gives sufficient conditions for the local character of buckling and for the
adequacy of the asymptotic approximation. The analysis taking into account the variation of stresses and shape inside the buckling zone results in a check of stability by hand calculations or by simple coding of a desk-top computer. The adequacy of the simplest representation of the stress and strain variation in the buckling zone is tested.


ABSTRACT: This paper is concerned with further development of tube-analysis methods which are as simple as necessary for design and as accurate as possible in the shell theory. The basic assumptions are stated in Section 2. For ‘long’ tubes their accuracy is estimated in the course of derivation and simplification of nonlinear equations of axisymmetric flexure (Section 3). These equations and the estimates of the assumptions are extended to two-dimensional problems in Section 4. Equations of the semi-momentless theory encompassing shear deformation and appropriate edge conditions are discussed in Sections 5 and 6. Their solution, including a simple approximation, is in Sections 7–9 preceded by known calculations and experiment.


ABSTRACT: Specialization of the general thin-shell theory for the class of large deformations realizable by small strain is considered. This leads in three different ways to the intrinsic nonlinear theory of flexible shells. As an illustration, large displacements and rotations culminating in collapse of finite-length tubes are investigated.

References listed at the end of the paper:

ABSTRACT: The thin-shell theory is specialized for those large deformations realizable by small strain. This provides three different ways leading from the general theory to the intrinsic non-linear theory of flexible shells. The theory is applied to large elastic displacements of finite-length tubes. Their collapse is described as starting by local instability.


ABSTRACT: For small-strain unrestricted deformation of thin elastic shells the field equations and variational principles are rederived in terms of variables immediately representing physical quantities. The relevant strain and stress tensors turn out to be identical to those commonly known as the ‘modified’ and the ‘best’. The nonlinear theory exhibits a static-geometric duality. For orthogonal coordinates the tensor-form theory leads to a modification of the Luré–Novozhilov formulation. The general theory is specialized to that of ‘quasi-shallow shells’, to the membrane theory and to flexible-shell theory, which are explored with respect to basic hypotheses and accuracy.


ABSTRACT: The theory of small-strain unrestricted deformation of thin elastic shells is specialized to the ‘Donnell-type’ theory of quasi-shallow shells, which owes its consequent - intrinsic and dual - formulation to
the idea first enunciated by Avinoam Libai. This theory is explored with respect to the accuracy, adequacy range and the physical meaning of its basic hypotheses.

ABSTRACT: This paper presents an analysis of the post-buckling behaviour of isotropic cylindrical and conical shells under axial compression. The starting point of the paper is Lagrange's variational principle, the application of which consists in assuming a kinematically admissible strain and displacement field. The field is determined considering the geometry of quasi-isometric deformations of the shell after buckling. That permits solving the problem with no limitation on the magnitude of the displacements.

ABSTRACT: The use of air-supported membranes has attracted considerable attention in recent years. There are, however, a number of problems in the behavior of these structures that have not been fully investigated. For example, the problem of lateral stability of such membranes has not been discussed heretofore. The present paper presents an analysis of the sidesway instability of a cylindrical air-supported membrane with vertical longitudinal axis, subjected to concentrated loads applied nonsymmetrically. A critical value of the load is established at which the configuration of these structures changes dramatically. During such change the lower portion of the membrane comes into contact with the support surface. For the problem treated, safe load limits, critical lengths, and critical weight densities for the membrane are derived. The Lagrangian variational method is used throughout the paper in obtaining solutions.

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SUMMARY: The paper is devoted to the description of the present state of knowledge in the theory of inelastic shells under concentrated and local loads. Problems of current interest, and in the broad sense, the analytical and numerical methods that can be brought to bear, are discussed. Other problems involving stress concentration in shells, such as crack propagation and concentration of stresses caused by irregularities of the shape, or holes and cutouts, are not the subject of the paper. The action of concentrated loads on shells has drawn the attention of many researchers for the last 20 years. The problems concerning stress and displacement distribution in linear, elastic thin shells under the static action of concentrated loads applied at one point of shell surface, or subjected to locally distributed loads, were examined at first and were the subjects of those early investigations. Many papers from the western countries as well as from the U.S.S.R. were published in those years. Mostly, the linear theory of shells was the starting point of these works. This area seems to be sufficiently explored at present. However, as far as we consider the similar problems in inelastic, non-linear shells, we recognize that many problems are not yet solved or are not solved in a satisfactory, general manner. The rapid expansion of numerical methods and techniques in recent years has enabled the solution of many difficult problems. However, these solutions usually concern particular situations and are often difficult to generalize. The state of knowledge concerning the following problems of inelastic shells is presented in the paper.
1) The geometrical non-linearities, large deformations of elastic shells under local loads and complex loads when the local, concentrated load is accompanied by a distributed general load.
2) Contact problems in shells involving the geometrical and physical non-linearities
3) Problems related to concentrated loads acting on shells made of inelastic materials
4) Elasto-plastic behaviour of shells under concentrated loads associated with large deformations of shells, collapse and limit local loads.
5) Simplified solutions of dynamical problems.
6) Optimum design of shells loaded by concentrated forces. The paper covers both the results of experimental investigations in each of the above-mentioned areas, as well as the description of the analytical and numerical methods used.

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ABSTRACT: Using Donnell-type shell theory a simple and exact procedure is presented for linear buckling analysis of laminated conical shells, with orthotropic stretching-bending coupling, under axial compressive load and external pressure. The solution is in the form of a power series in terms of a particularly convenient coordinate system. By analysing the buckling of a series of conical shells, under various boundary conditions and different material coefficients, the validity of the presented procedure is confirmed.

ABSTRACT: Vibration and buckling of curved plates, made of hybrid laminated composite materials, are studied using first-order shear deformation theory and Reissner's shallow shell theory. For an initial study, only simply-supported boundary conditions are considered. The natural frequencies and critical buckling loads are calculated using the energy method (Lagrangian approach) by assuming a combination of sine and cosine functions in the form of double Fourier series. The effects of curvature, aspect ratio, stacking sequence and ply-orientation are studied. The non-dimensional frequencies and critical buckling load of a hybrid laminate lie in between the values for laminates made of all plies of higher strength and lower strength fibres. Curvature enhances natural frequencies and it is more predominant for a thin panel than a thick one.

ABSTRACT: The paper is devoted to assessing the optimal arrangements of hybrid laminated faces of sandwich panels in order to maximize local buckling loads corresponding to the wrinkling of compressed faces. The analysis is carried out by modelling compressed faces as thin unsymmetric laminates resting on elastic two-parameter foundations. The First-order Shear Deformation Theory, in conjunction with the Rayleigh-Ritz method, has been used to evaluate buckling loads of simply supported flat laminates subjected to in-plane biaxial compression and shear forces. A numerical investigation is intended to support evidence for the
influence of laminate parameters (fibre orientation, geometrical dimensions) and foundation parameters (modulus of subgrade reaction and shear modulus); obtained results are reported and discussed in the paper.

ABSTRACT: The structural performance of sandwich panels made with hybrid laminated faces and a transversely flexible core can be optimised by varying the mechanical and geometrical parameters characterising both the faces and the core, taking into account also the whole cost. In particular the hybridisation technique applied to the faces seems to be a very attractive solution, giving an improvement from both a mechanical and economical point of view. However, because of the out of plane flexibility of the core and the great slenderness of these structures, instability problems assume a relevant role from a static point of view, becoming a complex phenomenon as well. In this paper a modified first order shear deformation theory has been used, which treats the displacement field of the sandwich panels as a combination of different buckling modes. Buckling loads are finally obtained as a solution of an eigenvalue problem by means of an energetic algorithm solved by the Rayleigh-Ritz method. The influence of mechanical and geometrical parameters, characterising the composite laminated faces and the core, on buckling phenomena were investigated for different in plane load conditions. A numerical FEM approach was also employed; comparisons between FEM and analytical results, in which some key parameters were varied, show the effectiveness of the analytical model.

ABSTRACT: A free vibration response of arbitrarily laminated – crafted with advanced fiber reinforced composite materials – thin and shallow cylindrical panels on rectangular planform with simply supported boundary conditions is analytically investigated. The thin shallow shell formulation of Reissner that follows the classical Kirchhoff–Love hypothesis of small displacements is considered to include arbitrarily laminated behaviors. The simply supported boundary condition having normal, tangential, and transverse displacements restrained at the edges is implemented. The solution functions in a form of mixed boundary continuous and discontinuous double Fourier series are assumed into the analytical solution formulation. The efficiency and accuracy of the solution methodology are determined by studying numerically the convergence behavior of frequencies for various parametric effects. The analytically obtained numerical results and mode shapes are compared with available finite element solutions, and the analytical results can be capitalized as base-line solutions for future comparisons.

ABSTRACT: Large deflections of shallow and deep spherical shells under ring loads are studied. The axisymmetric problem is solved through a Newton-Raphson technique on discretized nonlinear shell equations. Comparison of computed load-deflection curves to experimental data from both thick and thin shells generally
shows good agreement in peak loads and the type of instability. For a point load, the load increases monotonically with deflection; as the ring radius increases, transition-type (snap-through) and then local buckling occurs. In addition, the pre- and post-buckled mechanical behaviors of the shell are examined.

ABSTRACT: This paper examines the accuracy of a modified Reissner-Simmonds theory for thickwalled, rubberlike shells. The theory, which is valid for large membrane and moderately large bending strains, includes the effects of transverse shear deformation and transverse normal stress and strain. To these features, the present work adds hydrostatic pressure through a modified strain-energy density function. Shell theory and finite elasticity theory solutions are compared for two problems: cylindrical bending of a plate and combined extension, inflation, and torsion of a circular cylinder. The results show that the modified theory gives highly accurate stress distributions for most of the loading cases studied. Accuracy is good in cylinders as thick as R/h = 5 and generally improves with increasing reference surface stretching.

ABSTRACT: The problem of a steadily spinning shallow elastic shell of revolution under a uniform pressure distribution is investigated by perturbation and asymptotic methods. Accurate numerical solutions are also obtained to confirm the adequacy of perturbation and asymptotic solutions. The limiting case of a flat plate is first solved for the entire range of values of the two load parameters. The results provide a different interpretation of the existing nonlinear membrane solution for the same problem. Except for a narrow range of parameter values, the boundary value problem for the shell case is reduced either to the solution of a sequence of linear problems or to the solution of a previously solved nonlinear problem modified by the solutions of a sequence of linear problems. The analysis for the shell problem under a combined centrifugal and pressure loading shows a complex interplay among the load and geometric parameters. It also enables us to consider a number of previously investigated problems as special cases of our problem and to offer a unified treatment of these problems.

ABSTRACT: (none given)

References listed at the end of the paper:

ABSTRACT: The stretching of a square sheet along one of its diagonals, called “Yoshida Test”, has been developed to simulate the wrinkling behavior in press forming of steel sheets into autobody panels. The finite deformation, onset of wrinkling, and growth of wrinkles in such a specimen are investigated. Hill's yield criterion for sheet materials having the normal anisotropy and Hill's quasistatic bifurcation criterion are employed. The growth of wrinkles in the finite deformation process is incrementally and numerically determined by a thin shell finite element in a convected coordinate system. The Lagrangian formulation of the thin shell finite element is based on Hill's variational principle for elastic-plastic solids, a modification of Love-Kirchhoff postulates and a quasiconforming element technique. The shell element fulfills the interelement C1 continuity condition in a variational sense. Reasonable agreements between the present numerical results and available analytical and experimental results are shown.

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ABSTRACT: A solving method is applied to conduct research on the non-linear thermal buckling behavior of local delamination near the surface of fiber-reinforced laminated cylindrical shell. The shape of delaminated region considered is elliptic, triangular and lemniscates. Young's modulus and the thermal expansion coefficient of material are treated as a function of temperature, which leads to the force in the middle plane of the sub-laminated shells a non-linear function of temperature. The critical temperatures of laminated cylindrical shells with various shaped local delamination, different stacking patterns and different radius of the laminated cylindrical shells are obtained by making use of the energy principle. It has been found that linear solution of the critical buckling temperature gives a higher value than that of non-linear consideration.

ABSTRACT: A theoretical method is developed to investigate the effects of thermal load and ring stiffeners on buckling and vibration characteristics of the functionally graded cylindrical shells, based on the first-order shear
deformation theory (FSDT) considering rotary inertia. Heat conduction equation across the shell thickness is used to determine the temperature distribution. Material properties are assumed to be graded across the shell wall thickness of according to a power-law, in terms of the volume fractions of the constituents. The Rayleigh-Ritz procedure is applied to obtain the frequency equation. The effects of stiffener's number and size on natural frequency of functionally graded cylindrical shells are investigated. Moreover, the influences of material composition, thermal loading and shell geometry parameters on buckling and vibration are studied. The obtained results have been compared with the analytical results of other researchers, which showed good agreement. The new features of thermal vibration and buckling of ring-stiffened functionally graded cylindrical shells and some meaningful and interesting results obtained in this article are helpful for the application and the design of functionally graded structures under thermal and mechanical loads.


ABSTRACT: This article is the result of an investigation on the effect of thermal load on vibration, buckling and dynamic stability of functionally graded cylindrical shells embedded in an elastic medium, based on the first-order shear deformation theory (FSDT) considering rotary inertia and the transverse shear strains. A heat conduction equation along the width of the shell is applied to determine the temperature distribution. Material properties are assumed to be graded with distribution along the width according to a power-law in terms of the volume fractions of the constituents. Calculations, effects of material composition, thermal loading, static axial loading, medium stiffness and shell geometry parameters on vibration, buckling and the parametric resonance are described. The new features of thermal vibration, buckling and dynamic stability of functionally graded cylindrical shells embedded in an elastic medium and some meaningful and interesting results in this paper are helpful for the application and design of functionally graded structures under thermal and mechanical loads.

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ABSTRACT: This paper presents the report of an investigation into thermoelastic vibration and buckling characteristics of the functionally graded piezoelectric cylindrical, where the functionally graded piezoelectric cylindrical shell is made from a piezoelectric material having gradient change along the thickness, such as piezoelectricity and dielectric coefficient et al. Here, utilizing Hamilton’s principle and the Maxwell equation with a quadratic variation of the electric potential along the thickness direction of the cylindrical shells and the first-order shear deformation theory, and taking into account both the direct piezoelectric effect and the converse piezoelectric effect, the thermoelastic vibration and buckling characteristics of functionally graded piezoelectric cylindrical shells composed of BaTiO3/PZT - 4, BaTiO3/PZT - 5A and BaTiO3/PVDF are, respectively, calculated. The effects of material composition (volume fraction exponent), thermal loading, external voltage applied and shell geometry parameters on the free vibration characteristics are described, and
the axial critical load, critical temperature and critical control voltage are obtained.

ABSTRACT: (none given)

ABSTRACT: The results from studies into the vibrations and dynamic stability of thin elastic shells with initial geometric imperfections are analyzed. The corresponding dynamic problems are solved in both linear and nonlinear formulations. The influence of initial axisymmetric and nonaxisymmetric deflections on natural, forced, parametrically excited, and self-excited vibrations (flutter) is studied. The dynamic buckling of imperfect shells under short-term impulsive loading is examined. Some aspects of experimental investigation into the vibrations of shells with small geometric imperfections (deviations from the design shape) are considered.

ABSTRACT: Results of systematic study of the stability and nonlinear vibrations of thin cylindrical shells interacting with a fluid flow are presented. The main patterns of dynamical deformation of shells during divergence and flutter are considered. The effect of different structural features (initial geometrical imperfections, added concentrated masses, boundary conditions, longitudinal and transverse static loads) on the critical (divergence and flutter) velocities is analyzed. The amplitude–frequency response of shells to external periodic radial loads and internal periodic pressure caused by small pulsations of the fluid velocity is determined. A method is proposed to solve nonlinear problems describing nonstationary processes of passing resonance zones by shells interacting with the fluid flow.
References listed at the end of the paper:

ABSTRACT: The objective of this paper is to investigate numerically the influence of the winding-induced geometrical imperfection on the elastic buckling load of submersible composite hulls. A linear Sanders-type buckling model of laminated cross-ply cylinders is developed. The imperfection is modeled by an axisymmetric thickness default of each composite ply by analogy to the real laminate ply imperfections. The effects of these defaults are taken into account by correcting the laminated stiffness coefficients. Numerical examples have been performed analyzing three types of stacking sequences for thin carbon/epoxy cylinders. For each case, the geometrical imperfections induce significant buckling load reductions. The results of the proposed approach appear to be in good agreement with standard FEM code calculus.

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ABSTRACT: This paper deals with the optimal design of deep submarine exploration housings and autonomous underwater vehicles. The structures under investigation are thin-walled laminated composite unstiffened vessels. Structural buckling failure due to the high external hydrostatic pressure is the dominant risk factor at exploitation conditions. The search of fiber orientations of the composite cylinders that maximize the stability limits is investigated. A genetic algorithm procedure coupled with an analytical model of shell buckling has been developed to determine numerically optimized stacking sequences. Characteristic lamination patterns have been obtained. FEM analyses have confirmed the corresponding significant increases of buckling pressures with respect to initial design solutions. Experiments on thin glass/epoxy and carbon/epoxy cylinders have been performed. The measured buckling pressures appear to be in good agreement with numerical results and demonstrate the gains due to the optimized laminations.

References listed at the end of the paper:
ABSTRACT: Based on the concept of an “intermediate” class of deformations, a theory suitable for the nonlinear static and dynamic analysis of transverse shear deformable circular and noncircular cylindrical shells, composed of an arbitrary number of linearly elastic monoclinic layers, is developed. The theory is capable of satisfying zero shear traction boundary conditions at the inner and outer shell surfaces. Upon assuming that the shell is subjected to a certain initial stress state and applying the highly nonlinear governing equations derived to the adjacent equilibrium criterion, a set of Love-type linearized equations is further derived. These latter equations are suitable for buckling and/or vibration analyses; in a companion paper, they are solved and used for the study of the influence of transverse shear deformation on the buckling loads of axially compressed cross-ply laminated circular and oval cylindrical shells.

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ABSTRACT: This numerical study deals with the stiffened composite underwater vessel design. The structures under investigation are laminated cylinders with rigid end-closures and internal circumferential and longitudinal unidirectional composite stiffeners. Structural buckling induced by the high external hydrostatic pressure is considered as the major failure risk. An optimization design tool has been developed to obtain the reinforcement definition which maximizes the limit of stability: an analytical model of cylindrical composite shell buckling
has been coupled to a genetic algorithm procedure. The numerical optimization tests carried out corroborate design tendencies validated previously by experiments.

References listed at the end of the paper:


ABSTRACT: The present work deals with the numerical prediction of the post buckling progressive and final failure response of stiffened composite panels based on structural nonlinear finite element methods. For this purpose, a progressive failure model (PFM) is developed and applied to predict the behaviour of an experimentally tested blade-stiffened panel found in the literature. Failure initiation and propagation is calculated, owing to the accumulation of the intralaminar failure modes induced in fibre reinforced composite materials. Hashin failure criteria have been employed in order to address the fiber and matrix failure modes in compression and tension. On the other hand, the Tsai-Wu failure criterion has been utilized for addressing shear failure. Failure detection is followed with the introduction of corresponding material degradation rules depending on the individual failure mechanisms. Failure initiation and failure propagation as well as the post buckling ultimate attained load have been numerically evaluated. Final failure behaviour of the simulated stiffened panel is due to sudden global failure, as concluded from comparisons between numerical and experimental results being in good agreement.


ABSTRACT: An experimental study was conducted in order to verify a proposed equation for the minimum required stiffness for longitudinal stiffeners attached on compression plates. Nine test specimens of stiffened plates were fabricated and tested to their ultimate strengths. Test results are compared with the maximum strengths predicted for stiffened plates by finite element analysis and by the proposed SSRC type critical stress curve. Fairly good correlations were observed, thereby confirming experimentally the adequacy of the proposed
equation for the minimum required stiffness of the longitudinal stiffener attached to the compression panel and a modified SSRC type critical stress curve encompassing both the buckling ranges of plastic yield and the transition zones. A set of conclusions is drawn from the experimental studies as to the buckling behaviors of stiffened plates.


ABSTRACT: This paper presents an optimum design of longitudinal stiffeners for box-girder compression flanges. The buckling behavior of longitudinally stiffened compression flanges has drawn considerable interest from early pioneers of theoretical mechanics, as illustrated by Timoshenko and Gere and Bleich. The longitudinally stiffened compression plate structural members generally render an economical structure by efficiently proportioning the material to resist the induced compressive stresses. This study presents results that are based on 3D finite-element analysis of several hundred hypothetical compression flange models stiffened by varying numbers of longitudinal stiffeners with realistic dimensions. The thickness of the compression flange t was varied from 0.50 to 2.50 in. (from 12.7 to 63.5 mm), the number of longitudinal stiffeners n was varied from 1 to 4, and the aspect ratio of the plate panel α was varied from 1 to 5. Two different plate transverse slenderness ratios w/t were analyzed. Analytical data were reduced using nonlinear regression analysis to a simplified design equation suitable for practicing engineers. Several example problems are given to illustrate the use of the regression equation. Comparative analyses are also made to demonstrate the versatility and reliability of the analytical study conducted.


ABSTRACT: Optimization is a central concept in the design of composite structures because of the adaptability of composite materials to a given design situation. Design parameters such as layer thicknesses and ply angles can be employed to great effect to achieve an optimized structure with improved weight and stiffness characteristics. This chapter deals with the lay-up optimization of laminated plates subject to buckling loads. A survey of the subject is presented and the optimal configurations of rectangular laminates are discussed. Designs are studied with respect to layer thicknesses and ply angles for symmetrical and antisymmetrical laminates of hybrid and non-hybrid construction. The effect of bending-twisting coupling on optimal designs is discussed and the optimal configurations with and without this effect are compared. Several factors affecting optimal designs are highlighted. These factors include the use of discrete ply angles and layer thicknesses, restrained edges, shear deformation, cut-outs, thermal loading, strength and stiffness constraints, multiple design objectives and shape design.

References listed at the end of the paper:


ABSTRACT: Multiobjective design of a laminated cylindrical shell is obtained with the objectives defined as the maximization of axial load and external and internal pressures subject to a strength constraint. The failure under axial load and external pressure may occur by buckling. The ply angle is taken as the design variable. The weighted global criterion method is employed to solve the vector-optimization problem, which involves minimization of the distance to ideal solution vector in L2 metric. A symmetrically laminated and balanced shell is considered as an example. Pareto optimal solutions are given for two- and three-objective design problems, and numerical results are presented in the form of tradeoff curves and surfaces. The effects of problem parameters are investigated, and the results are given for various weighting factors and shape parameters.

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ABSTRACT: The multiobjective design of a symmetrically laminated shell is obtained with the objectives defined as the maximization of the axial and torsional buckling loads. The ply angle is taken as the optimizing variable and the performance index is formulated as the weighted sum of individual objectives in order to obtain
Pareto optimal solutions of the design problem. Single objective design results are obtained and compared with the multiobjective design. The effect of weighting factors on the optimal design is investigated. Results are given illustrating the dependence of the optimal fibre angle and performance index on the cylinder length, radius and wall thickness.

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ABSTRACT: The effects of large vibration amplitudes on the first and second coupled radial-circumferential mode shapes of isotropic circular cylindrical shells of infinite length are examined. A theoretical model based on Hamilton’s principle and spectral analysis developed previously for clamped–clamped beams and fully clamped rectangular plates is extended to shell type structures, reducing the large-amplitude free vibration problem to the solution of a set of non-linear algebraic equations. The transverse and circumferential displacements are assumed to be harmonic and expanded in the form of a finite series of functions. The Donnel–Mushtari shell theory, taking into account the coupling between extensional and flexural deformations is used. Then, the non-linear deformation energy is expressed by taking into account the non-linear term due to the considerable stretching of the middle surface of the shell induced by large deflections. Tables of numerical results are given for the first and second non-linear modes, for a wide range of the vibration amplitude, which may be used for engineering purposes. For each value of the vibration amplitude considered, the corresponding contributions of the basic functions defining the non-linear transverse and circumferential displacement shapes are given, with the corresponding non-linear frequencies. Selected plots of mode shapes and bending stress distributions are presented, with an extensive discussion of the effects of non-linearity on the dynamic behaviour of shells.

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ABSTRACT: The non-linear dynamic behaviour of infinitely long circular cylindrical shells in the case of plane strains is examined and results are compared with previous studies. A theoretical model based on Hamilton's principle and spectral analysis previously developed for non-linear vibration of thin straight structures (beams
and plates) is extended here to shell-type structures, reducing the large-amplitude free vibration problem to the solution of a set of non-linear algebraic equations. In the present work, the transverse displacement is assumed to be harmonic and is expanded in the form of a finite series of functions corresponding to the constrained vibrations, which exclude the axisymmetric displacements. The non-linear strain energy is expressed by taking into account the non-linear terms due to the considerable stretching of the shell middle surface induced by large deflections. It has been shown that the model presented here gives new results for infinitely long circular cylindrical shells and can lead to a good approximation for determining the fundamental longitudinal mode shape and the associated higher circumferential mode shapes \((n>3)\) of simply supported circular cylindrical shells of finite length. The non-linear results at small vibration amplitudes are compared with linear experimental and theoretical results obtained by several authors for simply supported shells. Numerical results (non-linear frequencies, vibration amplitudes and basic function contributions) of infinite shells associated to the first four mode shapes of free vibrations, are obtained, using a multi-mode approach and are summarized in tables. Good agreement is found with results from previous studies for both small and large amplitudes of vibration. The non-linear mode shapes are plotted and discussed for different thickness to radius ratios. The distributions of the bending stresses associated with the mode shapes are given and compared with those obtained via the linear theory.

Yasushi Uematsu, Noboru Tsujiguchi and Motohiko Yamada (Department of Architecture and Building Science, Tohoku University, Sendai 980-8579, Japan), “Mechanism of ovalling vibrations of cylindrical shells in cross flow”, Wind and Structures, Vol. 4, No. 2, pp 85-100, April 2001, DOI: [http://dx.doi.org/10.12989/was.2001.4.2.085](http://dx.doi.org/10.12989/was.2001.4.2.085)

ABSTRACT: The mechanism of wind-induced ovalling vibrations of cylindrical shells is numerically investigated by using a vortex method. The subject of this paper is limited to a two-dimensional structure in the subcritical regime. The aerodynamic stability of the ovalling vibrations in the second to fourth circumferential modes is discussed, based on the results of a forced-vibration test. In the analysis, two modal configurations are considered; one is symmetric and the other is anti-symmetric with respect to a diameter parallel to the flow direction. The unsteady pressures acting on a vibrating cylinder are simulated and the work done by them for one cycle of a harmonic motion is computed. The effects of a splitter plate on the flow around the cylinder as well as on the aerodynamic stability of the ovalling vibrations are also discussed. The consideration on the mechanism of ovalling vibrations is verified by the results of a free-vibration test.


ABSTRACT: This paper presents the effect of cone vertex angle on the crushing behaviour, energy absorption, failure mechanism and failure mode of filament-wound laminated (FWL) cone–cone intersection composite shell. The static crushing behaviour of FWL cone–cone intersection composite shell under uniform axial load is investigated experimentally. Two types of composites were tested, namely, carbon fibre/epoxy and glass fibre/epoxy. The cones vertex angles tested are 10°, 15°, 20° and 25°. Failure modes were examined using the photographs taken during crushing the specimens. The results showed that the initial failure was dominated by interfacial and shear failure, while the delamination and eventually fibre fracture dominated the failure mechanism after the initial first failure. The results also showed that the structure with vertex angles 20° and
25° exhibited good energy absorption capability. The volume reduction is obtained and found to be significant for these sets of angles.

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ABSTRACT: This paper examines the effect of residual fabrication stresses on the crushing behaviour, energy absorption, failure mechanism and failure mode of a filament wound laminated conical composite shell. The static crushing behaviour of the conical composite shell under uniform axial compressive load is investigated experimentally. The cone vertex angles were 0°, 6°, 12° and 18°. The numerical result shows that residual stresses developed have been concentrated at the small ends of cones. Experimental results obtained from this investigation show that the initial failure was dominated by interfacial and shear failure, while the delamination and eventually fibre fracture were dominated by the failure mechanism after the initial failure. It is also found that the static crushing behaviour of the conical shell is highly sensitive to the change in cone vertex angle, which strongly dominates the residual fabrication stress development. It can be deduced that as the axial residual stress increases, the initial failure load decreases.


ABSTRACT: For elastic-viscoplastic structures the classical elastic-plastic bifurcation approach to inelastic buckling is not valid. Only an elastic bifurcation point exists in the elastic-viscoplastic case, and the inelastic buckling behaviour is controlled by a strong sensitivity to small imperfections. However, in the last few years some papers have been published on an approximation that leads to a so-called viscoplastic bifurcation point. Results of accurate numerical analyses for elastic-viscoplastic columns are compared with predictions based on the approximate bifurcation approach. In some cases the bifurcation approach gives a poor approximation of the actual elastic-viscoplastic column behaviour, whereas in other cases the discrepancy is less pronounced. The simple column model gives a clear illustration of the effect, but similar results for plates are also mentioned briefly.


ABSTRACT: Free vibration of a thin spherical shell filled with a compressible fluid is investigated. The interactions at the interface between the elastic structure and the compressible fluid are taken into account. The objective of this study is to develop a hybrid numerical technique for the free vibration analysis of sound-structure interaction problems. The boundary element method is employed for modeling the acoustic disturbances in the cavity, while the finite element method is used for modeling the structural dynamics of the shell. The formulations are then combined into a coupled numerical scheme for the total pressure-displacement field. Natural frequencies and mode shapes are calculated by using the singular value decomposition algorithm.
Physical insights into the resonance phenomena associated with sound-structure interactions are derived from the comparison between the results of the thin spherical shell, with and without the fluid loading effect.


ABSTRACT: In offshore, aerospace and car industries, circular cylindrical shells are frequently used as structural components. In many applications, this is due to a requirement for a high axial compressive strength-to-weight ratio and an ability to absorb energy during complete structural collapse. On the other hand, the high imperfection sensitivity of circular cylindrical shells under axial compression requires a thorough knowledge of the occurrence of geometric imperfections and their influence on the collapse behaviour of the structure. In addition to the geometric imperfection sensitivity, a rate dependence of the material behaviour may have a significant influence on the collapse behaviour.

References listed at the end of the paper:


ABSTRACT: In this paper we develop a general theory of thin inelastic shells for finite deformations. In a first step we present a general three-dimensional theory of inelastic material behavior. Any inelastic constitutive model with internal state variables can be used which is formulated without the explicit notion of a yield surface. In a next step we investigate the simplifications of our constitutive theory resulting from the assumption of small elastic strains which is well established for metallic materials. Furthermore, we introduce the assumption of persistent isotropy. Finally, we present the weak form of the balance of equilibrium and
indicate its linearization. To formulate our shell theory we first present the geometrical description of thin shells in the reference and current configuration, respectively. Next we introduce strain measures for the shell where we include transverse shear strains and also thickness changes of the shell. The shell theory is formulated by application of the projection method, i.e. we integrate all relevant equations of the three-dimensional theory over the shell thickness. This projection leads to a strictly two-dimensional shell theory which is formulated entirely on the shell midsurface. Finally, we indicate the numerical implementation of our shell theory.

ABSTRACT: The viscoelastic buckling and postbuckling behaviors of fiber-reinforced plastic (FRP) circular cylindrical shells, operating in the hygrothermal environment, subjected to uniform external pressure are investigated in this study. The FRP is assumed to be a hygrothermoeologically simple material (HTSM). The analysis is conducted within the framework of the quasi-elastic approach. The finite element method is employed to examine both buckling and post-buckling behaviors for shells having arbitrary lay-ups. The arc-length algorithm is incorporated into the finite element formulations to trace the post-limit equilibrium path. The structural responses of Glass/Epoxy shells are reported.

N.N. Huang (Department of Mechanical and Marine Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.), “Influence of shear correction factors in the higher order shear deformation laminated shell theory”, International Journal of Solids and Structures, Vol. 31, No. 9, May 1994, pp. 1263-1277, doi:10.1016/0020-7683(94)90120-1
ABSTRACT: A third-order shell theory based on Reddy's parabolic shear strain distribution is presented. Upon applying the Donnell shallow shell approximation, the present theory leads to Reddy's formulation in the case that the laminate has a Euclidean middle surface and constant principal radii of curvatures. To accommodate the effect of the continuity condition of interlaminar transverse shear stresses, the shear correction factors are introduced to modify the shear strains in the present higher order theory. The shear correction factors are calculated using an iterative formulation based on the “shear strain energy equivalence”. The shell solutions are compared with the elasticity solutions to assess the improvement of using the higher order theory, coupled with the shear correction factors, in predicting the structural responses of moderately thick laminates.

ABSTRACT: Composite materials exhibit a scatter in their properties. This is generally ignored in conventional structural analysis leading to results that may be non-conservative. The present study discusses the critical buckling analysis for circular cylindrical shells of laminated composites incorporating the effects of randomness in the material properties. A perturbation approach has been employed to develop expressions for the mean and variance of the critical buckling load in terms of material property statistics. Working of the approach has been illustrated with an example.


ABSTRACT: A generalized layer-wise stochastic finite element formulation is developed for the buckling analysis of both homogeneous and laminated plates with random material properties. The pre-buckled stresses are considered in the derivation of geometric stiffness matrix and the effect of variation in these stresses on the mean and coefficient of variation of buckling strength is studied. The mean buckling strength of plates under uniform stress assumption exactly matches with those reported in the literature. However, it is shown that the actual mean buckling strength of plates can be significantly different based on the pre-buckled stress analysis which depends on boundary constraints, principal material directions, aspect and thickness ratios of plates. The statistics of buckling strength is determined using a Taylor series expansion based mean centered first order perturbation technique. The stochastic finite element solutions obtained using layer-wise plate theory is also validated with analytical solutions presented in this paper. Parametric studies are conducted for different aspect ratios, ply orientations and boundary conditions.


ABSTRACT: When a laminated composite plate is subjected to a compressive edge force lying in the plane of the plate, failure can occur by buckling at a stress below the strength of the material. Critical buckling loads of orthotropic plates are usually calculated using the analytical solutions which are based on the assumption of uniform end loads, despite the fact that real structures are subjected to various non-uniform inplane loads. This paper examines the buckling behavior of the orthotropic plates under non-uniform inplane loads with different boundary conditions (all edges simply supported, two loaded edges clamped and others simply supported, and all edges clamped) using the finite element method (FEM). Numerical results show that the existing formulas for buckling load based on the uniform load assumption leads to overestimation of buckling loads.


ABSTRACT: Optimum design of honeycomb sandwich constructions with buckling constraints is treated in this paper. Four modes of instability for honeycomb sandwich structures are considered in buckling constraints, including overall buckling, core shear instability, face wrinkling, and monocell buckling. The face thicknesses, core depth, cell wall thickness, and diameter of an inscribed circle in a honeycomb cell are taken as design variables. Eight-nodal quadrilateral honeycomb sandwich isoparametric shell elements and hybrid approximation techniques in combination with the dual solution are used. Some comparisons are also made between the cases with and without buckling constraints. Numerical results are given for four examples.

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ABSTRACT: The finite element method is applied to study the problem of moisture and temperature effects on the stability of a general orthotropic cylindrical composite shell panel subjected to axial or in-plane shear loading. The element employed is a nine-node isoparametric shell element. As the hygrothermal effects on the elastic properties of the matrices and the fibers are very different, the degradation of elastic moduli, the transverse shear effect and the induced initial stress are all considered. Numerical investigation shows that if the temperature increases from 300 to 422 K and the moisture concentration is saturated, the buckling load with both the degradation of elastic moduli and transverse shear deformation considered is ca. 12% lower than Snead and Papazotto’s result where only the degradation of elastic moduli was considered. In addition, it is shown that the influence of the initial stress, induced by the same environmental variations, on the buckling load is far less significant.


ABSTRACT: Based on the classical thin shell theory and the first-order shear deformation shell theory, two models are developed in this paper for predicting the torsional buckling loads of thin and thick shells of revolution. The material property of a shell of revolution is described as a general type of laminated composites and natural coordinates are used to define its geometry in which any kind of kinematic boundary condition can be applied precisely. To effectively use the axi-symmetric property of a shell of revolution in the analysis, a multi-level substructuring technique is employed in which only one substructure is involved in each substructuring level so the size of the problem in real computation is always kept very small. The torsional buckling behaviours of a circular cylinder, a conic shell, an elliptic hyperboloid shell and an ellipsoid shell are investigated using these models.


ABSTRACT: The large-amplitude oscillations and buckling of an anisotropic cylindrical shell subjected to the initial inplane biaxial normal stresses have been analysed. The concept of anisotropy used by Lekhnitsky has been introduced into the field equations for cylindrical shells of isotropic material deduced by Donnell. The method of Galerkin and the method of successive approximation have been used to obtain the desired approximate solution. The expression for the critical loads for the buckling of anisotropic cylindrical shells has been obtained during intermediate stages of analysis. Some relevant frequency response graphs of the obtained solution are also presented. The minimum critical loads for various classes of anisotropy have also been given at the end of the discussion, to exhibit the effects of large deflections and imperfections on elastic buckling.


ABSTRACT: The paper presents the differential equation system of buckling of shallow sandwich shells with thick faces in the case of general anisotropy. A closed form solution is derived for the determination of the buckling load which can be applied for a wide range of cases. It is also shown that, in the case of isotropic shells, the effect of shearing deformation can be taken into account in many cases analogously to Föppl's formula.


ABSTRACT: The aim of this paper is to determine the buckling shapes and loads of an isotropic cylinders subjected to temperature and/or mechanical loads. First, the governing differential equations for buckling are derived. Second, their solution is presented. The buckling shapes are found to be trigonometrical functions in a skew coordinate system. With the aid of these functions, closed form solutions are developed for calculating the buckling loads. The paper presents some examples which illustrate unexpected results, e.g., unconstrained cylinders subjected to a change in temperature may buckle at a critical temperature, and may buckle either with increasing or with decreasing temperature.


ABSTRACT: An analytical model describing the instability of specially orthotropic composite tubes with geometric imperfections subject to biaxial compressive loads and under clamped-clamped boundary conditions is developed. Furthermore, the range of validity of the present solution is clarified, and comparisons are made to some studies on isotropic cylindrical shells. Six E-glass woven fabric-epoxy composite tubes with the same internal radius and different thicknesses and longitudinal lengths were fabricated and subjected to various combinations of external hydrostatic pressure and axial compressive load simultaneously. The normalized buckling stresses were found to agree in general with the theoretical predictions at various biaxial loadings. The buckling envelopes in normalization form provide useful design data on the strength of specially orthotropic composite tubes under a realistic range of biaxial loading conditions.

References listed at the end of the paper:

Oscar Barton, Jr. (Mechanical Engineering Department, United States Naval Academy, Annapolis, MD 21402, USA), “Eigensensitivity analysis of moisture-related buckling of marine composite panels”, Ocean Engineering, Vol. 34, Nos. 11-12, August 2007, pp. 1543-1551, doi:10.1016/j.oceaneng.2006.12.007
ABSTRACT: In this paper, an approximate closed-form solution is presented to compute the moisture-related buckling of symmetric angle-ply laminates. The environment corresponds to a steady state condition, which provides a uniform moisture distribution for the laminate. The laminate consists of four layers [+theta/-theta] constructed of low, moderate and high stiffness ratio materials. Comparative results using the Rayleigh-Ritz method provides a means of assessing the accuracy of the expression. For certain laminate architectures, several modes must be computed to ascertain the lowest buckling mode, and once identified, provides an excellent approximation for the mode computed using the Rayleigh-Ritz method.

ABSTRACT: Due to the intrinsic heterogeneity of sandwich structures, phenomena at various scales can co-exist in these layered-like assembly of thick-soft and thin-stiff materials. Especially under in-plane compression loadings, geometrical instabilities can occur at both global (structure) and local (skins) scales. Therefore, the in-plane compressive response of sandwich structures is of major concern in designing structural applications. In the present paper, the first applications of a novel unified model for sandwiches are presented, with closed-form solutions for both global and local buckling. For the perfect structure, analytical critical loads are extracted for a simply supported beam, through the calculation of two eigenvalues leading to three buckling modes: it appears that the eigenvalue associated with the antisymmetrical mode can correspond to the occurrence of either global or local (wrinkling) buckling. These global and local loads from the present unified model are shown to compare very well with the predictions given by the most complete specific models from the literature. Moreover, it is shown that conversely to the classical models, our approach yields critical loads that depend only on rigorous well-founded mechanical hypotheses. The simple but general analytical expressions from the unified model permit to select quickly configurations against local and global buckling. In this simplified
framework, conclusions can be drawn from this unified model capable of properly predicting the phenomena at both scales. This simplified study is essential in getting an insight in the role played by each geometrical and material parameter, the combination of which is of importance for subsequent non-linear interactive post-buckling analyses.

ABSTRACT: This paper is dedicated to the study of global (at the sandwich scale) and local (at the component scale) buckling in sandwich structures. First, a unified analytical characterization is given for both global and local buckling. Then these analytical critical loads are translated into sandwich configuration selection diagrams. A 'light' FE model is then proposed to carry out low CPU-time non-linear post-buckling analyses. The post-buckling response computed for elastic materials are mostly super-critical, for small geometrical imperfections. But for some configurations, interactive buckling can develop yielding a highly sub-critical response due to the occurrence of some unsymmetrically distributed geometrical localizations. When an elastoplastic core is considered the response becomes systematically sub-critical, and limit loads reduce consequently. A strong imperfection sensitivity is also noticed.

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ABSTRACT: It is well known that the presence of bending-extension coupling in unsymmetrically laminated plates gives rise to bending curvatures under the action of pure in-plane loading. In view of this behaviour, it is generally believed that bifurcation buckling could normally not take place. In this investigation, the possibility of bifurcation instability in unsymmetrically laminated plates subjected to in-plane loading is examined. Based on the variationally consistent governing equations and edge conditions, conditions are derived which, if satisfied, ensure that the plate remains flat during the pre-buckling regime and thus guarantee bifurcation buckling. It is shown that these conditions are not essential for the bifurcation instability phenomenon to occur. A few plate configurations for which bending curvatures do occur during the pre-buckling stage but nevertheless still exhibit bifurcation instability are reported. The prescribed in-plane edge conditions assumed in the literature for the study of buckling phenomena are also examined with regard to their applicability. The existence of this phenomenon in the case of rectangular composite plates is demonstrated by modelling the plate with a four-node finite element having 10 degrees of freedom per node. a number of representative problems are examined, which reveal a number of interesting features.

ABSTRACT: The objective of the present paper is to investigate the influence of partial edge compression on the critical loads of moderately thick laminated plates. Towards this, an eight node isoparametric plate element is developed. The element has five degrees of freedom per node. The computer code developed accepts two sets of boundary conditions, one for pre-buckling stress analysis and the second for stability analysis. This flexibility is proposed to exploit the mid-line symmetry conditions. Two types of partial edge compression, viz., (I) uniform partial edge compression near the corners and (II) uniform partial edge compression at the middle of edges are considered. The effect of percentage of loaded edge length on the critical load of thin and thick composite plates with simply supported and clamped edge conditions is studied in detail.

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ABSTRACT: Post buckling behaviour of rectangular laminated plates subjected to thermal loads is investigated in this paper. For this purpose, a four-node, lock-free, rectangular composite plate finite element having six degrees of freedom per node viz three translations, two bending rotations about x- and y-axes and a twist is developed. The element is based on a bicubic representation of the transverse displacement field. The field descriptions for other variables are derived using equilibrium equations of strips along x- and y-axes of the plate. As a result field descriptions involve material properties apart from the usual geometric variables. 3◊3 Guass Quadrature formula is employed to compute the elemental matrices. Though an exact integration rule has been employed, the element is free of shear locking even in the extreme thin plate regimes. The effect of boundary conditions, aspect ratio, number of layers and lay-up sequence on the post-buckling behavior is studied in detail. The numerical examples solved herein reveal the possibility of secondary bifurcations from the primary post-buckling path.

ABSTRACT: Composites are known to display a considerable amount of scatter in their material properties due to a large number of parameters associated with their fabrication and manufacturing processes. In the present study, the material properties have been modeled as random variables for accurate prediction of the system behavior. Shear deformation effects have been incorporated in the governing equations. First-order perturbation technique has been employed to obtain the second-order buckling load statistics. The results have been presented for composite cylindrical panels with all edges simply supported. These results demonstrate the dependence of scatter in buckling loads on the basic random variables. The effects of side-to-thickness ratio, aspect ratio, curvature-to-side ratio and change in standard deviation of input random variables have been investigated for cross-ply symmetric and anti-symmetric laminates. The approach has been validated by a comparison of the results with those obtained with Monte Carlo simulation. The results for the mean buckling load with different shear deformation theories have also been compared with those available in the literature.
ABSTRACT: The initial buckling behavior of thick laminated composite curved panels with random material properties subjected to various in-plane edge loads has been investigated. For this purpose, an approach is presented to obtain the governing equation and the buckling load statistics with the help of an accurate C0 finite element in conjunction with first-order perturbation technique. A higher order shear deformation theory has been used for the laminate. The laminate material properties, subjected to inherent variations about the mean value, have been modeled as random variables. Results for second-order statistics of buckling load have been presented for laminated spherical panels and validated with available results in literature and Monte Carlo simulation. The influence of curvature-to-side ratio, side-to-thickness ratios and edge support conditions on buckling load statistics has been studied. The sensitivity of buckling load statistics for spherical panels to variations in material properties has been compared with that of cylindrical panels.

ABSTRACT: In this paper, the sensitivity of randomness in material parameters on the thermal buckling of conical shells embedded with and without piezoelectric layer is examined. A higher order shear deformation theory is used to model the system behaviour of the conical shell. The lamina material properties are modelled as basic random variables. A deterministic finite element method in conjunction with the first-order perturbation technique is employed to handle the randomness in the material properties. Typical numerical results for the second order statistics of the linear thermal buckling load of the composite conical shells/panels with and without piezoelectric layer are obtained. Mean value results are validated with those available in the literature and standard deviation results are also validated with an independent Monte Carlo simulation.

ABSTRACT: Post-buckling strength and the critical buckling load parameter of laminated composite cylindrical/hyperboloid shallow shell panel subjected to uniform temperature field is investigated in this paper. The mathematical model is developed taking into account the full nonlinearity effect in stiffness matrices in Green–Lagrange sense based on the higher order shear deformation theory. Governing equations are derived by minimizing the total potential energy of the system. The panel is represented with the nonlinear finite element model. The system equations are solved by a direct iterative approach to find out the thermal post-buckling equilibrium path. Influence of different parameters such as lamination scheme, modular ratio, amplitude ratio, thickness ratio, curvature ratio, aspect ratio and various support conditions have been examined in details. The results are compared with those available in literature.

ABSTRACT: Post-buckling analysis of a laminated composite spherical shell panel embedded with shape memory alloy fibres using non-linear finite element method”, Proceedings of the
In this article, the buckling and post-buckling behaviours of a laminated composite spherical shallow shell panel embedded with shape memory alloy (SMA) fibres are studied under a thermal environment. System equations for a laminated composite spherical shell panel embedded with SMA fibres are for the first time derived by modelling the geometric non-linearity in the Green–Lagrange sense and the material non-linearity in SMA fibres in the framework of the higher-order shear deformation theory. The shell panel model is discretized by using a non-linear finite-element approach. The governing algebraic equations are then derived by the variational approach and solved using a direct iterative technique. Influences of the thickness ratio, boundary condition, aspect ratio, curvature ratio, lamination scheme, SMA volume fraction, percentage of prestrain, and amplitude ratio on the buckling and post-buckling temperatures of a laminated composite shell panel with and without SMA have been examined in detail. The results are computed using the present model and compared with those available in the literature.


ABSTRACT: In this article, nonlinear free vibration behaviour of thermally post-buckled laminated composite spherical shallow shell panel is analyzed. The nonlinearity in geometry of the shell panel is considered in Green–Lagrange sense and the mathematical model is developed based on higher order shear deformation theory (HSDT). System of governing differential equations are derived using Hamilton’s principle. A direct iterative method in conjunction with nonlinear finite element approach is used to solve the system of equations. Effects of various geometries and material properties on the nonlinear free vibration frequencies are examined in detail and discussed. Results are obtained using the present model and are compared with those available in literature. The difference between the results speaks the necessity and the requirement of the present model for the prediction of actual nonlinear characteristics of the laminated structures having severe nonlinearity in thermal environment.


ABSTRACT: In the present paper, buckling loads of rectangular composite plates having nine sets of different boundary conditions and subjected to non-uniform inplane loading are presented considering higher order shear deformation theory (HSDT). As the applied inplane load is non-uniform, the buckling load is evaluated in two steps. In the first step the plane elasticity problem is solved to evaluate the stress distribution within the prebuckling range. Using the above stress distribution the plate buckling equations are derived from the principle of minimum total potential energy. Adopting Galerkin's approximation, the governing partial differential equations are converted into a set of homogeneous linear algebraic equations. The critical buckling load is obtained from the solution of the associated linear eigenvalue problem. The present buckling loads are compared with the published results wherever available. The buckling loads obtained from the present method for plate with various boundary conditions and subjected to non-uniform inplane loading are found to be in
excellent agreement with those obtained from commercial software ANSYS. Buckling mode shapes of plate for different boundary conditions with non-uniform inplane loadings are also presented.


ABSTRACT: Postbuckling equilibrium paths of simply supported cross-ply laminated cylindrical shell panels subjected to non-uniform (parabolic) inplane loads are traced in this paper. Love's shell theory with higher order shear deformation theory and von Kármán nonlinear strain–displacement relations are used in the mathematical formulation of the problem. In the first step, the plate membrane problem is solved to evaluate the stress distribution within the prebuckling range as the applied inplane edge load is non-uniform. The governing shell panel postbuckling equations are derived from the principle of minimum total potential energy using the above stress distributions. Adopting multi-term Galerkin's approximation, the governing equations are reduced into a set of non-linear algebraic equations. Newton–Raphson method in conjunction with Riks approach is employed to plot the postbuckling paths through limit points. Numerical results are presented for symmetric (0/90/0) crossply laminated cylindrical shell panels under parabolic inplane load, lateral distributed load and initial imperfections. Limit loads and snap-through behavior of shell panels are studied.

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ABSTRACT: The buckling behaviour of functionally graded cylindrical panels under thermal loading is investigated in this article. In functionally graded material, material properties vary smoothly from metal phase to ceramic phase. In this study, the effective material properties of the functionally graded panels are considered as temperature dependent and the gradation is taken in the transverse direction according to the power-law distribution of volume fractions of each constituent. Thermal buckling behaviour of cylindrical panel has been obtained numerically through ANSYS based on the ANSYS parametric design language code. The model has been discretised using an eight-node serendipity element with six degrees of freedom per node (SHELL281) from the ANSYS library. The solutions are obtained by solving the eigenvalue type buckling using Block Lanczos method. The accuracy of the model has been checked through corresponding convergence and comparison study with those available literatures. Finally, the simulation model has been extended to study the effect of different parameters such as power-law index, thickness ratio, curvature ratio and aspect ratio on buckling strength for both temperature independent and dependent material properties of each constituent.

References listed at the end of the paper:

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ABSTRACT: In this paper, the effect of random system properties on the post buckling load of geometrically nonlinear laminated composite cylindrical shell panel subjected to hygrothermomechanical loading is investigated. System parameters are assumed as independent random variables. The higher order shear deformation theory and von-Kármán nonlinear kinematics are used for basic formulation. The elastic and hygrothermal properties of the composite material are considered to be dependent on temperature and moisture concentration using micromechanical approach. A direct iterative based C0 nonlinear finite element method in conjunction with first-order perturbation technique proposed by present author for the plate is extended for shell panel subjected to hygrothermomechanical loading to compute the second-order statistics (mean and variances) of laminated composite cylindrical shell panel. The effect of random system properties, plate geometry, stacking sequences, support conditions, fiber volume fractions and temperature and moisture distributions on hygrothermomechanical post-buckling load of the laminated cylindrical shell panel are presented. The performance of outlined stochastic approach has been validated by comparing the present results with those available in the literature and independent Monte Carlo simulation.


ABSTRACT: An overview is presented of considerations involved and some of the more interesting results found in the buckling of laminated composite plates. In the case of plates which are symmetrically laminated, classical orthotropic or anisotropic plate theory applies, and numerous theoretical results are available. For unsymmetrical laminates coupling exists between bending of the plate and stretching of its midplane, and a considerably more complicated theory must be used. Additional complicating factors are considered, including: interior holes, shear deformation, sandwich construction involving other materials, local effects, nonlinear stress-strain relationships, and hygrothermal effects. Postbuckling behavior and the effects of initial geometric imperfections are also discussed. The results summarized are taken from a recent comprehensive study of the world’s literature on this subject, encompassing approximately 300 references.

References listed at the end of the paper:


24. Leissa, A. W., Conditions for laminated plates to remain flat under inplane loading, Composite Structures, 6 (1986), 261–270.


43. Harris, B. J., Strength properties and relationships associated with various types of fiberglass reinforced facing sandwich structures, Norman, Okla., University of Oklahoma Research Institute, Rept. No. 1386 - 16, 1964.

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ABSTRACT: Extensive and accurate numerical results are presented for the critical buckling loads of simply supported, rectangular, laminated composite plates subjected to five types of loading conditions: (1) uniaxial, (2) hydrostatic biaxial, (3) compression-tension biaxial, (4) positive shear and (5) negative shear. Considerably different results are found for the two types of shear loading for angle-ply composites. The Ritz method, along with displacements assumed in the form of a double sine series, is used to solve the problems. Convergence studies are presented to demonstrate the accuracy of the results. Contour plots of the buckled mode shapes are shown for some of the more interesting plate and loading configurations.

ABSTRACT: An optimal design is presented to determine the stacking condition that maximizes the lowest frequency of a laminated composite shallow shell with rectangular planform. The shallow shell considered has a symmetric laminate and is supported by shear diaphragms along the four edges. An analytical solution for natural frequencies is derived by discarding the cross-elasticity terms and then solving the governing equations of motion. In the optimization, fiber orientation angles in the layers are introduced as design variables, and a set of differential equations are presented which satisfy the Kuhn—Tucker optimality conditions. Formulas are then derived to give the possible optimal fiber orientation angles. Using numerical examples, the effects of various shell curvatures upon the optimal fiber orientation angles are discussed for a wide range of shallow shell configurations.

ABSTRACT: Based on the large deflection dynamic equations of axisymmetric shallow shells of revolution, the nonlinear forced vibration of a corrugated shallow shell under uniform load is investigated. The nonlinear partial differential equations of shallow shell are reduced to the nonlinear integral-differential equations by the method of Green’s function. To solve the integral-differential equations, expansion method is used to obtain Green’s function. Then the integral-differential equations are reduced to the form with degenerate core by expanding Green’s function as series of characteristic function. Therefore, the integral-differential equations become nonlinear ordinary differential equations with regard to time. The amplitude-frequency response under harmonic force is obtained by considering single mode vibration. As a numerical example, forced vibration phenomena of shallow spherical shells with sinusoidal corrugation are studied. The obtained solutions are available for reference to design of corrugated shells.

ABSTRACT: Based on the dynamic equations of nonlinear large deflection of axisymmetric shallow shells of revolution, the nonlinear free vibration and forced vibration of a corrugated shallow shell under concentrated load acting at the center have been investigated. The nonlinear partial differential equations of shallow shell were reduced to the nonlinear integral-differential equations by using the method of Green’s function. To solve the integral-differential equations, the expansion method was used to obtain Green’s function. Then the integral-differential equations were reduced to the form with a degenerate core by expanding Green’s function as a series of characteristic function. Therefore, the integral-differential equations became nonlinear ordinary differential equations with regard to time. The amplitude-frequency relation, with respect to the natural frequency of the lowest order and the amplitude-frequency response under harmonic force, were obtained by considering single mode vibration. As a numerical example, nonlinear free and forced vibration phenomena of shallow spherical shells with sinusoidal corrugation were studied. The obtained solutions are available for reference to the design of corrugated shells.

References listed at the end of the paper:

ABSTRACT: The nonlinear thermal buckling of symmetrically laminated cylindrically orthotropic shallow spherical shell under temperature field and uniform pressure including transverse shear is studied. Also the analytic formulas for determining the critical buckling loads under different temperature fields are obtained by using the modified iteration method. The effect of transverse shear deformation and different temperature fields on critical buckling load is discussed.


ABSTRACT:


ABSTRACT: Experiments have been carried out to determine the failure envelopes which describe the leakage and fracture strengths of thin walled ±55° filament wound E-glass fibre/epoxy tubes under a variety of biaxial stress states produced by applying combinations of internal pressure and axial tensile and compressive loads. The fracture strengths vary from 70 MPa to 900 MPa depending on the ratio of applied circumferential to axial stresses. For some combinations of loading leakage occurs at much lower stresses than final failure.

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ABSTRACT: Experimental data are presented to show the effects of winding angle on the strength of 100 mm diameter, 1 mm thick, filament wound E-glass fibre reinforced epoxy resin tubes tested under various combinations of internal pressure and axial tension or compression. Leakage and fracture strength envelopes are presented for ±45°, ±55° and ±75° winding angle tubes subjected to a wide range of different biaxial membrane stress states. Strengths range from 30 to 1250 MPa. Axial compression test results for tubes with wall thicknesses ranging from 1 to 3.6 mm establish the influence of shell buckling. Stress/strain curves up to fracture under three different types of loading show the effects of the winding angle on elastic constants and on nonlinear stress strain behaviour.

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ABSTRACT: Thin-walled filament wound glass fibre reinforced tubes supported on a rigid flat plate were loaded laterally by a rigid spherical indenter. The finite element technique was used for the prediction of deformation and strains in the tube up to failure which occurred at high levels of indentation. The analysis made allowance for the large displacements. The tube wall material was modelled as a monolithic, orthotropic continuum. The theoretical results are compared with experimental data from tube indentation tests. Final failure is shown to be due to local axial shell buckling.

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ABSTRACT: The finite element method has been used to analyse the behaviour of thin-walled, 100 mm diameter filament-wound GRP tubes supported on a flat plate and indented with a 50 mm diameter spherical indenter. The tube wall was treated as an angle-ply laminate and a half-tube model was employed with appropriate rotational symmetry conditions. The strain results were compared with those from a quarter-tube monolithic material model (homogeneous throughout and orthotropic with principal axes coincident with the axial and circumferential directions). The theoretical predictions were compared with experimental results. Local resin cracks occurred under the indenter. Two-cover (four-layer), 1 mm thick, ±55° and ±75° winding angle tubes finally failed at large indenter displacements by local shell buckling caused by the development of local axial compressive forces some distance away from the indenter. Four-cover (eight-layer), 2 mm thick, ±55° tubes delaminated under the indenter and failed by shell fracture, again some distance away from the indenter.


ABSTRACT: (cannot cut and paste)


ABSTRACT: The buckling and vibration of thick, orthotropic laminated composite shells is modelled using a simple layerwise higher-order theory. The theory accounts for a cubic variation of both the in-plane displacements and the transverse shear stresses within each layer, the latter being zero at the free surfaces without the need for shear correction factors. By imposing the continuity of the in-plane displacements and the transverse shear stresses at the interfaces, the number of variables is shown to be the same as that given by the FSDT, irrespective of the number of layers considered. A non-dimensionalized parameter called the General
Performance Index is defined in order to assess the overall performance of the models based on their flexural frequencies and the largest component of stress within the laminate. Numerical results for moderately short, one-, two- and three-layer shell panels are obtained for a range of base layer-to-core modulus of elasticity ratios. The normalized natural frequencies and stresses of the present theory are compared with a simple layerwise first-order theory and two other global higher-order theories that despite their similarity, indicate some interesting differences. The critical buckling loads are also given for a range of modulus and thickness ratios. Results indicate the present theory generally performs better over a range of the parameters mentioned predicting conservatively lower natural frequencies, smaller buckling loads and larger stresses for symmetric shells.


ABSTRACT: Unstiffened composite cylindrical shells show a large scatter in the load levels that the structure can withstand before buckling occurs. Such scatter is greatly influenced by the unavoidable imperfections of the structure, introduced during the fabrication phase. It is thus of key importance to be able to accurately model such imperfections in a numerical computation, in order to recreate and predict the scatter shown in experimental buckling tests. The imperfections can be analyzed by means of random fields, inferring their statistical properties from available measurements. In this manuscript, evolutionary spectra are used to derive random fields of surface and material imperfections of cylindrical shells. A procedure based on a moving window averaging technique is proposed in order to accurately capture the variation of material properties due to imperfect thickness and laminate manufacturing. Finally, Monte Carlo simulations of compression and torsional buckling of cylinders are carried out to show the combined effect of surface and thickness imperfections in the scatter of the buckling limit load.


ABSTRACT: An axisymmetric finite element is developed which includes such features as orthotropic material properties, doubly curved geometry, and both the first and second order nonlinear stiffness terms. This element can be used to predict the equilibrium state of an axisymmetric shell structure with geometrically nonlinear large displacements. Small amplitude vibration analysis can then be performed based on this equilibrium state. The nonlinear path is predicted by using the self-correcting incremental procedure and any point on the path can be checked by using the Newton-Raphson iterative scheme. The present formulation and solution procedure are evaluated by analyzing a series of examples with results compared with alternative known solutions. Examples include: free vibration of an isotropic cylindrical shell, a conical frustum, and an orthotropic cylindrical shell; buckling of a cylindrical shell; large deflection of a clamped disk, a spherical cap, and a steel belted radial tire. The final example is a free vibration analysis of the inflated tire and the natural frequencies obtained compared well with published experimental data.

ABSTRACT: To develop geometrically nonlinear, doubly curved finite shell elements the basic equations of nonlinear shell theories have to be transferred into the finite element model. As these equations in general are written in tensor notation, their implementation into the finite element matrix formulation requires considerable effort. The present paper will demonstrate how to derive the nonlinear element matrices directly from the incrementally formulated nonlinear shell equations using a tensor-oriented procedure. This enables the numerical realization of all structural responses, e.g. the calculation of pre- and post-buckling branches in snap-through analysis and especially in bifurcation analysis, including the detection of critical points and the consideration of geometric imperfections. To avoid loss of accuracy care is taken for a realistic computation of the geometric properties as well as of the external loads. Finally, the developed family of shell elements will be presented and its efficiency will be demonstrated by some applications to linear and geometrically nonlinear structural phenomena.


ABSTRACT: A 48-degree-of-freedom (d.o.f.) skewed quadrilateral thin shell finite element, including the effect of geometrical non-linearity, is formulated and appropriate numerical procedures are adopted for the development of an efficient approach for the static and dynamic analysis of general thin shell structures. The element surface is described by a variable-order polynomial in curvilinear co-ordinates. The displacement functions are described by bicubic Hermitian polynomials in curvilinear co-ordinates. The directions of the curvilinear co-ordinates at each nodal point are uniquely defined to coincide with the directions of the boundaries of the element. In the present case of a skewed quadrilateral with non-orthogonal curvilinear coordinates, the coupling terms of the metric tensor and curvature tensor of the surface no longer vanish, such as in the case of orthogonal co-ordinates. The tensor form is used in the setup of the shape functions, geometric derivatives, stiffness matrix and computer code. This allows for the treatment of shells with irregular shapes and variable curvatures. To evaluate the efficiency and accuracy of this formulation, a systematic list of examples is chosen: (i) linear and non-linear static analysis of square and rhombic plates, cylindrical and spherical shells; (ii) linear vibrations of trapezoidal flat and curved plates; (iii) large amplitude vibrations of a rhombic plate. For the square plate and cylindrical and spherical shell, skewed element meshes with various distortion angles are used to study the effect of the distortion angles on the accuracy of the results and to demonstrate the versatility of the present element. All results are compared with alternative available solutions including those obtained using regular rectangular meshes. Pinched thin cylindrical and spherical shells are studied using different skewed meshes and various Gauss integration meshes, and no membrane locking phenomenon is observed.


ABSTRACT: The emphasis of this paper is to use a thin shell finite element to study the dynamic buckling behavior of a class of thin shell problems due to the effects of three parameters with design significance: (1) axisymmetric and asymmetric imperfections; (2) orthotropic and anisotropic material properties; and (3) Rayleigh viscous damping. Five types of thin shells were considered: (1) an orthotropic annular spherical cap; (2) an orthotropic, axisymmetrically imperfect, whole spherical shell; (3) an axially compressed, laminated,
asymmetrically imperfect, cylindrical shell; (4) an orthotropic, axisymmetrically imperfect, spherical cap; and
(5) an orthotropic, asymmetrically imperfect, spherical cap. While some basic results are compared with
available solutions, extensive new results are also presented. The results quantify the effect of amplitude of
imperfections, which can significantly reduce the dynamic buckling load. The results also quantify the effects
of orthotropic material parameter and viscous damping.

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ABSTRACT: A 48 degree-of-freedom doubly-curved quadrilateral laminated thin shell element including the
effect of anisotropic plasticity is formulated to study the static, dynamic response and buckling of thin shell
structures. The effect of geometric nonlinearity is also included. The formulation is based on the Kirchhoff-
Love thin shell theory and classical lamination theory. In the plastic range, the Huber-Mises yield criterion
combined with the Prandtl-Reuss flow rule are used. The state of stresses and strains of each layer is calculated
individually, and then integrated through the whole thickness of the shell to obtain the stress and moment
resultants, and the stress-strain relation. The stress and strain components, the stress-strain relation, and the
yield function which is used to identify the plastic surface are obtained in principal material directions of each
layer and then transformed to those in local coordinate axes of the element. The formulation and solution
procedure are evaluated by comparing results of two examples with existing alternative solutions. The practical
applicability is demonstrated by performing a series of static and dynamic buckling analyses of laminated thin
spherical and cylindrical shells.

Beakou, A. and Touratier, M. (Laboratoire Génie de Production-ENIT, Avenue d'Azereix, B.P. 1629-65016
Tarbes Cedex, France), “A rectangular finite element for analysing composite multilayered shallow shells in
pp. 627–653. doi: 10.1002/nme.1620360406
ABSTRACT: This paper presents a new 32-degree-of-freedom finite element of multilayered composite,
moderately thick, shallow shells. The element is a four-node C1 rectangular element and is built from standard
interpolations but with a new kind of kinematics which allows us to exactly ensure the continuity conditions for
displacements and stresses at the interfaces between the layers of a laminated structure and the boundary
conditions at the upper and lower surfaces of the shell. The transverse shear deformation which is represented
by cosine functions is of a higher order and allows us to avoid shear correction factors. The element is evaluated
on standard problems and in comparison with exact three-dimensional and analytical solutions for multilayered
plates and shells in statics, vibrations and stability.

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“On a refined model in structural mechanics: Finite element approximation and edge effect analysis for
axisymmetric shells”, Computers & Structures, Vol. 54, No. 5, March 1995, pp. 897-920,
ABSTRACT: A two dimensional kinematics is proposed for moderately thick plates and curved shells without
any assumption other than neglecting the transverse normal strain. The transverse shear is taken into account by
using a function $f$ depending on the thickness coordinate and which is introduced in the assumed kinematics. The boundary value problem is derived from the principle of virtual power. With the function $f$ in the kinematics, all equations are directly applicable to Kirchhoff-Love, Reissner-Mindlin, Reddy theories and, obviously, our theory by using a certain sine function $f$. This latter is justified in plates from three-dimensional elasticity theory. The corresponding theory has been found efficient in statics (buckling) and in dynamics (free vibrations) for composite structures without needing shear correction factors. In addition, a new finite element is proposed to analyse axisymmetric semi-thick shells in elasticity and for small displacements. The element has three nodes and ten degrees of freedom, is of $C_1$ continuity for the transverse displacement and $C_0$ for the membrane displacement and the ‘membrane-shear’ rotation. Finally, an introduction to the edge effects for axisymmetric shells is presented. The study has shown some surprises concerning the hard clamped edge, in comparison with a two-dimensional eight node isoparametric solid finite element model used in reference.

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ABSTRACT: The aim of this work is to analyze the geometrically nonlinear mechanical behaviour of multilayered structures by a high order plate/shell finite element in order to predict displacements and stresses of such composite structures for design applications. Based on a conforming finite element method, a $C_1$ triangular six node finite element is developed using trigonometric functions for the transverse shear stresses. The geometric nonlinearity is based on von-Kármán assumptions and only five generalized displacements are used to ensure:

1. a cosine distribution for the transverse shear stresses with respect to the thickness co-ordinate, avoiding shear correction factors;
2. the continuity conditions between layers of the laminate for both displacements and transverse shear stresses;
3. the satisfaction of the boundary conditions at the top and bottom surfaces of the shells.

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ABSTRACT: This work deals with the performances of a refined shell model for modelizing cylindrical multilayered deep or shallow, thin or thick shells. To this end, new 3D analytical solutions are built from the well known Ren cylindrical shell panel and stand for reference solutions. Next, a parametric study varying the shell geometry (radius of curvature, thickness, curve side length of the panel) and the number of layers is carried out numerically using a $C_1$ finite element based on the present shell model. Numerical results are then compared to the new set of reference solutions established for laminates of 1, 2, 3 and 5 layers. Finally, use restrictions according to the shell geometry can be done. Moreover, indications about shell curvature can be obtained considering the ratio between radius and curve length.
References listed at the end of the paper:


ABSTRACT: The buckling behavior of circular cylindrical composite shells under axial compression, bending, and combined compression-bending is studied. Both Donnell-and refined Love-type equations of motion are solved using Galerkin's method. Numerical results reflecting a wide range of radius-to-thickness and length-to-thickness ratios are presented and discussed. The interaction between axial compression and bending in the combined loading case show significant deviation from the linear noninteracting beam-column type solutions.


ABSTRACT: A two-dimensional global higher-order deformation theory is presented for the evaluation of critical temperatures in cross-ply laminated composite shallow shells subjected to thermal loading. The effects of prebuckling deformations of the shells subjected to a temperature change that is independent of the in-plane coordinates are taken into account in the present analysis. By using the method of power series expansion of continuous displacement components, a set of fundamental governing equations which can take into account the effects of both transverse shear and normal stresses are derived through the principle of virtual work. Several sets of truncated $M$th order approximate theories are applied to solve the thermal buckling problems of a simply supported multilayered shell. Critical temperatures are shown for two cases of including the effects of prebuckling displacements and neglecting these effects. The modal stresses can be calculated by integrating the three-dimensional equations of equilibrium in the thickness direction, and satisfying the continuity conditions at the interface between layers and stress boundary conditions at the external surfaces. The present results are verified to be accurate enough for cross-ply laminated composite shallow shells through the convergence study and energy balance computations.


ABSTRACT: We analyze thermal buckling of both circular isotropic plates and square antisymmetric angle-ply laminates with a hole in the middle, and subject to a uniform temperature rise, by either closed form solution for the former or finite-element method for the latter. Thin-plate theory is used to analyze the isotropic plates. However, a high-order displacement theory including high-order terms along the transverse direction taking into account transverse normal strain is used in the case of laminates. Results for the isotropic plates indicate that in contrast to the reduction in mechanical buckling loads due to the hole, the thermal buckling temperature actually rises as the size of the hole increases, which indicates that the effect on stress reduction exceeds that on stiffness decrease. Results are more complicated for laminated plates, due to anisotropy.

Jeng-Shian Chang (Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan 10764, Republic of China), “FEM analysis of buckling and thermal buckling of antisymmetric angle-ply laminates according to transverse shear and normal deformable high order displacement theory”, Computers & Structures, Vol. 37, No. 6, 1990, pp. 925-946, doi:10.1016/0045-7949(90)90006-N
ABSTRACT: Buckling and thermal buckling of the antisymmetric angle-ply laminates clamped and subject to in-plane edge loads or a uniform temperature rise are analyzed by the finite element method. A higher order displacement theory including higher order terms along the transverse direction, taking into account transverse normal strain, is applied through the analysis. Effects of important parameters, such as ply angle, ratio of thickness to edge length, number of layers, ratio of in-plane to transverse modulus, etc. are studied. The numerical results are presented.


ABSTRACT: A higher-order deformation theory, which accounts for transverse shear and transverse normal strains, is derived for the thermal buckling analysis of antisymmetric angle-ply laminates that are simply supported and subject to a uniform temperature rise. The theory includes six dependent variables but can account for cubic distribution of in-plane displacements and parabolic distribution of transverse normal displacement. By using the present higher-order displacement field and the three-dimensional Hooke's law, exact-closed form solutions of the thermal buckling temperature are obtained. For purposes of comparison, numerical values of buckling temperature based on the first-order shear deformation theory and Reddy's higher-order shear deformation theory are also calculated, by reducing the present higher-order deformation theory. The results show that surprising discrepancies exist among the present theory and the other two theories, which indicates the importance of incorporating the effect of transverse normal strain in the thermal buckling analysis of antisymmetric angle-ply laminates.


ABSTRACT: The thermal buckling analysis of antisymmetric angle-ply laminated cylindrical shells that are simply supported and subjected to a uniform temperature rise is analyzed by a finite element method based on the higher order displacement functions. Comparisons to the first order displacement theory are made. Both theories allow transverse shear deformation, but only the higher order one takes into account the transverse normal strain. The numerical results show that first order theory overestimates the thermal buckling temperature of the shell panel, which suggests that the higher order displacement fields should be used in the analysis of thermal buckling for a laminated shell. Effects of important parameters are also studied.


ABSTRACT: The problem of overall buckling and postbuckling behavior of beam-like sandwich plates, which are composed of orthotropic face sheets and soft cores and are rigidly joined at one pair of opposite sides, are analyzed in this work. The other pair of edges is unsupported and widely separated so that the sandwich plates in fact act like wide beams and the complexity of analysis is reduced. The in-plane loads are assumed to apply at the middle of the rigid joints. A set of equilibrium equations and compatibility conditions are then formulated.
for the buckling and postbuckling behavior. Numerical examples based on finite difference methods and Newton-Raphson iterations for the nonlinear governing equations are presented. As the results indicate, the postbuckling behavior for such plates is found to be slightly unstable.

Jeng-Shian Chang and Chen-Hong Lin (Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan 10764), “Buckling and free vibration of cross-ply laminated circular cylindrical shells subjected to axial thrust and lateral pressure loading according to a higher order displacement field”, Thin-Walled Structures, Vol. 13, No. 3, 1992, pp.177-196, doi:10.1016/0263-8231(92)90040-4
ABSTRACT: An analytical solution is presented for the stability and free vibration of the cross-ply laminated thin circular cylindrical shells which are simply supported at both ends and subject to axial and lateral pressure. Based on the principles of virtual work and a nine-term higher order transverse shear and transverse normal deformable displacement field, a set of governing equations for thermal buckling of thin circular cylindrical shells together with the associated boundary conditions are derived. Navier double series method is then applied to find the closed-form solutions. Effects of important parameters such as degree of orthotropy, ratio of length to radius, ratio of radius to thickness, etc., are studied.

ABSTRACT: This work is concerned with a two-dimensional finite element study of the transient response of laminated thin circular cylindrical shell panels subjected to thermal impact under the framework of linear coupled thermoelasticity. A nine-node isoparametric element is applied to the FEM formulation. Numerous examples are given, in which the shell panels are assumed to be thermally isolated at four edges and the bottom surfaces and a heat flux is then imposed suddenly on their top surfaces. The effects of boundary conditions, ply-angles and radii of curvature are discussed. In addition, the differences between uncoupled and coupled problems are especially addressed.

ABSTRACT: The natural frequencies and critical velocities of laminated circular cylindrical shells with fixed-fixed ends conveying fluids are studied. Equations of motion are derived by the Hamilton principle under the scope of the Mindlin-type first-order transverse shear deformable cylindrical shell theory. Fluid pressure acting on the wall is obtained through the nonpenetration condition and the assumption of ideal flow. Dynamic characteristic equations are then obtained under the assumption of harmonic motion. Using linear superposition, the natural frequencies corresponding to each flow velocity are found by satisfying dynamic characteristic equation and boundary conditions. Critical velocities are those where the natural frequencies vanish, wherein the static divergence, i.e. buckling, occurs. Numerical examples are presented, in which the parameter studies include stacking angle, length-to-thickness and radius-to-thickness ratios.
ABSTRACT: A review of the analytical research of smart composite structures that have a relevance to buckling, vibrations, parametric vibrations, and dynamic stability of one and two-dimensional mechanical systems applied in mechanical and civil engineering is presented. Special attention is paid to the dynamic behavior of circular cylindrical shells due to nonuniform time-dependent temperature fields. The shell is heated, and it is assumed that a time- and space-dependent temperature field is known. To stabilize thermally induced transverse vibrations the host structure is integrated with a control system consisting of piezoelectric sensors and actuators. Distributed piezoelectric elements are implemented to suppress the motion caused by thermal disturbances. Two particular problems are analyzed in detail. The first is devoted to the stability analysis of a closed cylindrical shell subjected to a time-dependent temperature field. The stabilization is obtained by applying the velocity feedback and electroded piezoelectric sensors/actuators with a suitable polarization profile. In the second problem the technique of the dynamic stability analysis is extended to the thermally activated shape memory alloy hybrid rotating cylindrical shell.

ABSTRACT: Nonlinear vibrations of thin circular cylindrical shells are investigated in this paper. Based on Love thin shell theory, the governing partial differential equations of motion for the rotating circular cylindrical shell are formulated using Hamilton principle. Taking into account the clamped-free boundary conditions, the partial differential system is truncated by using the Galerkin method. Sequentially, the effects of temperature, geometric parameters, circumferential wave number, axial half wave number and rotating speed on the nature frequency of the rotating circular cylindrical shell are studied. The dynamic responses of the rotating circular cylindrical shell are also investigated in time domain and frequency domain. Then, the effects of nonlinearity, excitation and damping on frequency responses of steady solution are investigated.

References listed at the end of the paper:

ABSTRACT: Vibration characteristics of micro-scale simply supported cylindrical shells conveying fluid and embedded in an elastic medium are analysed using the new equations of motion developed based on the modified couple stress theory. It is found that the natural frequencies predicted by the established model are size-dependent, and change with the fluid flow velocity and elastic medium parameter. The size dependence is shown when the characteristic radius size is comparable with the material length-scale parameter, but decreases with the increase in characteristic size. The fluid inside the shell is also found to help in decreasing natural frequency sharply.

ABSTRACT: In this paper, a simple process is suggested to estimate the interfacial toughness of the material system 'aluminum film/soft PDMS substrate'. The specimen, i.e. the aluminum film deposited on the soft polydimethylsiloxane (PDMS) substrate, is subject to a tensile load, and delaminating and buckling of aluminum film are observed in the perpendicular direction to the tensile strain. With the aid of the buckling blisters, the interfacial toughness of the material system is estimated. Large deformation is considered during the buckling of the thin film, and the interfacial toughness is deduced from a fracture theory. Besides, the evolution from one single blister to three blisters and then four blisters is observed in situ under microscope. This simplified method has potential applications to flexible electronics in which interfacial toughness of the metal film/soft substrate must be well controlled.


ABSTRACT: An investigation is carried out to understand the thermal buckling behavior of local delamination near the surface of fiber-reinforced laminated cylindrical shells and the delaminated growth. The shape of the delaminated region considered is elliptic and triangular. The direction of the fiber material's axis is arbitrary. The relationships between the critical thermal load and the geometrical and physical parameters of base laminated shells and sublaminated shells are described and some valuable conclusions are obtained. Finally, the possible expanding direction of the elliptic and triangular delaminated shape under thermal load is discussed.


ABSTRACT: In this article, a novel numerical approach for the delamination growth simulation in composite panels under compressive load is proposed. This approach, suitable for preliminary design and optimization purposes, is able to simulate the delamination propagation by means of a limited number of linear analyses. It is based on the determination of the delamination buckling and on the evaluation of the energy released during the delamination propagation by means of eigenvalue and linear static analyses. The proposed approach has been implemented into the finite element code ANSYS and applied to composite panels with circular embedded and rectangular through-the-width delaminations under compressive load. A first validation has been carried out by comparing the results in terms of delamination growth load and energy release rate distributions along the delamination front to two-dimensional and three-dimensional nonlinear results taken from literature.

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ABSTRACT: In this paper, the postbuckling governing equations and the analytical expression of the energy release rates associated with delamination growth in a compression-loaded cylindrical shell are derived by using the variational principle of moving boundary and the Griffith fracture criterion. The finite difference method is used to generate the postbuckling solutions of the delaminated cylindrical shells, and with these solutions, the values of the energy release rates are determined. In simulational examples, the effects of a wide range of parameters, such as delamination sizes and depths, boundary conditions, geometrical parameters, material properties and laminate stacking sequences on the energy release rates of axisymmetrical laminated cylindrical shells are intensively discussed.

References listed at the end of the paper:
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ABSTRACT: The growth of delamination in cylindrical shells under external pressure may lead to structural failure. Based on the variational principle of moving boundary (Qian WC. Variational calculus and finite element. Beijing: Science Press; 1980 [in Chinese].) and considering the contact effect between delamination regions, in this paper, the nonlinear governing equations for the delaminated cylindrical shells are derived, and the corresponding boundary and matching conditions are given. Moreover, according to the Griffith criterion, the formulas of energy release rate along the delamination front are obtained. As the numerical example, the delamination growth of axisymmetrical laminated cylindrical shells is analyzed, and the effects of delamination sizes and depths, geometrical parameters, material properties and laminate stacking sequences on delamination growth are discussed.


ABSTRACT: The dynamic stability is studied for isotropic viscoelastic cylindrical shell and symmetrically cross-ply laminated viscoelastic cylindrical shell under constant axial loading. The basic equations are established based on Timoshenko-Mindlin theory, the characteristics equation are derived by Laplace transformation for those two kinds of cylindrical shells with two simply supported ends. The stability condition applied in the calculation of critical loads is determined through Routh-Hurwitz theorem. In the numerical examples, critical loads are reduced due to the relaxation feature of the materials and greater effects of transverse shearable deformation on the critical loads are observed in symmetrically cross-ply laminated viscoelastic cylindrical shell than in isotropic viscoelastic cylindrical shell. The influence of rotary inertia is rather small and can be ignored.

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ABSTRACT: The delamination growth may occur in delaminated cylindrical shells under external pressure. This will lead to failure of structure. By using the variational principle of moving boundary and considering the contact effect between delamination regions, in this work, the delamination growth was investigated for cylindrical shells under the action of external pressure. At the same time, according to the Griffith criterion, the formulas of energy release rate along the delamination front were obtained. In the numerical calculation, the
delamination growth of axisymmetrical laminated cylindrical shells was analyzed, and the effects of delamination sizes and depths, the geometrical parameters, the material properties, and the laminate stacking sequences on delamination growth were discussed.

References listed at the end of the paper:


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ABSTRACT: The delamination growth may occur in delaminated cylindrical shells subjected to external dynamic load and it will further cause structural failure. Based on the variational principle of moving boundary and considering the contact effect between delamination regions, in this paper, the nonlinear governing equations for the delaminated cylindrical shells under the action of circumferential concentrated dynamic load are derived, and the corresponding boundary and matching conditions are given. At the same time, according to the Griffith criterion, the formulas of energy release rate along the delamination front are obtained and the delamination growth is studied. In the numerical calculation, the delamination growth of axisymmetrical
laminated cylindrical shells is analyzed, and the effects of the delamination sizes and depths, the geometrical parameters, the material properties and the laminate stacking sequences on delamination growth are discussed.

Hong Xiang, Yi-ming Fu and Yong-hong Lu, “Post-buckling analysis of orthotropic plate considering damage”, Journal of Hunan University (Natural Sciences), 2007-09
ABSTRACT: On the basis of algebra invariant theory, the expression of Helmholtz's free energy for orthotropic material considering damage effect was derived. Then, the corresponding constitutive relationship and damage evolution equations were obtained, based on irreversible thermodynamics theory. From Von Karman's plate theory, the nonlinear buckling equations for orthotropic material considering damage effect were founded. Numerical results have indicated that the deflection of the plate under constant load cannot remain unchanged but increases with time due to the damage evolution, and the influences of damage on the deflection of the plate are more and more obvious with the load and initial deflection increase and the length-width ratio decrease.

ABSTRACT: A set of nonlinear motion equations for laminated shallow spherical thick shell subjected to impact loading is established. According to the Hertzian law and the effect of contact between the striking object and the shallow spherical shell, the contact force acted on the shell is determined. By using the finite difference method and the time increment procedure, the nonlinear equations are resolved. In the numerical examples, the effects of initial impact velocity, the radius of the middle surface and the point of contact on the impact forces and displacements of the shells are discussed.

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ABSTRACT: The good performance of the mixed degenerate shell finite element with drilling degrees of freedom (DDSE) in linear and nonlinear static analysis problems is in the basis of the present work concerned with its extension to nonlinear dynamic regime. The 9-noded element (DDSE9) has exhibit in a previous work the best performance among the other elements of the DDSE family. It is, consequently, chosen to experience the nonlinear dynamic behaviour in this paper. Both geometrical and material nonlinearities are taken into account and the different integration schemes are considered in the present investigation. The results of the benchmarks treated by the DDSE proved its accuracy and efficiency when compared to those available in the literature. This conclusion will enhance the main advantage of this kind of elements which remains their suitability to model many engineering problems without any numerical "tricks" or adjustments.
References listed at the end of the paper:
Dynamic stability of piezoelectric laminated cylindrical shells with delamination

ABSTRACT: The dynamic stability of a composite laminated cylindrical shell containing a throughout delamination along circumferential direction integrated with piezoelectric layers at both inner and outer surfaces is investigated in this article. The Heaviside step function is used to describe the displacement components in the regions with and without delamination. Based on the classical shell theory, linear piezoelectric constitutive...
relationship, and variational principle, the governing equations of motion are derived and then solved by employing Rayleigh–Ritz method and Bolotin method to obtain the principal unstable region. Numerical results are presented in both tabular and graphical forms to show the effects of the piezoelectric layer; the length, depth, and location of the delamination; and the static axial force on the resonance frequency and the principal unstable region of the delaminated piezoelectric laminated shell.


Abstract: Based on the first order shear deformation theory and classic buckling theory, the paper investigates the creep buckling behavior of viscoelastic laminated plates and laminated circular cylindrical shells. The analysis and elaboration of both instantaneous elastic critical load and durable critical load are emphasized. The buckling load in phase domain is obtained from governing equations by applying Laplace transform, and the instantaneous elastic critical load and durable critical load are determined according to the extreme value theorem for inverse Laplace transform. It is shown that viscoelastic approach and quasi-elastic approach yield identical solutions for these two types of critical load respectively. A transverse disturbance model is developed to give the same mechanics significance of durable critical load as that of elastic critical load. Two types of critical loads of boron/epoxy composite laminated plates and circular cylindrical shells are discussed in detail individually, and the influencing factors to induce creep buckling are revealed by examining the viscoelasticity incorporated in transverse shear deformation and in-plane flexibility.


Abstract: The present study employs the method of atomistic simulation to estimate the thermal stress experienced by Si/Ge and Ge/Si, ultrathin, core/shell nanowires with fixed ends. The underlying technique involves the computation of Young’s modulus and the linear coefficient of thermal expansion through separate simulations. These two material parameters are combined to obtain the thermal stress on the nanowires. In addition, the thermally induced stress is perceived in the context of buckling instability. The analysis provides a trade-off between the geometrical and operational parameters of the nanostructures. The proposed methodology can be extended to other materials and structures and helps with the prediction of the conditions under which a nanowire-based device might possibly fail due to elastic instability.


Abstract: The aim of this paper is to establish a continuum elastic model for core–shell nanowires with weak interfacial bonding. In order to achieve it, a new beam model is proposed, which vanishes the surface shear stress and satisfies the interfacial cohesive law automatically. Critical buckling loads and resonant frequencies of simply supported nanowires are obtained by using the Ritz method. Numerical examples indicate that the weak interface's effect reduces the overall structural stiffness, which is most significant when the inner–
outer radius ratio of the shell is near 0.65. It is also found that the shear deformation and weak interface's effects only need consideration when the nanowire is not quite long, and they affect buckling behaviors more significantly than vibration characteristics.

ABSTRACT: The lithiation and de-lithiation during the electrochemical cycling of lithium–ion batteries (LIBs) can introduce local deformation in the active materials of electrodes, resulting in the evolution of local stress and strain in the active materials. Understanding the structural degradation associated with lithiation-induced deformation in the active materials is one of the important steps towards structural optimization of the active materials used in LIBs. There are various degradation modes, including swelling, cracking, and buckling especially for the nanowires and nanorods used in LIBs. In this work, a shear-lag model and the theory of diffusion-induced stress are used to investigate diffusion-induced buckling of core–shell nanowires during lithiation. The critical load for the onset of the buckling of a nanowire decreases with the increase of the nanowire length. The larger the surface current density, the less the time is to reach the critical load for the onset of the buckling of the nanowire.

ABSTRACT: Yeast cells can be regarded as micron-sized and liquid-filled cylindrical shells. Owing to the rigid cell walls, yeast cells can bear compressive forces produced during the biotechnological process chain. However, when the compressive forces applied on the yeast go beyond a critical value, mechanical buckling will occur. Since the buckling of the yeast can change the networks in its cellular control, the experimental research of the buckling of the yeast has received considerable attention recently. In this paper, we apply a viscoelastic shell model to study the buckling of the yeast. Meanwhile, the turgor pressure in the yeast due to the internal liquid is taken into account as well. The governing equations are based on the first-order shear deformation theory. The critical axial compressive force in the phase space is obtained by the Laplace transformation, and the Bellman numerical inversion method is then applied to the analytical result to obtain the corresponding numerical results in the physical phase. The concepts of instantaneous critical buckling force, durable critical buckling force, and delay buckling are set up in this paper. And the effects of the transverse shear deformation and the turgor pressure on the buckling phenomena are also given. The numerical results show that the transverse shearing effect will decrease the instantaneous critical buckling force and the durable critical buckling force, while the turgor pressure will increase both of them.

ABSTRACT: An asymptotic theory is developed for dynamic response of anisotropic inhomogeneous and laminated cylindrical shells. The formulation is based on three-dimensional elasticity without a priori
assumption. By means of asymptotic expansion with multiple time scales, the basic equations are decomposed into differential equations of various orders which can be integrated successively. It is shown that the three-dimensional asymptotic solution to the problem can be determined hierarchically by solving the two-dimensional equations in the classical laminated shell theory. Modifications to the solution are obtained in a systematic way by treating the higher-order equations and eliminating the secular terms. Various thickness effects, such as transverse shear and rotary inertia, can be accounted for in a natural and consistent manner. It is demonstrated along the way that a uniform expansion that yields asymptotic solution valid regardless of the time span is obtained with the use of multiple time scales, whereas a straightforward expansion fails to produce valid results for long times. The theory is illustrated by determining the vibration characteristics of a multilayered cross-ply cylindrical shell.


ABSTRACT: An asymptotic theory for dynamic analysis of doubly curved laminated shells is formulated within the framework of three-dimensional elasticity. Multiple time scales are introduced in the formulation so that the secular terms can be eliminated in obtaining a uniform expansion leading to valid asymptotic solutions. By means of reformulation and asymptotic expansions the basic three-dimensional equations are decomposed into recursive sets of equations that can be integrated in succession. The classical laminated shell theory (CST) is derived as a leading-order approximation to the three-dimensional theory. Modifications to the leading-order approximation are obtained systematically by considering the solvability conditions of the higher-order equations. The essential feature of the theory is that an accurate elasticity solution can be determined hierarchically by solving the CST equations in a consistent way without treating the layers individually. Illustrative examples are given to demonstrate the performance of the theory.


ABSTRACT: The asymptotic theory developed recently for dynamic analysis of doubly curved laminated shells is refined by including the transverse rotations as auxiliary variables. The theory embraces the first-order shear deformation theory (FSDT) and the higher-order shear deformation theory (HSDT) as the first-order approximation. Higher-order corrections to the approximation are determined by solving the FSDT or HSDT equations in a hierarchic way. The secular terms in the asymptotic solution are eliminated systematically by means of multiple scales and solvability conditions for the higher-order equations. The performance of the refined theory is illustrated by applying it to benchmark problems. Numerical comparisons are made to examine the convergence of the solutions.

ABSTRACT: On the basis of 3D elasticity, asymptotic solutions for buckling analysis of multilayered anisotropic conical shells under axial compression are presented. By means of proper nondimensionalization, asymptotic expansion, and successive integration, the classical shell theory is derived as a first-order approximation to the 3D theory. Because the governing equations for various orders consist of partial differential equations with variable coefficients, the use of analytical techniques is restricted. The method of differential quadrature is adopted in the present study. The modifications of the buckling loads and associated buckling modes can be determined in a consistent and hierarchic manner by considering the solvability and normalization conditions for various orders. The critical loads of cross-ply conical shells with simply supported-simply supported boundary conditions are studied to demonstrate the performance of the present asymptotic theory.

References listed at the end of the paper:


ABSTRACT: Laminated composite plates are fabricated of laminae (also called layers or plies), where each lamina consists of high-strength fibres (e.g. glass, boron, graphite) embedded in a surrounding matrix material
(e.g. epoxy resin). The present work is limited to laminae wherein the fibres are assumed to be all parallel and continuous (i.e. long fibres). Thus each layer may be treated in a macroscopic sense as being a homogeneous, orthotropic material, for which the deformation behaviour is linearly elastic.

References listed at the end of the paper:


**ABSTRACT:** Within the framework of three-dimensional (3D) elasticity, an asymptotic theory is presented for the thermoelastic buckling analysis of laminated composite conical shells subjected to a uniform temperature change. A dimensionless parameter of thermal load related to the temperature change is defined. The method of perturbation is applied in the present formulation where the critical thermal loads and the primary field variables are expanded as a series of even powers of a small perturbation parameter. Through a straightforward derivation, the asymptotic formulation leads to recursive sets of governing equations for various orders. The
classical shell theory is derived as a first-order approximation to the 3D theory. The method of differential quadrature is used to solve for the asymptotic solutions at each order level. The solvability conditions and normalization conditions for higher-order problems are derived. By considering these conditions, we can obtain the higher-order modifications. The critical thermal loads of simply supported, cross-ply conical shells are studied to demonstrate the performance of the present asymptotic theory.


ABSTRACT: A refined asymptotic theory for the static analysis of laminated circular conical shells is presented. The formulation begins with the basic equations of three-dimensional (3D) elasticity in curvilinear circular conical coordinates. By means of proper nondimensionalization and asymptotic expansion, the 3D equations can be decomposed into recursive sets of differential equations at various levels. After bringing the effect of transverse shear deformations to the picture earlier and then applying successive integration, we obtain the recursive sets of governing equations leading to the ones of first-order shear deformation theory (FSDT). The FSDT becomes a first-order approximation to the 3D theory. The method of differential quadrature (DQ) is used for determining the present asymptotic solutions for various orders. The illustrative examples are given to demonstrate the performance of the present asymptotic theory.


ABSTRACT: Thermally induced dynamic instability of laminated composite conical shells is investigated by means of a perturbation method. The laminated composite conical shells are subjected to static and periodic thermal loads. The linear instability approach is adopted in the present study. A set of initial membrane stresses due to the elevated temperature field is assumed to exist just before the instability occurs. The formulation begins with three-dimensional equations of motion in terms of incremental stresses perturbed from the state of neutral equilibrium. After proper nondimensionalization, asymptotic expansion and successive integration, we obtain recursive sets of differential equations at various levels. The method of multiple scales is used to eliminate the secular terms and make an asymptotic expansion feasible. Using the method of differential quadrature and Bolotin's method, and imposing the orthonormality and solvability conditions on the present asymptotic formulation, we determine the boundary frequencies of dynamic instability regions for various orders in a consistent and hierarchical manner. The principal instability regions of cross-ply conical shells with simply supported–simply supported boundary conditions are studied to demonstrate the performance of the present asymptotic theory.

ABSTRACT: A methodology to select the best material combination and optimally design composite sandwich cylinders having fibre reinforced skins and low density cores for minimum mass is described. Sandwich constructions generally provide improved stiffness/mass ratios and more tailoring opportunities than monolithics, and thus greater chance of satisfying design constraints. The objective of the optimisation is to minimise the laminate mass by selecting the skin and core material combination, layer thicknesses and skin fibre angles optimally, subject to load and cost constraints. As the optimisation problem contains a number of continuous (ply angles and thicknesses) and discrete (material combinations) design variables, a sequential solution procedure is devised in which the optimal variables are computed in different stages. The procedure and its benefits are demonstrated using Graphite, Glass or Kevlar/Epoxy facings, and Balsa or PVC cores.


ABSTRACT: This paper presents an efficient numerical integration scheme for evaluating the matrices (stiffness, mass, stress-stiffness and thermal load) for a doubly curved, multilayered, composite, quadrilateral shell finite element. The element formulation is based on three-dimensional continuum mechanics theory and it is applicable to the analysis of thin and moderately thick composite shells. The conventional formulation requires a 2 x 2 x 2 or 2 x 2 x 1 Gauss integration per layer for the calculation of element matrices. This method becomes uneconomical when a large number of layers is used owing to an excessive amount of computations. The present formulation is based on explicit separation of the thickness variable from the shell surface parallel variables. With the through-thickness variables separated, they are combined with the thickness dependent material properties and integrated separately. The element matrices are computed using the integrated material matrices and only a 2 x 2 spatial Gauss integration scheme. The response results using the present formulation are identical to those obtained using the conventional formulation. For a small number of layers, the present method requires slightly more CPU time. However, for a larger number of layers, numerical data are presented to demonstrate that the present formulation is an order-of-magnitude economical compared to the conventional scheme.


ABSTRACT: This study presents the dynamic equations of a stiffened composite laminated conical thin shell under the influence of initial stresses. The governing equations of a truncated conical shell are based on the Donnell-Mushtari theory of thin shells including the transverse shear deformation and rotary inertia. The extension-bending coupling is considered in the derivation. The composite laminated conical shell is also reinforced at uniform intervals by elastic rings and/or stringers. The stiffening elements are relatively closely spaced, and therefore the stiffeners are smeared out along the conical shell. The inhomogeneity of material properties because of temperature, moisture, or manufacturing processes is taken into account in the constitutive equations. A generalized variational theorem is derived so as to describe the complete set of the fundamental equations of the conical shell. Next, the uniqueness is examined in solutions of the dynamic equations of the conical shell, and the boundary and initial conditions are shown to be sufficient for the uniqueness in solutions. The equations of the laminated composite conical shell are solved by the use of the finite difference method as an illustrative example. The accuracy of results is tested by certain earlier results, and a good agreement is found.

References listed at the end of the paper:


ABSTRACT: (none given)


ABSTRACT: The buckling behavior of laminated composite plates subjected to a uniform temperature field is studied. Transverse shear flexibility is accounted for in the analysis using the thermo-elastic version of the first-order shear deformation theory. The prebuckling behavior of the plate under a uniform temperature field is studied prior to predicting the initial thermal buckling load. Numerical results are presented for thermal buckling problems using a nine-noded isoparametric quadrilateral finite element. The influence of boundary conditions, ply orientation, and plate geometries on the critical buckling temperature is examined.

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ABSTRACT: The thermal stress analysis of laminated doubly curved shallow shells is presented using a shear flexible finite element model. The basic equations of the laminated shell theory are the extensions of Sanders' shell theory to include shear deformation and the thermal strains. The present finite element solution for isotropic and composite plates is compared with the closed form solutions available in the literature. A wide variety of laminated shell problems subjected to different temperature fields are studied. The influence of temperature dependent material properties, panel sizes, and boundary conditions on the thermal deformations are demonstrated.

K. Chandrashekhara and D. V. T. G. Pavan Kumar (Department of Civil Engineering, Indian Institute of
ABSTRACT: This paper examines the accuracy of classical shell theories (CST) according to Flugge, Sanders, Love and Donnell, with respect to the recently available three-dimensional elasticity solution, for cross-ply laminated circular cylindrical shells under static loads. Further, a study has also been made to examine to what extent incorporation of first order shear deformation (FSDT), in aforementioned shell theories, improves the results. In general, all the basic equations (for both CST and FSDT), of aforementioned shell theories, have been presented in a unified form using tracer coefficients. A Navier type solution has been used to analyse both a simply supported circular cylindrical shell of revolution and an all round simply supported circular cylindrical shell panel. A parametric study has been carried out keeping in view the lamination schemes and geometrical parameters of the shell. From the detailed comparisons of the results it has been shown that (i) Donnell's theory (CST and FSDT) could be in error for certain lamination schemes and geometrical parameters and (ii) improved results for stresses and displacements could be obtained by incorporating shear deformation on more accurate theory like Flügge’s.


ABSTRACT: A detailed study, on the static response of cross-ply laminated composite circular cylindrical shell of revolution and shell panel with various support conditions, has been made using Levy type of solution and the classical shell theories of Fl Sanders, Love and Donnell in an unified form. It has been shown that while developing a Levy type of solution using aforementioned theories, certain difficulty is encountered for determining the particular integral in respect of Fl Sanders and Love theories. This difficulty has been overcome by making use of the membrane solution as a particular integral. A comparative study has been carried out using the above shell theories for different geometrical parameters, lamination schemes and support conditions. It has been shown that Donnell theory predicts inaccurate results for certain lamination schemes, support conditions and geometrical parameters of the shell. It is suggested that, for developing shear deformation shell theories, it would be better to use a more accurate shell theory like Flügge.

References listed at the end of the paper:


ABSTRACT: The buckling analysis of cross-ply laminated square plates subjected to three types of in-plane forces and various edge boundary conditions is presented on the basis of a unified five-degree-of-freedom shear deformable plate theory. The employment of the appropriate “shear deformation shape functions” in the theory leads to certain shear deformable plate theories developed previously, also, fulfills the requirement of the continuity conditions among the layers. The governing equations of buckling behaviour of completely simply supported cross-ply laminated plates are solved analytically. For the plates with different combinations of free, clamped and simply supported boundary conditions at their edges, the Ritz method is applied by assuming the displacement components as the double series of simple algebraic polynomials. The numerical results obtained on the basis of various plate theories for uniaxial, biaxial compression and compression–tension types of loading and different length-to-thickness ratios are presented and compared with the ones available in the literature.


ABSTRACT: In the present study, unified shear deformation theory which was proposed by Soldatos, K.P. and Timarci, T. (1993). A Unified Formulation of Laminated Composite, Shear Deformable Five-degrees-of-freedom Cylindrical Shells on the Basis of a Unified Shear Deformable Shell Theory, Compos. Struct., 25(1–4): 165–171 is used to analyze simply supported symmetric cross-ply rectangular plates for deflections, stresses, natural frequencies, and buckling loads. This theory enables the selection of different in-plane displacement components to represent shear deformation. Exponential shear deformation theory, which is proposed by Karama et al., 40(6) (2003). Mechanical Behavior of Laminated Composite Beam by New Multi-layered Laminated Composite Structures Model with Transverse Shear Stress Continuity, Int J Solids Struct., 40: 1525–1546, is used for the first time to analyze the problem considered. Results which are found by exponential

Noureddine El Meiche (1), Abdelouahed Tounsi (1 and 2), Noureddine Ziane (1), Ismail Mechab (1) and El Abbes Adda.Bedia (1)
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ABSTRACT: A new hyperbolic shear deformation theory taking into account transverse shear deformation effects is presented for the buckling and free vibration analysis of thick functionally graded sandwich plates. Unlike any other theory, the theory presented gives rise to only four governing equations. Number of unknown functions involved is only four, as against five in case of simple shear deformation theories of Mindlin and Reissner (first shear deformation theory). The plate properties are assumed to be varied through the thickness following a simple power law distribution in terms of volume fraction of material constituents. The theory presented is variationally consistent, does not require shear correction factor, and gives rise to transverse shear stress variation such that the transverse shear stresses vary parabolically across the thickness satisfying shear stress free surface conditions. Equations of motion are derived from Hamilton's principle. The closed-form solutions of functionally graded sandwich plates are obtained using the Navier solution. The results obtained for plate with various thickness ratios using the theory are not only substantially more accurate than those obtained using the classical plate theory, but are almost comparable to those obtained using higher order theories with more number of unknown functions.


ABSTRACT: The present study is concerned with the buckling analysis of cross-ply laminated beams subjected to different sets of boundary conditions. The analysis is based on a three-degree-of-freedom shear deformable beam theory. The requirement of the continuity conditions between layers for symmetric cross-ply laminated beams are satisfied by the use of the shape function incorporated into the theory which also unifies the one-dimensional shear deformable beam theories developed previously. The governing equations are obtained by means of Minimum Energy Principle. Three different combinations of free, clamped and simply supported edge boundary conditions are considered. The critical buckling loads are obtained by applying the Ritz method where the three displacement components are expressed in a series of simple algebraic polynomials. The numerical results were obtained for different length-to-thickness ratios and lay-ups are presented and compared with the
ones available in the literature.


ABSTRACT: The present study is concerned with the thermal buckling analysis of cross-ply laminated beams subjected to different sets of boundary conditions. The analysis is based on a three-degree-of-freedom shear deformable beam theory. The requirement of the continuity conditions between layers for symmetric cross-ply laminated beams is satisfied by the use of the shape function incorporated into the theory which also unifies the one dimensional shear deformable beam theories developed previously. The governing equations are obtained by means of minimum energy principle. Three different combinations of clamped and hinged edge boundary conditions are considered. The critical thermal buckling temperatures are obtained by applying the Ritz method where the three displacement components are expressed in a series of simple algebraic polynomials. The numerical results obtained for different length-to-thickness ratios and lay-ups are presented and compared with the ones available in the literature. It is interesting to note that some cross-ply beams buckle upon cooling instead of heating and some of them do not buckle irrespective of whether they are heated or cooled.

Metin Aydogdu (Department of Mechanical Engineering, Trakya University, 22180 Edirne, Turkey), “A general nonlocal beam theory: Its application to nanobeam bending, buckling and vibration”, Physica E: Low-dimensional Systems and Nanostructures, Vol. 41, No. 9, September 2009, pp. 1651-1655, doi:10.1016/j.physe.2009.05.014

ABSTRACT: In the present study, a generalized nonlocal beam theory is proposed to study bending, buckling and free vibration of nanobeams. Nonlocal constitutive equations of Eringen are used in the formulations. After deriving governing equations, different beam theories including those of Euler–Bernoulli, Timoshenko, Reddy, Levinson and Aydogdu [Compos. Struct., 89 (2009) 94] are used as a special case in the present compact formulation without repeating derivation of governing equations each time. Effect of nonlocality and length of beams are investigated in detail for each considered problem. Present solutions can be used for the static and dynamic analyses of single-walled carbon nanotubes.

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ABSTRACT: The hybrid nonlocal Euler-Bernoulli beam model is applied for the bending, buckling, and vibration analyzes of micro/nanobeams. In the hybrid nonlocal model, the strain energy functional combines the local and nonlocal curvatures so as to ensure the presence of small length-scale parameters in the deflection expressions. Unlike Eringen’s nonlocal beam model that has only one small length-scale parameter, the hybrid nonlocal model has two independent small length-scale parameters, thereby allowing for a more flexible and
accurate modeling of micro/nanobeamlike structures. The equations of motion of the hybrid nonlocal beam and
the boundary conditions are derived using the principle of virtual work. These beam equations are solved
analytically for the bending, buckling, and vibration responses. It will be shown herein that the hybrid nonlocal
beam theory could overcome the paradoxes produced by Eringen’s nonlocal beam theory such as vanishing of
the small length-scale effect in the deflection expression or the surprisingly stiffening effect against deflection
for some classes of beam bending problems.

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“On nonconservativeness of Eringen’s nonlocal elasticity in beam mechanics: correction from a discrete-based
approach”, Archive of Applied Mechanics, Vol. 84, No. 9, pp 1275-1292, October 2014
ABSTRACT: In this paper, the self-adjointness of Eringen’s nonlocal elasticity is investigated based on simple
one-dimensional beam models. It is shown that Eringen’s model may be nonself-adjoint and that it can result in
an unexpected stiffening effect for a cantilever’s fundamental vibration frequency with respect to increasing
Eringen’s small length scale coefficient. This is clearly inconsistent with the softening results of all other
boundary conditions as well as the higher vibration modes of a cantilever beam. By using a (discrete)
microstructured beam model, we demonstrate that the vibration frequencies obtained decrease with respect to an
increase in the small length scale parameter. Furthermore, the microstructured beam model is consistently
approximated by Eringen’s nonlocal model for an equivalent set of beam equations in conjunction with
variationally based boundary conditions (conservative elastic model). An equivalence principle is shown
between the Hamiltonian of the microstructured system and the one of the nonlocal continuous beam system.
We then offer a remedy for the special case of the cantilever beam by tweaking the boundary condition for the
bending moment of a free end based on the microstructured model.

References listed at the end of the paper:
ABSTRACT: The axisymmetric dynamic behaviour of clamped isotropic and orthotropic spherical cap with central circular hole under a uniform step pressure of infinite duration is investigated. The critical loads are determined by using the rapidly converging Chebyshev series in a space domain and a Houbolt numerical integration scheme in time domain. Three different cases of openings are investigated and detailed numerical results have been obtained for the isotropic case and two different cases of orthotrophy, which may be useful for design engineers.

ABSTRACT: The problem of axisymmetric non-linear behaviour of laminated orthotropic spherical shells is formulated using the principle of virtual work. The efficacy and applicability of the method of global interior collocation for the solution of the title problem are investigated. The zeroes of a Chebyshev polynomial are used as the collocation points. Parametric studies are conducted to bring out the effects of factors like orthotropic ratio, R/h ratio, shear deformation and opening angle on the non-linear static response of two-layered annular cross-ply shells. The results using the analytical solution presented herein should serve as bench-mark numerical results to test the accuracy of non-linear composite shell elements employed in finite element analysis.

ABSTRACT: Dynamic response of laminated orthotropic spherical shells under axisymmetric dynamic load is investigated. The shell is assumed to be composed of layers of orthotropic materials whose principal material directions coincide with the shell curvature directions. The motion of the shell is described by a displacement field so as to include the effects of transverse shear deformation. Three coupled differential equations in terms of three generalized displacements at a point of the shell reference surface are written neglecting the rotatory inertia effects. These equations are then discretized in the time domain using the unconditionally stable Newmark–β integration scheme. The time discretized equations at any time step are solved by the method of global interior collocation at zeros of a Chebyshev polynomial of suitable order. Numerical results are presented to show the efficacy of the method. Results of parametric studies are presented to bring out the effects of the opening angle, material orthotropy, and shear deformation on the transient response.

ABSTRACT: The governing differential equations for the problem of laminated axisymmetric spherical shells undergoing large deformations are formulated using the principle of virtual work. An analytical solution of the governing equations based on the Chebyshev-Galerkin spectral method is investigated. The efficacy and applicability of the solution procedure is discovered using numerical results. Parametric studies are conducted to bring out the effect of factors like orthotropy ratio, R/h ratio, shear deformation and opening angle on the large deflection behaviour of laminated orthotropic spherical shells and interesting observations are made. The numerical results should prove helpful in testing the nonlinear composite shell finite elements.


ABSTRACT: The effect of low density polyurethane foam on the axial crushing of thin-walled (D/t>600) circular metal tubes is studied under quasi-static and dynamic loading conditions. The mode of deformation of the tube is found to change from irregular diamond crumpling to axisymmetric bellows folding due to the filler. Assuming the axisymmetric mode of crushing and using the model of foam recently developed (M.F. Ashby, Metals Trans.14A, 1755–1769, 1983), the behaviour is analysed. Theoretical predictions agree well with experiments. Numerical results show that there is an optimum foam density which produces a maximum specific energy absorption of the filled cylinders.

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“Bending crush behavior of foam-filled sections”, 1999, (publisher not given in the pdf file)

ABSTRACT: Bending crush behavior of thin--walled columns filled with closed-cell aluminum foam is studied experimentally and numerically. Non linear dynamic finite element code was used to simulate quasi-static three point bending experiments. Two strengthening mechanisms are observed. First, the aluminum foam filler retards inward fold formation in the compressive flange, therefore preventing the drop in load carrying capacity due to sectional crush. Then, the inward fold retardation changes the crushing mode from single stationary fold, a typical bending crush behavior of an empty beam, to multiple propagating folds. The progressive fold formations spread plastic deformations, thus dissipating more energy. These phenomena are captured from both experiments and numerical simulations. High bending resistance is also maintained when the foam is placed only locally in the zone of high bending moment. The concept of the effective foam length is then developed, and potential applications of foam-filled sections for crashworthy structures are suggested.

References listed at the end of the paper:

ABSTRACT: This paper deals with the post-buckling deformation characteristics of aluminum alloy extruded polygonal section tubes subjected to dynamic axial impacts. The explicit finite element code LS-DYNA is the primary analytical tool used in this investigation. The study focuses on investigating a post-buckling deformation phenomenon that is primarily manifested by an axial crumpling action that generates material folds as the impact energy is dissipated. The research is conducted in two phases. The first phase consists of validating the LS-DYNA model parameters and numerical results pertaining to thin-walled aluminum extruded square tubes with actual published experimental data. The post-buckling deformation characteristics of the specimens such as the overall final configuration and the various folding deformation modes (extensional, symmetric and asymmetric) resulting from the axial collapse of the member is also investigated in a subsequent phase. Based on the numerical simulation results, it is apparent that the increase in the number of walls (flanges) has a direct impact on the mean axial crushing force and permanent displacement parameters. In particular, the adoption of a hexagonal tube section as an axially loaded energy absorbing column yields an average increase of 11% in the mean axial crushing force and an average decrease of 10% in the permanent displacement. The greatest benefits are obtained in the specimens with the thinnest nominal wall thickness, where the upper bound results show an average increase of 27% in the mean axial crushing force and average decrease of 20% in the permanent displacement.


ABSTRACT: The three-dimensional theory of elasticity in curvilinear coordinates is employed to investigate the dynamic buckling of an imperfect orthotropic circular cylindrical shell under mechanical and thermal loads. Accurate form of the strain expressions of imperfect cylindrical shells is established through employing the general Green’s strain tensor for large deformations and the equations of motion are derived in terms of the second Piola-Kirchhoff stress tensor. Then, the governing equations are properly formulated and solved by means of an efficient and relatively accurate solution procedure proposed to solve the highly nonlinear equations resulting from the above analysis. The proposed formulation is very general as it can include the
influence of the initial imperfections, temperature distribution, and temperature dependency of the mechanical properties of materials, effect of various end conditions, possibility of large-deformation occurrence and application of any combination of mechanical and thermal loadings. No simplifications are done when solving the resulting equations. Furthermore, in contrast to the displacement-based layer-wise theories and the three-dimensional approaches proposed so far, the stress, force and moment boundary conditions as well as the displacement type ones, can be incorporated accurately in these formulations. Finally, a few examples of mechanical and thermal buckling of some orthotropic cylindrical shells are considered and results of the present three-dimensional elasticity approach are compared with the buckling loads predicated by the Donnell’s equations, some single-layer theories, some available results of the layer-wise theory and the recently published three-dimensional approaches and the accuracy of the later methods are discussed based on the exact method presented in this paper.


ABSTRACT: Only static buckling of the hybrid functionally graded material (FGM) cylindrical shells has been investigated so far. In the present paper, dynamic buckling of imperfect FGM cylindrical shells with integrated surface-bonded sensor and actuator layers subjected to some complex combinations of thermo-electro-mechanical loads is investigated. The general form of Green's strain tensor in curvilinear coordinates and a high-order shell theory proposed earlier by the author are used. The complicated nonlinear governing equations are solved using the finite-element method. Buckling load is detected by a modified Budiansky's criterion proposed earlier by the author. Effects of temperature dependency of material properties, volume fraction index, load combination, and initial geometric imperfections on thermo-electro-mechanical post-buckling behavior are evaluated. Results reveal that the volume fraction index, temperature gradient, layer sequence, and the adaptive feedback control somewhat may affect the buckling load.


ABSTRACT: FGM components are constructed to sustain high temperature gradients. There are many applications where the FGM components are vulnerable to transient thermal shocks. If a component is already under compressive external loads (e.g. under a combination of axial compression and external pressure), the mentioned thermal shocks will cause the component to exhibit dynamic behavior and in some cases may lead to buckling. On the other hand, a preheated FGM component may undergo dynamic mechanical loads. Only static thermal buckling investigations were developed so far for the FGM shells. In the present paper, dynamic buckling of a pre-stressed, suddenly heated imperfect FGM cylindrical shell and dynamic buckling of a mechanically loaded imperfect FGM cylindrical shell in thermal environment, with temperature-dependent properties are presented. The general form of Green’s strain tensor in curvilinear coordinates and a high order shell theory proposed already by the author are used. Instead of using semi-analytical solutions that rely on the validity of the separation of variables concept, the complicated nonlinear governing equations are solved using the finite element method. Buckling load is detected by a modified Budiansky criterion proposed by the author.
The effects of temperature-dependency of the material properties, volume fraction index, load combination, and initial geometric imperfections on the thermo-mechanical post-buckling behavior of a shell with two constituent materials are evaluated. The results reveal that the volume fraction index and especially, the differences between the thermal stresses created in the outer and the inner surfaces may change the buckling behavior. Furthermore, temperature gradient and initial imperfections have less effect on buckling of a shell subjected to a pure external pressure.

M. Shariyat (Faculty of Mechanical Engineering, KNT University of technology, Pardis Street, Molla-Sadra Street, Vanak Square, Tehran, Iran), “Dynamic buckling of imperfect laminated plates with piezoelectric sensors and actuators subjected to thermo-electro-mechanical loadings, considering the temperature-dependency of the material properties”, Composite Structures, Vol. 88, No. 2, April 2009, pp. 228-239, doi:10.1016/j.compstruct.2008.03.044

ABSTRACT: Dynamic buckling of piezolaminated plates under thermo-electro-mechanical loads has not been investigated so far. In the present paper, effects of the thermo-piezoelectricity on the dynamic buckling under suddenly applied thermal and mechanical loads are investigated for imperfect rectangular composite plates with surface-bonded or embedded piezoelectric sensors and actuators. A finite element formulation based on a higher-order shear deformation theory is developed. Both the initial geometric imperfections of the plate and the temperature-dependency of the material properties are taken into account. Complex dynamic loading combinations include in-plane mechanical loads, heating, and electrical actuations are considered. A nine-node second order Lagrangian element, an efficient numerical algorithm for solving the resulted highly nonlinear governing equations, and an instability criterion already proposed by the author are employed. A simple negative proportional feedback control is used to actively control the transient response of the plate. Results show that buckling mitigation due to utilizing integrated piezoelectric sensors and actuators is mainly achieved in extremely high gain values. It is also noticed that in many cases, effects of the control voltage on the results may be ignored compared to the temperature-dependency of the material properties and initial geometric imperfections effects.


ABSTRACT: The available accurate shell theories satisfy the interlaminar transverse stress continuity conditions based on linear strain–displacement relations. Furthermore, in majority of these theories, either influence of the transverse normal stress and strain or the transverse flexibility of the shell has been ignored. These effects remarkably influence the non-linear behavior of the shells especially in the postbuckling region. Furthermore, majority of the buckling analyses performed so far for the laminated composite and sandwich shells have been restricted to linear, static analysis of the perfect shells. Moreover, almost all the available shell theories have employed the Love–Timoshenko assumption, which may lead to remarkable errors for thick and relatively thick shells. In the present paper, a novel three-dimensional high-order global-local theory that satisfies all the kinematic and the interlaminar stress continuity conditions at the layer interfaces is developed for imperfect cylindrical shells subjected to thermo-mechanical loads. In comparison with the layerwise, mixed, and available global-local theories, the present theory has the advantages of: (1) suitability for non-linear analyses, (2) higher accuracy due to satisfying the complete interlaminar kinematic and transverse stress
continuity conditions, considering the transverse flexibility, and releasing the Love–Timoshenko assumption, (3) less required computational time due to using the global-local technique and matrix formulations, and (4) capability of investigating the local phenomena. To enhance the accuracy of the results, compatible Hermitian quadrilateral elements are employed. The buckling loads are determined based on a criterion previously published by the author.

References listed at the end of the paper:

M. Shariyat (Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Pardis Street, Molla-Sadra Avenue, Vanak Square, Tehran, Iran), “A generalized high-order global-local plate theory for nonlinear bending and buckling analyses of imperfect sandwich plates subjected to thermo-mechanical loads”, Compos. Struct 92 (1) (2010), pp. 130–143, DOI: 10.1016/j.compstruct.2009.07.007

ABSTRACT: The available plate theories have been generally calibrated using linear strain–displacement expressions. Furthermore, many of them do not consider the transverse normal stress continuity and the transverse flexibility of the sandwich plates. Majority of the investigations performed so far in the buckling analysis of the sandwich plates, have been restricted to linear buckling analysis of the perfect sandwich plates based on theories that either violate the continuity condition of the transverse stresses at the layer interfaces or do not satisfy the mentioned condition when nonlinear strain–displacement expressions are used. Therefore, their results may be unreliable for nonlinear stress and buckling (especially in the postbuckling region) analyses. In the present paper, nonlinear strain–displacement expressions are employed for imperfect sandwich plates subjected to thermo-mechanical loads to propose an accurate global–local theory that satisfies the continuity of all of the transverse stress components. The theory is presented in a compact matrix form. Compatible Hermitian elements with C1 continuity are employed to enhance the results. Buckling and wrinkling loads are detected employing a criterion previously published by the author. Comparisons made in the paper with results reported by well-known references, confirm the accuracy and the efficiency of the proposed theory and the relevant solution algorithm.

M. Shariyat (Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Tehran, Iran), “A general nonlinear global-local theory for bending and buckling analyses of imperfect cylindrical laminated and sandwich shells under thermomechanical loads”, Meccanica (Springer), published online 2011, DOI: 10.1007/s11012-011-9438-9

ABSTRACT: The accurate shell theories proposed so far have been calibrated based on linear kinematic relations. Many of them have ignored either the interlaminar stress continuity conditions at the interfaces or the transverse flexibility of the layers. Therefore the available shell theories may encounter accuracy problems when analyzing the nonlinear behaviors, especially for sandwich shells with soft cores. Moreover, almost all of the available shell theories have been proposed employing the Love-Timoshenko assumption. Ideas of the previous global-local plate theory of the author are extended to develop the present nonlinear high-order global-local shell theory. The present theory has the advantages of: (1) suitability for nonlinear analyses, (2) higher accuracy due to satisfying the complete interlaminar kinematic and transverse stress continuity conditions at the layer interfaces under thermo-mechanical loads, employing the exact Green’s strain tensor of the curvilinear coordinates, considering the transverse flexibility, and releasing the Love-Timoshenko assumption, (3) less required computational time due to using the global-local technique and matrix formulations, and (4) capability of investigating the local phenomena. To enhance the accuracy of the results, compatible Hermitian elements
are employed. Various comparative examples are included in the present paper to validate the theory and to examine its accuracy and efficiency.

References listed at the end of the paper:

ABSTRACT: The objective of this research is determining the buckling load of composite truncated conical shells under external loading by theoretical and numerical methods. The boundary conditions are assumed to be clamped. At first, basic equations and stability relations of conical shells were derived. The analysis is carried out using Donnell-type stability equations for thin cross-ply conical shells. By applying Galerkin’s method, these equations are converted to a system of ordinary time dependent differential equations. Ritz method is employed for finding the dynamic stability load. Finally, the critical static and dynamic buckling loads and the corresponding wave numbers have been found analytically. Then comparison of results is considered. Results of analytical calculations are compared with numerical results and with other researchers’ analytical results. The effects of geometric parameters, the cone semi-vertex angle, number of layers and material of fibers on buckling loads are discussed.

References listed at the end of the paper:

[20] Y. Chung, Buckling of composite conical shells under combined axial compression external pressure and bending, for the degree of doctor of philosophy in mechanical engineering, New Jersey Institute of Technology (2001).

ABSTRACT: Dynamic buckling of an orthotropic cylindrical shell which is subjected to rapidly applied compression is considered. A nonlinear differential equation of Donnell–Kármán type is derived with the initial imperfection taken into account. An energy method is used to obtain the equation of motion which is then solved numerically by means of a Runge-Kutta method. These numerical results show that the critical load is increased over the corresponding static case. An analytical solution is also obtained for the problem of hydrostatic pressure.

References listed at the end of the paper:


ABSTRACT: The Nonlinear dynamic buckling and stability of nonlinearly elastic autonomous discrete systems under conservative step loading (of infinite or finite duration), impact and impulsive loading is examined in detail. Discrete structural systems which under the same loading applied statically exhibit snap-through buckling are mainly considered. Emphasis is focused on the coupling effect of nonlinearities (geometric and/or material) and structural damping. A qualitative discussion of the dynamic buckling mechanism is comprehensively presented on the basis of energy and topological concepts in the light of recent progress of
nonlinear dynamics and chaos. This leads to useful criteria for establishing exact, approximate and lower-upper bound dynamic buckling estimates without integrating the highly nonlinear equations of motion. It is shown that dynamic buckling can be defined as an escaped motion through a saddle of the (static) unstable postbuckling equilibrium path which leads either to an “unbounded” motion or to a point attractor associated with a remote stable equilibrium point. As byproducts of this analysis various phenomena such as restabilization (metastability), loading discontinuity, sensitivity to initial-conditions and to damping as well as chaoticlike Phenomena, are revealed. The theory is illustrated with analyses of single, two and three degrees of freedom models.

References listed at the end of the paper:


ABSTRACT: In this paper the effect of the interaction of two loadings, and of the deviation from right angle on the buckling mechanism of a rectangular two-bar frame is discussed. Using a nonlinear stability analysis it is found that there is a critical value of the ratio of the two loadings, as well as of the deviation from right angle, for which the physical equilibrium path and the physically unacceptable complementary path meet each other at an asymmetric bifurcation point. At this point, the response of the frame changes from an elastic limit point
instability to a stable equilibrium path associated with inelastic buckling. The analysis is supplemented by a variety of numerical results obtained by an efficient and reliable simplified nonlinear stability analysis applied for the first time to a non-rectangular frame.

References listed at the end of the paper:

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ABSTRACT: The nonlinear lateral buckling response of perfect stocky beams in the vicinity of the critical bifurcational state is discussed. Attention is focused on the initial post-buckling response. This depends on the nature of the critical branching point which is explored by using a nonlinear (lateral) bending-curvature relationship. It is found that the plane of loading (associated with the major moment of inertia) looses its stability through a stable symmetric bifurcation point. Hence, the above beams are not sensitive to imperfections, exhibiting post-buckling strength. However, the post-buckling equilibrium path is quite shallow, so that the load-carrying capacity of such beams above the critical state is rather limited. The analysis is supplemented by illustrative examples for I-beams for which the effect of various parameters on the initial postbuckling path is also discussed.

References listed at the end of the paper:


ABSTRACT: The pre-critical, critical, and post-critical nonlinear response of an imperfect due to loading eccentricity two-bar frame is thoroughly discussed. In seeking the maximum load-carrying capacity of this non-sway frame, it was qualitatively established that its loss of stability occurs through a limit point and hence, the case of an asymmetric bifurcation can be considered only in an asymptotic sense. After deriving the nonlinear equilibrium equations with unknowns for the two bar axial forces, we can consider such a continuous system as a two-degree-of-freedom model with generalized coordinates the above axial forces. Then, the equilibrium equations and the stability determinant of the frame can be determined in terms of the first and second derivatives of its total potential energy (TPE) with respect to the axial forces. The vanishing of the second variation of the TPE together with the equilibrium equations allows a simple and direct evaluation of the buckling load. Numerical examples demonstrate the efficiency and the reliability of the proposed method.

References listed at the end of the paper:

ABSTRACT: The design optimization of axially loaded, simply supported stiffened cylindrical shells for minimum mass is considered. The design variables are thickness of shell wall, thicknesses and depths of rings and stringers, number-spacing of rings and stringers. Natural frequency, local and overall buckling strengths and direct stress constraints are considered in the design problems. Three different combinations of stiffeners are considered. In each case, the independent effects of behaviour constraints are also studied. The optimum designs are achieved with one of the standard nonlinear constrained optimization techniques (Davidon-Fletcher-Powell method with interior penalty function formulation) and few optimal solutions are checked for the satisfaction of Kuhn-Tucker conditions.

ABSTRACT: The design optimization of axially loaded, simply supported stiffened conical shells for minimum weight is considered. The design variables are thickness of shell wall, thicknesses and depths of rings and stringers, number-spacing of rings and stringers. Natural frequency, overall buckling strength and direct stress constraints are considered in the design problems. Optimization results are obtained by placing the stiffeners inside as well as outside the conical shell. In both these cases, the independent effects of behavior constraints are also studied. The optimum designs are achieved with one of the standard nonlinear constrained optimization techniques (Davidon-Fletcher-Powell method with interior penalty function formulation) and few optimal solutions are checked for the satisfaction of Kuhn-Tucker conditions.

ABSTRACT: The effect of nonlinear material behavior on the buckling of an infinitely long cylindrical shell under pure bending is studied. The maximum moment and associated curvature is determined as a function of material and geometric parameters. The curvature at which short wave-length bifurcations occur is also determined. The results are compared with behavior in the elastic range.

S. Gellin (Dept. of Civil Engineering, State University of New York at Buffalo, New York, USA), “Effect of an

ABSTRACT: The effect of a sinusoidal axisymmetric shape imperfection on the plastic buckling of a long cylindrical shell under axial compression is studied. The load at which nonaxisymmetric bifurcation from the axisymmetric state occurs is determined as a function of the imperfection amplitude for relatively thin shells. Imperfection-sensitivity in the plastic range is contrasted with that in the elastic range.


ABSTRACT: The buckling of a short, elastic cylindrical shell in pure bending is explored. A set of solutions is found which appears to give slightly more conservative bifurcation load estimates than those obtained by previous investigators. Some explanations are put forth to explain the difference in results.


ABSTRACT: Composite cylindrical shells are being used more extensively for structural applications in both rotary- and fixed-wing aircraft where low weight and high strength are important design issues. This paper addresses the energy absorption capability of such shells, under axial compressive loading. A design optimization procedure is developed to improve the energy absorption by maximizing the buckling and postbuckling characteristics of the shells. The sensitivity of both geometric and material properties is investigated by studying thin-walled shells of several thicknesses, made of different types of orthotropic laminates. Constraints are imposed on the longitudinal, normal, and in-plane shear stresses of each ply by utilizing a failure criteria. Design variables include shell diameter and ply orientations. The optimization is performed using the nonlinear programming method of feasible directions. A two-point exponential approximation is also used to reduce computational effort. Results are presented for Graphite/Epoxy, Glass/Epoxy, and Kevlar/Epoxy composite cylindrical shells with symmetric ply arrangements.


ABSTRACT: A higher-order shear deformation theory has been employed for evaluating accurately the transverse shear effects in delamination buckling of cylindrical shells under axial compression. The governing differential equations of the present theory are obtained by applying the principle of the stationary value of the total potential. The Rayleigh-Ritz method is used to solve the equations by assuming a double Fourier expansion of the displacements with trigonometric coordinate functions. Numerical results for linear delamination buckling of axially compressed cylindrical shells with clamped ends are presented to validate the theory. Comparisons are made with the classical laminate theory and first-order theory results.

Haozhong Gu and Aditi Chattopadhyay (Arizona State University, Tempe, Arizona), "Delamination buckling

ABSTRACT: A higher-order deformation theory is developed for accurately evaluating the transverse shear effects in delamination buckling and postbuckling of cylindrical shells under axial compression. The theory assures a more accurate description of displacement field and the satisfaction of stress-free boundary conditions for the delamination problem. The governing differential equations of the present theory are obtained by applying the principle of virtual displacement. The Rayleigh-Ritz method is used to solve both linear and nonlinear equations by assuming a double trigonometric series for the displacements. Both linearized buckling analysis and nonlinear postbuckling analysis are performed for axially compressed cylindrical shells with clamped ends. Comparisons made with the classical laminate theory and a first-order theory show significant deviations.


ABSTRACT: Variational finite-difference methods of solving linear and nonlinear problems for thin and non-thin shells (plates) made of homogeneous isotropic (metallic) and orthotropic (composite) materials are analyzed and their classification principles and structure are discussed. Scalar and vector variational finite-difference methods that implement the Kirchhoff–Love hypotheses analytically or algorithmically using Lagrange multipliers are outlined. The Timoshenko hypotheses are implemented in a traditional way, i.e., analytically. The stress–strain state of metallic and composite shells of complex geometry is analyzed numerically. The numerical results are presented in the form of graphs and tables and used to assess the efficiency of using the variational finite-difference methods to solve linear and nonlinear problems of the statics of shells (plates)

References listed at the end of the paper:


ABSTRACT: The buckling of the piezoelectric laminated cylindrical shell with throughout circumference delamination is analyzed in this paper. By introducing the Heaviside step function into assumed displacement components and using elastic piezoelectric theory, the constitutive relations of the piezoelectric laminated shell with delamination are established. Then the buckling governing equations of the structure are derived through variational principle. In numerical examples, the effects of delamination length, depth, material property and thickness of piezoelectric layer on the buckling load of piezoelectric laminated shell with delamination are investigated.


ABSTRACT: High precision finite elements for both thin plate and stiffener are developed in this paper to analyse the stability of thin plates subjected to arbitrary membrane loading with arbitrarily oriented stiffeners. Application of these elements to some complex stability problems show high accuracy even with a relatively coarse finite element mesh. For all the problems considered the predicted critical loads are accurate upper bounds.

ABSTRACT: The behaviour of thin tubes made of sheet metal and not so thin extruded tubes filled with wood and subjected to axial crushing is studied. Experiments show that the mode of elastic buckling is changed by the presence of the wood filler. The plastic crushing of thin tubes resulted in Euler-type buckling, while a considerable enhancement in the load carrying capacity and energy absorption was seen in the case of thicker walled tubes which were examined both under quasi-static and dynamic loading conditions. A new idealized deformation mechanism for the progressive crushing of the wood-filled tube is suggested and analysed. The results obtained for the mean loads agree reasonably with experimental observations. An alternative method employed to predict the mean crushing load of empty tubes and using a thickness that provides an equivalent stiffness to that of a filled tube is also seen to produce reasonable agreement with the experiment.
ABSTRACT: The response to pure bending of tubes with rectangular cut-outs is considered. Experiments on 1000-mm long, 100-mm diameter, and 2.55-mm wall thickness DIN 2391 ST NBK supported steel tubes are described. Such a thickness-to-diameter ratio is typical of structural columns, rather than shell structures. Tubes containing cut-outs with an axial dimension of up to 30 mm and a circumferential size of up to 180° were tested. It was found that plastic hinge mechanisms dominated the response when the cut-out was on the compressive side, whereas fracture behaviour dominated the response when the cut-out was on the tensile side. Finite element and semi-empirical analyses were carried out to predict the global load-deformation behaviour of the tubes. All analyses gave reasonable predictions of the experimental results for the majority of the cut-out parameters investigated. The aim of this study is to investigate the feasibility of using cut-outs to initiate and control the toppling of offshore jacket structures.

T.Y. Yang, Rakesh K. Kapania and Sunil Saigal (School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, USA), “Linear and nonlinear dynamic response analysis of complex shell structures”, (no publisher or date given in the pdf file; most recent reference is 1983)
ABSTRACT: The elastic-inelastic and geometrically nonlinear formulations and solution procedures have been developed for two types of finite elements, a six d.o.f beam element and a 48 d.o.f. quadrilateral curved shell element, for the static or dynamic response analysis of beam and shell structures with one or both types of nonlinearities. Three example structures are studied: an R.C. beam, a spherical cap, and a full spherical shell. The elastic formulations are used to analyze a cooling tower shell due to earthquake and wind loads. For earthquake loads, response spectrum analysis is performed. For wind loads, frequency domain analysis is performed.

ABSTRACT: Formulations and computational procedures are presented for the finite element analysis of laminated anisotropic composite thin shells including imperfections. The derivations of the nonlinear geometric element stiffness matrices were based on the total Lagrangian description. A 48 degree-of-freedom (d.o.f.) general curved shell element with arbitrary distribution of curvatures was used to model the shell middle-surface. Numerical results include the large deflection behavior of a variety of perfect plate and shell examples; buckling of a spherical shell with an axially symmetric imperfection; and buckling of a cylindrical panel using measured initial transverse imperfections. A good comparison with existing results is obtained.

ABSTRACT: Structural failure under dynamic loads may occur at load levels that are less than the
corresponding static load. Presence of local geometric imperfections may induce an early failure for both static and dynamic loadings. The phenomenon of ‘dynamic weakening’ is studied for a general class of shell structures under a general class of time dependent loadings. A doubly curved quadrilateral Love-Kirchhoff shell finite element is used. Geometric deviations of the shell middle surface are included within the element formulation by suitably modifying the strain-displacement relations. This is accomplished by retaining additional terms that are quadratic in spatial derivatives of imperfections and displacement components. The nonlinear equations of motion are written in the Lagrangian system and are solved by using an incremental algorithm based on Newmark's generalized operator. The dynamic buckling responses of a spherical cap with and without local imperfections are presented. The formulation is general and can be applied to obtain the dynamic buckling response of a wide variety of shell structures.

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ABSTRACT: Natural frequencies and forced responses of thin laminated composite shells of general form are investigated using a high-order curved shell finite element. The effect of geometric nonlinearity is included in the determination of the forced responses which are obtained using Newmark’s numerical integration scheme. A class of shell problems which are general with respect to geometry; boundary conditions; number, stacking sequence, and angle of orientation of the lamina; and load function can be solved using the present formulations. Numerical results and their comparisons with existing solutions are presented for cylindrical shells, shells of positive and negative Gaussian curvature, spherical caps, and shells of translation with different boundary conditions.

ABSTRACT: Linear and nonlinear analysis of shell structures are performed using finite elements. Shell elements are formulated to capture the linear and nonlinear behavior of shell structures. Although general, the elements are specially suited for tubular joints. An automatic geometric modeling and mesh generation procedure for T, K and DT-joints is first developed. A set of shell elements are then developed and implemented in a general purpose, research oriented finite element analysis program (FEAP) to carry out linear, materially-nonlinear only, geometrically-nonlinear-only and geometric and material nonlinear analyses of thin shell structures with special emphasis on tubular joints which represent essential components of offshore platforms. A six-degree-of-freedom per node (including a true drilling degree of freedom) assembly allows easy modeling of complicated shell structures such as tubular joints or stiffened shells. The displacement interpolation is carefully chosen in order to avoid shear and membrane locking in linear and nonlinear problems. The curvature effects (initial curvature and changes in curvature due to large displacements and rotations) are incorporated by a simple modification of the flat linear shell element. This computationally very inexpensive modification increases the performance of the element by several folds. The total corotational formulation, a Lagrangian formulation, is used to treat geometric nonlinearity. Each point in the thickness of the shell is considered to be under plane stress conditions. Von Mises yield criterion with linear isotropic and kinematic hardening and the associated Prandtl-Reuss flow rule is used to model the plastic flow behavior of the
shell material. The flow rule and hardening law are integrated using the return map algorithm. The robustness of the analysis tool developed is demonstrated by solving a range of linear and nonlinear problems of shell analysis. It is demonstrated through examples and comparison with known analytical or reliable numerical solutions that the elements developed are accurate in predicting both displacements and stresses. The ultimate test of the predictive ability of the analysis tool developed is performed by considering three well documented tubular joint examples (T-, K-, and DT-joints) for which experimental results in terms of load deflection curve are available. The prediction of the collapse load and load-deflection curve for the T-joint is in excellent agreement with the experimental results. This agreement between numerical and experimental results for both the K- and DT-joints is also very good considering the complexity of the actual joint structure. Finally, a parametric study of tubular T-joints is conducted to study the effects of the various geometric parameters on the collapse load.

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ABSTRACT: Stability analysis of perfect and imperfect cylindrical shells under wind pressures is performed using the finite element method. A 48 degree-of-freedom (d.o.f.) thin shell element previously developed by the present authors is used. The element is free from both shear and membrane locking and is capable of modelling shells with arbitrary imperfections. Nonlinear effects due to prebuckling rotations are taken into account. The nonlinear response is obtained using Riks-Wempner algorithm. Effects of the imperfection amplitude and that of the material orthotropy on the limit load points are studied. Wherever possible, the present results are compared with existing results. A favorable agreement is observed.


ABSTRACT: The spectral method is a powerful numerical technique for solving engineering differential equations. The method is a specialization of the method of weighted residuals. Trial functions that are easily and exactly differentiable are used. Often the functions used also satisfy an orthogonality equation, which can improve the efficiency of the approximation. Generally, the entire domain is modeled, but multiple sub-domains may be used. A Chebyshev-Collocation Spectral method is used to solve a two-dimensional, highly nonlinear, two parameter Bratu's equation. This equation previously assumed to have only symmetric solutions are shown to have regions where solutions that are non-symmetric in x and y are valid. Away from these regions an accurate and efficient technique for tracking the equation's multi-valued solutions was developed. It is found that the accuracy of the present method is very good, with a significant improvement in computer time.

ABSTRACT: The objective of this paper is to analyze the effect of complex, arbitrary in-plane and out-of-plane loads on the transverse vibrations of thin arbitrarily laminated panels with or without geometric imperfections. The finite-element method is used. A 48 degree-of-freedom thin shell element previously formulated by the senior author is employed. The formulation is general with respect to the boundary conditions, types of imperfections, and number, orientation, and stacking sequence of the lamina. A large radius to thickness ratio is assumed so as to ignore the shear and rotary inertia effects. The results are presented for angle-ply rectangular plates and cross-ply cylindrical panels, with both of these having simply supported edge conditions along all the four edges, and isotropic square plates involving free edges under non-uniform combined loads. The panels are subjected to both axial and shear in-plane stresses. The effects of geometric parameters (aspect ratio, panel curvature, and geometric imperfections) and material properties (varying the number of layers but the same thickness) are examined. The results are presented in the form of frequency-load interaction curves for various geometric parameters. Whenever possible, the present results are compared with those available in the existing literature. A good agreement is observed.


ABSTRACT: The nonlinear transient response of thin imperfect laminated plates subjected to impact loads is studied using a 48 DOF finite element based on the classical laminated plate theory. Comparison between the first-order shear deformation theory and the classical laminated plate theory is also made to study the effect of shear deformation. The modified Hertzian law by Tan and Sun is incorporated to evaluate the impact loads due to a projectile. The transient response of an example problem is obtained using both full and reduced equations of motion. A reduction method using Ritz vectors as the basis vectors is employed to reduce the size of the nonlinear problem and thus save computational effort. The resulting reduced (but still coupled) set of equations is integrated in a step-by-step fashion using the Newmark constant-average acceleration time integration scheme along with an iterative scheme for dynamic equilibrium. It is observed that geometric imperfections cause significant changes in the impact response of thin laminated plates. The reduction method used in this study was not found to be very efficient for obtaining the nonlinear impact responses. Further research is needed to develop reduction methods that are more suitable for studying nonlinear impact responses.


ABSTRACT: The paper analyzes the effect of geometric imperfections on the free-vibration, and static and dynamic responses of hyperbolic shells. The effect of geometric nonlinearity is included. A 48 degree-of-freedom thin shell element, capable of modeling arbitrary geometric imperfections, is employed. A reduced basis method using the normal modes as the basis vectors is employed to reduce the size of the nonlinear problem and thus save computational effort. The resulting reduced (but still coupled) set of equations is integrated in a step-by-step fashion using the Wilson-theta method along with an iterative scheme. The integration scheme, first evaluated on a series of examples (both linear and nonlinear) is employed to obtain the dynamic response of hyperbolic shells with geometric imperfections. The shell is subjected to wind loads with
an assumed time history. The results are presented for the nonlinear static response of a cooling tower under wind loads; for the fundamental frequencies of a hyperbolic shell under increasing axisymmetric pressure loads; and finally for the dynamic response (normal displacements and the in-plane stress resultants) of an example hyperbolic shell under dynamic wind loads. Whenever possible, the present results are compared with those available in the existing literature. A good agreement is observed.


ABSTRACT: Reduction methods using eigenvectors and Ritz vectors as basis vectors are employed to reduce the finite element nonlinear system of equations using a 48 D.O.F. doubly curved thin plate/shell element. With and without basis updating, the solutions obtained by reduction methods are compared with the direct solutions. It is observed that basis updating is essential to obtain accurate solutions. The present reduction methods need a large number of basis vectors (eigenvectors and Ritz vectors) to account for the impact load which has high frequency characteristics. Furthermore, for nonlinear analysis, the reduction achieved in the CPU time are only marginal since most of the CPU time was spent in the calculation of the internal nodal force vector. These considerations indicate that reduction methods may not be efficient for the impact response analysis.


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ABSTRACT: We conducted a fundamental study to investigate the dynamic behavior of laminated structures. Both finite element and analytical solutions were developed. Using a 48 degree-of-freedom shell finite element (FE) developed by Kapania and coworkers, the effect of arbitrary inplane and out-of-plane loads on the transverse vibrations of thin arbitrarily laminated panels with or without geometric imperfections was analyzed. The element was used to investigate the effect of geometric imperfections on geometrically nonlinear impact response of thin laminated plates and cylindrical panels using reduced basis methods. A FE model was also developed to study the linear and geometrically nonlinear transient behavior of laminated beams. A postprocessor was developed that can use the transverse displacements from a classical laminated plate theory (CLPT) or a first order shear deformation theory (FSDT) to determine the transverse normal and shear stresses. The nonlinear dynamic equations of the first-order shear deformation theory and the third-order shear deformation plate theory of Reddy was reformulated to describe the interior and edge zone problems of rectangular plates. A three-dimensional elasticity solution for the free vibration analysis of general cross-ply laminated plates has been carried out by combining Fourier series solution with a state space representation and the transfer matrix approach. A close theoretical examination have clarified the accuracy of the various single layer theories and a layerwise theory with the exact elasticity solution. Composite materials, Impact response, Imperfect plates, Plates, Reduced basis methods, Response due to short duration loads, Shells, Transverse effects.

Rakesh K. Kapania and Tom-James G. Stoumbos (Department of Aerospace and Ocean Engineering, Virginia
ABSTRACT: Although a large number of studies dealing with the impact response of flat laminated panels has been conducted in the past, relatively little work seems to be available on impact of laminated cylindrical panels. In this paper an analytical study is conducted to predict the nonlinear transient response of thin imperfect laminated cylindrical panels subjected to impact loads. A review is also given regarding the state of the art on the impact response of laminated plates and shells. The imperfect panels are modeled using a 48 degree-of-freedom (DOF) finite element based on the classical laminated plate theory. Linear and nonlinear transient responses are obtained using the modal superposition method (MSM) and a reduction method based on Ritz vectors (R-R), both in conjunction with direct integration schemes (Wilson-theta or Newmark methods). The effect of the number of modes used is also discussed. A modified contact law is incorporated to evaluate the impact loads due to a projectile. Different nondimensional shell radii $[r/h]$ are used in order to study the effect of nondimensional shell radii $[r/h]$ on the impact response of laminated cylindrical panels. The effect of geometric imperfections on linear and nonlinear transient response under sudden impact loads is also analyzed. Both the MSM and R-R methods used in the analysis are found to have acceptable accuracy and the accuracy increased with the number of modes used. It is observed that the reduction of the nondimensional shell radius $[r/h]$ causes significant changes in the impact response of the cylindrical panel: a significant decrease in the central deflection and contact force histories. The introduction of geometric imperfections led to similar conclusions.

ABSTRACT: The layerwise theory of Reddy is used to study the low velocity impact response of laminated plates. Forced-vibration analysis is developed by the modal superposition technique. Six different models are introduced for representation of the impact pressure distribution. The first five models, in which the contact area is assumed to be known, result in a nonlinear integral equation similar to the one obtained by Timoshenko in 1913. The resulting nonlinear integral equation is discretised using a time-element scheme. Two different interpolation functions, namely: (i) Lagrangian and (ii) Hermite, are used to express the impact force. The Hermitian polynomial-based representation, obviously more sophisticated, is introduced to verify the Lagrangian-based representation. Due to its modular nature the present numerical technique is preferable to the existing numerical methods in the literature. The final loading model, in which the time dependence of the contact area is taken into account according to the Hertzian contact law, resulted in a relatively more complicated but more realistic, nonlinear integral equation. The analytical developments concerning this model are all new and are reported for the first time in this paper. Also a simple, but accurate, numerical technique is developed for solving our new nonlinear integral equation which results in the time-history of the impact force. Our numerical results are first tested with a series of existing example problems. Then a detailed study concerning all the response quantities, including the in-plane and interlaminar stresses, is carried out for symmetric and antisymmetric cross-ply laminates and important conclusions are reached concerning the usefulness and accuracy of the various plate theories.

ABSTRACT: A layer-wise theory is used to study the low velocity impact response of laminated plates. The forced-vibration analysis is developed by the modal superposition technique. Six different models are introduced for representation of the impact pressure distribution. The first five models, in which the contact area is assumed to be known, result in a nonlinear integral equation similar to the one obtained by Timoshenko in 1913. The resulting nonlinear integral equation is discretised using a time-finite-element scheme. Two different interpolation functions, namely: (i) Lagrangian and (ii) Hermite are used to express the impact force. The Hermitian-polynomials based representation, obviously, more sophisticated, is introduced to verify the Lagrangian based representation. Due to its modular nature the present numerical technique is preferable to the existing numerical methods in the literature. The final loading model, in which the time dependence of the contact area is taken into account according to the Hertzian contact law, resulted in a relatively more complicated but more realistic, nonlinear integral equation. The analytical developments concerning this model are all new and reported for the first time in this paper. Also a simple, but accurate, numerical technique is developed for solving our new nonlinear integral equation which results in the time-history of the impact force. Our numerical results are first tested with a series of existing example problems. Then a detailed study concerning all the response quantities, including the in-plane and interlaminar stresses, is carried out for cross-ply laminates and important conclusions are reached concerning the usefulness and accuracy of the various plate theories.


ABSTRACT: Finite element static, free vibration and thermal analysis of thin laminated plates and shells using a three noded triangular flat shell element is presented. The flat shell element is a combination of the Discrete Kirchhoff Theory (DKT) plate bending element and a membrane element derived from the Linear Strain Triangular (LST) element with a total of 18 degrees of freedom (3 translations and 3 rotations per node). Explicit formulations are used for the membrane, bending and membrane-bending coupling stiffness matrices and the thermal load vector. Due to a strong analogy between the induced strain caused by the thermal field and the strain induced in a structure due to an electric field the present formulation is readily applicable for the analysis of structures excited by surface bonded or embedded piezoelectric actuators. The results are presented for (i) static analysis of (a) simply supported square plates under doubly sinusoidal load and uniformly distributed load (b) simply supported spherical shells under a uniformly distributed load, (ii) free vibration analysis of (a) square cantilever plates, (b) skew cantilever plates and (c) simply supported spherical shells; (iii) Thermal deformation analysis of (a) simply supported square plates, (b) simply supported-clamped square plate and (c) simply supported spherical shells. A numerical example is also presented demonstrating the application of the present formulation to analyse a symmetrically laminated graphite/epoxy laminate excited by a layer of piezoelectric polyvinylidene fluoride (PVDF). The results presented are in good agreement with those available in the literature.

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ABSTRACT: The study focuses on the development of a simple and accurate global/local method for calculating the static response of stepped, simply-supported, isotropic and composite plates with circular and elliptical cutouts. The approach primarily involves two steps. In the first step a global approach, the Ritz method, is used to calculate the response of the structure. Displacement based Ritz functions for the plate without the cutout are augmented with a perturbation function, which is accurate for uniform thickness plates only, to account for the cutout. The Ritz solution does not accurately satisfy the natural boundary conditions at the cut-out boundary, nor does it accurately model the discontinuities caused by abrupt thickness changes. Therefore, a second step, local in nature is taken in which a small area in the vicinity of the hole and encompassing other points of singularities is discretized using a fine finite element mesh. The displacement boundary conditions for the local region are obtained from the global Ritz analysis. The chosen perturbation function is reliable for circular cutout in uniform plates, therefore elliptical cutouts were suitably transformed to circular shapes using conformal mapping. The methodology is then applied to the analysis of composite plates, and its usefulness successfully proved in such cases. The proposed approach resulted in accurate prediction of stresses, with considerable savings in CPU time and data storage for composite flat panels.

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ABSTRACT: This paper presents a simple and accurate global-local method to calculate the static response of simply-supported, composite plates with small cracks. The approach primarily involves two steps. In the first step a global approach, the Ritz method, is used to calculate the response of the structure. Displacement based Ritz functions for the plate without the crack are augmented with a perturbation function, which is accurate for isotropic plates only, to account for the crack. The Ritz solution does not accurately satisfy the natural boundary conditions at the crack boundary. Therefore, a second step, local in nature, is taken in which a small area in the vicinity of the crack and encompassing other points of singularities, is discretized using a fine finite element mesh. The displacement boundary conditions for the local region are obtained from the global Ritz analysis. The methodology is applied for the local model including the crack. The proposed approach resulted in accurate prediction of stresses, with 85% savings in computational time and 92% in data storage for the analysis of composite flat panels.

A. Vafai, M. Javidruz, J.F. Chen and J.C. Chilton, “Effect of cracks on vibration, buckling and parametric instability of cylindrical shells”, 3rd International Conference on Advances in Steel Structures, 2002

ABSTRACT: (none given).
PARTIAL ABSTRACT: GMRES(k) is widely used for solving nonsymmetric linear systems. However, it is inadequate either when it converges only for k close to the problem size or when numerical error in the modified Gram-Schmidt process used in the GMRES orthogonalization phase dramatically affects the algorithm performance. An adaptive version of GMRES(k) which tunes the restart value k based on criteria estimating the GMRES convergence rate for the given problem is proposed here. This adaptive GMRES(k) procedure outperforms standard GMRES(k), several other GMRES-like methods, and QMR on actual large scale sparse structural mechanics postbuckling and analog circuit simulation problems…

ABSTRACT: A triangular flat shell element for large deformation analysis of linear viscoelastic laminated composites is presented. Hygrothermomechanically simple materials are considered for which a change in the hygrothermal environment results in a horizontal shifting of the relaxation moduli curves on a log timescale, in addition to the usual hygrothermal loads. Recurrence relations are developed and implemented for the evaluation of the viscoelastic memory loads. The nonlinear deformation process is computed using an incremental/iterative approach with the Newton-Raphson method used to find the incremental displacements in each time step. The presented numerical examples consider the large deformation and stability of linear viscoelastic structures under deformation-independent mechanical loads, deformation-dependent pressure loads, and thermal loads. Unlike elastic structures that have a single critical load value associated with a given snapping or buckling instability phenomenon, viscoelastic structures will usually exhibit a particular instability for a range of applied loads over a range of critical times. Both creep buckling and snap through examples are presented here. In some cases, viscoelastic results are also obtained using the quasi-elastic method in which load-history effects are ignored, and time-varying viscoelastic properties are simply used in a series of elastic problems. The presented numerical examples demonstrate the capability and accuracy of the formulation.

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ABSTRACT: Because of the inherent complexity of fiber-reinforced laminated composites, it can be challenging to manufacture composite structures according to their exact design specifications, resulting in unwanted material and geometric uncertainties. Thus the understanding of the effect of uncertainties in laminated structures on their static and dynamic responses is highly important for a reliable design of such structures. In this research, we focus on the probabilistic stability analysis of laminated structures subject to subtangential loading, a combination of conservative and nonconservative tangential loads, using the dynamic
criterion. In order to study the dynamic behavior by including uncertainties into the problem, three models were developed: exact Monte Carlo simulation, sensitivity-based Monte Carlo simulation, and probabilistic FEA. These methods were integrated into the existing finite element analysis. Also, perturbation and sensitivity analysis have been used to study nonconservative problems to study the stability analysis using the dynamic criterion.

References listed at the end of the 2002 PhD dissertation with the same title by Vijay K. Goyal (VPISU):


Jeong Seo Koo (1) and Byung Man Kwak (2)
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Post-buckling analysis of nonfrictional contact problems using linear complementarity formulation”, Computers & Structures, Vol. 57, No. 5d, pp 783-794, December 1995, DOI: 10.1016/0045-7949(95)00077-T

ABSTRACT: A linear complementary problem formulation is proposed for post-buckling analysis of geometrically nonlinear structures with nonfrictional contact constraints. The arc-length method with updated normal plane constraint used to trace the equilibrium paths of the structures is combined to generate a path-following algorithm as a predictor-corrector procedure. The initial load increment is determined in the predictor phase, considering the change of contact status. For the corrector phase, the unknown load scale parameter is eliminated using the arc-length constraint. The unknown contact variables such as contact status and contact forces can be directly solved by the linear complementarity problem without any ad-hoc technique. Several newly defined buckling and post-buckling with contact constraints are solved to illustrate the algorithm and the detail complex behaviors. It is demonstrated that the algorithm is very stable and efficient in dealing with the rather difficult class of buckling problems with obstacles.

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ABSTRACT: A stability analysis of laminated beam structures subject to subtangential loading, a combination of conservative and nonconservative tangential follower loads, using the dynamic criterion is performed. These loads are characterized using a nonconservativeness loading parameter. This parameter allows us to study the effect of the level of load conservativeness on the stability of laminated beams. The element tangent stiffness and mass matrices are obtained using analytical integration through the dynamic version of the principle of virtual work for laminated composites. Results for the conservative loading, for both isotropic and laminated beams, are in very good agreement with those available in the literature. For the case of partially conservative loads, results show that for both isotropic and laminated composite beams, and in the absence of damping, all values of the nonconservativeness loading parameter less than or equal to 0.5 will be governed by the divergence instability, and by flutter instability otherwise.


ABSTRACT: Innovative manufacturing techniques like Electron Beam Free Form Fabrication (EBF3), Friction Stir Welding (FSW), and Selective Laser Sintering (SLS) are additive in nature as opposed to subtractive, meaning that the material is deposited wherever necessary on the contrary to removal of unnecessary material from the structures. These techniques have created new opportunities and much bigger design space to optimize structures of complex shapes especially the aerospace vehicles without much material wastage and energy (Green Technologies). Earlier research has shown that panels with curvilinear stiffeners may have a reduced weight than panels with straight stiffeners having the same strength performance (buckling and stress
constraints). Fuselage, supersonic and subsonic wing panels which are curved can be stiffened using curvilinear (alignment) stiffeners. Our research in supersonic wing optimization using curvilinear spars and ribs has realized that the panels bounded by these spars and ribs may have 3 to 6 curved edges that created a new opportunity and complexity in design of curved panels with curvilinear stiffeners. To design and optimize such panels, a framework is developed which consists of MD-PATRAN, MDNASTRAN, VisualDoc and MATLAB. To create the geometry of stiffened curved panels in the parametric fashion using MD PATRAN, three approaches are proposed, namely, 1) Bounding Box Method, 2) Interpolation of the Shell and Manifold Method, and 3) Interpolation of the Shell and Curve Projection Method. Advantages and disadvantages of these approaches are discussed, including remedies for some of the limitations. Amongst these approaches, the last one, Interpolation of the Shell and Curve Projection Method is the best to create and analyze the arbitrary geometry panel with curvilinear blade-stiffeners. These approaches efficiency and accuracy are compared for flat rectangular panel with curved edges and cylindrical shell with curved edges during optimization.

ABSTRACT: The objective of the current paper is to present a Ritz type analytical model for the buckling analysis of cracked stiffened structures. Complex structures typically used in aerospace and marine engineering such as a cracked stiffened panel is considered. In the Ritz-type model, we use the local trigonometric trial functions to define the displacement function of the crack-stiffened panel, which is discretized into several elements based on the crack location and stiffener location. The interface continuity conditions for cracked thinwalled structures are derived and investigated in detail; the interface conditions are used to condense the global eigenvalue problem by eliminating redundant Ritz coefficients. Examples are presented to illustrate the effectiveness of the current model for the buckling analysis. Buckling results from the current model are found to agree well with those obtained using a shell finite element method.

ABSTRACT: The objective of the current paper is to present a Ritz-type analytical model for predicting the behavior of discontinuous beams such as thin-walled beams with cracks and multiply-stepped beams. The beam is discretized in the cracked as well as the un-cracked domains for a cracked thin-walled beam and in uniform beams for a multiple-stepped beam. A set of local trigonometric trial functions is used to define the twist angle for the cracked domain and the un-cracked domains, as well as to define the displacement field for uniform domains. A global equation system of unknown Ritz coefficients is derived by minimizing the Lagrangian functional or the total potential energy. In the present Ritz model, the interface continuity conditions between sub-domains are investigated and enforced into the global equation system using the condensation procedure or the Lagrange multipliers. Examples are presented to illustrate the effectiveness of the current model for free vibration and torsional analysis. Results obtained from the current model are found to agree well with those obtained using a detailed finite element method or with existing results in literature. The proposed model offers an efficient approach to reduce the modeling efforts and computational time required to analyze complex beams with cracks or multiple steps.
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ABSTRACT: Thin-walled circular cylinders, and frusta (truncated circular cones) of aluminium alloy were subjected to axial static loading. Their initial axial length and the outside diameter of the cylinders and frusta (the larger top end) were kept constant whilst their wall thickness was varied. The load-deformation or compression behaviour of the cylinder and frusta of various thicknesses and semi-apical angles were recorded and the modes of collapse were observed and studied. The main purpose of results for circular cylinders is to give a basis of comparison for the frusta. Relatively thick tubes fail by collapsing into circumferential axisymmetric rings and thin ones by folding progressively into diamond-shaped lobes after assuming an initially axisymmetric ring mode of deformation. In the latter case the initial axisymmetric rings developed into nonsymmetric diamond patterns (elliptic, triangular and square, etc.) as loading progressed. Also, initially non-symmetric diamond buckle patterns were observed to be characteristic modes of frustum collapse. Initial peak failure loads and mean post-buckling loads for the various modes of deformation were obtained experimentally. It is shown that buckling loads for both cylinders and frusta increase with increasing slenderness ratio (t/D for cylinders and t/Dbar for frusta) following, broadly, a parabolic law. Empirical expressions for the post-buckling load required to effect crumpling have been obtained.

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ABSTRACT: The crumpling of thin-walled frusta, under axial compression, in the ‘concertina’ mode is studied. The energy expended in bending at the plastic hinges and in stretching the metal between the hinges is minimized for the total decrease in height due to collapse. The thinning of the cross-section due to stretching is neglected. A theoretical model has been developed and numerical results are obtained that show the effect of slenderness, t/D, and the semi-apical angle of the frusta. Good qualitative agreement in trends is exhibited when comparison with available experimental results is made.

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ABSTRACT: Experimental investigations were conducted into the quasi-static collapse and energy absorption characteristics of thin-walled steel tubes containing a number of geometrical discontinuities in the form of grooves of constant depth and axial length. The failure modes and load-deflection characteristics are discussed and compared with the corresponding theoretical values. An inextensional collapse mechanism is used to describe a non-symmetrical diamond mode shell folding which takes into account the concept of stationary circumferential and inclined travelling hinges.

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ABSTRACT: A theoretical model describing the progressive extensible plastic collapse of thin-wall conical and cylindrical shells is presented. The proposed theory enables the load-deflection curves during axial compression following the deformation history of the shell to be evaluated. The comparison of theoretical curves with experimental ones shows a fair degree of accuracy.

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ABSTRACT: A theoretical analysis of the observed stable collapse mechanism of thin-walled circular frusta and tubes, crushed under axial static and/or dynamic loading, for calculating crushing loads and the energy absorbed during collapse, is reported. The analysis is based on experimental observations regarding the energy-absorbing collapse mechanisms developed during the crushing process. The proposed theoretical model was experimentally verified and proved to be very efficient for theoretically predicting the energy-absorbing capability of the conical shells.

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ABSTRACT: The present paper deals with the implementation of the explicit FE Code LS-DYNA to simulate the crash behaviour and energy absorption characteristics of steel thin-walled tubes of octagonal cross-section subjected to axial loading. The collapse procedure is successfully simulated and the obtained numerical results are compared with actual experimental data from small-scale models and useful concluding remarks pertaining to the design requirements of the crushing process are drawn.

ABSTRACT: In this paper the results of experimental works pertaining to the crash behaviour, collapse modes and crashworthiness characteristics of carbon fibre reinforced plastic (CFRP) tubes that were subjected to static axial compressive loading are presented in detail. The tested specimens were featured by a material combination of carbon fibres in the form of reinforcing woven fabric in thermosetting epoxy resin, and they were cut out at various lengths from three CFRP tubes of the same square cross-section but different thickness, laminate stacking sequence and fibre volume content. CFRP tubes were compressed in a hydraulic press of 1000 kN loading capacity at very low-strain rate typical for static testing. The influence of the most important specimen geometric features such as the tube axial length, aspect ratio and wall thickness on the compressive response and collapse modes of the tested tubes is thoroughly analysed. In addition, the effect of the laminate material properties such as the fibre volume content and stacking sequence on the energy absorbing capability of the thin-wall tubes is also examined. Particular attention is paid on the analysis of the mechanics of the tube axial collapse modes from macroscopic and microscopic point of view, emphasizing on the mechanisms related to the crash energy absorption during the compression of the composite tubes.


ABSTRACT: In the simulation works described in this paper the LS-DYNA3D explicit finite element code is used to investigate the compressive properties and crushing response of square carbon FRP (fibre reinforced plastic) tubes subjected to static axial compression and impact testing. A series of models was created to simulate some of the static and dynamic tests performed in the National Technical University of Athens using CFRP tubes featured by the same material combination (woven fabric in thermosetting epoxy resin) and external cross-section dimensions, but different length, wall thickness, laminate stacking sequence and fibre volume content. Simulation works focused on modelling the three modes of collapse (i.e. progressive end-crushing with tube wall laminate splaying, local tube-wall buckling and mid-length collapse) observed in the series of static and dynamic compression tests. Satisfactory level of agreement between calculations and test results was obtained regarding the main crushing characteristics of the tested CFRP tubes—such as peak compressive load and crash energy absorption and the overall crushing response—as the finite element models were refined several times in order to obtain optimum results.


ABSTRACT: In the present paper Artificial Neural Networks (ANN) are applied in order to predict the buckling modes of thin-walled PVC tubes under compressive axial forces. For the development of the models the neural network toolbox of Matlab was applied. The results show that these models can satisfactorily face these problems and they constitute not only a fast method, compared to time consuming experiments, but also a
A reliable tool that can be used for the studying of such parts which are usually employed as structural elements for the absorption of the energy of an impact, in automotive and aerospace applications.

References listed at the end of the paper:


ABSTRACT: The behaviour of orthogonal layers of aluminium and mild steel tubes under lateral compression is considered. The results for each material are presented separately in Parts I and II of the paper. In all the tests the initial separation of tubes in the same layer is sufficiently large to preclude contact being established between adjacent tubes as they deform.

Part I: Aluminium systems are examined and two principal categories of behaviour are identified. As well as providing basic load-deflection data in a suitably non-dimensionalised form, certain particular features of the modes of deformation of individual tubes in the systems are examined in detail.

Part II: This presents data and observations concerning mild steel systems. Of especial interest is the difference between the behaviour of as-received tubes, which develop cracks in the regions of greatest deformation, and that of annealed mild steel tubes which show similar characteristics to those of the aluminium systems.


ABSTRACT: Experimental results are provided for the quasi-static and dynamic axial crushing of thin-walled square and rectangular tubes manufactured from sheet metal. The tubes were tested both empty and filled with polyurethane foam of various densities. Both the stability and the energy absorbing characteristics of the tubes
are described and discussed. Simple theoretical models are proposed to explain and quantify the interaction between the foam and the sheet metal tubes.


ABSTRACT: Following earlier work on the axial crushing of foam-filled sheet metal tubes of square and rectangular cross-section and empty tapered tubes the behaviour of foam-filled tapered tubes is considered. Theoretical estimates of the variation in the mean crushing loads for both quasi-static and dynamic loading conditions are provided and compared with experimental data.


ABSTRACT: The linear and geometric nonlinear buckling load including transverse shear deformation are calculated by Timoshenko first-order shear deformation theory and Reddy higher-order shear deformation theory respectively. The effects of lamination angle, number of layers and radius-to-thickness ratio on the buckling pressure are analyzed. The combination of a Random-Search approach and the flexible-tolerance method is employed to search for the optimization lamination angles. The Mixed-discrete-optimization program is used to solve the optimization problem in which the lamination angles are assumed to have discrete values. The experiments of the carbon-epoxy cylindrical shell models show that the results presented in this paper are reliable.

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ABSTRACT: The bending, buckling and free vibration problems of non-homogeneous composite laminated cylindrical shells are considered. Hamilton–Reissner's mixed variational principle is used to deduce a consistent first-order theory of composite laminated cylindrical shells with non-homogeneous elastic properties. The governing equations with their required boundary conditions are derived without introducing any shear correction factors. Numerical results for the transverse deflections, stresses, natural frequencies and critical buckling loads are presented to show the advantages of this theory. The influences of the non-homogeneity and thickness ratio on the shell structural response are investigated. The study concludes that the inclusion of the non-homogeneity effect is required, even if it is weak, for predicting the actual structural response of the shells.

ABSTRACT: A two-dimensional solution is presented for bending analysis of simply supported functionally graded ceramic–metal sandwich plates. The sandwich plate faces are assumed to have isotropic, two-constituent material distribution through the thickness, and the modulus of elasticity and Poisson’s ratio of the faces are assumed to vary according to a power-law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic ceramic material. Several kinds of sandwich plates are used taking into account the symmetry of the plate and the thickness of each layer. We derive field equations for functionally graded sandwich plates whose deformations are governed by either the shear deformation theories or the classical theory. Displacement functions that identically satisfy boundary conditions are used to reduce the governing equations to a set of coupled ordinary differential equations with variable coefficients. Numerical results of the sinusoidal, third-order, first-order and classical theories are presented to show the effect of material distribution on the deflections and stresses.


ABSTRACT: The sinusoidal shear deformation plate theory, presented in the first part of this paper, is used to study the buckling and free vibration of the simply supported functionally graded sandwich plate. Effects of rotatory inertia are considered. The critical buckling load and the vibration natural frequency are investigated. Some available results for sandwich plates non-symmetric about the mid-plane can be retrieved from the present analysis. The influences of the transverse shear deformation, plate aspect ratio, side-to-thickness ratio and volume fraction distributions are studied. In addition, the effect of the core thickness, relative to the total thickness of the plate, on the critical buckling load and the eigenfrequencies is investigated.


ABSTRACT: Thermal buckling response of functionally graded plates is presented in this paper using sinusoidal shear deformation plate theory (SPT). The material properties of the plate are assumed to vary according to a power law form in the thickness direction. Equilibrium and stability equations are derived based on the SPT. The non-linear governing equations are solved for plates subjected to simply supported boundary conditions. The buckling analysis of a functionally graded plate under various types of thermal loads is carried out. The influences of many plate parameters on buckling temperature difference will be investigated. Numerical results are presented for the SPT, demonstrating its importance and accuracy in comparison to other theories.

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Matsunaga, H. (2009) Thermal buckling of functionally graded plates according to a 2D higher-order deformation theory. Composite Structures, 90(1), 76-86.


H. Altenbach, O. Morachkovsky, K. Naumenko and A. Sychov, “Geometrically nonlinear bending of shells and
DOI: 10.1007/s004190050122

ABSTRACT: A phenomenological constitutive model for characterization of creep and damage processes in metals is applied to the simulation of mechanical behaviour of thin-walled shells and plates. Basic equations of the shell theory are formulated with geometrical nonlinearities at finite time-dependent deflections of shells and plates in moderate bending. Numerical solutions of initial/boundary-value problems have been obtained for rectangular thin plates (two-dimensional case) and axisymmetrically loaded shells of revolution (one-dimensional case). Based on the numerical examples for the two problems, the influence of geometrical nonlinearities on the creep deformation and damage evolution in shells and plates is discussed.


ABSTRACT: Modern design rules for thin-walled structures which operate at elevated temperatures are based on the demand that the creep and may be the damage behaviour should be taken into account. In the last four decades various models including the scalar or tensor valued hardening and damage variables are established. These models reflect the influence of the deformation or the damage induced anisotropy on the creep response. One problem in creep analysis of thin-walled structures is the selection of the structural mechanics model which has to be adequate to the choice of the constitutive equations. Considering complex loading conditions the structural mechanics model has to reflect for instance the different constitutive behaviour in tension and compression. Below the applicability of classical engineering models for beams, plates and shells to the creep-damage analysis is discussed. It will be shown that a first improvement of the classical approach can be given within the assumptions of the first order shear deformation theory. Based on the beam equations we demonstrate that the shear correction factors have to be modified within the time-step analysis.

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PARTIAL INTRODUCTION: At present the shell theory finds out new branches of applications. Biological membranes, thin polymeric films and thin structures made from shape memory materials may be pointed out as examples. In addition, the manufacturing technology of shells leads to significant changes of the material properties. As a result the conventional variants of the shell theory, based on the derivation of the basic equations from the 3D-theory of elasticity, cannot be used….


ABSTRACT: From the practice of power and petrochemical plants it is well known that pipe bends are the most
critical structural components with respect to possible creep failures. In this paper we review recent approaches to analyze non-linear behavior of plate and shell structures under creep-damage conditions. Furthermore, we perform a numerical analysis of the long-term behavior for a real spatial pipeline. We take into account the non-uniformity of the wall thickness in the pipe bends as a result of processing by induction bending. The material behavior is described by a Kachanov-Rabotnov-Hayhurst type constitutive model with a scalar valued damage parameter. The results are compared with data from in-service observation of the pipeline.


ABSTRACT: One of the research direction of Horst Lippmann during his whole scientific career was devoted to the possibilities to explain complex material behavior by generalized continua models. A representative of such models is the Cosserat continuum. The basic idea of this model is the independence of translations and rotations (and by analogy, the independence of forces and moments). With the help of this model some additional effects in solid and fluid mechanics can be explained in a more satisfying manner. They are established in experiments, but not presented by the classical equations. In this paper the Cosserat-type theories of plates and shells are debated as a special application of the Cosserat theory.

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ABSTRACT: A finite element based on the efficient higher-order zig-zag theory with multiple delaminations is developed. The bending part of the formulation is constructed from the concept of DKQ element. Unlike conventional elements, a developed element has its reference in the bottom surface which simplifies zig-zag terms on formulation. Exact patch solutions are developed on elements which have the bottom reference system. The present element passes proper bending patch tests in the arbitrary mesh configurations in isotropic materials. Zig-zag formulation is adopted to model laminated plates with multiple delaminations. To assess the accuracy and efficiency of the present element based on higher-order zig-zag theory with multiple delaminations, the linear buckling problem of laminated plates with multiple delaminations has been analysed. The results have been compared with three-dimensional elasticity solutions. The present element works as an efficient tool for analysing the behaviour of the laminated composites with multiple delaminations.

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“Buckling analysis of a composite shell with multiple delaminations based on a higher order zig-zag theory”,

ABSTRACT: A new three-node triangular shell element based on a higher order zig-zag theory is developed for laminated composite shells with multiple delaminations. The baseline higher order zig-zag composite shell theory for multiple delaminations has been developed in a general curvilinear coordinate system and in general tensor notation. All the complicated curvatures of the surface including twisting curvatures can be described in an exact manner since the developed shell finite element is based on the geometrically exact surface representation. It is therefore possible to apply the present finite element formulation to the composite structures with arbitrary shaped multiple delaminations, general layup configurations and arbitrary boundary conditions. The slopes of deflections are included as independent degrees of freedom, which require the normal slope continuities between element interfaces. The nonconforming shape functions of Specht's three-node triangular plate bending element are employed to interpolate out-of-plane displacements. The developed element passes the bending and twisting patch tests for flat surface configurations. The element is then used to analyze the linear buckling problem of composite cylindrical shells with multiple delaminations. Throughout the numerical examples, it is demonstrated that the developed shell finite element is numerically efficient because it has minimal nodal degrees of freedom to describe the composite shells having multiple delaminations. The finite element realization of a higher order zig-zag shell theory with multiple delaminations can be served as a powerful numerical tool to analyze the complicated shell structures for the critical buckling loads as well as the corresponding mode shapes.

References listed at the end of the paper:

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ABSTRACT: A new two-dimensional theory for the analysis of deep, doubly curved, multilayered shells is proposed. The theory is based on a kinematical approach in which the continuity conditions for displacements and shear stresses at layer interfaces and on the bounding surfaces of the shell are exactly satisfied, while, at the same time, refinements of the shear and membrane terms are taken into account, by means of trigonometric functions. The accuracy of the model is assessed in statics and dynamics through investigation of significant problems, for which an exact three-dimensional elasticity solution is known. In statics, the cylindrical bending of a cylindrical panel, of thickness h, and inner radius R, is examined. The results obtained are in good agreement with the analytical solution of Ren [Comput. Sci Technol. 29 (1987) 169–187], and prove that no shear-correction factors are requested. In dynamics, wave propagation in a three-layered elastic cylinder is explored. The accuracy of the theory is assessed by comparison with the exact three-dimensional elasticity solution of Armenakas [J. Acoust. Soc. Am. 49 (5, Part 2) (1971) 1511–1520]. The model is then applied to the exploration of the dispersive behavior of a viscoelastic cylinder.

A V Krishna Murthy and T S R Reddy, “A higher order theory of laminated composite cylindrical shells”, 1986 (publisher not given, mendeley.com)

ABSTRACT: A new higher order theory has been proposed for the analysis of composite cylindrical shells. The formulation allows for arbitrary variation of inplane displacements. Governing equations are presented in the form of a hierarchy of sets of partial differential equations. Each set describes the shell behavior to a certain degree of approximation. The natural frequencies of simply-supported isotropic and laminated shells and stresses in a ring loaded composite shell have been determined to various orders of approximation and compared with three dimensional solutions. These numerical studies indicate the improvements achievable in
estimating the natural frequencies and the interlaminar shear stresses in laminated composite cylinders.

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ABSTRACT: Vibration analysis of a rotating composite blade is the main purpose of this study. A general formulation is derived for an initially twisted rotating shell structures including the effect of centrifugal force and Coriolis acceleration. In this work, the blade is assumed to be a moderately thick open cylindrical shell that includes the transverse shear deformation and rotary inertia, and is oriented arbitrarily with respect to the axis of rotation to consider the effects of disc radius and setting angle. For a thick shell, we must consider the transverse shear deformation as well as rotary inertia. Thus, based on the concept of the degenerated shell element with the Reissner–Mindlin’s assumptions, the finite element method is used for solving the governing equations. In the numerical study, effects of various parameters are investigated: initial twisting angles, thickness to radius ratios, layer lamination and fiber orientation of composite blades. Also, they are compared with the previous works and experimental data.

ABSTRACT: Three-dimensional thermal buckling analysis is performed for functionally graded materials. Material properties are assumed to be temperature dependent, and varied continuously in the thickness direction according to a simple power law distribution in terms of the volume fraction of a ceramic and metal. The finite element model is adopted by using an 18-node solid element to analyze more accurately the variation of material properties and temperature field in the thickness direction. Furthermore, the assumed strain mixed formulation is used to prevent locking as well as maintaining kinematic stability of the finite element model for thin plates and shells. The thermal buckling behavior under uniform or nonuniform temperature rise across the thickness is analyzed. Numerical results are compared with those of the previous works. In addition, the changes of critical buckling temperature due to the effects of temperature field, volume fraction distributions, and system geometric parameters are studied.

ABSTRACT: Three-dimensional thermomechanical buckling analysis is investigated for functionally graded composite structures that composed of ceramic, functionally graded material (FGM), and metal layers. Material properties are assumed to be temperature dependent, and in FGM layer, they are varied continuously in the thickness direction according to a simple power law distribution in terms of the ceramic and metal volume fractions. The finite element model is adopted by using an 18-node solid element to analyze more accurately the
variation of material properties and temperature field in the thickness direction. Temperature at each node is obtained by solving the thermomechanical equations. For a time discretization, Crank–Nicolson method is used. In numerical results, the thermal buckling behavior of FGM composite structures due to FGM thickness ratios, volume fraction distributions, and system geometric parameters are analyzed.

ABSTRACT: In this article, the elastic buckling behavior of orthotropic small scale plates under biaxial compression is studied. Analysis is carried out with the consideration of small scale effects. Employing nonlocal elasticity theory (Eringen, 1983) governing equations for the aforementioned problems are derived. Explicit expressions for modified buckling loads are obtained for micro/nanoplates with isotropic and orthotropic properties; and under uniaxial and biaxial compressions. The effects of the small scale on the buckling loads of plates considering various material and geometrical parameters are examined.

ABSTRACT: Classical plate theory (CLPT) and first-order shear deformation plate theory (FSDT) of plates are reformulated using the nonlocal elasticity theory. Developed nonlocal plate theories have been applied to study buckling behavior of nanoplates. Nonlocal elasticity theory, unlike traditional elasticity theory introduces a length scale parameter into the formulation to take into account the discrete structure of the material to some extent. Both single-layered and multilayered nanoplates have been included in the analysis. Navier's approach has been used to obtain exact solutions for buckling loads for simply supported boundary conditions. Dependence of the small scale effect on various geometrical and material parameters has been investigated. Present study reveals the presence of significant small scale effect on the buckling response of nanoplates. The theoretical development and the numerical results presented in the present work are expected to promote the use of nonlocal theories for more accurate prediction of stability behavior of nanoplates and nanoshells.

ABSTRACT: Thermo-mechanical buckling behaviour of Single Walled Carbon Nanotube (SWCNT) on Winkler foundation is reported. Non-local elasticity theory and differential transformation method are applied. Effects of (i) size of SWCNT, (ii) non-local parameter, (iii) Winkler modulus, (iv) boundary conditions and (v) temperature on buckling load are investigated.

References listed at the end of the paper:
1. Arıkoğlu A 2004 Istanbul Technical University

ABSTRACT: This paper studies the thermal effect on axially compressed buckling of a multi-walled carbon nanotube. The effects of temperature change, surrounding elastic medium and van der Waals forces between the inner and outer nanotubes are taken into account. Using continuum mechanics, an elastic multi-shell model with thermal effect is presented for axially compressed buckling of a multi-walled carbon nanotube embedded in an elastic matrix under thermal environment. Based on the model, numerical results for the general case are obtained for the thermal effect on axially compressed buckling of a multi-walled carbon nanotube. It is shown that the axial buckling load of multi-walled carbon nanotube under thermal loads is dependent on the wave number of axially buckling modes. And a conclusion is drawn that at low and room temperature the critical load for infinitesimal buckling of a multi-walled carbon nanotube increase as the value of temperature change increases, while at high temperature the critical load for infinitesimal buckling of a multi-walled carbon nanotube decrease as the value of temperature change increases.
ABSTRACT: Bending manipulation and direct force measurements of ultrathin boron nitride nanotubes (BNNTs) were performed inside a transmission electron microscope. Our results demonstrate an obvious transition in mechanics of BNNTs when the external diameters of nanotubes are in the range of 10 nm or less. During in situ transmission electron microscopy bending tests, characteristic “hollow” ripple-like structures formed in the bent ultrathin BNNTs with diameters of sub-10 nm. This peculiar buckling/bending mode makes the ultrathin BNNTs hold very high post-buckling loads which significantly exceed their initial buckling forces. Exceptional compressive/bending strength as high as ∼1210 MPa was observed. Moreover, the analysis of reversible bending force curves of such ultrathin nanotubes indicates that they may store/adsorb strain energy at a density of ∼400 × 10⁶ J m⁻³. Such nanotubes are thus very promising for strengthening and toughening of structural ceramics and may find potential applications as effective energy-absorbing materials like armor.


ABSTRACT: One of the best approaches for modeling large deformation of shells is the Cosserat surface. However, the finite-element implementation of this model suffers from membrane and shear locking, especially for very thin shells. The basic assumption of this theory is that the mid-surface of the shell is regarded as a Cosserat surface with one inextensible director. In this paper, it is shown that by constraining the director vector normal to the mid-surface, besides very good and accurate results, shear locking is also eliminated. This constraint is in fact a limiting analysis of the Cosserat theory in which Kirchhoff’s hypothesis is enforced. Numerical solution is performed using nine-node isoparametric element. The principal of virtual work is used to obtain the weak form of the governing differential equations and the material and geometric stiffness matrices are derived through a linearization process. The validity and the accuracy of the method are illustrated by numerical examples.


ABSTRACT: In this paper a new element is developed that is based on Cosserat theory. In the finite element implementation of Cosserat theory shear locking can occur, especially for very thin shells. In the present investigation the director vector is constrained to remain perpendicular to the mid surface during deformation. It will be shown that this constraint yields accurate results in very large deformation of thin shells also the rate of convergency is very good. For plastic formulation, the model introduced by Simo is used and it has been reduced for constrained director vector and the consistent elasto-plastic tangent moduli is extracted for finite element solution. This model includes both kinematic and isotropic hardening. For numerical investigations an isoparametric nine node element is employed then by linearization of the principle of virtual work, material and
geometric stiffness matrices are extracted. The validity and the accuracy of the proposed element is illustrated by the numerical examples and the results are compared with those available in the literature.


ABSTRACT: The elastic buckling behavior of quadrilateral single-layered graphene sheets (SLGS) under bi-axial compression is studied employing nonlocal continuum mechanics. Small-scale effects are taken into consideration. The principle of virtual work is employed to derive the governing equations. The Galerkin method in conjunction with the natural coordinates of the nanoplate is used as a basis for the analysis. The buckling load of skew, rhombic, trapezoidal, and rectangular nanoplates considering various geometrical parameters are obtained. It is shown that nonlocal effects are very important in arbitrary quadrilateral graphene sheets and their inclusion results in smaller buckling loads. Also the effects of geometrical parameters such as aspect ratio, angle, and mode number on the buckling load decrease when scale coefficient increases, for all arbitrary quadrilateral SLGS.

References listed at the end of the paper:


ABSTRACT: Minute concentrations of suspended particles can dramatically alter the behavior of a drying droplet. After a period of isotropic shrinkage, similar to droplets of a pure liquid, these droplets suddenly buckle like an elastic shell. While linear elasticity is able to describe the morphology of the buckled droplets, it fails to predict the onset of buckling. Instead, we find that buckling is coincident with a stress-induced fluid to solid transition in a shell of particles at a droplet's surface, occurring when attractive capillary forces overcome stabilizing electrostatic forces between particles. When replacing water by a mixture of ethanol and water, the buckling threshold changes. For a fixed colloid solid fraction, the buckling threshold evolves as a function of ethanol content, due to changes of the solvent mixture physical properties, such as viscosity and evaporation rate. A simplified model predicting the qualitative behaviour of the buckling threshold as a function of the initial ethanol mass fraction has been developed that fits well experimental results.


ABSTRACT: Morphological transformation during evaporation-induced self-assembly of a mixed colloidal suspension in micrometric droplets has been investigated. It has been demonstrated that a buckling-driven shape transition of drying droplets of mixed colloidal suspension takes place during evaporation-induced self-assembly. Further, it is also shown that the distortion modulations get significantly amplified with enhancement
in volume fraction of anisotropic soft colloidal component of the mixed colloids. It has been argued that the reduction in elastic modulus of formed shell, at the boundary of a drying droplet, and the anisotropic nature of one of the colloidal components facilitate the deformation process. Hierarchical structures of these assembled colloidal grains have been probed using electron microscopy and scattering techniques.

References listed at the end of the paper:

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ABSTRACT: In this paper, buckling phenomenon of single walled carbon nanotubes under torsional and axial combined loading by finite element method is investigated. Models are constructed via an individual structural model in Ansys software. CNTs hexagon geometrical structure is simulated by means of porous shell. Single walled carbon nanotubes of zigzag (12,0) and (21,0) with various aspect ratios (length to diameter ratio) are selected and they are subjected to torsional and axial combined loads. In this study, the effects of radius, length and aspect ratio on the critical buckling loads are investigated. Numerical results indicate that with increment of length and aspect ratio, the critical buckling loads will decrease generally. Also diagrams show that in lengths greater than 5 nm, nanotubes (21,0) will endure more critical buckling loads relative to nanotube (12,0). This result is followed by the increase in surface area by increasing the diameter of the nanotube. In this study the changes trend of critical buckling loads in terms of the different variables is good agreement with previous studies.

References listed at the end of the paper:


ABSTRACT: In the present work differential transformation method (DTM) is used to predict the buckling behaviour of single walled carbon nanotube (SWCNT) on Winkler foundation under various boundary conditions. Four different boundary conditions namely clamped–clamped, simply supported, clamped hinged and clamped free are used to study the critical buckling loads. Effects of (i) size of SWCNT (ii) nonlocal parameter and (iii) Winkler elastic modulus on nonlocal critical buckling loads are being investigated and discussed. The DTM is implemented for the nonlocal SWCNT analyses and this yields results with high degree of accuracy. Further, present method can be applied to linear and nonlinear problems.

J. Patrick Wilber (Dept. of Theoretical and Applied Mathematics, University of Akron, Akron, Ohio, USA), “Buckling of graphene layers supported by rigid substrates”, arXiv:1002.0724v1 [cond-mat.mes-hall] 3 Feb 2010

ABSTRACT: We formulate a nonlinear continuum model of a graphene sheet supported by a flat rigid substrate. The sheet is parallel to the substrate and loaded on a pair of opposite edges. A typical cross-section of the sheet is modeled as an elastica. We use elementary techniques from bifurcation theory to investigate how the buckling of the sheet depends on the boundary conditions, the composition of the substrate, and the length of the sheet. We also present numerical results that illustrate snap-buckling of the sheet.

References listed at the end of the paper:


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ABSTRACT: Atomistic simulations are used to study the bending of rectangular graphene nano ribbons subjected to axial stress both for free boundary and supported boundary conditions. The shape of the deformations of the buckled graphene nano ribbons, for small values of the stress, are sine waves where the number of nodal lines depend on the longitudinal size of the system and the applied boundary condition. The buckling strain for the supported boundary condition is found to be independent of the longitudinal size and estimated to be 0.86%. From a calculation of the free energy at finite temperature we find that the equilibrium projected two-dimensional area of the graphene nano ribbon is less than the area of a flat sheet. At the optimum length the boundary strain for the supported boundary condition is 0.48%.


ABSTRACT: In this paper, buckling analysis of biaxially compressed graphene sheets with non-local elasticity theory is reported. The equations of motion for graphene sheet are derived using non-local local elasticity theory. Levy’s approach has been used to solve the governing equations for various boundary conditions of the
graphene sheet. Present results from Levy’s solution agree with the results for all edges simply supported available in the literature. Further, the effect of the (i) non-local parameter, (ii) size of the graphene sheet and (iii) various boundary conditions on the critical buckling loads of the graphene sheets are investigated. It is observed that non-local parameter and boundary conditions significantly influence the critical buckling loads of the small size graphene sheets.

Jin-Xing Shi, Toshiaki Natsuki, Xiao-Wen Lei and Qing-Qing Ni (Shinshu University, Tokida, Japan), “Buckling instability of carbon nanotube atomic force microscope probe clamped in an elastic medium”, Journal of Nanotechnology in Engineering and Medicine, Vol. 3, No. 2, September 2012
ABSTRACT: Carbon nanotubes (CNTs) can be used as atomic force microscope (AFM) probes due to their robust mechanical properties, high aspect ratio and small diameter. In this study, a model of CNTs clamped in an elastic medium is proposed as CNT AFM probes. The buckling instability of the CNT probe clamped in elastic medium is analyzed based on the nonlocal Euler–Bernoulli beam model and the Whitney–Riley model. The clamped length of CNTs, and the stiffness of elastic medium affect largely on the stability of CNT AFM probe, especially at high buckling mode. The result shows that the buckling stability of the CNT AFM probe can be largely enhanced by increasing the stiffness of elastic medium. Moreover, the nonlocal effects of buckling instability are investigated and found to be larger for high buckling mode. The theoretical investigation on the buckling stability would give a useful reference for designing CNT as AFM probes.

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ABSTRACT: In this paper, we study the buckling properties of circular double-layered graphene sheets (DLGSs), using plate theory. The two graphene layers are modeled as two individual sheets whose interactions are determined by the Lennard-Jones potential of the carbon–carbon bond. An analytical solution of coupled governing equations is proposed for predicting the buckling properties of circular DLGSs. Using the present theoretical approach, the influences of boundary conditions, plate sizes, and buckling-mode shapes on the buckling behaviors are investigated in detail. The buckling stability is significantly affected by the buckling-mode shapes. As a result of van der Waals interactions, the buckling stress of circular DLGSs is much larger for the anti-phase mode than for the in-phase mode.

ABSTRACT: In this paper, a theory for non-linear bending of symmetrically laminated, cylindrically orthotropic, shallow, conical shells subjected to an axisymmetrically distributed load including transverse shear effects is established. By means of this theory and the modified iteration method, the analytical solution of the critical buckling pressure for a symmetrically laminated, cylindrically orthotropic, shallow, conical shell with a rigidly clamped edge under the action of uniform lateral pressure is obtained.
ABSTRACT: In this paper, a non-linear buckling problem of a symmetrically laminated, cylindrically orthotropic, truncated, shallow, spherical shell with a rigidly clamped outer edge and a non-deformable rigid body at the center under the action of uniform pressure, taking into account the effect of the transverse shear deformation, has been solved by the modified iteration method. Finally, this paper discusses the effects of transverse shear on the buckling of the shell.

ABSTRACT: In this paper, a model of cusped catastrophe at nonlinear dynamic buckling of a symmetrically laminated cylindrically orthotropic shallow spherical shell is presented. The shell is subjected to an axisymmetrical load. Effects of transverse shear are taken into account. Effects of the shear modulus, geometry and parameters of the material on the nonlinear dynamic buckling are discussed.

ABSTRACT: In this paper, a nonlinear bending theory for a corrugated shallow spherical shell is constructed. By means of this theory and the modified iteration method, the analytical solution of the critical buckling pressure for a corrugated shallow spherical shell with a rigidly clamped edge under the action of uniform pressure is obtained.

ABSTRACT: This paper is presented to solve the nonlinear dynamic buckling problem of a new type of composite cylindrical shells, made of ceram/metal functionally graded materials. The material properties vary smoothly through the shell thickness according to a power law distribution of the volume fraction of the constituent materials. The dynamic axial load is set in a linear increase form with regard to time. By taking the temperature-dependent material properties into account, the effect of environmental temperature rise is included. The nonlinear dynamic equilibrium equation of the shell was obtained by applying an energy method, and was then solved using the four-order Runge–Kutta method. The critical condition was eventually determined using B-R dynamic buckling criterion. Numerical results show the dynamic buckling load is higher than its static counterpart. Meanwhile, various effects of the inhomogeneous parameter, loading speed, dimension parameter, environmental temperature rise and initial geometrical imperfection on nonlinear dynamic buckling are discussed.

ABSTRACT: By using the Ritz energy method and finite element method, buckling behaviors of combined-loaded functionally graded cylindrical shells are investigated. The combined loads are composed of axial, lateral, and torsional loads. Results show that the contribution of lateral pressure to buckling is more significant than that of axial compression or torsion and the contributions of axial compression and torsion are almost the same. Also, a practical method is proposed in this article to determine the load-dominant bound between the single buckling mode due to one dominant load and the mixed buckling mode due to interaction of the two loads.

References listed at the end of the paper:

ABSTRACT: The linear and geometric nonlinear buckling load including transverse shear deformation is calculated by Timoshenko first-order shear deformation theory and Reddy higherorder shear deformation theory respectively. The effects of lamination angle, number of layers and radius-to-thickness ratio on the buckling pressure are analyzed. The combination of a Random-Search approach and the Flexible-Tolerance method is employed to search for the optimum lamination angles that have the highest buckling loads. The Mixed-Discrete-Optimization program is used to solve the optimization problem in which the lamination angles are assumed to have discrete values. The experiments of the carbonepoxy cylindrical shell models show that the results presented in this paper are reliable.

ABSTRACT: Focusing upon finding an optimum shape of crash box, which is one of the most important part of an automobile body to absorb impact energy at the time of a collision, for ensuring large energy absorption, the effect of introducing notch into a crash box on controlling plastic buckling behaviour was examined by three-dimensional finite element analyses. The influences of notch shape and arrangement on the deformation mode of a polygonal crash box was numerically examined and an optimum range of the dimensions of notch was quantitatively determined for ensuring stable buckling deformation. As a result, a fundamental scheme to optimise the shape and arrangement of the notches to ensure large energy absorption was proposed, which is applicable to a crash box with optional cross-sectional shape.

ABSTRACT: The present study proposes a simple procedure to evaluate the seismic risk of the spatial structures by using grid computing system. As an example for calculating the seismic risk by using the system, numerical studies for single layer lattice domes supported by substructure implemented with buckling restricted braces are presented considering a simple rule for judging the damages of the structural and non-structural elements. The effectiveness of the system is discussed through the numerical example for dome structures.
ABSTRACT: The nonlinear mathematical theory for initial and post local buckling analysis of plates of abruptly varying stiffness based on the principle of virtual work is established. The method is programmed, and several numerical examples are presented to demonstrate the scope and efficacy of the procedure. Local buckling coefficients of perforated and stepped plates are obtained and the results are compared with known solutions. Post-buckling behaviour of perforated and stepped plates is studied for different geometries. The non-dimensional applied loads (P/Pcr), dimensionless lateral displacements and stress distribution of plates with varying stiffness in the post buckling region are given in several tables and graphs.

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ABSTRACT: This paper addresses the finite strip formulations for the stability analysis of viscoelastic composite plates with variable thickness in the transverse direction, which are subjected to in-plane forces. While the finite strip method is fairly well-known in the buckling analysis, hitherto its direct application to the buckling of viscoelastic composite plates with variable thickness has not been investigated. The equations governing the stiffness and the geometry matrices of the composite plate are solved in the time domain using both the higher-order shear deformation theory and the method of effective moduli. These matrices are then assembled so that the global stiffness and geometry matrices of a moderately thick rectangular plate are formed which lead to an eigenvalue problem that is solved to determine the magnitude of critical buckling load for the viscoelastic plate. The accuracy of the proposed model is verified against the results which have been reported elsewhere whilst a comprehensive parametric study is presented to show the effects of viscoelasticity parameters, boundary conditions as well as combined bending and compression loads on the critical buckling load of thin and moderately thick viscoelastic composite plates.

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ABSTRACT: This paper addresses the inelastic local buckling of the curved plates using finite strip method in which buckling modes and displacements of the curved plate are calculated using sinusoidal shape functions in the longitudinal direction and polynomial functions in the transverse direction. A virtual work formulation is employed to establish the stiffness and stability matrices of the curved plate whilst the governing equations are then solved using a matrix eigenvalue problem. The accuracy and efficiency of the proposed finite strip model is verified with finite element model using ABAQUS as well as the results reported elsewhere while a good agreement is achieved. In order to illustrate the proposed model, a comprehensive parametric study is
performed on the steel and aluminum curved plates in which the effects of curvature, the length of the curved plate as well as circumferential boundary conditions on the critical buckling stress are investigated. The developed finite strip method is also used to determine the buckling loads of the curved plates with thickness-tapered sections as well as critical stresses of the aluminum cylindrical sectors that are subjected to uniform longitudinal stresses.


ABSTRACT: This paper is concerned with the determination of exact buckling loads and vibration frequencies of multi-stepped rectangular plates based on the classical thin (Kirchhoff) plate theory. The plate is assumed to have two opposite edges simply supported while the other two edges can take any combination of free, simply supported and clamped conditions. The proposed analytical method for solution involves the Levy method and the state-space technique. By using this analytical method, exact buckling and vibration solutions are obtained for rectangular plates having one- and two-step thickness variations. These exact solutions are extremely useful as benchmark values for researchers developing numerical techniques and software for analyzing non-uniform thickness plates.

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ABSTRACT: This paper presents new exact solutions for vibration of thin circular cylindrical shells with intermediate ring supports, based on the Goldenveizer–Novozhilov shell theory (Theory of thin shells; The theory of thin elastic shells). An analytical method is proposed to study the vibration behaviour of the ring supported cylindrical shells. In the proposed method, the state-space technique is employed to derive the homogenous differential equation system for a shell segment and a domain decomposition approach is developed to cater for the continuity requirements between shell segments. Exact frequency parameters are presented in tables and design charts for circular cylindrical shells having multiple intermediate ring supports and various combinations of end support conditions. These exact vibration frequencies may serve as important benchmark values for researchers to validate their numerical methods for such circular cylindrical shell problems.


ABSTRACT: This paper presents an analytical procedure for determining the free vibration frequencies of open
circular cylindrical shells with intermediate ring supports based on the Flügge thin shell theory. The shell can be divided into several segments at the locations of the ring supports. The state-space technique is adopted to derive the homogenous differential equations for a shell segment, and the domain decomposition method is employed to impose the equilibrium and compatibility requirements along the interface of the shell segments. Shells with any number of intermediate ring supports and various combinations of edge support conditions are studied. Furthermore, the effects of the intermediate ring support and their locations, boundary conditions, number of ring supports as well as the variation of the included angle on the natural frequencies are examined.


ABSTRACT: This paper presents the Ritz method for the elastic buckling analysis of shells with ring-stiffeners under general pressure loading. The stiffeners may be of any cross-sectional shape and arbitrarily distributed along the shell length. Using polynomial functions multiplied by boundary equations raised to appropriate powers as the Ritz functions, the method can accommodate any combination of end conditions. As far as it is known, the Ritz method has not been automated in this way for the buckling of ring-stiffened shells. By formulating in a nondimensional form, generic buckling solutions for shells with various end conditions, stiffener distributions and under various pressure distributions, were presented. These new buckling solutions should serve as useful reference sources for checking the validity and accuracy of other numerical methods and software for buckling of cylindrical shells. This paper also shows that the appropriate distribution of ring stiffeners can lead to a significant increase in the buckling capacity over that of a stiffened shell with evenly spaced and identical ring stiffeners.

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ABSTRACT: This paper is concerned with the elastic buckling of axially compressed, circular cylindrical shells with intermediate ring supports. The simple Timoshenko thin shell theory and the more sophisticated Flügge thin shell theory have been adopted in the modeling of the cylindrical shells. We used these two representative theories to examine the sensitivity of the buckling solutions to the different degree of approximations made in shell theories. By dividing the shell into segments at the locations of the ring supports, the state-space technique is employed to derive the solutions for each shell segment, and the domain decomposition method is utilized to impose the equilibrium and compatibility conditions at the interfaces of the shell segments. First-known exact buckling factors are obtained for cylindrical shells of one and multiple intermediate ring supports and various combinations of boundary conditions. Comparison studies are carried out against benchmark solutions and independent numerical results from ANSYS and p-Ritz analyses. The influence of the locations of the ring supports on the buckling behaviour of the shells is examined.

ABSTRACT: A solid shell element model is proposed for the elastic bifurcation buckling analysis of double-walled carbon nanotubes (DWCNTs) under axial compression. The solid shell element allows for the effect of transverse shear deformation which becomes significant in a stocky DWCNT with relatively small radius-to-thickness ratio. The van der Waals (vdW) interaction between the adjacent walls is simulated by linear springs. Using this solid shell element model, the critical buckling strains of DWCNTs with various boundary conditions are obtained and compared with molecular dynamics results and those obtained by other existing shell and beam models. The results obtained show that the solid shell element is able to model DWCNTs rather well, with the appropriate choice of Young’s modulus, tube thickness, and spring constant for modeling the vdW forces.

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ABSTRACT: Molecular dynamics simulations are performed on single- (SWCNTs) and double-walled carbon nanotubes (DWCNTs) to investigate the effects of strain rate on their buckling behavior. The Brenner’s second-generation reactive empirical bond order and Lennard-Jones 12-6 potentials are used to describe the short range bonding and long range van der Waals atomic (vdW) interaction within the carbon nanotubes, respectively. The sensitivity of the buckling behavior with respect to the strain rate is investigated by prescribing different axial velocities to the ends of the SWCNTs and DWCNTs in the compression simulations. In addition, the effects of vdW interaction between the walls of the DWCNTs on their buckling behavior are also examined. The simulation results show that higher strain rates lead to higher buckling loads and buckling strains for both SWCNTs and DWCNTs. A distinguishing characteristic between SWCNTs and DWCNTs is that the former experiences an abrupt drop in axial load whereas the axial load in latter decreases over a finite, albeit small, range of strain after buckling initiates. The buckling capability of DWCNT is enhanced in the presence of vdW interaction. DWCNTs can sustain a higher strain before buckling than SWCNTs of similar diameter under otherwise identical conditions.

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ABSTRACT: Buckling of multiwalled carbon nanotubes (MWCNTs) subjected to bending deformation is studied using molecular dynamics simulations. We show that the initial buckling mode of a thick MWCNT is quite different from that of a thin MWCNT. Only several outer layers buckle first while the rest inner layers
remain stable in a very thick MWCNT, while in a relatively thin MWCNT, all individual tubes buckle simultaneously. Such a difference in the initial buckling modes results in quite different size effects on the bending behavior of MWCNTs. In particular, the critical buckling curvature of a thick MWCNT is insensitive to the tube thickness, which is in contrast with linear elasticity. It is found also that the initial buckling wavelength is weakly dependent on the thickness of the MWCNT. We demonstrate that rippling deformation does decrease the effective modulus of a bent MWCNT, as observed in experiments. Finally, we show that the interlayer van der Waals interactions have little effect on the bending behavior of a MWCNT in the linear elastic regime.

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ABSTRACT: This paper presents an assessment of continuum mechanics (beam and cylindrical shell) models in the prediction of critical buckling strains of axially loaded single-walled carbon nanotubes (SWCNTs). Molecular dynamics (MD) simulation results for SWCNTs with various aspect (length-to-diameter) ratios and diameters will be used as the reference solutions for this assessment exercise. From MD simulations, two distinct buckling modes are observed, i.e. the shell-type buckling mode, when the aspect ratios are small, and the beam-type mode, when the aspect ratios are large. For moderate aspect ratios, the SWCNTs buckle in a mixed beam–shell mode. Therefore one chooses either the beam or the shell model depending on the aspect ratio of the carbon nanotubes (CNTs). It will be shown herein that for SWCNTs with long aspect ratios, the local Euler beam results are comparable to MD simulation results carried out at room temperature. However, when the SWCNTs have moderate aspect ratios, it is necessary to use the more refined nonlocal beam theory or the Timoshenko beam model for a better prediction of the critical strain. For short SWCNTs with large diameters, the nonlocal shell model with the appropriate small length scale parameter can provide critical strains that are in good agreement with MD results. However, for short SWCNTs with small diameters, more work has to be done to refine the nonlocal cylindrical shell model for better prediction of critical strains.


ABSTRACT: Seismic response of cylindrical storage tanks anchored to rigid base slabs is considered. Finite elements are used for the liquid and tank wall, idealized as a thin shell. For steel tanks of practical dimensions, design charts are presented for natural frequencies, maximum shear and overturning moment on the foundation, and maximum stress resultants in the tank wall. Furthermore, an analytical expression for the superelevation of the free surface is presented.
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ABSTRACT: This paper is concerned with the elastic buckling of super ellipsoidal shells under external uniform pressure. The middle surface of a super ellipsoidal shell is defined by the following equation:
\[(x/a)^n + (y/b)^n + (z/c)^n = 1,\]
where \(n\) is an integer varying from unity to infinity. It is clear from the equation that the range of shell shapes covered sphere (\(n=1, a=b=c\)) to cube (View the MathML source) and ellipsoid (\(n=1\)) to cuboid (\(n=∞\)). By adopting a recently proposed solid shell element for the buckling analysis, the critical buckling pressures of thin to thick super ellipsoidal shells are obtained and tabulated for engineers. The shell element allows for the effect of transverse shear deformation which becomes significant in thick shells. Their buckling shapes are also examined. In addition, a simple approximate formula for predicting the critical buckling pressure of thick spherical shells is proposed.

ABSTRACT: Based on the classical nonlinear von Kármán plate theory, axisymmetric large deflection bending of a functionally graded circular plate is investigated under mechanical, thermal and combined thermal–mechanical loadings, respectively, and axisymmetric thermal post-buckling behavior of a functionally graded circular plate is also investigated. The mechanical and thermal properties of functionally graded material (FGM) are assumed to vary continuously through the thickness of the plate, and obey a simple power law of the volume fraction of the constituents. Governing equations for the problem are derived, and then a shooting method is employed to numerically solve the equations. Effects of material constant \(n\) and boundary conditions on the temperature distribution, nonlinear bending, critical buckling temperature and thermal post-buckling behavior of the FGM plate are discussed in details.

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ABSTRACT: Based on the first-order shear deformation theory of plate, governing equations for the axisymmetric buckling of functionally graded circular/annular plates are derived. The coupled deflections and rotations in the pre-buckling state of the plates are neglected in analysis. The material properties vary continuously through the thickness of the plate, and obey a power law distribution of the volume fraction of the
constituents. The resulting differential equations are numerically solved by using a shooting method. The critical buckling loads of circular and annular plates are obtained, which are compared with those obtained from the classical plate theory. Effects of material properties, ratio of inter to outer radius, ratio of plate thickness to outer radius, and boundary conditions on the buckling behavior of FGM plates are discussed.


ABSTRACT: This work presents the analysis of critical thermo electromechanical buckling (TEMB) of a micro elastic and isotropic annular plate that is simultaneously subjected to a thermal load and symmetric electrostatic force. The annular plate is assumed to be rigidly clamped at its outer radius edge and free at the inner radius edge. TEMB is the bifurcation response which results from the coupling of electromechanical bifurcation and thermo-mechanical buckling. It will be shown that the TEMB state depend on the value of two different loading parameters. The capability to determine the value of the critical buckling temperature or the critical buckling voltage enable us to instigate buckling even when the in-plane thermal stresses are in tension. The most interesting result that will be shown is that TEMB allow us to determine the number of buckled elastic flexures along the circumference of the annular plate. On other words, TEMB of annular plate permit manipulating of the critical buckling values and the shape mode of the buckling response. Finally, it will be shown for the first time that symmetric electrostatic forces can be modeled as an active “virtual” elastic foundation with a stiffness that can be manipulated to achieve the desired thermo-electro-mechanical response.

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ABSTRACT: High load-bearing efficiency is one of the advantages of biological structures after the evolution of billions of years. Biomimicking from nature may offer the potential for lightweight design. In the viewpoint of mechanics properties, the culm of bamboo comprises of two types of cells and the number of the vascular bundles takes a gradient of distribution. A three-point bending test was carried out to measure the elastic modulus. Results show that the elastic modulus of bamboo decreases gradually from the periphery towards the centre. Based on the structural characteristics of bamboo, a bionic cylindrical structure was designed to mimic the gradient distribution of vascular bundles and parenchyma cells. The buckling resistance of the bionic structure was compared with that of a traditional shell of equal mass under axial pressure by finite element simulations. Results show that the load-bearing capacity of bionic shell is increased by 124.8%. The buckling mode of bionic structure is global buckling while that of the conventional shell is local buckling.


ABSTRACT: Based on von Kármán-Donnell kinematic assumptions for laminated shells, the non-linear vibration and postbuckling behaviour of unsymmetrically laminated cross-ply circular cylindrical shells with
clamped and simply-supported ends are studied by a multi-mode approach. A solution is formulated and satisfies the associated compatibility equation and all boundary conditions. The transverse equation of motion is fulfilled by the Galerkin procedure. In the case of non-linear vibration problems, the solution is obtained by the method of harmonic balance. The effect of initial imperfection is also included. Results in non-linear vibration and postbuckling are presented for different amplitudes of initial imperfection and four sets of boundary conditions. Present results are compared with available data.


ABSTRACT: Based on the Timoshenko-Mindlin kinematic hypothesis, the Donnell-type shell theory is extended to include transverse shear and rotary inertia for the nonlinear analysis of an anti-symmetrically laminated cross-ply circular cylindrical shell. The resulting governing equations are expressed in terms of a stress function, two rotations and transverse displacement. The shell is assumed to be all-simply-supported and all-clamped. A solution is formulated by a multi-mode approach and the method of harmonic balance for non-linear vibrations. The corresponding postbuckling problem is treated as a special case. The results are compared with available data.


ABSTRACT: A multi-mode solution to the dynamic Marguerre-type nonlinear equations is presented for the nonlinear free vibration of doubly curved, symmetrically laminated, imperfect shallow shells of rectangular planform on a Winkler-Pasternak elastic foundation. The shell edges are assumed to be transversely supported and the variation of rotational stiffness is identical along opposite edges. Generalized double Fourier series with time-dependent coefficients and the method of harmonic balance are used in the solution. The boundary condition for the varying rotational stiffness is fulfilled by replacement of bending moments along the four edges by an equivalent lateral pressure. Based on a single-mode approximation numerical results for the amplitude-frequency response of doubly curved isotropic, orthotropic, cross-ply and angle-ply shallow shells with square planform are presented for various boundary conditions, material properties, curvature ratios, initial imperfections, edge tensions, and moduli of the elastic foundation. Graphical results for postbuckling behavior of an imperfect angle-ply cylindrical panel are also presented as a special case.


ABSTRACT: A dynamic non-linear theory for generally laminated shallow cylindrical panels is developed with the aid of Hamilton's principle. The effects of transverse shear deformation, rotatory inertia and geometrically initial imperfection are included in the analysis. A multi-mode solution is formulated for non-linear free vibration of an anti-symmetric angle-ply cylindrical laminate with its edges elastically restrained against rotation. The resulting equations for time functions are solved by the method of harmonic balance. The postbuckling behavior of the panel is treated as a special case. Numerical results in non-linear vibration and
postbuckling are presented for different values of the amplitude of initial imperfection, side-to-thickness ratio, rotational edge stiffness, aspect ratio, orientation angle, number of layers and material properties. Present results are compared with available data.


ABSTRACT: Non-linear vibrations of generally laminated circular cylindrical shells are examined using the Timoshenko-Mindlin kinematic hypothesis and an extension of the Donnell-type shell theory. The effects of transverse shear deformation, rotatory inertia and geometrically initial imperfection are included in the analysis. A solution for non-linear free vibrations of these cylindrical shells is formulated using a multimode approach. The boundary condition for the varying rotational end stiffness in the circumferential direction is satisfied by replacement of the end bending moments by an equivalent lateral pressure near the shell ends. The Galerkin procedure furnishes an infinite system of equations for time functions which are solved by the method of harmonic balance. The postbuckling behavior of the shell is treated as a special case. Numerical results in non-linear vibration and postbuckling of cylindrical laminates are presented graphically for different parameters and compared with available data.

M.M. Banerjee and S. Chanda (A.C. College, Jalpaiguri, W.B., India), “Nonlinear vibration of doubly-curved orthotropic shallow shells under a thermal gradient”, Transactions of the Thirteenth International Conference on Structural Mechanics in Reactor Technology (SMiRT 13), Porto Alegre, Brazil, August, 1995

ABSTRACT: The present investigation aims at the finding of the effect of a thermal gradient on a doubly-curved orthotropic shallow shell. The basic governing differential equations have been derived under the effect of a temperature distribution varying linearly and uniaxially.


ABSTRACT: The static and dynamic non-linear axisymmetric response of a shallow spherical shell with a circular opening at the apex has been investigated. The shell consists of a number of radially orthotropic layers perfectly bonded together but symmetrically laminated. The governing equations are expressed in terms of the transverse displacement, rotation and stress function. The effects of transverse shear and rotatory inertia are included in the analysis. The shell edge is elastically restrained against rotation and in-plane displacement. The vanishing of the rotation and in-plane displacement at the opening are assumed. A Fourier-Bessel series solution is formulated for the postbuckling and large amplitude free vibration of the shell. The Galerkin procedure furnishes a set of non-linear ordinary differential equations for time functions which are solved by the method of harmonic balance. Numerical results in postbuckling response and non-linear free vibration are presented for various boundary conditions, ratios of base radius to thickness, and shell rise to thickness, and numbers of layers. The results are also compared with available data.

ABSTRACT: This research investigates the free vibration and buckling of a two-layered cylindrical shell made of inner functionally graded (FG) and outer isotropic elastic layer, subjected to combined static and periodic axial forces. Material properties of functionally graded cylindrical shell are considered as temperature dependent and graded in the thickness direction according to a power-law distribution in terms of the volume fractions of the constituents. Theoretical formulations are presented based on two different methods of first-order shear deformation theory (FSDT) considering the transverse shear strains and the rotary inertias and the classical shell theory (CST). The results obtained show that the transverse shear and rotary inertias have considerable effect on the fundamental frequency of the FG cylindrical shell. The results for nondimensional natural frequency are in close agreement with those in literature. It is inferred from the results that the geometry parameters and material composition of the shell have significant effect on the critical axial force, so that the minimum critical load is obtained for fully metal shell. Good agreement between theoretical and finite element results validates the approach. It is concluded that the presence of an additional elastic layer significantly increases the nondimensional natural frequency, the buckling resistance and hence the elastic stability in axial compression with respect to a FG hollow cylinder.

DOI: 10.1016/j.apm.2013.03.020

ABSTRACT: This paper investigates the nonlinear vibration and instability of the embedded double-walled boron nitride nanotubes (DWBNNTs) conveying viscous fluid based on nonlocal piezoelectricity cylindrical shell theory. The elastic medium is simulated as Winkler–Pasternak foundation, and adjacent layers interactions are assumed to have been coupled by van der Walls (vdW) force evaluated based on the Lennard–Jones model. The nonlinear strain terms based on Donnell’s theory are taken into account. The Hamilton’s principle is employed to obtain coupled differential equations, containing displacement and electric potential terms. Differential quadrature method (DQM) is applied to estimate the nonlinear frequency and critical fluid velocity for clamped supported mechanical and free electric potential boundary conditions at both ends of the DWBNNTs. Results indicated that some parameters including nonlocal parameter, elastic medium’s modulus, aspect ratio and vDW force have significant influence on the vibration and instability of the DWBNNT while the fluid viscosity effect is negligible. In addition, the low aspect ratio should be taken into account for DWBNNT in optimum design of nano/micro devices.

ABSTRACT: In this paper, free vibration and buckling analysis of functionally graded cylindrical shells subjected to combined static and periodic axial forces is presented considering the effect of transverse shear and rotary inertia. Material properties of functionally graded cylindrical shells are considered as temperature dependent and graded in the thickness direction according to a power-law distribution in terms of the volume fractions of the constituents. Numerical results for silicon nitride-nickel cylindrical shells are presented based on two different methods of first-order shear deformation theory (FSDT) considering the transverse shear strains and the rotary inertias and the classical shell theory (CST). The results obtained show that the effect of transverse shear and rotary inertias on free vibration and buckling of functionally graded cylindrical shells subjected to combined static and periodic axial forces is dependent on the material composition, the temperature environment, the amplitude of static load, the deformation mode, and the shell geometry parameters.

Farzad Ebrahimi and Erfan Saleri (Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran), “Size-dependent thermo-electrical buckling analysis of functionally graded piezoelectric nanobeams”, Smart Materials and Structures, Vol. 24, No. 12, October 2015, https://doi.org/10.1088/0964-1726/24/12/125007

ABSTRACT: In the present study, thermo-electrical buckling characteristics of functionally graded piezoelectric (FGP) Timoshenko nanobeams subjected to in-plane thermal loads and applied electric voltage are carried out by presenting a Navier type solution for the first time. Three kinds of thermal loading, namely, uniform, linear and nonlinear temperature rises through the thickness direction are considered. Thermo-electro-mechanical properties of FGP nanobeam are supposed to vary smoothly and continuously throughout the thickness based on power-law model. Eringen's nonlocal elasticity theory is exploited to describe the size dependency of nanobeam. Using Hamilton's principle, the nonlocal governing equations together with corresponding boundary conditions based on Timoshenko beam theory are obtained for the thermal buckling analysis of graded piezoelectric nanobeams including size effect and they are solved applying analytical solution. According to the numerical results, it is revealed that the proposed modeling can provide accurate critical buckling temperature results of the FG nanobeams as compared some cases in the literature. In following a parametric study is accompanied to examine the effects of the several parameters such as various temperature distributions, external electric voltage, power-law index, nonlocal parameter and aspect ratio on the critical buckling temperature difference of the size-dependent FGP nanobeams in detail. It is found that the small scale effect and electrical loading have a significant effect on buckling temperatures of FGP nanobeams.

PARTIAL INTRODUCTION: Behavior of buckling for shell structure has been wide attention for absorption of impact energy [1]. Both high strength and the ability to absorb energy during structural collapse are important factors for structural design in crush problems. The collapse analyses have been carried out analytically and experimentally [2-4]. Recently, numerical techniques have become available and computer simulation for collapse analysis has become very attractive [5,6]. …


ABSTRACT: A dynamic nonlinear theory for layered shallow shells is derived by means of the von Karman-Tsien theory, modified by the generalized Berger-approximation. Moderately thick shells with polygonal planform composed of multiple perfectly bonded layers are considered. The shell edges are assumed to be prevented from in-plane motions and are simply supported. A distributed lateral force loading is applied to the structure, and additionally, the influence of a static thermal prestress, corresponding to a spatial distribution of cross-sectional mean temperature, is taken into account. In the special case of laminated shells made of transversely isotropic layers with physical properties symmetrically distributed about the middle surface, a correspondence to moderately thick homogeneous shells is found. Application of a multi-mode expansion in the Galerkin procedure to the governing differential equation, where the eigenfunctions of the corresponding linear plate problem are used as space variables, renders a coupled set of ordinary time differential equations for the generalized coordinates with cubic as well as quadratic nonlinearities. The nonlinear steady-state response of shallow shells subjected to a time-harmonic lateral excitation is investigated and the phenomenon of primary resonance is studied by means of the “perturbation method of multiple scales”. A unifying non-dimensional representation of the nonlinear frequency response function is presented that is independent of the special shell planform.

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ABSTRACT: Deterministic and random vibrations are considered for the case of shear deformable shallow shells composed of multiple perfectly bonded layers. The nontrivial generalization of the flat plate vibrations is expressed by the fact of “small amplitude” vibrations existing about the curved equilibrium position together with the snap-through and snap-buckling type large amplitude vibrations about the flat position. The geometrically nonlinear vibrations are treated by applying Berger’s approximation to the generalized von Karman-type plate equations considering hard hinged supports of the straight boundary segments of skew or
even more generally shaped polygonal shells. Shear deformation is considered by means of Mindlin’s kinematic hypothesis and a distributed lateral force loading is applied. Application of a multi-mode expansion in the Galerkin procedure to the governing differential equation, where the eigenfunctions of the corresponding linear plate problem are used as space variables, renders a coupled set of ordinary time differential equations for the generalized coordinates with cubic and quadratic non-linearities. For reasons of convergence, a light viscous modal damping is added. The nonlinear steady-state response of shallow shells subjected to a time-harmonic lateral excitation is investigated and the phenomenon of primary resonance is studied by means of the “perturbation method of multiple scales”. The use of a nondimensional formulation and introduction of the eigen-time of the basic mode of the associated linearized problem provides a unifying result with respect to the planform of the shell. Within the scope of random vibrations, it is assumed that the effective forces can be modelled by uncorrelated, zero-mean wide-band noise processes. Considering the set of modal equations to be finite, the Fokker-Planck-Kolmogorov (FPK) equation for the transition probability density of the generalized coordinates and velocities is derived. Its stationary solution gives the probability of eventual snapping after a long time has elapsed. However, the probability of first occurrence follows from the (approximate) integration of the nonstationary FPK equation. The probability of first dynamic snap-through is derived for a single mode approximation with the influence of higher modes taken into account. Using the two-mode expansion, the probability distribution of the asymmetric snap-buckling is also evaluated.

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PARTIAL ABSTRACT: In the course of transient random vibrations of shallow structures the phenomenon of dynamic snap-buckling is observed. The nontrivial generalization of the flat plate vibrations is expressed by the fact of “small amplitude” vibrations to exist about the curved equilibrium position together with the snap-through and the snap-buckling type large amplitude vibrations about the flat position….
space variables, renders a coupled set of ordinary time differential equations for the generalized coordinates with (mixed) cubic and quadratic non-linearities. The nonlinear steady-state response of panels subjected to a time-harmonic lateral excitation is investigated and the phenomena of primary, superharmonic, and subharmonic resonances are studied by means of the perturbation method of multiple scales. Numerical results are cast in the form of graphs with a structural parameter varying in a wide range.

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“Non-linear random response of laminated composite shallow shells using finite element modal method.
doi: 10.1002/nme.1672
ABSTRACT: This paper investigates the large-amplitude multi-mode random response of thin shallow shells with rectangular planform at elevated temperatures using a finite element non-linear modal formulation. A thin laminated composite shallow shell element and the system equations of motion are developed. The system equations in structural node degrees-of-freedom (DOF) are transformed into modal co-ordinates, and the non-linear stiffness matrices are transformed into non-linear modal stiffness matrices. The number of modal equations is much smaller than the number of equations in structural node DOF. A numerical integration is employed to determine the random response. Thermal buckling deflections are obtained to explain the intermittent snap-through phenomenon. The natural frequencies of the infinitesimal vibration about the thermally buckled equilibrium positions (BEPs) are studied, and it is found that there is great difference between the frequencies about the primary (positive) and the secondary (negative) BEPs. All three types of motion: (i) linear random vibration about the primary BEP, (ii) intermittent snap-through between the two BEPs, and (iii) non-linear large-amplitude random vibration over the two BEPs, can be predicted.

ABSTRACT: This paper reports numerical analyses of free vibration of laminated composite plate/shell structures of various shapes, span-to-thickness ratios, boundary conditions and lay-up sequences. The method is based on a novel four-node quadrilateral element, namely MISQ20, within the framework of the first-order shear deformation theory (FSDT). The element is built by incorporating a strain smoothing method into the bilinear four-node quadrilateral finite element where the strain smoothing operation is based on mesh-free conforming nodal integration. The bending and membrane stiffness matrices are based on the boundaries of smoothing cells while the shear term is evaluated by 2 x 2 Gauss quadrature. Through several numerical examples, the capability, efficiency and simplicity of the element are demonstrated. Convergence studies and comparison with other existing solutions in the literature suggest that the present element is robust, computationally inexpensive and free of locking.

References listed at the end of the paper:
ABSTRACT: This paper presents buckling and free vibration analysis of composite plate/shell structures of various shapes, modulus ratios, span-to-thickness ratios, boundary conditions and lay-up sequences via a novel smoothed quadrilateral flat element. The element is developed by incorporating a strain smoothing technique into a flat shell approach. As a result, the evaluation of membrane, bending and geometric stiffness matrices are based on integration along the boundary of smoothing elements, which leads to accurate numerical solutions even with badly-shaped elements. Numerical examples and comparison with other existing solutions show that the present element is efficient, accurate and free of locking.

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ABSTRACT: This paper further extends a cell-based smoothed finite element method for free vibration and buckling analysis of shells. A four-node quadrilateral Mindlin-Reissner shell element with a gradient smoothing operator is adopted. The membrane-bending and geometrical stiffness matrices are computed along the boundaries of the smoothing cells while the shear stiffness matrix is calculated by an independent interpolation in the natural coordinates as in the MITC4 (the Mixed Interpolation of Tensorial Components) element. Various numerical results are compared with existing exact and numerical solutions and they are in good agreement. The advantage of the present formulation is that it retains higher accurate than the MITC4 element even for heavily distorted meshes without increasing the computational cost.

References listed at the end of the paper:


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ABSTRACT: This study focuses on the buckling of cylindrical shells with small thickness variations under external pressure. Asymptotic formulas in terms of the thickness non-uniformity parameter are derived by the combined perturbation and Bubnov–Galerkin methods. In addition to the analytic investigation based on the thin shell theory, a numerical analysis is also performed. Results from these formulas are discussed and compared with those obtained by other authors.

References listed at the end of the paper:


as for a ring, the present model obtains a slightly lower buckling pressure which depends on the length.


ABSTRACT: The governing Flügge stability equations in coupled form are used for cylinders subjected to external pressure that varies circumferentially. Three cases are considered: fluid (hydrostatic) pressure, wind pressure and partial (patch) circumferential pressure. The wind load follows the Australian Standard AS 1170.2 (1989). Longitudinal variation of the load is not considered. The numerical process gives the stagnation buckling pressure for different shell geometry and simple support conditions at each end. The Galerkin method is employed to orthogonalize the error made with the introduction of the finite series into the governing equations. The solutions are compared with a few published solutions in the literature.


ABSTRACT: In this paper, the problems of thermal buckling in axial direction of cylindrical shells made of functionally graded materials are discussed. Based on the Donnell’s shell theory, the equilibrium and stability equations of the cylindrical shell subjected to thermal loads are derived firstly. Then the closed form solutions are presented for the shell with simply supported boundary conditions subjected to three types of thermal loading. The material properties are assumed varying as a power form of thickness coordinate variable. The influences of the aspect ratio, the relative thickness and the functionally graded index on the buckling temperature difference are carefully discussed.

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ABSTRACT: A thermal buckling analysis of imperfect circular cylindrical shells of functionally graded material is considered. The material properties are assumed varying as a power form of thickness coordinate variable. The Donnell equilibrium and stability equations are considered and the Wan-Donnell model for initial geometrical imperfection is adopted. The thermal loads include the uniform temperature rise and nonlinear temperature change across the thickness of shell. A closed form solution for the thermal buckling of simply supported cylindrical FG shell under the described thermal loads is obtained. The influences of the relative thickness, the imperfection size and the power law index on buckling thermal loads are all discussed.

References listed at the end of the paper:
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ABSTRACT: This paper presents an analytical approach to investigate nonlinear response of functionally graded cylindrical panels under uniform lateral pressure with temperature effects are incorporated. Material properties are assumed to be temperature-independent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Equilibrium and compatibility equations for cylindrical panels are derived by using the classical shell theory with both geometrical nonlinearity in von Karman–Donnell sense and initial geometrical imperfection are taken into consideration. The resulting equations are solved by Galerkin method to determine explicit expressions of nonlinear load-deflection curves. Stability analysis for a simply supported panel shows the effects of material and geometric parameters, in-plane restraint and temperature conditions, and imperfection on the nonlinear response of the panel.

References listed at the end of the paper:


ABSTRACT: A titanium-matrix orthotropic cylindrical shell with the principal direction of orthotropy following a parallel constant angle helix, has been studied when it is subjected to uniform loading conditions of internal pressure, axial load and pure twisting moment. Nondimensional parameters pertaining to loading and deformations have been calculated and results plotted. The results obtained can be usefully applied in robotic actuators where lightweight considerations with high strength are of prime importance. The study is further extended to investigate the effect of temperature on the deformations. Through parametric studies, deformation patterns are calculated and plotted that are unique to orthotropy. In most of the cases, it is observed that deformation patterns are same, but deformation is increasing with temperatures.

References listed at the end of the paper:
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“Buckling Of A Shallow Rectangular Bimetallic Shell Subjected To Outer Loads And Temperature”, SDSS’Rio 2010 Stability And Ductility Of Steel Structures E. Batista, P. Vellasco, L. de Lima (Eds.) Rio de Janeiro, Brazil, September 8 - 10, 2010

ABSTRACT: In the article, we have formulated a geometric non-linear mathematical-physical model of the snap-through of the system of a thin-walled shallow bimetallic translation shell in a homogenous temperature field according to the theory of large displacements, moderate rotations, and small strains of the shell element. The model enables the calculation of the geometric conditions, of shallow translation shells, due to the influences of temperature and mechanical loads. The results are based on the numeric solution of a non-linear system of partial differential equations with boundary conditions according to the finite difference method.

References listed at the end of the paper:

Marko Jakomin, "Shallow Axi-symmetric Bimetallic Shell as a Switching Element in a Non-Homogenous

ABSTRACT: In this contribution we discuss the stability of thin, axi-symmetric, shallow bimetallic shells in a non-homogeneous temperature field. The presented model with a mathematical description of the geometry of the system, displacements, stresses and thermoelastic deformations on the shell, is based on the theory of the third order, which takes into account not only the equilibrium of forces on a deformed body but also the nonlinear terms of the strain tensor. The equations are based on the large displacements theory. As an example, we present the results for a bimetallic shell of parabolic shape, which has a temperature point load at the apex. We translated the boundary-value problem with the shooting method into saving the initial-value problem. We calculate the snap-through of the system numerically by the Runge-Kutta fourth order method.

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ABSTRACT: In this contribution, we discuss the stress, deformation, and snap-through conditions of thin, axisymmetric, shallow bimetallic shells of so-called parabolic-conic and plate-parabolic type shells loaded by thermal loading. According to the theory of the third order that takes into account the balance of forces on a deformed body, we present a model with a mathematical description of the system geometry, displacements, stress, and thermoelastic deformations. The equations are based on the large displacements theory. We numerically calculate the deformation curve and the snap-through temperature using the fourth-order Runge-Kutta method and a nonlinear shooting method. We show how the temperature of both snap-through depends on the point where one type of the rotational curve transforms into another.

References listed at the end of the paper:

14. M. Jakomin, F. Kosel, and T. Kosel, “Buckling of a shallow rectangular bimetallic shell subjected to outer loads and


ABSTRACT: Bimetallic shallow shells are thermal sensors. The paper presents relevant technical information on bimetallic shallow shells and describes some interesting physical experiments. It is shown how, through simple measurements and calculations, it is possible to determine the initial speed (~3.5 m/s), the acceleration (~30000 m/s²) and the lower and upper snap temperature (~22 °C; ~32 °C) of the bimetal. The results from simple measurements and calculations are comparable to those obtained by a high speed camera. The videos give an even deeper insight into the phenomenon of the snap-through.

References listed at the end of the paper:


ABSTRACT: (not available)

Sigurd Wagner (1), Stephanie P. Lacour (1), Joyelle Jones (1), Pai-hui I. Hsu (1), James C. Sturm (1), Teng Li (2) and Zhigang Suo (2)
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ABSTRACT: Conceptual hardware architecture of skin-like circuits is described. An elastomeric skin carries rigid islands on which active subcircuits are made. The subcircuit islands are interconnected by stretchable metallization. We concentrate on recent advances in stretchable thin-film conductors, by covering their construction, evaluation, and laboratory and theoretical analysis. Reversibly stretchable conductors with electrically-critical strains ranging from 10% to 100% have been made.

Teng Li (Department of Mechanical Engineering and Maryland NanoCenter, University of Maryland, 2181 Glenn L. Martin Hall, College Park, MD 20742, USA), “A mechanics model of microtubule buckling in living cells”, Journal of Biomechanics, Vol. 41, No. 8, 2008, pp. 1722-1729, doi:10.1016/j.jbiomech.2008.03.003
ABSTRACT: As the most rigid cytoskeletal filaments, microtubules bear compressive forces in living cells, balancing the tensile forces within the cytoskeleton to maintain the cell shape. It is often observed that, in living cells, microtubules under compression severely buckle into short wavelengths. By contrast, when compressed, isolated microtubules in vitro buckle into single long-wavelength arcs. The critical buckling force of the microtubules in vitro is two orders of magnitude lower than that of the microtubules in living cells. To explain this discrepancy, we describe a mechanics model of microtubule buckling in living cells. The model investigates the effect of the surrounding filament network and the cytosol on the microtubule buckling. The results show that, while the buckling wavelength is set by the interplay between the microtubules and the elastic surrounding filament network, the buckling growth rate is set by the viscous cytosol. By considering the nonlinear deformation of the buckled microtubule, the buckling amplitude can be determined at the kinetically
constrained equilibrium. The model quantitatively correlates the microtubule bending rigidity, the surrounding filament network elasticity, and the cytosol viscosity with the buckling wavelength, the buckling growth rate, and the buckling amplitude of the microtubules. Such results shed light on designing a unified experimental protocol to measure various critical mechanical properties of subcellular structures in living cells.

Yuanwen Gao and Le An (Key Laboratory of Mechanics on Western Disaster and Environment, Ministry of Education, Department of Mechanics and Engineering Science, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, PR China), “A nonlocal elastic anisotropic shell model for microtubule buckling behaviors in cytoplasm”, Physica E: Low-dimensional Systems and Nanostructures, Vol. 42, No. 9, July 2010, pp. 2406-2415, doi:10.1016/j.physe.2010.05.022
ABSTRACT: The buckling behaviors of microtubules (MTs) in a living cell have been studied based on the nonlocal anisotropic shell theory and Stokes flow theory. The analytical expressions for the buckling load and the growth rate of the buckling are obtained and discussed. In addition, the pressure on MTs, resulting from cytosol motion, is derived on the basis of the Stokes flow theory. The influences of filament network elasticity and the shear modulus of MTs, especially the cytosol viscosity and MT small scale effects on MT buckling behaviors, are investigated. The analytical results show that the MT buckling growth rate increases with the MT small scale parameter, while decreases as the filament network elastic modulus, the MT shear modulus and cytoplasm viscosity increase. Although the cytosol viscosity has a significant influence on the value of the growth rate, it shows little effects on the range of the axial wave number of buckling as well as the critical axial wave number that corresponds to the maximal growth rate. Finally, the MT buckling growth rates have been calculated using the beam model, the isotropic shell model, and the anisotropic shell model. The results indicate that using the anisotropy shell theory to model the buckling behavior of MTs is necessary.

ABSTRACT: The analytical solutions of the first-order shear deformation theory are developed to study the buckling behaviour of functionally graded (FG) cylindrical shells under three types of mechanical loads. The Poisson's ratios of the FG cylindrical shells are assumed to be constant, while the Young's moduli vary continuously throughout the thickness direction according to the volume fraction of constituents given by power-law or exponential function. The stability equations are employed to obtain the closed-form solutions for critical buckling loads of each loading case. The dependence of the critical buckling loads on the variations of the material properties with a power-law or exponential function is studied. It is observed that these effects change appreciably the critical buckling loads. Results for critical loads are tabulated for thin and moderately thick shells. Although the critical buckling load of FG cylindrical shells decreases as the circumferential wave numbers increase, it rises for axially compressed long shells as the longitudinal wave numbers increase.

ABSTRACT: This paper presents the buckling analysis of short and long functionally graded cylindrical shells under thermal and mechanical loads. The shell properties are assumed to vary continuously from the inner
surface to the outer surface of the shell. The equilibrium and stability equations are derived using the total potential energy equations, Euler equations and first order shear deformation theory assumptions. The resulting equations are solved for simply supported boundary conditions. The critical temperature and pressure loads are calculated for both short and long cylindrical shells. Comparison studies show the effects of functionally graded index, loading type and shell geometry on critical buckling loads of short and long functionally graded cylindrical shells.

References listed at the end of the paper:


ABSTRACT: Layerwise finite element analyses of geodesically stiffened cylindrical shells are presented in this work. The Layerwise Laminate Theory of Reddy (LWTR) is developed and adapted to circular cylindrical shells. The Ritz variational method is used to develop an analytical approach for studying the buckling of simply supported geodesically stiffened shells with discrete stiffeners. This method utilizes a Lagrange multiplier technique to attach the stiffeners to the shell. The development of the layerwise shells couples a one-dimensional finite element through the thickness with a Navier solution that satisfies the boundary conditions. The buckling results from the Ritz discrete analytical method are compared with smeared buckling results and with NASA testbed finite element results. The development of layerwise shell and beam finite elements is presented and these elements are used to perform the displacement field, stress, and first-ply failure analyses. The layerwise shell elements are used to model the shell skin and the layerwise beam elements are used to model the stiffeners. This arrangement allows the beam stiffeners to be assembled directly into the global stiffness matrix. A series of analytical studies are made to compare the response of geodesically stiffened shells as a function of loading, shell geometry, shell radii, shell laminate thickness, stiffener height, and geometric nonlinearity. Comparisons of the structural response of geodesically stiffened shells, axial and ring stiffened shells, and unstiffened shells are provided. In addition, Interlaminar stress results near the stiffener intersection are presented. First-ply failure analyses for geodesically stiffened shells utilizing the Tsai-Wu failure criterion are presented for a few selected cases.
ABSTRACT: The nonlinear dynamic response of doubly curved shallow shells resting on Winkler–Pasternak elastic foundation has been studied for step and sinusoidal loadings. Dynamic analogues of Von Karman–Donnel type shell equations are used. Clamped immovable and simply supported immovable boundary conditions are considered. The governing nonlinear partial differential equations of the shell are discretized in space and time domains using the harmonic differential quadrature (HDQ) and finite differences (FD) methods, respectively. The accuracy of the proposed HDQ-FD coupled methodology is demonstrated by numerical examples. The shear parameter $G$ of the Pasternak foundation and the stiffness parameter $K$ of the Winkler foundation have been found to have a significant influence on the dynamic response of the shell. It is concluded from the present study that the HDQ-FD methodology is a simple, efficient, and accurate method for the nonlinear analysis of doubly curved shallow shells resting on two-parameter elastic foundation.


ABSTRACT: In this paper, size effect of microtubules (MTs) is studied via modified strain gradient elasticity theory for buckling. MTs are modeled by Bernoulli–Euler beam theory. By using the variational principle, the governing equations for buckling and related boundary conditions are obtained in conjunctions with the strain gradient elasticity. The size effect for buckling analysis of MTs is investigated and results are presented in graph form. The results obtained by strain gradient elasticity theory are discussed through the numerical simulations. The results based on the modified couple stress theory, nonlocal elasticity theory and classical elasticity theories have been also presented for comparison purposes.

Ömer Civalek (Akdeniz University, Civil Engineering Department, Division of Mechanics, Antalya, Turkey), “Geometrically nonlinear dynamic and static analysis of shallow spherical shell resting on two-parameters elastic foundations”, International Journal of Pressure Vessels and Piping, Vol. 113, pp 1-9, 2014 DOI: 10.1016/j.ijpvp.2013.10.014

ABSTRACT: In the present study nonlinear static and dynamic responses of shallow spherical shells resting on Winkler–Pasternak elastic foundations are carried out. The formulation of the shells is based on the Donnell theory. The nonlinear governing equations of motion of shallow shells are discretized in space and time domains using the discrete singular convolution and the differential quadrature methods, respectively. The validity of the present method is demonstrated by comparing the present results with those available in the open literature. The effects of the Winkler and Pasternak foundation parameters on nonlinear static and dynamic response of shells are investigated. Some results are also presented for circular plate as special case. Damping effect on nonlinear dynamic response of shells is studied. It is important to state that the increase in damping parameter causes decrease in the dynamic response of the shells. It is shown that the shear parameter of the foundation has a significant influence on the dynamic and static response of the shells. Also, the response of the shell is decreased with the increasing value of the shear parameter of the foundation. Parametric studies considering different geometric variables have also been investigated.

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ABSTRACT: In order to show the significance of considering nonlinear deformations in piezoelectrical structures, a geometrical nonlinear shell element with integrated piezoelectric layers is introduced. The strain-displacement relations are implemented using first-order shear deformation theory with small strains but moderate rotations. The element has been tested on several benchmark problems and it can be concluded that the effect of geometrical nonlinearity is significant when the sensor properties of the piezoelectrical layers are predicted.


ABSTRACT: In this paper a geometrically nonlinear composite shell element with integrated magnetostrictive layers is presented. Three translational and two rotational nodal degrees of freedom are used for the first-order transverse shear approximation. The finite element is used in order to investigate shape and stability control problems of structures with magnetostrictive actuator layers in the range of large deformations. The numerical approximations to this static problem are obtained using the total Lagrangian formulation for the moderate rotation shell theory. The aforementioned finite element is used to numerically investigate the actuation behaviour of the integrated magnetostrictive layers. Since the magnetic field is prescribed, the coupled magnetoelastic problem turns into a decoupled problem.

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“Geometrically nonlinear finite element simulation of smart piezolaminated plates and shells”, Smart Materials and Structures, Vol. 16, No. 6, October 2007, DOI: 10.1088/0964-1726/16/6/029

ABSTRACT: In this work a geometrically nonlinear finite shell element is presented, incorporating piezoelectric layers. The finite element is implemented in a total Lagrangian approach, which requires special attention to be given to the proper definition of the mechanical and electrical quantities. The strain–displacement relations are based on the assumption of small strains and moderate rotations. The transverse displacement field and the transverse electric potential are assumed to vary linearly through the thickness. With the presented finite element, static as well as dynamic examples are calculated. The differences between the results obtained with linear and nonlinear theory are emphasized.

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ABSTRACT: By using the mixed Lagrangian–Eulerian description and adopting the von Kármán's strain approximation, the non-linear magnetoelastic interactions of a circular cylindrical thin shell experiencing
moderately large deflections are fully explored. The shell is assumed to be perfectly electroconductive and immersed in an applied magnetic field and carrying electric current. The magnetoelastic loads acting on the shell associated with the Lorentz forces and Maxwell's stress jumps are explicitly represented and the approximated governing systems for the induced magnetic fields outside the shell in total Lagrangian description are obtained. Case study on a shell's cross section model is conducted and pertinent conclusions are drawn.

ABSTRACT: The generalized Donnell-type equations governing large deflection of antisymmetrically laminated cross-ply cylindrical shells counting for transverse shear deformations are derived and presented. An asymptotic series solution is constructed by regular perturbation technique for postbuckling behaviors of the cylindrical shells with simply supported edges subjected to axial compression. Boundary layer influence at both ends of the shells on overall buckling and postbuckling are considered, and for consistency of the boundary valued problem, the boundary layer solutions are also designed to match the out-of-plane edge conditions by singular perturbation approach. Effects of transverse shear deformation, Batdorf’s parameter, elastic moduli ratio, and initial geometric imperfection on buckling and postbuckling performance of the shells are examined. Some numerical examples are taken for comparison of the present results of buckling loads and load–deflection curves of the shells with corresponding theoretical predictions to show effectiveness and accuracy of the present asymptotic perturbation solution.

ABSTRACT: A theoretical development is presented for the parametric resonance of layered anisotropic circular cylindrical shells. The shell's ends are clamped and subjected to axial loading consisting of a static part and a harmonic part. The shell is modelled by using linear shell theory; classical lamination theory is used to determine the stiffness of the overall composite shell structure. The shell's response is divided into a pre-instability (unperturbed) part and an incremental perturbation--which can be dynamically unstable. Rather than assuming the unperturbed state to be a static membrane state of stress, here unperturbed response inertia and spatial variations are retained. A successful solution strategy is developed by employing several Fourier expansions. By means of it, the equations of motion of the perturbed response are reduced to a system of Mathieu equations. The stability of such a system can be determined by known methods. Numerical results are presented in part II.
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ABSTRACT: Numerical results for the parametric resonance response of layered anisotropic circular
cylindrical shells are presented based on a theoretical development given in part I [1]. The principal regions of parametric resonance are determined numerically from the system of Mathieu equations derived in part I. Results are given for two particular graphite-epoxy shells. The effects of pre-instability inertia in the composite shell is shown to be similar to that discussed previously [2] in connection with isotropic shells. Specifically, it is found that inclusion of pre-instability inertia may result in increased widths of the instability regions of modes having instability forcing frequency very close to a natural frequency of the pre-instability motion of the shell. Also, the effect of pre-instability spatial variation on the principal regions of parametric resonance is separately studied. It is found that the widths of the instability regions may be greatly increased by inclusion of these spatial variations.

ABSTRACT: The dynamic stability of thin, clamped, composite circular cylindrical shells is studied for combined axial and torsional loading. Each load is taken to be harmonically varying; the frequencies of the two loads differ, in general. For the case in which the frequencies are commensurate, the applied load function is periodic. The equations of motion for the shell are reduced to a system of Hill equations by means of Fourier series expansions. Instability regions of principal and combination parametric resonance are determined by use of the monodromy matrix. Numerical results are generated for boron-epoxy layered shells for various cases of pure axial, pure torsional, and combined loading. The width of the principal instability region is presented as a function of fiber orientation for a laminate case. Stability diagrams are presented covering about 6 times the lowest natural frequency for various ratios of the applied axial and torsional frequencies.

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ABSTRACT: The purpose of this work is to analyse the problem: what is the effect of the assumed types and intensities of random initial geometrical imperfections on the equilibrium paths and the limit loads? To this end a new method of simulation of nonhomogeneous two-dimensional random fields on regular nets has been developed. The method is based on two concepts: an envelope of the random field and local covariance matrices classified according to the symmetry groups. The numerical examples deal with post-buckling responses of FEM models of shallow shells with different types of imperfections (whitenoise, Wiener and degenerated fields) using a Monte Carlo approach.

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“Consistent mixed model for stability of stiffened panels with cut-outs”, Computers & Structures, Vol. 54,
ABSTRACT: In contrast to the familiar Kirchoff approach, a simple, consistent, shear flexible model for the stability analysis of stiffened panels has been developed in the context of hybrid mixed technique. This model is composed of a quadrilateral plate element, as well as its complementary skeletal grid element. The formulation is based on the Hellinger/Reissner mixed variational principle with independently assumed displacement and strain fields. The proposed model has been utilized to develop a general finite element code for determination of critical buckling stresses of stiffened panels for any case of in-plane loadings and boundary conditions. The effectiveness and practical usefulness of this model have been demonstrated by a variety of numerical results for practical applications. In particular, design curves for buckling stresses of simply supported rectangular panels with central cut-outs and lateral stiffeners have been developed under in-plane load-type. These curves provide a valuable insight into the behavior of stiffened panels and could be useful for design codes.

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ABSTRACT: Modern theory for applications of laminated plates and shells calls for detailed study of the effect of large spatial rotations on the geometric stiffness for stability analysis as well as inertia operators for vibrations. These two issues are carefully examined here in conjunction with the recently developed mixed finite element formulation for plates and shells with low-order displacement/strain interpolations. An extensive set of stability and vibration problems has been solved to demonstrate the effectiveness and general utilities of the formulation described for laminated plate and shells with arbitrary geometry.

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ABSTRACT: From a more recent and comprehensive perspective, work on the nonlinear dynamic response of plates and shells calls for detailed studies of several important factors. These include the effect of large spatial rotations on the geometric stiffness and inertia operators, the accurate updating procedures for nodal rotations and associated angular velocities and accelerations, as well as material inelasticity (especially for finite strains). Several of these issues are examined here in conjunction with a recently developed mixed finite element formulation for plates and shells with low-order displacement/strain interpolations. To this end, and restricting the scope to the case of large overall motions but small strains, low-order displacement/strain interpolations are utilized, together with a radial return algorithm (backward-Euler-integration scheme) for plasticity effects. The Newmark implicit scheme has been employed to integrate the semi-discrete equations of motion. A selective set of elastic as well as elasto-plastic problems has been solved to demonstrate the effectiveness and practical utility of the formulation described for plate and shells with arbitrary geometry.

ABSTRACT: The finite element method based on the total Lagrangian description of the motion and the Hellinger–Reissner principle with independent strain is applied to investigate the non-linear static and dynamic responses of spherical laminated shells under external pressure. The non-linear dynamic problem is solved by employing the implicit time integration method. The critical load of thin spherical laminated panels is investigated by examining the static and dynamic responses. The critical dynamic load is determined by the phase-plane and the Budiansky–Roth criteria. The effect of the artificial coefficient of Rayleigh damping on the dynamic response is considered. The dynamic response with damping included converges to the static response. The damping coefficient greatly affects a highly non-linear dynamic response. For a thin spherical panel with the snapping phenomena, the critical dynamic load is lower than the static one.

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ABSTRACT: This paper investigates the effect of intertube van der Waals interaction on the stability of pristine and covalently functionalized carbon nanotubes under axial compression, using molecular mechanics simulations. After regulating the number of inner layers of the armchair four-walled (5, 5)-(10, 10)-(15, 15)-(20, 20) and zigzag four-walled (6, 0)-(15, 0)-(24, 0)-(33, 0) carbon nanotubes, the critical buckling strains of the corresponding tubes are calculated. The results show that each of the three inner layers in the functionalized armchair nanotube noticeably contributes to the stability of the outermost tube, and together increase the critical strain amplitude by 155%. However, the three inner layers in the corresponding pristine nanotube, taken together, increase the critical strain of the outermost tube by only 23%. In addition, for both the pristine and functionalized zigzag nanotubes, only the (24, 0) layer, among the three inner layers, contributes to the critical strain of the corresponding outermost tube, by 11% and 29%, respectively. The underlying mechanism of the enhanced stability related to nanotube chirality and functionalization is analyzed in detail.


ABSTRACT: The buckling of multiwalled carbon nanotubes under torsional load coupling with temperature change is researched. The effects of torsional load, temperature change, surrounding elastic medium, and van der Waals forces between the inner and outer nanotubes are taken into account at the same time. Using continuum mechanics, an elastic multishell model with thermal effect is presented for buckling of a multiwalled carbon nanotube embedded in an elastic matrix under thermal environment and torsional load. Based on the model, numerical results for the general case are obtained for the thermal effect on buckling of a multiwalled carbon nanotube under torsional load. It is shown that the buckling torque of a multiwalled carbon nanotube under a certain value of temperature change is dependent on the wave number of torsional buckling modes, and a conclusion is drawn that at room or lower temperature the critical torsional load for infinitesimal buckling of a multiwalled carbon nanotube increases as the value of temperature change increases, while at temperature
higher than room temperature the critical torsional load for infinitesimal buckling of a multiwalled carbon nanotube decreases as the value of temperature change increases.

References listed at the end of the paper:

ABSTRACT: An elastic double-shell model is presented for the buckling and postbuckling of a double-walled carbon nanotube subjected to axial compression. The analysis is based on a continuum mechanics model in which each tube of a double-walled carbon nanotube is described as an individual elastic shell and the interlayer friction is negligible between the inner and outer tubes. The governing equations are based on the Kármán–Donnell-type nonlinear differential equations. The van der Waals interaction between the inner and outer nanotubes and the nonlinear prebuckling deformations of the shell are both taken into account. A boundary layer theory of shell buckling is extended to the case of double-walled carbon nanotubes under axial compression. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. Numerical results reveal that the single-walled carbon nanotube and the double-walled carbon nanotube both have an unstable postbuckling behavior.


ABSTRACT: The curvature effects of interlayer van der Waals (vdW) forces on pressure-induced buckling of empty or filled double-walled carbon nanotubes (DWNTs) are studied for various radii, length-to-radius ratios, end conditions and internal-to-external pressure ratios. The analysis is based on a double-elastic shell model and assumes that the interlayer vdW pressure at a point between the inner and outer tubes depends not only on the change of the interlayer spacing, but also on the change of the curvatures of the inner and outer tubes at that point. Here the role of filling substances inside DWNTs is modeled by a uniformly distributed internal pressure. The present work aims to study the curvature effects on critical radial pressure. An explicit formula is obtained for the external buckling pressure of empty or filled DWNTs. The critical value of external pressure is estimated with various internal-to-external pressure ratios. It is shown that the curvature effects play a more significant role in buckling problems under radial pressure for small radii DWNTs than under pure axial stress. Our results show that loading transfer through vdW forces prior to buckling is important for the pressure-induced buckling of DWNTs rather than axially compressed buckling.

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H. Qian and K.Y. Xu (Shanghai Institute of Applied Mathematics and Mechanics, Department of Mechanics,
ABSTRACT: Based on a curvature model for van der Waals (vdW) pressure between the interlayer of a double-walled carbon nanotube (DWNT), explicit expressions are derived for the critical buckling load of a DWNT which is modeled as a double-elastic shell under combined axial compression and lateral pressure. The critical load is calculated for various radii, length-to-radius ratios and load combinations. New results show that the curvature effects play a significant role in buckling problems for DWNTs of small radii. Neglecting the curvature effect usually leads to an under-estimate of the critical load for DWNTs when lateral pressure dominates. In addition, unlike Wang et al (2003b Int. J. Solids Struct. 40 3893) and Qian et al (2005 Int. J. Solids Struct. 42 5426), the buckling mode corresponding to the minimum axial buckling strain is unique, even when the lateral pressure is very small. For the DWNTs under combined axial compression and lateral pressure, the critical axial strain is reduced due to the external pressure.

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ABSTRACT: In this paper, a theoretical analysis of the torsional buckling instability of double-walled carbon nanotubes (DWCNTs) and the DWCNTs embedded in an elastic medium is presented based on the continuum elastic shell model and Winkler spring model. Using the proposed theoretical approach, the influences of the aspect ratio, the buckling modes and the surrounding medium on the torsional stability are examined in detail. The simulation results show that the torsional instability of DWCNTs can occur in different buckling modes according to the aspect ratio. The van der Waals (vdW) interaction force between nanotubes reinforces the stiffness of nanoshells. Thus, the DWCNTs possess higher buckling stability than the SWCNTs without considering vdW interaction force.

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ABSTRACT: Carbon nanotubes (CNTs) can be used as atomic force microscope (AFM) probes due to their robust mechanical properties, high aspect ratio and small diameter. In this study, a model of CNTs clamped in an elastic medium is proposed as CNT AFM probes. The buckling instability of the CNT probe clamped in elastic medium is analyzed based on the nonlocal Euler–Bernoulli beam model and the Whitney–Riley model. The clamped length of CNTs, and the stiffness of elastic medium affect largely on the stability of CNT AFM probe, especially at high buckling mode. The result shows that the buckling stability of the CNT AFM probe can be largely enhanced by increasing the stiffness of elastic medium. Moreover, the nonlocal effects of buckling instability are investigated and found to be larger for high buckling mode. The theoretical investigation on the buckling stability would give a useful reference for designing CNT as AFM probes.
**ABSTRACT:** A layerwise (zigzag) finite element formulation is developed for the buckling analysis of stiffened laminated plates. The laminated plate is discretized into layers along the thickness direction. Each layer of the laminated plate is modeled by the degenerated shell elements, and the stiffener is modeled by the general 3-D beam elements. Layers are stacked together according to the interlayer continuity. In-plane displacements are considered in the derivation of geometric stiffness matrix. The advantage of the proposed model is its applicability to both thin and thick laminated plates. The significance of this study lies in the disclosure of the interaction between the lateral buckling of the stiffener and the buckling of the laminate. The inverse iteration method is adopted to extract the lowest eigenvalue corresponding to buckling. Parametric and comparative studies are conducted for different plate aspect ratios, plate thickness to length ratios, degrees of layer orthotropy, ply orientations, and stiffener depth to plate thickness ratios.


**ABSTRACT:** The free vibration analysis of stiffened laminated composite plates has been performed using the layered (zigzag) finite element method based on the first order shear deformation theory. The layers of the laminated plate is modeled using nine-node isoparametric degenerated flat shell element. The stiffeners are modeled as three-node isoparametric beam elements based on Timoshenko beam theory. Bilinear in-plane displacement constraints are used to maintain the inter-layer continuity. A special lumping technique is used in deriving the lumped mass matrices. The natural frequencies are extracted using the subspace iteration method. Numerical results are presented for unstiffened laminated plates, stiffened isotropic plates, stiffened symmetric angle-ply laminates, stiffened skew-symmetric angle-ply laminates and stiffened skew-symmetric cross-ply laminates. The effects of fiber orientations (ply angles), number of layers, stiffener depths and degrees of orthotropy are examined.


**ABSTRACT:** An 18-node solid element has been developed to model the behavior of laminated composite shells undergoing large deflection. The element formulation utilizes independently assumed strain in addition to assumed displacement. The strain and the determinant of the Jacobian matrix are assumed to be linear in the thickness direction. This allows analytical integration through the thickness regardless of ply layups. Numerical results demonstrate the validity of the present formulation.

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ABSTRACT: The aim of this article is to compare Donnell's, Love's, Sanders' and Flügge's thin shell theories in the evaluation of natural frequencies of cylinders stiffened with rings and stringers, whose effect is smeared over the entire surface of the cylinder. It is demonstrated that due to the large increase in bending stiffness related to rings, Donnell's theory provides highly inaccurate results with respect to the other three theories. Numerical results related to aluminum and composite stiffened cylinders and a comparison with results obtained with a finite element model of a stiffened cylinder complete the work.

ABSTRACT: In this paper a set of stability equations for thick cylindrical shells is derived and solved analytically. The set is obtained by integration of the differential stability equations across the thickness of the shell. The effects of transverse shear and the non-linear variation of the stresses and displacements are accounted for with the aid of the higher order shell theory proposed by [Voyiadjis, G.Z. and Shi, G., 1991, A refined two-dimensional theory for thick cylindrical shells, International Journal of Solids and Structures, 27(3), 261–282.]. For a thick shell under external hydrostatic pressure, the stability equations are solved analytically and yield an improved expression for the buckling load. Reference solutions are also obtained by solving numerically the differential stability equations. Both the full set that contains strains and rotations as well as the simplified set that contains rotations only were solved numerically. The relative magnitude of shear strain and rotation was examined and the effect of thickness was quantified. Differences between the benchmark solutions and the analytic expressions based on the refined theory and the classical shell theory are analysed and discussed. It is shown that the new analytic expression provides significantly improved predictions compared to the formula based on thin shell theory.

References listed at the end of the paper:
ABSTRACT: The purpose of this paper is to examine computationally the stability of shells consisting of two layers when subjected to external circumferential strain. This loading appears often in biomechanics when the smooth muscle surrounding various organs such as esophagus, lung airways, or gastrointestinal tract contracts. The differential stability equations are discretized using the finite volume method and the resulting generalized eigenvalue problem is solved using the QZ decomposition technique. The predicted number of folds agrees well with available experimental measurements. The present results show that the buckling behavior under circumferential strain loading is entirely different compared with external hydrostatic pressure loading. More specifically, in the latter case, the number of folds with the smallest critical load is always equal to 2. In the former case, however, it depends on the thickness and modulus of elasticity of each layer. The thickness of the inner layer significantly affects the number of folds and the critical buckling load. The influence of the thickness of the outer layer and the ratio of the two moduli of elasticity was also examined, but their effect was not as strong as that of the thickness of the inner layer.

Asokendu Samanta and Madhujit Mukhopadhyay (Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology, Kharagpur 721 302, India), “Finite element large deflection static analysis of

ABSTRACT: Geometric nonlinear static analysis of shallow and deep stiffened shells has been conducted on the basis of a combination of Allman's plane stress triangle and Discrete Kirchhoff triangle (DKT) plate bending element. The compatibility condition at the shell beam junction is ensured as the same displacement function used for both the shell and the stiffener element. The formulation of the stiffener is done in such a manner that it can be placed anywhere within the shell element. The large deflection equations are based on von Kármán's theory. An iterative solution procedure, either Newton–Raphson method or modified Riks method, is employed to trace the nonlinear equilibrium path. The nonlinear static analysis of deep stiffened shell has been done for the first time. A variety of numerical examples are presented to demonstrate the versatility and efficiency of the present stiffened shell element.


ABSTRACT: An essential problem in dealing with composite laminates is an accurate prediction of interlaminar stresses playing an important role in the design, particularly in the failure analysis of these structures. The objective of the present paper is to develop a multi-layer shell-element family capable to deal with this aspect in the presence of strong nonlinearities. First a multi-director shell theory is presented on the basis of a quadratic approximation of the displacement field. A particular attention is given to the parametrization of the inextensible shell director in order to make the formulation accessible to finite rotations. This is accomplished by using Euler-angles as well as an updated rotation formulation. The single layer theory is then coupled with a multi-layer concept, which has been shown to be very predictive in dealing with complex through-thickness stress distributions. The constitutive relations are formulated so as to consider the particularities of composite materials. After standard linearization, shell equations are transformed into multi-layer finite shell elements using assumed strain concept and enhanced strain formulation as stabilization algorithms. The performance of the finite elements concerning various aspects is discussed on adequate examples.

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ABSTRACT: Free vibration analysis of composite cylindrical shells with different boundary conditions is presented in this paper using differential quadrature method (DQM). Equations of motion are derived based on first order shear deformation theory taking the effects of shear deformation and rotary inertia terms into account. By applying the differential quadrature formulation and the required modified relationships for implementing the different boundary conditions, equations of motion of a circular cylindrical shell are transformed into a set of algebraic equations. By solving this algebraic system natural frequencies of circular cylindrical shells made of fibrous composite materials with different fibre angles are evaluated. The results thus obtained are then compared with some available results and a good agreement is observed. In all the cases studied here efficiency, ease and usefulness of the DQM are well illustrated.
References listed at the end of the paper:


ABSTRACT: In this paper, the thermal buckling of piezoelectric composite shells of revolution under uniform and linear thermal distributions and selected boundary conditions is investigated by using the semi-analytical finite element. The effects of different parameters such as the type of temperature distributions through the thickness, fiber angles, arrangements of piezoelectric patches and amount of displacement feedback control gain are examined. The results obtained from the present analysis are validated, where possible, with those available in the literature.

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“An investigation of the buckling behavior of composite elliptical cylindrical shells with piezoelectric layers under axial compression”, Acta Mech, 2012, (no volume number or page numbers given) DOI: 10.1007/s00707-012-0705-1

ABSTRACT: The paper is focused on the elastic buckling behavior of piezocomposite elliptical cylindrical shell finite element formulation. The formulation is based on the shear deformation theory, and the serendipity quadrilateral eight-node element is used to study the elastic behavior of elliptical cylindrical shells. The strain-
displacement relations are accurately accounted for in the formulation. The contributions of work done by the applied load are also incorporated. A constant gain displacement control algorithm coupling the direct and inverse piezoelectric effect is applied to provide active control of composite non-circular shells in a self-monitoring and self-controlling system. The governing equations obtained using the principle of minimum potential energy are solved through an eigenvalue approach. The influences of elliptical cross-sectional parameter and displacement feedback gain \((G_d)\) values on the critical buckling loads of elliptical cylindrical shells are examined.

References listed at the end of the paper:
ABSTRACT: The present paper is concerned with the free vibration analysis of double-walled carbon nanotubes embedded in an elastic medium and based on Eringen's nonlocal elasticity theory. The effects of the transverse shear deformation and rotary inertia are included according to the Timoshenko beam theory. The governing equations of motion which are coupled with each other via the van der Waals interlayer forces have been derived using Hamilton's principle. The thermal effect is also incorporated into the formulation. Using the statically exact beam element with displacement fields based on the first order shear deformation theory, the finite element method is employed to discretize the coupled governing equations which are then solved to find the natural frequencies. The effects of the small scale parameter, boundary conditions, thermal effect, changes in material constant of the surrounding elastic medium, and geometric parameters on the vibration characteristics are investigated. Furthermore, our analysis includes nonlocal double-walled carbon nanotubes with different boundary conditions between inner and outer tubes which seem to be scarcely considered in the literature, and the corresponding given results for this case can be considered as a benchmark for further studies. Comparison of the present numerical results with those from the open literature shows an excellent agreement.

References listed at the end of the paper:


ABSTRACT: Minute concentrations of suspended particles can dramatically alter the behavior of a drying droplet. After a period of isotropic shrinkage, similar to droplets of a pure liquid, these droplets suddenly buckle like an elastic shell. While linear elasticity is able to describe the morphology of the buckled droplets, it fails to predict the onset of buckling. Instead, we find that buckling is coincident with a stress-induced fluid to solid transition in a shell of particles at a droplet's surface, occurring when attractive capillary forces overcome stabilizing electrostatic forces between particles.

D.A. Head (Department of Applied Physics, Faculty of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan), “Modeling the elastic deformation of polymer crusts formed by sessile droplet evaporation”, Phys. Rev. E, Vol. 74, 021601 (2006) [8 pages], doi: 10.1103/PhysRevE.74.021601

ABSTRACT: Evaporating droplets of polymer or colloid solution may produce a glassy crust at the liquid-vapor interface, which subsequently deforms as an elastic shell. For sessile droplets, the known radial outward flow of solvent is expected to generate crusts that are thicker near the pinned contact line than the apex. Here we investigate, by nonlinear quasistatic simulation and scaling analysis, the deformation mode and stability properties of elastic caps with a nonuniform thickness profile. By suitably scaling the mean thickness and the contact angle between crust and substrate, we find that data collapse onto a master curve for both buckling pressure and deformation mode, thus allowing us to predict when the deformed shape is a dimple, Mexican hat, and so on. This master curve is parameterized by a dimensionless measure of the nonuniformity of the shell. We also speculate on how overlapping time scales for gelation and deformation may alter our findings.


ABSTRACT: Motivated by observing the buckling of glassy crusts formed on evaporating droplets of polymer and colloid solutions, we numerically model the deformation and buckling of spherical elastic caps controlled by varying the volume between the shell and the substrate. This volume constraint mimics the incompressibility of the unevaporated solvent. Discontinuous buckling is found to occur for sufficiently thin and/or large contact angle shells, and robustly takes the form of a single circular region near the boundary that 'snaps' to an inverted shape, in contrast to the externally pressurized shells case. Scaling theory for shallow shells is shown to approximate well the critical buckling volume, the subsequent enlargement of the inverted region and the contact line force.

References listed at the end of the paper:
doi; 10.1103/PhysRevE.68.052801

ABSTRACT: Drying of a sessile drop of a complex liquid can lead to intriguing complex shapes. We report here a study dealing with a model system, made of a hydrophilic polymer that is glassy when pure. Under solvent evaporation, polymers accumulate near the vapor/drop interface and may form a glassy skin, which bends as the volume of liquid it encloses decreases. The conditions for the occurrence of this buckling instability have been investigated; the experimental results are well explained by a model that compares the characteristic times for drying and for the formation of a glassy skin. Depending on the experimental conditions, different types of shape distortion take place; secondary instabilities that break the axisymmetry are also observed.


ABSTRACT: Spray drying of complex liquids to form solid powders is important in many industrial applications. One of the challenges associated with spray drying is controlling the morphologies of the powders
produced; this requires an understanding of how drying mechanics depend on the ingredients and conditions. We demonstrate that the morphology of powders produced by spray drying colloidal polystyrene (PS) suspensions can be significantly altered by changing the molecular weight of dissolved poly(ethylene oxide) (PEO). Samples containing high-molecular-weight PEO produce powders with more crumpled morphologies than those containing low-molecular-weight PEO. Observations of drying droplets suspended by a thin film of vapor suggest that this occurs because the samples with high-molecular-weight PEO buckle earlier in the drying process when the droplets are larger. Earlier buckling times are likely caused by the decreased stability, demonstrated by bulk rheology experiments, of PS particles in the presence of high-molecular-weight PEO at elevated temperatures. We present a consistent picture in which decreased particle stability hastens droplet buckling and leads to more crumpled powder morphologies; this underscores the importance of interparticle forces in determining the buckling of particle-laden droplets.


ABSTRACT: We visualize the drying of droplets of colloids suspended in a mixture of two miscible solvents, namely water and ethanol. After a period of isotropic shrinkage, droplets suddenly buckle like elastic shells. For a fixed colloid solid fraction, the buckling threshold evolves as a function of ethanol content, due to changes of the solvent mixture physical properties, such as viscosity and evaporation rate. A simplified model predicting the qualitative behavior of the buckling threshold as a function of the initial ethanol mass fraction has been developed that fits well experimental results.

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17. J.G. Leidenfrost, De Aqueae Communis Nonnullis Qualitatibus Tractus (J. Straube, Duisburg, Germany, 1756).
ABSTRACT: Building on the new droplet drying framework developed by the authors in their previous work Handscomb et al., Chem. Eng. Sci. 64(4) 628–637 and Chem. Eng. Sci. 64(2) 228–246 this paper develops physically motivated criteria for dynamically deciding the appropriate structural sub-model to use at each stage of the drying process. Such criteria create a spatially resolved mechanistic droplet drying model which is capable of simulating multiple dried-particle morphologies based on evolving droplet composition and drying conditions. The new criteria are used in conjunction with the previously described model framework to simulate colloidal silica droplets, investigating the relationship between suspended particle size and dried-particle morphology.

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ABSTRACT: The origin of the buckling of micrometer-sized colloidal droplets during evaporation-induced self-assembly (EISA) has been elucidated using electron microscopy and small-angle neutron scattering. Doughnut-like assembled grains with varying aspect ratios are formed during EISA at different physicochemical conditions. It has been revealed that this phenomenon is better explained by an existing hypothesis based on the formation of a viscoelastic shell of nanoparticles during drying than by other existing hypotheses based on the inertial instability of the initial droplets and hydrodynamic instability due to thermocapillary forces. This conclusion was further supported by the arrest of buckling through modification of the colloidal interaction in the initial dispersion.

ABSTRACT: Micrometric grains of anisotropic morphology have been achieved by evaporation-induced self-assembly of silica nanoparticles. The roles of polymer concentration and its molecular weight in controlling the buckling behavior of drying droplets during assembly have been investigated. Buckled doughnut grains have been observed in the case of only silica colloid. Such buckling of the drying droplet could be arrested by attaching poly(ethylene glycol) on the silica surface. The nature of buckling in the case of only silica as well as modified silica colloids has been explained in terms of theory of homogeneous elastic shell under capillary pressure. However, it has been observed that colloids, modified by polymer with relatively large molecular weight, gives rise to buckyball-type grains at higher concentration and could not be explained by the above theory. It has been demonstrated that the shell formed during drying of colloidal droplet in the presence of polymer becomes inhomogeneous due to the presence of soft polymer rich zones on the shell that act as
buckling centers, resulting in buckyball-type grains.


ABSTRACT: The structural evolution in the center of a droplet of a dialyzed styrene–n-butyl acrylate copolymer latex dispersion on a solid surface during drying was studied by means of an in situ synchrotron ultra small-angle X-ray scattering technique. During water evaporation, as the droplet shrinks the shell yields and thickens, as evidenced by the appearance of diffraction peaks at the early stage combined with TGA measurement. As the droplet dried further, colloidal crystalline structure transformation is identified. The transition is attributed to the collapse of the thin shell made of densely packed particles at the surface of the droplet caused by capillary forces that drive the deformation of the shell. As there is a small amount of water remaining beneath the surface layer, charged particles are able to explore new configurations to reestablish a stable structure after leaving the initially formed face-centered cubic structure. Finally, a torus-shaped solid film with a central flat thin film is produced.


ABSTRACT: Arrays of half-symmetric Fabry-Perot micro-cavities were fabricated by controlled formation of circular delamination buckles within a-Si/SiO$_2$ multilayers. Cavity height scales approximately linearly with diameter, in reasonable agreement with predictions based on elastic buckling theory. The measured finesse ($F > 10^3$) and quality factors ($Q > 10^4$ in the 1550 nm range) are close to reflectance limited predictions, indicating that the cavities have low roughness and few defects. Degenerate Hermite-Gaussian and Laguerre-Gaussian modes were observed, suggesting a high degree of cylindrical symmetry. Given their silicon-based fabrication, these cavities hold promise as building blocks for integrated optical sensing systems.


ABSTRACT: A nonlinear structural mechanics based approach for modeling the structure and the deformation of single-wall and multiwall carbon nanotubes (CNTs) is presented. Individual tubes are modeled using shell finite elements, where a specific pairing of elastic properties and mechanical thickness of the tube wall is identified to enable successful modeling with shell theory. The effects of van der Waals forces are simulated with special interaction elements. This new CNT modeling approach is verified by comparison with molecular dynamics simulations and high-resolution micrographs available in the literature. The mechanics of wrinkling of multiwall CNTs are studied, demonstrating the role of the multiwalled shell structure and interwall van der Waals interactions in governing buckling and postbuckling behavior.

A. Pantano, M. C. Boyce, and D. M. Parks (Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA), “Mechanics of Axial Compression of Single and Multi-Wall
ABSTRACT: A recently developed procedure for modeling the deformation of single and multi-wall carbon nanotubes [13,14] is applied to nanotube buckling and post-buckling under axial compression. Critical features of the model, which is grounded in elastic shell theory, include identification of (a) an appropriate elastic modulus and thickness pair matching both the wall stretching and bending resistances of the single atomic layer nanotube walls, and (b) a sufficiently stiff interwall van der Waals potential to preserve interwall spacing in locally buckled MWNTs, as is experimentally observed. The first issue is illustrated by parametric buckling studies on a SWNT and comparisons to a corresponding MD simulation from the literature; results clearly indicating the inadequacy of arbitrarily assigning the shell thickness to be the equilibrium spacing of graphite planes. Details of the evolution of local buckling patterns in a nine-walled CNT are interpreted based on a complex interplay of local shell buckling and evolving interwall pressure distributions. The transition in local buckling wavelengths observed with increasing post-buckling deformation is driven by the lower energy of a longer-wavelength, multiwall deformation pattern, compared to the shorter initial wavelength set by local buckling in the outermost shell. This transition, however, is contingent on adopting a van der Waals interaction sufficiently stiff to preserve interlayer spacing in the post-buckled configuration.

ABSTRACT: Wrinkling (buckling) during a sheet forming process is a major consideration when designing part shape, die geometry and processing parameters. In most instances, the sheet metal is constrained to some extent between binders and/or matching dies at some stage during processing. In this paper, we will examine the wrinkling behavior of both elastic and elastic-plastic sheet subjected to edge compression and lateral constraint. A criterion for wrinkling under such constraint is established using a combination of finite element analysis and energy conservation. Various methods of incorporating imperfections into a finite element model in order to capture buckling and post-buckling behavior are discussed. A simple and practical form of imperfection for predictive modeling of buckling is given along with a discussion of the sensitivity of the solution to the magnitude and distribution of imperfections. Using the proposed form of imperfection, we are able to accurately simulate the wrinkling behavior under complicated boundary conditions in a predictive manner.

ABSTRACT: In the sheet metal forming industry, there is increasing demand to lower manufacturing costs while also providing a decrease in product development turnaround period as well as lighter weight products. These demands have put increasing pressure on the development and use of predictive numerical simulations and in the design and optimization of new forming technologies. In this paper, two of the primary in-process failure modes of sheet metal, wrinkling and tearing, are examined followed by construction of an advanced forming technology – Variable Binder Force – using numerical tools. Specifically, a methodology of capturing the onset of wrinkling and postbuckling behavior proposed in Cao and Boyce (1997) is used to predict wrinkling failure in conical and square cup forming. The results obtained from simulations and experiments demonstrate that the proposed method is not only accurate, but also robust. A tearing criterion based on Forming Limit Diagrams of
non-proportional loading paths is then developed and again shows excellent predictability. Finally, a Variable Binder Force (VBF) trajectory for conical cup forming is designed using simulations which incorporate feedback control to the binder based on the predictions of wrinkling and tearing of the sheet. Experiments using this predefined VBF trajectory show a 16 percent increase in forming height over the best conventional forming method, that is, constant binder force. The uniqueness of this paper is that numerical simulation is no longer utilized only as a verification tool, but as a design tool for advanced manufacturing process with the help of the predictive tools incorporated directly into the numerical model.


ABSTRACT: Wrinkling is one of the major defects in sheet metal forming. The ability to accurately predict the occurrence of wrinkling is critical to the design of tooling and processing parameters. An analytical approach for predicting the onset of flange wrinkling is presented. This method is based on the wrinkling criterion proposed by Cao and Boyce for predicting the buckling behavior of sheet metal under normal constraint. Using a combination of energy conservation and plastic bending theory, the analysis provides the critical buckling stress and wavelength as functions of normal pressure. The results are in excellent agreement with those obtained from Cao and Boyce’s numerical approach, and also match well with the experimental results of a square cup forming. In addition, the effects of material properties on the wrinkling behavior are also discussed. The analytical method significantly reduces computational time and is suitable for direct engineering application.


ABSTRACT: Thin-walled tube bending has found many of its applications in the automobile and aerospace industries. This paper presents an energy approach to provide the minimum bending radius, which does not yield wrinkling in the bending process, as a function of tube and tooling geometry and material properties. A doubly-curved sheet model is established following the deformation theory. This approach provides a predictive tool in designing/optimizing the tooling parameters in tube bending.

References listed at the end of the paper:


J. Cao (Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111), “Prediction of plastic wrinkling using the energy method”, ASME J. of Applied Mechanics, Vol. 66, September 1999

ABSTRACT: The prediction and prevention of wrinkling during a sheet metal forming process have been challenging issues on the design of part shape, die geometry, and processing parameters. In an effort to provide a reliable and efficient tool to assess the onset of wrinkling, analytical models for flange wrinkling and straight side-wall wrinkling are presented here. Using a combination of energy conservation and plastic bending theory, the critical buckling wavelength and stress are calculated as functions of the boundary conditions (displacement constraint and binder pressure). Comparisons between the numerical and experimental results are given for both cases and excellent agreement is obtained.


ABSTRACT: Prediction and prevention of side-wall wrinkling are extremely important in the design of tooling and process parameters in sheet metal forming processes. The prediction methods can be broadly divided into two categories: an analytical approach and a numerical simulation using finite element method (FEM). In this paper, a modified energy approach utilizing energy equality and the effective dimensions of the region undergoing circumferential compression is proposed based on simplified flat or curved sheet models with approximate boundary conditions. The analytical model calculates the critical buckling stress as a function of material properties, geometry parameters and current in-plane stress ratio. Meanwhile, the sensitivities of various input parameters and integration methods of FEM models on the prediction of wrinkling phenomena are investigated. To validate our proposed method and to illustrate the sensitivity issue in the FEM simulation, comparisons with experimental results of the Yoshida buckling test, aluminum square cup forming and aluminum conical cup forming are presented. The results demonstrate excellent agreements between the proposed method and experiments. Our model provides a reliable and effective predictor for the onset of side-wall wrinkling in sheet metal forming processes.

ABSTRACT: The prediction and prevention of wrinkling have been challenging issues in sheet metal forming processes. In an effort to provide the design and process engineers a reliable and efficient tool in assessing the onset of flange wrinkling, an analytical model, based on the wrinkling criterion proposed by Cao and Boyce [1], is presented here. The critical buckling stress and wavelength as functions of normal pressure are calculated using a combination of energy conservation and plastic bending theory. The present results are in excellent agreement with those obtained from Cao and Boyce’s numerical approach which has demonstrated its excellent predictive capability by comparing the experimental study of a conical cup [1] and a square cup forming [2]. Additionally, the effects of the tension in the plane of sheet and material properties on the initiation of flange wrinkling are investigated.

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ABSTRACT: Flanging is a commonly used sheet forming operation to increase the stiffness of a sheet panel and/or to create the mating surface for subsequent assemblies. This paper presents an energy approach to predict the onset of wrinkling during a shrink flanging operation. A curved sheet model is established to obtain the critical buckling stress in terms of stress state, geometry properties and material properties. The predictions of wave number agree well with the experimental results. The results indicate that the sensitivity of wave number on the plan view radius (PVR) increases as PVR decreases, and the wave number decreases with the increase of flange length. The critical flange length is significantly influenced by PVR, sheet thickness and material work-hardening, and is not sensitive to material strength and anisotropy.


ABSTRACT: A corner type constitutive equation is developed using the general quadratic anisotropic yield function. The wrinkling point of square plates subjected to diagonal tension was obtained by the bifurcation and Mindlin type plate theories, in conjunction with the finite element approximation. The growth of wrinkles was traced by a three-dimensional analysis in flanging terms of an isoparametric shell element. The numerical investigation was performed for the thin plates characterized by Hill's anisotropic yield function. The effects of such material characteristics as yield stress, hardening rate, orthotropy and normal anisotropy on the wrinkling limit and wrinkle height have been clarified.

ABSTRACT: The onset of wrinkling in sheet metals is first analysed as an elastic–plastic bifurcation for thin and shallow shells with compound curvatures. Plastic yielding is described using a criterion recently proposed for transversely anisotropic materials. A local analysis is developed, which allows us to define wrinkling limit curves depending on material properties and local geometry. Finite element (FE) simulations of the conical cup test are also performed using the Abaqus/Explicit code. The FE results relating to the initiation of wrinkling in the wall are compared with the predictions of the bifurcation model. In addition to the intrinsic effect of anisotropy on wrinkling tendencies, it is shown that the attainment of critical wrinkling conditions is significantly affected by the influence of anisotropy on the stress state and sheet curvature developed in the wall prior to bifurcation.


ABSTRACT: An analysis of the onset of wrinkling is first developed for a doubly curved, elastic–plastic shell element submitted to a biaxial plane stress loading. Plastic yielding is described using a criterion recently proposed for anisotropic sheet metals. The wrinkling limit curves obtained with this analysis are compared with previous results based on different yield criteria. Finite element (FE) simulations of a deep-drawing experiment are also performed using the Abaqus/Explicit code with the aim of comparing the FE results relating to the initiation of wrinkling with the predictions of the analytical model and with experiments from the literature.


ABSTRACT: Stamping industries tend to use thin, high-strength metallic sheets, in an effort to lighten the weight of structures. As a result wrinkles frequently develop during stamping processes. In practice wrinkling can occur on the flange or on the wall of the blank. The aim of this paper is to forecast the occurrence of wrinkling on the wall of the blank. Two methods have been developed to capture the onset of wrinkling. The first method is based on a bifurcation analysis for a doubly curved sheet. Wrinkling limit curves are determined by this analytical study. The second method uses finite element (FE) simulations. Two deep drawing tests are simulated using the dynamic explicit FE code ABAQUS/Explicit. FE results combined with analytical predictions allow us to outline the influence of normal anisotropy on the onset of wrinkling. The analytical and the numerical predictions are in fair agreement with experiments from the literature.

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ABSTRACT: The onset of wrinkling in sheet metal forming is investigated using an analytical approach and
finite element (FE) simulations. In both cases the yield criterion proposed by Ferron et al. [Int. J. Plast. 10 (1994) 431] for orthotropic sheets is employed. The analytical approach is developed on the basis of the bifurcation criterion developed by Hutchinson [J.W. Hutchinson, Plastic buckling, in: C.-S. Yih (Ed.), Advances in Applied Mechanics, vol. 14, 1974, pp. 67–144] for thin and shallow shells submitted to a biaxial plane stress loading. Wrinkling limit curves obtained with the bifurcation analysis are drawn for different orientations of the orthotropic axes with respect to the principal stress axes, assuming also different orientations with respect to the geometric axes of principal curvatures. The numerical simulations are performed with the FE code ABAQUS/Explicit. Experimental results of deep-drawing processes taken from the literature are also analysed to check the reliability of the wrinkling predictions obtained with the bifurcation analysis and with the FE simulations. Both analytical and numerical predictions compare reasonably well with experiments.

ABSTRACT: A number of researchers have studied the mechanical properties of skin and developed constitutive models to describe its behaviour. Typically, many of these studies have concentrated on the uniaxial tensile behaviour of the skin, on the grounds that it will wrinkle under in-plane compression and have minimal stiffness. However, although there is a substantial body of literature on wrinkling models, the practical implementation of such a model of skin in a finite element setting has not been widely addressed. This paper presents computational details of a wrinkling, hyperelastic membrane model and aspects of its implementation and areas requiring further research are discussed. The model is based on an Ogden constitutive model, which provides accurate results at moderate strains, but it would be straightforward to implement other constitutive models such as the Fung or Arruda-Boyce models using a similar approach. Example results are presented which demonstrate that the model can provide a good approximation to experimental data. The model has many other possible applications, both for biological materials and for other thin hyperelastic membranes.

ABSTRACT: We apply the two-dimensional elastic continuum model to describe the wrinkling of elastic Langmuir layers (membranes) subjected to unidirectional compression. The effects of the dilatational, shear, and bending elasticities are taken into account. Among the numerous solutions of the generalized Laplace equation, corresponding to different membrane tensions, we determine the membrane shape as the profile that minimizes the energy of the system. In the case of small deformations, the problem can be linearized. Its solution predicts a wavelike shape of the compressed membrane. At negligibly small bending elasticity, the energy of the system is minimal for a sinusoidal profile, whose amplitude and wavelength tend to zero. In the opposite limiting case, where the effect of bending elasticity prevails over the effect of gravity, the membrane has a half-wave profile. When the two effects are comparable, the membrane shape exhibits multiple periodic wrinkles (ripples). An expression is derived for calculating the bending elasticity (rigidity) from the wavelength, and reasonable values are obtained from available experimental data. To determine the membrane shape at larger out-of-plane deformations, we solved numerically the respective nonlinear problem. Depending on the values of the physical parameters, the theory predicts various shapes: nonharmonic oscillations, toothed profiles, and profiles with two characteristic wavelengths. The results can be used for determining the bending
elastic modulus of Langmuir films (membranes) as well as for the interpretation of buckling and collapse of monolayers.

ABSTRACT: The mechanical response to compression of a self-assembled gold nanoparticle monolayer and trilayer at the air-liquid interface is examined. Analysis of the film's buckling morphology under compression reveals an anomalously low bending rigidity for both the monolayer and the trilayer, in contrast with continuum elastic plates. We attribute this to the spherical geometry of the nanoparticles and poor coupling between layers, respectively. The elastic energy of the trilayers is first delocalized in wrinkles and then localized into folds, as predicted by linear and nonlinear elastic theory for an inextensible thin film supported on a fluid.

ABSTRACT: The nanomechanical properties of micropatterned nanomembranes containing gold nanoparticle microarrays were investigated with the buckling instability method. An unusual, complex pattern of buckling instability was observed for the nanoscale polymeric films under compressive stresses. An intriguing two-stage wrinkling was observed for these nanoscale films with spatially correlated instabilities. Two concurrent strain-dependent buckling modes were observed above a certain critical strain. Transformation from conventional transversal buckling mode to zigzag buckling is attributed to the development of the biaxial stress along the boundary lines for micropatterned areas. The binary buckling pattern observed here allowed the "one-shot" evaluation of the elastic moduli of two compositionally different regions (with and without gold nanoparticles).

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DOI: 10.1021/la0507378
ABSTRACT: We study shape and buckling transitions of particle-laden sessile and pendant droplets that are forced to shrink in size. Monodisperse polystyrene particles were placed at the interface between water and decane at conditions that are known to produce hexagonal, crystalline arrangements on flat interfaces. As the volumes of the drops are reduced, the surface areas are likewise diminished. This effectively compresses the particle monolayer coating and induces a transition from a fluid film to a solid film. Since the particles are firmly attached to the interface by capillary forces, the shape transitions are reversible and shape/volume curves are the same for drainage and inflation. Measurements of the internal pressure of the drops reveal a strong transition in this variable as the buckling transition is approached.

ABSTRACT: We introduce a new experimental approach to study the structural transitions of large numbers of nanoparticle-coated droplets as their volume is reduced. We use an emulsion system where the dispersed phase is slightly soluble in the continuous phase. By adding a fixed amount of unsaturated continuous phase, the volume of the droplets can be controllably reduced, causing them to buckle or crumple, thereby becoming nonspherical. The resultant morphologies depend both on the extent of volume reduction and the average droplet size. The buckling and crumpling behavior implies that the droplet surfaces are solid.


ABSTRACT: Finite element solutions for the steady-state buckle propagation pressure in a pipeline with non-uniform thickness are given. The results are useful in finding buckle propagation pressures in corroded pipelines. It has been found that when corrosion is equal to or less than 10% of the original pipeline thickness, the pipeline collapses in an overall shell buckling mode; otherwise, the pipeline experiences local buckling. The propagation pressure decreases with both the thickness and angular extent of the reduced section, but the rate of decrease with thickness reduction is almost independent of the angular extent of corrosion when it is greater than 90°.


ABSTRACT: Rigid–plastic solutions for the steady-state, quasi-static buckle propagation pressure in corroded pipelines are derived and compared to finite element predictions (ABAQUS). The corroded pipeline is modeled as an infinitely long, cylindrical shell with a section of reduced thickness that is used to describe the corrosion. A five plastic hinge mechanism is used to describe plastic collapse of the corroded pipeline. Closed-form expressions are given for the buckle propagation pressure as a function of the amount of corrosion in an X77 steel pipeline. Buckles that propagate down the pipeline are caused by either global or snap-through buckling, depending on the amount of corrosion. Global buckling occurs when the angular extent of the corrosion is greater than 90°. When the angular extent is less than 90° and the corrosion is severe, snap-through buckling takes place. The buckle propagation pressure and the corresponding collapse modes also compare well to finite element predictions.


ABSTRACT: Analytical solutions for elastic buckling of a non-uniform, long cylindrical shell that is subjected to external hydrostatic pressure are presented in this paper. The non-uniform shell has two regions: one with a nominal thickness and the other with reduced thickness. Symmetric and anti-symmetric buckling modes have been found to occur depending on the relative thickness of the two different regions and the angular extent of
the section with the reduced thickness. A diagram showing the ranges of relative thickness and angular extent of the section with the reduced thickness is given for the occurrence of symmetric and anti-symmetric modes. In general, the buckling pressure decreases when either the relative thickness or the angular extent of the section with the reduced thickness increase. Finite element solutions for the elastic buckling pressure and modes are also found using ABAQUS and the results from analytical solutions are found to be in close agreement with finite element predictions.

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ABSTRACT: Solutions for the steady-state buckle propagation modes and pressures in a corroded pipeline subjected to external hydrostatic pressure are presented. The buckle propagation pressure of a corroded pipeline is obtained analytically with a rigid-plastic analysis and numerically from finite element analysis (ABAQUS). Both the rigid-plastic analysis and ABAQUS program reveal symmetric and anti-symmetric buckling modes, depending on the depth and angular extent of the corrosion. Snap-through and global buckling of the pipeline are also distinguished in both solutions. The rigid-plastic solutions for buckle propagation pressure and corresponding collapse modes are found to be within 15% with numerical solutions.

ABSTRACT: A non-linear finite-element analysis for the steady-state buckle propagation phenomenon in subsea corroded pipelines subjected to external hydrostatic pressure is presented. The corroded pipeline is modeled as an infinitely long, cylindrical shell with a non-uniform thickness region. Using Maxwell's theory of two coexisting phases and principle of virtual work, the buckle propagation pressures for the corroded pipeline are calculated from pressure–volume change relations obtained from ABAQUS. The corresponding collapse modes of the corroded pipeline are generated from ABAQUS post-analysis. Symmetric and anti-symmetric collapse modes are found to occur, depending on the depth and angular extent of the corrosion. In addition, snap-through and global collapses are also identified. A parametric study shows how the buckle propagation pressures decrease when either the ratio of corrosion depth to the normal thickness or the angular extent of the corrosion increases. The finite-element model is validated using Timoshenko's classical solutions.

ABSTRACT: This paper deals with the buckling phenomenon of undersea corroded pipelines. The corrosion degree of the pipelines is characterized by two parameters: the angular extension and the corrosion depth. Previous work has shown that symmetric and antisymmetric buckling modes occur in pipelines when the corrosion is uniformly extended over part of pipelines along the circumferential direction. The presented research analyzes the stability condition in pipelines with generalized corrosion. Using WKB theory for
asymptotic expansion, the buckling mode and the eigenfunctions are derived for the corroded pipelines subjected to external hydrostatic pressure. Furthermore, asymptotic solutions are derived for pipelines with constant corrosion and compared with validated solutions obtained in previous work using equilibrium analysis. It shows that the buckling modes and buckling pressure from asymptotic analysis are identical to the exact solutions. Symmetric and antisymmetric buckling modes are found to occur for pipelines when the corrosion is not uniform but symmetric about its centerline.


ABSTRACT: This paper presents a unique approach to analyze the steady-state buckle propagation phenomenon in underwater pipelines. In previous work, we restudied the buckling of a very long pipeline subjected to external pressure and found that buckling happens only over a certain length of the pipeline. In this paper, the collapse mode of the pipeline obtained in previous studies is taken as the transition zone during steady-state buckle propagation. Kinematics in the transition zone is analyzed based on von Kármán–Donnell type of nonlinearity. Assuming linear elastic rigid plastic material properties, the mechanical responses in the transition zone are examined using the deformation theory. Two parameters, the yield coefficient and the membrane stretching factor, are introduced to depict the effects of transversal bending and the membrane stretching, respectively. Analytical solution of buckle propagation pressure is derived by considering the energy conversation calculated from shell theory. It is found that the buckle propagation performance is governed by the transversal bending, including the circumferential bending and longitudinal bending. The membrane stretching is significant only for thick wall pipeline, in particular when the ratio of radius-to-thickness is small than ten. The analysis is in effect by comparing the obtained solutions with the well-established predictions and the experimental results.

Jianghong Xue and Neng Gan (Department of Mechanics and Civil Engineering, Jinan University/Key Lab of Disaster Forecast and Control in Engineering, Ministry of Education, Guangzhou, 510632, P. R. China), “A comprehensive study on a propagating buckle in externally pressurized pipelines”, Journal of Mechanical Science and Technology, Vol. 28, No. 12, pp 4907-4919, December 2014

ABSTRACT: Buckle propagation is a unique phenomenon occurring in deep-sea pipelines. In previous works, this phenomenon was investigated using a ring technique in which the pipeline was assumed to be in plane strain condition and the energies absorbed in membrane stretching and longitudinal bending were ignored. This paper presents a three-dimensional analysis of the buckle propagation phenomenon with an emphasis to address more complete factors that were not accounted for in the ring analysis. The analyses are based on the available solutions of the transition zone obtained in our previous works. A comprehensive mechanism for buckle propagation phenomenon is described from the point view of plastic stability theory for shells which enables the incorporation of the effects of transverse and longitudinal bending, membrane stretching and material strain hardening. The nondimensionalized buckle propagation pressure is represented in terms of yield coefficient, strain hardening coefficient and membrane stretching factor. It is found that a buckle once initiated in a pipeline may or may not propagate along the pipeline depending on its radius-to-thickness ratio. By comparing with various experimental results the theoretical predictions from this analysis are shown to provide very accurate estimations of the buckle propagation pressure for different materials with diverse geometric parameters and material properties. This paper points to the need for more complete information regarding the effects of transverse bending, membrane stretching and material strain-hardening on the buckle propagation pressure.
Upon the requirement of application variations of the yield coefficient, strain hardening coefficient and membrane stretching factor with respect to the radius-to-thickness ratio are sketched out. This eliminates the need for recourse the curves and allows a fast and convenient resolution of buckle propagation pressure for certain pipeline. Most importantly, the present analysis offers the potential for future design of pipelines being at once more rationally and parametrically complete, and yet compact and simple to apply.

References listed at the end of the paper:

ABSTRACT: Dynamic pulse buckling of woven E-Glass/Vinyl Ester and laminated E-Glass/Epoxy cylindrical shells subjected to uniform overpressure and asymmetric pressure pulse (side-on explosion) were examined. The solutions for the radial shell deformations were represented by Mathieu differential equations. The dynamic instability of the shells was determined from a Mathieu stability diagram. It was found that the stability of the shells depended on lay-up, aspect ratio as well as impulse distribution. The stable vibration response of the shells with side-on explosion compared well with finite element solutions using a Dynamic, Implicit analysis in ABAQUS Standard. First-ply failure of the woven E-Glass/Vinyl Ester shell with side-on explosion was predicted using a modified Hashin–Rotem failure criterion. It was shown that the thinner woven E-Glass/Vinyl Ester shells were more likely to fail by dynamic instability, whereas the thicker woven E-Glass/Vinyl Ester shells were more likely to fail by first-ply failure.

Jianghong Xue (Dept. of Mechanical & Civil Engineering, Jinan University, Guangzhou, China), “Perturbation analysis of instability for non-uniform cylindrical shells with initial imperfection”, Control and Decision Conference (CCDC), 2011, 23-25 May 2011, pp 661-665, DOI: 10.1109/CCDC.2011.5968265

ABSTRACT: Buckle propagation in subsea corroded pipelines is one of the most concerned problems in offshore industries, while locating the plastic hinges in the corroded pipeline is the crux in determining the buckle propagation pressure. This paper presents a methodology to determine the locations of plastic hinges in non-uniform shells subjected to external pressure. The non-uniform shell used to model the corroded pipeline has two Regions: Region 1 of reduced, inconstant thickness and Region 2 of nominal thickness. Analytical formulas for the bifurcation load, radial deformation, initial yield pressure and stress distribution in the non-uniform shell are derived from perturbation analysis using WKB expansion. The locations of plastic hinges are identified at the stress peaks by taking the derivative of the stress with respect to circumferential coordinate. Imperfection sensitivity of the non-uniform shell is assessed with an emphasis on the role of initial yield pressure and the locations of plastic hinges. Special case when the thickness of Region 2 is constantly reduced is examined. It is found that both the initial yield pressure and the locations of plastic hinges depend on the non-uniform conditions of the cylindrical shell.


ABSTRACT: First-order generalized beam theory describes the behaviour of prismatic structures by ordinary uncoupled differential equations, using deformation functions for bending, torsion and distortion. In second-order theory, the differential equations are coupled by the effect of deviating forces. The basic equations for second-order generalized beam theory are outlined. Solutions for pin-ended supports are presented, demonstrating the coupling effect by modes and by loads. In the different ranges of length, the individual modes are sufficient approximations for the critical load. The application to a thin-walled bar with C-section under eccentric normal force demonstrates the quality of the single-mode compared to the exact solution.

ABSTRACT: For thin-walled sections, lateral and lateral-torsional buckling are often affected by distortion of the section and this can severely reduce the critical stress. A calculation method for the critical stress which takes account of distortional effects, based on Generalised Beam Theory (GBT), is presented in this paper. The limiting slenderness at which distortional effects begin to take effect is evaluated for channel- and hat-sections on the basis of parametric studies. Approximate formulae for the limiting slenderness are then given.

ABSTRACT: Following the intention of this special issue the most important contributions of Kloppel to light weight steel constructions are presented, A short history of the development of Generalized Beam Theory (GBT) is given. Applications of GBT are shown in the fields of distortion (batten plates, cold-rolled purlins and trapezoidal sheeting), stability (buckling and ultimate loads of special sections) and thin-walled cylinders (joint stiffness and buckling).

ABSTRACT: A previous paper presented a method of analysis for any open unbranched thin-walled section considering both rigid body movement and cross-section distortion (including local buckling). It described briefly the calculation procedures required in order to obtain section properties related to each of a number of cross-section distortion modes. These properties were generally calculated using first-order theory. This paper describes in full how second-order theory can be used to calculate the section properties for all modes, including each of the four rigid body modes. In the process of developing the second-order generalized beam theory, additional section properties evolve which enable the first-order equilibrium equation to be modified to consider second-order elastic critical load problems.

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ABSTRACT: This paper introduces the second-order terms associated with geometric nonlinearity into the basic equation of Generalised Beam Theory. This gives rise to simple explicit equations for the load to cause buckling in individual modes under either axial load or uniform bending moment. It is then shown how the explicit procedure can be extended to consider the interaction between local, distortional and global buckling modes. More general load cases require the use of numerical methods of analysis and the finite difference method offers a suitable procedure. The success of Generalised Beam Theory for a wide range of situations is demonstrated by comparing the results obtained using it with both test results and other analyses. It is shown that it offers particular advantages in the analysis of buckling problems in cold-formed sections.


ABSTRACT: Previous papers (Refs 1–4) have presented a method of analysis for any open unbranched thin walled section considering both rigid body movement and cross section distortion (including local buckling). Reference 1 described how the Generalized Beam Theory (GBT) can be used to calculate generalized section properties for all modes, including each of the four rigid body modes and the distortional modes. The additional section properties evolved from GBT were then used in Ref. 2 to consider second order elastic critical buckling problems. This paper compares the critical buckling predictions of GBT with the results obtained in two series of tests carried out on lipped and unlipped channels subject to a major axis bending moment. These predictions are then combined with the yield criteria of EC3 to allow a comparison with the analysis of these tests carried out by Lindner and Aschinger (Ref. 5). The paper concludes that the Generalized Theory is a powerful and effective analysis tool for the solution of interactive buckling problems where both local and overall buckling can occur.

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“Elastoplastic behavior of longitudinally stiffened girder webs subjected to patch loading and bending”, DYNA.rev.fac.nac.minas, Vol. 82, No. 189, January/February 2015

ABSTRACT: This paper is aimed at studying the elastoplastic behavior of longitudinally stiffened girder webs subjected to patch loading and bending. The investigation is carried out by means of nonlinear finite element analysis to study the structural behavior of the girder components (flanges, web and stiffener) at ultimate limit state. Initial geometrical imperfections, plastic material behavior and large deflection effects are considered in the model. For the numerical model validation, the computer results from the simulations are compared with experimental results taken from the literature. A parametric study was carried out in order to investigate the influence of the applied bending moment and the relative location of the stiffener on the ultimate strength to patch loading.


ABSTRACT: Finite element analysis of pinned cold-formed plain channel columns of different width-to-
thickness ratios is presented in this paper. The study is focused not only on axially loaded columns, but also on eccentrically loaded columns. The general purpose finite element software ABAQUS 6.12 was used, and the force controlled loading was adopted. Geometric and material nonlinearities were incorporated in the finite element model. The ultimate loads are compared with the direct strength method (DSM) for axially loaded columns. Also, a parametric study is done by varying the length of the column and width of the unstiffened element. It is observed that the results correlate better with the DSM values for columns having unstiffened elements of lower b/t ratios. The change in ultimate load is studied only in ABAQUS, as the position of load moves towards the free edge and the supported edge of the unstiffened element. A parametric study is done by varying the nonuniform compression factor for the columns. It is observed that the ultimate load increases as the position of load moves towards the supported edge and it is influenced by the b/t ratio of the unstiffened element.


ABSTRACT: This paper presents an experimental investigation of short cold-formed lipped channel columns compressed between pinned ends. The short columns are subjected to pure axial compressive loading. Twelve column specimens are tested and the columns are categorised into three groups, depending on the length and thickness. The buckling modes of failure that occurred include local buckling and distortional buckling. A comparison of the experimental results with the loads predicted by the South African standard for the design of cold-formed steelwork (SANS 10162-2) shows that the code is not conservative enough to cater for these columns.

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G. Beulah Gnana Ananthi, G.S. Palani and Nagesh R. Iyer (Department of Architecture, SAP Campus, Anna University, Chennai - 600025, India), “Numerical and theoretical studies on cold-formed steel unlipped channels subjected to axial compression”, Latin American Journal of Solids and Structures, Vol. 12, No. 1, January 2015

ABSTRACT: This paper presents both the analytical and theoretical investigations on ultimate load carrying capacity and behaviour of CFS unlipped channels with their ends fixed and subjected to axial compression. The numerical studies have been carried out in the elastic as well as in the plastic ranges of loading. The slenderness ratio of the channels chosen is 40, 80,100 and 120. Three different web depths [shallow, medium and deep] with five thicknesses have been chosen. In addition to the numerical studies, comparison with the design strengths predicted by using North American Standards for CFS structures. It is observed that the design strength predicted by the specifications are conservative for axially loaded columns. In the present investigation, an attempt is made to study the ultimate load carrying capacity and the mode of failure. Load versus axial shortening behaviour has been studied for various slenderness ratios for a few specimens.

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Cheng Yu and Benjamin W. Schafer, “Distortional buckling of cold-formed steel members in bending”, Ph.D. dissertation by Cheng Yu, Advisor B.S. Schafer, American Iron and Steel Institute Final Report, Baltimore, Maryland, January 2005

ABSTRACT: Laterally braced cold-formed steel beams generally fail due to local and/or distortional buckling in combination with yielding. For many cold-formed steel (CFS) studs, joists, purlins, or girts, distortional buckling may be the predominant buckling mode. However, distortional buckling of CFS beams remains a largely unaddressed problem in the current North American Specification for the Design of Cold-Formed Steel Structural Members (NAS). Further, adequate experimental data on unrestricted distortional buckling in bending is unavailable. Therefore, two series of bending tests on industry standard CFS C and Z-sections were performed and presented in this dissertation. The testing setup was carefully designed in the first series of tests (Phase 1) to allow local buckling failure to form while restricting distortional and lateral-torsional buckling. The second series of tests (Phase 2) used nominally identical specimens to Phase 1 tests, and a similar testing setup. However, the corrugated panel attached to the compression flange was removed in the constant moment region so that distortional buckling could occur. The experimental data was used to examine current specifications and new design methods. Finite element modeling in ABAQUS was developed and verified by the two series of bending tests and then applied to analyze more CFS beams. An analytical method was derived to determine the elastic buckling stress of thin plates under longitudinal stress gradient. And finite element analysis was used to study the stress gradient effect on the ultimate strength of thin plates. It was found that the stress gradient increases the buckling stress of both stiffened and unstiffened elements, and current design methods can include
the stress gradient effect if an appropriate elastic buckling coefficient is used. The moment gradient effect on the distortional buckling of CFS beams was also studied by the finite element analysis. The results show that the moment gradient increases both the elastic buckling moment and ultimate strength of distortional buckling of CFS beams. A draft design provision was proposed to account for the moment gradient effect. Research was conducted to explore the distortional buckling of CFS beams with partial restraint on the compression flange. A simple numerical model was proposed to calculate the elastic buckling moment of the CFS section-panel system. It was found that partial restraint has significant influence on distortional buckling, and that the influence could be considered by using a modified elastic buckling moment. For design purposes, simplified closed-form solutions for the elastic buckling moment of CFS C and Z-sections were proposed and verified. In the end, conclusions and recommendations for future research are presented.

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ABSTRACT: A nonlinear finite element (FE) model is developed to simulate two series of flexural tests, previously conducted by the authors, on industry standard cold-formed steel C- and Z-section beams. The previous tests focused on laterally braced beams with compression flange details that lead predominately to local buckling failures, in the first test series, and distortional buckling failures, in the second test series. The objectives of this paper are to (i) validate the FE model developed for simulation of the testing, (ii) perform parametric studies outside the bounds of the original tests with a particular focus on variation in yield stress and influence of moment gradient on failures, and (iii) apply the study results to examine and extend the Direct Strength Method of design. The developed FE model shows good agreement with the test data in terms of ultimate bending strength. Extension of the tested sections to cover yield stresses from 228 to 506 MPa indicates that the Direct Strength Method is applicable over this full range of yield stresses. The FE model is also applied to analyze the effect of moment gradient on distortional buckling. It is found that the distortional buckling strength of beams is increased due to the presence of moment gradient. Further, it is proposed and verified that the moment gradient effect on distortional buckling failures can be conservatively accounted for in the Direct Strength Method by using an elastic buckling moment that accounts for the moment gradient. An empirical equation, appropriate for use in design, to predict the increase in the elastic distortional buckling moment due to moment gradient, is developed.
number of sample simulations. In an attempt to curtail the need for multiple sample calculations, an alternative first-order perturbation expansion is proposed for approximating the mean and variance of the post-buckling behavior. However, the limitations of this first-order perturbation approximation are demonstrated to be significant. The simulations indicate that deterministic characteristics of the post-buckling response can be inadequate in the face of input randomness. In one case, a frame that is stable symmetric in the deterministic case is found to be asymmetric when randomness in the input is incorporated; therefore, this frame has real potential for imperfection sensitivity. The importance of random field models for the member stiffness as opposed to random variable models is highlighted. The simulations indicate that the post-buckling response can magnify input randomness, as variability in the post-buckling parameters can be greater than the variability in the input parameters.

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“Simplified methods for predicting elastic buckling of cold-formed steel structural members with holes”, 19th International Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri, USA, October 14-15, 2008

ABSTRACT: Simplified methods for approximating the local, distortional, and global critical elastic buckling loads of cold-formed steel columns and beams with holes are developed and summarized. These methods are central to the extension of the Direct Strength Method (DSM) to members with holes, as DSM employs elastic buckling properties to predict ultimate strength. The simplified methods are developed as a convenient alternative to shell finite element eigenbuckling analysis, which requires commercial software not always accessible to the engineering community. A variety of simplified methods are pursued including (a) hand methods founded primarily on classical plate stability approximations and (b) empirical extensions to the semi-analytical finite strip method (i.e., modifying and using the freely available, open source software, CUFSM). The proposed methods are verified with shell finite element eigenbuckling studies. The developed simplified methods are intended to be general enough to accommodate the range of hole shapes, locations, and spacings common in industry, while at the same time also defining regimes where explicit use of shell finite element analyses are still needed for adequate accuracy.

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"Elastic buckling of thin plates with holes in compression or bending", Thin-Walled Structures, Vol. 47, No. 12, December 2009, pp. 1597-1607, doi:10.1016/j.tws.2009.05.001

ABSTRACT: Closed-form expressions for approximating the influence of single or multiple holes on the critical elastic buckling stress of plates in bending or compression are developed, validated and summarized. The expressions are applicable to plates simply supported on 4 sides and plates simply supported on 3 sides, commonly called stiffened and unstiffened elements in design. The expressions serve as a convenient alternative to shell finite element eigen-buckling analysis, which requires commercial software not typically accessible to the engineering design community. The forms of the expressions are founded on classical plate stability approximations, and are developed and validated with parametric studies employing shell finite elements. The finite element parametric studies demonstrate that holes may create unique buckling modes, and can either decrease or increase a plate's critical elastic buckling stress depending on the hole geometry and spacing. The validated closed-form expressions and their associated limits are intended to be general enough to accommodate the range of hole shapes, locations, and spacings common in engineering practice, while at the same time also defining regimes where explicit use of shell finite element analyses is still needed for adequate accuracy.


ABSTRACT: In this study, a vibration analysis was carried out of symmetric angle-ply laminated composite
plates with and without square hole when subjected to compressive loads, numerically. A buckling analysis is also performed to determine the buckling load of laminated plates. For each fibre orientation, the compression load is taken equal to 50% of the corresponding buckling load. In the analysis, finite element method (FEM) was applied to perform parametric studies, the effects of degree of orthotropy and stacking sequence upon the fundamental frequencies and buckling loads are discussed. The results show that the presence of a constant compressive load tends to reduce uniformly the natural frequencies for materials which have a low degree of orthotropy. However, this reduction becomes non-uniform for materials with a higher degree of orthotropy.

References listed at the end of the paper:

three-dimensional continuum elements and calibrated constitutive models specific to metallic foams. The developed closed-form design expressions are employed to conduct parametric studies of steel foam sandwich panels, which (a) demonstrate the significant strength improvements possible when compared with solid steel, and (b) provide insights on the optimal balance between steel face sheet thickness and density of the foamed steel core. This work is part of a larger effort to help develop steel foam as a material with relevance to civil engineering applications.

References listed at the end of the paper:


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ABSTRACT: The objective of this paper is to provide a method for applying modal identification (i.e. the separation of general deformations into fundamental modal deformation classes: local, distortional, global, shear, and transverse extension) to the collapse analysis of thin-walled members modeled using material and geometric nonlinear shell finite element analysis. The advantage of such a modal identification is the ability to categorize and reduce the complicated deformations that occur in a shell finite element model—and ultimately to (a) quantitatively associate failures with particular classes, e.g. state a model as a local failure, and (b) track the evolution of the classes, e.g., mixed local and distortional buckling leading to a distortional failure in a given model. Ultimately, this capability will aid Specification development, which must simplify complicated behavior down to strength predictions in isolated buckling-induced limit states. The modal identification method is enabled by creating a series of base vectors, consistent with the fundamental deformation classes, that are used to categorize the general finite element displacements. The base vectors are constructed using the constrained finite strip method for general end boundary conditions, previously developed by the authors. A fairly sizeable minimization problem is required for assigning the contributions to the fundamental deformation classes. The procedure is illustrated with shell finite element examples of cold-formed steel members modeled to collapse with geometric or/and material nonlinearity. The failure modes of the member are tracked (i.e., identified as a function of displacement), and the collapse mechanism is investigated. The provided examples provide both proof of concept for the modal identification and demonstrate the potential of using such information to better understand the behavior of thin-walled members.


ABSTRACT: In this paper, flexural buckling of pin-ended thin-walled columns is discussed. The classical formulae for the critical force are based on a beam model. The simplest formulae use the classical Euler–Bernoulli beam theory, but solutions based on the shear-deformable beam theory are also known. In the presented research alternative formulae are derived. The column is modeled as a set of flat plane elements, and the in-plane membrane shear deformations are explicitly considered. The derivations can be carried out in various, slightly different ways, leading to different formulae. The derived critical force formulae are discussed through theoretical considerations and numerical studies.

Kremer, K., Liszkiewicz, A. and Adkins, J., “Development of steel foam materials and structures”, October 2004, Fraunhofer, Center for Manufacturing and Advanced Materials, Newark, Delaware

ABSTRACT: In the past few years there has been a growing interest in lightweight metal foams. Demands for weight reduction, improved fuel efficiency, and increased passenger safety in automobiles now has
manufacturers seriously considering the use of metal foams, in contrast to a few years ago, when the same materials would have been ruled out for technical or economical reasons. The objective of this program was to advance the development and use of steel foam materials, by demonstrating the advantages of these novel lightweight materials in selected generic applications. Progress was made in defining materials and process parameters; characterization of physical and mechanical properties; and fabrication and testing of generic steel foam-filled shapes with compositions from 2.5 wt. % to 0.7 wt. % carbon. A means of producing steel foam shapes with uniform long range porosity levels of 50 to 60 percent was demonstrated and verified with NDE methods. Steel foam integrated beams, cylinders and plates were mechanically tested and demonstrated advantages in bend stiffness, bend resistance, and crush energy absorption. Methods of joining by welding, adhesive bonding, and mechanical fastening were investigated. It is important to keep in mind that steel foam is a conventional material in an unconventional form. A substantial amount of physical and mechanical properties are presented throughout the report and in a properties database at the end of the report to support designer’s in applying steel foam in unconventional ways.

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ABSTRACT: Steel tubes have an efficient shape with large second moment of inertia relative to their light weight. One of the main problems of these members is their low buckling resistance caused from having thin walls. In this study, steel foams with high strength over weight ratio is used to fill the steel tube to beneficially modify the response of steel tubes. The linear eigenvalue and plastic collapse FE analysis is done on steel foam filled tube under pure compression and three point bending simulation. It is shown that steel foam improves the maximum strength and the ability of energy absorption of the steel tubes significantly. Different configurations with different volume of steel foam and composite behavior is investigated. It is demonstrated that there are some optimum configurations with more efficient behavior. If composite action between steel foam and steel increases, the strength of the element will improve, in a way that, the failure mode change from local buckling to yielding.

References listed at the end of the paper:
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ABSTRACT: Offshore wind turbine (OWT) support structures are subjected to non-proportional environmental wind and wave load patterns with respect to increases in wave height and with respect to wind and wave combined loading. Traditional approaches to estimating the ultimate capacity of offshore support structures are not ideally suited to analysis of OWTs. In this paper, the concept of incremental wind-wave (IWWA) analysis of the structural capacity of OWT support structures is proposed. The approach uses static push-over analysis of OWT support structures subject to wind and wave combined load patterns corresponding to increasing mean return period (MRP). The IWWA framework can be applied as a one-parameter approach (IWWA1) in which
the MRP for the wind and wave conditions is assumed to be the same or a two-parameter approach (IWWA2) in which the MRPs associated with wind and wave conditions are related to a joint probability density function characterizing the wind and wave conditions at the site. Example calculations for monopile and jacket supported OWTs at Atlantic marine sites are performed under both one parameter and two parameters IWWA framework. The analyses illustrate that: the results of an IWWA analysis are site specific; and structural response can be dominated by either wind or wave conditions depending on structural characteristics and site conditions. Finally, reliability analyses for both examples excluding uncertainties in structural resistance are estimated based on their IWWA results and probabilistic models for site environmental conditions.

Z. Li, S. Ádány, and B. W. Schafer (Wei-Wen Yu Center for Cold-Formed Steel Structures, Civil, Architectural and Environmental Engineering, Johns Hopkins University, Baltimore, MD 21218), "Modal Identification of Cold-formed Steel Members in Shell Finite Element Models", 21st International Specialty Conference on Cold-Formed Steel Structures. Paper 1, http://scholarsmine.mst.edu/iscss/21icfss/21icfss-session1/1, August 24, 2012

ABSTRACT: This paper illustrates new capabilities for modal identification of shell Finite Element Method (FEM) models of thin-walled cold-formed steel members. The separation of general deformations into fundamental buckling deformation classes: local, distortional, global, shear, and transverse extension, originated with the constrained Finite Strip Method (cFSM) and is extended here to shell element based FEM analysis. The cFSM base vectors for general end boundary conditions, previously developed by the authors, provide a series of general base functions capable of separating displacements into classes. FEM displacements are identified by minimizing error between the actual FEM displacements and those predicted by the cFSM base functions. This leads to the ability to quantify (i.e., modally identify) the global, distortional, and local participation in a FEM model. The ability to categorize the complicated deformations of a FEM model into simple classes is of great importance because of the different post-buckling and collapse behavior associated with each class. Further, the extension to general FEM models allows for modal identification of members with geometric changes along the length, such as holes, as well as concentrated loads and other characteristics difficult to capture in the finite strip formulation. The method is demonstrated for modal identification of FEM linear elastic analysis, FEM elastic buckling analysis (including highly coupled modes) and FEM nonlinear collapse analysis. Further, the examples include members with holes. The dominance of distortional buckling deformations in collapse regimes of lipped channel members is observed and provides new insight on the interaction of buckling modes in cold-formed steel members. Limitations of the method and future directions for the work are discussed.

References listed at the end of the paper:
2. AS/NZS, Cold-formed steel structures, AS/NZS 4600, 1996, Standards Australia/Standards New Zealand.

11. Li, Z. and B.W. Schafer. Buckling analysis of cold-formed steel members with general boundary conditions using CUFSM: Conventional and constrained finite strip methods. in 20th International Specialty Conference on Cold-Formed Steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction. 2010. St Louis, MO.

12. Schafer, B.W. and S. Ádány, Buckling analysis of cold-formed steel members using CUFSM: Conventional and constrained finite strip methods., in Eighteenth International Specialty Conference on Cold-Formed Steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction, 2006. p. 39-54.


http://dx.doi.org/10.1061/(ASCE)EM.1943-7889.0000591

ABSTRACT: The objective of this paper is to provide the theoretical background and illustrate the capabilities of the constrained finite strip method (cFASM) for thin-walled members with general end boundary conditions. Based on the conventional finite strip method (FSM), cFASM provides a mechanical methodology to separate the deformations of a thin-walled member into those consistent with global, distortional, local, and other (e.g., shear and transverse extension) modes. For elastic buckling analysis, this enables isolation of any given mode (modal decomposition) or quantitative measures of the interactions within a given general eigenmode (modal identification). Existing cFASM is only applicable to simply supported end boundary conditions. In this paper, FSM is first extended to general end boundary conditions, including simply–simply, clamped–clamped, simply–clamped, clamped–guided, and clamped–free. Next, with the conventional FSM for general end boundary conditions in place, the derivation of the constraint matrices for global, distortional, local, and other modes that play a central role in cFASM are summarized. Several bases (i.e., the constraint matrices) are presented for general end boundary conditions involving, in particular, different orthogonalization conditions. For modal identification, normalization schemes for the base vectors as well as the summation method employed for the modal participation calculation are also provided. Numerical examples of modal decomposition and identification are illustrated for a thin-walled member with general end boundary conditions. Recommendations on the choice of basis, orthogonalization, and normalization are provided.

CURRENT PRACTICE AND FUTURE RESEARCH NEEDS

ABSTRACT: The goal of this paper is to highlight promising methods in current thin metallic shell design practice and to define a future needs framework from which research can launch. Thin shell structural members are a staple in many industries – from aerospace, ship building, to offshore oil and gas to residential and commercial buildings. Shell types and geometries are numerous including ship hulls, silos, tanks, pipelines, chimneys and wind turbine towers. Despite large research investments there is still wide debate and uncertainty when designing thin shell structural members. Failure modes are complex and sensitive to initial geometric imperfections. The types of loadings vary widely – including axial, shear, flexure combined with internal or external pressure – making calculation-based methods challenging. Shell geometry – including longitudinal and transverse stiffeners and conical, tapered along a member – compound the complexity. This paper synthesizes these current approaches and organizes the most promising ideas into a framework for future research. A specific focus will be on research needed to expand current GMNIA (geometrically and materially nonlinear analysis with imperfections included) capabilities.

References listed at the end of the paper:
3. AISI (2012). AISI-S100-12, North American Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute, Washington, D.C.

ABSTRACT: Thin-walled stiffened or unstiffened, metallic or composite shells are widely used structural elements in aeronautical and space applications. These structures are often highly sensitive to initial imperfections and therefore have buckling loads much lower than those computed for perfect structures. Analysis and testing of imperfect shells have been a major research area during the last century. The proposed paper will present the results of the buckling analysis of small cylindrical shells, i.e. beer cans, with length of 100 mm, radius of 33 mm, and thickness 0.1 mm, and their comparison with experimental results. For the analytical work, a hierarchical multi-fidelity approach is used to solve the buckling problem. As a first level analysis some simple programs are used to investigate the behavior of perfect shells. The deformation in both axial and circumferential direction is described using goniometric functions. This is followed by more advanced analytical programs where the deformation in circumferential direction is still described using goniometric functions, but in axial direction the deformation is solved from the differential equations. Finally, the local buckling phenomena as observed during the experiment is looked at more carefully by investigating the energy behaviour.


ABSTRACT: This study reports the experimental investigation of the elastic, buckling and post-buckling response of unidirectional laminated and $0^\circ$ oriented E-glass/epoxy composite rectangular plate subjected to compressive load and liquid environment exposure. The plates were exposed to liquid rocket propellants like kerosene oil, hydrogen peroxide and hydrazine hydrate for different duration. The effects of liquid fuels, moisture concentration, fiber damage and plate parameters on elastic, buckling and post buckling response of the plate were studied. The effect of corrosion on composite plate and reduction in properties like weight changes, elastic, buckling and post-buckling strength were observed and found as a time dependent. The theoretical evaluation using classical thin plate theory showed the significant buckling load variation with response to experimental observation. In addition, hydrogen peroxide and hydrazine hydrate are found more corrosive compared to kerosene oil and reduced one fourth of the total strength of the composite plate.

Ali Fatemi and Shawn Kenny (Memorial University of Newfoundland and Labrador), “Continuum modeling framework for local buckling response of plain and girth welded pipes”, Offshore Technology Conference, 2-5 May 2011, Houston, Texas, USA

ABSTRACT: In this paper, the significance of boundary conditions (L/D ratio), initial geometric imperfections, anisotropic material properties, and material constitutive model on the local buckling response of plain and girth welded pipes was evaluated using continuum finite element modelling procedures. A numerical model was developed, using the finite-element simulator ABAQUS/Standard, to predict the local buckling and post-buckling response of high strength pipelines subject to combined state of loading. The numerical procedures were calibrated using test data from large-scale experiments examining the local buckling of high strength linepipe. The moment and strain response estimates, predicted by the numerical simulation tool, was consistent with the experimental data well into the post-yield range. As the models with high L/D ratio exhibit global Euler-type response, a numerical algorithm was developed to calculate the local section moment response based on FE predictions.
ABSTRACT: The elastic buckling and ultimate capacity of thin-walled steel circular hollow sections manufactured with spiral welding and subjected to axial force or pure bending are studied numerically in ABAQUS and experimentally validated to provide a numerical modeling protocol. This effort, focused on shell finite element analysis and the development of validated modeling protocols, is a part of a larger effort to definitively understand the limit-states and provide design standards for spirally welded steel wind turbine towers. The modeling protocol incorporates fundamental modeling parameters including element type, mesh aspect ratio, mesh style including structured mesh versus spiral mesh along the spiral welds, mesh size along the length, mesh size on the circular cross-section, material modeling, geometrical imperfections, and weld imperfections. The geometrical dimensions in the parametric analyses were selected in accordance with reasonable archetype dimensions and practical plate thicknesses and cross-sectional diameters applicable to wind turbine towers. An eigen-buckling convergence study including both buckling shapes and capacities was performed under pure bending and compressive axial force to find a base-line modeling protocol. To validate the base-line modeling protocol, a spirally welded tube specimen recently tested at Northeastern University was simulated via geometric and material nonlinear shell finite element analysis. The validated protocol will be applied to a larger parametric collapse analyses to generalize the experimental results and to develop reliability based design methods for spirally welded wind turbine towers.

References listed at the end of the paper:


ABSTRACT: Current design of cold-formed steel members is unduly complicated. Part of this complication arises from the need to perform elastic buckling calculations by hand. Also, complications occur in determining the effective width and resulting effective properties of members. Further, as cross-sections become more optimized (e.g., through the introduction of longitudinal stiffeners) both the elastic buckling and effective width calculations become markedly more complex. In order to investigate alternatives to current design a large amount of experimental data on flexural members of varying geometry is collected. The use of numerical elastic buckling solutions for the entire member is investigated as an alternative to current practice. Employing strength curves on the entire member, similar to the effective width strength curves for an element, it is found that a “direct strength” approach is a reliable alternative to current design. Such an approach leads to complete flexibility in cross-section geometry, thus greatly increasing the ability to optimize cold-formed steel members. Conservative limitations of the direct strength approach are also addressed.


ABSTRACT: Global stability of an innovative dome comprising of double-layer space frame sections together with curved flexural members has been studied. The dome had both an outer flat and an inner spherical double-layer grid space frames and formed the roof over a joint ballroom and meeting space of 3,100 square metres. The relatively wide spans between the outer and the inner space structures were covered using thirty six curved flexural pipe members laid on a synclastic surface. These members were employed for architectural purposes to provide a clear glazed area for the roof. Introducing relatively large span flexural members joining the two lattice space frames together complicated the overall structural response of the dome. It also made the dome susceptible to different premature instability modes. The non-linear FE program ABAQUS [1] was utilised to study the global stability of the dome and to investigate fully both its pre and post failure behaviour. Different member configurations were considered for the dome and their effects on the behaviour; stability, snap through buckling and the collapse load of the structure were investigated. In the dome responses, several failure modes such as overall torsional buckling, in-plane ring buckling and symmetrical and non-symmetrical vertical snap through were identified. It was noted that the presence of restraints placed between the flexural members could prevent the occurrence of premature torsional and vertical snap through buckling in the dome. The global behaviour of the dome appeared to be very sensitive to both the type and configuration of the restraints applied along the flexural members. The dome was also found to be remarkably sensitive to non-symmetric loads.

References listed at the end of the paper:
M. Zeinoddini (Dept. of Civil Engineering, University of Technology, Tehran, Iran), “In-situ quasi-static and dynamic behavioural response of steel tubular frames subjected to lateral impact loads”, Latin American Journal of Solids and Structures, Vol. 9, No. 3, June 2012

ABSTRACT: Steel tubular members are widely used as primary and secondary structural framing members in offshore oil and gas platforms. A platform is inherently liable to collisions from ships which can create severe structural damages in the rig. The effect of this damage has been studied by a number of researchers through investigating the impact behaviour isolated tubular members. This is while, the in-situ response of a member located in a structural frame, to lateral impact loads, is not necessarily the same as the response of an individual isolated impacted member. In this paper the behaviour of a chord member forming part of a tubular frame, subjected to impact loads, has been investigated. The tubular frame was tested experimentally by other researchers and reported in the literature. The non-linear numerical models of the frame presented by the authors have been validated against the experimental results. These validated models have been examined under both quasi-static and dynamic impact loads with operational pre-loading applied. It has been found that, in a pre-loaded frame, quasi-static impact loading results in the failure of the impacted member. Interestingly, dynamic modelling of the impact results in the dynamic instability of an adjacent bracing member. It has been noticed that, under a dynamic impact, the impacted in-situ member (located in the frame) behaves rather similarly to a pin ended isolated member. With a quasi-static impact, the impacted in-situ member follows fairly closely the response obtained for a fixed ended isolated member.

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ABSTRACT: The application of the finite element method to thin-walled structures often requires non-linear analysis. Whereas in linear finite element analyses errors are easily made, this is even more so in the non-linear analyses. This paper focuses on possible sources of error in linear and non-linear finite element solutions, and gives suggestions how to check and prevent these errors.


ABSTRACT: Thin-walled, cold-formed steel members exhibit a complicated post-buckling regime that is difficult to predict. Today, advanced computational modeling supplements experimental investigation. Accuracy of computational models relies significantly on the characterization of selected inputs. No consensus exists on distributions or magnitudes to be used for modeling geometric imperfections and for modeling residual stresses of cold-formed steel members. In order to provide additional information existing data is collected and analyzed and new experiments performed. Simple rules of thumb and probabilistic concepts are advanced for characterization of both quantities. The importance of the modeling assumptions are shown in the examples. The ideas are summarized in a preliminary set of guidelines for computational modeling of imperfections and residual stresses.

References listed at the end of the paper:
A. T. Sarawit (1), Y. Kim (1), M. C. M. Bakker (2) and T. Peköz (1)
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ABSTRACT: Traditionally numerous physical tests have been required to develop and verify newly proposed design procedures. The availability of powerful computers and software makes the finite element method an essential tool in such research. Analysis types, material models, elements and initial conditions that are taken into account in the finite element analysis of thin-walled structures are discussed. A list of programs developed in recent studies and example problems of the finite element method application to thin-walled structures are given.

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“Buckling Mode Classification of Members With Open Thin-Walled Cross-Sections”, CIMS ‘04 Fourth International Conference on Coupled Instabilities in Metal Structures Rome, Italy, 27-29 September, 2004. Also see: Johns Hopkins Research Report by Sandor Adany, 2004 (99 Pages http://www.ce.jhu.edu/bschafer/cFSM/sandor2004report.pdf )
ABSTRACT: This paper proposes a new approach for buckling mode definitions of open cross-section thin-walled members, which, unlike the existing phenomenological definitions, are based on simple mechanical assumptions which can easily be applied in the context of any numerical method. The application of the proposed definitions to the Finite Strip Method is briefly demonstrated. Numerical examples are provided to justify the applicability and efficiency of the proposed classification approach. References listed at the end of the paper:
(same as in the next paper)

B.W. Schafer (1) and S. Ádány (2)
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“Understanding and Classifying Local, Distortional and Global Buckling in Open Thin-Walled Members”, Annual Conference: Structural Stability Research Council, Montreal, Canada, 2005
ABSTRACT: Cross-section instability greatly complicates the behavior of thin-walled members. Current computational stability techniques do little to add clarity. The terms “global,” “distortional,” and “local buckling” permeate the literature, but there are no satisfactory definitions for the three characteristic modes. Despite this, design standards require the calculation of buckling stresses, as each characteristic mode has a differing degree of post-buckling capacity, and may trigger a different collapse response. Further, interaction
between all modes is possible, but poorly understood. This paper proposes a new approach for buckling mode definitions of open cross-section thin-walled members, which, unlike the existing heuristic definitions, are based on simple mechanical assumptions which can easily be applied in the context of any numerical method. The application of the proposed definitions to the Finite Strip Method is briefly demonstrated. The technique may be used either to classify results after performing an analysis (including the extent of interaction) or to constrain a model to a particular characteristic mode or modes before performing the analysis. Numerical examples are provided to justify the applicability and efficiency of the proposed classification

References listed at the end of the paper:
[3] Design of Cold-Formed Steel Structural Members using the Direct Strength Method, Appendix 1 of the NAS, 2004. (available also at http://www.ce.jhu.edu/bschafer/direct_strength)
[6] CUFSM v2.6, Elastic Buckling Analysis of Thin-Walled Members by Finite Strip Analysis, http://www.ce.jhu.edu/bschafer/cufsm

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ABSTRACT: This paper provides the first detailed presentation of the derivation for a newly proposed method which can be used for the decomposition of the stability buckling modes of a single-branched, open cross-section, thin-walled member into pure buckling modes. Thin-walled members are generally thought to have three pure buckling modes (or types): global, distortional, and local. However, in an analysis the member may have hundreds or even thousands of buckling modes, as general purpose models employing shell or plate elements in a finite element or finite strip model require large numbers of degrees of freedom, and result in large numbers of buckling modes. Decomposition of these numerous buckling modes into the three buckling types is typically done by visual inspection of the mode shapes, an arbitrary and inefficient process at best. Classification into the buckling types is important, not only for better understanding the behavior of thin-walled members, but also for design, as the different buckling types have different post-buckling and collapse responses. The recently developed generalized beam theory provides an alternative method from general purpose finite element and finite strip analyses that includes a means to focus on buckling modes which are consistent with the commonly understood buckling types. In this paper, the fundamental mechanical
assumptions of the generalized beam theory are identified and then used to constrain a general purpose finite strip analysis to specific buckling types, in this case global and distortional buckling. The constrained finite strip model provides a means to perform both modal identification relevant to the buckling types, and model reduction as the number of degrees of freedom required in the problem can be reduced extensively. Application and examples of the derivation presented here are provided in a companion paper.

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ABSTRACT: This paper derives a new method for fully decomposing the elastic stability solution, of a thin-walled single-branched open cross-section member, into mechanically consistent buckling classes associated with global, local, distortional, and shear and transverse extension buckling modes. The method requires a set of formal mechanical definitions for each of the buckling classes. For global and distortional buckling the definitions employed successfully by generalized beam theory are utilized herein, while for local and other (shear and transverse extension) buckling, new definitions are provided. The mechanical definitions for a given buckling class represent a series of constraint conditions on the general deformations that the thin-walled cross-section may undergo. These constraint conditions are derived as explicit constraint matrices within the context of the finite strip method, and provide the desired decomposition of the buckling deformations of the member. The decomposition is full in the sense that the union of the deformation spaces of the decomposed buckling classes is the same as the general deformation space in the original finite strip method. The resulting method is termed the constrained finite strip method (cFSM). The two primary applications for cFSM are modal decomposition and modal identification. Modal decomposition reduces the general finite strip solution to a desired set of buckling classes and performs a useful model reduction that allows the results to focus on a particular buckling class, e.g., distortional buckling. Modal identification provides a means to quantify the extent to which a given buckling class is contributing to a general buckling deformation. Application of cFSM, including graphical representation of the buckling classes, and the advantages of modal decomposition and modal identification, are provided in a series of numerical examples.

ABSTRACT: The aim of this report is to give a review of some recent progresses in the field of cold-formed steel members. Particular emphases are given to progresses in the field of distortional buckling and in recent development of new types of joints.

F. Kolcu, T. Ekmekyapar and M. Özakça (Department of Civil Engineering, University of Gaziantep, Gaziantep, Turkey), “Linear buckling optimization and post-buckling behavior of optimized cold formed steel members”, Scientific Research and Essays Vol. 5(14), pp. 1916-1924, 18 July, 2010  
ABSTRACT: Today's high-strength materials allow for significant increases in working and limit stresses. To
fully exploit material improvements as weight savings on structures, it is desirable to enhance the performance of structural components. The work presented in this paper proposes that the buckling behavior of cold form steel columns may be effectively improved without increased material volume. In order to achieve this goal, optimization algorithm which integrates finite strip analysis, geometric modeling, semi analytical sensitivity analysis and sequential quadratic mathematical programming methods can be used to find an optimum cross section of cold-formed steel columns under axial compression. The objective is the maximization of the critical buckling load with constraints on the volume of material used. Several examples are included to illustrate advantage of the optimization. The post buckling performance of optimized cold form steel columns was also investigated using nonlinear variable thickness finite strip analysis. Non-linear finite strip analysis helped to understand the behaviour of these cold form steel columns and select the most promising designs. The optimum forms found in this paper can be used to develop improved designs for cold formed steel columns.

References listed at the end of the paper:

structure increases. Thus this study presents coupled computational and experimental analyses, aimed at developing relationships between modelling fidelity and the size of the modelled structure, when the global static load to cause initial buckling is the required analysis output. Small, medium and large specimens representing welded lap-joined fuselage panel structure are examined. Two element types, shell and solid-shell, are employed to model each specimen, highlighting the impact of idealisation on the prediction of welded stiffened panel initial skin buckling.


ABSTRACT: This work presents a new metamodel for reinforced panels under compressive loads, typically used in light-weight aircraft structures. The metamodel represents a replicable cell structure of integrally machined panels. The presented formulation for conception is based on the synthesis of four stability criteria: section crippling, web buckling, flange buckling and column collapse. The aluminum alloy, a typical choice in modern aircraft industry, is selected and the structure is expected to work in the linear elastic domain. In order to evaluate the accuracy and to validate the analytical tool, the procedure is applied in the pre-sizing of the fuselage basic structural components of a 9-passenger executive aircraft. The pull-up maneuver, one of the critical load conditions in most of aircrafts, causes the maximum compressive stresses in lower fuselage panels. Finite element models are presented to the resulting fuselage configuration. The optimal configuration achieved through the application of the analytical tool yields to an innovative structure from those usually adopted in the aeronautical industry. This structural configuration is presented and discussed. The developed metamodel proved to be effective, presenting satisfactory results with adequate accuracy for the initial stages of light-weight aircraft structure.


ABSTRACT: Recent developments in the practical utilisation of cold-formed sections in building construction have taken place on three related fronts. There have been significant developments in the technology which result in more complex shapes with a higher yield stress so that cold-formed sections represent a particularly high-tech form of constructional steelwork. Developments in technology would be of little consequence unless there were parallel developments in practical applications and this is illustrated by the continual increase in the market share of cold-formed sections. This, in turn, makes demands on design procedures and requires parallel development in calculation models and design codes. In particular, sections have tended to become more highly stiffened and this necessitates a more sophisticated treatment of local buckling, distortional buckling and the interactions between them. The latest trend is to move from simplified design models to design procedures based on “whole section” analysis. In this paper, recent developments in technology and application are outlined and this is followed by more detailed consideration of the related design procedures.

ABSTRACT: A modular structure is one which is formed from a repeated module, most commonly a regular truss. These are often reduced to equivalent uniform continua so that standard beam theory can be applied. This paper examines the basis of standard beam theory, demonstrating it to be a particular case of a more general theory. It is shown that more accurate results can be obtained by a proper application of the theory to both discrete modular systems and to normal continuous beams.

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(2) Civil Engineering Department, University of Sakarya, Sakarya, Turkey
ABSTRACT: The process of prediction of distortional buckling stress of cold-formed steel members is often cumbersome and it is also difficult to perform parametric studies in this field to investigate the effect of geometric parameters on Elastic Distortional Buckling Stress (EDBS). To overcome this difficulty a neural network based model and formulation which was presented in a companion paper by the author [Pala M. A new formulation for distortional buckling stress in cold formed steel members. Journal of Constructional Steel Research 2006;62:716–22] is proposed as an alternative approach to investigate the effect of geometric parameters on distortional buckling stress. The model considers the effect of web height, flange width, angle of lip, lip length and flange thickness. The results of the Neural Network model are quite satisfactory and are consistent with the literature.

ABSTRACT: The main purpose of the research is to develop formulations for estimating the Elastic distortional buckling stress (EDBS) of cold-formed steel member under compressive loading using Genetic programming (GP) which has not been applied so far. The required data used for the training and testing is collected from the literature. Two GP-based formulations are proposed to predict the elastic distortional buckling of cold formed steel C sections. The results of proposed GP formulations are compared with experimental and analytical results of different researchers and methods and found to be accurate. The results obtained from the formulas have shown that GP is a promising technique for predicting EDBS of cold-formed steel C sections.

B.W. Schafer (Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, 21218, United States), “Review: The Direct Strength Method of cold-formed steel member design”, Journal of Constructional Steel Research, Vol. 64, Nos. 7-8, July-August 2008, pp. 766-778, Special Issue: International Colloquium on Stability and Ductility of Steel Structures 2006, doi:10.1016/j.jcsr.2008.01.022
ABSTRACT: The objective of this paper is to provide a review of the development and current progress in the Direct Strength Method for cold-formed steel member design. A brief comparison of the Direct Strength Method with the Effective Width Method is provided. The advantage of methods that integrate computational stability analysis into the design process, such as the Direct Strength Method, is highlighted. The development of the Direct Strength Method for beams and columns, including the reliability of the method is provided.
Current and ongoing research to extend the Direct Strength Method is reviewed and complete references provided. The Direct Strength Method was formally adopted in North American cold-formed steel design specifications in 2004 as an alternative to the traditional Effective Width Method. The appendices of this paper provide the Direct Strength Method equations for the design of columns and beams as developed by the author and adopted in the North American Specification.

Z. Li and B.W. Schafer, “Application of the finite strip method in cold-formed steel member design”, Journal of Constructional Steel Research, Vol. 66, Nos. 8-9, August-September 2010, pp 971-980
ABSTRACT: The objective of this paper is to explore solutions and provide design recommendations for two practical issues that develop when integrating computational member analysis with the conventional finite strip method (FSM) into cold-formed steel member design utilizing the direct strength method (DSM). First, FSM often fails to uniquely identify the relevant local and distortional member buckling modes. These elastic buckling loads (or moments) are required inputs for predicting the design strength. Second, the recently developed constrained finite strip method (cFSM) which can uniquely identify local and distortional buckling in all cases suffers from its own limitations, specifically (a) cFSM does not yield the same exact solution as FSM even when unique minima exists in the FSM solution, and (b) cFSM cannot include rounded corners in the model of the cross-section. Two methods are examined herein for overcoming these limitations, both of which utilize cFSM in an augmented form. The proposed methods are explored for lipped channel cross-sections both for elastic buckling and for ultimate strength prediction via DSM. Particular attention is paid to methods for handling cross-sections with rounded corners (in both elastic buckling and strength) since cFSM cannot include rounded corners and still meaningfully identify the modes. Finally, based on the study of lipped channel members a recommendation is provided for a methodology that enables automated analysis of cold-formed steel member elastic buckling modes for use in DSM.

ABSTRACT: This paper presents an isoparametric finite element for reinforced shells and plates. The formulation is based on general beam theory and takes into account both transverse shear deformation and torsional warping. The element exhibits complete two-line compatibility. Numerical examples are presented in order to demonstrate the validity of the formulation and the possibilities of application.

ABSTRACT: Consistent and simple lumped mass matrices are formulated for the dynamic analysis of beams with arbitrary cross section. The development is based on a general beam theory which includes the effect of flexural-torsion coupling, the constrained torsion warping and the shear center location. Numerical tests are presented to demonstrate the importance of torsion warping constraints and the acceptable accuracy of the lumped mass matrix formulation.

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ABSTRACT: The paper presents the development of a new plate/shell stiffener element and the subsequent application in determine frequencies, mode shapes and buckling loads of different stiffened panels. In structural modelling, the plate and the stiffener are treated as separate finite elements where the displacement compatibility transformation takes into account the torsion - flexural coupling in the stiffener and the eccentricity of internal (contact) forces between the beam - plate/shell parts. The model becomes considerably more flexible due to this coupling technique. The development of the stiffener is based on a general beam theory, which includes the constraint torsional warping effect and the second order terms of finite rotations. Numerical tests are presented to demonstrate the importance of torsion warping constraints. As part of the validation of the results, complete shell finite element analyses were made for stiffened plates.


ABSTRACT: This paper presents a displacement based finite element model for predicting the constraint torsion effect of stiffeners. In structural modelling, the plate/shell and the stiffeners are treated as separate elements where the displacement compatibility transformation between these two types of elements takes into account the constraint torsional warping effect in the stiffeners. The development is based on a general beam theory which includes flexural-torsion coupling, constrained torsion warping, and shear-centre location. The virtual work principle includes the second order terms of finite beam rotations. For finite element analysis, cubic Hermitian polynomials are used as shape functions of the straight space frame element with two nodes. Elastic stiffness and geometric stiffness matrices for an arbitrary cross-section are evaluated in a closed form, and load correction stiffness for eccentric stiffener loads are considered. To demonstrate the importance of torsion warping constraints and to illustrate the accuracy of this formulation, finite element solutions are presented and compared with available solutions.

References listed at the end of the paper:

ABSTRACT: The paper presents the development of a new plate/shell stiffener element and the subsequent application in determine buckling loads and modes of different stiffened panels. The formulation of the stiffener is based on a general beam theory, which includes the constraint torsional warping effect and the second order terms of finite rotations. As part of the validation of the method, complete shell finite element analyses were made for stiffened plates.

References listed at the end of the paper:


ABSTRACT: The paper presents the application of the new stiffener element with seven degrees of freedom per node and the subsequent application in determining frequencies, mode shapes and buckling loads of different stiffened panels. In structural modelling, the stiffener and the plate/shell are treated as separate elements where the displacement compatibility transformation between the seven and six degrees of freedom nodes of these two types of elements takes into account the torsion–flexural coupling in the stiffener and the eccentricity of internal (contact) forces between the beam–plate/shell parts. The model becomes considerably more flexible due to this coupling technique. The development of the stiffener is based on a general beam theory, which includes the constraint torsional warping effect and the second-order terms of finite rotations. Numerical tests are presented to demonstrate the importance of torsion warping. As part of the validation of the results, complete shell and the usual six degrees of freedom per node shell–beam finite element analyses were made for stiffened panels.


ABSTRACT: In recent years, the post-buckling behavior of thin walled cold-formed steel members under compressive or bending loads has been the object of several research studies. For the most relevant situations in practice the problem is assumed to be conservative, so that the system’s behavior can be described from a total potential energy (TPE) function. In order to apply the Rayleigh-Ritz method, a discretization procedure is needed and the TPE becomes a function of a load parameter P and of a set of nC generalized coordinates ia. The post-buckling analysis concerns the search of alternative equilibrium paths in the neighborhood of the critical states – the one associated with the lowest critical load parameter having physical interest. The paper presents a set of numerical techniques required to study the stability behavior of thin-walled members in the context of an extended formulation of GBT (Generalized Beam Theory). An application to the study of the equilibrium and buckling behavior of cold-formed members is also presented.

References listed at the end of the paper:
linear shallow shell equations are discretized by the Galerkin method. The shell is considered to be initially at rest, in a position corresponding to a pre-buckling configuration. Then, a harmonic excitation is applied and conditions to escape from this configuration are sought. By defining steady state and transient stability boundaries, frequency regimes of instability may be identified such that they may be avoided in design. Initially a steady state analysis is performed; resonance response curves in the forcing plane are presented and the main instabilities are identified. Finally, the global transient response of the system is investigated in order to quantify the degree of safety of the shell in the presence of small perturbations. Since the initial conditions, or even the shell parameters, may vary widely, and indeed are often unknown, attention is given to all possible transient motions. As parameters are varied, transient basins of attraction can undergo quantitative and qualitative changes; hence a stability analysis which only considers the steady-state and neglects this global transient behavior, may be seriously non-conservative.

References listed at the end of the paper:


ABSTRACT: The aim of this paper is to investigate the influence of internal resonances on the nonlinear dynamics and instabilities of a parametrically excited cylindrical shell. The case of a 1:1:1:1 internal resonance, a problem not treated in the technical literature, is investigated. For this, a modal solution that takes into account the modal interaction between two modes with the same frequency and their companion modes (modes with rotational symmetry) and satisfies the boundary and continuity conditions of the shell is derived. The shell is modeled using the Donnell nonlinear shallow shell theory and the discretized equations of motion are obtained by applying the Galerkin method. Solving numerically the governing equations of motion, a detailed parametric analysis is conducted to clarify the influence of the internal resonances on the bifurcations, stability boundaries and nonlinear vibration modes of the structure.

References listed at the end of the paper:


ABSTRACT: The buckling phenomenon of prismatic column is experimentally investigated in this work, being major structural design concern. A number of tests were performed on aluminum made prismatic columns with slenderness index \( \lambda_{ef} \) remaining within range of 15 to 460 submitted to programs of multiple in time compressive loads – force and displacement controlled. The experimental evidence obtained here for stocky and slender columns confirm already well known information that column failure results from structural material plastic flow deformation or lateral buckling, respectively. A new, interesting observation has been made for intermediate slenderness columns that “drop” of buckling load takes place (reaching in some cases over 20% of early critical force value) after the very initiation of elasto-plastic buckling process. The observation is in contradiction to adopted in elasto-plastic buckling models assumption of constant (Engesser model) or growing (Shanley model) buckling load during buckling process. The obtained experimental evidence indicates that mysterious scatter in buckling loads for apparently identical columns with intermediate slenderness index can be attributed to minute residual stresses, which easily and in hardly controlled manner can be introduced during industrial production processes.

References listed at the end of the paper:


ABSTRACT: The buckling and post-buckling behaviour of prismatic aluminium columns from stocky to very slender shapes is investigated. The unconventional, in terms of buckling tests, displacement control of compressive load and a series of loadings provided an enhanced insight into the buckling process. A phenomenon of buckling load drop has been detected in columns of intermediate slenderness, reaching over 20% of the load early critical value. This newly observed occurrence resembles finite disturbance instability, which until recently was commonly believed to only appear in cases of thin walled cylindrical shells, but not columns. The observation is in contradiction to predicted results from the elasto-plastic buckling models of Engesser or Shanley, with constant or growing values of load during the post-buckling process. Further tests on columns of intermediate slenderness, with strain gauges glued at node and anti-node locations of the buckled profiles, revealed that even minute buckling results in fields of highly non-symmetric residual microplastic strain. The results of the present study indicate that running column buckling tests under displacement control is worthy of being adopted as common practice. The envelope of column post-buckling states can be conveniently determined. This information will in turn allow for the quick and reliable estimation of the safety of a column, which has undergone accidental or deliberate damage in the form of limited buckling when under operational load.

References listed at the end of the paper:
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“Simplified analytical model and numerical simulations of finite-disturbance buckling of columns”,

ABSTRACT: Phenomenon of finite-disturbance buckling (FDB) is commonly attributed to thin elastic cylindrical and spherical shells and it has been rarely associated with columns. Ziolkowski and Imielowski’s, Experimental Mechanics 51(8), (2011) 1335–1345, recent experimental study, revealing appearance of FDB in aluminum columns with slenderness remaining within specific range only, raises questions about its physical sources and mechanism. The main objective of the presented work is to provide a theoretical explanation and quantitative evaluation on the phenomenon of finite-disturbance buckling of columns undergoing elasto-plastic deformation and expressing itself in the form of critical load drop. Elucidation of the issue may have some implications to the hitherto design procedures. The paper presents a coherent analytical model of the phenomenon supported by comprehensive finite element results, compared with experimental data.

References listed at the end of the paper:


ABSTRACT: The first scientific direction, “Buckling analysis of thin-walled members”, represents the
dominant part of the candidate’s research activity, it started with the scientific work developed during the
candidate’s PhD programme entitled “Stability aspects for metallic structures”, supervisor: prof. Cornel BIA,
and since then it has significantly evolved by new theoretical formulations in the field of thin-walled structures.
In this area, the candidate’s work is related to the Generalised Beam Theory (GBT), a specialised theory for
the analysis of thin-walled members, which is thoroughly presented in this thesis. The candidate extended GBT for
special cases of thin-walled members and analysis types, and his personal contributions of theoretical nature,
published in ISI and conference papers, can be summarised as follows:

- GBT formulation to analyse the behaviour of thin-walled members with variable cross-section. This
  formulation added new equations to GBT in order to handle tapered thin-walled members with small
  tapering slopes.
- GBT formulation to analyse the buckling behaviour of isotropic conical shells. GBT was already developed
  for cylindrical shells and tubes and through the candidate’s work, that formulation was extended for
  conical shells, yielding very promising results even for large values of the tapering slope.
- Buckling mode decomposition from Finite Element Analysis (FEA) of thin-walled members. The candidate
  proposed a method capable to quantify the modal participation of the pure deformation modes (of
  Global, Distortional and Local nature) in a general buckling mode. Even if similar methods were very
  recently reported by other researches, the method developed by the candidate is, at present time, the
  fastest and the most stable, due to a special algorithm based on the orthogonality features of the pure
  deformation modes.

The second scientific direction entitled “Vibration analysis of civil engineering structures” contains theoretical
and also experimental work. The theoretical work started under the topic “Vibration mode decomposition from
FEA of thin-walled members” and is mainly concentrated on the applicability of the modal decomposition
method (brieﬂy described above, at point c.) to the modal shapes derived from FEA, associated with the natural
frequencies of thin-walled members. The topics of the experimental work are (i) Experimental modal analysis,
and (ii) Tension estimation of cables based on vibration analysis. The candidate was recently (2011) nominated
as coordinator of the laboratory “Actions in Buildings and Structures”, Department of Structural Mechanics,
Faculty of Civil Engineering, Technical University of Cluj-Napoca. The laboratory contains Bruel&Kjaer and
PCB Piezotronics equipment and dedicated software suited to perform experimental vibration analyses. At
present time, under the candidate supervision, successful experimental modal analyses were performed on real-
world structures (beam and suspension bridges, metallic structures, tall concrete buildings, hollow-core slabs
etc.) and also on small elements inside laboratory. The candidate conducted many vibrations measurements and
analyses in time/frequency domain for bridges and other civil engineering structures (acceleration, velocity,
displacement, level of vibrations) with the purpose of: optimisation of structure’s dynamic characteristics (mass,
stiffness, damping), risk assessment of having the resonance phenomenon, prediction of dynamic behaviour,
evaluating the damping for inclusion in FE models, correlation of FE models with real structures, damage
detection and assessment, long term building monitoring, experimental assessment of traffic or other human
activities induced vibrations.

The tension estimation of cables by means of vibration response is another recent scientiﬁc area in which the
candidate obtained very promising results. The vibration method uses the experimental modal analysis to
extract the natural frequencies of the cable and next, the tension force is determined by using appropriate
analytical closed-form or numerical algorithm-form relationship between natural frequencies and the cable
tension. The cable response is mainly affected by its ﬂexural stiffness, sag-extensibility and the rotational
stiffness of the end-supports. Until present time, the candidate considered hinged supports for his experiments,
and the “sag” effect was neglected, but all the inﬂuencing terms were analysed in numerical studies.

The main achievements and results are presented in detail in Chapter (b-i): Scientiﬁc, professional and
academic achievements.
In what concerns the future research and development plans of the candidate, related to the fields of research presented above, the following research topics will continue or will be developed:

**Analysis of thin-walled members:**
- buckling/vibration analysis of tapered thin-walled members with arbitrary cross-sectional variation
- buckling/vibration analysis of conical shells based on GBT
- improving the modal decomposition method
- buckling/vibration mode decomposition for tapered thin-walled members, cylindrical and conical shells
- buckling/vibration mode decomposition for thin-walled members with arbitrary holes
- the effect of imperfections in non-linear analysis of thin-walled members

**Experimental vibration analyses:**
- perform new experimental modal analyses on real complex structures such as civil and industrial constructions and also on small structures and scale models inside laboratory
- tension estimation of cables by means of vibration response taking into consideration the “sag” effect and the real rotational stiffness of the end-supports

A short description of each topic has been done in Chapter (b-ii): Scientific, professional and academic future development plans.

Mihai Nedelcu (Faculty of Civil Engineering, Technical University of Cluj-Napoca, Str. C. Daicoviciu nr. 15, 400020 Cluj-Napoca, Romania), “GBT formulation to analyse the behaviour of thin-walled members with variable cross-section”, Thin-Walled Structures, Vol. 48, No. 8, August 2010, pp. 629-638, doi:10.1016/j.tws.2010.03.001

ABSTRACT: The generalised beam theory (GBT) provides a general solution for the linear/non-linear analysis of prismatic thin-walled structures, using bar elements capable of describing the cross-section rigid-body motions and distortions. Nowadays GBT is fully developed for thin-walled members having a large variety of constant cross-sections. This paper provides the extension of GBT for the special case of thin-walled members with variable open cross-section and the limits of its applicability. This offers a new analysis method for structures as box shaped bridges, beams, pylons of variable cross-section, conical shell towers, hyperbolic towers, etc. Regarding the 2nd order analysis, the effect of pre-buckling shear stresses is neglected.


ABSTRACT: The paper presents the formulation and illustrates the application of a second order Generalized Beam Theory (GBT) developed to analyze the stability behavior of thin-walled members displaying arbitrary orthotropy. After reviewing and physically interpreting the 2nd order GBT equations, a brief description of the main steps involved in performing a member GBT linear stability analysis is presented. Next, the paper addresses the issue of whether the critical stress value obtained from a member linear stability analysis corresponds to a “true bifurcation” or simply provides an “asymptotic limit load” and, in particular, a systematic procedure to detect true bifurcations is proposed. Finally, the application and capabilities of the 2nd order GBT are illustrated, by means of an investigation of the local and global buckling behavior of lipped channel columns and beams exhibiting asymmetric orthotropy.

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ABSTRACT: A geometrically nonlinear Generalized Beam Theory (GBT) is formulated and its application leads to a system of equilibrium equations which are valid in the large deformation range but still retain and take advantage of the unique GBT mode decomposition feature. The proposed GBT formulation, for the elastic post-buckling analysis of isotropic thin-walled members, is able to handle various types of loading and arbitrary initial geometrical imperfections and, in particular, it can be used to perform "exact" or "approximate" (i.e., including only a few deformation modes) analyses. Concerning the solution of the system of GBT nonlinear equilibrium equations, the finite element method (FEM) constitutes the most efficient and versatile numerical technique and, thus, a beam FE formulation is reported in some detail and then employed to obtain numerical results, which validate and illustrate the application and capabilities of the theory.
This paper provides an overview of the Generalised Beam Theory (GBT) fundamentals and
its Applications, edited by M. Pandey, Wei-Chau Xie and Lei Xu, Springer, 2006, pp 187-204
ABSTRACT: This paper provides an overview of the Generalised Beam Theory (GBT) fundamentals and
reports on the novel formulations and applications recently developed at the TU Lisbon: the use of conventional
GBT to derive analytical distortional buckling formulae and extensions to cover (i) the buckling behaviour of
members with (i) branched, closed and closed/branched cross-sections and (ii) made of orthotropic and elastic-
plastic materials, and (ii) the vibration and post-buckling behaviours of elastic isotropic/orthotropic members. In

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order to illustrate the usefulness and potential of the new GBT formulations, a few numerical results are presented and briefly discussed. Finally, some (near) future developments are briefly mentioned.

References listed at the end of the paper:
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“Gbt-Based Analysis and Design of Thin-Walled Metal and Frp Members: Recent Developments”, Proc. Int. Workshop Recent Advances and Future Trends in Thin-Walled Structures Technology (Loughborough, 25/6), 2004

ABSTRACT: This paper provides an overview of the Generalised Beam Theory (GBT) applications and formulations recently developed at the TU Lisbon. The conventional GBT is (i) applied to derive analytical distortional buckling formulae and (ii) extended to cover (ii1) orthotropic and elastic-plastic materials, (ii2) closed and branched cross-sections and (ii3) vibration and post-buckling analyses. In order to give an idea about the potential of the new GBT formulations, a few numerical results are presented and briefly discussed.

References listed at the end of the paper:

SUMMARY: Most cold-formed steel members display slender thin-walled open cross-sections, a feature making them highly susceptible to local buckling phenomena, characterised by the sole occurrence of cross-section (in-plane) deformations and classified into two major categories: (i) local-plate buckling and (ii) distortional buckling. The former concerns flexural displacements alone and the latter involves flexural and membrane displacements, including fold-line motions leading to cross-section distortions. Figures 99.1(a) and 99.1(b) show the deformed configurations of rack-section column segments experiencing local-plate and distortional buckling, respectively. Moreover, whenever cold-formed steel members display cross-section geometries and length values leading to similar local and/or global (flexural-torsional or flexural) critical buckling stresses, their structural behaviour is affected by mode interaction effects, namely coupling between (i)
local-plate and distortional or (ii) local and global buckling modes (the cross-section geometry determines the nature of the local mode). In the presence of relevant mode coupling and/or spread of plasticity effects, the "exact" structural behaviour of thin-walled steel members can only be determined by employing sophisticated numerical methods, such as the FEM, which require a computer power only routinely available in (well equipped) research institutions. Although this situation is rapidly changing, as attested by the number of commercial computer codes which are now readily available to perform complex geometrically and physically non linear structural analyses, it was only recently that it became feasible to use FEM analyses to investigate local buckling effects in slender thin-walled members. They will be very useful to validate and/or calibrate easy-to-use design methodologies, thus paving the way to a progressive replacement of several experimental tests by much more convenient computer simulations. Moreover, the above design methodologies are only rational (physically based) and efficient if the member local-plate and/or distortional post-buckling behaviour are accurately known. This paper presents, discusses and illustrates the application and efficiency of an unified approach to the use of FEM analyses to investigate the local buckling, post-buckling and mode interaction behaviour of cold-formed steel thin-walled members, both in the elastic and elastic-plastic ranges. Initially, a number of relevant modelling and numerical implementation issues are briefly addressed, namely related to (i) the finite element and mesh discretisation choice, (ii) the incorporation of the initial geometrical imperfections, (iii) the modelling of the local boundary conditions or (iv) the numerical solution techniques. Next, in order to assess how the FEM approach is able to handle the aforementioned problems, several aspects dealing with the non linear structural behaviour of rack section members are investigated. At this point, one should mention that all the numerical results displayed are obtained by means of analyses performed using the commercial code ABAQUS. Moreover, in order to validate such FEM results, some of them are compared with values available in the literature, most of which have been obtained by means of finite strip analyses. The different types of (non linear) analyses dealt with are:

(i) Elastic buckling (linear stability) analyses, involving the solution of standard eigenvalue problems and yielding critical stress values and buckling mode configurations. Attention is paid to the influence of the applied stress distribution and local support conditions.

(ii) Elastic and elastic-plastic local post-buckling analyses, concerning members which bifurcate in either the local-plate or distortional buckling modes. Such analyses account for the influence of initial geometrical imperfection, can only be performed by resorting to incremental-iterative numerical techniques and lead to the determination of non linear (post-buckling) equilibrium paths, which relate the evolutions of the applied stress value and the displacement component better suited to describe the member deformed configuration.

(iii) Elastic and elastic-plastic (local) mode interaction analyses, concerning the behaviour of members with similar local-plate and distortional buckling stress values. Such analyses also yield non linear equilibrium paths and particular attention is paid to identifying the configuration of the (elastic) coupled buckling mode and the nature of the elastic-plastic deformed configuration.

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ABSTRACT: A non-linear elastic Generalised Beam Theory (GBT) is formulated and used to investigate the
buckling behaviour of aluminium and stainless steel thin-walled columns. The modifications that must be incorporated in the conventional GBT, in order to handle the material non-linearity, are addressed and particular attention is paid to the need to define the stability problem in terms of instantaneous elastic moduli. After validating the proposed GBT, by means of its application to compressed rectangular plates, the unique features and capabilities of the theory are illustrated through the presentation and discussion of results concerning C-section and RHS columns. Stress–strain laws of the Ramberg–Osgood type are used to model the uniaxial behaviour and both J2-flow and J2-deformation plasticity theories are implemented.

Pedro Borges Dinis and Dinar Camotim (Civil Engineering Department, ICIST/IST, Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal), “Local-plate and distortional post-buckling behavior of cold-formed steel columns: Elastic and elastic-plastic FEM analysis”, (publisher and date not given in the pdf file; Proceedings of SSRC Annual Stability Conference, 2004?)

ABSTRACT: Following a brief discussion of a few relevant aspects dealing with the finite element modeling of the geometrically and materially non-linear behavior of thin-walled members, the paper presents an investigation on the elastic and elastic-plastic local-plate and distortional post-buckling behavior of rack-section (mostly) and lipped channel cold-formed steel columns. The FEM results displayed and discussed, obtained using the code ABAQUS and discretizing the columns with 4-node shell elements, consist of (i) post-buckling equilibrium paths, (ii) diagrams showing the evolution, along those paths, of the normal stresses acting on the most deformed cross-section and (iii) the column collapse mechanisms. All the columns analyzed contain critical-mode geometrical imperfections with small amplitudes and the issues addressed include the influence of the column (i) yield-to-critical stress ratio and (ii) support conditions (end section warping and rotation restraints). For validation purposes, some of the FEM (elastic) results presented are compared with values reported by other authors and obtained by means of finite strip analyses.

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ABSTRACT: A general variational formulation to analyze the elastic lateral–torsional buckling (LTB) behavior of singly symmetric thin-walled tapered beams is presented, numerically implemented, validated and illustrated. It (1) begins with a precise geometrical definition of a tapered beam; (2) extends the kinematical assumptions traditionally adopted to study the LTB of prismatic beams; (3) includes a careful derivation of the beam total potential energy; and (4) employs Trefftz’s criterion to ensure the beam adjacent equilibrium. In order to validate and illustrate the application and capabilities of the proposed formulation, several numerical results are presented, discussed and, when possible, also compared with values reported by other authors. These results (1) are obtained by means of the Rayleigh–Ritz method, using trigonometric functions to approximate the beam critical buckling mode, and (2) concern the critical moments of doubly and singly symmetric web-tapered I-section simply supported beams and cantilevers acted by point loads. In particular, one shows that modeling a tapered beam as an assembly of prismatic beam segments is conceptually inconsistent and may lead to rather inaccurate (safe or unsafe) results. Finally, it is worth mentioning that the paper includes a state-of-the-art review concerning one-dimensional analytical formulations for the LTB behavior of tapered beams.

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ABSTRACT: (none given)
Pedro B. Dinis and Dinar Camotim, “On the Use of Shell Finite Element Analysis to Assess the Local Buckling and Post-Buckling Behaviour of Cold-Formed Steel Thin-Walled Members”, III European Conference on Computational Mechanics, p. 689, 2006, DOI: 10.1007/1-4020-5370-3_689

ABSTRACT: This paper deals with the use of shell finite element analyses to assess the (i) elastic bifurcation and (ii) elastic and elastic-plastic local-plate and distortional post-buckling behaviours of cold-formed steel thin-walled members (mostly columns, i.e., uniformly compressed members) all the geometrically and physically non-linear analyses are performed using the code ABAQUS and adopting 4-node isoparametric shell elements to discretise the members. First, one addresses several relevant issues concerning (i) the member discretisation (shell element type and mesh refinement), (ii) the simulation of the member end support conditions (a key aspect in numerical structural analysis), (iii) the modelling of the applied loading and material behaviour, (iv) the incorporation of member initial geometrical imperfections and residual stresses, (v) the assessment of buckling mode interaction effects and (vi) the methods employed to solve either the eigenvalue problem or the system of non-linear algebraic equilibrium equations. Then, in order to illustrate the concepts and issues mentioned above and, at the same time, illustrate the power and versatility of the shell finite element analyses, one presents and thoroughly discusses a fairly large number of numerical results concerning the buckling and post-buckling behaviour of lipped channel (mostly), Zed-section and Rack-section cold-formed steel members some of the post-buckling analyses include interaction effects between local-plate and distortional buckling modes. These results consist of (i) buckling curves providing the variation of the critical stress with the member length (see Fig. 1(a)), (ii) elastic and elastic-plastic non-linear (post-buckling) equilibrium paths (see Figs. 1(b)-(c)), (iii) figures providing the evolution, along those equilibrium paths, of the elastic and elastic-plastic member deformed configurations, and (iv) figures showing the spread of plasticity along the members up to failure (see Fig. 1(d)) and conveying relevant information about the nature of their collapse mechanisms.


ABSTRACT: This paper presents the derivation, validates and illustrates the application of a Generalised Beam Theory (GBT) formulation developed to analyse the buckling behaviour of thin-walled members with arbitrarily ‘branched’ open cross-sections. Following a brief overview of the conventional GBT, one addresses in great detail the modifications that must be incorporated into its cross-section analysis procedure, in order to be able to handle the ‘branching’ points — they concern mostly issues related to (i) the choice of the appropriate ‘elementary warping functions’ and (ii) the determination of the ‘initial flexural shape functions’. The derived formulation is then employed to investigate the local-plate, distortional and global buckling behaviour of (i) simply supported and fixed asymmetric E-section columns and (ii) simply supported I-section beams with unequal stiffened flanges. For validation purposes, several GBT-based results are compared with ‘exact’ values, obtained by means of finite strip or shell finite element analyses.

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“Thin-walled member plastic bifurcation analysis using generalised beam theory”, Advances in Engineering
ABSTRACT: This paper presents the formulation and illustrates the application of a non-linear Generalised Beam Theory (GBT), which makes it possible to calculate bifurcation load factors of thin-walled members made of non-linear elastic–plastic materials and subjected to general loading conditions. This formulation is an extension of the non-linear GBT recently derived by the authors, which was valid for uniformly compressed members only. In order to illustrate the application of the proposed non-linear GBT, a beam finite element is formulated and some numerical results are presented and discussed. These results concern rectangular plates and thin-walled hat-section beams. The material instantaneous elastic moduli are determined on the basis of both the well known J2-flow and J2-deformation small strain plasticity theories.


ABSTRACT: This paper reports on the use of a recently developed Generalised Beam Theory (GBT) formulation, and corresponding finite element implementation, to analyse the local and global buckling behaviour of thin-walled members with arbitrary loading and support conditions — this formulation takes into account longitudinal normal stress gradients and the ensuing pre-buckling shear stresses. After presenting an overview of the main concepts and procedures involved in the performance of a GBT-based (beam finite element) member buckling analysis, one addresses in detail the incorporation of non-standard support conditions, such as (i) full or partial localised displacement or rotation restraints, (ii) rigid or elastic intermediate supports or (iii) end supports corresponding to angle connections. In order to illustrate the application and capabilities of the proposed GBT-based approach, one presents and discusses numerical results concerning cold-formed steel (i) lipped channel beams and (ii) lipped I-section beams and columns with various “non-standard” support conditions — while the beams are acted by uniformly distributed or mid-span point loads, applied at the shear centre axis, the columns are subjected to uniform compression. In particular, it is possible to assess the influence of the different support conditions on the beam and column buckling behaviour (critical buckling loads and mode shapes). For validation purposes, most GBT-based results are compared with values yielded by shell finite element analyses carried out in the code ANSYS.


ABSTRACT: This paper presents an investigation on the buckling behaviour of single-walled carbon nanotubes under various loading conditions (compression, bending and torsion) and unveils several aspects concerning the dependence of critical measures (axial strain, bending curvature and twisting angle) on the nanotube length. The buckling results are obtained by means of an atomistic-scale generalized beam theory (GBT) that incorporates local deformation of the nanotube cross-section by means of independent and orthogonal deformation modes. Moreover, some estimates are also obtained by means of non-linear shell finite element analyses using Abaqus code. After classifying the buckling modes of thin-walled tubes (global, local and distortional), the paper addresses the importance of the two-wave distortional mode (flattening or ovalization mode) in their structural
behaviour. Then, the well known expression to determine the critical strain of compressed nanotubes, which is based on Donnell theory for shallow shells, is shown to be inadequate for moderately long tubes due to warping displacements appearing in the distortional buckling modes. After that, an in-depth study on the buckling behaviour of nanotubes under compression, bending and torsion is presented. The variation of the critical kinematic measures (axial strain, bending curvature and twisting angle) with the tube length is thoroughly investigated. Concerning this dependence, some uncertainties that exist in the specific literature are meticulously explained, a few useful expressions to determine critical measures of nanotubes are proposed and the results are compared with available data collected from several published works (most of them, obtained from molecular dynamics simulations).


ABSTRACT: This paper presents some remarks on the use of shell models to analyse the stability behaviour of single-walled NTs under compression. It is shown that there are three different categories of critical buckling modes of NTs under compression: while the axi-symmetric mode is critical for very short NTs, the flexural buckling mode is critical for long tubes. While the former exhibits cross-section contour deformation but no warping deformation, the later is characterised by the opposite situation (warping deformation but no contour deformation). Additionally, a third category exists (distortional buckling): it takes place for NTs with moderate length, it is related to the transitional buckling behaviour between the shell (axi-symmetric mode) and the rod (flexural mode) and it is characterised by both cross-section contour deformation and warping deformation. Concerning the distortional buckling behaviour of moderately long NTs, it is also shown that the well known Donnell-type theory of shells leads to erroneous results.

References listed at the end of the paper:
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ABSTRACT: This paper presents the development and illustrates the application of semi-analytical solutions for plastic buckling (bifurcation) problems involving perfectly straight and uniformly compressed thin-walled metal members. These solutions are derived on the basis of a non-linear Generalised Beam Theory (GBT) formulation, recently proposed by two of the authors, that resorts to a linearised buckling analysis that adopts Hill’s hypo-elastic comparison solid method to obtain the plastic bifurcation loads and associated buckling mode shapes. Moreover, both J2 small-strain incremental and deformation plasticity theories are employed. Several numerical illustrative examples are presented and discussed throughout the paper and closed-form analytical formulae are also derived. The accuracy of the GBT-based semi-analytical plastic bifurcation predictions is assessed through the comparison with (i) available theoretical solutions and/or (ii) results yielded by a special shell finite element model developed by one of the authors.

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ABSTRACT: This paper presents the derivation, validation and illustration of a generalised beam theory (GBT) formulation intended to perform first-order and buckling analyses of arbitrary thin-walled members, namely members with cross-sections that combine closed cells with open branches. Following a brief overview of the so-called “conventional GBT formulation”, as well as of the available extensions for different specific cross-section types, the paper addresses in detail the modifications that must be incorporated into the GBT cross-section analysis procedure to handle the simultaneous presence of closed cells and open branches. The proposed formulation is then employed to analyse the first-order and buckling behaviours of thin-walled members (mostly beams) with complex cross-sections. For validation purposes, the GBT-based numerical results are compared with values yielded by shell finite element and finite strip analyses.

ABSTRACT: In this paper, the dynamic responses of the open cross section columns with intermediate stiffeners subjected to in-plane pulse loading of a rectangular shape were concerned. Columns made of isotropic material were assumed to be simply supported at both loaded ends. The problem of the interactive
buckling was solved by finite element method (FEM) – ANSYS 9. The critical dynamic load factors DLF has been determined using the most popular Budiansky–Hutchinson’s criterion and they have been verified with author’s versions of the phase portraits criterion.

References listed at the end of the paper:


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ABSTRACT: The structural components of an aircraft consist mainly of thin plates stiffened by arrangements of ribs and stringers. Thin walled structure is a structure whose thickness is small compared to its other dimensions but which is capable of resisting bending in addition to membrane forces. Which is basic part of an aircraft structure, Thin plates (or thin sections or thin walled structures) under relatively small compressive loads are prone to buckle and so must be stiffened to prevent this. The determination of buckling loads for thin plates in isolation is relatively straightforward but when stiffened by ribs and stringers, the problem becomes complex and frequently relies on an empirical solution. The buckling of the thin plates is a phenomenon which could lead to destabilizing and failure of the aircraft structure; in this paper it is considered C cross section with variable geometry and length. The critical buckling loads have been studied for several combinations of the geometry parameters of the beam with the help of ANSYS and drawn the result plots

References listed at the end of the paper:
5) Prof. Ing. Antonin Pistek. “Analytical Method for Limit Load Capacity Calculation of Thin Walled Aircraft Structures” 28th
ABSTRACT: This paper presents the formulation of a Generalised Beam Theory (GBT) developed to analyse the structural behaviour of composite thin-walled members made of laminated plates and displaying arbitrary orthotropy. The main concepts and procedures involved in the available isotropic first-order GBT are revisited and adapted/modified to account for the specific aspects related to the member orthotropy. In particular, the orthotropic GBT fundamental equilibrium equations and corresponding boundary conditions are derived and their terms are physically interpreted, i.e., associated with the member mechanical properties. Moreover, different laminated plate material behaviours are dealt with and their influence on the GBT equations is...
investigated. Finally, in order to clarify the concepts involved in the formulated GBT and illustrate its application and capabilities, a thin-walled orthotropic beam is analysed and the results obtained are thoroughly discussed.


ABSTRACT: This paper presents the derivation and illustrates the application of a non-linear orthotropic GBT formulation, which is intended to perform post-buckling analyses of laminated plate FRP open-section thin-walled members. Different types of loading and end support conditions can be dealt with and the theory can handle the presence of arbitrary initial geometrical imperfections. One is able to determine “exact” and “approximate” (only a few modes) post-buckling equilibrium paths and the evolution, along those paths, of (i) displacements and stresses and, using the GBT unique mode decomposition feature, also of (ii) the deformation mode participation in the member deformed configuration. To validate and illustrate the application and capabilities of the formulated GBT, numerical results, concerning the post-buckling behaviour of laminated plate FRP lipped channel members exhibiting different orthotropic behaviours, are presented and discussed. Some of them are compared with values obtained from finite element analyses, performed in the code ABAQUS and adopting shell element meshes to discretise the member.

References listed at the end of the paper:

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ABSTRACT: This paper provides an overview of the Generalised Beam Theory (GBT) fundamentals and reports on the novel formulations and applications recently developed at the TU Lisbon: the use of conventional GBT to derive analytical distortional buckling formulae and extensions to cover (i) the buckling behaviour of members with (i1) branched, closed and closed/branched cross-sections and (i2) made of orthotropic and elastic-plastic materials, and (ii) the vibration and post-buckling behaviours of elastic isotropic/orthotropic members. In order to illustrate the usefulness and potential of the new GBT formulations, a few numerical results are presented and briefly discussed. Finally, some (near) future developments are briefly mentioned.

ABSTRACT: A formulation of generalised beam theory (GBT) developed to analyse the elastic buckling behaviour of circular hollow section (CHS) members (cylinders and tubes) is presented in this paper. The main concepts involved in the available GBT are adapted to account for the specific aspects related to cross-section geometry. Taking into consideration the kinematic relations used in the theory of thin shells, the variation of the strain energy is evaluated and the terms are physically interpreted, i.e., they are associated with the geometric properties of the CHS. Besides the set of shell-type deformation modes, the formulation also includes axisymmetric and torsion deformation modes. In order to illustrate the application and capabilities of the formulated GBT, the local and global buckling behaviour of CHS members subjected to (i) compression (columns), (ii) bending (beams), (iii) compression and bending (beam-columns) and (iv) torsion (shafts), is analysed. Moreover, the GBT results are compared with estimates obtained by means of shell finite element analyses and are thoroughly discussed.


ABSTRACT: This paper presents several issues that characterize the buckling behaviour of elliptical cylindrical shells and tubes under compression. First, a formulation of Generalised Beam Theory (GBT) developed to analyse the elastic buckling behaviour of non-circular hollow section (NCHS) members is presented. Since the radius varies along the cross-section mid-line, the main concepts involved in the determination of the deformation modes are adapted to account for the specific aspects related to elliptical cross-section geometry. After that, two independent sets of fully orthogonal deformation modes are determined: (i) local-shell modes satisfying the null membrane shear strain but exhibiting transverse extension and (ii) shell-type modes satisfying both assumptions of null membrane shear strain and null transverse extension. In order to illustrate the application, capabilities and versatility of the formulation, the local and global buckling behaviour of elliptical hollow section (EHS) members subjected to compression is analysed. In particular, in-depth studies concerning the influence of member length on the variation of the critical load and corresponding buckling mode shape are presented. Moreover, the GBT results are compared with estimates obtained by means of shell finite element analyses and are thoroughly discussed. The results show that short to intermediate length cylinders buckle mostly in local-shell modes, exhibiting only transverse extension, while intermediate length to long cylinders buckle mostly in shell-type modes (distortional and global modes), which are characterized by transverse bending and primary warping displacements. It is also shown that the present formulation is very efficient from the computational point of view since only three deformation modes (one local-shell, one distortional and one global) are required to evaluate the buckling behaviour of EHS cylinders for a wide range of lengths.

References listed at the end of the paper:
CEN (Comité Européen de Normalisation), 2006. EN 10210-2: Hot finished structural hollow sections of non-alloy and fine grain steels – Part 2. Tolerances, dimensions, sectional properties.
ABSTRACT: This paper presents a formulation of Generalised Beam Theory (GBT) developed to analyse the influence of non-classical effects on the structural behaviour of FRP composite circular hollow section members. Unlike other existing beam theories, the present GBT formulation incorporates non-classical effects.
comprising (i) elastic material couplings, (ii) deformation of cross-section contour, (iii) warping deformation and (iv) shear deformation. With the purpose of solving the GBT system of differential equilibrium equations, a finite element formulation is briefly presented. In order to clarify the concepts involved in the formulated GBT and illustrate its application and capabilities, the linear (1st order) behaviour of two composite members exhibiting elastic couplings is analysed and the results obtained are thoroughly discussed and compared with estimates available in the literature. It is shown that accurate solutions can only be achieved if these non-classical effects are incorporated in the analysis.


ABSTRACT: This paper presents a state-of-the-art report on the use of Generalised Beam Theory (GBT) to assess the buckling behaviour of plane and space thin-walled steel frames. After a very brief overview of the main concepts and procedures involved in performing a GBT buckling analysis, one addresses the development and numerical implementation of a GBT-based beam finite element formulation that is able (i) to unveil local, distortional and global buckling modes, (ii) to handle arbitrary loadings (namely those causing non-uniform member internal force and moment diagrams) and (iii) to incorporate the presence of several frame joint configurations and arbitrary end and/or intermediate support conditions (including those associated with the modelling of bracing systems). In particular, one describes the procedures employed to establish the frame linear and geometric stiffness matrices – special attention is paid to the constraint conditions adopted to ensure the local displacement compatibility at the frame joints. The paper closes with the presentation and discussion of a number of numerical results that make it possible to illustrate the application and show the potential of the GBT-based approach to perform frame buckling analyses – they concern both plane and space frames. In order to validate and assess the numerical efficiency and accuracy of the GBT analyses and results (critical buckling loads and mode shapes), the frames are also rigorously analysed in the commercial code Ansys – both the members and joints are discretised by means of fine shell finite element meshes.


ABSTRACT: Following the Eurocode 3 philosophy, it is expected that the design of elliptical hollow section (EHS) tubes will be based on the slenderness concept, which requires the calculation of the EHS critical stress. The critical stress of an EHS tube under compression may be associated with local buckling, distortional buckling or flexural buckling. The complexity in deriving analytical expressions for distortional critical stress from classical shell theories, led us to apply Artificial Neural Networks (ANN). This paper presents closed-form expressions to calculate the distortional critical stress and half-wave length of EHS tubes under compression, using ANN. Almost 400 EHS geometries are used and based solely on three parameters: the outer EHS dimensions (A and B) and its thickness (t). Two architectures are shown to be successful. They are tested for several statistical parameters and proven to be very well behaved. Finally, some simple illustrative examples are shown and final remarks are drawn concerning the accuracy of the closed-formed formulas.
References listed at the end of the paper:

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“Examination Of Cylindrical Shell Theories For Buckling Of Carbon Nanotubes”, International Journal of Structural Stability and Dynamics”, Vol. 11, No. 6, December 2011, p. 1035,
DOI: 10.1142/S0219455411004464
ABSTRACT: This paper examines the validity and accuracy of cylindrical shell theories in predicting the critical buckling strains of axially loaded single-walled carbon nanotubes (CNTs). The shell theories considered are the Donnell thin shell theory (DST), the Sanders thin shell theory (SST), and the first-order shear deformation (thick) shell theory (FSDST). Molecular dynamic (MD) simulation solutions for armchair and zigzag CNTs with clamped ends were used as reference results to assess the shell models. The MD simulations were carried out at room temperature to eliminate the thermal effect on the buckling behavior. By adopting Young’s modulus of 5.5 TPa, Poisson’s ratio of 0.19, and tube thickness of 0.066 nm, it was found that DST is not able to capture the length dependency of the critical buckling strains and thus it should not be used for buckling analysis of CNTs. On the other hand, SST and FSDST are able to predict the critical buckling strains of armchair and zigzag CNTs reasonably well for all aspect ratios, especially the results produced by the FSDST are found to be closer to the MD simulation results, because it allows for the effect of transverse shear deformation that becomes significant for CNTs with small aspect ratios. Thus, FSDST is recommended as a very suitable and convenient continuum mechanics model for buckling analysis of CNTs. The superior FSDST model is used to generate critical buckling strains of axially loaded single-walled CNT with different boundary conditions. These results should be useful for designers of nanodevices that make use of CNTs as axially loaded members. It is worth noting that for long and moderately long CNTs, the Timoshenko beam model may be used instead due to its simplicity.

M. O. Oyesanya (Department of Mathematics, University of Nigeria, Nsukka, Nigeria), “Secondary bifurcation
ABSTRACT: The primary and secondary bifurcation states of a simply supported cylindrical shell of finite length subjected to lateral or hydrostatic pressure is studied using formal perturbation procedures. The effect of arbitrary stress-free initial displacement (imperfections) on the buckling load is studied following standard procedures. It is shown that the buckling load of the imperfect structures depends asymptotically only on the classical buckling load and a measure of the imperfection and not on the secondary bifurcation load.

ABSTRACT: We consider non-linear bifurcation problems for elastic structures modeled by the operator equation $F[w;a]=0$ where... are Banach spaces and ... We focus attention on problems whose bifurcation equations are of the form…. which emanates from bifurcation problems for which the linearization of $F$ is Fredholm operators of index 0. Under the assumption of $F$ being odd we prove an important theorem of existence of secondary bifurcation. Under this same assumption we prove a symmetry condition for the reduced equations and consequently we got an existence result for secondary bifurcation. We also include a stability analysis of the bifurcating solutions.

ABSTRACT: The bifurcation of a toroidal shell segment with initial imperfection which are subjected to lateral or hydrostatic pressure is studied under the assumption that the initial imperfection are Gaussian random stress-free displacement whose mean and autocorrelation function are given. We use a perturbation scheme developed by Amazigo [Amazigo, J.C., 1971. Buckling of stochastically imperfect columns on nonlinear elastic foundation. Quart. Appl. Math. 403–491]. A simple approximate asymptotic expression is obtained for the bifurcation load for small magnitudes of the imperfection. The result is compared with results obtained earlier under secondary bifurcation analysis for the imperfections in the shape of the buckling mode and the results in the literature, which shows some significant differences as a result of inclusion of extra terms in the buckling equation.

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ABSTRACT: The result of the study of dynamic response of an elastic circular plate to blast load is presented in this research work. Finite element method is used to derive the equation of motion for the circular plate element under the influence of exponential impulse forces. System stiffness and mass matrices were drive. The effects of transverse shear deformation and rotatory inertia were included. From the numerically simulated
results it is observed that the amplitude dies out quickly due to the effect of damping. The pulse duration is also one of the most important parameter because it gives serious influence to the vibration amplitude. It gives rise to the vibration amplitude on any small decrease on the pulse duration. It is also observed that the exponential blast loading brings faster rate of amplitude decay than those of triangular and sinusoidal blast loading.

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ABSTRACT: Improved fabrication techniques and the availability of higher strength steels have encouraged greater use of thin-walled containment vessels in recent years. A major increase in computing capability to analyse these structures for buckling modes has also occurred and this paper considers two recently constructed steel water towers. In particular, the effect of door cut-outs on buckling capacity is examined. The analysis techniques used in the paper provide powerful tools for readily estimating buckling modes and assessing the effects of various stiffener arrangements. By far the most effective stiffening element in the stem of a water tower is a horizontal diaphragm which maintains a circular cross-section.


ABSTRACT: The paper deals with an analysis of the bifurcation and initial post-buckling behaviour of highly imperfection-sensitive large spherical shells, such as cargo tanks for ship transportation of liquefied natural gas and large spherical containment shells for nuclear power plants. The numerical analysis procedure has sufficient generality to treat shells of revolution with arbitrary curved generators and with arbitrary variation of the thickness. The shells can be subjected to non-axisymmetric time-varying loadings. The purpose of the paper is to present simple procedures for scantling selections in the initial design phase and to propose an analysis procedure for verification of the final design of optimized thin-walled spherical shells.


ABSTRACT: The buckling characteristics of some composite stiffened plates are determined in this paper using a finite strip approach. The finite strip formulation is able to predict the complex buckling modes associated with in-plane shear loading and the method of approach can allow for other loading configurations whose associated pre-buckling stresses are not so obviously realised. Two loading conditions have essentially been considered in the paper, that of in-plane shear and that of partial edge loads being reacted by shear. The strip displacement fields before and after buckling are represented by algebraic polynomials across the strip and trigonometric functions along the strip length. The inclusion of sufficient harmonics in the appropriate
displacement representations thus allows the distorted nodal lines of the shear buckling mode and the complex pre-buckled stresses associated with partial edge loads to be determined with relative ease.


ABSTRACT: In this paper a study is made of the buckling behaviour of some composite stiffened panel structures subjected to in-plane compression and shear load combinations. The finite strip method, a computer aided engineering analysis procedure, is employed to determine the buckling solutions. Since the prediction of structural performance is quickly and accurately determined through computer simulation, the analysis capabilities of the finite strip method promotes the examination of many design alternatives. The designer is encouraged and indeed readily aided to make the most efficient use of materials and thus the development of highly reliable structural components, which are able to operate at optimised performance levels, can be achieved. A basic strip formulation for composite material construction is presented which is able to predict the complex buckling modes associated with in-plane load combinations. The buckling displacement fields are represented by algebraic polynomials across the strip and trigonometric functions along the strip length. The inclusion of sufficient harmonics in the appropriate displacement representations provides the required flexibility of the strip formulation to accommodate the more elaborate buckling modes associated with the presence of in-plane shear loading. The results presented in the paper are those pertaining to the buckling capabilities of stiffened panels manufactured from high strength carbon-epoxy composite material. The results illustrate, graphically, the effect on buckling performance of changes in stiffener geometry. Interaction curves are presented in the paper which detail the limiting boundaries for critical load combinations of specific structural configurations.


ABSTRACT: The presence of in-plane shear loading in thin plates is destabilising in nature and will cause buckling at a certain critical intensity. As a result of the shear, the buckling mode will have a complex configuration and will be associated with distorted nodal lines. A finite strip formulation is presented which is able to predict this behaviour for practical structural geometries and due to the considerable flexibility of the strip any flat sided, thin-walled structural configuration can be modelled with relative ease. The structural configuration considered is that of the transversely stiffened shear web manufactured from long fibre composite material and whose stiffeners take the form of plain flat outstands attached to one side of the thin composite skin. Results are presented in the paper which show the effect on the buckling capacity of composite stiffened shear webs of varying the stiffener size and pitch and of particular interest, the effect of fibre orientation in the stiffeners is highlighted in some detail. It is shown that for a given structural weight, shear buckling performance can be enhanced through favourable orientation of the stiffener fibres.

J. Loughlan (Structures and Materials Technology Group, College of Aeronautics, Cranfield University, Cranfield MK43 0AL, UK), “The influence of bend–twist coupling on the shear buckling response of thin

ABSTRACT: The finite strip method of analysis has been used in this paper to examine the effect of bend–twist coupling on the shear buckling behaviour of laminated composite constructions. The distorted nodal lines of the shear buckling mode and its complex deformation state in general are readily accounted for in the analysis procedure through the multi-term nature of the finite strip buckling displacement field and the appropriate level of structural modelling. The degree of bend–twist coupling in the laminated composite plates is varied by changing the level of anisotropy in the plies and by altering the lay-up configuration of the plies in the laminated stack. Symmetric laminates of a balanced and unbalanced nature are given consideration. It is shown that, for a given degree of anisotropy in the plies of a laminate and for a given laminate thickness, the stacking sequence of the plies significantly alters the degree of bend–twist coupling. The shear buckling performance of composite plates having the same dimensions and being made from the same material are therefore shown in the paper to be quite different. The preclusion of the bend–twist coupling coefficients in the solution procedure of the finite strip method allows the shear buckling orthotropic solution to be determined. Comparisons between the coupled and orthotropic solutions are shown in the paper to be markedly different.


ABSTRACT: Restoration forces, associated with embedded activated pre-strained shape memory alloy wires, have successfully been employed to enhance the post-buckling behaviour of various laminated plate structures. An extensive experimental and numerical programme has been conducted, the results of which will be presented. The manufacturing methodology of the hybrid SMA/carbon/epoxy plates is outlined. Such specimens feature 0.4-mm diameter shape memory alloy wires located within tubing at desired locations. Numerical thermal analysis has been employed to predict the non-uniform temperature profile, attributed to shape memory alloy activation through resistive heating, within the laminates. Structural finite element analysis has been employed to determine the hybrid plates' adaptive response while under the influence of a uniaxial compressive load in excess of its critical buckling value. It is shown that, utilising the considerable control authority generated, even for a small actuator volume fraction, the out-of-plane displacement of the post-buckled laminates can be significantly reduced. Such displacement alleviation allows for load redistribution away from the specimens' unloaded edges. With the increase in use of composite materials within aerospace platforms, it is envisaged that the hybrid adaptive SMA/laminate configuration will extend the operational performance over conventional materials and structures, particularly when the structure is exposed to an elevated temperature.


ABSTRACT: Restoration forces, associated with embedded activated pre-strained shape memory alloy wires, have successfully been employed to enhance the post-buckling behaviour of a laminated panel structure. An extensive experimental and numerical programme has been conducted, of which, results will be presented. The manufacturing methodology of the hybrid SMA/carbon/epoxy panel is outlined. The panel specimen features 0.3 mm diameter shape memory alloy wires embedded and partially consolidated to the host matrix at desired
locations. Numerical thermal analysis has been employed to predict the non-uniform temperature profile, attributed to shape memory alloy activation through resistive heating, within the laminate. Structural finite element (FE) analysis has been employed to determine the hybrid panel's adaptive response while under the influence of the uniaxial compressive load in excess of its pseudo-critical buckling value. It is shown that, utilising the control authority generated from the small SMA actuator volume fraction employed, the out-of-plane displacement of the post-buckled laminated panel can be reduced. With the increase in use of composite materials within aerospace platforms, it is envisaged that the hybrid adaptive SMA/laminate configuration will extend the operational performance over conventional materials and structures, particularly when the structure is exposed to an elevated temperature.


ABSTRACT: The compressive stability of anti-symmetric angle-ply laminated plates with particular reference to the degrading influence of membrane–flexural coupling is reported in this paper. The degree of membrane–flexural coupling in the laminated composite plates is varied, essentially, by altering the ply-angle and the number of plies in the laminated stack for a given composite material system. The coupled compressive buckling solutions are determined in the paper using the finite strip method of analysis and the buckling displacement fields of the strip formulation are those which are able to provide zero in-plane normal movement at the edge boundaries of the laminated plates. Results are given for anti-symmetric angle-ply laminated plates subjected to uniaxial compression and these have been obtained from fully converged finite strip structural models. Validation of the finite strip formulation is indicated in the paper through comparisons with exact solutions where appropriate. Increasing the number of plies in the laminated system is seen to reduce the degree of coupling and the critical stress levels are noted to tend towards the plate orthotropic solutions. The ply-angle corresponding to the optimised buckling stress for any particular laminate is noted in the paper to be influenced by the support boundary conditions at the plates unloaded edges. For any particular laminate the minimum critical buckling stress and corresponding natural half-wavelength of the buckling mode are shown to be highly sensitive to ply-angle variation. Some post-buckling results are presented in the paper and these have been determined using the finite element method of analysis. The influence of membrane–flexural coupling is shown to be significant throughout the compressive post-buckling history of the laminated plates. The optimised ply-angle with regard to the critical compressive buckling stress of square simply supported anti-symmetric angle-ply laminates is shown to be less effective in the post-buckling range with regard to post-buckled compressional stiffness.

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ABSTRACT: In this paper experimental tests are described and discussed which illustrate the feasibility of buckling control in composite structural elements using induced strain actuation in a smart technological manner. Compressive tests on simply supported square composite plates which utilise the shape memory effect for buckling control are shown to exhibit substantially reduced post-buckling deflections when under activated control in comparison to those experienced for the uncontrolled case. The alleviation of the post-buckling deflections is shown to result in reduced non-linear stress levels in the post-buckling range and thus it is intimated that the ultimate failure levels of the composite plates can be improved through the application of shape memory control. The influence of temperature, from ohmic heating of the actuated shape memory alloy wires, on the mechanical performance of the composite laminated plates is discussed and the analysis procedures for the determination of the resulting non-uniform stress profiles in the composite plates are duly outlined. It was found that temperature effects could be significant and that these in turn depended to a large extent on laminate lay-up configuration. Particular attention is paid in the paper to tests carried out to ascertain the characteristic behaviour of the Nickel–Titanium shape memory material employed for actuation purposes. The cyclic recovery force capabilities of the actuator wires utilised in the compressive plate tests is highlighted and a detailed account of the determination of the alloys characteristic transformation temperatures is given. The paper discusses, in some detail, the feasibility of the proposed smart structural concept and gives some thought to the implementation of smart advanced composite materials within the marketplace with particular reference to future aerospace applications.


ABSTRACT: The numerical simulation analyses were performed on the buckling and postbuckling behavior of laminated composite shells with embedded shape memory alloy (SMA) wires. These analyses using ABAQUS code were conducted to investigate the effect of embedded SMA wires on the characteristics of buckling and postbuckling caused by external and thermal loads. The nonlinear buckling analysis showed that the activation of eccentrically embedded SMA wires increased the critical buckling load when phase transformation of SMA wires occurred. The activated SMA wires embedded in the direction of buckling resulted in a sudden increase of the critical buckling load when both edges were simply supported. However, activated SMA wires embedded in the opposite direction of buckling, resulted in a sudden decrease of the buckling load. The thermal buckling analyses of the composite shells with embedded SMA wires showed that the critical buckling temperature increased and the thermal buckling deformation decreased by using the activation force of embedded SMA wire actuators.


ABSTRACT: An experimental study is presented of the dynamical behaviour of a cylindrical shell within a coaxial rigid cylindrical pipe, with flow in the annulus. The shell could be clamped at both ends or clamped at one end and free at the other. The frequencies of some of the principal modes of the shell were monitored with fibre-optic sensors as the flow velocity was incremented, and the signals were analyzed on a FFT Signal Analyzer, up to the point of loss of stability. It was found in these experiments that a clamped-clamped shell
loses stability by divergence (buckling) in its second or third circumferential mode, depending on the length/radius ratio and the internal pressure in the shell. The experimental observations are extensively compared with a previously developed theoretical model. The qualitative dynamical behaviour in general and the mode associated with instability are in good agreement with theory; the critical flow velocity for divergence, however, is substantially smaller than theoretically predicted, presumably as a result of imperfections. Clamped-free shells, on the other hand, lose stability by flutter, in these experiments in the third or fourth circumferential mode of the shell, depending on the annular-gap/radius ratio and the length/radius ratio.


ABSTRACT: The unstable region of a circular cylindrical aluminium shell subjected to internal leakage flow was investigated experimentally, changing the gap shape and leakage flow velocity. The changes in the natural frequency, damping ratio, and displacement were also investigated to clarify the type of instability that occurred and to obtain the vibration characteristics needed for predicting instability. Flutter-type instability was observed and for an unstable gap condition, the damping ratio decreased to zero, as is known to occur with flutter-type instability. Moreover, the natural frequency increased with the flow velocity. The change in the natural frequency was small and the damping ratio increased with the leakage flow velocity when the gap shape was stable. The repeatability of the flutter occurrence was good. Leakage flow through a straight gap did not cause instability, and the critical ratio of the size of the stepped annular gap for the unstable region was obtained.


ABSTRACT: The dynamic buckling of a finite damped imperfect circular cylindrical shell which is subjected to step-loading in the form of lateral or hydrostatic pressure is examined by means of a perturbation method. The imperfection is assumed to be small. An asymptotic expression for the dynamic buckling load is obtained in terms of the damping coefficient and the Fourier component of the imperfection in the shape of the classical buckling mode. A simple relation which is independent of the imperfection is then obtained between the static and dynamic buckling loads.


ABSTRACT: A circular cylindrical shell, periodically supported and subjected to step-loading in the form of lateral or hydrostatic pressure, is studied. Using the time-dependent von Kármán-Donnell equations, its imperfection sensitivity is examined and a simple asymptotic expression for the dynamic buckling load, valid for small imperfections, is obtained. There is a simple relation, independent of the imperfection, between the dynamic and static buckling loads.
ABSTRACT: In this paper, the axisymmetric dynamic behavior and snap-through buckling of thin elastic shallow spherical shells under harmonic excitation is investigated. Based on Marguerre kinematical assumptions, the governing partial differential equations of motion for a pre-loaded cap are presented in the form of a compatibility equation and a transverse motion equation. The continuous model is reduced to a finite degree of freedom system using the Galerkin method and a Fourier–Bessel approach. Results show that pre-loaded shells may exhibit co-existing stable equilibrium states and that with the application of sufficiently large dynamic loads the structure escapes from the well corresponding to pre-buckling configurations to another. This escape load may be much lower than the corresponding quasi-static buckling load. Indeed, complex resonances can occur until the system snaps-through, often signalling the loss of stability. As parameters are slowly varied, steady state instabilities may occur; these can include jumps to resonance, subharmonic period-doubling bifurcations, cascades to chaos, etc. Moreover a sudden pulse of excitation may lead to a transient failure of the system. In this paper, we examine how spherical caps under harmonic loading may be assessed in an engineering context, with a view to design against steady state instabilities as well as the various modes of transient failure. Steady state and transient stability boundaries are presented in which special attention is devoted to the determination of the critical load conditions. From this theoretical analysis, dynamic buckling criteria can be properly established which may constitute a consistent and rational basis for design of these shell structures under harmonic loading.

PARTIAL ABSTRACT: The problem is to determine the effect of axial compressive and tensile forces on the stability of a circular cylinder in torsion.….
References listed at the end of the paper:


ABSTRACT: A consistent methodology for the analysis of buckling phenomena in three dimensional solids developed in Part 1 is applied to a simple structure, i.e., the externally pressurized cylindrical shell structure. The primary state of the shell is investigated analytically, using asymptotic technique, and then the straightforward buckling analysis is followed up to the third order, adopting the general stability theory in Part 1. The full analysis is done through the analytical manner. Hence, the closed form solution is obtained. Finally, the result is compared with the classical one.

ABSTRACT: Bifurcation instability modes of axially compressed circular cylindrical shell are investigated in the limit of zero thickness (i.e., h (thickness) 0) analytically, adopting the general stability theory developed by Triantafyllidis and Kwon(1987) and Kwon(1992). The primary state of the shell is obtained in a closed form using the asymptotic technique, and then the straightforward bifurcation analysis is followed according to the general stability theory to obtain the bifurcation modes in the limit of zero thickness in a full analytical manner. Hence, the closed form bifurcation solution is obtained. Finally, the result is compared with the classical one.

ABSTRACT: A non-linear, large deformation, finite element analysis is presented for the general instability of ring stiffened shells of revolution subjected to combined end compression and circumferential pressure loading. The circumferential pressure loading is treated as a follower force. A combined load-increment and iteration method is used for solving the resulting equilibrium equations. Effect of varying degrees of initial imperfection in shell geometry on the load-displacement behaviour is reported.

ABSTRACT: The lattice cylindrical shells wound from the planar lattice plates, which have significant applications in aerospace engineering, exhibit different deformation modes with their planar counterparts because of the curvature of the cell wall. In this paper, deformation mechanisms are systematically investigated and failure analyses are conducted for the lattice cylindrical shells with various core topologies. Analytical models are proposed to predict the axial stiffness, critical elastic buckling load or effective yield strength of these shells. Finite element simulations are carried out to identify the validity of the models. The models can be employed for the optimal design. As an example, we construct the failure map for the Kagome lattice cylindrical shell made from an elastic ideally-plastic material. Various failure mechanisms, including yielding, global elastic buckling and local elastic buckling are taken into account. Moreover, optimizations are performed to minimize the weight for a given stiffness or load-carrying capacity for three types of lattice cylindrical shells. It is found that the Kagome and triangular lattice cylindrical shells have almost equivalent load-bearing capacity and both significantly outperform the hexagonal one under axial compression.

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ABSTRACT: We consider very large periodic trusses called lattice structures. In classical calculus, the periodic truss character and its global geometry are forgotten. With the homogenization method that we have developed, the lattice is replaced by a continuum model which approaches, in a certain sense, the real structure. This is true when the number of constitutive cells becomes large. The homogenization method has been developed in linear static cases and in free vibration. This paper generalises it for the large displacement assumption. The truss equilibrium is written on the unknown deformed configuration.


ABSTRACT: New techniques have been developed to make materials with a periodic three-dimensional lattice structure. The high stiffness per unit weight and multifunction of such lattice structures make them attractive for use in aeronautic and astronautic structures. In this paper, epoxy-soaked continuous carbon fibres were first introduced to make lattice composite structures, which maximize the specific load carrying capacity. A micromechanical analysis of several designs, each corresponding to a different manufacturing route, was carried out, in order to find the optimized lattice structure with maximum specific stiffness. An intertwining method was chosen and developed as the best route to make lattice composite materials reinforced by carbon fibers. A sandwich-weaved sample with a three-dimensional intertwined lattice structure core was found to be best. The manufacturing of such a composite lattice material was outlined. In addition to a high shear strength of the core and the integral manufacturing method, the lattice sandwich structure is expected to possess better mechanical
ABSTRACT: Fiber reinforced lattice composites are light-weight attractive due to their high specific strength and specific stiffness. In the past 10 years, researchers developed three-dimensional (3D) lattice trusses and two-dimensional (2D) lattice grids by various methods including interlacing, weaving, interlocking, filament winding and molding hot-press. The lattice composites have been applied in the fields of radar cross-section reduction, explosive absorption and heat-resistance. In this paper, topologies of the lattice composites, their manufacturing routes, as well as their mechanical and multifunctional applications, are surveyed.

References listed at the end of the paper:

ABSTRACT: Studies on the static stability and the ultimate bearing capacity of vierendeel latticed shells have been carried out. The buckling modal and the whole course of instability are shown using the Finite Element Method. The ultimate bearing capacity is compared with that of the single-layer latticed shell structure. The results show that the ultimate bearing capacity of the vierendeel latticed shells is 2.87 times more than that of the single-layer lattice shell in the condition of consuming the same steel. The vierendeel lattice shell structure not only has the advantages of concision and transparency like the single layer latticed shell structure, but also has the stability and carrying capacity like double-layer latticed shell structure.

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“Analytical study on dynamic buckling of reactor containment vessel”, Nuclear Engineering and Design,
ABSTRACT: The dynamic buckling of a reactor containment vessel under earthquake conditions is evaluated using a nonlinear finite element method. It is based on the four-node MITC (mixed interpolated tensorial components) shell element originally proposed by K.J. Bathe, which has been modified by the authors to include the effect of large rotational increments. At first, the buckling modes for a thin cylindrical shell under a simplified base excitation were classified, then the dynamic buckling analysis of a typical PWR steel containment vessel was carried out, considering both geometrical and material nonlinearities, to compare the results with those of a conventional static analysis. It was found that the global shear buckling of a steel containment vessel occurred under a load level several times greater than the design earthquake, and the buckling load estimated by the conventional analysis was smaller than the buckling load estimated by the dynamic analysis.

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ABSTRACT: In this paper, we establish a homogenization framework to analyze the microscopic symmetric bifurcation buckling of cellular solids subjected to macroscopically uniform compression. To this end, describing the principle of virtual work for infinite periodic materials in the updated Lagrangian form, we build a homogenization theory of finite deformation, which satisfies the principle of material objectivity. Then, we state a postulate that at the onset of microscopic symmetric bifurcation, microscopic velocity becomes spontaneous, yet changing the sign of such spontaneous velocity has no influence on the variation in macroscopic states. By applying this postulate to the homogenization theory, we derive the conditions to be satisfied at the onset of microscopic symmetric bifurcation. The resulting conditions are verified by analyzing numerically the in-plane biaxial buckling of an elastic hexagonal honeycomb. It is thus shown that three kinds of experimentally observed buckling modes of honeycombs i.e., uniaxial, biaxial and flower-like modes, are attained and classified as microscopic symmetric bifurcation. It is also shown that the multiplicity of bifurcation gives rise to the complex cell-patterns in the biaxial and flower-like modes.

ABSTRACT: In this study, microscopic buckling of elastic square honeycombs subject to in-plane compression is analyzed using a two-scale theory of the up-dated Lagrangian type. The theory allows us to analyze microscopic bifurcation and post-bifurcation behavior of periodic cellular solids. Cell aggregates are taken to be periodic units so that we can discuss the dependence of buckling stress on periodic length. Then, it is shown that microscopic buckling occurs at a lower compressive load as periodic length increases, and that long-wave buckling occurs just after the onset of macroscopic instability if the periodic length is sufficiently long. It is
further shown that the macroscopic instability is of the shear type, leading to a simple formula to evaluate the lowest in-plane buckling stress of elastic square honeycombs.


ABSTRACT: In this study, a method to evaluate sensitivities in post-buckling analysis is developed. The gradients of load values obtained under several constraint conditions are discussed. Unlike other methods for sensitivity analysis, the present method can cope with both snap-through and bifurcation problems without eigenvalue analysis. In addition, the load sensitivity at arbitrary points on an equilibrium path can be calculated. Using the MITC4 shell element, several numerical examples, such as a bifurcation buckling and a snap-through analysis of shell structures, are solved to show the performance of this sensitivity analysis method.


ABSTRACT: An analysis method for evaluating the sensitivity of buckling load in geometrically nonlinear finite element methods is developed. By searching for the pseudo critical point in the perturbed system on the surface of the hyper-cylinder where the original critical point exists, the sensitivity of buckling load is estimated. Compared with other methods, the present method can cope with both snap-through and bifurcation problems without an eigenvalue analysis. In addition, the load sensitivity at arbitrary points on the equilibrium path can be calculated under the total-displacement constraint condition. Two examples of sensitivity buckling analysis of shell structures are demonstrated to examine the validity of this method, and satisfactory results are obtained.

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ABSTRACT: To reveal the local buckling strength of periodic lattice composites, an important factor in optimal material design, analytical method based on the classical beam-column theory was applied. Buckling modes were decided according to the condition that the curvature of the strut columns is the smallest. Characteristic equations were built according to the equilibrium equations. The buckling strengths and constraint factors of various grids under uniaxial compression and tension were achieved. The strut network supports stronger rotation restrictions than pin-jointed nodes but weaker than the built-in ends. With more stacks of struts and connectivity at nodes, the restriction must be stronger and the buckling load is greater. Commonly, the constraint factors of isogrids and mixed triangle grids are greater than Kagome grids. The regular honeycomb and square grids possesses smaller buckling loads.

ABSTRACT: The purpose of this paper is to present a general theory for analysis of the effect of initial geometrical imperfections on vibration frequencies of undamped, conservatively loaded, linear elastic beam and shell structures. The theory will be restricted to single mode vibrations with imperfections in the same shape as the vibration modes. The mathematical tool is a perturbational procedure developed with the aid of the principle of virtual work. The approach is illustrated by applications to beams, plates and axisymmetric shell structures. The examples show that the vibration frequency of these structures may be significantly raised or lowered due to imperfections.


ABSTRACT: An initial buckling analysis for cylindrically curved panels made of generally layered composite materials is presented. Four kinds of boundary conditions and the combination of axial compression and shear forces are considered. Two coupled, fourth-order partial differential equations are solved by the use of multiple Fourier series, in which more exact constants within the characteristic beam functions are introduced so that better orthogonality of the series and, therefore, more exact buckling loads are obtained. The influence of curvature, fibre angles, stacking sequence and panel aspect ratios is investigated. An interesting relationship between the critical axial load and shear forces is found for mid-plane symmetric panels. Comparison of present work with experimental results shows fairly good agreement.


ABSTRACT: An analysis for the postbuckling behaviour of compressively loaded, cylindrically curved panels of generally layered anisotropic composite materials is presented. The 36 coefficients in the constitutive relations of the panels are all taken into account. A pair of coupled non-linear differential equations are solved in conjunction with simply supported boundary conditions. Both double sine series and double sine-squared series are used for the deflection function, while characteristic beam function series are used to express the stress function. Numerical computations are performed for a number of panels with different lay-ups, different curvatures and different materials. Comparison between the present work and available theoretical and experimental data is carried out for the special case of a flat plate.

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ABSTRACT: In this paper, the performance under compressive static load of I-section stiffened panels is reported. A pristine panel is compared with panels containing simulated damage and repaired panels. Modes of failure, stiffness and strains are studied and it is shown that the significant decreases in strength caused by the damage are almost fully recovered by the repair scheme used.

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ABSTRACT: In this paper the finite element modelling under compressive static load of I-section stiffened panels is reported. A pristine panel is compared with panels containing simulated damage and repaired panels. Predicted stiffness, stress distributions and strength of the panels are compared with experimental results.


ABSTRACT: The buckling behaviour of a liquid storage tank built up of circular cylindrical shell-sections with different thicknesses is investigated. In any partially filled state the critical vacuum for bifurcation is determined taking into account the weight of the structure. For a storage tank with small geometrical imperfections the behaviour is analysed asymptotically using Koiter's general post-buckling theory. The initial post-buckling analysis based on the assumption of linear pre-buckling behaviour indicates that the storage tank is imperfection-sensitive in any partially filled state. Finally, bifurcation analyses accounting for nonlinear pre-buckling show that the assumption of linear pre-buckling is a good approximation even at high liquid levels.


ABSTRACT: Delamination buckling analysis of composite panels is of considerable interest to aerospace industries. In this paper, finite element modelling of delamination buckling of composite panels is discussed. ANSYS 5.4 has been used for modelling the delamination buckling. A 3-D model with 8-node composite shell element is used. The panel is hypothetically divided into two sub-laminates by a plane containing the delamination. The two sub-laminates are modelled separately using 8-node composite shell element. Appropriate constraint conditions are added for the nodes in the undelaminated region using Coupled Nodes facility of ANSYS. The nodes in the delaminated region, whether in the top or bottom laminate, are left free. Using this modelling approach, a few typical test problems have been solved. The computed buckling loads and
strain energy release rate values for the test problems tally closely with that of thoery and other researchers. In addition to the test problems, some results on delamination buckling of a woven-fabric carbon-epoxy composite panel are also presented. The two sub-laminate model discussed here provides a convenient approach to delamination buckling analysis.

References listed at the end of the paper:

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ABSTRACT: Hot-rolled and cold-formed structural steel tubular members of elliptical cross-section have recently been introduced into the construction sector. However, there is currently limited knowledge of their structural behaviour and stability, and comprehensive design guidance is not yet available. This paper examines the elastic buckling response of elliptical hollow sections in compression, which has been shown to be intermediate between that of circular hollow sections and flat plates. The transition between these two boundaries is dependant upon both the aspect ratio and relative thickness of the section. Based on the results of numerical and analytical studies, formulae to accurately predict the elastic buckling stress of elliptical tubes have been proposed, and shortcomings of existing expressions have been highlighted. Length effects have also been investigated. The findings have been employed to derive slenderness parameters in a system of cross-section classification for elliptical hollow sections, and form the basis for the development of effective section properties for slender elliptical tubes.

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ABSTRACT: The elastic local post-buckling behaviour of elliptical tubes under compression is analysed in this
paper. A brief outline of the local, distortional and global buckling behaviour of EHS tubes is firstly provided, where it is shown that local buckling modes govern the stability of short to intermediate length tubes while distortional modes control the stability of intermediate length to moderately long tubes and global buckling dominates the behaviour of longer tubes. Following this, an in-depth numerical study employing shell finite element modelling, of the elastic local post-buckling behaviour of compressed elliptical hollow section (EHS) tubes is presented. It is concluded that EHS tubes with a low to moderate aspect ratio can support loads up to their limit loads but are imperfection sensitive (shell-type behaviour), while EHS tubes with a moderate to high aspect ratio can carry loads higher than their limit loads (plate-type behaviour) and are imperfection insensitive. The slope of the ascending post-buckling path increases with the EHS aspect ratio and can reach values up to 40% of the slope of the linear primary path. The bound imperfection amplitude concept, separating the imperfection amplitude ranges where the EHS tube is sensitive and insensitive, is proposed. It is also found that, for increasing EHS aspect ratio, the compressive stresses grow and accumulate near the zones of minimum radius of curvature while the zones of maximum radius of curvature possess an approximately uniform and relatively low compressive stress level. Therefore, it is expected that an approach based on the effective width concept widely used for the evaluation of the strength of flat plates may be adapted to the design of EHS tubes with moderate to high aspect ratios.


ABSTRACT: The plastic collapse response of structural steel elliptical hollow section (EHS) profiles in compression is examined in this paper. As an initial step, a parametric study to identify the factors that determine which plastic mechanisms would arise has been carried out using finite element (FE) results from the current work and experimental data from the literature. All investigated EHS had a cross-sectional aspect ratio of two. The parametric study revealed four plastic collapse mechanisms and showed that the “split flip disc” plastic collapse mechanism is the most likely to appear in compressed EHS. Thus, the present work is focussed on this failure mechanism, for which an analytical model to describe the relationship between load and deformation is developed. Coupled with the consideration of the elastic, yielding and strain hardening characteristics of steel, the derived analytical model enables construction of the full load–deformation behaviour of compressed EHS to be established. The parameters controlling the shape and size of the plastic hinges have been investigated and found to be of key importance; hence, special care has been taken in their definition. Finally, the developed load–displacement curves have been compared with both finite element results and experimental data. The comparisons have revealed good agreement, confirming the ability of the analytical model to predict the collapse response of elliptical tubes.


ABSTRACT: A one-dimensional model is presented in order to predict (a) delamination buckling loads of an across the width delaminated and axially loaded laminated plate and (b) the ultimate load-carrying capability of the above geometry, when delamination growth can take place. In order to study the possibility of spreading of the damaged (delaminated) area to the undamaged area, the post-buckling solution is employed. The energy release rate has been used to determine whether the delamination growth is stable or unstable. The results reveal that for a relatively small delamination length the buckling loads serve as a measure of the load-carrying
capacity of the damaged plate, while for a relatively large delamination length, the plate could carry larger loads depending on the fracture toughness of the plate material. Moreover, the present model can be used to study the effect of the presence of coupling between bending and stretching on delamination growth. Note that for such geometries the possibility of bifurcational buckling does not exist, regardless of the level of the applied load.


ABSTRACT: The influence of initial geometric imperfections is analysed at buckling and crack growth in compressed composite plates with delaminations present. First, initial buckling based on bifurcation theory and postbuckling is considered for initially flat laminates with appropriate crack parameters determined. For initially deflected plates, Marguerre shallow shell theory is drawn upon and by a scaling procedure pertinent results in the case of imperfections may be generated directly from those of perfect plates. The method is based on the assumption of affinity between initial and postbuckling transverse deflections. In particular for inextensible buckling states, the method is exact while in more general cases estimates are obtained. Illustrations of the method and procedures are given for several representative cases and especially the associated accuracy of the method is delineated.


ABSTRACT: A theoretical and experimental investigation of a laminated plate with an embedded, initially circular delamination, loaded in uniaxial compression is described. The main issue concerns the combined postbuckling and crack growth behaviour in general situations at arbitrary crack contours and applied to fibre-reinforced carbon-epoxy composite plates. In a numerical procedure a standard FE-code is used to solve the structural postbuckling problem and extended to account also for contact effects. To predict interlaminar crack growth an automatic finite element procedure was employed for the purpose. Delamination growth in laminates was detected by the aid of acoustic emission. After successive crack increments, the evolution of the delamination front was mapped using an ultrasonic C-scan technique and also for comparison by X-ray. Predicted and observed results are compared as regards postbuckling behaviour and in particular the magnitude and shapes of delamination growth fronts.

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ABSTRACT: A theoretical study of a buckling-driven, initially circular, delaminated thin film loaded in equal bi-axial compression is presented. The main objective of this investigation is to study the configurational
instability phenomena frequently observed for thin debonded coatings loaded in compression. The analyses are done with the aid of a kinematically non-linear finite element formulation of the plate problem to model the film, supplemented with a method to account automatically for the redistribution of the stress field as the shape of the advancing delamination is changing. By this procedure, not only the shape of the delaminated film but also the stability properties of the growth follow automatically. The configurational stability properties of the initially circular delamination are assessed by slightly perturbing the delamination front. The configurational instability is strongly related to the fracture mode dependence in the crack growth law. Finite growth of the buckling-driven thin film was also investigated. A load perturbation was employed as well as a front perturbation. It was found that the two perturbation methods can result in quite different shapes of the advancing buckled thin film. A few examples of extensive growth are also presented, and in some cases it was observed that a part of the delamination front may start tunnelling in the interface.

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“Delamination buckling and growth for delaminations at different depths in a slender composite panel”,
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ABSTRACT: A numerical and experimental investigation for delamination buckling and growth for slender composite panels loaded in compression is presented. The investigated panels consisted of 35 plies in a cross-ply layup with artificially embedded delaminations inserted after three, five or seven plies from the upper surface. The tests clearly and consistently showed that for all delamination depths, delaminated panels failed by delamination growth slightly below the global buckling load of the undamaged panel, whereas the undelaminated panels failed in compression at global buckling. The analysis was done with a finite element based computational model that accounts for contact between delaminated members and fracture mode separation and where crack propagation was simulated with a moving mesh scheme. For all delamination depths, the analysis showed a dramatic increase in the energy release rate when global buckling takes place. Features seen in the tests were captured in the computational analysis. Excellent agreement with tests was found for loads at which delaminated members buckle, the load for onset of delamination growth and the evolution of delamination, e.g., delamination shape and out-of-plane displacements.

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“Delamination growth of laminated composite cylindrical shells”, Theoretical and Applied Fracture Mechanics,

ABSTRACT: The local buckling may occur in delaminated cylindrical shells under axial compression. This often causes delamination growth and structure failure. Based on the variational principle of moving boundary, in this paper, the postbuckling governing equations for the laminated cylindrical shells are derived, and the corresponding boundary and matching conditions are given. At the same time, according to the Griffith criterion, the formulas of energy release rate along the delamination front are obtained and the delamination growth is studied. In the numerical calculation, the delamination growth of axisymmetrical laminated cylindrical shells is analyzed, and the effects of delamination sizes and depths, the boundary conditions, the material properties and the laminate stacking sequences on delamination growth are discussed.

ABSTRACT: It is shown that a simple method may be applied in order to determine the first order change of eigenmodes and critical loads at bifurcation buckling of slender structures when cavities or reinforcements are introduced. The perturbation procedure developed is applicable whenever a characteristic diameter of the structural geometry perturbation is one order less than the wave length of the unperturbed eigenmode and necessary computations involve at most the solution of two linear boundary value problems. Situations when the procedure may be further simplified are discussed and statements are made regarding requisite conditions for the buckling load definitely to increase or decrease due to geometry perturbations. Application of the method is illustrated by means of four cases of engineering interest, which involve perforated and reinforced beams and plates with holes and cracks.

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ABSTRACT: A finite element modeling is presented to study the buckling and postbuckling behavior of composite laminates with an embedded delamination. The buckling and postbuckling behavior of graphite/epoxy composite laminates with an embedded delamination are investigated for various delamination sizes, stacking sequence and boundary conditions. Three different possible modes of instability are identified at the critical load, which is global, mixed, and local buckling mode. The buckling load and postbuckling behavior depend on the buckling mode that is determined by the delamination size, stacking sequence and boundary conditions. It is found that the presence of a delamination in composite laminates may induce couplings, which have significant effects on the buckling and postbuckling behavior of composite laminates.


ABSTRACT: A finite element modeling is presented to study the effect of delamination on the buckling behavior of quasi-isotropic laminates. The effects of delamination on the buckling and postbuckling behavior of graphite/epoxy composite laminates are investigated for various delamination sizes, stacking sequence and boundary conditions. Three different possible modes of instability are identified at the critical load, which is global, mixed, and local buckling mode. The buckling load and postbuckling behavior depend on the delamination buckling mode that is determined by the delamination size, stacking sequence and boundary conditions. It is found that the presence of a delamination in composite laminates may induce couplings, which have significant effects on the buckling and postbuckling behavior of composite laminates.
ABSTRACT: A finite element modeling is presented to study the postbuckling behavior of composite laminates with an embedded delamination. The postbuckling analysis of graphite-epoxy composite laminates with a delamination is studied for a through-the-width delamination, and an embedded delamination. Three different possible modes of instability are identified at the critical load, which is global, mixed and local buckling modes. It is found that there exists three types of the postbuckling behavior, which depend on the delamination buckling mode. The postbuckling behavior of composite laminates with an embedded delamination shows the same pattern as that of composite laminates with a through-the-width delamination.

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analysis is very important for buckling analysis in some cases. The effects of various sizes, shapes and positions of the delamination and the fiber angle of the sublamine on the buckling load have also been investigated.

References listed at the end of the paper:

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ABSTRACT: In this paper, to investigate the buckling characteristics of carbon nanotubes, an equivalent beam model is first constructed. The molecular mechanics potentials in a C–C covalent bond are transformed into the form of equivalent strain energy stored in a three dimensional (3D) virtual beam element connecting two carbon atoms. Then, the equivalent stiffness parameters of the beam element can be estimated from the force field constants of the molecular mechanics theory. To evaluate the buckling loads of multi-walled carbon nanotubes, the effects of van-der Waals forces are further modeled using a newly proposed rod element. Then, the buckling characteristics of nanotubes can be easily obtained using a 3D beam and rod model of the traditional finite element method (FEM). The results of this numerical model are in good agreement with some previous results, such as those obtained from molecular dynamics computations. This method, designated as molecular structural mechanics approach, is thus proved to be an efficient means to predict the buckling characteristics of carbon nanotubes. Moreover, in the case of nanotubes with large length/diameter, the validity of Euler’s beam buckling theory and a shell model with the proper material properties defined from the results of present 3D FEM beam model is investigated to reduce the computational cost. The results of these simple theoretical models are found to agree well with the existing experimental results.

ABSTRACT: A theoretical and computational study has been carried out for compressive loading of a thin circular embedded delamination located below a cylindrical surface. The delaminated member is subjected to nominally uniaxial and balanced biaxial loading with the main objective to analyze its influence on surface curvature especially as regards imminent crack growth. The analysis is based on nonlinear shell theory combined with linear fracture mechanics. A finite element program earlier developed for delaminated plates has been generalized to apply also for shells and used to determine energy release rates and mode intensities along the delaminated front. A parameter study is made of the influence of curvature of the delaminated shell in particular as regards initiation and stability of crack growth.

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ABSTRACT: In this paper, a theory for the analysis of large deflection of squarely-latticed shallow spherical shells is constructed by adopting the equivalent continuum method. The von Kármán type non-linear differential equations of such latticed shells under actions of axisymmetrically distributed loads are derived. An approximate boundary value problem for a uniformly-loaded latticed shallow spherical shell is formulated with variational principles. A practical case of a latticed cap of a petroleum vessel subject to external uniform loads is investigated with this theory, and corresponding buckling loads are numerically presented.

ABSTRACT: The static stability capacity is the main index to measure the whole mechanical performance of single-layer latticed shells. Three single-layer cylindrical latticed shells with different height to span ratio were modeled, and their seismic damage were assessed by the degradation of static stability capacity incurred by earthquakes. Two different static load patterns were considered: dead load and the combination of dead load and half span live load. The results show that the damage assessment method is applicable to single-layer cylindrical latticed shells, and the static load patterns have no big influence on the damage assessment of the single-layer cylindrical latticed shells.


PARTIAL ABSTRACT: In this study the flexural and shear behaviour of large diameter fabricated steel cylinders have been experimentally investigated, and the results are compared with those obtained from existing design equations. The first part of the experimental program consisted of testing an unstiffened cylinder (R/t = 174) in pure flexure. The objective was to add to the scarce data base on cylinders in flexure. The results were compared to predictions made using the semi-empirical design equations of others for axially loaded cylinders…

J. Mok and A.E. Elwi (Department of Civil Engineering, The University of Alberta, Edmonton, Alberta, Canada), “Shear behavior of large diameter fabricated steel cylinders”, Structural Engineering Report No. 136, June 1986,

ABSTRACT: The shear behavior of large diameter fabricated steel cylinders is investigated analytically. The analysis is based on a nonlinear geometric finite element formulation coupled with a von Mises elastic-perfectly-plastic material response. The effects of initial imperfections as well as the boundary conditions on the shear behaviour of the cylindrical shells are examined. The development of a tension field in certain cases is also investigated. The study relies on the program NISA (“Nonlinear Incremental Structural Analysis”) a description of which is included….

ABSTRACT: Columns, stacks, conveyor galleries, and other similar civil engineering structures are often constructed in the form of an unstiffened tube or as a discretely stiffened tube that behaves in an essentially unstiffened manner. Tubes of this type are used extensively in the materials-handling operations of industrial plants. These are fabricated circular steel cylinders, typically 2.4 - 4 m in diameter, with radius-to-thickness ratios in the range of 150 - 400. They support and enclose conveyor systems, and they customarily span distances up to about 50 m. The task of the designer is similar to that faced with plate girders: the bending capacity, shear capacity, and the combined effects of shear and bending all must be examined. The results of a test program established to examine the flexural strength of large diameter fabricated steel tubes is reported herein. Although the number of tests is not great, the program is distinguished by the fact that the tests were done using relatively large specimens made in a way similar to that which would be employed in full-size tubes. These tests are believed to represent the best information currently available, and the results should be useful to both designers and other researchers who are approaching the problem using analytical tools.
ABSTRACT: Based on a blind spot in the current design standard of steel structures, the large diameter thin-walled tube beam-columns are analyzed using nonlinear finite element method in this paper. The influence of several factors on stability capacity of the large diameter thin-walled tube beam-columns is taken into account. Thus, according to the correlative design standard of steel structures, and on the basis of the numerical analytical results by the finite element methods, the calculation formulas of the stability bearing capacity are presented for beam-column members of the large diameter thin-walled tubes. Three tests of thin-walled steel tube beam-columns were reported. Test results for deformations and ultimate strength are found to be in a good agreement with the corresponding values predicted by the calculation formulas, and the proposed methods can be used in design practice.

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V. G. Roman and A. E. Elwi (Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada), “Postbuckling behavior of thin steel cylinders under transverse shear”, Structural Engineering Report no. 146, May 1987

PARTIAL ABSTRACT: The behavior of thin steel cylinders under transverse shear is investigated using a 16-node three dimensional degenerated plate shell element in the context of the nonlinear finite element analysis program NISA80, with an elastic-perfectly plastic material model. The analysis is carried out along the prebuckling and the postbuckling equilibrium paths for cylinders with initial measured imperfections, initial residual stresses due to longitudinal seam weld shrinkage and initial locked-in stresses due to the cold forming….


ABSTRACT: The decrease in lateral stiffness with increase in current and subsequent buckling of a flexible superconducting coil in a three coil partial torus is reported. The instability was observed for both clamped and clamped-pinned constraints on circular coils. Tests on the in-plane stability show an increase in stiffness with current in contrast with the out of plane or lateral buckling behavior. Along with the decrease in lateral natural frequencies of the coils, a significant increase in damping was observed. The critical buckling current was found to be in good agreement with theoretical calculations based on the authors’ previous work.

ABSTRACT: A 16 coil superconducting torus is used to study magnetoelastic instabilities in a set of current carrying elastic rings. The torus is a 1/75th model of a proposed magnetic fusion reactor. Up to 130 KA-turns were placed in the 30-cm-dia torus. Three different lateral constraint conditions on the elastic magnets are discussed. Both dynamic and static methods are used to determine the critical buckling currents. The coils are observed to pair up during buckling. A series of snap-type instabilities were observed near the critical buckling current for the lowest mode. A fair to good comparison between experimental and theoretical values of the buckling currents for all three modes is obtained when tension stiffening corrections are included.


ABSTRACT: This paper describes tests that have been performed on the buckling behaviour of symmetrical four ply laminated carbon fibre epoxy shells loaded in axial compression. Six shells were tested, two each of three lay up orientations, +30/-30/-30/+30, +45/-45/-45/+45, and +60/-60/-60/+60 (angles measured from the cylinder axis). Testing procedure was to firstly load the shell to collapse, reload to ensure collapse was elastic and no significant damage had been done during the buckling process, impose a defect and retest to determine the degrading effect. During all tests the deformations were monitored by a purpose built optical system based on the reflective moire technique. This inspection technique allowed the entire shell surface to be monitored all times. The degrading effect of the relatively large geometric defects appeared to be more dependent upon geometry than lamina orientation although the 45 degree shells generally exhibited slightly less defect sensitivity.


ABSTRACT: The static deformation of micromachined beams under prescribed in-plane compressive stress is studied by analytical and experimental means over the pre-buckling, transition, and post-buckling load ranges. The finite amplitude of the beam in its post-buckled state is predicted by modeling the non-linear dependence of its compressive stress on the out-of-plane deformation. In addition, the model explicitly considers the net effect of slight imperfections, which can include fabrication defects, geometric irregularities, or non-ideal loading, on the beam's behavior in the near-buckling regime. As an application, clamped-clamped silicon dioxide beams are fabricated through conventional bulk micromachining, and their deflected profiles are measured through three-dimensional optical profilometry. The measurements are compared to the post-buckled amplitudes and shapes that are predicted by the model, and by existing simpler models that do not include the effects of both non-linearity and imperfection. As borne out by the data, when imperfections are considered, the beams exhibit continuous growth of the out-of-plane amplitude during transition from the prebuckled state to a post-buckled one, in contrast to sudden bifurcation at a critical load. By accounting for this behavior, the estimate of residual stress in the thin film from which the beams are fabricated can be improved, and the amplitude of common post-
buckled micromachined structures can be predicted.


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ABSTRACT: Fabricated steel cylinders with large R/t ratios are often used in conveyor galleries, offshore platforms, storage tanks, towers, vessels, and the like. The use of longitudinal stiffeners in these large cylinders has proven to be an efficient way to promote structural stability. The increase of load capacity is significant. However, the attachment of the stiffeners complicates the problem by introducing additional buckling modes and new design parameters. Four large-scale specimens were tested. The collected data included the load versus deformation behavior, as well as the geometric imperfections and welding residual stresses of the specimens. The objective of the research program was to investigate the local buckling behavior and ultimate load capacity of longitudinally stiffened steel cylinders subjected to bending. The results showed two failure modes, a shell buckling mode and a general buckling mode. The occurrence of both modes and the corresponding capacity...
depend on the shell properties, as well as on the spacing and angle of arc covered by the stiffeners. The general buckling mode has strength and ductility much higher than those predicted by existing design guidelines.


ABSTRACT: Fabricated steel cylinders are often used as conveyor galleries, stacks or masts, or as members in offshore structures. The cylinders are fabricated by first cold rolling steel plates to form short cans and then joining these together by circumferential girth welds to yield long spans. Circumferential stiffeners are almost always present, in order that the circular shape of the tube is maintained and as an assistance when the cylinder is being handled. Longitudinal stiffeners may be used as well. If they are present, they will be welded to the cylinder surface, thereby improving the behaviour under axial compression or beam bending. The paper addresses the design of the type of cylinder commonly used as a conveyor gallery. In this application, diameters of from 2.5 to 4.0 m are typical and the radius to thickness ration, R/t, ranges from about 100 to 400. Spans can reach 60 m. The results of four large-scale flexural tests on large diameter fabricated steel cylinders that had longitudinal stiffeners and a parametric study of hypothetical cylinders of this configuration are used as the basis of the study. The paper reviews current design standards in the light of those test results, presents the results of the parametric study and makes recommendations for the design of longitudinally-stiffened fabricated steel cylinders.


ABSTRACT: In structural design, the preliminary synthesis stage derives judgmental knowledge from engineering heuristic and experience which are usually expressed in symbolic form. On the other hand, detailed design involves extensive numerical processing. An integrated computer-aided design system should be able to handle both symbolic and numerical processings. It must also be able to integrate engineering databases and CAD packages within a single environment. The knowledge-based system approach provides a venue for achieving all these requirements. This paper presents a prototype knowledge-based system for lattice design that can perform several essential tasks including preliminary synthesis, numerical model generation, nonlinear finite element analysis, code compliance checking and member sizing. The system user is guided throughout the design session by interactive graphical user interfaces which facilitate the design process.


ABSTRACT: This work develops a framework for SIMP-based topology optimization of a metallic panel structure subjected to design-dependent aerodynamic, inertial, elastic, and thermal loads. Multi-physics eigenvalue-based design metrics such as thermal buckling and dynamic flutter are derived, along with their adjoint-based design derivatives. Locating the flutter point (Hopf-bifurcation) in a precise and efficient manner is a particular challenge, as is outfitting the optimization problem with sufficient constraints such that the critical flutter mode does not switch during the design process. Results are presented for flutter-optimal topologies of an unheated panel, thermal buckling-optimal topologies, and flutter-optimality of a heated panel (where the latter case presents a topological compromise between the former two). The effect of various
constraint boundaries, temperature gradients, and (for the flutter of the heated panel) thermal load magnitude are assessed. Off-design flutter and thermal buckling boundaries are given as well.

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ABSTRACT: Many structural bifurcation buckling problems exhibit a scaling or power law property. Dimensional analysis is used to analyze the general scaling property. The concept of a new dimensionless number, the response number-Rn, suggested by the present author for the dynamic plastic response and failure of beams, plates and so on, subjected to large dynamic loading, is generalized in this paper to study the elastic, plastic, dynamic elastic as well as dynamic plastic buckling problems of columns, plates as well as shells. Structural bifurcation buckling can be considered when Rn(n) reaches a critical value.

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ABSTRACT: This paper is concerned with the geometrical optimum design and the aseismic analysis of double-layer reticulated shell structures. The characteristic of free vibration of reticulated shell structures, with respect to geometric parameter, is investigated. The variations of the eigenfrequency of shell structures, with respect to the ratio of height-to-span, span, grid division frequency and thickness of shell, are discussed. The Newmark method is used to calculate the stresses and displacements of the reticulated shell structure under earthquake action. The analysis results show that under a specified span, the eigenfrequency of the structure increases with the increase of the height-to-span ratio and then decreases afterwards. Therefore, there exists an optimum height-to-span ratio resulting in an optimum stiffness at the specified span. The optimum value of the ratio is found to be between 1/3 and 1/4 from the simulation study presented in this paper. At a specified height-to-span ratio, the increase of the value of structural span greatly reduces the eigenfrequency of the structure and then decreases the global stiffness of the structure. At the specified span and the specified height-to-span ratio, the eigenfrequency of the structure has a minor increase with the increase of the thickness and the grid division frequency of the reticulated shell structure. The partial double-layer reticulated shell structures have less stability compared with double-layer reticulated shell structures, but more stability in comparison with single-layer reticulated shell structures. The 1/6 partial double-layer reticulated shell structure has a best performance-to-price ratio. In other words, it has a higher buckling load, with smaller material consumption, compared with other partial double-layer reticulated shell structures. It is proposed to adopt the 1/6 partial double-layer reticulated shell structure in engineering if a double layer reticulated shell structure is required.


ABSTRACT: In this study a kind of buckling-restrained braces (BRBs) as energy dissipation dampers is attempted for seismic performance of large span double-layer reticulated shell and the effectiveness of BRBs to protect structures against strong earthquakes is numerically studied. The hysteretic curve of such members is obtained through the simulation of the cyclic-loading test, and the equations of motion of the system under earthquake excitations are established. BRBs are then placed at certain locations on the example reticulated shell to replace some normal members, and the damping effect of the two installation schemes of BRBs is
investigated by non-linear time-history analyses under various ground motions representing major earthquake events. Compared with the seismic behavior of the original structure without BRBs, satisfactory seismic performance is seen in the upgraded models, which clarifies the BRBs can reduce the vibration response of spatial reticulated structure effectively and the new system has wide space to develop double layer reticulated shell.


ABSTRACT: Plate-cone reticulated shell is a new type of space structures with good mechanical behavior and technical economy. In this paper, local buckling and influence factors of composite plates in plate-cone reticulated shell are analyzed with theory of composite plate and shell through composite structure finite element method, and the mechanical characteristics of composite plate-cone reticulated shell are studied, some important conclusions were obtained, which can provide theoretical foundation for practical design of composite plate-cone reticulated shell and composite plates.

References listed at the end of the paper:


ABSTRACT: In this paper some stability problems of reticulated shells are studied. Adequate mathematical models for the analysis of shell instability, using a direct method and a shell analogy method, are presented. It is assumed that the members of the analysed shells consist of a homogeneous, isotropic elastic material. The theoretical results, obtained from some numerical examples, are also presented.

Adrian Ivan and Marin Ivan (Politehnica University of Timisoara, Romania), “Typical failure modes of some single layered reticulated shells”, (publisher and date not given in the pdf file. The most recent citation is dated 2001)

ABSTRACT: The paper reveals the main cases of possible failure of some single layered reticulated shells working in the elastic domain. The structural members are pinned jointed everywhere, and all are of tubular cross section.

CONCLUSIONS: In order to predict stability for complex reticulated structures it is necessary to analyze the elastic buckling loads of these domes using geometrical nonlinear analysis. Unfortunately this should be followed by mode shape analysis. Both will reveal the sensitivity to certain coupled modes of instability. Attention should be focused on these ones. The lowest critical load is obtained in the vicinity of a coupled instability on the reticulated shells affected by geometrical imperfections. The initial imperfection pattern should be affine to the mode shape. Not always this represents the most unfavorable imperfection pattern. The
stability of reticulated shells requires a large computing effort.

References listed at the end of the paper:


ABSTRACT: We present a study on buckling of colloidal particles, including experimental, theoretical and numerical developments. Oil-filled thin shells prepared by emulsion templating show buckling in mixtures of water and ethanol, due to dissolution of the core in the external medium. This leads to conformations with a single depression, either axisymmetric or polygonal depending on the geometrical features of the shells. These conformations could be theoretically and/or numerically reproduced in a model of homogeneous spherical thin shells with bending and stretching elasticity, submitted to an isotropic external pressure.


ABSTRACT: The multiple complexities inherent to living objects have motivated the search for abiotic substitutes, able to mimic some of their relevant physical properties. Hydrogels provide a highly monitorable counterpart and have thus found many applications in medicine and bioengineering. Recently, it has been recognized that their ability to swell could be used to unravel some of the universal physical processes at work during biological growth. However, it is yet unknown how the microscopic distinctions between swelling and biological growth affect macroscopic changes (shape, stresses) induced by volume variations. To answer this question, we focus on a clinically motivated example of growth. Some solid tumors such as melanoma or glioblastoma undergo a shape transition during their evolution. This bifurcation appears when growth is confined at the periphery of the tumor and is concomitant with the transition from the avascular to the vascular stage of the tumor evolution. To model this phenomenon, we consider in this paper the deformation of an elastic ring enclosing a core of different stiffness. When the volume of the outer ring increases, the system develops a periodic instability. We consider two possible descriptions of the volume variation process: either by imposing a homogeneous volumetric strain (biological growth) or through migration of solvent molecules inside a solid network (swelling). For thin rings, both theories are in qualitative agreement. When the interior is soft, we predict the emergence of a large wavelength buckling. Upon increasing the stiffness of the inner disc, the wavelength of the instability decreases until a condensation of the buckles occurs at the free boundary. This short wavelength pattern is independent of the stiffness of the disc and is only limited by the presence of surface tension. For thicker rings, two scenarios emerge. When a volumetric strain is prescribed, compressive stresses accumulate in the vicinity of the core and the deformation localizes itself at the boundary between the disc and
the ring. On the other hand, swelling being an instance of stress-modulated growth, elastic stretches near the core saturate and the instability occurs primarily at the free boundary. Besides its implications for the mechanical stability of avascular tumors, this work provides important results concerning layered tissues growth and the role of hydrogels as biological tissues substitutes.


ABSTRACT: An overview is given on a new buckling instability that arises following the osmotically driven swelling of a polymer film. This instability yields a simple route to produce wells 10–100 nm deep and with a diameter on the order of micrometers. It is shown that by using a simple surface pretreatment, it is possible to create an ordered array of these wells.

References listed at the end of the paper:


ABSTRACT: The objective of this thesis is to develop an efficient multi–scale finite element frame-work to capture the macroscopic localization due to the micro–buckling of cell walls and the size effect phenomena arising in structures made of cellular materials.

Under the compression loading, the buckling phenomenon (so–called micro–buckling) of the slender components (cell walls, cell faces) of cellular solids can occur. Even if the tangent operator of the material of which the micro–structure is made, is still elliptic, the presence of the micro–buckling can lead to the loss of ellipticity of the resulting homogenized tangent operator. In that case, localization bands are formed and propagate in the macroscopic structure. Moreover, when considering a cellular structure whose dimensions are close to the cell size, the size effect phenomenon cannot be neglected since deformations are characterized by a strain gradient.

On the one hand, a classical multi–scale computational homogenization scheme (so– called first–order scheme) loses accuracy with the apparition of the macroscopic localization or the high strain gradient arising in cellular materials because the underlying assumption of the local action principle, in which the stress state on a macroscopic material point depends only on the strain state at that point, is no–longer suitable. On the other hand, the second–order multi–scale computational homogenization scheme proposed by Kouznetsova et al. (2004b) exhibits a good ability to capture such phenomena. Thus this second–order scheme is improved in this
thesis with the following novelties so that it can be used for cellular materials. First, at the microscopic scale, the periodic boundary condition is used because of its efficiency. As the meshes generated from cellular materials exhibit a large void part on the boundaries and are not conforming in general, the classical enforcement based on the matching nodes cannot be applied. A new method based on the polynomial interpolation without the requirement of the matching mesh condition on opposite boundaries of the representative volume element (RVE) is developed.

Next, in order to solve the underlying macroscopic Mindlin strain gradient continuum of this second-order scheme by the displacement–based finite element framework, the presence of high order terms (related to the higher stress and strain) leads to many complications in the numerical treatment. Indeed, the resolution requires the continuities not only of the displacement field but also of its first derivatives. This work uses the discontinuous Galerkin (DG) method to weakly impose these continuities. This proposed second–order DG–based FE2 scheme appears to be easily integrated into conventional parallel finite element codes.

Finally, the proposed second–order DG–based FE2 scheme is used to model cellular materials. As the instability phenomena are considered at both scales, the path following technique is adopted to solve both the macroscopic and microscopic problems. The micro–buckling leading to the macroscopic localization and the size effect phenomena can be captured within the proposed framework.


ABSTRACT: We present a modified version of a strain–induced buckling instability technique that relies on the analysis of a two–plate composite film deposited on an elastomeric poly(dimethylsiloxane) (PDMS) substrate. We have previously shown that the “strain–induced elastic buckling instability for mechanical measurements” (SIEBIMM) technique is suitable for testing polyelectrolyte multilayers (PEMs) that are amenable to deposition directly on the testing substrate. The method presented in this paper broadens the applicability of the SIEBIMM technique through the transfer of a thin layer of polystyrene (PS) to the PDMS surface prior to film deposition, which creates a deposition surface that can be treated to promote adhesion of films not amenable to transfer or assembly directly onto PDMS. Multilayers assembled onto the PS-coated PDMS substrates yield thin two-plate PS–PEM composite films on the surface of the PDMS substrates that buckle like their homogeneous counterparts. The mechanical contribution of the PS layer is mathematically deconvoluted from the behavior of the composite film to arrive at a Young’s modulus value for the PEM part of the two-plate film. We test the new method by comparing results from two systems evaluated with both conventional SIEBIMM and the two-plate technique. Following this, we use the two-plate method to perform measurements on two PEM assemblies comprised of poly(allylamine hydrochloride) (PAH) and poly(acrylic acid) (PAA) that could not be measured by the conventional SIEBIMM approach. In addition to confirming the accuracy of the two-plate approach, our results yield new insights into the mechanical properties of PEM films. We find that the dry-state stiffness of PEM films is affected primarily by the choice of polyelectrolytes and the ambient humidity and secondarily by assembly conditions. In addition, films assembled from PAH and PAA have moduli on the order of 10 GPa at low (20%) ambient humidities, an unusually high value for a nonreinforced cross-linked polymer network.

Jun Y. Chung, Adam J. Nolte and Christopher M. Stafford (Polymers Division at the National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg MD 20899, USA), “Surface wrinkling: a versatile

ABSTRACT: Surface instabilities in soft matter have captivated the scientific community for decades. Recently, surface wrinkling has received a great deal of attention due to its simplicity and well-established mechanics of formation. Particularly, the use of surface wrinkling as a measurement platform for material properties has gained widespread momentum in the material science community. In this article, we will review several applications of surface wrinkling for the measurement of thin film mechanical properties, highlighting particularly challenging materials systems such as ultrathin films, polymer brushes, polyelectrolyte multilayer assemblies, and ultrasoft materials. We will also offer a perspective on the future directions of this maturing field, both as a metrology for material properties as well as a route for robust surface patterning.

References listed at the end of the paper:
ABSTRACT: Nanocapsules that can be tailored intelligently and specifically have drawn considerable attention in the fields of drug delivery and bioimaging. Here we conduct a theoretical study on cell uptake of a spherical nanocapsule which is modeled as a linear elastic solid thin shell in three dimensions. It is found that there exist five wrapping phases based on the stability of three wrapping states: no wrapping, partial wrapping and full wrapping. The wrapping phase diagrams are strongly dependent on the capsule size, adhesion energy, cell membrane tension, and bending rigidity ratio between the capsule and membrane. Discussion is made on similarities and differences between the cell uptake of solid nanocapsules and fluid vesicles. The reported results may have important implications for biomedical applications of nanotechnology.

Jincheng Lv, Shike Zhang and Xinsheng Yuan (School of Civil Engineering and Architecture, Anyang Normal University, Anyang, Nenan, China), “A Green’s function approach for dynamic stress analysis of spherical shell under the isotropic impact load”, Mathematical Problems in Engineering, Vol. 2015, Article ID 169468

ABSTRACT: A Green’s function approach is developed for the analytic solution of thick-walled spherical shell
under an isotropic impact load, which involves building Green’s function of this problem by using the appropriate boundary conditions of thick-walled spherical shell. This method can be used to analyze displacement distribution and dynamic stress distribution of the thick-walled spherical shell. The advantages of this method are able to avoid the superposition process of quasi-static solution and free vibration solution during decomposition of dynamic general solution of dynamics, to well adapt for various initial conditions, and to conveniently analyze the dynamic stress distribution using numerical calculation. Finally, a special case is performed to verify that the proposed Green’s function method is able to accurately analyze the dynamic stress distribution of thick-walled spherical shell under an isotropic impact load.

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ABSTRACT: The three-dimensional patterns of surface wrinkling on a core-shell soft sphere are investigated through buckling and postbuckling analyses under differential tissue growth or shrinkage. With increasing deformation, the sphere first exhibits a buckyball-like wrinkling pattern and then undergoes a wrinkle-to-fold transition into labyrinth folded patterns, in agreement with experimental observations. This transition involves dynamic movement, rotation, and coalescence of polygons formed during the initial buckling.


ABSTRACT: The linear bifurcation theory is used to investigate the stability of soft thin films bonded to curved substrates. It is found that such a film can spontaneously lose its stability due to van der Waals or electrostatic interaction when its thickness reduces to the order of microns or nanometers. We first present the generic method for analyzing the surface stability of a thin film interacting with the substrate and then discuss several important geometric configurations with either a positive or negative mean curvature. The critical conditions for the onset of spontaneous instability in these representative examples are established analytically. Besides the surface energy and Poisson’s ratio of the thin film, the curvature of the substrate is demonstrated to have a significant influence on the wrinkling behavior of the film. The results suggest that one may fabricate nanopatterns or enhance the surface stability of soft thin films on curved solid surfaces by modulating the mechanical properties of the films and/or such geometrical properties as film thickness and substrate curvature. This study can also help to understand various phenomena associated with surface instability.

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Cao, G., Chen, X., Li, C., Ji, A., Cao, Z., 2008. Self-assembled triangular and labyrinth buckling patterns of thin films on spherical


ABSTRACT: A freely floating polymer film, tens of nanometers in thickness, wrinkles under the capillary force exerted by a drop of water placed on its surface. The wrinkling pattern is characterized by the number and length of the wrinkles. The dependence of the number of wrinkles on the elastic properties of the film and on the capillary force exerted by the drop confirms recent theoretical predictions on the selection of a pattern with a well-defined length scale in the wrinkling instability. We combined scaling relations that were developed for the length of the wrinkles with those for the number of wrinkles to construct a metrology for measuring the elasticity and thickness of ultrathin films that relies on no more than a dish of fluid and a low-magnification microscope. We validated this method on polymer films modified by plasticizer. The relaxation of the wrinkles affords a simple method to study the viscoelastic response of ultrathin films.
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ABSTRACT: Symmetry-breaking transitions associated with the buckling and folding of curved multilayered surfaces—which are common to a wide range of systems and processes such as embryogenesis, tissue differentiation and structure formation in heterogeneous thin films or on planetary surfaces—have been characterized experimentally. Yet owing to the nonlinearity of the underlying stretching and bending forces, the transitions cannot be reliably predicted by current theoretical models. Here, we report a generalized Swift–Hohenberg theory that describes wrinkling morphology and pattern selection in curved elastic bilayer materials. By testing the theory against experiments on spherically shaped surfaces, we find quantitative agreement with analytical predictions for the critical curves separating labyrinth, hybrid and hexagonal phases. Furthermore, a comparison to earlier experiments suggests that the theory is universally applicable to macroscopic and microscopic systems. Our approach builds on general differential-geometry principles and can thus be extended to arbitrarily shaped surfaces.

References listed at the end of the paper:

ABSTRACT: Using the nonlinear elastic stability theory and its applications to shells, we have investigated the post-buckling behaviour and imperfection sensitivity of spherical shells with amplitude modulation. For this purpose, we assume that the buckling modes have the form of Legendre polynomials with an exponential function as a modulating factor. Since the expressions of the second and the third variation of the energy functional of the spherical shell in the fundamental state are too complicated to obtain a closed form, we use a numerical analysis technique with high precision. The amplitudes of the post-buckling modes and the critical loading factors of the spherical shell with various imperfection modes are presented.


ABSTRACT: In this paper the effect of the interaction between two or more simultaneous buckling modes on the postbuckling behaviour of uniformly compressed thin-walled members (TWM) is analysed by means of the general theory of elastic stability. The analysis is restricted to third-order terms of the energy expansion and therefore can be fruitfully applied to the investigation of structures with asymmetric postbuckling behaviour only. Initial imperfection effect is taken into account. A simplified procedure is suggested for solving the nonlinear equations relative to the evaluation of the bifurcated paths. By using the finite strip method an extensive parametric analysis is performed. It is found that when the flexural-torsional (FT) buckling interacts with a local symmetric and antisymmetric mode, sensitivity to initial imperfections is remarkable and is comparable to the one arising from the interaction between the Euler (E) and any local buckling.

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ABSTRACT: Different perturbation methods for the analysis of non-linear interaction between simultaneous buckling modes of nearly symmetric structures are discussed. First, the perturbation method employed by Budiansky for a single buckling mode, is extended to consider modes interaction of a perfect structure, by determining both the slope and the curvature of the bifurcated paths. It is shown that the solution diverges, when a properly defined parameter which characterizes the asymmetry of the structure approaches zero, thus preventing to recover results of symmetric systems. A modified perturbation method which permits to surmount this drawback is then suggested; this method applies only to a class of structures and furnishes asymptotic series valid in a wide region around bifurcation. The two methods are applied to investigate the post-buckling behavior of a two-degree-of-freedom system. Finally, a novel perturbation method which follows to some extent the lines of the Galerkin method and is particularly powerful in the investigation of nearly symmetric systems is presented.

ABSTRACT: Localization phenomena in one-dimensional imperfect continuous structures are analyzed, both in dynamics and buckling. By using simple models, fundamental concepts about localization are introduced and similarities between dynamics and buckling localization are highlighted. In particular, it is shown that strong localization of the normal modes is due to turning points in which purely imaginary characteristic exponents assume a non zero real part; in contrast, if turning points do not occur, only weak localization can exist. The possibility of a disturbance propagating along the structure is also discussed. A perturbation method is then illustrated, which generalizes the classical WKB method; this allows the differential problem to be transformed into a sequence of algebraic problems in which the spatial variable appears as a parameter. Applications of the method are worked out for beams and strings on elastic soil. All these structures are found to have nearly-defective system matrices, so their characteristic exponents are highly sensitive to imperfections.

References listed at the end of the paper:
ABSTRACT: A method is derived for the analysis of mode interaction in thin walled elastic beams. A nonlinear plate theory is employed for the plate segments of the beam, in which the exact nonlinear expressions are used for the middle surface strain measures, but the bending measures are linearized. The beam is subjected to a combination of axial compression and a constant bending moment, and it is assumed to be simply supported at the ends. In the calculation of the total potential energy, the influence of the prebuckling deformations is neglected. The finite strip method is used with the transverse variation of all three displacement components described by cubic polynomials in the arc length. The nonlinear mode interaction is analysed by means of Koiter's asymptotic theory of stability. Some applications of the method to representative problems are presented in a subsequent paper by the authors. This shows that significant mode interaction and imperfection sensitivity occur in these structures.

ABSTRACT: Mode interaction between local and global buckling modes is studied for two types of thin-walled beam structures, using a method of analysis presented in Part I of the author's paper [Mollmann and Goltermann (1989). Int. J. Solids Structures 25, 715–728]. This method involves a combination of the finite strip method and Koiter's asymptotic theory of stability. It appears that the interaction essentially involves three buckling modes (one global and two local modes), and that the inclusion of additional nearly simultaneous local buckling modes in the analysis does not alter the results perceptibly (in the case of local imperfections). In both examples, substantial reductions of load-carrying capacity due to mode interaction and imperfection sensitivity (up to about 50%) are observed. Some of the 2nd order fields and 4-index coefficients exhibit a marked dependence on the value of the load factor at which they are evaluated. For both structures, the load-carrying capacities have been determined for different values of the ratio between global and local critical loads. When this ratio is greater than one (i.e. when the local critical load is smaller than the global), the load carrying capacity will exceed the local critical load if the imperfections are sufficiently small.


ABSTRACT: A consistent method for the analysis of bifurcation instabilities in shells of arbitrary thickness has been proposed. The advantages of this method, as compared to the classical approach followed so far, are the independence of the results on the nonlinear shell theory employed as well as the possibility of finding the dependence of the critical load and eigenmode on the shell's thickness up to any degree of accuracy desired. A brief description of the general method, which is asymptotic with respect to the shell's thickness, is followed by its application to the case of an internally or externally pressurized infinite cylindrical tube for which an analytical solution of the resulting asymptotic problem is possible. Critical loads and modes compare very favorably with a numerical solution of the exact three dimensional problem even for relatively thick tubes. The presentation is concluded with a short discussion on the application of this technique to the general wrinkling instability problem in metal forming.


ABSTRACT: The bifurcation problem of thin walled structures in contact with rigid surfaces is formulated by adopting the multiple scales asymptotic technique. The general theory developed in this paper is very useful for the bifurcation analysis of waviness instabilities in the sheet metal forming. The formulation is presented in a full Lagrangian formulation. Through this general formulation, the bifurcation functional is derived within an error of O(E^3) (E: shell’s thickness parameter). This functional can be used in numerical solutions to sheet metal forming instability problem.


ABSTRACT: Devices with feature size on the order of one micrometer have found widespread applications in
science and engineering. MEMS, is a rapidly growing technology for the fabrication of miniature devices which provides a way to integrate mechanical, fluidic, optical, and electronic functionality on very small devices, ranging from 0.1 microns to one millimeter. Recently, it has been proposed that regular patterns can be generated through the mechanical buckling of a thin film. In this thesis, we focus on the buckling mechanism. The wavy patterns are generated when the thin elastic film is subjected to an in-plane compressive stress and by the application of controlled heating. We first introduce the mechanism of developing wave patterns through buckling using beam buckling as an example and then the finite element formulation and the commercial analysis package Algor. Our study includes the "stress stiffening" component, which is not usually included in most finite element analyses. Both the "Critical Buckling Load" and the "Natural Frequency with Load Stiffening" analyses are made use of to determine the buckling loads. Finally, the buckling load for each case is determined through the analysis and a comparison with the theoretical values is made.

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ABSTRACT: The fracture mechanics of a straight-sided, thin film delamination at stress levels, which are high compared to the stress required to initiate the delamination is investigated. Buckling at a bifurcation point of the delaminated region, resulting from incompletely relieved stresses in this region, is analysed by a semi-analytical approach for delaminations of infinite extent. The results are compared to numerical predictions based on finite element calculations for finite sized delaminations. The finite element calculations are carried out in the post-buckling regime showing that parts of the crack front will close as a result of bifurcation buckling, while other parts will experience enhanced energy release rate and mode I stress intensity factor. The mode III stress intensity factor is shown to be negligible at the stress levels analysed.

References listed at the end of the paper:

ABSTRACT: The transition from a straight-sided wrinkle to a periodic distribution of bubbles has been experimentally studied by atomic force microscopy for a stressed thin film relying on a substrate. A non-linear numerical analysis has been carried out and the different steps of the wrinkle evolution have been characterized. Different parameters of the buckling structure such as the shape parameter of the blisters and the stress relaxation have been determined and compared to the experimental data. The comparison of elastic strain energies has highlighted the possible coexistence of structures with different wavelengths.
ABSTRACT: The post-critical regime of straight-sided wrinkles on compliant substrates of polycarbonate has been observed by atomic force microscope and investigated by means of finite element simulations. The effect of coupling between the film and its substrate has revealed a global buckling phenomenon, characterized by critical loads lower than those found in the case of a rigid substrate. Characteristic shapes of the buckled structure have been also found to spread over a region wider than the delaminated zone itself. A law relating the film deflexion to the stress has finally been established for any film/substrate system.

ABSTRACT: The postbuckling transition from an initially straight-sided wrinkle to a distribution of bubbles has been investigated by means of finite element simulations in the case of a thin film relying on a rigid substrate. The calculations show that a snapthrough occurs when the buckling wavelength exceeds a critical value. Experimental atomic force microscopy observations of this transition have been reported and found to be in good agreement with the calculations.

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ABSTRACT: We establish a quantitative mechanics framework of elastic buckling of a spheroidal thin film/substrate system, which is highly relevant to the morphologies of quite a few natural and biological systems. The anisotropic stress-driven bifurcation is governed by the ratios between the effective size/thickness, the equatorial/polar radii, and the substrate/film moduli. The possibilities of manipulating the undulations through external constraints, anisotropic growth/material properties, and substrate geometry/structure are discussed. Analytical equations correlating the undulation characteristics with the geometry/material properties are derived. The quantitative mechanics framework established herein not only has important implications on the morphogenesis of various fruits, vegetables, nuts, eggs, tissues, and animal body parts, but also could guide the three-dimensional micro-fabrications via controlled self-assembly on curved substrate surfaces.

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ABSTRACT: Mechanical buckling principles of conical film/substrate systems are explored in this study using extensive finite element simulations. The effects of geometrical and material parameters, including cone angle, normalized cone size, film/substrate thickness ratio, and modulus ratio between film and substrate, are explored systematically in terms of the resulting stress anisotropy (in particular the ratio between hoop and longitudinal stresses) and buckling morphology (longitudinal ridges, latitudinal stripes and reticular/herringbone patterns, as well as their transition and branching behaviours). The trends of buckling shape and wave numbers are also explored through analytical solutions of similar hollow cylindrical film/substrate systems. Finally, the mechanical buckling principles are employed to reproduce the morphological features of several types of mollusks, where each distinctive appearance corresponds to certain ranges of material and geometrical parameters. In addition to shedding some light on the morphogenesis of certain natural and biological systems, the study may also provide some useful insights on biomedical engineering and three-dimensional micro-fabrications.


ABSTRACT: The present paper deals with dynamic, coupled buckling of long, prismatic columns simply supported at the ends. This investigation concerns thin-walled structures of a square cross-section with or without intermediate stiffeners under in-plane pulse loading. The dynamic load of a rectangular shape has been assumed in the analysis. The structures are composed of rectangular plates interconnected along longitudinal edges. A plate model is adopted in the analysis. The material of the structure is isotropic. The problem has been investigated on the basis of the disturbance theory. The dynamic critical load factor DLF has been determined using the Budiansky and Hutchinson criterion. The results obtained with the analytical–numerical method (ANM), which employs the asymptotic perturbation theory, have been compared with the finite element method (FEM).


ABSTRACT: The dynamic coupled buckling loads were determined for the columns with intermediate stiffener subjected to in-plane pulse loading. The pulse loading of a rectangular shape was concerned. Columns made of isotropic material were assumed to be simply supported at loaded ends. A plate model was adopted in the analysis. The discussed problem of interactive buckling is solved by the analytical–numerical method (ANM) using Koiter’s perturbations method. The differential equations of motion were obtained from Hamilton’s Principle, taking into account all components of inertia forces. In this study, the interactions of two global modes with two local ones were presented. The results obtained by the analytical–numerical method (ANM) were compared with finite element method (FEM)—ANSYS. The dynamic critical loads using the most popular Budiansky–Hutchinson’s criterion, the Kleiber–Kotula–Saran’s criterion with Kubiak’s modifications and the phase plane criterion were determined. New versions of criteria: Kleiber–Kotula–Saran’s quasi-bifurcation
dynamic criterion and the phase plane criterion were proposed.

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ABSTRACT: The double singularities induced by bifurcation point and boundary layer in non-dimensionalized nonlinear boundary-layer Kármán-Donnell equations for axially compressed stiffened cylindrical shells can be treated by Koiter-boundary layer singular perturbation method in this paper. It is demonstrated that the method has high computing efficiency and accuracy based on the analysis of AS-2 shell, and some new conclusions can be directly obtained from the perturbation formulas which are very well in agreement with experimental phenomenon of axially compressed stiffened cylindrical shells.

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ABSTRACT: This paper presents a finite element investigation of the local buckling behaviour of the structural steel Elliptical Hollow Section (EHS) in compression. The theoretical elastic buckling load of an EHS is similar to that of a Circular Hollow Section (CHS) except that the diameter term, D, is replaced by D12/D2, representing the major and minor diameters of the ellipse. The overall aim is to examine whether an “equivalent CHS” can be used to model the local buckling of EHS when considering imperfections and non-linear material properties. The finite element program ABAQUS was used to examine the local buckling behaviour of EHS with a range of aspect ratios from 1:1 (CHS) to 10:1 to examine the transitional behaviour. Three types of analysis were considered. The first stage was elastic buckling with no material imperfection. The second stage considered inelastic material properties, followed by measured material properties. The final stage was to investigate how geometric imperfection affected the buckling modes. The results are benchmarked against experimental results. It was found that the use of an equivalent CHS was a reasonably good predictor of capacity of slender sections and the deformation capacity of compact sections. However, further benchmarking against experimental results is recommended.

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ABSTRACT: The most up-to-date research in the mechanics of delaminations and related crack-like defects in laminate and fiber composites is discussed. Both internal and near-surface delaminations are considered. In the latter case, local buckling of delaminations and the interaction between buckling, damage accumulation, crack growth and global buckling are considered. The problem of the evaluation of the residual load-carrying capacity of delaminated structural components is discussed, including the assessment of the fracture toughness with respect to impact loading.


ABSTRACT: (not available)


ABSTRACT: Optimal structural design of a noncircular cylindrical shell under overall bending and axial force is considered. The material is assumed to be governed by the Norton nonlinear steady creep law. Minimal cross-sectional area is the design objective, the middle line of the profile and the wall-thickness are the design variables and the constraints refer to local stability of the wall according to Gerard's criterion and to brittle creep rupture as described by the Kachanov-Robinson hypothesis. In view of bending, optimal design requires some concentrated areas (longitudinal ribs) located at the outer fibres of the cross-section.


ABSTRACT: The paper shows the effects of behaviour of loading during the buckling process on the value of critical force and initial stability of post-buckling path for elastic, non-prismatic columns. Perturbation method combined with Croll's manoeuvre makes it possible to derive general formulae for the first or the second correction of the force, and hence to analyze stability in the post-buckling range. The effects of behaviour of active and reactive forces may be essential: in numerous examples the boundary values of structural parameters separating stability and instability are evaluated. Pre-buckling geometry changes are analyzed as well.


ABSTRACT: An efficient numerical algorithm is created on the basis of the method of curvilinear meshes, the method of basis reduction, and the asymptotic Koiter theory. It enables us to study load curves to reveal singular (limit and bifurcation) points and to analyze their behavior at branch points. Such an approach allows analyzing the nonlinear deformation of shell structures of arbitrary form and their sensitivity to imperfections. The technique is illustrated by an example of a conic panel with imperfections in the shape.

E. A. Gotsulyak (National University of Building and Architecture, Kiev, Ukraine), “Mesh Discretization of the

ABSTRACT: Mesh methods for discretization of the differential vector relations are generalized as applied to problems of shell theory. In the finite-difference method, covariant derivatives are replaced by vector differences, which are then projected on the vectors of a local basis. In the finite-element method, vector functions are approximated by a Taylor series with tensor coefficients. It is shown that such schemes satisfy the condition of rigid displacement for a deformable body, which improves considerably the convergence of the solution. The proposed schemes, which are sensitive to approximation uncertainties, were tested by solving problems on deformation of shells.


ABSTRACT: Using detailed finite element models, compressive failure mechanisms of composite structures consisting of many laminae are analyzed. It is assumed that the structures contain interlaminar delamination and their failure mode to be characterized by either buckling or delamination growth. Our primary goal is to identify the effects of delamination and ply-arrangement on the multi-layered structures. Up to 32 laminae are distinctly modeled in this investigation. Our study considers two most basic geometry; one is flat panels under compressive load and the other is cylindrical shells subjected to external pressure. In both cases, the energy release rate and mixed-mode stress intensity factors are computed to quantify the crack driving force. The results are used to determine dominant failure initiation mode, structural buckling or delamination growth. Regardless of the structural type and total number of layers, a significant reduction in the load carrying capacity may occur when interlaminar delamination exists. In the flat panels, interlaminar delamination can generate unstable post-buckling behavior and lower the steady-state post-buckling load. However, delamination growth does not likely to occur during the pre-buckling stage. For the cylindrical shells, delamination growth may initiate prior to structural buckling. The location of delamination also plays an important role in defining the critical crack initiation load. When the delamination is located within 25% to 40% of shell thickness measured from the outer surface, the crack initiation load can be as low as half of the buckling load. In both types of structures, as the total number of plies increases, the layer effect diminishes. The overall deformation and failure behaviors of panels with large number of layers approach those of the infinite-layer model with homogenized material properties.

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ABSTRACT: The thin-walled composite columns with an open cross-section reinforced by intermediate stiffener under axial compression have been considered. The finite element method is employed to study the buckling behaviour of the thin-walled composite column. Eigenvalue analyses are carried out first to predict the buckling load and buckling mode shapes of the column, and then the geometric nonlinear analyses are performed to investigate the nonlinear buckling properties and post-buckling behaviour of the thin-walled
structures. The type of angle ply symmetric laminate is used. The investigation is performed over several values of ply arrangement angle and various values of stiffener parameter. The numerical results show a significant effect of the intermediate stiffeners and composite ply angle on loading capacity and buckling behaviour of the thin-walled composite column. The research provides insight into the thin-walled structure and composite laminate, which is employed to enhance the loading capacity of thin-walled composite structures.

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ABSTRACT: Based on the J_2 flow theory, an analysis is presented of the initial postbuckling behavior of circular cylindrical shells subjected to external pressure by using Hutchinson's general method. The elastic-plastic material forming the shells is taken to have an arbitrary strain-hardening exponent. It is shown that plastic deformation must be taken into account if the shells have a diameter-thickness ratio of less than 40. This kind of shell has a different postbuckling behavior from thin cylindrical shells and its imperfection-sensitivity is strong.

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ABSTRACT: A model of a column is proposed in order to analyse the post-buckling behaviour of a structural element in the elastic-plastic deformation range. The ideal two point I-section applied here simplifies the deformation analysis, that is, the problem of development of plastic zones in a section is eliminated, but still
gives the possibility for qualitative analysis and optimization of the post-critical equilibrium paths. The coefficients of linear or parabolic variability of thickness of the flanges and their distance (web width) are accepted as model parameters and hence could be used for design variables in the optimization procedure. Moreover, the stiffness of an additional elastic support of the free end of the beam is also included as a parameter or design variable. A material model is employed with non-linear asymptotic isotropic hardening without the Bauschinger effect. Change of the tangent modulus is continuous and smooth during the transition from the elastic to plastic deformation range. The main goal of the analysis is to determine the values of the design variables for which the post-critical equilibrium paths are stable at least in the specified range of a generalized displacement. The constraints for the constant volume of the flanges and web material are applied. The inequality constraints are imposed on the flange thickness and web width. Various formulations of the optimization problem are proposed for all types of non-linear behaviour, including elastic or plastic buckling and elastic or elastic-plastic post-buckling deformation.

ABSTRACT: A perturbation method based on the static stability criterion associated with the vanishing of the total potential energy on a certain equilibrium point on the unstable postbuckling path is presented for the determination of lower bound dynamic buckling loads of imperfection-sensitive structures under step load of infinite duration. Attention is focused on the effect of various possible sources of structural imperfections on the dynamic buckling strength of perfect structures. Under the assumption that the effect of structural imperfections is of the first order, the method can give any desired higher-order approximation to the lower bound dynamic buckling loads and the corresponding displacements without solving the system of differential equations of motion numerically. Especially, the method applies to finite-degree-of-freedom systems as well as continuous ones. The application of the method is illustrated on two examples. The results demonstrate the significant effect of other imperfection sources, besides the shape imperfections having the shape of the classical buckling mode.

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“A Simplified Model to Simulate Crash Behavior of Honeycomb”, Proceedings of the International conference on Advanced Design and Manufacture 8th-10th January, 2006, Harbin, China
ABSTRACT: Although to have an accurate result of Finite Element analysis of a system is always enviable, on most of engineering problems it is worthwhile to find simpler models with less required time to solve and acceptable degree of accuracy those keep the general characteristics of system. Available numerical methods, however consider effect of different characters like air drainage and adhesive influence on crash behavior of honeycomb, but usually these assumptions are not applicable on big models especially when a complicated geometry is appraised. This paper validates a simple Finite Element model for honeycomb witch has an acceptable accuracy in crash analysis and is easily applicable on intricate problems. This model is desirable not only for simple honeycomb systems but also for sophisticated samples such as multi-layer or multi-material honeycomb based structures. A comparison with experimental results shows good rate of exactitude for new
References listed at the end of the paper:


ABSTRACT: In the aeronautical field, sandwich structures are widely used for secondary structures like flaps or landing gear doors. The modeling of low velocity/low energy impact, which can lead to a decrease of the structure strength by 50%, remains a designer’s main problem. Since this type of impact has the same effect as quasi-static indentation, the study focuses on the behavior of honeycomb cores under compression. The crushing phenomenon has been well identified for years but its mechanism is not described explicitly and the model proposed may not satisfy industrial purposes. To understand the crushing mechanism, honeycomb test specimens made of Nomextrade, aluminum alloy and paper were tested. During the crushing, a CCD camera showed that the cell walls buckled very quickly. The peak load recorded during tests corresponded to the buckling of the common edge of three honeycomb cells. Further tests on corner structures to simulate only one vertical edge of a honeycomb cell show a similar behavior. The different specimens exhibited similar load/displacement curves and the differences observed were only due to the behavior of the different materials. As a conclusion of this phenomenological study, the hypothesis that loads are mainly taken by the vertical edge can be made. So, a honeycomb core subjected to compression can be modeled by a grid of nonlinear springs. A simple analytical model was then developed and validated by tests on Nomextrade honeycomb core indented by different sized spherical indenters. A good correlation between theory and experiment was found. This result can be used to satisfactorily model using finite elements the indentation on a sandwich structure with a metallic or composite skin and honeycomb core.

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ABSTRACT: Presented in the following pages is an experimental and numerical study of dynamic local buckling of skin on foam core. Impact tests on sandwich-type structures with skins stabilized by foam demonstrated that rupture appears by debonding of skins due to a local buckling phenomenon, and that the maximum stress in the skin, obtained at rupture, grows with the increase of the loading rate of the skin. A finite element analysis allows this phenomenon to be analyzed and understood, and a mass-spring-dashpot model is proposed to model the skin debonding initiation.

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ABSTRACT: This paper investigates the non-linear dynamic behavior and stability of the internal membrane of a ventricular assist device (VAD). This membrane separates the blood chamber from the pneumatic chamber, transmitting the driving cyclic pneumatic loading to blood flowing from the left ventricle into the aorta. The membrane is a thin, nearly spherical axi-symmetric shallow cap made of polyurethane and reinforced with a cotton mesh. Experimental evidence shows that the reinforced membrane behaves as an isotropic elastic material and exhibits both membrane and flexural stiffness. So, the membrane is modeled as an isotropic pressure loaded shallow spherical shell and its dynamic behavior and snap-through buckling considering different types of dynamic excitation relevant to the understanding of the VAD behavior is investigated. Based on Marguerre kinematical assumptions, the governing partial differential equations of motion are presented in the form of a compatibility equation and a transverse motion equation. The results show that the shell, when subjected to compressive pressure loading, may lose its stability at a limit point, jumping to an inverted position. If the compressive load is removed, the shell jumps back to its original configuration. This non-linear behavior is the key feature in the VAD behavior.


ABSTRACT: A combined experimental/finite element effort is carried out to elucidate the post buckling response of unilaterally constrained plates under monotonically increasing edge thrust. Real time observations, together with a wide range of plate aspect ratio and a large load level facilitate deep physical insight into the general behavior of this class of problems. The interaction of the plate with the rigid restraining plane following
buckling leads to interesting deformation sequences, characterized by the development of asymmetric bulges and contact zones following by a possible plate snapping. The latter is motivated by a secondary buckling evolving gradually from a contact zone(s) or a bulge(s). These two instability mechanisms are competitive, being dictated by the plate aspect ratio and other system parameters. The critical load for plate snapping agrees well with a finite element prediction based on an asymmetric deformation choice that minimizes the strain energy in the plate. A semi analytic relation for predicting the onset of secondary instability in the contact area and subsequent plate snapping is developed based on the numerical results. Finally, the present work seems to add a new dimension into the fracture of coatings and laminated composites containing near-surface defects.

References listed at the end of the paper:
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“Research Situation of the Unilateral Contact Buckling of Thin Wall Steel-Concrete Composite Panels”,
Advanced Materials Research (Volumes 255 - 260), pp. 333-337, May 2011,
10.4028/www.scientific.net/AMR.255-260.333

ABSTRACT: Thin wall steel-concrete composite wall panels can be used as bearing member and also as maintenance structural plates, which can satisfy functional requirements of building including bearing capacity, heat insulation and preservation. The problem relating unilateral contact buckling of thin wall steel composite panels has received attention from many construction engineers. The investigation progress is analyzed in general and the investigation questions are illustrated. The research approach and technical routes of delaminated critical load are also presented.


ABSTRACT: This paper comprises results which have been obtained in the course of studies on a unified approach to a variety of current static and dynamic problems of inelastic solids and structures. The objective of the first part of the paper is to review some concepts of constitutive and finite element modelling for novel plasticity applications. The specific topics covered here are: large elastic-plastic strains with infinitesimal or finite elastic strain contribution, non-associated viscous and non-viscous plasticity as applied to void-containing metals, and temperature and creep effects. The discussion to follow is aimed at showing the great potential of finite-element time stepping schemes in solving problems of structural and mechanical engineering. The numerical illustrations encompass a diversity of large scale computations such as geometrically and materially nonlinear analysis of frames and shells and bifurcation analysis in void-containing metals.


ABSTRACT: The general problem of sizing, material selection, load parameter and shape sensitivity of non-linear structural response is considered. The non-linear sensitivity path is followed by an incremental strategy employing the continuum-based updated Lagrangian description. The resulting finite element equations are derived. Both the direct differentiation and adjoint structure strategies are considered. The merits of using the consistent tangent matrix for sensitivity calculations are indicated. The formulation employs the so-called reference volume concept and may be seen as a further attempt to unify the shape and non-shape sensitivity analysis procedures.
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(2) Technical University of Szczecin, Piastow 41, 71-065, Szczecin, Poland
ABSTRACT: This paper is concerned with recent sensitivity results for buckling and post-buckling problems. The article starts with an overview of the FEM-based approach to inelastic structural mechanics systems with singular points along the equilibrium path. The existing sensitivity techniques are reviewed, their inherent drawbacks are indicated and a new methodology is suggested. The discretized formalism is mainly employed throughout but a continuum formulation appropriate for this class of problems is also given. Numerical studies illustrate the presentation.

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ABSTRACT: The Canadian Forces (CF) and the US Interagency Ship Structure Committee (SSC) jointly sponsored a full-scale testing project to study the load-carrying characteristics of single stiffened panels under different load combinations and with various types of damage. A full-scale testing system was designed and constructed, in which the stiffened panel was simply supported by cylindrical bearings at both ends and restrained by discrete carriages along the sides to simulate the boundary conditions resulting from a grillage environment in ship hull structures. Twelve full-scale panels, including seven “as-built”, two “dented” and three “corroded” specimens, were tested in this set-up. In the meantime, a series of nonlinear finite element analyses were conducted to simulate the test procedure and predict the collapse loads and buckling behavior of these stiffened panels. The finite element models were established by a direct mapping of measured imperfections to nodal points. Residual stresses were introduced using a thermal stress analysis procedure. For models with spatial discontinuities, locally refined meshes and the branch shifting technique were used to achieve the desired failure modes. In this paper, the finite element solutions are presented in detail and compared with the test observations. The good agreement between the experimental and numerical results indicates that the nonlinear finite element method is capable of predicting plastic post-buckling behavior of stiffened panel structures.

doi: 10.1002/nme.157
ABSTRACT: A method to analyse and solve symmetric bifurcations by establishing the bifurcation equations using an asymptotic expansion method is presented. The bifurcation equations are obtained using a decomposition of the spaces by means of the theory of Lyapunov–Schmidt. To solve the bifurcation equations an asymptotic expansion method along the lines of Koiter is applied. The expansion is presented in a form suited for implementation in a finite element context. The present paper is focused on the treatment of symmetric multiple bifurcations where new forms of the bifurcation equations are established. The accuracy of
the method is verified with three examples.


ABSTRACT: A nonlinear finite strip method of analysis is described for the post-local buckling of geometrically imperfect plate assemblies. The method is used to provide an accurate alternative to the Winter effective width formula for obtaining the effective section of a simply supported I-beam in the post-local buckling range of structural response. The effective section of a locally buckled beam with thin flange outstands is used to investigate the resistance of the beam to flexural-torsional buckling. The analytical methods developed to assess the nonlinear interaction of local and lateral buckling are compared with experimental tests performed by Cherry.


ABSTRACT: A finite strip method of analysis is presented for the inelastic local buckling of I-beams fabricated by welding. Stiffness and stability matrices for the section are developed at a monotonically increasing load factor, and the critical moment is that for which the buckling determinant vanishes. Critical moments determined in this way are shown to agree well with test results. The limiting depth-to-thickness ratios for the web which correspond to compact and semi-compact sections are investigated, and it is shown that the values given in BS 5950: Part I are unconservative for an extensive range of section geometries. Based on a parametric study, alternative and more accurate formulations for the critical web slendernesses are proposed.


ABSTRACT: The semi-analytical complex finite strip method is used to study the elastic local buckling of I-sections in bending containing a longitudinal stiffener attached to the web. The optimum position of this stiffener is calculated to maximise the web local buckling stress. The local buckling of the stiffener is then considered, and recommendations are made regarding the stiffener proportions that would cause yield of the stiffener before it buckled locally.


ABSTRACT: A complex finite strip method of analysis that includes inelasticity is described. The finite strip displacement functions are augmented with so-called bubble functions, which are extra modes associated with internal or nodeless degrees-of-freedom. It is shown that the use of bubble functions significantly improves the convergence of the inelastic finite strip method. The analytical procedure is then used to study the inelastic local buckling of plates in compression and shear, stiffened plates in compression and I-section beams in shear.
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ABSTRACT: A modified semi-analytical finite strip method of buckling analysis in which the usual restriction of two, opposite, simply supported ends is removed by assuming appropriate longitudinal functions is described. Two sets of basic functions (denoted I and II) are used in the buckling study and the accuracy of these basic functions is evaluated. It is shown that the use of so-called bubble functions significantly improves the convergence of the finite strip method for local buckling problems. The analytical procedure is used to investigate the local buckling behaviour of isotropic plates with different boundary conditions along all edges under both uniaxial and biaxial compression, and the buckling of stiffened plates under compression. The bubble formulation provides a powerful tool for the efficient analysis of a variety of local buckling problems.

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ABSTRACT: This paper is concerned with the inelastic local buckling of flat plate structures that contain plates with variable thicknesses. Use is made of the semi-analytical complex finite strip method, which is augmented with transverse bubble functions. Stiffness and stability matrices are derived for inclusion in the finite strip method, which is based on the deformation theory of plasticity. The numerical scheme is programmed, and several numerical examples are presented to illustrate the prowess and scope of the procedure. The inelastic local buckling of tapered plates subjected to compression and shear with different boundary conditions is studied first, and the method is then applied to the inelastic local buckling of channel sections with tapered flanges and stiffened plates with variable thickness and different geometries. Slenderness limits for channels that delineate between local buckling and yield (and that define the transition from non-compact to slender cross-sections) are discussed.

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ABSTRACT: Reinforced concrete cooling towers of hyperbolic shell configuration find widespread application in utilities engaged in the production of electric power. In designing critical civil infrastructure of this type, it is imperative to consider all of the possible loading conditions that the cooling tower may experience. One important loading condition in many nations is that of earthquake excitation, whose influence on the integrity and stability of cooling towers is profound. Previous research has shown that the columns supporting a cooling tower are sensitive to earthquake forces, as they are heavily loaded elements that do not possess high ductility,
and understanding the behaviour of columns under earthquake excitation is vital in structural design because they provide the load path for the self weight of the tower shell. This paper presents the results of a finite element investigation of a representative “dry” cooling tower, using realistic horizontal and vertical acceleration data obtained from the recent and widely-reported Tabas, Nahgan and Bam earthquakes in Iran. The results of both linear and nonlinear analyses are reported in the paper, the locations of plastic hinges within the supporting columns are identified and the ramifications of the plastic hinges on the stability of the cooling tower are assessed. It is concluded that for the (typical) cooling tower configuration analysed, the columns that are instrumental in providing a load path are influenced greatly by earthquake loading, and for the earthquake data used in this study the representative cooling tower would be rendered unstable and would collapse under the earthquake forces considered.

References listed at the end of the paper:

ABSTRACT: Elliptical tubes may buckle in an elastic local buckling failure mode under uniform compression. Previous analyses of the local buckling of these members have assumed that the cross-section is hollow, but it is well-known that the local buckling capacity of thin-walled closed sections may be increased by filling them with a rigid medium such as concrete. In many applications, the medium many not necessarily be rigid, and the infill can be considered to be an elastic material which interacts with the buckling of the elliptical tube that surrounds it. This paper uses an energy-based technique to model the buckling of a thin-walled elliptical tube containing an elastic infill, which elucidates the physics of the buckling phenomenon from an engineering mechanics basis, in deference to a less generic finite element approach to the buckling problem. It makes use of the observation that the local buckling in an elliptical tube is localised with respect to the contour of the ellipse in its cross-section, with the localisation being at the region of lowest curvature. The formulation in the paper is algebraic and it leads to solutions that can be determined by implementing simple numerical solution techniques. A further extension of this formulation to a stiffness approach with multiple degrees of buckling freedom is described, and it is shown that using the simple one degree of freedom representation is sufficiently accurate for determining the elastic local buckling coefficient.

References listed at the end of the paper:

ABSTRACT: Elliptical tubes may buckle in an elastic local buckling failure mode under uniform compression. Previous analyses of the local buckling of these members have assumed that the cross-section is hollow, but it is well-known that the local buckling capacity of thin-walled closed sections may be increased by filling them with a rigid medium such as concrete. In many applications, the medium many not necessarily be rigid, and the infill can be considered to be an elastic material which interacts with the buckling of the elliptical tube that surrounds it. This paper uses an energy-based technique to model the buckling of a thin-walled elliptical tube containing an elastic infill, which elucidates the physics of the buckling phenomenon from an engineering mechanics basis, in deference to a less generic finite element approach to the buckling problem. It makes use of the observation that the local buckling in an elliptical tube is localised with respect to the contour of the ellipse in its cross-section, with the localisation being at the region of lowest curvature. The formulation in the paper is algebraic and it leads to solutions that can be determined by implementing simple numerical solution techniques. A further extension of this formulation to a stiffness approach with multiple degrees of buckling freedom is described, and it is shown that using the simple one degree of freedom representation is sufficiently accurate for determining the elastic local buckling coefficient.

References listed at the end of the paper:


ABSTRACT: The accuracy of stability analysis depends on the accuracy of both the element stiffness matrix and geometry stiffness matrix. Therefore, when carrying out the stability analysis of thin cylindrical shells using the finite element methods will require, firstly, a refined non-conforming rectangular curved cylindrical shell element RCSR4 is proposed according to the refined non-conforming FE method, in which both the C1 and C0 weak continuity conditions are satisfied and as a result, can ensure the convergence of computation. At the same time, a refined geometrical stiffness matrix is introduced to replace the standard consistent geometrical stiffness matrix. Simple expressions of the refined constant strain matrices with adjustable constants are introduced with respect to the weak continuity conditions. Numerical examples are presented to show that the present method can indeed improve the performance and the accuracy in stability analysis.


ABSTRACT: A refined non-conforming triangular plate/shell element for geometric non-linear analysis of plates/shells using the total Lagrangian/updated Lagrangian approach is constructed in this paper based on the refined non-conforming element method for geometric non-linear analysis. The Allman's triangular plane element with vertex degrees of freedom and the refined triangular plate-bending element RT9 are used to construct the present element. Numerical examples demonstrate that the accuracy of the new element is quite high in the geometric non-linear analysis of plates/shells.


ABSTRACT: A refined non-conforming triangular plate/shell element for linear and geometrically nonlinear analysis of plates and shells is developed in this paper based on the refined non-conforming element method (RNEM). A conforming triangle membrane element with drilling degrees of freedom in Cartesian coordinates and the refined non-conforming triangular plate-bending element RT9, in which Kirchhoff kinematic assumption was adopted, are used to construct the present element. The displacement continuity condition along the interelement boundary is satisfied in an average sense for plate analysis, and the coupled displacement continuity requirement at the interelement is satisfied in an average sense, thereby improving the performance.
of the element for shell analysis. Selectively reduced integration with stabilization scheme is employed in this paper to avoid membrane locking. Numerical examples demonstrate that the present element behaves quite satisfactorily either for the linear analysis of plate bending problems and plane problems or for the geometrically nonlinear analysis of thin plates and shells with large displacement, moderate rotation but small strain.


ABSTRACT: We present in this research article, the improvements that we made to create a four nodes flat quadrilateral shell element for geometrically nonlinear analysis, based on corotational updated lagrangian formulation. These improvements are initially related to the improvement of the in-plane behaviour by incorporation of the in-plane rotational degrees of freedom known as “drilling degrees of freedom” in the membrane displacements field formulation. In the second phase, a co-rotational spatial local system of axes which adapts well to the problems of quadrilateral elements is adopted, while ensuring simplicity and effectiveness at numerical level. The required goal being mainly to have a robust thin shell element associated with a simplified formulation. The obtained element remains economic, and showing a robust behaviour in delicate situations of tests.


ABSTRACT: This paper proposes a simple and accurate 4-node, 24-DOF layered quadrilateral flat plate/shell element, and an efficient nonlinear finite element analysis procedure, for the geometric and material nonlinear analysis of reinforced concrete cylindrical shell and slab structures. The model combines a 4-node quadrilateral membrane element with drilling or rotational degrees of freedom, and a refined nonconforming 4-node 12-DOF quadrilateral plate bending element RPQ4, so that displacement compatibility along the interelement boundary is satisfied in an average sense. The element modelling consists of a layered system of fully bonded concrete and equivalent smeared steel reinforcement layers, and coupled membrane and bending effects are included. The modelling accounts for geometric nonlinearity with large displacements (but moderate rotations) as well as short-term material nonlinearity that incorporates tension, cracking and tension stiffening of the concrete, biaxial compression and compression yielding of the concrete and yielding of the steel. An updated Lagrangian approach is employed to solve the nonlinear finite element stiffness equations. Numerical examples of two reinforced concrete slabs and of a shallow reinforced concrete arch are presented to demonstrate the accuracy and scope of the layered element formulation.

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“Recent developments in finite element analysis for laminated composite plates”, Composite Structures, Vol.88,
ABSTRACT: A review of the recent development of the finite element analysis for laminated composite plates from 1990 is presented in this paper. The literature review is devoted to the recently developed finite elements based on the various laminated plate theories for the free vibration and dynamics, buckling and postbuckling analysis, geometric nonlinearity and large deformation analysis, and failure and damage analysis of composite laminated plates. The material nonlinearity effects and thermal effects on the buckling and postbuckling analysis, the first-ply failure analysis and the failure and damage analysis were emphasized specially. The future research is summarised finally.

Zora Vrcelj and Mark Andrew Bradford (School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia), “A simple method for the inclusion of external and internal supports in the spline finite strip method (SFSM) of buckling analysis”, Computers & Structures, Vol. 86, No. 6, March 2008, pp. 529-544, Special Issue: Civil-Comp, doi:10.1016/j.compstruc.2007.05.001

ABSTRACT: The SFSM is an attractive numerical technique for the buckling analysis of folded-plate structures where general loading regimes and boundary conditions need to be modelled. In implementing splines as interpolation functions in the longitudinal direction of the strip, amended splines have been used conventionally to model the variety of end conditions that may occur. These amended splines are fairly difficult to implement, particularly so if internal restraints are also to be specified. A simple technique for replacing the specification of dedicated amended splines is presented in this paper. The method is then employed to study the local buckling of flat plates under longitudinally and transversely varying compression and bending with different boundary conditions at the ends.


PARTIAL ABSTRACT: This paper presents a nonlinear inelastic analysis of the biaxial bending and torsion of thin-walled steel beam-columns based on the principle of virtual work. The effect of geometric nonlinearity is developed using position vector analysis. Approximations are not made in the early stage of the development, and thus some significant terms for buckling and postbuckling analysis are retained. The von Mises yield criterion, the associated flow rule, and the hardening rule are used in formulating the elastic-plastic constitutive matrix for the ...


PARTIAL ABSTRACT: This paper investigates the non-linear in-plane buckling and postbuckling behaviour of elastic arches using a curved finite element model for the non-linear analysis of elastic arches, which includes the effects of prebuckling deformations and second-order terms in the deformed curvatures and bending strains. It is found that the effects of prebuckling deformations on the buckling of shallow arches are significant, that the existence of a linear bifurcation buckling load is not a sufficient condition for linear bifurcation buckling to occur, ...


ABSTRACT: Many design codes do not give methods for designing steel arches against in-plane failure. The
few that do provide methods that are essentially based on a linear interaction equation for the in-plane strengths of an equivalent beam-column, which uses the maximum elastic bending moment and axial compression in the arch. However, the linear interaction equation for a beam-column may not be suitable for an arch because it does not consider the strength characteristics of steel arches. This paper studies the in-plane buckling of arches in uniform compression and uses a nonlinear inelastic finite-element model to develop a method for designing steel arches against uniform compression, and also to develop an interaction equation for the design of steel arches against nonuniform in-plane compression and bending. Analytical solutions for the buckling loads of shallow arches in uniform compression are obtained. It is found that the design equation for steel columns cannot be used directly for steel arches in uniform compression, nor can the design interaction equations for steel beam-columns be used directly for steel arches under nonuniform compression and bending. The proposed design equations provide close predictions for the in-plane buckling strengths of both shallow and nonshallow steel arches in uniform compression. The modified interaction equation proposed provides good lower bounds for the in-plane strengths of both shallow and nonshallow steel arches in bending and compression because it considers the nonuniform distributions of the bending moment and axial compression around the arch, the behavior of shallow arches, and the favorable moment redistribution after the first hinge forms.

References listed at the end of the paper (cannot cut and paste easily)


PARTIAL ABSTRACT: Classical buckling theory is mostly used to investigate the in-plane stability of arches, which assumes that the pre-buckling behaviour is linear and that the effects of pre-buckling deformations on buckling can be ignored. However, the behaviour of shallow arches becomes non-linear and the deformations are substantial prior to buckling, so that their effects on the buckling of shallow arches need to be considered. Classical buckling theory which does not consider these effects cannot correctly predict the in-plane buckling load.


ABSTRACT: When a shallow arch is subjected to an in-plane load that is applied suddenly, the arch will oscillate about an equilibrium position due to the kinetic energy imparted to the arch by the sudden load. If the suddenly applied load is sufficient large, the motion of the arch may reach an unstable equilibrium position, leading to dynamic buckling of the arch. This paper presents a study of the dynamic in-plane buckling of a shallow pin-ended circular arch under a central radial load that is applied suddenly with infinite duration. The method of conservation of energy is used to establish the criterion for dynamic buckling of the shallow pin-ended arch and analytical solutions for the lower and upper dynamic buckling loads of the arch under this sudden central load with infinite duration are obtained. It is found that the dynamic buckling loads of a shallow pin-ended arch under a sudden central load with infinite duration are lower than its static buckling loads, and that the dynamic buckling load increases with an increase of a dimensionless arch geometric parameter that is introduced. The effect of static preloading on the dynamic buckling of a shallow pin-ended arch is also investigated. It is found that the pre-applied static load decreases its dynamic buckling loads, but increases the sum of the pre-applied load and the dynamic buckling load.
ABSTRACT: The nonlinear long-term buckling behaviour (creep buckling) of spherical shallow, thin-walled concrete shells of revolution (including domes) subjected to sustained loads is investigated herein. A thorough understanding of their nonlinear time-dependent behaviour, as well as the development of comprehensive analytical models for their analysis, has hitherto not been fully established and further studies are required. A nonlinear axisymmetric theoretical model, which accounts for the effects of creep and shrinkage, and which considers the ageing of the concrete material and the variation of the internal stresses and geometry in time, is developed for this purpose. The governing field equations are derived using variational principles, equilibrium requirements, and integral-type constitutive relations. A systematic step-by-step procedure is used for the solution of the integral-type governing equations. First, the nonlinear short-term behaviour is studied to provide a benchmark for the long-term analysis. Different theories for the analysis of the shell structure are examined for this purpose and compared with results obtained by the finite element method. A numerical study, which highlights the capabilities of the nonlinear theoretical model and which provides insight into the nonlinear long-term behaviour of shallow concrete domes, is presented. The results show that long-term effects are critical for the design and structural safety of shallow, thin-walled concrete domes, and so these effects need to be fully understood and quantifiable.

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ABSTRACT: Ultimate strength tests on stiffened plates simply supported on all four edges and sub jetted to the combined action of axial and lateral loads are reported. A series of 10 stiffened plates having two different plate slenderness values were tested to failure under different combinations of axial and lateral loads. A description of test procedure is also presented. The test specimens were analysed by using the elasto-plastic finite element package to determine the behaviour and ultimate load capacity of stiffened panels and the comparison of these results with those obtained experimentally established the accuracy of the finite element modelling. In addition, stiffened plates tested by other researchers have been analysed to examine the behaviour of stiffened plates under combined loading.

ABSTRACT: From the mathematical standpoint one has a partial differential equation with variable coefficients. Perturbation procedure gives the possibility for an analytical solution of this eigenvalue problem. Self-adjoint equations and Padé approximants are used for improving the obtained results.
ABSTRACT: The coupled system of three partial differential equations governing a flexible shallow shell dynamics is analysed. No any prior assumptions about the temperature distribution through the shell thickness are applied. The efficiency of the method used here when applied to the solution of integral–differential equations with different dimensions (three-dimensional equations related to the Kirchhoff–Love model) and of different type (heat transfer equations and the hyperbolic equations of shell theory) is demonstrated. Many computational results are reported and discussed.


INTRODUCTION: The widest class of shells used in the civil and mechanical engineering is the class of shells with developable principal surface. The stress-strain state of shell structures under loads, which corresponds to buckling, is inhomogeneous, significantly bended, and nonlinear. Permanent interest of researchers in the problem of inhomogeneous compression of shells of zero Gaussian curvature has not led so far to a correct solution. Therefore, there is a need for the development and application of new methods that allow considering...
the problem in a complex setting, the most appropriate to study real behavior of structures. The approximate analytic integration of nonlinear differential equations of the theory of flexible elastic shells in most practical cases is based on the method of continuation of solution on the artificially introduced parameter. They can be satisfactorily applied only with an effective method of summation. The most natural analytical continuation method is that using Padé approximants (PAs). PAs effectively solves the problem of analytical continuation of power series, and this is a basis of their successful application in the study of applied problems. Currently, the method of PAs is one of the most promising non-linear methods of summation of power series, and the localization of its singular points. Recently, the method of PAs for single-variable functions has been successfully extended to the approximation of two variable functions (2D PAs). A method that provides polynomial asymptotics of the exact solution of the general form and its meromorphic continuation based on 2D Padé approximants is proposed in this work. Several examples of displacements, stability and vibration calculations for inhomogeneous loaded shells with developable principal surface are presented. The accuracy of 2D PAs theoretical results are confirmed by experiments with stainless steel specimens based on holographic interferometry. It is shown that the application of PAs provides sufficient accuracy in the studied area that confirms the advantage of our proposed approach.

References listed at the end of the paper:


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ABSTRACT: Nonlinear behaviour of flexible shallow rectangular spherical panels subjected to a uniformly distributed transversal load is analysed. Detection of bifurcation points and construction of bifurcation branches on a ‘load–deflection’ characteristic are mainly addressed. The proposed algorithm is based on a set-up method. Geometrical parameters of shallow shells bifurcations are estimated numerically, and an evolution of bifurcation diagrams vs geometrical parameters kx, ky is traced. An increase of geometrical parameters yields an increase of the set of solutions. Besides symmetrical ones, unsymmetrical solutions are detected, illustrated, and discussed as well.

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ABSTRACT: By the variational principle, the chaotic vibrations of deterministic geometrically nonlinear elastic spherical and conical axially symmetric shells with non-homogeneous thickness subjected to a transversal harmonic load are analyzed. The material of the shells is assumed to be isotropic and of the Hookean type. Inertial forces tangent to the averaged surface and inertia of rotation of the cross-section are neglected. By the Ritz procedure, the original PDEs are transferred to the ODEs (Cauchy problem), which are then solved by the fourth-order Runge–Kutta method. In the numerical studies, scenarios of transitions from harmonic to chaotic states for vibrations of flexible spherical and conical shells are detected. Various vibrational states for different combinations of the following control parameters: shell's deflection arrow, the amplitude and frequency of the exciting force, number of modes considered, boundary conditions, and the thickness and shape of the shell cross-section are studied. By adjusting the above parameters, we can detect the transition of a continuous system to the lumped one, and the transition from the harmonic to chaotic vibrations.

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ABSTRACT: A geometrically non-linear theory is presented for the dynamic analysis of thin, circular cylindrical shells which have wafer, stronger or ring stiffening. An asymptotic procedure is followed which separates the solution of the non-linear equations of motion into two parts, an inner part which applies to the boundary layer, and an outer part. The resulting approximate equations are relatively simple to deal with. A numerical example is solved for the free vibrations of a simply supported, stringer-stiffened shell.

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ABSTRACT: Engineering approach for computation of stringer stiffened cylindrical shells is realized mainly using the structurally orthotropic theory with momentless pre-buckling state. On the other hand, experimental results suggest that in many cases the mentioned theory provides excessive values of buckling load. The influence of imperfections for stringer stiffened shells seems to be less important than in an isotropic case. Considering axially symmetric momentous components of pre-buckling state cannot essentially improve theoretical results. Specific experiments showed a significant influence of stringer discreteness on the buckling loads of reinforced shells. The mentioned influence can be divided into two parts: excitation of essentially non-axially symmetric pre-buckling and buckling states. Usually, only the latter phenomenon is taken into account. In this paper we show that the first factor dominates. We propose simple analytical expressions governing non-axially symmetric pre-buckling state components. We also propose an asymptotic simplification of the buckling boundary value problem. Results obtained are compared numerically with the known theoretical and experimental data.

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ABSTRACT: This paper provides a state-of-the-art review of asymptotic methods in the theory of plates and shells. Asymptotic methods of solving problems related to theory of plates and shells have been developed by many authors. The main features of our paper are: (i) it is devoted to the fundamental principles of asymptotic approaches, and (ii) it deals with both traditional approaches, and less widely used, new approaches. The authors have paid special attention to examples and discussion of results rather than to burying the ideas in formalism, notation, and technical details.

References listed at the end of the paper:


ABSTRACT: The method of asymptotic expansions, with the thickness as the parameter, is applied to the nonlinear, three-dimensional, equations for the equilibrium of a special class of elastic plates under suitable loads. It is shown that the leading term of the expansion is the solution of a system of equations equivalent to those of von Kármán. The existence of solutions of this system is established. It is also shown that the displacement and stress corresponding to the leading term of the expansion have the specific form generally assumed in the usual derivations of the von Kármán equations; in particular, the displacement field is of Kirchhoff-Love type. This approach also clarifies the nature of admissible boundary conditions for both the von Kármán equations and the three-dimensional model from which these equations are obtained. A careful discussion of the limitations of this approach is given in the conclusion.

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ABSTRACT: Complex vibrations of closed cylindrical shells of infinite length and circular cross-section subjected to transversal local load in the frame of the classical non-linear theories are studied. A transition from partial differential equations (PDEs) to ordinary differential equations (ODEs) is carried out using a higher-order Bubnov-Galerkin approach and Fourier representation. On the other hand, the Cauchy problem is solved using the fourth-order Runge-Kutta method. In the first part of this work, static problems of the theory of closed cylindrical shells are studied. Reliability of the obtained results is verified by comparing them with the results taken from literature. The second part is devoted to the analysis of stability, bifurcation and chaos of closed cylindrical shells. In particular, an influence of sign-changeable external pressure and the control parameters
such as magnitude of pressure measured by \( \phi_0 \), relative linear shell dimension \( \lambda = \frac{L}{R} \), frequency \( \omega \), and amplitude \( q_0 \) of external transversal load, on the shell's non-linear dynamics is studied.

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"A mechanical basis for chromosome function", Proceedings of the National Academy of Sciences of the United States of America (PNAS), PNAS August 24, 2004 vol. 101 no. 34 12592-12597, 10.1073/pnas.0402724101

ABSTRACT: We propose that chromosome function is governed by internal mechanical forces generated by programmed tendencies for expansion of the DNA/chromatin fiber against constraining features. Chromosomal processes are generally considered to comprise the simple sum of a large number of individual biochemical changes. We present here a different idea in which internal mechanical forces play a governing role.

CONCLUSION: We propose that basic chromosome function is governed by internally generated mechanical forces generated by tendencies for DNA/chromatin expansion. An attractive feature of this model is that the DNA plays a governing role not only via its information content but also via its intrinsic mechanical properties.


ABSTRACT: Design formulas for calculating the critical stresses of unreinforced and reinforced cylindrical shells in axial compression are derived by analyzing experimental data. The curves obtained with the formulas bound the experimental data from below.

References listed at the end of the paper:


ABSTRACT: The nonlinear resonance properties of cylindrical shells filled with a fluid are experimentally studied. It is proved that travelling waves appear under resonance conditions due to the effect of the gyroscopic moment on the shell.


ABSTRACT: The paper presents the results from experimental study of the influence of reinforcement (rectangular plates) on the buckling loads and stresses of two sets of cylindrical shells subject to axial compression.

References listed at the end of the paper:
ABSTRACT: The report outlines the methodology and procedures used to manufacture the thin walled cylinder with its axial imperfections using a NUM 1060 CNC Lathe machine. By introducing the known geometries imperfections, the thin cylinder manufactured could be analyzed under different load conditions and with different type of applications. The cylinders manufactured were to have minimum thickness set up with their flat end were machined to follow a periodic sinusoidal wave’s function of specified amplitude and frequency. In addition, the flat end cylinder circumference surface was also required to have a constant chamfer angle either from the outside or inside cylinder surface. A number of experiments were attempted to determine the minimum thickness, the sinusoidal wave's function and the constant chamfer angles required. At the end of the project, the machining techniques and procedures used to manufacture the cylinder were successfully established as well as the CNC part programs which played a major role in producing the imperfections required. A result of a satisfactory final thin cylinder was manufactured even though some difficulties had occurred throughout the whole project. Finally, all the information contained were vital for understanding the concept of manufacturing the cylinders with axial imperfections. It indicates some essential findings for the clear description of the project purposes and the necessary works that undertaken through the completion of the project.

ABSTRACT: This paper presents numerical results on chaotic vibrations of a shallow cylindrical shell-panel under harmonic lateral excitation. The shell, with a rectangular boundary, is simply supported for deflection and the shell is constrained elastically in an in-plane direction. Using the Donnell--Mushtari--Vlasov equation, modified with an inertia force, the basic equation is reduced to a nonlinear differential equation of a multiple-degree-of-freedom system by the Galerkin procedure. To estimate regions of the chaos, first, nonlinear responses of steady state vibration are calculated by the harmonic balance method. Next, time progresses of the chaotic response are obtained numerically by the Runge--Kutta--Gill method. The chaos accompanied with a dynamic snap-through of the shell is identified both by the Lyapunov exponent and the Poincaré projection onto the phase space. The Lyapunov dimension is carefully examined by increasing the assumed modes of vibration. The effects of the in-plane elastic constraint on the chaos of the shell are discussed.

ABSTRACT: This paper presents effects of a concentrated mass on chaotic oscillations of a shallow cylindrical shell under gravity and periodic acceleration. The rectangular shell is simply supported and is elastically in-plane constrained. Assuming mode functions, the Donnell equation with inertia force is reduced to non-linear coupled differential equations by the Galerkin method. The chaotic response is calculated numerically and is examined by the maximum Lyapunov exponent. Dominant chaotic responses are generated within restricted frequency regions of sub-harmonic resonance of 1/2 order. As the concentrated mass increases, the chaotic response is shifted to the lower frequency region. The increment of the concentrated mass decreases the
maximum Lyapunov exponent.

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ABSTRACT: Detailed experimental results and analytical results are presented on chaotic vibrations of a shallow cylindrical shell-panel subjected to gravity and periodic excitation. The shallow shell-panel with square boundary is simply supported for deflection. In-plane displacement at the boundary is elastically constrained by in-plane springs. In the experiment, the cylindrical shallow shell-panel with thickness 0.24 mm, square form of length 140 mm and mean radius 5150 mm is used for the test specimen. All edges around the shell boundary are simply supported by adhesive flexible films. First, to find fundamental properties of the shell-panel, linear natural frequencies and characteristics of restoring for the shell-panel are measured. These results are compared with the relevant analytical results. Then, geometrical parameters of the shell-panel are identified. Exciting the shell-panel with lateral periodic acceleration, nonlinear frequency responses of the shell-panel are obtained by sweeping the frequency of periodic acceleration. In typical ranges of the exciting frequency, predominant chaotic responses are generated. Time histories of the responses are recorded for inspection of the chaos. In the analysis, the Donnell equation with lateral inertia force is introduced. Assuming mode functions, the governing equation is reduced to a set of nonlinear ordinary differential equations by the Galerkin procedure. Periodic responses are calculated by the harmonic balance method. Chaotic responses are integrated numerically by the Runge–Kutta–Gill method. The chaotic responses, which are obtained by the experiment and the analysis, are inspected with the Fourier spectra, the Poincaré projections, the maximum Lyapunov exponents and the Lyapunov dimension. It is found that the dominant chaotic responses of the shell-panel are generated from the responses of the sub-harmonic resonance of 1/2 order and of the ultra-sub-harmonic resonance of 2/3 order. By the convergence of the maximum Lyapunov exponent to the embedding dimension, the number of predominant vibration modes which contribute to the chaos is found to be three or four. Fairly good agreements are obtained between the experimental results and the analytical results.

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ABSTRACT: To clarify chaotic behavior of thin walled beams, detailed experimental results are presented on chaotic vibrations of a post-buckled beam subjected to periodic lateral acceleration. A thin steel beam of thickness 0.198 mm, breadth 12.7 mm and length 106 mm is used as a test beam. Both ends of the beam are clamped for deflection. One end of the beam is elastically constrained by an axial spring. The beam is compressed to the post-buckled configuration by the axial spring. First, characteristics of restoring force and natural frequency of the beam are obtained. Dynamic nonlinear responses of the beam are measured under periodic acceleration. In specific frequency regions, chaotic responses are generated. The chaotic responses are examined carefully with the Poincaré maps, the Fourier spectra, the maximum Lyapunov exponents and the
principal component analysis. The post-buckled beam shows the soften-and-hardening characteristics of restoring force. The dominant chaotic responses of the beam are bifurcated from the sub-harmonic resonances of 1/2 and 1/3 orders with the lowest mode of vibration. Changing the exciting frequency gradually, dynamical transition behaviors from these steady-state sub-harmonic response to the chaotic responses are precisely inspected by the Poincaré projection. The maximum Lyapunov exponent of the former chaotic response of 1/2 order is larger than that of the latter chaotic response of 1/3 order. The principal component analysis predicts that the contribution of the lowest mode of vibration to the chaos is dominant among other contributions of multiple vibration modes.

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ABSTRACT: Experimental results and analytical results are presented on chaotic vibrations of a shallow double-curved shell-panel subjected to gravity and periodic excitation. Modal interactions in the chaotic responses are discussed. The shell-panel with square boundary is simply supported for deflection. In-plane displacement at the boundary is elastically constrained. In the experiment, time histories of the chaotic responses at the spatial multiple positions of the shell-panel are measured for the inspection of modal interaction. In the analysis, the shallow shell-panel is assumed to have constant curvatures along to orthogonal directions and geometric initial imperfection. The Donnell–Mushtari–Vlasov type equation is used as governing equation with lateral inertia force. Assuming deflection with multiple modes of vibration, the governing equation is reduced to a set of nonlinear ordinary differential equations by the Bubnov–Galerkin procedure. Chaotic responses are integrated numerically. The chaotic responses, which are obtained by the experiment and the analysis, are inspected with the Fourier spectra, the Poincaré projections, the maximum Lyapunov exponents and the Lyapunov dimension. Contribution of modes of vibration to the chaotic responses is analyzed by the principal component analysis, i.e., Karhunen–Loève transformation.


ABSTRACT: Composite laminates are widely used in construction of mechanical, aerospace, marine and automotive structure. These structures exhibit inherent random dispersion in material properties, as absolute control of production process is neither feasible nor economical. Some composite structures are subjected to large amplitude vibration during their working life that may lead to non-linearity in the response. The present paper analyses the effect of material parameter dispersion on the large amplitude free vibration of especially orthotropic laminated composite plates. The basic formulation of the problem has been developed based on the classical laminate theory and Von-Karman non-linear strain–displacement relation. The system equations have been obtained by using Hamilton's principle and the solution has been found by term wise series integration. Perturbation technique has been used to obtain the second order response statistics. Typical results have been presented for a plate with all edges simply supported. Effects of side-to-thickness ratio, aspect ratio, oscillation
amplitude and mode shape along with change in standard deviation of material properties have been investigated for cross-ply symmetric and antisymmetric laminates.


ABSTRACT: This paper addresses nonlinear flexural vibrations of shallow shells composed of three thick layers with different shear flexibility, which are symmetrically arranged with respect to the middle surface. The considered shell structures of polygonal planform are hard hinged simply supported (i.e. all in-plane rotations and the bending moment vanish) with the edges fully restraint against displacements in any direction. The kinematic field equations are formulated by layerwise application of a first-order shear deformation theory. A modification of Berger's theory is employed to model the nonlinear characteristics of the structural response. The continuity of the transverse shear stress across the interfaces is specified according to Hooke's law, and subsequently the equations of motion of this higher order problem can be derived in analogy to a homogeneous single-layer shear deformable shallow shell. Numerical results of rectangular shallow shells in nonlinear steady-state vibration are presented for various ratios of shell rise to thickness, and non-dimensional load amplitude.


ABSTRACT: This paper is concerned with the non-linear free periodic vibrations of thin, open, cylindrical and shallow shells vibrating in the geometrically non-linear regime. A multi-degree-of-freedom model with hierarchical basis functions is adopted and the principle of the virtual work is used to define the time domain equations of motion. These equations are transformed into the frequency domain by the harmonic balance method and are finally solved by an arc-length continuation method. Shells of different thicknesses and of different curvature radius are analysed, and the variation of the non-linear natural frequencies of these shells with the vibration amplitude are investigated in some detail. The variation of the mode shapes with the vibration amplitude is demonstrated. It is found that both softening and hardening spring effects occur and that the number of couplings between vibration modes is rather large in undamped shells.

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ABSTRACT: The geometrically non-linear vibrations of linear elastic composite laminated shallow shells under the simultaneous action of thermal fields and mechanical excitations are analysed. For this purpose, a model based on a very efficient p-version first-order shear deformation finite element, with hierarchical basis functions, is employed. The equations of motion are solved in the time domain by a Newmark implicit time integration method. The model and code developed are partially validated by comparison with published data.
Parametric studies are carried out in order to study the influence of temperature change, initial curvature, panel thickness and fibre orientation on the shells’ dynamics.

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ABSTRACT: The chaotic vibrations of a bimetallic shallow shell of revolution under time-varying temperature excitation are investigated in the present study. The governing equations are established in forms similar to those of classical single-layered shell theory by re-determination of reference surface. The nonlinear differential equation in time-mode is derived by variational method following an assumed spatial-mode. The Melnikov function is established theoretically to estimate regions of the chaos, and the Poincaré map, phase portrait, Lyapunov exponent, and Lyapunov dimension are used to determine if a chaotic motion really appears. Further investigations are developed by means of detailed numerical simulation, and both the bifurcation diagrams and corresponding maximum Lyapunov exponent are illustrated. The influence of static and time-dependent temperature parameters, height parameter of the shell, and damping parameter on the dynamic characteristics is examined. Interesting phenomena such as the onset of chaos, transient chaotic motion, chaos with interior crisis and period window, period-doubling scenario and reversed period-doubling bifurcation leading to chaos, jump phenomena, and chaos suddenly converting to period orbit have been observed from these figures.


ABSTRACT: The axisymmetrically nonlinear free vibration of a bimetallic shallow shell of revolution under uniformly distributed static temperature changes is investigated. Based on the nonlinear bending theory of thin shallow shells, the governing equations are established in forms similar to those of classical single-layered shells theory by redetermination of reference surface of coordinate. These partial differential equations are reduced to corresponding ordinary ones by elimination of the time variable with Kantorovich averaging method following an assumed harmonic time mode. The resulting equations, which form a nonlinear two-point boundary value problem, are then solved numerically by shooting method, and the temperature-dependent characteristic relations of frequency vs. amplitude are obtained successfully. A detailed parametric study is conducted involving shell geometry and temperature parameters. The effects of these variables on the frequency–amplitude characteristics are plotted and discussed.


ABSTRACT: The non-linear free vibration of a functionally graded doubly-curved shallow shell of elliptical plan-form is investigated using the p-version of the finite element method in conjunction with the blending function method. The effects of transverse shear deformations, rotary inertia, and geometrical non-linearity are taken into account. It is assumed that the material properties vary through the thickness according to a power
law distribution. The harmonic balance method is used to derive the equations of free motion. The resultant non-linear equations are solved iteratively using the linearized updated mode method. The efficiency of the method is demonstrated through convergence study and comparison with published results. Three types of functionally graded doubly-curved shallow shells of elliptical plan-form are considered. The effects of the volume fraction exponent and thickness ratio on the linear and non-linear frequencies are discussed. It is shown that these parameters influence the hardening behaviour.

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“On the accuracy of the multiple scales method for non-linear vibrations of doubly curved shallow shells”,
International Journal of Non-Linear Mechanics, Vol. 46, No. 1, January 2011, pp. 170-179,
doi:10.1016/j.ijnonlinmec.2010.08.006

ABSTRACT: Non-linear free and forced vibrations of doubly curved isotropic shallow shells are investigated via multi-modal Galerkin discretization and the method of multiple scales. Donnell’s non-linear shallow shell theory is used and it is assumed that the shell is simply supported with movable edges. By deriving two different forms of the stress function, the equations of motion are reduced to a system of infinite non-linear ordinary differential equations with quadratic and cubic non-linearities. A quadratic relation between the excitation and the fundamental frequency is considered and it is shown that, although in case of hardening non-linearities the results resemble those found via numerical integration or continuation softwares, in case of softening non-linearity the solution breaks down as the amplitude becomes larger than the thickness. Results reveal that, expressing the relation between the excitation and fundamental frequency in this form, which was considered by many researchers as a useful tool in analyzing strong non-linear oscillators, yields in spurious results when the non-linearity becomes of softening type.

Kathleen Mae Gelera and Jong Sup Park (Sangmyung University, Korea), “Elastic lateral torsional buckling strength of monosymmetric stepped I-beams”, KSCE Journal of Civil Engineering, Vol. 16, No. 5, July 2012,
DOI: 10.1007/s12205-012-1255-8

ABSTRACT: This paper reports the results of parametric analyses for the lateral torsional buckling strengths of singly symmetric stepped I-beams with constant depth subjected to general loading conditions. Simply supported beams with varying monosymmetric ratios from 0.1 to 0.9 were analyzed using a finite element program ABAQUS and a regression program MINITAB. Stepped length ratios, flange width ratios and flange thickness ratios were taken from the geometry of real bridges. The beams were first subjected to pure bending to take account for the effect of steps in beams. And then ten-different loading conditions were applied to the beams to study the effect of varied moment along the unbraced span. Design solutions were suggested based on the results of the parametric analyses. The use of equations for beams with inflection point of zero and one is recommended for stepped beams with monosymmetric ratios from 0.1 to 0.9. In specialty, the use of new equation for beams with inflection point of two is recommended for doubly stepped beams with monosymmetric ratios between 0.1 and 0.9 and for singly stepped beams with monosymmetric ratios between 0.1 and 0.7.

References listed at the end of the paper:

Shun Li and Peng-Fei Yao (Key Laboratory of Systems and Control, Institute of Systems Science, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China), “On the modeling of a nonlinear plate and a nonlinear shell”, Intelligent Control and Automation (WCICA), 10th World Congress on…, 2012, DOI: 10.1109/WCICA.2012.6358131

ABSTRACT: We consider modeling of a nonlinear thin plate and a nonlinear thin shell under the following assumptions: (a) the materials are nonlinear; (b) the deflections are small (linear strain displacement relations). For a plate with a planar middle surface, we consider the bending of the plate to establish the strain energy, the equilibrium equations, and the motion equations. For a shell with a curved middle surface in IR3, we derive a nonlinear model where a deformation in three-dimensions is concerned.


ABSTRACT: On the basis of the nonlinear plate-shell and piezoelectric theory, the governing equations of motion for axisymmetrical piezoelectric delaminated cylindrical shell under hygrothermal conditions were derived. The governing equation of transverse motion was modified by contact force and thus the penetration between two delaminated layers could be avoided. The whole problem was resolved by using the finite difference method. In calculation examples, the effects of delamination length, depth and amplitude of load on the nonlinear dynamic response of the axisymmetrical piezoelectric delaminated shell under hygrothermal conditions were discussed in detail.


ABSTRACT: The vibrations of the shallow shell with geometrical nonlinearity submerged in a fluid are considered. Interaction of the shell with a fluid is described by linear hypersingular integral equation, which is solved by the boundary element method. The vibrations of the shell are described by the nonlinear finite-degree-of-freedom system. The vibrations are studied by the Shaw–Pierre nonlinear modes.
DOI: 10.1007/s00707-011-0556-1

ABSTRACT: The system of three partial differential equations with respect to displacements (Donnell equations) is used to analyze nonlinear vibrations of a cylindrical shell. The Galerkin method is applied to every partial differential equation to obtain a finite-degree-of-freedom model of the shell. The system of ordinary differential equations with respect to the general coordinates of the radial shell displacements is derived. The nonlinear modes of free vibrations are calculated using the harmonic balance method. The stability analysis of periodic motions is performed.

References listed at the end of the paper:

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ABSTRACT: In this study, the homotopy analysis method (HAM) is used to obtain an approximate analytical solution for geometrically non-linear vibrations of thin laminated composite plates resting on non-linear elastic foundations. Geometric non-linearity is considered using von Karman’s strain–displacement relations. Then, the effects of the initial deflection, ply properties, aspect ratio of the plate and foundation parameters on the non-linear free vibration is studied. Comparison between the obtained results and those available in the literature demonstrates the potential of HAM for the analysis of such vibration problems, whose governing differential equations include the quadratic and cubic non-linear terms. This study shows that only a first-order approximation of the HAM leads to highly accurate solutions for this type of non-linear problems.

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ABSTRACT: In this work, chaotic vibrations of shallow sector-type spherical shells are studied. A sector-type shallow shell is understood as a shell defined by a sector with associated boundary conditions and obtained by cutting a spherical shell for a given angle thetak, or it is a sector of a shallow spherical cap associated with the mentioned angle. Both static stability and complex nonlinear dynamics of the mentioned mechanical objects subjected to transversal uniformly distributed sign-changeable load are analyzed, and the so-called vibration charts and scales regarding the chosen control parameters are reported. In particular, scenarios of transition from regular to chaotic dynamics of the mentioned shells are investigated. A novel method to control chaotic dynamics of the studied flexible spherical shells driven by transversal sign-changeable load via synchronized action of the sign-changeable antitorque is proposed and applied. All investigations are carried out within the fields of qualitative theory of differential equations and nonlinear dynamics.
ABSTRACT: The buckling strength of a delaminated ring subjected to hydrostatic pressure is sought. The problem is solved by applying a weighted residual solution technique to the equation of the second variation of the potential energy for the ring. The effect of the position and the size of the delamination is investigated using a numerical example. The buckled mode shapes are analyzed and the contact problem between the adjacent layers is discussed.

ABSTRACT: The buckling and post-buckling behavior of arches is very sensitive to their geometric imperfections. The purpose of this paper is to develop a refined curved finite element that might accurately represent the actual geometry of arches so that the imperfection effects on their buckling behavior could be properly investigated. For an arch with known geometric imperfections, the element stiffness matrix is precisely formulated in terms of Lagrangian variables for a perfect arch from a general incremental variational principle. In general, the element stiffness matrix contains Lagrangian strain, first and second order incremental strain and imperfection terms. For any general planar imperfect arch with a variable curvature, the element stiffness matrix is evaluated by numerical integration; however, for a nominally circular arch, it can be represented in closed form. Numerical results in terms of load-deformation curves are presented for a number of circular arches with and without imperfections and compared with existing solutions.

J. I. Craig and M. F. Duggan (School of Aerospace Engineering, Georgia Institute of Technology), “Nondestructive shell-stability estimation by a combined-loading technique” (The variation of specimen lateral stiffness with compressive axial loading is studied experimentally and it is demonstrated that buckling loads can be predicted for monocoque shells for such data.), Experimental Mechanics, Vol. 13, No. 9, 1972, pp. 381-388, doi: 10.1007/BF02324040
ABSTRACT: Accurate nondestructive procedures for cylindrical-shell-stability investigations have long been a goal of experimentalists and practicing engineers. Stability criteria based on stress and deflection have been investigated intensively by researchers, but lateral-stiffness variation has been largely ignored. It is this aspect which is the foundation of the present work. The variation of specimen lateral stiffness with compressive axial loading is studied experimentally and it is demonstrated that buckling loads can be predicted for monocoque shells from such data. A study of the initial specimen geometry is presented and an evaluation is made of its effect on the distribution of stiffness at zero axial load. When the lateral test force used to determine the stiffness is considered as a destabilizing load in combination with the axial compression, it is shown that critical values of the force can be estimated by the “Southwell plot” procedure. These critical forces can be correlated with axial load and extrapolated to yield an accurate estimate of the buckling load. The approach greatly reduces the compressive load necessary for stability predictions over that required for other techniques.

ABSTRACT: A theoretical investigation of the effect of general imperfections on the buckling of a cylindrical shell under axial compression was carried out. A limit point analysis was performed to determine the buckling loads using a simplified imperfection and displacement model consisting of one axisymmetric and two asymmetric components with the same circumferential wave number. The wave number dependence of imperfections for a class of shells obtained by the same manufacturing processes was characterized by using an imperfection model to fit the experimental imperfection coefficients available. Buckling load calculations were performed using both experimental and fitted data as imperfection coefficients. For the experimental data available the three-mode solution was found to have only a small additional effect with respect to the two-mode solution. In addition, by extrapolating imperfection coefficients for high wave numbers by means of the imperfection model, it was found that a strong interaction effect would exist between a low wave number axisymmetric mode and two classical asymmetric modes.


ABSTRACT: A scheme for treating so-called floating rings is recommended for use in the buckling analysis of stiffened cylindrical shells. Critical stresses are calculated and compared to those for integral rings, for a design representative of the unpressurized Space Shuttle liquid hydrogen (LH2) tank. The ring rigidity required to prevent general instability is found to be much less than that required by the Shanley criterion, with a correspondingly significant weight saving. There is very little difference in total shell weight between floating and internal rings for equal strength designs.


ABSTRACT: The nonlinear flexural vibration behaviour of cylindrical shells has received considerable attention to date. It is pointed out that, although in a well-known reference case there seems to be a reasonable agreement, there are unresolved discrepancies between the results obtained by different authors. In the present paper, the problem is studied using various analytical–numerical models with different levels of accuracy and complexity. The frequency–amplitude curves from the different analysis models developed are compared both for isotropic shells and for an orthotropic composite shell. Secondary modes can play an important role. In more complicated cases modal interactions may significantly influence the nonlinear vibration behaviour, and the results obtained strongly depend on the analysis model chosen.

References listed at the end of the paper:
ABSTRACT: An analytical–numerical method involving a small number of generalized coordinates is presented for the analysis of the nonlinear vibration and dynamic stability behaviour of imperfect anisotropic cylindrical shells. Donnell-type governing equations are used and classical lamination theory is employed. The assumed deflection modes approximately satisfy simply supported boundary conditions. The axisymmetric mode satisfying a relevant coupling condition with the linear, asymmetric mode is included in the assumed deflection function. The shell is statically loaded by axial compression, radial pressure and torsion. A two-mode imperfection model, consisting of an axisymmetric and an asymmetric mode, is used. The static-state response is assumed to be affine to the given imperfection. In order to find approximate solutions for the dynamic-state equations, Hamilton’s principle is applied to derive a set of modal amplitude equations. The dynamic response is obtained via numerical time-integration of the set of nonlinear ordinary differential
equations. The nonlinear behaviour under axial parametric excitation and the dynamic buckling under axial step loading of specific imperfect isotropic and anisotropic shells are simulated using this approach. Characteristic results are discussed. The softening behaviour of shells under parametric excitation and the decrease of the buckling load under step loading, as compared with the static case, are illustrated.

References listed at the end of the paper:

ABSTRACT: A perturbation method is used to analyse the nonlinear vibration behaviour of imperfect general structures under static preloading. The method is based on a perturbation expansion for both the frequency parameter and the dependent variables. The effects on the linearized and nonlinear vibrations caused by geometric imperfections, a static fundamental state, and a nontrivial static state are included in the perturbation procedure. The theory is applied in the nonlinear vibration analysis of anisotropic cylindrical shells. In the analysis the specified boundary conditions at the shell edges can be satisfied accurately. The characteristics of the analysis capability are shown through examples of the vibration behaviour of specific shells. Results for single mode and coupled mode nonlinear vibrations of shells are presented. Parametric studies have been performed for a composite shell.

Hung-Peng Li, “Investigation Of The Stability Of Metallic/Composite-Cased Solid Propellant Rocket MotorsUnder External Pressure”, (Dissertation for Mechanical Engineering Dept. of Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA), September 1998

ABSTRACT: Solid rocket motors consist of a thin metallic or composite shell filled with a soft rubbery propellant. Such motors are vulnerable and prone to buckling due to sudden external pressures produced by nearby detonation. The stability conditions of rocket motors subjected to axisymmetric, external pressure loading are examined. The outer cases of motors are considered as isotropic (metallic) or anisotropic (composite), thin and high-strength shells, which are the main structures of interest in the stability analyses. The inner, low-strength elastic cores are modeled as linear and nonlinear elastic foundations. A general, refined, Sanders' nonlinear shell theory, which accounts for geometric nonlinearity in the form of von Karman type of nonlinear strain-displacement relations, is used to model thin-walled, laminated, composite cylindrical shells. The first order shear deformable concept is adopted in the analysis to include the transverse shear flexibility of composites. A Winkler-type linear and nonlinear elastic foundation is applied to model the internal foundations. Pasternak-foundation constants are also chosen to modify the proposed elastic foundation model for the purpose of shear interactions. A set of displacement-based finite element codes have been formulated to determine critical buckling loads and mode shapes. The effect of initial imperfections on the structural responses are also incorporated in the formulations. A variety of numerical examples are investigated to demonstrate the validity and efficiency of the proposed theory under various boundary conditions and loading cases. First, linear
eigenvalue analysis is used to examine approximate buckling loads and buckling modes as well as symmetry conditions. An iterative solution procedure, either Newton-Raphson or Riks-Wempner method, is employed to trace the nonlinear equilibrium paths for the cases of stress, buckling and post-buckling analyses. Both ring- and shell-type models are applied for the structural analyses with different internal elastic foundations and initial imperfections.

References listed at the end of the dissertation:
90 Reddy, J. N., "Bending of Laminated Anisotropic Shells by a Shear Deformable Finite Element," Fiber Science and Technology,


103 Winkler, E., "Die Lehre von der Elastizitaet und Festigkeit," Prague, Dominicus, 1867.


PARTIAL ABSTRACT: The objective of this work is to study the local and global nonlinear vibrations of isotropic single-layered and multi-layered cross-ply doubly curved shallow shells with simply supported boundary conditions. The study is based-on the full nonlinear partial-differential equations of motion for shells. These equations of motion are based-on the von Kármán-type geometric nonlinear theory and the first-order shear-deformation theory, they are developed by using a variational approach. Many approximate shell theories are presented.

References listed at the end of the dissertation:


ABSTRACT: This paper presents the free vibration analysis of arbitrary thin shell structures by using a newly developed spline finite element. The new element has three salient features in its formulation: (i) the use of B-spline shape functions for the interpolations of both in-plane and out-of-plane displacements of a general thin shell element; (ii) the use of “displacement constraints” and “parameters shifting” to construct a finite element model; (iii) that a proposed modified version of the Koiter’s thin shell theory is employed. The element is doubly curved, has nine primary nodes and eight auxiliary nodes, and has a total of 63 degrees of freedom. It is formulated through the conventional C1 displacement approach, and is capable of modeling sharp corners, arbitrary shapes and multiple junctions of thin shell structures. The numerical examples discussed include spherical panels, cylindrical panels and shells of revolution, as well as single- and double-cell boxes. These examples are typical shells of negative, zero and positive Gaussian curvatures. The effects of aspect ratios, distorted meshes and junctions of shells on the performance of the element are studied. It is shown that the new spline finite element is a reliable, versatile, accurate and efficient thin shell element suitable for the analysis of arbitrary thin shell structures.


ABSTRACT: Delamination type failures are often observed in carbon-epoxy composites, where catastrophic failure is generally preceded by constituent level damage accumulation. Out-of-plane loading such as internal pressure in a composite fuselage or out-of-plane deformations in compression-loaded post-buckled panel may lead to debonding of the frame or stiffener from the panel. On other hand, numerous investigations show the ability of stiffened composite structures to work in the post-buckling region, which is considered unsafe in the conventional design procedures. Experimental evaluation of damage influence on post-buckling performance of stiffened shells is essential for development of safe design guidelines that would allow exploitation of these structures in the post-buckling region. The results of this investigation show that a damaged stiffened composite shell can be loaded up to 200% of skin buckling load without any propagation of delaminations. This can serve as the base for more extended studies on the subject, including numerical modelling and improvement of the existing design guidelines.

Edgars Eglitis, Kaspars Kalnins and Olgerts Ozolins (Institute of Materials and Structures, Riga Technical University, Kalku Str. 1, Riga LV 1658, Latvia), “Experimental and numerical study on buckling of axially
PARTIAL INTRODUCTION: Thin shells are efficient structures that can support very high buckling loads. However, unlike columns and plates, shells usually have a very unstable post-buckling behaviour that strongly influences their buckling characteristics. Hence their buckling and post-buckling have presented scientific and engineering challenges for decades. [1] Axially compressed cylinder may be one of the last classical problems in structural mechanics for which it remains difficult to obtain close agreement between careful experiments and the best predictions from numerical modelling, therefore this is a subject of continuous research. Buckling and post-buckling of axially compressed, homogenous isotropic cylinders has been investigated since it was first identified in the beginning of the last century by “wrinkling” or “secondary flexure” in columns. [3] In practice, buckling of cylindrical shells under axial compression became important as their use in aircraft structures broadened as thin-walled columns and stressed-skin construction of fuselages and wings, introduced in the late twenties. Since then the shell buckling phenomena became the central design problem of aerospace structures. According to the well-known and accepted linear classical theory, the linear bifurcation buckling stress for a perfect isotropic cylindrical shell under ideal conditions (of medium length, with pre-buckling stresses by the boundary conditions and boundaries that restrain circumferential displacements during buckling) is...

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3. Lilly W. E. The Economic Design Of Columns // Transactions of Institution of Civil Engineers of Ireland (Dublin), March 1906, pp. 67-93.
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ABSTRACT: Multiple delaminations are more realistic damage types in the laminated composite structures. In this study, buckling and postbuckling analysis was conducted for the composite laminates with multiple delaminations under compressive loading. In a nonlinear finite element formulation, the updated Lagrangian description and modified arc-length method were adopted. For a finite element modeling of composite laminates, the eight-node degenerated shell element was used. To avoid the overlapping between delaminated areas, the contact node pair was defined by virtual beam element. Numerical results showed that multiple delaminations lower buckling loads and load carrying capacities in the postbuckling region.

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ABSTRACT: A model is selected for the study of delamination buckling of a short laminated orthotropic tube under axial compression. Delamination is assumed to exist prior to loading and it spans the entire circumference. On the basis of total Lagrangian description and axisymmetric assumption, a nonlinear finite element method is formulated to examine nonlinear post-buckling behavior. Then, for treating the contact of delamination face caused by the effect of curvature, the nonlinear finite element program is associated with a quadratic programming procedure. Using the path independent J-integral defined for axisymmetric finite deformation, the energy release rate is calculated. The load-carrying capacity of the delaminated tube and the stability of delamination growth are examined in terms of the critical buckling load and the energy release rate, respectively.


ABSTRACT: Delaminations weaken a laminated beam, which then fails prematurely under in-plane compression. An exact buckling analysis is performed for beams with double delaminations. Novel adoption of two coordinates and choice of slope as the unknown function reduce the buckling equations to simple solvable geometric equations. Complex buckling behaviors emerge for different sizes and depths of the delaminations. “Free mode” and “constrained mode” of buckling are identified. Both global and local buckling occurs, depending upon the slenderness ratios of the delaminations. In addition, an upper bound and a lower bound of buckling loads are obtained by assuming totally “constrained” and totally “free” deformation for the delaminated beam. These bounds are easy to compute and provide useful approximations.


ABSTRACT: In the present paper, new nondimensionalized parameters, namely, nondimensionalized axial and bending stiffnesses have been introduced to study analytically the buckling behavior of two-layer beams with separated delaminations. Numerical analysis has been carried out by using ANSYS software to validate the developed analytical model. Delaminations are modeled with gap elements in ANSYS. A detailed parametric study has been carried out and it is found that the buckling behavior strongly depends on these new nondimensionalized parameters. Another nondimensionalized parameter, effective-slenderness ratio is also introduced and it is found to be a controlling parameter of delamination buckling mode configurations.


ABSTRACT: Critical buckling loads of laminated fibre-reinforced plastic square panels have been obtained using the finite element method. Various boundary conditions, lay-up details, fibre orientations, cut-out sizes are considered. A 36 degrees of freedom triangular element, based on the classical lamination theory (CLT) has been used for the analysis. The performance of this element is validated by comparing results with some of
those available in literature. New results have been given for several cases of boundary conditions for $[0\deg./ \pm 45\deg./90\deg.]$s laminates. The effect of fibre-orientation in the ply on the buckling loads has been investigated by considering $[\pm \theta]_s$ laminates.


ABSTRACT: The stability behaviour of fibre reinforced plastic plates containing delaminations is studied. Embedded delaminations in the form of a circle or an ellipse, centrally located in $[0/90^\circ/0]$ square plates are considered. A 36 degrees of freedom triangular finite element based on classical laminated plate theory is utilized to idealize the two sublaminates in the delaminated and the undelaminated part of the laminate. Results are compared with some of those available in the literature. Effects of size, shape, thickness-wise location of delamination and fibre orientation on the buckling load are discussed. Generally, the buckling load reduces with increase in delamination size and three distinct types of buckling modes are possible depending upon the delamination parameters.


ABSTRACT: A study of residual compressive strength in delaminated laminates is presented. A methodology is proposed for simulating the whole compressive failure responses, such as initial buckling, postbuckling, contact of delamination front region, delamination propagation, fiber breakage, and matrix cracking etc. An finite element analysis (FEA) of the residual compressive strength is conducted on the basis of the Von Karman's nonlinearity assumption and the first-order shear deformation plate theory, combined with a stiffness degradation scheme. The numerical analysis models and methods are briefly introduced in this paper and some numerical examples are presented to illustrate it. From numerical results and discussion, it is clear that the compressive failure response involves complex multi-failure modes during compressive process. The method and numerical conclusions provide in this paper should of great value to engineers dealing with composite structures.

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ABSTRACT: This study investigates the applicability of scaled models for predicting the buckling behavior of delaminated composites. Such a study is important since it provides the necessary scaling laws, and the factors which affect the accuracy of the scale models. Employment of similitude theory to establish similarity among structural systems can save considerable expense and time, provided that the proper scaling laws are found and
validated. In this study a number of parametric studies are performed. The limitations and acceptable intervals of all parameters and corresponding scale factors are investigated. Particular emphasis is placed on the case of delamination buckling of orthotropic plates. Both complete and partial similarities are discussed. This study indicates that models with a different delamination size, depth and number of delaminations than those of the prototype are capable of predicting buckling loads of the prototypes with good accuracy.

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ABSTRACT: This study investigates buckling behaviors of laminated composite structures with a delamination using the enhanced assumed strain (EAS) solid element. The EAS three-dimensional finite element (FE) formulation described in this paper, in comparison with the conventional approaches, is more attractive not only because it shows better accuracy but also it converges faster, especially for distorted element shapes. The developed FE model is used for studying cross-ply or angle-ply laminates containing an embedded delamination as well as through-the-width delamination. The numerical results obtained are in good agreement with those reported by other investigators. In particular, new results reported in this paper are focused on the significant effects of the local buckling for various parameters, such as size of delamination, aspect ratio, width-to-thickness ratio, stacking sequences, and location of delamination and multiple delaminations.

PARTIAL ABSTRACT: In this paper the effect of material impact damage on buckling-driven delamination growth in composite laminates under compression is studied using a finite element method. The initial material damage, e.g. fibre fracture and matrix cracking due to impact, is modeled through a so-called soft-inclusion, in which an area with reduced stiffness is introduced in the analysis of buckling-induced delamination growth with an ADINA-based finite element program…

ABSTRACT: Based on the first order shear deformation theory(FSDT), the nonlinear dynamic equations involving transverse shear deformation and initial geometric imperfections were obtained by Hamilton's philosophy. Geometric deformation of the composite cylindrical shell was treated as the initial geometric imperfection in the dynamic equations, which were solved by the semi-analytical method in this paper. Stiffness reduction was employed for the damaged sub-layer, and the equivalent stiffness matrix was obtained for the delaminated area. By circumferential Fourier series expansions for shell displacements and loads and by using Galerkin technique, the nonlinear partial differential equations were transformed to ordinary differential
equations which were finally solved by the finite difference method. The buckling was judged from shell responses by B-R criteria, and critical loads were then determined. The effect of the initial geometric deformation on the dynamic response and buckling of composite cylindrical shell was also discussed, as well as the effects of concomitant delamination and sub-layer matrix damages.


ABSTRACT: Free vibration, nonlinear dynamic response, buckling and postbuckling, delaminarion buckling of composite circular cylindrical shells with stringer and ring stiffeners have been investigated theoretically, numerically, experimentally in this paper. The effects of the shells and stiffener parameters, delaminarion parameters on the stiffened composite shells are discussed. The aim is to provide appropriate analytical methods and theoretical basis for design of stiffened composite shells. The major work in this paper is as follows: At the beginning, the advances in the research of free vibration, nonlinear dynamic response under axial impact load, buckling and postbuckling under axial compression of the stiffened composite shells are reviewed comprehensively. The main comments are systematically remark on the delaminarion buckling. Research background and involved elementary theory of this thesis are emphatically expatiated. The second part of paper is about the analytical solution for the free vibration of simply supported composite circular cylindrical shells with stringer and ring stiffeners. Using the Love’s theory and the Rayleigh-Ritz energy method, the frequency equations can be deduced, which can be solved. The effects of shells and orthogonal stiffeners parameters such as the shell thickness-to-radius ratio, the shell length-to-radius ratio, the stiffener’s height, lamination angle and forms on the frequencies are studied. In addition, the effect of hydrostatic pressure is also discussed. The third part presents a simple and efficient semi-analytic method to solve the nonlinear dynamic response of composite circular cylindrical shells with circumferential stiffeners under axial impact load. Applying the discrete stiffened shells model, Based on the composite shell’s shear deformation theory, the motion equations of stiffened shells is deduced using Hamilton’s variation principle. The deformation of the shells and the load are expanded in double series. The motion equations expressed by deflection are obtained with the Galerkin method, and numerically solved by R-kutta approach. Examples are given for the nonlinear dynamic response of stiffened composite shells under axial impact. The effects of the stiffener geometric parameters, lamination angle, lamination forms, the numbers of lamination layers on the dynamic response of stiffened composite circular cylindrical shells are discussed. In the forth part, the generalized Donnell-type equations governing large deflection of laminated cross-ply circular cylindrical shells based on first-order shear deformation theory are presented. An asymptotic series solution is constructed by the perturbation technique for postbuckling behavior of the cylindrical shell under axial compression. The boundary layer solutions are also designed to match with the out-of-plane boundary conditions by singular perturbation approach, and then determined the critical buckling loads and postbuckling equilibrium paths. The effects of the stiffener and shell geometric parameters, lamination angle, lamination forms, initial imperfection on the buckling and postbuckling behavior of the shells are discussed. The fifth chapter analyzed the buckling behavior of composite circular cylindrical shells with throughout circumference delamination by using the first first-order shear deformation theory. And establish the buckling model by spanning the entire circumference is divided into multiple sublaminates shell. The deformations are expanded in double series. The variational principle is applied to obtain the governing equations, boundary conditions, the continuous conditions of displacements, the equilibrium conditions of the force and moment. The influences of the shell geometric parameters, lamination angle, lamination forms, length and depth of delamination on buckling load are analyzed. The final part offered an experiment of free vibration, buckling and postbuckling under axial compression of composite circular cylindrical shells with or without delamination. The effects of lamination angle, length and range of delamination on buckling load, postbuckling
behavior and the final damage form are discussed. The comparison between the experiment outcome and the numerical results indicates that those frequency results of the composite circular cylindrical shells are in good agreement with each other. However, the result of the crush experiment is inconsistent with the theoretical outcome. At last, the reasons for those discriminations are presented.


ABSTRACT: The effect of axial shallow groove on the nonlinear dynamic response and buckling of laminated cylindrical shells subjected to radial compression loading was investigated. Based on the first-order shear deformation theory (FSDT), the nonlinear dynamic equations involving the transverse shear deformation and initial geometric imperfections were derived with the Hamilton philosophy. The axial shallow groove of the laminated composite cylindrical shell was treated as the initial geometric imperfections in the dynamic equations. A semi-analytical method of expanding displacements and loads along the circumferential direction and employing the finite difference method along the axial direction and in the time domain is used to solve the governing equations and obtain the dynamic response of the laminated shell. The B-R criterion was employed to determine the critical loads of dynamic buckling of the shell. The effects of the parameters of the shallow groove on the dynamic response and buckling were discussed in this paper and the results show that the axial shallow grooves greatly affect the dynamic response and buckling.

References listed at the end of the paper:
ABSTRACT: Damage tolerance characteristics and results from experimental and analytical studies of a composite fuselage keel sandwich structure subjected to low-speed impact damage and discrete-source damage are presented. The test specimens are constructed from graphite-epoxy skins bonded to a honeycomb core, and they are representative of a highly loaded fuselage keel structure. Results of compression-after-impact (CAI) and notch-length sensitivity studies of 5-in.-wide by 10-in.-long specimens are presented. A correlation between low-speed-impact dent depth, the associated damage area, and residual strength for different impact-energy levels is described; and a comparison of the strength for undamaged and damaged specimens with different notch-length-to-specimen-width ratios is presented. Surface strains in the facesheets of the undamaged specimens as well as surface strains that illustrate the load redistribution around the notch sites in the notched specimens are presented and compared with results from finite element analyses. Reductions in strength of as much as 53.1 percent for the impacted specimens and 64.7 percent for the notched specimens are observed. References listed at the end of the report:


ABSTRACT: The sandwich composites fuselages appear to be a promising choice for the future aircrafts because of their structural efficiency and functional integration advantages. However, the design of sandwich composites is more complex than other structures because of many involved variables. In this paper, the fuselage is designed as a sandwich composites cylinder, and its structural optimization using the finite element method (FEM) is outlined to obtain the minimum weight. The constraints include structural stability and the composites failure criteria. In order to get a verification baseline for the FEM analysis, the stability of sandwich structures is studied and the optimal design is performed based on the analytical formulae. Then, the predicted buckling loads and the optimization results obtained from a FEM model are compared with that from the analytical formulae, and a good agreement is achieved. A detailed parametric optimal design for the sandwich composites cylinder is conducted. The optimization method used here includes two steps: the minimization of the layer thickness followed by tailoring of the fiber orientation. The factors comprise layer number, fiber orientation, core thickness, frame dimension and spacing. Results show that the two-step optimization is an effective method for the sandwich composites and the foam sandwich cylinder with core thickness of 5 mm and frame pitch of 0.5 m exhibits the minimum weight.


ABSTRACT: The present work introduces efficient methodologies based on the finite-element method for a quick evaluation of damage resistance and damage tolerance of composite aerospace structures. Monolithic, stringer-stiffened structures, and sandwich structures are considered. The presented methodologies cover the simulation of the dynamic response of a structure during a low velocity impact event including the prediction of the internal non-visible or barely visible damage that develops during the impact. Additionally, methods for the prediction of the compression-after-impact strength are presented. In order to permit an accurate and efficient calculation of deformations and stresses in sandwich structures, special finite-element formulations have been developed. A comparison of simulation results with experimental data is presented for a two-stringer monolithic panel and for a honeycomb sandwich plate. The examples demonstrate that the presented methodologies can be used to quickly assess the damage tolerance of composite structures.


ABSTRACT: An analysis of the buckling and post-buckling of a delaminated composite strut is presented using a simple 4 degree of freedom nonlinear Rayleigh–Ritz formulation. Bifurcation analysis indicates that instability occurs in general at an asymmetric point of bifurcation. Depending on the depth of delamination both thin-film and overall buckling can occur in the post-buckling range, the transition being seen at a point of secondary bifurcation. For certain combinations of parameters this becomes a stellar bifurcation, associated with a double eigenvalue, where there are three possible subsequent routes for the post-buckling. The method used is fast and reliable and can be readily extended to modelling a composite with several layers.

References listed at the end of the paper:
References listed at the end of the “Also see” 1998 paper: The lectures present the background to coupled instabilities, as phenomenon, types, classification, etc. The author gives the main aspects of this theory in the light of the well-known catastrophe theory and the companion theories of dissipative and synergetical systems. The principle of domination, determination and perturbation are presented and the symmetry test is used to determine the terms of potential energy. Three types of interaction between the coupled instability parameters are developed. Simple mechanical models are used for explaining or understanding the different types of coupled instabilities: Augusti, Luongo-Pignataro, Thompson-Gaspar, Budiansky-Hutchinson and Hunt-Burgan-Gioncu models, are the archetypes for these types.


ABSTRACT from the “Also see” 1998 paper: The lectures present the background to coupled instabilities, as phenomenon, types, classification, etc. The author gives the main aspects of this theory in the light of the well-known catastrophe theory and the companion theories of dissipative and synergetical systems. The principle of domination, determination and perturbation are presented and the symmetry test is used to determine the terms of potential energy. Three types of interaction between the coupled instability parameters are developed. Simple mechanical models are used for explaining or understanding the different types of coupled instabilities: Augusti, Luongo-Pignataro, Thompson-Gaspar, Budiansky-Hutchinson and Hunt-Burgan-Gioncu models, are the archetypes for these types.

References listed at the end of the “Also see 1998” paper:
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ABSTRACT: The governing equilibrium equations for strain gradient elastic thin shallow shells are derived, considering non-linear strains and linear constitutive strain gradient elastic relations. Adopting Kirchhoff’s theory of thin shallow structures, the equilibrium equations, along with the boundary conditions, are formulated through a variational procedure. It turns out that new terms are introduced, indicating the importance of the cross-section area in bending of thin plates. Those terms are missing from the existing strain gradient shallow thin shell theories. Those terms highly increase the stiffness of the structures. When the curvature of the shallow shell becomes zero, the governing equilibrium for the plates are derived.  
References listed at the end of the paper:  
Vardoulakis, I., (2004), Linear Micro-elasticity, in Degradations and Instabilities in Geomaterials (Darve & Vardoulakis editors), a CISM/DIGA- sponsored course, Springer, Chapter 4.  

ABSTRACT: The primary thrusts of this dissertation are to develop and test a new quadrilateral layered membrane element with drilling degrees of freedom (DOF) and a quadrilateral thin flat layered shell element for the nonlinear analysis of reinforced concrete walls. The drilling degrees of freedom refers to the incorporation of the in-plane rotation as a degree of freedom at each node of the element. The membrane element consists of a quadrilateral element with a total of 12 DOF, 3 per node, 2 displacements and 1 in-plane rotation, and uses a blended field interpolation for the displacements over the element. This formulation is an extension of the one developed by Xia et al. [151] in 2009. The shell element is created by the combination of the membrane element developed in this dissertation and a Discrete Kirchhoff Quadrilateral Element (DKQ, 12 DOF), formulated by Batoz and Tahar [11] 1982, to model the out of plane bending behavior of the element. The modeling of the section of the membrane and the shell element consists of a layered system of fully bonded, smeared steel reinforcement and smeared orthotropic concrete material with the rotating angle formulation. The layered section for the shell includes the coupling membrane and bending effects. These elements are implemented on a finite element framework using the object oriented programing language under MATLAB [62]. The framework or MATLAB toolbox for Finite Elements developed for this dissertation allows to incorporate, develop and test new elements, materials, sections and analysis algorithms in a easy and quick manner. The proposed elements are evaluated using experimental results that are available in the literature. It is shown that the new elements are in excellent agreement with the experimental results for the different load configuration, monotonic and cyclic loading, and they are able to predict the failure modes for the different wall configurations analyzed in this dissertation.

References listed at the end of the dissertation:


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ABSTRACT: In this paper, we study the temperature’s effect on a plate under global tensile stress. For this aim, the Fourier double scale method is used in order to develop a macroscopic model that is a generalized continuum. This model couples local and global instabilities in wrinkling phenomena. The advantage of this technique is to remain valid away from the bifurcation point while former techniques such as Landau-Ginzburg theory are valid only close to the bifurcation point. Due to its efficiency, this method is extended to plate structures. A finite element formulation of the plate model is made. The model developed was implemented using MATLAB code and a validation test has been conducted, comparing to ABAQUS simulation.

References listed at the end of the paper:

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ABSTRACT: Effects of axial forces on beam lateral buckling strength are investigated here in the case of elements with mono-symmetric cross sections. A unique compact closed-form is established for the interaction of lateral buckling moment with axial forces. This new equation is derived from a non-linear stability model. It includes first order bending distribution, load height level and effect of mono-symmetry terms (Wagner’s coefficient and shear point position). Compared to the so-called three-factors (C1–C3) formula commonly employed in beam lateral buckling stability, another factor C4 is added in presence of axial loads. Pre-buckling deflection effects are considered in the study and the case of doubly-symmetric cross sections is easily recovered. The proposed solutions are validated and compared to finite element simulations where 3D beam elements including warping are used. The agreement of the proposed solutions with bifurcations observed on the non-linear equilibrium paths is good. Dimensionless interaction curves are dressed for the beam lateral buckling strength and the applied axial load, where the flexural-torsional buckling axial force is a taken as reference.

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Mario M. Attard (School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia), “Global buckling experiments on sandwich columns with soft shear cores”, Electronic Journal of Structural Engineering, Vol. 11, No. 1, 2011

ABSTRACT: Several failure modes for sandwich columns under compression are said to be possible with shear crimping or shear buckling suggested for short columns with soft shear cores. The buckling formulas and theoretical assumptions of Engesser and Haringx for isotropic columns and soft shear core sandwich columns are reviewed. An important distinction is made between the isotropic column buckling formula attributed to Haringx and the theoretical assumptions underpinning his approach. It is shown that the theoretical approaches of Haringx and Engesser yield the same basic buckling equation for soft shear core sandwich columns when the thickness is very small in comparison to the core thickness, and the shear in the face sheets, the axial force in the core and the bending within the face sheets are ignored. To determine whether shear crimping (shear buckling) is a member or localised type of buckle, tests on low slenderness - short sandwich columns identified as possibly exhibiting shear crimping, were performed. The test specimens were constructed from 10 mm thick Divinycell H45, H80, H100 and H200 foam for the core and 1 mm face sheets made of Aluminum 2024-T3. The lengths of the columns varied from 20 to 500 mm. The columns were end-clamped according to ASTM C 364-99 [1] and placed in a servo-controlled compression testing machine. The width of the specimens was 100 mm and two specimens at each length were tested. The adhesive chosen was a toughened epoxy, trade name “Devcon Epoxy Plus”. Measurements of the mid-span lateral displacement were used in a Southwell type plot to determine the elastic global buckling load. The shear modulus of the core was determined from three point bending tests according to ASTM-C-393 [2]. Some of the very short specimens failed with buckling of the face sheet within the clamped region. None of the tests exhibited shear crimping or shear buckling modes and the
global buckling loads for very short columns were much higher than the shear buckling limit of Engesser. Wrinkling failure was not considered.

References listed at the end of the paper:

Jianbei Zhu, Mario M. Attard and David C. Kellermann (Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, 2052, Australia), “In-plane nonlinear buckling of circular arches including shear deformations”, Archive of Applied Mechanics, Vol. 84, No. 12, pp 1841-1860, December 2014

ABSTRACT: A numerical strategy is presented to trace the pre-buckling as well as the post-buckling nonlinear equilibrium paths for elastic circular arches in which the effects of shear deformations and the geometric nonlinearity due to large deformations are taken into account. Timoshenko beam hypothesis is adopted for
incorporating shear. The constitutive relations including shear effects for stress and finite strain are based on a hyperelastic constitutive model. The finite strain equilibrium equations are developed for the circular arches. Based on the derived transformed equilibrium equations and the boundary conditions, the nonlinear buckling behaviour of circular arches is investigated using the trapezoid method with Richardson extrapolation enhancement. The results are validated using available experimental results in the literature, the finite element package ANSYS and other solutions in the literature. Parametric studies are performed on examples to identify the factors that influence the nonlinear buckling of circular arches. The shear deformation effects on the nonlinear buckling behaviour and the buckling mode are investigated for circular arches under many different loading conditions and various boundary conditions.

References listed at the end of the paper:


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ABSTRACT: The present paper deals with the application of the finite element method to dynamic contact buckling problems. The penalty function method is applied to incorporate the contact conditions in the equation of motion and a trial-and-error method is employed to obtain the converged contact state. Numerical examples are analysed to show the effectiveness and the validity of the method, and it is applied to a dynamic buckling problem involving contact phenomena.


ABSTRACT: The creep buckling of viscoelastic structures is investigated analytically and experimentally. The theory of linear viscoelasticity is used to model polymeric column specimens subjected to constant compressive end loads. The growth of initial imperfections is calculated using the hereditary integral formulation. Solution techniques are developed for small displacements and also generalized to include the effects of non-linear kinematics. It turns out that the kinematically linear model represents the deformation process closely and conservatively; material non-linearities are not dominant since maximum strains of the order of only 2% are encountered. The analyses are exact with respect to (non-linear) kinematics and linearly viscoelastic material representation. A failure criterion based on maximum deformation allows the column life to be determined from the material relaxation modulus if the initial imperfections are known. A discussion on the possible generalization of the results to include plates and shells is presented. Results of creep buckling experiments performed on PMMA specimens at elevated temperatures (accelerating the creep behavior) are reported. The
relaxation modulus of PMMA is represented by a Prony-Dirichlet series and the model is used to simulate the laboratory experiments. Model and experimental results are compared and discussed especially with respect to uncontrollable material behavior.


ABSTRACT: During the last ten years, the French Research Institute for Nuclear Energy (Commissariat à l'Energie Atomique) achieved many theoretical as well as experimental studies for designing the first large size pool type fast breeder reactor. Many of the sensitive parts of this reactor are thin shells subjected to high temperatures and loads. Special care has been given to buckling, because it often governs design. Most of the thin shells structures of the French breeder reactor are axisymmetric. However, imperfections have to be accounted for. In order to keep the advantage of an axisymmetric analysis (low computational costs), a special element has been implemented and used with considerable success in the recent years. This element (COMU) is described in the first chapter, its main features are:
1. either non axisymmetric imperfection or non axisymmetric load,
2. large displacement,
3. non linear material behaviour,
4. computational costs about ten times cheaper than the equivalent three dimensional analysis.

This paper based on a careful comparison between experimental and computational results, obtained with the COMU element, will analyse three problems:
1. First: design procedure against buckling of thin shells structures subjected to primary loads.
2. Second: static post buckling.
3. Third: buckling under seismic loads.

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ABSTRACT: A cylindrical shell with a shape defect is studied. A one DOF modelling is derived. Its nonlinear behaviour is investigated by using both harmonic balance method and normal form theory. Stability domains are computed according to 2 parameters related to the frequency and the amplitude of the external forcing.


ABSTRACT: In this paper, a simplified method is proposed for the prediction of creep buckling. This simplified approach relies upon a model which yields an analytical evaluation of creep buckling times for cylinders under external pressure. This model is fully developed herein, and a ‘closed-form’ solution is given
for the evaluation of the critical creep collapse time. The collapse mechanism is assumed to be due to the formation of a plastic hinge which induces an unstable post-buckling of the ring. The analytical ‘closed-form’ creep collapse time is then compared to finite element buckling predictions using the quasi-axisymmetric COMU shell element in the INCA code of the CASTEM system. The model is then applied to four different cylinders under external pressure and compared to finite element predictions; the cylinders' radius-to-thickness ratio varies between 50 and 550. It is shown that the proposed model performs well for this type of prediction: in all cases, the times to failure predicted by the model are lower than the finite element predictions. These predictions prove to be rather conservative for thicker cylinders. It is shown that creep buckling is a very dangerous failure mode. If the shape of the structure is observed as a function of time, nothing seems to happen during a very long ‘incubation’ period; when the initial imperfection reaches some critical value, buckling then suddenly occurs. This phenomenon is shown by the two methods of evaluation presented herein.


ABSTRACT: In this paper, the simplified method, proposed in (Combescure, 1998), for the prediction of creep buckling is compared to experimental results. The model is applied to predict the buckling time of two sets of experiments on cylinders subjected to uniform external pressure. It is shown that the proposed model is satisfactory for this type of prediction: in all cases, the times up to failure predicted by the model are generally lower than the experimental failure times. The model is rather conservative for thicker cylinders. However, it appears that a very detailed geometrical imperfection survey would be necessary if a highly accurate assessment of the creep failure time were sought. It has been observed experimentally that creep buckling is a very dangerous failure mode: nothing seems to happen during a very long “incubation” period but, when the initial imperfection reaches some critical value, buckling then suddenly occurs. For thin cylinders, the level of creep strain at which the instability starts to develop is much lower than the strain at which the tertiary creep initiates; the instability is thus clearly generated from the interaction between the material and the geometrical nonlinearity.


ABSTRACT: The objective of this paper is to answer the question: "Can a 'shell' model always be used to predict the elastic buckling of a shell?" This paper shows that such a model leads to significantly overestimated critical loads in the case of sandwich shells and gives an explanation for this overestimation. A dependable model is proposed and applied to a few structures of revolution, for which it is shown that shell analyses are sometimes overly on the unsafe side. Of course, in such cases, 3D analysis is possible, but the associated computation cost is several orders of magnitude higher than that of the Fourier series analysis proposed in this paper.

References listed at the end of the paper:
Alain Combescure and Jean-Francois Jullien, “ASTER Shell: a simple concept to significantly increase the plastic buckling strength of short cylinders subjected to combined external pressure and axial compression”, Advanced Modeling and Simulation in Engineering Sciences 2015, 2:26, DOI: 10.1186/s40323-015-0047-3

ABSTRACT: This paper proposes a new type of shell, similar to a cylindrical shell, which has significantly higher buckling strength when subjected to an arbitrary combination of uniform external pressure and axial compression. The underlying principle consists in a slight modification of the perfect cylinder in order to counteract the natural deformations which get larger and larger and lead to the collapse of the structure. Such shells are called ASTER shells. The concept has been validated through experiments, then analyzed numerically in order to explain what was observed and to propose avenues for improvements. The shells were made of electrodeposited nickel. The material was characterized. The chosen specimens were carefully measured to characterize their thickness and initial imperfections, then tested under the various types of loading. Then they were analyzed using finite elements. Thus, we were able to compare the finite element predictions with the experimental results. This comparison shows that plasticity has a decisive influence on the critical load and that linear elastic dimensioning leads to a serious overestimation of the experimental critical load. Contrary to perfect cylindrical shells, this type of shell is not significantly affected by geometric imperfections: this is another advantage of this type of design. Finally, we propose a numerical analysis in order to optimize the choice of the shape and propose shapes which resist buckling much better than a smooth cylinder when subjected to uniform external pressure, axial compression or a combination of both.

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ABSTRACT: For validating the buckling analysis capability of CASTEM code, which is used for the buckling design of Prototype Fast Breeder Reactor (PFBR) vessels, a few experiments have been carried out at Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam. Experiments were conducted on aluminum cylindrical shells under axial compression and stainless steel cylindrical shells under external pressure and transverse shear loading. This paper presents the results of experimental and associated theoretical buckling studies performed using the code INCA.
Noriyuki Miyazaki (Department of Chemical Engineering, Faculty of Engineering, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812, Japan), “Creep buckling analysis of circular cylindrical shell under both axial compression and internal or external pressure”, Computers & Structures, Vol. 28, No. 4, 1988, pp. 437-441, doi:10.1016/0045-7949(88)90017-X

ABSTRACT: This paper deals with the creep buckling of a circular cylindrical shell subjected to both axial compression and internal or external pressure. The finite element method is applied to a creep deformation analysis to obtain the critical time when the creep buckling occurs. Two types of creep buckling are considered in the present analysis. One is the axisymmetric mode of creep buckling due to the quasi-static instability. The other is the asymmetric mode of creep buckling due to the bifurcation. The effects of internal or external pressure on the creep buckling are clarified by the present analysis.


ABSTRACT: This paper deals with the creep buckling of a circular cylindrical shell subjected to both axial compression and internal or external pressure. The finite element method is applied to a creep deformation analysis to obtain the critical time when the creep buckling occurs. Two types of creep buckling are considered in the present analysis. One is the axisymmetric mode of creep buckling due to the quasi-static instability. The other is the asymmetric mode of creep buckling due to the bifurcation. The effects of internal or external pressure on the creep buckling are clarified by the present analysis.


ABSTRACT: First two equations of equilibrium are utilized to compute the transverse shear stress variation through thickness of a thick laminated plate after in-plane stresses have been computed using an assumed quadratic displacement triangular element based on transverse inextensibility and layerwise constant shear angle theory (LCST). Centroid of the triangle is the point of exceptional accuracy for transverse shear stresses. Numerical results indicate close agreement with elasticity theory. An interesting comparison between the present theory and that based on assumed stress hybrid finite element approach suggests that the latter does not satisfy the condition of free normal traction at the edge. Comparison with numerical results obtained by using constant shear angle theory suggests that LCST is close to the elasticity solution while the CST is closer to classical (CLT) solution. It is also demonstrated that the reduced integration gives faster convergence when the present theory is applied to a thin plate.

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ABSTRACT: A method has been presented wherein the surface-parallel stresses in a laminated shell are first computed using standard finite element formulation and then approximate transverse shear stress variation through the shell thickness is obtained utilizing the first two (stress) equations of equilibrium and divergence theorem. Numerical results have been presented for both homogeneous isotropic and laminated anisotropic cylindrical shells using the Cartesian-like Riemann coordinate approximation and compared to the corresponding analytical solutions.


ABSTRACT: A post-processing semi-analytical approach, for prediction of the interlaminar shear stress distribution through the thickness of an arbitrarily laminated general shell, is presented. The starting point of the approach is an assumed displacement finite element analysis, based on the assumptions of transverse inextensibility and layerwise constant shear-angle theory (LCST). First, the problem is posed in the context of Taylor series expansions of the interlaminar shear stresses in terms of the thickness coordinate, dictated by the LCST assumption and the shell curvature. An “exact” (in the context of the problem thus posed) and three progressively approximate semi-analytical methods for prediction of interlaminar shear stresses are then presented. The throughthickness distribution of interlaminar shear stresses in an arbitrarily laminated thick plate can be obtained as a special case of the present solution. Numerical results are presented for two-layer thin and thick tubes with simply-supported edges, using the Cartesian-like local Riemann coordinate (CLRC) approximation and are compared to the corresponding analytical solutions, based on the classical lamination theory (CLT). Results for thin laminated tubes prove the accuracy of the present approach, while hitherto unavailable results for a thick laminated tube are expected to serve as baseline solutions for future comparisons.


ABSTRACT: Hitherto unavailable analytical solutions to the boundary-value problems of static response and free vibration of an arbitrarily laminated doubly-curved panel of rectangular planform are presented. Four classical shallow shell theories (namely, Donnell, Sanders, Reissner and modified Sanders) have been utilized in the formulation, which generates a system of one fourth-order and two third-order partial differential equations with constant coefficients. A novel double Fourier series approach has been developed to solve this system of three partial differential equations with the SS2-type simply supported boundary conditions prescribed at all four edges. The accuracy of the solutions is ascertained by studying the convergence characteristics of the lowest two natural frequencies, deflections and moments of angle-ply panels, and also by comparison with the available FSDT-based analytical and CLT-based Galerkin solutions. Also presented are comparisons of deflections and moments of antisymmetric angle-ply cylindrical panels, computed using the four classical shallow shell theories considered. Comparisons with the available FSDT (first-order shear deformation theory)-based analytical solutions are presented for the purpose of establishing the upper limit (with respect to the thickness-to-length ratio) of validity of the present CLT (classical lamination theory)-based solutions for angle-ply panels. Also studied is the highly complex interaction of bending-stretching type coupling effect with the effects of transverse shear deformation, rotatory inertias, inplane inertias, and membrane action due to shell curvature. Other important numerical results presented include variation of the
response quantities of interest with geometric and material parameters, such as radius-to-length ratio, length-to-thickness ratio and angle of fiber orientation.


ABSTRACT: A hitherto unavailable Fourier series solution to the boundary-value problem of thin cylindrical panels of rectangular planform, subjected to transverse loads, is presented. Sanders' kinematic relations (for classical shell theory) are utilized in the formulation, which generates one fourth-order (in terms of the transverse displacement component) and two second-order (in terms of the surface-parallel displacement components) partial differential equations with constant coefficients. A boundary-discontinuous double Fourier series approach is used to solve the system of three partial differential equations with the SS2-type simply-supported boundary conditions prescribed at all four edges. The final algebraic equations are expressed in terms of the boundary Fourier coefficients, which substantially reduce the size of the matrix, that is inverted using a digital computer. The accuracy of the series solution is ascertained by studying the convergence characteristics, and also by comparison with finite element solutions. Other important numerical results presented include variation of displacement and moment with the radius-to-thickness, length-to-thickness and length-to-width ratios. Also presented are variations of displacement and moment along the center line of the cylindrical panels. These numerical results contribute to our understanding of the complex deformation behavior of finite cylindrically curved panels—especially the influence of the boundary discontinuities on the computed displacements and stresses.


ABSTRACT: A fully nonlinear finite element analysis for prediction of localization/delocalization and compression fracture of moderately thick imperfect transversely isotropic rings, under applied hydrostatic pressure, is presented. The combined effects of modal imperfections, transverse shear/normal deformation, geometric nonlinearity, and bilinear elastic (a special case of hypoelastic) material property on the emergence of interlaminar shear crippling type instability modes are investigated in detail. An analogy to a soliton (slightly disturbed integrable Hamiltonian system) helps understanding the localization (onset of deformation softening) and delocalization (onset of deformation hardening) phenomena leading to the compression damage/fracture at the propagation pressure. The primary accomplishment is the (hitherto unavailable) computation of the mode II fracture toughness (stress intensity factor/energy release rate) and shear damage/crack bandwidth, under compression, from a nonlinear finite element analysis, using Maxwell’s construction and Griffith’s energy balance approach. Additionally, the shear crippling angle is determined using an analysis, pertaining to the elastic plane strain inextensional deformation of the compressed ring. Finally, the present investigation bridges a gap of three or more orders of magnitude between the macro-mechanics (in the scale of mms and up) and micro-mechanics (in the scale of microns) by taking into account the effects of material and geometric nonlinearities and combining them with the concepts of phase transition via Maxwell construction and Griffith-Irwin fracture mechanics.

ABSTRACT: An analytical (strong form) solution to the boundary value problem of moderately thick shallow cylindrical panels, with arbitrary laminations is presented. A double Fourier series approach is used to solve five second-order highly coupled partial differential equations that arise from the shallow shell formulation based on popular Donnell-Mushtari-Vlasov shell theory, and the first-order shear deformation-based through-thickness theory. An admissible boundary condition is considered to obtain numerical results that constitute the study of convergence of displacements, and moments; and spatial variations of them presented in the form of contour plotting for various parametric effects. These, hitherto unavailable, analytically obtained numerical results should serve as base-line solutions for future comparisons of popular approximate methods such as finite element, finite difference, Galerkin approach, Rayleigh-Ritz method, collocation method, least-squares method, and experimental results, for the case of arbitrary laminations.

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ABSTRACT: An analytical solution to thermal buckling response of moderately thick symmetric angle-ply laminated, all-edge clamped rectangular plates subjected to a uniformly distributed temperature load is presented. A boundary continuous solution methodology based on double Fourier series functions that satisfy the rigidly clamped boundary conditions is assumed. The through-thickness formulation of the plate considers transverse shear deformation effects by employing the first order shear deformation theory (FSDT) based on Reissner and Mindlin hypothesis that result in three highly coupled partial differential equations. The numerical results are presented for various parametric effects such as length-to-thickness ratio, plate aspect ratio and major-to-minor modulus of elasticity ratio. The results of the analytical method are compared with the results obtained using finite element method. The numerical results that are presented should serve as a benchmark for future comparisons of such popular approximate methods as finite element, finite difference, Rayleigh–Ritz, Galerkin approach, collocation, or experimental methods.


ABSTRACT: Analytical solutions to the boundary-value problems of static response under transverse load and free vibration of a general cross-ply doubly curved panel of rectangular planform are presented. Four classical shallow shell theories (namely, Donnell, Sanders, Reissner and modified Sanders) are used in the formulation, which generates a system of one fourth-order and two second-order (in terms of the transverse displacement) partial differential equations with constant coefficients. A recently developed boundary-discontinuous double Fourier series approach is used to solve this system of three partial differential equations with the SS2-type simply supported boundary conditions prescribed at all four edges. The accuracy of the solutions is ascertained by studying the convergence characteristics of deflections, moments and natural frequencies of cross-ply panels, and also by comparison with the available analytical solutions. Also presented are comparisons of numerical
results predicted by the four classical shallow shell theories considered for cross-ply panels over a wide range of geometric and material parameters. Comparisons with the available FSDT (first-order shear deformation theory)-based analytical solutions are presented for the purpose of establishing the upper limit (with respect to the thickness-to-length ratio) of validity of the present CLT (classical lamination theory)-based solutions for both symmetric and antisymmetric cross-ply panels. Other important numerical results presented include variation of displacements, moments and the two lowest natural frequencies with the shell geometric parameters, such as radius-to-length ratio.

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ABSTRACT: A fully nonlinear analysis for prediction of shear crippling (kinkband) type propagating instability in long thick laminated composite cylindrical shells is presented. The primary accomplishment of the present investigation is prediction of equilibrium paths, which are often unstable, in the presence of interlaminar shear deformation, and which usually deviate from the classical lamination theory (CLT)-based equilibrium paths, representing global or structural level stability. A nonlinear finite element methodology, based on a three-dimensional hypothesis, known as layerwise linear displacement distribution theory (LLDT) and the total Lagrangian formulation, is developed to predict the aforementioned instability behavior of long laminated thick cylindrical shell type structures and evaluate failure modes when radial/hydrostatic compressive loads are applied. The most important computational feature is the successful implementation of an incremental displacement control scheme beyond the limit point to compute the unstable postbuckling path. A long (plane strain) thick laminated composite [90/0/90] imperfect cylinder is investigated with the objective of analytically studying its premature compressive failure behavior. Thickness effect (i.e. interlaminar shear/normal deformation) is clearly responsible for causing the appearance of limit point on the postbuckling equilibrium path, thus lowering the load carrying capability of the long composite cylinder, and localizing the failure pattern, which is associated with spontaneous breaking of the periodicity of classical or modal buckling patterns. In analogy to the phase transition phenomena, Maxwell construction is employed to (a) correct the unphysical negative slope of the computed equilibrium paths encountered in the case of thicker cylinders modeled by the finite elements methods that fail to include micro-structural defects, such as fiber waviness or misalignments, and (b) to compute the propagating pressure responsible for interlaminar shear crippling or kinkband type propagating instability. This type of instability triggered by the combined effect of interlaminar shear/normal deformation and geometric imperfections, such as fiber misalignment, appears to be one of the dominant compressive failure modes for moderately thick and thick cylinders with radius-to-thickness ratio below the corresponding critical value. A three-dimensional theory, such as the LLDT, is essential for capturing the interlaminar shear crippling type propagating instability.

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“Influence of localized imperfection on the instability of isotropic/cross-ply cylindrical shells/rings under

ABSTRACT: Compressive response of two extreme cases of cylindrical shell type structures weakened by the presence of localized imperfections is investigated. These two extreme cases are (i) thin metallic cylindrical shells, which are characterized by the absence of transverse shear deformation, and (ii) thick laminated advanced fiber reinforced composite rings (very long cylindrical shells), whose response is dominated by the interlaminar or transverse (primarily shear) deformation. A fully nonlinear finite element analysis, that employs a cylindrically curved 16-node layer-element, and is based on the assumption of layerwise linear displacements distribution through thickness (LLDT) or linear displacements distribution through thickness (LDT), is utilized in the analysis of afore-mentioned cross-ply ring or thin homogeneous isotropic cylindrical shell, respectively. Hitherto unavailable numerical results pertaining to the two cases are also presented.

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ABSTRACT: Effect of lamination sequence on the compressive response of a thick plane strain cross-ply ring (very long cylindrical shell) weakened by the presence of a modal imperfection is investigated. A fully nonlinear finite element analysis, that employs a cylindrically curved 16-node layer-element, and is based on the assumption of layer-wise linear displacements distribution through thickness (LLDT), is utilized in the analysis of the afore-mentioned cross-ply ring. Hitherto unavailable numerical results pertaining to the influence of lamination sequence on the localization of buckling patterns and the ensuing shear crippling instability are also presented.

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ABSTRACT: Effect of thickness on the buckling of a perfect thick plane strain cross-ply ring (very long cylindrical shell) is investigated. A linearized version of a fully nonlinear finite element analysis, that employs a cylindrically curved 16-node layer-element, and is based on the assumption of layer-wise linear displacements distribution through thickness (LLDT), is utilized for computation of hydrostatic buckling pressure of the afore-mentioned cross-ply ring. Numerical results pertaining to the effect of thickness (interlaminar shear/normal deformation) on the hydrostatic buckling pressure of cross-ply rings and comparison with their classical lamination theory (CLT) counterparts are also presented.

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“Influence of localized imperfection and surface-parallel shear modulus nonlinearity on the instability of a thin
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pp.235–244, doi:10.1016/j.compstruct.2007.01.004
ABSTRACT: Compressive response of a thin cross-ply cylindrical shell of finite length and weakened by the
presence of a localized imperfection is investigated. A von Karman type nonlinear finite element analysis that
employs a cylindrically curved 16-node layer-element, and is based on the assumption of layer-wise linear
displacements distribution through thickness (LLDT), is utilized in the analysis of afore-mentioned cross-ply
thin cylindrical shell. Numerical results pertaining to the appearance of a limit or localization point on the
equilibrium path due to the combined effect of local imperfection and surface-parallel (intra-laminar) shear
modulus nonlinearity of the fiber reinforced lamina material are also presented.

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external pressure”, Composite Structures, Vol. 82, No. 4, February 2008, pp. 587-599,
doi:10.1016/j.compstruct.2007.02.006
ABSTRACT: The effect of transverse shear modulus on the compressive response of a thick plane strain cross-
ply ring (very long cylindrical shell) weakened by the presence of a modal imperfection is investigated. The
present study is primarily motivated to obtain the hitherto unavailable results pertaining to the effect of reduced
transverse shear modulus, G, of a lamina weakened by the presence of randomly distributed fiber
misalignments. A simple expression for the reduced transverse shear modulus, G, of a layer material is derived
in terms of the average fiber misalignment angle. A fully nonlinear finite element analysis, that employs a
cylindrically curved 16-node layer-element and is based on the assumption of layer-wise linear displacement
distribution through thickness (LLDT), is utilized in the analysis of the afore-mentioned cross-ply ring. The
interaction of a micro-structural defect in the form of initial fiber misalignments with its macro-structural
counterpart represented by a modal imperfection is a key to understanding this meso-structural level
phenomenon. Hitherto unavailable numerical results pertaining to the influence of this effect on the localization
of buckling patterns and the ensuing shear crippling instability are also presented.

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“Admissible boundary conditions and solutions to internally pressurized thin arbitrarily laminated cylindrical
shell boundary-value problems”, Composite Structures, Vol. 86, No. 4, December 2008, pp. 385-400,
ABSTRACT: Admissible boundary conditions are derived for an arbitrarily laminated internally pressurized
cylindrical shell of finite length, under the framework of Donnell’s, Love–Timoshenko’s and Sanders’
ikinematic relations, and the CLT (based on Love’s first approximation theory). Closed-form solutions for
the same cylindrical shell are presented for Love–Timoshenko’s theory, with two sets of asymmetrically placed
prescribed boundary conditions. As the first example, internally pressurized thin hybrid general (asymmetric)
four-layer cylindrical shells with RS2-C4 boundary conditions, made of glass and carbon fiber reinforced
composite layers, are numerically investigated. In the second example, the numerical results for two-layer asymmetrically laminated cylindrical shells, with RS2-SS1 boundary conditions, are compared with those, computed using triangular finite elements based on the layer-wise constant shear-angle theory (LCST), in order to evaluate the limit of applicability of the CLT.

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ABSTRACT: The large deflection behavior of a symmetrically laminated thin shallow circular arch subjected to a central concentrated load is studied using the Rayleigh–Ritz finite element method. The shape functions used in the finite element method maintain C1-continuity of the radial displacement (deflection) and C0-continuity of the tangential displacement, respectively. The nonlinear algebraic equations of equilibrium are solved to a high degree of accuracy using Taylor’s expansion technique in conjunction with the Newton–Raphson method. Nonlinear stability analysis provides accurate solutions for the symmetric and antisymmetric buckling of both pin-ended and fixed shallow arches. The stability of the symmetric deformation path is investigated for both pinned and fixed arches, and a detailed analysis is carried out at the point of bifurcation onto an asymmetric deformation path for a pinned symmetrically laminated shallow arch. The slope of this post-buckled path is also computed, and is shown to be accurate for deformations well beyond the point of bifurcation.

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ABSTRACT: The present investigation is concerned with the prediction of localization (onset of deformation softening) and post-localization and post-“yield” equilibrium paths for moderately thick and thick cross-ply [90/0/90] imperfect plane strain rings. These paths are often unstable in the presence of modal imperfections and material nonlinearity, and are considered to “bifurcate” from the primary equilibrium paths, representing periodic buckling patterns pertaining to global or structural level stability. The fully nonlinear finite element analysis, based on the total Lagrangian formulation, employs a three-dimensional theory, known as layer-wise linear displacement distribution theory (LLDT), to capture the three-dimensional interlaminar (especially, shear) deformation behavior, associated with the localized interlaminar shear-crippling failure. The combined effects of modal imperfections, interlaminar shear/normal deformation and nonlinear (hypo-elastic) material property for the transverse shear modulus, GTT, on the localization and delocalization (deformation hardening) phenomena are thoroughly investigated, and physically meaningful conclusions are drawn from these numerical results.

M. Farshad and G. Ahmadi (School of Engineering, Pahlavi University, Shiraz, Iran), “Influence of loading

ABSTRACT: In order to investigate the influence of motion-dependency of loading on the form of stability equations of circular cylindrical shells, certain types of deformation-dependent forces are characterized. The stability equations of rings and columns acted upon by motion-dependent (and possibly non-conservative) forces are obtained as special cases. Some new aspects of ring instability such as tension-induced modes of instability and rigid body modes are also studied.

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ABSTRACT: The strain energy release rate is calculated for buckled one-dimensional delamination (through-width delamination) in composite laminates subjected to in-plane compression. A crack closure method based on plate finite elements is used in this analysis. For some laminates containing a one-dimensional delamination in cylindrical bending, closed form solutions are available. The present finite element solutions show excellent agreement with the analytical solutions. The strain energy release rate for various types of laminates is also calculated using the present finite element method. The results show that the strain energy release rate strongly depends on the type of laminate.


ABSTRACT: In this paper, numerical methods for the evaluation of the energy-release-rate along a delamination periphery under conditions of local buckling of the delaminate, as well as global buckling of the entire laminate, are presented. A multi-plate model, using independent Reissner-Mindlin plate models for each of the delaminated and undelaminated plies, with Reissner-Mindlin constraints for relating the degrees of freedom of the delaminated plates to those of the undelaminated plate at the crack front, is used to model the laminate with embedded delaminations. Explicit expressions, in terms of finite element nodal or Gauss-point variables, are derived for the pointwise energy release rate in terms of the J-integral and the Equivalent Domain Integral in the context of a typical multi-plate model for characterising the delamination growth. A finite element method with a 3-noded quasi-conforming shell element, and an automated post-buckling solution capability, is used for conducting the numerical analyses in this paper. Using these numerical results, mechanisms of multiple buckling modes and their effect on the propagation of embedded delaminations in plates, are studied.

DTIC Accession Number: ADA327865, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA327865

ABSTRACT: BUCKDEL, performs geometrically nonlinear analysis of stiffened laminated composite plates with and without delaminations. BUCKDEL allows the user to perform: a linear static solution; a linear
buckling (eigenvalue) analysis; and a nonlinear post-buckling analysis through both limit and bifurcation points. There are two finite elements in BUCKDEL: a quasi-conforming triangular laminated plate element based on a refined first order shear theory with seven degrees of freedom per node and a fiber reinforced beam element with seven degrees of freedom per node. The behavior of all materials is assumed to be linearly elastic. The multi-domain modeling method is used for the analysis of laminated plates containing delaminations. In this model, the delaminate, base and the undelaminate are modeled as 3 distinct. On the delamination front, Mindlin's deformation assumption is applied to obtain the relationship between the displacements in the delaminate, base and undelaminate.

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ABSTRACT: Delamination reduces an elastic buckling load of the laminated composite structures and lead to global structural failure at loads below the design level. Therefore, the problem of the delamination buckling of laminated composite structures has generated significant research interest and has been the subject of many theoretical and experimental investigations. However, questions still remain regarding a complete understanding and details of the phenomena involved. In this paper an efficient finite element model is presented for analyzing the elastic buckling behavior of laminated composite plates with through-the-width delamination using a solid element based on a three-dimensional theory. The solid finite element, named by EAS-SOLID8, is based on an enhanced assumed strain method. The study for elastic buckling behavior of laminated composite plates with through-the-width delaminations are focused on various parameters, such as size of delamination, support condition, aspect ratio, width-to-thickness ratio, stacking sequences, and location of delamination and multiple delaminations.

References listed at the end of the paper:

ABSTRACT: Compressive buckling stability of composite panels with through-width, equally spaced multiple delaminations are investigated analytically and experimentally. An analytical method is formulated on the basis of Rayleigh-Ritz approximation technique. Timoshenko type shear effects are included. An experiment and a finite element analysis are also conducted on the present model. The analytical results agree very well with the experimental and finite element results. The buckling load, which is the compressive strength of the panel in the case of the present model, reduces significantly due to the existence of multiple delaminations. The mechanism causing the significant loss of the compressive buckling load due to the delaminations is well explained.

ABSTRACT: An experimental and analytical investigation is conducted on the compressive buckling behavior of an orthotropic plate with a free edge delamination. The plate is a simplified model of stiffener plates. In the present paper two loading edges are fixed and a side edge is simply-supported. The delamination locates at the free edge over the whole length. A Rayleigh-Ritz approximation method is adopted in the analysis. A constrained point is used to allow contacts between the two delaminated surfaces. At this point, relative displacement and two relative slopes are constrained through imaginary springs. The buckling load of the geometrically admissible buckling mode is obtained by an ordinary eigenvalue analysis. The analytical results are compared with the experiment and the results agree well. The effects of the width and the location of the delamination on the buckling behavior are studied analytically for the plates with various aspect ratios. Low local delamination buckling can occur at very low load when the delamination locates near the surface and its size is relatively large compared with that of the plate. The constrained point is shown to be effective for the buckling analysis of the delaminated plates.


ABSTRACT: The extended finite element method is applied to stress analyses of composite laminates modeled by shell elements. In the proposed method, a thin-walled structure containing an interface is modeled by shell elements, and the nodes on the interface are enriched in order to model the delamination. The X-FEM code for thin-walled structures based on the proposed method is developed and is applied to buckling analyses of Carbon Fiber-Reinforced Plastic laminate with delaminations. The proposed X-FEM for shell elements was shown to provide appropriate results, which agree well with those obtained by the X-FEM for solid elements and conventional FEM analyses.

Hiroshi Suemasu, Makoto Ichiki and Yuichiro Aoki, “Analytical study on low compressive strength of composite laminates with impact damage: Experiment and Finite Element Analysis”, UK-Japan Workshop, Bristol, UK, March 24-27, 2013

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ABSTRACT: Delamination growth is a phenomenon known to reduce the integrity of laminated composite structural elements and may lead to premature failures. In the present study, state of the art procedures of delamination growth analysis are overviewed. The energy release rate calculation is formulated for composite
delaminated tubular cross sections and specialized to a finite element model for delamination buckling and growth analysis of long laminated composite tubes taking into account initial geometric imperfections, large deformations, contact between delamination faces and material degradation. It is, then, used to study the potential of delamination growth in a hybrid composite tube. Parametric studies are conducted to assess the effects of delamination length, location and geometric imperfection on growth.

References listed at the end of the paper:


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ABSTRACT: The collapse of cylindrical shells under external pressure is known to be controlled by global elastic buckling, material failure, or a combination thereof. In the case of composites, delamination is another factor affecting the stiffness and stability of the structural component. Thin inner delaminated layers are expected to locally buckle inwards, under hoop compression, reducing the effective thickness of the ring wall. This may lead to a premature collapse of composite rings. The problem is numerically treated and parametrically studied. A Fourier series-based finite-element model is formulated for delaminated composite tubular cross sections. A special “chord length” procedure is developed to enable the convergence of the local buckling solution in quasi-static nonlinear analysis. Parametric studies are conducted to assess the influence of delamination length, depth, location, out-of-roundness imperfection, and ring layup on the pressure levels at delamination buckling and collapse.

DOI: 10.1007/s11340-011-9514-z

ABSTRACT: To characterize the materials parameters and deformation of a convex shell of axial symmetry, a hydrogel contact lens is mechanically deformed by two loading configurations: (a) compression between two parallel plates and (b) central load applied by a shaft with a spherical tip. A universal testing machine with nano-Newton and submicron resolutions is used to measure the applied force, F, as a function of vertical displacement of the plate/shaft, w₀, while a homemade laser aided topography system records the in-situ deformed shell profile and the contact radius or central dimple, a. A nonlinear shell theory and an iterative finite difference method are used to account for the large elastic deformation, the central buckling for the central load compression, and the interrelationship between the measureable quantities (F, w₀, a).
References listed at the end of the paper:

Eurocodes for the local buckling design of the shell have been compared. Concerning the design against earthquake, an eigenvalue analysis along with a response spectrum analysis has been performed according to the Eurocode 8 specifications. The behavior of the tower for earthquake loading is compared to the corresponding for wind loading one regarding both computational models.

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ABSTRACT: The present work deals with a generalization of geometrically linear shear deformation theory for multilayered anisotropic shells of general shape. No assumptions are made other than to neglect the transverse normal strain. The results, which include the effects of shear deformations and rotary inertia as well as initial curvature (included in the stress resultants and assumed transverse shear stresses) are deduced by application of the virtual work principle, with displacements and transverse shear as independent variables. These equations are applied to different shell geometries, such as revolution, cylindrical, spherical and conical shells as well as rectangular and circular plates.

ABSTRACT: A general approach, based on shearable shell theory, to predict the influence of geometric non-linearities on the natural frequencies of an elastic anisotropic laminated cylindrical shell incorporating large displacements and rotations is presented in this paper. The effects of shear deformations and rotary inertia are taken into account in the equations of motion. The hybrid finite element approach and shearable shell theory are used to determine the shape function matrix. The analytical solution is divided into two parts. In part one, the displacement functions are obtained by the exact solution of the equilibrium equations of a cylindrical shell based on shearable shell theory instead of the usually used and more arbitrary interpolating polynomials. The mass and linear stiffness matrices are derived by exact analytical integration. In part two, the modal coefficients are obtained, using Green’s exact strain–displacement relations, for these displacement functions. The second- and third-order non-linear stiffness matrices are then calculated by precise analytical integration and superimposed on the linear part of equations to establish the non-linear modal equations. Comparison with available results is satisfactorily good.

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“Large amplitude vibrations of anisotropic cylindrical shells”, Computers & Structures, Vol. 82, Nos. 23-26,
ABSTRACT: A semi-analytical method is developed in conjunction with shearable shell theory and modal expansion approach to predict the influence of geometrical non-linearities on free vibrations of anisotropic laminated cylindrical shells. Shear deformation and rotary inertia effects are taken into account in the equations of motion. The hybrid method developed in this theory is a combination of classical finite element approach, shearable shell theory and modal coefficient procedure. The displacement functions are obtained by the exact solution of the equilibrium equations of anisotropic cylindrical shells and thereafter, the mass and linear stiffness matrices are derived by exact analytical integration. Green exact strain–displacement relations are used to obtain the modal coefficients for these displacement functions. The second- and third-order non-linear stiffness matrices are then calculated by precise analytical integration and superimposed on the linear part of equations to establish the non-linear modal equations. The linear and non-linear natural frequency variations are determined as a function of shell parameters for different cases. The comparison shows that the numerical analysis is of good reliability on the prediction of the experimental results.


ABSTRACT: Many papers have been devoted to the panel flutter of shells [1-4], it is used the piston theory formula for pressure of the aerodynamical interactions between the flow and a shell. Inadequacy of such an approach is discussed in papers [5-7]; results of these studies were used in [8-9] for new statements of problems on the flutter of conical shells. In the proposed work, in elaborations of results of [6], it is considered a problem on the truncated conical shell flutter, it is adduced data on evaluative computations and comparison them with analogous ones, obtained by the piston theory.

References listed at the end of the paper:


ABSTRACT: Large amplitude vibration behavior of symmetrically laminated moderately thick doubly curved shallow open shells with simply-supported sides is investigated. The von Karman type nonlinear strains are incorporated into the first-order shear deformation theory. By applying a Galerkin approximation, five governing equations of motion are reduced to a single nonlinear time differential equation which involves the quadratic and cubic nonlinearities. The nonlinear equation is solved by the fourth-order Runge-Kutta time integration scheme. The validity of the present approach is established by comparing the results obtained by the present study with those available in the literature. The effects of curvature, vibration amplitude, degree of orthotropy, aspect ratio and inplane edge support conditions on the nonlinear vibration characteristics of isotropic, orthotropic and laminated anisotropic open shells are examined.


ABSTRACT: The postbuckling behavior of rectangular isotropic stiffened plates under inplane compressive load is investigated considering the phenomenon of buckled pattern change in the postbuckling load range. The finite deformation strains in the von Karman sense are incorporated in the geometrical nonlinear postbuckling analysis. The inplane and out-of-plane displacements are assumed as truncated Fourier series. The principle of minimum potential energy is applied. The total potential energy includes the strain energy due to bending and membrane action of plate, torsion of stiffeners, and the work done by external compressive force. The plates are assumed to be simply supported along the loaded sides and elastically restrained against rotation by longitudinal stiffeners along the unloaded sides. In numerical examples, the postbuckling load end-shortening curves and effective width curves are presented for the rectangular stiffened plates with various aspect ratios, torsional rigidities of stiffeners and inplane boundary conditions along unloaded sides.

References listed at the end of the paper:
86-13, MIT.

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ABSTRACT: For the coupled stability analysis of thin-walled composite beam with closed cross-section subjected to various forces such as eccentric constant axial force, end moments, and linearly varying axial force, the efficient numerical method to evaluate the element stiffness matrix is newly presented based on the homogeneous form of simultaneous ordinary differential equations. The general bifurcation type of buckling theory for thin-walled composite box beam is developed based on the energy functional corresponding to semitangential rotations and semitangential moments. The coupled stability equations including variable coefficients and the force–displacement relationships are derived from the energy principle and explicit expressions for displacement functions are presented based on power series expansions of displacement components. The element stiffness matrix is evaluated by applying member force–displacement relationships to these displacement functions. In addition, the finite element model based on the cubic Hermitian interpolation polynomial is presented. In order to verify the accuracy and validity of this study, numerical solutions are presented and compared with the finite element solutions using the Hermitian beam elements and the available results from other researchers. Particularly, the influence of the eccentricity and the force ratio of axial forces, the fiber orientation, and the boundary conditions on the buckling behavior of composite box beam are parametrically investigated. Also the emphasis is given in showing the phenomenon of buckling mode change.

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ABSTRACT: Dynamic responses of composite cylindrical shell panels under initial in-plane stress and impacted by a rigid ball are analyzed by the finite element method using nonlinear shell theory based on Donnell's shell theory with von-Karman's large deflection assumptions. The contact force is characterized by
modified indentation laws which account for the effect of curvatures of the composite cylindrical shell and impactor. Dynamic transient responses including deflections, stresses, strains and contact forces are presented and compared with those obtained by linear analysis. In addition, effects of curvature and initial stress in the shells on the impact responses are investigated and discussed.


ABSTRACT: The buckling behavior of multilayer shells is studied for composite structures subjected to combinations of uniform temperature change, applied external pressure, and applied and reactive circumferential edge loads. A stability criterion is established for the class of structures of interest and a transverse loading parameter is identified. Critical parameters are identified, and closed form analytical solutions are obtained for the associated non-linear problems. Numerical simulations, based on these solutions, are performed and the stability criterion is applied, revealing characteristic behavior of the structures of interest. Such behavior includes “sling-shot” buckling, whereby the structure slings from deflections in one direction to deflections in the opposite sense, in an unstable manner, at critical temperatures. The influence of external pressure on the critical temperature change of thermally loaded composite structures is elucidated, as is the influence of temperature change on the buckling behavior of pressure loaded multilayer shells.

S.E. Rutgerson and W. J. Bottega (Department of Mechanical and Aerospace Engineering, Rutgers University, 98 Brett Road, Piscataway, NJ 08854-8058, USA), “Pre-Limit-Point buckling of multilayer cylindrical panels under pressure, AIAA Journal, Vol. 42, No. 6 (2004), pp. 1272-1275.


ABSTRACT: An overview, unification and review of the mathematical models, stability criteria and critical parameters for two types of structures, patched plates and layered shells, subjected to uniform temperature change are presented. Results of numerical simulations based on analytical solutions are presented and critical behavior is reviewed and compared. In each case, a transverse loading parameter is seen to force the system. For both types of structure, the loading parameter is dependent on both the temperature and the membrane force, and a critical membrane force and critical temperature are identified. When the corresponding critical temperature is achieved, both types of structures considered are seen to exhibit sling-shot buckling, an instability in which the structure dynamically slings from equilibrium configurations associated with deflections in one direction to those associated with deflections in the opposite sense. Conclusions are drawn and explanations are given as to the physical reasons for this phenomenon.

ABSTRACT: The coupling of edge debonding and thermal buckling of patched beam-plates possessing initial edge detachment is examined for the case when the structure is subjected to a uniform temperature change. The geometrically nonlinear analytical model employed is that established by the authors in a prior work. The problem is recast in a mixed formulation in terms of the transverse deflection and the membrane force to aid in the analysis and physical interpretation. The interaction of edge-debond propagation and thermal buckling is studied. The phenomenon of buckle-trapping, originally observed by the authors in a congruent study, as well as the phenomenon of sling-shot buckling, is seen to manifest itself in the debonding behavior. The evolution of the structure is predicted as a function of given material and geometric parameters from numerical simulations based on analytical solutions of the nonlinear problem. A (propagating) contact zone adjacent to the bonded region is accounted for, and its presence or absence, as well as its nature, is seen to be highly influential in the global as well as local behavior of the structure.


ABSTRACT: Combined effects of modal imperfections, transverse shear/normal deformation with/without reduced transverse shear modulus, $G_{LT}$ (caused by distributed fibre misalignments), on emergence of interlaminar shear crippling type instability modes, related to localization (onset of deformation softening), delocalization (onset of deformation hardening) and propagation of mode II compression fracture/damage, in thick imperfect cross-ply very long cylindrical shells (plane strain rings) under applied hydrostatic pressure, are investigated. Of special interest is the question: what are the geometric and/or material parameters that induce localized and delocalized states in imperfect cross-ply (very) long cylindrical shells under hydrostatic compression simultaneously, and what would be the consequences of such occurrences? The primary accomplishment is the (hitherto unavailable) computation of the layer-wise mode II stress intensity factor, energy release rate and kink–crack bandwidth, under hydrostatic compression, from a nonlinear finite-element analysis, using Maxwell's construction and Griffith's energy balance approach. Additionally, the shear crippling angles in the layers are determined using an analysis, pertaining to the elastic inextensional deformation of the compressed (plane strain) ring. Numerical results include effects of (i) thickness-induced transverse shear/normal deformation and (ii) uniformly distributed fibre misalignments, on localization and delocalization, and consequently on compression fracture/damage characteristics of thick imperfect cross-ply very long cylindrical shells.

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ABSTRACT: The main objective of this paper is to investigate the validity of the finite element method (FEM) on the buckling and post-buckling behavior of laminated composite cylindrical shells that have been subjected to an external hydrostatic pressure. In addition, a buckling pressure equation that is based on the ASME and
American Bureau of Shipping (ABS) buckling equation and customized to USN125 composite material is also presented. In order to determine an application for composite material under external hydrostatic pressure, material tests were conducted for carbon–epoxy ply composite URN300 and USN125. The strength and stiffness of the fiber and resin of two composites were determined. Cylindrical panel tests were performed to investigate the behavior of post-buckling under vertical line load. Finite element analyses, using ABAQUS 6.6 code, have been performed, using a linear buckling model based on the solution of the eigenvalue problem, and a non-linear model based on the arc-length method for various cases. Furthermore, an external hydrostatic pressure test was conducted to verify numerical analysis. These results were compared with the previous results obtained by FEM on the buckling. Difference between FEM and the test result is expected to be approximately 18%.

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“Post-buckling behavior of laminated composite cylindrical shells subjected to axial, bending and torsion loads”, World Journal of Engineering and Technology (WJET), Vol. 3, No. 4, November 2015, DOI: 10.4236/wjet.2015.34019

ABSTRACT: In present work, post-buckling behavior of imperfect (of eigen form) laminated composite cylindrical shells with different L/D and R/t ratios subjected to axial, bending and torsion loads has been investigated by using an equilibrium path approach in the finite element analysis. The Newton-Raphson approach as well as the arc-length approach is used to ensure the correctness of the equilibrium paths up to the limit point load. Post-buckling behavior of imperfect cylindrical shells with different L/D and R/t ratios of interest is obtained and the theoretical knock-down factors are reported for the considered cylindrical shells.

References listed at the end of the paper:
H. Hernández-Moreno (1 and 2), B. Douchin (1), F. Collombet (1), D. Choqueuse (3) and P. Davies (3)

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ABSTRACT: The influence of winding pattern on the mechanical response of filament wound glass/epoxy cylinders exposed to external pressure is studied by testing cylindrical specimens having stacked layers with coincident patterns in a hyperbaric testing chamber. Different analytical models are evaluated to predict buckling pressure and modes of thin wall cylinders (diameter to thickness ratio d/h of 25) and satisfactory predictions are obtained which are in the same order of magnitude that those obtained in experimental results. Test results show no evident pattern influence on either strength (implosion pressure) or buckling behavior (buckling modes) of thin wall or thick wall (d/h of 10) cylinders.

References listed at the end of the paper:

ABSTRACT: A refined higher-order displacement model for the study of the behavior of concentrically and eccentrically stiffened laminated plates based on C0 finite element discretization is presented. The model incorporates non-linear variations of longitudinal displacements through the thickness and hence eliminates the need to use shear correction coefficient(s). Transverse shear deformations are included in the formulation making the model applicable for both moderately thick and thin composite stiffened plates. The plate element used is a nine-noded isoparametric one with seven degrees of freedom at each node. The stiffener element is a three-noded isoparametric beam element with four degrees of freedom at each node. The stiffness of a stiffener is reflected at all nine nodes of the plate element in which it is placed. Accordingly, the stiffeners can be positioned anywhere within the plate element along lines of constant natural coordinates and need not necessarily be placed on nodal lines which gives a great flexibility in the choice of mesh size. The integrals are evaluated by a selectively reduced integration (SRI) technique with three and two Gauss quadrature rules for membrane-flexure and shear parts, respectively. The present formulation is checked for different examples of stiffened plates made of isotropic and fiber-reinforced composites, and results are compared with existing analytical and other finite element solutions.


PARTIAL ABSTRACT: A viable aspect of fiber-reinforced composites is their elastic tailoring ability. Anticlastic curvature is one example of elastic tailoring that occurs with an unsymmetrical cross-ply layup. Residual stresses resulting from differences in coefficients of thermal expansion and elastic properties in each lamina can cause large out-of-plane deformations. In the case of thin unsymmetric cross-ply laminates under thermal curing load, a cylindrical shape is observed because of the inherent geometrical non-linearity as opposed to the saddle shape that Classical Lamination Theory predicts. In this paper a finite element approach using ABAQUS is implemented in order to predict the unsymmetric cross-ply laminate shapes under thermal curing stresses…

Samer Tawfik, Xinyan Tan, Serkan Ozbay and Erian Armanios (School of Aerospace Engineering, Georgia Institute of Technology Atlanta, GA 30332-0150, USA), “Anticlastic Stability Modeling for Cross-ply
ABSTRACT: A viable aspect of fiber-reinforced composites is their elastic tailoring ability. Anticlastic curvature is one example of elastic tailoring that occurs with an unsymmetric cross-ply layup. Residual stresses resulting from differences in coefficients of thermal expansion and elastic properties in each lamina can cause large out-of-plane deformations. In the case of thin unsymmetric cross-ply laminates under thermal curing load, a cylindrical shape is observed because of this inherent geometrical nonlinearity as opposed to the saddle shape that classical lamination theory predicts. In this article, a finite element approach, using ABAQUS, is implemented in order to predict the unsymmetric cross-ply laminate shapes under thermal curing stresses and understand the underlying limit point instability. Numerical results for curvatures of the predicted shapes are in agreement with published experimental and analytical data. The stability of the cylindrical laminates is also investigated. Depending on the aspect ratio of the rectangular laminate, a cylindrical shape may snap-through from its current stable configuration to another stable cylindrical shape with a different curvature. In particular, both the critical aspect ratio where snap-through will cease to occur and the buckling load are reported.

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ABSTRACT: This research aims at investigating the bistable characteristics of unsymmetric cross-ply laminates resulting from thermally induced stresses while curing. The bistable characteristics are examined with a focus on the change in geometry for a subset of configurations, namely, rectangular, trapezoidal and triangular. To this end, these geometries are systematically investigated leading to a set of non-dimensional parameters establishing the values required for bistable behavior. A new apparatus is designed to measure the magnitude of the force required for snap-through and snap-back. The influence of friction at the supports of the tested panels is minimized by utilizing air cushion for frictionless motion. Predictions from a nonlinear finite element based methodology using the ABAQUS code are validated through comparisons with test data.

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ABSTRACT: A composite panel, with a [0/90] unsymmetric layup, exhibits bi-stable anticlastic equilibrium configurations. One way to provide morphing capabilities to such a panel is attained by attaching piezoelectric actuators to its surface. In such a design an electric field is applied to the piezoelectric actuators in order to trigger snap-through behavior of the panel/actuator assembly. A simple cantilever beam configuration is discussed to perform actuator assessment. Results are compared to with predictions from Extended Classical Lamination Theory and finite element analysis. Guidelines are proposed to design a morphing unsymmetric
panel/actuator assembly. The panel/actuator(s) assembly is manufactured accordingly. Snap-through experiments are conducted and the ABAQUS finite element software is used to predict snap-through behavior. Analysis predictions are in good agreement with test results.

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ABSTRACT: Composite shells show a rich multistable behaviour of interest for the design of shape-changing (morphing) structures. Previous studies have investigated how the initial shape determines the shell stability properties. For uniform initial curvatures and orthotropic material behaviour, not more than two stable equilibria have been reported. In this paper, we prove that untwisted, uniformly curved, thin orthotropic shells can have up to three stable equilibrium configurations. Cases of tristability are first documented using a numerical stability analysis of an extensible shallow shell model. Including mid-plane extension shows that the shells must be sufficiently curved in relation to their thickness to be multistable. Thus, an inextensible model allows us to perform an analytical stability analysis. Focusing on untwisted initial configurations, we illustrate with simple analytical results how the material parameters of the shell control the dependence of its multistable behaviour on the initial curvatures. In particular, we show that when the bending stiffness matrix approaches a degeneracy condition, the shell exhibits three stable equilibria for a wide range of initial curvatures.

References listed at the end of the paper:
“Multiparametric Actuation of Bistable Plates: A Method to Avoid Snap-Through Instabilities”, 7th EUROMECH Solid Mechanics Conference J. Ambrosio et.al. (eds.) Lisbon, Portugal, 7–11 September 2009

ABSTRACT: Large changes in the shape of a given structural member can be obtained by exploiting geometric nonlinearities or instability phenomena; multistable structures, i.e. structures characterized by two or more stable configurations, can undergo large displacements under moderate actuation forces. This feature turns out to be a major advantage for some actuation problems. The study of multistability and of geometrical nonlinear effects in composite plates and shells has recently gained a relevant interest: it is expected that the industrial applications of multistable structures will encompass a large variety of engineering products from micro-electronics systems to human-scale systems. Previous numerical and experimental [5, 9, 13] studies have analyzed the possibility of using a piezoelectric actuation to drive a bistable composite plate from one stable configuration to the other; other recent contributions [11, 15] have investigated the influence of geometry and material properties on the stability properties of shallow shells. We propose new insights regarding both these aspects.

References listed at the end of the paper:

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ABSTRACT: This paper studies the stable equilibrium shapes of free multilayered orthotropic plates loaded by inelastic deformations induced by thermal and piezoelectric effects. Starting with a Von Kármán plate kinematics and an energetic formulation, a discrete intrinsic nonlinear model in terms of curvatures only is deduced. The model has 3 degrees of freedom, namely the components of the symmetric curvature tensor, which is supposed to be uniform in space. Despite of this rough assumption, the analytical results about the equilibrium shapes and their stability show a good agreement with the finite element simulations performed with a commercial code. Literature results about the bistable behavior of isotropic plates under a single-parameter loading are extended to the orthotropic case with two loading parameters. In light of a global stability analysis and a phase portrait as a function of the inelastic curvatures, we study possible actuation techniques for controlling the transition of the plate between its two stable configurations. We show that with a suitable two-parameter actuation, it is possible to get a controlled quasi-static transition, avoiding any instability phenomenon. Numerical simulations on a realistic case study support the technological feasibility of the proposed actuation technique when using active piezoelectric layers to control the inelastic curvature.

ABSTRACT: The paper presents a displacement incrementation procedure to handle multiple loadings in post-buckling analysis of structures by Dynamic Relaxation (DR). This procedure is generalized and a ‘variable-arc-length’ method is proposed to automate the tracing of load-deflection path. The resulting algorithm exactly traces limit points and can handle ‘snap-through’ or ‘snap-back’ problems. The efficiency of the proposed method is demonstrated by typical examples of truss, beam and shell structures.

ABSTRACT: This paper investigates the post-buckling analysis of structures using several proposed three-parameter constrained solution techniques. The family of three-parameter constraint equations is non-dimensional and comprises an elliptic constraint method, hyperbolic constraint method and a second degree polynomial constraint method. The proposed methods are numerically robust and are shown to be quadratically convergent. Their computational performance is demonstrated through various examples of truss, beam, plane stress and shell structures. The scope of the paper is limited only to the tracing of primary equilibrium path of the above structures, and hence the problems of bifurcation are not considered in the present study.

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(2) Department of Civil Engineering, IIT, Kanpur 208016, India
“Postbuckling response and failure of symmetric laminates under in-plane shear”, Composites Science and
ABSTRACT: This paper summarizes a study aimed at understanding the postbuckling behaviour and progressive failure of thin, simply supported symmetric rectangular laminates with various possible in-plane boundary conditions and under the action of in-plane shear loads. First-order shear deformation theory and geometric non-linearity, in the von-Karman sense, is used with a finite-element procedure. The 3D Tsai–Hill criterion is used to predict failure of lamina and the maximum stress criterion is used to predict the onset of delamination at the interface of two adjacent layers. The effect of in-plane boundary conditions, plate lay-ups, plate aspect ratio, fiber orientations and lamina material properties on the load deflection response, buckling load, first-ply failure load, ultimate load and the maximum transverse displacement associated with failure loads is presented.

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ABSTRACT: The objective of this work is to study the postbuckling behaviour and progressive failure response of thin, symmetric laminates under uniaxial compression and uniaxial compression combined with in-plane shear loads (positive and negative). First-order shear deformation theory and geometric non-linearity in the von Karman sense are used with a finite-element procedure. The 3-D Tsai–Hill criterion is used to predict failure of a lamina and the maximum stress criterion is used to predict onset of delamination at the interface of two adjacent layers. The effect of plate aspect ratio and ply lay-ups on the load deflection response is presented. Load interaction diagrams for (±45/0/90)2s, (±45)4s and (0/90)4s laminates are obtained in terms of the buckling, the first-ply and the ultimate failure loads. In addition, progressive failure response of the (±45/0/90)2s laminate is also presented to show the buckling loads, failure loads, maximum transverse displacements associated with the failure loads and failure modes and locations at various load ratios.


ABSTRACT: A nonlinear finite element method, which is based on the von Karman–Mindlin plate theory and the principle of minimum total potential energy, is used to study the response and the first-ply failure of thin laminated composite plates under uniform temperature rise. The temperature dependent mechanical and strength properties, their effect on response and failure of laminates and the onset of delamination in the process of first-ply failure computation are some of the features incorporated in the nonlinear formulation. The load–displacement curves for different types of graphite/epoxy laminates are obtained. Stresses are computed to determine the first-ply failure temperature based on the Tsai–Wu failure criterion. The effect of the fiber orientation, the number of lay-ups and the plate aspect ratio on the response as well as the first-ply failure is studied.

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“Postbuckling strengths of composite laminate with various shaped cutouts under in-plane shear”, Composite Structures, Vol. 92, No. 12, November 2010, pp. 2966-2978, doi:10.1016/j.compstruct.2010.05.008
ABSTRACT: The aim of present investigation is to study the buckling and postbuckling response and strengths under positive and negative in-plane shear loads of simply-supported composite laminate with various shaped cutouts (i.e., circular, square, diamond, elliptical-vertical and elliptical-horizontal) of various sizes using finite-element method. The FEM formulation is based on the first order shear deformation theory which incorporates geometric nonlinearity using von Karman’s assumptions. The 3-D Tsai-Hill criterion is used to predict the failure of a lamina while the onset of delamination is predicted by the interlaminar failure criterion. The effect of cutout shape, size and direction of shear load on buckling and postbuckling responses, failure loads and failure characteristics of quasi-isotropic [i.e., (+45/-45/0/90)2s] laminate has been discussed. In addition, the effect of composite lay-up [i.e., (+45/-45/0/90)2s, (45/-45)4s and (0/90)4s] has also been reported. It is observed that the cutout shape has considerable effect on the buckling and postbuckling behaviour of the quasi-isotropic laminate with large size cutout. It is also observed that the direction of shear load and composite lay-up have substantial influence on strength and failure characteristics of the laminate.

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ABSTRACT: The objective of this paper is to study the interaction curves along with buckling and postbuckling responses of a quasi-isotropic laminate with a centrally placed circular cutout of various sizes under uni-axial compression combined with in-plane shear loads (positive and negative). The present study is carried out using finite element method. The finite element formulation is based on the first order shear deformation theory and von Karman’s assumptions to incorporate geometric nonlinearity. The resulting nonlinear algebraic equations are solved by Newton–Raphson method. The 3-D Tsai-Hill criterion is used to predict the failure of a lamina while the onset of delamination is predicted by the interlaminar failure criterion. It is observed that pure compression-buckling, -first-ply failure and -ultimate failure strengths of the quasi-isotropic laminate with and without circular cutout decreases with increasing accompanying shear load. In addition, it is also noted that for a given uni-axial compression load, a quasi-isotropic laminate with and without a cutout can sustain higher negative shear load in comparison to the positive shear load.

ABSTRACT: Digital fringe projection profilometry (FPP) is suitable to inspect surface profile of object, with some apparent advantages of non-contact, full-field measurement, simple apparatus, high precision, and real-time profile automation. Four phase-shifted sinusoidal fringe patterns are circularly projected onto the surface of a composite laminates panel reinforced with crossed ribs. Phase shifting method is applied to inspect the surface profile variations during compression. The profile results reveal that different local buckling modes appear at different crossed ribs, where the wave villages locate at the middle and the wave peaks occur at the composite panel ends. From the details of the deflection analysis, it can be seen that the local buckling modes couple with the whole bending of the composite panel. The local buckling modes vary with the applied load and
the experimental results are helpful to understand its failure mechanism.


ABSTRACT: Exact elasticity solutions are obtained using the stress function approach, where the radial, circumferential and shear stresses are determined, taking into account the closed ends of the cylindrical shell. The system of the governing algebraic equations is derived to accurately analyse a multilayered pressure vessel with an arbitrary number of layers and any thickness. The approach used is straight-forward compared to other three-dimensional solutions found in the literature. The design of multilayered composite pressure vessels is accomplished using the genetic algorithm and subject to the Tsai–Wu failure criterion. The genetic algorithm is optimized to serve this particular problem.


ABSTRACT: This paper aims to obtain the optimal design of laminated composite structures. The design variables are specified as the ply angles and the laminate thicknesses. The objective is to obtain a structure with minimum weight that is capable of carrying a given set of static external forces without failure. The solution strategy consists of addressing the problem sequentially at two levels, each having a different algorithm and a separate set of design variables. The optimization techniques use a combination of sensitivity analysis combined with optimality criteria and mathematical programming. The adequacy of the solution is assured by constraints limiting stresses and displacements.


ABSTRACT: A design optimisation methodology for beam reinforced composite structures with non-linear geometric behaviour is proposed. The formulation involves displacement, stresses, buckling and size constraints. The Newton–Raphson iterative procedure and the arc-length method are used for tracing equilibrium path and later updating the buckling load and the first ply failure load. The proposed sensitivity analysis model is based on an approach of the adjoint variable method for structures with non-linear geometric behaviour. The optimal design performs on a multilevel scheme based on structural efficiency maximisation exploring the anisotropic properties of the composites and weight minimisation using the ply thickness and the cross-section variables of the stiffeners. To demonstrate the applicability of the proposed developments, optimisation problems considering first ply failure and buckling conditions are presented.

C. A. Conceição António (Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal), “A hierarchical genetic algorithm for reliability based design of geometrically non-linear composite
ABSTRACT: A design optimisation methodology based on structural reliability of beam reinforced composite shell structures with non-linear geometric behaviour is proposed. The formulation involves probabilistic stress, displacement and buckling constraints. The structural integrity is evaluated through the reliability index using a Lind–Hasofer second-order-second-moment approximation method together with the Newton–Raphson iterative procedure and the arc-length method. The random variables are the mechanical properties of the laminates treated as homogeneous orthotropic materials. A new methodology based on an evolutionary strategy searching the global most probable failure point (MPP) for composite structures under non-linear geometric behaviour is proposed. The optimal design performs on a hierarchical genetic algorithm (HGA) based on weight minimisation under prescribed reliability constraints. The design variables are the ply angle, the ply thickness and the geometric variables associated with the cross sections of the stiffeners. To demonstrate the applicability of the proposed developments, optimisation problems are presented.


ABSTRACT: A multilevel genetic algorithm aiming the global optimization of beam reinforced composite structures with nonlinear geometric behaviour is proposed. A unified approach based on load-displacement control for buckling and first ply failure analysis is adopted. The Newton-Raphson iterative scheme and the arc-length method are used for tracing the equilibrium path and later for updating the critical values. The proposed genetic algorithm performs several sequences of two optimization levels resulting from the decomposition of the original optimization problem. Independent genetic searches are implemented for each level where different fitness functions and sub-populations are considered. The genetic operators selection and crossover supported by an elitist strategy are used while the diversity of the sub-populations is guaranteed based on implicit mutation. A genetic material exchange between levels is performed using clones and so the offspring of matured sub-populations is guaranteed. To improve the efficiency of the multilevel genetic optimization a niche of population is induced after the first stage at both levels.


ABSTRACT: The optimum design of laminated composite structures in terms of their strength is a complex task because many different mechanisms are involved in the damage and rupture to which these materials are subject. The great diversity of the damage mechanisms and their patterns of evolution makes it extremely difficult to estimate the strength margins. It is still impossible, for instance, to perform simulations on industrial structures made of unidirectional ply laminates up to rupture. The strategy adopted in this study on designing laminated composite structures is based on the choice of materials (woven or unidirectional plies) and the use of simple models (focusing on the rupture of the first ply) with which industrial structure analyses can be carried out. The choice of materials (woven or unidirectional plies) does not depend only on mechanical criteria but also on the simplicity of the corresponding modelling procedures.
ABSTRACT: Parameter studies, genetic algorithms and Monte Carlo type calculations are examples of pleasantly parallel computational tasks. Pleasantly parallel computational tasks can be effectively calculated in computer clusters or grids. In this work, we consider a weight minimization problem of a laminated composite structure in the post-buckling region. The design variables are the number of layers and the layer orientations given in a discrete set of allowable angles for layer orientations. Optimization is carried out using a deterministic search process, where the lay-up configurations are generated iteratively in the design space from the selected design points of the population at the preceding cycle. Computation is performed using NorduGrid grid computing platform. In this work, we briefly go through some general grid concepts and the use of grid in optimization of laminated composite structures.
ABSTRACT: If major weight saving is to be realised it is essential that composites be used in “primary” structural components, i.e., wing and fuselage skins. To this end it is essential that analytical tools be developed to ensure that composite structures meet the FAA damage tolerance certification requirements. For stiffened composite panels one potential failure mechanism is the separation of the skin from the stiffeners; resulting from excessive “through the thickness” stresses. This failure mechanism is also present in bonded composite joints and composite repairs. Currently failure prediction due to in-plane loading appears to be relatively well handled. Unfortunately, this is not yet true for matrix-dominated failures. Consequently, it is essential that a valid analysis methodology capable of addressing all of the possible failure mechanisms, including failure due to interlaminar failure, be developed. To aid in achieving this objective the present paper outlines the results of a series of experimental, analytical and numerical studies into the matrix-dominated failures of rib stiffened structures.

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ABSTRACT: With the introduction of postbuckling lightweight composite structures, adhesively bonded joints with thin skins are susceptible to premature failure due to peel induced loading. This paper reports on the findings of a research programme to investigate the local and global responses of postbuckling rib-stiffened panels under shear loads. C- and I-section ribs, with and without taper in the flanges, have been studied experimentally and analysed numerically to assess their postbuckling behaviour and relative merit with respect to structural integrity of rib-stiffened shear panels. The rib-skin separation loads and locations for the different panels have been evaluated via mechanical tests, and the experimental data have been closely predicted using Finite Element Method models.

ABSTRACT: The buckling behavior of composite laminated square plates is analyzed with the aid of the finite-element method in which a modified isoparametric linear shell element is used. The in-plane and bending displacements are used together in the formulation of the finite-element method in the case of asymmetric laminates. A new method of modifying the constitutive law of composite materials to circumvent the shear-lock effect is also proposed. This new method has the useful property of removing the shear-lock effect in the case of very thin plates. Composite laminates of symmetric and asymmetric stacking sequences, with and without a central circular hole are analyzed. Using the developed program, various laminated cases are analyzed and discussed. The present results show an improvement over those found analytically when compared with experimental results for asymmetric laminates.
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ABSTRACT: Analytical solutions for the buckling of anisotropic cylinders and curved panels under arbitrary loadings are presented. Donnell-type equations, laminated shell constitutive relations and the Galerkin method are used to determine critical loads. Correlations to account for unsatisfied boundary conditions are developed. A method for calculating the transverse shear stiffness of a laminated shell is discussed. Numerical correlations between theoretical and experimental buckling loads are presented.

ABSTRACT: The in-plane load-bearing capacity of marine composite plates is an area that has received little attention, in contrast to the significantly larger buckling and post-buckling studies available on aeronautical composites. The aim of this study is to investigate experimentally the strength to failure of large woven composite panels and correlate the results with finite element analyses. The tests performed were able to demonstrate the well-known sensitivity of the panels to boundary conditions and panel imperfection size, which is also reflected in a parametric study carried out in Abaqus/Standard. Two-dimensional stress-based failure criteria were implemented via a user-defined field (USDFLD) subroutine to detect matrix and fiber damage, which allows progressive damage to be modeled. A modification of Hashin’s failure criteria proved to be the most effective in capturing both the size and location of the damage and obtain a good approximation of the load—displacement history and surface strains.

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ABSTRACT: The application of a shell/3D technique for the simulation of skin/stringer debond in a specimen subjected to three-point bending is demonstrated. The global structure was modeled with shell elements. A local three-dimensional model, extending to about three specimen thicknesses on either side of the delamination front was used to capture the details of the damaged section. Computed total strain energy release rates and mixed-mode ratios obtained from shell/3D simulations were in good agreement with results obtained from full solid models. The good correlations of the results demonstrate the effectiveness of the shell/3D modeling technique for the investigation of skin-stiffener separation due to delamination in the adherents.
References listed at the end of the paper:
ABSTRACT: The development of an approximate analysis for predicting stresses in the skin-stiffener interface region of composite plates and shallow shells is presented. The analysis determines interlaminar normal stress and transverse shear stresses in the direction of the stiffener axial coordinate and the direction of the in-plane coordinate perpendicular to the stiffener axis. The analysis accounts for skin-stiffener interfaces with nonzero thickness and for curvature in the skin and stiffener. The interlaminar normal stress and transverse shear stresses at the interface are applied to the lower face of the skin and the upper face of the stiffener flange as unknown functions, and the displacements in the skin and flange are related through the deformation of the interface bond layer. The Rayleigh-Ritz method is used to determine the unknown functions that yield the interlaminar stresses at the skin-stiffener interface. The addition of a failure criterion to the stress prediction capability of the analysis results in the prediction of separation failure. After validation of results from the model, the effects of geometric nonlinearities and aspects of the numerical convergence of the analysis are explored and presented. Furthermore, the influence of various design parameters on the interface stress distribution, and therefore on skin-stiffener separation, is presented.

References listed at the end of the paper:

172261, January 1984.


PARTIAL ABSTRACT: Experimental simulation of boundary conditions while carrying out a panel buckling test has been known to be difficult. In this paper, compression buckling tests on 6.0-mm-thick carbon fiber composite (CFC) panels have been described for which a reasonably good simulation of the boundary conditions was achieved, especially under the simple supported condition. Carefully designed test fixtures that provided excellent alignment of the panel with the load axis and adequate lateral stiffness for edge supports during buckling of the CFC panels were used to achieve this goal. Both simply supported and clamped boundary conditions have been studied. Tests in room-temperature-as-received (RT/AR) and hot-wet (H/W) conditions are described. A buckling test on a simply supported panel with prior moisture conditioning was performed under the H/W condition with an environmental test chamber mounted on the test rig to prevent any loss of moisture during the test at 100 degrees C and greater than 85 per cent relative humidity. Based on these results, a test procedure was developed to identify buckling loads through measurement of out-of-plane displacements rather than relying solely upon longitudinal strain measurement...

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PARTIAL ABSTRACT: In typical applications such as in the top skin of a wing or in control surfaces of an airframe, laminated composites are often found to be buckling-critical. Under excessive compression loading composite panels may undergo buckling and failure mechanisms that would generally involve delamination or fiber breakage. Tapered composite panels with ply drops, when employed in wing skin, are expected to be more prone to the above mode of failure. This is one important area of concern to the designers of composite structures and both analysis and experimental verification of the buckling behavior are recommended as a part of the design validation effort. However, data from such analyses are scarce in the open literature. In this paper, results of a study on buckling and fracture behavior of laminated carbon fiber composite (CFC) panels containing ply drops are presented. CFC panels of varying thickness with normal and inclined ply drops were tested under compression loading until buckling and ultimate failure. Nearly simply supported boundary conditions at the ends and along the edges were simulated with the help of specially designed test fixtures. Tests were conducted both under room temperature and hot-wet…

ABSTRACT: The response of honeycomb sandwich structure to disbond damage, in a compressive stress field, has been assessed. Two types of disbond were considered; those extending through the full width of a panel (through-width) and those enclosed within the panel boundaries (embedded). For each type of disbond the failure process was established through four-point bend testing of 56 sandwich specimens. For both types of disbond, failure was found to be governed by buckling-driven disbond growth and, consequently, models of buckling and disbond growth were developed. All of the models decoupled the face-sheets of the sandwich and treated the core as a spring foundation having a stiffness determined from equilibrium of a two-dimensional orthotropic solid. A linear Winkler beam model was used to predict buckling of a through-width disbond. The model buckling loads agreed with specimen test results with an average difference of 1.7%. A non-linear Winkler beam model was then developed to predict post-buckling behaviour and the initiation of disbond growth, through a fracture mechanics analysis. A characteristic growth curve, defining the work input required to initiate disbond growth, was developed and agreed with specimen test results with an average difference of 3.3%. The model also verified that disbond growth occurs in discrete increments approximately equal to the diameter of the honeycomb cells. A linear Winkler plate model was used to predict buckling of an embedded disbond. The model buckling loads agreed with specimen test results with an average difference of 3.7%. A non-linear Winkler plate model was then developed to predict post-buckling behaviour of a sandwich panel containing an embedded disbond. The model considered contact conditions and modelled disbond growth by releasing fractured nodes during load incrementation. Disbond growth initiation loads agreed with specimen test results with an average difference of 15.8%. Failure loads consistently over-predicted specimen test results by an average of 13.9%. It was concluded that the growth initiation loads should be used as a conservative estimate of failure. The models developed may be used to assess the criticality of disbond damage in sandwich structure having thin-gauge, composite face-sheets.

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ABSTRACT: In the present work, an avant-garde study on Buckling of honeycomb sandwich panel of hexagonal cell has been carried out by considering simply supported boundary constraints explicitly. A novel theoretical formulation has been developed for the buckling of honeycomb panel as per Mil Standard (MIL-HDBK-23A). The laminate element type has been considered for linear static analysis using Lanczos Method (finite element method (FEM)). The buckling analysis carried out by FEM has been compared and validated with theoretical and experimental investigation for different panel aspect ratio under static load.

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2. Gamziukas V, Samuelsson LA (1977) Buckling of sandwich panels subjected to axial compression, shear forces and lateral pressure. FFA Report 132
3. Norris CB (1958) Compressive buckling curves for sandwich panels with isotropic facings and isotropic or orthotropic cores. FPL report 1854 revised January

Zoh Gweon Kim, Chang Sun Hong and Chun Gon Kimt (Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusung-gu, Taejon, 305-701, Korea), “Postbuckling Analysis of Stringer- Stiffened Composite Laminated Cylindrical Panels”, Journal of Reinforced Plastics and Composites, August 1995, vol. 14, no. 8, pp. 827-846, doi: 10.1177/073168449501400804 ABSTRACT: The postbuckling behavior of stiffened composite cylindrical panels was studied analytically and experimentally. Progressive failure analysis was implemented for the prediction of failure characteristics and postbuckling ultimate load. For the progressive failure analysis, the maximum stress criterion is applied to the average stress in each layer of all the finite elements. Using the same degenerated three dimensional isoparametric solid element in order to model stiffeners and the skin, the global and the local buckling of the stiffened panel can be depicted exactly. The results show the effects of stiffener location, and various stiffener heights and thickness on the postbuckling behavior of stiffened composite cylindrical panels. The postbuckling ultimate load of stringer-stiffened composite cylindrical panel is not dependent of the initial buckling load, but becomes higher as the stiffener thickness and height increase.

ABSTRACT: The dynamic response and damage of laminated composite cylindrical shell subjected to impact load is numerically investigated using the finite element method. A nine-node isoparametric quadrilateral element based on Sander's shell theory is developed, in which the transverse shear deformation is considered. A semi-empirical contact law that accounts for the permanent indentation is incorporated into the finite element program to evaluate the contact force. The Newmark time integration algorithm is used for solving the time dependent equations of the shell and the impactor. The Tsai-Wu failure criterion is used to estimate the failure of the laminated shell. Numerical results, including the contact force history, interlaminate damage zone, and failure indices in the shell are presented. Effects of curvature, impact velocity and mass of impactor on the composite shell behaviors are discussed.


ABSTRACT: Low velocity impact and compression-after-impact characteristics of a typical plain weave E-glass/epoxy composite are studied experimentally. Atmospheric pressure was maintained on the top surface and different pressures were applied on the rear side during impact experiments. Pressure on the rear side of the impacted plate is referred to as back pressure in further discussion. Effect of back pressure on the impact behavior is studied. It is observed that the variation in peak contact force and maximum central deflection are governed by two opposing phenomena. The parameters influencing the opposing phenomena are: induced curvature because of back pressure, effective pre-stressing and effective thickness. The incident impact energy was the same in all the experiments. Post-impact compressive strength was also investigated.

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ABSTRACT: Fibre composite structures have become the most attractive candidate for civil engineering applications. Fibre reinforced plastic polymer (FRP) composite materials have been used in the rehabilitation and replacement of the old degrading traditional structures or build new structures. However, the lack of design standards for civil infrastructure limits their structural applications. The majority of the existing applications have been designed based on the research and guidelines provided by the fibre composite manufacturers or based on the designer’s experience. It has been a tendency that the final structure is generally over-designed. This paper provides a review on the available studies related to the design optimization of fibre composite structures used in civil engineering such as; plate, beam, box beam, sandwich panel, bridge girder, and bridge deck. Various optimization methods are presented and compared. In addition, the importance of using the appropriate optimization technique is discussed. An improved methodology, which considering experimental testing, numerical modelling, and design constrains, is proposed in the paper for design optimization of
composite structures.

Behzad D. Manshadi, Anastasios P. Vassilopoulos and Thomas Keller [Composite Construction Laboratory (CCLab), Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland], “Shear wrinkling of GFRP webs in cell-core sandwiches”, Advances in FRP Composites in Civil Engineering, pp 91-94, 2011

ABSTRACT: Slender webs of glass fiber-reinforced polymer (GFRP) beams are sensitive to shear buckling. Shear buckling can be seen as an in-plane biaxial compression-tension buckling problem. The transverse tensile load thereby delays the onset of buckling and increases the ultimate load. Thin-walled GFRP plates of two different fiber stacking sequences, [0/90]S and [90/0]S, were subjected to in-plane biaxial compression-tension loading. The buckling loads were almost duplicated by increasing the tensile load while the ultimate loads were increased by up to 20%. The fiber stacking sequence thereby had significant effects on buckling mode shape and buckling and ultimate loads.

References listed at the end of the paper:


doi: 10.1007/978-3-642-17487-2_18

ABSTRACT: Glass fiber-reinforced (GFRP) cell-core sandwich structures are increasingly used in bridge deck and roof construction. GFRP cell-core sandwiches are composed of the outer GFRP face sheets, a foam core and a grid of GFRP webs integrated into the core in order to reinforce the shear load capacity. One of the critical failure modes is shear wrinkling, a local buckling failure in the sandwich webs due to shear loading. Shear wrinkling is a biaxial compression-tension wrinkling problem and, for this reason, the numerous results of pure compressive wrinkling research are not necessarily applicable. The details and results of in-plane biaxial compression-tension wrinkling experiments on GFRP sandwich laminates, stabilized by a polyurethane foam core, are presented. It is shown that an increasing transverse tension load significantly decreases the wrinkling load. These results are confirmed by finite element calculations.


ABSTRACT: Slender webs of glass fiber-reinforced polymer (GFRP) beams are sensitive to shear buckling. Shear buckling can be seen as an in-plane biaxial compression-tension buckling problem. The transverse tensile load thereby delays the onset of buckling and increases the ultimate load. Thin-walled GFRP plates of two different fiber stacking sequences, [0/90]S and [90/0]S, were subjected to in-plane biaxial compression-tension loading. The buckling loads were almost duplicated by increasing the tensile load while the ultimate
loads were increased by up to 20%. The fiber stacking sequence thereby had significant effects on buckling mode shape and buckling and ultimate loads.

References listed at the end of the paper:


ABSTRACT: The laws of corrugation (wrinkling) that takes place in thin aluminum films on silicon substrates with styrene sublayers under the conditions of thermal treatment have been studied using atomic force microscopy techniques. Measurements of the amplitude and period (wavelength) of wrinkles revealed stages in the viscoelastic corrugation process at various temperatures. It is established that the evolution of wrinkles in the course of annealing is controlled by the periodic distribution of normal and tangential stresses at the film-sublayer interface.

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PARTIAL ABSTRACT: An analytic model, based on two-dimensional laminated plate theory, is developed to investigate the influence of ply waviness on the stiffness and strength reduction of [90/0/90] laminate constructions. The model predicts: . . .

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ABSTRACT: The objectives of this research are to investigate the effects of stacking sequence (orientation of plies adjacent to the 0° plies), free surfaces, fiber/matrix interfacial bond strength, initial fiber waviness, resin-rich regions, and nonlinear resin shear constitutive behavior on fiber microbuckling initiation. Three thermoplastic composite material systems are used in this investigation. The materials are the commercial APC-
2 (AS4/ PEEK), QUADRAX Interlaced Tape, and a poor interface experimental material, AU4U/ PEEK. Notched compression specimens are studied at 21°C, 77 °C, and 132°C. Observations indicate that the notch radius controlled fiber microbuckling initiation, and thus compression strength, by dictating the unsupported fiber length at the notch. The numerical results from a companion paper [1] are compared qualitatively with these experimental results. The results show that increasing the test temperature, locating 0° plies at the free surface of the laminate, and degrading the fiber/matrix interfacial bond strength reduce the resistance to fiber microbuckling initiation in these notched laminates. The fiber micro buckling initiation strain is shown to be a constant, regardless of stacking sequence, for these notched laminates. Experimental results show that resin-rich regions also reduced the resistance to fiber microbuckling initiation.

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DOI: 10.1177/073168449301200404
ABSTRACT: Layer waviness was investigated in T300/P1700 carbon/polysulfone com posite laminates under static compression loading. A three-step procedure was used to fabricate isolated layer waves into the central 0° layer of [902/02/902/02]s laminates. Efforts were made to insure that this three-step procedure itself did not degrade the laminate quality. Layer wave geometries up to 1.5 layer thicknesses in amplitude and as short as nine layer thicknesses in length were tested. The more severe wave geometries produced reductions in static strength as high as 36 %, although the wavy 0° layer accounted for only 20% of the load carrying capacity of the laminate. Specimen failures were sudden and catastrophic. Brooming failure, characterized by through-the-thickness splaying of the layers and numerous delaminations near the waviness, was the common failure mode.

ABSTRACT: Four properties of unidirectional fibre composites are shown to be influenced by fibre waviness. Compressive strength (and also modulus) can be related to fibre waviness by relatively simple equations. Loss in strength during fatigue does not lend itself so easily to simple analysis, but seems to be readily explicable if the fibres are not straight. Shear strength parallel to the fibres is greater than the matrix shear strength—and at high temperatures much greater—and simple equations can be used to explain this in terms of fibre waviness. Finally, some features of delamination resistance can be explained in terms of fibre waviness. However, both for shear and delamination resistance, more data is needed on the degree of fibre waviness in test samples.

ABSTRACT: An investigation has been conducted of the effect of fiber waviness on stiffness and strength
reduction of unidirectional composites under compressive loading. Analytical models have been developed for
determining the elastic properties and compressive strength as a function of fiber waviness for three types of
wavy patterns: uniform, graded and localized waviness. Compression tests were conducted to verify the
predictions. Experimental results were in good agreement with predictions based on the analytical models. It is
shown that in unidirectional composites both major Young's modulus and compressive strength are degraded
seriously with increasing fiber waviness. Material anisotropy is also shown to influence the degree of stiffness
and strength reduction. Interlaminar shear failure was found to be the dominant failure mechanism for
unidirectional wavy composites under compressive loading.

H.M. Hsiao and I.M. Daniel (Robert R. McCormick School of Engineering and Applied Science, Northwestern
University, Evanston, IL 60208, USA), “Elastic properties of composites with fiber waviness”, Composites Part
doi:10.1016/1359-835X(96)00034-6

ABSTRACT: An investigation was conducted of the effects of fiber waviness on the elastic properties of
composite materials theoretically and experimentally. Unidirectional and crossply carbon/epoxy composites
with uniform, graded and localized fiber waviness were studied. An analytical constitutive model was
developed to determine the elastic properties as a function of fiber waviness. Compression tests were conducted
to verify the constitutive relations. Experimental results were in good agreement with predictions based on the
constitutive model.

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“Ply waviness on in-plane stiffness of composite laminates” (publisher and date not given in the pdf file. Latest
reference is dated 1996; perhaps the paper was presented at ICCM12; Stanford University Ph.D. dissertation
with similar title and same author as the first author of this paper is dated 1997)

ABSTRACT: A model was developed to determine the effect of ply waviness on the in-plane stiffness of
composite laminates. On this model, plies containing waviness were mathematically described as in-phase sine-
waves. Several configurations were included as well as generalization for any symmetric lay-up. The effective
properties were calculated using both weighted average and springs in series approaches. A test program was
conducted to validate the model for quasi-isotropic lay-ups. Data from the literature was also compared to
model predictions for unidirectional and cross-ply laminates. These predictions correlated fairly well to test
data. Model can be used as part of a framework to quantitatively access the effects of regions containing ply
waviness on the global in-plane stiffness of structural composite parts. This information can be used to control
quality or to impose operational limitations on such parts.

References listed at the end of the paper:
    Loading”, Proceedings of the 1987 Spring Conference on Experimental Mechanics, SEM -- Society for Experimental Mechanics,
    Bethel, CT, USA, 1987, pp. 948-951.
    136.

ABSTRACT: Out-of-plane layer waviness, a manufacturing-induced imperfection in multidirectional composite laminates, can produce significant decreases in compression strength. To date, failure predictions based on initial “first-ply” failure analyses as well as compression strength reductions based on the ply fraction containing waviness have shown limited agreement for compression-loaded cross-ply laminates with idealized formations of layer waviness. The objective of this investigation was to extend previous research by employing progressive failure analysis to predict the ultimate compression strength of carbon/epoxy composite laminates with layer waviness. A finite element modeling methodology was developed using cohesive elements available in the commercial finite element code ANSYS to model the formation and growth of delaminations at layer interfaces. Progressive failure analysis within individual composite layers was performed using the Hashin failure criterion and subsequent reduction of appropriate stiffness properties of the failed elements. Strength predictions were compared to mechanical test results obtained for a variety of layer wave formations intentionally fabricated into otherwise wave-free cross-ply laminates. Results suggest that the computational approach used for progressive failure analysis is well suited for predicting strength reductions due to realistic formations of layer waviness in composite laminates.

References listed at the end of the dissertation:
Adams and Natalie Hammer.


[34] Ansys, Inc., ANSYS 11.0. Cannonburg, PA.


ABSTRACT: This paper present the model analysis for the predicating the behaviour of inflatable membrane structure of general L-shape with a thickness in millimetre using the various smart material which optimally within structural member subjected to pre-stressed rather than bending or moments. A numerical solution for membranes may also be found using the finite element method. In this paper flat thin membrane choose to analysis the behavioural effect of the membranes using the properties of different smart material and compare their results in terms of frequency and generalized mass with mode shape. This analysis makes more effective to selects the smart material in the space technology. Geometrically non-linear vibration analysis of arbitrary L-shape membrane is also done using a finite element package, ABAQUS. The analysis shows good agreement between finite element and analytical solutions.

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ABSTRACT: The effects of fiber waviness on the nonlinear behavior of unidirectional composites under tensile and compressive loadings have been investigated theoretically and experimentally. Unidirectional composites examined were composed of continuous fibers with sinusoidal waviness in a matrix. As a consequence of material and geometric factors, both the tensile and compressive behavior of these composites was generally nonlinear under finite deformation. Analytical models were proposed for predicting the nonlinear tensile and compressive behavior as a function of fiber waviness for three types of fiber waviness pattern: uniform, graded and localized fiber waviness. The material and geometric nonlinearities due to fiber waviness were incorporated into the models based on complementary energy density and an incremental method. Specimens with various degrees of fiber waviness were fabricated. Tensile and compressive tests were conducted on the specimens to obtain the elastic properties and behaviors of the composite materials with fiber waviness. The experimental results were in good agreement with the predictions.

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ABSTRACT: The effects of fiber waviness on the nonlinear behavior of unidirectional composites under tensile and compressive loadings have been investigated theoretically and experimentally. Unidirectional composites examined were composed of continuous fibers with sinusoidal waviness in a matrix. As a consequence of material and geometric factors, both the tensile and compressive behavior of these composites was generally nonlinear under finite deformation. Analytical models were proposed for predicting the nonlinear tensile and compressive behavior as a function of fiber waviness for three types of fiber waviness pattern: uniform, graded and localized fiber waviness. The material and geometric nonlinearities due to fiber waviness were incorporated into the models based on complementary energy density and an incremental method. Specimens with various degrees of fiber waviness were fabricated. Tensile and compressive tests were conducted on the specimens to obtain the elastic properties and behaviors of the composite materials with fiber waviness. The experimental results were in good agreement with the predictions.

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ABSTRACT: A fiber microbuckling calculation is presented for the effects of fiber misalignment and material nonlinearity on the compressive strength of fiber composites. The role of fiber bending stiffness is included by using a particular form of couple stress theory. In order to examine the effect of a distribution of fiber waviness, the fiber misalignment angle is assumed to vary along the fiber length but is taken to be uniform in the transverse direction. Thus, the effects of wavelength as well as amplitude of fiber waviness are taken into account. A consideration of sinusoidal initial waviness reveals that short wavelength imperfections are much less deleterious than long wavelengths. A statistical analysis is presented for the effect of random fiber waviness on compressive strength, using a Monte Carlo simulation technique. Compressive strength is found to be particularly sensitive to the area under the spectral density curve and to the minimum fiber wavelength.
the form of a finite elliptical region of fibre waviness. The calculations show that the compressive strength decreases with increasing imperfection spatial size from the elastic bifurcation value of Rosen (1965, Fibre Composite Materials, pp. 37–75, American Society Metals Seminar) to the imperfection-sensitive infinite band strength given by Fleck et al. [1995, J. Appl. Mech. 62, 329–337].

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ABSTRACT: A model is presented for the dynamic compressive response of polymer matrix fiber composites. The model includes the effects of fiber misalignment and material nonlinearity as well as material inertia. The role of fiber bending stiffness is included via a couple stress formulation. The response of fiber composites to suddenly applied, constant compressive axial load is examined. It is found that under constant load, inertial effects contribute to a reduction in the critical stress for composite failure. This reduction is greatest for composites with long initial fiber imperfection wavelengths. For a given load, there is a range of initial fiber imperfection wavelengths that will result in composite failure. Within this range, there is a preferred wavelength, which results in the shortest failure time.

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ABSTRACT: Microbuckle initiation from an open hole, from a filled hole, and from the free surface of a unidirectional fibre composite is examined by a finite element method. The role of fibre bending resistance is included in the formulation so that a hole size effect is predicted. It is found that the open hole knocks-down the compressive strength to the order of 20tauY, while the filled hole reduces the strength to about 40tauY, where tauY is the in-plane shear modulus of the composite. Pre-existing fibre waviness adjacent to the hole gives a further reduction in the compressive strength. The role of in-plane shear stress and transverse stress in reducing the open hole compressive strength is examined: the compressive strength is reduced by the presence of shear and transverse tension, but the effect is less pronounced than that observed previously for the case of a circular patch of waviness. The study concludes with an investigation of the influence of the free surface on microbuckle initiation from a band of waviness and from a semi-circular patch of waviness: a negligible effect of the free surface on the compressive strength is predicted.

ABSTRACT: A finite element couple stress formulation is used to predict microbuckle initiation from a patch of fibre waviness in a unidirectional fibre composite under remote compression and bending. Attention is
focused on the knock-down in strength due to large amplitude waviness, with the effects of the physical size of the imperfection included by incorporating the fibre bending resistance within the formulation. The predicted strengths deviate significantly from the simpler kinking theory which neglects the role of fibre bending. Initial imperfections in the form of an infinite band and a circular wavy patch are considered: when these imperfections are of large spatial extent and possess a large misalignment angle, the compressive strength approximates the steady state band broadening stress for an infinite band. The effect of an imposed spatial gradient of stress within the composite is explored by determining the compressive strength of beams of finite height for the loading cases of pure bending and axial compression. It is found that the compressive strength is sensitive to the magnitude of the imposed stress gradient: the compressive strength of the outer fibres of the beam in bending increases with diminishing height of the beam. This size dependence is much reduced for the case of uniform compression.


ABSTRACT: The compressive strength of unidirectional long fibre composites is predicted for plastic microbuckling from a random two-dimensional distribution of fibre waviness. The effect of the physical size of waviness is addressed by using couple stress theory, with the fibre bending resistance scaling with the fibre diameter d. The predicted statistical distribution of compressive strength is found using a Monte Carlo method. An ensemble of fibre waviness profiles is generated from an assumed spectral density of waviness and the compressive strength for each such realisation is calculated directly by the finite element method. The average predicted strength agrees reasonably with practical values, confirming the hypothesis that microbuckles can be initiated by fibre misalignment. It is found that the probability distribution of strength is well matched by a Weibull fit, and the dependence of the Weibull parameters upon the spectral density of waviness is determined. For the practical range of fibre distributions considered, it is concluded that the strength depends mainly upon the root mean square amplitude of fibre misalignment, with the shape of the power spectral density function playing only a minor role. An engineering model for predicting the compressive strength is proposed, akin to weakest link theory for materials containing flaws. A specimen containing randomly distributed waviness is examined to locate regions of high-fibre misalignment. The strength of each of these weak regions is estimated from a look-up table derived from calculations with idealised circular or elliptical patches of waviness. The strength of the composite is given by the failure stress associated with the weakest such patch. For random distributions of waviness, the predictions using this engineering approach are in good agreement with the direct calculations of strength using the finite element method.


ABSTRACT: An investigation was performed to study the response of cylindrical composite shells subjected to out-of-plane loads. During the investigation, an analytical model was developed to predict the mechanical behavior of the structures from the initial failure, through post-failure, to the final collapse. The model is also capable of predicting the residual stiffness and strength of the structures after a preload. Basically, the model consists of a structural analysis for calculating the global response of the structures, and a failure analysis for
predicting local damage of the structures and their residual stiffnesses and strengths. A nonlinear finite element code based on the updated Lagrangian formulation was developed for the model. To verify the model, experiments were also conducted. An excellent agreement was found between the computer simulations and the test results. It is expected that the model can be extended to more complicated structures with various loading conditions.


ABSTRACT: The aim of the present investigation is to examine the stability characteristics of laminated plates subjected to various types of in-plane loadings. Towards this, a rectangular four node finite element, having fourteen degrees of freedom per node, based on a simple higher-order shear deformation theory is developed. The theory employed herein involves four dependent variables. The element is found to be free of shear lock problems. A series of numerical problems are solved to study the effect of various parameters such as lay-up, side to thickness ratio, aspect ratio, type of loadings (uniaxial/biaxial/positive and negative shear/tension—compression/compression—tension) and boundary conditions. Some interesting observations regarding the considerable difference in the buckling resistance of angle-ply plates when subjected to positive and negative shear loading are made.


ABSTRACT: The objective of this paper is to investigate the buckling behavior of moderately thick laminated plates subjected to various in-plane edge loads. For this purpose, an accurate four noded rectangular plate element based on coupled displacement field is developed. Moment-shear and in-plane equilibrium equations are employed to derive the polynomial displacement field of the element. The resulting element has six degrees of freedom per node namely three translations, two bending rotations and a twist and allows higher-order polynomial description for the field variables. The element is not only lock-free but also yields excellent convergence characteristics. A series of numerical examples are solved to demonstrate the efficacy of the proposed element. The influence of lay-up sequence, side-to-thickness ratios, boundary conditions on the prediction capability of the element is studied in detail.


ABSTRACT: Following Flügge's exact derivation for the buckling of cylindrical shells, the equations of motion for transient dynamic loading of orthotropic circular cylindrical shells under external hydrostatic pressure have been formulated. The normal mode theory is used to provide transient dynamic response for the equations of motion. The effect of shell's parameters, external hydrostatic pressure and material properties on the shell response has been studied in detail. A part of tables and figures are given in this paper.
ABSTRACT: A new method for calculating the free vibration frequencies of a thin circular cylindrical shell is presented, based on Flügge's shell theory equations for orthotropic materials. A general displacement representation is introduced, and a type of coupled polynomial eigenvalue problem is developed in present study. Numerical examples are given for isotropic and orthotropic shells. Comparison with that from classical dynamic approach is studied for frequency of an isotropic shell.

ABSTRACT: Following Flügge's exact derivation for the buckling of cylindrical shells, the equations of motion for dynamic loading of a circular cylindrical shell under external hydrostatic pressure have been formulated. The normal mode theory is used to provide transient dynamic response for the equations of motion. The responses of displacements, strain, and stress are obtained for the area of impact, while those outside the area of impact are also calculated. The accuracy of normal mode theory and Timoshenko shell theory are examined in this paper.

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ABSTRACT: The theoretical analysis of finite element method for buckling phenomenon to finite-sized shell structure is first introduced. Then, a real application using a probe for detecting the pressure inside turboprops is analyzed thoroughly with ANSYS10.0, including section profile, dimensions, and local characteristics. Based on the solved results, several rules between critical load and influence factors are obtained, which would be helpful for similar structures design and application. Finally, several useful conclusions about the best profile and ratio between dimensions are obtained.

ABSTRACT: A theoretical analysis of the buckling problems of anisotropic laminated or sandwich, short or long, circular cylindrical shells under axial loads is presented. The theory is based on Flügge’s equations, improved by using first-order shear deformation theory. Nonlinear partial differential equations of equilibrium and boundary conditions are obtained by using a strain of finite-displacement theory and the principle of virtual work, and these nonlinear partial differential equations of equilibrium are linearized. Solutions that satisfy the partial differential equations of equilibrium and boundary condition are obtained, and the analytical model is verified by presenting some numerical results and comparing them with results from previous studies.
ABSTRACT: The effects of anisotropy, transverse shear stiffness, length, and their interactions on buckling under pure torsion and under combined axial compression and torsion were investigated using a previously derived analytical model based on deep shell theory including anisotropy and transverse shear stiffness. The model was verified only for buckling under pure axial compression, hence results for buckling under torsion have now been compared with the results of previous analyses, and the comparison showed that the model has good accuracy for buckling under torsion. Investigation showed that the buckling loads of a cylindrical shell are affected not only by anisotropy and transverse shear stiffness but also by shell length. This means that the shallow shell theory (Donnell-type theory) is not appropriate and deep shell theory including anisotropy and transverse shear stiffness must be used.

ABSTRACT: Statistical knockdown factors for the axial buckling of anisotropic cylinders were derived for practical design purposes. The solution with the least amount of simplification in the linear bifurcation theory was chosen from the previously published solutions, and it was compared with more than 100 experimental results from the open literature. A-basis values (99% probability with 95% confidence level) and B-basis values (90% probability with 95% confidence level) of knockdown factors were obtained by using inferential statistics, i.e., inference concerning unknown aspects of a population by using a small sample.

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ABSTRACT: The results of external air pressure buckling tests of thin-walled, truncated conical steel shells are presented, along with a description of the equipment developed for the testing program. The testing was conducted in support of Sandia National Laboratories Z-Pinch Inertial Fusion Energy Proof-of-Principle power plant design. Optimized stiffening ring locations were determined by using the finite element method, and were then tested, indicating an experimental improvement in initial buckling pressure of more than 300% over the unstiffened cone. An analytical method of determining buckling pressures of stiffened conical shells is also presented, based on the method of the equivalent cylindrical shell. The results of the analytical method agreed very closely to the finite element method for the stiffened cones, but are 20–40% higher than the experimental results.

References listed at the end of the paper:
3. HKS Inc. (2006) ABAQUS version 6.6-1 User’s and theory manuals. HKS Inc., Providence, RI, USA.

ABSTRACT: A theoretical investigation of the initial buckling response of laminated composite plates under uniform shear load is presented. The laminates under consideration are generally layered, thin, flat, rectangular and they are clamped along all four edges. Extensive numerical results highlighting the effect of fibre orientation, lay-up, aspect ratio, number of layers, different material properties and combinations of in-plane loading on the buckling response of laminated plates are presented.


ABSTRACT: Stiffened panels are structures that can be designed to efficiently support in-plane compression, bending, and shear loads. Although the stiffeners are usually discrete elements which are fastened or bonded to a flat or continuously curved plate, manufacturing methods such as thermoforming allow integral formation of the stiffeners in a panel. Such a configuration offers potential advantages in terms of a reduced number of parts and manufacturing operations. For thermoplastic composite panels stiffened by integrally formed open-section beads, the effects of bead spacing and bend cross-section geometry on the initiation of buckling under uniaxial compression and uniform shear loading were investigated. Finite elements results for a range of stiffened panel sizes and bead geometries are presented and compared with approximate closed-form solutions based on an effective flat plate size. Experimental verification of analytical predictions for one of the shear panels and one of the compression panels is described. Compensation of the forming tool to reduce the degree of initial curvature of the panels was found to be necessary.

ABSTRACT: The integral formation of stiffeners in a panel is economically attractive in terms of a reduced number of parts and manufacturing operations. For thermoplastic composite panels stiffened by integral formed open-section beads, the effects of bead spacing and bead cross-section geometry on the initiation of buckling under uniaxial compression and uniform shear loading have been investigated. Approximate analytical relationships for buckling of flat, orthotropic plates have been verified by the use of classical solution methods. Finite element results for a range of stiffened panel sizes and bead geometries are presented and compared with closed-form solutions based on an effective flat plate size. Experimental verification of analytical predictions for four of the panels is described.


ABSTRACT: The article presents the solution of symmetrical face sheet wrinkling problem for sandwich panel with composite facings and an orthotropic core. The new model is proposed for elastic core that takes into account compressive and shear stiffnesses as well as nonlinear change of transverse displacement over the core thickness at wrinkling. The governing buckling equation is derived using energy method. Analysis of cylindrical face wrinkling is performed for sandwich strips subjected to compressive loads applied to the two opposite simply supported edges. The effects of elastic and geometric parameters on the critical buckling stresses and wrinkling waves’ formation are examined.

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ABSTRACT: The paper deals with the solution of the buckling problem for a rectangular orthotropic plate with two parallel free edges. The other two parallel simply supported opposite edges of the plate are loaded by a linearly distributed in-plane load which is equivalent to the pure in-plane bending. Buckling analysis is performed using the Levy-type solution and subsequent finite-difference approximation of the boundary-value problem. Solution of the corresponding eigenvalue problem yields the critical buckling coefficient and critical load. The problem is solved for isotropic and orthotropic composite plates. The design chart has been obtained for the isotropic plates with various aspect ratios from which the corresponding critical loads can be found. Critical buckling coefficients are determined for composite plates with various aspect ratios and angles of the reinforcement orientation. The optimum material reinforcement structure providing the maximum value of critical load is determined.

ABSTRACT: Solution of the buckling problem for the CCFF orthotropic plate subjected to in-plane pure bending is presented. The two parallel clamped edges of the plate are loaded by linearly distributed in-plane loads statically equivalent to the in-plane bending moments. The problem is solved using method of lines for partial differential equations and Galerkin’s method. The buckling problems are solved for isotropic, orthotropic and multilayered CFRP composite plates with various aspect ratios. Results of calculations of critical loads are compared with those based on finite-element modelling and analyses. The comparisons demonstrate efficiency of the proposed approach to the buckling analysis of composite CCFF plates with various dimensional and stiffness parameters.

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ABSTRACT: The paper presents the solution of the buckling problem for an orthotropic rectangular plate having two parallel edges simply supported, one edge clamped and the remaining edge free (the SSCF plate). The plate considered is subjected to a linearly varying in-plane load that can take the form of uniform compression, combination of in-plane bending and uniform compression, or pure in-plane bending. The solution technique involves reduction of the relevant variational buckling equation to a one-dimensional form using the Kantorovich procedure and subsequent application of the generalised Galerkin method. The buckling problems are solved for isotropic and orthotropic plates with various aspect ratios. The analytical solution is verified using the finite-element analysis. The comparisons of computational results demonstrate the appropriateness and efficiency of the approach developed in this work for the calculation of critical loads of composite SSCF plates with various dimensional and stiffness parameters.

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“Buckling analysis and design of anisogrid composite lattice conical shells”, Composite Structures, Vol. 93, No. 12, pp. 3150-3162, November 2011, DOI: 10.1016/j.compstruct.2011.06.015

ABSTRACT: Composite lattice anisogrid shells have now become a popular choice in many aerospace applications. Their use in various structural components, such as rocket interstages, payload adapters for spacecraft launchers, fuselage components for aerial vehicles, and parts of the deployable space antennas requires the development of more advanced finite-element models and analysis techniques capable of predicting buckling behaviour of these structures under variety of loadings. A specialised finite-element model generation procedure (design modeller) is developed and applied to the buckling analysis of the composite anisogrid conical shells treated as three-dimensional frames composed of the curvilinear ribs made of unidirectional composite material. Featuring a dedicated control procedure for positioning the beam elements, the design modeller enables a close approximation of the original twisted geometry of the curvilinear ribs. The parametric finite-element buckling analyses of the anisogrid conical shells subjected to axial compression, transverse
bending, pure bending, and torsion showed the robustness and potential of the modelling approach. It was demonstrated that the buckling resistance can be significantly enhanced by either increasing the stiffness of a few hoop ribs located in the close proximity to the section with the larger diameter, or by introducing the additional hoop ribs in the same part of the conical shell. The effectiveness of the design analyses is demonstrated using particular examples. It has been shown that the resultant optimised designs can produce up to 22% mass savings in comparison with the non-optimised lattice shells.

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ABSTRACT: An exact solution for buckling of simply supported symmetrical cross-ply composite rectangular plates under a linearly varying edge load is presented. It is developed based on the first-order shear deformation theory for moderately thick laminated plates. Buckling loads of cross-ply rectangular plates with various aspect ratios are obtained and the effects of load intensity variation and layup configuration on the buckling load are investigated. The results are verified using the computer code ABAQUS.

ABSTRACT: The elastic buckling behavior of rectangular perforated plates was studied by using the finite element method in this study. Circular cutout was chosen at different locations along the principal x-axis of plates subjected to linearly varying loading in order to evaluate the effect of cutout location on the buckling behavior of plates. The results show that the center of a circular hole should not be placed at the end half of the outer panel for all loading patterns. Furthermore, the presence of a circular hole always causes a decrease in the elastic buckling load of plates subjected to bending, even if the circular hole is not in the outer panel.

ABSTRACT: A modified Hellinger-Reissner functional for thin shells of revolution is presented. A mixed finite element formulation is developed from this functional which is free from line integrals and relaxed continuity terms. This formulation is applied to the problem of free vibration of spherical and conical shells. Bilinear trial functions are used for all field variables. The quadrilateral curved elements here presented satisfy the C0 continuity requirement of the functional. In all the results obtained the accuracy is quite good even for a reasonable…

ABSTRACT: A mixed finite element formulation is developed from a weak variational principle. This formulation is applied to stability analysis of cylindrical shell structures subjected to follower loading. Bilinear trial functions are used for all field variables. The rectangular curved elements presented here satisfy the continuity requirements for the field variables at the element interface. Two examples of a cantilevered cylindrical shell panel under different kinds of loading are solved.

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ABSTRACT: An analysis of vibration and stability of conical and cylindrical shell panels with slight internal damping under follower forces is presented. An extended form of the principle of virtual work is utilized. Examples of cantilevered conical and cylindrical shell panels with and without small internal damping are solved. Plots of these solutions illustrate graphically the influence of internal damping.


ABSTRACT: A study is described which was carried out to investigate the dynamic response of an aircraft-type aluminium alloy plate, with fully clamped boundaries, subjected to combined acoustic excitation and uniaxial in-plane compression. Experiments were conducted in an acoustic tunnel with sound pressure levels up to 150 dB. The non-linear characteristics of the plate have been examined under sinusoidal and broad band random excitation and a study made of the statistical and spectral properties of the response. Theoretical and experimental estimates of the plate natural frequencies and mode shapes are described.

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ABSTRACT: Free-vibration characteristics of cantilever non-circular curved panels are analyzed by using the differential quadrature method (DQM) in this paper. The equations of motion of a curved panel are based on the Love's hypothesis and are expressed in an orthogonal curvilinear co-ordinate system. By applying the differential quadrature formulation and the proposed modified relationships for specified boundary conditions, the free-vibration equations of motion of the curved panel are transformed to a set of algebraic equations. Natural frequencies of a cantilever flat plate and a circular curved panel are obtained for verifying the
applicability of the present approach. Good convergent trend and accuracy are observed. Effects of shallowness, thickness and aspect ratios on the natural frequencies of a cantilever curved panel are also investigated. Furthermore, natural frequencies of parabolic curved panels are obtained. In all cases studied, the efficiency and convenience of the DQM are illustrated.

(No abstract given)

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ABSTRACT: The problem described is solved by approximating the displacement function using simple polynomial coordinate functions which identically satisfy the boundary conditions. The numerical determinations of the eigenvalues under investigation are determined using the Rayleigh-Ritz method assuming that the plate thickness varies according to the functional relation h(r) = ho[1 + 2(r/a)n], where n is an integer. It is shown that the frequency coefficients and critical buckling load parameters obtained by means of the analytical procedure are in excellent agreement with the results obtained employing a finite element algorithmic procedure. It is concluded that the value of Poisson's ratio has a significant effect upon the frequency and buckling parameters, especially in the case of plates of nonuniform thickness and with simply supported edges.

ABSTRACT: The lateral buckling of a laminated composite beam with channel section is studied. A general analytical model applicable to the lateral buckling of a channel-section composite beam subjected to various types of loadings is derived. This model is based on the classical lamination theory, and accounts for the material coupling for arbitrary laminate stacking sequence configuration and various boundary conditions. The
effects of the location of applied loading on the buckling capacity are also included in the analysis. A
displacement-based one-dimensional finite element model is developed to predict critical loads and
corresponding buckling modes for a thin-walled composite beam with arbitrary boundary conditions. Numerical
results are obtained for thin-walled composites under central point load, uniformly distributed load, and pure
bending with angle-ply and laminates. The effects of fiber orientation, location of applied load, and types of
loads on the critical buckling loads are parametrically studied.

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Davalos JF, Qiao PX. Analytical and experimental study of lateral and distortional buckling of FRP wide-
ABSTRACT: A combined analytical and experimental evaluation of flexural-torsional and lateral-distortional
buckling of fiber-reinforced plastic (FRP) composite wide-flange (WF) beams is presented. Based on energy
principles, the total potential energy equations for instability of FRP WF sections are derived using the
nonlinear elastic theory. For the analysis of lateral-distortional buckling, a fifth-order polynomial shape function
is adopted to model the deformed shape of web panels. The models are validated by testing two geometrically
identical FRP WF beams but with distinct material architectures produced by the pultrusion process. The beams
are tested under midspan concentrated loads to evaluate their flexural-torsional and lateral-distortional buckling
responses. To detect rotations of the midspan cross sections and onset of critical buckling loads, horizontal
transverse bars are attached to the beam's flanges, and the bar ends are connected to linear variable differential
transducers (LVDTs). For the same purpose, we use strain gauges bonded to the upper and lower surfaces near
to the free edges of the top flange. A good agreement between the proposed analytical approach and
experimental and finite-element analyses results is obtained, and simplified engineering equations for flexural-
torsional buckling are formulated. The proposed analytical solutions can be used to predict flexural-torsional
and lateral-distortional buckling loads for other FRP shapes and to formulate simplified design equations.
ABSTRACT: In this paper, a theoretical model is developed for the dynamic analysis of composite thin-walled beams with open or closed cross-sections. The present model incorporates, in a full form, the shear flexibility (bending and warping shear) as well as a state of initial stresses. This allows to study the free vibration and buckling problems in a unified fashion. An analytical solution of the developed equations is obtained for the case of simply supported thin-walled beams. Numerical examples are given to demonstrate the importance of the shear flexibility on the vibration and buckling behavior of the considered structures.

ABSTRACT: In this paper, a theoretical model is developed for the stability analysis of composite thin-walled beams with open or closed cross-sections. The present model incorporates, in a full form, the shear flexibility (bending and non-uniform warping), featured in a consistent way by means of a linearized formulation based on the Reissner’s Variational Principle. The model is developed using a non-linear displacement field, whose rotations are based on the rule of semi-tangential transformation. This model allows to study the buckling and lateral stability of composite thin-walled beam with general cross-section. A finite element with two-nodes and fourteen-degrees-of-freedom is developed to solve the governing equations. Numerical examples are given to show the importance of the shear flexibility on the stability behavior of this type of structures.

ABSTRACT: In this paper, a new theoretical model is developed for the generalized linear analysis of composite thin-walled beams with open or closed cross-sections. The present model incorporates, in a full form, the shear deformability by means of two features. The first one may be addressed as a mechanical aspect where the effect of shear deformability due to both bending and non-uniform warping is considered. The second feature is connected with the constitutive aspects, and it contemplates the use of different hypotheses adopted in the formulation. These topics are treated in a straightforward way by means of the Linearized Principle of Virtual Works. The model is developed by employing a non-linear displacement field, whose rotations are formulated by means of the rule of semitangential transformation. This model allows studying many problems of static's, free vibrations with or without arbitrary initial stresses and linear stability of composite thin-walled beams with general cross-sections. A discussion about the constitutive equations is performed, in order to explain distinctive aspects of the effects included in the theory. This paper presents the theoretical formulation together with finite element procedures that are developed with the aim to obtain solutions to the general equations of thin-walled shear deformable composite beams. A non-locking fourteen-degree-of-freedom finite element is introduced. Numerical examples are carried out in several topics of static's, dynamics and buckling problems, focusing attention in the validation of the theory with respect to experimental data and with 2D and 3D computational approaches. Also, new parametrical studies are performed in order to show the influence of
shear flexibility in the mechanics of the thin-walled composite beams as well as to illustrate the usefulness of the model.

Carlos P. Filipich and Marcelo Tulio Piovan, “The dynamics of thick curved beams constructed with functionally graded materials”, Mechanics Research Communications, Vol. 37, No. 6, pp 565-570, September 2010, DOI: 10.1016/j.mechrescom.2010.07.007
ABSTRACT: During the last two decades materials, that exhibit graded properties, left their spirit of conceptual laboratory specimens to become a technological reality with a well established background. However structural applications of these materials are not a fulfilled research. Models of straight and curved beams are normally reported in the scientific literature as the easiest way to understand some existing aspects in mechanics of structures. Most of these models are formulated appealing to numerical approaches such as the finite element method among others, without taking into account theoretical aspects that can be quite useful to reduce algebraic complexity. In the present work a technical theory for dynamic analysis of thick curved beams is deduced within the context of functionally graded materials. The concept of material neutral-axis shifting is employed in the deduction procedure in order to reduce the algebraic handling and complexity of the motion equations. This leads to find analytical solutions of the governing differential system, even if it has variable coefficients. Parametric studies on the dynamics of curved beams are offered to show the versatility of the adopted formulation by means of solutions handled with the power series method.

ABSTRACT: The dynamic stability of functionally graded thin-walled beams allowing for shear deformability is investigated in this article. The analysis is based on a model that has small strains and moderate rotations which are formulated through the adoption of a second-order non-linear displacement field. The beam is subjected to axial external dynamic loading. The model takes into account thermoelastic effects. The heat conduction equation is solved in order to characterize the temperature in the cross-sectional domain. Galerkin’s and Bolotin’s methods are employed with the scope to discretize the governing equations and to determine the regions of dynamic stability, respectively. Regions of stability are evaluated and expressed in non-dimensional form. The influence of the longitudinal vibration on the unstable regions is investigated. The numerical results show the importance of this effect when the forcing frequency approaches to the natural longitudinal frequency, obtaining substantially wider parametric stability regions. The effects of temperature gradients, shear flexibility and axial inertia, in beams with different cross-sections and different types of graded material are analyzed as well.

ABSTRACT: In this article a non-linear model for dynamic analysis of rotating thin-walled composite beams is introduced. The theory is deduced in the context of classic variational principles and the finite element method is employed to discretize and furnish a numerical approximation to the motion equations. The model considers shear flexibility as well as non-linear inertial terms, Coriolis effects, among others. The clamping stiffness of the beam to the rotating hub is modeled through a set of spring factors. The model serves as a mean
deterministic basis to the studies of stochastic dynamics, which are the objective of the present article. Uncertainties should be considered in order to improve the predictability of a given modeling scheme. In a rotating structural system, uncertainties are present due to a number of facts, namely, loads, material properties, etc. In this study the uncertainties are incorporated in the beam-to-hub connection (i.e. the connection angle and the springs) and the rotating velocity. The probability density functions of the uncertain parameters are derived employing the Maximum Entropy Principle. Different numerical studies are conducted to show the main characteristics of the uncertainty propagation in the dynamics of rotating composite beams.

ABSTRACT: In this paper the dynamic and buckling features of slender structures with curved axis are addressed. A survey on the literature concerning mechanics of beams constructed with non-homogeneous materials or with functionally graded materials reveals only a few papers devoted to the dynamics and buckling of curved beams constructed with such materials. This problem was tackled mainly through 2D or 3D numerical formulations, but comprehensive beam theories on the matter are scarce. In the present paper a model of non-homogeneous and/or FGM curved beams is developed. The model is deduced by adopting a consistent displacement field which incorporates second order rotational terms based on the semi-tangential rule. The model also incorporates the shear flexibility due to bending and warping due to twisting effects. Arbitrary initial stresses and initial off-axis loads are taken into account in the linearized principle of virtual works. The finite element method is employed to discretize the motion equations with the objective to solve problems of dynamics, statics and buckling. The model contains, as particular cases, several straight beam theories as well as curved beam theories. Some comparisons with the available experimental data of the open literature are performed in order to illustrate the predictive features of the model, and comparisons with 2D and 3D finite element approaches are also performed.

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ABSTRACT: In this work an analysis is performed on the nonlinear planar vibrations of a functionally graded beam subjected to a combined thermal and harmonic transverse load in the presence of internal resonance. Adopting the direct perturbation MMS technique, the partial differential equations of motion of the beam are reduced to sets of first-order nonlinear modulation equations in terms of the complex modes of the beam. The assumption of steady-state values of centrifugal loads is evaluated. It has to be said that there is a lack of information about modeling of rotating box beams made of functionally graded materials (FGMs) under thermo-mechanical loads. The influence of the transverse load amplitude and the internal detuning parameter on the strength of nonlinear modal interaction is illustrated. It is also shown that the system exhibits periodic and quasiperiodic responses for a typical range of parameter values.

ABSTRACT: This article is concerned with the stochastic dynamic analysis of structures constructed with composite materials. Depending on many aspects (manufacturing process, material uncertainty, boundary conditions, etc.) real composite structures may have deviations with respect to the calculated response (or deterministic response). These aspects lead to a source of uncertainty in the structural response associated with constituent proportions, geometric parameters or other unexpected agents. Uncertainties should be considered in a structural system in order to improve the predictability of a given modeling scheme. In this study a model of shear deformable composite beams is employed as the mean model. The probabilistic model is constructed by adopting random variables for the uncertain parameters of the model. This strategy is called parametric probabilistic approach. The probability density functions of the random variables are constructed appealing to the Maximum Entropy Principle. The continuous model is discretised by finite elements and the Monte Carlo method is employed to perform the simulations, thereafter a statistical analysis is performed. Numerical studies are carried out to show the main advantages of the modeling strategies employed, as well as to quantify the propagation of the uncertainty in the dynamics of slender composite structures.

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“Dynamics of magneto electro elastic curved beams: Quantification of parametric uncertainties”, Composite Structures, Col. 133, July 2015

ABSTRACT: The objective of this paper is the evaluation of uncertainty propagation associated to several parameters in the dynamics of magneto-electro-elastic (MEE) curved beams. These MEE structures can be employed as imbedded parts in high performance technological systems to control motions and/or attenuate vibrations, for energy harvesting, etc. Although a lot of research connected with these structures was done for dynamics and statics, it is remarkable the scarcity of articles analyzing random dynamics of MEE structure, provided that many models have uncertainties associated to their parameters: loads and/or material properties, among others. A theory for MEE curved beams is derived and assumed as the deterministic model. The response is calculated by means of a finite element formulation. The probabilistic model is constructed appealing to the finite element formulation of the deterministic approach, by adopting random variables for the uncertain parameters selected. The probability density functions of the random variables are derived with the Maximum Entropy Principle. The Monte Carlo method is used to perform simulations with independent realizations. Studies are carried out in order to evaluate the influence of Magneto-elastic and/or piezoelectric coupling in the dynamics of MEE curved beams in both contexts: the deterministic and the stochastic.


ABSTRACT: In this article we perform a quantification of the uncertainty propagation of the dynamics of slender initially curved structures constructed with fiber reinforced composite materials. Depending on the manufacturing process, composite materials may have deviations with respect to the expected response, often called nominal response in a deterministic sense. The manufacturing aspects lead to uncertainty in the structural response associated with constituent proportions, material and/or geometric parameters among others. Another aspect of uncertainty that can be sensitive in composite structures is the mathematical model that represents the mechanics of the structural member, that is: the assumptions and type of hypotheses invoked reflect the most relevant aspects of the physics of a structure, however in some circumstances these hypotheses are not enough,
and cannot represent properly the mechanics of the structure. Uncertainties should be considered in a structural system in order to improve the predictability of a given modeling scheme. There are two approaches to evaluate the propagation of uncertainties in structural models: The parametric probabilistic approach and the nonparametric probabilistic approach. In the first approach, one quantifies the uncertainty of given parameters (such as variation of the angles of fiber reinforcement, material constituents, etc.) by associating random variables to them. In the second approach, the propagation of uncertainty is quantified by considering uncertain the matrices of the whole system. In this study a shear deformable model of composite curved thin walled beams is employed as the mean or expected model. The probabilistic model is constructed by adopting random variables for the uncertain entities (parameters or matrices) of the model. The probability density functions of the random entities are derived appealing to the Maximum Entropy Principle under given constraints. Once the probabilistic model is discretized in the context of the finite element method, the Monte Carlo method is employed to perform the simulations. Then the statistics of the simulations is evaluated and the parametric and nonparametric approaches are compared.


ABSTRACT: Plane plates subjected to tensile loads are usually not considered to fail due to buckling. However if a plate contains a cut-out, regions of compressive stresses arise under a uniaxial tensile load. In thin-walled orthotropic composite plates these compressive stresses may cause local buckling. In general the stress concentration factors of cut-outs are very high, thus the buckling limits will not be exceeded before fracture. However cut-outs, optimised by a shape optimisation method, run risk to initiate buckling before exceeding the fracture load because the stress concentration factors for these cut-outs are very low. In this paper the influence of the shape of optimised cut-outs on the buckling behaviour is investigated. Besides the critical load the undercritical and post-critical behaviour of geometrical imperfect orthotropic composite plates is analysed. Methods that prevent local buckling under tensile stresses are discussed in order to provide the full advantage of optimised cut-outs.

References listed at the end of the paper:

ABSTRACT: A numerical and experimental study was carried out to determine the effects of antisymmetric laminate configuration, cutout and length/thickness ratio on the buckling behavior of E/glass-epoxy composite plates. The buckling loads were presented for symmetrically and anti-symmetrically laminated plates subjected to axial compression load. The study included two different laminate configurations ([90/45/-45/0]as and [90/45/-45/0]s), two different cutout shapes (circular and semi-circular), two different length/thickness ratios (L/t = 75 and 37.5) and three boundary conditions (clamped-clamped [CC], clamped-pinned [CP] and pinned-pinned [PP]). Firstly, the buckling loads of eight-ply E/glass-epoxy rectangular plates were determined experimentally. Then, the buckling loads of the laminated composites were calculated by ANSYS finite-element computer code. The changing in buckling load of the composites due to the presence of cutout and changing of length/thickness ratio was calculated. Finally, the experimental test results were compared to the buckling loads of plates obtained from the finite element analysis.

References listed at the end of the paper:


ABSTRACT: In this study, the influence of boundary conditions on the buckling load for rectangular plates of various cutout shape, length/thickness ratio, and ply orientation is examined. Boundary conditions consisting of clamped, pinned, and their combinations are considered. Numerical and experimental studies are conducted to investigate the effect of boundary conditions, cutout shape, length/thickness ratio, and ply orientation on the buckling behavior of E-glass/epoxy composite plates under in-plane compression load. Buckling analysis of the laminated composites is performed by using finite element analysis software ANSYS. Tests have been carried out on laminated composites with circular and semicircular cutouts under various boundary conditions. Comparisons are made between the test results and predictions based on finite element analysis. The results show a complex interaction between plate orthotropy and boundary conditions.

4090


ABSTRACT: This paper presents a new curved shell finite element formulation for linear static analysis of laminated composite plates and shells, where the displacement approximation in the direction of the shell thickness can be of an arbitrary polynomial order p, thereby permitting strains of at least (p - 1) order. This is accomplished by introducing additional nodal variables in the element displacement approximation corresponding to the Lagrange interpolating polynomials in the element thickness direction. The resulting element displacement approximation has an important hierarchical property i.e. the approximation functions and the generalized nodal variables corresponding to an approximation order p are a subset of those corresponding to an approximation order (p + 1). The element formulation ensures C0 continuity or smoothness of displacements across the interelement boundaries. The element properties (stiffness matrix and equivalent load vectors) are derived using the principle of virtual work and the hierarchical element approximation. The formulation is extended for generally orthotropic material behaviour where the material directions are not necessarily parallel to the global axes. Further extension of this formulation for laminated composites is accomplished by incorporating the material properties of each lamina by numerically integrating the element stiffness matrix for each lamina. The formulation has no restriction on either the number of laminas or the layup pattern of the laminas. Each lamina can be generally orthotropic, and the material directions and the lamina thicknesses may vary from point to point within each lamina. The geometry of the laminated shell element is described by the co-ordinates of the nodes lying on the middle surface of the element and the lamina thicknesses at each node. The formulation permits any desired order displacement or strain approximation in the shell thickness direction without remodelling. Numerical examples are presented to demonstrate the accuracy,
efficiency, and overall superiority of the present formulation. The results obtained from the present formulation are compared with those available in the literature as well as the analytical solutions.


ABSTRACT: This paper presents a new completely hierarchical three dimensional curved shell finite element formulation for linear static analysis of laminated composite plates and shells. The element displacement approximation can be of arbitrary polynomial orders p xi, p eta and p zeta in the xi, eta, and zeta directions thereby permitting strains of at least (p xi – 1), (p eta – 1) and (p zeta – 1) order. The element approximation functions as well as the nodal variables are hierarchical. The element formulation ensures C0 continuity. The lamina properties are incorporated by numerically integrating the element stiffness matrix for each lamina. The formulation has no restriction on either the number of laminas or the layup pattern of the laminas. The geometry of the laminated shell element is described by the coordinates of the nodes lying on the middle surface of the element and the lamina thicknesses at each node. The element formulation is equally effective for very thin as well as very thick laminated plates and curved shells. The results obtained from the present formulation are compared with those available in the literature as well as available analytical solutions.


ABSTRACT: This paper presents a nine-node three-dimensional laminated composite curved shell finite element formulation for geometrically nonlinear (GNL) analysis of laminated plates and shells where the displacement approximation for the laminate is piecewise hierarchical and is derived based on p-version. The displacement approximation for the element is developed first by establishing a hierarchical displacement approximation for each lamina of the laminate and then by imposing interlamina continuity conditions of displacements at the interfaces between the laminas. The nodal variables for the entire laminate are derived from the nodal variables of the laminas and the interlamina continuity conditions of displacements. The element formulation ensures C0 continuity of displacements across the interelement as well as interlamina boundaries. The lamina stiffness matrices and the equivalent nodal force vectors are derived using the principle of virtual work and the hierarchical displacement approximation for the laminas. Interlamina continuity conditions are used to construct the transformation matrices for the individual laminas which permit transformation of the lamina degrees of freedom to the laminate degrees of freedom. The interlamina behavior incorporated in this formulation is in total agreement with the physics of laminate behavior for composite plates and shells. In formulating the properties of the element, complete three-dimensional stresses and strains are considered, hence the element is equally effective for very thin as well as extremely thick laminated shells and plates. Incremental equations of equilibrium are derived and solved using standard Newton's method. The total load is divided in increments and for each increment of load equilibrium iterations are performed until each component of the residuals and the generalized nodal displacement vector are within preset tolerances. Numerical examples are presented to show the accuracy, p-convergence characteristics and overall advantages of the present formulation.

ABSTRACT: A method is introduced to determine the limit load of thin shells using the finite element method. The method is based on an upper bound limit and shakedown analysis with the elastic-perfectly plastic material model. A nonlinear constrained optimization problem is solved by using Newton’s method in conjunction with a penalty method and the Lagrange dual method. The numerical investigation of a pipe bend subjected to bending moments proves the effectiveness of the algorithm.


ABSTRACT: This paper presents a numerical procedure for reliability analysis of thin plates and shells with respect to plastic collapse or to inadaptation. The procedure involves a deterministic shakedown analysis for each probabilistic iteration, which is based on the upper bound approach and the use of the exact Ilyushin yield surface. Probabilistic shakedown analysis deals with uncertainties originated from the loads, material strength and thickness of the shell. Based on a direct definition of the limit state function, the calculation of the failure probability may be efficiently solved by using the First and Second Order Reliability Methods (FORM and SORM). The problem of reliability of structural systems (series systems) is handled by the application of a special technique which permits to find all the design points corresponding to all the failure modes. Studies show, in this case, that it improves considerably the FORM and SORM results.

References listed at the end of the paper:
ABSTRACT: A spline based method for approximating thin shell dynamics is presented here. While the method is developed in the context of the Donnell-Mushtari thin shell equations, it can be easily extended to the Byrne-Flugge-Lur’ye equations or other models for shells of revolution as warranted by applications. The primary requirements for the method include accuracy, flexibility and efficiency in smart material applications. To accomplish this, the method was designed to be flexible with regard to boundary conditions, material nonhomogeneities due to sensors and actuators, and inputs from smart material actuators such as piezoceramic patches. The accuracy of the method was also of primary concern, both to guarantee full resolution of structural dynamics and to facilitate the development of PDE-based controllers which ultimately require real-time implementation. Several numerical examples provide initial evidence demonstrating the efficacy of the method.

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ABSTRACT: In this study, finite element buckling analyses of transversely stiffened isotropic and orthotropic rectangular thin plates under shear loads are presented. Eigenvalue buckling analysis is used to predict critical buckling loads of mild steel and Boron—Aluminium MMC composite stiffened plates with different fiber orientations by using ANSYS. A simply supported boundary condition is applied through the edges of the plates and uniformly distributed shear loads are given to edge nodes. It is demonstrated that by adding more transverse rectangular stiffeners which are made of the same material with the plate, critical buckling stress of the plates increases linearly. The failure tests of unstiffened Boron—Aluminium plates were performed according to Tsai-Hill failure criteria.

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ABSTRACT: Local buckling in FRP profiles is analyzed. Some experimental results in compression and bending, where local buckling of the flanges in compression occurred, are described and the critical stresses are summarized. A numerical model by the finite element method (FEM) is introduced and validated by comparison of the numerical results with the experimental ones. This finite element model is applied for a wide parametric analysis in order to individuate a buckling curve for the local buckling of the flange. An analytical expression of the buckling curve is developed, taking into consideration the orthotropy of the material, in which the restraint action of the web on the flange is explicitly introduced as a function of the geometrical and mechanical data of the section sub-components. The reliability of the proposed curve as a design tool is confirmed by comparison with the experimental results.
ABSTRACT: The large-amplitude vibrational behavior of a shallow spherical-cap shell is investigated theoretically using simple arguments. The results of this approximate analysis are expressed in the form of appealingly simple nondimensional quantities. It is shown that the frequency of the fundamental mode of such a shell falls by as much as 50 per cent as the vibration amplitude is increased to approximately the shell depth. For even larger amplitudes the frequency rises, and it exceeds the small-amplitude frequency when the amplitude is more than about twice the shell depth. The influence of shell thickness is considered and increasing thickness is shown to decrease the frequency shift. This analysis is shown to account for the pitch glide behavior of certain Chinese opera gongs.

ABSTRACT: The effect of random initial geometric imperfections on the vibration behavior of rectangular plates is investigated in this paper using a statistical method. The random initial geometric imperfections of plates are described by Gaussian random fields and simulated numerically using Elishakoff's method. Lindstedt-Poincaré's perturbation technique is employed to solve Duffing's Equation with an additional quadratic spring term derived in the vibration analysis of imperfect rectangular plates. A Monte Carlo analysis for simply supported plates is carried out in detail to illustrate the proposed approach. It is shown that the effect of random geometric imperfections on the vibration behavior of the plates can be described quantitatively in terms of the frequency reliability function and the hardening type probability.

Huang Xiaoqing and Zhang Hong (Department of Mechanics, South China University of Technology, Guangzhou 510641, P.R. China), “Influence of compression-bending coupling on the stability behavior of anisotropic laminated panels”, Applied Mathematics and Mechanics, Vol. 20, No. 1, 1999, pp. 18-26, doi 10.1007/BF02459269
ABSTRACT: Dynamic-Relaxation Method (DRM) is applied to studying the influence of compression-bending coupling on nonlinear behavior of cylindrically slightly curved panels of unsymmetric laminated composite materials subjected to uniform uniaxial compression during loading and unloading. Numerical results are given for cross-ply plates and panels under S4 S4 and S4 S2 boundary conditions. The results show that the effects of absolute value and the sign of the coupling coefficient on the stability behavior of the panels are significant.

ABSTRACT: A method of estimating the manufacturing cost for composite stiffened panels was proposed on the basis of co-curing process. Considering cost as a major design parameter, an approach to optimize the configuration that minimizes the cost and weight of composite stiffened panels under compression and shear was presented, under structural requirements and manufacturing constraints. Based on the case of panel with T
stiffener, the objective function of cost and weight was minimized respectively to verify the cost estimation model. The results estimated are in good agreement with practical process time of lay up. In addition, the stiffened panel cost and weight were discussed for seven stiffener cross-sectional shapes. It is found that T stiffener gives the lowest time configuration while its weight is only 0.5% more than that of the J stiffener, while J is of the lowest weight among seven stiffeners. The optimization conclusion can be applied to guide design of composite stiffened panel.

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ABSTRACT: The axial compressive mechanical response of substrate-supported carbon nanotube (CNT) arrays with heights from 35 to 1200 micrometers is evaluated using flat punch nanoindentation with indentation depths to 200 micrometers. The compressive behavior is consistent with that of an open-cell foam material with array height playing a role similar to that of occupation density for traditional foam. Mechanical yielding of all arrays is initiated between 0.03 and 0.12 strain and arises from localized coordinated plastic buckling. For intermediate CNT array heights between 190 and 650 lm, buckle formation is highly periodic, with characteristic wavelengths between 3 and 6 micrometers. Buckle formation produced substantial force oscillations in both the compressive and lateral directions. The compressive elastic modulus of the arrays is obtained as a continuous function of penetration depth and attains a value between 10 and 20 MPa for all arrays during mechanical yield.

A qualitative model based upon concepts of cellular foam geometry is advanced to explain the observed CNT buckling behavior.

References listed at the end of the paper:


J. Xiao (1), S.Y. Ryu (2), Y. Huang (1,3), K.-C. Hwang (4), U. Paik (2) and J.A. Rogers (5)
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ABSTRACT: A continuum mechanics theory is established for the in-surface buckling of one-dimensional nanomaterials on compliant substrates, such as silicon nanowires on elastomeric substrates observed in experiments. Simple analytical expressions are obtained for the buckling wavelength, amplitude and critical buckling strain in terms of the bending and tension stiffness of the nanomaterial and the substrate elastic properties. The analysis is applied to silicon nanowires, single-walled carbon nanotubes, multi-walled carbon nanotubes, and carbon nanotube bundles. For silicon nanowires, the measured buckling wavelength gives Young's modulus to be 140 GPa, which agrees well with the prior experimental studies. It is shown that the energy for in-surface buckling is lower than that for normal (out-of-surface) buckling, and is therefore energetically favorable.


DOI: 10.1016/j.jmps.2011.05.002

ABSTRACT: We carry out axisymmetric, finite deformation finite element analyses of the uniaxial compression of cylindrical bundles of vertically aligned carbon nanotubes (VACNTs) firmly attached to a Si substrate. A compressible elastic–viscoplastic constitutive relation with a piecewise, linear hardening–softening–hardening flow strength is used to model the material. Calculations are performed for VACNTs both with uniform properties and with axially graded properties. We show that, with uniform properties, sequential buckling initiates at the substrate and propagates away from it, in agreement with previous experimental findings. We investigate the dependence of the magnitude and wavelength of the buckles on characteristics of the function defining the flow strength. When a property gradient giving a more compliant response at the end opposite to the substrate is specified, we find that sequential buckling initiates at that end and propagates toward the substrate. Results of the analyses are compared with the experimental observations and capture many of the experimentally obtained stress–strain and morphological features. The proposed model serves as a promising foundation for capturing the underlying energy absorption mechanisms in these systems. Comparison of the model predictions with the experimental results also suggests directions for model improvement.

ABSTRACT: For the first time, carbon nanotube (CNT) forests are fully characterized as transversely isotropic continuum material. Each of the five independent elastic constants is experimentally obtained using a combination of nanoindenter-based uniaxial compression and shear testing, in situ SEM compression, and digital image correlation (DIC) of vertically and laterally oriented CNT microstructure columns. Material properties are highly anisotropic, with an axial modulus (165–275 MPa) that is nearly two orders of magnitude greater than the transverse modulus (2.5–2.7 MPa) and the out of plane shear modulus (0.8–1.6 MPa). The Poisson’s ratios along three mutually orthogonal axes, measured directly by simultaneous in situ DIC evaluation of axial and transverse strain, are found to be similarly anisotropic ($\nu_{12} = 0.35$, $\nu_{23} = 0.1$, $\nu_{21} = 0.005$). A Timoshenko beam model is then developed to accurately predict the critical buckling stress of the vertically oriented columns using a subset of these anisotropic properties and considering inelastic column buckling. These results show that the critical buckling stress of CNT microstructures vary predictably with geometry and that continuum models with appropriate material constants may be applied to analyze CNT microstructures and evaluate their stability for many applications.


ABSTRACT: The investigation of stability of shell structures is a specialty which in its own right deserves a complete separate book. Here just some main aspects are explained, and the correspondence and difference with beam-column buckling is touched. We will successively discuss buckling of uni-axially loaded plates as a limit case of shells, arched beams, arched circular roofs, axially-pressed shells of rotation and domes.

Reference listed at the end of the paper:


ABSTRACT: We report on the mechanical behavior of a dense brush of small-diameter (1–3 nm) non-catalytic multiwall (2–4 walls) carbon nanotubes (CNTs), with ~10 times higher density than CNT brushes produced by other methods. Under compression with spherical indenters of different radii, these highly dense CNT brushes exhibit a higher modulus (~17–20 GPa) and orders of magnitude higher resistance to buckling than vapor phase deposited CNT brushes or carbon walls. We also demonstrate the viscoelastic behavior, caused by the increased
influence of the van der Waals’ forces in these highly dense CNT brushes, showing their promise for energy-absorbing coatings.

Zhan Kang, Ming Li and Qiqin Tang (State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China), “Buckling behavior of carbon nanotube-based intramolecular junctions under compression: Molecular dynamics simulation and finite element analysis”, Computational Materials Science, Vol. 50, No. 1, pp 253-259, November 2010

DOI: 10.1016/j.commatsci.2010.08.011

ABSTRACT: Intramolecular junctions (IMJs) formed by connecting two arbitrary carbon nanotubes (CNTs) can act as functional building blocks in circuits and components of CNT-based electronics devices. While extensive studies have been conducted on the atomic structural as well as electrical properties of IMJs and great advances have been achieved, mechanical response of IMJs under large deformation, which may exert significant effects on their electrical properties, are still not fully explored. In this paper, both molecular dynamics (MD) simulation and finite element (FE) analysis are employed to investigate the buckling behavior of IMJs under axial compression. The strain rate effects are firstly studied in the MD simulations. It is found that the critical compressive strain is not sensitive to the strain rate of relatively low range, but it exhibits a strong dependency upon the strain rate under high speed compression. In particular, a different failure mode may occur under ultra-high loading velocities. Based on the discussion on the strain rate effects, a reasonable loading velocity is suggested to be adopted in the subsequent MD simulations. In this study, the results of both the MD simulations and the FE analyses indicate that the critical compressive strain is dependent upon the length, radial dimensions of the IMJ but insensitive to the chirality of the IMJ. The comparison between the results of the MD simulations and the FE analyses also confirms that the FE analysis is able to provide useful insights into the compressive behavior of CNT-based IMJs with a much less computational cost.


ABSTRACT: The paper presents 3D results of a quasi-static buckling analysis of a funnel-flow cylindrical metal bin composed of horizontally corrugated sheets strengthened by vertical columns. A linear buckling and a non-linear analysis with geometric and material non-linearity were carried out with a perfect and an imperfect real silo shell by taking into account axisymmetric and non-axisymmetric loads imposed by a bulk solid following Eurocode 1 and different initial geometric imperfections and load non-uniformities around the circumference. The calculated buckling forces were compared with the permissible one given by Eurocode 3.

Biswarup Ghosh, “Consequences of simultaneous local and overall buckling in stiffened panels”, Master’s Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2003

ABSTRACT: In this thesis improved expressions for elastic local plate buckling and overall panel buckling of uniaxially compressed T-stiffened panels are developed and validated with 55 ABAQUS eigenvalue buckling analyses of a wide range of typical panel geometries. These two expressions are equated to derive a new expression for the rigidity ratio \( (EI_x/Db)_{co} \) that uniquely identifies “crossover” panels – those for which local and overall buckling stresses are the same. The new expression for \( (EI_x/Db)_{co} \) is also validated using the 55 FE models. Earlier work by (Chen, 2003) had produced a new step-by-step beam-column method for predicting
stiffener-induced compressive collapse of stiffened panels. An alternative approach is to use orthotropic plate theory. As part of the validation of the new beam-column method, ABAQUS elasto-plastic Riks ultimate strength analyses were made for 107 stiffened panels—the 55 crossover panels and 52 others. The beam-column and orthotropic approaches were also used. A surprising result was that the orthotropic approach has a large error for crossover panels whereas the beam-column method does not. Some possible reasons for this are suggested. Collapse patterns for the crossover panels are studied and classified from von Mises stress distribution at collapse. The collapse mechanism and load-deflection diagrams suggest stable inelastic post collapse behavior for most panels and an abrupt drop in load carrying capacity in only nine of the 55.

References listed at the end of the paper:

Hughes, O.F. and Ghosh, B. Improved Prediction of Simultaneous Local and Overall Buckling of Stiffened Panels, communicated for publication in Thin-Walled Structures.


ABSTRACT: In this paper, improved expressions for elastic local plate buckling and overall panel buckling of uniaxially compressed T-stiffened panels are developed and validated with 55 ABAQUS eigenvalue buckling analyses of a wide range of typical panel geometries. These two expressions are equated to derive a new expression for the rigidity ratio (EIx/Db)CO that uniquely identifies “crossover” panels—those for which local and overall buckling stresses are the same. The new expression for (EIx/Db)CO is also validated using the 55 FE models. Earlier work by Chen (Ultimate strength analysis of stiffened panels using a beam-column method.
PhD Dissertation, Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2003) had produced a new step-by-step beam-column method for predicting stiffener-induced compressive collapse of stiffened panels. An alternative approach is to use orthotropic plate theory. As part of the validation of the new beam-column method, ABAQUS elasto-plastic Riks ultimate strength analyses were made for 107 stiffened panels—the 55 crossover panels and 52 others. The beam-column and orthotropic approaches were also used. A surprising result was that the orthotropic approach has a large error for crossover panels whereas the beam-column method does not. Some possible reasons for this are suggested.

References listed at the end of the paper:

R.M.V. Pidaparti (Department of Mechanical Engineering, Purdue University at Indianapolis, Indianapolis, IN 46202, USA), “Flutter analysis of cantilevered curved composite panels”, Composite Structures, Vol. 25, Nos. 1-4, 1993, pp. 89-93, doi:10.1016/0263-8223(93)90154-1

ABSTRACT: A 48 degrees of freedom (dof) doubly curved quadrilateral thin shell finite element is used for studying the supersonic flutter of cantilevered curved composite panels. The composite material behavior is included using classical lamination theory and supersonic aerodynamic behavior is included using linearized piston theory. To reduce the number of dof of the finite element aeroelastic system, a normal mode approach is adopted. Results are presented to illustrate the behavior of flutter characteristics for composite curved cylindrical panels. The effects of fiber orientation and flow angle on the flutter characteristics are presented for selected examples. The accuracy, efficiency, and applicability of the present finite element method is demonstrated by illustrative examples with some results comparing well with the available alternate solutions in the literature.

ABSTRACT: The use of springs with very large stiffness to model constraints in vibratory systems has been a popular approach to overcome the limitations on the choice of admissible functions in the Rayleigh–Ritz method. The maximum possible error resulting from this asymptotic modelling can be determined by using positive and negative stiffness values, or in general terms using positive and negative penalty functions. This paper illustrates how this method could be used to determine the critical loads of structures.

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ABSTRACT: A numerical procedure for analyzing a common and catastrophic failure mode in pultruded composite material I-beams is presented in this paper. Pultruded wide-flange profiles (often referred to as I-beams) exhibit a number of different failure modes when loaded in flexure or axial compression. The particular failure mode of interest to this paper is that due to the local separation of the flange from the web of the profile following local buckling of the flange. A node-separation technique is used to simulate the progressive failure of the joint between the flange and the web of the wide-flange beam in the postbuckled regime. The procedure has been implemented in NIKE3D, a multipurpose nonlinear implicit finite-element code. The fundamentals of the separation algorithm and the mechanics of the implementation in NIKE3D are described. The results of simulations using the proposed procedure are compared with experimental observations.

References listed at the end of the paper:


ABSTRACT: Virtual testing using dynamic finite element simulations is an efficient way to investigate the mechanical behaviour of small- and large-scale structures reducing time- and cost-expensive prototype tests. Furthermore, numerical models allow for efficient parameter studies or optimisations. One example, which is the focus of this paper, is the configurational design of cellular sandwich core structures. From classical honeycomb cores to innovative folded core structures, a relatively large design space is provided allowing for tailoring of the cellular core geometry with respect to the desired properties. The method of determining the effective mechanical properties of such cellular sandwich core structures of different geometries using dynamic compression, tensile and shear test simulations is discussed covering a number of important modelling aspects: the cell wall material modelling, the influence of mesh size and number of unit cells, the inclusion of imperfections, etc. A comparison of numerical and experimental results is given for Nomex honeycomb cores and Kevlar or carbon fibre-reinforced plastic (CFRP) foldcore structures. A good correlation with respect to cell wall deformation mechanisms and stress–strain data was obtained. Therefore, these models not only allow for a complete mechanical characterisation of cellular core structures but also for a detailed investigation of cell wall deformation patterns and failure modes to get a better understanding of the structural behaviour, which can be difficult using solely experimental observations. To show that this efficient virtual testing method is suitable for the development of cellular core geometries for specific requirements, an optimisation study of a CFRP foldcore geometry with respect to its compressive behaviour was performed.


ABSTRACT: Thin-walled members that have one dimension relatively large in comparison to the cross-sectional dimensions are usually modelled by using beam-type one-dimensional finite elements. Beam-type elements, however, are based on the assumption of rigid cross-section, thus they only allow considerations associated with the beam axis behaviour such as flexural-, torsional- or lateral-buckling and cannot consider the effects of local deformations such as flange local buckling or distortional buckling. In order to capture the local effects of this type shell-type finite element models can be used. Based on the Bridging multi-scale approach, this study proposes a numerical technique that is able to split the global analysis, which is performed by using simple beam-type elements, from the local analysis which is based on more sophisticated shell-type elements.
As a result, the proposed multi-scale method allows the usage of shell elements in a local region to incorporate the local deformation effects on the overall behaviour of thin-walled members without necessitating a shell-type model for the whole member. Comparisons with full shell-type analysis are provided in order to illustrate the efficiency of the method developed herein.

References listed at the end of the paper:

ABSTRACT: Structural design codes and standards provide a foundation of good engineering practice. The process of developing probability-based codes has brought the structural reliability research community and engineers in professional practice together and led to research toward a common goal that otherwise would not have been possible. This paper reviews developments in probability-based codified structural design during the past two decades, assesses advantages and shortcomings of the current generation of probability-based codes, and suggests several avenues for new research.

PARTIAL ABSTRACT: Successful planning of complex structures of composite materials is possible only on the basis of reliable determination of the load bearing capacity. Experience shows [1,2] that a characteristic feature of the failure of composite materials is the stochastic growth and cumulation of microdefects in the process of loading (breakage of fibers, plastic deformation of the matrix, destruction of the boundary layer, delamination, etc.), and this leads subsequently to the appearance of zones of failure of the material…

P. Conti, S. Luparello and A. Pasta (Department of Mechanics and Aeronautics, University of Palermo, Viale
ABSTRACT: The paper describes a method to optimise the thickness balance within a composite laminate with layers oriented according to a limited set of angles. The laminate must be symmetric, balanced and loaded in-plane. The optimisation process is particularly suited to be used in conjunction with a finite element program. It provides the designer with the optimal overall engineering characteristics and a list of all the possible orientation combinations ranked with respect to their safety factor. The optimisation method is based on the first order gradient optimum search method and operates iteratively in the engineering elastic characteristics field. The cost function implemented up to now is the structure stiffness but no conceptual limitations exist for different functions. Some simple applications are listed at the end of the paper in order to verify the capabilities of the method.

ABSTRACT: A review of research in the area of large amplitude vibration of composite plates and shells is presented in this paper. The main focus of this paper is on the effects of geometric nonlinearity, transverse shear deformation and rotatory inertia on the vibration behaviour of single-layered plates and shells. Recent advances made in these areas are reviewed. Some literature on laminated plates and shells made of filamentary composite material is also included. Particular attention is given to the recent developments in the analytical methods of solution. Recent research leading to advances in numerical techniques is also included in the present overview.

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“Analysis and design of pultruded FRP shapes under bending”, Composites Part B: Engineering, Vol. 27, Nos.3-4, 1996, pp. 295-305, Special Issue: Structural Composites in Infrastructures, doi:10.1016/1359-8368(95)00015-1
ABSTRACT: A comprehensive approach for the analysis and design of pultruded FRP beams in bending is presented. It is shown that the material architecture of pultruded FRP shapes can be efficiently modeled as a layered system. Based on the information provided by the material producers, a detailed procedure is presented for the computation of fiber volume fraction (Vf) of the constituents, including fiber bundles or rovings, continuous strand mats, and cross-ply and angle-ply fabrics. Using the computed Vfs, the ply stiffnesses are evaluated from selected micromechanics models. The wall or panel laminate engineering constants can be computed from the ply stiffnesses and macromechanics, and it is shown that the predictions correlate well with coupon test results. The bending response of various H and box sections is studied experimentally and analytically. The mechanics of laminated beams (MLB) model used in this study can accurately predict displacements and strains, and it can be used in engineering design and manufacturing optimization of cross-sectional shapes and lay-up configurations. The experimental results agree closely with the MLB predictions and finite element verifications.
References at the end of the paper:

ABSTRACT: Fiber-reinforced plastic (FRP) beams are thin-walled or moderately thick-walled open or closed sections consisting of assemblies of flat panels. We present a computational approach with the computer program FRPBEAM (1994) for the response evaluation of pultruded FRP beams in bending. This program combines micro/macro-mechanics analyses with the Mechanics of Laminated composite Beams (MLB) model and an explicit stability solution to analyze, design, and optimize FRP shapes. In FRPBEAM, the ply stiffnesses are predicted by micromechanics formulas, based on the fiber volume fraction of each lamina, and the panel laminate properties are computed from the ply stiffnesses and macromechanics. The MLB model is used to analyze the overall response of FRP beams in bending, and the Tsai–Hill failure criterion is adopted to predict first-ply-failure loads. An example of a laminated box beam is used to demonstrate the accuracy of the computer program for predicting beam displacements and ply stresses in relation to finite element analyses. A stability Rayleigh–Ritz method is included in the program and used to evaluate the critical buckling loads for pultruded I-beams. Through parametric studies with FRPBEAM and a multiobjective optimization scheme, the fiber architecture of an existing I-beam is optimized, and based on a recommended practical design, the I-beam
section is produced by pultrusion and subsequently tested in bending. The predicted response with FRPBEAM correlates well with the experimental results. As illustrated by design analysis and optimization examples presented in this study, the experimentally and numerically verified computer program can be used to analyze existing FRP shapes and develop new optimized shapes for the civil structural market.

References listed at the end of the paper:

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ABSTRACT: An analytical study of local buckling of discrete laminated plates or panels of fiber-reinforced plastic (FRP) structural shapes is presented. Flanges of pultruded FRP shapes are modeled as discrete panels subjected to uniform axial in-plane loads. Two cases of composite plate analyses with different boundary
conditions and elastic restraints on the unloaded edges are presented. By solving two transcendental equations simultaneously, the critical buckling stress resultant and the critical value of the number of buckled waves over the plate aspect ratio are obtained. Using this new solution technique and regression analysis, simplified expressions for predictions of plate buckling stress resultants are efficiently formulated in terms of coefficients of boundary elastic restraints. The effects of restraint at the flange-web connection are considered, and explicit expressions for the coefficients of restraint for I- and box-sections are given; it is shown that actual cases lie between simply supported and fully restrained (clamped) conditions. The theoretical predictions show good agreement with experimental data and finite-element eigenvalue analyses for local buckling of FRP columns. In a similar manner, web plate elements of FRP shapes under in-plane shear loads are modeled with and without elastic restraints provided by the flange panels. The present formulation can be applied to several cases to determine local buckling capacities of laminated plates with elastic restraints along the unloaded edges and can be further used to predict the local buckling strength of FRP shapes, such as columns and beams.

References listed at the end of the paper:


ABSTRACT: The present paper addresses the optimal layout of stiffened fibre composite plates (Fig. 1) considering buckling constraints; these plates are increasingly applied in many fields of engineering (air- and spacecraft technology, automotive industries, boatbuilding etc.)

References listed at the end of the paper:


DOI: 10.4028/www.scientific.net/AMM.217-219.288

ABSTRACT: Finite element method (FEM) is applied to analyze the buckling performance of alloy aluminum stiffened panel subjected to uniform axial compression. With the skin thickness and stiffener pitch unchanged, the influence of flange thickness, flange length, stiffener thickness and stiffener height on compress buckling critical loads are studied by FEM. Important parameters influencing the buckling performance are identified and the results offer a referenced measure for the optimization design and engineering application of the structure.

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ABSTRACT: Finite element method is applied to analyze the buckling performance of composite stiffened panel. Compress buckling critical loads of six types panels with T or Z-section stiffeners are calculated by FEM. The emulational calculation results show that with same cross section area, critical buckling load of panel with T-section stiffeners increases with the reduction of stiffener pitch and the increase of stiffener numbers, while the buckling load of panel with Z-section stiffeners increases to a certain level and then keep almost changeless. To T-section stiffener panels, the relation between thickness of skin and buckling load is approximately quadratic trinomial. Conclusions obtained can offer a referenced measure for the optimization design and engineering application of the structure.
ABSTRACT: An experimental investigation of the local compression flange buckling and failure of commercially produced pultruded fiber-reinforced plastic (FRP) I-shaped beams is described in this paper. Results of tests on pultruded E-glass/polyester and E-glass/vinylester composite material beams are described. The test configuration was designed to cause local buckling and ultimate failure of the compression flange of the beams and to prevent global lateral-torsional buckling. The beams were stiffened to prevent crippling and warping at the supports, and local tensile failure at the load points. All beams were monitored with strain gages and LVDT’s. Buckling loads, failure loads, buckling stresses, deflections, and failure modes are reported. Effective mechanical properties of the beams, obtained from overall flexural and shear strain data, are presented. A discussion of the different failure characteristics of the polyester and the vinylester beams is provided.

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ABSTRACT: Fiber-reinforced plastic (FRP) composite decks have been increasingly used in highway bridge applications, both in new construction and rehabilitation and replacement of existing bridge decks. Recent applications have demonstrated that FRP honeycomb panels can be effectively and economically used for highway bridge deck systems. This paper is concerned with design modeling and experimental characterization of a FRP honeycomb panel with sinusoidal core geometry in the plane and extending vertically between face laminates. The analyses of the honeycomb structure and components include: (1) constituent materials and ply properties, (2) face laminates and core wall engineering properties, (3) equivalent core material properties, and (4) apparent stiffness properties for the honeycomb panel and its equivalent orthotropic material properties. A homogenization process is used to obtain the equivalent core material properties for the honeycomb geometry with sinusoidal waves. To verify the accuracy of the analytical solution, several honeycomb sandwich beams with sinusoidal core waves either in the longitudinal or transverse directions are tested in bending. Also, a deck panel is tested under both symmetric and asymmetric patch loading. Finite element (FE) models of the test samples using layered shell elements are further used to correlate results with analytical predictions and experimental values. A brief summary is given of the present and future use of the FRP honeycomb panel for bridge decks. The present simplified analysis procedure can be used in design applications and optimization of efficient honeycomb structures.
References listed at the end of the paper:

ABSTRACT: Designing an optimized composite laminate requires finding the minimum number of layers, and the best fiber orientation and thickness for each layer. To date, several optimization methods have been introduced to solve this challenging problem, which is often non-linear, non-convex, multimodal, and multidimensional, and might be expressed by both discrete and continuous variables. These optimization techniques can be studied in two parts: constant stiffness design and variable stiffness designs. This paper concentrates on the first part, which deals with composite laminates with uniform stacking sequence through their entire structure. The main optimization methods in this class are described, their characteristic features are contrasted, and the potential areas requiring more investigation are highlighted.

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ABSTRACT: This paper deals with an innovative integrated hollow space core sandwich composite construction that possesses several multi-functional benefits in addition to the providing lightweight and bending stiffness advantages. In comparison with traditional foam and honeycomb cores, the integrated space core provides a means to route wires/rods, embed electronic assemblies, and store fuel and fire-retardant foam, among other conceivable benefits. In the current work, the low-velocity impact (LVI) response of innovative integrated sandwich core composites was investigated. Three thicknesses of integrated and functionality-embedded E-glass/epoxy sandwich cores were considered in this study—including 6, 9 and 17 mm. The low-velocity impact results indicated that the hollow and functionality-embedded integrated core suffered a localized damage state limited to a system of core members in the vicinity of the impact. The peak forces attained under static compression and LVI were in accordance with Euler's column buckling equation. Stacking of the core was an effective way of improving functionality and limiting the LVI damage in the sandwich plate. The functionality-embedded cores provided enhanced LVI resistance due to energy additional
energy absorption mechanisms.

ABSTRACT: The search for lightweight and highly efficient structural components is a continuing process. Reducing the structural weight and improving the load carrying capabilities of these structures will allow designers to add additional capabilities while reducing cost. The basic functions of aerospace structures are to transmit and sustain the applied loads, provide a basic shape and to protect the payload. Shell stiffened structures have been used for many years to fulfill these applications. Most of the airframe components are normally plate or shell type structures. Efficiency dictates that they are stiffened or semi-monocoque in construction. The usual means of stiffening is to use longitudinal stringers and frames or ribs. An alternate approach to stiffening is the concept of isogrid, which employs a repetitive equilateral triangular pattern of ribs. The isotropic property and effective Poisson's ratio around 0.3 enables the isogrid to be mathematically transformed to an equivalent homogeneous material layer 1-2. Isogrids, in general, offer a unique set of advantages: (1) they possess a high stiffness to weight ratio; (2) stiffening results in high effective bending stiffness for circumventing local flutter, vibration and buckling problems; (3) stiffening members are useful for attachment of secondary structures and non-structural items and for the introduction of concentrated or localized loads; and (4) cutouts for access doors and windows are easily incorporated into the design.

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ABSTRACT: A procedure for simplifying the derivation of stiffness matrices used in the finite element analysis of instability and nonlinear structural problems is presented. The displacement functions assumed to derive the nonlinear components of element stiffness matrices provide inter-element continuity of displacement derivatives of order one less than appear in the energy functional and therefore comply with established convergence criteria for finite element analysis. For the class of problems discussed, this implies the use of linear polynomial displacement functions, which simplifies the derivation considerably and avoids the need for complex numerical integration. A number of practical examples are discussed to illustrate the effectiveness of this procedure.

ABSTRACT: Theoretical analyses are presented for the buckling of circular cylindrical shells partially subjected to external liquid pressure. The shells are assumed to stand vertically with the lower end clamped, and the upper end clamped or free. In the analyses, the Donnell equations are used for the basic equation, and prebuckling deformation as well as the membrane state of stress of the shell are taken into account. The
The Galerkin method is used, and the critical pressures at various liquid heights as well as the wave numbers, are obtained for a wide range of the geometrical parameters of the shell $Z$. A convenient chart which indicates the buckling liquid height for a given shell and liquid are presented. Experimental studies are also conducted by using test cylinders made of polyester film, and water. The theoretical and experimental results for the buckling liquid height, are in excellent agreement.


ABSTRACT: Theoretical analysis has been presented for the effect of internal liquid pressure on the buckling of circular cylindrical shells subjected to external liquid pressure. The shell is assumed to stand vertically with the lower end clamped, and the upper end clamped or free. In the analysis, the Donnell equation was used for the basic equation, and the prebuckling deformation of the shell was taken into account. The Galerkin method was used, and the critical pressures at various internal liquid heights as well as the buckling wave numbers, were obtained for a wide range of the geometrical parameters $Z$ a given shell. The effect of internal liquid on the buckling mode was also clarified. To confirm the validity of the analysis, experimental studies were also conducted by using test cylinders made of polyester film and water. Theoretical and experimental results were in good agreement.


ABSTRACT: Theoretical analyses are presented for the dynamic stability of a clamped-free cylindrical shell partially filled with liquid, under vertical excitation. In the analyses, the dynamic version of the Donnell equations and the velocity potential theory were used for the motions of the shell and the liquid, respectively. The problem was solved by using the modified Galerkin method so as to satisfy the boundary conditions. The equations of motion coupling the shell and the liquid were derived from a type of coupled Mathieu's equation. It is found that the parametric principal resonance could occur, as well as the parametric combination resonance of the sum type, involving two natural vibrations with the same circumferential wave number but with different axial mode number. The latter type of parametric resonance apparently has not been previously studied. The instability regions where parametric resonance occurs were determined by using Hsu's method. To compare with the experimental results which had been stated in a companion paper, detailed numerical calculations were carried out for the two test cylinders partially filled with water. Excellent agreement between theory and experiment was demonstrated for the instability regions.

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ABSTRACT: The aim of the present paper is to present numerical procedures, using two types of FE methods, for the secondary and higher order bifurcations (tertiary and quarternary bifurcations) which appear after the
first buckling of thin shell structures. With a limitation to a cylindrical shell under axial compression, the post-bifurcation behavior after the first bifurcation is analyzed precisely by considering modal coupling between several deformation modes of higher order harmonic wave numbers, and on all the way of post-bifurcation path the positive definiteness of incremental stiffness matrix of uncoupled modes is examined step by step to find if any higher order bifurcation or transcritical bifurcation appears. Based on the step-by-step examination, the higher order bifurcation points and the corresponding bifurcation modes are traced.

**Papers by Professor Peter von Buelow (Bülow) relating to shell-type parts of architectural creations:**


ABSTRACT: A mathematical model is constructed to study the buckling of rectilinearly orthotropic, truncated conical shells. The model consists of three coupled variable coefficient partial differential equations for the shell displacements; the formulation presented takes into account the action of locally supported applied forces normal to the lateral surface of the shell and contains two fundamental novelties: the introduction of special combinations of constitutive parameters to gauge the deviation from isotropy and a transformation of both coordinates and displacements on the developed cone surface to render the problem tractable.

ABSTRACT: In this paper, the axisymmetric and non-axisymmetric buckling of finite elastic cylindrical shell, which is impacted on the end by axial step loads, is discussed with the aid of the stress wave propagating and reflecting. By solving the disturbed equations, the bifurcation condition of the dynamic buckling, critical buckling load and buckling mode are obtained. The results show that when the thickness is not very small, non-axisymmetric critical buckling load is higher than axisymmetric one; that when the thickness is very small, non-axisymmetric buckling can occur first and that since the wave is reflected on the other end of the shell, the critical buckling load decreases further. The results are in agreement with the physical phenomenon in experiments.
ABSTRACT: Over the last few decades, storage tanks have become bigger and thinner. Because of this, the buckling capacity of these cylindrical shells may well be the determining factor of shell thickness. In this paper, the critical buckling load of isotropic and orthotropic cylinders subjected to different types of wind load distributions is investigated. The prebuckling displacements are obtained by using the membrane theory of shell analysis. The principle of minimum potential energy in conjunction with Ritz's approach is used to obtain the stability matrix. The size of the stability matrix in this analysis is $(81 \times 81)$. By solving the stability matrix as an eigenvalue problem, the critical pressures are obtained as eigenvalues and the deflection shapes as eigenvectors.

In the present study cylindrical shells of various dimensions, which are fixed at the base and free at the top, are investigated. The buckling load curves for isotropic and orthotropic cylinders of various dimensions are given for practical use.

ABSTRACT: The influence of concrete creep on the response of shallow reinforced concrete shells is analyzed in this contribution in the context of time-dependent shell buckling. The classical time-invariant stability analysis is extended to account for the long-term creep buckling, which is characterized by a continuous increase of deformation and time-dependent stability failure, if a certain critical load factor is exceeded. For a systematic study of these phenomena on a cylindrical roof shell, a recently proposed time-invariant and a time-dependent material model for concrete are combined in the framework of the long-term multi-level simulation concept, taking into account elasto-plastic deformation, crack damage and nonlinear basic creep of concrete. The performed numerical analyses provide an insight into the mechanisms of creep buckling of reinforced concrete shells as well as its sensitivity with respect to main influence factors and emphasize the relevance of interaction mechanisms between short- and long-term loadings.

ABSTRACT: The initiation of cracking and its location are of vital importance in the analysis and the design of concrete shell structures. Openings are common design requirement in shell roofs for light and ventilation. However, analysis and design procedures are lacking for such cases. Close-form elasticity solutions for concrete
shells with openings are unavailable. Therefore, FE modeling for such structures is required. The objective is to create a finite element model capable of predicting the nonlinear cracking loads of reinforced concrete shells. A rigorous evaluation of the role of openings and their dimensions are studied and design recommendations for shells with different opening dimensions and cracking loads are suggested. The FE model consists of a total of 17550 solid brick concrete elements with six layers across the shell thickness. Each element has 8 nodes with three translational degrees of freedom. The model predicts the nonlinear cracking load, and the crushing mechanism for thin concrete shells with varying thickness with and without openings. Results of the finite element predictions are validated with the finite strip theory for thin concrete shells. Good agreement between FE results and theory is observed for deflections and stresses. The failure model of concrete material used in this analysis proved to be accurate in predicting the nonlinear behavior of reinforced concrete thin shells. When the dimension of the opening increases along the mid-span axis of the shell, the cracking stress required increases because the increase in the opening dimension is directed away from the high stress levels in the shell center. On the other hand, if the opening dimension is increased in the longitudinal direction of the shell, the required load to initiate cracking will decrease because of the high level of stress concentration present in the vicinity.

Shawomir Koczubiej and Czeslaw Cichon (Kielce University of Technology, Poland), “Shell-beam model of thin-walled space structures for geometrically nonlinear analysis”, Computer Methods in Mechanics (CMM-2011, 9-12 May 2011, Warsaw, Poland)
ABSTRACT: In the paper, the finite shell-beam model for geometrically nonlinear analysis of thin-walled space structures with open cross-section has been proposed. The standard discretization using beam thin-walled elements is connected with the space discretization of the frame joints. The case of special construction of joints, where complete warping transmission is ensured, has also been considered. Examples confirmed the effectiveness of the proposed FEM analysis.

References listed at the end of the paper:

ABSTRACT: The main structural aspects considering offshore steel platforms, steel decks, concrete platforms and other structural components involving shell elements are reviewed. Outlines are given with regard to design and strength analysis of the most important types of shell structures involved.

ABSTRACT: Nonlinear strain is used to formulate the energy functional of combined structure with several kind of shells. The nonlinear finite element method (N.F.E.M.) is proposed for calculating bending and buckling of the structure subjected to external hydrostatic pressure. The numerical results are found to be in good agreement with experimental ones.


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ABSTRACT: An analysis of four-noded C0-shell elements is presented that assesses their ability to represent the membrane-bending coupling phenomena in the governing shell equations by facet approximations. It is shown that four-noded shell elements can capture the predominant coupling phenomena consistent with the classical assumptions invoked in the first-order linear shell theories. Encouraged by this ability, a new four-noded C0-shell element is presented that employs only one-point spatial integration rule. The inevitable spurious mechanisms resulting from reduced integration are compensated for by a systematic rank-correction technique that was previously developed for a plate-bending element. The element is applied to classical cylindrical buckling problems with encouraging results.


ABSTRACT: This paper presents the effects of elastic supports on the buckling of circular cylindrical shells under bending. Stability was investigated using Donnell’s equation and the Galerkin method, including the spring constant of the elastic support. The results of this investigation indicate that the effects are similar in the cases of bending and axial compression.

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ABSTRACT: Thin walled tubes of circular cross-section are efficient structural elements and thus, as would be expected, are not uncommon in plants, especially those which belong to the Monocotyledonae. Traditional analyses of the strength of these tubular members utilize formulae which were developed for isotropic materials. The present paper deals with the great influence of the high elastic anisotropy of the plant tissue on the mechanical behavior of such tubular stems and leaves in bending. It will be seen that under these circumstances the propensity of the tube to fail due to non-linear effects (deformation of the cross-section) is greatly increased.


ABSTRACT: The aim of this paper is to describe buckling deformations of hollow cylinders whose buckled configurations consist of inextensional deformations of their original middle surface, through minimization of two competing energy forms: a bulk elastic energy and an interface bending energy. These minimal energy configurations are obtained through descent minimization within the class of folding deformations. The non-
standard problem of minimization over variable triangulations is considered.

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20. S. Muller, On possible and impossible constructions: Hilbert's theorem, the folding of paper and phase transformation in elastic crystals, Notes from a lecture given at the Department of Aerospace Engineering and Mechanics University of Minnesota (November 1995).
ABSTRACT: The general instability of thin-walled orthotropic circular cylindrical shells under external pressure is investigated. The buckling pressure can be predicted with the use of simple analytical formulae derived from an asymptotic analysis of the corresponding eigenvalue problems. The results predicted by these formulae are compared with finite element solutions and the four types of experimental models investigated by Ross (Thin Walled Structures 1996;26(3):179–93). The comparison proved to be accurate enough for practical purpose except for experimental model 1.


ABSTRACT: In creep buckling analysis, small deflexion approximations generally influence the calculated displacement-time relations and may also result in the prediction of different phenomena from those indicated by exact analyses. Part II examines the nature of these approximations and the effects of using them. As in Part I, much significance is attached to the link between a structure's creep buckling behaviour at constant load and its instantaneous buckling and post-buckling behaviour under varying load. Analyses of simple single degree of freedom models are used for illustration. Some general conclusions are drawn which permit a better understanding of the relationships between the different types of analysis that have been used in previous creep buckling studies.


ABSTRACT: This paper has developed an efficient nonlinear finite element method that covers both initial deformations and initial stresses of general distribution in calculating the ultimate strength of ring-stiffened cylinders. The developed method and two world-widely used commercial codes(NASTRAN and ABAQUS) were simultaneously applied to the same analysis model within the extent those commercial codes can cover, to check the validity of the present method. After the validity check, it was used for parametric studies for more general case of initial stress distribution, which drew some useful information about the imperfection sensitivity of the ultimate strength of ring-stiffened cylinders.

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ABSTRACT: Two new variational functionals are introduced for buckling analysis of cylindrical shells. In the first, admissible functions satisfy all the equilibrium equations and the Euler-Lagrange equations emerge as a set of compatibility equations. In this sense this procedure complements the well known minimum potential energy method. In the second, the transverse equilibrium and membrane compatibility requirements are satisfied by the admissible functions and the system equations emerge as a set of membrane equilibrium and transverse compatibility equations. This formulation can be considered as complementary to Von Karman's well known method. The new functionals are used to obtain solutions for 2 classic examples.

ABSTRACT: The Semi-Loof Shell element originally developed by Irons [2] for linear elastic analysis of thin shell structures is formulated to include large deflection and plastic deformation effects. In this paper the details of the finite element formulation of the problem using total Lagrangian coordinate systems are presented and different element matrices are given. For plastic materials following the Prandtl-Reuss flow rule with isotropic strain hardening a multi-layer approach using a subincremental technique is employed. Numerical results on the performance of the element for a variety of applications are presented. These computer studies include complete load-deflection curves into the post-buckling range and comparisons are made with other existing results. Current experience with the element indicates that it is a reliable and competitive element for nonlinear analysis of shells of general geometry.

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ABSTRACT: Results are presented and some modifications made to problems posed in an earlier paper by the authors on the extension of the semi-loof element to the analysis of shell structures involving instabilities, snap-through and material nonlinearities. In this paper, by adopting a more refined method for solving problems of plasticity, in conjunction with a subincremental technique, more accurate results are obtained. The second-order Runge-Kutta method employed in this study shows significant improvement in the accuracy of the stresses in the shell as compared to the case when only the simple point-slope method of Euler is used. The detailed computational procedure for elastoplastic analysis of shell problems is presented in a way that can readily be incorporated into standard computer packages. Results obtained for large deflection analysis of plastic shells of different geometries and boundary conditions are compared with the available solutions and show very good agreement.

ABSTRACT: Aspects and theories of nonlinear analysis of structures, with special emphasis on structures that are discretized by the finite element method, are discussed. The updated Lagrangian formulation and the incremental Hellinger-Reissner variational principle are adopted. The independently assumed fields employed are the incremental displacements and incremental strains. Accordingly, the incremental second Piola-Kirchhoff stress and the incremental Washizu strain are selected as the incremental stress and strain measures. Various schemes for the transformation of the second Piola-Kirchhoff stress to Cauchy stress are included. Two versions of linear and nonlinear element stiffness and mass matrices are considered. These are the director and simplified versions. Variable thickness of the shell is considered so as to account for the ‘thinning effect’ due to large strain. Material nonlinearity studied in this paper is of elasto-plastic type with isotropic strain hardening. Cases in which small elastic but large plastic strain condition applies are considered and the J2 flow theory of plasticity, in conjunction with Ilyushin's yield criterion, is employed. To simplify the derivation of (small displacement) stiffness matrix and to facilitate the derivation of explicit expressions for the element matrices, the non-layered approach has been applied.


ABSTRACT: In a companion paper [M. L. Liu and C. W. S. To, Comput. Struct. 54, 1031–1056 (1995)] theories and incremental formulation of nonlinear shell structures discretized by the finite element method are discussed. The updated Lagrangian formulation and the incremental Hellinger-Reissner variational principle are adopted. The independently assumed fields employed are the incremental displacements and incremental strains. Based on the theory and incremental formulation explicit element stiffness and mass matrices of three node flat triangular shell finite elements are derived. In the present paper the derived element matrices are applied to nine examples. The latter include static and dynamic response analysis of shell structures with geometrical, material, and geometrical and material nonlinearities. The formulation adopted and element matrices derived are found to be accurate, flexible and applicable to various types of shell structures with geometrical and material nonlinearities.

ABSTRACT: The thick shell element of Ahmad, Irons and Zienkiewicz has been used in the study of plate and shell buckling and vibration problems. A concise tensor based theory for finite elements, in general, and the shell element, above, in particular is developed in this study. Using this theory, expressions for the geometric stiffness and mass matrix of the above element are developed. The computer implementation of the theory centred on two aspects. Firstly, the programming of the geometric stiffness and mass matrix expressions. Secondly a general review has been carried out to establish as efficient a program as possible. This efficiency is both in terms of user data preparation and computational effort within the program. In this regard, it should be noted that the numerical integration procedure used in creation of the element stiffness matrices involves many repetitive operations. Therefore any extraneous operations, for example, multiplication of zero terms, leads to
large inefficiencies. The subspace iteration method of Bathe and Wilson has been used for determining buckling loads and natural frequencies of vibration. A modified iteration method is developed, which allows use of the method for certain examples which previously were not solvable using the standard method. These examples are characterized by having as a solution set, pairs of eigenvalues, equal in magnitude, but opposite in sign. This modified method has been incorporated in the program with the basic standard method. Examples in the buckling field which exhibit this behaviour include the shear buckling of flat plates and the lateral buckling of beams. Both these cases have been investigated in this study.


ABSTRACT: The purpose of this study has been to explore the use of super-parametric finite elements for the determination of buckling loads for plates and shells. For this, it was necessary to develop the geometric stiffness matrix for the shell element. In addition to this, it was necessary to choose a numerical method for the solution of the large scale eigenvalue problem that arises from the formulation. The subspace iteration method was chosen for its versatility in handling large scale problems, but it was found that the standard technique broke down because of the presence of positive and negative eigenvalues. The paper describes how the method was modified to overcome this problem. Results are given for comparative studies on the buckling loads of both plates and shells.


ABSTRACT: The faceted representation is employed in the paper to derive a 24-dof triangular shell element for the instability analysis of shell structures. This element, without the deficiencies of displacement incompatibility, singularity with coplanar elements, inability to model intersections, and low-order membrane strain representation, which are normally associated with existing flat elements, has previously been found by the authors to perform well in linear static shell analyses. The total Lagrangian approach is used in the nonlinear formulation, and the results of the various numerical examples indicate that its performance is comparable to existing nonlinear shell elements. An extrapolation stiffness procedure, which will improve the convergence characteristics of the constant arc length solution algorithm used here, is also presented.


ABSTRACT: The large displacement analysis of flat faceted shell element, previously developed by Meek and Tan [15] is further developed. This element, has been already tested in the nonlinear range via the use of the total Lagrangian formulation and a somewhat cumbersome procedure for the calculation of the joint orientation matrices at each step of the calculations [25]. However, this approach is quite complex and by taking advantage of the positions of the rotational degrees of freedom, being located at the Loof nodes along the edges and normal to the edges, a simple and elegant formulation is obtained. The theory is developed in incremental form and the updated Lagrangian approach with the co-rotational formulation is employed. Numerical examples are
presented and compared with other published results to verify the proposed formulation.

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ABSTRACT: A plane circular ring is modeled by various elements, some straight and others curved. All formulations have two translations and one rotation as nodal df. We consider static deflection, under point loading, and bifurcation buckling, under constant-direction loading and fluid pressure loading. Matrices that account for fluid pressure loading are derived. Numerical examples show that excellent results are given by a standard straight beam element whose length is that of the arc it subtends.

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ABSTRACT: The similitude invariant and the scaling laws of the symmetric cross-ply laminated circular cylindrical shells for buckling and free vibration problems are derived by applying the similitude transformation to the governing differential equations directly. The scaling laws obtained by this approach are unique because they are forced by the governing differential equations. In the absence of the experimental data, the validity of the scaling laws is verified by numerical experiments. This is done by calculating theoretically the buckling loads and fundamental frequencies for free vibration of the model and substituting into the scaling laws. The predicted values of the prototype from the scaling laws are then compared with those values from the closed-form solution. Examples for the complete similitude cases with various stacking sequences, number of plies, and radius ratios show exact agreement. The presented relationships between the model and prototype will greatly facilitate and reduce the costly experiment. In reality, it may not be feasible to construct the model to fulfill the similarity requirements completely. Several cases of partial similitude are investigated and verified numerically. Modeling with distortion in stacking sequences is recommended, but model with distortion in material properties yields moderately high percent of discrepancy.

ABSTRACT: Structural buckling failure due to high external hydrostatic pressure is a major consideration in designing rings and long cylindrical shell-type structures. This paper presents a direct approach for enhancing buckling stability limits of thin-walled rings/long cylinders that are fabricated from multangle fibrous laminated composite lay-ups. The mathematical formulation employs the classical lamination theory for calculating the critical buckling pressure, where an analytical solution that accounts for the effective axial and flexural stiffness separately as well as the inclusion of the coupling stiffness terms is presented. The associated
design optimization problem of maximizing the critical buckling pressure has been formulated in a standard nonlinear mathematical programming problem with the design variables encompassing the fiber orientation angles and the ply thicknesses as well. The physical and mechanical properties of the composite material are taken as preassigned parameters. The proposed model deals with dimensionless quantities in order to be valid for thin shells having different thickness-to-radius ratios. Useful design charts are given for several types of anisotropic rings/long cylinders showing the functional dependence of the buckling pressure on the selected design variables. Excellent results have been obtained for cases of filament wound rings/long cylinders fabricated from three different types of materials: E-glass/vinyl-ester, graphite/epoxy and S-glass/epoxy. It was shown that significant improvement in the overall stability level can be attained as compared with a baseline shell design. In fact, the developed methodology has been proved to be a useful design tool for selecting an optimal staging sequence of a thin-walled anisotropic ring/long cylinder having arbitrary thickness-to-radius ratio.

References listed at the end of the paper:


ABSTRACT: This paper presents a generalized formulation for the problem of buckling optimization of anisotropic, radially graded, thin-walled, long cylinders subject to external hydrostatic pressure. The main structure to be analyzed is built of multi-angle fibrous laminated composite lay-ups having different volume fractions of the constituent materials within the individual plies. This yield to a piecewise grading of the material in the radial direction; that is the physical and mechanical properties of the composite material are allowed to vary radially. The objective function is measured by maximizing the critical buckling pressure while preserving the total structural mass at a constant value equals to that of a baseline reference design. In the selection of the significant optimization variables, the fiber volume fractions adjoin the standard design variables including fiber orientation angles and ply thicknesses. The mathematical formulation employs the classical lamination theory, where an analytical solution that accounts for the effective axial and flexural stiffness separately as well as the inclusion of the coupling stiffness terms is presented. The proposed model deals with dimensionless quantities in order to be valid for thin shells having arbitrary thickness-to-radius ratios. The critical buckling pressure level curves augmented with the mass equality constraint are given for several types of cylinders showing the functional dependence of the constrained objective function on the selected design variables. It was shown that material grading can have significant contribution to the whole optimization process in achieving the required structural designs with enhanced stability limits.

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Karam Y. Maalawi (Department of Mechanical Engineering, National Research Center, 12622 Dokki, Cairo, Egypt), “Use of material grading for enhanced buckling design of thin-walled composite rings/long cylinders under external pressure”, Composite Structures, Vol. 93, No. 2, January 2011, pp. 351-359, doi:10.1016/j.compstruct.2010.09.007

ABSTRACT: This paper presents a mathematical model for enhancing the buckling stability of composite, thin-walled rings/long cylinders under external pressure using radial material grading concept. The main structure to be analyzed is built of multi-angle fibrous laminated lay-ups having different volume fractions of the constituent materials within the individual plies. This leads to a piecewise grading of the material in the radial direction. The objective is to maximize the critical buckling pressure while preserving the total structural mass at a constant value equal to that of a baseline design. The fiber volume fractions are included among the standard design variables such as fiber orientation angles and ply thicknesses, which are used by many investigators in the field. The model employs the classical lamination theory, where an analytical solution that accounts for the effective axial and flexural stiffness separately is given. The critical buckling pressure contours subject to the mass equality constraint are given for several types of anisotropic rings/long cylinders showing the functional dependence of the constrained objective function on the selected design variables. It is shown that material grading can have significant contribution to the whole optimization process in achieving the required structural designs with enhanced stability limits.


PARTIAL INTRODUCTION: The theory of thin shells investigates the properties of rigid deformable bodies of extremely small thickness. It has become intuitively obvious for many researchers, therefore, that the mechanical properties of a thin-walled shell depend heavily on the geometric properties of its median surface. As early as 1908, therefore, Mallock [160], investigating postcritical deformations of long cylindrical tubes under axial compression, which may be accompanied by significant changes in the shape of the shell and small tension-compression deformations in the median surface…. 


ABSTRACT: A.V. Pogorelov developed a little-known theory of thin elastic shells. He considered a class of piecewise inextensional deformations, in which relatively sharp creases separate areas of inextensional deformation. Within a crease the deformation is inextensional in the plane perpendicular to the crease. The local form of the crease minimises the strain energy, which has bending and stretching components. The paper outlines the theory, applies it to radially loaded open-topped cylindrical shells, and compares it with measurements by Holst and Lukasiewicz.

References listed at the end of the paper:


ABSTRACT: The aim of this contribution is to propose a new averaged nonasymptotic model of stationary stability problems for thin linear-elastic cylindrical shells reinforced by stiffeners which are periodically, densely spaced along one direction tangent to the shell midsurface. As a tool of modeling we shall apply the tolerance averaging technique. The resulting equations have constant coefficients in the periodicity direction. Moreover, in contrast with models obtained by the asymptotic homogenization technique, the proposed one makes it possible to describe the effect of the periodicity cell size on the global shell stability (a length-scale effect). It will be shown that this effect plays an important role in the shell stability analysis and cannot be neglected.


ABSTRACT: A new averaged non-asymptotic model of stationary stability problems for thin elastic cylindrical shells reinforced by a dense system of stiffeners periodically spaced along one direction tangent to the shell midsurface has been proposed by Tomczyk (2005). The aim of this contribution is to apply this model to investigate the effect of a period length on the axially symmetric buckling of the shells under consideration.


DOI: 10.1155/DENM/2006/79853

ABSTRACT: The object of considerations is a thin linear-elastic cylindrical shell having a periodic structure along one direction tangent to the shell midsurface. The aim of this paper is to propose a new averaged nonasymptotic model of such shells, which makes it possible to investigate free and forced vibrations, parametric vibrations, and dynamical stability of the shells under consideration. As a tool of modeling we will
apply the tolerance averaging technique. The resulting equations have constant coefficients in the periodicity direction. Moreover, in contrast with models obtained by the known asymptotic homogenization technique, the proposed one makes it possible to describe the effect of the period length on the overall shell behavior, called a length-scale effect.

References listed at the end of the paper:


ABSTRACT: Stability analysis of noncircular shells is performed with allowance for nonlinear subcritical deformation. Explicit expressions for the rigid displacements of elements of noncircular cylindrical shells are obtained and used to construct shape functions of an effective quadrilateral finite element of natural curvature. A finite element algorithm for solving problems of nonlinear deformation and stability of shells is developed.
Stability problem of an elliptic cylindrical shell is considered. The effect of the ellipticity and subcritical nonlinear deformation of the shell on the critical load is studied. Results obtained are compared with available experimental data.


ABSTRACT: A study is made of the stability of cylindrical shells of oval cross section loaded by a shear force combined with torsional and bending moments. The variational method of finite elements in displacements is used. The subcritical stress-strain state of the shells is considered momental and nonlinear. The effects of the nonlinearity of shell deformation and shell ovalization on the critical load and buckling mode are determined.

References listed at the end of the paper:

D.V. Boiko, L.P. Zheleznov and V.V. Kabanov, “Analysis of nonlinear deformation and stability of reinforced elliptic cylindrical shells under bending with internal pressure”, Russian Aeronautics (Iz VUZ), Vol. 53, No. 2, pp 149-154, June 2010

ABSTRACT: A finite element statement of solving problems on stability of reinforced elliptic cylindrical shells taking into account momentness and nonlinearity of their subcritical stress strain state is presented. The explicit expressions for displacements of noncircular cylindrical shell elements as rigid bodies are determined by integrating the equations obtained by equating the components of linear strains to zero. These expressions were used to construct the form functions for an efficient quadrilateral finite element of natural curvature. An efficient numerical algorithm of nonlinear deformation and stability of shells was developed. The stability of reinforced elliptic cylindrical shells under combined loading by bending moment, transverse boundary force and internal pressure is analyzed. We also examine how the critical loads are affected by the strain nonlinearity and ellipticity of shell deformation at the subcritical stage.

References listed at the end of the paper:
4. Kabanov, V.V., Ustoichivost’ neodnorodnykh tsvilindricheskikh obolochek (Stability of Nonuniform Cylindrical Shells), Moscow: Mashinostroenie, 1982.
ABSTRACT: A boundary layer analysis is carried out to determine the possible form of large axisymmetrical deflection states for thin elastic spherical shells subjected to uniform external pressure. For the case of complete spheres it is shown that the governing equations admit boundary layer solutions corresponding to large deflections provided the pressure is sufficiently small. However, such solutions are found to exist for nonshallow clamped spherical caps for a much wider range of pressure. Numerical results are presented for the latter case.


ABSTRACT: This paper examines the post-buckling deformations of cylindrical shells conveying viscous fluid. The wall deformation is modelled using geometrically nonlinear shell theory, and lubrication theory is used to model the fluid flow. The coupled fluid–solid problem is solved using a parallelized FEM technique. It is found that the fluid–solid interaction leads to a violent collapse of the tube such that immediate opposite-wall contact occurs after the buckling if the volume flux is kept constant during buckling. If the pressure drop through the tube is kept constant during the buckling, the fluid–solid coupling slows down the collapse (compared to buckling under a dead load). The effects of various parameters (upstream pressure, axial pre-stretch and the geometry of the tube) on the post-buckling behaviour are examined and the exact geometrically nonlinear shell theory is compared to Sanders’ (1963) moderate rotation theory. Finally, the implications of the results for previous models which described the wall deformation using so called “tube laws” are discussed.

References listed at the end of the paper:


ABSTRACT: This paper is concerned with the problem of viscous flow in an elastic tube. Elastic tubes collapse (buckle non-axisymmetrically) when the transmural pressure (internal minus external pressure) falls below a critical value. The tube's large deformation during the buckling leads to a strong interaction between the fluid and solid mechanics. In this study, the steady three-dimensional Stokes equations are used to analyse the slow viscous flow in such a tube whose deformation is described by geometrically nonlinear shell theory. Finite element methods are used to solve the large-displacement fluid-structure interaction problem. Typical wall deformations and flow fields in the strongly collapsed tube are shown. Extensive parameter studies illustrate the tube's flow characteristics (e.g. volume flux as a function of the applied pressure drop through the tube) for boundary conditions corresponding to the four fundamental experimental setups. It is shown that lubrication theory provides an excellent approximation of the fluid traction while being computationally much less expensive than the solution of the full Stokes equations. Finally, the computational predictions for the flow characteristics and the wall deformation are compared to the results obtained from an experiment.


ABSTRACT: This research deals with several novel aspects of the nonlinear behaviour of thick-walled cylindrical hyperelastic tubes under external pressure. Initially, we consider bifurcation from a circular cylindrical deformed configuration of a thick-walled circular cylindrical tube of incompressible isotropic elastic material subject to combined axial loading and external pressure. In particular, we examine both axisymmetric and asymmetric modes of bifurcation. The analysis is based on the three-dimensional incremental equilibrium equations, which are derived and then solved numerically for a specific material model using the Adams-Moulton method. We assess the effects of wall thickness and the ratio of length to (external) radius on the bifurcation behaviour. The problem of the finite axisymmetric deformation of a thick-walled circular cylindrical elastic tube subject to pressure on its external lateral boundaries and zero displacement on its ends is formulated for an incompressible isotropic neo-Hookean material. The formulation is fully nonlinear and can accommodate large strains and large displacements. The governing system of nonlinear partial differential equations is derived and then solved numerically using the C++ based object-oriented finite element library Libmesh. The weighted residual-Galerkin method and the Newton-Krylov nonlinear solver are adopted for solving the governing equations. Since the nonlinear problem is highly sensitive to small changes in the numerical scheme,
convergence was obtained only when the analytical Jacobian matrix was used. A Lagrangian mesh is used to discretize the governing partial differential equations. Results are presented for different parameters, such as wall thickness and aspect ratio, and comparison is made with the corresponding linear elasticity formulation of the problem, the results of which agree with those of the nonlinear formulation only for small external pressure. Not surprisingly, the nonlinear results depart significantly from the linear ones for larger values of the pressure and when the strains in the tube wall become large. Typical nonlinear characteristics exhibited are the “corner bulging” of short tubes, and multiple modes of deformation for longer tubes. Finally the general fully nonlinear governing equations in Lagrangian form for the three dimensional large deformations of an elastic tube under external pressure are developed.

References listed at the end of the dissertation:

1954.


ABSTRACT: Recent advancements in computational methods has led to improvements in the compu- tational modeling of tensile failure of composite laminates. Models for compressive failure however, have not yet
reached the same level of maturity. Particularly in the case of fiber kinking there is a need for improved modeling techniques. Fiber kinking occurs when fiber imperfection combined with matrix failure lead to localized deformation in a band of finite width (kink bands). Current computational models have focused on micro-level, where matrix and fibers are modeled independently. The various experimental and analytical research on fiber kinking has led to numerous failure criteria and analytical models for kink bands. The collapse response of kink bands however, has yet to be incorporated in a meso-level computational model. A step is required to translate these micro-mechanical and analytical models to a meso-level framework and improve the state of the art of compressive failure modeling of composite laminates.

In this thesis an attempt is made at transitioning from a micro to a meso-level failure model for fiber kinking. A discontinuous approach is proposed for modeling kink bands. The kink bands are represented as strong discontinuities in the displacement field using the phantom node method. With this method the angle of failure propagation can be easily controlled. The discontinuities are introduced after violation of a stress-based failure criterion and therefore necessitates the use of an initially rigid cohesive law to incorporate the kink band response. To construct such a law a shifted formulation is used, meaning, the law is derived with a finite initial stiffness and shifted to achieve the initially rigid behavior. Strong discontinuity analysis and a discrete micromechanical model are used to derive two separate cohesive models in the local kink band coordinate frame, while a simplified approach is also applied to derive a third model in the discontinuity coordinate frame.

The nonlinear characteristics and bifurcation of the models necessitate the use of a capable solution algorithm that will follow the true equilibrium path. Therefore the crack opening displacement arclength method is used to; indirectly control direction of crack growth, pass the bifurcation point and capture possible snap-back behavior. Additionally an adaptive time stepping strategy is applied to increase efficiency and robustness. The model and algorithm have been implemented in a one dimensional framework using Timoshenko beam elements and verified against an analytical solution. The local models have shown to capture the trends derived using the analytical solution well, with the strong discontinuity model being the most accurate. The simplified approach however fails to properly account for these trends.

The current work has resulted in an initial step towards a meso-level computational model of fiber kinking. It is shown that the discontinuous approach provides a good representation of kink bands provided that a proper cohesive model is used that incorporates both material and geometrical parameters influencing kink bands.

References listed at the end of the thesis:
This paper addresses the question of strength and mechanical failure in exoskeletons and endoskeletons: a biomechanics analysis”, Journal of the Royal Society Interface, 12 September 2012, DOI: 10.1098/rsif.2012.0567

ABSTRACT: This paper addresses the question of strength and mechanical failure in exoskeletons and endoskeletons. We developed a new, more sophisticated model to predict failure in bones and other limb segments, modeled as hollow tubes of radius $r$ and thickness $t$. Five failure modes were considered: transverse fracture; buckling (of three different kinds) and longitudinal splitting. We also considered interactions between...
failure modes. We tested the hypothesis that evolutionary adaptation tends towards an optimum value of \( r/t \), this being the value which gives the highest strength (i.e. load-carrying capacity) for a given weight. We analysed two examples of arthropod exoskeletons: the crab merus and the locust tibia, using data from the literature and estimating the stresses during typical activities. In both cases, the optimum \( r/t \) value for bending was found to be different from that for axial compression. We found that the crab merus experiences similar levels of bending and compression \textit{in vivo} and that its \( r/t \) value represents an ideal compromise to resist these two types of loading. The locust tibia, however, is loaded almost exclusively in bending and was found to be optimized for this loading mode. Vertebrate long bones were found to be far from optimal, having much lower \( r/t \) values than predicted, and in this respect our conclusions differ from those of previous workers. We conclude that our theoretical model, though it has some limitations, is useful for investigating evolutionary development of skeletal form in exoskeletons and endoskeletons.


ABSTRACT: The main goal of this work is to prove the equivalence of various formulations existing in the current literature which give the governing equations of small displacements superimposed over initial static deformations of thin cylindrical shells. It is shown that the main difference comes from the definition of incremental stress resultants and the dependence of elastic coefficients on initial deformation. When the functional dependence of elastic coefficients on initial deformation is taken into consideration, it is shown that all the derivations are equivalent to each other.

References listed at the end of the paper:

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ABSTRACT: To model the competition between capillary and elastic forces in controlling the shape of a small lung airway and its interior liquid lining, we compute the equilibrium configurations of a liquid-lined, externally pressurized, buckled elastic tube. We impose axial uniformity and assume that the liquid wets the tube wall with
zero contact angle. Non-zero surface tension has a profound effect on the tube's quasi-steady inflation-deflation characteristics. At low liquid volumes, hysteresis arises through two distinct mechanisms, depending on the buckling wavenumber. Sufficient compression always leads to abrupt and irreversible collapse and flooding of the tube; flooding is promoted by increasing liquid volumes or surface tension. The model captures mechanisms whereby capillary-elastic instabilities can lead to airway closure.


ABSTRACT: The combined load case of bending and torsion of a cantilever inflated beam is a load case that has not been studied extensively. When a series of inflated beams is placed parallel to each other as can be the case for an inflatable wing, each beam experiences a combination of torque and bending. A theoretical model already exist for such a load case but it is limited to membrane like materials. This paper deals with beams made of materials that need to be treated like a shell. It requires a modification for the wrinkling load due to solely bending and solely torsion. Semi-empirical expressions for both cases are presented for both cylindrical and conical shaped beams.


ABSTRACT: Static and dynamic analysis of fully clamped shallow spherical shells, subjected to uniform normal pressure on concave side and continuously supported on Pasternak foundation on the convex side, is made using Berger's and modified Berger's techniques. Expressions for large static deflections are obtained and results compared with those of Nash and Modeer. The preceding techniques are employed to get the approximate expressions for natural frequency. Values of nondimensional natural frequency obtained by various methods are compared with results of Reissner, Nowacki, Bucco, and others. While a modified Berger's approach gives very good results for static analysis of fully clamped shells, the original Berger's approach is found to be more suitable for free vibration analysis, as results tally with those obtained by Réissner, using Rayleigh's method, even for higher ratios of (H/h). The modified Berger's technique gives sufficiently accurate values of natural frequencies only for smaller values of (H/h).

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ABSTRACT: Nonlinear static behaviour of clamped shallow spherical shell at elevated temperature and resting on Pasternak type elastic foundation is examined, using Berger's approximation. Variation of non-dimensional central deflection with foundation parameters for a given thermal loading is investigated.

Zhou Cheng-ti (1) and Zhou Chien-bin (2)
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(2) Chansha Institute of Technology, Chansha, China
ABSTRACT: In this paper, energy method and finite difference method are used to compute the instability behavior of multilayered fiber reinforced composite cylindrical shells under axial compression, hydrostatic pressure and torsion. The influences of initial imperfections, geometrical nonlinearities of shells and physical nonlinearities of the materials to the buckling and postbuckling behavior of the shells are considered. The effect of transverse shear is also discussed. The computational results of this paper are well agreed with the experimental data.

References listed at the end of the paper:

ABSTRACT: This paper proposes a theoretical method to analyze the buckling and postbuckling behavior of multi-layered fiber reinforced composite cylindrical shells under uniform axial or hydrostatic compression. The influences of shear nonlinearity of the composite material and the initial imperfection of the shell geometry are taken into account. For the computation of the critical form potential energy method is used. Numerical results are given for boron epoxy composite cylindrical shells with various fiber orientation and different layer
numbers. Results show that the shear nonlinearity of the composite materials and the initial imperfections of the shells are both important for the composite and postbuckling behavior of the composite cylindrical shells.

Yang Yang and William W. Liou (Department of Aeronautical and Mechanical Engineering, Western Michigan University, Kalamazoo, USA)
ABSTRACT: A reduced-order general continuum method is used to examine the mechanical behavior of single-walled carbon nanotubes (CNTs) under compressive loading and unloading conditions. Quasi-static solutions are sought where the total energy of the system is minimized with respect to the spatial degree of freedom. We provide detailed buckled configurations for four different types of CNTs and show that, among the cases studied, the armchair CNT has the strongest resistance to the compressive loading. It is also shown that the buckled CNT will significantly lose its structural strength with the zigzag lattice structure. The unloading post-buckling of CNT demonstrates that even after the occurrence of buckling the CNT can still return to its original state making its use desirable in fields such as synthetic biomaterials, electromagnetic devices, or polymer composites.

ABSTRACT: Thin-walled cylindrical shells are widely used in many industrial sectors as light structural elements. Determination of their buckling strength under various types of loading conditions is a crucial work for engineering design. Due to the needs of research of crashworthiness, dynamic buckling of cylindrical shells subjected to the strong axial impact becomes a frontier issue in recent years. The axial impact is a very complex dynamic process because of the coupling of multiple effects. In this paper, the buckling mechanism of cylindrical shells subjected to axial impact and the influences of boundary conditions, and energy absorption properties have been investigated by experiments.

ABSTRACT: The dynamic buckling of circular cylindrical shells subjected to axial impact by a rigid body is discussed in this paper in accordance with the energy law. Accounting for the propagation of stress wave, the power series solution of this problem has been obtained by the power series approach. The critical buckling criterion of this problem is proposed by analyzing the characteristics of solution. The relationship between critical velocity and impacting mass, as well as other conclusions, are obtained by using theoretical analysis and numerical computation.

Dino A. Oliveira (1), Michael J. Worswick (1), Rassin Grantab (1), Bruce W. Williams (1) and Robert Mayer

ABSTRACT: This research examines the effect of the tube-bending process on subsequent crashworthiness of aluminum alloy s-rail structures. Through experiments, the effects of bending process parameters, tube initial thickness, thickness changes, work hardening and bend radius on the energy absorption characteristics of s-rail impact structures are assessed. Finite element simulations of the manufacturing and impact testing of s-rail structures are developed to provide additional insight. The deformation history, including strains, thickness changes and residual stresses are transferred from the tube-bending models into the crash models. Through simulation, effects of thickness changes and work hardening on the energy absorption of s-rails are examined. The change in geometrical features of the s-rail due to a different bend radius, on crashworthiness of the s-rail structure was found to play a significant role in offsetting any potential increases in force and energy absorption due to work hardening and thickness changes in the material due to pre-bending. By not accounting for work hardening and thickness changes in the material due to the bending process during the modeling of the crash event, the predicted peak force as well as the energy absorption at the point of tearing was reduced by 25–30% and 18%, respectively.

Ashokanand Chathbai (Wichita State University, College of Engineering, Department of Mechanical Engineering, Wichita, Kansas, USA), “Parametric study of energy absorption characteristics of a rectangular aluminum tube wrapped with e-glass/epoxy”, Master’s Thesis, May 2007, URI: http://hdl.handle.net/10057/1119

ABSTRACT: Analysis of crashworthy structures has been a primary area of interest for many researchers for quite a few years now. The quest for a better energy absorbing structure or a better crashworthy structure has led researchers to carry out various analysis procedures experimentally and also by simulating the characteristics. E-glass fiber reinforced epoxy wrapped over aluminum tube has proven to possess better energy absorbing capabilities. This study attempts to analyze certain characteristics of such hybrid structures. This thesis examines the properties with respect to energy absorption of the abovementioned tubes when certain parameters such as ply orientation, angle of impact, speed of impact for different aspect ratios, are varied. The axial crushing behavior and the energy absorption capability of aluminum composite hybrid tube under quasi-static loading is studied using LS-Dyna finite element solver. A aluminum tube, externally wrapped with E-glass epoxy composite material with two layers and ply orientation of +/- 30deg., +/- 45deg. and 0/90deg., are used for finite element analysis. The speeds considered are 8mph, 15mph and 30mph. The angles of impact considered are 0deg., 15deg., and 30deg. The analysis is carried out for various permutations and combinations of the above mentioned Parameters, and the results obtained are studied and aims at optimum set of parameters for making the energy absorption of such hybrid structures.

References listed at the end of the thesis:
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ABSTRACT: Using a generalized quasi-continuum method, we characterize the post-buckling morphologies and energetics of thick multi-walled carbon nanotubes (MWCNTs) under uniaxial compression. Our simulations identify for the first time evolving post-buckling morphologies, ranging from asymmetric periodic rippling to a helical diamond pattern. We attribute the evolving morphologies to the coordinated buckling of the constituent shells. The post-buckling morphologies result in significantly reduced effective moduli that are strongly dependent on the aspect ratio. Our simulation results provide fundamental principles to guide the future design of high-performance, MWCNT-based nanodevices.


ABSTRACT: This paper presents the second of a series of solutions to the buckling of imperfect cylindrical shells subjected to an axial compressive load. In particular, the current problem reviewed is the case of a homogeneous cylindrical shell with random axisymmetric imperfections. The problem solution for the determination of the critical buckling load utilizes a statistical approach to define the random imperfections as opposed to the deterministic methods most often employed in the pressure vessel industry. The imperfections are treated as a random function of the axial (i.e., longitudinal) position on the shell. The Monte Carlo technique is utilized to create a large sample of random shell geometries from which to eventually calculate a critical buckling load for each randomly generated shell geometry. Having matched or predefined the statistical parameters (including the co-variance) of interest as determined from actual manufacturing statistics to the Monte Carlo simulation of shell geometries, the reliability of the critical buckling load is then calculated for the set of cylindrical shells with the random axisymmetric imperfections. The ASME Boiler and Pressure Vessel Code Section VIII fabrication tolerances as supplemented by ASME Code Case 2286-1 are reviewed and addressed in light of the findings of the current study and resulting solutions with respect to the critical buckling loads. The method and results described herein are in stark contrast to the “knockdown factor” approach currently utilized in ASME Code Case 2286-1. Recommendations for further study of the imperfect cylindrical shell are also outlined in an effort to improve on the current design rules regarding column buckling of large diameter shells designed in accordance with ASME Section VIII, Divisions 1 and 2 and ASME STS-1 in combination with the suggestions contained within Code Case 2286-1.

Gurinder Singh Brar (1), Yogeshwar Hari (1) and Dennis K. Williams (2)
**ABSTRACT:** This paper presents the third of a series of solutions to the buckling of imperfect cylindrical shells subjected to an axial compressive load. In particular, the initial problem reviewed is the case of a homogeneous cylindrical shell of variable thickness that is of an axisymmetric nature. The equilibrium equations as first introduced by Donnell over seventy years ago are discussed and reviewed in establishing a basis for embarking upon a solution that utilizes finite difference methods to solve the resulting equilibrium and compatibility equations. The ultimate objective of these calculations is to achieve a quantitative assessment of the critical buckling load considering the small axisymmetric deviations from the nominal cylindrical shell wall thickness. Clearly in practice, large diameter, thin wall shells of revolution that form stacks are never fabricated with constant diameters and thicknesses over the entire length of the assembly. The method and results described herein are in stark contrast to the “knockdown factor” approach currently utilized in ASME Code Case 2286-1. The results obtained by finite difference method agree well with those published by Elishakoff and Williams for the prediction of buckling load.

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**ABSTRACT:** This paper presents the comparison of reliability technique that employ Fourier series representations of random axisymmetric imperfections in axially compressed cylindrical shells with evaluations prescribed by ASME Section VIII, Division 2. The ultimate goal of the reliability type technique is to predict the buckling load associated with the axially compressed cylindrical shell. The representation of initial geometrical imperfections in the cylindrical shell requires the determination of appropriate Fourier coefficients. The buckling of cylindrical shells in any type of loading is sensitive to the form and amplitude of geometric imperfections present in the structure. Initial geometric imperfections have significant effect on the load carrying capacity of axisymmetrical cylindrical shells. Many deterministic and probabilistic techniques are there to predict shell behavior during buckling. Fourier decomposition is used to interpret imperfections as structural features can be easily related to the different components of imperfections. The mean vector and the variance-covariance matrix of Fourier coefficients are calculated from the simulated shell profiles. Recommendations for further use of Fourier coefficients through simulation by Monte Carlo Method are laid down. Large number of shells thus created can be used to calculate buckling stress for each shell. The probability of the ultimate buckling stress exceeding a predefined threshold stress can be calculated.

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“Fourier Series Analysis of Cylindrical Pressure Vessel Subjected to External Pressure”, ASME 2009 Pressure
ABSTRACT: This paper presents the comparison of a reliability technique that employs a Fourier series representation of random asymmetric imperfections in a cylindrical pressure vessel subjected to external pressure. Comparison with evaluations prescribed by the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 Rules for the same shell geometries are also conducted. The ultimate goal of the reliability type technique is to predict the critical buckling load associated with the chosen cylindrical pressure vessel. Initial geometric imperfections are shown to have a significant effect on the load carrying capacity of the example cylindrical pressure vessel. Fourier decomposition is employed to interpret imperfections as structural features that can be easily related to various other types of defined imperfections. The initial functional description of the imperfections consists of an axisymmetric portion and a deviant portion, which are availed in the form of a double Fourier series. Fifty simulated shells generated by the Monte Carlo technique are employed in the final prediction of the critical buckling load. The representation of initial geometrical imperfections in the cylindrical pressure vessel requires the determination of appropriate Fourier coefficients. Multi-mode analyses are expanded to evaluate a large number of potential buckling modes for both predefined geometries and associated asymmetric imperfections as a function of position within a given cylindrical shell. The probability of the ultimate buckling stress that may exceed a predefined threshold stress is also calculated. The method and results described herein are in stark contrast to the “knockdown factor” approach as applied to compressive stress evaluations currently utilized in industry. Recommendations for further study of imperfect cylindrical pressure vessels are also outlined in an effort to improve on the current design rules regarding column buckling of large diameter pressure vessels designed in accordance with ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 and ASME STS-1.

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ABSTRACT: This paper presents the first of a series of solutions to the buckling of imperfect cylindrical shells subjected to an axial compressive load. The initial problem is the case of a homogeneous cylindrical shell of variable thickness that is of an axisymmetric nature. The equilibrium equations as first introduced by Donnell over 70 years ago are thoroughly presented as basis for a solution employing perturbation methods. The ultimate objective of these calculations is to achieve a quantitative assessment of the critical buckling load considering the small axisymmetric deviations from the nominal shell wall thickness. Clearly in practice, large diameter thin wall shells of revolution that form stacks (as found in flue gas desulphurization absorber assemblies) are never fabricated with constant diameters and thicknesses over the entire length of the assembly. As such, ASME Boiler and Pressure Vessel Code Section VIII shell thickness tolerances as supplemented by ASME Code Case 2286-1 are reviewed and addressed in comparison to the resulting solutions with respect to the critical buckling loads. The method and results described herein are in stark contrast to the “knockdown factor” approach currently utilized in ASME Code Case 2286-1. Recommendations for further study of the imperfect cylindrical shell are also outlined in an effort to improve on the current rules regarding column buckling of large diameter shells designed in accordance with ASME Section VIII, Divisions 1 and 2 and ASME STS-1 in combination with the suggestions contained within Code Case 2286-1.
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“Optimum design of cylindrical shell under buckling pressure”, Journal of Lanzhou University, 2003-01,
doi: CNKI:SUN:LDZK.0.2003-01-005
ABSTRACT: The mechanism of bifurcation instability of shells is the instant course for shell-structure design. On the basis of energy criterion, the buckling lateral pressures of cylindrical shell with variable thickness and arbitrary axisymmetrical boundary conditions have been derived. The optimum model involves the maximum buckling pressure of the cylindrical shell subjected to constraints of the volume that is constant and to strength condition. Numerical results show the effectiveness of the method reported.

ABSTRACT: This paper investigates the combined torsional buckling of multi-walled carbon nanotubes (MWNTs) coupling with radial pressures. The analysis is based on the continuum mechanics model, and the effect of the van der Waals interaction between adjacent tubes is taken into account. A buckling condition is derived for determining the critical shear membrane force under combined torsional buckling, which clearly indicates the role of radial pressures. The critical shear membrane force and the buckling mode are worked out for three typical MWNTs subjected to various internal pressure or external pressure. It is shown that the effect of internal pressure or external pressure on the critical shear membrane force for combined torsional buckling of MWNTs is related to the types of MWNTs. This effect is strong for thin MWNTs, moderate for thick MWNTs and small for solid MWNTs. Numerical results also indicate that the buckling mode corresponding to the critical shear membrane force of MWNTs is unique and only dependent on the structure of MWNTs. In particular, for combined torsional buckling of MWNTs with very small internal pressure or external pressure, the buckling mode is just that for the corresponding pure torsional buckling.

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ABSTRACT: This paper reports the results of an investigation on combined torsional buckling of multi-walled carbon nanotubes (MWNTs) under combined torque, axial loading and radial pressures based on the continuum mechanics model, which takes into account the effect of the van der Waals interaction between adjacent tubes. A buckling condition is derived for determining the critical buckling torque and associated buckling mode. In particular, for combined torsional buckling of double-walled carbon nanotubes, an explicit expression is
obtained and some detailed results are demonstrated. According to the innermost radius-to-thickness ratio, MWNTs are classified into three types: thin, thick, and (almost) solid. Numerical results are worked out for the critical buckling torque and associated buckling mode for all the three types of MWNTs subjected to various axial stresses (axial tensile stresses or axial compressive stresses), internal pressures, and external pressures. It is shown that, the axial tensile stress or the internal pressure will make the MWNTs resist higher critical buckling torque, while the axial compressive stress or external pressure will lead to a lower critical buckling torque. The effect of axial stress (axial tensile stress or axial compressive stress) on the critical buckling torque of MWNTs is very small for all the three types of MWNTs, while the effect of the internal pressure or external pressure is related to the types of MWNTs, which is strong for the thin MWNTs, moderate for the thick MWNTs, and small for the solid MWNTs. Numerical results also indicate that, the associated buckling mode is unique and dependent on the structure of MWNTs. Especially, for combined torsional buckling of MWNTs with very small axial stress and radial pressures, the buckling mode is just the one for the corresponding pure torsional buckling.

ABSTRACT: This paper investigates the torsional buckling of multi-walled carbon nanotubes under combined axial and radial loadings based on the continuum mechanics model. In particular, an explicit expression is obtained for the torsional buckling of double-walled carbon nanotubes (DWNTs) under combined loadings. Numerical results show that axial tensile stress or internal pressure will make DWNTs resist higher critical shear membrane force, while axial compressive stress or external pressure will lead to a lower critical shear membrane force. Further, for torsional buckling of DWNTs coupling with small axial stress and internal pressure or external pressure, the effect of the axial stress, internal pressure or external pressure on the critical shear membrane force is linear, and the associated buckling wave numbers are unique and the same as that under corresponding pure torque.

Chao Guozhong Zhao Huilin (Department of Civil Engineering, Southeast University, China?), “The theoretical and experimental studies of elastic buckling of single layer sphere grids shell”, Journal of Southeast University (Natural Science Edition), 1988-01, doi: cnki:ISSN:1001-0505.0.1988-01-004, ABSTRACT: This paper presents the theoretical and model experimental studies of elastic buckling of single layer sphere grids shell. A finite element method program of elastic buckling of the structure was finished with consideration of large displacement behaviour. The analysis of the model structure was made by use of the program. The analysis results show that the analysis theory is reliable and the program is resultful. This paper has discussed this analysis theory and showed the further research direction.

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ABSTRACT: A linear analysis method is offered to predict the theoretical elastoplastic buckling of stringer
stiffened cylindrical shells subjected to longitudinal loading. Welding residual stresses are taken into account in the calculation, but effects of geometrical imperfections and pre-buckling displacements are ignored. The examples analysed show a good correlation between the analytical results and those obtained experimentally with stocky models of moderate geometrical imperfections.

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ABSTRACT: Based on fundamental assumptions, an analysis of the constitutive relations between the internal forces and deformations of discrete rectangular reticulated structures is given. On the basis of this, an equivalent continuum model is adopted and the application of the principle of virtual work leads to non-linear governing equations and corresponding boundary conditions.

ABSTRACT: This paper deals with non-linear vibration of rectangular reticulated shallow shells by applying non-linear elastic theory of such structures established by the author. Using the assumed (generalized) Fourier series solutions for transverse deflection (lattice joint transverse displacement) and force function, weighted means of the trial functions lead to the relations among the coefficients related to the solutions and vibration equation which determines the unknown time function, and then the amplitude-frequency relations for free vibration and forced vibration due to harmonic force are derived with the aid of the regular perturbation method and Galerkin procedure, respectively. Numerical examples are given as well.

ABSTRACT: An asymptotic solution is formulated for non-linear buckling of elastically restrained imperfect shallow spherical shells continuously supported on a non-linear elastic foundation. The asymptotic iteration method is introduced to result in a cubic non-linear analytical relation between the external load and central transverse displacement (deflection) of the structures incorporating the effects of geometrical imperfection, edge-restraint coefficients, moduli of foundation and characteristic geometrical parameter. The resulting expression can be used easily to evaluate the effects of these factors on buckling behaviors. Numerical examples are given, and comparisons of the available results show validity of the method suggested in the present work.

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ABSTRACT: Non-linear buckling behaviors of single-layer squarely-reticulated shallow spherical shells with geometrical imperfections and continuously supported on springs have been studied in this paper. The shell structure is subjected to uniform vertical load and the imperfection has been assumed to have the same mode as that of transverse displacement of the shell, but the specific form of mode has not been presumed. Using the asymptotic iteration method, an analytical solution is obtained on the basis of a theoretical model proposed by the author. The resulting nondimensional expression between the external load and central transverse displacement (deflection) can be conveniently adopted to analyze non-linear behaviors of the structures and evaluate the effects of various parameters (e.g., stiffness of spring, imperfect factor and boundary conditions, etc.) on buckling behaviors. Numerical examples are given and compared with available results. Effects of several factors are also demonstrated.

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ABSTRACT: The paper describes a combined analytical, numerical and experimental analysis on the compressive strength of hexagonal chiral honeycombs due to elastic buckling of the unit cells under flatwise compressive loading. Hexagonal chiral honeycombs are cellular structures composed noncentresymmetric unit cells, with an in-plane negative Poisson _s ratio (NPR) with a value of "_1. Cylinders connected by tangent ligaments at 60∞ degrees compose the unit cells. Approximated analytical models are proposed for the purpose of initial design assuming the main contribution to the elastic collapse stress being given by the nodes, and considering also the superposition of the critical elastic loads of each component of the unit cell. The models are expressed in terms of nondimensional geometric unit cell parameters (ligament to cylinder radius aspect ratio and relative density), and core material properties. Finite element calculations using shell and brick elements are also performed on unit cell models with periodic boundary conditions using linear bifurcation buckling analysis. The analytical and numerical results are compared with the outcome of a series of experimental flatwise compressive tests carried out on chiral honeycomb samples manufactured using rapid prototyping technique in PA sintered powder and ABS plastics. The comparison shows good convergence between the sets of results, and highlights the specific deformation mechanisms of the hexagonal chiral honeycomb cell.


ABSTRACT: The torsion of carbon nanotubes is studied by molecular dynamics simulations. The torsional behavior of a chiral single-walled carbon nanotube (SWCNT) is dependent on the loading directions due to its structural asymmetry. The critical buckling shear strain of a SWCNT in one direction may be 1.8 times higher than that in the opposite direction. This means that one can choose the most appropriate SWCNT for his special purpose in designing a torsional component (e.g., oscillators and springs) of nanomechanical devices using carbon nanotubes. Meanwhile, the finding indicates that a simple thin shell model is not suitable for predicting
torsional behavior of small SWCNTs at large strains.

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ABSTRACT: The impact behaviour of tubular hydroformed axial crush tubes is examined. The results of dynamic axial crush tests performed with both non-hydroformed and hydroformed AA5754 aluminum alloy tubes were compared to predictions from finite element models. Explicit dynamic finite element simulations of the hydroforming and crash events were carried out with particular attention to the transfer of forming history from the hydroforming simulations to the crash models. The values of tube thickness, work hardening, and residual stresses at the end of the hydroforming simulations were used as the initial state for the crash models. In general, simulations performed using the von Mises yield criterion with isotropic material behaviour gave reasonable predictions when compared to experimental data. It was found that it was important to account for the forming history of the hydroforming operation in the axial crush models. The results showed that work hardening resulting from hydroforming is beneficial to increasing the energy absorption during crash, whereas thickness reduction decreased the energy absorption. Residual stresses had little effect on the energy absorption characteristics. It was also shown that the energy absorption characteristics of tubes with the same mass could vary greatly by adjusting the geometry of the tube and the amount of work hardening experienced by the tube during hydroforming.


ABSTRACT: The mechanism of atherosclerotic plaque rupture is not fully understood. Mechanical stress may be one of the factors contributing to the instability of the fibrous plaque cap. The existence of a severe stenosis may lower the transmural pressure enough to cause the collapse of arteries leading to high concentrated compressive and tensile stresses. This study presents quantitative estimates of the stresses and deformations in the collapsed thick-walled artery. The results of large deformation finite element calculations identify the locations of the high stress concentrations and their magnitudes which cannot be precisely predicted under a thin-wall assumption. The maximum compressive stress calculated reached 80% of the Young's modulus for fairly small negative transmural pressures. Results are useful to predict likely locations of the plaque cap rupture due to compressive stresses. The tube law of area as a function of transmural pressure showed a large discrepancy from a thin-wall calculation. The buckling pressure calculated for the outer-to-inner wall surface radius ratio of 1.60 was nearly 30% lower than that of the elastic thin-wall buckling theory. An increase in eccentricity further reduced this buckling pressure. The results indicate that a thick plaque which is eccentric increases the likelihood of collapse of stenotic arteries.

Riaz, M., Fulati, A., Amin, G., Alvi, N. H., Nur, O., Willander, M. (Department of Science and Technology,
ABSTRACT: Buckling and elastic stability study of vertical well aligned ZnO nanorods grown on Si substrate and ZnO nanotubes etched from the same nanorods was done quantitatively by nanoindentation technique. The critical load, modulus of elasticity, and flexibility of the ZnO nanorods and nanotubes were observed and we compared these properties for the two nanostructures. It was observed that critical load of nanorods (2890 microN) was approximately five times larger than the critical load of the nanotubes (687 microN). It was also observed that ZnO nanotubes were approximately five times more flexible (0.32 nm/microN) than the nanorods (0.064 nm/microN). We also calculated the buckling energies of the ZnO nanotubes and nanorods from the force displacement curves. The ratio of the buckling energies was also close to unity due to the increase/decrease of five times for one parameter (critical load) and increase/decrease of five times for the other parameter (displacement) of the two samples. We calculated critical load, critical stress, strain, and Young modulus of elasticity of single ZnO nanorod and nanotube. The high flexibility of the nanotubes and high elasticity of the ZnO nanorods can be used to enhance the efficiency of piezoelectric nanodevices. We used the Euler buckling model and shell cylindrical model for the analysis of the mechanical properties of ZnO nanotubes and nanorods.

Todd O. Williams and Frank L. Addessio (Los Alamos National Laboratory, Theoretical Division, Fluid Dynamics T-3, MSB216, Los Alamos, NM 87545, U.S.A.), “A general theory for laminated plates with delaminations”, International Journal of Solids and Structures, Vol. 34, No. 16, June 1997, pp. 2003-2024, ABSTRACT: An approximate analytical model for the behavior of a laminated composite plate in the presence of delaminations and other local effects is presented. The model is based on a generalized displacement formulation implemented at the layer level. The governing equations for a layer are obtained using the principle of virtual work. These governing equations for a layer are used in conjunction with the explicit satisfaction of both the interfacial traction continuity and the interfacial displacement jump conditions between layers to develop the governing equations for a laminated composite plate, including delaminations. The fundamental unknowns in the theory are the displacements in the layers and the interfacial tractions. The theory is sufficiently general that any constitutive model for the interfacial fracture (i.e. delamination) as well as for the layer behavior can be incorporated in a consistent fashion into the theory. The interfacial displacement jumps are expressed in an internally consistent fashion in terms of the fundamental unknown interfacial tractions. The current theory imposes no restrictions on the size, location, distribution, or direction of growth of the delaminations. Therefore, the theory can predict the initiation and growth of delaminations at any location as well as interactive effects between delaminations at different locations within the laminate. Pagano's exact solution for the cylindrical bending of a laminated plate has been modified to include the effects of delamination. An interface model, which expressed the displacement jump as a linear function of the surface tractions, was implemented into this modification of the exact solution. This extension was used to validate the approximate plate theory. The correlation between the approximate approach and the exact solution is seen to be excellent. The approximate plate theory is seen to give very accurate predictions for the interfacial tractions in a direct and consistent fashion, i.e. without the need to use integration of the pointwise equilibrium equations. This allows the interfacial displacement jumps in the presence of delaminations to be modeled accurately. It is seen that these displacement jumps have a significant effect on both the macroscopic and microscopic behavior of a laminated plate.
ABSTRACT: A generalized theory for laminated plates, including delamination, is developed. The laminate model is based on a generalized displacement formulation implemented at the layer level. The equations of motion for a layer, which are explicitly coupled with both the interfacial traction continuity and the interfacial displacement jump conditions between layers, are used to develop the governing equations for a laminated composite plate. The delamination behavior can be modeled using any general constitutive fracture law. The interfacial displacement jumps are expressed in an internally consistent fashion in terms of the fundamental unknown interfacial tractions. The current theory imposes no restrictions on the size, location, distribution, or direction of growth of the delaminations. Therefore, the theory can predict the initiation and growth of delaminations at any location as well as interactive effects between delaminations at different locations within the laminate. The proposed theory is used to consider the dynamic response of laminated plates in cylindrical bending. First it is shown that the dynamic implementation agrees well with the exact predictions of a plate under static loading conditions. Static, cylindrical bending is considered to validate the numerical implementation. Next, different dynamic loading cases are considered. First, the required level of discretization through the thickness of the laminate necessary to accurately capture the wave propagation characteristics for monotonic tensile loading transverse to the plate is determined. Next, the influence of the delamination on the free vibration behavior of a plate is considered. It is shown that the presence of delaminations can result in significant deviations from the perfectly bonded free vibration behavior. Finally, the plate is subjected to dynamic loading conditions that demonstrate the influence of internal wave interactions on the overall behavior of the plate.

ABSTRACT: A new type of plate theory for the nonlinear analysis of laminated plates in the presence of delaminations and other history-dependent effects is presented. The formulation is based on a generalized two length scale displacement field obtained from a superposition of global and local displacement effects. The functional forms of global and local displacement fields are arbitrary. The theoretical framework introduces a unique coupling between the length scales and represents a novel two length scale or local-global approach to plate analysis. Appropriate specialization of the displacement field can be used to reduce the theory to any currently available, variationally derived, displacement based (discrete layer, smeared, or zig-zag) plate theory. The theory incorporates delamination and/or nonlinear elastic or inelastic interfacial behavior in a unified fashion through the use of interfacial constitutive (cohesive) relations. Arbitrary interfacial constitutive relations can be incorporated into the theory without the need for reformulation of the governing equations. The theory is sufficiently general that any material constitutive model can be implemented within the theoretical framework. The theory accounts for geometric nonlinearities to allow for the analysis of buckling behavior. The theory represents a comprehensive framework for developing any order and type of displacement based plate theory in the presence of delamination, buckling, and/or nonlinear material behavior as well as the interactions between these effects. The linear form of the theory is validated by comparison with exact solutions for the behavior of perfectly bonded and delaminated laminates in cylindrical bending. The theory shows excellent correlation with the exact solutions for both the inplane and out-of-plane effects and the displacement jumps due to delamination. The theory can accurately predict the through-the-thickness distributions of the transverse stresses.


without the need to integrate the pointwise equilibrium equations. The use of a low order of the general theory, i.e. use of both global and local displacement fields, reduces the computational expense compared to a purely discrete layer approach to the analysis of laminated plates without loss of accuracy. The increased efficiency, compared to a solely discrete layer theory, is due to the coupling introduced in the theory between the global and local displacement fields.

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ABSTRACT: The bifurcation buckling problem of laminated composite plates is formulated within the framework of a multilength scale plate theory. This theory is a combination of single-layer and layer-wise theories. It is generated by representing the displacement as the sum of global and local effects that introduce a coupling between the two length scales. Comparisons between the presently predicted buckling loads of homogeneous and orthotropic laminated plates and the exact solutions show a very good correlation. Furthermore, the theory accurately predicts the buckling load of symmetric cross-ply plates as compared with the results of a layer-wise approach. This accuracy is achieved with reduced computation expense. The global–local plate theory is general enough to incorporate delamination effects. As a result of the inclusion of these effects, the buckling loads of plates with imperfect interlaminar bonding are predicted.

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INTRODUCTION: The present paper summarizes a series of recent investigations that were conducted by the authors which address the analysis of bifurcation buckling, parametric stability, dynamic buckling and thermally induced dynamic buckling of composite plates and shells. Various types of material behavior are assumed including linearly elastic, nonlinearly elastic and thermo-inelastic.

References listed at the end of the paper:

ABSTRACT: A new type of general, theoretical framework for the development of comprehensive, nonlinear, multiscale plate theories for laminated structures is presented. The theoretical framework utilizes a generalized two scale description of the displacement field based on a superposition of global and local effects where the functional forms for the global and local displacement fields are arbitrary. The two scale nature of theory allows it to explicitly consider the layered nature of the structure. The subsequent development of the governing equations for the theory is carried out using the general nonlinear equations of continuum mechanics referenced to the initial configuration. The equations of motion and the lateral surface boundary conditions for the theory...
are derived using the method of moments over the different scales subject to an orthogonality constraint. The theory satisfies the interfacial constraints and the top and bottom surface boundary conditions in a strong sense. Delamination effects are incorporated into the theory through the use of cohesive zone models (CZMs). Arbitary CZMs can be incorporated into the theory without the need for reformulation of the governing equations. The theory is formulated in a sufficiently general fashion that any type of history-dependent material can be used to describe the inelastic response of the materials composing the layers. Furthermore, as a result of the multiscale nature of the theory it can be specialized to single scale theories of the equivalent single layer (ESL) or discrete layer (DL) types in a unified fashion and without the need for any reformulation. While the starting point for the proposed theory is the same as used by Williams [Williams, T.O., 1999. A generalized multilength scale nonlinear composite plate theory with delamination. Int. J. Solid Struct. 36, (20) 3015–3050; Williams, T.O., 2001. Efficiency and accuracy considerations in a unified plate theory with delaminations. Comp. Struct. 52, (1) 27–40; Williams, T.O., 2005. A generalized, multilength scale framework for thermo-diffusionally-mechanically coupled, nonlinear, laminated plate theories with delaminations. IJSS 42, (5–6) 1465–1490] the subsequent formulation is significantly different. The differences in the two theories allow the currently proposed theory to improve on the capabilities of the previous theory; particularly in the satisfaction of the traction continuity constraints at the interfaces. It is shown that the theory is capable of providing accurate predictions for all of the fields in perfectly bonded and delaminated plates even for relatively low orders of displacement approximations. In particular, the theory is shown to provide accurate predictions for the transverse stresses that are continuous across the interfaces directly from the constitutive relations.

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ABSTRACT: The initial imperfections criteria is used in the nonlinear finite element analysis, and the initial minute imperfect method is put forward to research the disturbance strategy of nonlinear bifurcation buckling. The basic thought, the step and the merits, and demerits of the method are analyzed. The method is used to research the behaviors of a truss dome, a Williams toggle frame and a K6 single-layer latticed dome. The model of the Williams toggle frame is experimented. Results indicate that the initial minute imperfect method is feasible and right. And it is disclosed that the reason of nonlinear bifurcation buckling is the initial minute imperfects of the actual structures.

Daniel King, “Collapse dynamics of ultrasound contrast agent microbubbles”, Ph.D dissertation, Mechanical Engineering, University of Illinois at Urbana-Champaign, February 2013

ABSTRACT: Ultrasound contrast agents (UCAs) are micron-sized gas bubbles encapsulated with thin shells on the order of nanometers thick. The damping effects of these viscoelastic coatings are widely known to significantly alter the bubble dynamics for linear and low-amplitude behavior; however, their effects on strongly nonlinear and destruction responses are much less studied. This dissertation examines the behaviors of single collapsing shelled microbubbles using experimental and theoretical methods. The study of their dynamics is particularly relevant for emerging experimental uses of UCAs which seek to leverage localized mechanical forces to create or avoid specialized biomedical effects. The central component in this work is the study of postexcitation rebound and collapse, observed acoustically to identify shell rupture and transient inertial
cavitation of single UCA microbubbles. This time-domain analysis of the acoustic response provides a unique method for characterization of UCA destruction dynamics. The research contains a systematic documentation of single bubble postexcitation collapse through experimental measurement with the double passive cavitation detection (PCD) system at frequencies ranging from 0.9 to 7.1 MHz and peak rarefactional pressure amplitudes (PRPA) ranging from 230 kPa to 6.37 MPa. The double PCD setup is shown to improve the quality of collected data over previous setups by allowing symmetric responses from a localized confocal region to be identified. Postexcitation signal percentages are shown to generally follow trends consistent with other similar cavitation metrics such as inertial cavitation, with greater destruction observed at both increased PRPA and lower frequency over the tested ranges. Two different types of commercially available UCAs are characterized and found to have very different collapse thresholds; lipid-shelled Definity exhibits greater postexcitation at lower PRPAs than albumin-shelled Optison. Furthermore, by altering the size distributions of these UCAs, it is shown that the shell material has a large influence on the occurrence of postexcitation rebound at all tested frequencies while moderate alteration of the size distribution may only play a significant role within certain frequency ranges. Finally, the conditions which generate the experimental postexcitation signal are examined theoretically using several forms of single bubble models. Evidence is provided for the usefulness of modeling this large amplitude UCA behavior with a size-varying surface tension as described in the Marmottant model; better agreement for lipid-shelled Definity UCAs is obtained by considering the dynamic response with a rupturing shell rather than either a non-rupturing or nonexistent shell. Moreover, the modeling indicates that maximum radial expansion from the initial UCA size is a suitable metric to predict postexcitation collapse, and that both shell rupture and inertial cavitation are necessary conditions to generate this behavior. Postexcitation analysis is found to be a beneficial characterization metric for studying the destruction behaviors of single UCAs when measured with the double PCD setup. This work provides quantitative documentation of UCA collapse, exploration into UCA material properties which affect this collapse, and comparison of existing single bubble models with experimentally measured postexcitation signals.


ABSTRACT: This dissertation reports the results of an analytical, numerical and experimental investigation dealing with hot-rolled I-section steel members acted by a combination of major-axis bending and axial tension (“beams subjected to tension”), which is relatively rare in practice and, therefore, has received little attention from researchers in the past. In particular, there are no guidelines for the design against buckling ultimate limit states of such members (only their cross-section resistance is checked). This means that the axial tension favourable effect on lateral-torsional buckling/failure is neglected, thus leading to over-conservative designs – indeed, a beam subjected to axial tension is currently designed against lateral-torsional failure as a “pure beam”.

In order to acquire scientific knowledge and provide design guidance on this topic, the lateral-torsional stability, failure and design of hot-rolled steel I-beams with fork-type end supports and acted by simple transverse loadings (mostly applied end moments) and various axial tension values are addressed in this work. After developing and validating an analytical expression to calculate critical buckling moments of beams under uniform bending and axial tension, numerical (beam finite element) buckling results are presented for the non-uniform bending cases. Then, two full-scale tests involving a narrow and a wide flange beams under eccentric tension are described and their results are used to develop shell and beam finite element models – the latter are subsequently employed to perform a parametric study aimed at gathering a fairly extensive ultimate strength/moment data bank. Finally, this data bank is used to assess the merits of a design approach proposed in this work for beams subjected to tension and collapsing in lateral-torsional modes – this design approach, which consists of slightly modifying the current procedure prescribed in Eurocode 3 to design beams against lateral-
torsional failure, is shown to provide ultimate moment estimates that correlate very well with the values obtained from the numerical simulations. The predictions of the proposed design approach are also compared with those of the design procedure included in the ENV version of Eurocode 3 (but later removed).

References listed at the end of the dissertation:
Vlasov VZ (1961), Thin-walled Elastic Beams, English translation by the National Science Foundation and Department of Commerce, Washington D.C.


ABSTRACT: This thesis investigates the behavior of small diameter composite tubes that are exposed to external pressure. Composite tubes have a superior strength to weight ratio compared to steel tubes. The oil industry is facing new challenges and the demand for more robust materials is increasing. Prior to substituting steel material with composites in tubes, it is important to gain knowledge about the behavior of composite tubes and develop reliable analytical methods.

An experimental and analytical study of small diameter carbon fiber tubes was carried out in this thesis. The tubes were made using filament winding with a layup of [+75] and a wall thickness of 1.5 mm. The tubes were tested under external pressure with optical fibers attached to measure the strain during the tests. A linear buckling analysis and Riks analysis was done using the Abaqus solver to predict buckling and compare strain results to the experimental tests. The transverse and longitudinal Young’s modulus were experimentally found and implemented into the finite element analysis.

The predicted buckling value deviated significantly from the experimental tests. In the experimental tests, the tubes buckled at 52.5% lower pressure than what was expected from the finite element analysis. The strain readings from the optical fibers gave higher values than the strains from the finite element analysis at equal
pressures. However, strain at equal pressure might not be comparable because the tube from the analysis could withstand higher pressure before it started showing tendencies of buckling.

In conclusion, the analytical model in this thesis has its weaknesses and can be further improved to capture the imperfections of the tube more accurately.


ABSTRACT: The finite element method has been employed to study the effects of different boundary conditions on the axial buckling of multiwall carbon nanotubes (MWCNTs). Unlike previous works, both homogeneous and heterogeneous end constraints are considered for the constituent tubes of various MWCNTs comprising shell-type (i.e., the length-to-diameter ratio L/D'<10), beam-type (i.e., L/D'>10), and the two different types of constituent tubes. The results show that clamping the individual tubes of simply supported or free MWCNTs exerts a variety of influences on their buckling behaviors depending on the type of the MWCNTs, the position, and the number of the clamped tubes. Clamping the outermost tube can enhance the critical buckling strain up to four times of its original value and can shift the buckling modes of those MWCNTs consisting both shell- and beam-type tubes. In contrast, little difference can be observed when simply supported ends of MWCNTs are replaced by free ends or vice versa. Explicit buckling mode shapes obtained using the finite element method for various physically realistic cases have been shown in the paper.

M. Elgaaly (Civil and Architectural Engineering Department, Drexel University, 32nd and Chestnut Streets, Philadelphia, PA, USA), “Post-buckling behavior of thin steel plates using computational models”, Advances in Engineering Software, Vol. 31, Nos. 8-9, August 2000, pp. 511-517, doi:10.1016/S0965-9978(00)00037-5

ABSTRACT: Thin plates loaded in plane will buckle at very small loads, and due to unavoidable out-of-plane imperfections, the theoretical buckling load cannot be observed experimentally. If the plate is adequately supported along its boundaries, it will be able to carry a much higher load than the theoretical buckling load. Computational models can be used to study the post buckling behaviour of thin plate structures up to failure. Failure of such structures is usually due to large out-of-plane deflections, yielding, and rupture. Therefore, the computational model should include the effects of geometric and material nonlinearities. In this paper, the nonlinear finite element analysis program NONSAP and ANSR-III were modified and used in the analysis. Since these programs did not include the suitable elements and material properties to conduct the subject study, new elements and new material properties were added to the programs. In particular, a thin shell element was added and the solution routines were modified to improve its accuracy and efficiency. The modified programs were used on a Super Computer to calculate the post buckling strength of stiffened and un stiffened plates subjected to uniaxial compression, and plates subjected to in plane bending or shear. Crippling of plates subjected to in-plane or eccentric edge compressive loads was also examined. The results from the computational models were compared with test results and reasonable agreements were obtained. A computational model was developed for a multi-story thin steel plate shear wall subjected to cyclic loading and the results from the model were compared with experimental results, and again agreement was achieved.

Zhi-Min Li (School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, 200030, People’s Republic of China), “Postbuckling of a shear-deformable anisotropic laminated cylindrical shell under

ABSTRACT: A postbuckling analysis is presented for a shear-deformable anisotropic laminated cylindrical shell of finite length subjected to external pressure in thermal environments. The material properties are expressed as linear functions of temperature. The governing equations are based on Reddy’s higher-order shear-deformation shell theory with the von Karman-Donnell-type kinematic nonlinearity. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. The boundary-layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling region, and the initial geometric imperfections of the shell, is extended to the case of shear-deformable anisotropic laminated cylindrical shells under lateral or hydrostatic pressure in thermal environments. The singular perturbation technique is employed to determine the interactive buckling loads and postbuckling equilibrium paths. The results obtained show that the variation in temperature, layer setting, and the geometric parameters of such shells have a significant influence on their buckling load and postbuckling behavior.

References listed at the end of the paper:

ABSTRACT: The nonlinear buckling and postbuckling of a shear-deformable anisotropic laminated cylindrical panel of finite length is investigated based on a boundary-layer theory for buckling. The layers of the panel are assumed to be linearly elastic. The governing equations are based on Reddy’s higher-order shear deformation theory of shells and include the von Karman-type kinematic nonlinearity and extension/twist, extension/flexure, and flexure/twist couplings. The nonlinear prebuckling deformations and the initial geometric imperfections of the panel are both taken into account. The postbuckling behavior of the panel under axial compression is analyzed. A singular perturbation technique is employed to determine its buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect moderately thick anisotropic laminated cylindrical panels with different geometric parameters and stacking sequences. The new finding reveals that there arises a compressive stress along with an associate shear stress and twisting when a moderately thick anisotropic laminated cylindrical panel is subjected to axial compression.

Zhi-Min Li, Zhong-Qin Lin and Guan-Long Chen (School of Mechanical Engineering and State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “Postbuckling of shear deformable geodesically stiffened anisotropic laminated cylindrical shell under external pressure”, J. Pressure Vessel Technology, Vol. 133, No. 2, February 2011, DOI: 10.1115/1.4001742

ABSTRACT: A boundary layer theory for buckling and postbuckling of anisotropic laminated thin shells is extended to shear deformable stiffened anisotropic laminated shells. A postbuckling behavior is investigated for a shear deformable anisotropic laminated cylindrical shell with geodesical stiffener of finite length subjected to lateral or hydrostatic pressure. The material of each layer of the shell is assumed to be linearly elastic, anisotropic, and fiber-reinforced. The governing equations are based on a higher-order shear deformation shell theory with von Kármán–Donnell-type of kinematic nonlinearity and including the extension/twist, extension/flexural, and flexural/twist couplings. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the buckling pressure and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, geodesically stiffened shells, axial and ring stiffened shells, and unstiffened shells with different values of shell parameters and stacking sequence. The results confirm that there exists a circumferential stress along with an associate shear stress when the shell is subjected to lateral pressure. The postbuckling equilibrium path is stable for the moderately long shell under external pressure and the shell structure is virtually imperfection-insensitive.


ABSTRACT: A mixed finite-element algorithm is proposed to study the dynamic behavior of loaded shells of revolution containing a stationary or moving compressible fluid. The behavior of the fluid is described by
potential theory, whose equations are reduced to integral form using the Galerkin method. The dynamics of the shell is analyzed with the use of the variational principle of possible displacements, which includes the linearized Bernoulli equation for calculating the hydrodynamic pressure exerted on the shell by the fluid. The solution of the problem reduces to the calculation and analysis of the eigenvalues of the coupled system of equations. As an example, the effect of hydrostatic pressure on the dynamic behavior of shells of revolution containing a moving fluid is studied under various boundary conditions.


ABSTRACT: We consider a finite element algorithm intended to study the dynamic behavior of an elastic cylindrical shell filled with an immovable or flowing fluid. To describe the fluid, we use the perturbed velocity potential whose equations with the corresponding boundary conditions are solved by the Bubnov-Galerkin method. To describe the shell, we use the variation principle, which includes the linearized Bernoulli equation for calculating the hydrodynamic pressure acting on the shell on the side of the fluid. Solving the problem is reduced to calculating and analyzing the eigenvalues of the coupled system of equations obtained as a result of combining the equations for the perturbed velocity potential and the shell displacements. We consider several test problems in which, along with the comparison of the computational results with the earlier published experimental, analytic, and numerical data, we also study the dynamic behavior of the “shell-fluid” system for various boundary conditions for the perturbed velocity potential.


ABSTRACT: A finite-element algorithm is proposed to investigate the dynamic behavior of elastic shells of revolution containing a quiescent or a flowing inviscid fluid in the framework of linear theory. The fluid behavior is described using the perturbed velocity potential. The shell behavior is treated in the framework of the classical shell theory and variational principle of virtual displacements incorporating a linearized Bernoulli equation for calculation of hydrodynamic pressure acting on the shell. The problem reduces to evaluation and analysis of the eigenvalues in the connected system of equations obtained by coupling the equations for velocity perturbations with the equations for shell displacements. For cylindrical shells, the results of numerical simulations are compared with recently published experimental, analytical and numerical data. The paper also reports the results of studying the dynamic behavior of shells under various boundary conditions for the perturbed velocity potential. The investigation made for conical shells has shown that under certain conditions an increase in the cone angle can change a divergent type of instability to a flutter type.


ABSTRACT: The finite element method is applied to analyze a stationary or rotating cylindrical shell containing a co-rotating compressible fluid. The motion of the rotating fluid is described in the framework of
the potential theory. The behavior of shells is analyzed using the classical shell theory. It has been found that the loss of stability in the stationary shells occurs in the form of a flutter. It has been shown that in the case of rotating shells the loss of stability is prevented by taking into account the initial circumferential tension caused by the centrifugal forces.

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“Uncertain multimode failure and limit analysis of shells”, 11th World Congress on Computational Mechanics (WCCM XI), 5th European Conference on Computational Mechanics (ECCM V), 6th European Conference on Computational Fluid Dynamics (ECFD VI) E. Oñate, J. Oliver and A. Huerta (Eds), Barcelona, Spain, 2014

PARTIAL INTRODUCTION: The plastic collapse limit and the shakedown limit which define the load-carrying capacity of structures are important in assessing the structural integrity. Due to the high expenses of experimental setups and the time consuming full elastic-plastic cyclic loading analysis, the determination of these limits by means of direct plasticity methods has been of great interest to many designers. Moreover, a certain evaluation of structural performance can be conducted only if the uncertainty of the actual load-carrying capacity of the structure is taken into consideration since all resistance and loading variables are random in nature. To ensure the safety of the structures to be designed, two approaches are normally used [1]. The classical approach fixes the values of the safety factors and chooses the values of the design variables to satisfy the safety conditions. All the variables involved are then assumed to be deterministic and fixed to particular quantiles, i.e. mean value or characteristic values [2]. The probability-based approach deals directly with realistic random variables to find the global probability of failure as the basic design criterion. Obviously, the later problem is more difficult since the evaluation of the probability of failure is not an easy task, especially when the structure has more than one failure mode (multimode failure or multiple design points). In this case, analysis of the structural system is required to evaluate the safety of the structure as a whole [1]. To handle problems of this kind, the real structure is sometimes modelled by an equivalent system in such a way that all relevant failure modes can be treated [2].

References:


ABSTRACT: We present a simplified numerical method which can be used to predict efficiently the response of long thin plates under effects of residual stresses induced by production process such as rolling or continuous annealing. The principle consists in assuming harmonic buckling mode along the sheet length, and we consider Koiter-Budiansky post-buckling theory to compute the stress-deflection curve. In this way, only the width of the sheet has to be discretized by 1D finite elements. The size and shape of the flatness defects can be predicted efficiently and for a large number of cases. Various types of residual stresses and loadings can be accounted for. In particular, we will see the influence of the global traction on the buckling and post-buckling behavior. The numerical results are compared with experimental data and full numerical computations.

ABSTRACT: The paper summarizes a part of the activity currently carried out by the CEN/TC250 SC9 Committee, which is presently engaged in setting up the “Second Generation” of EC9 on aluminium structures. In particular, new expressions of imperfection reductions factors $\alpha$ for unstiffened shells are proposed. The new formulation, which is calibrated on the basis of simulation buckling data available in literature, corrects a small issue of the previous one, giving at the same time more reliable and consistent results.


ABSTRACT: A generalization of the Euler–Plateau problem to account for the energy contribution due to twisting of the bounding loop is proposed. Euler–Lagrange equations are derived in a parametrized setting and a buckling analysis is performed. A pair of dimensionless parameters govern buckling from a flat, circular ground state. While one of these is familiar from the Euler–Plateau problem, the other encompasses information about the ratio of the torsional rigidity to the bending rigidity, the twist density and the size of the loop. For sufficiently small values of the latter parameter, two separate groups of buckling modes are identified. However, for values of that parameter exceeding the critical twist density arising in Michell's study of the stability of a twisted elastic ring, only one group of buckling modes exists. Buckling diagrams indicate that a loop with greater torsional rigidity shows more resistance to transverse buckling. Additionally, a twisted flexible loop spanned by a soap film buckles at a value of the twist density less that the value at which buckling would occur if the soap film were absent.


ABSTRACT: A variety of technical applications, which use functionally graded materials (FGM) generates a need for stability analysis of structures made of these materials. Generally, these investigations have focused on natural vibrations and stability of empty shells and only a small number of research papers are devoted to functionally graded shells containing fluid. To our knowledge there is only one paper in the literature [1], which analyzes the shells filled with incompressible fluid. However, fluid conveying structures with slightly non-circular or non-circular cross-sections are extensively used in modern technologies. This is a strong reason for the development of advanced numerical algorithms allowing us to simulate their behavior. This paper presents a 3D formulation of the spectral problem and finite element algorithm (FEM) for its numerical implementation, designed to investigate natural vibrations and stability of prestressed functionally graded shells with arbitrary cross-section interacting with a quiescent or flowing compressible fluid. The motion of non-viscous fluid is described by the wave equation, which together with the impermeability condition and appropriate boundary conditions are transformed using the Bubnov–Galerkin method. Simulation of the shell with arbitrary cross-section is carried out on the assumption that its curvilinear surface is approximated to sufficient accuracy by a set of plane rectangular elements [2]. The strains are calculated using the relations of the Kirchhoff–Love’s thin shells theory. A mathematical formulation of the dynamic shell
problem has been developed by applying the variational principle of virtual displacements.

References listed at the end of the paper:

ABSTRACT: This paper is concerned with the numerical investigation of hydroelastic stability of stationary or rotating coaxial cylindrical shells, interacting with compressible fluid flows having the axial and tangential velocity components. The behavior of a flowing and rotating compressible fluid is considered in the framework of the potential theory. Elastic shells are described using the model of the classical shell theory. Numerical implementation was accomplished based on the semi-analytical variant of the finite element method. The paper presents the results of numerical experiments on the stability of shells interacting with different flow patterns for a variety of boundary conditions, geometrical dimensions, width of the annular gap between the outer and inner shell under the constraint of the outer shell rigidity. It has been shown that the elasticity of the outer shells has the greatest effect on the dynamic behavior of coaxial shells interacting with fluid flows having different combinations of velocity components.

ABSTRACT: A method aimed at the optimization of locally varying laminates is investigated. The structure is partitioned into geometrical sections. These sections are covered by global plies. A variable-length representation scheme for an evolutionary algorithm is developed. This scheme encodes the number of global plies, their thickness, material, and orientation. A set of genetic variation operators tailored to this particular representation is introduced. Sensitivity information assists the genetic search in the placement of reinforcements and optimization of ply angles. The method is investigated on two benchmark applications. There it is able to find significant improvements. A case study of an airplane’s side rudder illustrates the applicability of the method to typical engineering problems.

ABSTRACT: Interaction curves for vibration and buckling of thin-walled composite box beams with arbitrary lay-ups under constant axial loads and equal end moments are presented. This model is based on the classical lamination theory, and accounts for all the structural coupling coming from material anisotropy. The governing differential equations are derived from the Hamilton’s principle. The resulting coupling is referred to as triply flexural–torsional coupled vibration and buckling. A displacement-based one-dimensional finite element model with seven degrees of freedoms per node is developed to solve the problem. Numerical results are obtained for
thin-walled composite box beams to investigate the effects of axial force, bending moment, fiber orientation on the buckling loads, buckling moments, natural frequencies and corresponding vibration mode shapes as well as axial-moment–frequency interaction curves.


ABSTRACT: This report describes a systems approach to the nonlinear finite element analysis of shell structures. The research objective is to understand the structure a small language and computational environment should take so that matrix and nonlinear finite element computations can interact in a seamless manner. One four-node-thick shell finite element and one eight-node-thick shell finite element is formulated and implemented in ALADDIN [1]. The finite elements are based on a three-dimensional continuum formulation, and are simplified by assuming a flat element geometry. Numerical experiments are presented for in-plane displacements of a flat plate, and out-of-plane bending of a cantilever structure. In each case, material nonlinearities are modeled with bi-linear and Ramberg-Osgood stress-strain curves. The report concludes with recommendations for further work in the areas of nonlinear finite element solution procedures and enhancements to ALADDIN's problem-solving infrastructure.

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ABSTRACT: By analysing the possible failure modes at each level, we propose a hierarchical design for highly efficient mechanical structures to withstand hydrostatic crush pressure, which becomes fractal in the limit of zero pressure. We deduce the Hausdorff dimension of these designs (over the range of length scales where this applies), and show that through changing the number of hierarchical levels, the power law scaling relation between applied external pressure and volume of material required can be altered in a systematic way. The design can be applied to arbitrary shapes, but for clarity we present two examples (cylinder and sphere).

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ABSTRACT: A multi-level analysis of skin/stiffener debonding is used for the fuselage design of future aircraft during postbuckling. The specimens composed of a laminate (the skin) to which an over-thickness (the flange) had been added were subjected to four-point bending, which led to interface failure between the flange and the skin. These tests were performed with several configurations and parameters, such as the orientation of the plies located at the interface, temperature (-50, 20 and 70 deg.C), ageing and manufacturing mode: co-cured or co-
bonded. The flange shape (tapered or not) and thickness were also considered. Test data are presented and analyzed and critical configurations are identified. Finite element models were developed and the flange debonding loads computed, firstly by use of cohesive models and then through a fracture mechanics approach (Virtual Crack Closure Technique). In both cases, the Benzeggagh-Kenane criterion was selected and proved its efficiency but the fracture mechanics approach was an order of magnitude less time consuming, which will enable future modelling to include larger sizes.

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ABSTRACT: In the framework of test analysis pyramid, large specimens were studied. To represent the bending behaviour during postbuckling, specimens composed of a plate with a stiffener were supported on five points and loaded transversely by two points, thus being subjected to “seven point” bending. By modifying the positions of the two loading points, symmetrical and antisymmetrical buckles that led to interface failure between the flange and the skin could be simulated. First a global numerical model of the test was made in order to assess the efficiency of the approach developed in the first part of this study. Predictions were in accordance with experiments despite strong scatter. Then, a global/local test method was considered. In this method, the global model considered shell elements although the local model used volume elements. The onset of delamination was correctly predicted at local level. Finally, the method was applied to two large stiffened panels subjected to compression and shear.


ABSTRACT: This paper is devoted to the optimal design of laminated composite structures. The goal of the study is to assess the quality and the performance of an algorithm based on the directional derivative method. Particular attention is paid to the one-dimensional search, a critical step of the process, performed by cubic splines approximation. The optimization problem is formulated as weight minimization, under constraints on the mechanical behavior of the structure. The assumed design variables are the ply thicknesses, treated as continuous design variables, constrained by technological requirements. The structural analysis is performed making use of quadrilateral four-node composite elements, based on the first order shear deformation theory. The algorithm is applied to the optimization of a rectangular laminated plate. The results obtained are compared with those obtained by other similar studies and show the effectiveness and accuracy of the proposed approach.


ABSTRACT: This work determines the maximal possible deformations of a corrugated sheet where the
corrugation pattern consists of two circular segments. The influence of the lay-up of cross-ply laminates and the influence of the geometry is investigated. The calculations are based on considerations of layerwise strains that are calculated with the help of an analytical singly-curved shell model. For the evaluation of the influence of geometric nonlinearities according finite element simulations are performed and compared to the linear strain limit calculations. The influence of scalable geometry parameters is also investigated.

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ABSTRACT: This paper describes and applies a theory for practical second-order analysis and design of steel frames. The practicality, convenience and high precision of the method of ‘Non-linear Integrated Analysis and Design (NIDA)’ that allows for the second-order effects for design of steel frames and trusses is demonstrated. The need for using two or more elements per member to accurately simulate the axial load effect on the element stiffness and to locate the maximum moment along an element is eliminated. Unlike previous work for ‘Advanced Analysis' which is difficult to use in practice as it ignores many important practical features such as element imperfection, the proposed method meets the current design code requirements and is based on the first-plastic-hinge concept which is currently adopted by engineers. Furthermore, the element by itself can predict the beam-column load carrying capacity using a single element per member to model the P-Δ effect and, therefore, it can be used for simultaneous analysis and design. The use of several elements per member still possesses an error of idealising a physically smoothly curved member by a series of segments of straight elements. Conceptually, the suggested method designs a structure by modelling accurately its true behaviour, instead of making use of empirical formulae for individual member checks. It is readily available for design application of realistic structures and it is envisaged that the NIDA will initiate a revolution in the practical design of steel structures.


ABSTRACT: Ultra-lightweight thermoformed stiffened structures are emerging as a viable option for spacecraft applications due to their advantage over inflatable structures. Although pressurization may be used for deployment, constant pressure is not required to maintain stiffness. However, thermoformed stiffening features are often locally nonlinear in their behavior under loading. This thesis has three aspects: 1) to understand stiffness properties of a thermoformed stiffened ultra-lightweight panel, 2) to develop finite element models using a phased-verification approach and 3) to verify panel response to dynamic loading. This thesis demonstrates that conventional static and dynamic testing principles can be applied to test ultra-lightweight thermoformed stiffened structures. Another contribution of this thesis is by evaluating the stiffness properties of different stiffener configurations. Finally, the procedure used in this thesis could be adapted in the study of similar ultra-lightweight thermoformed stiffened spacecraft structures.

References listed at the end of the dissertation:
[3] The proceedings of the 2nd Gossamer Spacecraft forum
[16] Daniel Todd Griffith, “Experimental and Analytical Modal Analysis of an Inflated Thin Film Torus”, (the rest of the citation is missing on the original)


ABSTRACT: The ability of modulating the dynamic response of structural elements may play a fundamental role in terms of noise and vibration propagation and reduction levels. Specifically, controlling some dynamic features, like stiffness and damping, may remarkably extend the working range of a specific component, with consequent integration and efficiency benefits. Smart Materials, combined with innovative design philosophies (i.e., ‘Self-Adaptive Structures’, ‘Self-Repairing Structures’)... gave rise to real possibilities for the implementation of non-conventional solutions. Within the noise and vibration field, a family of strategies, focused on damping (active constrained layer dampers, rheological layers) and stiffness (embedded Shape Memory Alloys, SMA, acting on the stress field) control, is developing, by giving birth to original and efficient
solutions. SMA, due to their capability of transmitting large forces and deformations, and producing remarkable stiffness variations, represent good candidates for actuation problems and stiffness control solutions. The idea of using embedded SMA components to affect the structural dynamic response was already considered by several authors; among the others, Diodati and others focused their attention on the prediction of the effects due to the heat activation of SMA wires, embedded within a fiber-glass laminate. SMA induced stress originated significant FRF peaks shift, encouraging the authors to develop an optimization procedure to find out the most efficient placement and orientation of the active elements within the panel, aimed at maximizing the achievable frequency peak shift. In this article, a numerical model already introduced was examined and upgraded to suit the logic of a generic optimization process. The specific connections between the structure and the wires (sliding wires) was realized by proper constraint architecture, able to catch the best the physical nature of the mutual interaction. Then, due to the large amount of the parameters to be identified (in plane angle and location of each wire) and the non-continuous nature of some of them, a genetic optimization approach was picked up and implemented, assuming the peak shifts as the fitness function. The activated is then compared with the non-activated response, in order to estimate the attained performance.

ABSTRACT: For the numerical analysis of shells undergoing finite rotations doubly curved finite shell elements are developed via the displacement formulation. The derivation starts from a consistent finite-rotation shell theory which is transformed by a variational procedure into an incremental formulation. Thus, the non-linearity can be treated by an incremental-iterative technique. The non-linear element matrices are obtained by a tensor-oriented procedure permitting a direct transformation of the initial equations into efficient numerical models. Unlike in the usual procedure, the KIRCHHOFF-LOVE assumption is treated as a subsidiary condition at the element level. This computer-oriented approach permits the elimination of the dependent rotational degrees of freedom without loss of accuracy. Finally, some examples are presented to demonstrate the ability of the resulting finite elements to deal with finite-rotation problems.

ABSTRACT: For composite laminates consisting of an arbitrary number of orthotropic laminae first a finite-rotation theory is presented as basis of isoparametric finite-element formulations. The derivation is achieved by a Reissner-Mindlin type kinematic assumption which allows a constant shear deformation distribution across the thickness. The constitutive equations are presented in a general form such that orthotropic material behaviour with material axes varying arbitrarily across the thickness may easily be considered in numerical implementation, also when using curvilinear coordinates. Special attention is taken to predict the force distribution in the deformed shell structure. This theory is then transformed into a four-node isoparametric assumed-strain finite element. Unlike in the degeneration approach, interpolation polynomials are introduced directly for rotation variables determining the deformed position of the unit normal vector. The capability of the finite element developed to deal with strongly nonlinear situations is demonstrated by many examples. Also numerical results are presented permitting a systematical comparison of classical and isoparametric approaches concerning the numerical efficiency.

ABSTRACT: For arbitrary multilayered shell structures made particularly of composite material layers a refined finite-rotation theory with seven independent displacement variables is developed, approximating the displacement field by a cubic series expansion of thickness coordinates. This model allows a quadratic shear deformation distribution across the thickness. Procedures are given permitting a unique determination of the first order displacement term in the case of finite rotations. Kinematic relations are formulated in two alternative forms suitable for both classical and isoparametric finite element formulations. The constitutive relations presented model orthotropic material properties varying arbitrarily across the thickness. This third order single-layer theory is then transformed, by introducing further constraints, into three simplified models: a third order theory with five independent displacement variables, a Mindlin-Reissner type theory and a Kirchhoff-Love type theory. These four models differ, however, from each other essentially in the constraints imposed on the first and third order displacement variables: a significant advantage for a unified finite element development. Finally, the Mindlin-Reissner type theory is generalized to a layer-wise model being the most predictive one in dealing with local interlaminar effects. The theoretical models are transformed into adequate finite shell elements and then compared by means of appropriate examples concerning their prediction capability. Also examples are given demonstrating their applicability to finite-rotation phenomena.


ABSTRACT: The objective of this contribution is the development of theoretical and numerical models applicable to large strain analysis of hyperelastic shells confining particular attention to incompressible materials. The theoretical model is developed on the basis of a quadratic displacement approximation in thickness coordinate by neglecting transverse shear strains. In the case of incompressible materials this leads to a three-parametric theory governed solely by mid-surface displacements. The material incompressibility is expressed by two equivalent equation sets considered at the element level as subsidiary conditions. For the simulation of nonlinear material behaviour the Mooney-Rivlin model is adopted including neo-Hookean materials as a special case. After transformation of nonlinear relations into incremental formulation doubly curved triangular and quadrilateral elements are developed via the displacement method. Finally, examples are given to demonstrate the ability of these models in dealing with large strain as well as finite rotation shell problems.


ABSTRACT: The objective is the theoretical and numerical simulation of large-strain phenomena of rubber-like shells by means of shear deformation models. The development starts with a general applicable shell model constructed on the basis of quadratic displacement approximation which involves two thickness stretching parameters. This model is then coupled with incompressible material models of Mooney-Rivlin and neo-Hookean types. Material incompressibility is described by two-dimensional constraints considered at the
element level as subsidiary conditions. A special care is given to the stress prediction in the presence of large-strains. After transformation of the theoretical model into an incremental formulation a four-node isoparametric finite element is derived. Examples are finally given to demonstrate the ability of this model to deal with very strong deformations and to predict the related stresses.

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ABSTRACT: This paper considers the crushing which occurs in a spherical shell made of ductile material on striking a rigid wall. A static analysis is developed which allows for strain hardening, while for relatively low impact velocities, such as to permit the effect of inertia to be neglected, strain rate sensitivity is allowed for in an empirical manner. The analysis presented is applicable to spherical shells with a mean radius to thickness ratio exceeding seven, constructed in ductile material obeying a simple power law work hardening relationship. The deformation is assumed to occur in two phases. In the first phase a local flattening of the shell in contact with the rigid wall occurs, while in the second, an axisymmetric dimpling of the previously flattened portion takes place. Other workers have discovered that at radius to thickness ratios exceeding one hundred, a third mode of behaviour takes place when a number of non-axisymmetric nodes can be formed. The analysis in this paper, however, is only applicable to lower ratios when the crushing deformation, although reaching a value of half the radius, remains axisymmetric, as is borne out in all the experimental results examined for correlation. A number of assumptions and simplifications are made, all of which are clearly stated below. Reference is made to earlier papers on this subject and a comparison is made of correlations by such earlier work and by the present analysis in respect of a group of quasi-static tests carried out by the Civil Engineering Department of the Queen's University of Belfast under a Leverhulme Trust fellowship funding: this is described in detail in Appendix 1. The result of a moderate velocity impact test on a spherical shell of 625 mm diameter is utilized to examine the correlation given by the present analysis taking strain rate effect into account. Note: the first author was mainly concerned with the analysis, while the co-authors carried out the experimental work detailed in Appendix 1.


ABSTRACT: Traditionally assessment of ship's longitudinal strength has been made by comparing the elastic stresses at the deck or bottom shell to fractions of the material yield strength. This results in high reserve capacity due to inherent redundancies in ship structures. Residual strength, which is defined as the strength of the structure after damage, has rarely been considered either during design or at the time of repair. In this report, key elements required to undertake an engineering analysis to evaluate the residual strength have been identified. Emphasis has been placed on assessing the residual strength of marine structures damaged due to normal operating loads. Methods available to industry for evaluation of damage such as, fracture and ultimate strength have been summarized. An example problem, illustrating the application of an integrated approach to residual strength assessment on a particular ship type, is presented.
DTIC Accession Number: ADA294040, Handle / proxy Url : http://handle.dtic.mil/100.2/ADA294040
ABSTRACT: Current ship structural design criteria for stiffened plate panels is based upon a strength of materials approach using either linear plate or beam theory. This approach neglects the effects of vertical shear (normal to the plate surface), membrane and torsional stress components induced by the flexibility of the panel's supporting structure. Recent trends towards the use of higher strength materials have resulted in the design of grillage structures which are more flexible and therefore increase the vertical shear, membrane and torsional stress components in the plate panel. This report presents the results of a study undertaken to determine the effect of the stiffness characteristics of the supporting members of the grillage structure on the plate panel stress. Grillage scantlings were developed using first principals based approach and then analyzed using finite element techniques to take into account the flexibility of the grillage stiffeners and to quantify the effects of vertical shear, membrane and torsional stress components.

PARTIAL INTRODUCTION: The finite element method is conceptually straightforward in that complex structures are idealized, in a representation, by a network or mesh of simpler interlocking structures, the simpler structures or finite elements being amenable to mathematical analysis…

ABSTRACT: A Multidisciplinary-Design-Optimization (MDO) approach for the initial design of wing structures based on the integrated modeling of structures, aerodynamics, flight dynamics, and aeroelasticity, has been developed. The procedure is based on the use of a standard numerical optimizer which employs structural, aeroelastic, and aerodynamic analyzers (a finite-element analyzer for structures, panel method analyzer for aerodynamics, and a longitudinal trim analyzer for flight mechanics) in the MDO process. The space discretizations of the numerical models – namely, the structural and aerodynamic meshes – are dynamically updated as function of wing-structure geometry variables during the optimization process. The geometric-updating procedure has been validated using available analytical solutions for a structural optimization problem. The obtained MDO solutions are essentially based on a first-principle formulation but, in the meanwhile, they do not result to be computationally expansive. Moreover, in order to make the implemented MDO algorithm more computationally efficient and effective, an analytical method based on Matched-Filter Theory (MFT) has been used to evaluate the worst aeroelastic-response case due to a gust input having an assigned energy level with the purpose of obtaining a final design also optimizing the gust-response performance. The optimization capabilities of using geometry design variables vs the standard structural design variables in the MDO process have been highlighted. Moreover, the use of a composite objective function, combining structure and aerodynamic issues, has been shown further capabilities of the presented MDO procedure. Finally, some results are also presented for a benchmark regional aircraft wing to show the potentiality of the approach.
ABSTRACT: A nonlinear aeroelastic analysis method using computational fluid dynamics/computational structure dynamics (CFD/CSD) is presented and applied to the nonlinear flutter and limit-cycle-oscillation (LCO) research of a cropped delta wing. This computational method couples a nonlinear finite element method (FEM) model with a CFD solver by using a high-fidelity interface interpolation, and is capable of investigating aeroelastic problems with both structural and aerodynamic nonlinearities. The structural analysis is based on a quadrilateral flat-shell element and an updated Lagrange (UL) formulation, which can be employed to model geometric nonlinearities arising from large deflections. With the Navier-Stokes (N-S) equations as the control equations, a finite volume CFD solver is formulated to calculate transonic aerodynamics. The nonlinear flutter calculation demonstrates the validity of the presented method. Finally the cropped-delta-wing LCO is computed, and the calculation precision is obviously better than the existing results.

ABSTRACT: A simple nonlinear analysis is presented to evaluate the displacements and stresses which arise from an axi-symmetric band of geometric imperfection in a pressurised sphere. The displacements and stresses solutions are derived in terms of Fourier series. Different shapes of initial geometric imperfections can be readily analysed by representing the shapes by Fourier series. It is concluded that the peak meridional stress is greater than the peak circumferential stress. Furthermore, the magnitude of the peak stress is scarcely influenced by the location of the imperfection shape. Generally, the stress distribution at the distorted region of the sphere can be characterised by the shape of imperfection and the membrane stress value; it is not so much affected by the different ‘radius to thickness’ ratio. The simple analysis highlights some important results which are not apparent in the other solution approaches.

ABSTRACT: A procedure to analyze axisymmetric solids undergoing large nonaxisymmetric deformation is presented. The plane of axisymmetry is modeled by isoparametric quadrilateral finite elements with dependence in the circumferential direction determined by a continuous Fourier series. Although the Fourier harmonics are coupled for such analyses, the size of the resulting model can be much smaller than it would be if brick elements were to be used. This model reduction can significantly decrease the amount of computational effort needed for analyzing this class of problems. Different schemes for solving the coupled nonlinear equations are evaluated by analyzing two structures subjected to different loadings and exhibiting various amounts of geometric nonlinearity. The coupled systems of linear simultaneous equations occurring at each Newton-Raphson iteration are solved by both direct and indirect solution schemes. Several types of Gauss-Seidel and conjugate gradient iterations are shown to be quite efficient and robust. The effectiveness of these indirect solution techniques are a result of using the uncoupled stiffness matrices to precondition the coupled systems of
linear simultaneous equations. The continuous Fourier series approach also provides a very simple, efficient, and reliable way to conduct adaptive refinement in the circumferential direction.


SUMMARY: Deformation of the outermost parts of single-plate planetary bodies is often modelled in terms of the response of a spherical elastic shell to surface or basal loading. As the thickness of such elastic lithosphere is usually much smaller than the radius of the body, the deformation is commonly approximated by that obtained for a thin elastic shell of uniform thickness. The main advantage of the thin shell approximation is its simplicity—the solution can be expressed analytically if the thickness of the shell is uniform, but even in the case of a thin shell of variable thickness, when the problem must be solved numerically, the computational costs are much lower than in a fully 3-D case. Here we analyse the error of the thin shell approximation by comparing it with the solution obtained for a shell of finite thickness using finite element methods. Special attention is paid to a shell of variable thickness and, in general, to the effect of elastic thickness variations on local deformation. For a shell of uniform thickness with the outer radius corresponding to Mars, we find that the error in radial displacement at low harmonic degrees ($l \leq 20$) does not exceed 5 per cent for small shell thicknesses ($d \leq 50$km) and 10 per cent for thick shells ($d \sim 250$km). Similar accuracy is also found for a shell of variable thickness if the thin shell approximation is used. Our numerical tests indicate that local deformation of a shell is mostly sensitive to the average thickness of the shell in the near zone while the effect of thickness variations in the far zone can be neglected in the first approximation. Consequently, the extremely simple thin shell method, designed for shells of uniform thickness, can be effectively used to obtain a reasonably accurate estimate of deflection even in the case of a shell with varying thickness. Finally, we investigate the deformation of an elastic lithosphere due to viscous flow beneath the shell, and we propose an extension of the concept, recently developed to correct dynamic topography for the effect of an elastic lithosphere, to the case of a shell of variable thickness.


ABSTRACT: A C0 continuous finite element formulation of a higher order shear deformation theory is presented for predicting the linear and geometrically non-linear, in the sense of von Karman, transient responses of composite and sandwich laminated shells. The displacement model accounts for the non-linear cubic variation of the tangential displacement components through the thickness of the shell and the theory requires no shear correction coefficients. In the time domain, the explicit central difference integrator is used in conjunction with the special mass matrix diagonalization scheme which conserves the total mass of the element and includes effects due to rotary inertia terms. Numerical results for central transverse deflection and stresses are presented for composite and sandwich laminated shells with various boundary conditions subjected to different types of loads and are compared with the results from other sources. Some new results are also included for future reference.

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ABSTRACT: A C0 continuous displacement based finite element formulation of a higher order theory for linear and geometrically non-linear analysis which accounts for large displacements in the sense of von Karman of symmetrically laminated composite and sandwich shells under transverse loads is presented. The displacement model accounts for non-linear and constant variation of tangential and transverse displacement components, respectively, through the shell thickness. The assumed displacement model eliminates the use of shear correction coefficients. The discrete element chosen is a nine-node quadrilateral element with nine degrees of freedom per node. The accuracy of the present formulation is then established by comparing the present results with the available analytical, closed-form two-dimensional solutions, three-dimensional elasticity solutions and other finite element solutions. Some new results are generated for future comparisons to and evaluations of sandwich shells.


ABSTRACT: (none given)


ABSTRACT: A simple and effective method is developed in this paper for free vibration analysis of shells of revolution with either internal or external fluids. The fluid region is treated analytically by the use of eigenfunction expansions, and the collocation method using the roots of the orthogonal polynomial as collocation points is used to solve the integro-differential equations which describe the motion of the shell. The proposed approach is formulated in some detail. The versatility and accuracy are illustrated through several numerical examples. The method appears to be relatively easy to set up and gives satisfactory results.

ABSTRACT: Free vibration characteristics of filament wound anisotropic shells of revolution are investigated by using multisegment numerical integration technique in combination with a modified frequency trial method. The applicability of multisegment numerical integration technique is extended to the solution of free vibration problem of anisotropic composite shells of revolution through the use of finite exponential Fourier transform of the fundamental shell equations. The governing shell equations comprise the full anisotropic form of the constitutive relations, including first-order transverse shear deformation, and all components of translatory and rotary inertia. The variation of the stiffness coefficients along the axis of the shell is also incorporated into the solution method. Filaments are assumed to be placed along the geodesic fiber path on the shell of revolution resulting in the variation of the stiffness coefficients along the axis of the composite shell of revolution with general meridional curvature. Sample solutions have been performed on the effect of the variation of the stiffness coefficients on the free vibration behavior of filament wound truncated conical and spherical shells of revolution.


ABSTRACT: An analytical solution procedure is presented for the free vibrations of shells of revolution having two bonded elastic layers and circular meridional curvature. A set of governing equations of motion are obtained by applying Hamilton's principle to the Lagrangian function of the shell vibration. These equations of motion are higher order partial differential equations having variable coefficients, and analytical solutions are obtained by expanding these variable coefficients into infinite power series. Effects of various parameters, such as material properties of the shell layers, upon natural frequencies and mode shapes are investigated.


ABSTRACT: In the present paper, experimental studies on dynamic plastic buckling of circular cylindrical shells under axial impact are carried out. Hopkinson bar and drop hammer apparatus are used for dynamic loading. Three groups of circular cylindrical shells made of copper are tested under axial impact. From the experiments, the first critical velocity corresponding to the axi-symmetric buckling mode and the second critical velocity corresponding to the non-axisymmetric buckling mode are determined. The present results come close to those of second critical velocity given by Wang Ren[4–6]. Two different kinds of non-axisymmetric buckling modes oval-shaped and triangle shaped are founded. The buckling modes under two loading cases, viz. with small mass but high velocity and with large mass and low velocity using Hopkinson bar and drop hammer, are different. Their critical energies are also discussed.

ABSTRACT: Shell triangular finite elements are examined which are parametrically represented by quadratic polynomials of the surface coordinates. It is shown that isoparametric representation of the rectangular components of displacement does not provide an acceptable description of inextensional bending of a curved surface—its bending is accompanied with middle surface strains which are too large to be ignored.
Considerable improvement is made in the approximation to inextensional bending when the displacements are parametrically represented by cubic polynomials. The approximate inextensional bending modes are determined by examining eigenvalues of the positive semi-definite matrix of the integrated sums of squares of the principal middle surface strains taken over the element surface. Numerical results are listed for specimen finite elements which have positive, zero or negative Gaussian curvature. The Fortran computer program written for this investigation is described elsewhere.

ABSTRACT: The role of bending in the finite element analysis of problems in the linear theory of thin shells is examined through an in-depth study of the behavior of a vehicle finite element. The chosen element is the very simple combined constant strain and constant bending moment flat triangle. It emerges that this vehicle element is a superb performer and the examination of its behaviour reveals that there are two quite different roles for the bending freedoms. One role concerns inextensional bending movements which extend over the whole model. The other role concerns local rotational movements which accompany the curvature changes of inextensional bending and of edge effect. Extensive numerical comparisons of demonstration inextensional bending movements are made against solutions obtained from the classical theory for shells which are very deep and which have strongly negative Gaussian curvature. Comparison of edge effect concerns a circular cylindrical thin shell. The paper concludes by giving details of a rudimentary matrix procedure which is currently under development and which is intended for use in the preliminary assessment of thin shell finite element models.

ABSTRACT: An expression for the strain energy of a shell of negative Gaussian curvature, including thickness shear deformations and without neglecting z/R in comparison with unity, is derived. Then a curved trapezoidal finite element formulation based on the principle of minimum potential energy is obtained. The shell element has eight nodes with 40 degrees of freedom and at each node there are three displacements and two rotations. The formulation is applicable for both thin and moderately thick shell analysis. The performance of this finite element is verified by applying it to some problems existing in the literature.

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ABSTRACT: Based on a total Lagrangian approach, the shell element formulation developed by two of the
authors is extended to non-linear field. The proposed shell element belongs to the degenerated 3D type, with a Mindlin–Reissner approach and five effective degrees of freedom per node. A detailed description of the geometry and kinematics characterisation of the element, as well as of the stress–strain relationship is presented. Numerical testing of the non-linear model indicates excellent performance of the proposed finite element shell, both in simulating large displacement and rotations, and in the buckling analysis of some classical test examples, e.g., cylinder and sphere.


ABSTRACT: The present investigation deals with the nonlinear analysis of the dynamic buckling response and global stability aspects of two 3-DOF spring-mass, initially imperfect dissipative simplified structural models under step loading, simulating elastic shell panels of revolution and in particular a spherical cap and a conical panel. It is found that snapping, which is the main characteristic of the actual continuous structures, is successfully captured by the proposed simulations, which following a straightforward nonlinear approach are found to exhibit dynamic snap-through buckling, associated with a point attractor response in the large, implying global stability. Furthermore, the presence of physically not accepted complementary equilibrium configurations does not affect the long term response of the autonomous systems dealt with, but only complicates the motion and elongates the time before the final steady state. Finally, the criterion of zero total potential energy yields excellent lower bounds of the exact dynamic buckling loads, very important for structural design purposes.


ABSTRACT: The buckling of a finite section of a cylindrical shell resembling a two-dimensional contact lens, and the collapse of a tubular shell of infinite extent are considered. The deformation is due, respectively, to the application of an edge force or to a negative transmural pressure. In both cases, the shell develops elastic bending moments due to the deformation from a specified resting shape according to a linear constitutive equation, accompanied by in-plane and transverse shear tensions. In the case of a section of a shell with a flat resting shape, classical results due to Euler and Love show that, as the applied edge force is increased beyond a sequence of thresholds, an infinite family of deformed shapes becomes possible corresponding to buckled states that bifurcate from the zero-curvature resting configuration. It is shown here that a corresponding infinite family of shapes is also possible for a finite shell whose resting shape is a section of circle. These shapes, however, no longer arise from bifurcations, but rather constitute disconnected solution branches of a nonlinear boundary-value problem. A closed cylindrical shell whose cross-section has a circular resting shape exhibits similar bifurcations when the difference between the exterior and interior pressure exceeds a sequence of thresholds, but a shell with a non-circular resting shape deforms into a multitude of shapes described by isolated solution branches. The computed two-dimensional buckled shapes are used to reconstruct the three-dimensional shape of a slowly collapsing fluid-conveying vessel. The reconstruction procedure involves stacking together cross-sections at axial positions that are found by integrating the differential equation determining the axial pressure distribution in unidirectional pressure-driven flow, subject to a constant flow rate. The dimensionless coefficient
relating the local pressure gradient to the flow rate is computed by solving the Poisson equation governing unidirectional viscous flow using a boundary-element method, and expressing the flow rate as a boundary integral involving the shear stress which is available from the solution of the boundary-integral equation. In an appendix, the energy of the bending state is discussed with reference to specific choices made by previous authors in various branches of science and engineering.

References listed at the end of the paper:

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ABSTRACT: The buckling and collapse of empty and liquid-filled thin-wall cylindrical tubes resting on a horizontal or inclined plane is considered. The deflection is due to the action of gravity causing the tube to deform under the influence of its own weight, or due to a negative transmural pressure pushing the tube inward on the outside. Classical thin-membrane theory is used to formulate a boundary-value problem describing the shell deformation, and the results illustrate families of deformed shapes of inextensible shells with point or segment contact occurring between the shell and the supporting surface or between two collapsed sections of the shell. The computed two-dimensional deformed shapes are used to reconstruct the three-dimensional shape of a slowly collapsing fluid-conveying vessel in the absence of significant hydrostatic pressure variations over the cross section.  

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C. Pozrikidis (Department of Chemical Engineering, University of Massachusetts, Amherst, MA 01003, USA), “Flow-induced deformation of an elastic membrane adhering to a wall”, International Journal of Solids and
ABSTRACT: The flow-induced deformation of a two-dimensional membrane with a circular unstressed shape clamped at the two ends on a plane wall at an arbitrary contact angle is considered. Working under the auspices of generalized shell theory, the membrane is allowed to develop in-plane tensions, transverse tensions, and bending moments determined by the curvature of the resting and deformed shapes. A system of ordinary differential equations governing the membrane shape is formulated, and the associated boundary-value problem is solved by numerical methods. Numerical results are presented to illustrate the deformation of a clamped membrane due to gravity or a negative transmural pressure. The shell formulation is coupled with a boundary-integral formulation for Stokes flow, and an efficient iterative scheme is developed to describe deformed equilibrium shapes of a membrane attached to a plane wall in the presence of an overpassing shear flow. Computations for different contact angles and shear rates reveal a wide variety of profiles and illustrate the distribution of the membrane tension developing due to the flow-induced deformation.


ABSTRACT: There is a need for reliable methods to determine approximate solutions of nonlinear continuous systems. Recently, it has been proved that finite–degree–of–freedom Galerkin–type discretization procedures applied to some distributed–parameter systems may fail to predict the correct dynamics. By contrast, direct procedures yield reliable approximate solutions. Starting from these results and extending some of these concepts and procedures, we compare the outcomes of these two approaches (the Galerkin discretization and the direct application of a reduction method to the original governing equations) with experimental results. The nonlinear planar vibrations of a buckled beam around its first buckling mode shape are investigated. Frequency–response curves characterizing single-mode responses of the beam under a primary resonance are generated using both approaches and contrasted with experimentally obtained frequency–response curves. It is shown that discretization leads to erroneous quantitative as well as qualitative results in certain ranges of the buckling level, whereas the direct approach predicts the correct dynamics of the system.

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PARTIAL INTRODUCTION: In this paper we study the global qualitative behavior of axisymmetric buckled states of homogeneous isotropic nonlinearly elastic shells that can suffer flexure, compression, and shear. Our model is geometrically exact in the sense that a geometric quantity, such as $\sin \theta$, is not replaced by an approximation such as $\theta$ or $\theta^3/6$...
“Parametric instabilities of nonlinearily viscoelastic cylindrical shells and rings subject to periodic hydrostatic excitations”, (date & publisher not given in the pdf file; most recent reference is 2005)

ABSTRACT: Refined theories for accurate predictions of the onset of the parametric instabilities and the ensuing post-critical solutions are employed to investigate on how these instabilities are influenced by commonly neglected effects in shells and rods such as inertia terms, shear deformations, and material nonlinearities (Antman, 2005; Antman and Calderer, 1987; Antman, 2001).

Parametrically excited systems are pervasive in mechanics (e.g., dynamic buckling of columns, rings and shells, water waves in vertically forced containers, stability of general motions). In particular, parametrically forced rings and cylindrical shells are of significant interest in engineering applications such as aircraft fuselages or turbo machineries where the forcing is represented by the gradient between the inner and outer pressures. Although the theory of parametrically excited linear discrete systems governed by linear ordinary differential equations is well established (Yukubovich and Starzhinskii, 1975; Nayfeh and Mook, 1979), a comprehensive theory of parametrically excited nonlinear systems is far from being achieved. Moreover, only a few works have treated parametrically excited structural systems taking into account inertia, geometric and material nonlinearities.

Among others, Bolotin (1964) studied the Mathieu equation with cubic nonlinearities while, more recently, Rand and co-workers (2004) have investigated nonlinear Mathieu equations with either quadratic damping or cubic springs. In the quadratically-damped Mathieu equation, they showed the existence of a secondary bifurcation in which a pair of limit cycles come together and disappear (a saddle-node of limit cycles). In parameter space, this secondary bifurcation appears as a curve which emanates from one of the transition curves of the linear Mathieu equation. Further, Rand (1996) studied a two-term truncation of a parametrically excited PDE, and showed, using averaging, that the normal form of the system exhibits a rich diversity of dynamical behaviors.

When dealing with parametric excitations in spatially continuous structural systems, to overcome discretization errors, that can be also qualitative in the worst scenario, there is a need to rigorously treat, e.g. via asymptotics, the governing parametrically forced PDE’s instead of dealing with their reduced-order counterparts (Lacarbonara, 1999). In the present work, an asymptotic multiple-scale treatment of parametrically forced nonlinear PDE’s, representative of cylindrical shells and rods suffering bending, extension and shear deformations, is presented. Considering nonlinearly visco-elastic cylindrical shells and rings under hydrostatic pressure, general results about the leading classes of motions are discussed; namely, breathing motions, shearless motions and general motions of shells and rings undergoing extension, bending and shear deformations.

It is shown that when the shell or ring are subject to uniform pulsating pressure with frequency being nearly twice the frequency…

References listed at the end of the paper:
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“...and transverse shear strains”, Composite Structures, Vol. 92, No. 12, November 2010, pp. 3011-3019, doi:10.1016/j.compstruct.2010.05.017
ABSTRACT: The onset of buckling in square laminated multi-layered composite plates, subject to unidirectional in-plane loads, is investigated within the framework of a generalized higher-order shear deformation theory suitable to capture significant transverse shear and thickness-wise deformation effects. The displacement field is expanded in a Taylor series of the thickness coordinate with arbitrary polynomial degree; in turn, the series coefficients, expressed as a superposition of admissible functions, are determined according to the Rayleigh–Ritz method. Truly higher-order polynomial terms, along with a sufficient number of in-plane admissible functions, are shown to be necessary for convergence towards the fundamental buckling load multiplier. As a by-product, reduced-order models are identified for various plate geometries and lamination schemes. The sensitivity of the lowest buckling load with respect to the nondimensional parameters (the thickness ratio, the ratio between the elastic moduli, the ply angle) is investigated. In particular, the attention is focused on the cross-over phenomenon between the lowest two buckling eigenvalues in multi-layered composite square plates with different lamination schemes. The presented results shed light onto the buckling behavior of thick shear-deformable multi-layered plates.

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ABSTRACT: The general, statically and kinematically exact, six-field theory of branched shell structures, extended to nonlinear problems of shell dynamics involving also large overall motion, is discussed. The generalized Newmark algorithm on the proper orthogonal group SO(3) with Newton iterations is proposed. Numerical simulations of the behavior of an elastically twisted T-shaped shell structure in forced and free rotations with large overall motion are presented.


ABSTRACT: We propose a new four-node C0 finite element for shell structures undergoing unlimited translations and rotations. The considerations concern the general six-field theory of shells with asymmetric strain measures in geometrically nonlinear static problems. The shell kinematics is of the two-dimensional Cosserat continuum type and is described by two independent fields: the vector field for translations and the proper orthogonal tensor field for rotations. All three rotational parameters are treated here as independent. Hence, as a consequence of the shell theory, the proposed element has naturally six engineering degrees of freedom at each node, with the so-called drilling rotation. This property makes the element suitable for analysis of shell structures containing folds, branches or intersections. To avoid locking phenomena we use the enhanced assumed strain (EAS) concept. We derive and linearize the modified Hu–Washizu principle for six-field theory of shells. What makes the present approach original is the combination of EAS method with asymmetric membrane strain measures. Based on literature, we propose new enhancing field and specify the transformation matrix that accounts for the lack of symmetry. To gain knowledge about the suitability of this field for asymmetric strain measures and to assess the performance of the element, we solve typical benchmark examples with smooth geometry and examples involving orthogonal intersections of shell branches.


ABSTRACT: The paper summarises some findings on torsional buckling of thin-walled I-beam columns. The study is divided into two parts. Firstly, the effect of initial deflection on torsional buckling load of thin-walled I-beam column is discussed. Starting from the description of kinematics, strain and stress, the governing differential equations of torsional buckling are derived from the principle of stationary potential energy. The critical load of torsional buckling is determined with the aid of the perturbation approach. The numerical example concerning simply supported I-beam column is presented and discussed on the grounds of the theory of thin-walled members and compared with the result obtained from non-linear 6-parameter theory of shells. Secondly, the localisation of local buckling modes is studied. This effect, observed during the modelling by shell theory, strongly affects the I-beam columns behaviour with relatively wide flanges.
ABSTRACT: A 4-node C0 shell element with drilling degrees of freedom is presented in this paper. The element is developed within the nonlinear 6-field shell theory. Kinematics of the shell is described by two independent fields: the vector field for translations and the proper orthogonal tensor field for rotations. Within the theoretical formulation no restriction is applied on magnitudes of displacements and rotations. To avoid locking phenomena the proposed element combines two interpolation schemes: the assumed natural strain (ANS) for transverse shear strains and the enhanced assumed strain (EAS). The latter interpolation is used with asymmetric (in-plane) membrane strains. The performance of the element is evaluated by example of benchmark problems with special emphasis on shell structures containing orthogonal intersections.

ABSTRACT: The whole process of dynamic elastic-plastic analysis was carried out for Schwedler elliptical shell structure by using the theory of elastic-plastic finite element, and in combination with the force characteristics of reticulated shell. Its elastic-plastic aseismatic performance was explored. Emphasis is laid on the dynamic performance and failure modes of the shell structure when helped by BRB under strong earthquakes. The results show that BRB has a valid effect on the shell's elastic-plastic performance.

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[Co-citations]

ABSTRACT: Stability analysis of the radial pulsations of a gas microbubble that is encapsulated by a thin viscoelastic shell and surrounded by an ideal incompressible liquid is carried out. Small axisymmetric disturbances in the microbubble shape are imposed and their long and short term stability is examined depending on the initial bubble radius, the shell properties, and the parameters, i.e., frequency and amplitude, of the external acoustic excitation. Owing to the anisotropy of the membrane that is forming the encapsulating shell, two different types of elastic energy are accounted for, namely, the membrane and bending energy per unit of initial area. They are used to describe the tensions that develop on the shell due to shell stretching and bending, respectively. In addition, two different constitutive laws are used in order to relate the tensions that develop on the membrane as a result of stretching, i.e., the Mooney-Rivlin law describing materials that soften as deformation increases and the Skalak law describing materials that harden as deformation increases. The limit for static buckling is obtained when the external overpressure exerted upon the membrane surpasses a critical value that depends on the membrane bending resistance. The stability equations describing the evolution of axisymmetric disturbances, in the presence of an external acoustic field, reveal that static buckling becomes relevant when the forcing frequency is much smaller than the resonance frequency of the microbubble, corresponding to the case of slow compression. The resonance frequencies for shape oscillations of the microbubble are also obtained as a function of the shell parameters. Floquet analysis shows that parametric instability, similar to the case of an oscillating free bubble, is possible for the case of a pulsating encapsulated microbubble leading to shape oscillations as a result of subharmonic or harmonic resonance. These effects take place for acoustic amplitude values that lie above a certain threshold but below those required for static buckling to occur. They are quite useful in providing estimates for the shell elasticity and bending resistance based on a frequency/amplitude sweep that monitors the onset of shape oscillations when the forcing frequency resonates with the radial pulsation, $\omega_f = \omega_0$, or with a certain shape mode, $\omega_f = 2\omega_n$. An acceleration based instability, identified herein as dynamic buckling, is observed during the compression phase of the pulsation, evolving over a small number of periods of the forcing, when the amplitude of the acoustic excitation is further increased. It corresponds to the Rayleigh-Taylor instability observed for free bubbles, and has been observed with contrast agents as well, e.g., BR-14. Finally, phase diagrams for contrast agent BR-14 are constructed and juxtaposed with available experimental data, illustrating the relevance and range of the above instabilities.
ABSTRACT: Two new finitely deformed dynamical beam models are established for serious study on non-linear vibrations of thick beams subjected to arbitrarily given external loads. The total potentials of these beam models are non-convex with double-well structures, which can be used in post-buckling analysis and frictional contact problems. Dual extremum principles in unstable dynamic systems are developed. A pure complementary energy principle (in terms of the second Piola-Kirchhoff type stress only) in finite deformation mechanics is actually constructed. An interesting triality theory in post-buckling analysis is proved. This theory shows that if the gap function introduced by Gao and Strang in 1989 in positive, the generalized pure complementary energy has only one saddle point, which gives a global stable buckling state. However, if the gap function is negative, the generalized complementary energy may have two so-called super-critical points: the one which minimizes the pure complementary energy gives another relatively stable buckling state; and the other one which maximizes the complementary energy is an unstable buckling state. Application in unilateral buckling problem is illustrated, and an analytic solution for non-linear complementarity problem is obtained. Moreover, the general duality theory proposed recently is generalized into the non-linear dynamical systems. A pair of dual Duffing equations are obtained.

References listed at the end of the paper:

ABSTRACT: This paper treats the finite axisymmetric deflection and snapping of spherical caps which are point loaded at the apex and simply supported at the boundary. The problem is formulated using a stationary potential energy principle and solved numerically. The response of caps up to critical loads and into the postbuckling regime to eversion and beyond is studied and detailed. Phenomena such as snapthrough, snapback, multiple load free equilibria, aversion and irreversibility, are found to occur.


ABSTRACT: A theory for the axisymmetric deformation of isotropic, hyperelastic circular plates which is valid for arbitrarily large strains and rotations is developed. The theory is implemented numerically and used to perform an extensive analysis of uniformly-loaded circular plates with hinged and clamped edges. Particular
attention is paid to large-strain and large-rotation effects.


ABSTRACT: This paper presents a study on the use of the tension field theory for efficient representation of textiles. A highly buckled membrane model provides the simplest approach for visualization of vertical fabrics. The differential equation of tension lines gives the outline of the wrinkles. An equation system is presented, which, when iteratively solved supplies the basic variables of realistic fabric displacements: the number and positions of wrinkles, and the wrinkle depth. The model can also represent important physical characteristics of textiles, as malleability, elasticity and weight. However the tension field theory does not attempt to describe the field of displacements normal to the membrane surface, which are the main point of the work here presented. Experimental measures have been developed as a way to verify the adequacy of the equations and to subsidize empirical propositions for improvement of the model. How to use this approach for textile visualization is the objective of this work. Although the original theory is complex, the resulting algorithm is simpler and faster than many numerical treatments already used for prediction of the cloth aspect. The idea is to nd a simple realistic model that turns possible the addition in the displacement field of other important necessities of the fashion industry like animations and textures.

References listed at the end of the paper:
ABSTRACT: This paper presents a study on the use of the tension field theory for efficient representation of fabrics. A highly buckled membrane model provides the simplest approach for visualization of vertical fabrics. The differential equation of tension lines gives the outline of the wrinkles. An equation system is presented, which, when iteratively solved supplies the basic variables of realistic fabric displacements: the number and positions of wrinkles, and the wrinkle depth. The model can also represent important physical characteristics of textiles, as malleability, elasticity and weight. Experimental measures have been developed as a way to verify the adequacy of the equations and to subsidize empirical propositions for improvement of the model. How to use this approach for textile visualization is the objective of this work. Although the original theory is complex, the resulting algorithm is simpler and faster than many numerical treatments already used for prediction of the cloth aspect. The idea is to find a simple realistic model that turns possible the addition in the displacement field of other important necessities of the fashion industry like animations and textures.

References listed at the end of the paper:


ABSTRACT: True membranes are no-compression structures which exhibit the unique response of wrinkling. Prediction of the associated wrinkle parameters is of practical importance. Accurate measurement of membrane wrinkling has heretofore not been presented in the literature; among other requirements, noncontact methods must be used. First, some background information on membrane wrinkling prediction and measurement is given. Then, an experimental apparatus is discussed within which a membrane was subject to planar loading. The measurement system consisted of a capacitance-based noncontact displacement sensor mounted in an XYZ frame. A computer controlled the forces applied to the membrane, as well as the motion of the XYZ frame during data acquisition. Results are presented and conclusions are drawn regarding the wrinkle parameters.


ABSTRACT: We investigated solvent induced transition of surface instability from wrinkles to creases in poly(2-hydroxyethyl methacrylate) (PHEMA) gels with depth-wise crosslinking gradients. The mode of surface instability and morphology of surface patterns was found to be dependent on the equilibrium linear expansion, which was a function of crosslinker concentration and the solvent–polymer interaction. The maximum linear expansion was obtained when the PHEMA film was swollen in a good solvent, which had the Hildebrand solubility parameter ($\delta_s$) close to that of PHEMA gels, 26.6 to 29.6 MPa$^{1/2}$. In a relatively poor solvent (e.g. water), wrinkling patterns were obtained and the morphology was determined by the concentration of the crosslinker, ethylene glycol dimethacrylate (EGDMA). In a good solvent, such as alcohol and alcohol/water mixture, the equilibrium linear expansion ratio increased significantly, leading to the transition from wrinkling to creasing instability. In an ethanol/water mixture, we systematically varied the ratio between ethanol and water and observed the transition from wrinkling to creasing when gradually adding ethanol to water, and the reverse transition when adding water in ethanol. The onset of the linear expansion ratio for creasing ($\alpha_{cw}$) was again found dependent on EGDMA concentration: $\alpha_{cw} \approx 2.00$ and 1.3, respectively, for gels with 1 and 3 wt% EGDMA. Finally, we demonstrated confinement of the creases by combining swelling and photopatterning.

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ABSTRACT: Approximate closed-form solutions are obtained for the static stress and deformation as well as
the stability of an orthotropic layered shell of revolution with properties which vary along the meridian and through the wall thickness. The shell is subjected to axisymmetrical load and temperature distributions. The nonlinear “prestress” or “pressurization” effect is taken into consideration. It is of interest that due to the nonhomogeneity of the shell wall significant bending stresses can occur far from support points. The asymptotic results agree with numerical values obtained from two computer programs using direct numerical methods, even for shells that are relatively shallow.


INTRODUCTION: Extensive plans are in progress for large structures in space applications, as discussed in the 2nd National Space Inflatables Workshop (1998). The consensus is that much of this will be possible only with inflatable structural elements. There are considerable challenges in the development of such devices as reliable tools. Analytical simulation can play a significant role in speeding the development and increasing the reliability. However, the analysis of an inflated tube undergoing large displacements is prohibitive for a direct calculation using thin shell theory. An evaluation of the approximate techniques in use for inflatables is given by Jenkins (1991). A comprehensive study of nonlinear shell theory is given by Libai and Simmonds (1998). However, a convenient method, both sufficiently accurate and numerically efficient, for dealing with the deployment of membranes and complex structures has not seemed to be available.

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ABSTRACT: Two experiments quantified the forces necessary for large deformation of an inflated cylindrical tube made of a material with a high elastic modulus. In the first experiment, the end force required to maintain a buckled cylinder at a given kink angle was determined. In the second experiment, the lateral force required to pinch the membrane symmetrically between two flat blades was measured. An approximate theory is used, based on the observation that during deformation the membrane conserves its initial zero Gaussian curvature in regions free of wrinkling. The novel feature is a simple approximation for the cross-sectional shape. This permits the volume of the deformed cylinder to be quickly calculated. For walls that have negligible extensional and bending energy, the potential energy consists of only the pressure multiplied by the volume and the work of the prescribed load. Minimization of this potential energy yields results for the indentation and buckling problems that are in reasonable agreement with the experimental measurements. For small displacements in the blade pinching experiment, the volume approximation overestimates the force. It is found that a local solution analogous to the Hertzian contact problem provides a better approximation. For the kinked tube with end loading, an interesting feature is a decrease in the load when the fold from one side contacts the opposite side of the tube. The calculations indicate that a minimum potential energy exists with the fold straight. For slightly larger kink angles, however, the fold buckles out of the plane of symmetry. The moment at the single kink, due to the end loads, remains between bounds from the analysis of a pressurized elastic tube with nonpositive stresses.
ABSTRACT: The motivation for this work is the need for efficient means of computing the deployment of large, inflatable, space structures. Recent work has been on the load-deformation properties of folded and rolled pressurized tubes. The approach is to use basic properties of thin shells to determine appropriate approximations for the deformed shape. This is then used in an energy formulation in which the work of the pressure and the external loads dominates. For some problems, the stretching of the tube wall is also significant. In the present work the behavior of a tube with symmetric rigid blade loading is considered. Previous results are inadequate for the moderate values of the blade displacement. A satisfactory solution is obtained with a modified shape function for the tube cross section and with elastic stretching of the wall.

ABSTRACT: With respect to an arbitrary configuration of a deformed structure, two sets of incremental equations are proposed for the deformation analysis of revolution shells and diaphragms loaded by both lateral pressures and the initial stresses produced in manufacturing. These general equations can be reduced to the simplified Koiter's Reissner-Meissner-Reissner (RMR) equations and the simplified Reissner's equations, when the initial stresses are set to zero. They can also be deduced to the total Lagrange form or the updated Lagrange form, respectively, as the structure is specified as the undeformed or the former-deformed configurations. These incremental equations can be easily transformed into finite difference forms and solved by common numerical solvers of ordinary differential equations. Some numerical examples are presented to show the applications of the incremental equations to the deep shell of revolution and the corrugated diaphragms used in microelectro-mechanical system (MEMS). The results are in good agreement with those from finite element method (FEM).

ABSTRACT: In this paper, we consider bifurcation from a circular cylindrical deformed configuration of a thick-walled circular cylindrical tube of incompressible isotropic elastic material subject to combined axial loading and external pressure. In particular, we examine both axisymmetric and asymmetric modes of bifurcation. The analysis is based on the three-dimensional incremental equilibrium equations, which are derived and then solved numerically for a specific material model using the Adams–Moulton method. We assess the effects of wall thickness and the ratio of length to (external) radius on the bifurcation behaviour. References listed at the end of the paper:


ABSTRACT: The problem of the finite axisymmetric deformation of a thick-walled circular cylindrical elastic tube subject to pressure on its external lateral boundaries and zero displacement on its ends is formulated for an incompressible isotropic neo-Hookean material. The formulation is fully nonlinear and can accommodate large strains and large displacements. The governing system of nonlinear partial differential equations is derived and then solved numerically using the C++ based object-oriented finite element library Libmesh. The weighted residual-Galerkin method and the Newton-Krylov nonlinear solver are adopted for solving the governing equations. Since the nonlinear problem is highly sensitive to small changes in the numerical scheme, convergence was obtained only when the analytical Jacobian matrix was used. A Lagrangian mesh is used to discretize the governing partial differential equations. Results are presented for different parameters, such as wall thickness and aspect ratio, and comparison is made with the corresponding linear elasticity formulation of the problem, the results of which agree with those of the nonlinear formulation only for small external pressure. Not surprisingly, the nonlinear results depart significantly from the linear ones for larger values of the pressure and when the strains in the tube wall become large. Typical nonlinear characteristics exhibited are the “corner bulging” of short tubes, and multiple modes of deformation for longer tubes.

References listed at the end of the paper:

Karl-Heinz Hoffmann and Nikolai D. Botkin (Center of Advanced European Studies and Research, Bonn, Germany), “A fully-coupled model of a nonlinear thin plate excited by piezoelectric actuators”, (Publisher and date not given in the pdf file; most recent citation is dated 1999)

ABSTRACT: A model describing oscillations of nonlinear thin plates excited by patches made of a piezoelectric ceramic is considered. The specific of the model is that the mutual coupling between elastic deformations and electric fields is assumed. Partial differential equations describing the model are stated and their solvability is proved. The question of homogenization when the number of the piezoelectric patches goes to infinity whereas their dimension goes to zero is discussed.

References listed at the end of the paper:

Ulrike G. K. Wegst (1) and Michael F. Ashby (2)
ABSTRACT: An optimised structure is one which uses the smallest quantity of the best material to perform its function, with adequate safety factor or margin for error. Structural optimisation occurs not only in mechanical engineering, but also in nature: plants with hollow stems or stalks gain a height advantage, and are thus more efficient, by approaching the optimum shape. Here we consider the optimisation of orthotropic tubes, typifying, in a mechanical sense, stalk and stem. The stiffness and strength of orthotropic tubes of initially circular section are reviewed, and diagrams are proposed which allow the optimum section shape to be selected.


ABSTRACT: Eight variations of higher-order transverse shear deformation (HTSD) theory were developed for composite shells. Three attributes were varied to produce the eight variations. These attributes include the order of the thickness expansions used to approximate the shell shape factors and the assumed linear displacement field and the nonlinearity of transverse shear strain. Several cylindrical shell problems were investigated using SHELL, a finite-element code with a 36 degree of freedom cylindrical shell element. MACSYMA, a symbolic manipulation code, was used to formulate the element independent stiffness arrays for each variation of the theory. When all nonlinear strain-displacement terms for transverse shear were included for thin shallow isotropic cylindrical shells, the theory predicted a more flexible response during collapse. Higher-order thickness expansions had negligible effect upon results for shallow shell problems investigated. For deeper shells, the linear displacement assumption prohibited the use of nonlinear strain-displacement relations for transverse shear strains. Thus, for deep shells nonlinearity was limited to in-plane strain-displacement relations.

References listed at the end of the dissertation:
Landon M. Kanner (Department of Civil Engineering, University of Virginia), “Inflation of strain-stiffening rubber-like thin spherical shells”, publisher and date not given in the pdf file. This is probably a thesis.)

ABSTRACT: In this paper, we investigate the predictions of several widely used strain-stiffening phenomenological constitutive models for the classical limit point instability that is well-known to occur in the inflation of internally pressurized rubber-like spherical thin shells (balloons). The shells are composed of incompressible isotropic nonlinearly elastic materials. For a variety of specific strain-energy densities that give rise to strain-stiffening in the stress-stretch response, the inflation pressure versus stretch relations are given explicitly and the monotonicity, or lack thereof, of the inflation curves is examined. While such results are known for constitutive models that exhibit a gradual stiffening (e.g. exponential and power-law models), our primary focus is on materials that undergo severe strain-stiffening in the stress-stretch response. In particular, we consider two recently developed constitutive models that reflect limiting chain extensibility at the molecular level. Results for classical models are also presented for comparison. It is shown that for materials with sufficiently low extensibility no limit point instability occurs and so stable inflation is then predicted for such materials. The results have a variety of aerospace applications, e.g. to deployable space structures and NASA Weather Balloons.

References listed at the end of the paper:

ABSTRACT: A theoretical and numerical analysis of rubber-like shells of revolution undergoing finite strains and finite rotations with the application to the problem of a spherical shell subject to a uniformly distributed internal pressure is presented. The comparison of the results corresponding to two different definitions proposed for the reference surface of deformed rubber-like shells, an asymptotical solution, and the membrane solution is presented, as well.

ABSTRACT: An approach for the derivation of two-dimensional strain energy density functions of incompressible, rubber-like shells of arbitrary geometry undergoing finite rotations and finite strains, including transverse normal strains, is presented. Transverse shear strains are neglected.

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doi: 10.1177/0095244310393930
ABSTRACT: In this study, the effect of compressibility on the nonlinear buckling of the simply supported polyurethane spherical shells subjected to an apical concentrated load is presented. The problem is strongly nonlinear both physically and geometrically. Since the closed form solution of the corresponding algebraical and differential equations is not possible, numerical methods are used unavoidably. The governing equations of the problem are converted to algebraical difference equations via the finite difference method and the obtained algebraical equations are solved numerically by using the Newton—Raphson method. Several numerical experiments corresponding to the various values of a thickness parameter, a depth parameter and a material constant related with the compressibility of polyurethane are performed and the force—apex deflection curves are drawn. Concluding remarks pertaining to the effect of the variation of the material constant related with the compressibility on the buckling loads and buckling deflections of the simply supported polyurethane spherical shells, subjected to an apical load, with various thicknesses and depths are presented.

ABSTRACT: Previously, the effect of compressibility on the nonlinear buckling behaviour of thin, polyurethane, simply-supported spherical shells subjected to apical loads has been presented without
considering the orders of the thickness and height of the spherical shells. In the meantime; it has been observed that although the variations of the thickness and height of the spherical shells do not affect the comments made for the effect of the compressibility on the buckling loads, they do affect the comments made for the effect of the compressibility on the buckling deflections considerably. In this study; combined effect of the compressibility, height and thickness on the buckling loads, buckling deflections and the apical load-apical deflection diagrams of polyurethane, thin, simply-supported spherical shells subjected to apical loads is investigated. Comparing the force-deflection diagrams corresponding to various values of the parameters pertaining to the compressibility of the material used, the height and the thickness of the shell; the variations of the buckling loads, buckling deflections and forms of the force-deflection diagrams corresponding to the various combinations of the mentioned parameters are discussed.

References listed at the end of the paper:
· Koçak AE, Yükseler RF (1999). Finite axisymmetric strains and rotations of shells of revolution with application to the problem of a spherical shell under a point load, 6th Annual International Conference on Composites Engineering, Florida, 421-422.

ABSTRACT: (not available)

SUMMARY: The great interest of mixed, hybrid, or complementary energy principles lies in the search of more refined stress-fields than by use of the primal method, in particular in zones of high stress-gradients. Moreover the accuracy of the stresses is of primary importance in buckling and post-buckling problems.
After having recalled the author’s extension of the buckling criterion to various mixed principles by means of a very general method, one applies these criteria to the case of thin elastic or elastoplastic shells without shear strain, and in particular in the case of a surface principle of complementary energy with finite rotation. It is also provided post-buckling formulae for mixed principles in the classical cases of limit points or symmetric and asymmetric bifurcation point with or without imperfections. The criteria can be applied through a partitioning primal-mixed strategy.

References listed at the end of the paper:

47. Marcal P.V. Finite element analysis with material non-linearities. Theory and Practice. MARC CDC Background papers.


ABSTRACT: The computational problem of shell structures in large displacements and large rotations has prompted numerous theories and approximations. The introduction of the finite rotation was successfully realized in 1972 by Fraeijs de Veubeke in three-dimension, and led to the creation of a dual nonlinear variational principle where the stresses as new unknowns were statically admissible. Following this line, its extension to shells, though not so easy, allows to provide statically admissible surface stresses. Now stability problems are directly governed by accurate stresses, and particularly in case of shells. After a recall of the dual variational principle for shells with large displacements, finite rotations and transverse shear deformations, a dual theory of stability is developed, namely the stability criterion and the post-buckling in the dual theory.


ABSTRACT: Dual nonlinear stability of a new kind of thin concrete shell-spherical steel-concrete ribbed shell-is analyzed, and critical loads are determined by all course tracing, considering double nonlinear geometrical and material nonlinear. A comprehensive parametric stability analysis of composite ribbed shell with various geometric parameters has been carried out. The critical loads and the unstable areas distribution are discussed thoroughly. Based on these results, the behaviors of nonlinear stability are concluded, the change trend of critical loads and instability mode under different situation are obtained, and at last the degree of critical loads decreasing is defined under initial imperfection.

Kevin J. Silva (School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, Ohio), “Finite
Element Investigation of a Composite Cylindrical Shell Under Transverse Load with through Thickness Shear and Snapping”, Master’s Thesis, December 1989

ABSTRACT: The static response of a circular cylindrical open shell (curved panel) constructed of an orthotropic graphite/epoxy laminate is numerically investigated in this thesis. The shell is subjected to an inward point load, centered on and normal to the shell surface, which maintains its original orientation through deformation (i.e. dead load). The shell displacement response is seen to vary widely with shell geometry and boundary conditions, not only in magnitude of deformation but also in the nature and progression of the collapse under critical load. The finite element analysis is conducted with a quasi-two dimensional thin shell element which incorporates parabolic transverse shear stress through the thickness. The element can be formulated with either large displacement/rotation kinematics or the simpler Donnell relations. To enable tracking through critical load and displacement points and investigation of the post-critical regime, a solution algorithm other than the popular Newton-Raphson technique with displacement control or load control is required. The algorithm employed here uses a modified Riks/Wempner technique. It allows continuous tracing of the load-deflection response through critical load and critical displacement points. Step size is automatically scaled to follow the solution path closely in the areas of large load or displacement changes which surround critical points.

References listed at the end of the thesis:

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ABSTRACT: Guided by the three-dimensional theory of coupled thermoelasticity with second sound, a system of shear-deformable shell equations is consistently derived in invariant, differential and variational forms for the high-frequency vibrations of temperature-dependent materials. The first part of the paper is concerned with a unified variational principle describing the fundamental equations of thermoelasticity. The differential type of variational principle is presented by expressing Hamilton's principle for the thermal part of a thermoelastic region and then combining it with its mechanical part. In the second part, the hierarchic system of non-isothermal shell equations is systematically established by use of the variational principle together with
Mindlin's kinematic hypothesis for shells. The system of two-dimensional approximate equations which may take account of all the significant mechanical and thermal effects, including the temperature dependency of material, governs the extensional, thickness-shear, flexural and torsional as well as coupled vibrations of shells of uniform thickness. Lastly, in the third part, emphasis is placed on certain cases involving special material, geometry and kinematics. Besides, a theorem is devised so as to enumerate the initial and boundary conditions sufficient for the uniqueness in solutions of the system of non-isothermal shell equations.

ABSTRACT: This note derives an analytical relationship for an inextensible network when it buckles. According to the relationship, the applied compressive force can be determined according to the maximum absolute values of deflection and angle of deflection in the network's wrinkles.

ABSTRACT: The existence of stable solutions for geometrically nonlinear theory of shells has been widely discussed by mechanicians during the last century. But, certainly because of the difficulty met in the classical three dimensional nonlinear elasticity, few mathematical results have been obtained. A possibility is to apply the polyconvexity introduced in nonlinear elasticity by J. Ball [1] to ad'hoc shell theories. But unfortunately the positive results are restricted to a special class of materials. Another approach consists in using the so-called G-convergence. This theory has been suggested by the italian school (E. De Giorgi and G. Dal Maso, [9]), and an application to shell models has been given by H. Ledret and A. Raoult [19]. But the main drawback, in our opinion, is that the solution transgresses the equilibrium equations and the difficulty is to make sense to the model obtained. Therefore, it is not yet possible to use these results for the physical problem to be solved. In this paper, we suggest another theory based on some nonlinear mathematical tools which have already been used for particular shell models in [12]. The first part gives a formulation of a general geometrically nonlinear shell model based on a full description of the large kinematical movement induced by a Kirchhoff-Love field. The objectivity property is checked for a class of materials (energy invariance under the only effect of a nonlinear rigid body motion). Then the existence of stable solutions is proved using minimizing sequences and some mathematical tricks based on compactness of few nonlinear terms.

ABSTRACT: The paper presents some results from a study being undertaken at Liverpool into the application of laser welding technology to the design and fabrication of blast and impact resistant structures in the transportation industries. A novel facility has been developed at Liverpool for analysis of dynamic pressure loading of structures, such as aircraft fuselage panels. In the initial work to compare riveted and laser welded panels, the study has included experiments to lap weld AA2024-T3 sheet with both CO2 and YAG lasers, initial
dynamic loading tests on a riveted panel, quasi-static and uniaxial tensile tests on laser welded and riveted AA2024-T3 specimens and FE modelling of the trial riveted structures under loading. In conclusion, more consistent weld penetration on lap joints of 1.6mm thick alloy were obtained with a 3.5kW Nd:YAG laser, than a CO2 laser of equivalent power. Initial tests on a riveted panel identified some boundary conditions and failure loads for future tests. Uniaxial tests on laser welded and riveted specimens of AA2024-T3 indicated that the laser-welded joints have higher strength per unit joint length than the riveted ones, but exhibit more brittle failure. For the initial test panel, failure under dynamic loading occurred at a peak pressure of only 0.6 bar. The FE models of the preliminary tests compare well with experiment, based on mid-panel displacement measurements, but need further development to account for weak points in the frames where the test panel eventually failed.

References listed at the end of the paper:


ABSTRACT: The main aim of the work reported in this paper was to assess the response of panels representative of aircraft structures, to pulse pressure loading by means of experimental and finite element (FE) techniques. A series of experiments were conducted to compare the responses and failure modes of stiffened, aluminium alloy panels, joined using conventional riveting techniques and laser welding. The failure pressures of the riveted panels ranged from 29 to 36 kPa and a number of principal modes of failure were identified, namely (1) rivet shear/tensile failure, (2) frame buckling, (3) stringer buckling and (4) frame rupture. In the case of the laser-welded panels, failure pressures were between 28 and 33 kPa and failure was dominated by significant tearing along the weld heat affected zone at the frame–skin interface. The FE models correctly modelled most of the principal modes of failure observed experimentally and central panel displacement was also predicted well up until the time at which failure initiated.


ABSTRACT: Results from experiments on partially restrained corrugated panels exposed to uniformly distributed quasi-static pressure loading are presented. The corrugated panels were 910 mm long and 880 mm wide, with semi-rigid connections top and bottom, and free sides. The corrugated profile was asymmetric with a pitch of 220 mm. Three types of boundary connections were investigated which offered varying levels of support flexibility, and all failed due to localised buckling at the centre of the corrugations. The results are compared to finite element modelling predictions.


ABSTRACT: Applying the uniform-approximation technique, consistent plate theories of different orders are derived from the basic equations of the three-dimensional linear theory of elasticity. The zeroth-order approximation allows only for rigid-body motions of the plate. The first-order approximation is identical to the classical Poisson-Kirchhoff plate theory, whereas the second-order approximation leads to a Reissner-type
theory. The proposed analysis does not require any a priori assumptions regarding the distribution of either
displacements or stresses in thickness direction.

ABSTRACT: This writing is meant to restitute — a year later, to the best of my recollection — the contents of a series of six lectures I gave in Udine, at the Centro Internazionale di Scienze Meccaniche, within the framework of the Course on Classical and Advanced Theories of Thin Structures: Mechanical and Mathematical Aspects (June 5–9 2006). For this reason, I have made an effort to keep my presentation style informal and colloquial, even when, here and there, I have added some complementing material. There are three parts. In the Premiss, I try and explain why and how, to my taste, the mechanics of thin structures should be presented; in particular, I introduce the direct and deductive approaches and I collect a few bits of history of the latter, in its two main variants, the asymptotic method and the method of internal constraints. Section 2 is devoted to an exposition of the method of formal scaling, a unified approach to classic rod and plate theories that is an outgrowth of the method of internal constraints. Finally, in Section 3, I discuss how to best approximate the stress field in a linearly elastic structure-like body, by exploiting the freedom in the choice of reactive stress fields that maintain the constraints.

ABSTRACT: Structural design is a mature field of engineering. The relatively recent efforts for lightweight structures have motivated increasing use of formal mathematical optimization techniques for selecting the shape and sizes of structural members. How to obtain rigorous optimal topologies has been an elusive goal until the very recent introduction of the homogenization method. The present article describes a system for designing complete structures from only an initial space and loading specifications. A three-phase design process is followed: generate an approxiamate topological image with homogenization, process the image to obtain a practical realistic structure, and refine the final topology by detailed shape and size optimization. An overview of the system at its present state of development is given together with some examples.

ABSTRACT: Out-of-plane deformations of paper, such as fluting, significantly deteriorate the quality of a printed product. There are several explanations of fluting presented in the literature but there is no unanimously accepted theory regarding fluting formation and retention which is consistent with all field observations. This paper first reviews the existing theories and proposes a mechanism that might give an answer to most of the questions regarding fluting. The fluting formation has been considered as a post-buckling phenomenon which has been analysed with the help of the finite element method. Fluting retention has been modelled by introducing an ink layer over the paper surface with the ink stiffness estimated from experimental results. The impact of fast drying on fluting has been assessed numerically and experimentally. The result of the study suggests that fluting occurs due to small-scale hygro-strain variations, which in turn are caused by the moisture variations created during fast convection (through-air) drying. The result also showed that ink stiffening alone
cannot explain the fluting amplitudes observed in practice, but that high drying temperatures promote inelastic (irreversible) deformations in paper and this may itself preserve fluting.

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ABSTRACT: A tensegrity structure is a special truss structure in a stable equilibrium, with selected members designated for only tension loading, and the members in tension form a continuous network of cables separated by a set of compressive members. This paper develops an explicit analytical model of the nonlinear dynamics of a large class of tensegrity structures, constructed of rigid rods connected by a continuous network of elastic cables. The kinematics are described by positions and velocities of the ends of the rigid rods, hence, the use of angular velocities of each rod is avoided. The model yields an analytical expression for accelerations of all rods, making the model efficient for simulation, since the update and inversion of a nonlinear mass matrix is not required. The model is intended for shape control and design of deployable structures. Indeed, the explicit analytical expressions are provided herein for the study of stable equilibria and controllability, but the control issues are not treated in this paper.

ABSTRACT: Tensegrity structures consist of strings (in tension) and bars (in compression). Strings are strong, light, and foldable, so tensegrity structures have the potential to be light but strong and deployable. Pulleys, NiTi wire, or other actuators to selectively tighten some strings on a tensegrity structure can be used to control its shape. The article describes some principles we have found to be true in a detailed study of mathematical models of several tensegrity structures. We describe properties of these structures which hold quite generally. We describe how pretensing all strings of a tensegrity makes its shape robust to various loading forces. Another property asserts that the shape of a tensegrity structure can be changed substantially with little change in the potential energy of the structure. Thus shape control should be inexpensive. This is in contrast to the control of classical structures which require substantial energy to change their shape.

References listed at the end of the paper:
communication.


ABSTRACT: This paper summarizes the literature on reconciliation of finite element analyses with in-plane bending experiments on piping elbows. It then describes in detail two four-point-bending tests on straight pipes and two in-plane bending tests on elbows and the corresponding nonlinear finite element analyses. Using a new procedure for obtaining a stress-strain curve for stainless steel using only values for E, Sy, and Su and a representative stress-strain curve from a test on a similar material specimen, the nonlinear responses of the piping components tested are shown to be simulated more accurately than previously published results.


ABSTRACT: Most design codes for circular shell structures include a limit on out-of-round imperfections. However, commonly used measures of out-of-roundness fail to identify shapes that have constant diameter but are not circular. It is shown that out-of-roundness imperfections that take these forms can significantly affect the strength of nominally circular shell structures. An alternative measure of out-of-roundness is proposed that captures all out-of-round shapes, gives the same measure of out-of-roundness for elliptical structures as currently used measures and is easy to apply.


ABSTRACT: To get in touch with mesh refinement techniques a program is developed to perform such a mesh refinement for the STAGS-A computer code. After consulting some articles on this subject I decided to use the so-called strain energy density method. To illustrate the working of the program a few examples are dealt with. These examples prove the mesh refinement program to yield excellent results for values of N (rows x columns) small compared to the ones found in the traditional way of calculating. Finally in Appendix 1 the input and output files for this program are described and explained.
ABSTRACT: In the first stage of sheet metal stamping, a binder ring, an annular surface surrounding the die cavity, clamps down on the flat blank, bending it to a developable binder wrap surface which may be smooth or buckled. Buckles generally appear in the binder wrap when the binder ring does not lie on a smooth developable surface that spans the die cavity. However, sometimes buckles can improve the formability of the stamped part, so the ability to design buckled developable surfaces becomes desirable. Designing buckled developable surfaces requires geometric modeling of creases and other singularities in the interior a flat sheet. In this paper we review the properties of such surfaces, show how to approximate buckled binder wrap surfaces by developable three-dimensional triangulations and discuss the insights gained from specific examples.


ABSTRACT: Cardboard honeycomb energy dissipating material (EDM) is used extensively for protection of cargo that is air dropped. Whilst air dropped containers are deployed with parachutes, a significant amount of energy still requires dissipating on impact with the ground. The specification of cardboard EDM in dynamic applications has tended to be ad-hoc with no thorough understanding of the energy absorbing characteristics of the material. This paper seeks to address this gap in knowledge.


ABSTRACT: In this paper, based on the theory of Donnell-type shallow shell, a new displacement-type stability equations is first developed for laminated composite circular conical shells with triangular grid stiffeners by using the variational calculus and generalized smeared stiffener theory. The most general bending stretching couplings, the effect of eccentricity of stiffeners are considered. Then, for general stability of composite triangular grid stiffened conical shells without twist coupling terms, the approximate formulas are obtained for critical external pressure by using Galerkin's procedure. Numerical examples for a certain C/E composite conical shells with inside triangular grid stiffeners are calculated and the results are in good agreement with the experimental data. Finally, the influence of some parameters on critical external pressure is studied. The stability equations developed and the formulas for critical external pressure obtained in this paper should be very useful in the astronautical engineering design.

References listed at the end of the paper:

PARTIAL INTRODUCTION: Great attention is being paid to the problems of stability of revolution shells made of composite materials when they are loaded by axial compressive stresses. The published material generally deals, as shown in [1-4], with theoretical studies. In the present work we describe the method and results of testing slightly conical axially loaded shells made of glass-carbon- and synthetic-fiber-reinforced plastics; the experimental results and calculated data are also compared...

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“Dynamic crushing characteristics of high strength steel cylinders with elliptical geometric discontinuities”, Theoretical and Applied Fracture Mechanics, Vol. 54, No. 1, August 2010, pp. 44-53
doi:10.1016/j.tafmec.2010.06.014
ABSTRACT: Thin-walled members are commonly used as energy absorbers in engineering structures and often contain cutouts. This study performed numerical simulations of high strength steel cylindrical shells with elliptical cutouts subjected to dynamic axial impact. The LS-DYNA code was the primary analytical tool used to analyze the influence of cutout locations, cutout shapes and symmetry of cutout on the energy absorption capabilities and the crush characteristics of tubes with a cutout. For high strength steel tubes made from a rate sensitive material, the stress–strain curves of different strain rates were used to elucidate the effect of dynamic impact on the strain rate. Our results show that collapse crushing behavior is strongly influenced by the location and symmetry of cutouts and the variation of major axis influences the peak crush load.

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ABSTRACT: Composite tubes can be reinforced with continuous fibers. When such tubes are subjected to crushing loads, the response is complex and depends on interaction between the different mechanisms that control the crushing process. The modes of crushing and their controlling mechanisms are described. Also, the resulting crushing process and its efficiency are addressed.

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ABSTRACT: The properties of fibre-reinforced composite straps and struts that are used for thermal isolation and mechanical support of cryogenic systems are reviewed. The review includes compilation and discussion of the mechanical (tension, compression, fatigue) and thermal (contraction, conductivity, specific heat) aspects of both structures. The role of fibre lay-up is discussed, and the two types of support modes are compared.

doi: http://doi.ieeecomputersociety.org/10.1109/ICIC.2009.359
ABSTRACT: The plastic buckling calculation of the centrifugal concreted-filled steel tubes under torsion was derived from the cylindrical shells with spiral stiffeners analogy. In applying the analogy, it is assumed that
Ahmed Elmarakbi and Niki Fielding (Department of Computing, Engineering & Technology, Faculty of Applied Sciences University of Sunderland, Sunderland, SR6 0DD, United Kingdom), “New Design of Roadside Pole Structure: Crash Analysis of Different Longitudinal Tubes using LS-DYNA”, 7th European LS-DYNA Conference, 2009, DYNAmore GmBH

ABSTRACT: This paper is an investigation into the design of an energy absorbing street pole, concerning the frontal impact of a vehicle. With design engineers now are looking at other ways to improve vehicle occupant safety by focusing on the advantages that can be achieved by improving the crashworthiness of street furniture. The study of axial crush behaviour of metal materials are investigated along with a number of variables such as cross-sectional shape, shell thickness, materials, as well as the velocity affects on tubes. Different simulations are carried out on the effects of bedded crumple initiators placed a various heights from the top of the tube, in determining the desired value of peak load reduction, along with the effect in energy absorption of the tube. With the conclusion of the desired variables for the design of an energy absorbing tube, the tubes are placed 90 degrees to that of the base of the model street pole to modify the pole design. Simulation of frontal impact of a vehicle and street pole are analysed and compared to that of the energy absorbing street pole concept. Studies are carried out by numerical simulation via the explicit finite element code LS-DYNA. Results compare the absorbed energy and the deflection of each variable, and recommend optimum design for the pole structure which improved vehicle crashworthiness.

References listed at the end of the paper:
[1] Department for Transport (http://www.dft.gov.uk/)
[7] NCAC. National Crash Analysis Centre (http://www.ncac.gwu.edu/about.html)


ABSTRACT: The high thickness of heads used in pressure vessels is always one of the main concerns of designers and manufacturers. A comprehensive analytical and experimental study has been conducted by the authors on all types of heads including torispherical heads (under external and internal pressure) to come up
with a procedure to reduce their thicknesses using stiffening-rings. The result of the experiments and Finite Element Analysis (FEA) on torispherical heads with pressure on their concave side are presented in this paper. A method for determining the dimensions of the most suitable ring and its location on heads as well as its effect on the reduction of head thickness is addressed. The experimental results show good agreement with the analytical calculations and confirm that suitable stiffening-rings, in most cases, could considerably reduce head thicknesses.

References listed at the end of the paper:


INTRODUCTION: All around us, in natural forms, art, architecture, engineering, and consumer products, we
find surfaces whose geometry is vastly richer than the Euclidean geometry we learn in high school. To treat surface geometry analytically requires rather advanced tools, but it is possible to gain much insight into the subject by performing measurements on the surfaces of physical objects. Beem [1] suggested some activities along these lines, and Henderson [6] has made ample use of physical models. Casey [3,4] has described a series of experiments that are designed to bring modern geometrical concepts within the reach of students who might no yet be in a position to study differential geometry formally. In the present paper, as an illustration, a method of estimating the Gaussian curvature of surfaces from surface measurements is described.

INTRODUCTION: This chapter is concerned with basic assumptions and equations of plates and basic concepts of elastic stability. Herein, we shall illustrate the concepts and the applications of these equations by means of relatively simple examples; more complex applications will be taken up in the following chapters.

ABSTRACT: The design and analysis of the large span steel latticed shell structure in site of Yuyao Tianluoshan is introduced, and some key problems are dwelled on in this paper. By the geometrical nonlinear finite element method, the nonlinear stability analysis is carried out. The buckling modal and the whole course of instability are shown by two analysis method, the eigen-buckling analysis and the geometrical nonlinear finite element method. The influence of spring support to the stability of the structure is analyzed. It is shown that the structure has good wind-resisting capacity, which is fit to the circumstance near sea with lots of typhoon. Large compressive membrane stresses arise in the structure under the condition of temperature rise, leading to a significant reduction in the stability load-carrying capacity of the structure.

ABSTRACT: In modern engineering there is a considerable interest in predicting the behavior of post-buckled structures. With current lightweight, aerospace, and high performance applications, structural elements frequently operate beyond their buckled load. This is especially true of plates, which are capable of maintaining stability at loads several times their critical buckling load. Additionally, even structures such as cylindrical shells may be pushed into a post-buckled range in these extreme applications. Because of the nature of these problems, continuation methods are particularly well suited as a solution method. Continuation methods have been extensively applied to a range of problems in mathematics and physics but have been used to a lesser extent in engineering problems. In the present work, continuation methods are used to solve a variety of buckling and stability problems of discrete dynamical systems, plates and cylinders. The continuation methods, when applied to dynamic mechanical systems, also provide very useful information regarding the modal behavior of the structure, including linearized natural frequencies and mode shapes as a by-product of the solution method. To verify the results of the continuation calculations, the commercial finite element code ANSYS is used as an independent check. To confirm stable equilibrium shapes for square plates, a set of experiments on polycarbonate plates is also presented.
References listed at the end of the dissertation:

Experimental results.

Numerical results.

Theoretical analysis.


ABSTRACT: To serve the common needs of the society, structural engineers should achieve impressive gains over high strength, light weighted, safe and economical structures. As rapid advances in the construction materials, in many situations, fibre reinforced polymer (FRP) composites provide opportunities for enhanced efficiency, primarily because of their high strength to weight ratio. They can also be combined with steels to form composites enabling them to be used as structural members and have become an attractive option which may produce a confident retrofitting of steel structures, attracting a great deal of attention in these recent years. Carbon fibre reinforced polymer (CFRP) is a comparatively new and revolutionary class of composite material manufactured from fibres and resins and has proven effect for the development of new as well as repairing of deteriorated material. The strength properties of CFRPs jointly make up one of the ultimate reasons for which civil engineers prefer them in the design of structures. However, like most structural materials, CFRPs have a few drawbacks that would create some doubts to civil engineers to apply it in practical field: brittle behaviour, susceptibility to deformation under long-term loading, UV degradation and temperature and moisture effects. Also, another downside to the age of these advanced composites is the relatively lower stiffness exhibited by CFRPs. As a consequence, serviceability rather than strength limit tends to provide the controlling influence on design. In the context of thin-walled shell structures, the relatively low stiffness to strength ratio of CFRP makes that buckling driven largely by elastic buckling behaviour and becomes the dominant design constraint. At this time, it becomes difficult to achieve the required levels of load carrying capacity by using shells constructed from just CFRP. For this reason too, the high stiffness of steel contributes to make it an attractive material for the design of shells in which buckling is likely to be an important issue. On the other hand, steel cylindrical shells when exposed to the hostile chemical on marine environments show their vulnerability to corrosion. That’s why a novel way to protect steel shells from corrosion and to make CFRP shells strengthened is to coat them with these veneers of suitable amount of CFRP. In this context CFRP, if collectively used with thin steel shells, the mechanical properties of the new composite material will be tremendously increased. Since the mechanical properties of CFRP make them ideal for widespread applications in construction of civil engineering field, buckling behaviour determines the relationship between strength, life span and economy of any structures. Also, it is necessary to introduce the fibres’ position, direction and volume in the matrix material at highly stressed regions in certain positions, direction and volume in order to obtain the maximum efficiency from the reinforcement to a minimal amount at a region of low stressed value. For this reason too, buckling mechanism is likely to be an important issue. Similarly, CFRP composite materials exhibit collapse modes that are significantly different from the collapse modes of steel materials. That’s why, investigation over strengthening of thin-walled steel shells with the application of small amount of CFRP could become an important issue. To lower down the downside of the lower stiffness exhibited by CFRP shells and to diminish the major problem associated with steel shells, a new composite sandwich structure has been introduced in this research and the effect of CFRP reinforcements under axial as well as lateral compression has been studied through three kinds of analytical procedures; the linear eigen value analysis, the modified RS (reduced stiffness) analysis and the fully non-linear numerical experiment, presenting a novel way of strengthening thin-walled steel cylindrical shells against buckling. With these multiple treatments, valuable information for the design of CFRP-based hybrid structural elements has been predicted and suggested the influence of CFRP to increase the load-carrying capacity of the thin-walled steel structures having complex buckling collapse behaviour. The research thesis has total 10 chapters. Firstly, a survey of recent FRP applications, objective of research and preliminary numerical equations has been derived. Secondly, the analytical model has been proposed and the analytical procedure related to the proposed model has been discussed. Thirdly, investigation as well as results has been predicted for nonlinear buckling behaviour, effects of reinforcement thickness and effects of angle of fibre orientation for both the lateral and axial loading conditions. Finally, these results are summarized in the conclusion part along with the suggestions for the better prediction of the result. 

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http://www.graduate.technion.ac.il/theses/Abstracts.asp?Id=22501
ABSTRACT: ElectroMechanical Buckling (EMB) is the bifurcation response which results from the coupling of electromechanical bifurcation and mechanical buckling. The work presented here is seemingly the first time ever this coupling is considered and analyzed. This work also includes a first ever experimental validation of EMB. Mechanical buckling occurs in slender structures that are subjected to an axial compressive load which is larger than a critical value. In this dissertation it is shown that an electrostatic field can instigate buckling even when the compressive load is below the critical value. The EMB voltage is a monotonically increasing function of the axial load. Motivated by this, a novel method for measuring residual stress in micro-structures is presented. This method enables to measure compressive as well as tensile stresses, in a continuous wide range. The EMB response of a pre-stressed slender microbeam that is bonded to a linear elastic foundation and is subjected to electrostatic forces is also investigated. In this dissertation it is shown that the EMB of such a microbeam can be used to achieve reversible, electrostatic on/off switching of surface flexures. In this work, the electromechanical buckling and postbuckling of a circular cylindrical micro shell that is subjected to a radial axi-symmetric electrostatic force is also investigated. It is found that the initial electromechanical postbuckling of such a micro shell is unstable for the range of parameters considered.

ABSTRACT: Fibre reinforced composite plates and shells are increasingly replacing traditional metallic ones. The manufacturing process and service of the composite laminates frequently lead to delamination. Delamination reduces the stiffness and strength of composite laminates because they allow out of plane displacement of plies to occur more easily. Dynamic stability analysis is an integral part of most engineering structures. The present work deals with the study of the effects of free vibration, buckling and dynamic stability of delaminated cross ply composite plates and shells. A first order shear deformation theory based on finite element model is developed for studying the instability region of mid plane delaminated composite plate and shell. The basic understanding of the influence of the delamination on the natural frequencies, non-dimensional buckling load and non-dimensional excitation frequency of composite plates and shells is presented. In addition, other factors affecting the vibration, buckling and dynamic instability region of delaminated composite plates and shells are discussed. The numerical results for the free vibration, buckling and dynamic stability of laminated cross-ply plates and shells with delamination are presented. As expected, the natural frequencies and
the critical buckling load of the plates and shells decrease with increase in delamination. Increase in delamination also causes dynamic instability regions to be shifted to lower excitation frequencies.


ABSTRACT: In several industries such as civil, mechanical, and aerospace, thin-walled structures are often used due to the high strength and effective use of the materials. Because of the increased consumption there has been increasing focus on optimizing and more detailed calculations. However, finely detailed calculations will be very time consuming, if not impossible, due to the large amount of degrees of freedom needed. The present thesis deals with a novel mode-based approach concerning more detailed calculation in the context of distortion of the cross section which model distortion by a limited number of degrees of freedom. This means that the classical Vlasov thin-walled beam theory for open and closed cross sections is generalized as part of a semi-discretization process by including distortional displacement fields. A novel finite-element-based displacement approach is used in combination with a weak formulation of the shear constraints and constrained wall widths. The weak formulation of the shear constraints enables analysis of both open and closed cell cross-sections by allowing constant shear flow. Variational analysis is used to establish and identify the uncoupled set of homogeneous and non-homogeneous differential equations and the related solutions. The developed semi-discretization approach to Generalized Beam Theory (GBT) is furthermore extended to include the geometrical stiffness terms for column buckling analysis based on an initial stress approach. Through variations in the potential energy a modified set of coupled homogeneous differential equations of GBT including initial stress is establish and solved. In this context instability solutions are found for simply supported columns and by solving the reduced order differential equations the cross-section displacement mode shapes and buckling load factor are given. In order to handle arbitrary boundary conditions as well as the possibility to add concentrated loads as nodal loads the formulation of a generalized one-dimensional semi-discretized thin-walled beam element including distortional contributions is developed. From the full assembled homogenous solution as well as the full assembled non-homogeneous solution the generalized displacements of the exact full solution along the beam are found. This new approach is a considerable theoretical development since the obtained GBT equations including distributed loading found by discretization of the cross section are now solved analytically and the formulation is valid without special attention and approximation also for closed single or multi-cell cross sections. Furthermore, the found eigenvalues have clear mechanical meaning, since they represent the attenuation of the distortional eigenmodes and may be used in the automatic meshing of approximate distortional beam elements. The magnitude of the eigenvalues thus also gives the natural ordering of the modes. The results are compared to results found using other computational methods taking distortion of the cross section into account. Thus, the results are compared to results found using the commercial FE program Abaqus as well as the free available software GBTUL and CUFSM concerning conventional GBT and the finite strip method, respectively. Reasonable matches are obtained in all cases which confirm that this new approach to GBT provides reasonable results with a very small computational cost making it a good alternative to the classical FE calculations and other available methods.

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ABSTRACT: The nonlinear vibrations of a thin, elastic, laminated composite circular cylindrical shell, moving in axial direction and having an internal resonance, are investigated in this study. Nonlinearities due to large-amplitude shell motion are considered by using Donnell's nonlinear shallow-shell theory, with consideration of the effect of viscous structure damping. Differently from conventional Donnell's nonlinear shallow-shell equations, an improved nonlinear model without employing Airy stress function is developed to study the nonlinear dynamics of thin shells. The system is discretized by Galerkin's method while a model involving four degrees of freedom, allowing for the traveling wave response of the shell, is adopted. The method of harmonic balance is applied to study the nonlinear dynamic responses of the multi-degrees-of-freedom system. When the structure is excited close to a resonant frequency, very intricate frequency-response curves are obtained, which show strong modal interactions and one-to-one-to-one-to-one internal resonance phenomenon. The effects of different parameters on the complex dynamic response are investigated in this study. The stability of steady-state solutions is also analyzed in detail.


ABSTRACT: This thesis studies the possibilities of determination of the critical buckling force of laminated composite cylindrical shells through analytical as well as through FEM approach. The analytical solution is presented in detail and a Matlab program is made to allow its calculation. FEM solutions are done using two different solvers of the MSC.Nastran software, the effects of different settings of the solvers are explored as well as the general behaviour of the solvers. All of the approaches are in the end compared and a several conclusions are proposed.

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“Experimental investigation on buckling of GFRP cylindrical shells subjected to axial compression”, Journal of Mechanical and Civil Engineering (IOSR-JMCE), Vol. 9, No. 5, pp 20-25, November-December 2013
ABSTRACT: Composite cylindrical shells are being used in submarine, underground mines, aerospace applications and other civil engineering applications. Thin cylindrical shells are more prone to fail in buckling rather than material failure. An experimental study on buckling of glass fiber reinforced plastics layered composite cylindrical shells under displacement and load controlled static axial compression are reported. The experimental results are compared with general purpose finite element program (ANSYS). Limit point loads evaluated for geometric imperfection magnitudes shows an excellent agreement with experimental results which clearly indicates the confidence gained on the numerical results presented. Present study finds direct application to qualitatively investigate the influence of geometric imperfection on other advanced grid-stiffened structures.

References listed at the end of the paper:

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ABSTRACT: The main key performance factors of honeycombs are represented by the ability to withstand through-thickness compression and to absorb energy by plastic deformation of the cell walls. The knowledge of the constituent material properties, including the sensitivity of these structures to material defects, and of the folding mechanism occurring during the crushing mode represents a basic step to perform reliable finite element analyses able to accurately reproduce the behavior of such structures. The present paper reports a comprehensive study of the compressive response of hexagonal honeycomb structures made of phenolic resin-impregnated aramid paper (Nomex); the compressive response is numerically investigated and compared with experimental results. A shell model of a representative single cell made of expanded Nomex has been created using the implicit ABAQUS finite element solver. Imperfections due to the manufacturing process are taken into account including material imperfections (elastic modulus variability) and geometrical defects (thickness variability). Imperfections are included in the model by defining different material and thickness properties for each element according to a pre-defined statistical distribution. The effects of imperfections on the honeycomb structure behavior are investigated. The predicted structural response, numerically obtained using different sets of imperfections, shows a good correlation with experimental results.

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ABSTRACT: The increasing number of successful applications of fibre reinforced polymer (FRP) laminates in realizing civil structures as well as their subsequent technological development have attracted the attention of the international scientific community, a special interest being given to understand in greater detail all aspects connected to the use of new materials. This paper deals to manufacture composite laminate by using glass fiber as reinforcing material and unsaturated polyester as matrix material. Here the investigation of critical buckling load has been done with changing the fiber orientation at succeeding lamina by 45°.

ABSTRACT: Wind turbine towers are belonging to towering cylinder shell structures, which are easy to appear buckling instability under wind or other complicated loads, and on which integral elastic-plastic buckling analyses have great theoretical and practical significances. This paper used large deflection nonlinear pre-buckling and Koiter initial post-buckling theories, and adopted the finite element scheme of updated integration algorithm and LDC nonlinear solution method, then analyzed the linear buckling, elastic-plastic static buckling, and post-buckling response of the towers with initial imperfections in different location and size. It has obtained that: 1) the critical load of towers with elastic-plastic buckling is much smaller than it with elastic buckling; 2) gravity has certain influence on the critical buckling load; 3) the critical buckling load is insensitive to initial imperfections, meanwhile the imperfections which located on the top or the bottom of the tower are inferior for the stability of tower.

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“Mechanical behavior of glass/epoxy tubes under combined static loading. Part I: Experimental”, Composites Science and Technology, Vol. 69, No. 13, October 2009, pp. 2241-2247, Special Issue: Smart Composites and Nanocomposites, doi:10.1016/j.compscitech.2009.06.009
ABSTRACT: A series of biaxial static tests of E-glass/epoxy tubular specimens [±45]2, subjected to combined torsion and tension/compression were performed to simulate complex stress states encountered in a wind turbine rotor blade. The failure locus in the effective axial-shear stress plane was derived experimentally while in-plane strain tensor components were measured in the tube outer surface. By means of shell theory and strain measurements in the surface of the specimen, the in-plane shear response of the outer ply was obtained, revealing dependence each time to the combined tube loading. The correlation established between the ratio of transverse normal and in-plane shear stress in the principal coordinate ply system and the elastic shear modulus, suggested a strong dependence, warning on the implications for design and certification procedures.

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ABSTRACT: Experimental results from a series of biaxial static tests of E-Glass/Epoxy tubular specimens [±45]2, were compared successfully with numerical predictions from thick shell FE calculations. Stress analysis was performed in a progressive damage sense consisting of layer piece-wise linear elastic behavior, simulating lamina anisotropic non-linear constitutive equations, failure mode-dependent criteria and property degradation strategies. The effect of accurate modeling of non-linear shear stress–strain response, dependent on the plane stress field developed, was proved of great importance for the numerical FEA predictions, concerning macroscopic stress–strain response. Ultimate load prediction was influenced more decisively when degradation strategies for the compressive strength along the fiber direction were considered.


INTRODUCTION: Many papers have been published and they have demonstrated that the finite strip method has higher efficiency than the finite element method as a smaller number of degrees of freedom are involved in the solution. The increase in the popularity and the number of potential applications of the finite strip method has created a demand for a definitive text/reference on the subject. Fulfilling this demand, The Finite Strip Method provides practicing engineers, researchers, and students with a comprehensive introduction and theoretical development, and a complete treatment of current practical applications of the method. This paper takes the review of some of the important paper finds conclusion that semi-energy FSM formulation is more economical compared to the full-energy FSM and FEM analyses.

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ABSTRACT: It has been previously demonstrated that increasing structural complexity can lead to lighter weight structures. However, it is not clear that structural complexity or hierarchy enables lighter weight structures for all architectures and load cases. In this paper, the performance trends in linear truss structures are investigated as a function of self-similar hierarchy order and of loading conditions. The investigations show the order of structural hierarchy resulting in a lightest weight self-similar four longeron solid element truss-column is 2nd (a truss made from trusses) for requirements representative of space structures. The resulting truss-column is typically an order of magnitude lighter than the corresponding 1st order truss-column and two to four times larger in diameter. Long and lightly loaded columns are shown to have the greatest potential for mass reduction with increasing hierarchy. Optimization results for 1st and 2nd order self-similar triangular single-laced double-bay trusses subject to bending strength and stiffness requirements are also presented. A comparison of 1st and 2nd order results show a factor of 30 reduction in truss mass and a simultaneous factor of nine increase in truss diameter.

References listed at the end of the paper:
5 Mikulas, Martin M., Bush, Harold G., and Card, Michael F., “Structural Stiffness, Strength and Dynamics Characteristics of Large


ABSTRACT: A new approach to the study of the effects of randomly distributed imperfections on grid-shell structures is presented. The simulation of randomly distributed out-of-scheme imperfections has been performed, introducing a kind of spatial correlation in order to avoid events that even if statistically possible, has to be considered not achievable from a pragmatic point of view. The fields of imperfections take into account the initial stress state of the imperfect structure that may appear as a consequence of the geometric perturbation. Some computational tests have been finally carried out on a sample structure.

Armeni, Giulia; Borri, Claudio; De Bartolomeis, Paolo; Di Naso, Vincenzo; Orlando, Maurizio, “Geodetic Domes for great-span structures: Mandela Forum Project proposal in Florence”, IABSE Symposium, Venice 2010: Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas , pp. 41-47(7), International Association for Bridge and Structural Engineering

ABSTRACT: The paper concerns the design of a new sports arena and in particular of a aluminium roof structure for the Mandela Forum, which is the major sports arena of Florence. The project key-element is the aluminium geodesic dome, chosen in order to set up a covering with optimal and functional structure and shape. The key topic discussed in this paper concerns the geometrical issue of the structural optimization, in fact comparing several types of iron framework domes, the geodesic one seemed to be the best choice, as proved
through mathematical and computational models. The numerical analyses showed that the geodesic framework is stiffer than other configurations, moreover it minimizes the material used: indeed the overall beam length is optimized. Furthermore, due to the framework regularity, the stress state is almost uniform in the whole structure beams.

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ABSTRACT: The energy absorption characteristics of E-glass/Polypropylene (PP) isogrid composite panels under quasi-static transverse load conditions have been investigated. Experimental tests and finite element simulations were performed for isogrid composite panels in three-point bending boundary condition. Results of tests and simulations show that loading the panels on rib side results in greater specific energy absorption along with larger displacements compared to skin side loading which is more abrupt. These results can be used to advantage in weight-critical automotive side impact crashworthy applications. Vibration response measurements which were used as a non-destructive tool for evaluating the quality of as-manufactured isogrid plates and monitoring induced damage in one of the plates are also presented.

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ABSTRACT: This paper presents a numerical method of analysing the elastic stability of thin laminated and longitudinally stiffened shells of revolution. The anisotropic elastic properties of composite materials are taken into account. The discrete longitudinal stiffener is dealt with as a beam-column, and its eccentricity effect is also considered. The basic elastic and geometric stiffness properties of the stiffeners are synthesized into a stiffness matrix compatible with an axisymmetric shell element by a series of transformations to be used in conjunction with a finite element representation of a thin axisymmetric shell, where the displacements are decomposed into Fourier harmonics. Thus, the effect of the stiffeners can be rigorously accounted for in stability analysis. Examples are given to show that the results agree well with existing solutions by other analytical methods and by experiments.

References listed at the end of the paper:

ABSTRACT: The stability of arch and shell structures with random imperfections subjected to random loading is investigated. Arches are analyzed under different types of transverse loads while axial and/or pressure loading are considered for cylindrical shells. A probabilistic analysis of the randomness in the geometric imperfections along with the uncertainty in both loading and material properties is presented. The study investigates the effect of spatial variability of the different random parameters in the problem on the buckling load and the associated displacements. The imperfection sensitivity is studied for several geometrical configurations of the arches and shells and for various values of the statistical parameters for the random shape imperfections. One- and two-dimensional random fields are introduced with different types of autocorrelation functions to characterize the structures and the imperfections. A sufficient number of terms is considered using two series expansion methods to express the field in terms of its spectral decomposition. The first employs the Karhunen-Loeve theorem where the autocorrelation coefficient function is expanded in terms of its eigenvalues and eigenfunctions, while the second method utilizes any complete set of orthogonal functions. These techniques are compared with both the midpoint and local averaging methods for random field discretization and prove to be more computationally efficient within a given level of accuracy. Both first- and second-order reliability methods (FORM/SORM) along with Monte Carlo simulation are used to evaluate different modes of instability based on the buckling load or the associated displacements. The probability density and the cumulative distribution functions of the buckling load are presented for various distributions of the imperfections. The sensitivity of the buckling load and the postbuckling displacements to different parameters is also presented. An extensive parametric study through many numerical examples is performed to establish a better understanding of the effects of the spatially variable imperfections on the buckling of arches and shells.


ABSTRACT: The article presents the results of the experimental investigation of the process of deformation of cylindrical shells with circular nonreinforced notches. It is shown that the dependences of the load bearing capacity of shells on the parameters determining the notches (radius and their number) have sections each of which is characterized by wave formation determining the mechanism of failure.

ABSTRACT: Tests of cross-ply composite tubes were performed under combined axial and torsional loading up to failure. Strength properties and failure mechanisms were evaluated with reference to the biaxiality ratio of the loading. The scattering of the biaxial strength data was analyzed using the Weibull distribution. The axial contraction of carbon fiber-reinforced plastic (CFRP) tubes under biaxial loading was investigated theoretically and experimentally. Artificial neural networks were introduced to predict the failure strength using the algorithm of the error back-propagation. The prediction was also made by the Tsai-Wu theory using the experimental data and by the combined optimized tensor-polynomial theory. A comparison shows that the artificial neural network has the smallest root-mean-square (RMS) error of the three prediction methods. The prediction of the axial contraction of the tubes correlates well with the results of a linear variable differential transformer (LVDT) of the testing machine. From the phenomenological analysis of the failure and the fractographic observations of the fracture surface, three types of failure modes and microscopic failure were investigated, depending on the biaxiality ratio, and the corresponding failure mechanisms are suggested.


ABSTRACT: Biaxial tests have been conducted on cross-ply carbon/epoxy composite tube under combined torsion and axial tension/compression up to failure. Strength properties and distributions were evaluated with reference to the biaxial loading ratio. The scatter of the biaxial strength data was analyzed by using a Weibull distribution function. Artificial neural networks were introduced to predict failure strength by means of the error back-propagation algorithm for learning, providing a different and new approach to the representation of complicated behavior of composite materials. Further prediction is made from experimental data by the use of Tsai–Wu theory and a combined optimized tensor polynomial theory. Comparison shows that the artificial neural network has the smallest root-mean-square error of the three prediction methods.


ABSTRACT: This paper presents a hybrid meta-heuristic algorithm called multiple start guided neighbourhood search (MSGNS) algorithm for combinatorial optimisation which combines the good features of popular guided local search algorithms like simulated annealing and tabu search. It has been organized as a multiple start algorithm to maintain a good balance between intensification and diversification. The proposed hybrid meta-heuristic algorithm has been employed to solve optimal stacking sequence design problem of laminate composite structures. First, the algorithm has been employed to solve the problem of optimal stacking sequence of a composite plate for which the results of various algorithms are available in the literature. This study is basically to validate and also to demonstrate the effectiveness of the proposed algorithm over several existing
meta-heuristic algorithms. Later, a practical design example of fiber-reinforced composite cylindrical skirt of solid rocket motor of aerospace vehicle is investigated. A skirt is a potential element for weight reduction in rocket motors as it leads to reduction of the total weight of solid rocket motor. Due to its significance for solid rocket motors, it is proposed to optimise the weight as well as cost of the fiber-reinforced composite cylindrical skirt subjected to a buckling strength constraint and an overstressing strength constraint under aerodynamic torque and axial thrust. This is achieved by arriving at an optimal stacking sequence for the cylinder satisfying all the design constraints and also by employing multiple composite materials. Classical laminate theory combining with elastic stability theory of thin shells is used to arrive at buckling strength and overstressing strength of the fiber-reinforced composite cylindrical skirt. The Tsai-Wu failure criterion is employed to assess the first ply failure. Buckling strength and failure strength of the cylindrical skirt is described by using buckling load factor and overstressing load level factor. Numerical simulations carried out in this paper clearly demonstrate the superiority of the proposed MSGNS algorithm over the popularly used combinatorial algorithms like genetic algorithm and simulated annealing.


CONCLUSIONS: 1. Analysis of the results obtained for the example of boron-plastic and hybrid three-layer shells leads us to conclude that the kinematically uniform model cannot be used to calculate the PRDS of three-layer shells with bearing layers having a stiffness three to four times greater and a density roughly one order greater than the stiffness and density of the filler material. 2. The replacement of the rigid fiber-reinforced material of the middle layer of the shell by a “soft” and light material such as foam plastic leads to a situation whereby the initial sections of the RDI connected with vibrations of the shell as a whole in the x, y, and z directions are shifted toward smaller frequencies θ. Here, the number of regions ηθ(ℓ, n)/ρ=1, 3, ..., 10 forming the RDI is greater, at least on the initial sections, due to the fact that regions corresponding to different modes of parametric vibration are brought closer together. The width of these regions of dynamic instability is decreased by several factors compared to the width of the corresponding ηθ of the RDI spectrum of a shell having all of its layers made of a stiff material. 3. Calculated results obtained in the present study but not reported in this article show that the RDI's connected with vibration of the middle layer in the transverse shear planes and in the direction of the z axis change in a manner similar to that described in Part 2 (compressive vibrations). The remaining six RDL's connected with the same vibrations of the bearing layers of the shell are shifted toward larger θ. The width of all of the regions of the nine RDI's indicated here is negligibly small.

References listed at the end of the paper:
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ABSTRACT: To account for plastic deformation in plate and shell structures an elasto-viscoplastic solution algorithm is considered based on Perzyna's model for material behaviour. This algorithm can be employed to solve for time-dependent elasto-viscoplastic situations and by allowing steady-state conditions to be reached, elasto-plastic problems can also be considered. For the large displacement elasto-viscoplastic analysis of thin shells, an incremental stiffness procedure is employed together with a Lagrangian description of the stress and strain vectors. The Šemiloof plate and shell elements are used for finite element space discretization. The procedures developed are applied to the solution of several numerical examples and the solutions compared with results from other sources where available.

ABSTRACT: This paper presents the application of a refined finite element model to the elastic and elastic-plastic dynamic analysis of anisotropic laminated plates. Dynamic analysis is based on Newmark's algorithm used in conjunction with the Hughes and Liu predictor-corrector scheme resulting in an ‘effective static problem’ which is solved using a Newton-Raphson-type process. Flow theory is used in the inelastic range and the Huber-Mises yielding surface extended by Hill for anisotropic materials is adopted. Numerical results obtained for two categories of anisotropic structures, namely cross-ply laminated plates and angle-ply laminated plates, are presented and the effects of anisotropy and bending/stretching coupling on the dynamic elastic and elastic-plastic responses are discussed. The effects of lamina stack sequences and lamina angle sequences on the dynamic responses are also considered.

ABSTRACT: The New Zealand Society for Earthquake Engineering (NZSEE) has a study group working on the seismic design of storage tanks. The study group is preparing a revision of the widely acknowledged NZSEE 1986 document “Seismic Design of Storage Tanks”. Draft amendments of the loading procedures in the 1986 document have been prepared. This paper presents a summary of the proposed approach. …
References listed at the end of the paper:
Wan Li (1), Tao Wei-ming (2), Wu, Xin-xin (1), He, Shu-yan (1)  
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ABSTRACT: This paper focuses on the localized nonlinear buckling of pressure vessel under internal pres-sure caused by initial geometric imperfection. The localized plastic buckling occurred in the transition region in the torispherical end closure of a pressure vessel has been analyzed by FEM. By introducing two types of initial geometrical imperfections, the arc-length method of modified-Riks/Ramm procedure is employed to simulate the deformation process during loading. The first type of imperfection is determined from the elasto-static displacements, into the zone where it is circumferentially compressed. The second type of imperfection is the irregular thickness of the vessel, also into the zone where it is circumferentially com-pressed. The buckling point is captured from the load-deflection curve of a typical point within the buckled zone, and the corresponding buckling load is calculated. The results show that after the first buckling initiated, the succeeding loading will lead to more wrinkles within the compressive transition region, which agree well with the results of experiments.

ABSTRACT: The paper presents theoretical and numerical studies of the buckling of steel shells subjected simultaneously to axial and pressure loading. The type of combined non-uniform loading used for this analysis (horizontal pressure and wall frictional pressure which occurs in the silos) is given in the Eurocode 1 part 4. An Abaqus program was used to study the influence of the parameters affecting the strength of the shell. The results of this parametric study were used to develop a new semi-analytical method for the prediction of the critical stress of the stiffened and isotro-pic shells. The corresponding formulae are compared, in different examples of geometrical shells, with the results obtained by finite element simulation and by the formulae for buckling design given in recommendation EC3.

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ABSTRACT: A solid shell element model with six degrees of freedom per node is applied to buckling and postbuckling analysis of geometrically nonlinear shell structures. The present model allows changes in the thickness direction and does not require rotational angles or parameters for the description of the kinematics of deformation. The finite element model is constructed based on the assumed strain formulation in which an assumed strain field is chosen to prevent locking while maintaining kinematic stability. Numerical results show that the present model allows large increments in the iterative solution scheme for pre- and postbuckling analysis. In particular, it appears that the model provides a means to pinpoint a bifurcation point on the
geometrically nonlinear deformation path.

Daniel Trybula (Institute of Applied Mechanics, Faculty of Mechanical Engineering, Cracow University of Technology, Poland), “Stabilization of Post-Buckling Path By Axial Loading Controlled By Displacements for Cylindrical Shells under Torsion”, Mechanics, Technical Transactions, Politechniki Krakowskiej, Issue 8, Year (Vol.?)107

ABSTRACT: A post-buckling path for a cylindrical shell under torsional moment is unstable one. It means that the loss of stability of a shell can be associated with a snap-through, which can lead to very large displacements and, finally, to destruction of the structure. The effect of modification of the post-buckling behavior in most cases has been obtained by changing of geometry of a structure. In this paper an alternative concept is applied, namely stabilization of the post-buckling path is obtained by application of an additional loading acting to the structure without changing its geometry. This additional loading is applied to a structure by imposing a certain axial displacement to the ends of the shell. It causes an axial tensional force, which can stabilize the post-buckling path. The problem was formulated as a problem of optimization, namely the minimum value of the axial load - the initial pretension u, which leads, together with the passive force, to stabilization of the post-buckling path is looked for. Calculations were performed using ANSYS code.

References listed at the end of the paper:

ABSTRACT: The post-buckling path for a cylindrical shell under compressive radial pressure is unstable. The effect of modification of the post-buckling behaviour is in most cases obtained by changing sizing variables, which are usually dimensions of the design element. In this article an alternative concept is applied, namely stabilization of the post-buckling path for a simply supported cylindrical shell under radial compressive pressure is obtained by application of additional loadings acting on the structure without changing the shape or sizes of the optimized element. These loadings can be either active forces applied to the structure or passive ones (reactions of the additional supports) or both active and passive forces acting simultaneously. All three types of stabilizing forces were investigated. Calculations were performed using the ANSYS 11.0 Academic Research code for elastic and elastic–plastic deformations of shells of different length and thickness.


ABSTRACT: The effect of stabilization of unstable post-buckling behavior of a structure usually is obtained by changing its geometry. In this paper, a possibility of stabilization of the initially unstable post-buckling path for a cylindrical shell under torsion by application of additional independent loadings acting on the structure without changing the shape and size of the shell is investigated. It occurred that axial tension improves the resistance against buckling for the cylindrical shell under torsion and can stabilize the unstable post-buckling path. On the other hand, internal pressure does not stabilize the post-buckling path but it improves the resistance of such a structure against instability.

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2. Bochenek B., 1997, Optimisation of geometrically nonlinear structures with respect to buckling and postbuckling constraints, Engineering Optimization, 29, 401-415
Methods in Engineering, 42, 7, 1231-1262


ABSTRACT: Shell structures are widely used in many industries thanks to their high efficiency in terms of load carrying capacity vs. weight optimal ratio. However, it is well known that these structures are also characterized by a high sensitivity to buckling instabilities, triggered by ineluctable initial shape imperfections, space-varying material properties and/or boundary conditions, unknown to some extent. These imperfections or rather unknown properties, inherent to the manufacturing process, are highly unpredictable and thus hard to take into account at the design stage. In this paper, the authors propose a stochastic approach to model those initial shape imperfections, considered as random, and accounting for uncertain spatially varying material properties and thicknesses, based on the random field theory. The assessment of the failure probability is addressed by means of subset simulations, which outperform crude Monte Carlo performance when estimating small probabilities. Critical buckling loads of the shell structure are determined using an original Finite Element-based method known as the Asymptotic Numerical Method (ANM), which accounts both for geometric and material nonlinearities. The ANM was proved to be less computationally demanding and robust than classical incremental-iterative methods offered in general purpose FE codes. Finally, for illustration purposes, the whole approach is applied to an example derived from the well-known Scordelis-Lo shell roof.

References listed at the end of the paper:


ABSTRACT: We present a new 6-node triangular bending element (called DKTP) based on a discrete Kirchhoff model. A corresponding new flat-shell element, DLTP, having quadratic variation of in-plane displacement is also presented. This element has 6 degrees-of-freedom (u, v, w, thetax, thetay, thetaz) at each corner node and 3 degrees-of-freedom (u, v, w) at each mid-side node. Detailed numerical experimentation is presented to demonstrate the efficiency and reliability of these elements.

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ABSTRACT: The comparative efficiency of three flat triangular shell elements is being assessed for analysing non-linear behaviour of general shell structures. The bending formulation of the three elements is based on a discrete Kirchhoff model (namely the well-known 3-node DKT element and a new 6-node DKTP element). The in-plane behaviour is defined by constant (CST), linear (LST) and quadratic (QST) strain approximations. The super-position of bending and membrane elements leads to the 3-node DCT element (DKT plus CST), the 3-node DQT element (DKT plus QST) and the 6-node DLT element (DKTP plus LST). The geometrically non-linear formulation is based on an approximate updated Lagrangian formulation (AULF) and the solution is obtained by using the Newton-Raphson method with an automatic arc-length control method. Illustrative examples include pre- and post-buckling of different shell structures showing, in particular, some bifurcation points, large rotations and displacements and very important membrane-bending coupling.


ABSTRACT: In the paper the linear and non-linear stability analysis of columns and beams made of steel coldformed thin-walled sigma profiles is presented. Both single (asymmetric) and double (symmetric) sigma sections are considered. Local and global buckling phenomena are studied for a wide range of lengths from short columns and beams to long ones. Particular attention is paid to coupled instability, when local buckling occurs close to global one. Coupled modes can take flexural, torsional or combined flexural-torsional forms.
Usually this kind of instability strongly influences the overall post-buckling behaviour. It is well known that these structures are sensitive to initial geometric imperfections [3]. Simplified theories proposed by Timoshenko and developed by Vlasov provide good results only in the case of global buckling. Therefore, in the paper FEM employing shell elements is used to capture the interactive buckling effects. The influence of initial imperfections on buckling and post-buckling behaviour is studied using nonlinear stability analysis with Riks method. The results are compared with results provided by simplified theories. Buckling and nonlinear post-buckling analyses in compression, in simple and skew bending are performed. These issues were also studied in [2]. Imperfections are usually introduced by perturbations in the geometry as a linear superposition of buckling modes, obtained from the linear eigenvalue problem. We follow this approach, however, the patterns and amplitudes of imperfections refer to our own measurements performed “in situ” and processed statistically. These measured imperfections are transferred to FEM model, using discrete Galerkin method for error minimization. Special attention is focused on modelling the double sigma members, which cross-sections are composed of two sigma members connected in discrete points distributed along the webs. It was found that buckling loads may strongly differ with those obtained from analysis for continuous web connection [1]. The influence of head plates, stiffness and spacing of connectors and slenderness coefficients on buckling behavior is studied by the way of examples. The examples are solved using the general purpose finite element program, ABAQUS.

N. Hosseinzadeh (Dept. of Structural Engineering, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran), “Seismic Vulnerability Analyses of Steel Storage Tanks in an Oil Refinery Complex Using Dynamic Analyses”, The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China

ABSTRACT: Cylindrical steel above ground tanks extensively used in oil refinery complexes and oil depots in Iran. Average capacity of this kind of tanks is about 20,000 kl with diameter of about 40 m and height of about 14 meter. Past earthquake experiences in Japan, U.S. and Turkey show that these tanks are very vulnerable to strong ground motions. Failure modes such as settlement, shell buckling, Roof Damage and overturning are the main causes of extensive material leakage and fire immediately after an earthquake. In this paper 181 tanks in an oil refinery complex are categorized into 30 types in order to seismic vulnerability evaluation and retrofit design. International documented references such as new revisions of API650 and ASCE standards and Finite Element Method is used in this study. Important parameters such as Liquid sloshing, tank bottom uplift and liquid-shell interaction considered in dynamic analyses. Site-specific spectrum, as well as site compatible earthquake records considered as input motions. The results show that about 60 percent of the existing tanks are vulnerable and require retrofitting or strengthening.

References listed at the end of the paper:
2. API 650, (2005), Welded Steel Tanks for Oil Storage, American Petroleum Institute API Standard 650, Washington, USA

Zhang, Chonghou (Dept. of Civil Engineering, Tsinghua University, Beijing, China), “Plastic buckling of cylindrical shells under transverse loading”, Tsinghua Science and Technology, Vol. 13, No. 2, pp. 202-210,
ABSTRACT: Thick cylindrical shells under transverse loading exhibit an elephant foot buckling mode, whereas moderately thick cylindrical shells show a diamond buckling mode. There exists some intermediate geometry at which the transition between buckling modes can take place. This behavior is significantly influenced by the radius-to-thickness ratio and the material yield strength, rather than the length-to-radius ratio and the axial force. This paper presents a critical value at which the transition of buckling modes occurs as a function of the radius-to-thickness ratio and the material yield strength. The result shows that the circumferential wave number of the diamond buckling mode increases with decreasing wall thickness. The strain concentration is also intensified for the diamond buckling modes compared with the elephant foot buckling modes.

Hong Pu Liu, Xiao Jing Li, Di Wang, Jian Sheng Tang, Xue Ling Yang, Cheng Jun Zhu (Non-traditional Machining Center, Henan Polytechnic Institute, Nanyang 473009, China), “The Structural Dynamical Buckling Analysis for a Novel Vacuum Autoclave under the Extreme Operating Conditions”, Advanced Materials Research (Volumes 143 - 144), October 2010, pp. 888-893, doi: 10.4028/www.scientific.net/AMR.143-144.888

ABSTRACT: The elastic buckling load is physically important in design of the pressure vessel with shell framework because it is actually the critical step in a thin-walled shell configuration that will eventually lead to complete failure. An finite element model of vacuum autoclave was established and the buckling load calculations under the extreme operating conditions have been carried out to obtain the modal deformation condition and the safety factor. The results showed that the structure has a higher safety factor, which indicated that the vacuum autoclave design can meet the working condition requirements.


ABSTRACT: Stability is one of the serious problems associated with slender structural elements. Column is an important member of such elements that the study of its complex behavior is necessary due to their significant use in the structural applications. In this paper, the influence of initial imperfection on the stability of a compressible column with load-dependant support is studied. The column model is introduced, considering compressibility and load-dependant behavior of the support. The effect of initial imperfection is considered in the equilibrium equation of the column and the equilibrium paths are plotted in each state of reference support stiffness functions for specific imperfection magnitudes. In each state, the change of critical load of the column versus the values of the imperfection is extracted and the effect of initial imperfection on the stability of the column is discussed.


ABSTRACT: The rocking dynamics of the tank is discussed through introduction of the rock–translation interaction. Firstly, the discussion on the ideal rigid bottom plate tank ensures the necessity of the rock–translation interaction for evaluating rocking responses of the tank. Secondly, to trace rocking behaviors of the actual tank, the proposed method is expanded by employing an assumption of the effective moment inertia of
liquid for rocking motion. The comparison of analytical results with the experimental ones corroborates its applicability. Finally, the sufficient friction on the pivoting edge to enter and sustain the rocking motion of the tank is examined.

Iunio Iervolino, Giovanni Fabbrocino and Gaetano Manfredi (Dept. of Structural Analysis and Design, University of Naples Federico II, Italy), “Seismic Vulnerability of Standardised Industrial Components: Application to Oil Storage Tanks”, Paper No. 552, 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004

ABSTRACT: Industrial risk requires taking into account natural hazards including earthquakes. In the Quantitative Risk Analysis (QRA) perspective seismic failure may be added to system faulty events. Fragility analysis of industrial components presents some aspects that requires the development of specific reliability tools. The present paper discusses the definition of a rational procedure for seismic vulnerability assessment of standardized industrial constructions in a probabilistic framework.

The coverage of a category of components by a single analysis process and the independence on the assumptions on the structural model, even if dynamic analyses are performed, can be addressed as the main advantages of the proposed method. Both seismic capacity and demand are considered as probabilistic. The application example is focused on the elephant foot buckling of unanchored sliding tanks. A regression-based method is applied to relate fragility curves to parameters varying in the domain of variables for structural design.

References listed at the end of the paper:
G. Fabbrocino, I. Iervolino, G. Manfredi (Department of Structural Analysis and Design University of Naples Federico II), "Structural issues in seismic risk assessment of existing oil storage tanks", (no publisher or date given in the pdf file, latest reference is dated 2001)

ABSTRACT: Large regions in many countries are exposed to earthquakes, thus seismic risk evaluation is a relevant issue and requires specific knowledge development and integration between different skills. Failure of critical constructions can have direct and indirect influence on public safety; in fact, pollution or damages due to explosions can be related to collapse of industrial facilities. In the present paper, after a review of available data concerning industrial plants in Italy with specific reference to their exposure to earthquake actions, the main aspects related to structural design and seismic evaluation of existing facilities for oil storage are discussed and the main features of probabilistic procedures able to give fragility curves of structures and components to be used in seismic risk assessment are outlined.

References listed at the end of the paper:
[2] Italian Association for Environmental Protection, www.legambiente.it
[3] Italian Environmental Department, www.minambiente.it

ABSTRACT: FPSOs have a risk profile different from fixed platforms and commercial trading tankers. Being stationed in one location and routinely visited by supply boats and shuttle tankers. FPSOs can be collided by these ships. In addition, passing ships also pose a collision risk if an FPSO is close to a sailing route. This paper presents a systematic approach to address the risk of collision and contact damage. It is aimed to propose a framework that can be applied in structural designs and risk assessment schemes. The focus is placed on accident scenarios, evaluation approaches and acceptance criteria, the three major issues for a risk assessment and also for a relevant design standard. Accident scenarios and the associated occurrence frequency may be determined through statistics from historical data, expert opinions, and risk analysis, depending on different situations. A spectrum of tools has been developed in recent years that predicts the structural damage of collisions, including simple formulae, simplified analytical methods, simplified FEM, and non-linear FEM simulations. Those based on the advanced structural crashworthiness theory provide powerful and practical tools, and are well suited for design evaluations and risk analysis. Contact damage is more likely to occur than accidents resulting in rupture of shell plating. However, this type of accident has received very limited attention. An analytical approach is presented for analyzing contact damage that can be used during earlier design stage. Acceptance criteria for collision and contact accidents are discussed. The emphasis is on structural integrity including local strength and hull performance.


ABSTRACT: The static stability of thin-walled composite beams, considering shear deformation and geometrical non-linear coupling, subjected to transverse external force has been investigated in this paper. The theory is formulated in the context of large displacements and rotations, through the adoption of a shear deformable displacement field (accounting for bending and warping shear) considering moderate bending rotations and large twist. This non-linear formulation is used for analyzing the prebuckling and postbuckling behavior of simply supported, cantilever and fixed-end beams subjected to different load condition. Ritz's method is applied in order to discretize the non-linear differential system and the resultant algebraic equations are solved by means of an incremental Newton–Rapshon method. The numerical results show that the beam loses its stability through a stable symmetric bifurcation point and the postbuckling strength is in relation with the buckling load value. Classical predictions of lateral buckling are conservative when the prebuckling displacements are not negligible and the non-linear buckling analysis is required for reliable solutions. The analysis is supplemented by investigating the effects of the variation of load height parameter. In addition, the critical load values and postbuckling response obtained with the present beam model are compared with the results obtained with a shell finite element model (Abaqus).

ABSTRACT: Based on a seven-degree-of-freedom shear deformable beam model, analytical solutions are derived for the lateral stability analysis of cross-ply laminated thin-walled beams subjected to combined axial and bending loads. The model includes shear deformability in a full form, i.e., shear flexibility due to both bending and nonuniform warping is considered. The theory is formulated in the context of large displacements and rotations, considering moderate bending rotations and large twist. Composite is assumed to be made of symmetric balanced laminates and especially orthotropic laminates. The closed-form analytic expressions obtained in this paper are valid for simply supported bisymmetric beams. These fundamental solutions explicitly identify the influence of geometric nonlinear effects due to the prebuckling deformation. The numerical results are compared with the bifurcation loads of the postbuckling response. In addition, the effects of the variation of load height parameter and fiber angle orientation are investigated.

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“Post Buckling Analysis of the Ariane 5 Front Skirt (Rosetta-Mission)”, EUROPEAN CONFERENCE FOR AEROSPACE SCIENCES (EUCASS), (no publisher or date given in the pdf file; latest reference is dated PARTIAL INTRODUCTION: This contribution addresses the analysis of the behaviour of the ARIANE 5 front skirt concerning the nonlinear structural stability in the launching phase of the Rosetta-Mission. The front skirt consists of a stiffened shell structure and is part of the main stage of the ARIANE 5 … transmitting the booster loads into the actual launcher. The main load carrying elements are load introduction structures, circumferential frames and axial stiffened cylindrical shells. Within the framework of the flight worthiness assessment for the Rosetta mission, a nonlinear analysis of the front skirt for two critical flight cases was performed. The contracting body for this job was MAN-Technologie AG in Augsburg, Germany. The crucial points of the analysis strategy itself, which had to be considered for the flight worthiness assessment, were: (1) Load case selection, (2) Boundary conditions, (3) Post buckling behavior and (4) Imperfection sensitivity. The computations described in the following were carried out by means of the general purpose program ABAQUS [7], Version 6.4.1.

References listed at the end of the paper:
ABSTRACT: In the design of a modern lightweight structure, it is of technical importance to assure its safety against the buckling under the applied loading conditions. For this issue, the determination of the critical load in an ideal condition is not sufficient, but it is further required to clarify the post-buckling behavior, that is, the behavior of the structure after passing through the critical load. One of the reasons is to estimate the effect of practically unavoidable imperfections on the critical load and the second is to evaluate the ultimate strength to exploit the load-carrying capacity of the structure. For the buckling problem of circular cylindrical shells under axial compression, a number of experimental and theoretical studies have been made by many researchers. In the case of the very thin shell that exhibits elastic buckling, experimental results show that after the primary buckling, secondary buckling takes place accompanying successive reductions in the number of the circumferential waves in each mode change on one-by-one step. In this paper we traced this successive buckling of circular cylindrical shells using some of the general purpose implicit FEM codes currently available. For geometrically nonlinear static problems including buckling and post-buckling, we carried out our studies with two approaches; one is to use the arc length method (the modified Riks method), and the other is stabilizing with the aid of (artificial) damping especially for the local instability. Our analysis procedure consists of the following 2 steps. Before reaching the point exhibiting the comparatively stable state after the primary buckling, the arc length method is applied. After that point, the artificial damping is applied. The results simulate unstable successive buckling and show good agreement with experiments.

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“Corotational formulation for nonlinear dynamics of beams with arbitrary thin-walled open cross-sections”,
ABSTRACT: A new consistent corotational formulation for nonlinear dynamics of beams with arbitrary thin-walled cross-section is presented. The novelty is that the warping deformations and the eccentricity of the shear center are fully taken into account. Therefore, additional terms are introduced in the expressions of the inertia force vector and the tangent dynamic matrix. Their contribution is then investigated considering several numerical examples. Besides, the element has seven degrees of freedom at each node and cubic shape functions are used to interpolate local transverse displacements and axial rotations. The formulation’s accuracy is assessed considering five examples with comparisons against 3D-solid solutions.

ABSTRACT: In the framework of the direct approach shells are considered as deformable surfaces consisting of particles, and the relations of the theory are obtained with the methods of analytical mechanics. In the present work we assign to each particle five degrees of freedom, namely three translations and two in-plane rotations. The principle of virtual work produces all the relations of the theory of shells: equations of equilibrium,
boundary conditions, definition of the force factors and the general form of constitutive equations. Remarkable consistency and clarity is achieved both in the relations of the theory and in the derivation process. A new formulation of the Piola tensors for a shell is suggested in order to transform the equations to the reference configuration. To analyze the effects of buckling or geometric stiffening, we linearize these equations in the vicinity of a pre-deformed configuration. Some new semi-analytical results on buckling and supercritical behavior of an axially compressed cylindrical shell are presented. The correspondence between the equations and the variational formulation is discussed in view of development of efficient numerical procedures for modeling nonlinear deformations of shells. Results of finite element modeling of the nonlinear deformation of a shell structure are discussed in comparison with the fully three-dimensional solution of the problem.

DOI: 10.1007/978-3-7091-1777-4_4
ABSTRACT: We begin with the asymptotic splitting of the equations of the three-dimensional theory of elasticity for a thin plate into a problem over the thickness and the equations of the classical plate model. All groups of the three-dimensional equations (equilibrium, compatibility, etc.) are processed separately. Both the material anisotropy and inhomogeneity in the thickness direction are included in the analysis along with the electromechanical coupling in the form of piezoelectric effects. The classical nonlinear theory of curved shells follows with the direct approach to a material surface with five degrees of freedom of particles: three translations and two rotations. Equations of equilibrium, boundary conditions and general constitutive relations are the consequences of the principle of virtual work. Further we transform the equations to the differential operator of the reference configuration with the Piola tensors, which allows linearizing the equations in the vicinity of a pre-stressed and pre-deformed state. Several example problems for a cylindrical shell are considered. A novel finite element scheme with a smooth approximation of the surface of the shell concludes the chapter. The method is presented in Mathematica environment for linear plate problems, and then a general implementation for large deformations of curved shells is discussed. We demonstrate the convergence properties of the numerical scheme on several examples, some of which have been considered in the literature before. This chapter quotes extensively from Eliseev and Vetyukov (Acta Mech. 209(1–2):43–57, 2010) with permission from Springer Science and Business Media, from Vetyukov et al. (Int. J. Solids Struct., 48(1):12–23, 2011) with permission from Elsevier, from Vetyukov (Z. Angew. Math. Mech., 94(1–2):150–163, 2014) with permission from Wiley-VCH and from Eliseev and Vetyukov (Shell Structures: Theory and Applications, vol. 3, pp. 81–84, CRC Press, London, 2014) with permission from Taylor & Francis Group. Other results of the author, previously presented in Vetyukov and Belyaev (Proceedings of the Tenth International Conference on Computational Structures Technology, p. 19, Civil-Comp Press, Stirlingshire, 2010) and Vetyukov and Krommer (Proceedings of SPIE—The International Society for Optical Engineering, vol. 7647, 2010), were included in the material of the present chapter.

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“Thin shells with piezoelectric transducers: Theory, numerical modelling and verification”, 7th ECCOMAS
Thematic Conference on Smart Structures and Materials (SMART), 2015
ABSTRACT: For the modelling of thin elastic shells with attached piezoelectric transducers, we consider a material surface with certain mechanical degrees of freedom in each point. Additionally, electrical unknowns are present within the domain, where the piezoelectric transducers are attached, such that the sensing and actuating behavior can be properly accounted for. The modelling is done in the geometrically nonlinear regime, but the electromechanically coupled constitutive relations are treated within the framework of Voigt’s linear theory of piezoelectricity. Owing to the assumed thinness of the shell the influence of shear is neglected in the modeling. A Finite Element scheme for the solution of the resulting model is implemented and the solutions computed with the present theory are compared to results computed with the commercially available FE code Abaqus. Different examples are presented ranging from large deformations, to snap through instability and to a linear analysis. A very good agreement between the results is obtained, from which the accuracy of the thin shell formulation as a material surface is concluded. Next, an existing physical shell is modeled within the linearized version of the present theory and the computational results are compared to measurement results from the physical experiment. The agreement is reasonably good; natural frequencies as well as eigenmodes are considered for the comparison. Concerning the eigenmodes the MAC criterion is used. Finally, the resulting linear time invariant dynamical system for the simulation of the physical shell is imported into Mathematica and different strategies for passive and active control are tested and compared to each other. Concerning passive control methods classical single mode shunt-damping using an optimized RL-network is studied.

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Shunqi Zhang, “Nonlinear FE Simulation and Active Vibration Control of Piezoelectric Laminated Thin-Walled Smart Structures”, Ph.D. dissertation, Dept. of Machine Knowledge, Technical University of Aachen, 2014
ABSTRACT: This dissertation deals with nonlinear finite element modeling and active vibration control for piezoelectric integrated smart structures, and is presented in two parts. In the first part, an electro-mechanically coupled large rotation finite element model is developed for static and dynamic analysis of thin-walled structures with piezoelectric sensor and actuator layers. The present large rotation theory is based on the first-
order shear deformation hypothesis, which has six independent kinematic parameters but expressed by five
nodal degrees of freedom. Unrestricted finite rotations are described by two rotations using the Euler angle
representation method. Due to the assumption of small strains and weak electric potential, linear piezoelectric
coupled constitutive equations and a linearly distributed electric potential through the thickness are considered.
In order to show the necessity of the large rotation theory in the application of thin-walled composite or smart
structures undergoing large rotations, several simplified nonlinear shell theories are implemented into finite
elements for thin-walled structures as well. The second part develops a disturbance rejection control with a
Proportional-Integral (PI) observer which uses step functions to construct a fictitious model of disturbances for
active vibration control of smart structures. To improve the dynamic behavior of the existing PI observer, a
Generalized PI (GPI) observer is proposed and developed. Therefore, any unknown disturbances can be
estimated and compensated by the present disturbance rejection control with either a PI or GPI observer.
Additionally, PID, LQR and LQG control strategies are implemented to show the advantages of the proposed
disturbance rejection control.
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energy harvesting performance of shear mode piezoelectric cantilever. Sensors and Actuators A: Physical, 179:185–192,
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ABSTRACT: Composite materials have been extensively used in engineering thanks to their lightweight,
superior mechanical performances and possibility to tailor the structural behavior, increasing the available design space. Variable Angle Tow (VAT) structures exploits this advantage by adopting a curvilinear patterns for the fibers constituting the lamina. This work, for the first time, extends the Generalized Unified Formulation (GUF) to the case of fourth-order triangular shell elements and VAT composites. Functionally graded material properties in both the thickness and in-plane directions are also possible. The finite element has been formulated with layers of variable thickness with respect to the in-plane coordinates.

GUF is a very versatile tool for the analysis of Variable Stiffness Composite Laminates (VSCLs); it is possible to select generic element coordinate systems and define different types of axiomatic descriptions (Equivalent Single Layer, Layer Wise, and Zig-Zag enhanced formulations) and orders of the thickness expansions. Each displacement is independently treated from the others. All the infinite number of theories that can be generated with GUF are obtained by expanding six theory-invariant kernels (formally identical for all the elements), allowing a very general implementation. Finally, the possibility of tailoring the theory/order to increase the accuracy in desired directions makes the GUF VAT capability a very powerful tool for the design of aerospace structures.

References listed at the end of the paper:


ABSTRACT: The concept of snap divergence and post-critical states are theoretically formulated for Joined Wings with the arc length technique. The true critical condition is compared with the divergence speed evaluated by solving an eigenvalue problem about a steady state equilibrium, showing how in some cases this last approach is not reliable and even nonconservative.

The work assesses the difference of the nonlinear responses relative to mechanical loads (both conservative and follower ones) used to mimic the real loading condition and the aerodynamic forces. Two joined-wing configurations, characterized by a different location of the joint, are investigated. It is demonstrated that the lift/displacement response may hide the physical snap divergence occurrence, leading to non-physical interpretation of the stability properties of the system. Thus, as a consequence, use mechanical loading to mimic aerodynamic effects should be meditated since they may not give a reliable picture.

Aeroelastic stiffening and softening effects are observed for the different cases, and it is discussed how practical instability situation may not be encompassed by the formal mathematical criterion (singularity of the system tangent matrix).

Finally, physical interpretation of the static aeroelastic deformation is provided with particular emphasis on the conditions that lead to the snap divergence. The bending/torsion coupling at geometric (sweep angle of the wings) and material (composite materials) level for each wing can not be thought as an isolate property, since, due to the overconstrained nature of the system, the actions are transferred between different parts of the system. In other words, an intuitive approach that tries to fine tune the design of a part as an isolate entity may
not lead to meaningful results.

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Rizzo, E., Optimization Methods Applied to the preliminary design of innovative non conventional aircraft configurations, Edizioni ETS.


ABSTRACT: This paper analyses the free vibration response of sandwich curved and flat panels by introducing the zig-zag function $(-1)^k$ in the displacement models of classical and higher order two-dimensional shell theories. The main advantage of ZZF is the introduction of a discontinuity in the first derivative, zig-zag effect, of the displacements distribution with correspondence to the core/faces interfaces. Results including and discarding ZZF are compared. Several values of face-to-core stiffness ratio (FCSR) and geometrical plate/shell parameters have been analyzed. Both fundamental vibration modes and those corresponding to high wave numbers are considered in the analysis. It is concluded that: (1) ZZF is highly recommended in the free vibration analysis of sandwich plates and shells; (2) the use of ZZF makes the error almost independent by
FCSR parameter; (3) ZZF is easy to implement and its use should be preferred with respect to other ‘more cumbersome’ refined theories.

References listed at the end of the paper:


ABSTRACT:
The linear equivalent plate approach developed and used for the aeroelastic optimization of composite wings at the conceptual design stage is a Ritz approach based on simple polynomial functions as generalized coordinates.
Generalization to the case of geometrically nonlinear structural behavior is presented here in an effort to assess accuracy and performance of the method in the nonlinear static and dynamic cases. Using the von-Karman plate formulation for moderately large deformations, 3-dimensional assemblies of thin-plate segments are modeled using a penalty function approach to impose boundary conditions and compatibility of motion between adjacent segments. Closed form expressions for mass and stiffness terms (linear and nonlinear) make numerical integration unnecessary. Numerical results obtained by the present method for a variety of plate structures, in both static and dynamic cases, show good correlation with published results and results by other computer codes. The present formulation is also compared with large-deformation Updated Lagrangian formulation results. Limits of applicability, in terms of the range of deformations still captured accurately by the equivalent plate method, are studied in all test cases.

References listed at the end of the paper:


ABSTRACT: Two-dimensional theories and finite elements are assessed to analyze displacement and stress fields in sandwich, composites plates. Two benchmarks are used to conduct the assessment. The first benchmark is a sandwich plate loaded by harmonic distribution of transverse pressure for which a three-dimensional closed-form solution exists in the literature. The second benchmark is a rectangular sandwich plate loaded by a transverse pressure located at the center. More than 20 plate theories and finite elements were implemented in a unified formulation recently proposed by the authors. Classical theories based on displacement assumptions are compared to advanced mixed models formulated on the basis of Reissner’s mixed variational theorem. Both equivalent single-layer models as well as layerwise models are considered. Analytical closed-form solutions and finite elements are given. The considered benchmarks highlight both the performance and limitations of the considered two-dimensional theories. The convenience of layerwise description and advanced mixed theories has been demonstrated. The second benchmark especially proved the need for layerwise models to capture the local effects.

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47. R. Valid, La théorie linéaire des coques et son application aux calculs inélastiques, Thèse, Université de Poitiers, 1973.


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ABSTRACT: In the first part of this paper we have deduced a classification of asymptotic shallow shell models with respect to the level of applied forces, from the non-linear threedimensional elasticity. We have used a constructive approach based on a dimensional analysis of the non-linear three-dimensional equilibrium equations, which naturally makes appear dimensionless numbers characterizing the applied forces (F and G) and the geometry of the shell (ε and C). To limit our study to one-scale problems, these dimensionless numbers are expressed in terms of the relative thickness ε of the shell, considered as the perturbation parameter. In the first part, we have studied the case of shallow shells corresponding to C = ε². In the second part of this paper, we will study the case of strongly curved shells for which C = ε. The classification that we obtain is then more complex. It depends not only on the force levels, but also on the existence of inextensional displacements which keep invariant the metric of the middle surface of the shell.

References listed at the end of the paper:


ABSTRACT: We show the local existence and the regularity of the nonlinear thin shell model of Donnell-Mushtari-Vlasov, using the implicit function theorem at the neighbourhood of the origin and the classical results of regularity for linear elliptic partial differential equations and sytems, for the case of a clamped shell.

-------- Some papers on buckling in a Special Issue of a journal, August 2014 --------
Dan Dubina (1), H.H. Snijder (2) and L. Simoes da Silva (3) (Guest Editors)
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(2) University of Eindhoven, The Netherlands
(3) University of Coimbra, Portugal
Brief description of the contents of this special issue (written by the Guest Editors):
The topics of the papers included in this volume are diverse enough, tackling stability problems of steel structures with thin and thick walled bar members, open and hollow sections, plated structures and curved
sandwich panels. There are theoretical, numerical and experimental approaches and combinations of them used in solving stability problems. The 12 papers have been framed into two parts: 
Part I: Theoretical background, numerical and experimental advanced studies – 7 papers; 
Part II: Design codification oriented studies – 5 papers.

Titles and abstracts of some of the papers in PART 1 of the Special Issue:
Dan Dubina (1,2) and Viorel Ungureanu (1,2)
(1) “Politehnica” University of Timisoara, Civil Engineering Faculty, Department of Steel Structures and Structural Mechanics, Ioan Curea 1, 300224, Timisoara, Romania
(2) The Romanian Academy, Timisoara Branch, Laboratory of Steel Structures, Mihai Viteazu 24, 300223, Timisoara, Romania

“Erosion of interactive buckling load of thin-walled steel bar members: Contribution of ‘Timisoara School’”
ABSTRACT: The paper presents a summary of the activity and research achievements of the Romanian researchers of Timisoara School in the field of stability of cold-formed steel members. Both, fundamental theory and applied instability contributions are focussed. Post-critical theory of elastic structures, the analysis of stable and unstable components of bifurcation load, coupling of bifurcations modes (e.g. mod interaction), erosion of critical load are the topics in which the theoretical contributions of Timisoara School are significant. Present paper focuses the mode interaction problems of thin-walled steel bar members only, integrating some relevant results obtained by the authors through a state-of-art review.

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Giovanni Garcea, Antonio Bilotta, Antonio Madeo, Giuseppe Zagari and Raffaele Casciario (University of Calabria, Italy), “A numerical asymptotic formulation for the post-buckling analysis of structures in case of coupled instability”

ABSTRACT: The analysis of slender structures, characterized by complex buckling and postbuckling phenomena and by a strong imperfection sensitivity, is heavily penalized by the lack of adequate computational tools. Standard incremental iterative approaches are computationally expensive and unaffordable, while FEM implementation of the Koiter method is a convenient alternative. The analysis is very fast, its computational burden is of the same order as a linearized buckling load evaluation and the simulation of different imperfections costs only a fraction of that needed to characterize the perfect structure. The main objective of the present work is to show that finite element implementations of the Koiter method can be both accurate and reliable and to highlight the aspects that require further investigation.

References listed at the end of the paper:
33. Poulsen, P.N., Damkilde, L., Direct determination of asymptotic structural postbuckling behavior by the finite element method,
Rodrigo Goncalves (1) and Dinar Camotim (2)
(1) UNIC, Faculdade de Ciências e Tecnologia, Department of Civil Engineering, NOVA University Lisbon, 2829-516 Caparica, Portugal
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“Effect of distortion on the structural behavior of thin-walled steel regular polygonal tubes”

ABSTRACT: This paper addresses the effect of cross-section distortion on the structural behaviour of thin-walled tubes with single-cell regular convex polygonal cross-sections (RCPS) and provides an in-depth view on the underlying mechanical aspects. In particular, the first-order, buckling (bifurcation) under uniform compression and undamped free vibration behaviours are characterised using the modal decomposition features and computational efficiency of a GBT (Generalised Beam Theory) specialization for RCPS recently developed by the authors [1]. Several analytical and illustrative numerical results are presented and discussed within the paper.

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3. GONÇALVES, R., CAMOTIM, D., Buckling behaviour of thin-walled regular polygonal tubes subjected to bending or torsion, Thin-Walled Structures, 73, pp. 185–97, 2013.

Maria Kotelko (1), Artur Moldawa (1) and Marcin Jankowski (2)
(1) Lódz (1) University of Technology, Department of Strength of Materials, 90-924 Łódz, Stefanowskiego
“Axial impact of open-section TWCF columns – experimental study”

ABSTRACT: The paper is devoted to the results of experimental study into the crushing behaviour of TWCF open section columns subjected to axial impact. Steel channel and top-hat section was under investigation. The paper contains a results summary of quasi-dynamic and dynamic impact tests performed on about 100 of those sections of different dimensions subjected to axial load of different velocities. Experimental quasi-dynamic tests were conducted on the testing machine with different loading velocities up to 600 mm/min. The impact tests were performed on the drop hammer rig with the impact energy up to 5 kJ and impact velocity up to 10 m/s. An influence of the column initial length and impact velocity on the crushing behaviour (failure mode) was investigated. Particularly, the critical length of the transition from progressive buckling to global bending failure mode and its dependence on section dimensions and the impact velocity was under investigation. Experimental results were compared with the results of the analytical calculations of critical (transition) buckling length based on the simplified analytical theoretical models. The results are presented in load-time and load-shortening diagrams and failure patterns. Some conclusions concerning the determination of critical buckling length, applicability of the theoretical models applied and an influence of the impact velocity upon the critical buckling length and final mode of failure related to the energy absorption capability of columns are derived.

References listed at the end of the paper:


Joao Pedro Martins, L. Simoes da Silva, Liliana Marques and Martin Pircher (Dept. of Civil Engineering, University of Coimbra, Portugal), “Eigenvalue analysis of curved sandwich panels loaded in uniaxial compression”

ABSTRACT: An energy formulation of a simply supported cylindrically curved sandwich panel loaded in compression is introduced and the corresponding potential energy function is evaluated. The mechanical model
of a cylindrically curved sandwich panel comprises three interacting buckling modes, corresponding to nine degrees of freedom comprising $q_s$, $q_x$ and $q_y$ components of local snake $(m, n)$ and overall $(k, l)$ modes, the related local hourglass $(m, n)$ mode. Finally, closed-form solutions are presented for the global and local buckling modes.

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1. SCHRÄDT, R., Verallgemeinerte Technische Biegetheorie (in German), Springer-Verlag, Berlin, 1989.
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Franc Sinur (1), Primoz Moze (1) Klemen Rejec (1), Gasper Luzar (2) and Darko Beg (1)
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(2) Bürogemeinschaft Kuhlmann Gerold Günther Eisele, Germany
“Imperfection sensitivity of thin plates loaded in shear”

ABSTRACT: The paper deals with imperfection sensitivity analysis of longitudinally stiffened thin plates loaded in shear. The aim of this paper is to demonstrate the use of optimization method for direct determination of the worst imperfection shape. New linear constraints are considered in optimization method in order to find not only the worst but also realistic imperfection shape. Further on, different solutions of arbitrary shapes that are used to estimate the worst imperfection are introduced and compared. Finally, a parametric analysis seeking the worst imperfection shape is performed and discussed.

References listed at the end of the paper:
INTRODUCTION: Elastic buckling of cylindrical shells under axial compression is regarded as one of the most difficult tasks involved in the buckling phenomenon. Buckling of a thin-walled shell is typically a local phenomenon that may be triggered by a small, local disturbance. In the case of a very thin shell that exhibits elastic buckling, experimental results show that the first single buckle is initiated at the local portion of the cylinder, the number of buckles sharply increases, and thus the cylinder loses its overall structural stability. In this paper, we trace this successive buckling process using the latest in finite element analysis technology. This paper also describes the generation of singularities in a large-deformed viscoelastic cylindrical shell.

References listed at the end of the paper:

PARTIAL INTRODUCTION: Corrugated steel buried structures (CSBS) have been in use in the United Kingdom in various forms for many decades. The smaller structures are largely circular or near circular in form and are usually enclosed by the corrugated steel sheeting. Arch forms known as super-span structures have been introduced in recent years to span wider crossings…The aims of this project were to:
1. evaluate the comparative reliability of long span structures designed in terms of the draft standard and short span structures designed in terms of the existing standard.
2. evaluate the nature and degree of possible undue conservatism in the proposed draft standard.
3. evaluate the relative reliability of CSBS compared to other bridge types...

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ABSTRACT: The newly developed p-M diagram provides a means for readily evaluating the collapse and/or buckling load of pressure equipment with external flaws simultaneously subjected to internal pressure, p and external bending moment, M due to earthquake, etc. In this paper, some FEAs for large diameter vessels with an external flaw were conducted under (1) pure external bending moment, and (2) subjected simultaneously to both internal pressure and external bending moment, in order to determine the plastic collapse load by applying the twice-elastic slope (TES) as recommended by the ASME and to determine the buckling load. The p-M line adopted in the Ibaraki FFS rule based on the measured yield stress indicates that the safety margin for the TES loads at the LTA is about 1.2–1.8, and 1.5–2.0 for the buckling loads. The Ibaraki FFS rule that prevents buckling by applying Donnell's equation of FS = 2 can assure adequate levels of integrity and safety.

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ABSTRACT: Damage generally refers to the more or less gradual development of micro-voids and micro-cracks. Damage mechanics is the modelling of these phenomena on a structural analysis scale. In this paper we first recall the non-linear behaviour models we have developed to model composite laminates. Then we present two examples of implementations of such models in a structural analysis code in order to simulate the inner-failure of a structure, or to study delamination initiation.

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ABSTRACT: The problem of multilayered degenerated 3-D shell elements for which the numerical integration is performed for each ply is that of the high generation time in non-linear analysis when the number of plies is important. But these elements give accurate results for thin and moderately thick shells, so in order to reduce the generation time explicit thickness integration is investigated. We first write an expansion of the strain-displacement matrix in power series of the thickness variable in order to obtain explicit expressions of the tangent stiffness matrix and internal force vector, appearing in the non-linear formulation. Explicit expressions
of non-linear stiffness matrices are presented, using the explicit integration-first approximation. Simple expressions of several matrices, sub-matrices and vectors appearing in the formulation are given here in order to obtain an important computing-time gain. Next, some numerical validation tests comparing the classical element with numerical thickness integration and this one are discussed to prove validity of this formulation.


ABSTRACT: A nomograph is introduced, which is based on the stability equations for an orthotropic cylindrical shell. The equations are derived from the assumption of the exact displacement versus strain relationship and of linear-elastic material behaviour. The displacement versus strain relationship is the same as Flügge indicated for the isotropic cylindrical shell. The nomograph can be used to determine in a fast and direct way the ideal local and global buckling pressure and the critical buckling form of a ring-stiffened circular cylindrical shell under external pressure. The determining values are useful for the preliminary design. They can serve as input values for an idealization concept that describes the method for obtaining a representative substructure for a finite element calculation. The subsequent geometrically and physically non-linear stability analysis of the subsystem is performed using two ring-reinforced cylinders as an example, and then compared with experimental results.


ABSTRACT: In this paper, a review of past and recent developments in the dynamics of flexible multibody systems is presented. The objective is to review some of the basic approaches used in the computer aided kinematic and dynamic analysis of flexible mechanical systems, and to identify future directions in this research area. Among the formulations reviewed in this paper are the floating frame of reference formulation, the finite element incremental methods, large rotation vector formulations, the finite segment method, and the linear theory of elastodynamics. Linearization of the flexible multibody equations that results from the use of the incremental finite element formulations is discussed. Because of space limitations, it is impossible to list all the contributions made in this important area. The reader, however, can find more references by consulting the list of articles and books cited at the end of the paper. Furthermore, the numerical procedures used for solving the differential and algebraic equations of flexible multibody systems are not discussed in this paper since these procedures are similar to the techniques used in rigid body dynamics. More details about these numerical procedures as well as the roots and perspectives of multibody system dynamics are discussed in a companion review by Schiehlen [79]. Future research areas in flexible multibody dynamics are identified as establishing the relationship between different formulations, contact and impact dynamics, control-structure interaction, use of modal identification and experimental methods in flexible multibody simulations, application of flexible multibody techniques to computer graphics, numerical issues, and large deformation problem. Establishing the relationship between different flexible multibody formulations is an important issue since there is a need to clearly define the assumptions and approximations underlying each formulation. This will allow us to establish guidelines and criteria that define the limitations of each approach used in flexible multibody dynamics. This task can now be accomplished by using the “absolute nodal coordinate formulation” which was recently introduced for the large deformation analysis of flexible multibody systems.
ABSTRACT: Many flexible multibody applications are characterized by high inertia forces and motion discontinuities. Because of these characteristics, problems can be encountered when large displacement finite element formulations are used in the simulation of flexible multibody systems. In this investigation, the performance of two different large displacement finite element formulations in the analysis of flexible multibody systems is investigated. These are the incremental corotational procedure proposed by Rankin and Brogan and the nonincremental absolute nodal coordinate formulation recently proposed. It is demonstrated in this investigation that the limitation resulting from the use of the nodal rotations in the incremental corotational procedure can lead to simulation problems even when very simple flexible multibody applications are considered. The absolute nodal coordinate formulation, on the other hand, does not employ infinitesimal or finite rotation coordinates and leads to a constant mass matrix. Despite the fact that the absolute nodal coordinate formulation leads to a complex expression for the elastic forces, the results presented in this study, surprisingly, demonstrate that such a formulation is efficient in static problems as compared to the incremental corotational procedure. The excellent performance of the absolute nodal coordinate formulation in static and dynamic problems can be attributed to the fact that such a formulation does not employ rotations and leads to exact representation of the rigid body motion of the finite element.

ABSTRACT: The objective of this study is to develop simple and accurate elastic force models that can be used in the absolute nodal co-ordinate formulation for the analysis of two-dimensional beams. These force models which account for the coupling between bending and axial deformations are derived using a continuum mechanics approach, without the need for introducing a local element co-ordinate system. Four new different force models that include different degrees of complexity are presented. It is shown that the vector of the elastic forces can be significantly simplified as compared to the elastic force model developed for the absolute nodal co-ordinate formulation using a local element frame [1]. Despite the simplicity of the new models, they account for elastic non-linearity in the strain–displacement relationship. Therefore, they lead to more accurate results as compared to the more complex models developed using the local frame method which does not account for the non-linearities in the strain–displacement relationships. Numerical results are presented in order to demonstrate the use of the new models and test their performances in the analysis of large deformations of flexible multibody systems.

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ABSTRACT: In this investigation, a non-incremental solution procedure for the finite rotation and large deformation analysis of plates is presented. The method, which is based on the absolute nodal coordinate formulation, leads to plate elements capable of representing exact rigid body motion. In this method, continuity conditions on all the displacement gradients are imposed. Therefore, non-smoothness of the plate mid-surface at the nodal points is avoided. Unlike other existing finite element formulations that lead to a highly nonlinear inertial forces for three-dimensional elements, the proposed formulation leads to a constant mass matrix, and as a result, the centrifugal and Coriolis inertia forces are identically equal to zero. Furthermore, the method relaxes some of the assumptions used in the classical and Mindlin plate models and automatically satisfies the objectivity requirements. By using a general continuum mechanics approach, a relatively simple expression for the elastic forces is obtained. Generalization of the formulation to the case of shell elements is discussed. As examples of the implementation of the proposed method, two different plate elements are presented; one plate element does not guarantee the continuity of the displacement gradients between the nodal points, while the other plate element guarantees this continuity. Numerical results are presented in order to demonstrate the use of the proposed method in the large rotation and deformation analysis of plates and shells. The numerical results, which are compared with the results obtained using existing incremental procedures, show that the solution obtained using the proposed method satisfies the principle of work and energy. These results are obtained using explicit numerical integration method. Potential applications of the proposed method include high-speed metal forming, vehicle crashworthiness, rotor blades, and tires.
Per Hyldahl, “Rectangular shell elements based on the absolute nodal coordinate formulation”, PhD dissertation, Dept. of Engineering, Aarhus University, Aalborg, Denmark, July 2015

ABSTRACT: This thesis concerns the development of tools that are useful for designing machine systems and components in an virtual environment using flexible multibody dynamics. Initially, flexible multibody dynamics is briefly reviewed to explain available formalisms and possible applications of this method. Subsequently, attention is turned towards the analysis of structures that undergo large deformations and rotations using shell finite elements based on the absolute nodal coordinate formulation, ANCF. This topic is the focus for the remainder of the thesis. The thesis is divided into three main parts. The first part acts as a general introduction to ANCF based shell finite elements and sums up available elements found in the research literature. In the end, a new ANCF element developed during this PhD project is presented which gives enhanced modeling capabilities of problems including e.g. moving boundary conditions. The second part concerns the performance and behavior of a certain class of ANCF shell elements that are developed for analysis of thin shell structures. This includes discussions on differences concerning their kinematic descriptions and disclosure of certain issues regarding their performance. Those being sensitivity to irregular mesh, poor representation of curved structures and load dependent convergence when analyzing curved structures. The final part concerns the development of a new versatile ANCF shell element. This element is distinguished by being able to describe both thin and thick curved structures. This part contains a thorough derivation of its kinematics and stiffness description, as well as numerical examples to demonstrate its performance. However, this part of the study is not yet complete. Finally, the findings of this PhD project are summed up in a conclusion and possibilities for further studies and perspectives are outlined.

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Fan Jiashen (Department of Civil Engineering, Yunnan Polytechnic University, Kunming 650051, People's Republic of China), “Static and dynamic stability for geometrical nonlinear governing equations of elastic thin shallow shells”, Applied Mathematical Modelling, Vol. 25, No. 9, pp 775-792, September 2001

ABSTRACT: In this study, the governing equations for large deflection of elastic thin shallow shells are deduced into an algebraic cubic equation to determine the unknown coefficient of the assumed deflection by applying Galerkin’s method in combination with the algebraic polynomial and Fourier series. For the dynamic problem, the coefficient is replaced by an unknown function of time; after the same process is applied, the governing equations are deduced to be a nonlinear ODE of order two called the Duffing equation, and its analytical solution is known. The combination of the algebraic polynomial and Fourier series gives very rapid convergence in the asymptotic solutions.

References listed at the end of the paper:


ABSTRACT: We are presenting a simple low-order solid-shell element formulation—having only displacement degrees of freedom (dofs), i.e., without rotational dofs—that has an optimal number of parameters to pass the patch tests, and thus allows for efficient and accurate analyses of large deformable multilayer shell structures using elements at extremely high aspect ratio. With the dynamics referred to a fixed inertial frame, the elements
can be used to analyze multilayer shell structures undergoing large overall motion. The formulation of this element is based on the mixed Hu-Washizu variational principle leading to a novel enhancing strain tensor (enhanced assumed strain (EAS) method) that renders the computation particularly efficient, with improved in-plane and out-of-plane bending behavior (Poisson thickness locking), especially in refined analyses of composite structures involving a large number of high aspect-ratio layers. The energy–momentum conserving algorithm in the context of current solid shell element is presented. We discuss the EAS formulation based on the displacement gradient and its complexity compared to formulation on the Green–Lagrange strain. Shear locking and curvature thickness locking are treated using the assumed natural strain (ANS) method. The element has an optimal combination of the ANS method and the minimal number of EAS parameters required to pass the plate bending patch test. Numerical examples involving dynamic analyses (with conservation of energy and momentum) of multilayer shell structures having a large range of element aspect ratios are presented. Several implicit direct integration methods with/without numerical dissipation are used and compared in terms of the accuracy, stability and cost in multilayer shell structure. Finally, we note that the topic in this paper is a fitting dedication to Professor Ekkehard Ramm, who has made important pioneering contributions in this research direction.

ABSTRACT: Multigrid finite-element solvers using the corotational formulation of finite elements provide an attractive means for the simulation of deformable bodies exhibiting linear elastic response. The separation of rigid body motions from the total element motions using purely geometric methods or polar decomposition of the deformation gradient, however, can introduce instabilities for large element rotations and deformations. Furthermore, the integration of the corotational formulation into dynamic multigrid elasticity simulations requires to continually rebuild consistent system matrices at different resolution levels. The computational load imposed by these updates prohibits the use of large numbers of finite elements at rates comparable to the small-strain finite element formulation. To overcome the first problem, we present a new method to extract the rigid body motion from total finite element displacements based on energy minimization. This results in a very stable corotational formulation that only slightly increases the computational overhead. We address the second problem by introducing a novel algorithm for computing sparse products of the form RKR(transpose), as they have to be evaluated to update the multigrid hierarchy. By reformulating the problem into the simultaneous processing of a sequential data and control stream, cache miss penalties are significantly reduced. Even though the algorithm increases memory requirements, it accelerates the multigrid FE simulation by a factor of up to 4 compared to previous multigrid approaches. Due to the proposed improvements, finite element deformable body simulations using the corotational formulation can be performed at rates of 17 tps for up to 12k elements.

Chao-Chieh Lan (Department of Mechanical Engineering, National Cheng Kung University, No. 1 University Road, Tainan 701, Taiwan), “Analysis of large-displacement compliant mechanisms using an incremental linearization approach”, Mechanism and Machine Theory, Vol. 43, No. 5, May 2008, pp. 641-658, doi:10.1016/j.mechmachtheory.2007.03.010
ABSTRACT: Compliant mechanisms transmit motion and force by deflection of their flexible members. They are usually made of a monolithic piece of material and thus involve no wear, backlash, noise, and lubrication. To predict more accurately their deflected shape in larger working range, the analysis of compliant mechanisms has usually based on nonlinear numerical techniques such as the finite element method. However, the problems
of nonlinear analyses are their numerical instability and extensive computation time. These have limited further applications of compliant mechanisms. In this paper, the global coordinate model (GCM) with an incremental linearization approach is presented to turn the nonlinear problem into a sequence of linear problems. Both geometric and material nonlinearities are considered. As a result, numerous linear analysis techniques can be applied to facilitate design and prototyping of compliant mechanisms. Systematic procedures are developed to analyze generic compliant mechanisms that may include non-uniform or initially curved segments. Illustrations are shown with results validated experimentally and by comparing with the nonlinear finite element method. It is expected that the proposed approach can serve as a basis for broader applications of compliant mechanisms.


ABSTRACT: The nonlinear vibrations of a composite panel subjected to uniform edge compression and a high-supersonic coplanar flow is analysed. Third-order piston theory aerodynamics is used and the effects of in-plane edge restraints, small initial geometric imperfections, transverse shear deformation, and transverse normal stress are considered in the structural model. Periodic solutions and their bifurcations are determined using a predictor-corrector type Shooting Technique, in conjunction with the Arclength Continuation Method for the static state. It is demonstrated that third-order aerodynamic nonlinearities are destabilizing, and hard flutter oscillations (both periodic and quasiperiodic) of the buckled panel are obtained. Furthermore, chaotic motions of an uncompressed panel, as well as a buckled-chaotic transition, and chaos via period-doubling are possible, and the associated Lyapunov exponents are computed. A coexistence of the buckled state with flutter motion may also occur. Results indicate that edge restraints parallel to the flow do not significantly affect the immediate post-critical response, and that a higher-order shear deformation theory is required for a moderately thick/flexible-in-transverse-shear composite panel.


ABSTRACT: The non-linear dynamic behavior of a uniformly compressed, composite panel subjected to non-linear aerodynamic loading due to a high-supersonic co-planar flow is analyzed. The effects of in-plane edge restraints, small initial geometric imperfections, transverse shear deformation, and transverse normal stress are considered in the structural model which satisfies the traction-free condition on the panel faces. The panel flutter equations, derived via Galerkin's Method, are solved using Arclength Continuation for the static solution and a predictor-corrector type Shooting Technique to obtain periodic solutions and their bifurcations. The possibility of hard flutter is demonstrated when considering non-linear aerodynamics. Furthermore, edge compression could yield multiple buckled states or coexistence of multiple periodic solutions with the stable static solution, that is, the panel could either remain buckled or flutter. Edge restraints normal to the flow appear to stabilize the panel, whereas those parallel to the flow may result in a buckled-flutter-buckled transition. Quasi-periodic and chaotic motions and associated Lyapunov exponents are also obtained. For perfect panels, results obtained by the Shooting Technique and the Method of Multiple Scales are in agreement only within the immediate post-flutter regime. Results indicate that a shear deformation theory is required for moderately thick composite panels.
ABSTRACT: A flexible material, such as a woven or braided fabric, may be tailored to form an arch when inflated. Such arches have been used as the framework for transportable shelters and are analyzed in this paper. It is assumed that the cross section of the pressurized arch is circular and that only in-plane (membrane) stresses are present. An analytical solution for these initial stresses is given for an arbitrary arch centerline shape. Then external loads are applied, and the additional stress resultants include bending and twisting moments. The linear thin-shell theory of Sanders is used to formulate the governing equations, including the effect of the initial membrane stresses. The material is linearly elastic, nonhomogeneous, and orthotropic. Approximate solutions are obtained using the Rayleigh–Ritz method. In the examples, the centerline of the arch is a semi-circle, the ends are fixed, and the material is homogeneous and isotropic. Four loads are treated: a symmetric (‘full’) snow load, an asymmetric (‘half’) snow load, a wind load symmetric with respect to the plane of the arch centerline, and a distributed load acting sideways. The resulting deflections are computed and plotted.

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ABSTRACT: Cylindrical shells are widely used in civil engineering. Examples include cooling towers, nuclear containment vessels, metal silos and tanks for storage of bulk solids and liquids, and pressure vessels. Cylindrical shells subjected to non-uniform wind pressure display different buckling behaviours from those of cylinders under uniform external pressure. At different aspect ratios, quite complex buckling modes occur. The geometric nonlinearity may have a significant effect on the buckling behavior. This paper presents a widely study of the nonlinear buckling behavior of cylindrical shells of uniform thickness under wind loading. The finite element analyses indicate that for stocky cylinders, the nonlinear buckling modes are the circumferential compression buckling mode, which is similar to cylinders under uniform external pressure, while for cylinders in mediate length, pre-buckling ovalization of the cross-section has an important influence on the buckling strength.

ABSTRACT: This is the last of three companion papers which examine the elastic buckling and collapse of laser-welded sandwich panels with an adhesively bonded core and unidirectional vertical webs. By evaluation of the buckling stress in the first two papers it has been found that the buckling stress in compression parallel and normal to the webs typically reaches the proportional limit of the face plate and web material well before elastic buckling occurs. Hence, this paper presents an extension of the buckling model into the elastoplastic regime, with the aim of determining the ultimate (local) strength of the sandwich and of allowing experimental verification of the results. Using tangent modulus theory to 'plasticize' the elastic buckling model, the ultimate
strength is evaluated for a sandwich configuration with high-strength steel face plates and a broad range of core moduli. The critical load predicted by the inelastic buckling model agrees well with non-linear finite element results and experimental values obtained from compression testing.

Gin Boay Chai and Chun Wee Yap (School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore), “Coupling effects in bending, buckling and free vibration of generally laminated composite beams”, Composites Science and Technology, Vol. 68, Nos. 7-8, June 2008, pp. 1664-1670, doi:10.1016/j.compscitech.2008.02.014

ABSTRACT: A closed form expression to determine the effective flexural modulus of a laminated composite beam is developed and presented in this contribution. This effective flexural modulus is applied to the bending, buckling and free vibration response of generally laminated composite beams with various boundary supports. The expression was developed using the combination of the Euler-Bernoulli beam and classical lamination theory. In addition the results of an extensive finite element analysis are used to validate the analytical model. The comparison of the analytical results, the finite element results and the experimental results showed good correlation. It is also observed that coupling response is an important variable that must be included in the computation of the effective flexural stiffness of generally laminated beam.

Chun Wee Yap and Gin Boay Chai (School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore), “Analytical and numerical studies on the buckling of delaminated composite beams”, Composite Structures, Vol. 80, No. 2, September 2007, pp. 307-319, doi:10.1016/j.compstruct.2006.05.010

ABSTRACT: In this article, an innovative approach is proposed using the Euler-Bernoulli beam and classical lamination theory (CLT) to create an analytical model that can be used to obtain the buckling load of a delaminated composite beam. Furthermore, the finite element method is used as a tool to validate the analytical model. An 8-noded shell element and a contact pair are used in the numerical simulation. Studies are carried out on ply orientation, stacking sequence, through-the-width location of the delamination, delamination length and effect of total number of plies. It is found that application of R2 to the analytical model will always yield a more accurate answer than use of R1. It is also observed that $B16^2/A66$ is an important expression that must be included to compute the flexural stiffness of the individual sub-laminates of the anti-symmetric laminated beam considered more accurately. Moreover, it is noted that the length of the delamination will affect the accuracy and difference between the analytical predictions. Nevertheless, the analytical results and simulation values are in good agreement.


ABSTRACT: This paper is concerned with the theoretical analysis and correlation with the numerical results of the displacement time histories of the cylindrically curved laminated composite shells exposed to normal blast shock waves. The laminated composite shell is clamped at its all edges. The dynamic equation of the cylindrical shell used in this study is valid under the assumptions made in Love's theory of thin elastic shells. The constitutive equations of laminated composite shells are given in the frame of effective modulus theory. The governing equation of the cylindrical shell is solved by the Runge-Kutta method. In addition, a finite element
modeling and analysis are presented and compared with the theoretical results. The peak deflections and response frequencies obtained from theoretical and numerical analyses are in agreement. The effects of material properties and geometrical properties are examined on the dynamic behaviour.

ABSTRACT: Locking phenomena in C0 curved finite elements are studied for displacement, hybrid-stress and mixed formulations. It is shown that for a curved beam element, shear and membrane locking are interrelated and either shear or membrane underintegration can alleviate it. However, reduced shear integration tends to diminish the membrane-flexural coupling which characterizes curved elements. Locking can also be expected in certain types of mixed formulations, the hybrid-stress formulations avoids locking for beams (but not for shells). Methods for avoiding locking are explored and alternatives evaluated.

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ABSTRACT: A finite element formulation and algorithm for the nonlinear analysis of the large deflection, materially nonlinear response of impulsively loaded shells is presented. A unique feature of this algorithm is the use of a bilinear four-node quadrilateral element with single-point quadrature and a simple hourglass control which is orthogonal to rigid body modes on an element level and does not compromise the consistency of the equations. The geometric nonlinearities are treated by using a corotational description wherein a coordinate system that rotates with the material is embedded at the integration point; thus the algorithm is directly applicable to anisotropic materials without any corrections for frame invariance of material property tensors. This algorithm can treat about 200 element-time-steps per CPU second on a CYBER 170/730 computer in the explicit time integration mode. Numerous results are presented for both elastic and elastic-plastic problems with large strains that show that the method in most cases is comparable in accuracy with an earlier version of this algorithm employing a cubic triangular plate-shelf element, but substantially faster.

ABSTRACT: A simple triangular shell element which incorporates the effects of coupling between membrane and flexural behaviour and avoids membrane locking is described. The element uses a discrete Kirchhoff bending formulation and a constant strain membrane element. For the purpose of permitting inextensional modes and thus avoiding membrane locking, a decomposition technique, which can also be viewed as a strain projection method, is used. The method is illustrated first for a beam element and then for a triangular shell element. Results are presented for a variety of linear static problems to illustrate its accuracy and some highly non-linear problems to indicate its applicability to collapse analysis.

ABSTRACT: The numerical quadrature of the stiffness matrices and force vectors is a major factor in the accuracy and efficiency of the finite element methods. Even in the analysis of linear problems, the use of too many quadrature points results in a phenomenon called locking whereas the use of insufficient quadrature points results in a phenomenon called spurious singular mode. Therefore, efficient numerical quadrature schemes for structural dynamics are developed. It is expected that these improved finite elements can be used more reliably in many structural applications. The proposed developed quadrature schemes for the continuum and shell elements are straightforward and are modularized so that many existing finite element computer codes can be easily modified to accommodate the proposed capabilities. This should prove of great benefit to many computer codes which are currently used in structural engineering applications.

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ABSTRACT: In the safety analysis of components of nuclear reactors, it is important to be able to analyze the postbuckling response. For shell structures of complicated shapes, triangular finite elements possess the most versatility in that they can easily be used to represent complicated geometries with openings, cutouts, and other features, whereas quadrilateral elements encounter difficulties in these situations. Therefore, they have added a triangular element to the SAFE/RAS code. The element was specifically designed to eliminate membrane locking. A finite element program with explicit time integration, SAFE/RAS treats both material and geometric nonlinearities. The purpose of this study was to test the performance of this element in postbuckling problems. In these highly nonlinear situations, the triangular element does not perform as well and is substantially stiffer than the quadrilateral. This is illustrated in the comparison of the response of the above-core support columns for the triangular and quadrilateral element models, respectively.


ABSTRACT: In this paper, a resultant-stress degenerated-shell element is described and a variety of numerical examples, including the post-buckling analysis of an axially loaded perfect cylinder, are presented. The general degenerated nonlinear shell theory of Hughes and Liu is employed in deriving this resultant-stress degenerated-shell element. Contrary to the traditional integration through the thickness approach, which assumes no coupling between the in-plane and transverse material and structural response matrices, the present approach can permit use of arbitrary, three-dimensional (3-D) nonlinear constitutive equations. Furthermore, explicit expressions of the element matrices for a 4-node shell element are developed. This rank-sufficient 4-node shell element, termed the resultant-stress degenerated-shell (RSDS) element, avoids the need for the costly numerical quadrature function evaluations of the element matrices and force vectors. And thus there are large increases in
computational efficiency with this method. The comparisons of this RSDS element with six other shell elements are also given in this paper.

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ABSTRACT: A triangular element which requires only one quadrature point per element is described along with its implementation in the nonlinear, explicit time integration program SAFE/RAS. The implementation of an Ilyushin flow law which eliminates the need for integration through the thickness and simple formulas for stable time steps is also described. The performance of the triangular and quadrilateral elements is compared in large deflection, elastic-plastic problems. Applications to the analysis of above-core structures in breeder reactors are also described.


ABSTRACT: An adaptive finite element procedure is developed for the transient analysis of nonlinear shells. The scheme is an h-method which employs fission and fusion. Criteria based on incremental work and deviation of the bilinear finite element approximation to the shell from a Kirchhoff-Love surface are used as criteria for adaptivity. The example problems show that the adaptive schemes are capable of achieving substantial improvements in accuracy for a given computational effort. They include both material and geometric nonlinearities and local and global buckling. In order to formulate an r-adaptive method, the conservation laws, the constitutive equations, and the equation of state for path-dependent materials are formulated for an arbitrary Lagrangian-Eulerian description. Both geometrical and material nonlinearities are included in this setting.


ABSTRACT: The effect of follower forces and initial stresses on the stability of the central difference method is studied. As a model, bar and beam elements are considered by means of the element eigenvalue inequality. It is shown that both follower-force pressure loads and tensile initial stresses decrease the stable timestep but the decrease becomes significant only when the pressure or stress is greater than about a tenth of the tangent modulus.

ABSTRACT: An adaptive finite element procedure is developed for the transient analysis of nonlinear shells. The scheme is an h-method which employs fission and fusion of elements to adaptively refine and coarsen the mesh. Incremental work and deviation of the bilinear finite element approximation to the shell from a Kirchhoff-Love surface are used as error criteria for adaptivity. The example problems show that the adaptive schemes are capable of achieving substantial improvements in accuracy for a given computational effort. They include both material and geometric nonlinearities and local and global buckling.


ABSTRACT: The evolution of computational methods for crashworthiness and related fields is described and linked with the decreasing cost of computational resources and with improvements in computational methodologies. The latter includes more effective time integration procedures and more efficient elements. Some recent developments in methodologies and future trends are also summarized. These include multi-time step integration (or subcycling), further improvements in elements, adaptive meshes, and the exploitation of parallel computers.

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ABSTRACT: A rank-sufficient flat triangular shell element with drilling degrees-of-freedom is described. A variational basis for this element has been provided by a three-field variational principle with relaxed interelement compatibility and traction continuity conditions. A generalized spurious mode control procedure has been developed in order to stabilize zero energy kinematical modes. Excellent performance has been found in an obstacle course and buckling problems.

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ABSTRACT: In the pinball contact-impact algorithm, the interpenetration check is simplified by enforcing it only on a set of spheres embedded within the elements. In the splitting pinball adaptation of this algorithm, the parent pinball is split into a hierarchy of descendent pinballs whenever interpenetration of the parent pinballs is detected. The interpenetration check is then applied to the descendent pinballs and contact forces are generated. This provides a better representation of the contact surface for thin shell elements. The implementation of the method with a penalty contact method is described and examples are given. It is also shown that the method easily and automatically handles edge-to-edge, edge-to-surface, and self-surface contact without any user specification.

ABSTRACT: A new four-node shell element for nonlinear analysis which is useful for explicit time integration with single point quadrature is presented. An assumed strain method is used to stabilize the zero-energy modes of the element. The stabilization procedure is based on the Hu-Washizu variational principle and does not require the input of any stabilization parameters. Example problems show good accuracy and rate of convergence compared with fully integrated 4-node elements, however the physically stabilized element is substantially faster than the fully integrated element.


ABSTRACT: A meshless approach to the analysis of arbitrary Kirchhoff shells by the Element-Free Galerkin (EFG) method is presented. The shell theory used is geometrically exact and can be applied to deep shells. The method is based on moving least squares approximant. The method is meshless, which means that the discretization is independent of the geometric subdivision into “finite elements”. The satisfaction of the C1 continuity requirements is easily met by EFG since it requires only C1 weights; therefore, it is not necessary to resort to Mindlin-Reissner theory or to devices such as discrete Kirchhoff theory. The requirements of consistency are met by the use of a polynomial basis of quadratic or higher order. A subdivision similar to finite elements is used to provide a background mesh for numerical integration. The essential boundary conditions are enforced by Lagrange multipliers. Membrane locking, which is due to different approximation order for transverse and membrane displacements, is removed by using larger domains of influence with the quadratic basis, and by using quartic polynomial basis, which can prevent membrane locking completely. It is shown on the obstacle course for shells that the present technique performs well.

References listed at the end of the paper:

ABSTRACT: Meshless approximations based on moving least-squares, kernels, and partitions of unity are examined. It is shown that the three methods are in most cases identical except for the important fact that partitions of unity enable p-adaptivity to be achieved. Methods for constructing discontinuous approximations and approximations with discontinuous derivatives are also described. Next, several issues in implementation are reviewed: discretization (collocation and Galerkin), quadrature in Galerkin and fast ways of constructing consistent moving least-square approximations. The paper concludes with some sample calculations. (cited by 1303 people as of August 2011!)

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ABSTRACT: The computability of non-linear problems in solid and structural mechanics problems is examined. Several factors which contribute to the level of difficulty of a simulation are discussed: the smoothness and stability of the response, the required resolution, the uncertainties in the load, boundary conditions and initial conditions and inadequacies and uncertainties in the constitutive equation. An abstract measure of the level of difficulty is proposed, and some examples of typical engineering simulations are
classified by this measure. We have put particular emphasis on engineering calculations, where many of the factors that diminish computability play a prominent role.

References listed at the end of the paper:
DeBorst R (2001) Some recent issues in computational failure mechanics, Int. J. for Numerical Methods in Engineering, ??same issue as this paper??

ABSTRACT: A general methodology to develop hyper-elastic membrane models applicable to crystalline films one-atom thick is presented. In this method, an extension of the Born rule based on the exponential map is proposed. The exponential map accounts for the fact that the lattice vectors of the crystal lie along the chords of the curved membrane, and consequently a tangent map like the standard Born rule is inadequate. In order to obtain practical methods, the exponential map is locally approximated. The effectiveness of our approach is demonstrated by numerical studies of carbon nanotubes. Deformed configurations as well as equilibrium energies of atomistic simulations are compared with those provided by the continuum membrane resulting from this method discretized by finite elements.
References listed at the end of the paper:


ABSTRACT: The formulation and finite element implementation of a finite deformation continuum theory for the mechanics of crystalline sheets is described. This theory generalizes standard crystal elasticity to curved monolayer lattices by means of the exponential Cauchy–Born rule. The constitutive model for a two-dimensional continuum deforming in three dimensions (a surface) is written explicitly in terms of the underlying atomistic model. The resulting hyper-elastic potential depends on the stretch and the curvature of the surface, as well as on internal elastic variables describing the rearrangements of the crystal within the unit cell. Coarse grained calculations of carbon nanotubes (CNTs) are performed by discretizing this continuum mechanics theory by finite elements. A smooth discrete representation of the surface is required, and subdivision finite elements, proposed for thin-shell analysis, are used. A detailed set of numerical experiments, in which the continuum/finite element solutions are compared to the corresponding full atomistic calculations of CNTs, involving very large deformations and geometric instabilities, demonstrates the accuracy of the proposed approach. Simulations for large multi-million systems illustrate the computational savings which can be achieved.


ABSTRACT: In the design of a modern lightweight structure, it is of technical importance to assure its safety against the buckling under the applied loading conditions. For this issue, the determination of the critical load in an ideal condition is not sufficient, but it is further required to clarify the postbuckling behavior, that is, the behavior of the structure after passing through the critical load. One of the reasons is to estimate the effect of practically unavoidable imperfections on the critical load and the second is to evaluate the ultimate strength to exploit the load-carrying capacity of the structure. For the buckling problem of circular cylindrical shells under axial compression, a number of experimental and theoretical studies have been made by many researchers. In the case of the very thin shell that exhibits elastic buckling, experimental results show that after the primary buckling, secondary buckling takes place accompanying successive reductions in the number of the circumferential waves at every mode shift on one-by-one step. In this paper we traced this successive buckling of circular cylindrical shells using the latest in general-purpose FEM technology. We carried out our studies with three approaches; one is to use the arc-length method (the modified Riks method), the second is static stabilizing with the aid of (artificial) damping especially for the local instability and the third is to use the explicit dynamic procedure. The studies accomplished the simulation of the successive buckling following unstable paths, and show good agreement with the experimental results.

References listed at the end of the paper:

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“Tracing nonlinear equilibrium paths of structures subjected to thermal loading”, Computational Mechanics, Vol. 38, No. 6, pp 505-520, November 2006

ABSTRACT: This work presents numerical methods for path tracing and nonlinear stability analysis, including critical point computation and branch-switching, of structures subjected to thermal loading. The differences between the thermal loading case and the standard case of mechanical loading are addressed from both conceptual and computational standpoints. The implementation of the presented methods in a nonlinear finite element system originally designed to deal with mechanical loading is discussed in detail. The techniques presented here are validated by numerical examples.

References listed at the end of the paper:
is illustrated in a numerical example where finite element solutions are obtained to a structural stability problem. The robustness of the criterion recently proposed by Y.T. Feng, D. Perić, D.R.J. Owen, [Determination of travel directions in path-following methods, Math. and Comput. Modelling 21 (1995) 43–59; A new criterion for determination of initial loading parameter in arc-length methods, Comput. Struct. 58 (1996) 479–485] produces a reliable path direction prediction even in the presence of bifurcations and/or ‘snap-backs’, when some popular criteria may fail to predict the continuation direction. The robustness of the criterion is illustrated in a numerical example where finite element solutions are obtained to a structural stability problem.
characterised by the existence of several bifurcation paths and `snap-back' phenomena.

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ABSTRACT: By the improvement of Riks’ and Crisfield's arc-length method, the adaptive parameter incremental method is presented for predicting the snapping response of structures. Its justification is fulfilled. Finally, the effectiveness of this method is demonstrated by solving the snapping response of spherical caps subjected to centrally distributed pressures.

References listed at the end of the paper:

ABSTRACT: A finite deformation continuum theory is derived from interatomic potentials for the analysis of the mechanics of carbon nanotubes. This nonlinear elastic theory is based on an extension of the Cauchy-Born rule called the exponential Cauchy-Born rule. The continuum object replacing the graphene sheet is a surface without thickness. The method systematically addresses both the characterization of the small strain elasticity of nanotubes and the simulation at large strains. Elastic moduli are explicitly expressed in terms of the functional form of the interatomic potential. The expression for the flexural stiffness of graphene sheets, which cannot be obtained from standard crystal elasticity, is derived. We also show that simulations with the continuum model combined with the finite element method agree very well with zero temperature atomistic calculations involving severe deformations.

References listed at the end of the paper:
Marino Arroyo (1) and Ted Belytschko (2)
ABSTRACT: The understanding of the mechanics of atomistic systems greatly benefits from continuum mechanics. One appealing approach aims at deductively constructing continuum theories starting from models of the interatomic interactions. This viewpoint has become extremely popular with the quasicontinuum method. The application of these ideas to carbon nanotubes presents a peculiarity with respect to usual crystalline materials: their structure relies on a two-dimensional curved lattice. This renders the cornerstone of crystal elasticity, the Cauchy–Born rule, insufficient to describe the effect of curvature. We discuss the application of a theory which corrects this deficiency to the mechanics of carbon nanotubes (CNTs). We review recent developments of this theory, which include the study of the convergence characteristics of the proposed continuum models to the parent atomistic models, as well as large scale simulations based on this theory. The latter have unveiled the complex nonlinear elastic response of thick multiwalled carbon nanotubes (MWCNTs), with an anomalous elastic regime following an almost absent harmonic range.


ABSTRACT: This paper improves the 16 degrees-of-freedom quadrilateral shell element based on pointwise Kirchhoff–Love constraints and introduces a consistent large strain formulation for this element. The model is based on classical shell kinematics combined with continuum constitutive laws. The resulting element is valid for large rotations and displacements. The degrees-of-freedom are the displacements at the corner nodes and one rotation at each mid-side node. The formulation is free of enhancements, it is almost fully integrated and is found to be immune to locking or unstable modes. The patch test is satisfied. In addition, the formulation is simple and amenable to efficient incorporation in large-scale codes as no internal degrees-of-freedom are employed, and the overall calculations are very efficient. Results are presented for linear and non-linear problems.

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ABSTRACT: Carbon nanotubes (CNTs) can undergo collapse from their customary cylindrical configurations to ribbons. The energy minima corresponding to these two states are identified using either atomistic molecular
mechanics or the theory of finite crystal elasticity with reduced dimensionality. The minimum energy path between these two minima is found using the nudged elastic band reaction-pathway sampling scheme. The energetics of CNT collapse is explored for both single- and multi-walled CNTs as well as small bundles. The process has a strong diameter dependence, with collapse being more favorable for the larger diameter tubes, but is nearly independent of chirality. The saddle point always lies close to the collapsed state, and the absolute barrier energies—even for fairly short tube lengths—are sufficiently high, even when the reaction is highly exothermic, that thermal activation cannot initiate collapse via this pathway. The hydrostatic pressure required to buckle and collapse CNTs of various diameters is discussed.

References listed at the end of the paper:


**ABSTRACT:** A meshfree method for thin shells with finite strains and arbitrary evolving cracks is described. The C1 displacement continuity requirement is met by the approximation, so no special treatments for fulfilling the Kirchhoff condition are necessary. Membrane locking is eliminated by the use of a cubic or quartic polynomial basis. The shell is tested for several elastic and elasto-plastic examples and shows good results. The shell is subsequently extended to modelling cracks. Since no discretization of the director field is needed, the incorporation of discontinuities is easy to implement and straightforward.

**INTRODUCTION:**

This paper describes a meshfree method for treating the dynamic fracture of shells. It includes both geometric and material nonlinearities and also includes a meshfree fluid model, so that complex fluid-structure interaction problems are feasible. Here we illustrate this capability with the fracture of a fluid-filled cylinder that is impacted by a penetrating projectile. The shell formulation is based on the Kirchhoff-Love (KL) theory. A meshfree thin shell based on the imposition of the KL constraints was first proposed by Krysl and Belytschko [1]. However, the shell was developed for small deformations, small strains and elasticity. Three dimensional modelling of shear deformable shells and degenerated shells in a meshfree context was studied by Noguchi et al. [2], Li et al. [3] and Kim et al. [4]. Usually, a low order polynomial basis was used, e.g. in [3], a trilinear polynomial basis was applied and the method was applied to several non-linear problems. However, for thin structures, three dimensional modelling of shell structures is computationally expensive. Garcia et al. [5] developed meshfree methods for plates and beams; the higher continuity of meshfree shape functions was exploited for Mindlin-Reissner plates in combination with a p-enrichment. Wang and Chen [6] proposed a meshfree method for Mindlin-Reissner plates. Locking is treated using second order polynomials for the approximation of the translational and rotational motion in combination with a curvature smoothing stabilization. Kanok-Nuukchai et al. [7] addressed shear locking for plates and beams in the element-free Galerkin method.

We develop a meshfree thin shell that combines classical shell theory with a continuum based shell. The kinematic assumptions of classical KL shell theory is adopted. We make use of the generality provided by the continuum description, so that constitutive models developed for continua are easily applicable to shells. The formulation is valid for finite strains.

We include in the shell the capability to model cracks, which are modeled either by cracked particles as in Rabczuk and Belytschko [8] or by a local partition of unity [9, 10, 11]. Due to the higher order continuity of meshfree methods, which enables the use of Kirchhoff-Love shell theories in pristine form, the incorporation of discontinuities is very simple and straightforward. The director field is not discretized, which simplifies the incorporation of discontinuities. In our meshfree model, the concepts for modelling cracks in continua can be adopted directly to shells.

The paper is arranged as follows: First, the kinematics of the shell is described. Then, the meshfree method, the element-free Galerkin (EFG) method, is reviewed and the concept how to incorporate continuum constitutive models is described. The extensions to modelling cracks is described in section 5. Finally, we test the meshfree shell for different elastic linear and nonlinear problems, plastic problems and cracking problems.

References listed at the end of the paper:


[27] P.M.A. Areias, J.M.A. Cesar de Sa, and Conceio Anto. A


ABSTRACT: This paper presents a formulation for a new family of thin shell finite elements. The element is formulated by using a convected material frame notion which offers an interesting framework to take into
account large transformations. Bending behaviour is calculated from the Love-Kirchhoff assumptions and from a finite difference technique between adjacent elements. We therefore called this element SFE for semi-finite element. This method allows us to keep C0 continuity without introducing other variables than the 3 classical displacements, which reduces computational time. In this paper, a full formulation of this element is described more precisely. It takes into account the coupling effect between both membrane and bending behaviour. Various sample solutions that illustrate the effectiveness of the element in linear and nonlinear analysis are presented, with some sheet metal forming examples.


ABSTRACT: This first of two companion papers develops a new variational principle for the buckling analysis of thin-walled members based on the principle of stationary complementary energy. Some of the aspects of the Vlasov thin-walled beam theory (the rigid cross section assumption, and the stress expressions) are postulated to describe the behavior of members while other aspects of the theory (i.e., the zero shear strain assumption at mid-surface) are discarded. Koiter's formulation based on polar decomposition theory in finite elasticity is adopted to formulate expressions for statically admissible stress resultant fields. The stationarity conditions of the complementary energy expression are then evoked to yield the conditions of neutral stability and associated boundary conditions in which the rotation fields appear explicitly. The formulation seamlessly incorporates shear deformation effects and load position effects. Also, the Wagner effect and the mono-symmetry property which arise in displacement based formulations arise in the present formulation in a natural way.


ABSTRACT: This paper presents an application of the spline strip method based on the first-order shear deformation Sanders shell theory to analyze vibration of antisymmetric angle-ply laminated cylindrical panels with two opposite circumferential edges simply supported and varying boundary conditions on the remaining two straight edges. To demonstrate the accuracy and convergence of the semi-numerical method, the results are compared with those obtained by the classical shell theory and by the first-order shear deformation shell theory. Stable convergence and good accuracy are obtained. The effects of the geometric parameters and material parameters on the frequencies of graphite-epoxy laminated cylindrical panels with some boundary conditions are analyzed.


ABSTRACT: This paper presents an application of the spline strip method based on the first-order shear deformation Sanders' shell theory to analyze vibration of symmetric and antisymmetric cross-ply laminated cylindrical panels with two opposite circumferential edges simply supported and some boundary conditions on the remaining two straight edges. To demonstrate the accuracy and convergence of the semi-numerical method,
the results are compared with those obtained by the classical shell theory and by the refined shear deformation shell theory. Stable convergence and good accuracy are obtained. The effects of the geometric parameters and material parameters on the frequencies of graphite-epoxy laminated cylindrical panels with some boundary conditions are analyzed.

ABSTRACT: This paper presents an application of the spline strip method based on the high-order shear deformation Donnell's shell theory to analyse vibration of thick laminated cylindrical panels with two opposite circumferential edges simply-supported and some boundary conditions on the remaining two straight edges. To demonstrate the accuracy and convergence of the semi-numerical method, the results are compared with those obtained by the first-order shear deformation shell theory. Stable convergence and good accuracy are obtained. The comprehensive comparison of both the high-order shear deformation Donnell's shell theory and the first-order shear deformation Donnell's shell theory is studied for graphite-epoxy laminated cylindrical panels with some boundary conditions.

ABSTRACT: This paper examines the post-buckling deformations of cylindrical shells conveying viscous fluid. The wall deformation is modelled using geometrically nonlinear shell theory, and lubrication theory is used to model the fluid flow. The coupled fluid-solid problem is solved using a parallelized FEM technique. It is found that the fluid-solid interaction leads to a violent collapse of the tube such that immediate opposite-wall contact occurs after the buckling if the volume flux is kept constant during buckling. If the pressure drop through the tube is kept constant during the buckling, the fluid-solid coupling slows down the collapse (compared to buckling under a dead load). The effects of various parameters (upstream pressure, axial pre-stretch and the geometry of the tube) on the post-buckling behaviour are examined and the exact geometrically nonlinear shell theory is compared to Sanders’ (1963) moderate rotation theory. Finally, the implications of the results for previous models which described the wall deformation using so called “tube laws” are discussed.

ABSTRACT: In this paper, a geometrically nonlinear hybrid/mixed curved quadrilateral shell element (HMSHEL4N) with four nodes is developed based on the modified Hellinger/Reissner variational principles. The performance of element is investigated and tested using some benchmark problems. A number of numerical examples of plate and shell nonlinear deflection problems are included. The results are compared with theoretical solutions and other numerical results. It is shown that HMSHEL4N does not possess spurious zero energy modes and any locking phenomenon, and is convergent and insensitive to the distorted mesh. A good agreement of the results with theoretical solutions, and better performance compared with displacement finite
element method, are observed. It is seen that an efficient shell element based on stress and displacement field assumptions in solution and time is obtained.

Chen Fangqi, Wu Zhiqiang and Chen Yushu (Department of Mathematics, Department of Mechanics, Tianjin University, Tianjin 300072, China), “The high codimensional bifurcations and universal unfolding problems of a viscoelastic circular cylindrical shell”, Acta Mechanica Sinica, 2001-05

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ABSTRACT: The nonlinear dynamical behavior of a viscoelastic circular cylindrical shell under a harmonic excitation applied at both ends is discussed. Using singularity theory and choosing nondegenerate germ, the universal unfolding problem of the bifurcation equation is studied. The results indicate that the universal unfolding is a high codimensional bifurcation problem with codimension 5 (contains a modal parameter). Additionally, all possible forms of the universal unfoldings are given, and the transition sets in parameter plane and the bifurcation diagrams are plotted under some conditions for unfolding parameters. It is well know that the dynamical behavior of nonlinear Mathieu equation in some special forms has been studied by many authors, such as, Bogoliubov N.N., Mitropolisky Y.A., Nayfeh A.H. and Mock D.T. Especially, by introduction of symmetry group action technique, Chen Yushu and Langford W.F. established the bifurcation classification results for stable responses of non-linear Mathieu equation in general form. A sense of theoretical and experimental results with Z2-symmetric bifurcations were obtained for a parametric excitation system with one degree of freedom. One knows that a symmetric unfolding of a bifurcation equation may describe possible dynamical behavior when original system is subjected to a small perturbation with the symmetry. However, when original system is subjected to a small perturbation which does not possess the symmetry's symmetric unfolding cann't present completely the dynamical behavior of original system. In this case, one should investigate the universal unfoldings of bifurcation equation including symmetry-breaking bifurcations. For a thin viscoelastic circular cylindrical shell with Flugge-type nonlinearity under a periodic excitation applied at axis. The present paper studies the symmetry-breaking bifurcation problem. The results obtained here indicate that, under symmetry-breaking cases, there exist richer dynamic buckling patterns than those obtained under symmetry case. Clearly, the new results provide some inspirations for the analysis and design of dynamic bulking experiments of this class of system, and improve the singularity analysis method proposed by Chen Yushu and Langford W.F.

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ABSTRACT: The nonlinear vibration fundamental equation of circular sandwich plate under uniformed load and circumjacent load and the loosely clamped boundary condition was established by von Karman plate theory, and then accordingly exact solution of static load and its numerical results were given. Based on time mode hypothesis and the variational method, the control equation of the space mode was derived, and then the amplitude frequency-load character relation of circular sandwich plate was obtained by the modified iteration method. Consequently the rule of the effect of the two kinds of load on the vibration character of the circular sandwich plate was investigated. When circumjacent load makes the lowest natural frequency zero, critical load is obtained.

ABSTRACT: The paper deals with the stability and some aspects of optimal design with respect to stability of geometrically nonlinear, elastic toroidal shells with open profiles. Shells rotationally symmetric in the narrower sense (toroidal segments) as well as in the broader sense (toroidal shell-arches), subjected to external pressure or to a combined loading (pressure and overall bending), are considered. The influence of the pressure distribution on its critical value as well as the post-buckling behaviour are discussed for the toroidal segments with various boundary conditions. The instability modes of the shell-arches for linear trajectories of the combined loading are also analysed. A double step parametrical optimization consisting of a midsurface design (1st step) and a design with respect to the thickness of the wall (2nd step) is performed for a toroidal segment. Constant distance between the supports and constant area of the meridional cross-section are applied as the constraints, respectively.

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ABSTRACT: The bounce of a hollow spherical ball from a hard flat surface results in large deformations of the thin-walled shell; these deformations increase the internal stresses in the shell near a knuckle of bending and also increase the internal gas pressure inside the shell. This paper calculates the deformation and consequent contact forces that repel the ball from the surface, and compares the results with both a finite element analysis and experimental data. A table tennis ball is considered as an example of a thin-walled elastic shell. Since for an elastic ball there are no energy losses due to inelastic material behaviour, the analysis assumes that all energy losses are due to either friction in the contact area or impulsive forces arising from the instantaneous rate-of-change of momentum in the knuckle. In practice, the table tennis ball shows energy losses that increase with increasing impact speed; these losses substantially exceed the losses taken into account by the elastic shell analysis.

DTIC Accession Number: ADA275544, Handle / proxy Url: http://handle.dtic.mil/100.2/ADA275544

ABSTRACT: The dynamic collapse behavior of thin, composite cylindrical shells subjected to transverse point loads is considered. The dynamic behavior of the undamped cylindrical shells of varying radii is analyzed with a finite element formulation that incorporates all nonlinear Green's strain terms in the in-plane directions; transverse strains are linear and vary parabolically through the shell thickness. This formulation is denoted as the simplified large displacement/rotation (SLR) theory. Graphical representations are used extensively to examine dynamic behaviors not noted in similar research that utilized the DSHELL finite element code. Composite plate behavior is also explored. Comparison of the higher-order formulations to Donnell and von Karman models, modified with transverse shear flexibility, is also made. Several deep shell configurations, using the SLR and Donnell models, are analyzed in an effort to determine the maximum displacement and rotational limits of these formulations. The nonlinear features of the plates and shells imply the potential for
chaotic behavior. Various techniques are used to characterize the chaotic behavior of these undamped shells in pre- and post-collapsed states. Nonlinear analysis, Nonlinear dynamics, Chaos, Finite element analysis, Collapse, Buckling, Composites, Structural mechanics, Cylindrical shells, Plates.

References listed at the end of the thesis:

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ABSTRACT: There has been much debate on the choice for the representative wall thickness for the thin-shell model, although this model has demonstrated remarkable success in capturing many types of behavior of single-walled carbon nanotubes (SWNTs), in determining the buckling strains under compression, torsion, and bending, in particular. This analysis, using the Tersoff-Brenner potential and ab initio calculations, shows that the elasticity of the model thin shell evolves from isotropic to square symmetric with the decreasing tube diameter, leading to significant diameter dependence for all the elastic moduli and the representative wall thickness. Furthermore, the elastic moduli of multiwalled carbon nanotubes of diameters up to 10 nm are also size dependent.

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ABSTRACT: Pre-stressed multi-walled carbon nanotube (PS-MWCNT), of which the interwall distance is less than 0.34 nm, holds for the highest Young's modulus while its interlayer shear strength is several orders higher than normal MWCNT. The buckling behaviors of PS-MWCNTs with two to six layers are studied using both molecular mechanics simulation and continuum mechanics models in this paper. Considering the interlayer distance as the key factor, we reveal three features of the buckling behavior of PS-MWCNTs subjected to axial loading: 1) the buckling membrane force is not a monotonic function of interlayer distance, depending on the nanotube index (i.e. diameter); 2) the buckling membrane force increases as the interlayer distance decreases for PS-MWCNTs with a fixed intertube chirality, which is a combined effect of interlayer distance and tube diameter; 3) for PS-MWCNTs with the same innermost tube, the buckling membrane force increases as the number of walls increases. Furthermore, molecular mechanics simulation and multi-shell continuum model show an agreement on the trend of the buckling membrane force as a function of interlayer distance, tube chirality index, and number of layers. These results can serve as a bridge between the molecular simulation and the continuum model for the buckling behaviors of PS-MWCNT.

ABSTRACT: Koiter’s shell model is derived systematically from nonlinear elasticity theory, and shown to furnish the leading-order model for small thickness when the bending and stretching energies are of the same order of magnitude. An extension of Koiter’s model to finite midsurface strain emerges when stretching effects are dominant.

References listed at the end of the paper:


ABSTRACT: Atomic simulations of the structures and stability of defect-free multiwalled carbon toroidal rings were performed using the second-generation empirical bond-order potential and a Morse-type van der Waals potential. It was found that a multiwalled toroidal ring improves the structural stability over its outermost single-walled counterpart, implying a stabilizing effect from the inner rings. This can be explained by the superlinear relation between the critical ring diameter and its tube diameter existing in single-walled rings. However, the findings that the critical diameter of an armchair ring is larger than that of a zigzag ring with the same tube diameters, and that the inclusion of torsion exhibits a negative effect on the stability of a multiwalled ring, are in contrast to that of a single-walled nanoring. In addition, the instability of a multiwalled nanoring always starts with the formation of many short-wavelength ripples on the compressed side of the outermost
tube. Subsequently, some of the ripples develop into buckles, resulting in buckling failures.

ABSTRACT: The article investigates the bifurcation phenomenon in plate welding. The evolution of the buckling phenomenon starts during the weld cooling cycle caused by an onset inelastic strain incompatibility condition. In this study, the researchers attempt to elucidate a numerical procedure to determine the peak temperature-based buckling criterion for welding thin steel plates.

ABSTRACT: The buckling in stability of a long multilayer linearly viscoelastic shell, composed of different materials and loaded with a uniformly distributed external pressure of given intensity, is investigated. By neglecting the influence of fastening of its end faces, the initial problem is reduced to an analysis of the loss of load-carrying capacity of a ring of unit width separated from the shell. The new problem is solved by using a mixed-type variational method, allowing for the geometric nonlinearity, together with the Rayleigh-Ritz method. The creep kernels are taken exponential with equal indices of creep. As an example, a three-layer ring with a structure symmetric about its midsurface is considered, and the effect of its physimechanical and geometrical parameters, as well as of wave formation, on the critical time of buckling in stability of the ring is determined. It is found that, by selecting appropriate materials, more efficient multilayer shell-type structural members can be created.

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ABSTRACT: Membranes enclosing capsules and biological cells undergo periodic compression and stretching due to an imparted hydrodynamic traction as they rotate in a shear flow. Compression may cause transient or permanent buckling manifested by the onset of wrinkled shapes. To study the effect of pre-compression and pre-stretching on the critical conditions for buckling, the response of an elastic circular plate flush mounted on a plane wall and deforming under the action of a uniform tangential load due to an over-passing simple shear flow is considered. Working under the auspices of the theory of elastic instability of plates governed by the linear von Karman equation, an eigenvalue problem is formulated resulting in a fourth-order partial differential equation with position-dependent coefficients parametrized by the Poisson ratio. Solutions are computed by applying Fourier series expansions to derive an infinite system of coupled ordinary differential equations, and then implementing orthogonal collocation. The solution space is illustrated, critical values for buckling are identified, the associated eigenfunctions representing possible modes of deformation are displayed, and the effect of the Poisson ratio is discussed.

References listed at the end of the paper:
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ABSTRACT: Single-wall carbon nanotubes (SWCNT) have been frequently modeled as thin shells, but the shell thickness and Young's modulus reported in literatures display large scattering. The order of error to approximate SWCNTs as thin shells is studied in this paper via an atomistic-based finite-deformation shell theory, which avoids the shell thickness and Young's modulus, but links the tension and bending rigidities directly to the interatomic potential. The ratio of atomic spacing (Delta approximately equal to 0.14 nm) to the radius of SWCNT, Delta/R, which ranges from zero (for graphene) to 40% [for a small (5,5) armchair SWCNT (R=0.35 nm)], is used to estimate the order of error. For the order of error O((Delta/R)^3), SWCNTs cannot be represented by a conventional thin shell because their constitutive relation involves the coupling between tension and curvature and between bending and strain. For the order of error O((Delta/R)^2), the tension and bending (shear and torsion) rigidities of SWCNTs can be represented by an elastic orthotropic thin shell, but the thickness and elastic modulus cannot. Only for the order of error O(Delta/R), a universal constant shell thickness can be defined and SWCNTs can be modeled as an elastic isotropic thin shell.

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“Efficient handling of stability problems in shell optimization by asymmetric ‘worst-case’ shape imperfection”,
doi: 10.1002/nme.2113

ABSTRACT: The paper presents an approach to shape optimization of proportionally loaded elastic shell
structures under stability constraints. To reduce the stability-related problems, a special technique is utilized, by
which the response analysis is always terminated before the first critical point is reached. In this way, the
optimization is always related to a precritical structural state. The necessary load-carrying capability of the
optimal structure is assured by extending the usual formulation of the optimization problem by a constraint on
an estimated critical load factor. Since limit points are easier to handle, the possible presence of bifurcation
points is avoided by introducing imperfection parameters. They are related to an asymmetric shape perturbation
of the structure. During the optimization, the imperfection parameters are updated to get automatically the
‘worst-case’ pattern and amplitude of the imperfection. Both, the imperfection parameters and the design
variables are related to the structural shape via the design element technique. A gradient-based optimizer is
employed to solve the optimization problem. Three examples illustrate the proposed approach.

N.A. Abrosimov (Scientific Research Institute of Mechanics, Lobachevskii Nizhegorod State University, N.
Novgorod, Russia), “Numerical modeling of nonlinear deformation and buckling of composite plate-shell
structures under pulsed loading”, Mechanics of Composite Materials, Vol. 35, No. 6, 1999, pp. 495-506,
doi: 10.1007/BF02259471

ABSTRACT: Nonlinear three-dimensional problems of dynamic deformation, buckling, and posteritical
behavior of composite shell structures under pulsed loads are analyzed. The structure is assumed to be made of
rigidly joined plates and shells of revolution along the lines coinciding with the coordinate directions of the
joined elements. Individual structural elements can be made of both composite and conventional isotropic
materials. The kinematic model of deformation of the structural elements is based on Timoshenko-type
hypotheses. This approach is oriented to the calculation of nonstationary deformation processes in composite
structures under small deformations but large displacements and rotation angles, and is implemented in the
context of a simplified version of the geometrically nonlinear theory of shells. The physical relations in the composite structural elements are based on the theory of effective moduli for individual layers or for the package as a whole, whereas in the metallic elements this is done in the framework of the theory of plastic flow. The equations of motion of a composite shell structure are derived based on the principle of virtual displacements with some additional conditions allowing for the joint operation of structural elements. To solve the initial boundary-value problem formulated, an efficient numerical method is developed based on the finite-difference discretization of variational equations of motion in space variables and an explicit second-order time-integration scheme. The permissible time-integration step is determined using Neumann's spectral criterion. The above method is especially efficient in calculating thin-walled shells, as well as in the case of local loads acting on the structural element, when the discretization grid has to be condensed in the zones of rapidly changing solutions in space variables. The results of analyzing the nonstationary deformation processes and critical loads are presented for composite and isotropic cylindrical shells reinforced with a set of discrete ribs in the case of pulsed axial compression and external pressure.

References listed at the end of the paper:

- Novozhilov, V. V. (1948) Fundamental Problems of the Nonlinear Theory of Shells. Gostekhizdat, Moscow-Leningrad
ABSTRACT: The purpose of doing probabilistic structural analysis is to provide the designer with a more realistic ability to assess the importance of uncertainty in the response of a high performance structure. The objective of this five-year contract effort (NASA Contrast NAS3-24389) on Probabilistic Structural Analysis Methods (PSAM) is the development of several modular structural analysis packages capable of predicting the probabilistic response distribution for key structural variables such as stress, displacement, natural frequencies, buckling loads, transient responses, etc. The structural analysis packages include stochastic modeling of loads, material properties, geometry (e.g. tolerances), and boundary conditions. The structural analysis solution is in terms of the cumulative distribution function (CDF) and confidence bounds. Two methods of probability modeling are included in the analysis packages. One of these is the well established Monte Carlo simulation method; the other is a fast probability integration (FPI) algorithm which will be discussed in the paper. PSAM tools can be used to estimate structural safety and reliability, while providing the engineer with information on the confidence that should be given to the predicted behavior. Perhaps most critically, the PSAM results provide information to the designer on those variables for which the design is most sensitive.

ABSTRACT: The buckling and fracture modes of thick (diameter >20 nm) multiwall carbon nanotubes (MWCNTs) under compressive stress were examined using in situ transmission electron microscopy. The overall dynamic deformation processes of the MWCNTs as well as the force/distance curves can be obtained. The buckling behavior of MWCNTs under compression falls into two categories, the first is non-axial buckling and subsequently complex Yoshimura patterns can be induced on the compressive side of the MWCNTs. The second is axial buckling followed by catastrophic failure. We find the buckling mode of thick MWCNTs is highly dependent on the diameter and length of the MWCNTs. A continuum mechanics model is employed to determine the buckling mode criterion for the MWCNTs. Moreover, the shell by shell fracture mode and planar fracture mode of MWCNTs are directly observed in our experiments.

Chu-lin YU, Zhi-ping CHEN, Ji WANG, Shun-juan YAN, Li-cai YANG (Institute of Process Equipment,
Zhejiang University, Hangzhou 310027, China), “Effect of weld reinforcement on axial plastic buckling of welded steel cylindrical shells”, Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) ISSN 1673-565X (Print); ISSN 1862-1775

ABSTRACT: The effect of weld reinforcement on axial plastic buckling of welded steel cylindrical shells is investigated through experimental and numerical buckling analysis using six welded steel cylindrical shell specimens. The relationship between the amplitude of weld reinforcement and the axial plastic buckling critical load is explored. The effect of the material yield strength and the number of circumferential welds on the axial plastic buckling is studied. Results show that circumferential weld reinforcement represents a severe imperfect form of axially compressed welded steel cylindrical shells and the axial plastic buckling critical load decreases with the increase of the mean amplitude of circumferential weld reinforcement. The material yield strength and the number of circumferential welds are found to have no significant effect on buckling waveforms; however, the axial plastic buckling critical load can be decreased to some extent with the increase of the number of circumferential welds.

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Zhao, Y., 2001. Stability and Strength of Steel Silo Transition Junctions. PhD Thesis, the Hong Kong Polytechnic University, Hong Kong.


ABSTRACT: The buckling behaviour and collapse mechanism of elastic-plastic cylindrical shells subjected to longitudinal impact were studied by impact experiments and computer simulations. Attention was focused on the influence of the geometry and material property of the shell and loading condition on dynamic buckling response. Varieties of bucking models and the switching between the modes in buckling process were observed. Particularly, the phenomenon of so called dynamic plastic buckling in relatively low impact velocity was captured by high speed photograph in impact test of cooper specimen. This experimentally confirms that the dynamic plastic buckling does not necessarily require high impact velocity. The whole process of impact buckling was simulated by LS-DYNA code. The effects of the stress wave and the transverse inertia and plastic hardening modulus, etc. on initiation of wrinkle in earlier phase of buckling are analysed.


ABSTRACT: The generality and simplicity has made the shell element employed in a wide rage of finite element analysis for mechanics problems. The demand of shell models are rapidly growing to perform large-
scale computations in important industrial applications to structural problems, sheet forming processes and composite shell structures. Since the general shell element has no stiffness associated with the drilling direction, any slight disturbance to the drilling rotation in the generalized load vector tends to amplify the rotation to an unrealistic large amount, which results in an unreliable solution. In addition, most shell elements fail in the analysis of non-smooth shell structures or shell structures with stiffener connections where three rotation components have to be considered. For remedy of that, many recent efforts have been done to include the sixth degree-of-freedom of the drilling rotation compatible to the physical meaning. In this paper, a four-node degenerated shell element with the implicit numerical scheme is developed to calculate non-linear problems based on the Belytschko-Leviathan's linear one-point quadrature shell element with the drilling degree of freedom. In formulating for the shell element, the physical stabilization scheme is used to control the zero-energy mode of the element for one-point quadrature shell elements. The element is then extended for the nonlinear elasto-plastic analysis of shell structures undergoing large deformation in conjunction with the updated Lagrangian formulation. Many numerical problems including patch tests and benchmark tests are solved to investigate the performance of the element in comparison with conventional ones. Typical problems are the shell structure subjected to drilling moments, warped shells, and structures with sharp edges within the shell. The performance tests have been carried out focusing on the accuracy of the deformed shape and the convergence as well as the computing time. In order to demonstrate the versatility and applicability of the present shell element, the static buckling analysis of a thin-walled S-beam structure has been solved and compared with commercial codes.

References listed at the end of the paper:

ABSTRACT: Under the effect of an inner pressure, a thick hyperelastic shell cylinder is susceptible to developing mechanical instabilities, leading to a bifurcated shape that no longer has the initial cylindrical symmetry. The considered problem has a strong resonance in a biomedical context, considering pathologies encountered for arteries, such as aneurysm. In this contribution, the mechanical behavior of thick elastic shells has been analyzed, considering a thick-walled cylindrical hyperelastic model material obeying a transversely isotropic behavior, first in a large-displacement situation and then in a large-deformation case. The response of the material is assumed to be instantaneous, so that time-dependent effects shall not be considered in this paper. The case of a Saint-Venant–Kirchhoff material is considered with special emphasis to exemplify a large-displacement small-strain situation; the neo-Hookean behavior is next considered to enlarge the constitutive law toward consideration of large strains. The stability conditions of the shell are studied and bifurcation conditions formulated in terms of the applied pressure and of the geometrical and mechanical parameters that characterize the shell. Analytical solutions of some bifurcation points are evidenced and calculated when the direction of the fibers coincide with the cylinder axis.
M. Sanjarani Pour (Mathematics College, Sistan and Balochestan University, Zahedan, Iran), “WKB Analysis Of The Buckling Of A Neo-Hookean Cylindrical Shell Of Arbitrary Thickness Subject To An External Pressure”, International Journal of Applied Mechanics, Vol. 02, No. 04, December 2010, DOI: 10.1142/S1758825110000792

ABSTRACT: By using the WKB method to solve the eigenvalue problem that results from a linear bifurcation analysis, we show that for a cylindrical shell of arbitrary thickness made of a neo-Hookean material which is subjected to an external hydrostatic pressure, the circular cross-section buckles into a non-circular shape at a value of \( \mu_1 \) which depends on \( A_1/A_2 \) and the mode number, where \( A_1 \) and \( A_2 \) are the undeformed inner and outer radii, and \( \mu_1 \) is the ratio of the deformed inner radius to \( A_1 \). We show that this problem is amenable to the WKB method based on the largeness of the mode number. Similar to the case of a Varga cylindrical tube [Sanjarani Pour, 2005], the dependence of \( \mu_1 \) on \( A_1/A_2 \) has a boundary layer structure. Simple asymptotic expressions for the bifurcation condition are obtained. It has been shown that the asymptotic results obtained in the outer and inner regions agree with the numerical results. The two sets of results obtained for the eigenfunction with the aid of WKB and determinant methods are almost indistinguishable.

M. Sanjarani Pour (Mathematics College, Sistan and Balochestan University, Zahedan, Iran), “A WKB analysis of the buckling condition for a cylindrical shell of arbitrary thickness subjected to an external pressure”, IMA Journal of Applied Mathematics, Vol. 70, No. 1, pp. 147-161, April 2013

ABSTRACT: We consider the plane-strain buckling of a cylindrical shell of arbitrary thickness which is made of a Varga material and is subjected to an external hydrostatic pressure on its outer surface. The WKB method is used to solve the eigenvalue problem that results from the linear bifurcation analysis. We show that the circular cross-section buckles into a non-circular shape at a value of \( \mu_1 \) which depends on \( A_1/A_2 \) and a mode number, where \( A_1 \) and \( A_2 \) are the undeformed inner and outer radii, and \( \mu_1 \) is the ratio of the deformed inner radius to \( A_1 \). In the large mode number limit, we find that the dependence of \( \mu_1 \) on \( A_1/A_2 \) has a boundary layer structure: it is constant over almost the entire region of \( 0 < A_1/A_2 < 1 \) and decreases sharply from this constant value to unity as \( A_1/A_2 \) tends to unity. Our asymptotic results for \( A_1 - 1 = O(1) \) and \( A_1 - 1 = O(1/n) \) are shown to agree with the numerical results obtained by using the compound matrix method.

Jinseok Kim and J.N. Reddy (Advanced Computational Mechanics Laboratory, Department of Mechanical Engineering, Texas A & M University, College Station, TX 77843-3123, USA), “Analytical solutions for bending, vibration, and buckling of FGM plates using a couple stress-based third-order theory”, Composite Structures, Vol. 103, pp 86-98, 2013, DOI: 10.1016/j.compstruct.2013.03.007

ABSTRACT: Analytical solutions of a general third-order plate theory that accounts for the power-law distribution of two materials through thickness and microstructure-dependent size effects are presented. The Navier solution technique is adopted to derive analytical solutions to simply supported rectangular plates. The modulus of elasticity and the mass density are assumed to vary only through thickness of plate and a single material length scale parameter of a modified couple stress theory captures the microstructure-dependent size effects. Examples of bending, buckling, and vibration problems are presented to show effects of the power-law distribution of two materials and the microstructure-dependent size parameter.

References listed at the end of the paper:
ABSTRACT: This paper presents a cylindrical strain based shallow shell finite element which is developed for


ABSTRACT: This paper presents a cylindrical strain based shallow shell finite element which is developed for
linear and geometrically non-linear analysis of cylindrical shells. The developed element is rectangular in plan and has the only five essential degrees of freedom at each corner node. The displacement fields of the element satisfy the exact requirement of rigid body modes. The efficiency of the element is demonstrated by applying it to the linear and geometrically nonlinear analysis of shell structures. The suitability of the element is also tested for natural frequencies’ calculations of cylindrical shells. Results obtained by the present element are compared with those available in the literature. These comparisons show that efficient convergence characteristics and accurate results can be obtained by using the present element.

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“Buckling of multicomponent elastic shells with line tension”, Soft Matter, 2012, 8, 636-644
DOI: 10.1039/C1SM06325A
ABSTRACT: We explore the effects of line tension on the shape of two component elastic shells. Segregation between components with different elastic properties combined with the subtleties related to the spherical topology leads to a rich variety of shapes. They range from irregular polyhedra at weak segregation to Janus-like morphologies with spherical and buckled regions coexisting on the same shell for large values of the line tension. We use Monte Carlo simulations to map a detailed phase diagram as a function of the relative fraction of the two components, the ratio of their bending rigidities, and the strength of the line tension.

ABSTRACT: We study how the stability of spherical crystalline shells under external pressure is influenced by the defect structure. In particular, we compare stability for shells with a minimal set of topologically-required defects to shells with extended defect arrays (grain boundary "scars" with non-vanishing net disclination charge). We perform Monte Carlo simulations to compare how shells with and without scars deform quasi-statically under external hydrostatic pressure. We find that the critical pressure at which shells collapse is lowered for scarred configurations that break icosahedral symmetry and raised for scars that preserve icosahedral symmetry. The particular shapes which arise from breaking of an initial icosahedrally-symmetric shell depend on the Foppl-von Karman number

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ABSTRACT: Thin elastic spherical shells are known to exhibit a buckling instability at a finite external pressure. We study how this buckling is influenced by a weak region in an otherwise uniform shell, focusing on the case of a single small circular soft spot that is thinner than the rest of the shell. Using numerical simulations and theoretical arguments, we show that the soft region fundamentally alters the buckling behavior of the shell. The soft spot influences both the pressure at which the shell buckles, and the postbuckling shape of the shell.
Depending on the properties of the soft spot, we find either a single buckling transition or two separate transitions as the external pressure is increased. We analyze the dependence of these buckling transitions on the size and thickness of the soft region. Besides contributing to our fundamental understanding of buckling transitions in inhomogeneous shells, our results can be applied to designing capsules with tunable shapes.


ABSTRACT: Thermal fluctuations strongly modify the large length-scale elastic behavior of cross-linked membranes, giving rise to scale-dependent elastic moduli. Whereas thermal effects in flat membranes are well understood, many natural and artificial microstructures are modeled as thin elastic shells. Shells are distinguished from flat membranes by their nonzero curvature, which provides a size-dependent coupling between the in-plane stretching modes and the out-of-plane undulations. In addition, a shell can support a pressure difference between its interior and its exterior. Little is known about the effect of thermal fluctuations on the elastic properties of shells. Here, we study the statistical mechanics of shape fluctuations in a pressurized spherical shell, using perturbation theory and Monte Carlo computer simulations, explicitly including the effects of curvature and an inward pressure. We predict novel properties of fluctuating thin shells under point indentations and pressure-induced deformations. The contribution due to thermal fluctuations increases with increasing ratio of shell radius to thickness and dominates the response when the product of this ratio and the thermal energy becomes large compared with the bending rigidity of the shell. Thermal effects are enhanced when a large uniform inward pressure acts on the shell and diverge as this pressure approaches the classical buckling transition of the shell. Our results are relevant for the elasticity and osmotic collapse of microcapsules.


ABSTRACT: The crumpling of spherical crystalline lattices where the topological defects are frozen is studied. The geometry of the crumpled membrane is found to depend on the set of topological defects and more exotic defect sets can result in crumpled shapes resembling that of the Platonic and Archimedean solids. The phase diagram of the crumpled spheres can be categorized by two dimensionless numbers h/R (aspect ratio) and R/a (lattice ratio), where h is the thickness of the shell, R is the radius of the initial sphere and a is the average bond length of the triangulation. The shapes of the crumpled membrane can be understood using rotationally invariant quantities formed from spherical harmonics coefficients and a Landau free energy can be written, involving quadratic and cubic rotational invariants. Shells with different topological defects have qualitatively different hysteresis behaviors and the transitions appear to be first order in general.

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ABSTRACT: Colloidal capsules can sustain an external osmotic pressure; however, for a sufficiently large pressure, they will ultimately buckle. This process can be strongly influenced by structural inhomogeneities in the capsule shells. We explore how the time delay before the onset of buckling decreases as the shells are made more inhomogeneous; this behavior can be quantitatively understood by coupling shell theory with Darcy’s law. In addition, we show that the shell inhomogeneity can dramatically change the folding pathway taken by a capsule after it buckles.

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PARTIAL INTRODUCTION: Many important natural or technological situations require understanding thin, spherical shells; examples include colloidal capsules for chemical encapsulation and release [1–3], biological cells [4,5], pollen grains [6], submersibles [7], chemical storage tanks [8], nuclear containment shells [8], and even the Earth’s crust [9]. In many cases, the utility of such a shell critically depends on its response to an externally imposed pressure. For small pressures, a homogeneous, spherical shell, characterized by a uniform thickness, supports a compressive stress, and it shrinks isotropically. Above a threshold pressure, however, this shrinkage becomes energetically prohibitive; instead, the shell buckles, reducing its volume by forming a localized indentation at a random position on its surface. For the case of a homogeneous shell, this threshold pressure can be calculated using a linearized analysis of shell theory [10,11], while the exact morphology of the shell after it buckles requires a full nonlinear analysis [12–14]. However, many shells are inhomogeneous, characterized by spatially varying thicknesses and elastic constants [6,15–18]. Such inhomogeneities can strongly influence how a shell buckles [6,10,19–23]. Unfortunately, despite its common occurrence in real shells, exactly how inhomogeneity influences the onset of buckling, as well as the shell morphology after buckling, remains to be elucidated. A deeper understanding requires careful investigation of the buckling of spherical shells with tunable, well-defined, inhomogeneities. In this Letter, we use a combination of experiments, theory, and simulation to study the buckling of spherical colloidal capsules with inhomogeneous shells of non-uniform thicknesses. We show that the onset of buckling, above a threshold external osmotic pressure, is well described by shell theory; however, even above this threshold, the capsules do not buckle immediately. We find that the time delay before the onset of buckling decreases as the shells are made more inhomogeneous; these dynamics can be quantitatively understood by coupling shell theory with…

Reference cited in this paper:

We study the behavior of thin elastic sheets that are bent and strained under the influence of weak, smooth confinement. We show that the emerging shapes exhibit the coexistence of two types of domains that differ in their characteristic stress distributions and energies, and reflect different constraints. A focused-stress patch is subject to a geometric, piecewise-inextensibility constraint, whereas a diffuse-stress region is characterized by a mechanical constraint - the dominance of a single component of the stress tensor. We discuss the implications of our findings for the analysis of elastic sheets that are subject to various types of forcing.

References listed at the end of the paper:

ABSTRACT: The dynamic analysis of laminated composite shell structures is performed using a simple displacement-based 18-degree-of-freedom triangular flat shell element, obtained by the superposition of a membrane element and a plate element. The membrane element is based on the assumed natural deviatoric strain formulation (ANDES), having corner drilling degrees of freedom and optimal in-plane bending response. The plate element employs the Timoshenko’s laminated composite beam function to define the deflections and rotations on the element boundaries. This formulation provides first-order shear flexibility to the element and naturally avoids shear-locking problems as thin shells are analyzed. The geometrically nonlinear behavior of the structures is achieved by the element independent corotational formulation (EICR) together with a consistent treatment of finite rotations. An energy conserving procedure for the time-integration of the nonlinear dynamic equations is also included. Finally, two examples are presented to show that the algorithm is able to solve highly nonlinear dynamic problems.

References listed at the end of the paper:

ABSTRACT: A new formulation for corotational nonlinear dynamic analysis of thin-shell structures involving large displacements and finite rotations has been presented in this paper. By introducing the kinematic description of the geometrically exact quasi-static shell model to describe the motion of an arbitrary material point in a triangular shell element, the new expressions for the inertial force vector and tangent inertia matrix were derived systematically. The elastic deformation was handled by using the consistent symmetrizable equilibrated corotational formulation, which is independent with respect to the local finite element modeling. An energy-momentum-conserving algorithm and an energy-decaying/momentum-conserving algorithm were developed for nonlinear dynamic analysis by applying the generalized energy-momentum method in the corotational formulation. Three classic numerical examples, including the dynamic response, free motion, and dynamic buckling of thin-shell structures, were computed to verify the accuracy and capability of the presented formulation for solving the nonlinear dynamic problems of thin-shell structures with finite rotations. In the relevant numerical example, the conservations of linear momentum and angular momentum of a shell structure due to the time-integration algorithms in the corotational formulation were investigated.


ABSTRACT: This work deals with the evaluation of the different modeling options based on the FEM to reproduce the structural performance of a composite stiffened panel in postbuckling regime under uniform pressure. Two fundamental modeling options are used for this purpose: monolithic and multi-part approaches. These strategies are based respectively on standard and 7-parameter finite element shell formulations as underlying mechanical theories. The numerical results obtained by means of these alternatives are compared with the experimental response of the panel with special emphasis in the postbuckling evolution of the behavior of the structure, and incorporating the initial geometric imperfections of the panel in the simulations.

References listed at the end of the paper:


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ABSTRACT: Carbon nanotubes (CNTs) are capable to absorb and encapsulate some molecules to create new hybrid nano-structures providing a variety of functionally useful properties. CNTs functionalized by encapsulating single-stranded deoxy-ribonucleic acid (ssDNA) promise great potentials for applications in nanotechnology and nano-biotechnology. In this paper, buckling instability of ssDNA-CNT i.e. hybrid nano-structure composed of ssDNA encapsulated inside CNT has been investigated using the nonlocal elasticity theory. The nonlocal elasticity theory is capable to capture the small scale effects due to the discontinuity of nano-structures at atomic scales. The nonlocal elastic rod and shell equations are derived for modeling ssDNA and CNT respectively. Providing numerical examples, it is predicted that, ssDNA-(10,10) CNT is more resistant than the pristine (10,10) CNT against the buckling instability under radial pressure due to the inter-atomic van der Waals interactions between DNA and CNT. Furthermore, nonlocal elasticity theory predicts lower critical buckling pressure than does the local elasticity theory.


ABSTRACT: This article reviews recent applications of controlled wrinkling for creating structured and/or patterned interfaces, and its use in metrology. We discuss how wrinkles develop as a result of in-plane compression of thin sheets. As the wavelength of wrinkles is only dependent on elastic properties and thickness of the sheets, the phenomenon can be used in metrology for determination of elastic properties. The second aspect is its use for patterning and topographical structuring of surfaces. If mechanical properties and thickness are well controlled, wrinkle orientation and geometry can be tailored. Wavelengths between fractions of a micron and many micrometers are feasible. This process is based on a macroscopic deformation and upscaling to larger areas is possible which provides an attractive alternative to bottom-up or top-down approaches for surface patterning. We describe the formation of stable surface wrinkles in thin sheets of different materials having different surface chemistries, report on applications, and discuss the usefulness of wrinkles for building hierarchical structures.

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ABSTRACT: In humans and many other mammals, the cortex (the outer layer of the brain) folds during development. The mechanics of folding are not well understood; leading explanations are either incomplete or at odds with physical measurements. We propose a mathematical model in which (i) folding is driven by tangential expansion of the cortex and (ii) deeper layers grow in response to the resulting stress. In this model the wavelength of cortical folds depends predictably on the rate of cortical growth relative to the rate of stress-induced growth. We show analytically and in simulations that faster cortical expansion leads to shorter gyral wavelengths; slower cortical expansion leads to long wavelengths or even smooth (lissencephalic) surfaces. No
inner or outer (skull) constraint is needed to produce folding, but initial shape and mechanical heterogeneity influence the final shape. The proposed model predicts patterns of stress in the tissue that are consistent with experimental observations.

Maan H. Jawad, “Buckling of cylindrical shells”, ASME Digital Collection, DOI: 10.1115/1.801993.ch13

CONTENTS: 13-1 Basic Equations, 13-2 Lateral Pressure, 13-3 Lateral and End Pressure, 13-4 Axial Compression, 13-5 Donnell’s Equations, 13-6 Design Equations; Page count = 38

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ABSTRACT: A methodology is introduced for calculating the allowable buckling stress in equipment operating in the time-dependent (creep) range. Norton’s equation coupled with various procedures such as the stationary stress method, classical creep buckling equations, and the isochronous stress–strain diagrams are utilized to obtain a practical design approach for equipment operating in the time-dependent range. Various components are investigated such as slender columns, cylindrical shells, spherical components, and conical transition sections.

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ABSTRACT: This paper studies the collapse of a void in an elastomer caused by osmosis. The void is filled with liquid water, while the elastomer is surrounded by unsaturated air. The difference in humidity motivates water molecules to permeate through the elastomer, from inside the void to outside the elastomer, leaving the liquid water inside the void in tension. When the tension is low, the void reduces size but retains the shape, a mode of deformation which we call breathing. When the tension is high, the void changes shape, possibly by two types of instability: buckling and creasing. The critical conditions for both types of instability are calculated. A tubular elastomer collapses by buckling if the wall is thin, but by creasing if the wall is thick. As the tension increases, a thin-walled tube undergoes a buckle-to-crease transition.

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ABSTRACT: We introduce a class of continuum shell structures, the Buckliball, which undergoes a structural
transformation induced by buckling under pressure loading. The geometry of the Buckliball comprises a spherical shell patterned with a regular array of circular voids. In order for the pattern transformation to be induced by buckling, the possible number and arrangement of these voids are found to be restricted to five specific configurations. Below a critical internal pressure, the narrow ligaments between the voids buckle, leading to a cooperative buckling cascade of the skeleton of the ball. This ligament buckling leads to closure of the voids and a reduction of the total volume of the shell by up to 54%, while remaining spherical, thereby opening the possibility of encapsulation. We use a combination of precision desktop-scale experiments, finite element simulations, and scaling analyses to explore the underlying mechanics of these foldable structures, finding excellent qualitative and quantitative agreement. Given that this folding mechanism is induced by a mechanical instability, our Buckliball opens the possibility for reversible encapsulation, over a wide range of length scales.

References listed at the end of the paper:

ABSTRACT: Buckling-induced reversible symmetry breaking and amplification of chirality using macro- and microscale supported cellular structures is described. Guided by extensive theoretical analysis, cellular structures are rationally designed, in which buckling induces a reversible switching between achiral and chiral configurations. Additionally, it is demonstrated that the proposed mechanism can be generalized over a wide range of length scales, geometries, materials, and stimuli.

ABSTRACT: In this paper, the elastic buckling stress of axisymmetric cylindrical shells under uniform axial load is determined analytically by using the first order shear deformation theory. The equilibrium equations are derived by the virtual work principle and then the stability equations are extracted from them. They are systems of differential equations, which are solved analytically by using the perturbation method. The effects of the geometrical properties on the buckling stress are investigated by a parametric study. The results are compared with the finite elements methods.

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ABSTRACT: This paper studies the dynamic shell buckling behavior of multi-walled carbon nanotubes
(MWNTs) embedded in an elastic medium under step axial load based on continuum mechanics model. It is shown that, for occurrence of dynamic shell buckling of MWNTs or MWNTs embedded in an elastic medium, the buckling stress is higher than the critical buckling stress of the corresponding static shell buckling under otherwise identical conditions. Detailed results are demonstrated for dynamic shell buckling of individual double-walled carbon nanotubes (DWNTs) or DWNTs embedded in an elastic medium. A phenomenon is shown that DWNTs or embedded DWNTs in dynamic shell buckling are prone to axisymmetric buckling rather than non-axisymmetric buckling. Numerical results also indicate that the axial buckling form shifts from the lower buckling mode to the higher buckling mode with increasing buckling stress, but the buckling mode is invariable for a certain domain of buckling stress. Further, an approximate analytic formula is presented for the buckling stress and the associated buckling wavelength for dynamic axisymmetric buckling of embedded DWNTs. The effect of radii is also examined.

References listed at the end of the paper:

ABSTRACT: Buckling experiments carried out on the shell structures show that these structures are sensitive to the initial imperfections. An early attempt to establish occasional discrepancies between theoretical and experimental buckling loads of cylindrical shells was reported by Donnell [1]. Later it was determined that the initial imperfections and the boundary conditions are the principal cause of disagreement. Development of new materials, however, has necessitated more research in the field of mechanical and thermal buckling of imperfect shell structures. Functionally graded materials (FGMs) are high-performance heat-resistant new materials able to withstand ultrahigh temperatures and minimize thermal stresses. Thermoelastic buckling analysis of imperfect FGM cylindrical shells under various thermal loads and/or axial ...

Jafar Eskandari Jam and Esmail Asadi (Composite Materials and Technology Center, Tehran, Iran), “Buckling Analysis of Composite Cylindrical Shells Reinforced by Carbon Nanotubes”, Archive of Mechanical Engineering, Vol. LIX, No. 4, pp. 413 – 434, February 2013, DOI: 10.2478/v10180-012-0022-1

ABSTRACT: In this paper, the authors investigate a cylindrical shell reinforced by carbon nanotubes. The critical buckling load is calculated using analytical method when it is subjected to compressive axial load. The Mori-Tanaka method is firstly utilized to estimate the effective elastic modulus of composites having aligned oriented straight CNTs. The eigenvalues of the problem are obtained by means of an analytical approach based on the optimized Rayleigh-Ritz method. There is presented a study on the effects of CNTs volume fraction, thickness and aspect ratio of the shell, CNTs orientation angle, and the type of supports on the buckling load of cylindrical shells. Furthermore the effect of CNTs agglomeration is investigated when CNTs are dispersed none uniformly in the polymer matrix. It is shown that when the CNTs are arranged in 90_ direction, the highest critical buckling load appears. Also, the results are plotted for different longitudinal and circumferential mode numbers. There is a specific value for aspect ratio of the cylinder that minimizes the buckling load. The results reveal that for very low CNTs volume fractions, the volume fraction of inclusions has no important effect on the critical buckling load.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: Structural elements in the form of cylindrical shells are often designed to be thin to save weight, and this can lead to buckling. The patterns and values of buckling loads depend greatly on the type of loading, the end support conditions, and effective laminate material properties and couplings. For many typical buckling loadings, there is a variety of similar buckling states, which causes sensitivity to initial imperfections. Understanding this phenomenon requires the consideration of nonlinear strain-displacement relations, usually in the von Kármán form. In addition, shells of composite materials require deformation assumptions that permit transverse shear deformation. A review of the results obtained using theoretical techniques is given as well as finite element predictions and experimental observations. A very brief summary of references is given for the optimization of shell buckling loads and for the additional effects of stringer reinforcement, thermal loadings, and other topics.

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ABSTRACT: Calculating the buckling load of structures is one of the main aspects of geometric structural instability. With reference to finite element software (ANSYS) and considering the weight of the structure as a constant load, the paper calculates the buckling load of steal arch shells as the main scope. Then, the article makes a prediction for the buckling load of steel arch shells applying 85 datasets prepared by the above mentioned method and using an artificial neural network by means of NeuroSolution 5.0 software. The radius of the periphery cylinder of an arch shell, the thickness of the shell and its internal angel are considered as inputs of construct models. Next, in order to attain an optimum model calculating and comparing the value of Root Mean Squared Error, RMSE, Mean Absolute Error, MAE and the coefficient of correlation, $R^2$, for all 1 and 2-layer constructed models, a model having architecture 3-7-1 was found to be optimum. A high confirmed correlation with calculated buckling loads employing the finite element method and considering the calculated values of RMSE (0.0126), MAE (0.011) and the obtained value $R^2$ (0.998) demonstrated high efficiency of a new developed neural network model.

ABSTRACT: Presence of cracks or similar imperfections can considerably reduce the buckling load of a shell structure. In this paper, the buckling of thin conical frusta with cracks under axial loads has been studied. At first, a frustum without any imperfection has been analyzed. In continuation, sensitivity of the buckling load to the crack presence with different length and orientation has also been investigated. This procedure has been investigated on three types of frusta with different heights and constant semi-apical angles. Some effective parameters on buckling have been studied separately and the required data for analysis have been gained through experimental tests. The finite element ABAQUS software has been used for the numerical analyses.

References listed at the end of the paper:
15. ABAQUS 6.4 PR11 user’s manual
ABSTRACT: Buckling behavior of plates and shells is one of the important characteristics in analysis of any structure. One the most significant parameter that must be considered in buckling phenomenon is imperfection. In this paper the effect of imperfection on buckling load of steel rectangular plates under uni-axial in-plane compressive loading is investigated by numerical and experimental methods. The plates were free on two opposite sides and simply supported at the load side whereas the opposite side is either clamped or simply supported. This means that the plate primarily exhibits a type of column’s buckling.

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5. Yetterman A.L. and Brown C.J. The Elastic Stability of Square Perforated Plates, Computer and Structures, 21(6),
13. ABAQUS 6.7 PR11 user’s manual.

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“Numerical modeling of stresses and buckling loads of isogrid lattice composite structure cylinders”,
DOI: http://dx.doi.org/10.4314/ijest.v5i1.4

ABSTRACT: Isogrid composite lattice cylindrical structure with or without skins which consists of a system of plus/minus phi (with respect to the shell axis) helical ribs and circumferential ribs, and has no skins or has skins was studied in a numerical method using ANSYS software, where in this model axial compression and/or pressure loads are applied, to determine the different failure modes which are, failure due to stress exceeds material strength, failure due to local buckling of ribs (crippling), failure due to general buckling of the cylinder and failure due to local buckling skin if the skin is existed. An example was studied to compare the results obtained from the numerical method and other research article.
References listed at the end of the paper:

ANSYS Release 9, 2006. ANSYS, Inc, Canonsburg, PA.


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ABSTRACT: The problem of dynamic stability is substantially more complex than the buckling analysis of a shell subjected to static loads. The fundamental aim of this paper is to present criteria for determining the critical load of dynamic buckling of thin shell. Another purpose of establishing such criteria is to guide engineers, scientists and researchers dealing with such problems, for a better comparison, verification and a validation of their experimental or numerical results. To illustrate the application of these criteria, two examples have been studied.

References listed at the end of the paper:


Ashutosh Mishra, R. Suresh Kumar and P. Chellapandi (Indira Gandhi Centre for Atomic Research, Kalpakkam, India), “Progressive deformation behaviour of thin cylindrical shell under cyclic temperature variation using combined hardening Chaboche model”, Latin American Journal of Solids and Structures, Vol. 11, No. 6, November 2014

ABSTRACT: This study intends to evaluate thermal ratchetting deformation due to cyclic thermal loading along the axis of a smooth cylindrical shell. Two cases of progressive deformation behaviour are discussed for different loading methods. The aim of the first case is to recognize the shakedown behaviour of the cylinder under applied loading cycles. Alternatively, second case is highlighting the ratchetting behaviour of the cylinder. Based on the loading method in second case, a smooth thin hollow cylinder is considered to simulate the progressive deformation. This condition simulates the 1/25th scale down model of the Prototype Fast Breeder Reactor (PFBR) main vessel.

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ABSTRACT: In this paper, the buckling strength of the lining shells inside the pressure vessel was investigated both theoretically and experimentally. First, the bifurcation buckling analysis of the lining shells was carried out with the aid of the newly developed computer program. In the analysis, the lining could be considered to be a shell subjected to external pressure and encased in a rigid cavity. The concepts of the matrix displacement approach to discrete element structural analysis were extended to predict the instability of shells of revolution encased in rigid cavity. The equilibrium solution for prebuckling was axisymmetric, but the perturbation-displacement field within each element was represented by Fourier circumferential components of the generalized displacements. Second, several experiments on the buckling of cylindrical shell under uniform external pressure were conducted. In the experiments, outward radial displacement of the shell specimen was constrained. The experimental results agreed with the analytical ones by the computer program. Furthermore, numerical calculations were conducted for several kinds of lining shells, whose results were compared with the analytical ones for unrestrained shells.


ABSTRACT: The objective of this paper is to investigate the progressive failure behaviour of laminated cylindrical/conical panels under meridional compression considering geometric nonlinearity and evolving material damage. The evolving microscopic damage such as fiber breakage, matrix cracking, fiber matrix debonding etc. is modeled through a generalized macroscopic continuum theory within the framework of irreversible thermodynamics. The analysis is carried out using field consistent finite element approach based on
first-order shear deformation theory. The nonlinear governing equations are solved using the Newton–Raphson iterative technique coupled with the adaptive displacement control method to trace the equilibrium path. The damage evolution equations are solved at every Gauss point using Newton-Raphson iterative technique within each iteration of a loading/displacement increment. To accurately model the transverse shear strain energy, shear correction factors are calculated using layers’ properties and lamination scheme. The detailed study is carried out to highlight the influences of evolving damage, span-to-thickness ratio, lamination scheme, radius-to-span ratio, boundary conditions and semi-cone angle on the postbuckling response and failure load of laminated panels.


ABSTRACT: In this paper, the effects of segmental joints, dimensions of segments, and ground conditions on buckling of the shield tunnel linings under hydrostatic pressure are studied by analytical and numerical analysis. The results show that radial joints have significant impacts on the buckling behavior: the shield tunnel linings with flexible joints buckle in a single wave mode in the vicinity of K joint, while those with rigid joints buckle in a multi-wave mode around the linings. Hydrostatic buckling strength is found to increase with the flexural rigidity of the radial joint and the thickness of segment increasing. This study shows that ground support increases the buckling strength dramatically, while earth pressure reduces the capacity to resist hydrostatic buckling. The tunnel linings during construction are found to be easier to buckle than that during operation. Meanwhile, the buckling of tunnel linings is studied by theoretical analysis of buried tube buckling.

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ABSTRACT: A comprehensive buckling analysis of axially compressed rectangular flat thin plate with simply supported edges was carried out. The study was accomplished through a theoretical formulation based on Taylor-Mclaurin's series and application of Ritz method. The Taylor Mclaurin's series was truncated at the fifth term, which satisfied all the boundary conditions of the plate and resulted to a particular shape function for SSSS plate. The resulting shape function was substituted into the total potential energy functional, which was subsequently minimized. After minimization, the critical buckling load for the plate was obtained by making Nx the subject of the formula. The resulting critical load was found to be a function of a coefficient, “H”, and the values of H from the present study were compared with the exact values within the range of aspect ratios from 0.1 to 1.0 as shown on table 1. The maximum percentage difference was found to be 0.098% for aspect ratio of 0.1, while the least percentage difference was found to be 0.05% for an aspect ratio of 1.0. Hence, the Taylor-Mclaurin series shape function obtained for the SSSS plate is a very good approximation of the exact shape function for the plate.

ABSTRACT: This study investigates the inelastic stability of a thin flat rectangular isotropic plate subjected to uniform uniaxial compressive loads using Taylor-Maclaurin series formulated deflection function. The plate has clamped and simply supported edges in both characteristic directions (CCSS boundary conditions). The governing equation is derived using a deformation plasticity theory and a work principle. Values of the plate buckling coefficient are calculated for aspect ratios from 0.1 to 2.0 at intervals of 0.1. The results compared favourably with the elastic stability values and the percentage differences ranged from -0.353% to -7.427%. Therefore, the theoretical approach proposed in this study is recommended for the inelastic stability analysis of thin flat rectangular isotropic plates under uniform in-plane compression.

References listed at the end of the paper:


ABSTRACT: Axial buckling critical load of large welded steel tanks is very sensitive to initial circumferential weld geometric imperfections on the tank walls. It is worth noting that some local geometric imperfections are also existed in the following service time. It is meaningful to explore effect of local geometric imperfections on axial buckling of welded steel tanks with circumferential weld imperfections already. FEM was used to learn effect of amplitude and distribution of local geometric imperfections on welded steel tanks with circumferential geometric imperfections. Results showed that the existence of local geometric imperfections give an additional
damage to axial buckling critical load and changed axial buckling deformation characteristics of welded steel tanks, while this adverse effect did not vary much with the increasing of amplitude and distribution of local geometric imperfections.


ABSTRACT: Drying a droplet of colloidal dispersion can result in complex pattern formation due to both development and deformation of a skin at the drop surface. The present study focuses on the drying process of droplets of colloidal dispersions in a confined geometry where direct observations of the skin thickness are allowed. During the drying process, a buckling process is followed by a single depression growth inside the drop. The deformation of the droplet is found to be generic and is studied for various colloidal dispersions. The final shape can be partly explained by simple energy analysis based on the competition between bending and stretching deformations. Particularly, the final shape enables us to determine precisely the critical thickness of the shell for buckling. This study allows us to validate theory in 2D droplets and apply it to the case of 3D droplets where the thickness is not accessible by direct observation.

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ABSTRACT: This study is aimed at representing efficient buckling analysis method by analyzing the buckling behavior and the buckling pressure of filament-wound cylindrical shell. First, finite element analysis was conducted to find the buckling pressure and the buckling behavior on the stacking angles of [+,-30/90]FW, [+,-45/90]FW and [+,-60/90]FW. The buckling formula (ASME 2007, NASA SP-8007) was employed to find the buckling pressure. These results were compared and verified through hydrostatic pressure buckling experiments. Second, the values of buckling formula and buckling pressure values of finite element analysis were compared, while the stacking angle was made to change by 5 degrees from 20 to 70 degrees. According to the conducted finite element analysis, stacking property showed the safety factor of about 1.0 at the buckling pressure values of such filament-wound stacking angles as [+,-30/90]FW, [+,-45,90]FW, and [+,-60,90]FW. ASME 2007 buckling formula showed the safety factor ranging from 1.84 to 2.76. On comparison, the values of the NASA SP-8007 formula showed relatively low safety factors ranging from 1.2 to 1.45. When it comes to the result to which various stacking angles from 20 to 70 degrees were applied, the values to which an equivalent material property was applied showed safety factors ranging from 0.8 to 0.97 while the ASME 2007 and the NASA SP-8007 buckling formula values showed safety factors ranging from 1.7 to 2.9 and 0.8 to 1.4, respectively. Based on the result above, the ASME 2007 formula, a simplified version of the NASA SP-8007 formula is regarded as a buckling formula in which more reliable safety factors are considered.
ABSTRACT: The paper deals with the validation of a recently proposed hexahedral solid-shell finite element in the buckling analysis of a laminated composite plate with delaminations. The object is to study the buckling behavior of structures with delaminations using the enhanced assumed strain (EAS) solid shell element with 5, 7 and 9 parameters. The EAS three-dimensional finite element formulation presented in this paper is free from shear locking and leads to accurate results for distorted element shapes. The developed FE model is used to study the effects of some parameters in the buckling load, such as the stacking sequences, delamination size, aspect ratio, width-to-thickness ratio. The feasibility of the proposed method is confirmed by numerical examples. Results show that using hexahedral solid-shell finite element in the buckling analysis is more efficient than using the enhanced solid finite element.

References listed at the end of the paper:


ABSTRACT: We study the effects of small-scale parameter on the buckling loads and strains of nanobeams, based on nonlocal Timoshenko beam model. However, the lack of higher-order boundary conditions leads to inconsistencies in critical buckling loads. In this paper, we apply a novel approach based on nonlocal Timoshenko kinematics, strain gradient approach and variational methods for deriving all classical and higher-order boundary conditions as well as governing equations. Therefore, closed-form and exact critical buckling loads of nanobeams with various end conditions are investigated. Moreover, the dependence of buckling loads on the small-scale parameter as well as shear deformation coefficient is studied using these new boundary conditions. Then, numerical results from this new beam model are presented for carbon nanotubes (CNTs). They illustrate a more accurate buckling response as compared to the previous works. Furthermore, the critical strains are compared with results obtained from molecular dynamic simulations as well as Sanders shell theory and are found to be in good agreement. Results show that unlike the other beam theories, this model can capture correctly the small-scale effects on buckling strains of short CNTs for the shell-type buckling. Moreover, the value of nonlocal constant is calculated for CNTs using molecular dynamic simulation results.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: (none given)

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ABSTRACT: This paper presents a study of a hybrid grid shell, which is made of quadrangular meshes diagonally stiffened by pre-tensioned thin cables. The construction of the hybrid structure by translating a spatial curve against another spatial curve is firstly described. Then the elasto-plastic buckling analyses of the perfect hybrid structure and the corresponding single-layer lattice shell are carried out, and the influence of the asymmetric load on the failure loads is discussed based on a finite element model. Furthermore, the different shapes and sizes of imperfections are considered in this study. Two schemes of imposing imperfections are chosen: the first several eigenvalue buckling modes and the deformed shape of the loaded structure obtained from a geometrical non-linear analysis are chosen as the imperfection shape. Finally, the effects of different structural parameters, such as the rise-to-span ratio, beam section dimension, area and pre-stress of cables and boundary conditions, on the failure loads are investigated.

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“Buckling and post-buckling of rotationally restrained columns with imperfections”, Science China Physics, Mechanics and Astronomy, Vol. 55, No. 8, pp 1519-1522
ABSTRACT: The stability of imperfect columns has been studied by many researchers. Often the ends of a column are not necessarily fixed or pin-ended for practical structures. Therefore, rotationally restrained columns having an initial imperfection in an asymmetric mode have been studied in this paper. An elastic formula using the large deflection theory was given, and the shooting method was used to obtain the equilibrium paths and critical loads. Then the relationship between the end rotation and rotational restraints has been studied and discussed followed by a detailed discussion on the influence of imperfection on the column behaviour.

References listed at the end of the paper:

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ABSTRACT: In this paper, we investigate the buckling capacity of a hybrid grid shell, which is made of quadrangular meshes diagonally stiffened by pre-tensioned thin cables. The eigenvalue buckling, geometrical nonlinear elastic buckling and elasto-plastic buckling analyses of the hybrid structure were carried out. Then the influences of the shape and scale of imperfections on the elasto-plastic buckling loads were discussed. Also, the effects of different structural parameters, such as the rise-to-span ratio, cross-section of beams, area and pre-stress of cables and boundary conditions, on the failure load were investigated. The results show that the buckling capacity is reduced when taking into account the material nonlinearity. Furthermore, the hybrid structure is highly imperfection sensitive and the reduction of the failure load due to imperfections can be considerable. The proper shape and scale of the imperfection are also important. It is also shown that there exists an optimal rise-to-span ratio resulting in a relatively high buckling capacity for a specific span. Moreover, the enlarging of the cross-section of steel beams notably improves the stability performance of the structure. However, the area and pre-stress of cables pose small effect on the structural stability.

References listed at the end of this paper:
ABSTRACT: We study the buckling of an axially symmetric elastic hemispherical shell, uniformly compressed, subject to a constraint to the radial shifting of the equatorial circumference. The static equilibrium equations, using tensorial notations, are obtained applying the virtual displacements principle to the energy functional. The presence of a constraint does not modify the field equations with respect to the case of a constraint-free buckling, but only influences the boundary conditions, so that, instead of a boundary value problem, we deal with a problem with complementarity conditions on the boundary. We revisit and improve some previously obtained mathematical results, adapting them for the subsequent numerical treatment. Finally, by suitably using a delicate quasi-static shooting technique, numerical results are obtained, which complete the theoretical analysis and give an interesting insight into the behavior of the bifurcation branches.

References listed at the end of the paper:
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“Buckling Behaviour Of Compression Loaded Composite Cylindrical Shells With Reinforced Cutouts”,

ABSTRACT: In the recent times, Composite thin cylindrical shells are most widely used structural forms in Aerospace and Missile applications. In designing efficient and optimized shell structure, they become increasingly sensitive to buckling. It is well known that the experimental display is mainly attributed to geometrical imperfection like damage in the structure, or ovality or local thining of material etc. in missile and Airframe, the composite cylindrical shell structure is generally provided with cutouts for accessing internal components during integration. The cutouts invariably reduce the strength of the composite cylindrical shell and more specifically the buckling load. It has been a design practice to improve strength by addition of reinforcement around cutouts. The cutout not only introduces stress concentration but also significantly reduce buckling load. Which will results to eliminate the Interlaminar and intralaminar failure by change in material properties through dimensional computational analysis was carried out using ANSYS as the preprocessing software and FE as the solver and post processor.

References listed at the end of the paper:


ABSTRACT: Grid stiffened composite structures are the most attractive lightweight which their optimal design would lead to a stretching dominated structure. In this paper, specific buckling load of a cylindrical grid stiffened shell, which has been created by a Kagome unit cells, has been investigated. First, a single unit cell has been analyzed individually and the forces and moments caused by each unit cell have been transferred to the skin of cylinder. Thus, the equivalent cylindrical shell, which consists of the shell and the unit cells stiffeners, is obtained. Then the equivalent cylindrical shell is analyzed as a composite cylindrical shell. After introducing the approximate displacement functions and Ritz method buckling load will be achieved. The specific buckling load of the cylinder will be presented by changing some parameters simultaneously. The winding angle of the shell, the cross section size of ribs, shell thickness, the number of the iso-angle ribs and ribs axial pitch are these parameters. All these results are presented for Glass/Epoxy material. Figures of specific buckling load versus new two parameters (rib pitch and rib numbers) have been shown and discussed. Also, comparison between presented theory and other papers results will be done to verify the analytical results. At last, a parametric study is discussed to check the geometrical parameters' effects on the specific buckling load for different kinds of mentioned grids.


ABSTRACT: Nonlinear dynamic buckling for sandwich shallow conical shell structure under uniform triangular pulse is investigated. Based on the Reissner’s assumption and Hamilton’s principle, the nonlinear dynamic governing equation of sandwich shallow spherical shells is derived. The corresponding nonlinear dynamic response equations are obtained by Galerkin method and solved by Runge-Kutta method. Budiansky-Roth criterion expressed by displacements of rigid center is employed to determine the critical impact buckling load. The effects of geometric parameters and physical parameters on impact buckling are discussed.


ABSTRACT: In this paper, nonlinear dynamic buckling of FGM shallow conical shells under the action of triangular pulse impact loads are investigated. The nonlinear dynamic governing equation of symmetrically FGM shallow conical shells is built. Using Galerkin method, the nonlinear dynamic governing equation is solved, and the nonlinear dynamic response equation of symmetrically FGM shallow conical shells is obtained.
The Runge-Kutta method is introduced to numerically solve the nonlinear dynamic response equation and the impact response curve is achieved. Budiansky-Roth motion criterion expressed by the displacement of the peak of the shell is employed to determine the critical impact buckling load. The influences of geometric parameters and gradient constants on impact buckling are discussed as well.

ABSTRACT: In the current work, the vibration characteristics of single-walled carbon nanotubes (SWCNTs) under different boundary conditions are investigated. A nonlocal elastic shell model is utilized, which accounts for the small scale effects and encompasses its classical continuum counterpart as a particular case. The variational form of the Flugge type equations is constructed to which the analytical Rayleigh–Ritz method is applied. Comprehensive results are attained for the resonant frequencies of vibrating SWCNTs. The significance of the small size effects on the resonant frequencies of SWCNTs is shown to be dependent on the geometric parameters of nanotubes. The effectiveness of the present analytical solution is assessed by the molecular dynamics simulations as a benchmark of good accuracy. It is found that, in contrast to the chirality, the boundary conditions have a significant effect on the appropriate values of nonlocal parameter.

Hessam Rouhi and Reza Ansari (Dept. of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Nonlocal Analytical Flugge Shell Model for Axial Buckling of Double-Walled Carbon Nanotubes with Different End Conditions”, Nano, Vol. 7, No. 3, 1250018 (10 pages), June 2012
DOI: 10.1142/S179329201250018X
ABSTRACT: In this paper, a nonlocal Flügge shell model is utilized to investigate the axial buckling behavior of double-walled carbon nanotubes (DWCNTs) under various boundary conditions. According to the nonlocal elasticity theory, the displacement field equations coupled by the van der Waals interaction are derived. The set of governing equations of motion is then solved by the Rayleigh–Ritz method. The present analysis can treat boundary conditions in a layer-wise manner. The effects of nonlocal parameter, layer-wise boundary conditions and geometrical parameters on the mechanical behavior of DWCNTs are examined. Furthermore, molecular dynamics simulations are performed to assess the validity of the results and also to predict the appropriate values of nonlocal parameter. It is found that the type of boundary conditions affects the proper value of nonlocal parameter.

ABSTRACT: Presented herein is the thermal buckling analysis of multi-walled carbon nanotubes on the basis of nonlocal Flügge shell model capturing small scale effects. Based upon the continuum mechanics, a multiple-shell model is adopted in which the nested tubes are coupled with each other through the van der Waals interlayer interaction. The utilized van der Waals model incorporating the interlayer interactions between any two layers, whether adjacent or non-adjacent is curvature dependent. To analytically solve the problem, the Rayleigh-Ritz method was implemented to the variational form equivalent to the Flügge type equations. The present analysis provides the possibility of considering different combinations of layerwise boundary conditions. It is shown that the shell-like thermal buckling is significantly sensitive to the nonlocal parameter.
variation, whereas the column-like thermal buckling remains unaffected when the nonlocal parameter is varied.

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ABSTRACT: In the present investigation, the axial buckling and post-buckling configurations of single-walled carbon nanotubes (SWCNTs) are studied including the thermal environment effect. For this purpose, Eringen’s nonlocal elasticity continuum theory is implemented into the classical Euler-Bernoulli beam theory to represent the SWCNTs as a nonlocal elastic beam model. A closed-form analytical solution is carried out to analyze the static response of SWCNTs in their post-buckling state in which the axial buckling load is assumed to be beyond the critical axial buckling load. Common sets of boundary conditions, named simply supported-simply supported (SS-SS), clamped-clamped (C-C), and clamped-simply supported (C-SS), are considered in the investigation. Selected numerical results are given to represent the variation of the carbon nanotube’s mid-span deflection with the applied axial load corresponding to various nonlocal parameters, length-to-diameter aspect ratios, temperature changes, and end supports. Moreover, a comparison between the post-buckling behaviors of SWCNTs at low- and high-temperature environments is presented. It is found that the size effect leads to a decrease of the axial buckling load especially for SWCNTs with C-C boundary conditions. Also, it is revealed that the value of the temperature change plays different roles in the post-buckling response of SWCNTs at low- and high-temperature environments.


ABSTRACT: Described in the current study is the thermal buckling behavior of multi-walled carbon nanotubes (WCNTs) via a nonlocal atomistic-based shell model. The model including the effects of small-scale length and the van der Waals (vdW) forces between adjacent nanotubes is established through the incorporation of the interatomic potential into the nonlocal Flügge shell theory. This model links the strain energy density induced in the continuum to Eringen's nonlocal constitutive relations. The set of coupled field equations are analytically solved for two types of temperature distribution. The present model is of a distinguishing feature which is its independence from the widely scattered values of Young's modulus and the effective wall thickness of carbon nanotubes.

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ABSTRACT: In this paper, the vibrational behavior of double-walled carbon nanotubes (DWCNTs) is studied
by a nonlocal elastic shell model. The nonlocal continuum model accounting for the small scale effects encompasses its classical continuum counterpart as a particular case. Based upon the constitutive equations of nonlocal elasticity, the displacement field equations coupled by van der Waals forces are derived. The set of governing equations of motion are then numerically solved by a novel method emerged from incorporating the radial point interpolation approximation within the framework of the generalized differential quadrature method. The present analysis provides the possibility of considering different combinations of layerwise boundary conditions. The influences of small scale factor, layerwise boundary conditions and geometrical parameters on the mechanical behavior of DWCNTs are fully investigated. Explicit expressions for the nonlocal frequencies of DWCNTs with all edges simply supported are also analytically obtained by a nonlocal elastic beam model. Some new intertube resonant frequencies and the corresponding noncoaxial vibrational modes are identified due to incorporating circumferential modes into the shell model. A shift in noncoaxial mode numbers, not predictable by the beam model, is also observed when the radius of DWCNTs is varied. The results generated also provide valuable information concerning the applicability of the beam model and new noncoaxial modes affecting the physical properties of nested nanotubes.


ABSTRACT: Multistable shells have been proposed for a variety of applications; however, their actuation is almost exclusively addressed through embedded piezoelectric patches. Additional actuation techniques are needed for applications requiring high strains or where remote actuation is desirable. Part of the reason for the lack of research in this area is the absence of appropriate models describing the detailed deformation and energetics of such shells. This work presents a bistable spherical cap made of iron carbonyl-infused polydimethylsiloxane. The magnetizable structure can be actuated remotely through permanent magnets while the transition is recorded with a high-speed camera. Moreover, the experiment is reproduced in a finite element (FE) dynamic model for comparison with the physical observations. High-speed footage of the physical cap inversion together with the FE modeling gives valuable insight on preferable intermediate geometries. Both methods return similar values for the magnetic field strength required for the snap-through. High-strain multistable spherical cap transformation is demonstrated, based on informed material selection. We discover that non-axisymmetric transition shapes are preferred in intermediate geometries by bistable spherical caps. We develop the methods for design and analysis of such actuators, including the feasibility of remote actuation methods for multistable shells.

References listed at the end of the paper:

ABSTRACT: Design of spatial reinforced concrete (RC) structures to dynamic loads is based on structural dynamic parameters. Experimental research on dynamic response of full scale RC structures is very limited. Therefore developing proper numerical techniques, allowing calculation of valuable dynamic parameters is extremely important. The purpose of the present study is to investigate efficiency of existing software and its suitability for modeling spatial RC structures. The object of the research is a dome over a public building. It is a shallow thin walled spherical RC shell. The numerical results are compared with available experimental data. ANSYS software was used for the analysis. The affect of different structural components on natural vibration parameters like mode shapes and frequencies was studied. Comparison of numerical and experimental results enabled to verify the accuracy and adequacy of the structural scheme. Realization of numeral experiments allows to understand properly the qualitative characteristics and to interpret the impact of various parameters in order to obtain reasonable recommendations for mock-up study or full scale experiments. It is shown that

A. Alikina (NPO Saturn, JSC, Russia), “Numerical investigation of dynamic parameters of a reinforced concrete dome”, (No publisher or date given in the pdf file. Most recent reference is dated 2016)

qualitative modeling of the system can be used for further investigation of spatial RC structures response to different dynamic loadings.

References listed at the end of the paper:

Yang Jinsong and Xia Pinqi (Nanjing University of Aeronautics and Astronautics), “Corotational Formulation for Nonlinear Static and Dynamic Analysis of Thin Shells with Finite Rotation, The 2nd Asian/Australian Rotorcraft Forum and the 4th International Basic Research Conference on Rotorcraft Technology, Tianjin, China, September 8-11, 2013
ABSTRACT: (cannot cut and paste)

DOI: 10.4028/www.scientific.net/AMR.712-715.822
ABSTRACT: Steel-concrete composite ribbed shell is a kind of shell structure based on the thin concrete shell, which has the advantages of two different materials, at the same time with steel nets shell and thin concrete shell structure. In this paper, the seismic performance of steel concrete composite ribbed shell is analyzed, in which the elastoplastic time-history analysis method is used to analyze internal force and deformation. Furthermore a parameter analysis is made to discuss the seismic performance, which considering different high-span ratio, section dimension, boundary conditions and structure division frequency. The influence on structure seismic performance and some structure dynamic response characteristics are obtained, which can be resulted for structural seismic design and referenced in steel-concrete thin shell design specification modification.

Franz-Joseph Barthold and Nikolai Gerzen (TU Dortmund), “Imperfection Modes for Non-Linear Buckling Analysis Based on Variational Design Sensitivities”, Abstract, 20/03/2013, UNS-204
ABSTRACT: Solid shell elements are frequently used to model thin structures because of their efficiency and accuracy. In detail, we consider the variational design sensitivity analysis of a non-linear solid shell element, which is based on the Hu-Washizu variational principle. The design of such structures is extremely important
for their stability, robustness and for their load-bearing capacity. Design sensitivity analysis provides
information which allow the engineer to find the appropriate shape of a shell and to understand the influence of
gometry and layout variants on its behaviour. Unfortunately, considering the coordinates of all finite element
odes as design parameters leads to a large amount of sensitivity information which can not be easily
interpreted by engineers. We apply singular value decomposition (SVD) to the pseudo load matrix and the
sensitivity matrix to detect the most valuable part of information and to transform sensitivity results in a form
which is comprehensible for engineers. The proposed theoretical concept is demonstrated on the example of
non-linear buckling analysis of shells. Here, proper imperfection modes which lead to the lowest load-bearing
capacity are created automatically applying SVD to the pseudo load matrix. Numerical examples illustrate the
advocated technique.

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“F-actin buckling coordinates contractility and severing in a biomimetic actomyosin cortex”, Proceedings of the
National Academy of Sciences of the USA (PNAS), December 3, 2012, DOI: 10.1073/pnas.1214753109
ABSTRACT: Here we develop a minimal model of the cell actomyosin cortex by forming a quasi-2D cross-
linked filamentous actin (F-actin) network adhered to a model cell membrane and contracted by myosin thick
filaments. Myosin motors generate both compressive and tensile stresses on F-actin and consequently induce
large bending fluctuations, which reduces their effective persistence length to <1 μm. Over a large range of
conditions, we show the extent of network contraction corresponds exactly to the extent of individual F-actin
shortening via buckling. This demonstrates an essential role of buckling in breaking the symmetry between
tensile and compressive stresses to facilitate mesoscale network contraction of up to 80% strain. Portions of
buckled F-actin with a radius of curvature "<300 nm are prone to severing and thus compressive stresses
mechanically coordinate contractility with F-actin severing, the initial step of F-actin turnover. Finally, the F-
actin curvature acquired by myosin-induced stresses can be further constrained by adhesion of the network to a
membrane, accelerating filament severing but inhibiting the long-range transmission of the stresses necessary
for network contractility. Thus, the extent of membrane adhesion can regulate the coupling between network
contraction and F-actin severing. These data demonstrate the essential role of the nonlinear response of F-actin
to compressive stresses in potentiating both myosin-mediated contractility and filament severing. This may
serve as a general mechanism to mechanically coordinate contractility and cortical dynamics across diverse
actomyosin assemblies in smooth muscle and nonmuscle cells.

Yury Grabovsky and Davit Harutyunyan, “Rigorous asymptotic analysis of buckling of thin-walled cylinders
under axial compression”, Cornell University Library, arXiv.1301.6079 [math.AP], January 2013
ABSTRACT: Using rigorous constitutive linearization of second variation introduced in [6] we study weak
stability of homogeneous deformation of the axially compressed circular cylindrical shell, regarded as a 3-
dimensional hyperelastic body. We show that such deformation becomes weakly unstable at the critical load that
coincides with value of the bifurcation load in von-Karman-Donnel shell theory. We also show that the linear
bifurcation modes described by the Koiter circle [11] minimize the second variation asymptotically. The key
ingredients of our analysis are the asymptotically sharp estimates of the Korn constant for cylindrical shells and
Korn-like inequalities on components of the deformation gradient tensor in cylindrical coordinates. The notion
of buckling equivalence introduced in [6] is developed further and becomes central in this work. A link between
features of this theory and sensitivity of the critical load to imprefections of load and shape is conjectured.
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“Scaling instability of the buckling load in axially compressed circular cylindrical shells”, Journal of Nonlinear Science, pp 1-37, August 2015

ABSTRACT: In this paper we initiate a program of rigorous analytical investigation of the paradoxical buckling behavior of circular cylindrical shells under axial compression. This is done by the development and systematic application of general theory of "near-flip" buckling of 3D slender bodies to cylindrical shells. The theory predicts scaling instability of the buckling load due to imperfections of load. It also suggests a more dramatic scaling instability caused by shape imperfections. The experimentally determined scaling exponent 1.5 of the critical stress as a function of shell thickness appears in our analysis as the scaling of the lower bound on safe loads given by the Korn constant. While the results of this paper fall short of a definitive explanation of the buckling behavior of cylindrical shells, we believe that our approach is capable of providing reliable estimates of the buckling loads of axially compressed cylindrical shells.

References listed at the end of the paper:
expressions are obtained which establish the dependency of the natural frequencies and buckling frequencies of vibrations. For the case of nanotubes with simply supported boundary conditions, explicit expressions are obtained which establish the dependency of the natural frequencies and buckling loads of the.
nanotube on the small-scale parameter and natural frequencies obtained by local continuum mechanics. The obtained solutions generalize the results of nano-bar and -beam models and are verified by the literature. Based on several numerical studies some conclusions are drawn about the small-scale effect on the natural frequencies and buckling pressure of the nanotubes.

References listed at the end of the paper:


[58] A. Ghorbanpour Arani, R. Rahmani, A. Arefmanesh and S. Golabi, Buckling analysis of multi-walled carbon nanotubes under


ABSTRACT: Various lengths and helical types (i.e., armchair, zigzag and chiral) of single-walled CNTs are considered in molecular dynamics simulations in order to systematically examine the length-to-radius ratio and chirality effects on the buckling mechanism. Proper boundary conditions are imposed to induce different buckling modes. It is observed that the buckling strain is getting smaller as the CNT becomes slender for most nanotubes, which implies that the slender nanotubes have lower buckling resistance regardless the buckling mode and chirality. The column buckling of the CNTs at lower buckling mode will transform into shell wall buckling at higher mode if the length-to-radius of each constrained section is less than 10. The applicability of the continuum buckling theory, which has been well developed for thin tubes, on predicting the buckling strain of the CNT is also examined. In general, the corresponding buckling strain at different modes predicted by the continuum column buckling theory could agree reasonably well with simulation results except those exhibit shell wall buckling.


ABSTRACT: Equilibrium and stability equations of a thin rectangular plate with length a, width b, and thickness h(x)=C1x+C2, made of functionally graded materials under thermal loads are derived based on the first order shear deformation theory. It is assumed that the material properties vary as a power form of thickness coordinate variable z. The derived equilibrium and buckling equations are then solved analytically for a plate with simply supported boundary conditions. One type of thermal loading, uniform temperature rise and gradient through the thickness are considered, and the buckling temperatures are derived. The influences of the plate aspect ratio, the relative thickness, the gradient index and the transverse shear on buckling temperature difference are all discussed.

References listed at the end of the paper:

Mostapha Raki (1), Reza Alipour (2) and Amirabbas Kamanbedast (2)  
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ABSTRACT: Equilibrium and stability equations of a rectangular plate made of functionally graded material (FGM) under thermal loads are derived, based on the higher order shear deformation plate theory. Assuming that the material properties vary as a power form of the thickness coordinate variable z and using the variational method, the system of fundamental partial differential equations is established. The derived equilibrium and stability equations for functionally graded plates (FGPs) are identical to the equations for laminated composite plates with 50 layers. A buckling analysis of a functionally graded plate under one type of thermal loads is carried out and results in closed form solutions, uniform temperature rise and gradient through the thickness are considered and the buckling temperatures are derived. The critical buckling temperature relations are reduced to the respective relations for functionally graded plates with a linear composition of constituent materials and homogeneous plates The results are compared with the critical buckling temperatures obtained for functionally graded plates ansys software (FEM) given in the literature. The study concludes that higher order shear deformation theory accurately predicts the behavior of functionally graded plates.  

References listed at the end of the paper:  
Shadmehri, Farjad (Mechanical and Industrial Engineering, Concordia University SPECTRUM Research Repository, Montreal, Quebec, Canada), “Buckling of Laminated Composite Conical Shells; Theory and Experiment”, 2012 PhD dissertation, Concordia University

ABSTRACT: Composite conical and cylindrical shells are gaining more application in aerospace industry (e.g., helicopter tailboom, airplane fuselage) due to their high specific strength and stiffness properties coming from material (composite) and geometry advantages. Stability is always a concern for these types of structures under different loading conditions. One of the major loading scenarios is the bending load in which composite conical shells can buckle under bending. Although there have been extensive studies on the buckling of conical and cylindrical shells under axial load, buckling under bending receives less attention in the literature from theoretical and experimental points of view. In this study, the bucking behavior of composite conical shells has been studied experimentally and theoretically.

In the theoretical approach, a first order shear deformation shell theory has been proposed to study buckling and bending behavior of composite conical shells. A semi-analytical approach (Ritz method) has been applied to study buckling under axial load and buckling under bending of composite conical shells. An analytical solution (Levy type solution) has been applied to study the bending response of cross-ply conical shells under sinusoidal bending load. Also, a new formulation has been proposed to study bending, buckling and vibration of cross-ply cylindrical shells using an analytical solution (Levy type solution). A different displacement field from what was assumed in the literature has been proposed and consequently a new formulation has been obtained for the problem. In the experimental approach, a composite tube-bending setup has been designed and developed to study bending, and buckling under bending load, behavior of composite shells. The setup has been designed to apply equal bending moments at the both ends of the structure, simulating pure bending test conditions. Experimental result has been obtained for buckling under pure bending of composite conical shells. Regarding the manufacturing technique, Automated Fiber Placement (AFP) has attracted the aerospace industry due to its fast production rate, repeatability, and minimum material waste. Advanced thermoplastic composites obtain special attention in the aerospace industry as well, considering their superior properties (e.g., fracture toughness) and their capability to make aero-structures without requiring autoclave treatment with respect to thermoset ones. Considerable challenges remained unresolved regarding optimum process parameters for manufacturing of thermoplastic composites made by AFP and their quality. This thesis also addresses the effect of autoclave treatment on the stiffness quality of the thermoplastic composite cones made by AFP. The determination of optimum process parameters for AFP in the manufacturing of thermoplastic composite (AS4/PEEK) has been performed from both stiffness and strength point of view.

References listed at the end of the dissertation:


ABSTRACT: A simple and efficient 3-node triangular planar shell element for the geometrical nonlinear analysis of laminated composite structures is developed based on corotational formulation (CR). The shell element is constructed by combining the generalized conforming membrane element GT9 with the drilling degree of freedom and the generalized conforming thick/thin plate element TMT with assumed rotation and transverse shear strain fields. In order to avoid membrane locking, one-point reduced integration scheme is employed for calculating the terms related to membrane strains, and a stabilization matrix is added to eliminate zero energy modes. Based on the first-order shear deformation theory (FSDT) for laminated composite plates, the correctional transverse shear stiffness is calculated, considering the real ply stacking sequence of the laminate, such that the shell can be applicable to modeling moderately thick laminated composite structures. The geometrically linear stiffness matrix in the core of CR formula can be calculated only once and can be saved to be used throughout the whole procedure for the nonlinear analysis. Numerical examples show that the present shell element is accurate and efficient for thin and thick shell structures, including laminated composite structures.

References listed at the end of the paper:
In bridge construction, the use of stiffened plates for box-girder or steel beams is common day to day practice. The advantages of the stiffening from the economical and mechanical points of view are unanimously recognized. For curved steel panels, however, applications are more recent and the literature on their mechanical behaviour including the influence of stiffeners is therefore limited. Their design with
commercial finite element software is significantly time-consuming, which reduces the number of parameters which can be investigated in an optimization procedure. The present paper is thus dedicated to the study of the behaviour of stiffened curved panels under uniform longitudinal compression. It addresses the linear buckling and the ultimate strength which are both influenced by the coupled effects of curvature and stiffening. It finally proposes a design methodology based on that for stiffened flat plates adopted by European Standards and a column-like behaviour.

References listed at the end of the paper:

ABSTRACT: The effect of assumed displacement field is investigated on the bending, buckling, and natural frequencies of cross-ply circular cylindrical shells using first-order shear deformation theory through an analytical solution. Linear strain-displacement relation is assumed. The governing equations are derived from Hamilton's principle. Assuming Levy-type solution, the governing equations are then converted to ordinary differential equations and changed to state-space form introducing ten unknown variables and solved for displacements. Different lamination sequences, including symmetric and asymmetric laminate, are studied and compared. The effect of various boundary conditions (i.e., clamped, simply supported, and free edge), radius-to-thickness, and radius-to-length ratio on the displacement of mid-surface is investigated.

Alice Mathai (Department of Ship Technology, Cochin University of Science & Technology), "Analytical investigations on collapse of cylindrical submarine shells", PhD dissertation, November 2004

ABSTRACT: Submarine hull structure is a watertight envelope, under hydrostatic pressure when in operation. Stiffened cylindrical shells constitute the major portion of these submarine hulls and these thin shells under compression are susceptible to buckling failure. Normally loss of stability occurs at the limit point rather than at the bifurcation point and the stability analysis has to consider the change in geometry at each load step. Hence geometric nonlinear analysis of the shell forms becomes a necessity. External hydrostatic pressure will follow the deformed configuration of the shell and hence follower force effect has to be accounted for. Computer codes have been developed based on all-cubic axisymmetric cylindrical shell finite element and discrete ring stiffener element for linear elastic, linear buckling and geometric nonlinear analysis of stiffened cylindrical shells. These analysis programs have the capability to treat hydrostatic pressure as a radial load and as a follower force. Analytical investigations are carried out on two attack submarine cylindrical hull models besides standard benchmark problems. In each case, the analysis has been carried out for interstiffener, interdeepframe and interbulkhead configurations. The shell stiffener attachment in each of this configuration has been represented by the simply supported-simply supported, clamped-clamped and fixed-fixed boundary conditions in this study. The results of the analytical investigations have been discussed and the observations and conclusions are described. Rotation restraint at the ends is influential for interstiffener and interbulkhead configurations and the significance of axial restraint becomes predominant in the interbulkhead configuration. The follower force effect of hydrostatic pressure is not significant in interstiffener and interdeepframe configurations where as it has very high detrimental effect on buckling pressure on interbulkhead configuration. The geometric nonlinear interbulkhead analysis incorporating follower force effect gives the critical value of buckling pressure and this analysis is recommended for the determination of collapse pressure of stiffened cylindrical submarine shells.

References listed at the end of the dissertation:
69. Omurtag, M.H., Akoz A.Y., A Compatible Cylindrical Shell Element for Stiffened Cylindrical Shell in a Mixed Finite Element
95. Tian, J., Wang, C.M., Swadidwudhipong. S; Elastic Buckling Analysis of Ring Stiffened Cylindrical Shells under General

ABSTRACT: Submarine is a watercraft capable of independent operation under water. Use of submarines includes marine science, offshore industry underwater exploration etc. The pressure hull of submarine is constructed as combination of cylinders and domes. The shell is subjected to very high hydrostatic pressure, which creates large compressive stress resultants. Due to this the structure is susceptible to buckling. The introduction of stiffeners in both directions considerably increases the buckling strength of the shell. Since the stiffened cylindrical shell is susceptible to initial imperfections, nonlinear analysis is essential. The objective of this work is the linear and nonlinear analysis of the stiffened cylindrical shell subjected to very high hydrostatic pressure. Finite element method is a powerful tool for analysis of complex structures. Finite element package ANSYS is used for modeling and analysis the submarine hull.

References cited at the end of the paper:

ABSTRACT: Container ships with wide hatch openings are thin walled open sections and have low torsional stiffness. Hence response arising from torsional loads is significant and subsequently the torsional analysis of container ship is necessary. Using the ANSYS software, the progressive collapse behaviour of a typical
container vessel under torsion was analysed. The effect of torsional moment on the ultimate strength of ship hull subjected to design vertical shear force was also determined. Full hull between the bulkheads was modeled with fully restrained warping displacement at the unloaded end. When pure torsion is applied, the hull corner regions are typically the most highly stressed areas, which may collapse. Thus, scantlings of the hull corner region should be sufficient for ship hulls with large deck openings. The ultimate strength based safety factor under pure torsion for the vessel, is 4.5, which is reduced by 30% when subjected to design vertical shear force also.

References listed at the end of the paper:


ABSTRACT: Structures consisting of thin plates stiffened by a system of ribs have found wide application for aircraft, ships, bridges, and buildings as well as in many other branches of contemporary structural engineering. Buckling analysis can be used to find critical compressive loads at which a structure becomes elastically unstable. In this paper buckling analysis of stiffened plates was carried out using finite element software NISA. The analytical investigations of stiffened plates are rarely found in literature; hence it is found apt to carry out such investigations to provide design recommendations.

References listed at the end of the paper:

S. K. Singh and A. Chakrabarti (Department of Civil Engineering, Indian Institute of Technology, Roorkee-247 667, India), “Buckling analysis of laminated composite plates using an efficient C0 FE model”, Latin American
ABSTRACT: Buckling analysis of laminated composite plates is carried out by using an efficient C0 FE model developed based on higher order zigzag theory. In this model the first derivatives of transverse displacement have been treated as independent variables to overcome the problem of C1 continuity associated with the FE implementation of the plate theory. The C0 continuity of the present FE model is compensated in the stiffness matrix calculations by using penalty parameter approach. Numerical results and comparison with other existing solutions show that the present model is very efficient in predicting the buckling responses of laminated composites.

References cited at the end of the paper:

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“Buckling and free vibration of non-homogeneous composite cross-ply laminated plates with various plate theories”, Compos. Struct, 44:279–287, 1999, DOI: 10.1016/S0263-8223(98)00135-4

ABSTRACT: Various theories of homogeneous laminated plates are extended to study the buckling and free vibration behavior of non-homogeneous rectangular composite laminates. The equations governing the dynamic response of non-homogeneous composite laminates are deduced. Numerical results for the natural frequencies and critical buckling loads of symmetric cross-ply laminates are presented. The influences of the degree of non-homogeneity, aspect ratio, thickness ratio and in-plane orthotropy ratio on the natural frequencies and critical buckling loads are investigated. The results obtained for homogeneous cases are compared with their counterparts in the literature. The study concludes that the classical plate theory is inadequate for predicting the structural response of non-homogeneous laminates, and that the free vibration and the state of the stability are affected strongly by the degree of nonhomogeneity.

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ABSTRACT: h resistance-weight ratio, the possibility to integrate service pipes within their height, and aesthetics. Such profiles usually exhibit a complex behavior, since they can experience many modes of failure, including local instability ones, i.e. those involving an out-of-plane instability of the web post at high shear locations and/or distortion of the cross-section. For what regards global instability, the members are usually designed by means of rough design rules, which often lead to an unduly conservative girder, the beams sometimes showing over 200% resistance reserve. Present research aims at improving this situation, by means of new adequate design formulæ. In this respect, both experimental and extensive numerical parametric studies have been undertaken. First, a series of 3 full-scale tests has been performed, the main goal of which being the validation of purposely-derived FE models. Since the numerical models showed a very good agreement with the tests, they have been further used to gather a large set of numerical reference results where many parameters were varied: the relative slenderness, steel grades, cross-section shapes, bending moment distributions, and relative sizes of the openings. Finally, a new set of dedicated design rules has been derived, that was proved to be accurate while leading to safe estimates of the resistance when compared to all reference results.

References listed at the end of this paper:
ABSTRACT: In case of lateral buckling, experimentally determined load versus deflection plots usually take a form where the critical load is masked by the large deformations which occur as a consequence of geometrical and material imperfections, and that the beam fails before the critical load of the perfect beam is reached. Therefore, it is necessary to use an extrapolation technique to obtain more accurate estimates of experimental critical loads than would be given by the experimental failure loads. Also, an extrapolation technique may be used to determine experimentally the critical load of a structure, without having to subject the structure to loading in the vicinity of critical. Based on the significance of these techniques, further studies on the use of Southwell, Modified, Massey, and Meck extrapolation techniques in case of lateral buckling of structures are reported in this paper, and the accuracy of the extrapolated loads is evaluated in various cases.


ABSTRACT: Nonlinear analysis of plate and shell structures can explain the phenomenon which cannot been explained by classical stability theory, and can obtain better validation of experimental results. Stability problems are essentially nonlinear and their nonlinear finite element solutions ultimately result in solving nonlinear algebraic equations and nonlinear eigenvalue problems. The solutions can define the shape of basic path and determine critical load by using the incremental method. The perturbation methods are used near the critical point, and the basic formulas are given for initial post-buckling analysis by FEM.


ABSTRACT: A cable-braced grid shell is a new type of single-layer latticed shell suitable for glass roofs. Compared with traditional single-layer latticed shells, this new type of shell has a unique mesh shape (planar quadrilateral mesh), mesh form (steel and crossing cables), and surface shape (from the translation surface method). The grid shell is a single-layer latticed structure, and therefore stability is one of the key factors in the structural design. Therefore, in this paper, an elliptic paraboloid cable-braced grid shell with imperfections is used as an example with which to determine the formulas for the buckling load based on the continuum analogy. The main contents of this paper include the formula for the linear buckling load of an elliptic paraboloid cable-braced grid shell with imperfections, which is determined based on the continuum analogy. The equivalent rigidity for the cable-braced grid shell is then determined, and the effect of the cables on the shear rigidity is discussed. Finally, the formula for the linear buckling load is verified with numerical examples, and the errors are analyzed and a corresponding correction factor is given.


ABSTRACT: Thin-walled cylindrical composite shell structures are often applied in aerospace for lighter and cheaper launcher transport system. These structures exhibit sensitivity to geometrical imperfection and are prone to buckling under axial compression. Today the design is based on NASA guidelines from the 1960’s [1] using a conservative lower bound curve embodying many experimental results of that time. It is well known that the advantages and different characteristics of composites as well as the evolution of manufacturing standards are not considered appropriately in this outdated approach. The DESICOS project was initiated to
provide new design guidelines regarding all the advantages of composites and allow further weight reduction of space structures by guaranteeing a more precise and robust design. Therefore it is necessary among other things to understand how a cutout with different dimensions affects the buckling load of a thin-walled cylindrical shell structure in combination with initial geometric imperfections. This work is intended to identify a ratio between the cutout characteristic dimension (in this case the cutout diameter) and the structure characteristic dimension (in this case the cylinder radius) that can be used to tell if the buckling structure is dominated by initial imperfections or is dominated by the cutout.

Li, B., Cao, Y.-P., Feng, X.-Q. & Gao, H. 2011 Surface wrinkling of mucosa induced by volumetric growth: theory, simulation and experiment. J. Mech. Phys. Solids 59, 758–774.  (doi:10.1016/j.jmps.2011.01.010) ABSTRACT: Mechanics of living tissues focusing on the relationships between growth, morphology and function is not only of theoretical interest but can also be useful for diagnosis of certain diseases. In this paper, we model the surface wrinkling morphology of mucosa, the moist tissue that commonly lines organs and cavities throughout the body, induced by either physiological or pathological volumetric growth. A theoretical framework of finite deformation is adopted to analyze the deformation of a cylindrical cavity covered by mucosal and submucosal layers. It is shown that compressive residual stresses induced by the confined growth of mucosa can destabilize the tissue into various surface wrinkling patterns. A linear stability analysis of the critical condition and characteristic buckling patterns indicates that the wrinkling mode is sensitive to the thicknesses of the mucosal and submucosal layers, as well as the properties of the tissues. The thinner the mucosal layer and the lower its elastic modulus, the shorter the buckling wavelength. A series of finite element simulations are performed to validate the theoretical predictions and to study local wrinkling or non-uniform patterns associated with inhomogeneous growth. Our postbuckling analysis shows that the surface pattern may evolve towards a period-doubling morphology due to continuous growth of mucosa or submucosa beyond the critical state. Finally, the theoretical predictions and numerical simulations are compared to experimental observations.

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ABSTRACT: Based on Giannakopoulos’s 2-D functionally graded material (FGM) contact model, a modified contact model is put forward to deal with impact problem of the functionally graded shallow spherical shell in thermal environment. The FGM shallow spherical shell, having temperature dependent material property, is subjected to a temperature field uniform over the shell surface but varying along the thickness direction due to steady-state heat conduction. The displacement field and geometrical relations of the FGM shallow spherical shell are established on the basis of Timoshenko–Mindlin theory. And the nonlinear motion equations of the FGM shallow spherical shell under low velocity impact in thermal environment are founded in terms of displacement variable functions. Using the orthogonal collocation point method and the Newmark method to discretize the unknown variable functions in space and in time domain, the whole problem is solved by the
Iterative method. In numerical examples, the contact force and nonlinear dynamic response of the FGM shallow spherical shell under low velocity impact are investigated and effects of temperature field, material and geometrical parameters on contact force and dynamic response of the FGM shallow spherical shell are discussed.

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1. E. Etemadi, A. Afaghi Khatibi, M. Takaffoli, 3D finite element simulation of sandwich panels with a functionally graded core subjected to low velocity impact, Compos. Struct., 89 (1) (2009), pp. 8–34

Jun Yin, Nicole Coutris and Young Huang (Dept. of Mechanical Engineering, Clemson University, Clemson, South Carolina), “Groove formation modeling in fabricating hollow fiber membrane for nerve regeneration”, ASME Journal of Applied Mechanics, Vol. 78, January 2011, DOI: 10.1115/1.4002001

Abstract: Hollow fiber membrane (HFM) is one of the most popular membranes used for different industrial applications. Under some controlled fabrication conditions, axially aligned grooves can be formed on the HFM inner surface during typical immersion precipitation-based phase inversion fabrication processes. Such grooved HFM are finding promising medical applications for nerve repair and regeneration. For better nerve regeneration performance, the HFM groove morphology should be carefully controlled. Toward this goal, this study has modeled the HFM groove number based on the shrinkage-induced buckling model in HFM fabrication. HFM has been modeled as a three-layer long fiber membrane. The HFM inner layer has been treated as a thin-walled elastic cylindrical shell and buckles due to the shrinkage of the compliant intermediate
ABSTRACT: Axially aligned grooves can be formed on the hollow fiber membrane (HFM) inner surface under some controlled fabrication conditions during a typical immersion precipitation-based phase inversion fabrication process. Such grooved HFMs are finding promising medical applications for nerve repair and regeneration. For better nerve regeneration performance, the HFM groove geometry should be carefully controlled. Towards this goal, in this study the polyacrylonitrile (PAN) HFM groove number has been modeled based on the radially inward pressure-induced buckling mechanism. HFM has been modeled as a long six-layer fiber membrane, and the HFM inner skin layer has been treated as a thin-walled elastic cylindrical shell under the shrinkage-induced inward radial pressure. The groove number has been reasonably estimated based on the resulting buckling mode as compared with the experimental measurements.

References listed at the end of the paper:

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ABSTRACT: We develop a model of the buckling (both planar and axial) of capillaries in cancer tumours, using nonlinear solid mechanics. The compressive stress in the tumour interstitium is modelled as a consequence of the rapid proliferation of the tumour cells, using a multiplicative decomposition of the deformation gradient. In turn, the tumour cell proliferation is determined by the oxygen concentration (which is governed by the diffusion equation) and the solid stress. We apply a linear stability analysis to determine the onset of mechanical instability, and the Liapunov–Schmidt reduction to determine the postbuckling behaviour. We find that planar modes usually go unstable before axial modes, so that our model can explain the buckling of capillaries, but not as easily their tortuosity. We also find that the inclusion of anisotropic growth in our model can substantially affect the onset of buckling. Anisotropic growth also results in a feedback effect that substantially affects the magnitude of the buckle.

References listed at the end of the paper:

ABSTRACT: Buckling is characterized by a sudden failure of a structural member subjected to high compressive stress and it is a structural instability leading to a failure mode. One of the major design criteria of thin shell structures that experience compressive loads is that the buckling load limit. Therefore it is important to know about the Buckling loads. The buckling load of thin shell structures are dominantly affected by the geometrical imperfections present in the cylindrical shell which are very difficult to alleviate during manufacturing process. In this paper, three types of geometrical imperfection patterns are considered for cylindrical shells with and without dent. Experiments are conducted for all the cases and results are compared with analytical results with ANSYS. It is found that buckling strength of plain cylindrical shell is different compared to cylindrical shell having dents.

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[2] Wilhelm Rust -Buckling and limit load analysis of thin-walled structures are usually started with a linear buckling analysis-Finite element limit load analysis of thin-walled structures by ansys11-12 (1919) (date seems wrong, maybe should be 1991)
[7] Jin Guang Teng There is a class of shell structures in which localized circumferential compressive stresses arise under loads - Appl Mech Rev vol 49, no 4, April 1996.

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ABSTRACT: Many thin cylindrical shells are used in structural applications in which the dominant loading condition is global bending. Key examples include chimneys, tubular piles, wind generation towers and tall silos. Their thickness lies in a tricky range which is extremely thin for the structural tube community and very thick for the shell buckling community. The buckling strength of these structures is dominated by extensive plasticity, but the fully plastic state is usually far from being attained. This paper explores the buckling strength of imperfect thin cylindrical shells under global bending in the elastic-plastic range. The capacity curves of the new Eurocode EN 1993-1-6 (2007) are used to match the final results. The results show that the capacity curves
can capture this buckling behavior accurately and safely for different types of material models. It is assumed that the shell is held circular by rings or boundaries at reasonable intervals, effectively restraining ovalisation. It is hoped that these results will make a useful contribution towards resolving the misunderstandings and controversy that has been evident in this field in recent years.


ABSTRACT: The paper deals with the influence of correlation length, of Gauss random field, and of yield strength of a hotrolled I-beam under bending on the ultimate load carrying capacity limit state. Load carrying capacity is an output random quantity depending on input random imperfections. Latin Hypercube Sampling Method is used for sampling simulation. Load carrying capacity is computed by the programme ANSYS using shell finite elements and nonlinear computation methods. The nonlinear FEM computation model takes into consideration the effect of lateral-torsional buckling on the ultimate limit state.


ABSTRACT: Metallic thin shell structures are used in different branches of industry, and the components of these structures such as dished ends show different modes of failure depending upon the geometrical and loading conditions. These are mainly gross plastic deformation under static load, loss of stability (buckling), fatigue crack initiation at highly stressed locations under cyclic loading (especially in the low cycle regime), progressive plastic deformation (ratcheting) and creep at high temperatures. In this paper, failure modes of a conical pressure vessel subjected to internal pressure has been investigated. Also, to study the effect of vessel geometry, a set of conical cylindrical vessels with the cap-cone apex half angles of 20 to 85 degrees, internal radius of 500 to 1000 mm and thickness of 1 to 10 mm has been selected. The failure modes of these vessels which include gross plastic deformation and bifurcation buckling have been taken into account. In this work, a new plastic criterion has been established which is based on the plastic work dissipation in the vessel by increasing the internal pressure. This plastic criterion can be used for structures subjected to single or a combination of loading condition. The calculated plastic limit loads, which have been obtained using the plastic criterion, are determined purely by the inelastic response of the vessel, and they are not altered by initial elastic behavior. In addition, a design graph for designing pressure vessels with conical heads subjected to internal pressure has been presented via comprehensive parametric study. The results show that when the ratio of the internal pressure to the limit pressure (Load Factor) approaches 0.5, the material yielding initiates and with further increase in the Load Factor, the plastic regions develop. Also, by increasing the ratio of cylinder radius to wall thickness (R/t), plastic buckling failure becomes more dominant.

References listed at the end of the paper:
ABSTRACT: When computational modeling is used to evaluate the true strength of an imperfect elastic-plastic shell structure, the current European standard on shell structures requires that two reference strengths are always determined: the linear bifurcation load and the plastic limit (plastic collapse) load. These two loads are used in more than one way to characterize the strength of all imperfect elastic-plastic systems. Where parametric studies of a problem are being undertaken, it is particularly important that these two loads are accurately defined, since all other strengths will be related to them. For complex problems in shell structures, it is not possible to develop analytical solutions for the plastic collapse strength, and finite element analysis must be used. Unfortunately, because a collapse mechanism often requires the development of very extensive plasticity involving large local strains, and the collapse load is simply at the end of a slowly rising load-deflection curve, it is sometimes difficult for the analyst to accurately determine this plastic collapse strength. This paper describes two methods, based on modifications of the Southwell plot, of obtaining very accurate evaluations of the plastic limit load, irrespective of whether a fairly complete plastic strain field has developed or not. These two methods allow plastic collapse limit loads to be reported with great precision.
ABSTRACT: This paper studies the dynamic buckling behavior of multi-walled carbon nanotubes (MWNTs) subjected to step axial loading. A buckling condition is derived, and numerical results are presented for MWNTs under fixed boundary conditions. It is shown that the critical buckling load of MWNTs is of multi-branches and decreases as the time elongates. The associated buckling modes for different layers of MWNTs can be either in-phase or out of phase, which is related to the branch that the critical buckling load belongs to. For MWNTs with the same innermost tube radius, the critical buckling load is decreased when increasing the layers.

ABSTRACT: Buckling is often the main design consideration for thin cylindrical shells. For most load cases, the stability behavior of the shell is acutely sensitive to circumferential weld-induced imperfections, and the corresponding residual stresses are some beneficial to buckling strength of the shell generally. However, these conclusions are all based on the cylinders with constant wall thickness, and the studies about the effect of residual stresses on buckling strength of tapered cylindrical shells under partial axial compression are few. This paper applies trapezoidal strain field approach to simulate circumferential weld-induced imperfections on tapered cylindrical shells, and studies the stability behavior of the cylinders with single circumferential weld and multiple circumferential welds under partial axial compression respectively. By comparing the results derived from the models with/without circumferential welds and corresponding residual stresses, the effects of weld depressions and residual stresses on tapered cylindrical shells under partial axial compression are obtained.

References listed at the end of the paper:

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ABSTRACT: The effect of random system properties on thermal post-buckling temperature of laminated composite cylindrical shell panel with temperature independent (TID) and dependent (TD) material properties subjected to uniform temperature distribution is examined in this study. System properties such as material properties, thermal expansion coefficients and lamina plate thickness are modeled as independent basic random variables. The basic formulation is based on higher-order shear deformation (HSĐT) theory with von-Karman nonlinearity using modified C0 continuity. A direct iterative-based C0 nonlinear finite element method (FEM) combined with Taylor series-based mean-centered first-order perturbation technique (FOPT) developed by the authors for composite plate is extended for shell panel with reasonable accuracy to compute second-order statistics of post-buckling temperature of cylindrical shell panel. Typical numerical results for second order statistics (mean and coefficient of variance) of thermal post-buckling temperature of laminated cylindrical shell panel are obtained through numerical examples for various support conditions, amplitude ratios, shell thickness ratios, aspect ratios, lamination lay-up sequences, curvature to length ratios, types of material properties with the effect of random system parameters. The performance of outlined approach has been validated with those results available in the literatures and independent MCS.

Ivana Mekjavic (Faculty of Civil Engineering, University of Zagreb, Zagreb 10000, Croatia), “Static and Buckling Analysis of Concrete Spherical Shells”, Journal of Civil Engineering and Architecture, Vol. 6, No. 7, pp. 899-905, July 2012 (See also: Tehnicki vjesnik, Vol. 18, No. 4, pp 633-639, 2011, from which come the images in the gallery Shell Buckling Images: “Art and Architecture”.)

ABSTRACT: A finite element analysis, including static and buckling analysis is presented for several notable concrete spherical shells around the world. Also, the structural optimization study of these shells was performed for thickness distribution and structure shape to reduce overall tensile stress, deflection and reinforcements. The finite element analysis using Sofistik software shows that a distributed concrete thickness reduces shell stresses, deflections and reinforcements. A geometrically non-linear analysis of these structures with and without imperfections was also performed. To take into account the possible plastification of the material an analysis with non-linear material was performed simultaneously with the geometrically non-linear analysis. This helps in developing an understanding of the structural behaviour and helps to identify all potential failure causes using failure analysis.

References listed at the end of the paper:

Z.S. Liu (1), S. Swaddiwudhipong (2), F.S. Cui (1), W, Hong (3), Z.Suo (4) and Y.W. Zhang (1)
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ABSTRACT: One of the unique properties of polymeric gel is that the volume and shape of gel can dramatically change even at mild variation of external stimuli. Though a variety of instability patterns of slender and thin film gel structures due to swelling have been observed in various experimental studies, many are not well understood. This paper presents the analytical solutions of swelling-induced instability of various slender and thin film gel structures. We have adopted the well developed constitutive relation of inhomogeneous field theory of a polymeric network in equilibrium with a solvent and mechanical load or constraint with the incremental modulus concept for slender beam and thin film gel structures. The formulas of buckling and wrinkle conditions and critical stress values are derived for slender beam and thin film gel structures under swelling-induced instability using nonlinear buckling theories of beam and thin film structures. For slender beam structure, we construct the stability diagram with the distinct stable and unstable zones. The critical slenderness ratio and corresponding critical stresses are provided for different dimensionless material parameters. For thin film gel structures, we consider the thin film gel on an elastic foundation with different stiffness. The analytical solutions of critical stress and corresponding wrinkle wavelength, as well as buckling condition (or critical chemical potential) are given. These analytical solutions will provide a guideline for gel structure design used in polymeric gels MEMS and NEMS structures such as sensors and actuators. More importantly, the work provides a theoretical foundation of gel structure buckling and wrinkle, instability phenomena are different from normal engineering or material buckling.

References listed at the end of the paper:


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ABSTRACT: Functionally gradient materials (FGMs) have attracted much attention as advanced structural
materials because of their heat-resistance properties. In this paper, a study on the vibration of cylindrical shells
made of a functionally gradient material (FGM) composed of stainless steel and nickel is presented. The
objective is to study the natural frequencies, the influence of constituent volume fractions and the effects of
configurations of the constituent materials on the frequencies. The properties are graded in the thickness
direction according to a volume fraction power-law distribution. The results show that the frequency
characteristics are similar to that observed for homogeneous isotropic cylindrical shells and the frequencies are
affected by the constituent volume fractions and the configurations of the constituent materials. The analysis is
carried out with strains–displacement relations from Love’s shell theory and the eigenvalue governing equation
is obtained using Rayleigh–Ritz method. The present analysis is validated by comparing results with those in
the literature.

T. Y. Ng, H. Li, K. Y. Lam and C. T. Loy, “Parametric Instability of Conical Shells by the Generalized
ABSTRACT: The parametric instability of truncated conical shells of uniform thickness under periodic edge
loading is examined. The material considered is homogeneous and isotropic. This is the first instance that the
Generalized Differential Quadrature (GDQ) method is used to study the effects of boundary conditions on the
parametric instability in shells. The formulation is based on the dynamic version of Love's first approximation
for thin shells. A formulation is presented which incorporates the GDQ method in the assumed-mode method to
reduce the partial differential equations of motion to a system of coupled Mathieu–Hill equations. The principal
instability regions are then determined by Bolotin's method. Assumptions made in this study are the neglect of
transverse shear deformation, rotary inertia as well as bending deformations before instability.

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“Vibration characteristics of functionally graded cylindrical shells under various boundary conditions”, Applied
ABSTRACT: In the recent years, functionally gradient materials (FGMs) have gained considerable attention in
the high temperature environment applications. In the present work, study of the vibration of a functionally
graded cylindrical shell made up of stainless steel and zirconia is presented. Material properties are graded in
the thickness direction of the shell according to volume fraction power law distribution. Effects of boundary
conditions and volume fractions (power law exponent) on the natural frequencies of the FG cylindrical shell are
studied. Frequency characteristics of the FG shell are found to be similar to those of isotropic cylindrical shells.
Further, natural frequencies of these shells are observed to be dependent on the constituent volume fractions and
boundary conditions. Strain displacement relations from Love's shell theory are employed. Rayleigh method is
used to derive the governing equations. Further, analytical results are validated with those reported in the literature.


ABSTRACT: This paper presents the nonlinear formulation for Functionally Graded Material (FGM) plates and shells using Semilooof Shell element. Results for buckling and vibration analysis of functionally graded plates and shells are reported.

PARTIAL INTRODUCTION: Functionally graded materials (FGM) are heterogeneous composite materials usually made from a mixture of metals and ceramics. The material properties of FGM are graded but continuous and are controlled by the variation of the volume fraction of the constituent materials. The concept of FGM was first proposed by Koizumi [1]. Functionally graded materials have the advantage of their ability to withstand high temperature gradients unlike fiber matrix composites, which show mismatch of mechanical properties across an interface of two discrete materials bonded together and resulting in de-bonding at high temperatures in some cases. In FGM, the ceramic material provides high temperature resistance due to its low thermal conductivity while the ductile metal component provides structural strength and fracture toughness. Functionally graded materials are now being strongly considered as a potential structural material for future high-speed spacecraft. They are widely applied where the operating conditions are severe, for example, wear resistant linings for handling large heavy abrasive exchanger tubes, thermo elastic generators, heat engine components etc.

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ABSTRACT: This review focuses mainly on the developments of element-free or meshless methods and their applications in the analysis of composite structures. This review is organized as follows: a brief introduction to shear deformation plate and shell theories for composite structures, covering the first-order and higher-order theories, is given in Section 2. A review of meshless methods is provided in Section 3, with main emphasis on the element-free Galerkin method and reproducing kernel particle method. The applications of meshless methods in the analysis of composite structures are discussed in Section 4, including static and dynamic analysis, free vibration, buckling, and non-linear analysis. Finally, the problems and difficulties in meshless methods and possible future research directions are addressed in Section 5.


ABSTRACT: In this study, the static response is presented for a simply supported functionally graded rectangular plate subjected to a transverse uniform load. The generalized shear deformation theory obtained by
the author in other recent papers is used. This theory is simplified by enforcing traction-free boundary conditions at the plate faces. No transversal shear correction factors are needed because a correct representation of the transversal shearing strain is given. Material properties of the plate are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The equilibrium equations of a functionally graded plate are given based on a generalized shear deformation plate theory. The numerical illustrations concern bending response of functionally graded rectangular plates with two constituent materials. The influences played by transversal shear deformation, plate aspect ratio, side-to-thickness ratio, and volume fraction distributions are studied. The results are verified with the known results in the literature.

References listed at the end of the paper:
[23] A.M. Zenkour, Thermal effects on the bending response of fiber-reinforced viscoelastic composite plates using a sinusoidal shear


ABSTRACT: New results of buckling and postbuckling analysis are presented for a shear deformable anisotropic laminated cylindrical shell of finite length subjected to torsion. The governing equations are based on a higher order shear deformation shell theory with von Kármán-Donnell-type of kinematic nonlinearity and including the extension/twist, extension/flexural and flexural/twist couplings. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The postbuckling equilibrium path is unstable for a moderately thick laminated cylindrical shell under torsion and the shell structure is virtually imperfection-sensitive.

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(4) School of Mechanical and Instrumental Engineering, Xi’an University of Technology, Xi’an, 710048 Shaanxi, China, “Molecular dynamics study on buckling of single-wall carbon nanotube-based intramolecular junctions and influence factors”, Computational Materials Science, Vol. 67, pp. 390-396, February 2013 DOI: 10.1016/j.commatsci.2012.09.034

ABSTRACT: Carbon nanotube-based intramolecular junctions can function as rectifying diodes and switches in circuits and thus possesses the promising potential to be applied in nano-scale electronic devices. Due to their slender and unsymmetrical geometry, intramolecular junctions are prone to buckling under compression and the resulting structural instability will eventually leads to structural or electrical failure. Thus, it is important to explore the mechanical behaviors of intramolecular junctions subject to compressive loads. In this study, molecular dynamical simulations are carried out to investigate the compressive behaviors of intramolecular junctions at finite temperature, while carbon nanotubes are also studied as reference. The simulation results indicate that the strain rate effect is negligible within relatively low loading-rate range but the critical strain increases significantly under higher loading rate. At an extremely high strain rate, the intramolecular junctions will crush immediately. It is also predicted that local deformation will be introduced at high environmental temperature. Moreover, with increasing tube length, the instability mode of the intramolecular junctions transfers from shell buckling to column buckling and the critical aspect ratio is lower than that of carbon nanotubes due to presence of the Stone–Wales defects.

F. A. Fazzolari and J. R. Banerjee (School of Engineering and Mathematical Sciences, City University of London), “Advances in the dynamic stiffness method for exact buckling analysis of aircraft panels”, DiPaRT
Xinsheng Xu (1), Jianging Ma (1), C. W. Lim (2) and Ge Zhang (1)
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ABSTRACT: In this paper the local buckling of cylindrical shell under torsion is discussed. The Hamiltonian system approach is employed to analyze the propagation of shear wave. In this system, critical torsional loads and buckling modes are reduced to a problem of eigenvalues and eigensolutions of increasing orders. Buckling modes are divided into two types, the local torsional buckling modes and the helical buckling modes. For short-time shear wave propagation, local torsional buckling occurs easily. On the contrary, the helical buckling modes appear when the wave propagates for a longer time and these modes correspond to the first-order eigensolution.

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ABSTRACT: In this paper, the dynamic buckling of an elastic cylindrical shell subjected to an axial impact load is analyzed in Hamiltonian system. By employing a symplectic method, the traditional governing equations are transformed into Hamiltonian canonical equations in dual variables. In this system, the critical load and
buckling mode are reduced to solving symplectic eigenvalues and eigensolutions respectively. The result shows that the critical load relates with boundary conditions, thickness of the shell and radial inertia force. And the corresponding buckling modes present some local shapes. Besides, the process of dynamic buckling is related to the stress wave, the critical load and buckling mode depend upon the impacted time. This paper gives analytically and numerically some new rules of the buckling problem, which is useful for designing shell structures.

ABSTRACT: By considering the effect of stress waves in a Hamiltonian system, this paper treats dynamic buckling of an elastic cylindrical shell which is subjected to an impact torsional load. A symplectic analytical approach is employed to convert the fundamental equations to the Hamiltonian canonical equations in dual variables. In a symplectic space, the critical torsion and buckling mode are reduced to solving the symplectic eigenvalue and eigensolution, respectively. The primary influence factors, such as the impact time, boundary conditions and thickness, are discussed in detail through some numerical examples. It is found that boundary conditions have limited influence except free boundary condition in the context of the scope in this paper. The localization of dynamic buckling patterns can be observed at the free end of the shell. The new analytical and numerical results serve as guidelines for safer designs of shell structures.

Jiabin Sun, Xinsheng Xu, C.W. Lim and Weiyu Qiao, “Accurate buckling analysis for shear deformable FGM cylindrical shells under axial compression and thermal loads”, Composite Structures, 05/2015; 123.
DOI: 10.1016/j.compstruct.2014.12.030
ABSTRACT: Based on the Reddy’s high-order shear deformation theory, buckling behaviors of the FGM cylindrical shells subjected to an axial compression in thermal environment are investigated analytically. Considering the temperature-dependent FGMs properties, the constituent distribution across the shell thickness is assumed to follow the volume fraction rule of mixture. Through the variational principle, basic equations are derived for shear deformable FGM cylindrical shell with the initial geometric imperfection. Method of separation of variables and Galerkin’s solving process are employed in dealing with the stability governing equations of perfect and imperfect shells, respectively. By changing the boundary conditions, material types, composition distributions, thermal load and temperature fields, the effect of the transverse shear deformation is evaluated by comparing with the results of the classical Donnell’s theory. Meanwhile, imperfection sensitivity for buckling of the shear deformable FGM cylindrical shell is discussed in detail.

ABSTRACT: Buried pipelines may be deformed due to earthquakes and also corrode despite corrosion control measures such as protective coatings and cathodic protection. In such cases, it is necessary to ensure the integrity of the corroded pipelines against earthquakes. This study developed a method to evaluate the earthquake resistance of corroded pipelines subjected to seismic ground motions. Axial cyclic loading experiments were carried out on line pipes subjected to seismic motion to clarify the cyclic deformation
behavior until buckling occurs. The test pipes were machined so that each one would have a different degree of local metal loss. As the cyclic loading progressed, displacement shifted to the compression side due to the formation of a bulge. The pipe buckled after several cycles. To evaluate the earthquake resistance of different pipelines, with varying degrees of local metal loss, a finite-element analysis method was developed that simulates the cyclic deformation behavior. A combination of kinematic and isotropic hardening components was used to model the material properties. These components were obtained from small specimen tests that consisted of a monotonic tensile test and a low cycle fatigue test under a specific strain amplitude. This method enabled the successful prediction of the cyclic deformation behavior, including the number of cycles required for the buckling of pipes with varying degrees of metal loss. In addition, the effect of each dimension (depth, longitudinal length and circumferential width) of local metal loss on the cyclic buckling was studied. Furthermore, the kinematic hardening component was investigated for the different materials by the low cycle fatigue tests. The kinematic hardening components could be regarded as the same for all the materials when using this component as the material property for the finite-element analyses simulating the cyclic deformation behavior. This indicates that the cyclic deformation behavior of various line pipes can be evaluated only based on their respective tensile properties and common kinematic hardening component.

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ABSTRACT: A growing tumor is subjected to intrinsic physical forces, arising from the cellular turnover in a spatially constrained environment. This work demonstrates that such residual solid stresses can provoke a buckling instability in heterogeneous tumor spheroids. The growth rate ratio between the outer shell of proliferative cells and the inner necrotic core is the control parameter of this instability. The buckled morphology is found to depend both on the elastic and the geometric properties of the tumor components, suggesting a key role of residual stresses for promoting tumor invasiveness.

ABSTRACT: We study the peculiar wrinkling pattern of an elastic plate stamped into a spherical mold. We show that the wavelength of the wrinkles decreases with their amplitude, but reaches a minimum when the amplitude is of the order of the thickness of the plate. The force required for compressing the wrinkled plate presents a maximum independent of the thickness. A model is derived and verified experimentally for a simple one-dimensional case. This model is extended to the initial situation through an effective Young modulus representing the mechanical behavior of the wrinkled state. The theoretical predictions are shown to be in good agreement with the experiments. This approach provides a complement to the "tension field theory" developed for wrinkles with unconstrained amplitude.

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ABSTRACT: A method to evaluate the structural safety of lateral buckling load is presented, using FEM analysis for a wind turbine tower with a thin circular wall. Europe, the U.S. and Japan already have long histories of research into wind power due to its high efficiency. The tower structure that supports a wind turbine is one important research area. There are three types of tower that vary by structural composition: a cylindrical tower with a circular cross-section, a jacket tower with a truss structure, and a hybrid tower. This paper investigates an accident involving a 600KW wind turbine that occurred in JeJu, Korea in October of 2010. The results from a numerical analysis are compared with the actual collapse mode observed at the accident. Some buckling modes and wind speeds at which non-linear buckling response occurs are predicted via the arc-length method for a land-based cylindrical stationary tower. The evaluation method is used accident (experiment), analytical, linear and nonlinear finite element method (beam and shell) to analyze the result of predicted buckling load of tower. The result of nonlinear FEM shell model was found to exhibit similar behavior to the accident situation during buckling. It is concluded that this paper provides buckling analysis process and method used for the slender shell structures: agreement with those of the analytical calculation, indicating that the arc-length method effectively improved the convergence. We found out buckling limit load of the accident wind turbine tower and wind speed at buckling point. The result of nonlinear FEM shell model was found to exhibit similar behavior of the actual accident (experiment) situation during buckling. The presented buckling evaluation method will be useful for both static design and dynamic performance evaluation of land-based wind turbines, as well as sea-based wind turbines.

ABSTRACT: The behavior of composite cracked pipes under the effect of buckling is explored by performing a linear buckling analysis using the finite element method. The pipe is pressed under compression in the presence of cracks longitudinal, radial, and inclined relative to the horizontal. The results indicate that increasing the radius of the pipe conduit to the reduction of buckling parameter and the maximum values are obtained for the lowest fiber orientations. The maximum stresses are obtained for the radius of 400 mm. Moreover, the increase in the number of plies in composite pipe leads to the increase of the parameter buckling. The size of the crack, its orientation and position in the pipe are identified.

ABSTRACT: Product: Abaqus/Standard
This example serves as a guide to performing a postbuckling analysis using Abaqus for an imperfection-sensitive structure. A structure is imperfection sensitive if small changes in an imperfection change the buckling load significantly. Qualitatively, this behavior is characteristic of structures with closely spaced eigenvalues. For such structures the first eigenmode may not characterize the deformation that leads to the lowest buckling load. A cylindrical shell is chosen as an example of an imperfection-sensitive structure.
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“Inelastic Buckling Simulation of Steel Braces through Explicit Dynamic Analyses”, American Institute of
And Applied Mathematics ICNAAM 2011, 19–25 September 2011, Halkidiki, Greece

ABSTRACT: This paper presents a veritable finite element approach for simulating the inelastic buckling
response of steel braces. A number of techniques are considered to identify computationally efficient modeling
approaches that yield consistent results with experimental data. Ultimately, brace members and gusset plates are
represented with deformable and rigid shell elements, respectively; and the overall method is based on dynamic
analyses with explicit time integration. There is inherent damping in the proposed model due to inelasticity;
additional viscous damping and mass scaling factors are used to extract-simulate the system’s quasi-static
responses. Static sensitivity analyses are conducted to optimize mesh sizes and the most suitable imperfection
shapes and amplitudes for the brace elements. Additional (dynamic) sensitivity analyses are employed to
calibrate the imperfection, loading amplitude, time period, artificial viscous damping and mass scaling factors.
Results indicate that the proposed techniques can accurately mimic experimentally observed quasi-static
responses.

Hart-Smith, LJ. A revolutionary approach to the analysis of buckling of thin cylindrical shells [online]. In:
AIAC14: Fourteenth Australian Aeronautical Conference. Melbourne: Royal Aeronautical Society, Australian
Division; Engineers Australia, 2011: 306-339. Availability:

ABSTRACT: New analytical analyses are presented here of the buckling of circular cylindrical thin shells
under a variety of applied loads: (1) cylinders acted on by uniform radial external pressure, (2) longitudinal
compression of unpressurized cylinders, (3) longitudinal compression of pressurized cylinders, including the
special case (4) of ring buckling, as distinct from diamond buckling, of highly pressurized cylinders under
longitudinal compression. The solutions cover both very long and very short cylinders with a transitional
solution in between. The solutions start with the equivalent solutions for the buckling of flat plates, which are
then generalized to the equivalent cylinders. This starting point is correct, beyond questioning. The new
analyses expose many errors in the classical solution to this problem, both quantitative and qualitative. The new
and old solutions are compared thoroughly. The major change with respect to past analyses, however, is the
recognition that, in most cases, buckling occurs in the absence of induced membrane stresses, leaving the shells
with no ability to resist deformation other than by the weaker bending stresses. This work is a summary of a set
of new detailed analyses for the buckling of circular cylindrical thin shells, starting from a corrected thin-shell
theory, and showing that the same new results can be derived from shell theory was well as plate theory now
that the correct answers have been established.

L.J. Hart-Smith (retired from the Boeing Company), “Incontrovertible proof that the ‘discrepancies’ in thin-
shell-buckling studies are in the classical theory, not the test data”, Journal of Materials: Design and
ABSTRACT: It is shown here that the classical shell-buckling analyses have been fatally flawed since they
were first derived. One reason cited is a failure to freeze the buckling stresses at the values at which buckling
commenced, which resulted in consistent over estimates of the true buckling stresses by large factors. Another is the misinterpretation of the inextensibility criterion, which is customarily expressed in terms of the linear equations pertaining prior to buckling instead of the nonlinear equations that govern once buckling has commenced. The consequence of not acknowledging these errors is that, for many decades, it has been assumed incorrectly that the classical analyses for the various shell geometries are valid and that the major discrepancies can all be attributed to imperfections in the testing. It is shown here that this is not the case, by deriving different governing equations for shell buckling, starting from the geometrically nonlinear equilibrium equations for thin shells. These equilibrium equations are shown to include both the linear terms governing prior to buckling, with the remaining terms pertaining during buckling. This shows that buckling is resisted entirely by bending stresses alone, just as is known to be the case for flat-plate buckling, instead of by the combination of membrane and bending stresses. Specific equations are included for cylindrical shells, along with test data showing that the correct buckling stress for longitudinally compressed unpressurized cylinders is only half the classical prediction. Future papers will include full analyses of the buckling of spherical shells under external pressure at half the classical prediction, and of cylindrical shells under external pressure at one third of the classical prediction, as well as the buckling of pressurized and unpressurized cylindrical shells under longitudinal compression showing how, as the internal pressure is increased, the diamond-buckling stress increases from half the classical prediction for zero pressure to the classical ring-buckling stress for high pressure.


ABSTRACT: The effect of bending buckling of carbon nanotubes (CNTs) on thermal conductivity of CNT materials is investigated in atomistic and mesoscopic simulations. Nonequilibrium molecular dynamics simulations of the thermal conductance through an individual buckling kink in a (10,10) single-walled CNT reveal a strong dependence (close to inverse proportionality) of the thermal conductance of the buckling kink on the buckling angle. The value of the buckling kink conductance divided by the cross-sectional area of the CNT ranges from 40 to 10 Gwm^-2 K^-1 as the buckling angle changes from 20 to 110 degrees. The predictions of the atomistic simulations are used for parameterization of a mesoscopic model that enables calculations of thermal conductivity of films composed of thousands of CNTs arranged into continuous networks of bundles. The results of mesoscopic simulations demonstrate that the conductivity of CNT films is sensitive to the angular dependence of the buckling kink conductance and the length of the individual CNTs. For a film composed of 1 lm-long CNTs, the values of the in-plane film conductivity predicted with a constant conductance of 20 Gwm^-2 K^-1 and the angular-dependent conductance obtained in atomistic simulations are about 40 and 20% lower than the conductivity predicted for the same film with zero thermal resistance of the buckling kinks, respectively. The weaker impact of the angular-dependent buckling kink conductance on the effective conductivity of the film is explained by the presence of a large fraction of kinks that have small buckling angles and correspondingly large values of conductance. The results of the simulations suggest that the finite conductance of the buckling kinks has a moderate, but non-negligible, effect on thermal conductivity of materials composed of short CNTs with length up to 1 lm. The contribution of the buckling kink thermal resistance becomes stronger for materials composed of longer CNTs and/or characterized by higher density of buckling kinks.

Yu-Gang Sun, Xiao-Hu Yao, Ying-Jing Liang and Qiang Han (Department of Engineering Mechanics, School
of Civil Engineering and Transportation, South China University of Technology - Guangzhou, 510640, PRC),
“Nonlocal beam model for axial buckling of carbon nanotubes with surface effect”, Europhysics Letters (EPL),
ABSTRACT: Small-size effect and surface effect are two of the most specific intrinsic properties of
nanostructures, both of which are of great significance to the related applications. In this letter, the nonlocal
Euler-Bernoulli beam model, together with surface elasticity and surface tension are implemented to investigate
the buckling behavior of axially compressed carbon nanotubes. Explicit expression of solutions to the critical
buckling loads corresponding to typical boundary conditions is presented. Through contrast to molecular
dynamics results, it is vitally important to note that both small-size effect and surface effect have a profound
consequence and should be taken into account thoroughly.

Qishan Wang, “Active Vibration and Buckling Control of Piezoelectric Smart Structures”, Ph.D dissertation,
Civil Engineering and Applied Mechanics, McGill University, Montreal, Quebec, Canada, 2012
ABSTRACT: The objective of this dissertation is the vibration and buckling control of piezo-laminated
composite structures with surface bonded or embedded piezo-electric sensors and actuators by using the finite
element analysis and LQR/LQG feedback control techniques.
The focus is mainly on two aspects: the finite element part and the active control part.
(1) The finite element part:
Two finite element formulations for the piezo-laminated beams based on the classical Bernoulli-Euler and the
Timoshenko beam theories are developed using the coupled linear piezoelectric constitutive equations, and the
Hamilton variational principle.
A C0 continuous, shear flexible, eight-node serendipity doubly curved shell element for the piezolaminated
composite plates and shells is also developed based on the layer-wise shear deformation theory, linear
piezoelectric coupled constitutive relations, and Hamilton variational principle.
The developed elements can handle the transverse shear strains, composite materials, and piezoelectric-
mechanical coupling. Higher modes of vibration can then be predicted more precisely for thin to medium-thick
multilayered composite structures. They are evaluated both for the vibration and buckling of beam, plate, and
shell structures.
(2) The active control part:
The suppression of vibration of a cantilever piezo-laminated beam and the control of the first two buckling
modes of a simply supported piezo-laminated beam are studied first. Then, the vibration and buckling control of
a cantilever piezo-laminated composite plate are studied. Furthermore, the vibration control of a piezolaminated
semicircular cylindrical shell is also studied.
The results of the finite element analysis are used to design a linear quadratic regulator (LQR) controller and a
linear quadratic Gaussian (LQG) compensator with a dynamic state observer to achieve all the controls. The
control design begins with an approximate reduced modal model which can represent the system dynamics with
the least system modes. A state space modal model of the smart structure which integrates the host structure
with bonded piezoelectric sensors and actuators, is then used to design the control system. The designed
LQR/LQG feedback controls are shown to be successful in suppressing the vibration and stabilizing the
buckling modes of structures.
Both the finite element analysis and the active control simulation results are consistent with the existing
theoretical analysis results and the experimental data in the literature. Some important conclusions and
interesting observations are obtained.
References listed at the end of the dissertation:


Eoin Dunphy, “Study and comparison of shell design codes for adaptation to design geometrically complex...

ABSTRACT: The Eurocode and American Bureau of Shipping code analytical methods of determining the buckling resistance of 6 axially loaded steel shell cylinders was studied. The Eurocode MNA/LBA and GMNIA numerical methods were also studied using finite element analysis and compared against the results of the analytical methods. Following these comparisons the intention was to give an overview of the different methods and their applicability. Further suggestions were then made on how these methods could be used in the future analyses of more geometrically complex steel shell structures.

It was found that the Eurocode significantly underestimates the buckling resistance of ring and stringer stiffened cylindrical shells when compared to the ABS code (34% to 54% lower). The MNA/LBA numerical method currently allows the determination of the buckling resistance of simple structures under load conditions not covered by the classical theory. The MNA/LBA method shows potential for greater usage in more geometrically complex analyses provided that the required buckling parameters for its use are pre-determined. If these parameters are available the MNA/LBA method would be a less time consuming design method than the more rigorous GMNIA method.

The GMNIA method is the most complex analysis and as it is purely computational the importance of correctly modelling the structure and its imperfections is paramount in the determination of a realistic buckling resistance. The pitfalls of these requirements is that the correct imperfection type is difficult and time consuming to determine and the introduction of these imperfections has implications on further modelling of the structure. However, the GMNIA method is adaptable to unique cases without precedent and there is potential for research based on its usage as opposed to through physical experimentation.

References listed at the end of the thesis:


Rotter, J. (2007). Recent advances in the practical design of shell structures, implemented in eurocode provisions, Proc. SEMC.


ABSTRACT: The paper describes a theoretical and an experimental investigation into the free vibration of three ring-stiffened circular cylinders subjected to various values of uniform external pressure. The experimental procedure involved a novel device, which was suitable for ferrous metals. The theoretical method involved the finite element method for both the structure and the fluid, where in the case of the latter, the wave equation was solved. The results showed that the resonant frequencies decreased with increasing values of external pressure, especially when the vibration eigenmode had the same shape as the static buckling mode.


ABSTRACT: The paper presents an experimental study on six circular corrugated cylinders which were tested to destruction under external hydrostatic pressure. The results obtained from these vessels, together with the results obtained from elsewhere, were used to provide a design chart. The design chart appears to be suitable for designing these vessels to guard against inelastic instability.

ABSTRACT: This paper presents a theoretical geometrical and material non-linear analyses of fifteen unstiffened conical shells, using the finite element computer program ANSYS, to calculate their buckling pressures. The cones buckle as a result of shell instability caused by the external hydrostatic pressure. Experimental tests were also carried to destruction of the fifteen vessels, under external hydrostatic pressure. The experimental results for the fifteen conical shells, were compared with multiple alternate theoretical methodologies, including ANSYS eigen-buckling, ANSYS nonlinear, together with other methodologies; which included PD5500 (BS5500), and the design charts produced by Ross. The ANSYS eigen-buckling results were poor; but the ANSYS nonlinear results were much more encouraging. PD5500 was too conservative, but Ross' design charts were the best and the easiest to use. Whereas most of the conical shells failed by plastic shell instability, some of the failures were initiated by axisymmetric deformation; prior to plastic shell instability taking place. The PD5500 code was hard to use and produced overly conservative results, which would lead to conservative pressure vessel designs, while the Ross design charts [1] produced good results, and were very easy to use and understand, and were not too conservative. The graphical displays from ANSYS were quite spectacular. From some of the ANSYS nonlinear analyses, it appeared that plastic axisymmetric yield initially took place at the larger ends of the cones; before triggering off plastic shell instability.

Reference:

Stipica Novoselac, Todor Ergic, Pavo Balicevic (Croatia) “Linear And Nonlinear Buckling And Post Buckling Analysis Of A Bar With The Influence Of Imperfections”, Tehnicki vjesnik 19, 3(2012), 695-701, ISSN 1330-3651 UDC/UDK 620.173.26:519.6

ABSTRACT: This paper presents a linear and nonlinear buckling and post buckling numerical analysis of a bar with the influence of imperfections. In the first step, we used an approach of analytic and numerical linear buckling analysis of a bar with linear-elastic material. After linear buckling analysis of the bar, we performed nonlinear buckling analysis with the Riks method. Since the nonlinear analysis was performed in the case of ideal loading, to get correct and more realistic information of post buckling response, imperfections and plastification of material must be considered. In this case, the imperfections are eccentric loads. This paper finally shows that the post buckling behaviour becomes unstable even for a very small value of eccentric load in nonlinear analysis with elasto-plastic behaviour of material. Numerical analysis was performed in software Abaqus 6.10.

References listed at the end of the paper:

ABSTRACT: We present a methodology to perform the identification and validation of complex uncertain dynamical systems using experimental data, for which uncertainties are taken into account by using the nonparametric probabilistic approach. Such a probabilistic model of uncertainties allows both model uncertainties and parameter uncertainties to be addressed by using only a small number of unknown identification parameters. Consequently, the optimization problem which has to be solved in order to identify the unknown identification parameters from experiments is feasible. Two formulations are proposed. The first one is the mean-square method for which a usual differentiable objective function and an unusual non-differentiable objective function are proposed. The second one is the maximum likelihood method coupling with a statistical reduction which leads us to a considerable improvement of the method. Three applications with experimental validations are presented in the area of structural vibrations and vibroacoustics.

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ABSTRACT: A methodology for analyzing the large static deformations of geometrically nonlinear structural systems in the presence of both system parameters uncertainties and model uncertainties is presented. It is carried out in the context of the identification of stochastic nonlinear reduced-order computational models using simulated experiments. This methodology requires the knowledge of a reference calculation issued from the mean nonlinear computational model in order to determine the POD basis (Proper Orthogonal Decomposition) used for the mean nonlinear reduced-order computational model. The construction of such mean reduced-order nonlinear computational model is explicitly carried out in the context of three-dimensional solid finite elements. It allows the stochastic nonlinear reduced-order computational model to be constructed in any general case with the nonparametric probabilistic approach. A numerical example is then presented for a curved beam in which the various steps are presented in details.

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ABSTRACT: The present work concerns the experimental identification of an uncertain nonlinear
computational model in the context of the post-buckling analysis of a cylindrical shell. It proposes an alternative approach to existing methodologies for which only system parameter uncertainties are modeled [5]. This methodology is adapted to the analysis of large static deformations of geometrically nonlinear structural systems in the presence of both system parameters uncertainties and model uncertainties. The available experimental data is made up of the nonlinear static deflection of a cylindrical shell. First, the deterministic nonlinear computational model is constructed using the finite element method and the corresponding nonlinear response is used as a reference deterministic solution for which a reduced-order basis is deduced using the POD (Proper Orthogonal Decomposition) analysis. The mean reduced-order nonlinear computational model is then explicitly constructed in the context of three-dimensional solid finite elements. Moreover, a positive-definite operator related to the nonlinear stiffness of the structure is defined, allowing the use of the nonparametric probabilistic methodology for constructing the uncertain nonlinear reduced-order computational model. Finally, the experimental identification of the uncertain nonlinear computational model is carried out in order to validate the proposed methodology.

References listed at the end of the paper:


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ABSTRACT: The construction of advanced numerical methodologies for the prediction of the dynamical behavior of complex uncertain structures represents an important current challenge. In the present work, structures undergoing large displacements and high strains are investigated. Of particular interest is the analysis of the post-buckling dynamics of a cylindrical shell submitted to an horizontal seismic excitation. The nominal (i.e. without uncertainties) computational model of the cylindrical shell is large, i.e. comprising about 4200000 degrees of freedom, obtained with the finite element method using three-dimensional solid elements. A nonlinear reduced-order modeling is first carried out. Then, model uncertainties (on geometry, material properties, etc.) are introduced using probabilistic methods and the corresponding stochastic reduced-order nonlinear computational model is obtained. The identification of its parameters is next carried out using nonlinear static post-buckling data. Finally, a numerical nonlinear dynamic analysis of the uncertain shell is performed in a seismic context, for which the base of the cylindrical shell is submitted to a prescribed rigid shear displacement, modeled through a centered non-stationary Gaussian second-order stochastic process. The stochastic displacement field is then calculated and the effects of uncertainties and of nonlinearities are analyzed in detail.

References listed at the end of the paper:
This paper presents the nonlinear dynamical post-buckling analysis of uncertain cylindrical shells. The proposed approach is adapted to the dynamical analysis of geometrically nonlinear structures subjected to a stochastic ground-based motion in the presence of both system parameter uncertainties and model imperfections.
uncertainties. The structure is modeled by a large finite element model using 3D elasticity theory. The ground-based motion is represented by a Gaussian centered non-stationary second-order stochastic process. Then, a reduced-order basis is constructed using the POD (Proper Orthogonal Decomposition) analysis of a nonlinear static reference response combined with selected linear eigenmodes of vibrations. The mean reduced-order nonlinear computational model is then explicitly constructed. A positive-definite operator involving the nonlinear stiffness of the structure is defined, allowing the nonparametric probabilistic approach to be used for constructing the uncertain non-linear reduced-order computational model. The dispersion parameter controlling the level of stiffness uncertainty is a scalar which has been previously identified experimentally in a nonlinear static context. Finally, the instantaneous spectral density power of the dynamical response is analyzed in order to quantify the influence of both geometrical nonlinearities and random uncertainties on the stochastic dynamical response.

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ABSTRACT: The paper presents a complete experimental validation of an advanced computational methodology adapted to the nonlinear post-buckling analysis of geometrically nonlinear structures in presence of uncertainty. A mean non-linear reduced-order computational model is first obtained using an adapted projection basis. The stochastic nonlinear computational model is then constructed as a function of a scalar dispersion parameter, which has to be identified with respect to the nonlinear static experimental response of a very thin cylindrical shell submitted to a static shear load. The identified stochastic computational model is finally used for predicting the nonlinear dynamical post-buckling behavior of the structure submitted to a stochastic ground motion.

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[10] W. Schneider, Y. Ribakov, Collapse analysis of thin walled cylindrical steel shell subjected to constant shear stress, Computers &
[38] H. Kanai, Semi-empirical formula for the seismic characteristics of the ground motion, Bulletin of the Earthquake Research Institute 35 (1957) 309–325.
[40] M. Crisfield, Non-linear finite element analysis of solids and structures, Vol. 1 : essentials, John Wiley and Sons, Chichester,

ABSTRACT: In this paper, the dynamic stability of shallow structures such as arches and curved panels under stochastically fluctuating loads is studied. Sufficient conditions guaranteeing the almost-sure stability in both symmetric modes and unsymmetric modes of deformation are obtained first by Infante's method. Necessary and sufficient conditions are determined by evaluating the largest Lyapunov exponent of the perturbed solution.

References listed at the end of the paper:
Masoud Nazaria, Mohammad Reza Khedmati and Amir Foad Khalaj (Dept. of Marine Technology, Amirkabir University of Technology, Tehran, Iran), “A numerical investigation into ultimate strength and buckling behavior of locally corroded steel tubular members”, Latin American Journal of Solids and Structures, Vol. 11, No. 6, November 2014

ABSTRACT: This paper presents the results of a numerical investigation into ultimate strength of locally corroded tubular members under axial compressive loads. A parametric finite element approach was used in order to simulate structural behavior of damaged members. The results were then examined against an available experimental test. Validated models were used to derive a semi-empirical formula for predicting ultimate strength of locally damaged tubes as a function of corrosion dimensions. Geometry of corrosion can be defined by its depth, length, width and location of damage along the tube. In this study it is focused on the effect of some parameters that have not been addressed yet by other researchers, e.g. slenderness of the tubes and location of patch corrosion. It was found that location of corrosion has great effect on reduction of ultimate strength. Effect of corrosion geometry was studied and formulated as well as tubular slenderness, and it was shown that tubes with different corrosion dimensions show different behaviors under compressive loads. In cases with severe corrosion damages, the occurrence of local buckling plays an important role on reduction of ultimate strength and deformation of damaged region.

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ABSTRACT: Corrosion makes structures more vulnerable to buckling and yielding failures. It is common practice to assume a uniform thickness reduction for general corrosion. To estimate the remaining strength of corroded structures, typically a much higher level of accuracy is required, since the actual corroded structures have irregular surfaces. Elastic buckling of simply supported rectangular corroded plates are studied with one- and both-sided irregular surfaces. Eigenvalue analysis by using finite element method (FEM) is employed for computing Euler stress. The influence of various geometric and corrosion characteristics are investigated and it is found that the aspect ratio of the plate, the average thickness diminution, the standard deviation of thickness diminution and the amount of corrosion loss have influence on the reduction of buckling strength of the corroded plates. Buckling strength of one- and both-sided corroded plates are the same. In plates with low value of aspect ratio, reduction of buckling strength is negligible. Reduction of buckling strength is more prominent in plates with higher aspect ratio. Reduction of buckling strength is very sensitive to the amount of corrosion loss: the higher the amount of corrosion loss, the more reduction of buckling strength. Reduction of buckling strength is less sensitive to the standard deviation of thickness diminution.

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Rahbar-Ranji A 2001 Stress analysis of a randomly undulated plate due to corrosion in marine structures. Ph.D. Thesis, Yokohama National University, Department of Naval Architecture, Japan
Rahbar-Ranji A and Zakeri A H 2010 Mechanical properties and corrosion resistance of normal strength and high strength steels in

ABSTRACT: Numerical simulation is used to study the influence of corrosion damage in stiffened plates focusing on elastic buckling strength. Three-dimensional specta are used to simulate geometries of corroded surfaces and finite element method is employed for computing Euler stress of stiffened plates. The influence of corrosion patterns, amount of corrosion loss and roughness of surface are investigated. Ratio of Euler stress of corroded stiffened plate over Euler stress of un-corroded stiffened plate is used to characterize the effects of corrosion on reduction of buckling strength. Results show that reduction of buckling strength is very sensitive to the amount of corrosion loss and roughness of surface, but less sensitive to the location of corroded region. The potential for decrease in buckling strength as a consequence of corrosion is found to depend on the dominant buckling mode. Residual buckling strength is reduced by as much as 12% for the interaction of plate-web-torsional buckling mode, and by 2% for column buckling.

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6. Oszvald K and Dunai L 2010 Effect of corrosion on the buckling of steel angle elements. 8th fib PhD Symposium in Kgs. Lyngby, Denmark
7. Rahbar-Ranji A 2001 Stress analysis of a randomly undulated plate due to corrosion in marine structures. Ph.D. Thesis, Yokohama National University, Department of Naval Architecture, Japan
15. SSC-394 1997 Strength assessment of pitted plate panels, ship structural committee

ABSTRACT: Stiffened plate buckles in different modes, including web/flange buckling, torsional buckling, plate buckling, and interactions of them. Generally, interactions of different buckling modes in stiffened plates are ignored and elastic buckling analysis of each mode is treated separately. In some design codes, to cope with interactions of different buckling modes, the influence of adjacent elements are considered as rotational springs. The main aim of this study is to compare literature- and rule-based expressions to assess the elastic buckling strength of T-bar stiffened plates and to identify the applicability of selected expressions for certain conditions. Different buckling modes and their interactions are investigated, and critical Euler stresses are evaluated. Upon comparison with given expressions and the finite element method, it is found that some of the proposed expressions are not applicable in certain conditions.

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ABSTRACT: This study investigated characteristics of bifurcation and critical buckling load by shape imperfection of space truss, which were sensitive to initial conditions. The critical point and buckling load were computed by the analysis of the eigenvalues and determinants of the tangential stiffness matrix. The two-free-nodes example and star dome were selected for the case study in order to examine the nodal buckling and global buckling by the sensitivity to the eigen buckling mode and the analyses of the influence and characteristics of the parameters as defined by the load ratio of the center node and surrounding node, as well as rise-span ratio were performed. The sensitivity to the imperfection of the initial shape of the two-free-nodes example, which occurs due to snapping at the critical point, resulted in bifurcation before the limit point due to the buckling mode, and the buckling load was reduced by the increase in the amount of imperfection. The two sensitive buckling patterns of the numerical model are established by investigating the displaced position of the free nodes, and the asymmetric eigenmode greatly influenced the behavior of the imperfection shape whether it was a limit point or bifurcation. Furthermore, the sensitive mode of the two-free-nodes example was similar to the inextensional basis mechanism of a simplified model. The star dome, which was used to examine the influence among several nodes, indicated that the influence of nodal buckling was greater than that of global buckling as the rise-span ration was higher. Besides, global buckling is occurred with reaching bifurcation point as the value of load ratio was higher, and the buckling load level was about 50% - 70% of the load level at limit point.


ABSTRACT: A finite strain formulation is developed for elastic circular arches and rings in which the effects of shear deformations are included. Timoshenko beam hypothesis is adopted for incorporating shear. Finite strains are defined in terms of the normal and shear component of the longitudinal stretch. The constitutive relations for stress and finite strain are based on a hyperelastic constitutive model. Virtual work and equilibrium
equations are derived. Closed-form in-plane buckling solutions are developed for circular rings and high arches under hydrostatic pressure. The effects of axial deformation prior to buckling as well as shear deformations are included in the buckling analysis. The formulation developed is compared with solutions in the literature and to the predictions of the finite element package ANSYS. The importance of including the effects of shear deformations for deep arches is investigated.

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ABSTRACT: Sandwich cylindrical shells are the major components of aerospace structures. In this paper, an analytical investigation was carried out to examine the response of carbon fiber reinforced composite (CFRC) sandwich cylinders with lattice cores. An equivalent monocoque shell theory, was developed in this paper to predict mechanical behaviors of the quasi-isotropic sandwich cylinder, including the deformation and the multi-mode failure criterion. Five failure modes were suggested for the sandwich cylinder, including global buckling, face sheet mono-cell buckling/dimpling, face sheet local buckling, lattice rib crippling and strength failure. Using the suggested criterion, failure mode maps of the sandwich cylinder were acquired to instruct the design of the hierarchical sandwich cylinder with five geometrical variables. The method also correctly predicted the failure modes of the tested sandwich cylinder within acceptable errors.

ABSTRACT: The concept behind sandwich construction and its application in naval and commercial fields is highlighted in this paper with special reference to underwater shell forms. This paper also examines the various shell finite elements generated by researchers for the analysis of sandwich shells. A comprehensive overview of finite elements available for analysis of sandwich structures in commercial software packages is presented. The accuracy of the axisymmetric finite element sandwich shell is evaluated by comparing the results with the numerical results available by analysing the shell using ANSYS. The results of reasonable accuracy have been realized at the cost of heavy computation using the software. The need for a sandwich shell finite element based on sandwich shell theory has been justified.  
References listed at the end of the paper:
ABSTRACT: In this paper, the buckling under an applied external pressure and the self-buckling of nanostructures, such as peapods, nanotubes and fullerenes, is numerically treated with Molecular Dynamics simulations and compared with theoretical calculations. The self-buckling is due to the interaction among the nanostructures caused by the surface energy; it is peculiar to the nanoscale and does not have a macroscopically analogous counterpart. Atomistic simulations confirm that the influence on a single nanostructure from the surrounding nanostructures in a crystal, is nearly identical to that of a liquid with surface tension equal to the surface energy of the solid.

References listed at the end of the paper:
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ABSTRACT: In this paper, we study the elastic buckling of a new class of honeycomb materials with hierarchical architecture, which is often observed in nature. Employing the toposedown approach, the virtual buckling stresses and corresponding strains for each cell wall at level $n = 1$ are calculated from those at level $n$; then, comparing these virtual buckling stresses of all cell walls, the real local buckling stress is deduced; also, the progressive failure of the hierarchical structure is studied. Finally, parametric analyses reveal influences of some key parameters on the local buckling stress and strength-to-density ratio; meanwhile the constitutive behaviors and energy-absorption properties, with increasing hierarchy $n$, are calculated. The results show the possibility to tailor the elastic buckling properties at each hierarchical level, and could thus have interesting applications, e.g., in the design of multiscale energy-absorption honeycomb light materials.

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Jingxuan, He; Mingfa, Ren; Qizhong, Huang; Shanshan, Shi; Haoran, Chen, “Buckling behavior of compression-loaded advanced grid stiffened composite cylindrical shells with reinforced cutouts”, Polymers and Polymer Composites, April 2011

PARTIAL INTRODUCTION: Advanced grid stiffened (AGS) composite cylindrical shells are widely used in the aerospace, marine, automobile and other engineering infrastructures. The necessary of cutouts in an AGS composite cylindrical shell surface is typically required to meet the practical application requirements that serve
as doors, windows, or access ports. However, the continuity of stress and deformation distribution in the AGS structures was interrupted by the cutouts. The stress concentration would occur in the cutout zone which leads to a decline in load capacity of the AGS structure. Generally, some types of reinforcing structures are applied to control local structural deformations and stresses around the cutouts. Thus the buckling and postbuckling response of the AGS structures with cutouts must be understood in order to determine the effective designs and safe operating conditions.

There are three investigative methods including analytical solution, experimental research and numerical simulation. However, for an AGS composite cylindrical shell with reinforced cutouts, it is of great difficulty using the analytical solution. And it appears less likely to obtain a series of design charts employing a large number of parameters of experimental research for a high cost, long cycle, in particular, the complex parameters of the cutouts. So the numerical simulation is a better approach to study the buckling behaviors of compression-loaded AGS composite cylindrical shells with reinforced cutouts.

It is found that a cutout in an isotropic shell structure can have a significant effect on the response of the shell in many studies. In particular, a cutout in a shell would cause a local response to occur near the cutout when the shell is subjected to compression loading. The local response can consist of large out-of-plane deformations and large magnitude rapidly varying stresses near the opening (1). And the opening can cause a local buckling response to occur on the structure at compressive load levels lower than the general instability load of the corresponding shell without a cutout (2).

Relatively a few studies have been presented on the buckling of curved panels. Kim and Noor (3,4) carried out the buckling and postbuckling responses of composite panels with central circular cutouts. Their results show the effects of variations in the cutout diameter; the aspect ratio of the panel; the laminate stacking sequence and the fiber orientation on the stability boundary, postbuckling response and sensitivity coefficients. Hilburger, Britt and Nemeth 5 performed the study of response of compression-loaded quasi-isotropic curved panels with a centrally located circular cutout using a geometrically nonlinear finite element analysis ...


ABSTRACT: This article focuses on the application of the Fourier-expansion based differential quadrature method (FDQM) for the buckling analysis of ring-stiffened composite laminated cylindrical shells. Displacements and rotations are expressed in terms of Fourier series expansions in longitudinal direction and their first order derivatives are approximated with FDQM in circumferential direction. The 'smeared stiffener' approach is adopted for the stiffeners modeling. Two FORTRAN programs prepared for linear and nonlinear analysis and results were compared by ABAQUS finite element software. Buckling loads of stiffened and unstiffened shells considering the effects of changes in shell and stiffener geometric and material properties and also shell lay-ups are investigated.

link.springer.com/chapter/10.1007%2F978-3-642-17961-7_12#page-1, Springer, (author, date, name of book not given on the online image available from Springer. Possible author: M. Shama; Possible date: 2013):

Chapter 12: Assessment of Buckling of Ship Structure

INTRODUCTION: This chapter presents a simplified procedure for the assessment of buckling of ship strength members. The main strength members of longitudinally and transversely stiffened bottom and deck structures sustaining compressive forces are identified. The compressive loadings are the compound in-plane stresses...
induced by the hull girder, secondary, and tertiary stresses. The assessment of buckling of strength members of bottom structure is carried out when the ship is in hogging condition and for strength members of deck structure when the ship is in sagging condition. For both cases, the compounding of stresses is carried out when the secondary and tertiary loadings are inducing compressive stresses. The assessment of buckling of web plates and face plates of deck and bottom girders is presented. The assessment of buckling of side shell plating for the various induced in-plane loading conditions is introduced. Assessment of buckling strength of plating for different end support conditions and for a variety of loading patterns is given. The importance of providing ship strength members sustaining compressive forces with adequate strength against buckling failure is stressed.


ABSTRACT: This paper investigates the stability analysis of a functionally graded (FG) plate integrated with a piezoelectric sensor and actuator at the top and bottom faces, subjected to electrical and mechanical loading. The material properties of the FG plates are assumed to be graded along the thickness direction according to simple power law distribution in terms of the volume fraction of the constituents, while the Poisson's ratio is assumed to be constant. The analysis is carried out on plates with different boundary conditions: for example, the plate is simply supported at all edges (SSSS) or the plate is simply supported along two opposite sides perpendicular to the direction of compression and clamped along the other two sides (CSCS). The finite element model is derived with the von Karman hypothesis and as a degenerate shell element using the FSDT. The displacement component of the present model is expanded in Taylor's series in terms of the thickness coordinate. The governing equilibrium equation is obtained using the minimum energy principle and the solution for critical buckling load is obtained by solving the eigenvalue problem. The stability analysis of the piezoelectric FG plate is carried out to present the effect of power law index, applied mechanical pressure and different boundary conditions.


ABSTRACT: In this article, a semi-analytical three-dimensional model based on the modified Hellinger–Reissner (H–R) variational principle and a nonlinear spring-layer model are presented for the buckling analysis of composite laminated cylindrical shells with a delamination. The method allows the effect of transverse shear deformation in the control equations of the composite laminated structures. In addition, it uses a two-dimensional mesh and can ensure that the number of variables is independent of the layer number. The nonlinear spring-layer model between the exterior and interior sub-laminates ensures the continuity of transverse stresses and displacements in the undelaminated region by specifying infinite values of springs and therefore avoids the possibility of material penetration phenomenon in the delaminated region. As an application of the present method, the influence of the delamination length on the critical buckling loads of delaminated composite laminated stiffened cylindrical shells is investigated.

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ABSTRACT: (None given)


ABSTRACT: I will present a series of experimental explorations on the rich mechanical behavior of thin elastic shells, subject to different forms of loading. First, I will discuss the geometry-induced rigidity of non-spherical pressurized shells under indentation, that can be used for non-destructive testing. I will proceed by characterizing the emergence and evolution of point and linear-like loci of localization on thin shells indented well into the nonlinear regime. I will then present a new mechanism that utilizes the compression of a thin-shell/soft-core system for switchable and tunable wrinkling on curved surfaces, that can be exploited for active aerodynamic drag control. Finally, I shall introduce the framework for buckling-induced folding (or “Buckligami”) that involves functional structural transformations of patterned shells that can be excited to achieve encapsulation, flexure and twist. The main common feature underlying these series of examples is the prominence of geometry in dictating the complex mechanical behavior of slender soft structures, thereby making our results relevant and applicable over a wide range of length scales. Moreover, our findings suggest that we rethink our relationship with mechanical instabilities which, rather than modes of failure, can be embraced as opportunities for functionality that are scalable, reversible, and robust.


ABSTRACT: The object of this study is a thin-walled beam made of carbon-epoxy composite with open cross-section. The material used was a composite of epoxy matrix reinforced with carbon fiber (system HexPly M12, Hexcel). The M12 system is used above all in aircraft structures. It exhibits high fatigue durability and good maintenance properties at relatively low specific gravity. The research was lead as the FEM numerical analyses and experimental tests in buckling and post-buckling state, as well. In the conducted research in order to evaluate the effort ratio of the composite the Tsai-Wu tensor criterion was exploited. The numerical tool used was the ABAQUS software.

References listed at the end of the paper:

1. Abaqus HTML Documentation.
2. Ansys HTML Documentation.


ABSTRACT: Vibration, linear elastic buckling and dynamic stability behaviors of a cracked cylindrical shell with time-varying rotating speed are analyzed. Finite element method is used to obtain the system mass and stiffness matrix, and Bolotin’s method is applied to explore the dynamic stability region. The effects of constant rotating speed, crack length and orientation, and length-diameter ratio of the cylindrical shell on the free-vibration and buckling behaviors are investigated. The stability characteristics of the cracked shell are also researched and the influences of crack length, crack orientation, rotating speed basic value, steady load factor, dynamic load factor and damping ratio are considered. Numerical examples show that crack length and orientation can affect the vibration, buckling and dynamic stability behavior of cylindrical shell significantly.


ABSTRACT: This article deals with the finite element modeling and analysis of functionally graded (FG) shell structures under different loading such as thermal and mechanical. Free vibration analysis of functionally...
graded (FG) spherical shell structure has also been presented. In order to study the influences of important parameters on the responses of FG shell structures, different types of shells have been considered. The responses obtained for FG shells are compared with the homogeneous shells of pure ceramic (AL2O3) and pure metal (steel) shells, and it has been observed that the responses of the FGM shells are in between the responses of the homogeneous shells. Based on the analysis, some important results are presented and discussed for thick as well as thin shells.

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ABSTRACT: The problem of buckling stability is very important in thin-walled cylindrical shell structure. In order to investigate the buckling phenomena, digital image correlation (DIC) method was applied in this experiment. The specimens have a thickness of 0.131mm and the ratio of external diameter (R0) to thickness (H) R0/H is 252. Due to its curved and thin walled elements, measurement of displacement and strains by using the traditional methods is difficult, because there is not enough space for sticking necessary torsion gauges to measure the out-of-plane behaviour, even if it is possible, the rigidity of the gauge itself will have an effect on the buckling strength. However, by using the optical image correlation method, the problem is solved. DIC method is an optical instrument which utilizes the full-field and non-contact measurement to gauge the three-dimensional displacement and strains on materials and structural parts. In this paper three dimensional digital image correlation system is applied to observe the buckling generation process in details and make a record of the surface displacement during the compression test by using two high resolution digital cameras, then the test data are analyzed and compared by a special correlation technique which can determine the surface displacements of cylindrical shells and it is shown in colour contour in full-field region. The buckling strengths obtained by the theoretical and experimental methods are compared and discussed in this paper. The experimental study shows that the buckling strength of theoretical value is much higher than that of experimental one, because the buckling strength is highly dependent on the imperfections.

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ABSTRACT: This paper deals with the elastic lateral-torsional buckling (LTB) strength of tapered I-girders with corrugated webs under two types of loading conditions: uniform moment and moment gradient with various end restraint conditions. A finite element (FE) program using beam elements is developed to study LTB behaviors. The results from this program are compared with those from the commercial software ABAQUS using shell elements. From the comparisons it is found that the developed FE program’s results agree well with the results from ABAQUS. For design purpose, the closed-form equations for the critical buckling moment of the tapered I-girder with corrugated webs under uniform moment and moment gradient with four types of end restraint conditions: simply supported, warping fixed, lateral bending fixed, and completely fixed are proposed based on the results from the developed FE program. From the numerical investigations the new design equations give reasonably accurate results. These equations increase efficiency in bridges and buildings design.

ABSTRACT: A systematically study on the new space structure steel - concrete composite ribbed shell is made, which is loaded by stepped load. The ultimate bearing capacity and failure modes are investigated based on the characteristic response indicators. In the foundation of large number of parameters analysis, the influence of the span ratio, span, boundary conditions and initial imperfection on the ultimate bearing capacity and instable dynamic failure are discussed in details. All the results will provide mass of data to the investigation of failure mechanism and the property under complex dynamical loads.

ABSTRACT: In the present paper the non-linear buckling analysis of functionally graded spherical shells subjected to external pressure is investigated. The material properties are graded in the thickness direction according to the power-law distribution in terms of volume fractions of the constituents of the material. In the formulation of governing equations geometric non-linearity in all strain-displacement relations of the shell is considered. Using Bubnov-Galerkin's method to solve the problem an approximated analytical expression of
non-linear buckling loads of functionally graded spherical shells is obtained, that allows easily to investigate stability behaviors of the shell.

References listed at the end of the paper:


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear buckling and post- buckling of thin annular spherical shells made of functionally graded materials (FGM) and subjected to mechanical load and resting on Winkler-Pasternak type elastic foundations. Material properties are graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Equilibrium and compatibility equations for annular spherical shells are derived by using the classical thin shell theory in terms of the shell deflection and the stress function. Approximate analytical solutions are assumed to simply supported boundary conditions and Galerkin method is applied to obtain closed-form of load-deflection paths. An analysis is carried out to show the effects of material and geometrical properties and combination of loads on the stability of the annular spherical shells.

References listed at the end of the paper:
ABSTRACT: In this article, stability of composite conical shells subjected to dynamic external pressure is investigated by numerical and experimental methods. In experimental tests, cross-ply glass woven fabrics were selected for manufacturing of specimens. Hand-layup method was employed for fabricating the glass-epoxy composite shells. A test-setup that includes pressure vessel and data acquisition system was designed. Also, numerical analyses are performed. In these analyses, effect of actual geometrical imperfections of experimental specimens on the numerical results is investigated. For introducing the imperfections to the numerical models,
linear eigen-value buckling analyses were employed. The buckling modes are multiplied by very small numbers that are derived from measurement of actual specimens. Finally, results are compared together while a good agreement between results of imperfect numerical analyses and experimental tests is observed.

Alessandro Serafini (Waseda University, Japan), authors, publisher and date (possibly 2009 not given in the pdf file), see [http://www.scribd.com/doc/207835140/Buckling-Free-Pipe-External-Pressure#scribd](http://www.scribd.com/doc/207835140/Buckling-Free-Pipe-External-Pressure#scribd)

“Chapter 2 Buckling of free pipe under external pressure”

ABSTRACT: In separated-type water tunnel structure, when the point supported steel liner is subjected to the uniform external pressure, the contact between tunnel lining and liner is difficult to happen because the developed compressive hoop thrust in pipe only shortens the circumference of liner and then enlarges the gap between liner and host. Therefore, the buckling of the uniformly point supported liner can be considered a rotary symmetric buckling likely the buckling of free pipe under external pressure. In this chapter, the buckling of free pipe is investigated.

References listed at the end of the paper:
ABSTRACT: The aim of present study is to investigate the effect of height and the shape of cross-hardening materials with the same material on the ultimate strength of reinforced pipe under external hydrostatic pressure. The possibility of reduction in thickness of pipe’s wall away from the beach and submerged in deep water is evaluated. In order to make the pipes economically affordable, buckling resistance has to be provided. To achieve this goal, in vitro study was conducted that has limited factors for investigating on the effect of annular ring on buckling and ultra-buckling capacity of marine submerged pipeline under external hydrostatic pressure; the pressure which is generated by the weight of water above the pipes. In this study, a laboratory-scale pipeline with the same narrowness was fabricated. The nonlinear cyclic stiffeners effect, buckling and post-buckling pipeline model behaviors were investigated. The samples under uniform external pressure were designed when they receive a certain pressure, samples have been buckled. The samples were buckled gradually under low pressures and they were buckled suddenly under heavy pressures. The pressure-shift diagram has moved up to reach the buckle point. The process in all experiments was under observation and showed specific failure in these shells. The results illustrate different samples with various cross section have different buckles and movement. In order to strengthen the pipeline, this study has used cyclic stiffeners with T-shaped, rectangular

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ABSTRACT: The aim of present study is to investigate the effect of height and the shape of cross-hardening materials with the same material on the ultimate strength of reinforced pipe under external hydrostatic pressure. The possibility of reduction in thickness of pipe’s wall away from the beach and submerged in deep water is evaluated. In order to make the pipes economically affordable, buckling resistance has to be provided. To achieve this goal, in vitro study was conducted that has limited factors for investigating on the effect of annular ring on buckling and ultra-buckling capacity of marine submerged pipeline under external hydrostatic pressure; the pressure which is generated by the weight of water above the pipes. In this study, a laboratory-scale pipeline with the same narrowness was fabricated. The nonlinear cyclic stiffeners effect, buckling and post-buckling pipeline model behaviors were investigated. The samples under uniform external pressure were designed when they receive a certain pressure, samples have been buckled. The samples were buckled gradually under low pressures and they were buckled suddenly under heavy pressures. The pressure-shift diagram has moved up to reach the buckle point. The process in all experiments was under observation and showed specific failure in these shells. The results illustrate different samples with various cross section have different buckles and movement. In order to strengthen the pipeline, this study has used cyclic stiffeners with T-shaped, rectangular
and cornerstone sections. Furthermore, finite element software, ABAQUS, have used for numerical analysis. Finally, the theoretical simulated results were compared with experimental results; the obtained results were in good agreement with projected data.

References listed at the end of the paper:

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ABSTRACT: The stability problem of a circular cylindrical shell composed of functionally graded materials with elasticity modulus varying continuously in the thickness direction under combined external pressure and axial compression loads is studied in this paper. The formulation is based on the first-order shear deformation theory. A load interaction parameter is defined to express the combination of applied axial compression and external pressure. The stability equations are derived by the adjacent equilibrium criterion method. These equations are employed to analyze the buckling behavior and obtain the critical buckling loads. A detailed
A numerical study is carried out to bring out the effects of the power law index of functionally graded material, load interaction parameter, thickness ratio, and aspect ratio on the critical buckling loads. The validity of the present analysis was checked by comparing the present results with those results available in literature.

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ABSTRACT: This paper presents the stability of two-dimensional functionally graded (2D-FG) cylindrical shells subjected to combined external pressure and axial compression loads, based on classical shell theory. The material properties of functionally graded cylindrical shell are graded in two directional (radial and axial) and determined by the rule of mixture. The Euler’s equation is employed to derive the stability equations, which are solved by GDQ method to obtain the critical mechanical buckling loads of the 2D-FG cylindrical shells. The effects of shell geometry, the mechanical properties distribution in radial and axial direction on the critical buckling load are studied and compared with a cylindrical shell made of 1D-FGM. The numerical results reveal that the 2D-FGM has a significant effect on the critical buckling load.

References listed at the end of the paper:
ABSTRACT: Fire safety design of building structures has received greater attention in recent times due to continuing losses of properties and lives in fires. However, the structural behaviour of thin-walled cold-formed steel columns under fire conditions is not well understood despite the increasing use of light gauge steels in building construction. Cold-formed steel columns are often subject to local buckling effects. Therefore a series of laboratory tests of lipped and unlipped channel columns made of varying steel thicknesses and grades was undertaken at uniform elevated temperatures up to 700°C under steady state conditions. Finite element models of the tested columns were also developed, and their elastic buckling and nonlinear analysis results were compared with test results at elevated temperatures. Effects of the degradation of mechanical properties of steel with temperature were included in the finite element analyses. The use of accurately measured yield stress, elasticity modulus and stress-strain curves at elevated temperatures provided a good comparison of the ultimate loads and load-deflection curves from tests and finite element analyses. The commonly used effective width design rules and the direct strength method at ambient temperature were then used to predict the ultimate loads at elevated temperatures by using the reduced mechanical properties. By comparing these predicted ultimate loads with those from tests and finite element analyses, the accuracy of using this design approach was evaluated.

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F. X. Li, Q. Liu, H. Q. Huang, "Buckling Behaviors of Steel-Concrete Composite Plate", Applied Mechanics and Materials, Vols. 405-408, pp. 2544-2549, 2013, DOI: 10.4028/www.scientific.net/AMM.405-408.2544
ABSTRACT: The flexibility of connection between the steel plate and concrete slab gives rise to interface slip and additional deflection. A method of analysis for steel-concrete composite plate with slip effect resulting from studs is presented. The basic idea is to place a hypothetical thin shear-layer between steel and concrete slab, where all the shear deformation is concentrated in the thin layer. Analytical solutions for elastic critical buckling load of composite plate considering slip effect under axial compressive and pure shear are derived. The theory model and the solutions are then validated by means of three-dimensional finite element analysis.

Poologanathan Keerthan and Mahen Mahendran (School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD, 4000, Australia), “Shear buckling characteristics of cold-form steel channel beams”, International Journal of Steel Structures, Vol. 13, No. 3, pp 385-399, September 2013
ABSTRACT: Cold-formed steel members are increasingly used as primary structural elements in the building industries around the world due to the availability of thin and high strength steels and advanced cold-forming technologies. Cold-formed lipped channel beams (LCB) are commonly used as flexural members such as floor joists and bearers. However, their shear capacities are determined based on conservative design rules. For the shear design of LCB web panels, their elastic shear buckling strength must be determined accurately including the potential post-buckling strength. Currently the elastic shear buckling coefficients of LCB web panels are determined by assuming conservatively that the web panels are simply supported at the junction between their flange and web elements. Hence finite element analyses were conducted to investigate the elastic shear buckling behavior of LCBs. An improved equation for the higher elastic shear buckling coefficient of LCBs was proposed based on finite element analysis results and included in the ultimate shear capacity equations of the North American cold-formed steel codes. Finite element analyses show that relatively short span LCBs without flange restraints are subjected to a new combined shear and flange distortion action due to the unbalanced shear flow. They also show that significant post-buckling strength is available for LCBs subjected to shear. New equations were also proposed in which post-buckling strength of LCBs was included.
References listed at the end of the paper:
ABSTRACT: The concept of buckling control using piezoelectric actuators is illustrated in Figure 1 and Figure 2. The slender column has a PZT strip pasted at the center, to apply a moment counteracting the moment due to the externally applied axial load. The actuator moment is produced when an actuating voltage is applied to the PZT as shown in Figure 1. The actuator moment enable the column to maintain its un deflected shape and thus achieve an increase in the load carrying capacity (capacity of the column for given lateral deflection) of the column.


ABSTRACT: In the design of plate girder web panels, it is required to evaluate accurately the elastic buckling strength under shear, whether or not the post-buckling strength is accounted for. Currently, elastic shear buckling coefficients of web panels stiffened by transverse intermediate stiffeners are determined by assuming conservatively that web panels are simply supported at the juncture between the flange and web. However, depending upon the geometry and the properties of the plate girder, the elastically restrained support may behave rather closer to a clamped support. In the present study, a series of numerical analyses based on a three-dimensional finite element modeling is carried out to investigate the effects of the geometric parameters on the boundary conditions at the juncture, and the resulting data are quantified in a simple design equation.


ABSTRACT: The concept of buckling control using piezoelectric actuators is illustrated in Figure 1 and Figure 2. The slender column has a PZT strip pasted at the center, to apply a moment counteracting the moment due to the externally applied axial load. The actuator moment is produced when an actuating voltage is applied to the PZT as shown in Figure 1. The actuator moment enable the column to maintain its un deflected shape and thus achieve an increase in the load carrying capacity (capacity of the column for given lateral deflection) of the column.
References listed at the end of the website:

Journals:

International Conferences:


ABSTRACT: Buckling control of space structures using piezoelectric actuators is an emerging area of research. In particular, cylindrical shells present several challenges as they exhibit multiple buckling modes. This work focuses on placement of ring actuators on cylindrical shells exhibiting axisymmetric buckling. A new method based on the characteristic wavelength of the cylindrical shell is proposed for actuator placement. It is shown by means of numerical studies that passive control of these shells shows a distinct advantage over the conventional actuator placement. It is possible to obtain a stiffer load–axial shortening response as well as a peak load enhancement of the shell using the present approach. The results obtained give important insights into the actuator placement problem for cylindrical shells undergoing axisymmetric buckling.

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ABSTRACT: The buckling behaviors as well as the load transfer mechanisms between the shells of double-walled nanotubes (DWNTs) are investigated through a series of molecular dynamics simulations. When buckling occurs, the strain energy of cross-linked (defective) DWNTs undergoes a modest transition indicating that energy gathered in one shell is shared by the other through the inter-shell crosslinks. It is confirmed that the compressive stress applied to the outer shell can be efficiently transferred to the inner shell through the covalent bonds between shells resulting in a uniform load distribution. The existence of inter-shell crosslinks leads to dramatic decreases of the sustainable loads and modest decreases of the Young’s modulus. The computational studies imply that the crosslinks can improve the loading conditions and reduce strain energy in carbon nanotubes based nanocomposites and nanoelectromechanical systems.

References listed at the end of the paper:

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ABSTRACT: Low cost and less weight are the two primary objectives of any aircraft structure. Efficient design of aircraft components is therefore, required to reduce cost and weight of the aircraft structure. For components with compressive loading, ribs and stringer spacings and stringer cross-section play a major role in achieving less weight. The main objective of the present study was aimed at establishing optimum stringer and ribs spacings and stringer cross-section for minimum weight of buckling design driven components using FEM packages. The analysis of effect of plate with ribs and stringer spacing was modeled in FEM to study the effect of these on the weight of aircraft structure using aluminum as material. The analysis was carried out through linear buckling analysis of the model. The software tools used were HyperMesh as a pre and post processor and Radioss as a solver.

References listed at the end of the paper:

ABSTRACT: A mixed atomistic and continuum model is applied to carbon nanotubes in order to study their buckling behavior. Herein the term “atomistic” refers to the underlying constitutive model that is formulated on the basis of interatomic potentials, whereas “continuum” means the application of the Cauchy-Born rule, which links the bond vectors before and after deformation via the deformation gradient of the continuum. Because the bond vectors are not infinitesimal and the continuum is modeled as surface, the Cauchy-Born rule has to be appropriately adapted to crystalline sheets. This is done via an exponential mapping in a new and surprisingly simple form such that in the analysis the current configuration has never to be left. The numerical buckling analysis of carbon nanotubes using the mixed atomistic and continuum model is carried out by means of the finite element method. For this purpose the linearization of the equilibrium equations is provided.


ABSTRACT: The effect of fibre orientation on buckling behaviour in a rectangular composite laminate with central circular hole under uniform in-plane loading has been studied by using finite element method. The critical buckling loads with different fibre orientation in an orthotropic composite laminate (E-glass/epoxy) were obtained. The deformation behaviour of the plate is shown for modes, i=1,2. Studies are carried out for three D/A ratio (where D is hole diameter and A is plate width) with different plate thickness (number of layers). The finite element formulation is carried out in the analysis section of the ANSYS software.

References listed at the end of the paper:
ABSTRACT: The present research work is to determine the buckling load in FRP (fibre reinforced plastic) thin cylinder, which is subjected to uniaxial compression using 2-D finite element analysis. The commercial finite element analysis software ANSYS has been successfully executed and the finite element model is validated. The buckling load is evaluated by varying the boundary conditions, length to diameter ratio \((L/d)\), thickness to diameter ratio \((h/d)\) and number of layers \((n)\). The effect of boundary conditions, \((L/d)\), \((h/d)\), \((n)\) on the buckling load is discussed. The results show that buckling load is more in clamped-clamped boundary condition, decreases with increase in length to diameter ratio, increases with increase in thickness to diameter ratio and remains constant with number of layers.

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3. Dr. Pizhong Qiao, Analysis and design optimization of fiber-reinforced plastic (FRP) structural beams, PhD dissertation, West Virginia University, Morgantown, West Virginia, 1997.
4. A. Arjangpay, M. Darvizeh, R. Ansari & Gh. Zarepour, Axial buckling analysis of an isotropic cylindrical shell using the meshless local Petrov-Galerkin method, Department of Mechanical Engineering, University of Guilan, Rasht, Iran.

ABSTRACT: In this paper the meshless local Petrov-Galerkin (MLPG) method is implemented to study the buckling of isotropic cylindrical shells under axial load. Displacement field equations, based on Donnell and first order shear deformation theory, are taken into consideration. The set of governing equations of motion are numerically solved by the MLPG method in which according to a semi-inverse method, a new variational trial-functional is constructed to derive the stiffness matrices and critical buckling loads are obtained in various boundary conditions. The moving least squares interpolation is employed to construct both trial and test functions. The present method is a truly meshless method based on a number of randomly located nodes upon which no global background integration mesh is needed and no element matrix assembly is required. In the present MLPG formulation, a local variational form is constructed over a local sub-domain instead of using the conventional weighted-residual procedure. The influences of some commonly used boundary conditions and effects of shell geometrical parameters are studied. The results show the convergence characteristics and accuracy of the mentioned method.

References listed at the end of the paper:
In this paper, based on the viscoelastic theory, the creep buckling and post-buckling behaviors of a viscoelastic functionally graded material (FGM) cylindrical shell with initial deflection subjected to a uniform in-plane load are investigated. The material properties of the viscoelastic FGM cylindrical shell are assumed to vary through the structural thickness according to a power law distribution of the volume fraction of constituent materials and Poisson's ratio is assumed as a constant. Considering the transverse shear deformation and geometric nonlinearity, the constitutive relation of the viscoelastic FGM cylindrical shell is established. By means of the Newton-Newmark method and the Boltzmann superposition principle, the problem for the creep buckling and post-buckling of the FGM cylindrical shell is solved. The numerical results reveal that the transverse shear deformation, volume fraction and geometric parameters have significant effects on the creep buckling and post-buckling of the viscoelastic FGM cylindrical shell.

References listed at the end of the paper:


ABSTRACT: Based on the Talreja’s tensor valued internal state variables damage model and the Helmhotlz free energy of piezoelectric material, the constitutive relations of the piezoelectric plates with damage are derived. Then, the nonlinear dynamic equations of the piezoelectric plates considering damage are established. By using the finite difference method and the Newmark scheme, these equations are solved and the effects of damage and electric loads on the nonlinear dynamic response of piezoelectric plates are discussed.


ABSTRACT: In this work, a fully geometrically nonlinear dynamic finite element (FE) model, which considers the kinematics of small strains but large rotations, is developed for transient analysis of piezolaminated thin-walled structures based on first-order shear deformation (FOSD) hypothesis. Linear electro-mechanically coupled constitutive equations and the assumption of linearly distributed electric potential through the thickness of the piezoelectric layers are employed. An eight-node quadrilateral plate/shell element with five mechanical degrees of freedom (DOFs) per node and one electrical DOF per smart layer is adopted in the finite element formulation. The second order differential dynamic equation is solved by the central difference algorithm. The mathematical method is validated by transient analysis of three different examples of a beam, a plate, and a cylindrical shell. The results illustrate that the geometrical nonlinearity affects the structural dynamic responses
DOI: 10.4028/www.scientific.net/AMR.709.320
ABSTRACT: Subjected to external pressure, buckling analysis is key problem in the roof shell design of large scale cylinder gasholder. Two simplified buckling analysis methods, the continuous orthotropic plate method and the split-rigidity method, are introduced to check the general instability of stiffened spherical shallow shell. Considering the plate and the stiffeners in two directions with the same contribution to the bending stiffness, the equivalent bending thickness formula is put forward. The finite element model for a 100,000 m³ cylinder gasholder roof is setup. The buckling critical loads obtained prove that the split-rigidity analysis method and formulae are applicable. The results can be referred in design of stiffened spherical shallow shell.
References listed at the end of the paper:

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ABSTRACT: Spider silk is extraordinarily strong, mollusk shells and bone are tough, and porcupine quills and feathers resist buckling. How are these notable properties achieved? The building blocks of the materials listed above are primarily minerals and biopolymers, mostly in combination; the first weak in tension and the second weak in compression. The intricate and ingenious hierarchical structures are responsible for the outstanding performance of each material. Toughness is conferred by the presence of controlled interfacial features (friction, hydrogen bonds, chain straightening and stretching); buckling resistance can be achieved by filling a slender column with a lightweight foam. Here, we present and interpret selected examples of these and other biological materials. Structural bio-inspired materials design makes use of the biological structures by inserting synthetic materials and processes that augment the structures' capability while retaining their essential features. In this Review, we explain this idea through some unusual concepts.
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“Bio-inspired structural bistability employing elastomeric origami for morphing applications”, Smart Mater.
Struct. Vol. 23, No. 12, 125011, 2014
ABSTRACT: A structural concept based upon the principles of adaptive morphing cells is presented whereby
controlled bistability from a flat configuration into a textured arrangement is shown. The material consists of
multiple cells made from silicone rubber with locally reinforced regions based upon kirigami principles. On
pneumatic actuation these cells fold or unfold based on the fold lines created by the interaction of the geometry
with the reinforced regions. Each cell is able to maintain its shape in either a retracted or deployed state, without
the aid of mechanisms or sustained actuation, due to the existence of structural bistability. Mathematical
quantification of the surface texture is introduced, based on out-of-plane deviations of a deployed structure
compared to a reference plane. Additionally, finite element analysis is employed to characterize the geometry
and stability of an individual cell during actuation and retraction. This investigation highlights the critical role
that angular rotation, at the center of each cell, plays on the deployment angle as it transitions through the
elastically deployed configuration. The analysis of this novel concept is presented and a pneumatically actuated
proof-of-concept demonstrator is fabricated.

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77042.
“Performance Testing of Underground Storage Tank against Buckling”, ASCE Pipelines 2012: pp. 1-10, doi:
10.1061/9780784412480.001
ABSTRACT: The Steel Tank Institute (STI) performed testing to demonstrate the stiffening effects from the
soil-structure interface with an underground storage tank. The test demonstrated the importance of the soil in
calculating the resistance to buckling in a buried environment. Current third party listing agencies do not take
the stiffening effect of the soil support into consideration with standardized steel wall thickness calculations.
Performance characteristics of a tank are similar to pipelines, although the tank heads provide additional
stiffness to the structure. As a result, atmospheric tank wall thicknesses are thinner than typical pressurized
potable water pipelines. Tanks are normally buried 4'-5' at petroleum service stations, however, sometime the
tanks need to be buried deeper. STI buried a 64 inch diameter by 24 foot long steel tank 7 foot below grade,
compacting the angular gravel backfill during placement to grade. A camera was placed in the tank to record
deformations during the actual test. The excavation was filled with water such that the bottom of the tank was
subjected to 12 feet-4 inches of static water head pressure. A vacuum pump was connected to a tank riser and a
vacuum was pulled. The intent was to pull the vacuum until the tank buckled. A vacuum of 16.5 inches Hg was
established and the pump was unable to pull additional vacuum. The backfill was removed and the tank
examined and the video of the inside of the tank reviewed. The tank did not buckle. The shell did not deform.
The heads experienced approximately 2 inches of permanent deformation. Calculations indicate that the tank
was subjected to a 15.0 psi total buckling load. Formulations suggest that the soil-structure would provide
resistance to buckling up to 21.0 psi. Third party standard formulations that do not take the soil support into
consideration suggest that the tank would buckle in a range from 1.3 psi to 6.0 psi. The test clearly demonstrates the importance of the soil in calculating the resistance to buckling in a buried environment. The soil-structure interaction provides significant additional stiffness to the structure, whether the structure is a pipeline or a tank, as demonstrated in this test.


ABSTRACT: A finite differences procedure is used to study the buckling of non-trivial equilibrium solutions for open thin-walled beams in a dynamic setting. A direct one-dimensional model with a coarse descriptor of warping is adopted. The algorithm describes non-trivial equilibrium paths by integrating discretized field equations, suitably written in terms of velocities. Some benchmark cases under conservative loading are discussed. Known results for the first critical loads are found to validate the procedure. New results are found accounting for non-trivial equilibrium paths, thus providing an estimate for the error made by linearizing around trivial equilibrium paths. The effect of warping on the critical loads is also investigated.

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ABSTRACT Large crystalline molecular shells, such as some viruses and fullerenes, buckle spontaneously into icosahedra. Meanwhile multicomponent microscopic shells buckle into various polyhedra, as observed in many organelles. Although elastic theory explains one-component icosahedral faceting, the possibility of buckling into other polyhedra has not been explored. We show here that irregular and regular polyhedra, including some Archimedean and Platonic polyhedra, arise spontaneously in elastic shells formed by more than one component. By formulating a generalized elastic model for inhomogeneous shells, we demonstrate that coassembled shells with two elastic components buckle into polyhedra such as dodecahedra, octahedra, tetrahedra, and hosohedra shells via a mechanism that explains many observations, predicts a new family of polyhedral shells, and provides the principles for designing microcontainers with specific shapes and symmetries for numerous applications in materials and life sciences.

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DOI: 10.1039/C1SM06325A

ABSTRACT: We explore the effects of line tension on the shape of two component elastic shells. Segregation between components with different elastic properties combined with the subtleties related to the spherical topology leads to a rich variety of shapes. They range from irregular polyhedra at weak segregation to Janus-like morphologies with spherical and buckled regions coexisting on the same shell for large values of the line
tension. We use Monte Carlo simulations to map a detailed phase diagram as a function of the relative fraction of the two components, the ratio of their bending rigidities, and the strength of the line tension.


ABSTRACT: The structural stability of thin-walled steel tanks becomes a major safety issue when these operate at low levels of contained liquid. Despite numerous tank failures due to buckling of their circumferential shell, provisions in current codes do not provide cost-efficient or high-safety-level solutions regarding this phenomenon. For example, the American standard API 650, which has worldwide applications, proposes only an empirical design method for stiffening the tank shell based on its thickness, height and the design wind velocity. More recent codes, such as the European standard EN1993-1-6, provide analytical relationships for evaluating the buckling resistance of shells, with stability being verified by relevant checks against appropriate design stresses. However, their provisions have not yet seen many field applications and results raise, in certain cases, doubts regarding the efficiency of the design. This paper presents a direct comparison between these two standards by attempting to evaluate the buckling resistance of two existing thin-walled steel tanks, filled at a low liquid level. Both tanks have large diameters (47m and 88m approximately), variable wall thickness, are self-supported (unanchored) and one of them supports a conical roof. The design stresses required by EN1993-1-6 were obtained from finite element simulations of the tanks (linear elastic analyses were performed) which included application of the actions specified in the provisions of the Eurocode. Results from both standards are discussed in detail, comparisons are made and discrepancies between the two standards are highlighted. Comments and conclusions to be drawn will help improve current specifications and resolve issues related to the safe design of liquid storage tanks filled at low liquid levels.

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Engineering and Design, 65, 221-238.

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ABSTRACT: Review of the literature on first-ply failure of composite shells shows that research reports on first-ply failure of moderately thin, laminated composite cylindrical shell panels, using a geometrically nonlinear approach, are not available. The present paper aims to fill this deficiency. It uses a finite-element code developed using eight-noded, doubly-curved elements combined with modified Sanders’ first-approximation theory for thin shells and von Kármán-type nonlinear strains. The accuracy of the present geometric nonlinear and first-ply failure formulations are verified separately through solutions of two benchmark problems. Failure loads, failure modes (for individual stress or strain failure) or tendencies (for interactive stress failures), and the locations from where the failures initiate are reported. The results are discussed critically to formulate design guidelines, suggesting practical values for factors of safety applicable to failure loads. Such suggestions also consider the serviceability requirements.

ABSTRACT: Theoretical bases of methods and algorithms developed for the analysis of stability and post critical behavior of thin elastic shells. The problem of numerical analysis the nonlinear deformation processes of spherical domes under the uniform external pressure is discusses. Describes the computer algorithm based on the parameter continuation method, using the technique of subspaces of the of the control parameter subspace changing. Efficiency of the proposed approach is illustrated by same examples.

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ABSTRACT: The purpose of this paper is to analyse the nonlinear flexural behaviour of laminated curved panel under uniformly distributed load. The study has been extended to analyse different types of shell panels by employing the newly developed nonlinear mathematical model. We have developed a novel nonlinear mathematical model based on the higher order shear deformation theory for laminated curved panel by taking the geometric nonlinearity in Green-Lagrange sense. In addition to that all the nonlinear higher order terms are considered in the present formulation for more accurate prediction of the flexural behaviour of laminated panels. The sets of nonlinear governing equations are obtained using variational principle and discretised using nonlinear finite element steps. Finally, the nonlinear responses are computed through the direct iterative method for shell panels of various geometries. The importance of the present numerical model for small strain large deformation problems has been demonstrated through the convergence and the comparison studies. The results
give insight into the laminated composite panel behaviour under mechanical loading and their deformation behaviour. The effects of different design parameters and the shell geometries on the flexural responses of the laminated curved structures are analysed in detail. It is also observed that the present numerical model are realistic in nature as compared to other available mathematical model for the nonlinear analysis of the laminated structure.


ABSTRACT: An approach for estimating critical buckling strain of pipe subjected plastic bending is established in the present paper. A rigid—perfectly plastic material model and cross section ovalization of pipe during bending are employed for the approach. The energy rates of the ovalised pipe bending and the cross section ovalising are proposed firstly. Furthermore, these energy rates are combined to perform the buckling analysis of pipe bending, an estimation formula of critical buckling strain for pipe subjected plastic bending is proposed. The predicting result of the new critical buckling strain formula is compared with the available experimental data, it shows that the formula is valid.

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ABSTRACT: Flat top and hemispherical shaped shells made by press forming were deformed by indentation using flat or round headed indentor. Effect of the shell shape, sheet thickness, indentor shape and the speed on the deformation behavior was investigated. The material was mild steel SPCE or aluminum alloy A5052. Speed effect of SPCE on the indentation force became remarkably large, when the indenting or loading direction was reversed to that in the forming. It was small for A5052 material. Energy absorption performance was also evaluated in considering the mass of the shell, which is used as an index for the light-weight structure design. The energy absorption efficiency was highest for case of the flat top shell indented by flat headed indentor. Almost constant collapse force was obtained when the spherical shell was deformed with hemispherical indentor.

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ABSTRACT: The choice of finite element to use in order to predict nonlinear static or dynamic response of complex structures becomes an important factor. Then, the main goal of this research work is to focus a study on the effect of the in-plane rotational degrees of freedom in linear and geometrically non linear static and dynamic analysis of thin shell structures by flat shell finite elements. In this purpose: First, simple triangular and quadrilateral flat shell finite elements are implemented in an incremental formulation based on the updated lagrangian corotational description for geometrically nonlinear analysis. The triangular element is a combination of DKT and CST elements, while the quadrilateral is a combination of DKQ and the bilinear quadrilateral membrane element. In both elements, the sixth degree of freedom is handled via introducing fictitious stiffness. Secondly, in the same code, the sixth degrees of freedom in these elements is handled differently where the in-plane rotational d.o.f is considered as an effective d.o.f in the in-plane filed interpolation. Our goal is to compare resulting shell elements. Third, the analysis is enlarged to dynamic linear analysis by direct integration using Newmark’s implicit method. Finally, the linear dynamic analysis is extended to geometrically nonlinear dynamic analysis where Newmark’s method is used to integrate equations of motion and the Newton-Raphson method is employed for iterating within each time step increment until equilibrium is achieved. The obtained results demonstrate the effectiveness and robustness of the interpolation of the in-plane rotational d.o.f. and present deficiencies of using fictitious stiffness in dynamic linear and nonlinear analysis.

References listed at the end of the paper:
ABSTRACT: A simple, effective finite element incremental formulation and procedure for geometrically nonlinear static and dynamic analysis of a shell structure with finite rotations are presented, based on both the total Lagrangian and updated Lagrangian description of motion. The co-rotation formulation is used for finite rotation. The element employed here to implement the present method is a faceted shell element with Loof nodes (DKL + LST). An incremental iterative method based on the constant arc length method in conjunction with Newton-Raphson method is implemented in the present study for static and Newmark's integration scheme for dynamic analysis. To demonstrate the accuracy and efficiency of the formulations and to compare the difference between the total and updated Lagrangian formulation, numerical studies are presented.

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ABSTRACT: A simple and effective finite element incremental formulation based on the updated lagrangian corotational description for geometrically nonlinear dynamic analysis of shell structure is presented in this work. The flat shell element used is the classical four-node quadrilateral DKQ shell finite element, combined with the improvements of the in-plane behaviour by incorporation of the drilling rotation degree of freedom. The main goal is to have a good flat shell element of quadrilateral geometry, leading to reliable solutions in linear and geometrically nonlinear dynamic analysis. The Newmark’s direct time integration method is adopted to integrate the equations of motion, while the Newton–Raphson method is used for iterating within each time step increment until equilibrium is achieved. The results obtained through a series of selected examples demonstrate the effectiveness of the used shell finite element to predict the nonlinear dynamic response of...
complex structures, and the robustness of this nonlinear dynamic investigation taking account of both linear and non-linear dynamic problems.

Chrysanthos Maraveas (School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M13 9PL, UK and C. Maraveas Partnership Consulting Engineers, 11 Metsovou street, Athens, 10682, Greece). “Thermal buckling analysis of thin-walled steel oil tanks exposed to an adjacent fire”, 23rd australiasian Conference on the Mechanics of Structures and Materials (ACMSM23), Byron Bay, Australia, 9-12 December 2014, S.T. Smith (Ed.)

ABSTRACT: This paper presents a finite element study of a steel oil storage tank with cylindrical shell shape and conical roof subjected to an adjacent fire. Fire is one of the main hazards associated with tanks containing combustible materials. Several catastrophic accidents have taken place during the last decades revealing the consequences and losses arising from such events and highlighting the importance for proper design against thermal buckling. Oil storage tanks are usually placed in large groups and closed distances. Therefore, it is assumed herein that the fire occurs outside the tank. Critical buckling temperatures are calculated considering that the temperature profile along the circumference of the tank is defined according to a cosine square distribution. The influence of the roof stiffness, of the circumferential area exposed to fire and of the filling level is examined. Apart from the thermal loads, the self-weight of the tank and the hydrostatic pressure exerted by the liquid are taken into account in the static analyses. The mechanical properties of steel are taken according to Eurocode 3.

References listed at the end of the paper:


PARTIAL ABSTRACT: Fire is one of the main hazards associated with storage tanks containing flammable liquids. These tanks are usually closely spaced and in large groups, so where a petroleum fire occurs, adjacent tanks are susceptible to damage leading to further development of the fire. The structural behaviour such as thermal stability and failure modes of the tanks under such fire scenario are very important to the safety design and assessment of oil depots. However, no previous studies on this problem are known to the best knowledge of the author. This thesis presents a systematic exploration of the potential thermal and structural behaviours of an oil tank when one of its neighbour tanks is on fire. Under such scenario, the oil tanks are found to easily buckle under rather moderate temperature rises. The causes of such buckling failures are the reduced modulus of steel
at elevated temperatures, coupled with thermally-induced stresses due to the restraint of thermal expansion. Since the temperatures reached in such structures can be several hundred Centigrade degrees, any restraint to thermal expansion can lead to the development of compressive stresses. The high susceptibility of thin shell structures to elastic buckling under low compressive stresses means that this type of failure can be easily provoked. The main objectives of this thesis were to reveal the thermal distribution patterns developed in an oil tank under the heating from an adjacent tank fire, to understand the underlying mechanism responsible for the buckling of tank structure, and to explore the influences of various thermal and geometrical parameters on the buckling temperature of the tanks. The study began with analytical solutions for stresses and deformations in a partially filled roofless cylindrical tank under an idealised axisymmetrical heating regime involving thermal discontinuity at the liquid level. The results demonstrate that large compressive circumferential membrane stresses occur near the bottom boundary for an empty tank and near the liquid level for a partially-filled tank.

Heat transfer . . .

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4 Anderson, M. S., and Card, M. F. (1962). "Buckling of ring-stiffened cylinders under a pure bending moment and a nonuniform temperature distribution." National Aeronautics and Space Administration

ABSTRACT: Structural stability is a major consideration in the design of lightweight shell structures. However, the theoretical predictions of geometrically perfect structures often considerably over predict the buckling loads of inherently imperfect real structures. It is reasonably well understood how the shell geometry affects the imperfection sensitivity of axially compressed cylindrical shells; however, the effects of shell anisotropy on the imperfection sensitivity is less well understood. In the present paper, the development of an analytical model for assessing the imperfection sensitivity of axially compressed orthotropic cylinders is discussed. Results from the analytical model for four shell designs are compared with those from a general-purpose finite-element code, and good qualitative agreement is found. Reasons for discrepancies are discussed, and potential design implications of this line of research are discussed.

References listed at the end of the paper:
ABSTRACT: Thin-walled cylindrical shell structures often have buckling as the critical failure mode, and the buckling of such structures can be very sensitive to small geometric imperfections. The buckling analyses of an 8-ft-diameter, 10-ft-long honeycomb-core composite cylinder loaded in pure axial compression is discussed in this document. Two loading configurations are considered: configuration 1 uses simple end conditions, and configuration 2 includes additional structure that may more closely approximate experimental loading conditions. Linear eigenvalue buckling analyses and nonlinear analyses with and without initial geometric imperfections were performed on both configurations. The initial imperfections were introduced in the shell by applying a radial load at the midlength of the cylinder to form a single inward dimple. The critical bifurcation buckling loads are predicted to be 924,190 lb and 924,020 lb for configurations 1 and 2, respectively. Nonlinear critical buckling loads of 918,750 lb and 954,900 lb were predicted for geometrically perfect configurations 1 and 2, respectively. Lower-bound critical buckling loads for configurations 1 and 2 with radial perturbations were found to be 33% and 36% lower, respectively, than the unperturbed critical loads. The inclusion of the load introduction cylinders in configuration 2 increased the maximum bending-boundary-layer rotation up to 11%.
ABSTRACT: The objective of the present paper is to investigate the bending, buckling and vibration behaviors of carbon nanotube-reinforced composite (CNTRC) beams. The beams resting on the Pasternak elastic foundation, including a shear layer and Winkler spring, are considered. The single-walled carbon nanotubes (SWCNTs) are aligned and distributed in polymeric matrix with different patterns of reinforcement. The material properties of the CNTRC beams are estimated by using the rule of mixture. Various shear deformation theories are employed to deal with the problems. The mathematical models provided in this paper are numerically validated by comparison with some available results. New results of bending, buckling and vibration analyses of CNTRC beams based on several higher-order shear deformation theories are presented and discussed in details. Several aspects of beam types, spring constant factors, carbon nanotube volume fraction, etc., are taken into investigation.


ABSTRACT: The paper presents a framework for design and optimization of curvilinear stiffened panels with any cross-section shape of stiffener. Within this framework, the weight of stiffened panel applied complex loads, is minimized under the constraints of structural responses include global buckling, maximum stress and crippling. Then, a stiffened panel with two blade curvilinear stiffeners is optimized using this framework, and the optimum performs better than another existing design. Finally, it is concluded that stiffening beam is suitable for simulate stiffener sustains part of applied load directly.


ABSTRACT: Since the subpanels of polygonal-section shell have the corners of an obtuse angle larger than 90 degree unlike general plate or box-section structures, this could have an influence on forming nodal lines against local plate buckling or stress distributions. However, there is not sufficient material in the relevant study results or design recommendations. The very feasible models of the initial imperfections were acquired through the literature studies and then the parametric studies were conducted along with the initial imperfection models by using the finite element method. The parameters like the size of residual stresses, the portion of compressive residual stresses, and steel grades were considered. From the parametric studies, it was found that the maximum residual stress is more influential factor than the distribution pattern of residual stresses. In addition, The design strength equations for the simply supported plates can be applicable to the determination of the local buckling strength of the polygonal cross-section shell structures.

Byung H. Choi, Choi Su-Young, Park Sang-Kyun (Dept. of Civil and Environmental Engineering, Hanbat National University, Korea), “Buckling analysis of laminated composite plates longitudinally stiffened with U-

ABSTRACT: Even though the longitudinally stiffened laminated composite plates with closed section ribs should be an effective system for axially compressed members, the existing researches on the applications of closed-section ribs, especially for the laminated composite plates, are not sufficient. This study is aimed to examine the influence of the sectional stiffness of U-shaped ribs on the buckling modes and strengths of laminated composite plates. Applying the orthotropic plates with eight layers of the layup [(0°)4]s and [(0°/90°)2]s, 3-dimensional finite element models for the U-rib stiffened plates were setup by using ABAQUS and then a series of eigenvalue analyses were conducted. From the parametric studies, the minimum required ply thicknesses as well as the buckling strengths were presented for the analysis models. The buckling strengths were compared with the theoretical critical stress equation for simply supported plates based on the Classical laminated plate theory. This study will contribute to the future study for evaluating the minimum required stiffness and optimum design of U-rib stiffened plates.

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Sung-Cheon Han (Dept. of Civil and Railroad Engineering, Daewon University College), “Geometrically nonlinear analysis of hinged cylindrical laminated composite shells”, Journal of the Korean Society for Advanced Composite Structures, Vol. 3, No. 2, pp 1-10, (date not given; most recent reference is dated 2011; paper probably published in the 2012 volume of the journal.)

ABSTRACT: In the present study, an Element-Based Lagrangian Formulation for the nonlinear analysis of shell structures is presented. The strains, stresses and constitutive equations based on the natural co-ordinate have been used throughout the Element-Based Lagrangian Formulation of the present shell element which offers an advantage of easy implementation compared with the traditional Lagrangian Formulation. The Element-Based Lagrangian Formulation of a 9-node resultant stress shell element is presented for the anisotropic composite material. The element is free of both membrane and shear locking behavior by using the assumed natural strain method such that the element performs very well in thin shell problems. The arc-length control method is used to trace complex equilibrium paths in thin shell applications. Numerical examples for laminated composite curved shells presented herein clearly show the validity of the present approach and the accuracy of the developed shell element.

References listed at the end of the paper:
Introduction

Conical shells occur frequently as components of aeronautic, marine and civil engineering structures. Often they are frequently used as transition elements joining cylinders of different diameters. Buckling and loss of stability of stiffened conical shells is one of the most important and crucial failure phenomena of such structures. It is well known that stability of conical shells is one of the most important and crucial failure phenomena of such structures.

ABSTRACT: The purpose of this paper is to describes the fabrication and testing of the grid stiffened composite conical shells. This paper presents the rib influence on the buckling behavior of filament wound, grid stiffened composite conical shells subjected to axially compressive load. A cheap and quick manufacturing process is presented. The buckling behavior of a grid stiffened composite conical shell is investigated by experiment and finite element analysis. The conical shells used in experiment are made from glass/epoxy by filament winding machine. The specimen was tested under pure axial compression based on the ASTM standard with a cross-head speed of 1 mm/min. The axial load versus the axial displacement curve for the specimen was recorded using the X-Y recorder available in the INSTRON testing system. The initial buckling load was obtained in stage. Using ABAQUS commercial finite element software for finite element analysis. Finite element modeling of the grid stiffened composite is carried out with eight node 3D layered brick elements and the skin is modeled with four node shell elements. Results are summarized to identify the performance of this method of grid structures manufacturing. Conclusions are drawn on the efficacies of performance of the grid stiffened composite conical shells. It is seen that there is increase in the buckling load as well specific buckling load indicating a net increase in the efficiency. Introduction Conical shells occur frequently as components of aeronautic, marine and civil engineering structures. Often they are frequently used as transition elements joining cylinders of different diameters. Buckling and loss of stability of stiffened conical shells is one of the most important and crucial failure phenomena of such structures. It is well known that stability of conical shells has...
been studied by many researchers with a variety of shell and plate theories [1-7]. The advent of high strength, light weight, composite materials has resulted in broad use of multi-layered shells. The Filament-wound composite shells of revolution have been extensively applied to the area of aerospace, aircrafts and military industries. The search for lightweight and efficient aerospace structural component is a continuing process. Grid stiffened composite shells a class of shells with very high reliability and mass efficiency. As is evident from the increased number of publications in the recent past, there is a growing interest in the grid stiffened structures. However, on the manufacturing front published literature is somewhat limited. Vasiliev et al. [9-11] have given a brief account on manufacturing, testing and optimization. A description of manufacturing of lattice structures by filament winding along grooves cut in plaster substrate is given by Hou and Gramoll [12]. Totaro and Gurdal [13] have given a numerical optimization of composite lattice structures. An analytical model for the local buckling modeling of isogrid and anisogrid lattice cylindrical shells with triangular cells has been performed by Totaro [14]. Morozov et al. [15] have given a special finite element model for buckling analysis of anisogrid composite lattice conical shells. In this article presents a manufacturing method for making a typical grid stiffened composite conical shell. Furthermore, buckling analysis of stiffened conical shells are present by experimental and finite element methods.

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ABSTRACT: A unified analytical approach is applied to investigate the vibrational behavior of grid-stiffened cylindrical shells with different boundary conditions. A smeared method is employed to superimpose the stiffness contribution of the stiffeners with those of shell in order to obtain the equivalent stiffness parameters of the whole panel. Theoretical formulation is established based on Sanders’ thin shell theory. The modal forms are assumed to have the axial dependency in the form of Fourier series whose derivatives are legitimized using Stoke's transformation. A 3D finite element model is also built using ABAQUS software which takes into consideration the exact geometric configuration of the stiffeners and the shell. The achievements from the two types of analyses are compared with each other and good agreement has been obtained. The Influences of variations in shell geometrical parameters, boundary condition, and changes in the cross stiffeners angle on the natural frequencies are studied. The results obtained are novel and can be used as a benchmark for further studies. The simplicity and the capability of the present method are also discussed.

References listed at the end of the paper:
rupture,” Proceedings of Meetings on Acoustics, Vol. 19, pp. 075097 (June 2013); (6 pages), Conference


Amin Jafari Sojahrood, Raffi Karshafian, and Michael C. Kolios (Ryerson University, Toronto, Ontario M5B2K3 Canada), “Bifurcation structure of the ultrasonically excited microbubbles undergoing buckling and rupture”, Proceedings of Meetings on Acoustics, Vol. 19, pp. 075097 (June 2013); (6 pages), Conference
ABSTRACT: Bubbles exposed to ultrasound are long known to exhibit highly nonlinear and chaotic dynamics. Bubbles stabilized by a shell material (MBs), are widely used as contrast agents in diagnostic ultrasound. However, the nonlinear behaviour of the shell significantly increases the complexity of the dynamics. In order to realize the full potential of the MBs, better understanding of the MB behaviour is necessary. In this study the bifurcation structure of the MB with nonlinear shell behaviour is investigated for the first time. The Marmottant model was numerically solved and the bifurcation diagrams of the radial oscillations of the MB were plotted versus the control parameters (e.g. buckling radius). In agreement with recent experimental observations, results predict the generation of subharmonics at very low acoustic pressures. In addition, the numerical simulations predict the generation of higher order subharmonics (e.g. period 3) at very low acoustic pressures (<300 kPa and 25 MHz), which contradicts the predictions by free bubble and viscoelastic shell MB models. Results revealed the strong influence of the buckling radius on the order of the subharmonics. The numerical results were verified by experimental observation of higher order subharmonics in the oscillations of Definity at 25 and 55 MHz.


ABSTRACT: An experimental–numerical investigation of the effect of welding residual stress on plastic buckling of axially compressed cylindrical shells with patterned welds is carried out. Two cylindrical shell specimens with different pattern of welds are made according to manufacturing process used in engineering. Their initial geometric imperfections, axial and circumferential strain, buckling load, etc., are experimentally obtained. Inherent strain method used for simulating welding residual stress field is presented. Two different numerical modeling methods for the purpose of evaluating the effect of welding residual stress on plastic buckling are illustrated and the validity is verified by experiment. It is found that, load–displacement curve before buckling is altered, plastic buckling critical load is decreased to some extent, and the buckling deformation such as the number and the uniformity of waveforms of circumferential welds are changed when welding residual stress exists. For the above phenomena, the reason why welding residual stress has an influence on plastic buckling is also quantitatively analyzed from the point of stress variation.


ABSTRACT: Thin-walled structures, when properly designed, possess a high strength-to-weight and stiffness-to-weight ratio, and therefore are used as the primary components in some weight critical structural applications, such as aerospace and marine engineering. These structures are prone to be limited in their load carrying capability by buckling, while staying in the linear elastic range of the material. Buckling of thin-walled structures is an inherently nonlinear phenomena. When the material stays within its linear elastic range, the source of the nonlinearity is purely geometric. Thus, the analysis of nonlinear response of structures, especially thin-walled structures which are buckling sensitive, is important for determining their load carrying capability. For this reason, structural geometric nonlinearities are increasingly taken into account in engineering design. Nowadays, with the expanding computational power of modern computers nonlinear finite element analysis using commercial software is becoming the standard technique used to obtain the nonlinear response of complex structures, however, the repeated analyses that are needed in the design phase are still computationally
intensive, in terms of the computation time required to run large models, even for modern computers. For this reason, reduced order techniques that reduce the problem size are attractive whenever repetitive analyses are required, such as in design optimization. Research on reduced order modeling of the nonlinear response of structures has attracted much attention from researchers. Some analytic techniques constitute very powerful tools for reducing the number of degrees of freedom (DOFs) in a nonlinear system, such as the Rayleigh-Ritz techniques and perturbation techniques. These two reduced basis techniques can be implemented in both analytical and numerical contexts, and due to the modeling versatility of the finite element method (FEM), most researchers prefer to reconstruct them within the FEM context, referred to as reduction methods. There are two families of reduction methods which can be recognized. The first family consists the path-following reduction methods which are based on some analytic techniques to reduce the number of DOFs in the full model and are able to trace the entire nonlinear equilibrium path of structures automatically, while they may find difficulties in the presence of buckling. Koiter reduction methods belong to the second family, and they are very good at handling the buckling sensitive cases due to the use of Koiter’s classical initial postbuckling theory, but the Koiter perturbation approach also limits the validity of these methods to a small range around the bifurcation point. The focus of the research reported in this thesis therefore is to find ways to synthesize the advantages of current reduction methods and obtain a new reduced basis path-following approach. In this thesis, a new approach called the Koiter-Newton (K-N) is presented for the numerical solution of a class of elastic nonlinear structural analysis problems. The method combines ideas from Koiter’s initial post-buckling analysis and Newton arclength methods to obtain an algorithm that is accurate over the entire equilibrium path of structures and efficient in the presence of buckling and/or imperfection sensitivity. The proposed approach is performed in a step by step manner to trace the entire equilibrium path, as is commonly used in the classical Newton arclength method. In every expansion step, the approach works by combining a prediction step using a nonlinear reduced order model (ROM) based on Koiter’s initial postbuckling expansion with a Newton arclength correction procedure. This nonlinear prediction provided by the reduced order model is much better compared to linear predictors used by the classical Newton-Raphson method, thus allowing the algorithm to use fairly large step sizes. The basic premise behind the proposed approach is the use of Koiter’s asymptotic expansion from the beginning rather than using it only at the bifurcation point in contrast to the traditional Koiter approaches. In each asymptotic expansion, the force space is reduced by the span of a set of perturbation loads that are chosen to excite the possible buckling branches. According to the stability of the equilibrium point, at which the asymptotic expansion is applied, different ways for selecting the perturbation loads are proposed. The proposed selection rules guarantee that the expansion step of the proposed approach can be applied at any point along the equilibrium path. The proposed technique requires derivatives of the element load vectors with respect to the degrees of freedom up to the third order. This is two orders more than what is traditionally needed for Newton’s method. To facilitate differentiation, nonlinear elements based on the element independent co-rotational frame are applied in the Koiter-Newton analysis. Automatic differentiation is used to find the derivatives of the co-rotational frame with respect to element degrees of freedom. In this way, full nonlinear kinematics are taken into account when constructing the reduced order model. In some cases, the nonlinear in-plane rotations of structures can be neglected, although the rotations of the normals to the mid-surface are finite. In such cases, Von Karman kinematics, which ignore some nonlinear items in the Green’s strain-displacement relations, possess an acceptable accuracy compared with the full nonlinear kinematics. Hence, the Koiter-Newton approach is also implemented based on Von Karman kinematics to achieve a better computational efficiency. Various numerical examples of beam and shell models are presented and used to evaluate the performance of the method. The Koiter-Newton analyses using the corotational kinematics and the Von K’armán kinematics are accurate and more computational efficient, compared with the results obtained using ABAQUS which adopts a full nonlinear analysis. The improved efficiency demonstrated by the Koiter-Newton technique will open the door to the direct use of detailed nonlinear finite element models in the design
optimization of next generation flight and launch vehicles.

Karol Daszkiewicz, Jacek Chroscielewski and Wojciech Witkowski (Dept. of Structural Mechanics, Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland), “Geometrically nonlinear analysis of functionally graded shells based on 2-D Cosserat constitutive model”, Engineering Transactions, Vol. 62, No. 2, pp 109-130, 2014

ABSTRACT: In this paper geometrically nonlinear analysis of functionally graded shells in 6-parameter shell theory is presented. It is assumed that the shell consists of two constituents: ceramic and metal. The mechanical properties are graded through the thickness and are described by power law distribution. Formulation based on 2-D Cosserat constitutive model is used to derive constitutive relation for functionally graded shells. Numerical results for typical benchmark geometries of smooth and irregular FGM shells under mechanical loading are presented. The influence of power-law exponent and micropolar material constants on the overall behaviour of functionally graded shells is investigated.

References listed at the end of the paper:


35. HSL, A collection of Fortran codes for large-scale scientific computation, http://www.hsl.rl.ac.uk/.


ABSTRACT: Buckling-critical launch-vehicle structures require structural concepts that have high bending stiffness and low mass. Fluted-core, also known as truss-core, sandwich construction is one such concept. In an effort to identify an analysis method appropriate for the preliminary design of fluted-core cylinders, the current paper presents and compares results from several analysis techniques applied to a specific composite fluted-core test article. The analysis techniques are evaluated in terms of their ease of use and for their appropriateness at certain stages throughout a design analysis cycle (DAC). Current analysis techniques that provide accurate determination of the global buckling load are not readily applicable early in the DAC, such as during preliminary design, because they are too costly to run. An analytical approach that neglects transverse-shear deformation is easily applied during preliminary design, but the lack of transverse-shear deformation results in global buckling load predictions that are significantly higher than those from more detailed analysis methods. The current state of the art is either too complex to be applied for preliminary design, or is incapable of the accuracy required to determine global buckling loads for fluted-core cylinders. Therefore, it is necessary to develop an analytical method for calculating global buckling loads of fluted-core cylinders that includes transverse-shear deformations, and that can be easily incorporated in preliminary design.


ABSTRACT: Many elliptical shells are used in structural applications in which the dominant loading condition is axial compression. Due to the fact that the radius varies along the cross-section midline, the buckling behavior is more difficult to identify than those of cylindrical shells. The general concerned aspects in cylindrical shell buckling analyses such as the buckling mode, the pre-buckling deformation and post-buckling deformation are all quite different related to specific elliptical shell geometry. The buckling behavior of elliptical cylindrical shells with uniform thickness has been widely studied by many researchers. However, the thickness around the circumference may change for some specific structural forms, the femoral neck for example, which makes the buckling behavior more complex. It is known that the buckling strength of thin cylindrical shells is quite sensitive to imperfections, so it is natural to explore the imperfection sensitivity of elliptical shells. This paper explores the buckling behavior of imperfect elliptical shells under axial compression. It is hoped that the results will make a useful contribution in this field.

S.M. Nowruzpour Mehrian (1), M. Molaaghaie Roozbahani (2), S. Samani Mehrain (3) and Ali Fathi (1) (1) Dept of Mechanical Engineering, University of Tehran, Tehran, Iran (2) Dept. of Mechanical Engineering, University of Semnan, Semnan, Iran (3) Dept. of Civil Engineering, Yasooj Branch, Islamic Asad University, Yasooj, Iran “Comprehensive investigation in buckling and free vibration of laminate composite cylindrical shell”, Journal of Basic and Applied Scientific Research, Vol. 3, No. 5, pp. 195-205, 2013

ABSTRACT: In this paper, the effect of compressive axial loading on natural frequency of the composite shell and the influences of geometrical parameter and the fiber orientation on the buckling load and natural frequency are studied. Bucking and free vibration of cylindrical laminate composite shell are inspected regarding to three approaches: classical theory of laminate, first order shear deformation, finite element method. The composite is taken into account as orthotropic laminate. Substituting strain-displacement based on Love’s first approximation into strain-stress equation lead to yield equilibrium equations respect to displacement components. The boundary conditions are considered clamp on one side and free on other. The components of displacement are
considered as double Fourier’s series which is more general and precise. A remarkable accuracy has been admitted by comparing the results with other available references.


ABSTRACT: In this paper, creep buckling and post-buckling of a hybrid laminated viscoelastic functionally graded material (FGM) cylindrical shell under in-plane loading are investigated. Considering the high-order transverse shear deformation and geometric nonlinear theory, the von Karman geometric relation of the hybrid laminated viscoelastic FGM cylindrical shell with initial deflection is established. Based on the Donnell theory, elastic piezoelectric theory and Boltzmann superposition principle, nonlinear creep governing equations of the hybrid laminated viscoelastic FGM cylindrical shell under in-plane loading are derived. By means of the finite difference method and the Newton–Newmark method, the problem for creep buckling and post-buckling of the laminated shell’s structure is solved. Numerical results are presented to show effects of geometric parameters, power law index and loading on creep buckling and post-buckling of the hybrid laminated viscoelastic FGM cylindrical shell.

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ABSTRACT: Postbuckling behavior of laminated shell panel in thermal environment is reported in this article. The geometric nonlinearity is introduced in Green–Lagrange sense and the model is developed for the geometrically large translations and/or rotations and the excess thermal deformation of the curved panel based on higher order shear deformation theory (HSDT) using nonlinear finite element. The governing equation of shell panel is derived by minimizing the energy expression. The postbuckling strength in terms of temperature ratio (postbuckling to buckling temperature) of the panel by obtained by a direct iterative method. The results are obtained using the developed model and compared with those of the available published literature. Some of the new results are computed for different parameters such as layup sequences, thickness ratios, amplitude ratios, boundary conditions, aspect ratios, and various curvature ratios and presented.


ABSTRACT: A nonlinear finite element analysis of impact response and impact-induced damage in curved composite laminates subjected to transverse impact by a foreign object is carried out. An eight-noded isoparametric quadrilateral shell element incorporating a nonlinear strain displacement relation due to large deflection is developed based on the total Lagrangian approach. The nonlinear system of equations is solved using a Newton–Raphson incremental-iterative method. Example problems of graphite/epoxy cylindrically curved laminates with different curvature are considered and the influence of geometrical nonlinearity on the impact response and the resulting damage is demonstrated. The concurrent effect of material degradation due to impact damage is also investigated.
References listed at the end of the paper:


ABSTRACT: The problem on normal low-velocity impact of an elastic sphere upon an elastic spherical shell is studied with considering the changes in the geometrical dimensions of the contact domain. At the moment of impact, shock waves (surfaces of strong discontinuity) are generated in the target, which then propagate along the body during the process of impact. Behind the wave fronts up to the boundary of the contact domain, the solution is constructed with the help of the theory of discontinuities and one-term ray expansions. Nonlinear Hertz’s theory is employed within the contact region. For the analysis of the processes of shock interactions of the elastic sphere with the spherical shell, nonlinear integro-differential equation has been obtained with respect to the value characterizing the local indentation of the impactor into the target, which has been solved analytically in terms of time series with integer and fractional powers.

References listed at the end of the paper:

ABSTRACT: The problem on normal low-velocity impact of an elastic falling body upon an elastic spherical shell is studied. At the moment of impact, shock waves (surfaces of strong discontinuity) are generated in the target, which then propagate along the body during the process of impact. Behind the wave fronts upto the boundary of the contact domain, the solution is constructed with the help of the theory of discontinuities and one-term or multiple-term ray expansions. Nonlinear Hertz’s theory and linearized elastic contact laws are employed within the contact region. For the analysis of the processes of shock interactions of the elastic sphere or elastic spherically-headed rod with the spherical shell, nonlinear integro-differential equation has been obtained with respect to the value characterizing the local indentation of the impactor into the target, which has been solved analytically in terms of time series with integer and fractional powers. In the case of the linear elastic shock interactions, the governing differential equations for the target and the impactor are solved analytically by the ray method.


ABSTRACT: Large amplitude (geometrically non-linear) vibrations of doubly curved shallow shells with rectangular base under the low-velocity impact by an elastic sphere are investigated. It is assumed that the shell is simply supported and partial differential equations are obtained in terms of shell's transverse displacement and Airy's stress function. The local bearing of the shell and impactor's materials is neglected with respect to the shell deflection in the contact region. The equations of motion are reduced to a set of infinite nonlinear ordinary differential equations of the second order in time and with cubic and quadratic nonlinearities in terms of the generalized displacements. Assuming that only two natural modes of vibrations dominate during the process of impact and applying the method of multiple time scales, the set of equations is obtained, which allows one to find the time dependence of the contact force and to determine the contact duration and the maximal contact force.

References listed at the end of the paper:
vibrations of thin bodies has been utilized for solving nonlinear equations. The new approach enables one to uncouple the linear parts of equations of motion of the plate, while the same method, coupled, were solved by the method of multiple time scales. A new approach proposed in [2] allows one to find an additional combinational resonance of the additive-difference type, as well as to solve the problems of vibrations of thin bodies more efficiently.
ABSTRACT: Based on the elasto-plastic mechanics, the damage analysis and dynamic response of an elasto-plastic laminated composite shallow spherical shell under low velocity impact are carried out in this paper. Firstly, a yielding criterion related to spherical tensor of stress is proposed to model the mixed hardening orthotropic material, and accordingly an incremental elasto-plastic damage constitutive relation for the laminated shallow spherical shell is founded when a strain-based Hashin failure criterion is applied to assess the damage initiation and propagation. Secondly, using the presented constitutive relations and the classical nonlinear shell theory, a series of incremental nonlinear motion equations of orthotropic moderately thick laminated shallow spherical shell are obtained. The questions are solved by using the orthogonal collocation point method, Newmark method and iterative method synthetically. Finally, a modified elasto-plastic contact law is developed to determine the normal contact force and the effect of damage, geometrical parameters, elasto-plastic contact and boundary conditions on the contact force and the dynamic response of the structure under low velocity impact are investigated.

References listed at the end of the paper:


ABSTRACT: Large deflection dynamic responses of laminated composite cylindrical shells under impact are analyzed by the geometrically nonlinear finite element method based on a generalized Sander’s shell theory with the first order transverse shear deformation and the von-Karman large deflection assumption. A modified indentation law with inelastic indentation is employed for the contact force. The nonlinear finite element equations of motion of shell and an impactor along with the contact laws are solved numerically using Newmark’s time marching integration scheme in conjunction with Akay type successive iteration in each step. The ply failure region of the laminated shell is estimated using the Tsai-Wu quadratic interaction criteria. Numerical results, including the contact force histories, deflections and strains are presented and compared with the ones by linear analysis. The effect of the radius of curvature on the composite shell behaviors is investigated and discussed.

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Natalia I. Obodan (1), Olexandr G. Lebedeyev (2) and Vasilii A. Gromov (1)
ABSTRACT: A boundary problem for thin elastic shells is formulated. The generally acceptable geometrical (straight normal) and physical (linear elasticity) hypotheses which underlie the relations are considered. Geometrical nonlinearity of shell deformation is taken into account. Equilibrium equations expressed via the displacements of shell middle surface are presented as governing relations. Tangent and bending boundary conditions along the arbitrary shell contour (free and clamped edge, free-hinge and fixed-hinge, elastic support) are formulated. A set of previously satisfied conditions (regularity of shell surface and material, piecewise continuity of shell contour and of boundary support parameters) is implemented and the concept of a generalized solution is introduced. The small perturbation of a vector-function of a generalized solution is considered, becoming the basis of investigation of non-uniqueness of the generalised solution, and of branching of the solutions.

References listed at the end of the paper:

Yury A. Rossikhin and Marina V. Shitikova (Research Center of Wave Dynamics, Voronezh State University of Architecture and Civil Engineering, Voronezh, 394006, Russia), “A new approach for studying nonlinear dynamic response of a thin fractionally damped plate with 2:1 and 2:1;1 internal resonances”, Chapter in Shell and Membrane theories in Mechanics and Biology, Vol. 45 of the series Advanced Structured Materials, pp 267-288, September 2014, DOI: 10.1007/978-3-319-02535-3_15
ABSTRACT: Dynamic behaviour of a nonlinear plate embedded in a fractional derivative viscoelastic medium and subjected to the conditions of the internal resonances two-to-one and one-to-one, as well as the internal combinational resonances has been studied by Rossikhin and Shitikova in [12, 13]. Nonlinear equations, the linear parts of which occur to be coupled, were solved by the method of multiple time scales. A new approach proposed in this paper allows one to uncouple the linear parts of equations of motion of the plate, while the same method, the method of multiple time scales, has been utilized for solving nonlinear equations. The new approach enables one to solve the problems of vibrations of thin bodies more efficiently.

References listed at the end of the paper:
ABSTRACT: Non-linear vibrations of a cylindrical shell embedded in a fractional derivative viscoelastic medium and subjected to the different conditions of the internal resonance of the order of \( \varepsilon \), where \( \varepsilon \) is a small value, are investigated. The displacement functions are determined in terms of eigenfunctions of linear vibrations. The procedure resulting in decoupling linear parts of equations is proposed with the further utilization of the method of multiple scales for solving nonlinear governing equations of motion, in so doing the amplitude functions are expanded into power series in terms of the small parameter and depend on different time scales. The influence of viscosity on the energy exchange mechanism is analyzed. It is shown that each mode is characterized by its damping coefficient connected with the natural frequency by the exponential relationship with a negative fractional exponent. Comparison of the results obtained in this paper for the nonlinear shallow cylindrical shell in the cases of the internal resonance of the order of \( \varepsilon \) with those for a nonlinear plate, the motion of which is described also by three coupled nonlinear equations in terms of three displacements, reveals the fact that the shell equations could produce much more diversified variety of internal resonances, including combinational resonances of the additive and difference types, than the plate equations.

References listed at the end of the paper:

ABSTRACT: Nonlinear vibrations of a cylindrical shell embedded in a fractional derivative viscoelastic medium and subjected to the different conditions of the internal resonance are investigated. The viscous properties of the surrounding medium are described by Riemann-Liouville fractional derivative. The displacement functions are determined in terms of eigenfunctions of linear vibrations of a free-simply supported shell. A novel procedure resulting in decoupling linear parts of equations is proposed with the further utilization of the method of multiple scales for solving nonlinear governing equations of motion by expanding the amplitude functions into power series in terms of the small parameter and different time scales. It is shown that the phenomenon of internal resonance can be very critical, since in a circular cylindrical shell the one-to-one, two-to-one, and three-to-one internal resonances, as well as additive and difference combinational resonances are always present. The three-to-one internal resonance is analyzed in detail. Since the internal resonances belong to the resonances of the constructive type, i.e., all of them depend on the geometrical dimensions of the shell under consideration and its mechanical characteristics, that is why such resonances could not be ignored and eliminated for a particularly designed shell. It is shown that the energy exchange could occur between two or three subsystems at a time: normal vibrations of the shell, its torsional vibrations and shear vibrations along the shell axis. Such an energy exchange, if it takes place for a rather long time, could result in crack formation in the shell, and finally to its failure. The energy exchange is illustrated pictorially by the phase portraits, wherein the phase trajectories of the phase fluid motion are depicted.


ABSTRACT: The buckling behaviour of functionally graded cylindrical panels under thermal loading is investigated in this article. In functionally graded material, material properties vary smoothly from metal phase to ceramic phase. In this study, the effective material properties of the functionally graded panels are considered as temperature dependent and the gradation is taken in the transverse direction according to the power-law distribution of volume fractions of each constituent. Thermal buckling behaviour of cylindrical panel has been obtained numerically through ANSYS based on the ANSYS parametric design language code. The model has been discretised using an eight node serendipity element with six degrees of freedom per node (SHELL281) from the ANSYS library. The solutions are obtained by solving the eigenvalue type buckling using Block Lanczos method. The accuracy of the model has been checked through corresponding convergence and comparison study with those available literatures. Finally, the simulation model has been extended to study the effect of different parameters such as power-law index, thickness ratio, curvature ratio and aspect ratioon buckling strength for both temperature independent and dependent material properties of each constituent.

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Thai, H.T. and Choi D.H. (2012), An efficient and simple refined theory for buckling analysis of functionally graded plates, Applied
ABSTRACT: The U.S. Department of Energy, Office of River Protection has commissioned a structural analysis of record for the Hanford single shell tanks to assess their structural integrity. The analysis used finite element techniques to predict the tank response to the historical thermal and operating loads. The analysis also addressed the potential tank response to a postulated design basis earthquake. The combined response to static and seismic loads was then evaluated against the design requirements of American Concrete Institute standard, ACI-349-06, for nuclear safety-related concrete structures. Further analysis was conducted to estimate the plastic limit load and the elastic-plastic buckling capacity of the tanks. The limit load and buckling analyses estimate the margin between the applied loads and the limiting load capacities of the tank structure. The potential for additional dome loads from waste retrieval equipment and the addition of large dome penetrations to accommodate retrieval equipment has generated additional interest in the limit load and buckling analyses. This paper summarizes the structural analysis methods that were used to evaluate the limit load and buckling of the single shell tanks.

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Some early papers by Dao Van Dung et al:

Other papers by Dao Van Dung:
Dao Van Dung and Hoang Van Tung (Dept. of Mathematics, College of Science, Vietnam National University, Hanoi, Vietnam), “Stability of the elastoplastic thin round cylindrical shells subjected to torsional moment at two extremities”, Vietnam National University Journal of Science, Mathematics, Physics, T.XXI, NO. 3, 2005

ABSTRACT: An elastic stability problem of the thin round cylindrical shells subjected to torsional moment at two extremities has been investigated in the paper [6]. By the small elastoplastic deformation theory and by the flow theory, this problem again has been studied in [2] and [4]. Basing on the theory of elastoplastic processes the above mentioned problem has been solved by approach simulation of instability form of the cylinder (see [1,][5]). In this paper, the solution of problem in the real bending form of structure has been found. We have also established the relations for determining critical force. Some numerical results for a linear hardening material have been given and discussed.

References listed at the end of the paper:

Dao Van Dung and Le Kha Hoa (Vietnam National University, Hanoi, Viet Nam), “Nonlinear analysis of
ABSTRACT: This paper presents an analytical approach to analyze the nonlinear stability of thin closed circular cylindrical shells under axial compression with material properties varying smoothly along the thickness in the power and exponential distribution laws. Equilibrium and compatibility equations are obtained by using Donnell shell theory taking into account the geometrical nonlinearity in von Karman and initial geometrical imperfection. Equations to find the critical load and the load-deflection curve are established by Galerkin’s method. Effects of buckling modes, of imperfection, of dimensional parameters and of volume fraction indexes to buckling loads and postbuckling load-deflection curves of cylindrical shells are investigated. In case of perfect cylindrical shell, the present results coincide with the ones of the paper [13] which were solved by Ritz energy method.
References listed at the end of the paper:
[14] Huang H., Han Q., Nonlinear buckling of torsion - loaded functionally graded cylindrical shells in thermal environment,
ABSTRACT: In this paper, the nonlinear buckling and post-buckling of an eccentrically stiffened cylindrical shell made of functionally graded materials, surrounded by an elastic medium and subjected to mechanical compressive loads and external pressures are investigated by an analytical approach. The cylindrical shells are reinforced by longitudinal and circumferential stiffeners. The material properties of cylindrical shells are graded in the thickness direction according to a volume fraction power-law distribution. The non-linear stability equations for stiffened cylindrical shells are derived by using the first order shear deformation theory and smeared stiffeners technique. Closed-form expressions for determining the buckling load and load-deflection curves are obtained. The effectiveness of stiffeners in enhancing the stability of cylindrical shells is shown. The effects of volume fraction indexes, material properties, geometrical parameters and foundation parameters are analyzed in detail.

ABSTRACT: This paper is concerned with the mechanical buckling load of an eccentrically stiffened truncated conical shells made of functionally graded materials and subjected to axial compressive load and external uniform pressure by analytical method. Shells are reinforced by stringers and rings. The change of spacing between stringers in the meridional direction is taken into account. Material properties of shell are graded in the thickness direction according to a volume fraction power-law distribution. The equilibrium and linearized stability equations for stiffened shells are derived based on the classical shell theory and smeared stiffeners technique. The resulting equations which they are the couple set of three variable coefficient partial differential equations in terms of displacement components are investigated by Galerkin method and the closed-form expression for determining the buckling load is obtained. The effects of stiffeners, material and dimensional parameters are analyzed in detail.

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ABSTRACT: A semi-analytical approach eccentrically stiffened functionally graded circular cylindrical shells surrounded by an elastic medium subjected to external pressure is presented. The elastic medium is assumed as two-parameter elastic foundation model proposed by Pasternak. Based on the classical thin shell theory with the geometrical nonlinearity in von Karman–Donnell sense, the smeared stiffeners technique and Galerkin method, this paper deals with the nonlinear dynamic problem. The approximate three-term solution of deflection shape is chosen and the frequency–amplitude relation of nonlinear vibration is obtained in explicit form. The nonlinear dynamic responses are analyzed by using fourth order Runge–Kutta method and the nonlinear dynamic buckling behavior of stiffened functionally graded shells is investigated according to Budiansky–Roth criterion. Results are given to evaluate effects of stiffener, elastic foundation and input factors on the frequency–amplitude curves, natural frequencies, nonlinear responses and nonlinear dynamic buckling loads of functionally graded cylindrical shells.


ABSTRACT: Using a simple constitutive law for elastic behavior that includes the feature of a maximum allowable strain, equations are derived for inflation pressure as a function of the amount of inflation for three rubber shells: a thin-walled spherical balloon, a small spherical cavity in a large rubber block, and a thin-walled cylindrical tube. The results are compared with those obtained using the neo-Hookean constitutive law. Uniform expansion is generally predicted to become unstable at a modest degree of inflation but the new relations give a second stable inflation state, in accord with experience.


ABSTRACT: The use of soft elastic biomaterials in medical devices enables substantial function integration. The consequent increased simplification in design can improve reliability at a lower cost in comparison to traditional (hard) biomaterials. Functional bi-stable buckling is one of the many new mechanisms made possible by soft materials. The buckling behavior of shells, however, is typically described from a structural failure point of view: the collapse of arches or rupture of steam vessels, for example. There is little or no literature about the functional elastic buckling of small-sized silicone rubber shells, and it is unknown whether or not theory can predict their behavior. Is functional buckling possible within the scale, material and pressure normally associated with physiological applications? An automatic speech valve is used as an example application. Silicone rubber spherical shells (diameter 30mm) with hinged and double-hinged boundaries were subjected to air pressure loading. Twelve different geometrical configurations were tested for buckling and reverse buckling pressures. Data were compared with the theory. Buckling pressure increases linearly with shell thickness and shell height. Reverse buckling shows these same relations, with pressures always below normal buckling pressure. Secondary hinges change normal/reverse buckling pressure ratios and promote symmetrical buckling. All tested configurations buckled within or closely around physiological pressures. Functional bi-stable buckling of silicone rubber shells is possible with adjustable properties in the physiological pressure range. Results can be predicted using the proposed relations and equations.

ABSTRACT: After a theoretical overview of the buckling phenomena of grid shells, current research on the stability check by numerical analysis will be discussed with a special attention on the applied geometrical imperfection. It is laborious to analyse the effect of initial member curvature and node deviation as constructional imperfections, therefore simplified methods exist such as the use of eigenshapes as imperfections. To demonstrate the effect of different imperfection shapes, a spherical cap with a Kiewitt-8 mesh type is analysed based on different analysis methods.

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ABSTRACT: This paper derives new analytical solutions for thermal bifurcation buckling of cylindrical shells made of functionally graded materials (FGMs) with temperature-dependent material properties. The Donnell’s shell theory is adopted and a symplectic solution methodology is established through the Hamiltonian variational principle. The fundamental buckling problem is then converted into the solving for the symplectic eigenvalues and eigenvectors. The solutions reveal that boundary conditions and temperature-dependent FGM properties have significant influence on thermal buckling behavior. It is also concluded that temperature field conditions cannot be neglected for FGCSs being rich in thermal sensitive compositions.

J.E. Jam and M.A. Nikjoo (Composite Materials and Technology Center, MUT, Tehran, Iran), “Buckling and free vibrations of cylindrical stiffened composite shells with internal liquid”, Research Journal of Applied Sciences, Engineering and Technology, Vol. 6, No. 19, pp. 3495-3505, October 2013

ABSTRACT: The free vibration and buckling of cylindrical composite shell with internal liquid is studied in
this study. The shell composed of several composite layers and stiffeners which are rings and stringers. The first order shear theory was used for shell and stiffeners. Stiffeners were used in equations as discrete elements. The effects of axial force, internal pressure and shell rotation about cylinder axis, were calculated. The Reily-Ritz method was used for solving the problem. The potential and kinetic energy of shell and each stiffener and kinetic energy of liquid are substituted in the functional of energy. The natural frequencies and the critical axial forces in each mode is obtained. The section shape of each stiffener is rectangle. The stringers can have variable height in their length (a parabolic shape for example) and its effect is studied for shell with and without liquid. Also stiffened composite shell with different internal pressure, different axial forces and different rotation speeds is studied. The liquid is ideal and sloshing was neglected.


DESCRIPTION: Buckling Test Facility: The buckling test facility has been continuously developed over the past 20 years and is especially designed for buckling tests on thin walled composite structures such as cylinders and panels. Due to its extreme stiffness, careful load introduction and shortening control, buckling tests of high precision can be conducted under well defined boundary conditions. The hydraulic cylinder is equipped with a small servo valve for static tests and additionally with a second valve for high dynamics. Axial compression up to 1,000 kN, torsion up to 20 kNm as well as internal pressure between 1 hPa (simulating external pressure) and 10 hPa can be applied simultaneously. The load history of axial compression ranges from static loading to shock loading. Tests of panels and shells with up to 1,600 millimeters in length and 1,200 millimeters in width (diameter) can be performed. The high-precision buckling test results serve as a reference for the development of fast computational procedures to simulate buckling and post buckling behavior of thin walled structures, as they are required for concurrent/integrated engineering. In addition, proof tests of real structural components with respect to their buckling and post-buckling behavior can be conducted. So far, several buckling tests were conducted within ESA contracts and EU projects such as DEVILS (Design and Validation of Imperfection-Tolerant Laminated Shells), POSICOSS (Improved Post-buckling Simulation for Design of Fiber Composite Stiffened Fuselage Structures) and the current project COCOMAT (Improved Material Exploitation at Safe Design of Composite Airframe Structures by Accurate Simulation of Collapse). Technical Details: The capacity of the axial load is 1,000 kN. The hydraulic cylinder is equipped with a small servo-valve for quasi-static tests which enables very smooth controlling of the displacement. Additionally, a second valve is provided for very high dynamics as required for dynamic buckling or shock tests. Axial compression = 1,000 kN, Piston acceleration = 1,500 m/s², Piston velocity = 0.675 m/s, Piston frequency (ampl.1 mm) = 100 Hz, Torsion moment = 50 kNm, Shear load (for panels) = 200 kN, Specimen length = 1,600 mm, Specimen width = 1,200 mm. Measurement Equipment: 200 measurement points for strain gauges and displacement transducers are scanned by 1 kHz for static tests, and 72 measuring points by 400 kHz for dynamic tests. Four self-sustaining fast ARAMIS systems, each of which is able to measure the 3-dimensional deformation field at a speed of 1,000/sec, can be coupled, resulting in a maximum speed of 4,000/sec. This system provides much more information on the dynamics of buckling deformations than previously achieved.

ABSTRACT: Nanomechanics and real-time buckling deformation of an individual multi-walled carbon nanotube (MWCNT) were investigated through in situ nanoindentation within a transmission electron microscope (TEM). These in situ observations reveal a significant shell-to-Euler phase transformation in the buckling response of the nanotube. Objective evidences that the MWCNT possesses time-dependent characteristic were first suggested by combining in situ TEM nanoindentation performed strain rate influences on an individual MWCNT with classical molecular dynamics simulations. Structural evolutions and buckling instabilities for thin-wall and thick-wall CNTs are theoretically studied, indicating the role of the tube thickness and interwall van der Waals interactions in governing buckling behavior.

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“Torsional buckling behavior of SWDNTs using a molecular structural mechanics approach considering vacancy defects”, Fullerenes, Nanotubes and Carbon Nanostructures, Vol. 20, No. 8, pp. 709-720, 2012
DOI: 10.1080/1536383X.2011.572311

ABSTRACT: In this paper, the influence of various vacancy defects on the critical buckling torques and twist angles in single-walled carbon nanotubes (SWCNTs) under torsional load is investigated using a new structural model built using the ABAQUS software. This model is a combination of other structural models and is designed to eliminate the deficiencies inherent in each of the individual approaches. For the first time, the effect of different types of vacancy defects on critical buckling torque and twist angle is studied for zigzag and armchair nanotubes of various lengths. The results show that vacancy defects have a considerable impact on the critical buckling torque. Moreover, zigzag nanotubes are found to be more sensitive to these defects than armchair nanotubes. The results obtained here are compared with those obtained using the continuum model, and reasonable agreement is observed.


ABSTRACT: Within this contribution, buckling of tubular steel shells with circular cutout will be analyzed. The experimental results will be compared by FEM simulation results within circular cutouts of the specimen. The experimental buckling tests have been conducted using a Servo-hydraulic machine (Instron 8802). Considering the broad application range of tubular thin-walled shells, prediction of the behavior of these elements in combined loading case (especially for buckling behavior) has gained a great level of importance. In this study, the influence of shell length, shell diameter, shell angle and diameter of circular cutouts on the predicted buckling values for the tubular shell has been explored. Numerical simulations of tubular shell subjected to combined loading were conducted. The analytical solutions show excellent agreement with the numerical results predicted by FEM.

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“Effect of sandwich shear deformation and shell taper angle on elastic buckling of large-scale composite

ABSTRACT: The elastic buckling problem of large-scale composite sandwich tubes in a satellite structure is analyzed. The geometry equations, constitutive equations and strain energy expressions of cylinder shell, conical shell and frames are constructed separately. And the potential energy of external forces is obtained under given loading conditions. According to the boundary conditions, the trigonometric series are applied to describing the displacement field. The principle of minimum potential energy is used to determine the critical load. The critical loads are obtained considering or neglecting the effects of sandwich shear deformation and shell taper angle separately, and then they are compared between the two conditions, demonstrating that the maximum error is less than 10%. Based on this research, a simplified method can be applied in the design stage of the large-scale composite sandwich tube in engineering.

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ABSTRACT: Using the static-dynamic analogy, work at Bath and Bristol has uncovered the vital organizing role of the Maxwell ‘energy criterion’ load in the advanced post-buckling of long-thin structures which exhibit severe shell-like imperfection sensitivity. It has become clear that above the Maxwell load, PL, there are localized solutions offering an order-of-magnitude increase in sensitivity to lateral side-loads, whether static or dynamic. We propose to call this ‘shock-sensitivity’, and notice that so far only the seminal paper by Horak, Lord and Peletier in 2006 has quantified this in terms of an E(P) energy-barrier versus load graph. In this paper we present three graphs of this nature for archetypal problems: the free twisted rod, the cylindrically constrained rod, and the strut on a softening elastic foundation. We find in all cases that the energy barrier of the localizing solution above PL is quite close to the energy of a single periodic wave. Now a single such wave is not kinematically admissible, and the corresponding periodic barrier must be for all the waves in the long structure, N, say. So in practice N will be large, and does indeed tend to infinity with the length of the structure. Thus the shock sensitivity increases by a factor of a large N as the Maxwell load is exceeded. This is important in its own right, and we do not seek to explain or fit curves to the scattered experimental buckling loads of shell structures.

References listed at the end of the paper:

ABSTRACT: The object of this paper is to obtain all the stress resultants of an anisotropic (2n+1) layers plywood shell. The differential equations of equilibrium of (2n+1) layers plywood shell under three simultaneous loads are obtained. The solution of the differential equations for anisotropic (2n+1) layers plywood shell in case of two way compressions is obtained here. The stable region for a plywood shell in this case is obtained. Buckling diagram for five layers plywood shell and seven layers plywood shell are shown graphically as special cases.

References listed at the end of the paper:

Yifan Zhang (1,2) Teng Lu (1) Xiping Zeng (1,2) Haijun Zhou (3) Hongxia Guo (1) Elmar Bonaccurso (4) Hans-Juergen Butt (5) Jianjun Wang (1) Yanlin Song (1) and Lei Jiang (1)
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ABSTRACT: In this paper we report a surface-mediated growth process for oriented anisotropic particles with
tunable morphologies. The morphology of the anisotropic particles can be tuned and the generality of this process is checked. This process also provides a new avenue for constructing ensembles of anisotropic particles.

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“Studying Effect of Geometrical Parameters on the Buckling of Cylindrical Shells under Hydrostatic Pressure”,
Indian Journal of Science & Technology, Vol. 6, No. 11, November 2013
ABSTRACT: In this paper, we study the effect of diameter and thickness of a shell as well as the reinforcement rings on buckling of cylindrical shells under external hydrostatic pressure. Bucking equations are based on standard of ABC underwater vessels. Using the relations in different diameters, tolerable buckling load has been obtained with shell, by changing the thickness of shell and distance of reinforcement rings in definite range. Results obtained from buckling pressure in different diameters and for different ratios of D/t and D/L are given and finally a diagram has been presented for designing and determining different parameters of reinforced cylindrical shell after comparing them.

References:


ABSTRACT: The present work aims the vibration and parametric instability of functionally graded material rectangular plates with simply supported boundary condition, subjected to a biaxial in-plane periodic loading. First order shear deformation theory is used for theoretical formulation of FGM plates. The properties of the
functionally graded material plates are assumed to vary along the thickness direction according to a power law distribution in terms of the volume fractions of the constituents. Hamilton’s principle is employed to convert the governing equations into a linear system of Mathieu–Hill equations from which the boundary of stable and unstable regions are determined by using Floquet’s theory on the parameter space. Natural frequency and buckling analysis are also discussed. Numerical results are presented in both dimensionless parameters and graphical forms for FGM plates made of steel and alumina. The influences of various parameters such as index value, aspect ratio on the buckling load and natural frequencies are examined. Power law index value and aspect ratio effects on the dynamic stability regions also studied in detail.

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ABSTRACT: This paper presents the results of complementary numerical study done in the continuation of the activities carried out by the Committee III.1 “Ultimate Strength” of ISSC’2003 (Ref. [28]). The main focus of the paper concerns the post-buckling behaviour and strength characteristics of the aluminium multi-stiffened panels under combined axial compression and lateral pressure. The finite element model proposed by the Committee III.1 “Ultimate Strength” of ISSC’2003 is used in the present investigation. Material is aluminium alloy AA6082-T6 and the multi-stiffened panel is a triple-span structure. Stiffeners are of either extruded or non-extruded angle-bar profiles. An initial deflection is imposed on the model in a procedure similar to that applied by the Committee III.1. General purpose finite element code ANSYS is used for non-linear elastic-plastic analyses. Main objectives are to study the influence of initial deflections and also HAZ on the post-buckling behaviour and collapse characteristics of aluminium stiffened panels under combined axial compression and lateral pressure. Different values of lateral pressure are exerted on the model in a systematic manner to simulate various levels of lateral pressure loading on multi-stiffened aluminium panels used in the construction of high-speed crafts.


ABSTRACT: The decomposition of buckling modes of thin-walled members subjected to axial stresses is a topic of great practical interest which can be achieved using the generalised beam theory (GBT) or the constrained finite strip method (cFSM). However, the latter is not general enough to study prismatic members with arbitrary cross-sections and the objective of this paper is to extend the cFSM to allow the buckling modes decomposition for prismatic members with branches and/or closed parts. To define the combined GD buckling mode, two assumptions are used: (i) cylindrical plate bending and (ii) negligible in-plane transverse/shear strains. The corresponding constraint matrix, RGD, is derived in a simple and general way. The methodology used to separate the global and distortional modes is similar to that used in the original cFSM while the derivation of the constraint matrix for local modes remains identical. Some examples are considered and the pure buckling curves are compared to the conventional FSM results. The conclusion is that the new cFSM has successfully computed the GD and the L modes of these sections.


ABSTRACT: In this paper, we study buckling of ionic polymer metal composite (IPMC) pipes under uniaxial compression. A novel methodology to fabricate shell-like IPMCs is developed by combining hot pressing and chemical reduction. In the compression tests, IPMC pipes of varying thickness are clamped at their ends through custom-made fixtures and both short-circuit current and deformation are recorded as a function of the applied load. Experimental results are interpreted using classical findings on the buckling of thin shells and finite element simulations. Our results demonstrate that IPMC buckling can be accurately sensed through the short-circuit current, which is nearly zero during the loading phase, before suddenly increasing at the onset of the elastic instability. The buckling patterns of the samples are largely non-axisymmetric with a number of lobes appearing along the axial and circumferential directions of the IPMC pipes.

Linfeng Shen; Youngsu Cha; Adel Shams; Maurizio Porfiri (Polytechnic Institute of New York University, USA), “Buckling of an ionic polymer metal composite shell under uniaxial compression”, SPIE Proceedings, Vol. 9056, Conducting Polymers and IMPC, Electroactive Polymer Actuators and Devices (EAPAD) 2014, 90561X (March 8, 2014); doi:10.1117/12.2044619

ABSTRACT: In this paper, we analyze buckling of an ionic polymer metal composite (IPMC) shell subjected to uniaxial compression. A new technique is developed to fabricate tubular IPMCs using hot molding and a chemical reduction process. The short-circuit current and the mechanical deformation of the sample are recorded during the compression test. Experimental findings demonstrate that IPMC buckling can be accurately sensed via the short-circuit current, which is approximately zero during the loading phase, before exhibiting a sudden increase at the onset of the elastic instability.

Badri Prasad Patel (Department of Applied Mechanics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, 110016, India), “Thermal buckling/postbuckling characteristics of laminated composite shells”, Encyclopedia of Thermal Stresses, pp 4926-4931

EXCERPT: The laminated conical-cylindrical shells may be subjected to extreme thermal environment during their service life. The developed compressive thermal membrane state of stress due to the boundary constraints may lead to thermoelastic instability/buckling. An estimate of the critical bifurcation temperature can be made through a linear eigenvalue analysis, whereas the sensitivity to the imperfections and postbuckling behavior can be evaluated by means of nonlinear analysis, generally, incorporating an imperfection affine to the critical buckling mode evaluated from the eigenvalue analysis. The circular shells can be analyzed using computationally efficient semi-analytical axisymmetric finite element incorporating axisymmetric and asymmetric deformation components in the circumferential approximation of the displacement field variables.
Noncircular shells are analyzed using two-dimensional (2D) shell finite elements formulated in curvilinear coordinate system. To eliminate ...

References listed at the end of the paper:

ABSTRACT: Syntactic foams are particulate composites that are obtained by dispersing thin hollow inclusions in a matrix material. The wide spectrum of applications of these composites in naval and aerospace structures has fostered a multitude of theoretical, numerical, and experimental studies on the mechanical behavior of syntactic foams and their constituents. In this work, we study static and dynamic axisymmetric buckling of single hollow spherical particles modeled as non-linear thin shells. Specifically, we compare theoretical predictions obtained by using Donnell, Sanders–Koiter, and Teng–Hong non-linear shell theories. The equations of motion of the particle are obtained from Hamilton’s principle, and the Galerkin method is used to formulate a tractable non-linear system of coupled ordinary differential equations. An iterative solution procedure based on the modified Newton–Raphson method is developed to estimate the critical static load of the microballoon, and alternative methodologies of reduced complexity are further discussed. For dynamic buckling analysis, a Newmark-type integration scheme is integrated with the modified Newton–Raphson method to evaluate the transient response of the shell. Results are specialized to glass particles, and a parametric study is conducted to investigate the effect of microballoon wall thickness on the predictions of the selected non-linear shell theories. Comparison with finite element predictions demonstrates that Sanders–Koiter theory provides accurate estimates of the static critical load for a wide set of particle wall thicknesses. On the other hand, Donnell and Teng–Hong theories should be considered valid only for very thin particles, with the latter theory generally providing better agreement with finite element findings due to its more complete kinematics. In this context, we also demonstrate that a full non-linear analysis is required when considering thicker shells, while simplified treatment can be utilized for thin particles. For dynamic buckling, we confirm the accuracy of Sanders–Koiter theory for all the considered particle thicknesses and of Teng–Hong and Donnell theories for very thin particles.

ABSTRACT: Shallow spherical shell is an important kind of sensor elastic element. Because of the particular metal material texture, it can work under high temperature field. The nonlinear buckling problems of shallow spherical shell in load and temperature field are very important. In this paper, nonlinear buckling of shallow spherical shell under uniform pressure and temperature field in simply supported boundary conditions is studied by the modified iteration method, and the analytic formulas for determining the critical buckling load are obtained. The effect of temperature field on critical buckling load and critical geometrical parameter are discussed.

ABSTRACT: Suction caissons are a foundation system, most commonly used in the offshore petroleum industry, and also considered applicable as a foundation for offshore wind turbines. Due to relative thin wall thickness compared to the caisson diameter, buckling of the cylindrical caisson during installation with underpressure becomes a structural design issue. Partial to full embedment of the suction caissons offer lateral support from the soil against shell buckling. Different simplified methods for incorporating the lateral soil support in the structural FEM-models are used by the industry in buckling design of suction caissons. This article compares two different methods for constructing non-linear soil springs. The two different sets of soil springs are applied to a case history, where the installation of four suction caissons is back-calculated.


ABSTRACT:


ABSTRACT: Axially crushed thin-walled tubular structures are extensively used as energy absorbers in various automotive and aerospace applications because of their high energy absorption efficiency and long strokes. Various experimental and numerical studies in the past have revealed that a thin-walled square tube can undergo mainly three modes of deformation, progressive crushing/buckling, dynamic plastic buckling and global bending depending up on the loading conditions and tube geometry among many factors. Out of these three, progressive crushing/buckling is the most desired mode of collapse for efficient energy absorption. Moreover, crushing starting from one end progressing systematically towards the other end is preferred because of availability of more space/material for plastic deformation without jamming resulting in increased peak forces. A thin square tube can show four possible modes of collapse during progressive crushing depending up on the ratio of width to thickness. The mean crush load for extensional mode of collapse is higher than the other three modes resulting in higher energy absorption during the overall crushing event. The crush behavior of thin square columns in case of oblique impact is highly dependent on the angle of impact. In the situations when impact angle is higher than a critical value, the mean crush load may drop by 40% than the axial crushing load because of global bending. In this paper, a novel approach based on compliant mechanism design which is extensively employed in topology optimization of MEMS is used to design the thin-walled square tubes. The ability of a compliant mechanism to transfer or transform displacement, force or energy from an input load location to the desired output locations is utilized to enforce the desired buckle zones in the axial member. A biologically inspired, gradient free hybrid cellular automata (HCA) method is used to synthesize compliant mechanisms with elemental thickness distribution governed by an energy like functional, mutual potential energy (MPE). Nonlinear explicit finite element code LS-DYNA is used to simulate quasi-static axial crushing of the thin square columns in this paper. Numerical results show that progressive crushing in a desired mode of collapse can be enforced in axial and oblique loading conditions using the proposed methodology.

Aviation Technology (ASAT-13), May 26-28, 2009, Military Technical College, Kobry Elkobbah, Cairo, Egypt

ABSTRACT: Typical steel square plates of 300mm side length and 1mm thickness were used to simulate six tubes with different cross-sections. These cross-sections were selected symmetric from round-shapes as circle and ellipse and polygon-shapes as triangle, square, pentagon and hexagon. The effect of varying configurations of tube cross-section shape on the deformation response, collapse mode and energy absorption characteristics of tubes under quasi-static axial compression have been studied numerically. The commercial finite element package ABAQUS/Explicit was used in the present analysis. The axial load-displacement results accompanied by the fold formation of various tubes were investigated and compared with published experimental work. Variation of the initial peak load and the mean crushing force with the tube side breadth and the fold depth were carefully examined. Based on the finite element simulation results, empirical formulas for the absorbed energy and the fold depth were developed as a function of the side breadth-to-thickness ratio of the tubes.

References listed at the end of the paper:


ABSTRACT: This paper presents an investigation concerning the mechanics of deformation of thin-walled steel tubular members with single-cell regular polygonal cross-sections, such as those employed to build transmission line structures, towers, antennas and masts. This type of cross-sections exhibit rotational symmetry of order equal to the number of walls, which leads to remarkable peculiarities concerning the cross-section in-plane and out-of-plane (warping) deformation. The investigation is based on a specialization of Generalised Beam Theory (GBT), aiming at fully uncoupling the main cross-section deformation mode sets, which makes it possible to obtain analytical results and thus extract in-depth information concerning the structural behaviour of this type of members. Several illustrative examples, employing both analytical and numerical (using GBT-based beam finite elements) strategies, are presented throughout the text. For validation and comparison purposes, results obtained with standard shell finite element models are also provided.

ABSTRACT: This paper investigates the elastic buckling (bifurcation) behaviour of uniformly compressed thin-walled tubular members with single-cell regular polygonal cross-sections (RCPS), such as those employed to build transmission line structures, towers, antennas and masts. A specialisation of Generalised Beam Theory (GBT) for RCPS, reported in a recent paper (Gonçalves and Camotim, 2013) [1], is used to obtain both analytical and numerical results concerning the most relevant buckling modes and provide novel and broad conclusions on the structural behaviour of this type of members. In particular, local, cross-section extensional, distortional and multi-mode (including global flexural) buckling phenomena are addressed. For validation purposes, the GBT-based results are compared with solutions taken from the literature and also with numerical values obtained from finite strip analyses.

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“Buckling behavior of thin-walled regular polygonal tubes subjected to bending or torsion”, Thin-Walled Structures, Vol. 73, pp 185-197, December 2013, DOI: 10.1016/j.tws.2013.08.006
ABSTRACT: In a recent paper (Gonçalves and Camotim, 2013 [1]), the authors presented an investigation concerning the buckling (bifurcation) behaviour of uniformly compressed thin-walled tubes with regular polygonal cross-sections (RCPS). The present paper complements the previous work by addressing the local and distortional buckling behaviour of RCPS members subjected to bending or torsion and aims at providing a novel insight into these phenomena. In particular, the specialization of Generalized Beam Theory (GBT) for RCPS, as recently proposed in Gonçalves and Camotim (2013) [2], is employed to obtain closed-form analytical solutions and also to carry out parametric studies by means of numerical analyses which are both computationally efficient (due to the small number of d.o.f. involved) and clarifying (due to the modal decomposition features of GBT). For validation purposes, solutions taken from the literature and also standard shell finite element model results are employed.

ABSTRACT: Main bridge of Nanning Bridge is taken as Research Object. Using the finite element program ANSYS, space finite element model of an arch bridge with two inclined thin-walled steel box ribs is build, stability safety factor of the bridge is calculated, eigenvalue buckling analysis and non-linear buckling analysis of inclined thin-walled ribs are carried out, and stability performance is discussed. The result shows that stability problems of this bridge mainly occur on the ribs and are out-of-plane buckling in general, and horizontal loads have greater influences on out-of-plane buckling. The calculation results can provide parameters for construction, health detection and maintenance in the operational phase of the bridge.

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ABSTRACT: The main objective of this paper is to propose a new closed form solution, useful in the pre-design stage, that allows one to calculate the mean load in the case of post-collapse of polygonal thin-walled columns in the axial crushing case. This model gives a rapid and accurate evolution of the normalized mean load as function of the corner element angle as well as the ratio between the corner length and the column thickness. To identify the parameters of this model, numerical simulations with an explicit finite element software have been carried out and then compared to experimental results reported in the literature. Finally, all these results combined with the findings based on the known generalized mixed model developed by other researchers working on this topic enabled one to establish the closed form solution. This is a unified and continuous closed form solution, which is suitable for different columns shapes, even non-conventional shapes obtained thanks to the development of extrusion techniques.

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ABSTRACT: We present a strategy for the design of gridshells where form-found structures are optimised for buckling resistance. A genetic algorithm is employed for the initialisation of pre-stress forces required in form-finding using dynamic relaxation. Dynamic relaxation takes this initial pre-stress, a flat grid, as well as self-weight and nodal loads to calculate a static equilibrium. The structure is then analysed for the estimation of the critical buckling load. Different boundary conditions, structural parameters and typology of connections are compared, including a gridshells with triangular and quadrangular patterns. Optimised structures are measured against the trivial solution, which is a structure where dynamic relaxation is initialised with uniform pre-stress. Our results show the proposed strategy can successfully form find gridshells with improved buckling performance.
References listed at the end of the paper:

ABSTRACT: In this paper, we study the structural performance of grid shells covered with triangles and hexagons. These meshes, also known as Kagome lattices have the same node valence as quad-meshes, and thus an equivalent complexity. We present a method that guarantees the covering of free-form shapes with a Kagome lattice with planar facets, making this mesh economically viable. The performance of the Kagome lattice is assessed with two comprehensive parametric studies that vary relevant geometrical parameters like rise-over-span ratio or grid density. The linear buckling load of quadrangular and Kagome lattices is compared and shows that the Kagome lattice is up to 100% more efficient than the quadrangular mesh in the models studied.


ABSTRACT: Elastic gridshells are doubly curved grids with a shell-like behaviour, obtained by elastic deformation and bracing of a flat grid with no shear rigidity. After a brief review of their design process, the buckling of elastic gridshells is numerically investigated through a geometrically nonlinear analysis; then a formula for predicting the local buckling load is derived from the results of a parametric study. The numerical study required the development of an accurate form-finding method named "the advanced compass method" and of a specific algorithm ensuring the quick convergence of the non-linear finite element simulations, both
presented in this paper. The influence of the prestress, the eccentricity and the anisotropy of the shell are discussed, giving hence indications for correct modeling and efficient design of elastic gridshells.

References listed at the end of the paper:


Romain Mesnil (1,2), John Ochsendorf (1) and Cyril Douthe (3),
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DOI: http://dx.doi.org/10.1260/0266-3511.30.1.27
ABSTRACT: The paper presents some results on the influence of the pre-stress induced by the erection method
of elastic grid shells on their buckling capacity. It starts with the numerical methods and their validation with the study of a pre-buckled arch. Then, a form-finding scheme using low-speed dynamics is used to generate automatically a family of elastic grid shells, and their buckling capacity is compared to the one of grid shells with the exact same geometry, but without any pre-stress. The paper demonstrates finally that the pre-stress decreases by a few percent the buckling capacity of elastic grid shells.


ABSTRACT: The elastic grid shell is a solution that combines double curvature and ease of mounting. This structural system, based on the deformation of an initially at grid without shear stiffness was invented more than fifty years ago. The apparition of new materials such as GFRP increased the potential of such structures whose properties depend on the deformation, or equivalently pre-stress of an initial structure. Elastic grid shells seem particularly promising as shelters, lightweight roofs, or kinetic structures. Although fundamental to the behavior of the structure, the influence of the pre-stress on the stability of elastic grid shells has yet to be studied. Understanding this phenomenon could allow engineers to design more efficiently elastic grid shells. This thesis studies the influence of pre-stress on the stability of elastic grid shells. The research conducts a parametric study that focuses both a pre-buckled arch and initially at circular elastic grid shells with different grid spacing and levels of pre-stress. Realistic values of the parameters are determined from existing projects. The buckling analysis as well as the form-finding of the different structures are performed using finite element analysis. The tools are validated with comparison of the shape and buckling capacity of a pre-buckled arch with existing experiments. The parametric studies lead to recommendations aiming to facilitate the design of elastic grid shells.

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T. Pradeep and N. Arun (Department of Civil Engineering, K.S.Rangasamy College of Technology, Tiruchengode, Namakkal Tamil Nadu India), “Numerical optimization of cold formed closed built-up steel column”, International Journal of Innovative Research in Science, Engineering and Technology, (volume/date not given; the most recent reference is dated 2012)

ABSTRACT: The optimization of cold formed closed steel built-up columns without stiffeners is performed using finite element analysis. An accurate finite element model is used for study in which different size of webs are investigated. The closed cold formed built-up steel column strength were studied with and without coupling of section. The final section of column buckling behaviour is predicted by the nonlinear finite element method and discusses the unfactored design column strength.

References listed at the end of the paper:


ABSTRACT: When numerical models are used to predict behaviour of open thin-walled steel cross-sections, the nonlinear analysis results can be influenced by the magnitudes introduced as initial imperfection. At present, a wide range of values is considered in research concerning this topic. This paper explores up to what point the nonlinear analysis results are sensitive to the choice of imperfection magnitudes and attempt to refine the
spectrum of magnitudes that should be used. The study focuses on rack uprights (with and without perforations) under compression and the numerical model has been validated with experimental tests conducted by the authors. Three different column lengths have been selected to reproduce a mainly local, distortional and global failure mode, so that coupled instabilities have not to be considered in this case. The results show that the ultimate load and collapse mode are both sensitive to imperfection amplitude, mainly in the case of distortional buckling.

SUMMARY: In this thesis a new two dimensional differential quadrature treatment for cylindrical shell is introduced. Special types of matrix products are used to treat the non-linearity of the presented problem. The presented solution is verified with previous works and shows good agreement. Using differential quadrature method, this study analyzes the stability and critical buckling load of circular cylindrical shells with delamination. The study uses the Griffith-Irwin concept to study the stability of delamination. Non-linear equations describing the development of delamination under axial load are obtained on the basis of fracture-mechanics. In order to study delamination growth, the present thesis examines the critical buckling load and the energy release rate under different boundary conditions, different elastic constants, different delamination thicknesses and lengths. Results are represented in both graphical and tabulated forms.

ABSTRACT: In this paper, ductility aspects of a light-weight composite gridshell are developed. A gridshell is a very light structure that can support relative high loads. For many reasons, the materials used by the Navier laboratory are glass fibre reinforced polymers (GFRPs) that have elastic brittle behaviour. To ensure the safety of people these structures have to behave in a ductile way, that is to say they must not collapse without showing signs of weakness. This paper deals with the pseudo-ductile behaviour of the GFRP gridshells designed by the Architected Structures and Materials research unit of Navier laboratory. After a reminding context about gridshells, the buckling of the Solidays’ festival gridshell prototype (June 2011) is considered. It is demonstrated that buckling has to be avoided carefully because it fosters high stresses in the beams and may lead to a brutal collapse of the structure. Then it is shown that, under Ultimate Limit State (ULS), the gridshell prototype is far from buckling. Finally, a simulation of accident is performed: from the ULS, several elements are broken in order to understand the behaviour of the structure in case of accident. The pseudo-ductility of the structure is demonstrated thanks to the redundancy of the structural concept of the gridshell.

ABSTRACT: Buckling instabilities of thin sheets of plates of viscous fluid occur in situations ranging from food and polymer processing to geology. Slim, Teichman & Mahadevan (J. Fluid Mech., Vol 694, pp. 5-28, 2012) study numerically the buckling of a sheared viscous plate floating on a denser fluid using three approaches: a classical ‘thin viscous plate’ model; full numerical solution of the three-dimensional Stokes equations; and a novel ‘advection-augmented’ thin-plate model that accounts (in an asymptotically inconsistent way) for the advection of perturbations by the background shear flow. The advection-augmented thin-plate
The model is markedly superior to the classical one in its ability to reproduce the predictions of the Stokes solution, illustrating the utility of judicious violations of asymptotic consistency in fluid-mechanical models.


ABSTRACT: Buckling of a cantilever steel pipe column under combined loads was studied through linear and nonlinear numerical analysis method. Firstly, linear buckling analysis of the cantilever column with linear-elastic material was used to select appropriate element type and element size for this problem. Then linear buckling and nonlinear buckling analyses for an imperfect cantilever column under different horizontal loads or displacements in the context of elasticity were performed to verify the ability of the linear buckling analysis to include large geometric changes. Thirdly, nonlinear analyses were carried out to examine the effect of plastification of material on the buckling limit loads for the imperfect cantilever column. Through these comparative studies, some aspects concerned with the numerical buckling analysis of structures such as columns were clarified.

References listed at the end of the paper:


ABSTRACT: The main purpose of this study is to investigate the effect of delamination shapes and sizes on the lateral buckling behavior of the woven E-glass/epoxy laminated composite plates, experimentally and numerically. In order to perform experimental study, composite plates having eight laminates reinforced with woven E-glass fabric layers as [W]s are produced by using hand lay-up technique. For the delamination, basically two different delamination shapes, square and circular, are used. To investigate the effect of the delamination shape on the lateral buckling behavior, these delamination shapes are diversified. Six different rectangular delamination shapes are obtained by the changing aspect ratio of the horizontal and vertical diameter of the circular delamination. These aspect ratios are 0.50, 0.67, 0.75, 1.33, 1.67 and 2.00. To better understand the effect of delamination on the lateral buckling behavior, the experimental and numerical results of the specimens with and without delamination are compared. The experimental results have good agreement with numerical results, and these results show that the delamination shapes and sizes affected the critical lateral buckling load.

ABSTRACT: This paper presents an analytical investigation on the nonlinear dynamic analysis of functionally graded double curved thin shallow shells using a simple power-law distribution (P-FGM) with temperature-dependent properties on an elastic foundation and subjected to mechanical load and temperature. The formulations are based on the classical shell theory, taking into account geometrical nonlinearity, initial geometrical imperfection, temperature-dependent properties and unlike other publications, Poisson ratio is assumed to be varied smoothly along the thickness $\nu = \nu(z)$. The nonlinear equations are solved by the Bubnov-Galerkin and Runge-Kutta methods. The obtained results show the effects of temperature, material and geometrical properties, imperfection and elastic foundation on the nonlinear vibration and nonlinear dynamical response of double curved FGM shallow shells. Some results were compared with those of other authors.


ABSTRACT: This paper first time presents an analytical investigation on the nonlinear postbuckling of imperfect eccentrically stiffened thin FGM plates under temperature and resting on elastic foundation using a simple power-law distribution (P-FGM). Both of the FGM plate and stiffeners are deformed under thermal loads. The formulations are based on the classical plate theory taking into account geometrical nonlinearity, initial geometrical imperfection, temperature-dependent properties and the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation. By applying Galerkin method and using stress function, effects of material and geometrical properties, temperature, elastic foundation and eccentrically stiffeners on the buckling and postbuckling loading capacity of the eccentrically stiffened FGM plate in thermal environments are analyzed and discussed. Some results were compared with the one of the other authors.


ABSTRACT: This paper presents the results of a numerical investigation for applying a combination of buckling mode shapes as an initial imperfection to shell geometries under external pressure. The effect that imposed imperfections had on the critical buckling pressure was found to be dependent upon both the shell geometry and the characteristics of the imposed imperfection. Imperfections were generated via linear combinations of the linear elastic buckling mode shapes, with the fundamental mode having the greatest influence. For a number of tests, inclusion of higher order modes into the initial imperfection caused an increase in the critical buckling pressure. This behaviour was observed for both elastic and plastic material models. For the purpose of limiting the extent of the analysis, the magnitudes of imposed imperfections were maintained within the industry required fabrication tolerances and in particular, acceptable out-of-roundness. The purpose of this paper is to present the methodology and results from this imperfection investigation. Additional testing and discussion may allow a design methodology to be developed that addresses the application of initial imperfections in shells under external pressure.

ABSTRACT: Designing a suitable, applicable and efficient support system for underground road structures have always been one of the most important engineering tasks for tunnel engineers. There are some different support systems applied to making underground structures safe against overburden and lateral pressures. Among these systems, permanent or temporary steel frames, wire meshes, rock bolts and shotcretes have been commonly used for suffering the exerted burdens and making the structure a safe place. This paper proposes a numerical analysis of the geometrical instability of steel-arch shells as one of the main bodies of underground road structure liners by means of calculating their buckling load and utilizing the finite element method. In this regard, a considerable number of structures (84) having different geometrical parameters have been modelled and their buckling loads have been calculated. For this purpose, the thickness, internal angle and radius of the periphery cylinder of the arch-shell system were considered taking into account geometrical parameters. Moreover, to accurately model the buckling load using the proposed algorithm, the weight of the structure has also been included in the made calculations. Finally, as the main scope is based on the Cosine Amplitude Method, sensitivity analysis is carried out to investigate the strength of the relationship between each input geometrical parameter and their buckling load. Based on the obtained relationships, the thickness of the structure is reported as the most affective geometrical parameter on buckling steel arch-shell support systems. In addition, the internal angle of arch supports is the least influential parameter.

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ABSTRACT: In the present work a model able to predict the buckling behavior of thin, orthotropic, stiffened plates and shells subject to axial compression is proposed. In the context of the Kirchhoff-Love plate theory and making use of different strain-displacement models – namely the von Kármán model, the Koiter-Sanders shell model, an enhanced von Kármán model and a spurious model commonly adopted in literature – the equilibrium equations have been solved by the Levy-type approach. The results obtained highlight the influence of each non-linear strain-displacement term and show that the von Kármán model can noticeably overestimate the buckling load when the critical mode involves significant in-plane displacements.


ABSTRACT: To increase the thermal resistance of various structural components in high-temperature environments, research reports focusing nonlinear axisymmetric response of thin FGM shallow spherical shells with ceramic – metal – ceramic layers (S-FGM) under uniform external pressure and temperature. Equilibrium and compatibility equations for shallow spherical shells are derived by using the classical shell theory and specialized for axisymmetric deformation with both geometrical nonlinearity and initial geometrical
imperfection. One-term deflection mode is assumed and explicit expressions of buckling loads and load–deflection curves are determined due to Galerkin method. Stability analysis for a clamped spherical shell shows the effects of material and geometric parameters, edge restraint and temperature conditions, and imperfection on the behavior of the shells. The results were compared with the P-FGM spherical shell symmetry axis (ceramic – metal).

References listed at the end of the paper:


Dao Huy Bich (Vietnam National University), “Non-linear buckling analysis of functionally graded shallow spherical shells”, Vietnam Journal of Mechanics, Vol. 31, No. 1, 2009, DOI: 10.15625/0866-7136/31/1/5491 ABSTRACT: In the present paper the non-linear buckling analysis of functionally graded spherical shells subjected to external pressure is investigated. The material properties are graded in the thickness direction according to the power-law distribution in terms of volume fractions of the constituents of the material. In the formulation of governing equations geometric non-linearity in all strain-displacement relations of the shell is considered. Using Bubnov-Galerkin's method to solve the problem an approximated analytical expression of non-linear buckling loads of functionally graded spherical shells is obtained, that allows easily to investigate stability behaviors of the shell.

Dao Huy Bich and Vu Do Long (Vietnam Academy of Science and Technology), “Non-linear dynamical analysis of imperfect functionally graded material shallow shells”, Vietnam Journal of Mechanics, Vol. 32, No. 1, 2010, DOI: 10.15625/0866-7136/32/1/312 ABSTRACT: Dynamical behaviors of functionally graded material shallow shells with geometrical imperfections are studied in this paper. The material properties are graded in the thickness direction according to the power-law distribution in terms of volume fractions of the constituents of the material. The motion, stability and compatibility equations of these structures are derived using the classical shell theory. The non-linear equations are solved by the Newmark's numerical integration method. The non-linear transient responses of cylindrical and doubly-curved shallow shells subjected to excited external forces are obtained and the dynamic critical buckling loads are evaluated based on the displacement responses using the criterion suggested by Budiansky and Roth. Obtained results show the essential influence of characteristics of functionally graded materials on the dynamical behaviors of shells.
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ABSTRACT: The present paper deals with the non-linear vibration of functionally graded shallow spherical shells. The properties of shell material are graded in the thickness direction according to the power law distribution in terms of volume fractions of the material constituents. In the derived governing equations geometric non-linearity in all strain-displacement relations of the shell is considered. From the deformation compatibility equation and the motion equation a system of partial differential equations for stress function and deflection of shell is obtained. The Galerkin method and Runge-Kutta method are used for dynamical analysis of shells to give expressions of natural frequencies and non-linear dynamic responses. Numerical results show the essential influence of characteristics of functionally graded materials and dimension ratios on the dynamical behaviors of shells.

References listed at the end of the paper:

Dao Huy Bich (1), Vu Hoai Nam (2), Nguyen Thi Phuong (2)
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ABSTRACT: The paper deals with the formulation of governing equations of eccentrically stiffened functionally graded plates and shallow shells based upon the classical shell theory and the smeared stiffeners technique taking into account geometrical nonlinearity in Von Karman-Donnell sense. Material properties are assumed to be temperature-independent and graded in the thickness direction according to a simple power law distribution in terms of the volume fraction of constituents. The shells are reinforced by eccentrically longitudinal and transversal stiffeners made of full metal or full ceramic depending on situation of stiffeners at metal-rich side or ceramic-rich side of the shell respectively. Obtained governing equations can be used in research on nonlinear post-buckling of mentioned above structures. By use of the Galerkin method an approximated analytical solution to the nonlinear stability problem of reinforced FGM plates and shallow shells is performed. The postbuckling load-deflection curves of the shells are investigated and analytical expressions of the upper and lower buckling loads are presented. A comparison of the effectiveness of stiffeners in enhancing the stability of FGM plates and shallow shells is given.

References listed at the end of the paper:

Dao Huy Bich (1) and Nguyen Thi Phuong (2),
(1) Vietnam National University, Hanoi, 144 Xuan Thuy, Cau Giay, Hanoi, Vietnam
“Buckling analysis of functionally graded annular spherical shells and segments subjected to mechanic loads”

ABSTRACT: An analytical approach is presented to investigate the buckling of functionally graded annular spherical segments subjected to compressive load and radial pressure. Based on the classical thin shell theory, the governing equations of functionally graded annular spherical segments are derived. Approximate solutions are assumed to satisfy the simply supported boundary condition of segments and Galerkin method is applied to obtain closed-form relations of bifurcation type of buckling loads. Numerical results are given to evaluate effects of inhomogeneous and dimensional parameters to the buckling of structure.

References listed at the end of the paper:

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ABSTRACT: An analytical approach is presented to investigate the linear buckling of eccentrically stiffened functionally graded thin circular cylindrical shells subjected to axial compression, external pressure and torsional load. Based on the classical thin shell theory and the smeared stiffeners technique, the governing equations of buckling of eccentrically stiffened functionally graded circular cylindrical shells are derived. The functionally graded cylindrical shells with simply supported edges are reinforced by ring and stringer stiffeners system on internal and (or) external surface. The resulting equations in the case of compressive and pressive loads are solved directly, while in the case of torsional load is solved by the Galerkin procedure to obtain the explicit expression of static critical buckling load. The obtained results show the effects of stiffeners and input factors on the buckling behavior of these structures.

References listed at the end of the paper:

ABSTRACT: This paper presents an analytical approach to investigate the nonlinear buckling of imperfect eccentrically stiffened functionally graded thin circular cylindrical shells subjected to axial compression and surrounded by an elastic foundation. Based on the classical thin shell theory with the geometrical nonlinearity in von Karman-Donnell sense, initial geometrical imperfection, the smeared stiffeners technique and Pasternak’s two-parameter elastic foundation, the governing equations of eccentrically stiffened functionally graded cylindrical shells are derived. The functionally graded cylindrical shells are reinforced by homogeneous ring and stringer stiffener system on internal and (or) external surface. The resulting equations are solved by the Galerkin method to obtain the explicit expression of static critical buckling load, post-buckling load-deflection curve and nonlinear dynamic motion equation. The nonlinear dynamic responses are found by using fourth order Runge-Kutta method. The dynamic critical buckling loads of shells are considered for step loading of infinite duration and linear-time compression. The obtained results show the effects of foundation, stiffeners and input factors on the nonlinear buckling behavior of these structures.


ABSTRACT: Stiffened composite panels are extensively used in aircraft structures because of their high stiffness to weight and high strength to weight ratios. Stiffened panels prone to buckle under in-plane loads and understanding the load carrying capacity beyond buckling is very important. The load carrying capacity of the panels depends on the post buckling behavior and strength. If the panels possess significant post buckling
strength then the structure can be allowed to buckle before the design load and this will significantly reduce the
cost and weight of the structures. The aim of the project is to analyze the buckling, post-buckling behavior and
failure characteristics of simply supported stiffened panels under uni-axial compressive load. Finite Element
Analysis (FEA) is a very good computational technique that can be used for the study. These FE results
obtained can be verified with the help of experimental results.
References listed at the end of the paper:
Techniques,” September 12, 1997 Blacksburg, VA

Vu Thi Thuy Anh and Nguyen Dinh Duc (Department of Mechanical Engineering and Automation, Vietnam
National University, Cau Giay, Hanoi, Vietnam), “The nonlinear stability of axisymmetric functionally graded
material annular spherical shells under thermo-mechanical load”, Mechanics of Advanced Materials and
Structures, Vol. 23, No. 12, 2016, DOI: 10.1080/15376494.2015.1091528
ABSTRACT: The authors of this article investigate the nonlinear stability of axisymmetric functionally graded
annular spherical shells with temperature-dependent material properties subjected to thermo-mechanical loads
and resting on elastic foundations. Equilibrium and compatibility equations are derived by using the classical
thin shell theory in terms of the shell deflection and the stress function. Approximate analytical solutions are
assumed to satisfy simply supported boundary conditions and Galerkin method is applied to obtain the closed-
form of load–deflection paths. An analysis is carried out to show the effects of material and geometrical
properties and combination of loads on the stability of the shells.

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"Buckling Analysis of Eccentrically Stiffened Functionally Graded Toroidal Shell Segments under Mechanical
ABSTRACT: An analytical approach is presented to investigate the linear buckling of eccentrically stiffened
functionally graded thin toroidal shell segments subjected to axial compression, lateral pressure, and hydrostatic
pressure. On the basis of classical thin shell theory, the smeared stiffener technique and the adjacent equilibrium
criterion, the governing equations of buckling of eccentrically stiffened functionally graded toroidal shell
segments are derived. The functionally graded toroidal shell segments with simply supported edges are
reinforced by a ring and stringer stiffener system on an external surface. The resulting equations in the case of
compressive and pressure loads are solved directly. The obtained results show the effects of stiffeners and input
factors on the buckling behavior of these structures. In this paper, the results are also compared with the
solutions published in the literature for the specific cases of a toroidal shell.

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"Non-linear buckling analysis of FGM toroidal shell segments filled inside by an elastic medium under external pressure loads including temperature effects", Composites Part B: Engineering, Vol. 87, pp 75-91, February 2016, DOI: 10.1016/j.compositesb.2015.10.021

ABSTRACT: The analytical approach is presented to investigate non-linear buckling analysis and post-buckling behavior of FGM toroidal shell segments filled inside by an elastic medium under external pressure loads including temperature effects. The governing equations of non-linear buckling of FGM toroidal shell segments are derived based on the classical thin shell theory with the geometrical nonlinearity in von Karman–Donnell sense, Stein and McElman assumption and elastic medium modeled by Pasternak's two-parameter elastic foundation. The static critical buckling loads and the post-buckling pressure–deflection curves in two cases: movable and immovable boundary conditions including temperature effects are obtained by using the Galerkin's method. In the paper, the results are also compared with the solutions published in the literature for the specific cases. Effects of geometrical and material parameters, elastic foundation and temperature on the nonlinear buckling behavior of shells are shown in obtained results.

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ABSTRACT: The nonlinear buckling and post-buckling of functionally graded stiffened toroidal shell segment surrounded by elastic foundation in thermal environment and under torsional load are investigated in this paper. The functionally graded toroidal shell segments are reinforced by ring and stringer stiffeners system in which material properties of shell are assumed to be continuously graded in the thickness direction. The two-parameter elastic foundation proposed by Pasternak is studied. Theoretical formulations are derived basing on the classical shell theory with the geometrical nonlinearity in von Karman sense and the smeared stiffeners technique. The three-term approximate solution of deflection is chosen more correctly and the explicit expression for finding critical load and post-buckling torsional load-deflection curves are found. The effects of geometrical parameters, temperature, stiffeners and elastic foundation are investigated.

A. Joshi, P. Ravinder Reddy, V.N. Krishnareddy and Ch.V. Sushma (Mechanical Engineering Dept., Chaitanya Bharathi Institute of Technology, Hyderabad-75, Andhra Pradesh, India), "Buckling analysis of thin carbon/epoxy plate with circular cut-outs under biaxial compression by using FEA", International Journal of Research in Engineering and Technology (IJRET), Vol. 02, No. 10, October 2013

ABSTRACT: The present research work is to determine buckling load per unit length in rectangular plate with circular cut-outs under bi-axial compression using 2D finite element analysis. The commercial finite element analysis software ANSYS has been successfully executed. The buckling factors are evaluated by changing the position of the holes, length to thickness ratio. The effect of changing the position of holes, a/b ratio, b/t ratio and buckling load per unit length is discussed. The results show that buckling load per unit length is in clamped-clamped boundary conditions and buckling load is more at top positioned hole, decrease with increase in aspect ratio, decrease with increase breadth to thickness ratio.

S. Kainuma, J. H. Ahn, I. T. Kim, "Corrosion Pattern for Critical Shear Buckling Load of a Web Panel with
DOI: 10.4028/www.scientific.net/AMM.421.778

ABSTRACT: Shear buckling strength of a web panel with local corrosion damage can be changed by web corrosion pattern. In this study, To find critical corrosion pattern for shear buckling of a web panel with local corrosion. Critical shear buckling loads of the corroded web panels were quantitatively evaluated. Thus, FE analysys models were created cosidering corrosion pattern in the plate girder bridge which was reported from the corroded bridge inpection. As corrosion pattern of the web panel in the plate girder bridge, three corrosion patterns were selected as main corrosion cases such as longitudinal, vertical, and triangular cases. Their critical shear buckling loads were compared according to their corroded web codition.

2013 SSRC Annual Stability Conference Proceedings, April 17-19 – St. Louis, MO

Session 1 - Technical Presentations: Topics in Stability Research
Intermediate Transverse Stiffeners in Stiffened Plate Girders, D. Beg, F. Sinur, University of Ljubljana, Ljubljana, Slovenia

Compression Members with Hollow Sections and Concentric Slotted Gusset Plates - Behavior and Recommended Design Model, H. Unterweger, A. Taras, Graz University of Technology, Graz, Austria

Three-Dimensional Joist Member Studies using Equivalent Beam Theory, S.J. Kilber, A.E. Surovek, South Dakota School of Mines and Technology, Rapid City, South Dakota

The Overall Interaction Concept: An Alternative Approach to the Stability and Resistance of Steel Sections and Members, N. Boissonnade, J. Nseir, E. Saloumi, University of Applied Sciences of Western Switzerland-Fribourg, Fribourg, Switzerland

Session 2 - Technical Presentations: Stability of Steel Shear Walls

The Post-Buckling Strength and Tension-Field Action Mechanism of Cold-Formed Steel Shear Walls with Steel Sheeting, S. Mohebbi, S.R. Mirghaderi, University of Tehran, Tehran, Iran, F. Farahbod, Building and Housing Research Center of Iran, Teran, Iran, S. Torabian, University of Tehran, Tehran, Iran

Analytical Model for Stiffened Steel Infill Plates, S. Sabouri, S. Mamazizi, K.N. Toosi, University of Technology, Tehran, Iran

Effective Strip Model for Cold-Formed Steel Shear Wall using Steel Sheet Sheathing, N. Yanagi, C. Yu, University of North Texas, Denton, Texas

Elastic Compressive Strength of Aluminum Open Circular-Arc Sections, C.M. Shepherd, Virginia Tech, Blacksburg, Virginia, R.D. Ziemian, Bucknell University, Lewisburg, Pennsylvania

Session 1 – Conference Presentations: Stability Under Fire Conditions
Performance of Steel Shear Tab Connections at Elevated Temperatures, M.S. Seif, J.A. Main, T.P. McAllister, National Institute of Standards and Technology, Gaithersburg, Maryland

Stability of Cold-Formed Steel Compression Members Under Thermal Gradients, J.C. Batista Abreu, B.W. Schafer, Johns Hopkins University, Baltimore, Maryland

**Session 2 – Conference Presentations: Stability of Web Tapered Members**

Shear Strength of Web-Tapered I-Shaped Members, R.P. Studer, American Buildings Company, D.B. Davis, University of Kentucky, Lexington, Kentucky

Mapping Web-Tapered Member to a Prismatic Member for Buckling Analysis of Sway Frames-Closed Form Equation, E.S. Salem, Al-Azhar University, Cairo Egypt

Stability Verification of Web-Tapered Beam-Columns - Possible Approaches and Open Questions, L. Marques, L.S. da Silva, C. Rebelo, University of Coimbra, Coimbra, Portugal

**Session 3 – Conference Presentations: Stability of Frames and Systems**

On Frame Stability Analysis, A.S. Doria, Petrobras, Brazil, M. Malite, University of Sao Paulo, Sao Paulo, Brazil, L.C.M. Vieria, Jr., University of New Haven, West Haven, Connecticut

Experimental and Analytical Study on Failure Modes of Structural Steel Scaffolds, Maheeb M.E. Abdel-Ghaffar, Abdullah N.S. Mahmoud, Cairo University, Cairo, Egypt

Analysis of Locally/Distortionally Buckled Beams, Xi Zhang, Kim J.R. Rasmussen, University of Sydney, Sydney, Australia

System Reliability of Steel Frames Designed by Inelastic Analysis, S. Shayan, K.J.R. Rasmussen, H. Zhang, University of Sydney, Sydney, Australia

**Session 4 – Conference Presentations: Cold Formed Steel Member Stability**

Buckling Strength and Axially Loaded Cold Formed Built-Up I-Sections, Metwally Abu-Hamd, Basel El-Samman, Cairo University, Giza, Egypt

Elastic Buckling of Thin-Walled Steel Columns with Periodic Perforations, F.H. Smith, C.D. Moen, Virginia Tech, Blacksburg, Virginia

Distortional Post-Buckling and Strength of Cold-Formed Steel Columns: How does the Cross-Section Geometry Affect it?, A. Landesmann, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, D. Camotim, Technical University of Lisbon, Lisbon, Portugal, C. Basaglia, University of Sao Paulo, Sao Paulo, Brazil

Shape Optimization of Cold-Formed Steel Columns with Manufacturing Constraints and Limited Number of Rollers, J. Leng, Z. Li, J.K. Guest, B.W. Schafer, Johns Hopkins University, Baltimore, Maryland
Session 5 – Conference Presentations: Stability Bracing

Bracing for Flexural Buckling in Cold-Formed Steel Framed Walls, H.B. Blum, Johns Hopkins University, Baltimore, Maryland, V.M. Zeinoddini, NBM Technologies, Springfield, Virginia, B.W. Schafer, Johns Hopkins University, Baltimore, Maryland

Brace Stiffness and Forces for X-Type, K-Type, and Z-Type Cross Frames in Steel I-Girder Bridge Systems, A.D. Battistini, S.M. Donahue, University of Texas at Austin, Austin, Texas, W.H. Wang, SBM Offshore, Houston, Texas, T.A. Helwig, M.D. Engelhardt, University of Texas at Austin, Austin, Texas, K.H. Frank, Hirschfeld Industries, Austin, Texas

Practical Design of Complex Stability Bracing Configurations, C.D. Bishop, Exponent, Inc. Menlo Park, California, D.W. White, Georgia Institute of Technology, Atlanta, Georgia

Session 6 – Conference Presentations: Stability of Steel Bridge Systems

Calculating the Impact of Partial Warp Restraint on Steel Girder Elastic Buckling Strength, C.E. Quadrato, K.A. Arnett, United States Military Academy, West Point, New York

Analytical Assessment of the Strength of Steel Truss Bridge Gusset Plates, Y.D. Kim, Georgia Perimeter College, Dunwoody, Georgia, Y. Mentes, MMI Engineering, Houston, Texas, D.W. White, Georgia Institute of Technology, Atlanta, Georgia, R.T. Leon, Virginia Tech, Blacksburg, Virginia

Axial Capacity of Partially Corroded Steel Bridge Piles, H. Karagah, M. Dawood, University of Houston, Houston, Texas

Session 7 – Conference Presentations: Stability Under Seismic and Other Lateral Loads

Modeling the Seismic Response of Cold-Formed Steel Framed Buildings: Model Development for the CFS-NEES Building, J. Leng, B.W. Schafer, Johns Hopkins University, Baltimore, Maryland, S.G. Buonopane, Bucknell University, Lewisburg, Pennsylvania

Cyclic Lateral-Torsional Buckling Response of Cold-Formed Steel C-Section Joists, D.A. Padilla-Llano, C.D. Moen, M. Eatherton, Virginia Tech, Blacksburg, Virginia

Strain Capacity of Cross-Section Elements and the Role of Local Slenderness in the Rotation Capacity of Structural Steel, S. Torabian, University of Tehran, Tehran, Iran, B.W. Schafer, Johns Hopkins University, Baltimore, Maryland

Session 8 – Conference Presentations: Stability of Angles, Cruciform, and Z-Shaped Members

Towards a More Rational DSM Design Approach for Angle Columns, P.B. Dinis, D. Camotim, Technical University of Lisbon, Lisbon, Portugal, A. Landesmann, Federal University of Rio De Janeiro, Rio De Janeiro, Brazil
Numerical and Experimental Investigation on the Post-Buckling Behavior, Ultimate Strength and DSM Design of Thin-Walled Cruciform Steel Columns, P.B. Dinis, Technical University of Lisbon, Lisbon, Portugal, P.S. Green, Bechtel Power Corporation, Frederick, Maryland, D. Camotim, Technical University of Lisbon, Lisbon, Portugal


Strength and Stiffness of Cold-Formed Steel Purlins with Sleeved and Overlapped Bolted Connections, A.H. Favero Neto, University of Sao Paulo, Sao Paulo, Brazil, L.C.M. Vieira, Jr., University of New Haven, West Haven, Connecticut, M. Malite, University of Sao Paulo, Sao Paulo, Brazil

Session 9 – Beedle Presentation Session

Beedle Presentation: Are Designers Sufficiently Instructed to Make the Most Rewarding Use of the Latest Steel Codes?, R.J. Maquoi, University of Liege, Liege, Belgium

Study of Residual Stresses in I-Section Members and Cellular Members, D. Sonck, R. Van Impe, Ghent University, Zwijnaarde, Belgium

Influence of Creep on the Stability of Steel Columns Subjected to Fire, M.A. Morovat, M.D. Engelhardt, T.A. Helwig, E.M. Taleff, University of Texas at Austin, Austin, Texas

Session 10 – Advances in Stability Analysis and Design

GBT-Based Structural Analysis of Elastic-Plastic Thin-Walled Members, M. Abambres, D. Camotim, N. Silvestre, Technical University of Lisbon, Lisbon, Portugal

Finite Prism Elastic Buckling Analysis and Application in Steel Foam Sandwich Membersl, Z. Li, Johns Hopkins University, Baltimore, Maryland, S. Szyniszewski, University of Surrey, Guildford, United Kingdom

Stability, Failure, and Design of I-Section Steel Beams Subjected to Tension, Joao Tomas, Technical University of Lisbon, Lisbon, Portugal, Joanna Nsier, University of Applied Sciences of Western Switzerland-Fribourg, Fribourg, Switzerland, Dinar Camotim, Technical University of Lisbon, Lisbon, Portugal, Nicolas Boissonnade, University of Applied Sciences of Western Switzerland-Fribourg, Fribourg, Switzerland

Session 11 – Vinnakota Award Session and Stability of Plates, Shells, and Girder Webs

Girders with Structured Web - Ongoing Research, S. Bartholome, H. Pasternak, Brandenburg University of Technology, Cottbus, Germany

Shell Buckling Evaluation of Thin-Walled Steel Tanks Filled at Low Liquid Level According to Current Design Codes, C. Maraveas, K. Miamis, C. Maraveas Partnership, Athens, Greece

Localized Web Buckling of Double-Coped Beams, Bo Dowswell, ARC International, LLC, Birmingham,

ABSTRACT: In a recent feature article in this journal, co-authored by Gert van der Heijden, I described the static-dynamic analogy and its role in understanding the localized post-buckling of shell-like structures, looking exclusively at integrable systems. We showed the true significance of the Maxwell energy criterion load in predicting the sudden onset of 'shock sensitivity' to lateral disturbances. The present paper extends the survey to cover non-integrable systems, such as thin compressed shells. These exhibit spatial chaos, generating a multiplicity of localized paths (and escape routes) with complex snaking and laddering phenomena. The final theoretical contribution shows how these concepts relate to the response and energy barriers of an axially compressed cylindrical shell. After surveying NASA's current shell-testing programme, a new non-destructive technique is proposed to estimate the 'shock sensitivity' of a laboratory specimen that is in a compressed meta-stable state before buckling. A probe is used to measure the nonlinear load-deflection characteristic under a rigidly applied lateral displacement. Sensing the passive resisting force, it can be plotted in real time against the displacement, displaying an equilibrium path along which the force rises to a maximum and then decreases to zero: having reached the free state of the shell that forms a mountain-pass in the potential energy. The area under this graph gives the energy barrier against lateral shocks. The test is repeated at different levels of the overall compression. If a symmetry-breaking bifurcation is encountered on the path, computer simulations show how this can be suppressed by a controlled secondary probe tuned to deliver zero force on the shell.

References listed at the end of the paper:


Hilburger, M. (Principal Investigator) [2013] Launch vehicle shell buckling knockdown factors testing underway, http://www.nasa.gov/offices/nesc/home/Feature_ShellBuckling.html#U2bJi1fN7qw

A. Takei (1), F. Brau (2), B. Roman (1) and J. Bico (1)
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“Stretch-induced wrinkles in reinforced membranes: From out-of-plane to in-plane structures”, EPL (Europhysics Letters), Vol. 96, No. 6, December 2011
ABSTRACT: We study, through model experiments, the buckling under tension of an elastic membrane reinforced with a more rigid strip or fiber. In these systems, the compression of the rigid layer is induced through Poisson contraction as the membrane is stretched perpendicularly to the strip. Although strips always lead to out-of-plane wrinkles, we observe a transition from out-of-plane to in-plane wrinkles beyond a critical strain in the case of fibers embedded into elastic membranes. We describe through scaling laws the evolution of the morphology of the wrinkles and the different transitions as a function of material properties and stretching strain.

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PARTIAL INTRODUCTION: The intriguing buckling patterns exhibited by bilayer systems composed of a thin stiff film bonded to a thick elastomeric substrate have been studied extensively in recent years both experimentally and theoretically. Under compression, the film is constrained by the substrate and buckles with a wavelength that is usually large compared to the film thickness, yet small compared to the substrate thickness. The most common patterns observed are the sinusoidal wrinkle mode when compression in one direction is dominant,[1] and the herringbone[2,3] and labyrinth[2–4] modes when compression is equi-biaxial. The present paper is part of the ongoing research effort in the soft-materials community to produce and manipulate specific
buckling patterns.\[^{5,6}\] Most of the previous work has focused on buckling patterns of bilayer systems under small compression. Recent work, however, has demonstrated that large compression of a bilayer system can engender other surface patterns such as period-doubling\[^{7}\] and folding\[^{8,9}\] opening the way for the creation of a wider array of surface patterns. These post-wrinkling modes involve the large strain behavior of the substrate and geometrical non-linearity of the films in an essential way. The focus of the present paper is on the most recent of the post-wrinkling modes to be discovered, the ridge localization mode. While folds and creases protrude into the substrate, the ridge is a large amplitude localization that pushes out from the substrate. This mode should be characterized as a localization because the large amplitude of the ridge is fed by flattening the nearby wrinkle undulations resulting in ridges that are separated from each other by expanses of relatively flat film. Thus, a distinct feature of the transition from wrinkles to ridges is the abrupt increase of spacing from crest to crest. The ridge localization was predicted to occur,\[^{10}\] and has been observed experimentally,\[^{5,6,11}\] only when a relatively large pre-stretch was imposed on the elastomeric substrate prior to film attachment. Controlled incremental release of the pre-stretch of the thick substrate then imposes compression on the film, which drives buckling.

References listed at the end of the paper:


DOI: 10.4028/www.scientific.net/AMR.941-944.1548
ABSTRACT: Geometrically nonlinear model and numerical solutions of large deformation of imperfect functionally graded materials conical shell subjected to both mechanical load and transversely non-uniform
temperature rise are given. The material properties of functionally graded shell are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. On the basis of geometrically nonlinear theory of shell, governing equations of the axisymmetrical deformation are derived. Numerical solutions are obtained by using a shooting method.

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“Delamination behavior of axymmetric sandwich shells under axial compressive loading”, 16th European Conference on Composite Materials (ECCM16), Seville, Spain, 22-26 June 2014

ABSTRACT: This work covers the experimental and numerical analysis of asymmetric sandwich shells introduced as innovative fuselage structure for transport aircraft in the research program “Citizen-friendly Aircraft”. The shells consist of a CFRP skin carrying the main loads, a rigid closed cell PMI foam core and a thin aluminum layer. The manufacturing process is illustrated and several test specimens are damaged by predefined delaminations in between the aluminum skin and the foam. It is shown that face sheet delaminations can significantly reduce the structures’ load bearing capacities and propagate suddenly through the entire structure when reaching the critical load. Comparison with a FE simulation showed good morphological agreement, however, the prediction of failure loads and out-of-plane deformation of the buckling skin can be improved.

References listed at the end of the paper:

S. Sankar Reddy (1), C. Yuvraj (2) and K. Prahlada Rao (3)
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(2) Department of Mechanical Engineering, Madanapalli Institute of Technology & Science, Andhra Pradesh,
ABSTRACT: Carbon Fiber Reinforced Polymers (CFRPs) have been widely used in numerous applications where high specific stiffness and strength offer structural weight reduction and fuel efficiency. RVS (re-entry vehicle system) structural protection to the weapon system during re-entry. These kinds of structures are realized using filament winding process. In this paper mechanical characterization of CFRP with Carbon Nano-fiber has been prented. Studies are carried out to characterize the strength and Young’s modulus of the composite structure. Carbon Nano-fibers are among the greatly potential reinforcing additives for polymeric composites due to their high axial Young’s modulus, high aspect ratio, large surface area, and excellent thermal and electrical properties. Various studies can be found in the literature regarding the incorporation of CNFs in polymeric matrices and the final mechanical and/or electrical properties of these materials. To prove the technology a composite cylinder having size Length of 600mm, Diameter 300mm and thickness 1.5mm is considered for experimental study. In the present work a method has been developed to analyze composite shell using Layered 46. In addition, 3D layered analysis of composite cylinder with end metallic plates have been performed to predict the Buckling behavior of the Composite shell. Composite shell were fabricated & tested with buckling load condition to verify the design and analysis procedure. It has been observed that the experimental results are in close agreement with the finite element analysis results, also the design stresses were within safe limits. Based on test results, the Longitudinal Strength of CFRP with CNF is achieved 1860 MPa, Young’s modulus is 118 GPa and improvement against CFRP with epoxy resin (LY556).

References listed at the end of the paper:


ABSTRACT: In this paper, the nonlinear behaviour of steel plate shear walls with corrugated plates under lateral pushover loading conditions in the models' top level has been analytically investigated by the finite element method. The one-storey frames have beams and columns as boundary elements. Steel plate shear walls are simulated using the finite element method, based on the available experimental models in the literature. After calibration of the analytical models, more parameters of steel shear walls with corrugated plates, such as the thickness of the corrugated plate, the stiffness of the boundary elements, the corrugation depth in the corrugated plates and the corrugation length of the infill of the corrugated plates, are investigated. The results of this study have demonstrated that in the wall with constant dimensions, the trapezoidal plates have higher energy dissipation, ductility and ultimate bearing than sinusoidal waves, while decreasing the steel material consumption.

References listed at the end of the paper:

ABSTRACT: In this study, we try to analyze the free nonlinear vibration of a stringer shell analytically. The nonlinear governing equation of the problem is derived. Homotopy perturbation method is applied completely to obtain the analytical solution of the problem. We try to provide engineers and designers to achieve the nonlinear frequency of nonlinear problems especially shell vibrations with an easy method. The effects of different parameters on the ratio of nonlinear to linear natural frequency of shells are completely studied. The homotopy perturbation method gives us an excellent agreement with numerical results for whole range of the oscillation amplitude. The first order of homotopy perturbation method leads us to highly accurate solutions as indicated in this paper.

References listed at the end of the paper:

M. Bayat (1), I. Pakar (1) and L. Cveticanin (2)

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ABSTRACT: In this paper, the nonlinear free vibration of a stringer shell is studied. The mathematical model of the string shell, which is the most convenient for frequency analysis, is considered. Due to the geometrical properties of the vibrating shell, strong nonlinearities are evident. Approximate analytical expressions for the nonlinear vibration are provided by introducing the extended version of the Hamiltonian approach. The method suggested in the paper gives the approximate solution for the differential equation with dissipative term for which the Lagrangian exists. The aim of this study is to provide engineers and designers with an easy method for determining the shell nonlinear vibration frequency and nonlinear behavior. The effects of different parameters on the ratio of nonlinear to linear natural frequency of shells are studied. This analytical representation gives excellent approximations to the numerical solutions for the whole range of the oscillation amplitude, reducing the respective error of the angular frequency in comparison with the Hamiltonian approach. This study shows that a first-order approximation of the Hamiltonian approach leads to highly accurate solutions that are valid for a wide range of vibration amplitudes.

References listed at the end of the paper:

25. Filippov, S.B.: Theory of Conjugated and Reinforced Shells. St. Petersburg State University (1999); in Russian

R. Wagner and C. Huehne (Institute for Composite Structures and Adaptive Systems, German Aerospace Center (DLR), Lilienthalplatz 7, 38108 Braunschweig, Germany), A new design concept for cylindrical composite shells under axial compression”, 16th European Conference on Composite Materials (ECCM16), Seville, Spain, 22–26 June 2014

ABSTRACT: Thin-walled cylindrical shells are prone to buckling. Imperfections which are defined as deviations from the perfect geometrical shape or homogeneous loading distribution can reduce the buckling load significantly compared to that of the perfect shell. For the design of unstiffened cylindrical shells mostly
the NASA SP-8007 guideline is used, which recommends reducing the buckling load of the perfect shell using a knock-down factor. Existing knock-down factors are conservative and structural behavior of composite shells is not considered. A new proposal for an improved guideline is the advanced Single-Perturbation Load Approach (a-SPLA). The design loads of the new approach are, depending on the ply-layup, at least 40% larger compared to the design loads of the NASA SP-8007 and the behavior of composite structures is taken into account. Based on test results the concept is validated.

References listed at the end of the paper:


ABSTRACT:


URL: http://vjs.ac.vn/index.php/vjmech/article/view/3986

ABSTRACT: Based on the classical thin shell theory with the geometrical nonlinearity in von Karman-Donnell sense, the smeared stiffener technique, Galerkin method and an approximate three-term solution of deflection taking into account the nonlinear buckling shape is chosen, the governing nonlinear dynamic equations of eccentrically stiffened functionally graded circular cylindrical shells subjected to time dependent axial compression and external pressure is established in part 1. In this study, the nonlinear dynamic responses are obtained by fourth order Runge-Kutta method and the nonlinear dynamic buckling behavior of stiffened functionally graded shells under linear-time loading is determined by according to Budiansky-Roth criterion. Numerical results are investigated to reveal effects of stiffener, input factors on the vibration and nonlinear dynamic buckling loads of stiffened functionally graded circular cylindrical shells.

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“Anti-buckling Fixture for Large Deformation Tension–Compression Cyclic Loading of Thin Metal Sheets”, Strain, 17 January, 2014, DOI: 10.1111/str.12078

ABSTRACT: Determination of cyclic properties of a material used for many engineering structures, e.g. airframes, requires preparation of specimens from two-dimensional, shell structures. A specimen must be cut
out from the structure component in the way allowing application of a load corresponding to that reflecting service cases. In order to fulfil this requirement, tension-compression testing of the flat specimen is necessary to obtain credible data. Problems associated with such kind of testing are discussed in this paper. In the first part, an extensive review of the anti-buckling fixtures developed up to now is given. Several representative solutions are discussed, with special emphasis on the technique limitations. In the second part of the paper, detailed description of the proposed design is given. Finally, the results of preliminary tests carried out using new fixture to mount the flat specimens cut from steel sheets are presented. Application of the proposed testing technique allowed tension-compression tests to be performed at the displacement amplitude within the range ±5 mm what corresponds to the maximum strain amplitude of ±0.4 for the specimen gauge length to be equal 12.5 mm. Taking into account all data captured by means of new fixture, one can conclude that the technique is promising with respect to providing data for modelling of cyclic deformation behaviour for shell structures.

IN MEMORIAM Dr. Charles C. Rankin (August 1942 – August 2012)

Charles Rankin is known for his salient fundamental contributions over more than 30 years to the field of solid and structural mechanics. All of these contributions have been formulated by Charles and implemented into his general-purpose nonlinear static and dynamic finite element code called STAGS (STructural Analysis of General Shells), widely used especially at NASA Langley Research Center. Charles was no mere programmer implementing into a code the mechanics theories of others; he developed these theories mainly by himself. Many of Charles’ fundamental contributions are now finding their way into the most widely used commercial structural computer programs such as MSC_NASTRAN, ANSYS and ABAQUS. In this way Charles’ important original contributions will for the foreseeable future have a major impact on research and engineering in academia, government and industry. Specifically Charles Rankin’s technical contributions include the formulation and implementation into STAGS of: 1. a finite-element-independent co-rotational theory that has now become an important standard in computational mechanics the world over, 2. an arc-length method that permits the traversal of limit points from pre-buckling to post-buckling, 3. an algorithm to determine multiple bifurcation eigenvalues and eigenvectors from nonlinearly determined pre-buckled equilibrium states, 4. a solution strategy that permits the successive introduction of a sequence of buckling modal imperfections into a nonlinear equilibrium analysis, 5. a strategy that permits successive smooth transitions from nonlinear static to transient and from nonlinear transient to static analyses, 6. a strategy that permits the simulation of unzipping of a through crack in a shell possibly with multiple crack tips and turning of a crack during loading, 7. a “sandwich” finite element that efficiently accounts for soft, shear-deformable cores and stiff face sheets, 8. unique nonlinear material models in separate “material modules” which are independent of the rest of the software. Charles was a great man, loved by many for his great sense of humor, respected by many for his towering intellect and superb accomplishments in the field of structural mechanics. He will remain forever in the minds and hearts of his many friends and colleagues.

AGENDA OF THE SYMPOSIUM IN MEMORY OF CHARLES RANKIN:

55th AIAA SDM meeting, National Harbor, Maryland, January 13 – 17, 2014
(Part of SCITECH 2014; there are two "Charles Rankin" sessions with 5 papers each.
Both sessions were held on Jan. 15, 2014.

Wednesday morning, January 15, 2014
Session Number: STR-11. Shell Bucking-Charles Rankin Special Session I
Chair(s): Mark Hilburger (NASA-Langley Research Center)
Co-Chair(s): Richard Young (NASA-Langley Research Center)
10:00 AM - 12:30 PM; Chesapeake Conference Room E

10:00 AM - 10:30 AM

10:30 AM - 11:00 AM
The Use Of The Stags Finite Element Code In Stitched Structures Development, AIAA Paper AIAA 2014-0845, Dawn C. Jegley; Andrew E. Lovejoy

11:00 AM - 11:30 AM
High-Fidelity Buckling Analysis of Composite Cylinders using the STAGS Finite Element Code, AIAA Paper AIAA 2014-0846, Mark W. Hilburger

11:30 AM - 12:00 PM
Post-buckling Response of Scarf Repaired Laminates Using a Refined Zigzag Element, AIAA Paper AIAA 2014-0847, Atila Barut; Erdogan Madenci; Alexander Tessler

12:00 PM - 12:30 PM
STAGS Developments for Residual Strength Analysis Methods for Metallic Fuselage Structures, AIAA Paper AIAA 2014-0848
Richard D. Young; Cheryl Rose

Wednesday afternoon, January 15, 2014
STR-13. Shell Bucking-Charles Rankin Special Session II
Chair(s): Mark Hilburger (NASA-Langley Research Center)
Co-Chair(s): Dawn Jegley (NASA Langley Research Center)
3:00 PM - 5:30 PM; Chesapeake Conference Room E

3:00 PM - 3:30 PM
Buckling Testing and Analysis of Honeycomb Sandwich Panel Arc Segments of a Full-Scale Fairing Barrel – Comparison of In- and Out-of-Autoclave Facesheet Configurations, AIAA Paper AIAA 2014-1052, Evan J. Pineda; David E. Myers; Daniel N. Kosareo; Bart Zalewski; Sotiris Kellas; Genevieve D. Dixon; Thomas M. Krivanek; Thomas G. Gyekenyesi

3:30 PM - 4:00 PM
Buckling Design and Analysis of a Payload Fairing 1/6th Cylindrical Arc-Segment Panel, AIAA Paper AIAA 2014-1053, Daniel N. Kosareo; Stanley T. Oliver; Brett A. Bednaryck


4:00 PM – 4:30 PM
Static and Dynamic Tests of Composite Cylindrical Shells under Axial Compression, AIAA Paper AIAA 2014-1055, Chiara Bisagni

4:30 PM - 5:00 PM
Structural Performance of Advanced Composite Tow-Steered Shells with Cutouts, AIAA Paper AIAA 2014-1056, K Chauncey Wu; Bret K. Stanford; Jason D. Turpin; Robert A. Martin

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end of Charles Rankin Symposium ---------------------

Recent Computer Methods in Applied Mechanics and Engineering Articles

Stochastic identification of imperfections in a submerged shell structure
15 April 2014
H.M. Reed | C.J. Earls | J.M. Nichols
Abstract: Accurate predictions of the buckling load in imperfection sensitive shell structures requires precise knowledge of the location and magnitude of any geometric imperfections in the shell (e.g. dents). This work describes a non-contact approach to identifying such imperfections in a submerged shell structure. By monitoring the acoustic pressure field at discrete points proximal to a shell structure excited by a cyclic membrane (i.e. in-plane) loading, it is noticed that parameters, describing small scale denting, can be identified. In order to perform the identification, a fluid-structure model that predicts the spatio-temporal pressure field is required. This model is described in detail and includes the predicted effects of the imperfection on the observations. A Bayesian, Markov chain Monte Carlo approach is then used to generate the imperfection parameter estimates and quantify the uncertainty in those estimates. Additionally: for cases involving the occurrence of an unknown number of dents, reversible jump Markov chain Monte Carlo (RJMCMC) methods are employed in this work.

Post-buckling nonlinear static and dynamical analyses of uncertain cylindrical shells and experimental validation
1 April 2014
E. Capiez-Lernout | C. Soize | M.-P. Mignolet
Abstract: The paper presents a complete experimental validation of an advanced computational methodology adapted to the nonlinear post-buckling analysis of geometrically nonlinear structures in presence of uncertainty. A mean nonlinear reduced-order computational model is first obtained using an adapted projection basis. The stochastic nonlinear computational model is then constructed as a function of a scalar dispersion parameter, which has to be identified with respect to the nonlinear static experimental response of a very thin cylindrical shell submitted to a static shear load. The identified stochastic computational model is finally used for
predicting the nonlinear dynamical post-buckling behavior of the structure submitted to a stochastic ground motion.

An isogeometric continuum shell element for non-linear analysis
1 April 2014
Saman Hosseini | Joris J.C. Remmers | Clemens V. Verhoosel | René de Borst
Abstract: An isogeometric continuum shell formulation is proposed in which NURBS basis functions are used to construct the reference surface of the shell. Through-the-thickness behavior is interpolated using a higher-order B-spline which is in contrast to the standard continuum shell (solid-like shell) formulation where a linear Lagrange shape function is typically used in the thickness direction. The present formulation yields a complete isogeometric representation of the continuum shell. The shell element is implemented in a standard finite element code using Bézier extraction which facilitates numerical integration on the reference surface of the shell. Through-the-thickness integration is done using a connectivity array which determines the support of a B-spline basis function over an element. The formulation has been verified using different linear and geometrically non-linear examples. The ability of the formulation in modelling buckling of static delaminations in composite materials is also demonstrated.

Numerical validation of a concurrent atomistic-continuum multiscale method and its application to the buckling analysis of carbon nanotubes
1 March 2014
Stefan Hollerer
Abstract: This work applies the framework of a concurrent multiscale approach to the buckling analysis of carbon nanotubes. In particular, the bridging domain method is used to couple a molecular statics model and a continuum mechanics model. The total potential energy of the entire structure is specified by weighted individual energy contributions of overlapping subdomains. In this handshake region, additional kinematics constraints enforce the compatibility between designated atoms and the continuum body. Three different methods are taken into consideration for the kinematics coupling and the corresponding governing equations are presented. The continuum subdomain is handled by means of a finite element approach and the molecular statics is formulated suitable for a common computational implementation. A series of numerical examples investigates the capability of the bridging domain method for its application in the analysis of carbon nanotubes. Initially, the individual approaches for integrating the kinematics constraints into the global equilibrium equations are compared. Then, in the major contribution of the work, the influences of several modelling parameters of the multiscale model on the buckling analysis of a bent single-walled carbon nanotube are numerically studied. In particular, the size of the atomistic section, the extent of the handshake region and the finite element discretisation are varied. Furthermore, the results obtained by the standard and the relaxed variant of the bridging domain method are compared against each other. In addition, the buckling behaviour of a defective carbon nanotube with varying defect locations is presented. The obtained results of the bridging domain multiscale method are persistently validated against full atomistic molecular statics simulations.

ABSTRACT: A cell-based smoothed three-node Mindlin plate element (CS-MIN3) based on the first-order shear deformation theory (FSDT) was recently proposed for static and dynamics analyses of Mindlin plates. In this paper, the CS-MIN3 is extended to geometrically nonlinear analysis of functionally graded plates (FGPs) subjected to thermo-mechanical loadings. In the FGPs, the material properties are assumed to vary through the
thickness by a simple power rule of the volume fractions of the constituents. The nonlinear formulation is based on the C0-type high-order shear deformation plate theory (C0-HSDT) and the von Kármán strains, which deal with small strains and moderate rotations. In the analysis process, both thermal and mechanical loadings are considered and a two-step procedure is performed including a step of analyzing the temperature field along the thickness of the plate and a step of analyzing the geometrically nonlinear behavior of the FGPs subjected to both thermal and mechanical loadings. The accuracy and reliability of the proposed method is verified by comparing its numerical solutions with those of available other numerical results.

Finite element modeling of a linear membrane shell problem using tangential differential calculus
1 March 2014
Peter Hansbo | Mats G. Larson
Abstract: We construct a new Galerkin finite element method for the membrane elasticity problem on a meshed surface by using two-dimensional elements extended into three dimensions. The membrane finite element model is established using a tangential differential calculus approach that avoids the use of classical differential geometric methods. The finite element method generalizes the classical flat element shell method where standard plane stress elements are used for membrane problems. This makes our method applicable to a wider range of problems and of surface descriptions, including surfaces defined by distance functions.

A consistent 3D corotational beam element for nonlinear dynamic analysis of flexible structures
1 February 2014
Thanh-Nam Le | Jean-Marc Battini | Mohammed Hjiaj
Abstract: The purpose of the paper is to present a corotational beam element for the nonlinear dynamic analysis of 3D flexible frames. The novelty of the formulation lies in the use of the corotational framework (i.e., the decomposition into rigid body motion and pure deformation) to derive not only the internal force vector and the tangent stiffness matrix but also the inertia force vector and the tangent dynamic matrix. As a consequence, cubic interpolations are adopted to formulate both inertia and internal local terms. In the derivation of the dynamic terms, an approximation for the local rotations is introduced and a concise expression for the global inertia force vector is obtained. To enhance the efficiency of the iterative procedure, an approximate expression of the tangent dynamic matrix is adopted. Four numerical examples are considered to assess the performance of the new formulation against the one suggested by Simo and Vu-Quoc (1988) [48]. It was observed that the proposed formulation proves to combine accuracy with efficiency. In particular, the present approach achieves the same level of accuracy as the formulation of Simo and Vu-Quoc but with a significantly smaller number of elements.

End of Recent Computer Methods in Applied Mechanics and Engineering Articles
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ABSTRACT: In this paper, the thermal buckling behavior of composite laminated plates under a uniform temperature distribution is studied. A finite element of four nodes and 32 degrees of freedom (DOF), previously developed for the bending and mechanical buckling of laminated composite plates, is extended to investigate the thermal buckling behavior of laminated composite plates. Based upon the classical plate theory, the present
finite element is a combination of a linear isoparametric membrane element and a high precision rectangular Hermitian element. The numerical implementation of the present finite element allowed the comparison of the numerical obtained results with results obtained from the literature: 1) with element of the same order, 2) the first order shear deformation theory, 3) the high order shear deformation theory and 4) the three-dimensional solution. It was found that the obtained results were very close to the reference results and the proposed element offers a good convergence speed. Furthermore, a parametrical study was also conducted to investigate the effect of the anisotropy of composite materials on the critical buckling temperature of laminated plates. The study showed that: 1) the critical buckling temperature generally decreases with the increasing of the modulus ratio $E_L/E_T$ and thermal expansion ratio $\alpha_T/\alpha_L$, and 2) the boundary conditions and the orientation angles significantly affect the critical buckling temperature of laminated plates.

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41. Matsunaga H. Thermal buckling of cross-ply laminated composite and sandwich plates according to a global higher-order deformation theory. Composite Structures, 2005, 68(4): 439–454
ABSTRACT: After an automotive body shell is built in a typical vehicle assembly plant, the body shell is then cleaned of stamping and/or protective oils, electro-coated for corrosion protection, and then painted. The electro-coating and painting processes in the automobile industry have three main stages each: pretreatment, electro coating or painting, and drying. The surface finishing coats applied during electro-coating and painting processes must be dried using an oven. With existing electro-coating and paint heating processes through the assembly plant ovens, body panels may have buckling issues. The buckling phenomenon must be understood to eliminate the concern. The phenomenon is caused by uneven temperature distribution on the panel, attached panels of dissimilar materials, or possibly both conditions. The uneven temperature distribution may be due to the heat source itself, heat sinks within the body, or radiant shielding. Another consideration for body panel buckling involves the joining and heating of panels attached to dissimilar material types. In this paper, a comprehensive methodology for vehicle body panel buckling simulation in paint oven temperature environment is described by coupling computational heat transfer analysis and structure analysis. The heat transfer analysis is used to predict temperature distribution throughout a vehicle body panel in the oven. The vehicle body temperature profile from the heat transfer analysis result is applied as an input for a stress analysis to predict buckling. This study is focused on the radiant section of the electro-coat and paint ovens where the section has largest thermal mass to heat the vehicle body. This methodology couples a fully transient thermal analysis for the body moving through the electro-coat and painting ovens and the Abaqus/Standard structural buckling simulation. The proposed method provides of the virtual assessment capability for simulating the sheet metal thermal buckling phenomenon as a directional tool in order to avoid late production changes to vehicle class “A” surfaces.


ABSTRACT: In this paper, an analysis on nonlinear dynamics of a simply supported functionally graded material (FGM) cylindrical shell subjected to the different excitation in thermal environment. Material properties of cylindrical shell are assumed to be temperature-dependent. Based on the Reddy’s third-order plates and shells theory[1], the nonlinear governing partial differential equations of motion for the FGM cylindrical shell are derived by using Hamilton’s principle. Galerkin’s method is utilized to transform the partial differential equations into a two-degree-of-freedom nonlinear system including the quadratic and cubic nonlinear terms under combined parametric and external excitation. The effects played by different excitation and system initial conditions on the nonlinear vibration of the cylindrical shell are studied. In addition, the Runge–Kutta method is used to find out the nonlinear dynamic responses of the FGM cylindrical shell.

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ABSTRACT: Imperfection sensitivity of cylindrical shells subjected to axial compressive load is investigated by means of non-linear buckling analysis and post-buckling analysis. Non-linear buckling analysis involves the determination of the equilibrium path (or load-deflection curve) up to the limit point load by using the Newton-Raphson approach, whereas post-buckling analysis involves the determination of the equilibrium path beyond the limit point load and up to the collapse load by using the arc-length approach. Limit point loads evaluated from these two approaches for various imperfection magnitudes show an excellent agreement which clearly confirms the numerical results obtained.

(no abstract given)


Course Objective: Buckling and postbuckling behavior is critical to the success of certain designs. For example, crash worthiness of an automobile requires that particular vehicle components collapse in ways that maximize energy absorption. On the other hand, successful designs of imperfection-sensitive, thin-walled shell structures, ranging from beverage containers to large pressure vessels, must prevent unintentional buckling. This course blends the theoretical background on such topics as geometric nonlinearity and the Riks method together with examples, guidelines and workshops to demonstrate how to: Identify an imperfection-sensitive structure, Extract closely spaced eigenvalues efficiently, Introduce imperfections into a "perfect" mesh, Use the Riks method effectively, Use damping to control unstable motions.


ABSTRACT: We introduce a new experimental method to encapsulate and release oils and fluorescent molecules, into preformed elastic colloidal microcapsules of PDMS filled siloxane shells, which are cross-linked with tetraethoxysilane. The method uses controlled buckling, where the volume of the capsule is reduced by dissolving the PDMS oil inside the capsule by surfactant micelles. This results in a change in the morphology of the capsule that depends on the ratio of shell thickness to total particle radius (d/Rt). Microcapsules of d/Rt in the range 0.007–0.05 formed microbowls upon decreasing the inner volume. The amount of oil released or dissolved by the micelles can be directly related to the concentration of surfactant. By tuning the amount of oil released we can make microbowls of variable depth. In addition, we demonstrate that the microbowls can be further used to load different oils like silicone oil, hydrocarbons, and apolar dyes. The elasticity of the capsule wall and the left-over PDMS oil inside the capsule provide the principal driving forces by which one can promote the uptake of different oils, including dissolved dye molecules.

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experimental dependences is greater.

satisfactory agreement. For lower values of these stresses, the difference between the theoretical and

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A comparison is made of the time dependences of the axial strain of the shells obtained in the experiment and

shell and asymmetric buckling modes with the formation of three or four waves in the circumferential direction.

that the buckling modes are a combination of axisymmetric bulges located near o

of thin shells using Norton’s law of steady creep. The results of the experiment and computer simulation show

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circular cylindrical shells of Zr2.5Nb zirconium alloy under creep conditions. Computer simulation using the

ABSTRACT: Experiments were performed to study the deformation and buckling of axially compressed

circular cylindrical shells of a zirconium alloy: Experiment and computer simulation”, Journal of Applied

Mechanics and Technical Physics, Vol. 55, No. 1, pp 105


ABSTRACT: Experiments were performed to study the deformation and buckling of axially compressed circular cylindrical shells of Zr2.5Nb zirconium alloy under creep conditions. Computer simulation using the MSC.Marc 2012 software was conducted by step-by-step integration of the equations of quasistatic deformation of thin shells using Norton’s law of steady creep. The results of the experiment and computer simulation show that the buckling modes are a combination of axisymmetric bulges located near one end or both ends of the shell and asymmetric buckling modes with the formation of three or four waves in the circumferential direction. A comparison is made of the time dependences of the axial strain of the shells obtained in the experiment and by computer simulation. It is shown that for large axial compressive stresses, these dependences are in satisfactory agreement. For lower values of these stresses, the difference between the theoretical and experimental dependences is greater.

References listed at the end of the paper:

ABSTRACT: Nonlinear explicit finite element (FE) simulations are used to study the axial collapse behavior of multi-corner, single- and multi-cell crush tubes under quasi-static and dynamic loading conditions. It is shown that the higher hardening modulus and yield stress increases the crush force and its resulting energy absorption. Moreover, the multi-cell tubes are found to have complicated collapse modes because of the geometrical complexity of the corner region unlike single-cell tubes. It was also shown that the stress wave propagation has a significant effect on the formation of crush modes in the tubes without imperfections whereas this effect can be ignored in tubes with imperfection or trigger mechanism. An analytical formula for the prediction of mean crush force of multi-corner multi-cell tubes is derived based on the super folding element theory. The analytical predictions for the mean crush force are found to be in good agreement with the FE solutions. Results also show a strong correlation between the cross-sectional geometry and the crush behavior with the method of connecting the inner to the outer walls having large influence on the energy absorption.

References listed at the end of the thesis:


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(2) PLY Technologies GmbH, Germany


ABSTRACT: Mathematical design optimization is utilized to perform design optimization on new sandwich panel concept called Opencell™. Opencell contains two facesheets including an integral cut-and-formed
facesheet joined to a flat or curved facesheet. Design optimization of this sandwich panel is challenging due to geometrical interrelations between the cell dimension and the cell depth as well as different forming/cutting geometries. In this study, the optimization performed only on a flat single type of Opencell topology called Opencell Delta, and the design optimization is performed to find an optimal geometric attributes for this design. Buckling, vibration and local-global static stress analysis is performed to form a multi-objective optimization problem through response surface approximation.

References listed at the end of the paper:
shells structures of positive curvature with. It would result in a structural system based on compressive membrane stresses combined a very efficient materials in compression. However, to reach a high degree of efficiency a shell structure has to be doubly curved, and doubly curved glass elements are very expensive to produce. When considering dome-type structures based on membrane action in plane elements, Ture Wester [1] thought of the idea to combine the very efficient plate based dome structures with the structural use of glass. In a Ph.D.-research at the Technical University of Denmark [2] this idea is being developed further by Anne Bagger. In this research a number of different problem areas have been acknowledged and one of them is the buckling behaviour of a facetted glass dome structure. Because of the compressive capacity of glass and the efficiency of the structural system, it is possible to create a slender structure. However, such a slender structure will also be highly susceptible to buckling, which is why a buckling analysis is likely to be critical. This buckling analysis is partly carried out at the Delft University of Technology. A glass plate dome is analyzed with the finite element program DIANA. The study is aimed at finding the buckling behaviour of a facetted glass dome, and to provide the designer with the influence of different design parameters, like thickness of the facets and stiffness of the joints, on the stability behaviour of such a structure.

References listed at the end of the paper:


HISTORY: The idea of the facetted glass shell structure was first put forward by Ture Wester in one of his papers on the behaviour of plate structures: “[...] if a reliable structural joint method, i.e. gluing is available, then eliminate the metal muntins as well, and leave the glass itself to carry and transfer all the forces. Such a plate dome challenges the vision for a dome design with forces distributed so evenly, that it can be made so ‘thin’ that it becomes totally transparent and nearly disappears - a structure as clear as air, only made visible by mirroring the clouds and the sky.” (Wester 1990) Combining flat glass with a plate structure is a very effective way to use the in-plane strength of glass panels in an efficient structural system. In addition, production of flat (or float) glass is very cheap compared to bent glass.

CONCLUSIONS: The most important conclusion that can be drawn from the research is that the structural concept is very promising. Sufficiently high safety factors are found even when introducing large imperfections. However, some aspects still need to be taken into consideration. One might think of the support conditions, different load conditions, etc. Furthermore, a suitable joint needs to be developed. Other interesting conclusions can be drawn from the different investigations. The fact that the normal and shear stiffness of the joint are crucial in the design is very important, as well as the imperfection sensitivity and glass stiffness. No real problems are found even though the influence of some factors is quite large. These aspects will need to be combined in future studies; also with the realistic support and load conditions.

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Bagger, A., J. Jonsson & T. Wester (2007b), Investigation of stresses in facetted glass shell structures. submitted to IASS.
Bagger, Anne (n.d.), Research into the influence of the joint stiffness in facetted shell structures. working title, part of undergoing
PhD. research.
Technical University of Denmark (DTU). (BYG-Rapport; No. R-221), April 2010

ABSTRACT: This thesis is a study of plate shell structures – a type of shell structure with a piecewise plane geometry, organized so that the load bearing system is constituted by distributed in-plane forces in the facets. The high stiffness-to-weight ratio of smoothly curved shell structures is mainly due to their curved shape. A plate shell structure maintains a high stiffness-to-weight ratio, while facilitating the use of plane structural elements. The study focuses on using laminated glass panes for the load bearing facets. Various methods of generating a plate shell geometry are suggested. Together with Ghent University, a script has been developed for an automated generation of a given plate shell geometry and a corresponding finite element (FE) model. A suitable FE modelling technique is proposed, suggesting a relatively simple method of modelling the connection detail’s stiffness characteristics. This modelling technique is used to model a plate shell structure with a span of 11.5 meters in the FE software Abaqus. The structure is analyzed with six different connection details with varying stiffness characteristics, to investigate the influence of these characteristics on the structural effects. Based on these investigations, and FE analysis of other plate shell models, the structural behaviour is described. Possible methods of estimating the stresses in a given plate shell structure are proposed. The nonlinear behaviour of a plate shell structure is investigated for varying parameters, such as facet size, imperfections, and connection characteristics. The critical load is compared to that of a similar, but smoothly curved, shell structure. Based on the investigations throughout the study, a set of guidelines for the structural design of plate shells of glass is proposed.

List of references at the end of the dissertation:

ABSTRACT: Six typical composite grid cylindrical shells are constructed by superimposing three basic types of ribs. Then buckling behavior and structural efficiency of these shells are analyzed under axial compression, pure bending, torsion and transverse bending by finite element (FE) models. The FE models are created by a parametrical FE modeling approach that defines FE models with original natural twisted geometry and orients cross-sections of beam elements exactly. And the approach is parameterized and coded by Patran Command Language (PCL). The demonstrations of FE modeling indicate the program enables efficient generation of FE models and facilitates parametric studies and design of grid shells. Using the program, the effects of helical angles on the buckling behavior of six typical grid cylindrical shells are determined. The results of these studies indicate that the triangle grid and rotated triangle grid cylindrical shell are more efficient than others under axial compression and pure bending, whereas under torsion and transverse bending, the hexagon grid cylindrical shell is most efficient. Additionally, buckling mode shapes are compared and provide an understanding of composite grid cylindrical shells that is useful in preliminary design of such structures.

References listed at the end of the paper:
18. Rahimi, G.H., Zandi, M., Rasouli, S.F.: Analysis of the effect of stiffener profile on buckling strength is composite isogrid


ABSTRACT: The paper investigates the buckling behaviour of anisogrid composite lattice cylindrical shells under axial compression, transverse bending, pure bending, and torsion. The lattice shells are modelled as three-dimensional frame structures composed of curvilinear ribs subjected to the tension/compression, bending in two planes and torsion. The specialised finite-element model generation procedure (model generator/design modeller) is developed to control the orientation of the beam elements allowing the original twisted geometry of the curvilinear ribs to be closely approximated. The effects of varying the length of the shells, the number of helical ribs and the angles of their orientation on the buckling behaviour of lattice structures are examined using parametric analyses. Buckling of the lattice shells with cutouts is also analysed. The results of these studies indicate that the modelling approach presented in this work can be successfully applied to the solution of design problems.


ABSTRACT: Distortional buckling which is one of the most important buckling modes for cold-formed lipped channel sections as well as local buckling and global buckling may change mechanical properties and decrease the ultimate load of members. This paper reviews research achievements in distortional buckling, compares the existed design methods according to five national (regional) codes and the latest research achievements. Based on the comparison between five calculating data and test results, it is shown that the design method of North American specification has widespread application and relatively high accuracy, which could supply references for structural design.


ABSTRACT: This paper presents a finite element simulation and buckling analysis of layered composite structures. The shell element is based on the Reissner-Mindlin first-order shear deformation theory and the finite element method account for full geometric nonlinearity imposing large deformations and rotations. Finite rotations are treated by Rodrigues parameterization. The combinations of enhanced assumed strain (EAS) in the membrane strains and assumed natural strains in the shear strains are implemented to improve the shell element behavior. Stability analysis of anisotropic short open cylinder, layered cylindrical shells with different lamina sequence and a hinged roof structure are presented including snap-through and snap-back problems. The present
simulations are compared with those obtained by finite element analyses based on first-order transverse shear deformation moderate or large rotation or refined von Kármán-type theories in earlier literature.

References listed at the end of the paper:


R.J. Alves de Sousa et al, (2006), A new one-point quadrature enhanced assumed strain EAS solid-shell element with multiple
loses contact with the shell in a series of well-defined "blisters" along the long axis of the ellipsoid. We defined "blisters" along the long axis of the ellipsoid. We observed a new instability that is not observed in spherical shells. While plastic deformation is well documented and is a familiar first stage in the crushing of a spherical shell such as a ping-pong ball. While spherical shells manifest such periodic structures as polygons, we present a new instability that is observed in the indentation of a highly ellipsoidal shell by a horizontal plate. Above a critical indentation depth, the plate loses contact with the shell in a series of well-defined "blisters" along the long axis of the ellipsoid. We
characterize the onset of this instability and explain it using scaling arguments, numerical simulations, and experiments. We also characterize the properties of the blistering pattern by showing how the number of blisters and their size depend on both the geometrical properties of the shell and the indentation but not on the shell’s elastic modulus. This blistering instability may be used to determine the thickness of highly ellipsoidal shells simply by squashing them between two plates.

References listed at the end of the paper:
[23] This approximation is consistent with the images in Fig. 1 and is correct in the limit that nb=a \( \ll 1 \).

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“Mechanics of elastic ellipsoidal shells”, Society of Engineering Science 51st Annual Technical Meeting, 1-3 October 2014, Purdue University, West Lafayette, Indiana, USA

ABSTRACT: Complicated structural features at a much smaller scale than overall structure size form during the deformation of elastic shells under mechanical loading. These features which can be seen by simple experiments in everyday life, as well as in biological and engineering systems, are associated with high energy density and evolve in intricate ways as the shell is further loaded deep into the nonlinear regime. The key
challenge in understanding these features is interaction of physics and geometry that leads to a mechanical response which is very different from the response of solid objects. The formation of localized periodic structures in the crushing of a spherical shell, such as a ping pong ball, is well documented in the literature and studies show that spherical shells manifest periodic structures as polygons under point and plate loading. We studied ellipsoidal shells under plate and point indentation and results are presented here. For plate indentation, we present a new instability that is observed in the indentation of a highly ellipsoidal shell. In this phenomenon, above a critical indentation depth, the plate loses contact with the shell in a series of well-defined “blisters” aligned with the smaller radius of curvature. We used detailed numerical model to study this instability and explained it using scaling arguments. We characterized the onset of instability and showed relation between number of blisters and their sizes with indentation depth and geometry of shell. Our study showed that properties of blister are independent of elastic properties of shell itself and this suggests a novel method for simply determining the thickness of highly ellipsoidal shells.

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(3) Dept. of Civil, Construction, and Environmental Engineering, Univ. of Alabama, Tuscaloosa, AL 35487-0205.
ABSTRACT: Local delamination buckling formulas for laminated composite beams are derived based on the rigid, semirigid, and flexible joint models with respect to three bilayer beam (i.e., conventional composite, shear-deformable bilayer, and interface-deformable bilayer, respectively) theories. Two local delamination buckling modes (i.e., sublayer delamination buckling and symmetrical delamination buckling) are analyzed and their critical buckling loads based on the three joint models are obtained. A numerical finite-element simulation is carried out to validate the accuracy of the formulas, and parametric studies of delamination length ratio, the transverse shear effect, and the influence of interface compliance are conducted to demonstrate the improvement of the flexible joint model compared to the rigid and semirigid joint models. The explicit local delamination buckling solutions developed in this study facilitate the design analysis and optimization of laminated composite structures and provide simplified and improved practical design equations and guidelines for buckling analyses.

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ABSTRACT: Main buckling and post-buckling analysis methods for composite structures are presented, along with the discussion on their potential challenges in handling the accuracy of prediction. Common buckling and post-buckling behaviors of composite structures are described, and the capabilities of corresponding analysis
techniques are reviewed. Compared with the structures made of metals, the anisotropy of composite materials is one of the key difference which could be considered in constitutive relations for buckling analysis. Commonly used analytical buckling prediction methodologies are based on the energy principle for approximation; while post-buckling investigations usually require iteration algorithms such as the arc-length method etc. to trace the entire equilibrium path. Semi-analytical methods, such as finite strip method, are also effective algorithms to predict critical buckling loads, and they could significantly save computing resources compared with full numerical analysis models. Practical engineering structures are usually under elastically supported boundary conditions, and the buckling behaviors of composite panels under elastic constraints are also discussed. This brief review is intended to help the readers in identifying starting points for research in analysis of buckling and post-buckling behavior of composite structures and in designing composite structures against buckling.

References listed at the end of the paper:

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ABSTRACT: The explicit arc-length method is simulated to trace the post-buckling equilibrium path of structures by using dynamic relaxation method with kinetic damping. This method based on the cylindrical arc-length method does not require the computation and formulation of any tangent stiffness matrix to search the snap-through or snap-back problems. The convergence to the solution is achieved by using only vector equation with kinetic damping technique. Two approaches for cylindrical arc-length control are formulated with incremental and total displacement constraint. The merits of the explicit arc-length method, in tracing the post-buckling behavior of structures, are demonstrated by analyzing the numerical examples.

References listed at the end of the paper:

Agricultural and Mechanical College.


References listed at the end of the paper:


Sajjad Tasuji and Gholam Hosein Majzoobi (Takestan University, Ghazvin-Takestan, Iran), “Study the Buckling of Defective Single-Walled Carbon Nanotubes in Ansys Software”, XII International Conference on Nanostructured Materials (NANO 2014), Moscow, Russia, July 13-18, 2014 [Section: Nanomaterials: Mechanics and Applications in Mechanical Engineering (Poster)]

ABSTRACT: In this review buckling in single-walled carbon nanotubes (SWCNTs) in static loading has been studied. Carbon nanotubes buckling has many influence on electrical and physical properties. Carbon nanotubes are as two forms of axial buckling. If the ratio of length to diameter become more column buckling and otherwise shell buckling will happen. In this study of structural mechanics has been used to determine the axial buckling of carbon nanotubes in both type of armchair and zigzag. after getting the normal amount of nanotubes buckling them while affected by defects (single vacancy, double vacancy and stone wales) have been studied and obtained the effect of defects on the buckling force. Results showed that reducing the amount of buckling force with making a defect in the nanotube structure and this reduction is due to the type of defects created in the structure is different. In this review of Ansys software and solutions of nonlinear Newton - Raphson is used to increase the accuracy. Analysis process to determine buckling is like this high that the nodes are moved the effect of pressure force and Considering the large deformation in the software can be obtained point that the structure will buckling from the graph (force - deflection). Buckling force values in the armature and zigzag nanotubes in the same length and diameter, is close together, and also the values of static analysis is more of dynamic analysis.


ABSTRACT: The stiffened rectangular plate was usually adopted in the blast airtight doors. In order to improve the buckling capacity of stiffened rectangular plate under uniform normal compression, the optimization model of stiffened rectangular plate was set up based on APDL and ANSYS commands, and the sequential linear programming method was executed to optimize the thickness of plate and the sizes of stiffeners. Moreover, we compared the mechanical property of the optimized stiffened rectangular plate with the theoretical value of no-stiffener plate with equal volume, and obtained the reasonable stiffener distribution based on the optimization results of five different longitudinal and transverse stiffener patterns. The results showed that the buckling
capacity of stiffened rectangular plate under uniform normal compression could be improved by approximately 50% on the condition of reasonable stiffeners distribution.

References listed at the end of the paper:

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DOI: 10.1016/j.ijnonlinmec.2013.01.019

ABSTRACT: In this paper, we study the equilibrium states of a compressible hyperelastic layer under compression after the primary and secondary bifurcations. Starting from the two-dimensional field equations for
a compressible hyperelastic material, we use a methodology of coupled series-asymptotic expansions developed earlier to derive two coupled non-linear ordinary differential equations (ODEs) as the model equations. The critical buckling stresses are determined by a linear bifurcation analysis, which are in agreement with the results in the literature. The method of multiple scales is used to solve the model equations to obtain the second-order asymptotic solutions after the primary bifurcations. An analytical formula for the post-buckling amplitudes is derived. Two kinds of numerical solutions are also obtained, the numerical solutions of the model equations by a difference method and those of the two-dimensional field equations by the finite elements method. Comparisons among the analytical solutions, numerical solutions and solutions obtained by the Lyapunov–Schmidt–Koiter (LSK) method in the literature are made and good agreements for the displacements are found. It is also found that at some places the axial strain is tensile, although the layer is under compression. To consider the secondary bifurcation, we superimpose a small deformation on the state after the primary bifurcation. With the analytical solution of the primary bifurcation, we manage to reduce the problem of the secondary bifurcation to one of the first bifurcations governed by a second order variable-coefficient ODE. And, our analysis identifies an explicit function and from the existence/non-existence of its zero one can immediately judge whether a secondary bifurcation can take place or not. The zero corresponds to a turning point of the governing ODE, which leads to non-trivial solutions. Further, by the WKB method the equation (in a very simple form) for determining the critical stress for the secondary bifurcation is derived. We further use AUTO to compute the secondary bifurcation point numerically, which confirms the validity of our analytical results. The numerical solution in the secondary bifurcation branch is also computed by AUTO. It is found that the secondary bifurcation induces a “wave number doubling” phenomenon and also the shape of the layer has a convexity change along the axial direction.


ABSTRACT: Thermal buckling analysis of multi-layered composite spheroidal spherical shells with clamped boundary condition under uniform distribution thermal load is investigated using the finite element method to produce the theoretical modeling. The results obtained are compared with the know data in the literature for composite shells. The effect of important parameter spherical angle, fiber orientation, number of layers of composite shell and radius to thickness ratio are taken in to consideration on the structure stability.

ABSTRACT: It is desired to calculate the critical buckling pressure in double wall cryogenic storage tank. These storage tanks are usually composed of two separated walls in which the inner wall is responsible to store the cryogenic liquid. The space between two walls should be filled by loose perlite to minimize heat transfer from ambient. So, it is expected to expose an external pressure more than vapor pressure on inner tank wall. The results show that the accuracy of analytical equations is not acceptable and should be revised. So, in this study, new correlations were proposed based on numerical results obtained by Ansys.
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6. Schiender W., 2005, A. Brede, Consistent equivalent geometric imperfections for the numerical buckling strength verification of cylindrical shells under uniform external pressure, Thin-Walled Structures 43(2): 175-188.

ABSTRACT: This paper discusses CAE simulation methods to predict the thermal induced buckling issues when vehicle body panels are subjected to the elevated temperature in e-coat oven. Both linear buckling analysis and implicit quasi-static analysis are discussed and studied using a quarter cylinder shell as an example. The linear buckling analysis could produce quick but non-conservative buckling temperature. With considering nonlinearity, implicit quasi-static analysis could predict a relative conservative critical temperature. In addition, the permanent deformations could be obtained to judge if the panel remains visible dent due to the buckling. Finally these two approaches have been compared to thermal bucking behavior of a panel on a vehicle going through thermal cycle of e-coat oven with the excellent agreement on its initial design and issue fix design. In conclusion, the linear buckling analysis could be used for quick thermal buckling evaluation and comparison on a series of proposals. The implicit quasi static analysis is must to conduct to determine if a body panel will buckle or not and how much permanent deformation may remain in any thermal circumstance.

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DOI: 10.1631/jzus.A1500016
ABSTRACT: A good understanding of the mechanical behavior of functionally graded material (FGM) cylindrical shells is necessary for designers and researchers. However, the 3D transient response of FGM
cylindrical shells under various boundary conditions has not yet been analyzed. In this paper, the problem is addressed by proposing an approach integrating the state space method, differential quadrature method, and Durbin’s numerical inversion method of Laplace transform. The laminate model is used to obtain the transient solution in the radial direction. At the edges, four kinds of boundary conditions are considered: Clamped-Clamped, Clamped-Simply supported, Clamped-Free, and Simply supported-Simply supported. The results of the proposed method and finite element (FE) method agree with each other excellently. Convergence studies show that the proposed method has a fast convergence rate. The natural frequencies obtained by the proposed method, experiment, and other theoretical methods are in close agreement with each other. The effects of the load frequency and duration, length/outer radius ratio, and the (outer radius-inner radius)/outer radius ratio on the transient response of FGM shells are investigated. Two laws of variation of material properties along the radial direction are considered: the first has material properties varying according to an exponential law along the radial direction, while the second has material properties varying according to a power law. The effect of a functionally graded index on the transient response of FGM shells is investigated in both cases. The results obtained in this paper can serve as benchmark data for further research.

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Yury Grabovsky (1) and Davit Harutyunyan (2)
“Scaling instability in buckling of axially compressed cylindrical shells”,

ABSTRACT: In this paper we continue the development of mathematically rigorous hyperelastic theory of “near-flip” buckling of slender bodies of arbitrary geometry. In order to showcase the capabilities of this theory
we apply it to buckling of axially compressed circular cylindrical shells. The theory confirms the classical formula for the buckling load, whereby the perfect structure buckles at the stress that scales as the first power of shell’s thickness. However, in the case of imperfections of load, the theory predicts scaling instability of the buckling stress. Depending on the type of load imperfections, buckling may occur at stresses that scale as thickness to the power 1.5 or 1.25, corresponding to the lower and upper ends, respectively, of the historically accumulated experimental data. Thus, the theory provides the first mechanically rational and mathematically rigorous explanation of experimentally observed scaling laws.

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ABSTRACT: The Suspended Latticed Intersected Cylindrical Shell (SLICS) is a new structural system, composed by the single layer Latticed Intersected Cylindrical Shell (LICS) and the prestressed cable-strut system. Mechanical properties of this structure were investigated through nonlinear buckling analysis by the consistent imperfect buckling analysis method, compared with the single layer LICS. Structure parameters including prestress level, member section, length of bar, rise-span ratio, obliquity were analyzed. And the effect of material nonlinearity on the stability was studied. Results show that the ultimate bearing capacity of the SLICS is improved as the introduction of prestress. However the prestress level has a limited impact on the ultimate bearing capacity. And the material nonlinear is very important to the stability of the SLICS.

ABSTRACT: This paper represents discussion about the Buckling mechanism in the cylindrical vessels and plates as buckling is characterized by sudden failure of structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is able to withstand. Pressure vessels are the equipments which are used for the storage of gases or liquids at specific temperature and pressure condition. The load carried by these pressure vessels also imparts forces on its shell structure which are likely to be buckle.

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ABSTRACT: An experimental study is designed to understand the effect of delamination on critical buckling load and mode of failure for glass/carbon hybrid laminates. Firstly, delaminated specimens are compressed using a universal testing machine and buckling tests performed after the ends of each specimen are hinged to a special fixture designed to permit rotational boundary conditions. Non-linear buckling analysis based on incremental iteration method is conducted using finite element analysis (FEA) package (ANSYS) after conducting tensile tests to find the material properties. Critical buckling loads are found for symmetric [C0/G45/G-45/G90]s and anti-symmetric [C0/G45/G-45/G90//G90/G45/G-45/C0] laminate configurations with four different delamination lengths (a/L= 0.2, 0.3, 0.4 and 0.5) created at two different delamination positions (t/h = 0.5 and 0.25). In this study, the critical buckling load decreased as the delamination length increased. Moreover, the critical buckling load tended to decrease when the delamination approached the surface.
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“An engineering analysis method for post-buckling of composite stiffened panels”, 29th Congress of the
ABSTRACT: The paper presents a project simplified theory and a method of calculating post-buckling loading capacity of composite stiffened panels based on the basic mechanics characters of composite materials, combining FEM theory and engineering experience. Composite J-stiffened panels are taken as an example to illustrate thinking and computational formula of post-buckling analysis from the perspective of engineering. The validity and effectiveness of the method are demonstrated with the experiment. It is shown the analysis method of stability loading capability can solve the geometric non-linear problem of composite stiffened panel structure load capability and keep high accuracy in the aero-structure design.

References listed at the end of the paper:

ABSTRACT: Most researches on the static performance of stiffened panel joined by friction stir welding (FSW) mainly focus on the compression stability rather than shear stability. To evaluate the potential of FSW as a replacement for traditional rivet fastening for stiffened panel assembly in aviation application, finite element method (FEM) is applied to compare compression and shear stability performances of FSW stiffened panels with stability performances of riveted stiffened panels. FEMs of 2024-T3 aluminum alloy FSW and riveted stiffened panels are developed and nonlinear static analysis method is applied to obtain buckling pattern, buckling load and load carrying capability of each panel model. The accuracy of each FEM of FSW stiffened panel is evaluated by stability experiment of FSW stiffened panel specimens with identical geometry and boundary condition and the accuracy of each FEM of riveted stiffened panel is evaluated by semi-empirical
calculation formulas. It is found that FEMs without considering weld-induced initial imperfections notably overestimate the static strengths of FSW stiffened panels. FEM results show that, buckling patterns of both FSW and riveted compression stiffened panels represent local buckling of plate between stiffeners. The initial buckling waves of FSW stiffened panel emerge uniformly in each plate between stiffeners while those of riveted panel mainly emerge in the mid-plate. Buckling patterns of both FSW and riveted shear stiffened panels represent local buckling of plate close to the loading corner. FEM results indicate that, shear buckling of FSW stiffened panel is less sensitive to the initial imperfections than compression buckling. Load carrying capability of FSW stiffened panel is less sensitive to the initial imperfections than initial buckling. It can be concluded that buckling loads of FSW panels are a bit lower than those of riveted panels whereas carrying capabilities of FSW panels are almost equivalent to those of riveted panels with identical geometries. Finite element method for simulating static performances of FSW and riveted stiffened panels is proposed and evaluated and some beneficial conclusions are obtained, which offer useful references for analysis and application of FSW to replace rivet fastening in aviation stiffened panel assembly.

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Jung Kwan Seo, Bong Ju Kim, Han Seong Ryu, Yeon Chul Ha and Jeom Kee Paik (The Lloyd's Register Educational Trust Research Centre of Excellence, Pusan National University, Busan 609-735, Republic of Korea), “Validation of the equivalent plate thickness approach for ultimate strength analysis of stiffened panels with non-uniform plate thickness”, Thin-Walled Structures, Vol. 49, No. 6, pp 753-761, June 2011
DOI: 10.1016/j.tws.2011.02.001
ABSTRACT: The stiffened plate structures in ships and ship-shaped offshore installations often consist of non-uniform plate thicknesses. Nonlinear finite element methods are usually employed to predict structural strength for such panels. However, the introduction of non-uniform plate thicknesses renders such calculations difficult when analytical methods and design equations are used. The authors have suggested an equivalent plate thickness method that is based on the weighted average approach to analyse the strength of stiffened panels with non-uniform plate thicknesses. In the present paper, the validity of the equivalent plate thickness method to the ultimate strength analysis of stiffened panels with non-uniform plate thicknesses is checked through nonlinear finite element method computations. It is concluded that the equivalent plate thickness method is accurate for the panel ultimate strength analysis under combined biaxial compression and lateral pressure loads.

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DOI: 10.1016/j.tws.2011.02.011
ABSTRACT: In this work, three optimization algorithms—Levenberg–Marquardt, simulated annealing and a newly developed and proposed hybrid differential evolution particle swarm optimization—are considered in the shape optimizations of cross-sections of integrally stiffened panels (ISP) for aeronautical applications, when subjected to buckling deformation modes within the elasto-plastic range. The proposed algorithm is shown to be robust and more effective, in the tested examples, than conventional optimization algorithms, leading to optimum designs of ISP cross-sections for a pre-defined buckling load-carrying capacity, combined with elasto-plastic nonlinear behaviors.

ABSTRACT: An experimental investigation was carried out to determine the ultimate strength of welded stiffened aluminium panels in alloy 6082 T6 subjected to in-plane compressive loads normal to the directions of the stiffeners. This load case is not treated in the European standard for aluminium structures, Eurocode 9. A total of 21 panel specimens with various side aspect ratios and both open and closed stiffener sections were tested in a purpose made test rig. Great care was taken to ensure the rig gave very precise boundary conditions. The panels were manufactured by metal inert gas arc welding and friction stir welding. An extensive measurement program was carried out to determine the distribution of material strength and initial geometric imperfections. Small imperfection amplitudes were found. Tensile tests revealed variation in material properties, but the strength values were on average higher than the values stated in Eurocode 9. The panels
failed by two different deformation modes; global flexural buckling and local buckling of the plate elements between the stiffeners.

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ABSTRACT: Lattice materials composed of hollow nanocrystalline struts have recently made it possible to access new regions of material property space, by exploiting structural efficiencies along multiple length scales (nanometre to centimetre range). An important design issue for these materials is to understand how the failure mechanisms that act at these scales affect the macroscopic mechanical properties. In this study, we tested hollow nanocrystalline cylinders of two different grain sizes (20 nm and 100 nm) in uniaxial compression to investigate the effect of grain size on dominant failure mechanisms, and the influence of the latter on the compressive strength. The finite element method was used to model the interaction of the three observed failure mechanisms: shell buckling (SB), yielding (Y) and fracture (F). Depending on the grain size and geometry, the failure sequence can be SB–Y–F, Y–SB–F, SB–Y or Y–SB, the order of which has important implications in defining the limits of mechanical performance. One such implication is that when shell buckling occurs in the inelastic regime of the material, the macroscopic strength increase due to grain size refinement can be greater than the inherent yield strength increase of the material. Second, material fracture and shell buckling may not be competing failure mechanisms, which means that the effectiveness of grain size reduction in increasing the structural efficiency of cylindrical strut members can span the entire Hall–Petch range of the material.

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Rekha Bhoi and L.G. Kalurkar (Dept. of Civil Engineering, Jawaharlal Nehru Engineering College, Aurangabad, Maharashtra, India), “Study of buckling behaviour of beam and column subjected to axial loading for various rolled I sections”, International Journal of Innovative Research in Science, Engineering and Technology (IIRSET), Vol. 3, No. 11, November 2014

ABSTRACT: In this paper the buckling behaviour of an I - beam under axial load on column and beam is examined. Buckling loads are critical loads where certain types of structure become unstable. The results of an extensive parametric study are presented in graphical form and summarized by simple design curves and evaluating the effect of critical buckling load for various symmetrical rolled I - sections like Indian Standard Junior Beam (ISJB), Indian Standard Light Weight Beam (ISLB), Indian Standard Medium Weight Beam (ISMB), Indian Standard Wide Flange Beam (ISWB), Indian Standard Heavy Weight Beam (ISHB) for different depth are calculated by using software ANSYS. The results of critical buckling load calculated using ANSYS are compared with the conventional method of Euler Buckling theory analytically.

References listed at the end of the paper:

ABSTRACT: Buckling is a critical state of stress and deformation, at which a slight disturbance causes a gross additional deformation, or perhaps a total structural failure of the part. Structural behavior of the part beyond 'buckling' is not evident from the normal arguments of static. Buckling failures do not depend on the strength of the material, but are a function of the component dimensions & modulus of elasticity. Therefore, materials with a high strength will buckle just as quickly as low strength ones. If a structure is subject to compressive loads, then a buckling analysis may be necessary. The study presented in this paper is intended to help designers of steel braced barrel vaults by identifying the significant differences in determining which configuration(s) would be best in different conditions of use. The study presented is of parametric type and covers several important parameters like rise to span ratio, different boundary conditions, such that barrel vault acts as an arch, as a beam or as a shell, The buckling strength of a three different configuration of a double layer braced barrel vaults are presented in this paper for rise/span ratio varying from 0.2-0.7 and having four different types of boundary conditions. Through consideration of these parameters, the paper presents an assessment of the effect of the vault configuration on the overall buckling strength.

References listed at the end of the paper:
ABSTRACT: This master thesis details the investigation of the effect of geometrical imperfection on thin shell structures using general FEM software packages. The author proposes a finite element based method for the analysis and design of thin shell structures, and describes the implementation of such a procedure on four different FEM packages. The procedure involves the assessment of imperfection sensitivity of a design, and imposing geometrical imperfection in the shape of the first buckling mode prior to a geometrically non-linear analysis. Starting with thin metallic cylinders, by incorporating imperfection to the surface, the author shows that ANSYS is capable of reproducing results similar to Koiter's asymptotic theory and to experimental data. The author further demonstrates the robustness and easy-to-use nature of the imperfection procedure by implementing it on four simple yet realistic structures with both symmetric and asymmetric load cases. For extremely imperfection sensitive structures such as an axially loaded cylinder, the author then introduces four different types of imperfection that may be imposed in place of the first buckling mode, and gauges the effectiveness of each with a modified knock-down factor. By varying the vertical curvature, it is discovered that an axisymmetric imperfection shape governs the ultimate buckling capacity of any near-cylindrical shells. An theory is being developed that explains the effect of the axisymmetric shape. Change in Gaussian curvature is calculated as the end of every load step in the FEM analysis. By plotting the change in Gaussian curvature, the onset of buckling can be readily defined. Finally, physical non-linearities are introduced to the FEM models to gauge the effect of yielding and cracking on a steel cylinder, and a reinforced concrete (RC) cooling tower respectively. It is found that metal buckles within the elastic range, and yielding eliminates post-buckling capacity without altering the ultimate capacity. With RC cracking, it is discovered that instability occurs soon after cracks develop at the buckles of the imperfection shape, therefore reducing the capacity by as much as 8 times from that of the elastic model.

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“Buckling Analysis for a Ring-Stiffened FGM Cylindrical Shell under Hydrostatic Pressure and Thermal Loads”, Journal of Mechanics, pp. 1-8, May 2014, DOI: http://dx.doi.org/10.1017/jmech.2014.34

ABSTRACT: This paper studies the buckling analysis for a ring-stiffened cylindrical shell consisted of functionally graded material (FGM) subjected to hydrostatic pressure and thermal loads. Material properties of the ring-stiffened FGM cylindrical shell are assumed to be temperature-dependent, and vary smoothly through the thickness direction of the structure according to a volume exponent. Based on the Donnell assumptions, buckling loads of the ring-stiffened FGM cylindrical shell are presented by utilizing the Galerkin method. Numerical results reveal that thermal loads, volume exponent and geometric parameters have significant effects on the buckling behavior of the ring-stiffened cylindrical shell.


19.1 INTRODUCTION: An efficiency of the membrane stress state, based on the strength conditions only, enables one to employ a very small shell thickness, as discussed in the preceding chapters of Part II. However, a possibility of the shell buckling impedes that, causing us either to increase the shell thickness or to reinforce the shell by stiffeners. It should be noted that the shell buckling is always disastrous, unlike, for example, a column or plate buckling. Therefore, the problem of the stability in designing shell structures is extremely vital. This problem is made worse because of some specific difficulties associated with determining correctly the critical values of loads applied to thin shells. Note that these difficulties are much greater than in the buckling analysis of columns, frames, and flat plates. They are associated with a complicated mathematical description of the deformed state of shells, and with a diversity of situations at which a shell can buckle. General postulations, definitions, and fundamentals of the structural stability theory, introduced in Chapter 8 for the plate buckling problems, can be applied also to the shell buckling analysis. In this chapter, we present a systematic but simplified analysis of shell buckling, and obtain some useful relationships between the critical values of applied loads and shell parameters. We limit ourselves to the consideration of thin shells for which elastic buckling without plastic deformation is possible.
ABSTRACT: It is widely accepted that for many buckling problems of plates and shells in the plastic range the flow theory of plasticity leads to a significant overestimation of the buckling stress while the deformation theory provides much more accurate predictions and is therefore generally recommended for use in practical applications. The present work aims to contribute to further understanding of the seeming differences between these two theories with particular regards to circular cylindrical shells subjected to axial compression. A clearer understanding of the two theories is established using accurate numerical examples and comparisons with some widely cited accurate physical test results. It is found that, contrary to common perception, by using a geometrically nonlinear finite element formulation with carefully determined and validated constitutive laws very good agreement between numerical and test results can be obtained in the case of the physically more sound flow theory of plasticity. The reasons underlying the apparent buckling paradox found in the literature regarding the application of deformation and flow theories and the different conclusions reached in this work are investigated and discussed in detail.

References listed at the end of the paper:

ABSTRACT: It is widely accepted that, for many buckling problems of plates and shells in the plastic range, the flow theory of plasticity either fails to predict buckling or significantly overestimates buckling stresses and strains, while the deformation theory, which fails to capture important aspects of the underlying physics of plastic deformation, provides results that are more in line with experimental findings and is therefore generally recommended for use in practical applications. This thesis aims to contribute further understanding of the reasons behind the seeming differences between the predictions provided by these two theories, and therefore provide some explanation of this so-called ‘plastic buckling paradox’.

The study focuses on circular cylindrical shells subjected to either axial compression or non-proportional loading, the latter consisting of combined axial tensile stress and increasing external pressure. In these two cases, geometrically nonlinear finite-element (FE) analyses for perfect and imperfect cylinders are conducted using both the flow and the deformation theories of plasticity, and the numerical results are compared with data from widely cited physical tests and with analytical results. The plastic buckling pressures for cylinders subjected to non-proportional loading, with various combinations of boundary conditions, tensile stresses, material properties and cylinder’s geometries, are also obtained with the help of the differential quadrature method (DQM). These results are compared with those obtained using the code BOSOR5 and with nonlinear FE results obtained using both the flow and deformation theories of plasticity.

It is found that, contrary to common belief, by using a geometrically nonlinear FE formulation with carefully determined and validated constitutive laws, very good agreement between numerical and test results can be obtained in the case of the physically more sound flow theory of plasticity. The reason for the ‘plastic buckling paradox’ appears to be the over-constrained kinematics assumed in many analytical and numerical treatments, such as BOSOR5 and NAPAS, whereby a harmonic buckling shape in the circumferential direction is prescribed.

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Buckling predictions of the deformation and flow

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ABSTRACT: Incremental launching of steel bridges is a demanding undertaking, on the erection site as well as on the designers desk. Not seldom, the structure itself is during the launching subjected to high concentrated forces on the lower flange when passing over a launching shoe or an intermediate support (e.g. column). These concentrated forces, commonly referred to as patch loads, may be of such magnitude that it governs the thickness of the web in the bridge girder. Though, a small increase in web thickness leads to a substantial gain of steel weight of the bridge. Hence also a higher material cost.

One solution to this problem is to increase the buckling resistance of the web with the use of a longitudinal stiffener of open (a plate) or closed type (closed profile of e.g. V-shape). The improved patch load resistance is in the european design code EN 1993-1-5 nowadays determined with the help of the yield resistance for the web and contributing parts of the loaded flange reduced with a factor dependent of the slenderness of the web and the influence of one or more longitudinal stiffeners. Parts in the expression for the yield resistance and the reduction factor have been somewhat questioned and over the years a substantial amount of tests and FE simulations of longitudinally stiffened webs has been carried out. This research work has produced a large amount of test data which has been used herein to further improve the prediction of the patch load resistance of longitudinally stiffened steel girder webs.

Based on the use of the gathered test data from the literature and previously done research, a calibrated patch load resistance function was developed for both open and closed longitudinal stiffeners. Furthermore, a partial safety factor for the proposal was determined according to the guidelines in EN 1990 (2002). In all, the proposal was shown to clearly improve the accuracy of resistance prediction when compared to other resistance models as well as the EN 1993-1-5.
Another questioned part in the commonly used design codes is the reduction function regarding local buckling under uniform in-plane compression. The nowadays used function (the Winter function) has been developed during the 1930’s and was based on tests on cold formed specimens. This reduction function has been criticized as being too optimistic regarding plates with large welds. A series of tests on welded specimens made of high strength steel with large welds was conducted to investigate the aforementioned concerns. Along with test data found in literature survey, the Winter function was proven to be too optimistic regarding these heavily welded plates. A new reduction function, based on the test data, was proposed and validated through a comparison with the available experimental results.

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Bossert, T.W. and Ostapenko, A. (1967). “Buckling and ultimate loads for plate girder web plates under edge loading”, Fritz Engineering Laboratory Report No. 319.1, Department of Civil Engineering, Lehigh University, Bethlehem-PA, USA.
ABSTRACT: Modern steel constructions such as long span bridges are characterised by slender plated structures with low material consumption and the optimisation of their fabrication, leading to low dead loads and a high utilisation. Since often several internal forces act at the same time on the cross-section, very complex multiaxial stress states may develop. The aim of this work is to analyse the buckling behaviour of multiaxially loaded plates in order to increase the insight and to allow the enhancement of the current design rules of unstiffened and stiffened plates under several load combinations focusing on the reduced stress method according to Chapter 10, EN 1993-1-5 [36] and especially to analyse the influence of tensile stress states. As in EN 1993-1-5 [36] according to the reduced stress method multiaxial stress states are already considered in the determination of the single plate slenderness, this theoretically allows for taking into account the positive effect of tensile stress on the buckling behaviour. However, only few studies have looked on this effect until now and systematic investigations are missing, so that this work clarifies this open issue.

In a first step the elastic buckling of flat plates and the effect of multiaxial stress states are described. The buckling coefficient for unstiffened panels is given as a function of the panel aspect ratio and the stress state resulting in significantly elevated values if tensile stresses are acting. However, the evaluation of the buckling
coefficient shows pronounced peaks for certain cases, where it is questionable if they should be taken into account for the design. Therefore, a formulation is presented for ignoring these peaks. For the assessment of the buckling coefficient in case of stiffened plates several possibilities are explained. The complexity in the determination of the buckling coefficient, which involves a variety of parameters, leads to the conclusion that nowadays numerical techniques are the most appropriate approaches. Furthermore, the current rules according to EN 1993-1-5 [36] are explained in detail with a particular look on multiaxially loaded plates showing the impact of the stress state on the plate slenderness and therefore on the interaction curves. The interaction curves according to EN 1993-1-5 [36] allow a systematic utilisation of the favourable effect of tensile stresses on the buckling behaviour, especially compared to the rules according to DIN 18800-3 [22]. However, studies to justify this beneficial effect are missing. Therefore, experimental and numerical investigations are conducted to give an insight in the buckling behaviour of multiaxially loaded plates.

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R. Maquoi and J. Rondal. From thick to thin or from thin to thick? In IABSE Colloquium: Thin Walled Metal Structures, Stockholm, 1986.


Thermal buckling analysis of cross-ply laminated rectangular plates under nonuniform temperature distribution: A differential quadrature approach

ABSTRACT: Differential quadrature method (DQM) is implemented for analyzing the thermal buckling behavior of the symmetric cross-ply laminated rectangular thin plates subjected to uniform and/or non-uniform temperature fields. The approach includes two steps: (1) solving the problem of in-plane thermo-elasticity to obtain the in-plane force resultants and (2) solving the buckling problem under the force distribution obtained in the previous step. Solution procedures are numerically performed by discretizing the governing differential equations and boundary conditions using DQM method. Applying the developed DQ formulation, the buckling loads are obtained for several sample plates. The numerical results compared well with those available in the literature as well as those obtained by ABAQUS. Parametric studies are conducted to investigate the influence of some important parameters including the plate aspect ratio, cross-ply ratio, and stiffness ratio on the critical temperature and mode shape of buckling.

References listed at the end of the paper:


ABSTRACT: This paper presents a finite element based numerical study on controlling the postbuckling behavior of thin-walled cylindrical shells under axial compression. With the increasing interest of various disciplines for harnessing elastic instabilities in materials and mechanical systems, the postbuckling behavior of thin-walled cylindrical shells may have a new role to design materials and structures at multiple scales with switchable functionalities, morphogenesis, etc. In the design optimization approach presented herein, the mode shapes and their amplitudes are linearly combined to generate initial geometrical designs with predefined imperfections. A nonlinear postbuckling finite element analysis evaluates the design objective function, i.e., the desired postbuckling force-displacement path. Single and multi-objective optimization problems are formulated with design variables consisting of shape parameters that scale base eigenvalue shapes. A gradient-based algorithm and numerical sensitivity evaluations are used. Results suggest that an optimized shape for a cylindrical shell can achieve a targeted response in the elastic postbuckling regime with multiple mode transitions and energy dissipation characteristics. The optimization process and the obtained geometry can be potentially used for energy harvesting and other sensing and actuation applications.

References listed at the end of the paper:
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ABSTRACT: We formulate in situ parameter identification techniques for multistable spring models of compressed CNT bundles, which capture the sequential buckling through the height of the bundle, as well as the overall mechanical response. The proposed techniques are validated against a SEM-assisted compression experiment on a CNT pillar [1]. Using multi-spring models, we propose a ‘microscopic’ identification technique based on the determination of stress–strain curves of vertical segments of the tested structure (featuring few micron height). We show that the in situ identified models can effectively reproduce the experimentally-observed stress–strain response (single-spring models), and strain localization effects (multi-spring model), within a simple 1D framework.

References listed at the end of the paper:


Y.Z. Sun (1,2) and K.M. Liew (2)
(1) Department of Civil Engineering and Architecture, Zhongyuan University of Technology, Zhengzhou, China
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ABSTRACT: (cannot cut and paste)

S. Ajori and R. Ansari (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Torsional buckling behavior of boron-nitride nanotubes using molecular dynamics simulations”, Current
ABSTRACT: Based on molecular dynamics simulations, the mechanical properties and buckling behavior of boron-nitride nanotubes under the action of torsional load are investigated. According to the results, the torsional properties of a boron-nitride nanotube are higher than those of its carbon counterpart. The effect of geometrical parameters on these parameters is also investigated. It is observed that by increasing the radius of nanotubes of the same length, unlike the critical shear strain, the critical torque considerably increases. The effect of chirality is also found to be negligible in the cases of critical shear strain and buckling mode, unlike the critical torque.

References listed at the end of the paper:
ABSTRACT: The buckling of cylindrical shells has long been regarded as an undesirable phenomenon, but increasing interests on the development of active and controllable structures open new opportunities to utilize such unstable behavior. In this paper, approaches for modifying and controlling the elastic response of axially compressed laminated composite cylindrical shells in the far postbuckling regime are presented and evaluated. Three methods are explored (1) varying ply orientation and laminate stacking sequence; (2) introducing patterned material stiffness distributions; and (3) providing internal lateral constraints. Experimental data and numerical results show that the static and kinematic response of unstable mode branch switching during postbuckling response can be modified and potentially tailored.

References listed at the end of the paper:

ABSTRACT: Elastic instability, long considered mainly as a failure limit state or a safety guard against ultimate failure is gaining increased interest due to the development of active and controllable structures, and the growth in computational power. Mode jumping, or snap-through, during the postbuckling response leads to sudden and high-rate deformations due to generally smaller changes in the controlling load or displacement input to the system. A paradigm shift is thus emerging in using the unstable response range of slender structures for purposes that are rapidly increasing and diversifying, including applications such as energy harvesting, frequency tuning, sensing and actuation. This paper presents a finite element based numerical study on controlling the postbuckling behavior of fiber reinforced polymer cylindrical shells under axial compression. Considered variables in the numerical analyses include: the ply orientation and laminate stacking sequence; the material distribution on the shell surface (stiffness distribution); and the anisotropic coupling effects. Preliminary results suggest that the static and dynamic response of unstable mode branch switching during postbuckling can be fully characterized, and that their number and occurrence can be potentially tailored. Use of the observed behavior for energy harvesting and other sensing and actuation applications will be presented in future studies.

References listed at the end of the paper:


References listed at the end of the paper:


Sen Lin (1), Shiwei Zhou (1), Yi Min Xie (1), Xiaodong Huang (1) and Qing Li (2)
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ABSTRACT: This paper investigates the reversible retraction of a spherical perforated shell that is made from nonlinear soft material. The buckling and post-buckling simulation in Abaqus shows the skeleton ligaments of such a buckliball rotate in the beginning and buckle thereafter, resulting in the shrinkage and encapsulation of the whole structure in the final stage. We used dynamic-explicit method in the simulation and its superiority over others is verified by obtaining correct buckling patterns efficiently and stably.
Lyubomir Zdravkov (University of Architecture, Civil Engineering and Geodesy, Russia?), “Use of LBA-MNA methodology for determination of bearing capacity of compressed shells”, 15th International Scientific Conference VSU, 2015

ABSTRACT: Using GNIA or GMNIA in new, still unmade shells is related with a large scope, heavy and continuous calculations. Main difficulty is modeling of imperfections with correct values. Ordinary designers who are usually hard pressed by time and are not familiar with computing software, enabling full GNIA or GMNIA analysis of shells, require simplified procedures in which imperfections are not included. Such a procedure, called LBA-MNA, is presented here. It allows analysis of real shells, modelled as perfect structures.

Jin-Wu Jiang, “The strain rate effect on the buckling of single-layer MoS2”, Scientific Reports, Vol. 5, Article Number 7814, January 2015, DOI: 10.1038/srep07814

ABSTRACT: The Euler buckling theory states that the buckling critical strain is an inverse quadratic function of the length for a thin plate in the static compression process. However, the suitability of this theory in the dynamical process is unclear, so we perform molecular dynamics simulations to examine the applicability of the Euler buckling theory for the fast compression of the single-layer MoS2. We find that the Euler buckling theory is not applicable in such dynamical process, as the buckling critical strain becomes a length-independent constant in the buckled system with many ripples. However, the Euler buckling theory can be resumed in the dynamical process after restricting the theory to an individual ripple in the buckled structure.

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ABSTRACT: In ship construction it is very much essential to keep the hull weight to a minimum in order to achieve higher fuel efficiency. The lighter the structure lesser will be the power requirement for certain speed of operation. This has led to the usage of more and more thinner structural components making them more vulnerable to buckling. The basic structural components of ships are orthogonally stiffened plate panels. The increased use of thin plates in panel fabrication results in significantly increased buckling distortion. Competitiveness in cost and time can be increased by eliminating or mitigating these distortions during the design and fabrication stage rather than allowing them to accumulate and then removing them. In this study an investigation on buckling phenomenon in fabrication of typical stiffened panels as used in shipbuilding was carried out. A method of distortion mitigation by counteracting the compressive forces developed due to welding of stiffeners was developed and investigated in detail. The method developed is named as Thermo-Mechanical Tensioning (TMT). It was found to be very effective yet simple-to-implement method of buckling distortion control. Extensive experimentation was carried out both in laboratory and in full scale in Cochin Shipyards Ltd. It was observed that, this pre-tensioning technique TMT can be very gainfully applied as an active in-process control method to avoid buckling distortion in stiffened panels.

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Ractliffe, M.A. 1983. The basis and essentials of thermal residual distortion in steel structures, The Royal Institution of Naval Architects.

ABSTRACT: In this paper, the displacements of a cylindrical shell with varying thickness and subjected to axial and external pressure are calculated analytically using the first-order shear deformation theory. The kinematics of the problem is defined by von Kármán theory, and the constitutive equation obeys Hooke’s law. The governing equations, which are a system of nonlinear differential equations, are extracted by applying the virtual work principle; the matched asymptotic expansion method of the perturbation technique is used to calculate the analytical solution. The effects of different load profiles and thicknesses on the results are investigated. Also, a comparison with the FEM is performed.

Yundong Sha and Xiyang Zheng (Liaoning Key Laboratory of Advanced Test Technology for Aeronautical propulsion System, Shenyang, 110136, China), “Response analysis of thin-walled structure under non-uniform temperature field and acoustic loads”, International Conference on Advances in Mechanical Engineering and Industrial Informatics (AMEE 2015)

ABSTRACT: With the raised performance of advanced aircraft, hypersonic vehicles are subjected to increasingly severe environment. Very severe elevated temperature and high intensity acoustic loads will cause the thin-walled structures of aircraft to respond in a strong nonlinear large deflection vibration, and leading to premature fatigue failure of the structure. According to the Von Karman large deflection theory, the large deflection governing equation of plate under thermo-acoustic loadings is obtained. The Galerkin method is employed to obtain the ordinary differential equation under modal coordinates and the stress expressed by modal displacement for the simply-supported plate and the clamped plate. The critical thermal buckling temperatures and modal frequencies of simply-supported plate and thin-walled cylindrical shell under thermal loads with linear temperature gradient, the dynamic responses of them under thermo-acoustic loads, are obtained using finite element numerical stimulation, The thermal-acoustic responses of simply-supported plate and thin-walled cylindrical shell with different combinations of thermal-acoustic loadings are obtained, including the random vibration in pre-buckled regime, snap-through motion between post-buckled equilibrium positions and nonlinear vibration around one post-buckled position.

References listed at the end of the paper:

S.W. Yang (1), Y.X. Hao (1), W. Zhang (1) and S.B. Li (2)
(1) Mechanical Engineering, Beijing Information Science and Technology University, Beijing 100192, P. R. China
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ABSTRACT: Nonlinear dynamic behaviors of ceramic-metal graded truncated conical shell subjected to complex loads are investigated. The shell is modeled by first-order shear deformation theory. The nonlinear partial differential governing equation in terms of transverse displacements of the FGM truncated conical shell is derived from the Hamilton's principle. Galerkin's method is then utilized to discretize the partial governing equations to a two-degree-of-freedom nonlinear ordinary differential equation. The temperature-dependent materials properties of the constituents are graded in the radial direction in accordance with a power-law distribution. The aerodynamic pressure can be calculated by using the first-order piston theory. The temperature field is assumed to be a steady-state constant-temperature distribution. Bifurcation diagrams, the maximum Lyapunov exponents, wave forms and phase portraits are obtained by numerical simulation to demonstrate the complex nonlinear dynamics response of the FGM truncated conical shell. The influences of the semi-vertex angle, the material gradient index, in-plane and aerodynamic load on the nonlinear dynamics are studied.

ABSTRACT: The first part reviews numerical procedures developed for stiffened panels subjected to explosive forces. The structural idealization, the theoretical basis, and the merits of these methods are discussed. The second part reviews the probabilistic procedures developed for analysis of deteriorering stiffened panels. The third part reviews recent work developed in several finite element modelling philosophies for analysis of stiffened panels. The influence of various parameters affecting the structural performance, such as geometric and material imperfections, corrosion, residual stresses, etc. is discussed. The fourth part reviews hybrid procedures developed to provide approximate solutions for the designers. Numerical procedure is presented using combination of energy formulations and mathematical programming techniques to model the interaction between the box girder components. Localized damage largely affects the performance of stiffened panels and must be accounted for in the design phase. Little emphasis was given in the published literature to developing simplified analytical models that can be used in practice to compute the residual strength of the stiffened panels under these types of loadings. Furthermore, analytical expressions are required to compute the reduction in the stiffness induced due to the structural or material defects. These expressions must be dependent on the type of damage. It must be noted that some of this damages is localized in nature and must be accounted for by using specialized functions to assess the structural defect accurately. Research work is required in this direction.

ABSTRACT: The paper offers to practitioners economical procedures that can be utilized to optimize the design of built up box sections subject to compression and biaxial bending. Little emphasis appeared in the published literature that addressed this general loading condition. The analysis methodology and structural idealization are first overviewed. Diagrams are presented showing buckling behavior of the section by accounting rotational and lateral restraints. The post-buckling response is also illustrated for various applied stress ratios. A design space concept is then introduced showing interaction of serviceability and strength limit states. These procedures are cost effective and appropriate for industrial implementation to optimize the structural design.


ABSTRACT: In this paper, the dynamic stability and bifurcation phenomenon for a class of isotropic functionally graded plates including power-law, sigmoid and exponential function under lateral stochastic loads are studied and compared. Due to the existence of random loads, both the behavior investigation and response analysis are not conventional deterministic methods. So, the instability region and border curves of bifurcation are evaluated via a probability density function of the response. The latter is computed from a completely exact solution of the Fokker–Planck–Kolmogorov equation. The three-dimensional instability region and the border curves of bifurcation are drawn with respect to material parameter, in-plane forces and the mean value of lateral forces. To generalize the results, all the parameters are transformed to some suitable nondimensional variables, and then, the effects of all mentioned parameters on the dynamic stability are completely discussed and compared. Finally, the analytic results are validated by drawing numeric bifurcation diagrams for the nondimensional deflections of plates.

References listed at the end of the paper:
ABSTRACT: Buckling of soft matter is ubiquitous in nature and has attracted increasing interest recently. This paper studies the retractile behaviors of a spherical shell perforated by sophisticated apertures, attributed to the buckling-induced large deformation. The buckling patterns observed in experiments were reproduced in computational modeling by imposing velocity-controlled loads and eigenmode-affine geometric imperfection. It was found that the buckling behaviors were topologically sensitive with respect to the shape of dimple (aperture). The shell with rounded-square apertures had the maximal volume retraction ratio as well as the lowest energy consumption. An effective experimental procedure was established and the simulation results were validated in this study.

References listed at the end of the paper:


ABSTRACT: The buckling behaviour of pin ended cold-formed steel lipped channel columns affected by local / distortional / global buckling mode interaction under axial loading is simulated by using finite element software ABAQUUS, and the results are compared with the test results available in the literature. The comparisons show that the proper analysis model can simulate the buckling behaviour and ultimate capacity of cold-formed steel columns. Then a parametric analysis is carried out for 15 column geometries of 3 yield stress values of different dimension, thickness and lengths. The cross sectional dimensions and length of the specimen have been chosen such that to have almost equal local, distortional and global critical buckling stresses by using the CUFSM software. The selected sections also satisfied the limitations given for pre-qualified sections in Direct Strength Method (DSM). After comparing the FEM column ultimate loads with the estimates predicted by the current Direct Strength Method (DSM) design curves against local, distortional and global failures, which clearly shows that they lead to inaccurate and often very unsafe ultimate load estimates. At the end, a design recommendation is made for current design practice of evaluating the ultimate strength of the lipped channel columns.

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ABSTRACT: The structural performance of two advanced composite tow-steered shells with cutouts, manufactured using an automated fiber placement system, is assessed using both experimental and analytical methods. The shells' fiber orientation angles vary continuously around their circumference from +/−10 degrees on the crown and keel, to +/−45 degrees on the sides. The raised surface features on one shell result from application of all 24 tows during each fiber placement system pass, while the second shell uses the system's tow drop/add capability to achieve a more uniform wall thickness. These unstiffened shells were previously tested in axial compression and buckled elastically. A single cutout, scaled to represent a passenger door on a commercial aircraft, is then machined into one side of each shell. The prebuckling axial stiffnesses and bifurcation buckling loads of the shells with cutouts are also computed using linear finite element structural analyses for initial comparisons with test data. When retested, large deflections were observed around the cutouts, but the shells carried an average of 92 percent of the axial stiffness, and 86 percent of the buckling loads, of the shells without cutouts. These relatively small reductions in performance demonstrate the potential for using tow steering to mitigate the adverse effects of typical design features on the overall structural performance.

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“Conflicting Axial Buckling Strains from Two Criteria to Detect Instability in Single-Walled Carbon Nanotubes”, XII International Conference on Nanostructured Materials (NANO 2014), July 13-18, 2014, Moscow, Russia

ABSTRACT: Until today mechanical characterization of single-walled carbon nanotubes remains a challenging issue due to an ambiguity in definition of its wall thickness. This leads to a wide scatter in its Young’s modulus [1]. However, very recently Gupta et al. [2] have derived a mathematical relationship between the wall
thickness and radius of single-walled carbon nanotubes (SWCNTs) using molecular mechanics simulations. They used inextensional modes of vibrations of SWCNTs and continuum mechanics to deduce the aforementioned relationship. Another route to characterize a SWCNT is to study its axial buckling using molecular mechanics/dynamics and employing continuum theories [3,4]. In general, in simulations axial buckling due to compressive strains is determined by a sudden drop in the potential energy [5] or a sudden drop in the load-deflection curve in experiments [6] with increasing compressive strain. Inspired by the fact that at the onset of buckling of beams and shells their fundamental frequency becomes zero we determine the critical buckling strain by computing vanishing eigen values [7] of the Hessian of a SWCNT under compression using molecular mechanics. In the present study several molecular mechanics simulations using MM3 potential [8] have been carried out to identify an appropriate criterion for detecting initiation of buckling of slender (aspect ratio ~ 15), clamped-clamped SWCNTs subjected to axial compressive strains. Armchair and zigzag chiralities of SWNTs have been considered to study the two criteria for detecting onset of instability in SWCNTs. In Fig. 1 we show the eigen value loci of bending modes and potential energy of (7,0) SWCNT for each incremental compressive strain. It is found that the two criteria yield different values of the critical buckling strain. Furthermore, if SWCNTs were modelled as continuum beam or shell, both these criteria will result in the same values of the critical buckling strain.

References listed at the end of the paper:


Summary: We focus on the graphene wrinkling, from its formation to collapse, and its dependence on aspect ratio and temperature using molecule dynamics simulation. Based on our results, the first wrinkle is not formed on the edge but in the interior of graphene. The fluctuations of edge slack warps drive the wrinkling evolution in graphene which is distinguished from the bifurcation in continuum film. There are several obvious stages in wrinkling progress, including incubation, infancy, youth, maturity and gerontism periods which are identified by the atomic displacement difference due to the occurrences of new wrinkles. The wrinkling progress is over when the C–C bonds in highly stretched corners are broken which contributes to the wrinkling collapse. The critical wrinkling strain, the wrinkling pattern and extent depend on the aspect ratio of graphene, the wrinkling level and collapsed strains do not. Only the collapsed strain is sensitive to the temperature, the other wrinkling parameters are independent of the temperature. The results would benefit the understanding of the physics of graphene wrinkling and the design of nanomechanical devices by tuning the wrinkles.

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924 Łódź, Poland
“Collaborative Research On Thin-Walled Structures By The University Of Strathclyde And The Technical University Of Lodz”, Stability of Structures, XIII-th Symposium, Zakopane 2012

ABSTRACT: This paper describes the collaborative research carried out into various aspects of the behaviour of thin-walled structures at the University of Strathclyde and the Technical University of Lodz over the past 40 years or so. The two Universities have had links over the past 45 years, and collaboration has been carried out in many disciplines. The collaboration between the Department of Mechanical Engineering at Strathclyde and the Department of Strength of Materials at Lodz has been largely concentrated on thin-walled structures, and some aspects of this collaboration are outlined in this paper.

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lipped channel beam. Proc. of 5th Int. Conference on Coupled Instabilities in Metal Structures (CIMS 2008), v.1., University of Sydney, Australia, 2008, pp. 85-90.


ABSTRACT: Numerical simulations of thin sheets undergoing large deformations are computationally challenging. Depending on the scenario, they may spontaneously buckle, wrinkle, fold, or crumple. Nature’s thin tissues often experience significant anisotropic growth, which can act as the driving force for such instabilities. We use a recently developed finite element model to simulate the rich variety of nonlinear responses of Kirchhoff-Love sheets. The model uses subdivision surface shape functions in order to guarantee convergence of the method, and to allow a finite element description of anisotropically growing sheets in the classical Rayleigh–Ritz formalism. We illustrate the great potential in this approach by simulating the inflation of airbags, the buckling of a stretched cylinder, as well as the formation and scaling of wrinkles at free boundaries of growing sheets. Finally, we compare the folding of spatially confined sheets subject to growth and shrinking confinement to find that the two processes are equivalent.

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ABSTRACT: We present the results of an experimental investigation on the crystallography of the dimpled patterns obtained through wrinkling of a curved elastic system. Our macroscopic samples comprise a thin hemispherical shell bound to an equally curved compliant substrate. Under compression, a crystalline pattern of dimples self-organizes on the surface of the shell. Stresses are relaxed by both out-of-surface buckling and the emergence of defects in the quasi-hexagonal pattern. Three-dimensional scanning is used to digitize the topography. Regarding the dimples as point-like packing units produces spherical Voronoi tessellations with cells that are polydisperse and distorted, away from their regular shapes. We analyze the structure of crystalline defects, as a function of system size. Disclinations are observed and, above a threshold value, dislocations proliferate rapidly with system size. Our samples exhibit striking similarities with other curved crystals of charged particles and colloids. Differences are also found and attributed to the far-from-equilibrium nature of our patterns due to the random and initially frozen material imperfections which act as nucleation points, the presence of a physical boundary which represents an additional source of stress, and the inability of dimples to rearrange during crystallization. Even if we do not have access to the exact form of the interdimple interaction, our experiments suggest a broader generality of previous results of curved crystallography and their robustness on the details of the interaction potential. Furthermore, our findings open the door to future studies on curved crystals far from equilibrium.
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ABSTRACT: Graphene/hexagonal boron nitride (h-BN) heterostructure has showed great potential to improve the performance of a graphene device. A graphene on an h-BN substrate may buckle due to the thermal expansion mismatch between the graphene and h-BN. We used an energy method to investigate the periodic buckling patterns including one-dimensional, square checkerboard, hexagonal, equilateral triangular and herringbone mode in a graphene/h-BN heterostructure under equi-biaxial compression. The total energy, consisting of cohesive energy, graphene membrane energy and graphene bending energy, for each buckling pattern is obtained analytically. At a compression slightly larger than the critical strain, all buckling patterns have the same total energies, which suggests that any buckling pattern may occur. At a compression much larger than the critical strain, the herringbone mode has the lowest total energy by significantly reducing the membrane energy of graphene at the expense of a slight increase of the bending energy of graphene and cohesive energy. These results may serve as guidelines for strain engineering in graphene/h-BN heterostructures.


ABSTRACT: Corrugated shell structures are widely used in civil, naval, automotive, and aerospace engineering because of their superior properties. In this paper, the nonlinear dynamic deformation of a class of longitudinally corrugated shell with a second-order differentiable wave under a uniform load was investigated. On the basis of their previous research result—that the corrugated shell undergoes large deformation but small strains—the authors proposed an assumption that the dynamic configuration of the corrugated shell is the same as the static configuration with a different load. Then the governing equations of the dynamic deformation of the corrugated shell were derived using Lagrange’s equation, and an efficient numerical method without element discretization to solve those nonlinear differential equations was formulated. The accuracy of the present simplification was proved by comparing it with results obtained from a widely used nonlinear finite-element program, and the assumption on the dynamic configuration was shown to be applicable for most engineering applications. Furthermore, the developed method was adopted to perform parametric studies and it is found that the loading rates, the depth of wave, and the number of wave can greatly change the expansion velocity of the corrugated ring. And most importantly, the authors revealed that different corrugation types with the same ratio of the radius of the median surface to the depth of wave $R_0/L_w$, the number of waves $N$ and the circumference $C_t$ can yield similar dynamic expansion responses, which should be useful for future design of corrugated shell.

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DOI: 10.1140/epje/i2014-14062-9

ABSTRACT: We theoretically explain the complete sequence of shapes of deflated spherical shells. Decreasing the volume, the shell remains spherical initially, then undergoes the classical buckling instability, where an axisymmetric dimple appears, and, finally, loses its axisymmetry by wrinkles developing in the vicinity of the dimple edge in a secondary buckling transition. We describe the first axisymmetric buckling transition by numerical integration of the complete set of shape equations and an approximate analytic model due to Pogorelov. In the buckled shape, both approaches exhibit a locally compressive hoop stress in a region where experiments and simulations show the development of polygonal wrinkles, along the dimple edge. In a simplified model based on the stability equations of shallow shells, a critical value for the compressive hoop stress is derived, for which the compressed circumferential fibres will buckle out of their circular shape in order to release the compression. By applying this wrinkling criterion to the solutions of the axisymmetric models, we can calculate the critical volume for the secondary buckling transition. Using the Pogorelov approach, we also obtain an analytical expression for the critical volume at the secondary buckling transition: The critical volume difference scales linearly with the bending stiffness, whereas the critical volume reduction at the classical axisymmetric buckling transition scales with the square root of the bending stiffness. These results are confirmed by another stability analysis in the framework of Donnel, Mushtari and Vlasov (DMV) shell theory, and by numerical simulations available in the literature.

References listed at the end of the paper:

ABSTRACT: This thesis presents research results on the deformation of elastic shells, especially concerning buckling and wrinkling instabilities. The theoretical description of such deformations is used to develop methods of shape analysis, which serve to infer material properties from simple experimental observations of deformed shells. When an initially spherical shell is deflated, two successive instabilities can typically be observed. In a first buckling transition, an axisymmetric dimple appears. It grows with proceeding deflation and acquires a polygonal shape in a secondary buckling transition. The onset of the first instability is well known. Here, we draw a complete picture of axisymmetric buckled shapes from the onset to a fully collapsed state, where opposite sides of the shell are in contact. Furthermore, it is shown that the stability of buckled shapes with respect to further spontaneous deflation depends decisively on whether the interior shell volume is prescribed (buckled shapes are stable), the pressure difference is fixed (shapes are unstable and collapse immediately after the onset) or the deflation is controlled by osmosis (intermediate between the former cases).

For the description of axisymmetric buckled shapes, we use two approaches: firstly non-linear shell theory and secondly a simple analytic model proposed originally by Pogorelov. The secondary buckling instability has so far only been observed in simulations and experiments. Here, we provide a theoretical explanation and analyse its onset quantitatively. A compressive circumferential stress in the vicinity of the dimple edge is identified as the driving force of the secondary buckling transition. Using the stability equations for shallow shells, we derive a critical circumferential stress which leads to wrinkles along the dimple edge, similar to the Euler buckling of straight rods. Subsequently, we introduce a model for capsules that are created from liquid drops by an interfacial reaction and hang from a capillary. The interior liquid can be removed by suction through the capillary, which usually leads to wrinkling of the capsule membrane. The theoretical model is applied to completely characterise the elastic moduli of the membrane by an analysis of the capsule contour and wrinkle wavelength detected in experimental images. A test on two different capsule systems, polymerised polysiloxane capsules and bubbles coated with a layer of the protein hydrophobin, proves the concept of the proposed elastometry method. In the analysis of the hydrophobin capsule, we find an interesting non-linear elastic
response which can be attributed to the molecular structure of the proteins consisting of a hard core and a softer shell. This motivates the development of a custom elasticity model based on the microscopic view of a bead-spring model including steric repulsions and can in part explain the experimental results of the hydrophobin capsule.

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Dortmund, 2013.

ABSTRACT: Thin shells are found in nature at scales ranging from viruses to hens’ eggs; the stiffness of such shells is essential for their function. We present the results of numerical simulations and theoretical analyses for the indentation of ellipsoidal and cylindrical elastic shells, considering both pressurized and unpressurized shells. We provide a theoretical foundation for the experimental findings of Lazarus et al. [following paper, Phys. Rev. Lett. 109, 144301 (2012)] and for previous work inferring the turgor pressure of bacteria from measurements of their indentation stiffness; we also identify a new regime at large indentation. We show that the indentation stiffness of convex shells is dominated by either the mean or Gaussian curvature of the shell depending on the pressurization and indentation depth. Our results reveal how geometry rules the rigidity of shells.

ABSTRACT: Smooth wrinkles and sharply crumpled regions are familiar motifs in biological or synthetic sheets, such as rapidly growing plant leaves and crushed foils. Previous studies have addressed both morphological types, but the generic route whereby a featureless sheet develops a complex shape remains elusive. Here we show that this route proceeds through an unusual sequence of distinct symmetry-breaking instabilities. The object of our study is an ultrathin circular sheet stretched over a liquid drop. As the curvature is gradually increased, the surface tension stretching the sheet over the drop causes compression along circles of latitude. The compression is relieved first by a transition into a wrinkle pattern, and then into a crumpled state via a continuous transition. Our data provide conclusive evidence that wrinkle patterns in highly bendable sheets are not described by classical buckling methods, but rather by a theory which assumes that wrinkles completely relax the compressive stress. With this understanding we recognize the observed sequence of transitions as distinct symmetry breakings of the shape and the stress field. The axial symmetry of the shape is broken upon wrinkling but the underlying stress field preserves this symmetry. Thus, the wrinkle-to-crumple transition marks symmetry-breaking of the stress in highly bendable sheets. By contrast, other instabilities of sheets, such as blistering and cracking, break the homogeneity of shape and stress simultaneously. The onset of crumpling occurs when the wrinkle pattern grows to half the sheet’s radius, suggesting a geometric, material-independent origin for this transition.

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“Scale effects on buckling analysis of orthotropic nanoplates based on nonlocal two-variable refined plate theory”, Acta Mechanica, Vol. 223, No. 2, pp 395-413, February 2012

ABSTRACT: This article presents the buckling analysis of orthotropic nanoplates such as graphene using the two-variable refined plate theory and nonlocal small-scale effects. The two-variable refined plate theory takes account of transverse shear effects and parabolic distribution of the transverse shear strains through the thickness of the plate, hence it is unnecessary to use shear correction factors. Nonlocal governing equations of motion for the monolayer graphene are derived from the principle of virtual displacements. The closed-form solution for buckling load of a simply supported rectangular orthotropic nanoplate subjected to in-plane loading has been obtained by using the Navier’s method. Numerical results obtained by the present theory are compared with first-order shear deformation theory for various shear correction factors. It has been proven that the nondimensional buckling load of the orthotropic nanoplate is always smaller than that of the isotropic nanoplate. It is also shown that small-scale effects contribute significantly to the mechanical behavior of orthotropic graphene sheets and cannot be neglected. Further, buckling load decreases with the increase of the nonlocal scale parameter value. The effects of the mode number, compression ratio and aspect ratio on the buckling load of the orthotropic nanoplate are also captured and discussed in detail. The results presented in this work may provide useful guidance for design and development of orthotropic graphene based nanodevices that make use of the buckling properties of orthotropic nanoplates.

References listed at the end of the paper:

Partial Introduction: There are various methods for increasing the resistance of a circular plate to buckling. We can apply diverse supports on the boundaries of the structure or at an appropriate inner location where the structure functioning is not disturbed. A possible solution is the simultaneously applied supports at the boundary and in the middle of a solid circular plate or at the inner and outer boundaries of an annular plate. Instead of a support, or in addition to the existing supports we could mount further concentric ring support(s) in order to improve stability of the plate. Additionally, if the applied support restrains rotation of the plate, the stiffening effect can be further increased. We shall derive those nonlinear equation(s) which provide the critical load for a circular plate which is stiffened by a cylindrical shell on its boundary symmetrically to its middle plane or stiffened by a cylindrical shell only on one side of the middle plane.

References listed at the end of the dissertation:


ABSTRACT: The present paper is concerned with the stability problems of a thin solid circular plate and some annular plates, each stiffened by a cylindrical shell on the external boundary. Assuming an axisymmetric dead load and non-axisymmetric deformations we determine the critical load in order to clarify what effect the stiffening shell has on the critical load. Using Kirchhoff’s theory of thin shells and plates the paper presents the governing equations both for the circular plate and for the cylindrical shell, where the displacement field of the shell is obtained from a Galerkin function. The deflection of the plate and the Galerkin function are expanded into Fourier series and consequently all physical quantities in the structural elements as well. The boundary- and continuity conditions and last but not least numerical results are also presented.

References listed at the end of the paper:

ABSTRACT: We investigate buckling of soft elastic capsules under negative pressure or for reduced capsule volume. Based on nonlinear shell theory and the assumption of a hyperelastic capsule membrane, shape equations for axisymmetric and initially spherical capsules are derived and solved numerically. A rich bifurcation behavior is found, which is presented in terms of bifurcation diagrams. The energetically preferred stable configuration is deduced from a least-energy principle both for prescribed volume and prescribed pressure. We find that buckled shapes are energetically favorable already at smaller negative pressures and larger critical volumes than predicted by the classical buckling instability. By preventing self-intersection for strongly reduced volume, we obtain a complete picture of the buckling process and can follow the shape from the initial undeformed state through the buckling instability into the fully collapsed state. Interestingly, the sequences of bifurcations and stable capsule shapes differ for prescribed volume and prescribed pressure. In the buckled state, we find a relation between curvatures at the indentation rim and the bending modulus, which can be used to determine elastic moduli from experimental shape analysis.


ABSTRACT: We study the buckling of elastic spherical shells under osmotic pressure with the osmolyte concentration of the exterior solution as a control parameter. We compare our results for the bifurcation
behavior with results for buckling under mechanical pressure control, that is, with an empty capsule interior. We find striking differences for the buckling states between osmotic and mechanical buckling. Mechanical pressure control always leads to fully collapsed states with opposite sides in contact, whereas uncollapsed states with a single finite dimple are generic for osmotic pressure control. For sufficiently large interior osmolyte concentrations, osmotic pressure control is qualitatively similar to buckling under volume control with the volume prescribed by the osmolyte concentrations inside and outside the shell. We present a quantitative theory which also captures the influence of shell elasticity on the relationship between osmotic pressure and volume. These findings are relevant for the control of buckled shapes in applications. We show how the osmolyte concentration can be used to control the volume of buckled shells. An accurate analytical formula is derived for the relationship between the osmotic pressure, the elastic moduli and the volume of buckled capsules. This also allows use of elastic capsules as osmotic pressure sensors or deduction of elastic properties and the internal osmolyte concentration from shape changes in response to osmotic pressure changes. We apply our findings to published experimental data on polyelectrolyte capsules.

References listed at the end of the paper:

ABSTRACT: This paper was aimed to investigate the post buckling behaviour of moderately thick-walled filament-wound carbon–epoxy composite cylinders under external hydrostatic pressure through finite element analysis for under water vehicle applications. The winding angles were [±30/90] FW, [±45/90] FW and [±60/90] FW. Finite element software ANSYS 14.0 were used to predicted the buckling pressure of filament-wound composite cylinders. For the finite element modeling of the composite cylinder, an eight-node shell element is used. To verify the finite element results for comparison, three finite element software, MSC/NASTRAN, MSC/MARC and an in-house program ACOS were used. Among these software’s, the finite element software ANSYS predicts the buckling loads within 1.5% deviation.

References listed at the end of the paper:

ABSTRACT: A program to extend the operating depth of Seaglider from 1000 m to 6000 m began in 2002 at the University of Washington. The Deepglider program used carbon fiber composites for the pressure hull because of their ability to achieve weight to displacement ratios of less than 0.5. Advanced fabrication technology, more common in the aerospace industry, allowed the pressure hull to be identical to the shape of the Seaglider AUV so that many of the Seaglider components could be used on Deepglider. In this paper, we describe the development of the carbon fiber/epoxy pressure hull, including material characterization, the design of the interlaminar shear control sleeve, and pressure testing of six pressure vessels. Three of these hulls used a unique tapering diameter, tapering wall thickness construction. A more complete description of the Deepglider program is provided in a companion paper.


ABSTRACT: This presentation introduces a freely available tool for performing automated thin-shell finite element (FE) eigen-buckling modal identification. Commercial finite element software is commonly used to study thin-walled members because it can easily handle complex geometries, perforations, and arbitrary loading and boundary conditions. Each buckling analysis produces many mode shapes that are mixtures of fundamental modes, for example, local buckling, distortional buckling, and global buckling. These fundamental modes are important for use in strength prediction and design code development, however their relative participation can be difficult to quantify in an FE analysis. A modeler may have to sift through hundreds of modes, and even then, the modal identification and participation is subjective. A custom-built Matlab program is presented that performs automated FE eigen-buckling modal identification. Recent research advances have led to software that performs automated eigen-buckling modal identification and participation with the constrained finite strip method (cFSM) and the generalized beam theory (GBT). Our program wraps around this existing code to perform modal decomposition on an FE-generated buckled mode shape. The FE mode shape is input as 3D coordinates from a text file that can be generated by any commercial finite element program. Cross-sectional mode shapes provided by cFSM or GBT are employed to approximate each buckling mode and to determine the modal participation of the fundamental modes. The novelty of the presented method lies in using only the cross-section deformation modes instead of member base shapes. Using the special orthogonality properties of the cross-section deformation modes, the GBT amplitude functions of the fundamental modes are extracted from the FEM displacement field, with great speed and stability.


ABSTRACT: The analysis of slender structures, characterized by complex buckling and postbuckling phenomena and by a strong imperfection sensitivity, is heavily penalized by the lack of adequate computational tools. Standard incremental iterative approaches are computationally expensive and unaffordable, while FEM implementation of the Koiter method is a convenient alternative. The analysis is very fast, its computational burden is of the same order as a linearized buckling load evaluation and the simulation of different imperfections costs only a fraction of that needed to characterize the perfect structure. In this respect it can be considered as a direct method for the evaluation of the critical and post-critical behaviour of geometrically nonlinear elastic structures. The main objective of the present work is to show that finite element
implementations of the Koiter method can be both accurate and reliable and to highlight the aspects that require further investigation.

References listed at the end of the paper:


ABSTRACT: A new quadrilateral four node membrane finite element based on a mixed Hellinger–Reissner variational formulation is proposed. Displacement and stress interpolations are defined by 12 kinematical DOFs (two displacements and one drilling rotation per node) and 9 stress parameters. The displacement interpolation is obtained as a sum of three contributions. The first two correspond to compatible modes that assume a linear and quadratic (Allman-like) shape along the sides. The latter corresponds to a cubic incompatible mode depending on the average nodal rotations of the element. The stress interpolation is obtained from a complete quadratic polynomial by enforcing the internal bulk equilibrium and three further u-sub-lambda Pian equilibrium conditions, so obtaining an equilibrated and non-redundant field. The compliance and compatibility matrices are derived analytically, using an efficient boundary integration scheme. Numerical comparisons show that the proposed element performs better and is less sensitive to mesh distortion than similar elements in the literature. The constant stress states are recovered exactly and a very accurate recovery, for both stress and rotation fields, is also obtained in bending as well as in shear contexts. As shown by some numerical tests in buckling problems, the element is suitable for extension to nonlinear analysis.

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ABSTRACT: A mixed, quadrilateral, 3D plate element is proposed for static linear and buckling analysis of folded laminated composite structures. Numerical results show accuracy, comparing to analytical and numerical references, and convergence rate h2 measured using an s-norm. These characteristics are due to the self-equilibrated, isostatic state of stress in the element, and to the element kinematics leading to element compliance and compatibility matrix calculations based solely on the interpolation along the element edges. For folded plates, the drilling rotations do not require penalty functions or non-symmetric formulations, thus avoiding spurious energy modes. Buckling analysis is achieved by a corotational formulation, which is possible thanks to the accuracy of rotation approximations. Benchmarking for laminated composite plates includes convergence of displacements and stress-resultants, global error measures, and comparison with literature
results.

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E. J. Barbero (1), A. Madeo (2), G. Zagari (2), R. Zinno (2) and G. Zucco (2)
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ABSTRACT: Koiter’s asymptotic approach is a powerful alternative to path-following techniques in the analysis of slender structures. Its reliability for the evaluation of post-critical behavior, including strong nonlinear pre-critical and modal interaction, is well known. The most recent finite element implementations of Koiter’s approach are based on corotational formulation, which allows to automatically reuse linear finite elements into a nonlinear context once the geometrically non-linear corotational kinematics are developed. Beam assemblages, folded plates structures are extended here to laminated composite slender structures. By reusing the mixed finite element MISS-4 into a corotational framework, an analysis of folded plate structures
within an FSDT theory is developed. The analysis of a box structure is presented to highlight the accuracy of the Koiter analysis in the recovery of buckling and post-buckling behavior with low computational cost.

References listed at the end of the paper:


ABSTRACT: The wrinkling phenomenon is a commonly-known problem in many fields of engineering applications. Using a general structural analysis framework of the vector-form hybrid particle-element method (VHPEM), this paper presents a newly developed shell-based numerical model for the geometrically nonlinear wrinkling analysis of thin membranes. VHPEM is rooted in vector mechanics and physical perspective. It discretizes the analyzed domain into a group of finite particles linked by canonical elements, and the motions of the free particles are governed by Newton’s second law while the constrained ones follow the prescribed paths. An adaptive convected material frame is adopted for a general kinematical description. Internal forces related to the non-zero bending rigidity of a membrane can be efficiently evaluated by the rotation deformation in a set of deformation coordinates after eliminating rigid body motions simply by a fictitious reverse motion. To overcome the numerical difficulties associated with wrinkles, a pseudo-dynamic scheme using the explicit time integration is introduced into this method. Structural nonlinearity can be easily handled without iterative operations or any other special modification. The wrinkling behavior can be readily obtained by performing a pseudo bifurcation analysis incorporated into the VHPEM. The numerical results reveal that the VHPEM has good reliability and accuracy on solving the membrane wrinkling problem.

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"Collapse of Roorda's frame, including the effect of imperfections of arbitrary magnitude", Computational Mechanics 2012 (28th conference with international participation), Spicak, November 12-14, 2012

Text from the paper:
In the present paper we investigate the complete postcritical behavior of an L-shaped frame as well as the complete nonlinear response of imperfect Roorda's frame. We use a dynamical simulation of a frame with 200 mm length, 4 mm width and 0.5 mm depth made of steel. The load vs rotation curve for an imperfection in load eccentricity e = 0.1 is considered. Figure 2 of the paper shows the equilibrium curve of the frame. By controlling the velocity of load we can make a motion picture of the process. As an example, for ten thousands frames we need near 100 MB to calculate and save the motion picture. In conclusion a new post-critical solution of Roorda's frame including the effect of imperfections of arbitrary magnitude was presented in this paper. The presentation include a desk top experiment and a Java applete of Roorda's frame after buckling to right with a 30 mm imperfection of the load eccentricity.

References from the paper:

56th AIAA SDM Meeting, January 5-9, 2015, Kissammee, Florida.
Session STR-15 Structural Stability, January 5, 2015

STR-15. Structural Stability
Imperfection-Insensitive Cylindrical Shells Subject to Multiple Loading Conditions
Xin Ning; Sergio Pellegrino

Effect of Buckling Modes on the Fatigue Life and Damage Tolerance of Stiffened Structures
Carlos G. Davila; Chiara Bisagni; Cheryl Rose

A Comparison of FEM and Semi-Analytical Method in the Buckling and Vibration of Non-Prismatic Columns under Tip Force and Self-Weight
Jonathan Cifuentes; Rakesh K. Kapania

Buckling of stiffened variable angle tow panels: optimisation and experimental demonstration
Broderick H. Coburn; Byung Chul Kim; Zhangming Wu; Paul Weaver

Analysis of Unitized Stiffened Triaxial Braided Composite Panels with Geometric Imperfections in Compression
Cyrus J. Kosztowny; Anthony M. Waas

Minimum weight design by GENOPT/BIGBOSOR4 of an externally pressurized circumferentially corrugated cylindrical shell and verification by STAGS (Paper withdrawn Aug.22, 2014 because of dystonia)
David Bushnell (paper withdrawn because author cannot speak clearly due to facial dystonia)

Optimization of Damaged Composite Plates Under Buckling and Post buckling condition in Hygrothermal Environment employing an Inverse Hyperbolic Shear Deformation Theory
Veloorillom M. Sreehari; Dipak K. Maiti

DOI: 10.1016/j.compstruct.2013.12.029

ABSTRACT: Variable angle tow (VAT) laminates have previously shown enhanced buckling performance compared to conventional straight fibre laminates. In this study, an analytical method is developed for the buckling analysis of a novel blade stiffened VAT panel to allow this potential to be more fully exploited. The prebuckling and buckling analysis, performed on a representative section of a blade stiffened VAT panel, are based on a generalised Rayleigh–Ritz procedure. The buckling analysis includes a first order shear deformation
theory by introducing additional shape functions for transverse shear and is therefore applicable to structures with thick skins relative to characteristic length. Modelling of the stiffener is achieved with two approaches; idealisation as a beam attached to the skin’s midplane and as a rigidly attached plate. Comparing results with finite element analysis (Abaqus) for selected case studies, local buckling errors for the beam model and plate model were found to be less than 3% and 2% respectively, whilst the beam model error for global buckling was between 3% and 10%. The analytical model provides an accurate alternative to the computationally expensive finite element analysis and is therefore suitable for future work on the design and optimisation of stiffened VAT panels.

Minimum weight design by GENOPT/BIGBOSOR4 of an externally pressurized circumferentially corrugated cylindrical shell and verification by STAGS, David Bushnell, Fellow, AIAA, semi-retired, Palo Alto, CA 94303 USA, accepted for the 56th AIAA Structures, Structural Dynamics and Materials Meeting, Kissamme, Florida, January 5 – 9, 2015 (The paper was withdrawn by the author because of lack of ability to speak clearly due to oro-mandibular dystonia)

ABSTRACT: The results reported here are analogous to those reported in a previous paper on minimum weight design of elastic axially compressed prismatic complexly corrugated panels and shells in which the corrugations, each of which is a little cylindrical segment, run in the longitudinal direction. Here the corrugations, each of which is a little toroidal segment, run in the circumferential direction. The complexly corrugated shell of revolution is loaded by uniform external lateral normal pressure. There is no axial load component equal to pr/2, and the shell of revolution is free to expand or contract in the axial direction as the external pressure is applied. As before, the GENOPT/BIGBOSOR4 system is used to build the model and to perform the optimization. The minimum weight of the circumferentially corrugated shell is determined in the presence of the following behavioral constraints: 1. The shell shall not buckle locally, 2. The shell shall not buckle in a general mode that is symmetric at the plane of symmetry, 3. The shell shall not buckle in a general mode that is anti-symmetric at the plane of symmetry, 4. The maximum effective stress in the wall of the shell shall be less than a specified value. “Corners” at junctions between adjacent toroidal segments are eliminated by the automatic insertion of small “smoothing” toroidal segments. The circumferentially corrugated shells are optimized with and without the inclusion of nonlinear geometric effects, and it is found that these nonlinear effects are significant. Optimized designs are extremely sensitive to small changes in certain of the decision variables, making it difficult to find “global” optimum designs, especially when nonlinear theory is used. Several optimized designs determined with GENOPT/BIGBOSOR4 are verified by comparison with predictions from the general-purpose computer program STAGS. The agreement between the predictions of GENOPT/BIGBOSOR4 and STAGS is always good when linear theory is used, good for local buckling when either linear or nonlinear theory is used and fair for general buckling when nonlinear theory is used. There is always good agreement between BIGBOSOR4 and STAGS for the prediction of axisymmetric pre-buckling maximum effective stress.


ABSTRACT: Buckling behavior of functionally graded materials cylindrical shell under pure bending is studied in this paper. The stability equations of functionally graded materials cylindrical shell are derived using the classical plate and shell theory with Kirchhoff hypothesis, importing the bending boundary condition to obtain
the critical buckling load. The result shows that the critical moment is linear with the radius, quadratic with the thickness and irrelevant with the length of the cylindrical shell. In addition, the critical moment is decreased by increasing the power law index of the material bulk, trending to a constant finally.

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conical shells undergoing external pressure was investigated by numerical analysis. Results are compared with experimental data. It is established that initial imperfections significantly influence the buckling pressure value only for large imperfection amplitude (an order of magnitude more than the shell thickness). The existence is established of the effect of a ‘static resonance’.

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“Strong, lightweight, and recoverable three-dimensional ceramic nanolattices”, Science, Vol. 345 no. 6202 pp. 1322-1326, DOI: 10.1126/science.1255908  

ABSTRACT: Ceramics have some of the highest strength- and stiffness-to-weight ratios of any material but are suboptimal for use as structural materials because of their brittleness and sensitivity to flaws. We demonstrate the creation of structural metamaterials composed of nanoscale ceramics that are simultaneously ultralight, strong, and energy-absorbing and can recover their original shape after compressions in excess of 50% strain. Hollow-tube alumina nanolattices were fabricated using two-photon lithography, atomic layer deposition, and oxygen plasma etching. Structures were made with wall thicknesses of 5 to 60 nanometers and densities of 6.3 to 258 kilograms per cubic meter. Compression experiments revealed that optimizing the wall thickness-to-radius ratio of the tubes can suppress brittle fracture in the constituent solid in favor of elastic shell buckling, resulting in ductile-like deformation and recoverability.

M. S. Razzaghi and F. Karimi T. (Qazvin Branch, Islamic Azad University), “Buckling of Stiffened Thin Walled Cylindrical Tanks with Shell Imperfections due to Global Shear and Seismic Loads”, 15 WCEE, Lisboa, Portugal, 2012  
SUMMARY: Thin walled cylindrical shells are important components of industrial structures such as liquid storage tanks, silos, etc. Shell buckling is usually a major failure mode of thin walled shells under extreme loads such as earthquakes. Longitudinal and radial stiffeners are generally used in order to increase buckling capacity of thin walled shells. During an earthquake, cylindrical shells may experience global shear and suffer shear buckling. Buckling of thin walled shells is highly dependent to imperfections. In this study buckling of imperfect cylindrical stiffened tanks due to global shear and seismic loads are studied. To this end nonlinear FE static analyses have been performed in order to estimate buckling capacity of imperfect cylindrical stiffened tanks due to global shear. Herein cylindrical tanks of a constant height and different height to diameter (H/D) ratios were considered. Different arrangements of stiffeners were considered for each tank. Random patterns of imperfection with moderate imperfection amplitude were considered in all tanks. Design relations have been presented based on the results of numerical analyses. Finally, time history analyses were performed in order to evaluate the validity of suggested design relations for buckling of cylindrical stiffened tanks due to seismic loads.  
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ANSYS (V. 5.45). Reference Manuals (Theoretical and element reference). SAS IP Inc.  
ABSTRACT: Thin-walled cylindrical shells are important components of many industrial complexes. Most of these components have circular cutouts in manholes and pipe-to-shell junctions. Performance of cylindrical shells due to the extreme loading conditions shows that buckling is the major failure mode in such components. This study aims to indicate the effect of circular cutouts on buckling capacity of cylindrical shells due to pure axial compression. To this end, cylindrical shells of different geometric specifications and various arrangements and sizes of cutouts were considered. Numerical nonlinear analyses were conducted using ANSYS software. Result of this study revealed that cutouts can play a noticeable role in creating stress concentration and affect destructively the stability of structures. It is shown that there is a noticeable difference between the effects on cutouts in buckling of thinner shells and thicker ones. Cutouts reduce the local buckling capacity of shell about 10–15 % in the cylindrical shells, with the diameter to thickness ratio of less than 1,000. Meanwhile in shells with diameter to thickness, more than 1,000 such cutouts reduce the shell capacity about 30–35 %.

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O. Mouhat and A. Khamlichi (Communications Systems and Detection Laboratory; Abdelmalek Essaadi University, Tetouan 93002, Morocco), “Effect of loading pulse duration on dynamic buckling of stiffened panels”, MATEC Web of Conferences, Vol. 16, 07006 (2014), DOI: 10.1051/matecconf/2014 1607006, Published by EDP Sciences, 2014

ABSTRACT: Design of stiffened panels requires evaluating their stability under various loading combinations for all possible scenarios regarding material degradation or initial geometric imperfections that could affect them. Both static and dynamic loading conditions are to be investigated for assessing the buckling strength. In this work, dynamic buckling under in-plane uniform axial compression loading having the form of a transient pulse with finite duration is evaluated through nonlinear finite element modelling. A welding induced defect that consists of an initial geometric imperfection modifying the skin plate curvature in the longitudinal direction was incorporated. The Budiansky buckling criterion was employed to predict instability under this dynamic loading. The obtained results have shown that the pulse period yields a drastic effect on the buckling strength. For the considered boundary conditions, half-sine like pulses having periods that are comparable to two times the period of the first mode of natural vibrations of the stiffened plate were found to reduce hugely the buckling strength, with the dynamic buckling load representing almost only half its static value.

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DOI: 10.1016/j.proeng.2015.11.154

ABSTRACT: Design of stiffened panels requires evaluating their behavior under any loading circumstances by considering initial geometric imperfections and the altering effects resulting from eventual material degradation. Both static and dynamic loading scenarios are to be investigated in order to assess safety for buckling strength of these vital structures. In this work, dynamic buckling under in-plane uniform axial compression loading
having the form of finite duration pulse is analyzed through nonlinear finite element modeling of the structure. Welding induced defects that consist of initial geometric imperfections modifying the skin plate curvature in the longitudinal direction were incorporated. Material degradation in the heat affected zone was also taken into account. The Budiansky and Roth buckling criterion was employed to predict instability under a given dynamic load pattern. Various profiles including rectangular, triangular, double-triangular and half-sine were considered. The obtained results have shown that both the pulse period and the pulse shape have a drastic effect on the buckling strength. For the considered boundary conditions, pulses having periods that are comparable to two times the period of the first natural mode of vibrations were found to reduce the static buckling strength up to 66% in the elastic regime and 33% in the elastic plastic regime.

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Hong, Tao, 2000 Dissertation: “Nonlinear, buckling and postbuckling analysis of shells of revolution”, The Hong Kong Polytechnic University, PolyU Institutional Repository, Civil and Environmental Engineering, CEE Theses, http://hdl.handle.net/10397/3062

ABSTRACT: This thesis presents a series of developments leading to an efficient and accurate finite element analysis for nonlinear, buckling and postbuckling behaviour of thin elastic shells of revolution. An accurate isoparametric doubly-curved axisymmetric shell element is employed in these developments, with circumferential variations of loads, deformations and internal forces all represented by Fourier series. The work represents an important step towards the eventual development of a so-called 'advanced analysis' for stability design of steel shell structures in which imperfections, residual stresses and material plasticity are all realistically modelled. A review of the existing literature reveals that while there have been many studies on the finite element analysis of shells of revolution, only a limited number of analyses have been developed for nonlinear shells of revolution under arbitrary loads. A number of deficiencies are identified in existing studies. Among these are the uncertainty concerning the accuracy of existing nonlinear shell theories, the inability to trace the descending part of the load-deflection path of unsymmetrically loaded shells when the pseudo-load concept is used, and the lack of efficient and powerful techniques to predict postbuckling responses with mode
switching. The present developments overcome these existing deficiencies and result in a computer analysis which is both accurate and efficient. A study on suitable nonlinear strain-displacement relations for numerical analysis of complex branched shells is first described. Such relations are a basic building block in any numerical nonlinear, buckling and postbuckling analysis. A number of nonlinear strain-displacement relations have been developed in the past for thin shells. Most of these theories were developed in the pre-computer era for analytical studies when simplicity was emphasized more than accuracy. With the availability of greatly increased computing power in recent years, accuracy rather than simplicity is given more emphasis. A new set of nonlinear strain-displacement relations for thin shells of general form developed directly from the nonlinear elastic theory of three-dimensional solids is thus presented in this thesis. In this new theory, all nonlinear terms, large and small, are retained. This new theory is found to reduce to that of Rotter and Jumikis and others for shells of revolution. This new theory is compared with other nonlinear shell theories both analytically and numerically.

Shells and plates on elastic foundations are found in many practical applications. A large deflection analysis of axisymmetric shells and plates on a nonlinear tensionless elastic foundation is next presented in this thesis. Through the use of discrete data points, any form of nonlinear elastic foundation behaviour can be easily modelled. The analysis is applied to investigate the behaviour of shallow spherical shells subjected to a central concentrated load on tensionless linear elastic foundations. A number of insightful conclusions regarding the behaviour of such structure-foundation systems are drawn. The numerical results for shells are believed to be the first correct results which may be useful in benchmarking results from other sources in the future. A new finite element formulation is then presented for the nonlinear and collapse (limit point buckling) analysis of elastic doubly-curved segmented and branched shells of revolution subject to arbitrary loads. The circumferential variations of all quantities are described by truncated Fourier series with an appropriate number of harmonic terms. Coupling between different harmonics is dealt with directly rather than by the use of pseudo-loads. This coupled harmonics approach allows an easy implementation of the arc-length method. As a result, the postbuckling load-deflection path can be traced efficiently and accurately. The results from the present study are independently verified using ABAQUS, while those from other studies are found to be inaccurate in general. Post-bifurcation buckling analysis of shells of revolution subject to axisymmetric loads is a key to understanding their postbuckling behaviour and imperfection sensitivity. Two efficient and accurate methods are thus developed to trace the postbuckling equilibrium path: the direct method and the load-disturbance method. In the direct method, an automated solution procedure is employed to determine the bifurcation buckling load and the bifurcation buckling mode. Then, a displacement increment parallel to this bifurcation buckling mode is introduced. In the load-disturbance method, small non-symmetric loads in appropriate harmonic modes are added so that the post-bifurcation buckling analysis is converted into a nonlinear non-symmetric analysis. The advantage of the direct method is that the bifurcation load and the postbuckling path in its vicinity can be determined precisely. On the other hand, the load-disturbance method is able to follow mode switching and interaction which cannot be handled by the direct method as presented here. Numerical results obtained here lead to some important conclusions concerning postbuckling analysis and behaviour. Finally, the finite element formulation for perfect shells under arbitrary loading mentioned earlier is extended to shells with non-symmetric imperfections. The initial imperfections are also arbitrary and expanded into truncated Fourier series. As a special case of this analysis, the imperfection-disturbance method is presented for tracing complex postbuckling paths involving mode switching and interaction. In addition, the imperfection sensitivity of a number of problems is examined using the developed analysis.

Xu, Hailan (Ph.D Dissertation, Professor David Hui advisor, Engineering and Applied Science, Dept. of Mechanical Engineering, University of New Orleans), "Buckling, Postbuckling and Imperfection Sensitivity
Analysis of Different Type of Cylindrical Shells by Hui's Postbuckling Method" (2013). University of New Orleans Theses and Dissertations. Paper 1781.

ABSTRACT: Buckling and postbuckling has been critical design parameters for many engineering structures. In recent years, this topic has continued to be of major concern due to (1) the discovery of new materials with amazingly superior properties, (2) increasingly more stringent safety requirements, (3) lighter, and more durable requirements. Such applications can be routinely found in aerospace, naval, civil, and electrical, and nuclear engineering structures and especially in the vehicle industries. Koiter is the first one to show that the imperfection-sensitivity of a structure is determined by its initial postbuckling behavior. In Koiter’s 1945 general postbuckling theory, it defines the initial postbuckling behavior and imperfection sensitivity behavior by the postbuckling b coefficient. Hui and Chen (1986) were the first to show that the well-known Koiter’s General Theory of Elastic Stability of 1945 can be significantly improved by evaluating the postbuckling b coefficient at the actual applied load, rather than at the classical buckling load. The reason for such significant improvement in predicting the imperfection sensitivity is due to the fact that for an imperfection-sensitive structure, the slope of the buckling load versus imperfection amplitude curve approaches negative “infinity” as the imperfection amplitude approaches to zero. Thus for “finite” amplitude of the geometric imperfection, the applied load is significantly lower than the classical buckling load, leading to significant overestimate of imperfection using Koiter’s General theory of 1945. Such improvement method was demonstrated to be (1) very simple to apply with no tedious algebra, (2) significant reduction in imperfection sensitivity and (3) although it is still asymptotically valid, there exists a significant extension of validity involving larger imperfection amplitudes. Strictly speaking, Koiter’s theory of 1945 is valid only for vanishingly small imperfection amplitudes. Hence such improved method is termed Hui’s Postbuckling method. This study deals with the Postbuckling and imperfection sensitivity of different kinds of cylinders by using the Hui’s postbuckling method. For unstiffened cylinder and laminate cylinder, the solution of Hui’s postbuckling method is compared with ABAQUS simulation result. A parameter variation of stringer/ring stiffened cylinder is also evaluated. A positive shift of the postbuckling b coefficient has been observed, which indicates a significant overestimate of the imperfection sensitivity by Koiter's general stability theory. More importantly, the valid region is significantly increased by using Hui's postbuckling method compared with the Koiter's general stability theory.

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geometric imperfection level in thin-walled cylindrical shells for less conservative knock-down factors," Thin-Walled Structures, 72, p. 76–87, 2013.


ABSTRACT: This paper deals with the buckling and initial-postbuckling behavior and imperfection-sensitivity of stringer or ring stiffened cylindrical shells under pure torsion. In particular, the effectiveness of stringer versus ring stiffened shells is examined for various types of stiffener and shell parameters under different boundary condition. The initial-postbuckling single-mode analysis is performed using Koiter’s general theory of elastic stability. By changing the parameters of stringer or ring, we are able to find out how does the stringer or ring affecting the buckling and post-buckling behavior of cylindrical shells.

References listed at the end of the paper:

ABSTRACT: Stability analyses of perfect and imperfect cylindrical shells under axial compression and torsion were presented. Finite element method for the stability analysis of perfect cylindrical shells was put forward through comparing critical loads and the first buckling modes with those obtained through theoretical analysis. Two typical initial defects, non-circularity and uneven thickness distribution, were studied. Critical loads decline with the increase of non-circularity, which exist in imperfect cylindrical shells under both axial...
Compression and torsion. Non-circularity defect has no effect on the first buckling mode when cylindrical shell is under torsion. Unfortunately, it has a completely different buckling mode when cylindrical shell is under axial compression. Critical loads decline with the increase of thickness defect amplitude, which exist in imperfect cylindrical shells under both axial compression and torsion, too. A greater wave number is conducive to the stability of cylindrical shells. The first buckling mode of imperfect cylindrical shells under torsion maintains its original shape, but it changes with wave number when the cylindrical shell is under axial compression.


**ABSTRACT:** Composite stiffened plate structure is widely used in aviation, aerospace and marine areas, in order to ensure the structural reliability, stability analysis is absolutely necessary. The finite element models are established. In this paper, subspace method and arc-length method are applied to analyze the stability of stiffened panel structure, both two methods are effective. Different stringer parameters will have some impact on the stability, including the number and height. Through analyzing the results, some conclusions are drew for increasing the stability. They have a certain value for engineering application.


**ABSTRACT:** Buckling of a thin cylindrical sandwich shell composed of elastic isotropic layers with different elastic properties under normal external pressure is the subject of this investigation. Differential equations based on the assumptions of the generalized kinematic hypothesis for the whole sandwich are used as the governing ones. Two variants of the joint support conditions are considered at the shell edges: a) there are the infinite rigidity diaphragms inhibiting relative shears of layers along the shell edges, b) the diaphragms are absent. Using the asymptotic approach, the critical pressure and buckling modes are constructed in the form of the superposition of functions corresponding to the main stress-strain state and the edges integrals. As an example, a three-layered cylinder with the magnetorheological elastomer (MRE) embedded between elastic layers under different levels of magnetic field is studied. Physical properties of the magnetorheological (MR) layer are assumed to be functions of the magnetic field induction. Dependencies of the buckling pressure on the variant of boundary conditions and the intensity of applied magnetic field are analyzed.

References:

ABSTRACT: Functionally graded materials (FGMs) are microscopically inhomogeneous spatial composite materials typically composed of a ceramic-metal or ceramic-polymer pair of materials. Therefore, it is important to investigate the behaviors of engineering structures such as beams and plates made from FGMs when they are subjected to thermal loads for appropriate design. Therefore, using an improved third order shear deformation theory (TSDT) based on more rigorous kinetics of displacements to predict the behaviors of functionally graded plates is expected to be more suitable than using other theories. In this paper, the improved TSDT is used to investigate thermal buckling of functionally graded plates. Temperature dependent material property solutions are adopted to investigate thermal buckling results of functionally graded plates. To obtain the solutions, the Ritz method using polynomial and trigonometric functions for defining admissible displacements and rotations is applied to solve the governing equations.


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ABSTRACT: This paper provides a methodology for the structural reliability analysis of marine vessels based on failure modes of their hull girders, stiffened panels including buckling, fatigue, and fracture and corresponding life predictions at the component and system levels. Factors affecting structural integrity such as operational environment and structural response entail uncertainties requiring the use of probabilistic methods to estimate reliabilities associated with various alternatives being considered for design, maintenance, and repair. Variability of corrosion experienced on marine vessels is a specific example of factors affecting structural integrity requiring probabilistic methods. The Structural Life Assessment of Ship Hulls (SLASH) methodology developed in this paper produces time-dependent reliability functions for hull girders, stiffened panels, fatigue details, and fracture at the component and system levels. The methodology was implemented as a web-enabled, cloud-computing-based tool with a database for managing vessels analyzed with associated stations, components, details, and results, and users. Innovative numerical and simulation methods were developed for reliability predictions with the use of conditional expectation. Examples are provided to illustrate the computations.

Khoeilar AR, Zirakian T, Boyajian D, Maalouf S, Dermendjian N, “Case Study on Retrofit of Steel Plate Shear Walls Using Low Yield Point Steel Infill Plates”, J Steel Struct Constr 2:106. December 2015,
Steel plate shear walls (SPSWs) have been frequently used in seismic design and retrofit of buildings over the past three decades or so. Employment of infill plates made of low yield point (LYP) steel with considerably low yield stress and high elongation capacity is believed to provide the possibility in order to improve the structural and seismic characteristics of such lateral force-resisting systems. Among the various benefits is the early yielding of LYP steel infill plates, which can result in greater energy absorption capacity and limitation of the plastic deformation demand to the surrounding frame structure. On this basis, a case study is performed using numerical simulations and reported in this paper on the seismic retrofit of SPSWs using LYP steel infill plates of double thickness. It is shown that the retrofit of a steel shear wall using a LYP steel infill plate of double thickness can result in desirable plate-frame yielding sequence and interaction. Moreover, this retrofit strategy can improve the initial stiffness, buckling stability, and energy dissipation capacity of the existing SPSW system.

References listed at the end of the paper:

(Abstract not given)

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ABSTRACT: The free vibration of curvilinearly stiffened shallow shells is investigated by the Ritz method. Based on the first-order shear deformation shell theory and three-dimensional (3D) curved beam theory, the strain and kinetic energies of the stiffened shells are introduced. The stiffener can be placed anywhere within the shell, without the need for having the stiffener and shell element nodes coincide. Numerical results with different geometrical shells and boundary conditions and different stiffener locations and curvatures are analyzed to verify the feasibility of the presented Ritz method for solving the problems. The results show good agreement with those using other methods, e.g., using a converged set of results obtained by NASTRAN.


ABSTRACT: Pipes for deep-water applications possess a diameter-to-thickness ratio in a region where failure is dominated by both instability and plastic collapse. This implies that prior to failure the compressive yield strength of the material must be exceeded, followed by ovalisation and further local yielding. This paper presents an investigation into the mechanics of this specific problem and develops an analytical approach that accounts for the effects of geometrical and material data on the collapse pressure of inhomogeneous rings under external hydrostatic pressure. The analytical expressions have been correlated to numerical and experimental test data, proving their accuracy.

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ABSTRACT: The elastic-plastic collapse of circular beams under uniform lateral pressure with an initial imperfection represented by a combination of different modes and amplitudes and with varying material properties is analysed from a computational viewpoint. The work is stimulated by a number of accurate experimental tests recently performed and it is found that both the initial imperfection and the material inhomogeneity along the beam axis can affect the collapse and produce a sensible variation in the carrying capacity of the structure on account of the changes between the underlying buckling modes. This can give reason for some apparently anomalous observed experimental results.


ABSTRACT: Many authors in the literature agreed that the flow theory of plasticity either fails to predict buckling or overestimates plastic buckling stresses and strains of plates and shells while the deformation theory succeeds in forecasting buckling and provides estimates that are more in line with the experimental results. Following a previous study by the same authors focused on compressed cylinders, the present work aims to investigate the reasons for the discrepancy between the flow and deformation theory predictions in the case of cylinders subjected to combined axial tensile load and increasing external lateral pressure. To this end, geometrically nonlinear finite-element calculations of selected cylindrical shells using both the flow theory and the deformation theory of plasticity have been conducted, and the results are compared with some accurate physical test results and with numerical results obtained by other authors using the code BOSOR5. It is found, contrary to common belief, that very good agreement between numerical and test results can be obtained in the case of the flow theory of plasticity. The reasons underlying the apparent plastic buckling paradox are discussed in detail.

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ABSTRACT: This study analyzes the buckling capacity of steel cylindrical shells that exhibit the lower segment of 2MW, 3MW and 5MW wind towers. Four cases of steel cylindrical shells are modeled: shell with neither door opening nor collar stiffener; shell with door opening but without collar stiffener; shell without door opening but with collar stiffener; and shell with both door opening and collar stiffener. Buckling capacity is analyzed numerically using finite element analysis and parametrically using Eurocode 3: Design of Steel Structures and Guideline for the Certification of Offshore Wind Turbines. In finite element analysis, buckling capacity is calculated linearly using eigenvalue analysis and non-linearly using static Riks. Results show that steel cylindrical shell with discontinuity or modification in geometry such as door opening and collar stiffener indicates local buckling. Furthermore, a 35% decline of critical (bifurcation) buckling capacity is observed when linear buckling analysis is compared to nonlinear buckling analysis. Linear buckling analysis provides a
good starting point in solving buckling collapse load, but non-linear analysis delivers a more accurate assessment due to the consideration of influences in material and geometrical nonlinearity.

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ABSTRACT: The paper presents problems related to the numerical modeling of profiled steel sheets used as self-supporting arch structures for roof covering. The rules of preparing and full analysis of a set of numerical models of these elements with a different level of complexity are given. The models are evaluated by comparing numerical results with the results of extended experimental tests performed by 3D Digital Image Correlation (DIC) method. For each model the comparison of numerical and experimental results has been made for samples of a single-wave trapezoidal profile with corrugated web and lower flanges subjected to compression and bending. The full-field analysis allows to determine the allowed simplification of numerical models which do not affect in significant way the reliability of the results. The proposed methodology is the first step in the development of full assessment methodology for different types of self-supporting arch structures produced by ABM technology.

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ABSTRACT: A new formulation for plates/shells with large deformations and large rotations is derived from the principles of continuum mechanics and calculated using the absolute nodal coordinate formulation (ANCF) techniques. A class of triangular elements is proposed to discretize the plate/shell formulation, which does not suffer from shear locking or membrane locking issue, and full quadrature can be performed to evaluate the integrals of each element. The adaptability of triangular elements enables the current approach to be applied to plates and shells with complicated shapes and variable thicknesses. The discretized mass matrix is constant, and the elastic force and stiffness matrix are polynomials of the generalized coordinates with constant coefficients. All the coefficients can be evaluated accurately beforehand, and numerical quadrature is not required in each time step of the simulation, which makes the current approach superior in numerical efficiency to most other approaches. The accuracy, robustness, and adaptability of the current approach are validated using both finite element benchmarks and multibody system standard tests.

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ABSTRACT: In this paper, nonlinear dynamical behavior of a rectangular plate traveled by a moving mass as well as an equivalent concentrated force with non-constant velocity is studied. The nonlinear governing coupled partial differential equations (PDEs) of motion are derived by energy method using Hamilton’s principle based on the large deflection theory in conjunction with the von-Karman strain-displacement relations. Then
Galérkin’s method is used to transform the equations of motion into a set of three coupled nonlinear ordinary differential equations (ODEs) which then is solved in a semi-analytical way to get the dynamical response of the plate. Also, by using the Finite Element Method (FEM) with ANSYS software, the obtained results in nonlinear form are verified by FEM results. Then, a parametric study is conducted by changing the size of moving mass/force and the velocity of the traveling mass/force with a constant acceleration/deceleration, and the outcome nonlinear results are compared to the results from linear solution.

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“Effect Of Initial Geometrical Imperfections On The Buckling Load Of Cylindrical Sandwich Shells Under Axial Compression”, DESICOS (www.DESICOS.eu), 2014 or 2015. [3rd Int. Conf. on Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures with DESICOS Workshop (25.-27.03.2015)]

ABSTRACT: The impact of geometrical imperfections on the general instability of laminated cylindrical sandwich shells was assessed by means of a numerical investigation. Five forms of ‘ideal’ initial geometrical imperfection patterns were studied: eigen-mode shaped, axisymmetric dimple, geometric dimple, single perturbation load and single stress-free dimple. Implementation of such imperfections, despite their simplicity, can provide a method for predicting lower-bound buckling loads during the preliminary design phase, when the structural defects of the real hardware are unknown. Numerical prediction of the non-linear instability of the cylinders under axial compression was performed using the finite element method. A typical launcher Inter Stage Skirt (ISS) structure is used as the basis for the chosen geometry and materials. In order to make design and qualification tests more affordable, it is common to use representative sub-scaled hardware. This paper verifies the validity of the chosen sub-scaling method of an ISS cylindrical shell. Buckling mechanisms are described and the different lower-bound methods are discussed.

References listed at the end of the paper:
ABSTRACT: A numerical investigation was carried out to assess the impact of geometrical imperfections on the stability of laminated sandwich cylindrical shells. This paper summarizes the most interesting results of a more extensive investigation in which a number of geometrical imperfection patterns were implemented. Specifically, eigenmode-shaped and single perturbation load imperfections are discussed herein. Such imperfections might provide a method for fast prediction of lower-bound buckling loads during the design phase, when details about the real structural and material defects are unknown. In order to make design and qualification more affordable, it is common practice to use sub-scaled hardware for testing. As part of the DESICOS project, a sandwich cylinder product of the sub-scaling of a typical launcher Inter Skirt Structure (ISS) will be tested. This paper verifies the sub-scaling method, validates the test setup and makes a prediction of the test results. Buckling mechanisms are described and the different lower-bound methods are discussed.

References listed at the end of the paper:

ABSTRACT: A buckling analysis of rectangular laminated composite plates with an edge delamination under in-plane compressive loading is performed using the finite element method. Such plates may be considered as simplified models of stiffener plates of a stiffened panel. The buckling load and buckling mode are obtained by solving an eigenproblem. In an unconstrained analysis physically inadmissible sublaminates may appear because of the overlap between separated sublaminates in the delaminated region. To eliminate overlap, constraints are added iteratively on the entire overlapped area using penalty function method. The validity and superiority of the analysis method in predicting buckling load and buckling mode are shown in comparison with the experimental and analytical results available in the literature. Numerical results show the effect of delamination width and depth and boundary conditions on the buckling load.

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ABSTRACT: We consider the form of an elastic loop adhered to a rigid substrate: the ‘Sticky Elastica’. In contrast to previous studies of the shape of delamination ‘blisters’, the theory developed accounts for deflections with large slope (i.e. geometrically nonlinear). Starting from the classical Euler Elastica we provide numerical results for the dimensions of such blisters for a variety of end–end confinements and develop asymptotic expressions that reproduce these results well, even up to the point of self-contact. Interestingly, we find that the width of such blisters does not grow monotonically with increased confinement. Our theoretical predictions are confirmed by simple desktop experiments and suggest a new method for the measurement of the
elastocapillary length for deformations that cannot be considered small. We discuss the implications of our results for applications such as flexible electronics.

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ABSTRACT: We study theoretically the deposition of few layer graphene sheets onto a grooved substrate incorporating adhesion between substrate and sheet. We develop a model to understand the equilibrium of the sheet allowing for partial conformal deformation of sheet to substrate. This model gives physical insight into recent observations of “snap-through” from flat to conforming states and emphasizes the crucial role of substrate shape in determining the nature of this transition. Our analytical results are consistent with numerical simulations using a van der Waals-like interaction. Finally, we propose a substrate shape that should exhibit a continuous, rather than “snap-through”, transition.

Dominic Vella, Amin Ajdari, Ashkan Vaziri and Arezki Boudaoud, “The indentation of pressurized elastic shells: from polymeric capsules to yeast cells”, Journal of the Royal Society Interface, August 2011,
DOI: 10.1098/rsif.2011.0352
ABSTRACT: Pressurized elastic capsules arise at scales ranging from the 10 m diameter pressure vessels used to store propane at oil refineries to the microscopic polymeric capsules that may be used in drug delivery. Nature also makes extensive use of pressurized elastic capsules: plant cells, bacteria and fungi have stiff walls, which are subject to an internal turgor pressure. Here, we present theoretical, numerical and experimental investigations of the indentation of a linearly elastic shell subject to a constant internal pressure. We show that, unlike unpressurized shells, the relationship between force and displacement demonstrates two linear regimes. We determine analytical expressions for the effective stiffness in each of these regimes in terms of the material properties of the shell and the pressure difference. As a consequence, a single indentation experiment over a range of displacements may be used as a simple assay to determine both the internal pressure and elastic properties of capsules. Our results are relevant for determining the internal pressure in bacterial, fungal or plant cells. As an illustration of this, we apply our results to recent measurements of the stiffness of baker’s yeast and infer from these experiments that the internal osmotic pressure of yeast cells may be regulated in response to changes in the osmotic pressure of the external medium.

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M. Shakouri and M.A. Kouchakzadeh (Department of Aerospace Engineering, Sharif University of Technology, P.O. Box 11155-8639, Tehran, Iran), “Stability analysis of joined isotropic conical shells under axial compression”, Thin-Walled Structures, Vol. 72, pp 20-27, November 2013
DOI: 10.1016/j.tws.2013.06.012
ABSTRACT: In this study, the buckling of two joined isotropic conical shells under axial compression and simply supported boundary conditions is investigated. The governing equations are obtained using thin-walled shallow shell theory of Donnell-type and theorem of minimum potential energy. The continuity conditions at the joining section of the cones are appropriate expressions among stress resultants and deformations. The equations are solved by assuming trigonometric response in circumferential and series solution in meridional direction. The results are validated in comparison with the available results in the literature. Effects of semi-vertex angles and meridional lengths on the buckling load and typical mode shape and circumferential wave number are investigated. In addition, the application of the results of this study on the load carrying capacity of these structures is presented.

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ABSTRACT: Elastic stability of shell structures under certain loading conditions is characterized by a dramatically unstable postbuckling behavior. The presence of simultaneous ‘competing’ buckling modes (corresponding to the same critical buckling load) is understood to be largely responsible for such behavior. In this paper, within the framework of linear bifurcation eigenvalue analysis and Donnell shallow shell theory, the presence of simultaneous buckling modes in axially compressed isotropic cones is determined using the semi-analytical method of Galerkin. The results are presented in the plane of the dimensionless reciprocal meridional and circumferential buckling half wavelengths, and are compared with the locus of simultaneous buckling modes of axially compressed cylinders, described by the so-called Koiter circle. By using an optimizing procedure, it is shown that the cluster of simultaneous buckling modes in cones is well described by the Koiter circle of an equivalent cylinder with appropriate length and radius. Such optimizing values of length and radius allow us to gain some insight into the simplifying treatment of the buckling of cones through the concept of equivalent cylinder.

Rohit Kumar Singh, “Thermal buckling analysis of laminated composite shell panel embedded with shape memory alloy fibre under TD and TID”, Master’s Thesis, Department of Mechanical Engineering, National Institute of Technology Rourkela Odisha, India, June 2014 (Professor S. K. Panda, Advisor)
ABSTRACT: Laminated composite shell panels are increasingly used in aeronautical, marine and mechanical industries as well as in other fields of modern technology because of its advance mechanical properties. It is well known that the composites have high strength to weight ratio and stiffness to weight ratio as compared to any conventional materials like concrete, metal, and wood. As the uses of the composites in different industries have increased which leads to their analysis through mathematical, experimental and/or simulation based model for accurate design and subsequent manufacturing. The structural components of aircraft, launch vehicle and
missiles are subjected to various types of combined loading and exposed to large acoustic, vibration, inertia excitation during their service life. In addition to that the structural components are also exposed to elevated thermal environment due to the aerodynamic heating. This often changes the original geometry of the panel due to excess deformation and the structural performances reduce. In this work, thermal buckling behaviour of laminated composite curved panel embedded with shape memory alloy fibre (SMA) is investigated. The material properties of composite laminate and SMA fibres are taken as temperature dependent. The mathematical model is developed based on higher order shear deformation theory (HSDT) to count the exact flexure of the laminate. The buckling behaviour is evaluated based on the Green-Lagrange strain-displacement equations for in-plane strains to account the large deflections under uniform temperature loading. The nonlinear material behaviour of shape memory alloy is introduced through a marching technique. The responses are obtained using variational principle in conjunction with suitable isoparametric finite element modelling based on the MATLAB code. In addition to that, a simulation model is also being developed in ANSYS environment using ANSYS parametric design language code for laminated composites curved panel and the corresponding responses are compared with those available literatures. The effects of layup sequence, thickness ratio, ply angle, support conditions and temperature dependence material properties on thermal buckling load are obtained and discussed.

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ABSTRACT: The nonlinear forced vibration of infinitely long functionally graded cylindrical shells is studied using the Lagrangian theory and multiple scale method. The equivalent properties of functionally graded materials are described as a power-law distribution in the thickness direction. The energy approach is applied to derive the reduced low-dimensional nonlinear ordinary differential equations of motion. Using the multiple scale method, a special case is investigated when there is a 1:2 internal resonance between two modes and the excitation frequency is close to the higher natural frequency. The amplitude–frequency curves and the bifurcation behavior of the system are analyzed using numerical continuation method, and the path leading the system to chaos is revealed. The evolution of symmetry is depicted by both the perturbation method and the numerical Poincaré maps. The effect of power-law exponent on the amplitude response of the system is also discussed.

ABSTRACT: Thin cylindrical shells are commonly employed in civil and structural applications in which the dominant loading condition is global bending. In applications such as wind turbine towers and offshore piles, the design of the structure is commonly limited by buckling. The traditional approach to improving buckling strength pursuant of greater design economy is to use steel ring and/or axial stiffeners. However, the total steel tonnage may be reduced with stiffeners, but the additional fabrication costs can limit the cost advantage. Meanwhile, it has long been observed in the silo industry that granular filled cylinders exhibit strength gains due to the internal pressure and stiffness of the granular bulk solid against the shell wall. For
large diameter fabricated steel tubes in bending, an elastic granular fill may be useful in replacing ring stiffeners, increasing critical buckling moments, and reducing risk by providing more stable postbuckling behaviour. However, the strength gains related to the elastic stiffness of a granular core has received very little attention and has been limited to the axial loading condition. In the project work, the candidate uses theoretical and computational methods to investigate the effects of an elastic granular fill on the buckling strength of cylindrical shells subject to global bending. In particular, cylinders in the elastic-plastic range will be considered in order to represent applications such as wind turbine towers and offshore piles. Effects of an elastic bulk fill on strength gains and imperfection sensitivity are considered with interest in improving design economy.

References listed at the end of the thesis:


ABSTRACT: IPN and IPE sections, which are commonly used European I shapes, are widely used in steel structures as cantilever beams to support overhangs. A considerable number of studies exist on calculating lateral torsional buckling load of I sections. However, most of them provide series solutions or complex closed-form equations. In this paper, a simple equation is presented to calculate lateral torsional buckling load of IPN and IPE section cantilever beams. First, differential equation of lateral torsional buckling is solved numerically for various loading cases. Then a parametric study is conducted on results to present an equation for lateral torsional buckling load of European IPN and IPE beams. Finally, results obtained by presented equation are compared to differential equation solutions and finite element model results. ABAQUS software is utilized to generate finite element models of beams. It is seen that the results obtained from presented equation coincide with differential equation solutions and ABAQUS software results. It can be suggested that presented formula can be safely used to calculate critical lateral torsional buckling load of European IPN and IPE section cantilevers.

References listed at the end of the paper:
ABSTRACT: In this paper, mechanical buckling analysis of open circular cylindrical shell reinforced by single-walled carbon nanotubes subject to axial loading is studied. Based on the first order shear deformation theory, the equilibrium and stability equations have been derived using the total potential energy equations and Euler equations. To estimate the material properties, the rule of mixture has been used. The governing equations are solved by considering the boundary conditions of problem and the effects of geometrical parameters and material properties on the critical buckling load have been studied. In order to validate obtained results, comparison study with other available literature has been carried out.

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S.K. Singh and A. Chakrabarti (Department of Civil Engineering Indian Institute of Technology Roorkee-247
667, INDIA), “Static, Vibration and Buckling Analysis of Skew Composite and Sandwich Plates Under Thermo
2013

ABSTRACT: Static, vibration and buckling behavior of laminated composite and sandwich skew plates is
studied using an efficient C0 FE model developed based on refined higher order zigzag theory. The C0 FE
model satisfies the interlaminar shear stress continuity at the interfaces and zero transverse shear stress
conditions at plate top and bottom. In this model, the first derivatives of transverse displacement have been
treated as independent variables to overcome the problem of C1 continuity associated with the plate theory. The
C0 continuity of the present element is compensated in the stiffness matrix formulation by adding a suitable
term. In order to avoid stress oscillations observed in the displacement based finite element, the stress field
derived from temperature is made consistent with the total strain field by using field consistent approach.
Numerical results are presented for different static, vibration and buckling problems by applying the FE model
under thermo mechanical loading, where a nine noded C0 continuous isoparametric element is used. It is
observed that there are very few results available in the literature on laminated composite and sandwich skew
plates based on refined theories. As such many new results are also generated for future reference.

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theory. - Compos. Struct., vol.37, No.1, pp.5-19.

Yun-Che Wang and Chun-Yi Wu (National Cheng Kung University, Tainan, Taiwan), “Buckling mode

ABSTRACT: Nondestructive experimental methods to calculate the buckling load of imperfection sensitive thin-walled structures are one of the most important techniques for the validation of new structures and numerical models of large scale aerospace structures. Vibration correlation technique (VCT) allows determining equivalent boundary conditions and buckling load for several types of structures without reaching the instability point. VCT is already widely used for beam structures, but the technique is still under development for thin-walled plates and shells. This paper intends to explain the capabilities and current limitations of this technique applied to two types of structures under buckling conditions: flat plates and cylindrical shells prone to buckling. Experimental results for a flat plate and a cylindrical shell are presented together with reliable finite element models for both cases. Preliminary results showed that the VCT can be used to determine the realistic boundary conditions of a given test setup, providing valuable data for the estimation of the buckling load by finite element models. Also numerical results herein presented show that VCT can be used as a nondestructive tool to estimate the buckling load of unstiffened cylindrical shells. Experimental tests are currently under development to further validate the approach proposed herein.

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ABSTRACT: Nondestructive methods, to calculate the buckling load of imperfection sensitive thin-walled structures, are one of the most important techniques for the validation of new structures and numerical models of large scale aerospace structures. The vibration correlation technique (VCT) allows determining the buckling load for several types of structures without reaching the instability point, but this technique is still under development for thin-walled plates and shells. This paper presents and discusses an experimental and numerical validation of a novel approach, using the vibration correlation technique, for the prediction of realistic buckling loads on unstiffened cylindrical shells loaded in compression. From the experimental point of view, a batch of three composite laminated cylindrical shells are fabricated and loaded in compression up to buckling. An unsymmetric laminate is adopted in order to increase the sensitivity of the test structure to initial geometric imperfections. In order to characterize a relationship with the applied load, the first natural frequency of vibration and mode shape is measured during testing using a 3D laser scanner. The proposed vibration correlation technique allows one to predict the experimental buckling load with a very good approximation, without actually reaching the instability point. Furthermore, a series of numerical models, including non-linear effects such as initial geometric and thickness imperfection, are carried-out in order to characterize the variation of the natural frequencies of vibration with the applied load and compare the results with the experiment
findings. Additional experimental tests are currently under development to further validate the proposed approach for metallic and balanced composite structures.

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“The Influence of Geometrical Parameters on the Buckling Behavior of Conical Shell by the Single Perturbation Load Approach”, Applied Composite Materials, Vo. 22, No. 4, pp 405-422, August 2015, DOI: 10.1007/s10443-014-9414-3

ABSTRACT: Since the development of the first theories to predict the buckling induced by axial compression in shells sensitive to imperfections, a significant discrepancy between theoretical and experimental results has been observed. Donnell and Koiter are among the first authors demonstrating, for these structures, the relevant influence of the geometrical imperfections on the reduction of the buckling load. Currently, the preliminary design of imperfections sensitive shell structures used in space applications is carried out according to the NASA SP-8007 guideline. However, several studies have proven that this guideline leads to over-conservative design configurations when considering the geometrical and material imperfections existing in real cones. Since the pioneer work of Arbocz, alternative methods have been investigated to overcome this issue. Among the different approaches, in this paper, the Single Perturbation Load Approach (SPLA), originally developed by Hühne as a deterministic way to calculate the knock-down factor of imperfection sensitive shells, is further studied. Indeed, a numerical investigation about the application of the SPLA to the simulation of the mechanical behavior of imperfection sensitive composite conical structures under axial compression is presented. This study is related to part of the work performed in the frame of the European Union (EU) project DESICOS.

References listed at the end of the paper:


ABSTRACT: The importance of taking into account geometric imperfections for cylindrical and conical thin-walled structures prone to buckling had been already recognized by the first authors dealing with new formulations. Nowadays, the analysts still use empirically based lower-bound methods such as the NASA SP-8007 guideline to calculate the required knock-down factors (KDFs), which does include important mechanical properties of laminated composite materials, such as the stacking sequence. New design approaches that allow taking full advantage of composite materials are required. The single perturbation load approach (SPLA), a new deterministic approach first proposed by Hühne, will be investigated with unstiffened composite conical structures varying the geometry, lamina and layup. The SPLA’s capability for predicting KDF is compared with the NASA approach. The SPLA was applied to the geometrically perfect structures and to the structure with geometric imperfections of two types, mid-surface imperfections and thickness imperfections. The study contributes to the European Union (EU) project DESICOS, whose aim is to develop less conservative design guidelines for imperfection sensitive thin-walled structures.

Junle Cai, Zhanjie Li, Cristopher Moen, Mihai Nedelcu, Benjamin Schafer, “Automated modal identification for thin shell finite element eigen-buckling solutions”,

EMI 2014 Engineering Mechanics Institute Conference August 5-8, 2014

ABSTRACT: This presentation introduces a freely available tool for performing automated thin-shell finite element (FE) eigen-buckling modal identification. Commercial finite element software is commonly used to study thin-walled members because it can easily handle complex geometries, perforations, and arbitrary loading and boundary conditions. Each buckling analysis produces many mode shapes that are mixtures of fundamental modes, for example, local buckling, distortional buckling, and global buckling. These fundamental modes are important for use in strength prediction and design code development, however their relative participation can be difficult to quantify in an FE analysis. A modeler may have to sift through hundreds of modes, and even then, the modal identification and participation is subjective. A custom-built Matlab program is presented that performs automated FE eigen-buckling modal identification. Recent research advances have led to software that performs automated eigen-buckling modal identification and participation with the constrained finite strip method (cFSM)1 and the generalized beam theory (GBT)2. Our program wraps around this existing code to perform modal decomposition on an FE-generated buckled mode shape. The FE mode shape is input as 3D coordinates from a text file that can be generated by any commercial finite element program. Cross-sectional mode shapes provided by cFSM or GBT are employed to approximate each buckling mode and to determine the modal participation of the fundamental modes3. The novelty of the presented method lies in using only the cross-section deformation modes instead of member base shapes. Using the special orthogonality properties of the cross-section deformation modes, the GBT amplitude functions of the fundamental modes are extracted.
from the FEM displacement field, with great speed and stability.

ABSTRACT: Based the nonlinear elastic shell theory, the governing equations of motion for axisymmetrical laminated cylindrical shell with delamination were derived. The governing equation of transverse motion was modified by introducing pseudo spring to calculate the contact force to avoid the penetration between two delaminated layers. The problem was solved by finite difference method. In numerical examples, the effects of various sizes, depths, delamination positions and loads on the nonlinear dynamic response of the axisymmetrical delaminated laminated cylindrical shell were discussed in detail. Numerical results demonstrate the importance of considering the contact effect in the dynamic response analysis of the structures with delamination. It can prevent physically impossible interpenetration from emerging for delaminated structures.

A. Shahbazian and Y.C. Wang (School of Mechanical, Aerospace and Civil Engineering, the University of Manchester, UK), “Calculating the global buckling resistance of thin-walled steel members with uniform and non-uniform elevated temperatures under axial compression”, Thin-Walled Structures, Vol. 49, No. 11, pp 1415-1428, November 2011, DOI: 10.1016/j.tws.2011.07.001
ABSTRACT: This paper develops a method, based on the Direct Strength Method (DSM) global buckling curve, to calculate the global buckling ultimate strength of cold-formed thin-walled (CF-TW) steel members under uniform and non-uniform elevated temperatures. The assessment is carried out by checking the DSM curve-based results with numerical simulation results using the general finite element software ABAQUS. The numerical model has been validated against a series of ambient temperature and fire tests on panels made of two different lipped channel sections tested to their ultimate load carrying capacities at ambient temperature or to their fire resistance at different load levels. The validated numerical model has been used to generate a database of numerical results of load carry capacity of CF-TW members with different uniform and non-uniform temperature distributions in the cross-sections under different boundary and loading conditions and with different dimensions. It is concluded that the DSM global buckling column curve is directly applicable for uniform temperature but a simple modification is required for non-uniform temperature distributions.

ABSTRACT: Based on the nonlinear theory of shallow spherical thick shells and the damage mechanics, a set of nonlinear equations of motion for the laminated shallow spherical thick shells with damage subjected to a normal concentrated load on the top are established. According to Hertz law, the contact force acted upon the shells is determined due to the impact of a mass, and it is related to the mass and initial velocity of the striking object, the geometrical and physical character of the shell. By using the finite difference method and the time increment procedure, the nonlinear equations are resolved. In the numerical examples, the effects of the damage, the initial velocity, and mass of the striking object, the shells’ geometrical parameters on the dynamic responses and dynamic buckling of the laminated shallow spherical thick shells are discussed.

ABSTRACT: Advanced Grid Stiffened (AGS) composite cylindrical shells are widely used in aerospace industry. This study analyzes the buckling loads for various types of grid structures of AGS composite cylindrical shells. The grid structures are classified as Angle-grid, Iso-grid, Kagome-grid, Ortho-grid, Orthotropic-grid and the characteristics had been analyzed for each grid type. In this study, the various types of grid structure were designed that weight of the whole structure keeps a constant. Under the condition of constant-weight, design variables such as grid angle, number of the grid, h/t ratio of the grid were controlled, and buckling loads of the grid structures were analyzed. The results were analyzed for each type of grid and each design variable of the structures. This study was performed through finite element method and the accuracy of the analysis was verified by previous studies. Finally, buckling modes were analyzed with the thickness of the skin. The selection for the most appropriate design variables had been verified for each grid type and the result can be applied to the optimization of grid structure design, and is also very helpful for reducing the computational cost and obtaining optimization values more accurately.

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ABSTRACT: Advanced grid stiffened composite cylindrical shell is widely adopted in advanced structures due to its exceptional mechanical properties. Buckling is a main failure mode of advanced grid stiffened structures in engineering, which calls for increasing attention. In this paper, the buckling response of advanced grid stiffened structure is investigated by three different means including equivalent stiffness model, finite element model and a hybrid model (H-model) that combines equivalent stiffness model with finite element model. Buckling experiment is carried out on an advanced grid stiffened structure to validate the efficiency of different modeling methods. Based on the comparison, the characteristics of different methods are independently evaluated. It is arguable that, by considering the defects of material, finite element model is a suitable numerical tool for the buckling analysis of advanced grid stiffened structures.

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ABSTRACT: In this study, a two-stage optimization framework is proposed for cylindrical or flat stiffened
panels under uniform or non-uniform axial compression, which are extensively used in the aerospace industry. In the first stage, traditional sizing optimization is performed. Based on the buckling or collapse-like deformed shape evaluated for the optimized design, the panel can be divided in sub-regions each of which shows characteristic deformations along axial and circumferential directions. Layout optimization is then performed using a stiffener spacing distribution function to represent the location of each stiffener. A layout coefficient is assigned to each sub-region and the overall layout of the panel is optimized. Three test problems are solved in order to demonstrate the validity of the proposed optimization framework: remarkably, the load-carrying capacity improves by 17.4 %, 66.2 % and 102.2 % with respect to the initial design.

References listed at the end of the paper:

Peng Hao (1), Bo Wang (1), Gang Li (1), Zeng Meng (1), Kuo Tian (1), Ziaohan Tang (2)
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“Hybrid optimization of hierarchical stiffened shells based on smeared stiffener method and finite element method”, Thin-Walled Structures, Vol. 82, pp 46-54, September 2014, DOI: 10.1016/j.tws.2014.04.004

ABSTRACT: In this study, Smeared Stiffener Method (SSM) of hierarchical stiffened shells is derived to release the prediction burden of buckling loads. Then, a minimum-weight optimization formulation for hierarchical stiffened shells is developed based on SSM, attempting to demonstrate the higher lightweight potential of hierarchical stiffened shells compared to the traditional ones. Further, the main aim of this paper is to present a hybrid optimization framework of hierarchical stiffened shells including imperfection sensitivity, combining the efficiency of SSM with the accuracy of FEM, since there are currently no closed-form solutions to take imperfections into account accurately. The illustrative example demonstrates that the proposed
framework has a higher optimization efficiency and global optimization capability compared to the conventional methods.


ABSTRACT: A two-dimensional variant of connected nonlinear equations of electrodynamics of the current—carrying orthotropic rotation shells, under no stationary loads is presented. A procedure for solution of asymmetrical problems of magneto elasticity of flexible current-carrying orthotropic rotation shells under no stationary actions of mechanical and electromagnetic forces is plotted. A stress-strained state of flexible current-carrying orthotropic rotation shells is geometrically nonlinear statement.

References listed at the end of the paper:


ABSTRACT: According to previous studies, stiffened shells with convex hyperbolic generatrix shape are less sensitive to imperfections. In this study, the effects of generatrix shape on the performances of elastic and plastic buckling in stiffened shells are investigated. Then, a more general description of generatrix shape is proposed, which can simply be expressed as a convex B-spline curve (controlled by four key points). An optimization framework of stiffened shells with a convex B-spline generatrix is established, with optimization objective being measured in terms of nominal collapse load, which can be expressed as a weighted sum of geometrically imperfect shells. The effectiveness of the proposed framework is demonstrated by a detailed comparison of the optimum designs for the B-spline and hyperbolic generatrix shapes. The decrease of imperfection sensitivity allows for a significant weight saving, which is particularly important in the development of future heavy-lift launch vehicles.

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ABSTRACT: Aircraft wings are the major lift-load carrying members in the airframe structure. 80% of the lift load will be carried by wing structure in a transport category aircraft. Because of the lift load, wings will bend upward during flight. This action makes the upper skin of the wing to experience compression and the lower skin tension. This will cause the upper skin to buckle. Buckling will reduce the load carrying capability and the component may fail below the design limit load. For a structure to be safe against buckling buckling factor should be greater than one. In this work a standard transport aircraft wing is considered and buckling analysis is carried out. The initial design was found to buckle. So several design modifications were made to make the design safe in buckling. Linear static analysis is also carried out.
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4. Sridhav Chintapalli, “Preliminary structural design optimization of an aircraft wing box”, Concoraia University, Montreal, Quebec, Canada, Aug 2006.

ABSTRACT: The transient behaviour of laminated composite spherical shell cap is investigated using the finite element method. An eight node degenerated isoparametric shell element is considered with five degrees of freedom at each node. The governing equations of forced vibration are solved using the Newmark’s direct integration method. Results are presented for dynamic response of deflection and stresses of orthotropic and laminated spherical shell caps subjected to suddenly applied uniform normal pressure.

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ABSTRACT: Numerical–experimental correlation study for small scale damaged stiffened panels was
performed. Six small scale models were fabricated. Two of them were employed for the correlation of intact panels and the remaining four for the correlation of dented panels. Ultimate strength analyses were carried out in order to adjust the numerical model for further use in parametric studies. The damage was imposed by a local indentation of the panels. Measurements of geometric imperfection distributions and damage shapes have been performed before and after the damage using a laser tracker equipment. The numerical models were represented by shell elements assuming finite membrane strains and large rotations, considering both geometric and material nonlinearities. Results obtained showed very good agreement between experimental and numerical analyses for both intact and dented panels. Additionally, numerical simulations of damaged stiffened panels were performed. The aim of the parametric study was to evaluate the behavior up to and beyond buckling, to observe the strength loss due to the presence of the damage on the panel. The explicit nonlinear finite element code from ABAQUS program was employed to simulate the dent damage. Therefore, distortions and the residual stresses due to the damage were both considered in subsequent numerical compression analyses.


ABSTRACT: The effects of water filling and electric field on the mechanical property of carbon nanotubes (CNTs) are investigated with molecular dynamics simulations. The simulation results indicate that the water filling and electric field could enhance the elastic modulus but reduce the Poisson’s ratio of the CNTs. As for the buckling behaviors, a significant enhancement could be observed in the yield stress and average post-buckling stress of the CNTs. In particular, the enhancement in the yield stress induced by the water filling and electric field could be even higher than that resulted from the solid filling. Moreover, a transition mechanism from the rod instability to shell buckling is shown to explain the nonmonotonic variation of yield stress, and the critical diameter can be tuned through filling the water molecules and applying the electric field. The present findings provide a valuable route for the optimized design and application of the nanoscale functional devices based on the water-filled CNTs.

References listed at the end of the paper:

ABSTRACT: The problem of buckling of a thin elastic spherical shell inside a spherical cavity of uniformly contracting massive body is considered. This problem arises, for example, when designing pressure vessels made of composite materials with a thin metal cap layer. It is assumed that at the beginning of the compression the shell fits tightly against the wall of the cavity (to the rigid frame). An algorithm for searching the equilibrium state of the shell in the supercritical state is described. As a result of solving the problem, among other things, critical values of compressive strain and shell configuration in the supercritical state were obtained.
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ABSTRACT: The synthesis of sound based on physical models of 2-D percussion instruments is problematic and has been approached only infrequently in the literature. Beyond the computational expense inherent to the simulation of 2-D systems, a deeper difficulty is in dealing with the strong nonlinearity exhibited by thin structures when struck—this nonlinearity leads to phenomena which are not captured, even approximately, by a linear model, and nearly all synthesis work is based on the assumption that the distributed resonating component of a musical instrument is linear. Perceptually, the effects of the vibration of a thin structure at high amplitudes can be heard as crashes, pitch glides, and the slow buildup of high-frequency energy characteristic of gongs. A large family of instruments may be described, approximately, as circular thin shells, of approximately spherical geometry, in which case a tractable PDE description, described here, is available. Time-domain finite-difference schemes, in radial coordinates, are a suitable method for synthesis. Stability conditions, numerical boundary conditions both at the edge and center, and implementation details are discussed, and simulation results are presented, highlighting the various perceptual effects mentioned above.

References listed at the end of the paper:
ABSTRACT: Nonlinear vibrations of thin rectangular plates are considered, using the von kármán equations in order to take into account the effect of geometric nonlinearities. Solutions are derived through an expansion over the linear eigenmodes of the system for both the transverse displacement and the Airy stress function, resulting in a series of coupled oscillators with cubic nonlinearities, where the coupling coefficients are functions of the linear eigenmodes. A general strategy for the calculation of these coefficients is outlined, and the particular case of a simply supported plate with movable edges is thoroughly investigated. To this extent, a
A numerical method based on a new series expansion is derived to compute the Airy stress function modes, for which an analytical solution is not available. It is shown that this strategy allows the calculation of the nonlinear coupling coefficients with arbitrary precision, and several numerical examples are provided. Symmetry properties are derived to speed up the calculation process and to allow a substantial reduction in memory requirements. Finally, analysis by continuation allows an investigation of the nonlinear dynamics of the first two modes both in the free and forced regimes. Modal interactions through internal resonances are highlighted, and their activation in the forced case is discussed, allowing to compare the nonlinear normal modes (NNMs) of the undamped system with the observable periodic orbits of the forced and damped structure.

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coupling coefficients for reduced-order shell models”, Computational Mechanics, Springer Verlag, 2014, 54, pp 567-580, DOI: 10.1007/s00466-014-1006-4

ABSTRACT: We propose a direct method for computing modal coupling coefficients – due to geometrically nonlinear effects – for thin shells vibrating at large amplitude and discretized by a finite element (FE) procedure. These coupling coefficients arise when considering a discrete expansion of the unknown displacement onto the eigenmodes of the linear operator. The evolution problem is thus projected onto the eigenmodes basis and expressed as an assembly of oscillators with quadratic and cubic nonlinearities. The nonlinear coupling coefficients are directly derived from the finite element formulation, with specificities pertaining to the shell elements considered, namely, here elements of the “Mixed Interpolation of Tensorial Components” family (MITC). Therefore, the computation of coupling coefficients, combined with an adequate selection of the significant eigenmodes, allows the derivation of effective reduced-order models for computing – with a continuation procedure – the stable and unstable vibratory states of any vibrating shell, up to large amplitudes. The procedure is illustrated on a hyperbolic paraboloid panel. Bifurcation diagrams in free and forced vibrations are obtained. Comparisons with direct time simulations of the full FE model are given. Finally, the computed coefficients are used for a maximal reduction based on asymptotic nonlinear normal modes (NNMs), and we find that the most important part of the dynamics can be predicted with a single oscillator equation.

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ABSTRACT: This paper deals with the linear and nonlinear vibrations of a truncated conical shell; both internal and external surfaces are covered by functionally graded coatings (FGCs). The theoretical formulation is based on the von Karman–Donnell–type nonlinear kinematics. The material properties of FGCs are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The fundamental relations, the modified Donnell-type nonlinear motion, and compatibility equations of the truncated conical shell with FGCs are derived. The basic equations are reduced to the ordinary differential equation depending on time with geometric nonlinearity using the Superposition and Galerkin methods. By applying the homotopy perturbation method to the foregoing equation, the relation between nonlinear frequency parameters with the dimensionless amplitude of a truncated conical shell with FGCs is obtained. Parametric studies are performed to illustrate the effect of different values of thickness and material composition of the FGCs on the frequency-amplitude relationships. The validity of the present solution is demonstrated by comparison with solutions available in the literature.

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“Geometrically nonlinear dynamic response of stiffened plates with moving boundary conditions”, Science China Physics, Mechanics & Astronomy, Bol. 57, No. 8, pp 1536-1546, August 2014
DOI: 10.1007/s11433-014-5523-0

ABSTRACT: An approach is presented to investigate the nonlinear vibration of stiffened plates. A stiffened plate is divided into one plate and some stiffeners, with the plate considered to be geometrically nonlinear, and the stiffeners taken as Euler beams. Lagrange equation and modal superposition method are used to derive the dynamic equilibrium equations of the stiffened plate according to energy of the system. Besides, the effect caused by boundary movement is transformed into equivalent excitations. The first approximation solution of the non-resonance is obtained by means of the method of multiple scales. The primary parametric resonance and primary resonance of the stiffened plate are studied by using the same method. The accuracy of the method is validated by comparing the results with those of finite element analysis via ANSYS. Numerical examples for different stiffened plates are presented to discuss the steady response of the non-resonance and the amplitude-frequency relationship of the primary parametric resonance and primary resonance. In addition, the analysis on how the damping coefficients and the transverse excitations influence amplitude-frequency curves is also carried out. Some nonlinear vibration characteristics of stiffened plates are obtained, which are useful for engineering design.

References listed at the end of the paper:


ABSTRACT: This paper discusses the dynamic analysis of thin-walled composite shells under axial load. Analytical and numerical methods are used to analyze and validate the results with experimental results has been made. In this paper effects of orthotropic of materials, boundary conditions, geometry, geometric imperfections and time course load on the linear and nonlinear analysis of thin-walled composite shells are studied. In the first analyze the sample without to consider geometric imperfections and then the effects of imperfections equal to the actual shell. The critical buckling dynamic is reported in load time that will show the sharp reduction in the buckling load with in increases load time and stiffens of shell is inversely to load time. This effect is more pronounced in the case of layup. With the increase of load time, the dynamic critical load dropped quickly and smaller than the critical buckling load is static. So in general, the choice of the static critical load is wrong as a criterion for dynamic design. In addition to the static buckling load, dynamic buckling load is reduced with increasing geometric imperfections of sample. Sensitivity to geometric imperfections is dependent on the type of the lay up. The geometric imperfections are the same effect on the dynamic critical load and static critical load for unlimited periods.

ABSTRACT: In the field of structural mechanics the word shell refers to a spatial, curved structural member. In shells, the external loads are carried by both membrane and bending response. The effect of such responses needs careful observation. This project fulfills the need on study of behavior of shell structures by both mathematical and numerical methods. In the present development, the Donnell’s relation forms the basis of stability equation for circular cylindrical shells. The effect of stiffeners on cylindrical structures has been studied, by varying the geometry and orientation of stiffeners. The paper aims to analyze the cylindrical section of an underwater pressure hull, using finite element analysis and strengthen it accordingly. The project considers the finite element method for static structural and deflection analysis of underwater cylindrical structure by using ANSYS15 software.

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ABSTRACT: This paper proposes an approximate formulation to estimate the bifurcation buckling loads of cylindrical shells with soft elastic cores under the conditions of axial compression. In general, thin-walled, axially compressed cylindrical shells buckle into a diamond pattern in the elastic range. However, buckling symmetrical with respect to the axis of the cylinder may occur when the cylindrical shell is supported by an elastic medium. By considering this characteristic, we introduce the simplified approximate formulation that can give sufficiently accurate results for the bifurcation buckling loads of cylindrical shells. Moreover the results are compared with the exact buckling loads in order to confirm the accuracy of the proposed approximate formulation.

M. Sato (1), Y. Konishi (1) and S.-J. Park (2)
ABSTRACT: This study examined the critical buckling characteristics of hydrostatically pressurized double-walled complete spherical shells. An analytical model based on small deflection thin shell theory is presented; the equations are solved in conjunction with variational principles. Axisymmetric and inextensional assumptions are not initially used in the exact formulation. This approach therefore avoids any discussion about the validity of the solution and allows the model to be extended to cover more generic nonaxisymmetric cases with relative ease. The analytical results are presented using illustrative buckling modes. Based on the developed formulation, only axisymmetric eigenmodes were found to occur despite the inclusion of the effect of interactions between outer and inner shells. Critical modes that are symmetric or antisymmetric about the equator may be determined depending on the combination of the stiffness connecting the outer and inner shells and the radius-to-wall thickness ratios.


ABSTRACT: Rise/span ratio has been mentioned as one of the reasons which contribute to the lower buckling load as compared to the Classical theory buckling load but this ratio has not been quantified in the equation. The purpose of this study was to determine a more realistic buckling load by quantifying the effect of the rise/span ratio because experiments have shown that the Classical theory overestimates the load. The buckling load equation was derived based on the theorem of work done and strain energy. Thereafter, finite element modeling and simulation using ABAQUS was done to determine the variables that determine the constant in the derived equation. The rise/span was found to be the determining factor of the constant in the buckling load equation. The derived buckling load correlates closely to the load obtained from experiments.

References listed at the end of the paper:

ABSTRACT: This paper presents a free-form optimization method for maximizing the elastic buckling load of a shell structure. A shell structure is assumed to be movable in the normal or the tangent direction to the surface for the shape optimization. The 1st buckling load factor is maximized under a volume constraint. The 1st eigenvalue constraint is employed to avoid the repeated eigenvalues problem in this max-min problem. This problem is formulated as a distributed-parameter shape optimization problem, and the shape gradient function for this problem is theoretically derived using the Lagrange multiplier method, the adjoint variable method and the formulae of the material derivative. The shape gradient function derived is applied to the free-form optimization method for shells, a gradient method in the Hilbert space, where the optimal shape variation is calculated as the displacement field of the linear elastic analysis of the fictitious shell model. With this method, the optimal free-form surface or boundary is determined without shape parameterization. The effectiveness of the 1st eigenvalue constraint is also studied. The results show the validity of this method to determine the optimal free-form of shell structures for the elastic buckling design problem.

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ABSTRACT: In this research, linear thermal buckling of a composite conical shell made from a polymeric matrix and reinforced with carbon nanotube fibres is investigated. Distribution of reinforcements across the shell thickness is assumed to be uniform or functionally graded. Thermomechanical properties of the constituents are temperature dependent. Under the assumption of first order shear deformation shell theory, Donnell kinematic assumptions and von Kármán type of geometrical nonlinearity, the complete set of equilibrium equations and boundary conditions of the shell are obtained. A linear membrane analysis is carried out to obtain the pre-buckling thermal stresses of the shell. Adjacent equilibrium criterion is implemented to establish the stability equations associated with the buckling state. The resulting equations are discreted by means of trigonometric expansion through the circumferential direction and discrete singular convolution method through the shell length. The established eigenvalue problem is solved iteratively to obtain the critical buckling temperature and critical mode number. Parametric studies are presented to explore the influences of semi-vertex angle, volume fraction of CNTs, distribution pattern of CNTs and boundary conditions. It is shown that, conical shells with intermediate carbon nanotube volume fraction do not have, necessarily, intermediate critical buckling temperature.

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(1) Department of Dies and Tools Engineering, Technical College- Baghdad
ABSTRACT: The low velocity axial impact of thin-walled circular CK45 tubes is taken. The wrinkles develop progressively and the phenomenon is known as dynamic progressive buckling. In the present paper, experimental and theoretical studies on dynamic plastic buckling of circular cylindrical shells under axial impact are carried out by designing and building a device to study the behavior of CK45 under low speed impact (3.8-6.25) m/s. The work consists of experimental and theoretical (Abramowicz model) for the energy absorbers and dynamic load under different velocities. The results show that when the velocity of impact increases, the value of the dynamic crushing stress for CK45 will increase, also for elastoplastic collapse deformation, a tube initially goes through elastic deformation, then plastic deformation occurs, after that the tube goes through plastic collapse. As the force decreases, the displacement still increases. Abramowicz model for dynamic impact shows well coincide with discrepancy 45%. It can be indicated that the increasing in the velocity or kinetic energy leads to increase in the load in the practical part while it seems to be horizontally linear in the theoretical part.

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Arman Amini (Safir-E-Andisheh Language Academy, Iran), “Buckling of cylindrical composite shells under deformation-related loads by using finite strip method”, European Scientific Journal, Vol. 11, No. 27, September 2015
ABSTRACT: Current advances in today’s industries increasingly expand the need for using composite materials in order to achieve desirable characteristics. Regarding the important role these materials play in...
engineering sciences, conducting precise analysis on such composites is admitted to be of great significance. One of the greatest weaknesses of these composites is their Shear Strength; hence, since the shear deformation has been ignored in the Classic Theory, the First Order Shear Theory has been adapted in the present paper. Deformation-related loads are loads in line with the loads resulted from deformation process which are usually being considered constant to facilitate load direction analyses. Shell materials have been set to be layered composites and the calculation method is of semi-analytical type. Displacement functions are defined as the combination of Fourier series in the perimeter dimension of shell and polynomial functions in the length dimension of shell. Results gathered from the proposed software for buckling of cylindrical shells have been compared with results from other references and also with those from ABAQUS finite element software suite. References listed at the end of the paper:


ABSTRACT: The object of this paper is to investigate the effects of geometry and load perturbation to buckling in multilayered pressure vessel heads. The pressure vessel head in concern is thin walled torispherical geometry. Geometric and load perturbation can alter both the critical load for buckling and the buckled shape. Two and three layered torispherical heads are considered. Two layered models include steel–aluminum and titanium–aluminum configurations and three layered models include copper–steel–copper configuration. Internally pressurized three-dimensional torispherical pressure vessel head model that is previously used in literature is constructed. As a first step eigenvalue solutions are obtained for each model. After this instability solutions with large deformation effects are conducted to obtain more realistic instability pressure values nonlinear. The solution is performed by finite element program ANSYS Workbench. In nonlinear analyses, perfectly plastic material model is used. It is concluded that geometric and load perturbations cause the instability pressure to decrease and cause the structure to buckle at a lower pressure value. It is also observed that for steel-aluminum configuration geometric perturbation is more critical than load perturbation whereas for aluminum-titanium the reverse is valid.

References listed at the end of the paper:
References listed at the end of the paper:


DOI: 10.1016/j.tws.2013.08.012

ABSTRACT: This paper investigates theoretically the compressive load-carrying behaviour of geometrically imperfect web-core sandwich plates. Slender plates, which first buckle globally, are considered. The study is carried out using two approaches, both solved with the finite element method. The first is the equivalent single-layer theory approach. First-order shear deformation theory is used. The second approach is a three-dimensional shell model of a sandwich plate. Plates are loaded in the web plate direction. Simply supported and clamped boundary conditions are considered with a different level of in-plane restraint on the unloaded edge. The results show that the behaviour of the sandwich plate is qualitatively equal to the isotropic plate of the same bending stiffness for deflections lower than the plate thickness. As the deflections increase, the lower in-plane stiffness of the sandwich plate results in lower post-buckling stiffness. Local buckling of face plates in the post-buckling range of the sandwich plate further reduces the structural stiffness.


ABAQUS, User’s manual, version 6.9.


Det Norske Veritas, Rules for the classification of steel ships. Høvik; 2005.
Furthermore, clamped plates were influenced more than simply supported. The intersection between buckling modes shifted towards higher aspect ratios, in the maximum case by 24%. The results show the importance of considering the deforming weld in buckling analysis.

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Jasmin Jelovica (Aalto University, School of Engineering, Dept. of Applied Mechanics, Marine Technology, Helsinki Finland), “Global buckling response of web-core steel sandwich plates influenced by general corrosion”, Doctoral dissertation 140/2014, Aalto University, 

ABSTRACT: A web-core steel sandwich plate is a lightweight, orthotropic structure. The constituent thin plates (2-4 mm) are joined by laser-welding. This thesis investigates the buckling and post-buckling behaviour of slender web-core sandwich plates loaded in the direction of the web plates. The influence of corrosion on the plate buckling is studied via finite element method (FEM). The corrosion scenario used is based on experimental observations from specimens submerged into the sea for 1 and 2 years. The plate strength analyses are performed with two methods: FEM having shell element mesh of the three-dimensional topology and the equivalent single-layer theory (ESL). In the latter, the sandwich plate is represented with constant, homogenised stiffness coefficients, which are related to physical properties of the structure. The first buckling mode of slender web-core sandwich plates is characterised with global deformation between the edge supports. The buckling strength depends on the bending and transverse shear stiffnesses. This thesis revealed that the buckling
strength is very sensitive to the variation in transverse shear stiffness opposite to the web plate direction, especially in sandwich plates with high bending stiffness. Furthermore, the stiffness of the sandwich plate as a whole in the post-buckling is controlled by that of the in-plane stiffness. The web plates impose high, shear-induced, secondary bending stresses on the face plates and these were found to be important for accurate estimation of the onset of yielding. The deformation resulting from the secondary bending of the face plates makes the unloaded edge stiffer. Although membrane stress can be higher there, local buckling during global post-buckling occurs further away where the secondary deformations are smaller, primarily in the centre of the face plate. Furthermore, the corrosion tests revealed that the cross-section is primarily affected by general corrosion. Under this circumstance, the reduction of the thickness of the face and web plates reduces the stiffness coefficients and also the buckling strength linearly. The buckling strength reduces rapidly, especially because of the reduction in the transverse shear stiffness. The reduction of buckling strength doubles if, in addition to the outer faces, corrosion also occurs inside the sandwich plate. Beam bending tests also showed rapid reduction of the ultimate strength but, in addition, that it can be maintained using different protection methods. The results thus indicate that the protection against corrosion should be carefully performed. The future work will involve improving the accuracy of the ESL theory in the presence of local buckling.

ABSTRACT: A homogenization method for geometric nonlinear analysis of structural core sandwich panels is proposed. The method provides high computational performance based on an efficient separation of scales. In the macroscale, the sandwich panel is discretized with an equivalent single layer of shell elements. The macroscale shell stiffness matrix is nonlinear, obtained from the analysis of a representative volume element. Prescribed displacement boundary conditions are applied to the representative unit based on the strain definitions of the first-order shear deformation theory. Changes in local wavelength in the post-buckling are considered in the analyses. Manufacturing-induced imperfections are introduced to local and global scales. The method allows for description of buckling in these two scales and is shown to hold good accuracy with respect to equivalent 3D FEM models. Examples include web-core and corrugated-core sandwich panels. The method can be extended to any periodic structure of complex local topology. It can be easily implemented to commercial FE packages.

Jacek Kruzelecki and Rafal Proszowski (Cracow University of Technology, Poland), “Shape and thickness optimization of thin-walled pressure vessel end closures”, Third International Conference on Engineering Optimization, Rio de Janeiro, Brazil, 1-5 July, 2012
ABSTRACT: In this paper the problem of shape and thickness optimization of thin-walled pressure vessel heads is investigated. The optimal geometry of a closure, which minimizes the design objective containing both depth and capacity or both depth and volume of the material of a closure (two variants) is looked for in the class of the uniform strength structures. Three types of optimization problems are considered: the optimal shape is sought for a prescribe wall thickness, the optimal wall thickness is sought for a prescribed shape of a closure and the case when we look for both shape functions. Domes consisting of both two- and one-arc are considered. The optimal solutions are obtained using the simulated annealing algorithm.
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ABSTRACT: In the paper, the influence of support compliances on the stability and the limiting slenderness ratio of compression helical springs was investigated. To analyze the stability of helical springs, the concept of an equivalent column was applied and a general system of supports described by three independent compliances was utilized. In the general case, the solution obtained, which describes the critical force, depends on two rotational compliances and a lateral compliance of a transverse shift of the support. The influence of the individual compliances on the critical load and on the limiting slenderness ratio was studied. Simple approximation formulas were proposed to describe these relationships.

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ABSTRACT: Cylindrical Shell Buckling Strength according to the "Overall Method" of Eurocode 3 Background and Applicability to the Design of High Strength Steel Slender Circular Hollow Sections.” Proceedings of the Structural Stability Research Council, Toronto, Canada, 2014

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“Cylindrical Shell Buckling Strength according to the "Overall Method" of Eurocode 3 Background and Applicability to the Design of High Strength Steel Slender Circular Hollow Sections.” Proceedings of the Structural Stability Research Council, Toronto, Canada, 2014

ABSTRACT: With the introduction of the Eurocodes, a new design philosophy for the design of cylindrical...
shells against buckling was made available to structural engineers in Europe: the "Overall Method", which makes use of the so-called "Overall Slenderness" of the shell to determine the appropriate (local) buckling reduction factor. There is a certain similarity between this concept and the Direct Strength Method (DSM) used in North America for the design of thin-walled cross-sections: the "Overall Method" also makes use of the results of (numerical) linear buckling analyses (LBA) for the whole shell to determine the slenderness and consequently the buckling reduction factor. In the case of the "Overall Method", the combined load case, which may lead to shear, hoop and axial stresses, is thereby considered in the LBA. The paper discusses the background and application of this method and complications arising in certain cases. In particular, the application of the Eurocode rules to the design of slender ("class 4") cylindrical hollow sections (CHS) will be discussed. While generally suitable for the design of large diameter cylindrical shells (tanks, silos), the application of the rules to the design of locally slender CHS requires a significant amount of interpretation by the code user and is generally not very accurate. Due to the increased use of (very) high strength steel grades for hollow sections in Europe (with yield strengths of fy=770 MPa and beyond), the local buckling design of HS steel CHS is becoming increasingly relevant. First steps by the authors towards the development of DSM-like design rules for high strength steel CHS under combined load cases will be discussed.


ABSTRACT: The purpose of this paper is to investigate on the behaviour of a delaminated stiffened panel; the delamination growth is simulated via fracture elements implemented in B2000++® code based on the Modified Virtual Crack Closure Technique (MVCCT), matrix cracking and fibre failure have been also taken into account. In order to correctly apply the MVCCT on the delamination front a very fine three-dimensional (3D) mesh is required very close to the delaminated area, while a 2D-shell model has been employed for the areas of minor interest. In order to couple the shell domain to the solid one, shell-to-solid coupling elements based on kinematic constraints have been used. Results obtained with the global/local approach are in good correlation with those obtained with experimental results.


ABSTRACT: The most important aspects in the aircraft design are safety and weight of the structure. Fuselage is one of the major components of the aircraft. Depending on the mass distribution of the fuselage structure the inertia forces will vary along the length of the fuselage. The inertia force distribution makes the fuselage to bend downward about wing axis. This bending will create tension in the upper portion of the fuselage; simultaneously the bottom portion of the fuselage will undergo compression. The current investigation addresses the issue of the compression buckling of the panels in the bottom portion of the fuselage. The panels with maximum compression load will be identified as critical panels for buckling analysis. Classical approach will be followed to calculate the critical buckling load on each panel. These calculations will be substantiated by panel buckling analysis through finite element method.

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ABSTRACT: A numerical study is carried out using finite element method, to examine the effects of square and rectangular cutout on the buckling behavior of a sixteen ply quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plate [0 / +45 / -45 / 90]2s subjected to various linearly varying in-plane compressive loads. Further, this paper addresses the effects of size of square/rectangular cutout, orientation of square/rectangular cutout, plate aspect ratio(a/b), plate length/thickness ratio(a/t), boundary conditions on the buckling behaviour of symmetrically laminated rectangular composite plates subjected to various linearly varying in-plane compressive loading. It is observed that the various linearly varying in-plane loads and boundary conditions have a substantial influence on buckling strength of rectangular composite plate with square/rectangular cutout.

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ABSTRACT: We use a proof-of-concept experiment and two mathematical models to explore growth-induced tissue buckling, as may occur in colorectal crypt formation. Our experiment reveals how growth of a cultured epithelial monolayer on a thin flexible substrate can cause out-of-plane substrate deflections. We describe this system theoretically using a ‘bilayer’ model in which a growing cell layer adheres to a thin compressible elastic...
beam. We compare this with the ‘supported-monolayer’ model due to Edwards and Chapman (Bull Math Biol 69:1927–1942, 2007) for an incompressible expanding beam (representing crypt epithelium), which incorporates viscoelastic tethering to underlying stroma. We show that the bilayer model can exhibit buckling via parametric growth (in which the system passes through a sequence of equilibrium states, parameterised by the total beam length); in this case, non-uniformities in cell growth and variations in cell–substrate adhesion are predicted to have minimal effect on the shape of resulting buckled states. The supported-monolayer model reveals how competition between lateral supports and stromal adhesion influences the wavelength of buckled states (in parametric growth), and how non-equilibrium relaxation of tethering forces influences post-buckled shapes. This model also predicts that non-uniformities in growth patterns have a much weaker influence on buckled shapes than non-uniformities in material properties. Together, the experiment and models support the concept of patterning by growth-induced buckling and suggest that targeted softening of a growing cell layer provides greater control in shaping tissues than non-uniform growth.

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ABSTRACT: We derive the equations for a thin, axisymmetric elastic shell subjected to an internal active stress giving rise to active tension and moments within the shell. We discuss the stability of a cylindrical elastic shell and its response to a localized change in internal active stress. This description is relevant to describe the cellular actomyosin cortex, a thin shell at the cell surface behaving elastically at a short timescale and subjected to active internal forces arising from myosin molecular motor activity. We show that the recent observations of cell deformation following detachment of adherent cells (Maître J-L et al 2012 Science 338 253–6) are well accounted for by this mechanical description. The actin cortex elastic and bending moduli can be obtained from a quantitative analysis of cell shapes observed in these experiments. Our approach thus provides a non-invasive, imaging-based method for the extraction of cellular physical parameters.

References listed at the end of the paper:
ABSTRACT: Biological soft tissues exhibit elastic properties which can be dramatically different from rubber-type materials (elastomers). To gain a better understanding of the role of constitutive relationships in...
determining material responses under loads we compare three different types of instabilities (two in compression, one in extension) in hyperelasticity for various forms of strain energy functions typically used for elastomers and for soft tissues. Surprisingly, we find that the strain-hardening property of soft tissues does not always stabilize the material. In particular we show that the stability analyses for a compressed half-space and for a compressed spherical thick shell can lead to opposite conclusions: a soft tissue material is more stable than an elastomer in the former case and less stable in the latter case.

References listed at the end of the paper:

ABSTRACT: Based on a new improved higher-order sandwich panel theory, the buckling analysis of a truncated conical composite sandwich panel with simply supported and fully clamped boundary conditions was performed for the first time. This panel was subjected to axial compression and external pressures. The governing equations were derived by using the principle of minimum potential energy. The first-order shear deformation theory was used for the composite face sheets, and for the core, a polynomial description of the displacement fields was assumed. Geometry was used for the consideration of different radii curvatures of the face sheets and the core was unique. The effects of types of boundary conditions, conical angles, length to smaller radius of core ratio, core to panel thickness ratio, and smaller radius of core to panel thickness ratio on the buckling response of truncated conical composite sandwich panels were also studied. The results were validated by the results published in the literature and the presented FE results were obtained by ABAQUS software.


ABSTRACT: Composite thin cylindrical shells are most widely used structural forms in aerospace and missile applications. In missile and airframe, the composite cylindrical shell structures are generally provided with cut-outs for accessing internal components during integration. The cut-outs invariably reduce the strength of the composite cylindrical shell and more specifically the buckling load. It has been a design practice to improve strength by addition of stiffener around cut-out. The cut-out not only introduces stress concentration but also significantly reduces buckling load.


ABSTRACT: In this present study the post buckling characteristics of moderately thick-walled filament-wound carbon–epoxy composite cylinders under external hydrostatic pressure were investigated through finite element analysis for under water vehicle applications. The winding angles were [±30/90] FW, [±45/90] FW and [±60/90] FW. Finite element software ANSYS 14.0 were used to predicted the buckling pressure of filament-wound composite cylinders. For the finite element modeling of a composite cylinder, an eight-node shell element is used. To verify the finite element results for comparison, three finite element software, MSC/NASTRAN, MSC/MARC and an in-house program ACOS were used. Among these software’s, the finite element software ANSYS predicts the buckling loads within 1.5% deviation. The analysis and test results...
showed that the cylinders do not recover the initial buckling pressure after buckling and that this leads directly to the collapse. Major failure modes in the analysis were dominated by the helical winding angles. The finite element analysis shows global buckling modes with four waves in the hoop direction.

References listed at the end of the paper:

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ABSTRACT: The objective of this research is to develop a layer-wise finite prism method for studying the elastic buckling of steel foam sandwich members. Foamed steel, literally steel with internal voids, enables lightweight and stiff components. Steel foam sandwich panels (steel face sheets and low-density, highly porous foam core) exhibit higher bending rigidity and plate buckling strength in comparison to slender, steel plates with the same weight. Analytical sandwich plate buckling solutions are not applicable to buckling analysis of cold-formed sandwich members with interaction between local and global buckling modes. Finite element analysis (either solid 3D or shell representation) provides the most reliable solution; however, its use is complicated, computationally expensive, and not practical for engineers. The proposed layer-wise finite prism solution is an alternative, easy-to-use tool, which builds upon the shape functions available in the literature, and
is verified against eigenbuckling finite element solutions implemented in LS-DYNA software. Future research is needed to incorporate the elastic buckling solutions in the direct strength design of sandwich panel members. References listed at the end of the paper:

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ABSTRACT: Mannobiose-modified polyethylenimines (PEI) are used in gene therapy to generate nanoparticles of DNA that can be targeted to the antigen-presenting cells of the immune system. We report that the sugar modification alters the DNA organization within the nanoparticles from homogenous to shell-like packing. The depth-dependent packing of DNA within the nanoparticles was probed using AFM nano-indentation. Unmodified PEI–DNA nanoparticles display linear elastic properties and depth-independent mechanics, characteristic of homogenous materials. Mannobiose-modified nanoparticles, however, showed distinct force regimes that were dependent on indentation depth, with ‘buckling’-like response that is reproducible and not due to particle failure. By comparison with theoretical studies of spherical shell mechanics, the structure of mannobiosylated particles was deduced to be a thin shell with wall thickness in the order of few nanometers, and a fluid-filled core. The shell–core structure is also consistent with observations of nanoparticle denting in altered solution conditions, with measurements of nanoparticle water content from AFM images, and with images of DNA distribution in Transmission Electron Microscopy.

ABSTRACT: GFRP (Glass Fiber Reinforced plastic) composite materials are find many applications in engineering fields like mechanical and civil engineering applications. It is because of the properties of these materials like light weight when compared to other materials, durability, rust proof and many more. The composite cylindrical shells are being used very widely in underground pipelines, Aerospace industries, submarines and so on. In present study, the buckling of thin walled glass reinforced polymer cylindrical shells with and without cutouts has been investigated by applying axial load on the shells. The results which were obtained in this experiment will show how the imperfections like cutouts will affect the buckling behavior of the shells.

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ABSTRACT: The results of an experimental study on the buckling behavior of thin-walled GFRP cylindrical shells are presented. The specimens were fabricated from continuous glass fiber using a specially-designed filament winding machine. The buckling behaviors of unstiffened shells and stiffened shells with lozenge, triangular and hexagonal grids were then studied under quasi-static axial loading at room temperature. Due to the thin skin of the shells, all specimens first experienced a general buckling mode as well as barreling under the applied loading. Following this general buckling damage, local buckling mode was seen on all specimens. Based on the experimental results, the critical buckling load was higher for the shells with hexagonal and triangular grids while the unstiffened shells and stiffened shells with lozenge grids exhibited much lower critical buckling load. On the other hand, in very small skin thicknesses, when the specific buckling loads for all specimens were compared, the unstiffened shells showed the highest specific buckling load.

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Wodesenbet E, Kidane S, Optimization for buckling loads of grid stiffened composite panels, Composite Structures 60: 159-169.

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ABSTRACT: The buckling behavior of single layer space structure is very sensitive. The joint rigidity, moreover, is one of the main factors of stability which may determine the entire failure behavior. Thus, the reasonable stiffness of joint system, which is neither total pin assumption nor perfect fix condition, is very important to apply to the real single layer space one. Therefore, the purpose of this work was to investigate the buckling behavior of single layer space structure, using the development of the upgraded stiffness matrix for the joint rigidity. To derive tangential stiffness matrix, a displacement function was assumed using translational and rotational displacement at the node. The geometrical nonlinear analysis was simulated not only with perfect model but also with imperfect one. As a result, the one and two free nodal numerical models were investigated
using derived stiffness matrix. It was figured out that the buckling load increases in proportion to joint rigidity with rise-span ratio. The stability of numerical model is very sensitive with the initial imperfection, responding of bifurcation in the structure.

References listed at the end of the paper:
ABSTRACT: This summary report is based on the experimental and numerical research of thin-walled cross-section compression resistance and shear strength of their joints carried out in St. Petersburg State Polytechnical University and HAMK University of Applied Sciences, Sheet Metal Centre. Current situation on the Russian market concerning the usage of cold-formed thin-walled cross-sections is aimed to find out a base foundation to start up application of the elements under discussion in the building industry (Kolesov et al. 2007; Peleshko, Urchenko 2009; Zhmarin 2012). Some questions about the compression resistance of such cross-sections were raised at different conferences (Vatin, Sinelnikov 2013; Winter 1952; Yu Wei-Wen et al. 1996) by scientific community and by companies such as Rautaruukki Oyj (Finland). Steel galvanized C- and U-profiles and thermo-profiles are types of thin-walled cross-sections that are normally used in small house construction (Shatov 2011; Smaznov 2011). Thermo-profiles have slots in webs that decrease the thermal flow through the web, but have a negative effect on strength of the profiles (Schafer, Pekoz 1998). These profiles were object of the research. Investigations carried out included tests to prove the compression resistance of the thin-walled cross-sections and shear strength of stud-to-rack joints. Numerical modelling of thin-walled cross-sections (Cheng, Schafer 2007) was done with contemporary analysis software (SCAD Office, Lira) (Kriksunov et al. 2010; Perel'muter et al. 2009) using the finite element method (FEM) (Bayan et al. 2011; Gordeeva, Vatin 2011; Rasmussen 2009).

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EN 1993-1-3, Design of Steel Structures: Cold-formed thin gauge members and sheeting.
ABSTRACT: The present paper examines the thermal effect on axially compressed buckling of a multiwalled carbon nanotube based on the gradient elasticity theories. The small-size effect, which plays an essential role in the buckling behavior with large aspect ratios under axial compression coupling with temperature change, is captured by applying different gradient elasticity theories including stress and strain. In this model, each of the nested concentric tubes is regarded as an individual column and the deflection of all the columns is coupled together through the van der Waals interactions between adjacent tubes.

References listed at the end of the paper:


Amit Srivastava and G.L. Sivakumar Babu (Dept. of Civil Engineering, Jaypee University of Engineering &
ABSTRACT: Response of buried flexible pipe-soil system is studied, through numerical analysis, with respect to deflection and buckling in a spatially varying soil media. In numerical modeling procedure, soil parameters are modeled as two-dimensional non-Gaussian homogeneous random field using Cholesky decomposition technique. Numerical analysis is performed using random field theory combined with finite difference numerical code FLAC 5.0 (2D). Monte Carlo simulations are performed to obtain the statistics, i.e., mean and variance of deflection and circumferential (buckling) stresses of buried flexible pipe-soil system in a spatially varying soil media. Results are compared and discussed in the light of available analytical solutions as well as conventional numerical procedures in which soil parameters are considered as uniformly constant. The statistical information obtained from Monte Carlo simulations is further utilized for the reliability analysis of buried flexible pipe-soil system with respect to deflection and buckling. The results of the reliability analysis clearly demonstrate the influence of extent of variation and spatial correlation structure of soil parameters on the performance assessment of buried flexible pipe-soil systems, which is not well captured in conventional procedures.

References listed at the end of the paper:
The buckling behavior of steel jacking pipes is analyzed by introducing the Winkler Foundation Model. The steel pipes are subjected to complicated loads so that the buckling phenomenon sometime occurs on the pipes. In this paper, the elastic analysis is carried out, in which the stratum provides constraining effect on the outward deflection; whereas, the non-uniform stratum considerably different from the conventional buckling problems due to the pipe-soil interactive behavior. For instance, the stratum may lead to the reduction in the critical elastic buckling load. The tradeoff between economic benefits and engineering safety renders the wall thickness of such pipes becoming increasingly thinner. Meanwhile, the stratum and surrounding environment become more complex. The buckling of steel jacking pipes is analyzed by introducing the Winkler Foundation Model. The steel pipes are subjected to complicated loads so that the buckling phenomenon sometime occurs on the pipes. In this paper, the elastic buckling behavior of steel jacking pipes is analyzed by introducing the Winkler Foundation Model.
Jacking pipes are modeled as cylindrical shells with two simply supported ends. Buckling eigenvalue analysis is conducted for such a model subjected to the axial force. The friction resistance is neglected due to the application of grouting. The surrounding soil is modeled as a series of closely spaced, mutually independent, and linear elastic spring elements. The influences of various parameters are discussed using the numerical analysis. Results obtained will inform the design of an economic and efficient steel jacking pipe.


ABSTRACT: In this paper, a two-layer partial composite columns model is built based on Reddy’s higher order beam theory, and two novel displacement based finite elements for this and Timoshenko composite beams are respectively formulated by means of the principle of minimum potential energy. Subsequently, the buckling analyses of pinned-pinned and clamped-guided composite columns are performed using the proposed finite elements, and the results are compared with those obtained by plane stress model, Timoshenko and Newmark composite beams model respectively. The superior quality of Reddy composite columns model over Timoshenko composite columns model and the correctness of the proposed Timoshenko composite columns model are demonstrated by the numerical comparison. Finally, the parametric study explores effects of parameters including stiffness of shear connectors, span-to-depth ratios, Young’s modulus ratios and sub-layer’s depth on the buckling load. The discrepancies between the performance of higher order and Timoshenko composite columns have also been numerically investigated.


ABSTRACT: In modern weight sensitive applications, especially in marine and offshore engineering, thin shells have been greatly used as structural components due to their efficient load-carrying capacities. Imperfection-sensitive buckling is a critical design factor for this kind of structures when they are under compression. Traditional design method purely relies on experimentally-derived lower-bounds to the scatter of test results and is suggested to be no longer tenable for the buckling design of thin shells with novel material applications and structural forms due to the multitude of additional material and geometric parameters. It is in this context that an analytical lower-bound design method, the so-called reduced stiffness method (RSM) is proposed. The RSM has been shown to be capable of predicting safe and reliable lower bounds for a range of metallic and stiffened shells. The RSM observes that mode coupling, precipitated by initial geometric imperfections, will in the postbuckling state annihilate the membrane energy which provides important contribution to shell’s initial resistance to buckling. By dismissing these energy terms in a modified classical critical load analysis, an analytical lower bound to the imperfection sensitive buckling can be obtained. This paper intends to systematically present the method and validate it through carefully controlled finite element analysis by comparing with the results from other nonlinear buckling analysis.


ABSTRACT: Fuselage buckling of a stiffened composite cylinder is a very complex phenomenon that involves
complex interactions between the skin and the stiffeners. Considering different configurations of the skin and stiffener, different types of buckling failure modes and failure loads are observed in stiffened cylinders. In this work failure modes and the buckling loads of stiffened composite cylinders under uniaxial loading condition is investigated by using analytical and experimental approaches. Initially, a developed model for buckling problem of an isogrid stiffened composite cylinder. In these models the stiffness contributions of the stiffeners is computed by analyzing the moment and force effect of the stiffener on the unit cell. The equivalent stiffness of the stiffener/shell panel is computed by superimposing the stiffness contribution of the stiffeners and the shell. Once the equivalent stiffness parameter is determined for the whole panel buckling load is calculated using the energy method. A 3-D finite-elements model was also built which takes into consideration the exact geometric configuration and the orthotropic properties of the stiffeners and the shell. Based on finite-elements model, a discussion is made on the different buckling failure modes observed. The results of these three types of analysis methods are compared and comments are made on the reliability of the analytical models developed and finally a parametric study was carried out and general conclusions were drawn regarding the optimum configurations of the different parameters of the grid-stiffened cylinder.

References listed at the end of the paper:


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“Improved methods for modeling imperfections for buckling analysis of composite cylindrical shells”, 29th Congress of the International Council of the Aeronautical Sciences, September 7-12, 2014
ABSTRACT: Carbon-fibre reinforced polymer (CFRP) cylindrical shells are used in a variety of aerospace applications. Such shells are extremely imperfection sensitive [1, 2] and feature a large scatter in buckling load levels induced from imperfections introduced in their manufacturing process. This paper aims to improve the stochastic modelling of cylindrical thickness imperfections in order to better replicate the stochastic variation of the actual thickness and material imperfections for FE analysis. These results will reduce the cost of producing and aid in improving the design and reliability of newly designed and untested cylinders by accurately modelling thickness and material imperfections for improved
stochastic analysis and robust design.

References listed at the end of the paper:


ABSTRACT: There is a strong requirement for more robust, lighter and cheaper launch vehicle structures. Unstiffened composite cylindrical shells, which are essential to the fabrication of launch vehicle airframes, are prone to buckling and are highly sensitive to imperfections which arise during the manufacturing process. The buckling load is an important characteristic in design, and may vary drastically from the buckling load of the perfect structure when realistic imperfections are present. [1] The current design guidelines for imperfection
sensitive shells are based on the NASA-SP 8007 [2] which dates from 1965. Typically, the theoretical buckling load of a given cylinder design is predicted by performing a linear bifurcation analysis using closed-form equations of the geometrically perfect structure. This theoretical buckling load is then reduced by applying an empirical knockdown factor to account for the differences between theory and test. From recent literature [3-5], the NASA-SP 8007 knockdown factors used in the design of aerospace-quality shell structures were found to be overly conservative and inappropriate.

References listed at the end of the paper:


ABSTRACT: Helical structures, ubiquitous in nature, have inspired design and manufacturing of helical devices with applications in nanoelectromechanical systems, morphing structures, optoelectronics, micro-robotics and drug delivery devices. Meanwhile, multi-stable structures have attracted increasing attention for their applications in bio-inspired robots and deployable aerospace components. Here we show that mechanical anisotropy and geometric nonlinearity can lead to novel selection principle of shape and multi-stability in helical ribbons, with table-top experiments performed to demonstrate the working principle. Our work will promote understanding of large deformation and instability of thin objects, and serve as a tool in developing functional structures for broad applications.

References listed at the end of the paper:

Dayu Liu (1), Xinxing Peng (1,2), Binghui Wu (1,2), Xueyun Zheng (1), Tracy T. Chuong (1), Jialuo Li (1), Shigang Sun (2) and Galen D. Stucky (1)
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“Uniform concave polystyrene-carbon core-shell nanospheres by a swelling induced buckling process”, Journal of the American Chemical Society, Vol. 137, No. 31, pp 9772-9775, 2015, DOI: 10.1021/jacs.5b05027
ABSTRACT: We have developed a facile procedure that can create asymmetrical building blocks by uniformly deforming nanospheres into $C_\infty v$ symmetry at low cost and high quality. Concave polystyrene-carbon (PS-C) core–shell nanospheres were produced by a very simple microwave-assisted alcohol thermal treatment of spherical PS-C nanoparticles. The dimensions and ratio of the concave part can be precisely controlled by temperature and solvents. The concavity is created by varying the alcohol-thermal treatment to tune the swelling properties that lead to the mechanical deformation of the PS-C core–shell structure. The driving force is attributed to the significant volume increase that occurs upon polystyrene core swelling with the incorporation of solvent. We propose a mechanism adapted from published models for the depression of soft capsules. An extrapolation from this model predicts that the rigid shell is used to generate a cavity in the unbuckled shell, which is experimentally confirmed. This swelling and deformation route is flexible and should be applicable to other polymeric nanoparticles to produce asymmetrical nanoparticles.

ABSTRACT: In this paper, the stability of cylindrical panels with circular cross section in elastic form is estimated using both analytical and Numerical methods. The Donnell equations for linear buckling of cylindrical shells are assumed and finally the equations are resulted to numerical values with the use of Galerkin method. Boundary condition in this case is such that the two curved edges are simply supported and two straight edges are free. The effects of geometrical parameters such as thickness, radius, length and central angle on buckling of cylindrical shells have been investigated both numerically and analytically. Also, the results of both methods are presented in figures.

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http://dx.doi.org/10.1016/b978-0-08-023275-1.50001-2
Mahmoud Shariati, Masoud Mahdizade Rokhi, Buckling of steel cylindrical shells with an elliptical cutout, International journal of
ABSTRACT: Helical structures are among the most universal building blocks in nature and engineering. In this work, I performed three-dimensional finite element simulations to study the transitions of shapes and multi-stability in the mechanically self-assembled helical structures driven by anisotropic misfit strains. The shape transition between a purely twisted ribbon, or a helicoid, and a general helical ribbon can be achieved by tuning a few relevant geometric and mechanical parameters, including the misfit strains, the geometric misorientation angle, the dimensions, and the mechanical properties of the composite layers. The results of our work show good agreement with the recent theoretical works and will serve as a powerful tool to facilitate on-demand designs of spontaneously curved structures at both macroscopic and microscopic scales, for a number of engineering applications including nanoelectromechanical systems, drug delivery, sensors, drug delivery, active materials, optoelectronics, and microrobotics.

References listed at the end of this paper:
ABSTRACT: Self-shaping of curved structures, especially those involving flexible thin layers, is attracting increasing attention because of their broad potential applications in, e.g., nanoelectromechanical and microelectromechanical systems, sensors, artificial skins, stretchable electronics, robotics, and drug delivery. Here, we provide an overview of recent experimental, theoretical, and computational studies on the mechanical self-assembly of strain-engineered thin layers, with an emphasis on systems in which the competition between bending and stretching energy gives rise to a variety of deformations, such as wrinkling, rolling, and twisting. We address the principle of mechanical instabilities, which is often manifested in wrinkling or multistability of strain-engineered thin layers. The principles of shape selection and transition in helical ribbons are also systematically examined. We hope that a more comprehensive understanding of the mechanical principles underlying these rich phenomena can foster the development of techniques for manufacturing functional three-dimensional structures on demand for a broad spectrum of engineering applications.

Jendi Kepple, Manudha T. Herath, Garth Pearce, B. Gangadhara Prusty, Rodney Thomson, Richard Degenhardt, “Stochastic analysis of imperfection sensitive composite cylinders using realistic imperfection models” (CRC-ACS, University of New South Wales, Advanced Composite Structures Australia), Third International Conference on Buckling and Postbuckling behavior of Composite Laminated Shell Structures with
ABSTRACT: The important role of imperfections on decreasing the buckling load of structural cylinders has been investigated by scientists and engineers for the past century, yet there is currently no method that is able to stochastically replicate the full range of realistic imperfections for a full account of possible buckling loads. This drawback impairs optimised design as designers are restrained to using an outdated and conservative design philosophy which dates from 1968. Modern manufacturing methods and materials such as composites require new, optimised design measures to take full advantage of their efficiencies. Stochastic analyses can optimise and improve the reliability of such cylinders through accurate prediction of the range of conceivable buckling loads by realistic simulation and sensitivity analyses. A stochastic procedure which realistically models imperfection sensitive composite shells is investigated in this paper. Monte-Carlo simulations of axially compressed cylinders with the full range of imperfection types are performed to show that the stochastic methods described here are able to accurately capture the scatter in the buckling load introduced from the imperfections. The results from a sensitivity analysis indicate that loading imperfections play the largest role in reducing the buckling load knockdown factors of the shell.

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ABSTRACT: An experimental investigation was performed on stainless steel hemispherical shells under axial compression. Eight kinds of shells with radius-to-thickness ratios that range from 57.1 to 125 were designed and manufactured for this study. The shells were compressed to more than 50% of their radii by a solid flat plate. To avoid contact between the base plate and the deformed central part of the shells, most of the shells were placed on a plate with a hole in the center. Nonetheless, one type of shell was placed on a solid base plate without a hole to analyze the effect of the base plate. As per an observation of collapse modes and load-deformation shell relations, the deformation process of a hemispherical shell that is compressed by a flat plate can be divided into four stages: local flattening (Stage I), axisymmetric inward dimpling (Stage II), non-symmetric multiple lobes (Stage III), and peripheral deformation and buckling stage (Stage IV). The present study mainly studies Stage IV, which can be categorized into peripheral compression (Stage A), peripheral buckling (Stage B), buckling expanding (Stage C), and overall collapse (Stage D).

References listed at the end of the paper:

http://dx.doi.org/10.2514/1.C033107

ABSTRACT: Experiments have been conducted to investigate the buckling and postbuckling behavior of aluminum alloy 7050-T7651 integrally stiffened panel under a combined compression–shear load. A new combined-load test fixture was designed and used in these experiments. There were a total of six large rectangular stiffened panels in the size of 960 by 850 mm, which were classified in two groups according to the cross section and layout of their stiffeners. Three panels, named J panels, were designed in four parallel J-shaped stiffeners. Another three panels, named X panels, were designed in eight orthogonal blade-shaped stiffeners. Strain rosettes bonded back-to-back on the skin were used to measure the strains of skin at their locations in three directions (0, 45, and 90 deg), whereas the strain gauges installed on the stiffeners were used to measure the strains of stiffeners in a single direction. The integrally stiffened panels were loaded up to a sudden drop of the applied load and an accompanying harsh noise caused by the stringers splitting from skins. All the test panels failed in the same modes of global flexural buckling and the spitting of the stiffeners from skins. The mean value of the first buckling loads of X panels is 11.6% higher than that of the J panels. The mean value of the failure loads of X panels is 1.5% less than that of the J panels. All experimental results will be employed for the validation of finite element models and optimization method on the buckling and postbuckling analyses of integrally stiffened aluminum panel in further studies.


ABSTRACT: Postbuckling response, long considered mainly as a failure limit state is gaining increased interest for smart applications, such as energy harvesting, frequency tuning, sensing, actuation, etc. This letter explores the potential of cylindrical shells under axial compression, for which localized buckling events along with high-rate local deformations can be attained in their elastic postbuckling regime under smaller axial system
deformation input, as a prototype for harnessing elastic instabilities. Three avenues are presented to tailor and control the elastic postbuckling response of axially-compressed shells: (1) by introducing seeded geometric imperfections (SGI); (2) by introducing non-uniform stiffness distributions (NSD); and (3) by providing lateral constraints and interactions (LCI). Prototyped cylindrical shells were fabricated through 3D printing and tested under loading–unloading cycles. Experimental results show that, with appropriate selection of geometry, material, and stiffness distribution, these three concepts offer significant advantages over uniform cylindrical shells for use of their notoriously unreliable elastic postbuckling response. This work provides new knowledge on the possibilities and means to design the cylindrical shells with controlled elastic postbuckling behavior and opens new avenues for using this structural form for applications in smart materials and structures.

Rigoberto Burgueño, Nan Hu, Annelise Heeringa and Nizar Lajnef (Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA), “Tailoring the Elastic Postbuckling Response of Thin-walled Cylindrical Shell under Axial Compression”, Thin-Walled Structures, Vol 84, pp 14-25, November 2014, DOI: 10.1016/j.tws.2014.05.009

ABSTRACT: The buckling of cylindrical shells has long been regarded as an undesirable phenomenon, but increasing interests on the development of active and controllable structures open new opportunities to utilize such unstable behavior. In this paper, approaches for modifying and controlling the elastic response of axially compressed laminated composite cylindrical shells in the far postbuckling regime are presented and evaluated. Three methods are explored (1) varying ply orientation and laminate stacking sequence; (2) introducing patterned material stiffness distributions; and (3) providing internal lateral constraints. Experimental data and numerical results show that the static and kinematic response of unstable mode branch switching during postbuckling response can be modified and potentially tailored.

James Bernasconi (Consulting Engineer, Brisbane, Australia), “Buckling studies into large scale hyperbolic paraboloid shell and lattice structures”, ASEC Conference, 2014

ABSTRACT: This paper covers some aspects of the bifurcation and elastic geometric non-linear buckling behaviour of hyperbolic paraboloid lattice and concrete shells up to 100 metres in plan size. The paper summaries the important design parameters discovered by earlier research and used variations in the rise to span ratio and edge beam flexural stiffness to undertake a parametric study. The bifurcation buckling of lattices was found to be similar to that of shells. The elastic geometric non-linear analysis was always found to be unstable for shells and stable for rectangular lattices. However, diagonal lattices behaved in a similar fashion to the unstable shells.

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Aristophanes J. Yiotis and John T. Katsikadelis (School of Civil Engineering, National Technical University of Athens, Athens, Greece), “Buckling of cylindrical shell panels: a MAEM solution”, Archive of Applied
Mechanics, November 2014, DOI: 10.1007/s00419-014-0944-9

ABSTRACT: The meshless analog equation method, a purely mesh-free method, is applied to the buckling analysis of cylindrical shell panels. The method is based on the principle of the analog equation, which converts the three governing partial differential equations in terms of displacements into three uncoupled substitute equations, two Poisson’s equations and one plate equation, under fictitious sources. The fictitious sources are represented by series of radial basis functions (RBFs) of multiquadric type, and the substitute equations are integrated. This integration allows the representation of the sought solution by new RBFs, which approximate accurately not only the displacements but also their derivatives involved in the governing equations. Then, by inserting the approximate solution in the original differential equations and the associated boundary conditions and collocating at a predefined set of mesh-free nodal points, a linear algebraic eigenvalue problem results, the solution of which gives the buckling loads and modes. The optimal value of the shape parameter of the RBFs is obtained as that minimizing eigenvalues. The method is illustrated by analyzing several shell panels. The studied examples demonstrate the efficiency and the accuracy of the presented method.

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Ping-Chi Tsai and Yeau-Ren Jeng (Mechanical Engineering, National Chung Cheng University, Taiwan), “Experimental and numerical investigation into the effect of carbon nanotube buckling on the reinforcement of CNT/Cu composites”, Composites Science and Technology, Vol. 79, pp 28-34, April 2013
DOI: 10.1016/j.compscitech.2013.02.003

ABSTRACT: Carbon nanotube reinforced copper matrix (CNT/Cu) composites with high strength and good damping have been developed using acid treatment, sintering processes and consolidation techniques. Strengthening of the composites as a result of nanotube buckling has been demonstrated by experimental nanoindentation tests and molecular dynamics (MD) simulations. The experimental results show that the buckling behavior of additional CNTs in the CNT/Cu composites varies with the slenderness ratio of CNTs. Specifically, this study shows that the significant buckling behavior of CNTs in the CNT/Cu composites where the shorter CNTs (with a smaller slenderness ratio) give rise to a global buckling and the slender CNTs (with a larger slenderness ratio) induce local buckling. The MD simulation results reveal that the buckling behavior of the CNTs plays a key role in increasing the mechanical strength of CNT/Cu composites by acting as a “buffer” in releasing excess strain in the Cu matrix.

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ABSTRACT: The subject of the paper is a metal foam circular cylindrical shell subjected to combined loads. Combinations of the external pressure and axial load are taken into account. The shell is simply supported on all outer edges. The mechanical properties of the metal foam vary continuously in the thickness direction. A non-linear hypothesis of deformation of a plane cross section of the shell is formulated. The field of displacements of any cross section and non-linear geometric relationships are assumed. The system of partial differential equations for the shell is derived on the basis of the
principle of stationarity of the total potential energy. This system is approximately solved by the Bubnov-Galerkin method. The critical loads for shells are numerically determined. Results of the calculation are shown in figures.

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Behnam Namiranian, Saeed Shaikhzadeh Najar and Ali Salehzadeh Nobary (B. Namiranian is with the
Department of Textile Engineering of Islamic Azad University, Yazd Branch, Yazd, Iran. S. Shaikhzadeh Najar is with the Department of Textile Engineering and A. Salehzadeh Nobary is with the Department of Aerospace Engineering of Amirkabir University of Technology, Tehran, Iran.), “Shell Buckling Behavior of Fused Composite Worsted Fabrics”, Journal Of Textiles And Polymers, Vol. 3, No. 1, January 2015

ABSTRACT: The aim of this paper is investigation of some important parameters in shell buckling of fused interlining worsted fabric with different weight and considering five different relative orientation angles (0°, 22.5°, 45°, 67.5°, 90°) according to the machine direction of non-woven fusible interlining and a face fabric. The formability of the prepared fused fabric composite based on shell buckling curves and Lindberg's hypothesis is also reported. The shell buckling compression behavior of fused fabric composite is investigated using a special corrugated clamp based to Dahlberg's test method. The result show that with increasing the interlining relative orientation angle, buckling loads and buckling energy parameters decrease, whereas, hysteresis and compression remaining increase. The fused fabric composites exhibit the highest formability at 67.5° relative orientation angle. The results show that at 0° relative orientation angle, the lowest buckling hysteresis, compressibility and compression remaining are obtained.

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“Silo Collapse: An experimental study”, (publisher and date not given in the pdf file; most recent citation is 2003.)

ABSTRACT: The purpose of this experimental work is to develop some basic insight into the pre-buckling behavior and the buckling transition toward plastic collapse of a granular silo by studying different patterns of deformation generated on thin paper cylindrical shells during granular discharge. We study the collapse threshold considering the influence of the bed heights, flow rates and grain sizes. We compare the patterns that appear during the discharge of spherical beads, with those obtained in the axially compressed cylindrical shells.
When the height of the granular column is close to the collapse threshold, we observe a ladder like pattern that rises around the cylinder surface in a spiral path of diamond shaped localizations, and develops into a plastic collapsing fold that grows around the collapsing silo.

References listed at the end of the paper:


G. Gutiérrez (1,2), C. Colonello (1), P. Boltenhagen (2,3), J. R. Darias (1), R. Peralta-Fabi (2,4), F. Brau (5), and E. Clément (2)
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DOI: http://dx.doi.org/10.1103/PhysRevLett.114.018001

ABSTRACT: We investigate, at a laboratory scale, the collapse of cylindrical shells of radius R and thickness t induced by a granular discharge. We measure the critical filling height for which the structure fails upon discharge. We observe that the silos sustain filling heights significantly above an estimation obtained by coupling standard shell-buckling and granular stress distribution theories. Two effects contribute to stabilize the structure: (i) below the critical filling height, a dynamical stabilization due to granular wall friction prevents the localized shell-buckling modes to grow irreversibly; (ii) above the critical filling height, collapse occurs before the downward sliding motion of the whole granular column sets in, such that only a partial friction mobilization is at play. However, we notice also that the critical filling height is reduced as the grain size d increases. The importance of grain size contribution is controlled by the ratio d/sqrt(Rt). We rationalize these antagonist effects with a novel fluid-structure theory both accounting for the actual status of granular friction at the wall and the inherent shell imperfections mediated by the grains. This theory yields new scaling predictions which are compared with the experimental results.

References listed at the end of the paper:


References for “Supplemental Material” for “Silo collapse under granular discharge”:
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ABSTRACT: This paper presents results of a numerical study on the nonlinear behavior of shells undergoing snap-through instability. This research investigates the problem of snap-through buckling of spherical shells applying nonlinear finite element analysis utilizing ANSYS Program. The shell structure was modeled by axisymmetric thin shell of finite elements. Shells undergoing snap-through buckling meet with significant geometric change of their physical configuration, i.e. enduring large deflections during their deformation process. Therefore snap-through buckling of shells basically is a nonlinear problem. Nonlinear numerical operations need to be applied in their analysis. The problem was solved by a scheme of incremental iterative procedures applying Newton-Raphson method in combination with the known line search as well as the arc-length methods. The effects of thickness and depth variation of the shell is taken care of by considering their geometrical parameter l. The results of this study reveal that spherical shell structures subjected to pressure loading experience snap-through instability for values of l≥2.15. A form of ‘turn-back’ of the load-displacement curve took place at load levels prior to the achievement of the critical point. This phenomenon was observed for values of l=5.0 to l=7.0.

References listed at the end of the paper:
Computational Buckling Analysis Of Thin-Walled Structures, First Pan American Congress on Computational Mechanics PANACM 2015 April 27-29, 2015, Buenos Aires, Argentina

ABSTRACT: Thin walled structures, including plates and shells, are widely used in aeronautical, aerospace, civil, mechanical, industrial and automotive engineering. Typical applications in industrial processes include containment structures for the chemical industries, tanks and silos for storage of granular and fluid products, shell structures employed as architectural roof systems, metal sheets employed in the construction of industrial buildings, parts of car bodies, shells in aerospace and aeronautical vehicles, and many others. More recently, thin walled structures have become of great interest in applications at the nanoscale (nanotubes) and in bioengineering.

Engineers design structures with a well-defined shape thoughtfully chosen to fulfill some purpose. But under certain critical conditions the structure cannot withstand further load with the same shape and changes its shape in a slow or sometimes in a violent way. Because those are structures designed to resist loads with a very thin wall, then they are prone to failure by buckling under various load systems. Buckling belongs to a class of problems in mechanics for which some form of singularity occurs in an equilibrium situation.

There are several levels of theories involved in the computational buckling analysis of thin-walled structures: First, there are predictive theories at the level of computations, in which results are obtained; Second, explanatory theories, in which results make sense; and third, classification theories, in which possible solutions are classified. Computational mechanics tends to be associated only to predictive theories, but explanations and classifications are also essential components in any adequate analysis.

This Mini Symposium attempts to embrace all problems involved in the computational buckling analysis of thin-walled structures, including the development of elements with nonlinear capabilities as to address buckling problems, algorithms for tracing nonlinear equilibrium paths, understanding of buckling and post-buckling behavior with the support of computational mechanics, and the application of existing software to the solution of industrial needs. Static as well as dynamic buckling studies are welcomed.
Organizer: DLR (German Aerospace Center), Institute of Composite Structures and Adaptive Systems, Braunschweig, Germany.
Conference Place: Technical University of Braunschweig, Pockelsstrasse 4, Braunschweig, Germany

The conference aims at presenting scientific achievements from the running EU project DESICOS which stands for New Robust DESIgn Guideline for Imperfection Sensitive COMposite Launcher Structures (www.desicos.eu). In addition, papers with related topics outside the project on buckling, postbuckling and collapse behaviour of composite laminated shell structures are presented.

Within the workshop 10 partners demonstrate different improved simulation software and test hardware related to composite structures.

Chairman of the Conference
Prof. Richard Degenhardt, DLR, Braunschweig, D and PFH Göttingen, D

Conference Secretariat
E-mail: desicos@dlr.de

Technical and Scientific Committee
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Mr. Patrice Blanchard, ASTRIUM-F, F
Mr. Jesus Gomez, ASTRIUM-D, D
Mr. Jochen Albus, ASTRIUM-D, D
Mr. Avi Wieder, GRIPHUS, Haifa, IL

Publications
Conference handout: Will contain all short abstracts giving an overview
Conference CD: Will contain all extended abstracts
Special issue: Selected presentations of high quality will be published in a special issue of the Int. Journal of Structural Stability and Dynamics.

Please note that the PhD session on 25 March (3.10 pm – 5.50 pm Brussels/Paris/Berlin time) on Buckling of aerospace composite structures is online accessible for free for everybody. For details see below.

Register for free at http://goo.gl/6cWRwR

The conference contains 85 presentations including the following keynote speakers and topics:

1) Prof. Hansjörg Dittus (DLR, Member of executive board, responsible for space) Reusability – DLR’s new R&D-programme for launch technologies
2) Prof. JN Reddy (Texas AM University) Refined theories and finite element models for the analysis of laminated composite structures: An overview
3) Dr. Mark Hilburger (NASA, Senior researcher) Recent Developments in the Analysis and Testing of Large-Scale Buckling-Critical Cylinders
4) Dr. Jochen Albus (Airbus, Senior expert) Parametric Instability of Pressurized Propellant Tanks
5) Dr. Peter Linde (Airbus) Structural Modelling and Simulation of Aircraft Composite Structures; State of the Industry
6) Prof. Andreas Rittweger (DLR, Head of the Institute of Space Systems) Pre-Dimensioning of Launch Vehicles due to Booster Load Introduction based on Semi-Analytical Methods
7) Prof. Jan Blachut (University of Liverpool) Composite spheroidal shells under external pressure
8) Prof. Brian Falzon (Royal Academy of Engineering - Bombardier Chair in Aerospace Composites, Queen’s University Belfast) Modelling damage in thin-walled composite structures
9) Prof. Christian Hühne (DLR, Institute of Composite Structures and Adaptive Systems, Head of department Composite Design) Single perturbation load approach – From the initial idea until today
10) Dr. habil. Christian Mittelstedt (SOGETI High Tech GmbH, Hamburg) Recent developments in the rapid and efficient closed-form analytical modeling of buckling problems in composite lightweight engineering
11) Dr. Tobias Wille (DLR, Institute of Composite Structures and Adaptive Systems, Head of department Structural Mechanics) Challenges in Structural Mechanics of Composite Structures
12) Prof. Ralf Cuntze (retired) Reliable strength design verification - Fundamentals, requirements and some hints
13) Dr. John Hart-Smith (retired) The use of simple strain-energy concepts to debunk the classical thin-shell buckling analyses for once and for all

A1 Keynote lectures
Hansjörg Dittus (DLR, Member of executive board, responsible for space) Reusability DLR’s new R&D-programme for launch technologies
Mark Hillburger (NASA, Senior researcher) Recent Developments in the Analysis and Testing of Large-Scale Buckling-Critical Cylinders
Jochen Albus (Airbus, Senior expert) Launcher Structural Design and Margins
Peter Linde (Airbus) Structural Modelling and Simulation of Aircraft Composite Structures; State of the
A2 DESICOS - Workpackage summaries

Richard Degenhardt (DLR) New Robust Design Guideline for Imperfection Sensitive Composite Launcher Structures - The DESICOS project
K. Kalnins (Riga Technical University) WP 1 Benchmarking
C. Bisagni (Politecnico di Milano) WP 2 Design of test structures
M. Ruess (TU-Delft) WP 3 Development of new design methods
H. Abramovich (Technion) WP 4 Manufacturing and buckling tests
P. Blanchard (Airbus) WP 5 Contribution to improved design guidelines

A3 DESICOS - Achievements of the PhD students Design concepts, tests)

K. Liang, M. Ruess (TU-Delft) New robust knock-down factors for the stiffened cylinder
A. Meurer, M. Dannert, R. Rolfes (Leibniz University Hannover) New Design Approach for Axially Compressed Composite Cylindrical Shells combining the Single Perturbation Load Approach and Probabilistic Analyses
M. Alfano, C. Bisagni (Politecnico di Milano) Reliability assessment of buckling response of an axially compressed sandwich composite shell with and without cut-outs
L. Friedrich, H. Reimerdes, K. Schröder (RWTH Aachen) Advanced sizing strategies for preliminary design of orthotropic grid stiffened shell structures
R. Khakimova, R. Degenhardt (DLR) Assessment of the Single Perturbation Load Approach on composite conical shells
J. Kepple, M. Herath, G. Pearce, G. Prusty, R. Thomson (CRC-ACS) Stochastic analysis of imperfection sensitive composite cylinders using realistic imperfection models (CRC-ACS, University of New South Wales, Advanced Composite Structures Australia)

B1 Keynote lectures

Andreas Rittweger (DLR, Head of Institute of Space Systems) Pre-Dimensioning of Launch Vehicles due to Booster Load Introduction based on Semi-Analytical Methods
JN Reddy (Texas AM University, USA) Refined theories and finite element models for the analysis of laminated composite structures: An overview
John Hart-Smith The use of simple strain-energy concepts to debunk the classical thin-shell buckling analyses for once and for all

B2a Semi-analytical concepts

V. K. Mantzaroudis, D.G. Stamatelos (Hellenic Air Force Academy) Closed-form local skin buckling solution for orthotropic and anisotropic stiffened panels braced with omega stringers
E. Carrera, E. Zappino, T. Cavallo (Politecnico di Torino) Buckling analysis of thin-walled composite Structures using refined one-dimensional models
M. A. Castillo-Acero, C. Cuerno-Rejado, M. A. Gómez-Tierno (Aernnova, UPM) Zero Poisson panels buckling sizing procedure based on Farrar theory
H. Assaee (Shiraz University of Technology) Application of different versions of finite strip Method as fast tools for buckling analysis of Composite stiffened shells
T. A. Schmid Fuertes, H.-G. Reimerdes (Airbus, RWTH Aachen) Buckling and post-buckling analyses of circular composite cylinders under axial compression using a semi-analytical approach

B2b  Damaged structures / Buckling with piezos
A. Köllner, C. Völlmecke (TU-Berlin) Buckling and post-buckling behaviour of delaminated composite struts
K.C. Gopalakrishnan and R. Ramesh Kumar (Government Engineering College, Delamination of secondary bonding around cuts in a compressively loaded CFRP skinned sandwich structure
J.P. Delsemme, M. Bruyneel, Ph. Jetteur, B. Magneville, T. Naito, Y. Urushiyama (SAMTECH) Progressive damage modeling in composite: from aerospace to automotive industry
A. Muc, P. Kedziora (Cracow University of Technology) Buckling enhancement of laminated structures with piezoelectric actuators
L. Czechowski (Lodz University of Technology) Analysis of dynamic buckling of FGM plate under pulse of heat flux and compression force

B2c Design and Analysis
H. Haller (INTALES) Industrial Branching analysis and assessment of the structural load carrying behaviour of composites in the post buckling regime
H. Starmans Industrial Branching analysis and assessment of the structural load carrying behaviour of composites in the post buckling regime
T. Kubiak (Lodz University of Technology) Numerical model of postbuckling behaviour of GFRP beams subjected to pure bending
B. Brank, A. Stanic, B. Hudobivnik (University of Ljubljana) Simulations of surface wrinkling of bi-layer composite
A. Watson, B. Wang, S. Wang, C. Harvey (Loughborough University) Couple Instabilities of Stiffened Panels with Multiple Stiffener Sizes

B2  Keynote lectures
Ralf Cuntze Reliable strength design verification - Fundamentals, requirements and some hints
Christian Mittelstedt (Sogeti) Recent developments in the rapid and efficient closed-form analytical modeling of buckling problems in composite lightweight engineering
Christian Hühne (DLR, Head of department Composite Design) Single perturbation load approach – From the initial idea until today

B3a  Improved theories / concepts
E.L. Jansen, T. Rahman, R. Rolifes (Uni. Hannover, TNO DIANA BV) Towards mode selection criteria for multi-mode initial postbuckling analysis of composite cylindrical shells
S. G. P. Castro, M. A. Arbelo, R. Degenhardt, G. Ziegmann (PFH, DLR, TU Single perturbation load approach: new definition for PI and explaining the constancy of the buckling load (PFH, DLR, TU Clausthal)
V.M.Trach, N.P.Semenyuk, A.V.Podvornyi, N.B.Zhukova (National University of Water Management and
Nature Resources Use, Timoshenko Institute) On the method of calculation of buckling and postbuckling behavior of laminated shells with small arbitrary imperfections  
F. da Cunha, T. Wille, R. Degenhardt, M. Sinapius (DLR) Structural Robustness Assessment of Thin-Walled Composite Structures in the Postbuckling Regime  
E. Jansen, H. Abramovich, R. Rolfes (Leibniz University Hannover, TECHNION)  
Improving the vibration correlation technique for shells using analysis tools  
John-Hart Smith A necessary correction of the classical analyses for buckling of circular arches, rings, and tubes

B3b Experiments  
M. Brojan, D. Terwagne, R. Lagrange, P. Reis (Uni. of Ljubljana, ULB, MIT) Wrinkling of thin spherical shells on elastic substrates  
M. Schultz, L. Oremont, M. Hilburger (NASA) Experimental and analytical characterization of fluted-core sandwich composite structures  
H. Abramovich, D. Govich and A. Grunwald (TECHNION) Curved panels buckling prediction using the Vibration Correlation Technique  
A. Al-Azzawi, J. McCrory, L.F. Kawashita, C.A. Featherston, R. Pullin and K. M. Holford (Cardiff University) Buckling and postbuckling behaviour of glare laminates containing splices and doublers: experimental and numerical investigations  
K. Kalnins, E. Skukis, O. Ozolins, M. A. Arbelo (RTU, PFH) Experimental determination of the buckling load of composite cylindrical shells using Vibration Correlation Technique  
L. Friedrich, A. Dafnis, H. Reimerdes, K. Schröder (RWTH Aachen) Influence of load application on the collapse load of imperfection sensitive shell structures  
Aditi Sharma (Rajalakshmi Engineering College) Design, fabrication and testing of hybrid nano composite structures

B3c Design and Analysis  
S. Freund, A. Sauerbrei, R. Zimmermann (DLR) Multilevel Skin Buckling Analysis using Hierarchical Metamodels  
F. Odermann, M. Geier (DLR) Buckling tests of unstiffened cylindrical composite shells under dynamic axial pulse loading  
R. J. Mania (Lodz University of Technology) Buckling and post-buckling of FML compressed open cross section profiles  
T. Ungwattanapanit, H. Baier (TU Munich) Weight optimization using equivalent static loads of postbuckled, stiffened panels made by steered-fiber laminates  
P. Le Grognec, K. Sad Saoud (Mines Douai) Analytical and numerical analysis of the elastic/plastic local/global buckling and postbuckling of composite structures  
A. Gliszczynski, T. Kubiak (Lodz University of Technology) Load-carrying capacity of thin-walled composite beams subjected to pure bending  
P. Weaver (University of Bristol) Imperfection-insensitive shells using variable stiffness composites

C2a Experiments  
C. Wolff, D. Wilckens (DLR) Testing and Modelling of impact damaged orthotropic stiffened CFRP-Panels  
D. Wilckens, F. Odermann (DLR) Buckling and Post Buckling of Stiffened CFRP Panels under Compression and Shear  
R. Khakimova, S. Castro, R. Degenhardt, D. Wilckens, M. Kepke, B. Hildebrandt, F. Odermann (DLR, PFH) Buckling experiments on imperfection sensitive thin-walled structures using additional perturbation loads
A. Muc, P.D. Pastuszak (Cracow University of Technology) Remarks on buckling analysis of composite plates and shells

C. Bisagni (Politecnico di Milano) Buckling tests of laminated sandwich cylindrical shells

C2b Design and Analysis
R. Wagner, C. Hühne (DLR) Numerical investigation on experimental buckling loads of unstiffened cylindrical composite shells with varying ratio of radius/wall thickness
M. Arbelo, K. Kalnins, O. Ozolinš, S. Castro, R. Degenhardt (ITA, RTU, DLR) Buckling of imperfection sensitive shell structures: experimental characterization of the knock-down factor using the Multiple Perturbation Load Approach
S. Castro, R. Khakimova, G. Ziegmann, D. Degenhardt, R. Degenhardt, Mark Hilburger (PFH, DLR, TU Clausthal, Sogeti, NASA) Simulation of geometric imperfections and uneven edges in thin-walled cylinders
S. G. P. Castro, C. Mittelstedt, M. A. Arbelo, R. Degenhardt, R. Khakimova, M. W. Hilburger, G. Ziegmann (PFH, Non-linear buckling response of unstiffened laminated composite cylinders using different geometric imperfections
D. Degenhardt, M. Hilburger, S. Castro, R. Khakimova, R. Degenhardt (DLR, NASA) Buckling studies under non-uniform loading
T. Kubiak (Lodz University of Technology) Numerical model of postbuckling behaviour of GFRP beams subjected to pure bending

C2c Design and Analysis
C. Schillo, D. Krause (TU Hamburg Harburg) Experimental and numerical study regarding the influence of traditional and non-traditional imperfections on the buckling load of unstiffened cylindrical CFRP shells

C3a Semi-analytical concepts
David Gao (Australian National University) Complete Solutions to Post-Buckling Problems of Large Deformed Elastic Beam
M. J. Weber, P. Middendorf (Airbus, TU Stuttgart) Semi-analytical global and panel buckling of composite grid-stiffened cylindrical shells
Zhang Guofan, Sun Xiasheng (ASRI) A fast approach on postbuckling analysis of composite stiffened structures
T. Kühn, H. Pasternak, C. Mittelstedt (EADS EFW, TU Cottbus, Sogeti) Closed-form local buckling analysis of shear-deformable composite laminated beam structures
A. Baucke, C. Mittelstedt (HAW, Sogeti) Influence of bending-twisting-coupling on the buckling behaviour of composite laminated plates – a new look at an old

C3b Design and Analysis
T. Le-Manh, Z. Gurdal, M. Abdalla (Skoltech, TU-Delft) Nonlinear buckling of tapered composite plates in isogeometric analysis framework
S. R. Henrichsen, E. Lindgaard, E. Lund (Aalborg University) Discrete material buckling optimization of laminated composite structures considering “worst” shape imperfections
Zia R. Tahir, P. Mandal (University of Manchester) Effect of Asymmetric Meshing on the Buckling Behaviour of Composite Cylindrical Shells under Axial Compression
F. Runkel, A. F. Arrieta, P. Ermanni (ETH Zurich) Structural Tailoring for Enhanced Bending-Twist Coupling through Elastic Instability
E. J. Barbero, A. Madeo, G. Zagari, R. Zinno, G. Zucco (West Virginia University, University of Calabria)
Imperfection sensitivity analysis of composite cylindrical shells using Koiter’s method

C1  Keynote lectures
Jan Blachut (Uni Liverpool) Composite spheroidal shells under external pressure
Brian Falzon (Royal Academy of Engineering) Modelling damage in thin-walled composite structures
Tobias Wille (DLR, Head of department Structural mechanics) Challenges in Structural Mechanics of Composite Structures

R. Degenhardt  Closing words

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Virtual conference on PhD RESEARCH in Buckling of aerospace composite structure held in connection with the 3rd International Conference on Buckling and Postbuckling Behavior of Composite Laminated Shell Structures
Date: Wednesday 25 March 2015
Time: 3.10 pm – 5.50 pm Brussels/Paris/Berlin time
Location: Virtual (Online) Conference
Contacts: DLR: Richard Degenhardt
NASA: Rebecca Vieyra

IFAR – Young Researchers Networking Virtual Conference “PhD RESEARCH in Buckling of aerospace composite structures” Organized by IFAR and DLR in collaboration with NASA Free registration at http://goo.gl/6cWRwR This virtual conference takes place as a self-standing internet conference as part of the 3rd Int. Conf. on Buckling and Postbuckling Behavior of Composite Laminated Shell Structures held from 25 - 27 March 2015 organized by DLR in Braunschweig, Germany.

Topic:
Seven PhD students present their final results in the development of new design guidelines for imperfection sensitive composite light weight structures as used in aerospace applications. The current guideline NASA SP 8007 is from 1968 and was developed for metallic structures. The use of composite materials allows lighter structures but new design guidelines need to be developed. This was the aim for all students. Their work differs in the kind of structure considered (monolithic or sandwich, cylinder or cone) and type of new approach.

Aim of the virtual conference:
· Stimulate technical and scientific interaction between young researchers.
· It will be interactive and participation is free.
· The question-answer session will be accessible from participating IFAR organizations and partner universities.

Who can participate?
The main focus is for young researchers from IFAR organizations and partner universities, but the event is fully open to all researchers from other organizations.

Registration: – Register for free at http://goo.gl/6cWRwR

Pre-Discussion with the Presenters (for IFAR members only):
· Log into IFARlink (www.ifarlink.aero) or register as a new user.
Click on “Discussion Groups” and select the DLR Virtual Conference – click on the discussion group to interact with the presenter(s) of interest to you.

The following virtual conference takes place as a self-standing internet conference as part of the 3rd Int. Conf. on Buckling and Postbuckling Behavior of Composite Laminated Shell Structures held from 25 - 27 March 2015 organized by DLR in Braunschweig, Germany.

Chair of the Virtual Conference: Chiara Bisagni (TU-Delft)
Date: 25 March, 2015 (The times given below are Brussels, Paris, Berlin times.)
3.10 pm Richard Degenhardt (DLR+PFH) Introduction
3.20 pm K. Liang, M. Ruess (TU-Delft) New robust knock-down factors for the stiffened cylinder
3.40 pm A. Meurer, M. Dannert, R. Rolfes (Leibniz University Hannover) New Design Approach for Axially Compressed Composite Cylindrical Shells combining the Single Perturbation Load Approach and Probabilistic Analyses
4.00 pm S. G. P. Castro, C. Mittelstedt, F. A. C. Monteiro, M. A. Arbelo, R. Degenhardt, G. Ziegmann (PFH, DLR, TU Clausthal. Sogeti) A semi-analytical approach for linear and non-linear analysis of unstiffened laminated composite cylinders and cones under axial, torsion and pressure loads
4.20 pm M. Alfano, C. Bisagni (Politecnico di Milano) Reliability assessment of buckling response of an axially compressed sandwich composite shell with and without cut-outs
4.40 pm L. Friedrich, H. Reimerdes, K. Schröder (RWTH Aachen) Advanced sizing strategies for preliminary design of orthotropic grid stiffened shell structures
5.00 pm R. Khakimova, R. Degenhardt (DLR) Assessment of the Single Perturbation Load Approach on composite conical shells
5.20 pm J. Keppe, M. Herath, G. Pearce, G. Prusty, R. Thomson (CRC-ACS, University of New South Wales, Advanced Composite Structures Australia) Stochastic analysis of imperfection sensitive composite cylinders using realistic imperfection models
5.40 pm Discussion
5.50 pm End of Virtual Conference

End of 3rd International Conference on Shell Buckling and Postbuckling

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Tsuboi Award Recipients [awarded by The International Association for Shell and Spatial Structures (IASS)]

The Tsuboi Award was established in 1991 with the help of a donation from the late Mrs. Kazuko Tsuboi. This award honors the memory of Professor Yoshikatsu Tsuboi (Japan, 1907-1990), former President and Honorary Member of the IASS, and his outstanding contributions to structural and architectural design.

Tsuboi Awards are awarded annually by the Tsuboi Awards Committee in two categories:
(A) For the most meritorious paper published in the Journal of the IASS in the preceding calendar year.
(B) For the most outstanding paper presented and published in the Proceedings of the previous year's annual IASS Symposium.
Each award consists of a Japanese lacquerware sculpture with an appropriate engraved plaque attached to its base. The sculpture was designed by Hiroko Hatekenaka and Ryohei Miyata, and the awards are handcrafted by Takju Ogimura, with important contributions to the design and fabrication efforts by Yoshiaki Tsuboi, the son of Professor Tsuboi.

The first Tsuboi Award for the best paper published in the Journal of the IASS was conferred to the German Architect, Michael Balz and for the proceedings paper to the German engineer, Prof. Ekkehard Ramm in 1991. So far in the last 18 years, 17 awards were conferred in the Journal category and 19 awards in the Proceedings category.

**Recipients for the best papers published in the Journal of the IASS:**

1991 M. Balz (Germany): "Architectural Aspects of Organic Forms and Design of Concrete Shells"
1993 H. Isler (Switzerland): "Generating Shell Shapes by Experiments"
1994 M. Levy (USA): "The Innovation of Lightness"
1995 M.E. Giuliani (Italy): Innovative Composite Spatial Structures for the New Milano Fair Exhibition Facilities"
1997 B. Maurin, R. Motro (France): "Investigation of Minimal Forms with Density Methods"
1999 P. Huybers (The Netherlands): "The Chiral Polyhedra"
2000 C. Otero, V. Gil and J. I. Alvaro (Spain): "CR-Tangent Meshes"
2002 T. Kokawa (Japan): "Field Study of a 30-M Span Ice Dome"
2003 C. Cui, H. Ohmori and M. Sasaki (Japan): "Computational Morphogenesis of 3D Structures by Extended ESO Method"
2006 C. Douthe, O. Baverel and J.F. Caron (France): "Form-Finding of a Grid Shell in Composite Materials"
2007 Y.B Yang, L.J. Chen and C.W. Lin (Taiwan): "Cable Vibrations Caused by Moving Loads in Cable-Stayed Bridges"
2010 P. Casinello and J.A. Torroja (Spain): "Félix Candela: His Vocational Training at the University and his Subsequent Relationship with the Institute Founded by Eduardo Torroja"
2011 F. Escrig (Spain): "Geometry and Structures: Historical Impressions about Architecture"
2012 T. Tachi and K. Miura (Japan): "Rigid-Foldable Cylinders and Cells"
2013 D.S. Hensel and G.B. Bover (Norway): "Nested Catenaries"

**Recipients for the best papers published in Proceedings of IASS Annual Symposia:**

1991 E. Ramm (Germany): "Shape Finding Methods in Shells"
1993 G. Groci and A. Visicovic (Italy): "Causes of the Failure of Coliseums over the Centuries, and Evaluation of Safety Levels"
1994 J. Schlaich and H. Schober (Germany): "Glass-Covered Lightweight Spatial Structures"
1995 F. Escrig, J.P. Valcarcel and J. Sanchez (Spain): "Deployable Structures Squared in Plan: Design and Construction"
1996 M. Saitoh and A. Okada (Japan): (a) Space and Structure-Learning of Conceptual Design in Education: What Can One Learn form Building Structures; (b) From Image to Technology: The Role of String in Hybrid String Structures
1998 Y. Hangai (Japan): "Buckling Analysis of Stress Unilateral Structural Systems"
1999 N. Imagawa (Japan): "Shells and Spatial Structures: From Recent Past to the Millennium"
2000 G. Croci (Italy): "The Restoration of the Basilica of Francis of Assisi"
2001 T. Tarnai (Hungary): "Origami in Structural Engineering"
2001 M. Uchikoshi, S. Kato, S. Nakazawa and Y. Mukaiyama (Japan): "How Do We Realize a Super Large Dome Under Severest Earthquake?: A Dome with Seismic Isolation System"
2002 M. Bechtholt (USA): "Wood-foam Sandwich Shells: Computer-Aided Manufacturing of Complex Shapes"
2004 F. V. Jensen and S. Pellegrino (United Kingdom): "Expandable Blob Structures"
2006 A. Smaili and R. Motro (France): "Folding and Unfolding of Curved Tensegrity Systems by Finite Mechanism Activation"
2007 P. Winslow, S. Pellegrino and S.B. Sharma (UK): "Mapping Two-Way Grids on to Free-Form Surface"
2008 L. De Laet, R. Luchsinger, R. Crettol, M. Mollaert and N. De Temmerman (Belgium): "Deployable Tensairity Structures"
2010 T. Van Mele and P. Block (Switzerland): "A Novel Form Finding Method for Fabric Formwork for Concrete Shells"
2011 F. Dieringer, R. Wüchner, and K.U. Bletzinger (Germany): "Practical advances in numerical form finding and cutting pattern generation for membrane structures"
2012 S. Neuhäuser, M. Weickgenannt, C. Witte, W. Haase, O. Sawodny and W. Sobek (Germany): "Stuttgart Smart Shell - A Full Scale Prototype of an Adaptive Shell Structure"
2013 P. Eisenbach, R. Vasudevan, M. Grohmann, K. Bollinger and S. Hauser (Germany): "Parapluie - Ultra Thin Concrete Shell Made of UHPC Activating Membrane Effects"

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International Conference on Shells, Plates and Beams (SPB2015), Bologna, ITALY, 9-11 September 2015
Conference Website: http://www.spb2015.dicam.unibo.it/
Welcome to the web site of 1st International Conference on Shells, Plates and Beams (SPB2015).
This conference intends to bring forward the best research and applications on shells, plates and beams.
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Conference Venue: School of Engineering and Architecture at University of Bologna.

Aims and Scope of the Conference: Thin-walled structures are crucial in modern engineering applications. The computational and experimental methods for shells, plates, beams and arches are the general topics of this conference. We seek papers on buckling, vibrations, repair, reinforcements, concrete, composites, wood, metals, and more recent metamaterials, and advanced materials, nonlinearities, masonry, finite elements, bridges, nano-plates and nano-beams, piezoelectric plates and shells, as prospective topics.

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Supporting Organizations and Partners:
IASS - The International Association for Shell and Spatial Structures
SEWC-IG - Structural Engineers World Congress - Italian Group

Important Dates:
Submission of abstract: 1st March 2015
Early Registration: 1st June 2015
Deadline for registration: 1st August 2015

Plenary Lectures and Sessions:
Workshops (to be updated):
Abstract of the workshop: The synergistic integration of smart materials, structures, machines, sensors, actuators, and control electronics can transform conventional passive structures and machines to active, adaptive, and smart _ structronic (structure + electronic) or mechatronic systems with inherent self-sensing, diagnosis, and control capabilities. Research and development of the emerging technology of smart structures and structronic systems have been evolving for nearly three decades. Sophisticated multi-field/control coupling theories have been developed and numerous practical applications have also been proposed. This report focuses on histories, smart materials (e.g., piezoelectrics, electro-/magneto-/photo-strictive materials, shape memory materials, electro- and magneto-rheological fluids, polyelectrolyte gels, pyroelectric materials, magneto-optical materials, superconductors, etc.), precision devices (sensors and actuators), micro-/nano-actuations, smart structures, mechatronic and structronic systems, and photo-thermo-electro-magneto-mechanical systems encompassing elastic, temperature, electric, magnetic, light, and control interactions. Modern research issues are also discussed.

Tutorial Outline of the workshop:
1. Introduction and overview.
3. Design principles, micro-/nano-actuations, precision devices and control.
4. Case studies.
5. Design clinic: Special and customized applications.

Plenary Talks (to be updated):
Smart Shells: Sensing, Actuation and Control. Horn-Sen (H.S.) Tzou, ZheJiang Univ., China.
Virtual element methods for plates and shells. Claudia Chinosi, Univ. of Pavia, Italy.
(being defined). Francesco Ubertini, Univ. of Bologna, Italy.
Precasting of large span shells and plates. Gian Carlo Giuliani, Redesco (Research-Design-Consulting), Italy.

Sessions (to be updated):
RC Beams with NSM FRP rods. Roberto Capozucca, Univ. Politecnica delle Marche, Italy.
Shell theory. Gennady Kulikov, Tambov Univ., Russia

ABSTRACT: The results of buckling tests performed during the project DESICOS funded by the European Commission in the FP7 Programme are here presented. The tested structures are sandwich cylindrical shells that consist of reduced models of a component of the Ariane 5 launcher: the Dual Launch System. In particular, the scaled component is studied with and without the presence of cut-outs. Before performing the tests, the geometric imperfections as well as the thickness variations were measured. The tests were performed using the
buckling testing equipment of Politecnico di Milano. The results of the tests contributed to understand the complex phenomenon of buckling of sandwich cylindrical shells, and to study the effect of initial geometric imperfections. They were also used to validate finite element models useful for the design of future launcher structures, and to set-up a probabilistic approach for the buckling analysis of cylindrical shells.

References listed at the end of the paper:
1. NASA SP-8007 - Buckling of Thin-Walled Circular Cylinders. 1968. National Aeronautics and Space Administration, Washington, DC, USA.


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“Lower Bound Buckling Loads for Design of Laminate Composite Cylinders”, 3rd International Conference on
ABSTRACT: Over a period of more than 45 years, an extensive research programme has allowed a series of very simple propositions, relating to the safe design of shells experiencing imperfection sensitive buckling, to be recast in the form of a series of lemmas. These are briefly summarised and their practical use illustrated in relation to the prediction of safe lower bounds to the imperfection sensitive buckling of axially loaded, fibre reinforced polymeric, laminated cylinders. With a fundamental aspect of the approach, sometimes referred to as the reduced stiffness method, being the delineation of the various shell membrane and bending stiffness (or perhaps more appropriately energy) components contributing to the buckling resistance, the method will be shown to also provide a powerful way of making rational design decisions to optimise the use of fibre reinforcement.

References listed at the end of the paper:

Lui Feng, Xiwen Li and Tielin Shi (State Key Laboratoty of Digital Manufactueing, Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, China), “Nonlinear large deflection of thin film overhung on compliant substrate using shaft-loaded blister test”, ASME Journal of Applied Mechanics, Vol. 82, No. 9, September 2015, DOI: 10.1115/1.4030739

ABSTRACT: This paper presents the nonlinear large deflection of the thin film and the effect of substrate deformation on the thin film deflection through the shaft-loaded blister test. The blister of thin film can be divided into two parts, namely, the annular contact brim and the central noncontact bulge. A two-coupled line spring model is developed to describe the deformation of the contact part, and Föppl–Hencky equations are employed to study the constitutive relation between the applied load and the central deflection. The analytical and numerical solutions for the constitutive relation between the applied load and the deflection of thin film with considering the deformation of substrate are derived.

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(2) Centre of Advanced Manufacturing and Materials Processing, Department of Mechanical Engineering,
ABSTRACT: It is widely reported that no efficient guidelines for modelling imperfections in composite structures are available. In response, this work evaluates the imperfection factors of axially compressed Carbon Fibre Reinforced Polymer (CFRP) cylinder with different ply angles through finite element (FE) analysis. The sensitivity of imperfection factors were analysed using design of experiment: factorial design approach. From the analysis it identified three critical factors that sensitively reacted towards buckling load. Furthermore empirical equation is proposed according to each type of cylinder. Eventually, critical buckling loads estimated by empirical equation showed good agreements with FE analysis. The design of experiment methodology is useful in identifying parameters that lead to structures imperfection tolerance.

References listed at the end of the paper:

[6] Prabu B 2010


ABSTRACT: Thin-walled cylindrical shells are susceptible to buckling failures caused by the axial compressive loading. During the design process or the buckling failure evaluation of axially-compressed cylindrical shells, initial geometric and loading imperfections are of important parameters for the analyses. Therefore, the engineers/designers are expected to well understand the physical behaviours of shell buckling to prevent unexpected serious failure in structures. In particular, it is widely reported that no efficient guidelines for modelling imperfections in composite structures are available. Knowledge obtained from the relevant works is open for updates and highly sought. In this work, we study the influence of imperfections on the critical buckling of axially compressed cylindrical shells for different geometries and composite materials (Glass Fibre Reinforced Polymer (GFRP), Carbon Fibre Reinforced Polymer (CFRP)) and aluminium using the finite
element (FE) analysis. Two different imperfection techniques called eigenmode-affine method and single perturbation load approach (SPLA) were adopted. Validations of the present results with the published experimental data were presented. The use of the SPLA for introducing an imperfection in axially compressed composite cylindrical shells seemed to be desirable in a preliminary design process and an investigation of a buckling failure. The knockdown factors produced by the SPLA were becoming attractive to account for uncertainties in the structure.

References listed at the end of the paper:


Sheng Xu,1 Zheng Yan,1 Kyung-In Jang,1 Wen Huang,2 Haoran Fu,3,4 Jeonghyun Kim,1,5 Zijun Wei,1
ABSTRACT: Complex three-dimensional (3D) structures in biology (e.g., cytoskeletal webs, neural circuits, and vasculature networks) form naturally to provide essential functions in even the most basic forms of life. Compelling opportunities exist for analogous 3D architectures in human-made devices, but design options are constrained by existing capabilities in materials growth and assembly. We report routes to previously inaccessible classes of 3D constructs in advanced materials, including device-grade silicon. The schemes involve geometric transformation of 2D micro/nanostructures into extended 3D layouts by compressive buckling. Demonstrations include experimental and theoretical studies of more than 40 representative geometries, from single and multiple helices, toroids, and conical spirals to structures that resemble spherical baskets, cuboid cages, starbursts, flowers, scaffolds, fences, and frameworks, each with single- and/or multiple-level configurations.

References listed at the end of the paper:
Haoran Fu,1,2 Sheng Xu,3 Renxiao Xu,2 Jianqun Jiang,1 Yihui Zhang,2,4 John A. Rogers,3 and Yonggang Huang2

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ABSTRACT: Fractal-inspired designs for interconnects that join rigid, functional devices can ensure mechanical integrity in stretchable electronic systems under extreme deformations. The bonding configuration of such interconnects with the elastomer substrate is crucial to the resulting deformation modes, and therefore the stretchability of the entire system. In this study, both theoretical and experimental analyses are performed for postbuckling of fractal serpentine interconnects partially bonded to the substrate. The deformation behaviors and the elastic stretchability of such systems are systematically explored, and compared to counterparts that are not bonded at all to the substrate.

References listed at the end of the paper:

ABSTRACT: The aim of this work is to investigate the final failure response of damaged composite stiffened panels in post buckling regime under compressive load, by using progressive failure analysis (PFA) methodology. The selected panel is characterized by T shaped stringers and it is representative of the upper skin panel, toward the wing tip, of the wing box of a typical regional aircraft. PFA methodology has been applied in order to predict in addition to the initiation of the local failure also its propagation up to the final collapse of the panel, in presence of local damage (barely visible impact damage, BVID) and in post-buckling regime. For this purpose, discrete damages have been considered in the skin of the panel. According to the indications contained in many guidelines finalized to the preliminary design of composite structures, a simplified design model of BVID has been considered in this work, in particular a hole 1/4 inch in diameter has been used to simulate this damage. The collapse load of the panel has been evaluated considering different locations of a single damage and also considering multi-damage maps (the latter are more representative of a real damage scenario). The results of PFA presented in this work illustrate the combined effect of the reduction of the panel stiffness and of
the damage propagation, and the sensitivity of the buckling onset and of the residual strength of the panel with respect to different damage locations and damage density.

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ABSTRACT: This work presents the robustness assessment of stiffened thin-walled composite structures in post-buckling, which is based on a new design strategy that satisfies weight, load-based performance and energy-based robustness requirements. In this approach, robustness is understood as collapse insensitivity due to a local failure, where global buckling for instance is assumed as a local failure, once the stiffness reduction after this event can lead to a sharp collapse. Following this concept, robustness measures are derived from the structural energy, the area under the load-shortening curve obtained from geometrical nonlinear finite element analysis with material progressive failure. Since inherent uncertainties in geometry, material properties, ply orientation and thickness affect the structural performance and robustness, those variations are accounted for.

As a result, a new argument is given to shift collapse closer to ultimate load, so that lighter structures are achievable with both performance and robustness requirements satisfied. This trade-off is valuable to aerospace applications, where light weight and safety are mandatory. Finally, this innovative strategy is demonstrated for stiffened thin-walled composite structures in post-buckling, and its results compared to others obtained from current practice.


ABSTRACT: Up to today there are no design guidelines which allow designing imperfection sensitive CFRP structures in an efficient way. The upcoming EU project DESICOS (New Robust DESIgn Guideline for Imperfection Sensitive COMposite Launcher Structures) contributes to this aim by a new design procedure exploiting the worst imperfection approach efficiently by implementation of the Single Perturbation Load Approach. Preliminary studies already demonstrated high potential. This paper deals with the objectives of the DESICOS project, describes the line of actions of the new approach, and specifies the theoretical and experimental work to be carried out in order to meet the objectives.

References listed at the end of the paper:


A novel knock-down factor is proposed composed of two parts for the metallic stiffened cylinders. A deterministic study is applied to achieve the first part of the knock-down factor.
considering the measured geometric imperfection, the other types of imperfections are considered in the second part using a stochastic analysis. A smeared model is used to achieve the implementation of the measured geometric imperfection for the stiffened cylinder. This new robust and less conservative design for the stiffened cylinders is validated by using test results.

References listed at the end of the paper:

Ashutosh Kumar (1) and Rachayya R. Arakerimath (2)
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ABSTRACT: It happens many times that the structure is safe in normal stress and deflection but fails in buckling. Buckling analysis is one of the methods to go for such type of analysis. It predicts various modes of buckling. Plates are used in many applications such as structures, aerospace, automobile etc. Such structures are subjected to heavy uniformly distributed load and concentrated load many times over its life span. Strength of these structures are increased by adding stiffeners to its plate. This paper deals with the analysis of rectangular stiffened plates which forms the basis of structures. A comparison of stiffened plate and unstiffened plate is done for the same dimensions. In order to continue this analysis various research papers were studied to understand the previous tasks done for stiffened plate. Hyper mesh and Nastran is used to do the analysis. Buckling analysis is done with aspect ratio of 2. Rectangular flat bar is used as stiffener.

References listed at the end of the paper:

[1]. J Rhodes, Some observation of the post-buckling behavior of thin plates and thin walled members, Science direct, 2003
[7]. Khosrow Ghavami, Mohammad Reza Khedmati, Numerical and Experimental investigations on the compression behavior of stiffened plates, ScienceDirect, 2006
[10]. Esuard Ventsel, Theodor Krauthammer, Thin Plates and shell, 2001


ABSTRACT: One of the most important static analyses for thin plates, is buckling analysis. The most common method to study the Critical Buckling Load of thin plates, is equilibrium method. This method is based on solving a fourth order partial differential equation. This paper presents a finite element model for a simply supported and simply supported-fixed-free rectangular plate. The study uses ABAQUS (v.6.7) software to derive the finite element model of the rectangular plate. Finally, the obtained results through FEM would be compared with an exact solution for both boundary conditions.

References listed at the end of the paper:

ABSTRACT: One of the main failure modes of an aircraft is buckling. Stringers are often bonded to composite panel skins to help increase the panel’s buckling strength; however, if there is a defect in the bond between the stringer and the panel, the structure may be weakened. Developing analysis tools that can accurately simulate the behavior of composite materials is critical to the successful design and use of composite structures. The pre-design of aircraft wing structures relies on finite element models of significantly reduced complexity in which only spar and rib components are explicitly modeled, whereas the wing skin-stringers stiffened panels are implicitly represented by stiffness-equivalent elements. This conventional procedure enables a fast solution technique for large problems.
References listed at the end of the paper:

ABSTRACT: Thin walled integrally stiffened shell structures are frequently used in primary structures of space launcher vehicles. These structures are prone to buckle and thus fail due to a loss of structural stability. It has to be distinguished between two major modes of instability, namely a global buckling of the entire structure and a local buckling of skin sections, longitudinal as well as circumferential stiffeners. Due to the large number of design variables when designing an integrally stiffened shell structure, the preliminary design of these structures is a demanding problem. To allow an efficient preliminary design, advanced sizing strategies have to be developed. For this purpose, analytical methods to allow assessing the local as well as global instability of the integrally stiffened shell structure are employed. Within this contribution, sizing strategies basing on closed form efficient analytical methods are introduced and applied to identify proper designs of integrally orthotropic stiffened shell structures.

ABSTRACT: We present the pre and post buckling analysis of stiffened composite panels based on the finite element models. Individual buckling studies are conducted on the stiffened composite panel made up of woven fabric CFC/epoxy, E-glass/epoxy and the Kevlar/epoxy composites. Straight, T shaped and I shaped stiffeners are considered to stiffen the panel. The panel is fabricated with 8 layers and the stiffeners are made up of 16 layers, of equal thickness arranged in different orientations. The panel is subjected to a uniform axial compression load of 10 kN. The distribution of the buckling stresses and the buckling loads with different panel and stiffener combinations are estimated for three different layup sequences. The variation of the buckling stresses and the buckling loads from the numerical model are compared with the experiment. The results are in excellent agreement.

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ABSTRACT: Values of characteristic parameters such as thickness have big influence on the impact behavior of a laminated armor. Determination of those values for an optimum laminated armor usually requires evaluation of many computationally costly impact analyses. In this paper, automated, efficient and effective determination of design parameters in a laminated armor for best impact performance is investigated using an approximate optimization method. The approximate optimization method is generated by coupling a parametric preprocessor, finite element analysis software, response surface approximations and a numerical optimization algorithm. The whole coupling is achieved through a commercial code, ANSYS Design Optimization Module. The laminated armor of interest consists of three layers. The frontal layer is alumina ceramic, and it is supported by a 4340 steel mid-layer and a 2024-T3 aluminum rear layer. The armor is impacted by a projectile with velocities of 1000 and 2000 m/s. The surface normal to the armor has an oblique angle with the projectile’s moving direction. The 3-D impact analysis of the armor is conducted using non-linear explicit dynamic finite element code ANSYS/LS-DYNA. Optimization of the armor is performed to find the best thickness values of layers and oblique (orientation) angle towards the least penetration of the projectile.

-----BOOK
ABSTRACT: Optimization methods are increasingly used to design structures. Structural optimization with linear static analysis is pretty much mature in methodology and therefore several codes now have optimization capability for linear analysis. This is in contrast to optimization with crash and impact responses encountered in automotive, defense, transportation safety and other fields. Impact responses do not present simplicities as with linear static responses. They are highly nonlinear and noisy (i.e. non smooth) preventing the use of conventional optimization methods based on gradients or sensitivities. Also, impact analyses are usually computationally costly. Such difficulties motivated the development of effective and efficient methods for impact optimization. This book elaborates structural optimization procedure under crash and impact loading. For this purpose, analysis and optimization methods are discussed in detail. Impact optimization problems are solved from
several areas.


ABSTRACT: In this article, shape effect on free vibration behavior of functionally graded plates is investigated. Square, rectangular, skew, circular, elliptical, annular and equilateral triangular plates with the same surface area and thickness are considered. Frequency values of these plates are compared for simply supported and clamped boundary conditions. Finite element method (FEM) is used in calculating frequency values and mode shapes. Since commercial codes do not allow inputting functionally graded material properties directly, MATLAB code was developed for FEM solution. Findings of this study can be useful for designers that have freedom to choose the plate shape in engineering applications.

References listed at the end of the paper:

Toh Yen Pang, Dale Waterson, Rees Veltjens and Tristan Garcia (School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora East Campus, Bundoora, Melbourne, VIC, Australia), “Nonlinear finite element and post-buckling of large diameter thin walled tubes”, Chapter 8 in Nonlinear Approaches in Engineering Applications, Edited by Liming Dai and Reza N. Jazar, pp 219-233, Springer, 2015

ABSTRACT: This study investigates the crush behaviour of a relatively large diameter, thin walled tube through both experimental and finite element methods. The experiments were conducted using test specimens of cylindrical tube which were placed into a load press, and crushed by a distance of 150 mm. The thin walled tubes were found to collapse through localised buckling, with a folding layered mode of failure. Numerical analysis of the cylindrical tube was conducted using finite element (FE) methods through an explicit analysis (utilising a three dimensional shell model). Through the use of both ductile damage criteria and the Müschenborn–Sonne forming limit diagram (MSFLD), the model was able to initiate buckling failure without creating imperfections. The numerical model exhibited a similar layered, ring-folding mode of failure as observed in the experiment. Shear failure was also analysed, however caused a large amount of element distortion. The model showed a large degree of sensitivity to the coefficient of friction used in contact between the tube and the press. With the careful selection of mesh density, friction coefficient, and material properties, the FE model demonstrated very good correlation with the experiment in terms of critical buckling force and post-buckling response.

References listed at the end of the paper:
ABSTRACT: The stretch-induced wrinkling of thin films is solved through the modified von Kármán large deflection equations by first selecting the suitable deformation expressions that satisfy boundary conditions. Then, adopting the principle of minimum potential energy we obtain the deformation equations analytically and experimentally. The methodology also indicates the limit load impending of simply supported rectangular thin films. The obtained significant deflections are nonlinearly elastic and of the lowest order of infinite solutions. The parameters of aspect ratio, the thickness and material of thin films are studied analytically and numerically. The highlighted results of wrinkle amplitude and load are in good agreement with experiments. The methodology also indicates the limit load impending plasticity and predicts the applied load precisely for each wrinkle. Further, it can be extended to the variety of multifunctional orthotropic and multilayered thin films.

References listed at the end of the paper:
3. E. Sharon et al., Nature 419, 579 (2002). http://dx.doi.org/10.1038/419579a
References listed at the end of the paper:


5. L. Scatteia, G. Tomassetti, M. Kivel Mazuy, S. Cantoni, 'Prora USV- Tech cryotank project Applicability of CFRP to tank manufacturing for cryogenic liquid propulsion', 54th International Astronautical congress of international astronomical federation, the international academy of astrophysics, and the international institute of space law, 29 September-3 October 2003, Bermen, Germany.


DOI: 10.5120/19704-1523

ABSTRACT: Buckling analysis of laminated composite simply supported cylindrical shell under cryogenic environment is solved by using exact approach. The theoretical formulation is based upon the third-order shear deformation theory, then equation of motion are derived and solved using Fourier series to obtain critical buckling load by solving eigenvalue problem for different cryogenic gradients. Many design parameters are changed such as using different material, number of laminate, aspect ratio (L/R) and thickness ratio (R/h).

Results show that changing cryogenic temperature improve buckling load for all material of cylindrical shell, the results show good agreement with those published by other researchers.

References listed at the end of the paper:


5. L. Scatteia, G. Tomassetti, M. Kivel Mazuy, S. Cantoni, 'Prora USV- Tech cryotank project Applicability of CFRP to tank manufacturing for cryogenic liquid propulsion', 54th International Astronautical congress of international astronomical federation, the international academy of astrophysics, and the international institute of space law, 29 September-3 October 2003, Bermen, Germany.


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ABSTRACT: The present paper deals with the nonlinear thermal instability of geometrically imperfect sandwich cylindrical shells under uniform heating. The sandwich shells are made of a shape memory alloy (SMA)-fiber-reinforced composite and functionally graded (FG) face sheets (FG/SMA/FG). The Brinson phenomenological model is used to express the constitutive characteristics of SMA fibers. The governing equations are established within the framework of the third-order shear deformation shell theory by taking into account the von Karman geometrical nonlinearity and initial imperfection. The material properties of constituents are assumed to be temperature dependent. The Galerkin technique is utilized to derive expressions of the bifurcation points and bifurcation paths of the sandwich cylindrical shells. Using the developed closed-form solutions, extensive numerical results are presented to provide an insight into the influence of the SMA fiber volume fraction, SMA pre-strain, core thickness, non-homogeneity index, geometrical imperfection, geometry parameters of sandwich shells and temperature dependency of materials on the stability of shells. The results reveal that proper application of SMA fibers postpones the thermal bifurcation point and dramatically decreases thermal post-buckling deflection. Moreover, the induced tensile recovery stress of SMA fibers could also stabilize the geometrically imperfect shells during the inverse martensite phase transformation.
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“Multiscale computational homogenization of heterogeneous shells at small strains with extensions to finite displacements and buckling”, International Journal for Numerical Methods in Engineering, article published online: 20 May 2015, DOI: 10.1002/nme.4927

ABSTRACT: In this paper, a framework for computational homogenization of shell structures is proposed in the context of small-strain elastostatics, with extensions to large displacements and large rotations. At the macroscopic scale, heterogeneous thin structures are modeled using a homogenized shell model, based on a versatile three-dimensional seven-parameter shell formulation, incorporating a through-thickness and pre-integrated constitutive relationship. In the context of small strains, we show that the local solution on the elementary cell can be decomposed into six strains and six-strain gradient modes, associated with corresponding boundary conditions. The heterogeneities can have arbitrary morphology but are assumed to be periodically distributed in the tangential direction of the shell. We then propose an extension of the small-strain framework to geometrical nonlinearities. The procedure is purely sequential and does not involve coupling between scales. The homogenization method is validated and illustrated through examples involving large displacements and buckling of heterogeneous plates and shells.

Martin Psotny (Department of Structural Mechanics, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11, 813 68 Bratislava, Slovakia), “Nonlinear Analysis of Buckling & Postbuckling”, Transactions of the VŠB – Technical University of Ostrava, Civil Engineering Series.. Volume 14, Issue 1, Pages 75–80, ISSN (Online) 1804-4824, DOI: 10.2478/tvsb-2014-0010, July 2014

ABSTRACT: The stability analysis of slender web loaded in compression was presented. To solve this problem, a specialized computer program based on FEM was created. The nonlinear finite element method equations were derived from the variational principle of minimum of potential energy. To obtain the nonlinear equilibrium paths, the Newton-Raphson iteration algorithm was used. Corresponding levels of the total potential energy were defined. The peculiarities of the effects of the initial imperfections were investigated. Special attention was focused on the influence of imperfections on the post-critical buckling mode. The stable and unstable paths of the nonlinear solution were separated. Obtained results were compared with those gained using ANSYS system.


ABSTRACT: Self-assembly of nano sized particles during natural drying causes agglomeration and shell formation at the surface of micron sized droplets. The shell undergoes sol-gel transition leading to buckling at the weakest point on the surface and produces different types of structures. Manipulation of the buckling rate with inclusion of surfactant (sodium dodecyl sulphate, SDS) and salt (anilinium hydrochloride, AHC) to the nano-sized particle dispersion (nanosilica) is reported here in an acoustically levitated single droplet. Buckling in levitated droplets is a cumulative, complicated function of acoustic streaming, chemistry, agglomeration rate,
porosity, radius of curvature, and elastic energy of shell. We put forward our hypothesis on how buckling occurs and can be suppressed during natural drying of the droplets. Global precipitation of aggregates due to slow drying of surfactant-added droplets (no added salts) enhances the rigidity of the shell formed and hence reduces the buckling probability of the shell. On the contrary, adsorption of SDS aggregates on salt ions facilitates the buckling phenomenon with an addition of minute concentration of the aniline salt to the dispersion. Variation in the concentration of the added particles (SDS/AHC) also leads to starkly different morphologies and transient behaviour of buckling (buckling modes like paraboloid, ellipsoid, and buckling rates). Tuning of the buckling rate causes a transition in the final morphology from ring and bowl shapes to cocoon type of structure.

References listed at the end of the paper:

structures along with interlaminar through-the-thickness cracks have been carried out. The developed FEM based modelling and simulation technique has been yielding results in close agreement with literature. Interlaminar cracks of similar sizes have been considered at edge and internal locations in order to study their effect on natural frequency of vibration of the cantilevered cylindrical composite shell structure. Cracks have been simulated in different locations from the clamped towards the free edge in order to study their effect on free vibration of the laminated shell structure. Interlaminar cracks have been observed to be reducing the natural frequency of vibration of the shell structures to a great extent, hence affecting the stiffness of the structure. However, for similar damage size and locations, internally-cracked composite cylindrical shells are comparatively stiffer than the edge-cracked cylindrical shell structures. Both the edge and internal cracks have been seen to be affecting the stiffness of the shell structure to a great extent through reducing the frequency of vibration, as they are close to the clamped edge. Composite shell structures with cracks towards the free edge have been comparatively safe as they marginally affect the frequency of vibration.

References listed at the end of the paper:
order to get the best compromise among spring performances (minimum mass, maximum strength, ...), with constraints on local and global stability, on resonance frequency, ..., The method is based on Multi-Objective Programming (a branch of Operations Research), which provides a theoretically correct way for defining the values of many design variables when many objectives (performance indexes) have to be taken into account. Mathematical models are developed for describing the mechanical behaviour of the spring. The models have been validated with satisfactory results. The design solutions coming from the application of the method suggest the best parameter setting for obtaining the desired spring performances.

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Muna H. Jaber (Civil Engineering, Babylon University), “Strength of tubular hollow steel sections externally reinforced by carbon FRP sheets”, (publisher & date not given in the pdf file; most recent reference is 2008).

ABSTRACT: The experimental research reported is aimed using small quantities of CFRP strips to provide tubular section against local buckling for (five) specimens of steel beams. The tubular hollow steel beams sections are made from welding thin plates at their edges. The use of high-strength advanced composite materials tends to accompany the minimum of structural weight, and is hence presently being assessed for effectiveness as supplementary external reinforcing materials. Composite beams of fiber-reinforced polymers (FRP) and steel formed as tubular steel sections externally reinforced by thin-bonded carbon FRP (CFRP) sheets, exhibit many phenomena not found in conventional structural steel components, and these can have a marked bearing both on the behavior of members composed of these materials and, by connotation, on the way in which such members are designed. The type of strengthen carbon fiber is a unidirectional woven fiber mat of mid strength which is a product of Sika coded as SikaWrap-230C. The CFRP is fixed using a resin Sikadure-330. The study is focusing on the local stability of such members. Also formulation of the finite element method used for analyzing the tested beams. The finite element model will be using the experimental load-deflection results of the steel beams. The use of ANSYS-9 to create the finite element model is adopted, the maximum different between experimental results and ANSYS-9 results is 8.7%.

References listed at the end of the paper:


ABSTRACT: This paper evaluates the vibration characteristics of thin/thick rotating cylindrical shells made of metallic and composite materials. A previous theory of the authors is extended here to include the effects of
geometrical stiffness due to rotation. To this end, variable kinematic one-dimensional (1D) models obtained by applying the Carrera Unified Formulation (CUF) were used. The components of the displacement fields are $x$, $z$ polynomials of arbitrary order $N$, making it possible to go beyond the rigid cross section assumptions of the classical beam theories. A significant contribution of this formulation consists in the possibility to include the in-plane cross-sectional deformations allowing the introduction of the in-plane initial stress effects, e.g., the effect of the geometrical stiffness. Equations of motions, including both Coriolis and in-plane initial stress contributions, were solved through the finite element method. Several analyses were carried out on both thin and thick cylinders made of either metallic or composite materials with different boundary conditions. The results are compared with analytical and numerical shell formulations and three-dimensional solutions available in the literature. Various laminate lay-up have been considered in the case of composites shells. Numerical evaluations of the effect of geometric stiffness are provided, demonstrating its importance in the analyses presented. The 1D models appear very effective to investigate the dynamics of spinning shells and, contrary to shell theories, they do not require any amendments with thick shell geometry. From the computational point of view, the present refined beam models are less expensive than the shell and solid counterparts.


ABSTRACT: The use of thin-walled composite beams in Engineering has attracted great interest in recent years. Composite beams and other structural elements tend to have thin walls due to the high strength of the material. Other important aspect is that, even without reaching large strains and without overcoming the elastic limit of the material, such as beams present geometric nonlinear behavior due to their high slenderness, leading to large displacements and rotations. In this paper, a three-dimensional frame finite element for geometric nonlinear analysis of thin-walled laminated composite beams is presented. The finite element uses the Total Lagrangian formulation in order to allow the treatment of large displacements, but with moderated rotations. The constitutive matrix of the laminated beams is evaluated through a suitable thin-walled beam theory. In this theory, the effects of the couplings for several layups are considered, but the effects of the warping and transverse shear are neglected. Comparisons with numerical experiments demonstrate the very good accuracy of the proposed finite element.

References listed at the end of the paper:


ABSTRACT: There is a renewed interest in grid-stiffened composite structures; they are not only competitive with conventional stiffened constructions and sandwich shells in terms of weight but also enjoy superior damage tolerance properties. In this paper, both global and local buckling is investigated for orthogrid- and isogrid-stiffened composite panels. Homogenized properties corresponding to classical lamination theory are obtained by matching the strain energy of stiffened and equivalent unstiffened cells, and then used in global buckling analysis. Bloch wave theory is adopted to calculate the local buckling load, where the interaction of adjacent cells is fully taken into account. Instead of considering skin buckling and stiffener crippling separately, the skin and stiffeners are assembled together at the level of a characteristic cell. The critical instabilities can be captured whether they are related to the skin, stiffener or their interaction. The proposed combination of global/local models can also be used to predict the material failure. Numerical examples of isotropic panels show that the local buckling loads predicted by the proposed method match detailed finite element calculations well for eccentric or symmetrically located stiffeners with different torsional stiffness. The proposed method is further validated using typical composite configurations of flat panels and circular cylinders.

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V. M. Dubrovin and T. A. Butina (Bauman Moscow State Technical University), “Simulation of the dynamic stability of cylindrical shell under the action of external overpressure”, publisher and date not given in the pdf file; most recent reference is 2011
ABSTRACT: The suggested method is to calculate dynamic stability of cylindrical shells under loading of external excessive pressure, distributed over shell surface. As an example, we consider the case where the pressure varies in accordance with the linear law.

References listed at the end of the paper:

ABSTRACT: The article describes a method for calculating the dynamic stability of cylindrical shell under axial compressive time-varying load. The case of linearly varying load was considered as an example.
H. Keppler and A. Kirichuk, “Numerical algorithms and computer modeling for nonlinear analysis of shell structures”, (no publisher or date given. The most recent reference is dated 1991.)
ABSTRACT: (none given)
References listed at the end of the paper:

ABSTRACT: This investigation examines the dynamic stability of a damped imperfect spherical shell within the precinct of a random dynamic load applied just after the initial time. The statistical characterizations of the random load, such as the mean and the autocorrelation, are assumed given and non-vanishing. In particular, the autocorrelation of the random dynamic load is a stationary noise that is correlated as an exponentially decaying harmonic function of time. Such stochastic and random characterizations of the dynamic load function confer some element of randomness on the normal displacement whose statistical mean we shall first seek for the determination of the dynamic buckling load. Lastly, the dynamic buckling load is determined via a suitable maximization and certain useful deductions are made. Assuming that the variance of the random load is and using the mean normal displacement as a relevant statistical characterization of the response, it is observed that the dynamic buckling load is of order $R_0^{-1}$, that is $O(1/R_0)$, of the load variance $R_0$

ABSTRACT: This paper is concerned with asymptotic solution, using multi-timing technique, of a nonlinear coupled elastic system in a dynamical setting where the structure investigated is a discretized imperfect spherical shell .The normal displacement at a point on the shell surface is assumed to be partly in the form of a symmetric pre-buckling mode, and partly in the form of buckling modes that have both axisymmetric and non-axisymmetric components. The geometric imperfection is assumed to be in the shape of the buckling modes. The explicitly time-dependent load function is assumed harmonic (or periodic) and the dynamic buckling load is obtained nontrivially with specializations of the results made. The results show, among other things, that (i) the only condition under which the effects of any coupling is felt is if none of the imperfections in the shapes of the modes coupling is neglected and (ii) neglecting an imperfection automatically nullifies the effects of the nonlinearity that is in the shape of the neglected imperfection.

ABSTRACT: (There is no abstract.)
DOI: 10.1243/14750902JEME168
ABSTRACT: (There is no abstract)

ABSTRACT: On the base haft-momentum Vlasov theory the problem of stability of cylindrical homogeneas shell with variation of thicknees atv radial symmetrical racitial pressure variated onalong axe distance. At one relation between thickness and pressure values the accurate solution was produced for one values in pressure variation law when stability of shell is sailed.

References listed at the end
ABSTRACT: Retaining walls are structures used to provide stability for earth or other material where conditions disallow the mass to assume its natural slope and are commonly used to hold back or support soil banks coal or ore piles, and water. Retaining walls must be of adequate proportions to resist overturning (or excessive tilting) and sliding as well as being structurally adequate. Recognition of retaining walls behavior, selection of the best and the most economical design, and the most logical form and their required specifications are the most important issues and worries of designing engineers during designing period. So recognition of the main effective elements on wall construction expenses, and the effect of limitations on acquiring the most economical wall can be a proper help and deserves being completely studied from all points of view in order to acquire the most economical and from the point of technical aspect the most suitable one. According to the elements of design resulting from the theoretical researches on former retaining walls, and for lightening them; in this article a new constructing design of lightened retaining walls is suggested. Meanwhile common proportions and stability of multi cylindrical shell retaining wall have been discussed in this paper.

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BS5337-1976, Structural use of concrete for retaining aqueous liquids, British Standards Institute.
ABSTRACT: The article is devoted to the influence of carrying capacity on the stability of laterally loaded cylindrical shells. The influence of initial imperfections on the stability of the laterally loaded shell is also taken into consideration. The investigated structure is a simplified variant of the case of cylindrical shell (road tank – for example Paščenko, 2009; Paščenko, Stejskal, 2008) located on two saddle supports. The initial shape imperfections are created by pushing the saddle support into the shell. The new deformed shape is used as an imperfect shell in the following nonlinear analysis of stability. The main objective of the analysis is to find the reduction factor $\alpha$ depending on the change of geometric parameters of the numerical model (embracing angle $2\theta$, wall thickness $t$). The shell deformation around the saddle support is also monitored. Numerical analysis is carried out by means of a computer program COSMOS/M based on the finite element method (FEM).

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ABSTRACT: The effect of length and thickness on dynamic stability analysis of cantilever cylindrical shells under follower forces is addressed. Beck’s, Leipholz’s, and Hauger's problems were solved for cylindrical shells with different length-to-radius and thicknesses-to-radius ratios using the Galerkin method. First-order shear theory was used, and rotary inertias were considered in deriving the differential equations. Critical circumferential and longitudinal mode numbers and loads were evaluated for each case. Diagrams containing nondimensional load parameters vs. length and thickness parameters were plotted for each problem. For some shells with small length-to-radius ratios, flutter occurred in high longitudinal mode numbers where the first-order shear theory may not suffice to accurately evaluate the deformations. However, for long and moderately thick shells, there are ranges in which the shell can be analyzed using the simplified equivalent beam model.

References listed at the end of the paper:
example shows the effect of the ribs and cylinder to the shell’s instability domain. The number of ribs installation places. The number of problem reduces to the system of algebraic equation in reference to components of shell’s displacement in the elastic foundation with coefficient of soil reaction that defined from equations tridimensional theory of components of contact interaction between the shell and ribs are accounted. The cylinder is represented as cylinder, loaded with external pressure, changed harmonically, is inve

ABSTRACT: The stability and sensitivity analysis of anisotropic polymeric material circular cylindrical shells used in underground applications is considered in this work. The presence of helicoidal ribs produces a shell with anisotropic characteristics. The conditions of the surrounding soil have an important effect on the buckling load and the load carrying capacity of the structure. The analysis begins by considering the equations corresponding to the isotropic case and specializing them for the anisotropic case. The anisotropic behavior is due to the effect of the presence of the reinforcement, which is nearly circumferential. The soil-structure interaction has a significant influence in the structural response of the shell, including its buckling load. This is due to the fact that the shell can be considered as a large and flexible one. Several effects on the buckling load are taken into account, those caused by changes in the rheological properties of the soil due to its level of saturation or water content, how compacted it is, empty zones around the shell, asymmetry of the loads and the proximity of other pipelines. Computational tools based on the Finite Element Method are used to solve the shell stability equations under the several conditions mentioned above. A parametric study is carried out where different geometrical configurations are considered. Variations in the thickness/diameter ratio, length/diameter ratio and offset reinforcement angle are included in the analysis. In this way new design structural criteria are obtained and with these criteria, structural designs with higher reliability are expected.


ABSTRACT: Dynamic stability of a sandwich cylindrical shell, supported by both the annular ribs and the cylinder, loaded with external pressure, changed harmonically, is investigated. The normal and tangential components of contact interaction between the shell and ribs are accounted. The cylinder is represented as elastic foundation with coefficient of soil reaction that defined from equations tridimensional theory of elasticity. Solution of differential equations is found in the shape of trigonometric sequence. As a result, the problem reduces to the system of algebraic equation in reference to components of shell’s displacement in the ribs installation places. The number of equation is three for ribs are installed regularly. In the numerical example shows the effect of the ribs and cylinder to the shell’s instability domain.
Mohammad Ebrahim Torki (1), Mohammad Taghi Kazemi (2), Hassan Haddadpour (2) and Saeed Mahmoudkhani (2)

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ABSTRACT: Flutter of cantilevered, functionally graded cylindrical shells under an end axial follower force is addressed. The material properties are assumed to be graded along the thickness direction according to a simple power law. Using the Hamilton principle, the governing equations of motion are derived based on the first-order shear deformation theory. The stability analysis is carried out using the extended Galerkin method and minimum flutter loads and corresponding circumferential mode numbers are obtained for different volume fractions, length-to-radius, and thickness-to-radius ratios. Two different configurations are considered for the FGM: one in which the metal phase is the outer layer and the ceramic phase is the inner one, and the other vice versa. Results indicate the ranges of major influence due to the volume fraction, and the combined effect of thickness and volume fraction on the flutter load. Also, the optimum and critical power parameters between zero and infinity for which the flutter loads are maximum and minimum are determined.

References listed at the end of the paper:

ABSTRACT: This Theme Issue is dedicated to the topic ‘Mechanics: from nano to macro’ and marks the 75th birthday of Dr J. Michael T. Thompson, Fellow of the Royal Society, whose current affiliations are as follows: (i) Honorary Fellow, Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge; (ii) Emeritus Professor of Nonlinear Dynamics, Department of Civil, Environmental and Geomatic Engineering, University College London; and (iii) Professor of Theoretical and Applied Dynamics (Distinguished Sixth Century Chair, part-time), University of Aberdeen. He also serves as Chairman of the Board of Directors at ES-Consult (consulting engineers) in Copenhagen, Denmark. The pertinent question that arises from the very start is: should we first salute Michael and then describe the Theme Issue, or vice versa? Indeed, according to Blaise Pascal (1623–1662), the last thing one discovers in composing a work is what to put first. I would like to take the liberty of deviating from the tradition of the Philosophical Transactions and start with the tribute to Michael; after all he is the prime cause of this Theme Issue.

References listed at the end of the paper:


ABSTRACT: In this work we consider the buckling problem for a filled thin-walled transversally isotropic spherical shell under the external pressure and homogeneous heating in the framework of Timoshenko's model. The Winkler's model with the constant coefficient is used to describe the interaction between the shell and the filler. The heating of the filler is neglected and the assumptions of the local buckling theory are accepted. The various cases of the dependence of the critical loading parameter on the parameters of shear, heating and rigidity of the filler are studied. The results are presented in analytical and graphical forms. It is found, that during uniform compression of spherical shell the critical loading decreases with the increase of the temperature and shift. For the filler with the small stiffness the shift exerts main influence, for the higher stiffness the heating of the shell plays the main role. Wherein the increase of the stiffness of the filler the value of critical load may either increase or decrease depending on the interrelations of the parameters of shift and temperature.

ABSTRACT: Studies on the deformation behaviours of cellular entities, such as coated microbubbles and liposomes subject to a cavitation flow, become increasingly important for the advancement of ultrasonic imaging and drug delivery. Numerical simulations for bubble dynamics of ultrasound contrast agents based on the boundary integral method are presented in this work. The effects of the encapsulating shell are estimated by adapting Hoff’s model used for thin-shell contrast agents. The viscosity effects are estimated by including the normal viscous stress in the boundary condition. In parallel, mechanical models of cell membranes and liposomes as well as state-of-the-art techniques for quantitative measurement of viscoelasticity for a single cell or coated microbubbles are reviewed. The future developments regarding modelling and measurement of the material properties of the cellular entities for cutting-edge biomedical applications are also discussed.

ABSTRACT: In this paper the free vibrations and buckling analysis of laminated plates is performed using a global meshless method. A refined version of Kant’s theorie which accounts for transverse normal stress and through-the-thickness deformation is used. The innovation is the use of oscillatory radial basis functions. Numerical examples are performed and results are presented and compared to available references. Such functions proved to be an alternative to the tradicional nonoscillatory radial basis functions.

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Vu Thi Thuy Anh, Dao Huy Bich and Nguyen Dinh Duc, “Nonlinear stability of thin FGM annular spherical

ABSTRACT: To increase the thermal resistance of various structural components in high-temperature environments, the present research deals with nonlinear stability analysis of thin annular spherical shells made of functionally graded materials (FGM) on elastic foundations under external pressure and temperature. Material properties are graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Classical thin shell theory in terms of the shell deflection and the stress function is used to determine the buckling loads and nonlinear response of the FGM annular spherical shells. Galerkin method is applied to obtain closed – form of load – deflection paths. An analysis is carried out to show the effects of material, geometrical properties, elastic foundations and combination of external pressure and temperature on the nonlinear stability of the annular spherical shells.


ABSTRACT: The nonlinear stability of eccentrically stiffened functionally graded (FGM) annular spherical segment resting on elastic foundations under external pressure is studied analytically. The FGM annular spherical segment are reinforced by eccentrically longitudinal and transversal stiffeners made of full metal or ceramic depending on situation of stiffeners at metal-rich or ceramic-rich side of the shell respectively. Based on the classical thin shell theory, the governing equations of FGM annular spherical segments are derived. Approximate solutions are assumed to satisfy the simply supported boundary condition of segments and Galerkin method is applied to study the stability. The effects of material, geometrical properties, elastic foundations, combination of external pressure and stiffener arrangement, number of stiffeners on the nonlinear stability of eccentrically stiffened FGM annular spherical segment are analyzed and discussed. The obtained results are verified with the known results in the literature.


ABSTRACT: The paper investigates the elastoplastic buckling of thin circular shells subjected to nonproportional loading consisting of axial tensile stress and external pressure. The governing equations of buckling for cylindrical shells derived by Flugge serve as the basis of analysis. To capture the elastic/plastic behavior, two plasticity theories are considered; the flow theory and the deformation theory of plasticity. Plastic buckling pressures for cylinders with various combinations of boundary conditions are presented for which no analytical solutions are available. The results obtained from the flow and deformation theories confirm that, under over-constrained kinematic assumptions, the deformation theory tends to provide lower values of buckling pressure and the discrepancies in the results from the two plasticity theories increase with increasing thickness-to-radius ratios, tensile stresses, boundary clamping and E/σy ratios. The plastic buckling results obtained by means of the differential quadrature method are compared with carefully conducted FEA results for both the flow and the deformation theory of plasticity. The reasons underlying the apparent plastic buckling paradox are thus investigated for a vast class of boundary conditions and loads.
SUMMARY: The spherical shell is a typical form of revolution shells, which is widely used in pressure vessel and piping industry, nuclear power industry and ocean engineering for its specific structural shape to obtain kinds of performance. However compared to the cylindrical or conical shell, the spherical shell is mainly used as main structure or pressure hull in underwater engineering because of the superiority of theoretical solution and its manufacture. For the significance of the spherical shell, many researchers in the region of engineering and mechanics have spent great efforts to solve it and do lots of experiments in order to obtain its accurate theoretical analysis and design method as the engineering rule. To show the characteristics of a spherical shell with some initial imperfections, both material nonlinear and geometric nonlinear Finite Element Analysis (FEA) has been presented in this paper. In this presented Finite Element Method (FEM), the elastic-plasticity stress-strain relations have been adopted, and the initial deflection of spherical shell created by manufacture was also taken into account. It is shown that the nonlinear structural characteristics of the spherical shell vary from its different dimension parameters for initial imperfection through nonlinear FEM. Compared with the different rule’s methods, nonlinear FEM could exactly show sphere’s stability varying by initial imperfections. Then two experiments of spherical model, made by some high strength steel and with same sizes but different initial deflection, have been presented in presentation. The experiment results eventually indicate that the stability of a spherical shell varies by its initial imperfection and such sphere stability could not be accounted by currently rules except nonlinear FEM. It is essential to obtain the design method for spherical shell made by high strength steel used in deep sea vehicle and ocean engineering.

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(2) Institute of Applied Mechanics, Jinan University, Guangzhou, P.R. China
(3) Guangzhou Entry-Exit Inspection and Quarantine Bureau, Guangzhou, P.R. China
ABSTRACT: By means of the modified iteration method, the nonlinear stability problem of a double-deck reticulated truncated circular shallow spherical shell under uniform pressure was investigated. According to the fundamental equations of double-deck reticulated circular shallow spherical shells, the critical buckling load for the shell with two types of boundary conditions was obtained and the effect of geometric parameters of the shell on the critical buckling load was discussed.

ABSTRACT: In all aircrafts developed by Saab, the structure has to be designed in a way that minimizes weight. This often implies that thin structures are used, for example as machined frames. But, when using thin structures, there is always a risk of buckling. To prevent failure due to buckling, either a post-buckling analysis has to be performed or a non-buckling design has to be used. In order to have a quick and robust tool for a large number of linear buckling calculations, a buckling method for an in-house program has been developed in this thesis. The program handles arbitrary quadrilateral plates with different loads and boundary conditions. In the thesis, a new calculation method called BucklingMesh2D has been created in the existing Saab dimension program DIM that handles linear buckling problems with the Finite Element Method. The module includes a
graphical interface where the user can generate the desired geometry and connect it to a material as well as choosing boundary conditions and defining the element mesh. The loads can be defined using three different load groups with different complexity. The chosen elements are two shell elements, four-noded and eight-noded, called Quad4 and Quad8. Calculations with the Quad8 element generate results that are consistent with results from the FE program Nastran and the other buckling calculation method in DIM, which is not based on FEM. However, the Quad4 element implemented is not recommended to be used since it does not converge fast enough during refinement of the mesh. Investigations have been made to speed up the program code. As a result, superposition of the stress stiffness matrix and reducing sparse matrices are used. Even reduced integration of the stiffness matrix and the stress stiffness matrix has been analysed which produces trustworthy result and speeds up the calculations, compared to fully integration.

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ABSTRACT: When a spherical elastic capsule is deflated, it first buckles axisymmetrically and subsequently loses its axisymmetry in a secondary instability, where the dimple acquires a polygonal shape. We explain this secondary polygonal buckling in terms of wrinkles developing at the inner side of the dimple edge in response to compressive hoop stress. Analyzing the axisymmetric buckled shape, we find a compressive hoop stress with parabolic stress profile at the dimple edge. We further show that there exists a critical value for this hoop stress, where it becomes favorable for the membrane to buckle out of its axisymmetric shape, thus releasing the compression. The instability mechanism is analogous to the formation of wrinkles under compressive stress. A simplified stability analysis allows us to quantify the critical stress for secondary buckling. Applying this secondary buckling criterion to the axisymmetric shapes, we can determine the critical volume for secondary buckling. Our analytical result is in close agreement with existing numerical data.

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ABSTRACT: This paper presents effects of boundary conditions and axial loading on frequency characteristics of rotating laminated conical shells with meridional and circumferential stiffeners, i.e., stringers and rings, using Generalized Differential Quadrature Method (GDQM). Hamilton's principle is applied when the stiffeners are treated as discrete elements. The conical shells are stiffened at uniform intervals and it is assumed that the stiffeners have similar material and geometric properties. Equations of motion as well as equations of the boundary condition are transformed into a set of algebraic equations by applying the GDQM. Obtained results discuss the effects of parameters such as rotating velocities, depth to width ratios of the stiffeners, number of stiffeners, cone angles, and boundary conditions on natural frequency of the shell. The results will then be compared with those of other published works particularly with a non-stiffened conical shell and a special case where angle of the stiffened conical shell approaches zero, i.e. a stiffened cylindrical shell. In addition, another comparison is made with present FE method for a non-rotating stiffened conical shell. These comparisons confirm reliability of the present work as a measure to approximate solutions to the problem of rotating stiffened conical shells.

References listed at the end of the paper:
This paper focuses on an analysis of free vibration of thick rotating stiffened composite cylindrical shells with different boundary conditions. The analysis is performed on the basis of a three-dimensional theory by using the layerwise-differential quadrature (LW-DQM) method. The equations of motion are derived employing Hamilton’s principle. In order to accurately allow for the thickness effects, a layerwise theory is used to discretize the equations of motion and related boundary conditions through the thickness of the shells. Then, the equations of motion and the boundary conditions are transformed into a set of algebraic equations by using the DQM in the longitudinal direction. This study demonstrates the applicability, accuracy, stability, and fast rate of convergence of the present method in free vibration analyses of rotating stiffened cylindrical shells. The presented results are compared with those of other shell theories obtained by conventional methods and with a special case where the number of stiffeners approaches zero, i.e., an nonstiffened cylindrical shell, and excellent agreements are achieved. Finally, some new results are presented, which can be used as benchmark solutions for future investigations.

References listed at the end of the paper:


ABSTRACT: An approximate solution is presented to investigate the effects of thermal load on the frequency of ring-stiffened rotating FG conical shell. Material properties and the temperature field are assumed to be graded and varied in the thickness direction. The shell is reinforced by equal interval rings. The equations of motion are derived by the Hamilton's principle. Approximate analytical solutions are assumed to satisfy clamped boundary conditions and then Fourier decomposition and Galerkin method are applied to achieve relations of frequencies. To validate, the comparisons are made with a number of particular cases in literature and with the FEM solutions.


ABSTRACT: This paper provides a review of recent research advances and trends in the area of thin shell buckling. The application of thin-walled cylindrical shells, as the essential structural members, has been known for engineers and functional duty of them is basic necessaries of modern industries. These structures are mostly failing by buckling under external pressure. The Buckling load is usually the most used criteria in designing of a long thin shell. Although the buckling capacity of the shells is mainly depends on two geometric conditions i) ratios of "length to radius" (L/R) and ii) ratios "radius to thickness" (R/t), but the effect of thickness variation on the behavior of the shells is complicated to be studied. The effect of thickness variation and Conix angle on the buckling behavior of conical support of pressure vessel is investigated in this paper. Top end of the specimens has conical shape and the bottom end has simply supported conditions. The measured data and obtained results are reported for the specimens under the effect of axial compression. Each specimen has different variation in thickness. The study is carried out using finite element analysis. The widely implemented software ANSYS Workbench is used to perform the analysis.

References listed at the end of the paper:
1. Aghajari, S., Abedi, K., Showkati, H., “Buckling and post-buckling behavior of thin walled cylindrical shells with varying thickness subjected to uniform external pressure,” Thin-Walled Structures, 2006; 44; pp.904–909


ABSTRACT: We consider three variants of algorithms for studying the stability of thin-shell: An algorithm based on the Ritz method and iterative processes, an algorithm based on the method of steepest descent, the algorithm based on a method of extending the solution to the parameter. Analyzes the results of the study of shells produced using these algorithms.

DOI: 10.5829/idosi.wasj.2014.30.12.13981

ABSTRACT: The work investigates thin walled orthotropic shells. Their deformation model is built taking into account the geometrical non-linearity and transverse shifts. The investigation algorithm of this model is based on the Ritz method and the method of continuing solution employing the best parameter. This enables the study of strength and stability of the shells under consideration. For analysis of special points (upper and lower critical loads, bifurcation points) the Jacobian matrix of linear equation systems is used. Based on the developed algorithm, a software product is made. A study was carried out on the strength and stability of some versions of sloping shells from different types of carbon fiber-reinforced plastic. It has been shown that the loss of stability of thin-walled shells under consideration occurs before the strength is lost. The loss of strength in different shells takes place in different components of maximum tension. It was established that in case of a geometrically non-linear approach, the critical loads in the event of strength reduction are essentially lower than in case of the linear computing method.

References listed at the end of the paper:
John E. Theisinger and Dr. Robert D. Braun (Georgia Institute of Technology, Atlanta, Georgia, 30332-0150), “Multiobjective Hypersonic Entry Aeroshell Shape Optimization”, (publisher and date not given in the pdf file. Probably an AIAA paper presented at one of the Structures, Structural Dynamics and Materials Meetings. The most recent reference is January 2007.)

ABSTRACT: A capability has been developed that utilizes multiobjective optimization to identify hypersonic entry aeroshell shapes that will increase landed mass capability. Aeroshell shapes are parameterized using non-uniform rational B-splines to generate complete aeroshell surfaces. Hypersonic aerodynamic objectives and constraints are computed by numerically integrating pressure coefficient distributions obtained using Newtonian flow theory. An integrated optimization environment is created using iSIGHT with single- and multiobjective evolutionary algorithms. Results are presented based on optimization using constraints derived from the aeroshell for the Mars Science Laboratory mission. Resulting solutions clearly demonstrate the trade-offs between drag-area, static stability, and volumetric efficiency for this particular mission.

References listed at the end of the paper: (Cannot cut and paste them easily.)

Daniel Burmeister (Dept. of Mechanics, University of Miskolc, 3515 Miskolc-Egyetemvaros, Hungary), “Stability of a circular plate stiffened by a cylindrical shell”, PhD dissertation (date not given), University of Miskolc, Hungary

INTRODUCTION: In the engineering practice stability problems of plates loaded in their own plane are especially interesting ones. To the author’s knowledge paper [1, 1981] by Brian was the first one which dealt with the stability problem of a circular plate. Since then a number of papers have been devoted to this issue. Here we have cited only a few [2, 1933], [3, 1984] and remark that further references can be found in the papers cited.

A circular plate can be stiffened in various ways. For example we can apply a corrugation to it, or it can be stiffened by a cylindrical shell attached to the plate on its boundary. The present paper investigates the stability of a circular plate provided that the plate is stiffened by a cylindrical shell. This problem was partly solved by Szilassy [4, 1971], [5, 1976] who set up a differential equation for the rotation field and solved the corresponding eigenvalue problem under the assumption that the shell is subjected to a constant radial load in the middle plane of the plate. First we shall consider the governing equations of the stability problem if there is no stiffening. Then we shall clarify what conditions are to be satisfied on the circle where the middle surfaces of
the plate and shell meet. By solving the differential equations set up both for the shell and for the plate in terms of the displacements we derive a non-linear equation from the eigenvalue problem to be solved. We shall also present the results of our computations.

References listed at the end of the paper:


ABSTRACT: The present paper is concerned with the stability problems of a solid circular plate and some annular plates each stiffened by a cylindrical shell on the external boundary. Assuming an axisymmetric dead load and axisymmetric deformations we determine the critical load in order to clarify what effect the stiffening shell has on the critical load.

References listed at the end of the paper:

DOI: 10.4028/www.scientific.net/AMM.274.78
ABSTRACT: In this paper, the dynamical stability analysis of anisotropic cylindrical shells under uniformly distributed periodic extensional axial force is presented, while the winding angle varies. Fiberglass reinforced plastic is considered as a homogeneous solid anisotropic material. The shell’s elastic properties depend on the winding angle of fiberglass. The effect of the winding angle on the critical axial force is investigated. The intervals of winding angles at which the parametrically unstable vibration happen are determined.

Some University of Cambridge, School of Engineering, Structures Research Group (CUSRBG) Ph.D. Dissertations Relating to Buckling of Beams, Plates and Shells (http://www-structures.eng.cam.ac.uk/pubs/phd):

Mark Shenk, “Folded shell structures”, Ph.D. dissertation University of Cambridge, August 2011

ABSTRACT: A novel type of shell structure was analysed, folded shell structures. These shell structures have a distinct structural hierarchy: globally they can be regarded as thin-walled shells, but at a meso scale they consist of tessellated unit cells, which in turn are composed of thin-walled shells joined at distinct fold lines. It is this structural hierarchy that imbues the folded shell structures with their interesting mechanical properties. The global sheet deformations are a combination of bending along the folds, and deformation of the interlying material. The former is primarily a kinematic problem, with a parallel in the flexibility of hinged plate structures. A review of the mathematics of rigid origami provides the necessary background to develop non-trivial geometries of these folded shells that still exhibit a soft deformation mode. Two example folded shell structures are introduced, the Miura and Eggbox sheet. Both consist of a tessellation of parallelogram facets; the first is developable, while the other has points of positive and negative Gaussian curvature. The first property of interest is their increased in-plane flexibility, by virtue of the opening and closing of folds. The Miura and Eggbox sheet respectively have an effective negative and positive in-plane Poisson’s ratio. Secondly, both sheets can modify their global Gaussian curvature, with no stretching at the material level. Thirdly, both sheets exhibit an oppositely signed Poisson’s ratio for in-plane and out-of-plane deformations; e.g. when bending the Miura sheet it exhibits a negative Poisson’s ratio behaviour and deforms anticlastically. The salient global deformations of the sheets were analysed in terms of the kinematics of the constituent unit cells. The characteristic in-plane and out-of-plane properties of the sheets followed directly from developable deformations of the tessellated unit cells. A more holistic top-down numerical approach modelled the sheets as an array of unit cells. The sheets were represented by a pin-jointed bar framework, and additional planarity constraints between facets enabled the inclusion of a bending stiffness for the facets and fold lines. A modal analysis of the sheet’s stiffness matrix showed that the characteristic deformation modes are among the dominant eigenmodes of the sheets for a wide range of geometries and material properties. Many folded shell structures can be folded from flat sheet material, with only minimal material deformations. The manufacturing processes must overcome the intrinsic kinematics of the sheets, whereby the sheet contracts in two directions simultaneously. Existing methods were reviewed, and classified into synchronous folding, gradual folding and pre-gathering techniques. A novel cold gas pressure manufacturing method was introduced, and it was shown that a simple plastic hinge model cannot yet fully account for the total required forming energy.

References listed at the end of the dissertation:


Shtampovocha Proizvodstvo (Obrabotka Metallov Davleniem), 17–24.
Miura, K. (1972). Zeta-Core Sandwich-Its Concept and Realization. ISAS Report, 37, 137–164, institute of Space and Aeronautical
Science, University of Tokyo report, no 480.


V. R. Seereeram, “Compliant shell mechanisms and inextensional theory”, Ph.D. dissertation University of Cambridge, November 2012
ABSTRACT: Compliant shell mechanisms are a new class of lightweight structures, comprising discrete shell elements interconnected along hinge-lines. They undergo large changes in overall shape by deforming between, and by articulating about, these hinge-lines, and promise to offer novel solutions for reconfigurable structures such as morphing shells and deployable membranes. This seminar will focus on characterising the behaviour of one type known as a curved corrugated shell. Despite its simplicity, it displays a remarkable range of deformation in the global sense, including coupling between extension and bending as well as changes in Gaussian curvature. Locally, it may be assumed that the shell deforms inextensibly, in order to permit a tractable framework for capturing the overall kinematics and for modelling the load-displacement response. This will be demonstrated for a variety of deformed shapes and will be validated by finite-element analysis and experimental methods.

(http://www-structures.eng.cam.ac.uk/phdabs/wrinkling-in-polygonal-membranes-1)
ABSTRACT: Larger telescopes are required by astronomers to see further into the depths of our Universe, in order to understand its origins and the origins of life. A solution is to replace conventional primary mirrors in space-telescopes by membrane reflectors that can be folded and fitted into a spacecraft before launch. Once deployed, the membrane would provide a large reflective surface necessary to obtain images of faraway celestial objects. Whilst the primary mirror of a space-telescope needs to have a very precise shape, membranes can have an uncertain shape for they are prone to wrinkling. For this reason, there is hesitation in using these structures for telescopes, as the technology needs to mature. In this thesis, regular polygonal membranes tensioned at their vertices are proposed as reflectors; their discrete nature necessitates a lighter support structure compared to circular membranes. Analysis has been made to assess the effect of the wrinkling in these polygonal membranes, where the primary focus has been on nominally flat membranes, alongside parabolic membranes. The area of reflectance of the membrane must be maximal and it is vital to mitigate wrinkles. In this thesis, the origins of the wrinkles are investigated and two novel stress analysis methods for polygonal membranes are developed initially. The first uses Airy stress functions: by superposing a number of these functions, and deriving from it a solution for a free body disk, the stress field of a polygon is approximated with a high degree of accuracy both in terms of distribution and magnitude. The second method uses the analogy of the governing equations of in-plane stresses and of curvatures in the shallow bending of plates. The solution produces the shape of stress fields accurately. The results from these two distinct methods have been validated using Finite Element Analysis (FEA) and, together, they conclude that compressive regions are located close to the corners of all regular polygons, no matter the number of sides. This information is used to develop a method to prevent compressive stresses in membranes; furthermore, the analogy is adapted to show that with a given amount of edge trimming, the tensioned membrane does not produce any compressive stresses and this is confirmed in practise. The minimum amount of trimming required is derived for any regular polygon.

Long, Q, 2010, “Subdivision finite elements for geometrically complex thin and thick shells”
(http://www-structures.eng.cam.ac.uk/phdabs/q-long)
ABSTRACT: The thesis deals with non-smooth and non-manifold subdivision finite elements for general shells and corresponding applications. In the presented approach subdivision surfaces are used for geometric modeling as well as mechanical analysis of shells. The key motivation for performing finite element analysis of the “exact
geometry” provided by subdivision models is the promise of side-stepping the error prone and often user guided generation of finite element meshes. The use of the same shape functions also enables rapid data exchange between design and analysis models, which is, for instance, crucial to design optimisation. The subdivision approach is powerful technique for generating smooth surfaces on arbitrary connectivity meshes. An important feature of the subdivision shape functions is that each shape function reaches beyond the element boundaries with which it is associated. As a result, the enforcement of boundary conditions and the treatment of non-manifold shell geometries are more difficult that the conventional Lagrangian or Hermit-type finite element shape functions. This thesis systematically develops methods for subdivision shells with non-smooth and non-manifold geometries. The introduced methods generalise the original subdivision shells and enable their application to industrial strength geometries. The developed techniques include a new strategy to extract shape functions from highly irregular mesh topologies, control of surface normal at the domain boundaries and corresponding data structures in object oriented C++. As a result, it is possible to exactly discretise shell geometries with intersections and non-smooth features. The developed non-smooth subdivision shells are applied to thin-shell fracture and fragmentation. The original approach of embedding cracks in a shell discretised with subdivision shape functions relied on the introduction of cracks between all element edges with the attendant duplication of mesh entities and high memory usage. The new strategy adaptively introduces cracks along the physical crack path and hence considerably reduces the number of the degrees of freedom.

Norman, A., 2009, “Mulktistable and morphing corrugated shell structures”
ABSTRACT: (cannot cut and paste)

Xu, Y., 2008, “A computational study of lobed balloons”
ABSTRACT: (cannot cut and paste)

Pagitz, M., 2008, “Analytical and numerical studies of superpressure balloons”
http://www-structures.eng.cam.ac.uk/phdabs/Markus%20Pagitz.pdf
ABSTRACT: (cannot cut and paste)

Ye, H., 2007, “Bistable cylindrical space frames”
http://www-structures.eng.cam.ac.uk/phdabs/H%20Ye.pdf
ABSTRACT: (cannot cut and paste)

http://www-structures.eng.cam.ac.uk/phdabs/S%20D%20Waller.pdf
ABSTRACT: (cannot cut and paste)

ABSTRACT: (cannot cut and paste)

Schioler, T., 2005, “Multi-stable structural elements”
http://www-civ.eng.cam.ac.uk/abstract/schiolerabs.html
ABSTRACT: This dissertation considers a number of concepts for discretely stable structural elements. All of the concepts can be manufactured entirely out of non metallic components and have no sliding parts. A review
of current manipulator designs, possible actuation technologies and the expected requirements of discretely stable structural elements is made. Discretely stable structural elements are found to have possible applications in serpentine manipulators and variable geometry trusses. Two concepts for discrete rotation elements suitable for serpentine manipulators are presented. One is based on hoops of five non-linear springs, whilst the other is based on a modification of an existing rolling hinge design. An analysis predicting the maximum stresses developed in this modified hinge is presented. Four concepts for linear bistable elements are also presented, along with analytical and experimental results for the behaviour of each. Three of these are based on non-linear springs, whilst the fourth is based on inverting pairs of shallow arches. Out of the four, the most promising were found to be a design based on a four bar linkage with tape springs connecting opposing corners, and a design based on shallow arches. Prototypes of the latter concept were developed, with research presented on possible variations in design and manufacturing technologies, as well as the material behaviour of nylon 6/66. Analytical tools partly based on an extension of the classical elastica analysis are developed to predict the behaviour of the design. Results obtained using these tools agreed relatively well with results obtained from finite element analyses and experimental data. A variable geometry truss incorporating thirty variable length elements was designed and built after research into the most suitable truss architectures had been completed. This truss is shown to behave much as predicted by analytical tools, and serves to demonstrate the possibilities offered by the use of discretely stable structural elements.

Farmer, S.M., 2004, “Large-displacement buckling of centrally loaded simply supported circular plates”
http://www-civ.eng.cam.ac.uk/abstract/farmerabs.html

ABSTRACT: The surface of a thin sheet (of paper or any other material) which has been crumpled can be seen to be covered by a series of high-curvature ridges that meet at sharp points. Indeed, the Föppel-von Kármán (FvK) equations for the large-displacement of a thin elastic sheet predict just such a geometry; and they also show that the point-like regions have the geometry of a so-called ‘developable cone’. ‘Developable Cones’ can be isolated and studied in detail by the application of a central point load to a flat circular plate resting on a circular support. The plate is seen to buckle, with the post-buckled plate containing two distinct regions. First, due to the fact that bending a thin plate is ‘easier’ than stretching it, a region of the plate lifts off the support to form a large buckle. Second, the remainder of the plate forms a shallow conical region. The post-buckled geometry is developable everywhere except in a small crescent-shaped region at the centre of the plate, where a combination of bending and stretching occur. We have studied experimentally the geometry of ‘developable cones’ in both the elastic and elastic-plastic regimes. Subsequently, a finite-element analysis has been conducted for similar plates to the experiments, and shown to give corresponding results. It has then been used to extend both the range of the geometry and the material properties of the plates considered. Hence, empirical relationships have been derived between measurable plate parameters to describe the geometry of ‘developable cones’. In particular, the crease which separates the buckled and conical regions of a deformed plate which is best described as a curve on the plate in its initial, flat configuration – here called the Flattened Curve - has been shown to be approximately stationary on the surface of the plate, apart from in the region of its apex where its geometry changes a little as the deformation proceeds. Also, the regions of highest energy density and stress have been found to be concentrated along the ‘flattened curve’ and along the ridge that runs from the centre of the plate to its edge along the centre of the buckle. Furthermore, analytical models have shown that the stretching and bending behaviour of the crease in the apex region is analogous to the ‘knuckle’ found in an inverted sphere. Thus, using simplified models for the buckled geometry of a plate the energy of the crease has been found; and by a balance of this energy with the bending energy in the remainder of the plate, an empirical relationship between the central force and the deformation of the plate has been found that agrees with the experimental and numerical results.
ABSTRACT: Wrinkling of thin membranes due to different in-plane loading and boundary conditions has drawn a lot of attention among researchers in the field of structural engineering since the development of tension field theory for the designs of thin webs for early aircraft structures. More recently, prestressed lightweight membrane structures have been proposed for future space missions, for example solar sails, the Next Generation Space Telescope sunshield and some space-based radar systems. These structures are often partially wrinkled during operation. The formation of wrinkles alters the load paths and structural stiffness of the membranes. More importantly its occurrence degrades the surface accuracy of these structures, which is a key design parameter. This dissertation provides two methods to predict the details of wrinkles, namely wrinkle wavelength and amplitude in these membrane structures. Both of these proposed methods exploit the key observation, shown by physical models, that the main parameter which governs the wrinkle details is the bending stiffness of the membrane. The first method models the membrane using thin shell elements available in the commercial non-linear finite element code ABAQUS. The analysis uses a buckling prediction analysis to obtain the initial imperfections that, once introduced in the structure, would induce the formation of wrinkles. This analysis predicts the final wrinkle shapes and the out-of-plane deformation of the membrane, which quantify the wrinkle details. Compressive stresses are allowed to develop in this model. A simple analytical wrinkle model is the proposed second method, based on the assumption that a membrane is able to resist a small compressive stress once it has wrinkled. This critical wrinkling stress is a function of the bending stiffness and wrinkle wavelength. The wrinkle amplitude can be predicted by considering the total strain in the membrane, as the sum of two components, a material strain and a wrinkling strain.

Two membrane structures subjected to in-plane loads are investigated. The first structure is a classical rectangular membrane under shear. The second structure is a square membrane loaded with tension forces at its four corners. In the first case, the wrinkle pattern consists of primarily of wrinkles at 45 degrees and the state of stress in the membrane can be readily determined by tension field theory. The predicted wrinkle wavelength is inversely proportional and the amplitude is directly proportional to the imposed shear angle. In the second case, two wrinkling regimes are identified by varying the corner load ratio. The first regime occurs for symmetric and moderately asymmetric loading; it is characterised by small, radial corner wrinkles. The second regime occurs for strongly asymmetric loading with the formation of a single, large diagonal wrinkle in addition to small radial corner wrinkles. Several simple equilibrium, no-compression stress fields are proposed to capture the behaviour of this wrinkled membrane. Analytical solutions for predicting the wrinkle details are hence derived. The analytical predictions are validated against experimental measurements and detailed finite element simulation results. It is shown that thin shell finite element simulations can provide very detailed and accurate predictions of wrinkle details, although they are computationally expensive. The simple theory provides an alternative solution to obtain this information and is useful for preliminary design of thin membrane structures.

http://www-civ.eng.cam.ac.uk/abstract/lennonabs.htm
ABSTRACT: A lobed parachute with meridional cords adopts a shape where the cords take the shape of the isotensoid curve. The isotensoid is the three dimensional surface that has zero hoop stress and carries load only in the meridional direction. This dissertation investigates the equilibrium and stability of inflated membrane structures. Structures that adopt the shape and the isotensoid curve are of particular interest. It is shown that the isotensoid has two forms, the existing axisymmetric form and a polygonal form that is introduced in this dissertation. It is shown analytically that both forms are in equilibrium and these results are supported by finite element analyses. The inflated shape of these structures depends on stability considerations in addition to the equilibrium requirement. The potential energy for inflated structures is proportional to the negative of the
enclosed volume hence the configuration with the largest enclosed volume will be the most stable configuration. Two example problems show the importance of stability considerations in inflated membranes. The first example concerns the stability of a membrane structure, such as a “pumpkin” balloon, with longitudinal lobes separated by load bearing meridional cords in the shape of isotensoid curves. A deformation mode is postulated and calculations show that structures in this mode can have a larger enclosed volume than structures in the nominal configuration. The relationship between the volumes in the normal and deformed configurations depends on the lobe size and the number of lobes. The volume initially decreases with increasing perturbation size, showing that the nominal configuration is stable for an infinitesimal perturbation. However, for large numbers of lobes only a small perturbation is required for the deformed configuration to be more stable than the nominal configuration. The second example concerns the inflated shape of a structure made from two identical, circular membrane sheets, joined along their edges. The final shape of the structure approximates a polygonal isotensoid in the region away from the apex, with excess material forming folds which separate the sides of the isotensoid. It is shown that the polygonal isotensoid with the minimum number of sides encloses the maximum volume hence is the most stable. This surface requires more material than an axisymmetric isotensoid, which is provided by the membrane pulling inwards during inflation. Elastic stretching near the apex limits the size of the polygonal isotensoid and a geometric constraint at the transition to uniaxial stress can be used to impose a limit on the minimum number of sides of the isotensoid, hence determining the number of folds. Finite element analyses are used to support the work on the shape of the inflated membrane. These analyses confirm the expected shape and the stress distribution in the inflated membrane. Additional analyses are used to study the radius of the transition which is used in conjunction with the method for predicting the number of folds.

http://www-civ.eng.cam.ac.uk/abstract/aberleabs.htm
ABSTRACT: The low shear stiffness of certain gridshells can result in a different behaviour than that generally observed for shell structures. This thesis investigates the nonlinear behaviour of such shear-weak gridshells. The current methods of analysis of these structures are reviewed and the importance of various parameters on their pre- and post-buckling behaviour is studied. To model the individual gridshell members, new stability functions and bowing expressions that allow for the effect of axial loads on the bending stiffness and the change in effective axial stiffness due to bending moments, are derived and verified by numerical and experimental studies. These new formulations, based on power series, are applicable for any degree of shear stiffness and any axial load. This is followed by the presentation of a solution procedure, which combines the Dynamic Relaxation method with different iteration control procedures. The new element formulations, together with the proposed solution procedures are implemented into an essentially new computer program. This program is verified against examples found in the literature, and by comparison with the results obtained from buckling experiments conducted on a 1.2m span gridshell model made of thermoplastic polyester. The program is then employed to assess the post-buckling behaviour of a 12m span shear-weak gridshell model built in Japan, and the results are compared to the available experimental values of this structure. The study indicates that the limit load along with the imperfection sensitivity, and the sensitivity to asymmetric loading of gridshells are directly dependent on their in-plane and out-of-plane shear stiffnesses, and also on the size of the loaded area.

Galletly, D., 2001, “Modelling the equilibrium and stability of slit tubes”
http://www-civ.eng.cam.ac.uk/abstract/galletlyabs.htm
ABSTRACT: A novel shell structure, a bi-stable composite slit tube, is presented. This structure is formed like a coilable tape measure; unlike tape measures, however, it is stable in both the extended form and the coiled form, without any need for a spindle or casing to hold it in either position. The structure is initially modelled linearly, as a beam. Various applications of this model are presented: an algorithm for rapidly locating the
second equilibrium point, the investigation of the strain state as the path is followed from one equilibrium state to the second, and generalised plots throughout longitudinal curvature--transverse curvature space. Various examples (two composites with layups which are anti-symmetric about the middle layer, one which is symmetric about the middle layer, and an isotropic case) are presented. The inability of this model to determine the stability of an equilibrium is noted, as the results for the anti-symmetric and symmetric cases appear to be similar, whilst their experimental behaviour is very different. The model is then extended to incorporate non-linear geometric effects, and stability criteria are determined. The examples considered for the original model are re-evaluated using the new model; the equilibrium locations for the anti-symmetric and isotropic cases are found to be unchanged, whilst the symmetric case develops more twist. The stability of the anti-symmetric layups, and the instability of the symmetric layup and the isotropic case, are accurately predicted. The structure is then modelled as a shell of arbitrary cross-section. An expression for this cross-sectional shape is derived, and the same examples once again examined. The stability of the anti-symmetric layups, and the instability of the symmetric and isotropic cases, are again predicted correctly. The constant transverse curvature assumption of the extended beam model is found to be valid for cross-sectional angles greater than about 180 degrees. Various reasons for the disparity between the experimental and theoretical results are then investigated, including inaccuracies in the material properties and inelasticity in the matrix. It is thought that matrix inelasticity is the cause of the difference and initial results to support this are presented.

http://www civ.eng.cam.ac.uk/abstract/kimabs.htm
ABSTRACT: (page not found)

Bulbul, M.Y.I., 1999, “The geometric nonlinear behavior of spade structures with imperfect laterally loaded slender members”
http://www civ.eng.cam.ac.uk/abstract/myibabst.htm
ABSTRACT: Imperfections in geometric nonlinear reticulated space structures can have significant effects on their stiffness characteristics and load carrying capacity. These imperfections can be defined as deviations from the theoretical node geometry of the structure or imperfections within the length of the elements spanning between these nodes. An analytical model is presented by which the spatial behaviour of a beam-column element with an initial sinusoidal profile supporting a lateral load of general triangular distribution along its length is described. Nonlinear force-deformation equations are developed in the natural coordinate system of the element based on the conventional beam-column theory. A tangent stiffness matrix consistent with the equilibrium equations is also derived. Using a Eulerian frame of reference, appropriate transformations are employed to express the derived quantities in the fixed global coordinate system allowing for large displacement and rotations in the structure. The beam-column formulations are implemented in a geometric nonlinear analysis program, developed by the author, using an incremental iterative algorithm based on automatic load incrementation in a modified version of the arc-length method. A general stability analysis is incorporated in the program, based on a consistent tangent stiffness matrix formulated at each successive equilibrium state. The numerical algorithm developed is applied to the analysis of four 1000mm-span reticulated shallow domes tested by the author for various lateral load configurations. These included a uniform pressure loading designed to emulate the triangular distribution of lateral loading along the elements length expected in full size structures. Using the as-built geometry, good agreement between the numerical predictions and the experimental results was obtained for the cases of vertical nodal loading as well as the pressure loading.

King, S.A., 1999, “Nonlinear and chaotic dynamics of thin-walled open-section deployable structures”
http://www civ.eng.cam.ac.uk/abstract/kingabst.htm
ABSTRACT: This dissertation studies the behaviour of straight, thin-walled shell-beams with a curved cross-section, or "ribs". Recent proposals for the design of large deployable structures exploit the structural simplicity and robustness of ribs as deployment actuators on spacecraft. Under dynamic loading, the low torsional rigidity of ribs, however, may cause coupling between flexural and torsional modes of vibration. Modal interactions of this type, which exhibit an energy-transfer from one mode to another, can be many orders greater than the magnitude of input excitation and may lead to catastrophic failure of the structure. An identification and prediction of nonlinear dynamic effects in ribs is critical to ensure that excessive vibrations do not compromise their performance. This dissertation describes research into the nonlinear dynamic behaviour of cantilevered ribs subjected to sinusoidal base excitation. Regions of nonlinear resonance with single- and multi-mode periodic and aperiodic responses are studied. A finite-element model is developed to predict natural frequencies and mode shapes, to investigate flexural and torsional buckling, to characterise geometric nonlinearities quantitatively, and to simulate nonlinear dynamic behaviour at primary resonance. A series of ribs were constructed and tested to validate the results from the finite-element model and to establish three different types of energy-transfer between modes. These include subharmonic resonances, combination resonances and nonresonant interactions between widely separated modes. It was found that subregions of some nonlinear resonance zones exhibit aperiodic motion. Lyapunov exponents and correlation dimensions are used both to characterise the observed aperiodic motion of the ribs and to establish whether chaotic motion exists. Correlation dimension estimates show, in conjunction with dimension theory, that the bending-torsional instability is low-dimensional and that it can, in principle, be modelled with as few as two or at most three degrees of freedom. An algorithm is developed to calculate the moment-curvature relationships from the axis of a flexible rib, whose deflected shape has been determined from the finite-element model. These relationships are used with analytical expressions to derive the strain energy in the rib. A two-degree-of-freedom analytical model of the dynamic system is developed using Lagrange's equations and the assumed-modes method. The resulting equations of motion are integrated numerically to investigate the possible complexities in the system response.


http://www-civ.eng.cam.ac.uk/abstract/milesabs.htm

ABSTRACT: Subsea oil and gas exploration is increasingly moving into deeper water, where trenching of a pipeline for protection and to mitigate against upheaval buckling becomes increasingly impractical. In addition, the exploration of new reservoirs at higher temperatures and pressures than before leaves a submarine pipeline on the seabed more susceptible to lateral thermal buckling. A novel small-scale compressible base model, with an expanded polystyrene base compressed beneath a silicone rubber strip, has been developed to represent the constrained thermal loading of a pipeline lying on the seabed. This physical model is used, in addition to a nonlinear finite-element analysis, for a case study of a real buckled pipeline. Dimensional analysis is used to provide a means of comparing the post-buckled behaviour of the model strip with that of the full-size pipeline. There is good agreement between the results of the post-buckled behaviour for the physical and finite-element models, and these results compare well with the survey data for the buckled real pipeline. General results from the physical model are also presented for strips with differing geometric and material properties, laid both straight and on a scaled lay-away curve. A useful measure of the evolution of a buckle, the free end
displacement is introduced. This is the axial displacement of the free end of a cut pipe, constrained to remain straight while undergoing thermal loading. This measure used in a study of the parameters which affect the far-post-buckling behaviour of a beam on a frictional foundation. The phenomenon of buckle lobe extinction, when a buckle lobe stops growing, is discovered for certain combinations of beam bending stiffness, axial friction coefficient and lateral friction coefficient. When the buckle length, buckle amplitude and free end displacement are formed into non-dimensional groups with these three parameters, curves for many parameter combinations are found to fall onto a single curve. The conditions for buckle lobe extinction, in terms of these dimensionless groups, may be determined directly from this universal curve. Finally, the closely-related problem of the stability of a pipeline being built up a slope is investigated. A case study is made of a real pipeline, incorporating numerical and physical models and also a simplified analytical model. These models correlate well with each other, and enable the conditions for collapse of the real pipeline to be predicted.

http://www-civ.eng.cam.ac.uk/abstract/memeabs.htm
ABSTRACT: The focus of this dissertation is the small free vibration of thin elastic hyperboloidal shells of revolution, which are often used as cooling towers in thermal power stations. The aim of the present study is to obtain a comprehensive understanding of such phenomena, in order to develop design charts that map the different regimes of structural behaviour of these shells. The work begins with the simpler case of the cylindrical shell and encompasses tests on a range of simplified models that have been proposed in the literature, but which have not been assessed thoroughly hitherto. A first-order approximation theory for the analysis of cylindrical shells has been developed. The proposed theory aims to bridge the gap between the classical Love-Kirchhoff theory, which permits an accurate description of the shell behaviour, and the simplified version of Vlasov which only considers the effects of longitudinal stretching and circumferential bending. A direct analogy is established between the shell behaviour and the behaviour of a Timoshenko beam mounted on a Pasternak foundation. Approximate explicit formulae are derived for the fundamental frequency of the beam-foundation system, and by analogy for the shell. Criteria defining the domains of validity for the proposed theory are established. Attention is then turned to shells with slightly curved meridians (waisted, nearly-cylindrical shells) and finally to hyperboloidal shells, both of which exhibit various complex degenerate-case effects. A simple model of waisted, nearly-cylindrical shells demonstrates cross-over phenomena when geometric parameters are varied. Further investigation shows that these phenomena are replaced by curve-veering when a more accurate shell model is used. Hyperboloidal shells predominantly demonstrate curve-veering phenomena, however there are particular geometries at which cross-over occurs. Most of the above phenomena are dominated by membrane effects. The sensitivity of these phenomena to the shell geometric parameters is examined and explained in simple terms. An experimental investigation, using a small-scale silicone rubber model shell, confirms some main points of the analysis.

Parthasrathi Mandal, 1997, “Buckling of thin cylindrical shells under axial compression”
http://www-civ.eng.cam.ac.uk/abstract/mandalabs.htm
ABSTRACT: Thin-walled cylindrical shell structures are widely used in many industries. Due to the increasing use of high-strength materials in construction, and optimisation methods in analysis, the design of such structures is often buckling-critical. Unfortunately, the theoretical predictions (by classical theory) for buckling loads are often much higher than those found from experimental studies conducted since the 1930s. Moreover, there is large scatter of the experimental buckling loads of identical specimens, tested in a similar fashion. The concepts of non-linearity and imperfection-sensitivity are widely accepted as explanations for these features of shell buckling. Some simple experiments on self-weight buckling of thin, open-top, fixed-base, small-scale silicone rubber cylindrical shells are presented in this dissertation. The thicker shells buckled at almost the
heights predicted by the simple classical theory. But in general the buckling heights were found to be proportional to thickness raised to the power of approximately 1.5 compared to 1.10 as in the classical theory. Moreover, the results showed very little scatter, although there was no conscious attempt to manufacture very accurate shells, and indeed, there were measurable imperfections in terms of thickness variations. These observations somehow defy the accepted hypothesis of imperfection-sensitivity. Much of this dissertation reports various attempts to resolve this paradox. The most successful of these involved a non-linear finite-element analysis, which showed that there is post-buckling plateau load corresponding to the experimental buckling loads. Although no formal explanation of this plateau load is presented here, the recurrence of this feature for more than one shell suggests that the post-buckling, unusually is something like a classical phenomenon, in the sense that there exists a plateau load much like the eigenvalue predictions of classical theory, and with small scatter. In an attempt to find out the relationship of our experimental results to the vast experimental data in the literature, it was found out that the slope of the best-fit line through the large quantity of test data in the literature has also a slope of approximately 1.5. However, the scatter in the literature data is much greater than in the present experiments. The most obvious explanation of the difference is that the open-topped shells in the present study are statically determinate, whereas the usual closed-ended shells used in the tests in the literature are statically indeterminate: the possibility of high initial stresses, may explain the scatter.

http://www-civ.eng.cam.ac.uk/abstract/kasabs.htm

ABSTRACT: Tape-springs are straight, thin-walled strips with a curved cross-section. Following recent proposals for large deployable structures exploiting the structural simplicity and robustness of such springs as deployment actuators, this dissertation begins by investigating the formation of elastic folds in a tape-spring. It is shown that the spring deforms by forming an elastically deformed region with zero transverse curvature and uniform longitudinal curvature. It is also shown that the process of formation and growth of elastic folds belongs to a wide class of propagating instabilities. It is characterised by a high peak moment and a lower propagation moment. A compact characterisation of the moment-rotation relationship for an elastic fold is presented. A key feature is that the bending moment on either side of a fold located anywhere along a uniform tape-spring, but far away from the ends of the spring, is constant, whereas this moment increases near a rigid support. Compact and accurate two-dimensional theories are developed to simulate the self-actuated deployment of tape-springs that are either coiled around a circular hub, or folded into a zig-zag pattern. It is shown that conservative energy formulations are appropriate for coiled springs, where the velocity field is smooth, but not for springs with localised folds. To simulate the motion of such localised folds a non-conservative impulse-momentum formulation is proposed, and it is found that this model can accurately predict both the steady motion of the folds along the tape-spring and their rebound against the end supports. The use of tape-springs in deploying a panel of similar inertia properties to an actual satellite radar panel is investigated. Deployment of the panel to approximately its intended configuration is governed by the value of the fold propagation moment in the tape-spring, whereas the high peak moment controls “locking out” of the panel; the velocity field of the deploying springs is similar to that of self-actuated coiled tapes. It is demonstrated, by theory and experiment, that mounting tape-springs in pairs, with their centres of curvature in opposite directions, results in an energy well which traps the kinetic energy of the panel on lock-out. The panel does not overshoot its fully deployed configuration and collision with other parts of the spacecraft is thus prevented. Disturbing torques applied by the panel to the spacecraft can also be computed.

http://www-civ.eng.cam.ac.uk/abstract/holstabs.htm
ABSTRACT: More than a hundred years after the publication of Love's seminal paper on the vibrations and deformation of a thin elastic shell, engineers, scientists, and mathematicians continue to struggle with some of the more complicated issues relating to such structures, despite the advent in recent years of extremely powerful computers and appropriate software. In particular the buckling of cylindrical shell structures under axial loading has received a great deal of attention since the turn of the century. This case has been addressed from a number of different points of view. However, none of these have yielded wholly satisfactory solutions to the stability problems faced. In this thesis a new approach is proposed for analysing some of the more challenging examples relating to shell buckling. It is suggested that a careful examination of a heavily deformed shell structure in the post-buckling regime - and the processes leading up to this state of deformation - will establish some of the principles involved in its loss of stability. The complex deformation patterns observed experimentally after buckling may be reduced to a much more elementary description consisting of inextensional and transitional regions. Hence in this dissertation two relatively simple shell inversion problems exhibiting corresponding representative features are studied in detail. Experiments investigating the inversion of a cylindrical shell under a radial point load are outlined. Due to a free boundary large elastic inextensional deformations may occur. Some straightforward empirical formulae are found that well describe the characteristics of the deformed geometry; and the applied load is established as a function of the deformation. The inversion of a spherical shell under a radial point load is considered as a means of examining some of the basic features observed in the experiments performed, whilst eliminating the complexities arising from the lack of symmetry in the cylindrical case. A 'simple model' is detailed which clearly highlights the major components of the total strain energy of the deformed surface and their origin. A number of formulae are found that relate the loading and peak stresses to the radial displacement under the load. The results from this model are confirmed using a finite-element analysis, which also provides a more comprehensive description of the overall stress state of the shell. The finite-element method is likewise applied to the case of the cylindrical shell as an extension of the experiments. Findings from the latter are employed to confirm the validity of the numerical analysis. A detailed account is given of the distribution of stresses and strains over the deformed surface; and the similarities with the case of the spherical shell are outlined. Finally, an analytical model is established for the case of the cylindrical shell using the empirical formulae. The derivation of a condensed expression (Equation 6.61) for the total strain energy is presented. It is shown that the model represents well the relevant data obtained numerically. Notably, it is discovered that the two terms of Equation 6.61 correspond to the two most prominent regions of the deformed shell surface.

http://www-civ.eng.cam.ac.uk/abstract/erlabs.htm

ABSTRACT: Mechanical damage to oil and gas pipelines is considered to be the most serious cause of in-service failures in real pipelines. Damage in the form of combined dents and gouges may be of arbitrary shape and size and has from time to time resulted in failures at very low pressures. Full size experiments on pipes with dents and gouges have identified dent size, gouge size and pipe material fracture toughness as the main factors which influence failure. These tests have however exhibited much scatter. This experimental study has focused on understanding the problem through small-size testing on model pipes. An experimental model material was selected and pipe dimensions were carefully scaled to ensure that the small-size pipe was an exact model of a real pipeline. Damage was also appropriately scaled but cracks were specifically excluded. Model testing concentrated on 'short dents'. The gouge length, gouge depth, dent depth, gouge position and gouge orientation were varied extensively. A few tests were carried out with dents formed under non-zero pressure. Tests showed that the position of the gouge relative to the dent, and the gouge depth are the most relevant parameters affecting failure pressures. Zones of high straining were identified using photoelasticity and strain gauging. The off-centre and long gouges which failed at low pressures were observed to pass through these regions of high
straining. Nonetheless, failures occurred at pressures generally higher than those observed in full-size tests and very little scatter was observed. From comparison of the full-size and small-size tests, the importance of initial cracks was established. Cracks are now believed to be responsible for the transition from a stable yielding type failure to a fracture dependent type failure in combined dent and gouge defects resulting in low pressure failures. The Battelle Flow Stress Dependent Model for gouges of infinite length has been shown to be the best method for predicting failure in pipes with short central axial gouges. Model testing, using an equivalent pipeline steel and the correct D/t ratio, is the cheapest known method of determining burst pressures and understanding the behaviour of pipes containing dents and gouges.

Maltby, T.C., 1993, “The upheaval buckling of buried pipelines”
http://www-civ.eng.cam.ac.uk/abstract/tcmabs.htm

ABSTRACT: Upheaval buckling is a serious problem which can be encountered during the operation of buried, submarine, oil and gas pipelines. These pipelines are usually operated at high temperatures and pressures (well above the conditions under which the pipe was laid), and the resulting axial expansion can cause significant axial compressive loads in the pipe wall. Under certain circumstances buckling can occur, with potentially disastrous consequences. An important requirement for pipeline design is therefore to ensure that upheaval buckling does not occur. Most previous models of pipeline buckling have been based on the rigid base model; which is an old railway-track model that has been modified to suit the pipeline conditions. According to this model, a so-called minimum, buckling load can be calculated, and provided that the axial load is kept below this value, then buckling should not occur. In practice however, this model is unsatisfactory because buckling does occur at axial loads well below the so-called minimum value. The model is useful for analysing the post-buckling profile of the pipeline, but a better theory is required to explain the buckling process. A number of modified buckling models have been proposed in the literature. However, despite the volume of literature available on this subject, there appears to be very little experimental data published to verify the numerous theoretical models. The purpose of this project has been to perform a number of experiments on a small-scale model of a buried pipe, in order to determine various aspects of the upheaval buckling behaviour. These aspects included: the force-displacement interaction of the pipeline and the soil, and the behaviour of the pipeline due to various combinations of horizontal and axial loading. A simplified buckling model has been developed, and the results have been discussed in relation to this model. The model concentrates on the conditions under which buckling is initiated, and takes into account the force-displacement interaction between the pipe and the soil. The effect of cyclic loading was also investigated. Under repeated loading, the pipeline can displace by an incremental creep mechanism. A simple design model is suggested for the creep phenomenon.

http://www-structures.eng.cam.ac.uk/phdabs/r-phaal

ABSTRACT: A Two-Surface discrete computational model has been developed which is suitable for the analysis of general doubly curved, elastic, deep, classical, and then shell structures. The stretching effects are modelled by means of either a pin-jointed truss network or the constant strain triangular (CST) finite element, while the bending effects are modelled by a system of overlapping hinged facets, which cover the truss or CST network exactly, like scales. The two surfaces are automatically coupled by the compatibility condition that the two surfaces must be coincident, sharing the same nodes and degree of freedom. The principal innovation has been the development of the hinged bending elements, which, although based on a simple physical analogy, are closely related to both the finite difference and finite element methods. The hinged bending elements are based on local quadratic overlapping assumed displacement functions, which results in constant local stress representation, and permits simple rectangular Cartesian translational nodal degrees of freedom to be employed. This is a significant advantage over most other currently available thin shell finite elements, which employ
The use of rotational and higher order degrees of freedom has, in general, resulted in considerable difficulties in the implementation and application of shell finite elements. This, together with the complexities of shell theories and geometry has ensured that no single finite element has so far achieved acceptance by the engineering community. The Two-Surface model has been applied to a range of linear elastic small-deflection “benchmark” shell problems, including flat plate, cylindrical and hemispherical shell problems. These problems test various aspects of the performance of the model, including stress evaluation, bending stretching interaction, cost of analysis, and numerical control of analyses. The method has been extended to model geometrically nonlinear large-deflection problems, and also shell vibration problems. A limited experimental programme has been undertaken to test the performance of the nonlinear version of the model. The Two-Surface model is simple in concept, implementation and application, and performs competitively against some standard shell finite elements that appear in the literature, and which employ up to four times as many degrees of freedom per node.

http://www.structures.eng.cam.ac.uk/phdabs/p-a-hodgetts
ABSTRACT: This thesis starts with a thorough literature survey on work carried out on both shell and lattice hyperbolic paraboloids, leading to the observation that further investigations of collapse behaviour is justified. Existing methods of analysis, including their development are also researched. A suitable experimental program is drawn up, which involves the testing of four model structures. A detailed account of the rig design and the experimental procedure is given. Against these findings an attempt is made to predict the behaviour of the model structures, using the linear membrane theory in conjunction with an appropriate shell analogy. It is found that what appears to be realistic boundary conditions, produces answers that are either nonsensical or totally unrealistic. Attempts at using more sophisticated methods of shell analysis are also unsuccessful, due to the huge algebraic complexities which quickly appear. Buckling predictions made by previous researchers are not validated by the experimentation. A thorough numerical analysis is then carried out with success. It is found that advanced methods of iteration control are required for certain analyses. A full discussion includes a detailed comparison between experimental results and those predicted by analysis. Reasons for discrepancies are given. Finally, there is a last review the entire research work and the major conclusions drawn. A simplified design aid, suitable for preliminary design, is outlined, based on the findings of the research work. Suggestions for suitable further research are also given.

Kamel Sayed Kandil, 1989, “Interaction between local and Euler buckling modes in thin-walled columns”
http://www.structures.eng.cam.ac.uk/phdabs/k-s-kandil
ABSTRACT: The stability of the buckling process in thin-walled columns depends on non-linear interaction between different buckling modes. This dissertation aims at understanding these phenomena by means of relatively simple conceptual models. The results of the ‘exact’ analysis for the classical buckling of a general rectangular tube, loaded in axial compression, are examined with a view to understanding them in simple, physical terms. Computer graphics are used to re-plot these results according to various hypotheses. On this basis, it is found that most of the results can be reproduced to a satisfactory first approximation by considering one set of plates as ‘active’ and the other as ‘passive’. Some simple, rational approximate formulae are presented. These give a very good description of the exact curves. A simple approach to predict the classical buckling stress (for a given half wavelength) of lipped channel cross-sections, loaded in axial compression, is proposed. The main idea is to consider each of the four classical buckling modes for these cross-sections as existing separately. This approach is verified against algorithm which uses an ‘exact’ matrix where the correlation is very good. Two simple models for the interactive buckling in thin-walled columns are developed. The first is based on the van der Neut two-flange model and has the virtue of being capable of taking account of
the initial overall and local imperfections and material plasticity. The second, which, is based on a Perry-type analysis, produces a simple post-buckling analysis for columns with general cross-sectional geometries. The results of two series of tests conducted small-scale silicone rubber lipped channel models and aluminium thin-walled lipped channel columns are reported. In the latter series, different types of initial imperfections were identified and measured. In the main tests, the columns were loaded over a wide range of positive and negative eccentricities about the minor axis; in addition, several stub (short) columns of different lengths were also tested between rigid flat platens. The theoretical classical and interactive buckling analyses described above are used to examine these results; the theoretical predictions are presented along with the corresponding experimental observations. These analyses are also compared with the experimental results of other researchers. The results of both the present experimental investigation and those of other researchers establish the validity of the present theoretical analyses.

http://www-structures.eng.cam.ac.uk/phdabs/a-affan-1
ABSTRACT: This dissertation is concerned with the behaviour of square-on-square double-layer space grids (DLSG’s) and in particular their collapse mechanisms after initial buckling. A detailed review of the methods used for collapse analysis of these structures is conducted, which shows, that their collapse can be of progressive nature. An outline of the remedies that have been suggested to make safe their collapse behaviour is given, and it traces the line for further study. The present investigation starts by describing the redundancy in these regular pin-jointed assemblies in terms of unit states of self stress. This enables us to understand, by means of the extended Maxwell rule, how it is that mechanisms of collapse can occur when relatively few bars in the assembly have failed. The influence of boundary conditions on the mechanisms of collapse and its progressive nature is also investigated. This method of analysis is verified by detailed examination of several previously reported experimental results, and some conclusions can be drawn. The pre-stressing of statically indeterminate assemblies by means of lack-of-fit is investigated in the hope of changing their collapse characteristics. The unit state of self-stress has been used to explain a method of selecting the bars that can be short-ended/lengthened in order to impose a prescribed state of self-stress, and the scope for achievable patterns of bar tensions has been described. A by-product of the investigation is an algorithm which calculates the required lack-of-fit to impose an initial state if self stress which maximises the load-carrying capacity of indeterminate trusses. Using the formulae derived for pre-stress, a statistical analysis is developed to estimate initial bar tensions due to random lack-of-fit in order to obtain realistic estimate of the load-factor of an assembly before initial failure. Furthermore, we have argued and demonstrated how backlash at the bar-joint connection may have a beneficial effect in reducing substantially initial bar tensions due to the inevitable lack-of-fit on account of manufacturing errors of bars. An extensive experimental program has been conducted to verify the assumptions adopted and formulae derived in this dissertation.

http://www-structures.eng.cam.ac.uk/phdabs/f-a-fathelbab
ABSTRACT: Considerable improvements in the technology of space frame joints have been achieved in recent years. The conventional procedure for the analysis and study of space structure stability assumes that the joints of these structures behave as either pure pins or are fully rigid despite the fact that the joints of most space structures are semi-rigid. The actual behaviour of joints has been shown to have a significant effect on the behaviour of space structures, especially for shallow single layer lattice domes. In this thesis the development of a general space frame member tangent stiffness matrix is reported. This matrix incorporates, in addition to the effects of axial force and bowing, the effects of joint characteristics. An algorithm for following the pre and post
buckling behaviour of shallow single layer lattice domes has also been developed. The tangent stiffness matrix and the new algorithm have been implemented in a computer program for the geometrically nonlinear analysis of space frames. Results obtained using the modified computer program, have been tested against the available published results. The computer program developed is then used to analyse and study the stability of a number of experimental shallow single layer lattice dome models. In these tests, various combinations of member size, joint type, and load pattern were tested. The results of all these tests along with the corresponding computer predictions are presented in this thesis. The ability of the program to model accurately the observed experimental behaviour is clearly demonstrated as is clearly demonstrated as is the significant influence that joint bending stiffness has on behaviour of shallow single layer lattice domes. In particular, realistic levels of joint bending stiffness are shown to produce a considerable improvement in load carrying capacity as compared with predictions based on pin jointed behaviour.


http://www-structures.eng.cam.ac.uk/phdabs/d-t-hatzis

ABSTRACT: Initial geometric imperfections and small loads applied laterally to the members of space frames can have similar and significant effects on the behaviour of such structures. In particular, their presence in shallow, single layer, lattice domes has been shown to lead to considerable reductions in the stiffness and the strength of the domes. An analytical model is presented, that enables the effects of geometric imperfections and lateral loads to be directly incorporated in the equilibrium equations that describe the spatial behaviour of beam-columns, and then by differentiating these equations with respect to deformations, in the derived expressions for their stiffness. The new analytical model obtained, has been incorporated in an already available computer program for the geometrically nonlinear analysis of space frames. This program us is used in this thesis to analyse some standard problems and to reproduce solutions found in the literature or obtained with alternative methods. The results of a series of tests, conducted on shallow, single layer, lattice domes containing members with geometric imperfections or lateral loading are reported. The modified computer program was used for the analysis of these test structures, and the computer predictions are presented along with the corresponding experimental observations.

Kamalarasa, S., 1987, “Buckle propagation in submarine pipelines”

http://www-structures.eng.cam.ac.uk/phdabs/s-kamalarasa

ABSTRACT: The main interest in this thesis has been directed towards the predication of the buckle propagation pressure (Pp) in submarine pipelines. Several empirical formulae for Pp has been derived by various researchers in the past; however, the few who analysed the problem have treated the buckling of the pipe as a problem concerning the collapse of a ring, thus neglecting the longitudinal stretching effects. The present work clearly distinguishes the longitudinal stretching effects from cumferential bending effects. A satisfactory way of incorporating the mechanical properties of the material, without actually measuring them, has been presented. A simple theoretical model, based on a ‘plastic beam on a plastic foundation’ has been developed, and a definite method for the prediction of the buckle propagation pressure has been suggested.

Kollek, Richard John, 1987, Collapse mechanisms of locally loaded reinforced concrete shells”

http://www-structures.eng.cam.ac.uk/phdabs/richard-john-kollek

ABSTRACT: Experiments are presented on the local lateral loading of steel-reinforced micro-concrete hollow cylinders supported by heavily reinforced end diaphragms. The tests exhibit three distinct ultimate modes of failure; global flexural beam collapse, more localised ovalisation, and local punching shear/flexure interaction. The theoretical work concentrates on the behaviour of locally loaded shells, wide beams and arches in plane strain, and axisymmetric and domes. Families of kinematically admissible symmetrical mechanisms are
developed for each case and analysed using the upper bound theorem of plasticity assuming rigid plastic material behaviour, the modified Mohr-Coulomb failure criterion for concrete and the associated flow law. The concept of the shear/flexure interactive failure zone is developed to provide a range of solutions from pure punching shear to pure flexural failure. Calculation of the internal energy dissipation in the narrow interactive zone is facilitated by consideration of the instantaneous centre of relative rotation between the rigid blocks surrounding the zone. The optimum position of the interactive zone is found by variational calculus for a given instantaneous centre and boundary conditions. It is explicitly defined for beams and arches, but numerical analysis is required for the axisymmetric cases. The remaining dissipation terms are substituted into the work equation and provide the upper bound load for any chosen mechanism. By placing the instantaneous centre in different positions, the regimes of ultimate behaviour are explored for certain pertinent cases of beams, arches, slabs and domes. Particular consideration is given to the effect of shell dimensions, material properties and support and loading conditions. Comparisons are made between the present theory, simpler theory and experimental data on beams, arches, slabs and domes. The insight provided by these comparisons is used to illuminate the more complicated ultimate behaviour of the locally loaded cylinders investigated in the present experiments.

Mofflin, D.S., 1984, “Plate buckling in steel and aluminium”

ABSTRACT: Consideration is given to the ultimate strength in compression of both stiffened and unstiffened plates, as well as to plate assemblages. The work is primarily concerned with local buckling, although overall and interactive buckling has also been studied. The effects of a rounded material stress-strain curve have been examined, in particular the behaviour of aluminium alloys. Attention is given to the effects of initial out of flatness and residual stresses. Tests are reported on 76 aluminium plates with controlled initial out of flatness and residual stress. Two alloys were studies, namely 5083-M and 6082-TF. Some specimens were transversely welded. Their sizes ranged from 20 < b/t < 85, corresponding to a non-dimensional slenderness range of 0.58 < β < 2.85. Comparison is made with theoretical predictions and design rules. The results indicate the importance of the roundness of the stress-strain curve on the ultimate strength of non-welded plates. A simple method is described for predicting the complete load-shortening curve of simply supported rectangular plates in uniaxial compression. The method is developed by considering the plate to be comprised of two non-buckling edge zones and a buckling centre zone. It is applicable to either steel or aluminium type materials. Results are in close agreement with other theories and experiments. A full analysis Finite Strip program has been developed to analyse the buckling behaviour of both plates and plate assemblages. The method takes proper account of large deflection theory, elasto-plastic behaviour, residual stresses, HAZ softening and initial out-of-flatness. Different material types can be considered. The method is applicable to local, overall, and interactive buckling problems, loaded in either uniaxial compression or bending. The predicted results compare closely with experiments.

See, T., 1984, “Large displacement of elastic buckling of space structures”

ABSTRACT: Light weight space structures are a product of structural optimisation and are thus prone to suffer from elastic instability. For simple structures with only a few effective degrees-of-freedom the failure mode and the associated failure load can be calculated, but the problems associated with stability are often intractable for a complex space structure particularly when it is also sensitive to small initial imperfections in geometry. A nonlinear stiffness matrix based computer program is used to investigate the stability of such structures, whose likely failure modes are determined by examining the tangent stiffness matrix of the structure near its collapse load. For a structure whose exact initial geometry is known the actual behaviour under any given load can be calculated. Where the imperfections are unknown the initial geometry is altered by adding those combinations
of small imperfections that will excite the likely failure modes. A separate analysis for each of these cases reveals the degree of imperfection sensitivity of the respective failure mode in the structure. Limit point behaviour is correctly analysed because the program is geometrically nonlinear but the present procedure can also take into account possible bifurcation behaviour. Experiments on four different model structures were performed, in which both bifurcation type and limit point behaviour were observed. Separate tests on a large dome produced a snap-through collapse in one case and collapse involving member buckling in another. Where the exact initial geometry was unknown the addition of a suitable set of imperfections produced results in agreement with the experiments. In cases where more significant real imperfections could be measured before the tests, good agreement was obtained between experiment and analysis.

Whaley, Brian, 1982, “The application of the reflective Moire method to the buckling and bending of steel plates”
http://www-structures.eng.cam.ac.uk/phdabs/B%20Whaley.pdf

ABSTRACT (cannot cut and paste)


ABSTRACT: Whilst working in the aerospace industry, the author realised that the structural use of thin cylindrical shells was hampered by a lack of understanding of their buckling behaviour. This dissertation embodies research which examines this behaviour in physical, as opposed to mathematical terms. The work proceeds from a simplified re-working of classical methods of analysis. The physical behaviour of the perfect shell is discussed in terms of the interaction of stretching and bending effects, and the details of the interaction are investigated for a variety of buckling modes. The simplified method also gives a more immediate derivation of standard classical results and suggest the adoption of a second dimensionless geometric parameter for long cylindrical shells under radial (and hydrostatic) pressure, in addition to the well-known parameter of Batdorf, and hence a common load ordinate for a unified plot of theoretical curves and experimental values. Imperfection sensitivity of short cylindrical shells under hydrostatic pressure is discussed, and a theoretical curve devised to allow for it. Finally, conclusions are drawn concerning the differing roles played by longitudinal and circumferential shell stiffeners. Two loading cases of practical importance are examined experimentally using cylindrical shell specimens moulded in Silicone RTV rubber by a centrifugal casting technique which is described.

Bradfield, C.D., 1977, “Problems in strength of stiffened steel compression panels”

ABSTRACT: The dissertation describes work on the failure, in compression, of elements of stiffened steel panels. Attention is directed to geometries where local buckling and yielding interact, and where analysis should account for the presence of residual stresses and initial out-of-flatness and out-of-straightness of the structure. Tests are described on plates loaded in compression, constrained by transverse stiffeners to buckle with a short buckle length, giving aspect ratios of 0.4 to 1.0. Strength was found to rise as aspect ratio was reduced. Residual stresses due to welding were measured, and were not as expected from previous work. Measurements made on steel box-girder bridges are examined to determine the magnitudes, form and variability of initial out-of-flatness and out-of-straightness of plates and stiffeners. For plates, the variations in compressive strength due to varying out-of-flatness are considered, and compared with strength due out-of-flatness are considered, and compared with strength variations due to the variability of material properties. Values are proposed for incorporation in design rules. A method for the analysis of a single stiffener, loaded in compression is described. The governing equations are written in finite difference form and solved numerically.
In the plastic range, an approximate full-section yield criterion is used in an extension of the Ilyushin “method of successive elastic solutions”. Initial out-of-flatness may be included in the analysis. The method has been too used to examine the performance of plain flat stiffeners, including the effect of rotational restraint to the supported unloaded edge. A rig for testing single stiffeners in compression is described. Boundary conditions are those appropriate to a stiffener in eccentrically stiffened plating. In tests on a single bulb flat stiffener, the effects of initial out-of-flatness, eccentric loading and restraint to the supported unloaded edge were examined. Tests are described on single welded splices to plain flat and bulb flat stiffeners. Despite an apparent eccentricity of loading the performance of the splice is satisfactory. Tests covered plain flat and single sided bulb flat stiffeners and their splices.

Reddy, B.D., 1977, “The elastic and plastic buckling of circular cylinders in bending”
http://www.structures.eng.cam.ac.uk/phdabs/B%20D%20Reddy_Abstract.pdf
ABSTRACT: An analytical and experimental study of the buckling of circular cylinders in bending is carried out, with emphasis on the elastic-plastic problem. A review of past work on this problem shows that many of its aspects require further investigation. A set of linear equations is derived, and used to investigate the bifurcation characteristics of both linear-elastic as well as elastic-plastic cylinders subjected to end moments. In most general case, and J2 incremental theory is used. The replacement of the tangent modulus in the general buckling equation by the elastic modulus reduces this equation to Donnell’s linear stability equation. In the treatment of the elastic problem, the circumferential distribution of lateral buckling displacement is approximated by a Gaussian distribution, and results are obtained from a relatively simple analysis for both the cases of pure bending as well as combined bending and internal pressure. These results compare very well with those obtained by others in more rigorous analyses. Some of the results of the elastic buckling analysis are then made use of in the treatment of the corresponding elastic-plastic problem. New results are presented for the bifurcation of elastic-plastic problem cylinders under pure bending. These results are compared with corresponding results for elastic-plastic axially compressed cylinders. The results of an experimental study of the collapse of cylinders in pure bending are presented. The tubes tested were thick enough to buckle in the plastic range. Collapse of these specimens was due mainly to wrinkling on the compressive side though a small amount of cross-sectional ovalisation also occurred. Measurements of the ripples are presented and discussed. The presence of these ripples before collapse took place indicated the presence of initial imperfections. A comparison between experimental critical strains and various theoretical strains shows that the experimental values are closest to deformation theory predictions for axially compressed cylinders. A similar conclusion is reached with regard to the comparison of experimental and theoretical critical stresses.

Mohr, G.A., 1976, “Analysis and design of plate and shell structures with finite elements”
ABSTRACT: The main emphasis in this work is upon the development and application of simple finite displacement element solutions with particular reference to design oriented problems in slabs and shells. In the work of element development a new approach to bending elements is employed and this is also recommended for future work. Several other new elements, as well as variations in the derivation and working of many established elements, are also presented. An attempt is also made to extend the present understanding of the convergence behaviour of displacement elements and a simple modification of the Southwell Plot is suggested for extrapolating monotonically convergent solutions. An iterative procedure for the uniform strength design of slabs is developed and much used, showing consistent agreement with the fibre optimum theory developed by Lowe and Melchers, and further more detailed work is worthwhile in this area. For the design of shells an iterative optimality criterion approach is developed and used to yield a new and apparently feasible solution for the design of an arch dam. Finally, however, it is an improved method that is recommended for future work in
this area. Finally, a number of other slab and shell problems are investigated leading to recommendations for future work upon structural shell analysis, incipient buckling problems and composite constructional systems.

Rogers, N.A., 1975, “Local buckling of welded steel outstands”

http://www-structures.eng.cam.ac.uk/phdabs/N%20A%20Rogers_Abstract.pdf

ABSTRACT: The design of plain flat outstands (beam or column flanges, plain flat stiffeners in stiffened plating) is based on setting limits to the outstand slenderness. For the plastic design of beams and columns, the width-thickness ratio of the compression flanges is limited to prevent buckling and enable to fully-plastic moment of the section to be developed and maintained over considerable rotations. For conventional elastic design, the allowable slenderness is slightly higher, but must still be sufficiently low that the outstand strength in compression is equal to the material yield stress. In this stocky region, the effect of residual stresses on strength is small. For more complex outstand shapes (bulb flats, angles, tees), past practice has been to assume these sections to be fully effective. Following the collapse of a number of box-girder bridges, and the setting up of the Merrison Committee, an allowable stress for outstands in stiffened plating can be calculated, based on the elastic critical stress for torsional buckling of the outstand. Since little was known about the effect of initial imperfections on the strength of outstands, the Merrison Committee also recommended stringent tolerances on the allowable out-of-straightness of such members. Detailed information (both experimental and theoretical) concerning the behaviour of outstands in compression is limited, especially in the more slender range where initial imperfections and residual stresses are more important. This dissertation contains details of a theoretical analysis for predicting the load-deflection characteristics of slender simply supported plain flat outstands in compression, including the effect of welding stresses and initial imperfections. A comprehensive experimental study of hinged plain flat outstands in compression is also described, and the results enable a design curve of strength against slenderness to be drawn. The agreement between experimental and predicted strengths is quite good. For bulb flats, high rolling residual stresses and a considerable variation in the yield stress across the section have been found. Compression tests have been conducted on the bulb-flat cruciform columns to investigate the effect of different imperfection shapes on strength. The results indicate that a relaxation in the Merrison fabrication tolerance could be made. Finally, a design method is presented for outstand failure in stiffened steel compression panels. This is based on calculating an “affective slenderness” for the outstand restrained by the plating, and entering in the strength curve derived from the results of tests on simply-supported outstands.


ABSTRACT: Two problems are considered in this dissertation:

i. the effect of web buckling on the behaviour of hybrid plate girders, and
ii. the residual stresses induced in steel structures fabricated by welding.

Part I describes an experimental investigation into the behaviour and strength of hybrid girders having high yield strength steel flanges and mild steel webs. The project set out to consider whether the limits specified by current British Standards for webs in mild steel girders could be used for hybrids and whether the design philosophy of these standards could be applied to hybrids. The webs of the test specimens were either unstiffened or transversely stiffened and were designed to the limits permitted by current standards. They were subjected to a wide range of loading conditions to study the effect of moment-shear interaction. The results are compared with predictions of available theories. Part II describes an experimental and theoretical investigation into the residual stresses caused by welding. The wide ranging experimental programme of Chapter 6 first considers the relationship between the heat input to a weld and the shrinkage force and then studies the effect of various welding (intermittent welding and multi-pass welding) and of specimen geometry. A study of the
welding residual stresses to be expected in the Rising Sector Gates of the Thames Barrier structure is described in Chapter 7. The stresses were measured on a full-scale specimen. A numerical method for determining welding residual stresses in free plates is developed in Chapter 8. The problem is treated as one of two-dimensional elastoplastic thermal stress analysis. A finite difference approximation is used to solve the governing differential equation of the problem and plasticity is allowed for using the method of successive elastic solutions. The relationship between the welding parameters and the shrinkage force is obtained theoretically and the effect of coincident two-pass welding is examined.

Gilbert, R.B., 1973, “Topics in the elastic buckling of plates and columns”
ABSTRACT: The thesis is divided into two parts, the first of which considers the buckling of anisotropic plates, and the second is concerned with a problem in the buckling of an elastic box column. Anisotropic materials are manufactured by incorporating layers of stiff glass of carbon fibres in flexible matrices of epoxy or other polymeric resins. Plates made from such materials have bending and stretching rigidities much greater than their transverse shearing rigidities, which are determined by the low shearing moduli of the resin matrices. Because of this it has been suggested that a “thick-plate” analysis of their behaviour is necessary, as conventional “thin-plate” theory neglects the transverse shearing strains. This thesis examines the small deflection buckling of anisotropic thick plates, the eigen-values being found by a novel numerical method derived from the technique known as Dynamic Relaxation. It is found that the buckling-loads may be considerably over estimated by a thin-plate analysis, and that the magnitude of the error is strongly dependant upon the boundary conditions. An elastic box column may either buckle locally or by overall flexure. It has been shown that a small “local” imperfection can substantially reduce the load-carrying capacity of the column, particularly when the buckling-loads for the two modes acting separately are nearly the same. In the second part of the thesis the effects of both local and overall (column-axis) imperfections behaviour is characterised by the value of a single, combined imperfection parameter. The analysis has been performed by considering the finite-deflection behaviour of a simplified model system but the results agree well with the results of a number of tests on small-scale rubber box columns.

Gill, J.I., 1972, “Computer aided design of shell structures using the finite element method”
ABSTRACT: The object of the research described in this dissertation is to develop and evaluate computer techniques for the design of shell structures. A computer aided design system for thin elastic shells is described. Shell surfaces are defined geometrically using an existing surface design program, MULTIPATCH, which is based on the surface patches proposed by S.A. Coons. The structural design system, SHELL, provides facilities for preparing data for a finite element analysis, performing an analysis and examining the result in printed or pictorial form. Interactive computer graphics is used extensively during both input and output. A new algorithm for automatically triangulating a surface for a finite element analysis is described. The density of triangular elements on any part of the surface depends on an “element density function” whose values are interpolated from values specified by the designer at the corners of the patches which define the surface. The algorithm produces near-equilateral triangles which are well graded in regions of varying density. The designer defines loads and boundary conditions in terms of the patch definition of the surface, and these are automatically mapped on to the finite element idealisation. An interactive method for obtaining a near-minimum bandwidth for a structural stiffness matrix is described. The method utilises the ability of an engineering designer to appraise the overall structure of a finite element layout and decide on a near-optimum node order. The main disadvantages of previous methods of bandwidth reduction are overcome. Lengthy finite element analyses may be run as batch-processing jobs and the results may be examined interactively using convenient graphics.
facilities. The data pertaining to a given structure is stored in a single magnetic disc file to which all phases of
the design system have access. Having evaluated the results of analysis, the designer can modify the geometric
definition or the structural data and run a further analysis. The techniques developed, as incorporated into an
integrated computer system, accelerate the design process by drastically reducing the amount of input data
required for an analysis and by providing convenient output facilities. The evaluation of the system on a number
of structures is described and suggestions are given for further work.

ABSTRACT: This work is concerned with the effect of local buckling on the rotation capacity of composite
steel concrete beams in regions of negative bending. Experiments were made in which both stiffened and
unstiffened beams were subjected to a moment gradient in negative bending. The sizes of the joists varied so
that a wide range of flange and web slenderness ratios could be investigated. In only a few tests were true
composite steel-concrete specimens used; many had the reinforced concrete slab simulated by rolled steel flat.
Comparison between the test results and existing theories on local buckling in plane steel structures revealed
that much of the existing work can be applied to composite beams. Not all of the past work, however, agreed
well with the observations, and it is concluded that the applicability of some existing recommendations for
plastically designed member should be re-examined. An approximate method, deriving from the upper bound
theorem of limit analysis, of predicting the moment-rotation characteristics of a locally buckling I-shape is
presented. Two buckling mechanisms for unstiffened sections, and one for a stiffened section are analysed.
Extension of the analysis to composite and cover-plated beams is discussed. The predicted curves are compared
with actual characteristics as observed by the author and by others. Reasonable agreement is found for the
unstiffened shapes, and it is concluded that the method provide a useful tool for further research. Both the actual
and predicted behaviour of the longitudinally stiffened sections showed significant improvements over their
unstiffened counterparts. There were too few results, however, for definite conclusions to be drawn. Tentative
conclusions are given to aid the development if design recommendations, and to act as guides for future studies.

Gunaratnam, D.J., 1968, “Finite elastic-plastic displacements of shells”
ABSTRACT: A detailed theoretical and experimental study is presented for large deflection elastic and elastic-
plastic behaviour of thin spherical shells subjected to uniform external pressure, and concentrated inward load
applied at the apex through a rigid boss. The theoretical study is carried out using the rate problem, This is a
boundary value problem for the rates of stress velocities and rates of surface tractions which takes geometry
changes into account. The rate problem is first derived for a general continuum in terms of Cartesian tensors.
The corresponding rate equations for an axisymmetric shell are then derived in terms of generalised stress rates,
and strain rates. In the elastic region the governing differential equations are linear in the rates and are solved
numerically by expressing it in finite difference form. By solving a sequence of such rate problems the entire
load-deflection characteristic of the shell is determined to any desired stage. In the plastic region the governing
equations are non-linear, and are solved using the strain-bound iteration technique. The experimental study was
carried out on aluminium and P.V.C. hemispherical shells. The theoretical results are in fair agreement with
previous and present experimental results. Further the results show that the boss size does influence the
buckling behaviour of spherical shells under point load. Also an initial external pressure is shown to cause
dramatic collapse under point load. Finally in the sixth chapter the rate equations are derived for a general shell.

ABSTRACT: The dissertation is concerned with the ultimate strengths in compression of columns up of thin plates. The columns are proportioned in such way that local buckling occurs when the section is still entirely elastic. The ultimate average stress of short columns is then primarily determined by the plastic yielding of the plates in their post-buckled range, but in the case of longer columns, this ultimate stress is somewhat reduced because of a tendency towards overall buckling. The dissertation is divided into two parts, the first containing an account of the theoretical derivation of ultimate stresses, the second, a description of the experimental research carried out to support the theory. The theory has involved essentially the development of two computer programs. The first predicts the post-buckled behaviour of a short thin-walled rectangular column under uniform axial compression, giving information about the regions of plasticity within the plates at various applied strains and evaluating the ultimate stress. The second obtains the internal bending moment – curvature relationship if the column at stages in its post-buckled range. From the variation of this latter parameter with the average applied axial stress the interaction curve of ultimate stress versus slenderness-ratio for the column may be derived. Interaction curves are presented for sections with various values of yield stress, and the effect of initial geometrical imperfections is also demonstrated. Experimental interaction curves have been obtained by performing tests on model columns cut from square-section thin-walled drawn tubing and they appear to be in good agreement with the theoretical curves.

http://www-structures.eng.cam.ac.uk/phdabs/A%20T%20Ractliffe_Abstract.pdf

ABSTRACT: The dissertation covers work by the author over the past three years and is concerned with the post-buckled behaviour of rectangular plates compressed primarily in one direction into the plastic regime. Particular emphasis is placed on the study of ultimate strength, and it sensitivity to residual welding stresses, initial imperfections, boundary conditions and material properties. The “load-shedding” problem in plate buckling is investigated experimentally for the first time with particular reference to the problem of assessing the strength of built-up columns and other structural members made from welded plates. Chapter 1 states the problem and reviews the present state of knowledge in this field. Chapter 2 presents a simplified analysis of the simply-supported square plate which takes into account residual stresses, initial imperfections and work-hardening. Typical results are shown graphically. Chapter 3 describes a rigorous method based on strain energy. Unfortunately lack of time curtailed work on the computer program and no result emerged, but the method embodies some novel ideas and is presented as a powerful approach which will take into account a fairly general loading system and boundary conditions, in addition to accommodating residual stresses and work-hardening. Chapter 4 moves on to experimental work and the design of a test rig to simulate clamped or simply-supported boundary conditions in an individual plate. Another feature discussed is the stiffening of a testing machine in order to observe behaviour after the ultimate load. Chapters 5 – 7 describe actual tests on steel cruciform columns, and plates in steel, H30WP-alloy and Chapter 8 discusses these results and compares theory with experiment. Appendices are devoted to topics indirectly connected to the main thesis, including the measurement and prediction of residual stresses, material properties, elasto-plastic theory etc.

The main results to emerge are:

a) Local buckling strength is adversely affected by residual stresses and imperfections, most severely when the elastic critical stress is of the same order as the yield stress.

b) In plates of certain sizes, intrinsic instability arises i.e. at or beyond the maximum load the effective load may fall off catastrophically under no further compression, with possible serious consequences for the rest of the structure.

c) Boundary conditions do not greatly affect the ultimate strength of plates.

d) Further evidence, experimental and theoretical, emerges to suggest that the BS449 and 153 “effective width” rules may not be very reliable.
Massey, Campbell, 1965, The inelastic lateral stability of mild steel I beams”
http://www-structures.eng.cam.ac.uk/phdabs/Campbell%20Massey_Abstract.pdf

ABSTRACT: A basic assumption in the proportioning of structures for ultimate strength by plastic design methods is that large inelastic rotations, and consequent redistribution of moments, are possible at certain regions. This assumption implies that premature failure by buckling does not occur. It is the purpose of this dissertation to examine the phenomenon of lateral buckling of beams, more particularly mild steel I beams, which have been strained beyond yield by bending in the plane of maximum rigidity. Existing theories are studied critically and modified where necessary, a programme of uniform bending tests on small scale model steel I beams is described and the result are correlated with theoretical predictions. First, a new theory to describe the reduction in torsional rigidity with increase in primary bending moment beyond yield is formulated and supported experimentally. Then the lateral stability in the inelastic range generally is discussed, with a comparison of theoretical and experimental findings, a variation of the Southwell Plot is developed and used for inelastic stability predictions. Rotation capacity is next examined and a relation between laterally unsupported length and amount of possible rotation before collapse is determined. It is also shown that sufficient rotation may be possible in cases where the full plastic moment of the beam cannot be developed before it becomes unstable. The effect of residual stresses is studied theoretically and it is shown quantitatively how much stresses precipitate the onset of instability in the plastic range. Beams with non uniform are then discusses and examined analytically by means of an approximate method of calculation, based on the moment are principles, which is developed for the purpose. Finally, a theory is formulated to predict the required force applied horizontally at mid span to prevent lateral instability up to the full plastic moment. This theory is also supported experimentally.

Augsti, Giuliano, 1964, “Some problems in structural instability with special reference to beam of I-section”

ABSTRACT: This thesis consists of two Parts: Part I is concerned with the basic types of elastic buckling and post-buckling; Part II with the theory of instability in the inelastic range and the actual behaviour and practical design of I-section metal beam-columns. Semi-rigid models with one or two degrees of freedom are used in Part I to present and illustrate the different cases: namely, the models are constituted by a rigid compressed strut loaded at the top and either pinned or ball-ended at the bottom (one or two degrees of freedom respectively); a similar model illustrated the lateral-torsional buckling of deep beams, but in this case the load is applied at one end at 90 degrees to the limb, which is restrained at the other end by two cylindrical hinges. Different behaviours are obtained by changing the elastic restraints; for each case the complete equations of equilibrium, valid for any value of the rotations, are written. For the “strut” models, the load-deformation curves are plotted in both cases of perfectly vertical or slightly inclined (“imperfect”) strut, the loading force being vertical. It is noted in particular that in the second case separate paths of equilibrium exist, which tend to touch each other in the “bifurcation points” as the imperfections tend to vanish; in the “perfect” case, the buckled branches of the equilibrium path can be either rising or falling, depending on the restraints. Only perfect “deep beam” models are studied, and it is noted that the torsional and lateral bending stiffnesses have different importance in determining the post-buckling strength. General conclusion from the different examples are derived at the end of Part I, and these are put in relation with the results of more general researches. The first Chapter of Part II deals with the general principles and fundamental cases of inelastic buckling, presenting firstly a critical synthesis of the present knowledge and then examples again obtained by means of a semi-rigid strut model, with a variety of inelastic stress-strain relationships. The rest of Part II (Chapter 5 to 8) deals with an investigation on I-section “beam-columns”, and comprise

(i) a search of literature, with particular emphasis on practical design procedure;
(ii) description and results of two groups of experiments, respectively on aluminium-alloy and mild-steel miniature stanchions, subjected to a compressive axial load and one end moment acting in the plane of the web;

(iii) comparison of the experimental results with theoretical and empirical predictions, and proposal of a simple empirical “interaction curve”, which fits the experimental results to the “rotation capacity” of beam-columns, that is, the ability to withstand end rotations with out excessive decrease of strength.

Wasti, Syed Tanvir, 1964, Finite plastic deformations of spherical shells”
http://www-structures.eng.cam.ac.uk/phdabs/Syed%20T%20Wasti_Abstract.pdf
ABSTRACT: A detailed theoretical and experimental study of the behaviour of copper, aluminium and steel hemispherical shells tested under concentrated loads at the apex and under water pressure is presented. There shells are not “perfect”, but obtained commercially. The description of loading apparatus designed to test shells under the above conditions, and suitable for use in a small laboratory, is given in Chapter I. Chapter III deals specifically with the starting point of the present investigation – the work of Reissner and Ashwell. The result of 39 tests on shallow and deep shells are given. Short notes on the shells written during each experiment comprise of Chapter II. Theoretical load-deflexion relationships are derived in Chapter IV on the basis of several postulated collapse mechanisms, and reasonable agreement is obtained for some of the theoretical analyses. The need for a convenient method of designing shells has also been borne in mind. Close attention is paid to the way in which, a shell deform under increasing load, and it is shown that the work done on thick shells at least is plastic almost from the very beginning. A cine-film has been obtained, showing the outward propagation of circular yield-hinges along the shell from the apex. Finally in Chapter V, some observations are made on the problem of the inextensional large-deflexion behaviour of spherical shells.

Grundy, Paul, 1961, “The strength of elastically restrained steel tubular struts”
http://www-structures.eng.cam.ac.uk/phdabs/Paul%20Grundy_Abstract.pdf
ABSTRACT: Current design methods of struts in trusses are examined and it is found that there is no exact general solution of the ultimate strength based upon elastoplastic material. One solution is found for tubular struts bent in single curvature with end restraints for equal rotational stiffness, which is the worst condition for moments of a given magnitude. In the analysis only struts at collapse are considered. For each strut configuration the end rotational stiffnesses necessary for the strut to be at collapse are found using an adjacent equilibrium criterion. The solutions are found using an electronic computer to integrate the moment-curvature functions, and charts of results applicable to all practical lengths of tubular struts are found. A supplementary analysis shows the effect of the stiffness of end restraint and a safe method of including the effect of initial curvature in the inelastic analysis. A further analysis develops the idea of an “elastic hinge” to compare the collapse load conditions of struts in single curvature with struts of other shapes. A significant reduction in the necessary end stiffness of restraint is found for unsymmetrical struts. The design and operation of a testing rig for small tubular struts is described and the results of fifty eight tests are given. The single curvature tests are compared with the theory, which is found to be conservative, and the reasons for this are discussed. The tests show the significance of various factors, in particular that the nett initial central deflection before the load is applied is the most significant factor affecting the proximity if the collapse load to the squash load, and the load generally falls steeply with contraction after the collapse load is obtained.

Thompson, J.M.T., 1961, “The elastic instability of spherical shells”
ABSTRACT: Part I of the dissertation represent an investigation into the well-known discrepancy between experimental and theoretical (eigenvalue) analyses of elastic shell instability. The buckling and post-buckling of
a ‘perfect’ and ‘imperfect’ complete spherical shell under uniform external pressure are studied. An electrolytic method, applicable to the manufacture of thin shells of various profiles, is developed for the production of near-perfect metallic specimens. The shells are suitable for instability and model stress analyses. Pressure tests on electroplated copper, and polyvinyl chloride shells confirm the reported premature experimental failures. Many types of ‘imperfection’ were eliminated from the shells, and the magnitudes of the remaining imperfections are assessed. The ‘classical’ nature of the experimental snap is demonstrated, and the rotationally symmetric post-snapping states are analysed. The initial and post-buckling behaviours of a perfect shell are analysed theoretically by a well established energy method. The use of a digital computer allows a considerable advance over previous theoretical treatments, and the uniqueness of the post-buckling states is discussed. The experimental and theoretical post-buckling analyses show good agreement equilibrium states in the field of shell instability. Theoretical analyses of an imperfect shell, together with the experimental shell, together with experimental conclusions, show that middle-surface and thickness irregularities can, and in many cases do represent the primary cause of the premature failures. Loading imperfections are unimportant. Part II represents a unified presentation of several fundamental stability concepts of large-deflection elasticity. Four theorems concerning the stability of the system, which includes both a general structure and its loading device, are established. The first theorem incorporates the ‘classical’ stability concept, which identifies the ‘critical’ condition with the existence of an ‘adjacent position of equilibrium’. Used conjointly the theorems are a powerful tool in any investigation into the stability of a structure, for which the load-deflection characteristics are known. This practical usefulness of the theorems is demonstrated in several examples.

Cotterell, B., 1960, “Thermal buckling of circular plates”
http://www-structures.eng.cam.ac.uk/phdabs/B%20Cotterell_Abstract_1.docx.pdf
ABSTRACT: (cannot cut and paste)

ABSTRACT: The investigation into the elastic-plastic behaviour of mild steel plates has aimed at determining the ultimate load carrying capacity of square and circular plates loaded in the plane of the plate. It has been restricted to the simplest of boundary conditions by assuming simple supports along the perimeter of the plate and strain hardening effects have been excluded, the analysis being confined to an elastic perfectly plastic material obeying a Johansen Yield Criterion of constant maximum stress. The ultimate load has been obtained from the intersection of an elastic-plastic loading path, which occurs subsequent to the elastic-plastic buckling of the plate, and a rigid plastic unloading line. For stocky plates, whose elastic critical stress is equal to or greater than the yield stress, it has been shown that the ultimate load is equal to the yield load. It has also been shown that the ultimate load is related to the magnitude of the initial imperfections in the plate, this load being a maximum for an ideal initially plane plate. The problem of the behaviour of circular plates has been limited to a theoretical investigation. Experiments were not carried out owing to the difficulty of applying radial loads of large magnitude to a plate of this shape. The theoretical investigation, however, has been supplemented by suggesting an elastic-plastic loading path for a circular plate with clamped edges. Extensive experiments have been carried out on square plates and the theory has been verified to large transverse deflexions of such plates. There experiments have been conducted on thin walled tubes of square cross-section where the walls of the tube have been found to approximate the conditions of a simply supported plate. Tests have also been carried out on the webs of I sections though these experiments have not proved too successful owing to the effects of elastic restraints along the unloaded edges. The general analysis developed in this dissertation has been compared with previous solutions for the ultimate strength of plates in compression.
Ariaratnam, S.T., 1959, “The collapse load of elastic-plastic structures”
http://www-structures.eng.cam.ac.uk/phdabs/S%20T%20Ariaratnam_Abstract.pdf

ABSTRACT: The investigation is concerned with the overall stability and collapse behaviour of elastic-plastic structures. The discussions are restricted to plane rigid-jointed frames loaded in their plane. Fundamental ideas put forward intuitively by previous investigators and verified by them using specific numerical examples, are proved rigorously for structures in general. It is shown that the elastic critical loads play a significantly part in determining the stability of elastic-plastic structures. The critical loads are defined as eigenvalues in terms of a variational problem. Using this definition some useful results concerning critical loads are established for structures generally. The “Southwell Method” for predicting critical loads of struts from experimental observations, is extended to the problem of plane frameworks which buckle within and out of their plane. A proof of Hoff’s Convergence Criterion for stability of elastic frameworks is presented as an appendix to the main body of the analysis. The collapse behaviour of elastic-plastic structures which fail through frame instability is explained in mathematical terms. The general procedure adopted is the study of the equilibrium problem of the response of a structure to proportional loading in relation to the associated eigenvalue buckling problem, the solutions being obtained as series in the buckling modes using the Theorem of Minimum Potential Energy. The special case of the collapse of frames, in which the external loading does not excite in the deflexions a component in the first buckling mode, is discussed by considering the problem of the slender symmetrically loaded symmetrical frame. Equations for the stability analysis of elastic-plastic structures are developed in a form suitable for evaluation on a digital computer. Empirical methods for predicting collapse loads are reviewed and suggestions for possible improvements made where necessary. The result of an experimental investigation on frame instability in the plastic range is presented. The programme consists of tests on a series of model multi-story frames of rectangular and tubular members under the action of vertical and horizontal loading in the plane of the frames.

Ellis, John Stewart, 1957, “The plastic behavior of tubular compression members”

ABSTRACT: The problem was to investigate theoretically and experimentally the plastic behaviour of mild steel compression members of an annular cross-section when subjected to end loads of equal and unequal end eccentricities. In order to provide a theoretical answer to this problem, it was first necessary to specify a collapse criterion. This was used to find the critical length of a compression member under a known thrust and subjected to end loads of equal or unequal eccentricities. It was then necessary to compute the physical characteristics of compression members on the point of collapse. These computations were made for a comprehensive range of axial loads and ratios of end eccentricities. An electronic digital computer was used in this work, and the results are expressed as graphs in which all the quantities are non-dimensional. It should be noted that the theory does not take into account the effect of shear, strain history, residual stresses, shakedown, fatigue and local buckling. A total of fifteen stanchion tests were conducted, using specimens of an annular cross-section with an outside diameter of 4.5 in. and thickness of 0.138 or 0.25. The lengths of the specimens were either 5 ft. or 9 ft., and three types of loading were used: (1) single curvature bending with equal end eccentricities, (2) single curvature bending with no moment at one end, and (3) single curvature bending with equal but opposite end eccentricities. The agreement between the plastic theory and the experimental collapse loads is considered to be good. It would appear that considerable economy will result from using the plastic theory to analyse stanchions rather than the elastic one. A method of analysing stanchions in a framework is advanced.

Ashwell, Derek George, 1953, “The finite deformation of thin plates and shells”

ABSTRACT: This investigation is concerned with the elastic-plastic response of thin plates and shells subjected to compressive loadings in their plane. The effects of elastic-plastic transverse shear are neglected. The plate and shell equations are developed in the form of a variational problem for a given boundary condition. The plate and shell equations are solved under the assumption of perfect plasticity. The results are presented in a form suitable for the use of a digital computer. It is shown that the solution of a given problem can be obtained by a series of calculations using the computer. The agreement between the theoretical and experimental results is considered to be good.
ABSTRACT: A number of fundamental large-deflexion problems in the elastic bending, compression, and torsion of thin plates and thin-walled members are investigated in detail. From the general equations for the extensional bending of thin plates an equation is obtained governing the bending of rectangular plates into certain types of surfaces of revolution. This equation is applied in turn to the pure bending about one axis of initially curved and corrugated plates, to flat-square, or rectangular plates loaded by distributed bending moments applied to all four edges, and to plates with initial curvature loaded by compressive forces parallel to the axis of curvature. All these problems exhibit the type of instability characteristics of thin-walled structures which depend in curvature of their stiffness. Curves are drawn showing the deformation suffered by the plates, the critical loads are found, and the post-buckling behaviour is described. The final chapter considers the finite torsion of a twisted elastic cantilever. It is well known that the displacement of such a cantilever relative to its support is a rotation about its flexural axis, to so-called axis of twist. It is here shown that, by considering the distortion of the cantilever without reference to its support, an axis of distortion can be found that is, in general, quite different from the accepted axis of displacement. General expressions are derived for the determination of the axis of distortion, and it is found that the finite deformation of thin-walled sections depends on the position of both axes, in a manner which is described. Various experiments are described which were designed to test the analyses of all types of problem considered in the dissertation and their results are found to confirm them satisfactorily.

Gross, Nicol, 1950, “Experiments on curved thin-walled tubes”
http://www-structures.eng.cam.ac.uk/phdabs/N%20Gross_Abstract.pdf

ABSTRACT: The stresses and the flexibility of curved thin-walled tubes have been estimated in the past by Karman’s approximate analysis, but experiments have shown that misleading results are obtained when the radius of curvature is not considerably larger than the radius of the tube. In this dissertation, Karman’s analysis is extended to pipe bends in which the radius of curvature and the pipe radius are of the same order of magnitude, by introducing the second and the third approximations for the shape of the deformed centre-line, as well as a correction of Karman’s assumption that this deformation does not alter the length of the centre-line. By measuring strains, for the first time, not only on the outside but also on the inside surface of curved tubes, this extension was checked for the usual small-radius pipe bends and was also applied to an extreme case. The measurements of the strain confirmed that the largest stress occurred on the inside surface, that it was a stress in the transverse direction, and that it was induced in the cross-section where, from similarity with curved bars, the stress-free axis was assumed to be. It was also found that after local yielding has taken place, the load can be roughly doubled before unduly large deflexions occur. A comparison of the behaviour of seamless and pressed-welded pipe bends showed that neither the flexibility nor the stresses are significantly influenced by the presence of the weld. Experiments are also described in which the pipe-bends were subjected to uniform internal pressure, strain measurements being taken for the first time inside pipes under high water-pressure. The stresses can be estimated by assuming that the pipe-bend behaves like a thin-walled torus of circular cross-section. But initial deviations from circularity superimpose additional bending stresses. In the course of comparing the behaviour of seamless and pressed-welded bends when they were subjected to internal pressure, it was found that the ultimate pressure that could be sustained was lower in the latter because of imperfections in the weld.

Neal, Bernard George, 1948, “The lateral instability of mild steel beams of rectangular cross-section bent beyond the elastic limit”
http://www-structures.eng.cam.ac.uk/phdabs/B%20G%20Neal_Abstract.pdf

ABSTRACT: It is well known that a thin deep beam, loaded in a vertical plane so as to cause flexure about the stronger, or primary principal axis of the cross-section, may fail by buckling laterally out of that plane.
type of instability is characterised by the development of twist in the beam. A component of the applied load then causes flexure about the weaker, or secondary principal axis, and lateral deflection occurs. The critical load causing instability in an initially straight beam therefore depends on the flexural rigidity of the beam about its secondary principal axis, and its torsional rigidity. Values of the critical load have been calculated for many loading systems and types of end-constraint for beams that behave elastically under the applied loads. This dissertation discusses rectangular section beams of mild steel in which yield occurs in the more highly strained outer fibres before the critical condition causing lateral instability is reached. For such beams the secondary flexural rigidity decreases progressively as the load increased above the value at which yield first occurs. The torsional rigidity, however, remains constant at its elastic value. In the first part of the dissertation the reduction of the secondary flexural rigidity is calculated, and the critical lateral buckling moment is estimated for a beam bent by pure terminal couples, the ends of which are prevented from twisting but a free to rotate about the secondary principal axis. Experimental confirmation of the results is given. In the second part of the dissertation the calculations are extended to problems in which the primary bending moment varies linearly along the beam, so that a constant shear force exists. The two particular examples considered are a simply supported beam with a central concentrated load, and a cantilever. No experimental evidence in support of these calculations is available.

End of Ph.D. theses about buckling of beams, plates and shells from Cambridge University Structures Research Group (CURSG)
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ABSTRACT: (none given)

ABSTRACT: The problem of optimal design of rotationally symmetrical shells of uniform stability stiffened by ribs was discussed in the current paper. The structure was modelled in ANSYS software and solved by FEM method. The formulation of uniform local stability was successfully verified by the linear buckling solution. The optimization tasks were solved numerically using the modified Particle Swarm Optimization algorithm. The critical loading multiplier was increased by determining the optimal shape of the meridian, distribution of a wall thickness in a coat of shell and the placement of ribs inside the shell.

References listed at the end of the paper:

ABSTRACT: A three-dimensional (3D) method of analysis is presented for determining the free vibration frequencies of joined hemispherical-cylindrical shells of revolution with a top opening. Unlike conventional shell theories, which are mathematically two-dimensional (2D), the present method is based upon the 3D dynamic equations of elasticity. Displacement components $u_r$, $u_\theta$, and $u_z$ in the radial, circumferential, and axial directions, respectively, are taken to be periodic in $\theta$ and in time, and algebraic polynomials in the $r$ and $z$ directions. Potential (strain) and kinetic energies of the joined shells are formulated, and the Ritz method is used to solve the eigenvalue problem, thus yielding upper bound values of the frequencies by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies. Natural frequencies are presented for different boundary conditions. The frequencies from the present 3D method are compared with those from 2D thin shell theories.


ABSTRACT: (none given)

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“Eigen value and buckling load measurement of stiffened panel using FEM”, IJME, Vol. 1, Special Issue 1, 2014 (NCETADM-2014)

ABSTRACT: One of the main failure modes of an aircraft is buckling. Stringers are often bonded to composite panel skins to help increase the panel’s buckling strength; however, if there is a defect in the bond between the stringer and the panel, the structure may be weakened. Developing analysis tools that can accurately simulate the behaviour of composite materials is critical to the successful design and use of composite structures. The pre-design of aircraft wing structures relies on finite element models of significantly reduced complexity in which only spar and rib components are explicitly modelled, whereas the wing skin-stringers stiffened panels are implicitly represented by stiffness-equivalent elements. This conventional procedure enables a fast solution technique for large problems. The panel was loaded beyond buckling and strains, and out-of-plane displacements were extracted. The experimental data were compared with the strains and out-of-plane deflections from a high-fidelity non-linear element analysis. The test data indicated that the panel buckled at the
linear elastic buckling Eigen value when continuous load is applied. This value is obtained from graph. References listed at the end of the paper
3. Airplane stress analysis, NACA report No. 82.

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ABSTRACT: The design of deep submersible pressure hull’s structure is one of the core technologies of submersible development of human history. Submersible pressure hulls with fiber-reinforced multilayer constructions have been developed in the recent years as substitutes for classical metallic ring-stiffened pressure hulls; strength and stability are its top priority. This paper investigates the optimum design of a composite elliptical deep-submerged pressure hull under hydrostatic pressure to minimize the buoyancy factor of the submersible pressure hull under constraints on the failure criteria and the buckling strength of the hulls to reach the maximum operating depth. The thickness and the fiber orientation angles in each layer, the radii of the ellipse, and stringers dimensions were taken as design variables and determined in the design process. The optimization procedures are performed using commercial finite element analysis software ANSYS. Additionally, a sensitivity analysis is performed to study the influence of the design variables on the structural optimum design. Results of this study provide a valuable reference for designers of underwater vehicles.

References listed at the end of the paper:


ABSTRACT: The method of solving static problems of nonlinear deformation, buckling, and postbuckling behavior of thin elastic inhomogeneous shells is based on the geometrically nonlinear equations of the 3D thermoelasticity theory and use of the moment finite-element scheme. A unified model has been created based on the universal spatial finite element with additional variable parameters. The model considers the multilayer structure of a material and geometrical features of structural elements of an inhomogeneous shell: casing of varying thickness, ribs, cover plates, cavities, channels, holes and sharp bends of the mid-surface. In a number of the authors’ works the reliability of linear and nonlinear solutions for a wide class of inhomogeneous shells has been numerically justified by analyzing their convergence and comparing them with those obtained by other authors. This paper is devoted to the comparative analysis of finite-element models and results of calculation of thin elastic shells using the moment finite-element scheme, and LIRA and SCAD program complexes. The effect of different types of weakening on nonlinear deformation and buckling of shells was studied on the example of isotropic panels under uniform pressure.

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53. Solovei N.A., Krivenko O.P. “Comparative analysis of solutions to buckling problems for flexible shells subject to different laws


ABSTRACT: An imperfection sensitivity analysis of cold-formed steel members in compression is presented. The analysis is based on Koiter’s approach and Monte Carlo simulation. If the modes interaction is correctly accounted, than the limit load and the erosion of critical buckling load can be easily evaluated. Thousands of imperfection can be analysed with very low computational cost and an effective statistical evaluation of limit performance can be carried out. The analysis is done on pallet rack uprights in compression, based on an intensive experimental study carried out at the Politehnica University of Timisoara.

Yuan-Hung Kuo, Bo-Siou Wei and Jeff Measamer (McDermott International Inc.), “A study on suction pile shell buckling and soil failure utilizing predicted and real-time monitored suction pressures during installation”, International Society of Offshore and Polar Engineers, 25th International Offshore and Polar Engineering Conference, 21-26 June, Kona, Hawaii, USA, 2015

ABSTRACT: Suction piles have been widely used for subsea foundations, since they are reliable and cost effective for subsea installation. Traditionally, suction piles were designed to sustain installation pressure against upper and lower limits derived from soil failure and tubular buckling. This traditional approach does not take into account the variation between the predicted required suction pressure and the real installation suction pressure and assumes the real suction pressure time history will fall into the zone between the predicted upper bound and lower bound pressure curves. For the traditional tubular buckling check, the thin plate effect and the
pile geometric imperfection are not well considered and experimented; therefore, the buckling capacity of the piles with large D/t ratios may be overestimated in certain circumstances. Recent studies on piles with large diameters have suggested that those piles often fail in plate buckling modes instead of tubular buckling mode during pile installation. In this paper, we presents the in-situ pump-in pressure history extracted from the real-time monitoring data during suction pile installation. The installation pressure curve is distinct from the predicted curve based on soil friction theory both in shape and in magnitude. The actual required suction pressure built overtime is found to be greater than the upper bound pressure curve and is dangerously close to the lower bound pressure curve of soil plug heave failure, even when the pile self-penetration depth falls into the predicted range. This observation suggests that the required pump-in pressure curve for a suction pile installation is not well predicted using traditional approach. The soil uncertainty cannot explain enough for the pressure curve deviation because a considerably large suction pressure is also observed at the initiation of the pressure-forced penetration minutes after the self-weight penetration stops. This initial large suction pressure suggests the initial soil setup effect was not fully understood before and this excessive pressure jump may fail the suction pile at this stage when the pile unbraced buckling length is at the longest. Lastly, in addition to developing the allowable suction pressure envelops using industrial codes specifically for plate and shell buckling, this paper recommends to structurally stiffen a suction pile so that the allowable structural buckling pressure curve is always greater than the soil-failure-based allowable suction pressure curve. Through this approach, the pile installability and structural integrity can be ensured. In the case when the soil plug failure occurs, the structurally sound pile will be still retrievable and reusable.


ABSTRACT: This paper discusses macro-geometrical, micro-geometrical and biomechanical features of eggshell, and proposes its inspiration for bionic design of submersible pressure hull. The results show that eggshell has excellent bionic performance on the weight-strength ratio, the span-thickness ratio, the aesthetic characteristics, the distribution of material and so on. The pressure endurance of the eggshell under uniform pressure is quite remarkable. Bionic design based on eggshell structure can effectively coordinate variable features of deep-sea pressure hull such as strength, stability, reserve buoyancy, streamline shape, space utilization in the crust and occupant comfort.

References listed at the end of the paper:


Sumec, J., & Jendželovský, N., et al. (2010). Architectural Bionics in civil engineering. Retrieved from http://www.e-bookspdf.org/view/aHR0cDovL21lY2gtaW5nLmNvbS9qb3VybmFsL0FyY2hpdmVvMjAxMC82LzIudGVobm9sb2dpeS8yMV9Lb3RyYXNvdmFSlMtTkotRUstS0stTVRNMjAxMC5wZGY=/QXJjaGl0ZWN0dXJhbCBCaW9uaWNzIEluIENpdmlsIEVuZ2luZWVyaW5n.


ABSTRACT: The material, form and geometric shape of egghave been designed in a way that nobody could
ever break an egg squeezing it lengthwise. This research is based on the pattern of human palm. Two soft and concave seating bases are built in order to hold the two ends of the chicken egg. Different chicken eggs with various geometric shapes were examined by Zwick compression strength test while they were raw, baked and empty. The maximum failing force (breaking of the egg) was 988 Newton. Static linear and nonlinear analysis and modeling of material and geometry is done by Ansys software or with Shell181 element. Early results show that chicken egg content has no effect on its load-application capacity and the reason of breaking are exceeded orbital tensile stresses. With the same thickness, eggs with length to width ratio of 1.4 have the highest load-application capacity and eggs with length to width ratio of 1.7 have the lowest load-application capacity.

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12. Ebubeir Aluntas, Ahmet Sekeroğ, "Effect of egg shape index on mechanical properties of chicken eggs", CANADIAN Received 28 May 2007; received in revised form 22 August 2007; accepted 30 August 2007 Available online 24 October 2007.

ABSTRACT: ANSYS 14.0 structural analysis software is used in order to make a ring rib-reticulated shell for the overall stability analysis. Considering the geometric nonlinear analysis and initial geometric imperfections influence, obtain a key node of the load-displacement curve and assess the ultimate strength of the structure. The results showed that the structure meets the "Space grid rules" for monolayer shells stability requirements. And it is found that load distribution form and initial geometry defect has a great deal with bearing capacity of single-layer lattice shell stability by comparison.

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ABSTRACT: We propose a method of modelling sail type structures which captures the wrinkling behaviour of such structures. The method is validated through experimental and analytical test cases, particularly in terms of wrinkling prediction. An enhanced wrinkling index is proposed as a valuable measure characterizing the global wrinkling development on the deformed structure. The method is based on a pseudo-dynamic finite element procedure involving non-linear MITC shell elements. The major advantage compared to membrane models generally used for this type of analysis is that no ad hoc wrinkling model is required to control the stability of the structure. We demonstrate our approach to analyse the behaviour of various structures with spherical and cylindrical shapes, characteristic of downwind sails over a rather wide range of shape and constitutive parameters. In all cases convergence is reached and the overall flying shape is most adequately represented, which shows that our approach is a most valuable alternative to standard techniques to provide deeper insight into the physical behaviour. Limitations appear only in some very special instances in which local wrinkling-related instabilities are extremely high and would require specific additional treatments, out of the scope of the present study.


ABSTRACT: The influence of alternating curvature on the dynamic instability domains of shells under combined static and dynamic loading is studied. It is shown that the range of safe harmonic loads for shells of revolution with sinusoidal generatrix can be extended compared with cylindrical shells.

References listed at the end of the paper:

ABSTRACT: Results are presented of investigations into determining the limit of the magnitudes of uniform external pressure, which when exceeded may cause the possible stability loss of equilibrium states of geometrically perfect ideally elastic spherical shells. Results of calculations of pressures corresponding to this boundary and understanding the necessary conditions of instability of the shells under consideration are close qualitatively and quantitatively to the lower boundary of their experimentally determined critical values. Investigations are performed based on the dynamic criterion of stability and equations of the unperturbed motion of shells linearized in the vicinity of the equilibrium states under consideration.

References listed at the end of the paper:

ABSTRACT: This project analyzes the effect of delamination size on the localized critical buckling load of a partially delaminated composite plate sublaminate under uniform, uniaxial compression. The plate being analyzed is a square, 24-layered, symmetric graphite/epoxy laminate composite of uniform thickness, with a centrally-located circular delamination between the fourth and fifth layers. A model, based on the code outlined in Reference (1), was built in the symbolic computation program Maple to conduct this analysis. The model first applies Classical Laminate Plate Theory to define the composite behavioral response to compression. It then applies the Ritz variational method to minimize the total potential energy of the system and create an expression from which the critical buckling load of the composite sublaminate can be predicted. The potential energy term is initially expressed in terms of known geometric dimensions and material properties, and unknown polynomial coefficients. The Newton-Raphson method solves for the values of the polynomial coefficients, which can then be substituted back into the sublaminate stress, strain, and displacement equations to fully describe the sublaminate behavior. By conducting this analysis at various loads, a load-strain plot illustrates the critical buckling load as a maximum point in the resulting curve. This process was repeated for delaminations of various diameters to understand the relationship between delamination size and the compressive-tolerance capabilities of composites. This analysis was validated by recreating the results of a model created in the Reference (1) study. After verifying the Maple model, the initial study was able to be expanded to support the goals of this project. Ultimately the project determined that as the delamination size increases, the strength of the composite can be severely reduced.

References listed at the end of the paper:

ABSTRACT: Free vibration of simply supported circular cylindrical shell made of Functionally Graded Material (FGM) under internal pressure was investigated. The effective material properties are assumed to vary continuously along the thickness direction according to a volume fraction power law distribution. First order shear deformation theory based on Love's first approximation theory was utilized in the equilibrium equations. The effects of FGM parameters such as material configuration and power law exponent, internal pressure as well as geometrical parameters such as thickness to radius and length to radius ratios on the vibration behavior were investigated. The validation of the results was achieved by comparing with those available in the literature. The results show that the vibration characteristics of Functionally Graded (FG) shells are greatly influenced by FGM parameters. Moreover, internal pressure and geometrical parameters considerably influence the frequency behavior regarded to different values of FGM parameters.


PARTIAL INTRODUCTION: The static stability analysis as a key problem for design of single-layer reticulated shells has become attractive to many researchers since late 1980s. Instead of traditional analytical method based upon “continuum theory”, the procedure of whole-course response analysis based upon non-linear finite element analysis and method for tracing equilibrium path was developed, by which the structural behavior along with the whole loading course of a complicated structure such like reticulated shell can be revealed clearly by the complete load-deflection curve, and the critical load can be accurately obtained. The effects of some practical factors such like the initial geometric imperfection of the structure and the unsymmetrical distribution of load can also be considered in this procedure. Based upon such a procedure, systematical elastic complete load-deflection analyses for different types of reticulated shells with varying geometric and structural parameters have been carried out. By nearly 20 years effort, the elastic stability of reticulated shells has been solved up to now [1-2]. Recently, the problem of elasto-plastic stability of reticulated shells gradually has become more attractive to researchers [3-4]. However, the analysis on elasto-plastic stability is much more complicated than elastic analysis because of distinguished characteristics between elastic stability and elasto-plastic stability. Plastic instability of reticulated shells exhibits obvious nonlinear and non-conservation features, it will be found that some new phenomena and mechanism of instable behaviors not seen before. Taking into consideration of material nonlinearity, the elasto-plastic stability performance of reticulated shells will change greatly, which
will be recognized only by plentiful elasto-plastic whole-course response analysis.

Four kinds of single-layer latticed domes constructed widely (Kiewitt 8, Kiewitt 6, Geodesic and Schwedler), are studied systematically with the software ANSYS, in which more than 144 cases of elasto-plastic whole-course analysis were carried out with different initial imperfection, geometric, structural and load parameters… References listed at the end of the paper:


ABSTRACT: Thin-walled cylindrical shells subjected to axial compression are sensitive to initial geometrical imperfections. Firstly, the influence of a single dimple imperfection on the load-carrying capacity of cylindrical shells is investigated by varying the amplitudes, directions and positions of the dimple imperfection. Then a single delta function is introduced to describe the profile of the dimple imperfection in a more general form, which enables to analyze conveniently the effect of the imperfect zone area on the load-carrying capacity of cylindrical shells. Thereafter, a surrogate-based optimization framework of determining the worst realistic imperfection is proposed to study the reduction of the buckling load of cylindrical shells based on a finite number of dimple imperfections. The possible dimple imperfections may be introduced during the service of cylindrical shells. Finally the effectiveness of the present method is demonstrated by an illustrative example.

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“Surrogate-based optimization of stiffened shells including load-carrying capacity and imperfection sensitivity”, Thin-Walled Structures, Vol. 72, pp 164-174, November 2013, DOI: 10.1016/j.twss.2013.06.004
ABSTRACT: Stiffened shells are very sensitive to initial imperfections, especially for geometrical imperfections. In this study, based on a 3-m-diameter orthogrid stiffened shell, post-buckling and imperfection sensitivity analyses are performed by use of explicit dynamic method. Result indicates that stiffened shell with outward hyperbolic generatrix shape shows a lower imperfection sensitivity as compared to the cylindrical one. Then, a framework of surrogate-based optimization including load-carrying capacity and imperfection sensitivity for stiffened shells is introduced, and the illustrative example demonstrates that the proposed framework has the potential to provide robust optimum design for realistic stiffened shells.

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DOI: 10.1016/j.twss.2014.05.004
ABSTRACT: An optimization framework of determining the worst realistic imperfection was proposed by the present authors to study the reduction of the load-carrying capacity of unstiffened cylindrical shells. However, with regard to stiffened shells, especially when cutouts are included, the dimple combination pattern should be judged in a more rational manner. In this study, node coordinates are utilized to describe the position of each dimple-shape imperfection for Worst Multiple Perturbation Load Approach (WMPLA), which is an improvement of the MPLA using an optimization algorithm to find the application positions that will reduce the buckling load. Further, a novel method to determine the density of possible positions of dimple-shape imperfections is proposed based on eigenmode shape for stiffened shells without cutout. In addition, the effects of cutouts on the proposed method are investigated in detail. The effectiveness of the proposed method is demonstrated by comparison of several conventional methods to obtain improved knockdown factors (KDFs).

ABSTRACT: Axial compression of metallic and composite spherical shells, and aluminium conical frusta were performed under both quasi-static and dynamic loading conditions. Quasi-static tests were conducted on an INSTRON machine and the impact tests on the gravity drop hammer setup. Spherical shells of different radii and thicknesses, and frusta of different semi-apical angles and different slenderness ratios were tested to identify various failure modes and to study the energy absorption capacities. Analysis was carried out in each case and the results obtained have been compared with experiments. A comparative study of the results obtained from the quasi-static and impact tests is also presented. A brief description of the work done on spherical shells and conical frusta is given below.


SUMMARY: Occurrence of non-axisymmetric collapse modes in axial compression of thin tubes has been studied both experimentally and with the help of FE simulation. Variables considered are tube diameter to thickness ratio, annealing, variation in tube wall thickness, eccentricity, and boundary conditions. It is seen that amongst other factors, a certain combination of thickness eccentricity and unsymmetrical in plane end conditions favours formation of diamond mode.

References listed at the end of the paper:


ABSTRACT: The present paper deals with the experimental and computational study of axial collapse of the aluminum metallic shells having combined tube-frusta geometry between two parallel plates. Shells were having bottom two third lengths as frusta and remaining top one third lengths as tube. Shells were compressed to recognize their modes of collapse and associated energy absorption capability. An axisymmetric Finite Element computational model of collapse process is presented and analysed, using a non-linear FE code FORGE2. Six noded isoparametric triangular elements were used to discretize the deforming shell. The material of the shells was idealized as rigid visco-plastic. To validate the computational model experimental and computed results of the deformed shapes and their corresponding load-compression and energy-compression curves were compared. With the help of the obtained results progress of the axisymmetric mode of collapse has been presented, analysed and discussed.

References listed at the end of the paper:
DOI: 10.1177/0021998302036008511

ABSTRACT: Composite domes made of short, randomly oriented glass fiber mats with polyester resin were subjected to axial compression in an Instron machine, in both empty and foam filled conditions. The domes were of different sizes and their generator was a parabola. The mechanics of deformation and the energy absorbing characteristics of the shells were studied, and their load compression curves are presented. The effect of foam filling on the response of the domes is discussed. Based on the experimental observations analytical expressions were formulated to find the average crush load and total strain energy by considering the energy absorbed in different mechanisms involved in the crushing process. The results thus obtained were compared with experimental results and these match well. Some conical shells made of the same material, height and diameter as those of domes were also subjected to axial compression, and their behavior is compared with those of the corresponding domes.

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ABSTRACT: Composite domes made of short, randomly oriented glass fiber mats with polyester resin were subjected to axial compression in an Instron machine, in both empty and foam filled conditions. The domes were of different sizes and their generator was a parabola. The mechanics of deformation and the energy absorbing characteristics of the shells were studied, and their load compression curves are presented. The effect of foam filling on the response of the domes is discussed. Based on the experimental observations analytical expressions were formulated to find the average crush load and total strain energy by considering the energy absorbed in different mechanisms involved in the crushing process. The results thus obtained were compared with experimental results and these match well. Some conical shells made of the same material, height and diameter as those of domes were also subjected to axial compression, and their behavior is compared with those of the corresponding domes.

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ABSTRACT: The paper presents experimental and analytical studies on axial compression of aluminium spherical shells having Radius/wall thickness \((R/t)\) ratios between 23 and 135. Quasi-static compressive load was applied centrally and with offset through a indenter having diameter of 22 mm. Testing was carried out on an INSTRON machine having 250 T capacity. Shells having different radius and wall thickness were tested, to classify their modes of collapse and their corresponding energy absorption mechanism. In experiments shells of lower \(R/t\) values were found to collapse due to formation of an inward dimple associated with a rolling plastic hinge in central as well as in offset loading. On the other hand, shells of higher \(R/t\) values were collapsed initially with formation of an axisymmetric inward dimple, but in later stage of compression showed buckling of non-symmetric shape consisting of integral number of lobes and stationary plastic hinges. The stationary hinges were formed between consecutive lobes. Experimental observations are used to propose an analytical model for prediction of load–compression and energy–compression curves. The results obtained from analytical model compared with the experimental results and found match fairly well.

Jayashree Sengupta and Dipankar Chakravorty (Jadavpur University, Kolkata, India), “Progressive failure analysis of laminated composite shells – a review”, (publisher and date not given; Most recent citation is 2012.)

http://www.academia.edu/7423161/Progressive_Failure_Analysis_of_Laminated_Composite_Shells_A_Review

ABSTRACT: Composite materials present striking potentials to be tailored for advanced engineering applications. Thin walled composite panels are one of the most utilized structural elements in construction. The increasing use of the composites necessitates for the precise and viable methods of analysis- the life prediction being an important issue. The initiation and propagation of failure until final fracture of the structure assesses the life of the structure. Unnoticed internal failures may lead to fatal collapse, thus making first ply and progressive failure of much concern to researchers. This paper addresses the various literatures that have been published so far associated with the progressive failure of the composite laminated shells; also it reflects the five failure theories working behind. References listed at the end of the paper:

(cannot easily cut and paste them.)


ABSTRACT: An experimental and numerical study of the buckling behavior of cantilevered shells with opening and stiffening is presented in this paper. Unlike previous experimental studies, the present work focuses on shell slenderness as well as opening and stiffening reflecting the main geometric characteristics of wind turbine towers. The specimens can be classified as medium slenderness shells affected mainly by inelastic effects and secondarily by geometric imperfections. Both load–displacement curves as well as strain measurements are presented and compared with numerical predictions by finite element analyses, accounting for both inelastic effects and geometrical nonlinearity as well as for contact interaction between the various parts of the specimens. A good agreement between numerical and experimental results was found in terms of load–displacement curves and ultimate load. Due to the influence of the shape and size of geometric imperfections, a complete match of the numerically obtained strains to the corresponding experimental ones was not possible. The provided stiffening was found to be able to compensate the strength loss due to the presence of the cut-out.

ABSTRACT: Objective of this paper is to compare linear buckling analysis formulations, available in commercial finite element programs. Modern steel design codes, including Eurocode 3, make abundant use of linear buckling loads for calculation of slenderness, and of linear buckling modes, used as shapes of imperfections for nonlinear analyses. Experience has shown that the buckling mode shapes and the magnitude of buckling loads may differ, sometimes significantly, from one algorithm to another. Thus, three characteristic examples have been used in order to assess the linear buckling formulations available in the finite element programs ADINA and ABAQUS. Useful conclusions are drawn for selecting the appropriate algorithm and the proper reference load in order to obtain either the classical linear buckling load or a good approximation of the actual geometrically nonlinear buckling load.


DOI: 10.1016/j.jmps.2014.09.005

ABSTRACT: Surface wrinkling of a cylindrical shell supported by a soft core subjected to axial compression is investigated via combined experimental, computational and theoretical efforts. Our experiments show that the post-bifurcation deformation mode of the system is axisymmetric when the modulus ratio of the surface layer to the core is small while a non-axisymmetric wrinkling pattern appears when the modulus ratio is large. Our nonlinear finite element simulations have confirmed this experimental finding. A theoretical analysis based on Koiter’s elastic stability theory is carried out to reveal the mechanisms underpinning the phenomenon of morphological evolution. The critical buckling analysis shows that the first bifurcation mode is axisymmetric for arbitrary modulus ratios of the shell to the core. Post-bifurcation analysis reveals that the system will evolve into a diamond-like mode when the modulus ratio is large enough but keep the axisymmetric mode if the modulus ratio is smaller than a critical value. The results can guide the creation of controlled surface wrinkles on a cylindrical surface under compression. Besides, the analysis approach presented here may be adopted to understand the wrinkling patterns observed in some natural systems generated by, for instance, differential growth.

References listed at the end of the paper:

ABSTRACT: Buckling mode interaction of elastic systems in the presence of, thus obtaining results with questionable validity in the post-buckling range. In order to acquire additional insight into this issue, in the first part of the present paper, two different versions of the well-known 2-DOF Augusti model, whose independent buckling modes are both stable, are studied analytically without any simplifying assumptions with respect to the magnitude of deformation, in order to accurately demonstrate the coupling phenomena in the presence of imperfections in the pre- and post-buckling range. Depending on the nature of the structure’s rotational springs, its post-buckling equilibrium path may be either stable or unstable. Afterward, the elastic response of two examples of laced built-up columns is illustrated numerically, one characterized by interaction between in-plane global and local buckling and the other by in- and out-of-plane global buckling, featuring similar response to that of the two 2-DOF models, respectively, thus demonstrating occurrence of such behavior in actual structural systems.

References listed at the end of the paper:


ABSTRACT: An approximate analytical method for quantifying the lateral resistance offered by inclined cables to guyed towers, such as the pylons of cable-stayed bridges, is presented first. For this purpose, an analytical expression was derived for the evaluation of the pylon's effective buckling length. Taking into account the cables’ inclination and prestressing and approximating the nonlinearity caused by sag using Dischinger's formula, the cables were substituted by horizontal translational springs of equivalent stiffness. Then, an analytical solution of the linear buckling load of the equivalent spring model was obtained. The presented analytical method can be very useful at the preliminary design stage. Then, the approximate results were compared to the ones extracted from geometrically nonlinear finite element analysis with imperfections (GNIA) of both the more exact cable–pylon model and the spring–pylon model. The results show that the critical buckling load is predicted with very good accuracy for a wide range of values of cable inclination and pretensioning and indicate an unstable post-buckling behavior. In- and out-of-plane buckling of pylons with single or multiple levels of cables, in either a fan or a harp arrangement, with either a fixed or a hinged base, is addressed. A parametric analysis showed a strong imperfection sensitivity leading to significantly smaller ultimate loads of the imperfect structures compared to the linear buckling loads.

Stelios Vernardos and Charis Gantes, “Preliminary feasibility investigation of initial imperfections is well known to have a detrimental effect on the response of a wide range of structural systems. This has been demonstrated mostly analytically for simple models, assuming small displacements sandwich type shells for wind turbine towers”, 8th Hellenic National Conference on Steel Structures, Tripoli, Greece (year not given, probably 2015; abstract not given).


ABSTRACT: A methodology is presented on assessing the effectiveness of flexible joints in mitigating the consequences of faulting on buried steel pipelines through a comprehensive analysis that incorporates the uncertainty of fault displacement magnitude and the response of the pipeline itself. The proposed methodology is a two-step process. In the first step the probabilistic nature of the fault displacement magnitude is evaluated by applying the Probabilistic Fault Displacement Hazard Analysis, considering also all pertinent uncertainties. The second step is the “transition” from seismological data to the pipeline structural response through the fault displacement components as the adopted vector intensity measure. To mitigate the consequences of faulting on pipelines, flexible joints between pipeline parts are proposed as innovative measure for reducing the deformation of pipeline walls. Thus, the mechanical behavior of continuous pipelines and pipelines with flexible joints is numerically assessed and strains are extracted in order to develop the corresponding strain hazard curves. The latter are a useful engineering tool for pipeline – fault crossing risk assessment and for the effectiveness evaluation of flexible joints as innovative mitigating measures against the consequences of faulting on pipelines.

References listed at the end of the paper:

ABSTRACT: The effectiveness of the numerical methods GMNIA and MNA/LBA proposed in EN1993-1.6 for the design of steel shells is studied for cylindrical steel shells with an unreinforced or reinforced rectangular cutout chamfered elliptically at the four ends and for the corresponding shells without cutout. Moreover, another design method proposed in the literature and denoted here as MNA/GNA, which is based on a modified slenderness, is also evaluated. GMNIA is considered as the most reliable analysis type, provided that a judicious choice of shape and amplitude of initial imperfections is made. Thus, GMNIA results are used as basis for comparison, except for shells without cutout where the EN1993-1.6 normative strengths could serve the same purpose as well. For shells without cutout it is found that the modified slenderness gives similar results to the corresponding results of the conventional slenderness definition. In the case of unreinforced cutout the modified slenderness gives better results, thus the use of MNA/GNA is recommended. However, in the case of reinforced cutout the GMNIA results are approximated better by employing the conventional slenderness, thus MNA/LBA is more appropriate.


ABSTRACT: An analytical solution is presented to predict the mean axial collapse forces of fiber reinforced conical shells under thermal loading, in which the fibers wrapped orientation is arbitrary; Analytical method and finite element simulate; The influences of thermal loading, fibers wrapped orientations, geometrical eccentricity factor and proportionality coefficient on the axial collapse force of fiber reinforced conical shells are given. The collapse loading Pm of fiber-reinforced conical shells appears in the maximum value under different thermal environment when the fibers wrapped direction equals 45°. By optimizing the wrapping orientation of fiber layers, the capability of energy absorption of fiber-reinforced conical shells can be enhanced.

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ABSTRACT: We consider the point indentation of a pressurized, spherical elastic shell. Previously it was shown that such shells wrinkle once the indentation reaches a threshold value. Here, we study the behaviour of
this system beyond the onset of instability. We show that rather than simply approaching the classical “mirror-buckled” shape, the wrinkled shell approaches a new, universal shape that reflects a nontrivial type of isometry. For a given indentation depth, this “asymptotic isometry”, which is only made possible by wrinkling, is reached in the doubly asymptotic limit of weak pressure and vanishing shell thickness.

References listed at the end of the paper:


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ABSTRACT: A simple and effective in situ method for strengthening or healing thin-wall structures is presented. In this method, a liquid-state gap-sealing foam is injected within the enclosed spaces of a structure.
After injection it expands to fill and pressurize the cavities, then solidifies in few hours. The stiff pressurized foam enhances load carrying capacity both by supporting part of the load, and by retarding the buckling of thin-wall structural components. A simple demonstration of the proposed technique is provided by load-testing thin-wall beverage cans, and also both intact and damaged aluminum honeycomb, filled with commercially available gap-sealing polyurethane foam. By adding foam, the structures’ peak load and energy absorption were significantly enhanced. The injected foam partially restored the original undeformed shape during unloading, highlighting the potential advantage to apply this method for multiple-use energy absorbing components.

References listed at the end of the paper:
ABSTRACT: We present a straightforward method for fabricating nanochannels that exploits a type of thin film instability called folding, which emerges during post-instability evolution of surface wrinkles. In our experiments, a flat PDMS substrate was uniaxially stretched and treated with oxygen plasma for varying durations, resulting in formation of a stiff-oxidized skin of varying thickness on the surface. Thereafter, the stretch was released to induce a compressive strain, defined as the change in length per unit of the initial length of the substrate, in the skin. At small strain levels, wrinkles appeared on the substrate surface, forming open channels with a specific wavelength and amplitude. Further increase in the strain level triggered the transition from wrinkles to folds, creating well-defined closed channels with a diameter in the nanoscale range. The characteristic dimensions of the channels such as wavelength, amplitude, and diameter were robustly tunable by changing the duration of oxygen plasma treatment and strain level. Furthermore, the configuration of the channels was switchable from open to closed and vice versa by controlling the strain level.

References listed at the end of the paper:
ABSTRACT: A hierarchical modeling of planar steel frames that is based on a weak coupling of shell and beam computational models is studied in detail. A shell finite element is used to compute failure response of a representative part of each column and each beam of a frame under consideration; elasto-plasticity, geometrical nonlinearity and material softening (along with a localization limiter) are taken into account. The computed results, which naturally include local buckling and/or localized material failure effects, are further incorporated into a beam inelastic stress-resultant constitutive model; the embedded-discontinuity-in-rotation Euler-Bernoulli finite element is considered in this work. The designed beam finite element formulation can be effectively used for the failure analysis of the steel frame. Important issues of such weak coupling concept are presented and results of several numerical simulations are discussed. A concept for analysis of steel frames, which couples shell and beam models, has been studied. The resulting steel frame analysis takes into account local buckling and localized material failure. The concept has large potential for practical applications.

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ABSTRACT: Nonlinear finite element (FE) collapse pressure predictions are compared to experimental results for submarine pressure hull test specimens with and without artificial corrosion and tested to collapse under external hydrostatic pressure. The accuracy of FE models, and their sensitivity to modeling and solution procedures, are investigated by comparing FE simulations of the experiments using two different model generators and three solvers. The standard FE methodology includes the use of quadrilateral shell elements, nonlinear mapping of measured geometric imperfections, and quasi-static incremental analyses including nonlinear material and geometry. The FE models are found to be accurate to approximately 11%, with 95% confidence, regardless of the model generator and solver that is used. Collapse pressure predictions for identical FE models obtained using each of the three solvers agree within 2.8%, indicating that the choice of FE solver does not significantly affect the predicted collapse pressure. The FE predictions are found to be more accurate for corroded than for undamaged models, and neglecting the shell eccentricity that arises due to one-sided shell thinning is found to significantly decrease the resulting accuracy of the FE model.


ABSTRACT: The subject of the numerical investigation is an ellipsoidal head with a central (axis-symmetrical) nozzle. The nozzle is loaded by axial load force. The ellipsoidal head is under axial-symmetrical compression load. The numerical FEM model is elaborated. The calculation will provide the critical loads and equilibrium paths for the sample head. The investigation will measure the influence of the diameter of the nozzle on the critical state of the ellipsoidal head.

References listed at the end of the paper:

Deyu Liu (1), Xinxing Peng (1,2), Binghui Wu (1,2), Xueyun Zheng (1), Tracy T Chuong (1), Jialuo Li (1), Shigang Sun (2), and Galen D. Stucky (1)
ABSTRACT: We have developed a facile procedure that can create asymmetrical building blocks by uniformly deforming nanospheres into $C_{\infty v}$ symmetry at low cost and high quality. Concave polystyrene-carbon (PS-C) core–shell nanospheres were produced by a very simple microwave-assisted alcohol thermal treatment of spherical PS-C nanoparticles. The dimensions and ratio of the concave part can be precisely controlled by temperature and solvents. The concavity is created by varying the alcohol-thermal treatment to tune the swelling properties that lead to the mechanical deformation of the PS-C core–shell structure. The driving force is attributed to the significant volume increase that occurs upon polystyrene core swelling with the incorporation of solvent. We propose a mechanism adapted from published models for the depression of soft capsules. An extrapolation from this model predicts that the rigid shell is used to generate a cavity in the unbuckled shell, which is experimentally confirmed. This swelling and deformation route is flexible and should be applicable to other polymeric nanoparticles to produce asymmetrical nanoparticles.

Konstantinos Tsavdaridis and Christopher Pilbin (School of Civil Engineering, University of Leeds), “Finite Element modelling of steel connections with web openings: Aseismic design and avoidance of progressive collapse”, The 7th European Conference on Steel and Composite Structures, Napoli, Italy, September 2014
PARTIAL INTRODUCTION: Events of extreme loading on structures such as the 1994 Northridge, California earthquake and the 2001 attack on the World Trade Centres, New York have not only lead to loss of life but highlighted structural deficiencies and lack of existing knowledge of the progressive collapse behaviour. As a result, Governmental bodies such as the GSA [1] and DoD [2] have established design codes and guidelines to reduce the possibility of progressive collapse through the promotion of redundancy, ductility and continuity in structural systems. The design codes do not provide guidelines for the complete prevention of progressive collapse but rather mitigate a ‘disproportionate’ area of collapse. In collapse scenarios, following the removal of a load bearing column, the ability for the beams and columns to develop catenary action is essential for the structure to resist further collapse. Beam-to-column connections should provide sufficient ductility to sustain large rotations and allow structural members to carry loads in tension. . . . In order to enhance the ductility of post Northridge connections, researchers suggested the weakening of the beam to shift the stresses away from the column’s face. One method to achieve this is by removing portions of the flanges or the web weakening the beam locally, referred to as Reduced Beam Section (RBS) and Reduced Web Section (RWS), respectively. . . . References listed at the end of the paper:
ABSTRACT: Liquid storage steel tanks are vertical above-ground cylindrical shells and as typical thin-walled structures, they are very sensitive to buckling under wind loads, especially when they are empty or at low liquid level. Previous studies revealed discrepancies in buckling resistance of empty tanks between the design method proposed by the American Standard API 650 and the analytical formulas recommended by the European Standard EN1993-1-6 and EN1993-4-2. This study presents a comparison between the provisions of current design codes by performing all types of numerical buckling analyses recommended by Eurocodes (i.e. LBA-linear elastic bifurcation analysis, GNA-geometrically nonlinear elastic analysis of the perfect tank and GNIA-geometrically nonlinear elastic analysis of the imperfect tank). Such analyses are performed in order to evaluate the buckling resistance of two existing thin-walled steel tanks, with large diameters and variable wall thickness. In addition, a discussion is unfolded about the differences between computational and analytical methods and the conservatism that the latter method imposes. An influence study on the geometric imperfections and the boundary conditions is also conducted. Investigation on the boundary conditions at the foot of the tank highlights the sensitivity to the fixation of the vertical translational degree of freedom. Further, it is indicated that the imperfection magnitude recommended by the EN1993-1-6 is extremely unfavorable when applied to large diameter tanks. Comments and conclusions achieved could be helpful in order to evaluate the safety of the current design codes and shed more light towards the most accurate one.

References listed at the end of the paper:

References listed at the end of the paper:


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ABSTRACT: Stiffened shells are affected by numerous uncertainty factors, such as the variations of manufacturing tolerance, material properties and environment aspects, etc. Due to the expensive experimental cost of stiffened shell, only a limited quantity of statistics about its uncertainty factors are available. In this case, an unjustified assumption of probabilistic model may result in misleading outcomes of reliability-based design optimization (RBDO), and the non-probabilistic convex method is a promising alternative. In this study, a hybrid non-probabilistic convex method based on single-ellipsoid convex model is proposed to minimize the weight of stiffened shells with uncertain-but-bounded variations, where the adaptive chaos control (ACC) method is applied to ensure the robustness of search process of single-ellipsoid convex model, and the particle swarm optimization (PSO) algorithm together with smeared stiffener model are utilized to guarantee the global optimum design. A 3 m-diameter benchmark example illustrates the advantage of the proposed method over RBDO and deterministic optimum methods for stiffened shell with uncertain-but-bounded variations.

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MA Weilin (1), YU Jianxing (1), ZHOU Qingji (1), XIE Bin (2), CAO Jing (2) and LI zhibo (1)
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“Nonlinear contact between inner walls of deep sea pipelines in buckling process”, J. Ocean Univ. China

ABSTRACT: In order to study buckling propagation mechanism in deep sea pipelines, the contact between pipeline’s inner walls in buckling process was studied. A two-dimensional ring model was used to represent the pipeline and a nonlinear spring model was adopted to simulate the contact between inner walls. Based on the elastoplastic constitutive relationship and the principle of virtual work theory, the coupling effect of pipeline’s nonlinear large deformation and wall contact was included in the theoretical analysis with the aid of MATLAB, and the application scope of the theoretical model was also discussed. The calculated results show that during the loading process, the change in external pressure is closely related to the distribution of section stress, and once the walls are contacting each other, the external pressure increases and then remains stable after it reaches a specific value. Without fracture, the pipeline section will stop showing deformation. The results of theoretical calculations agree well with those of numerical simulations. Finally, in order to ensure reliability and accuracy of the theoretical results, the collapse pressure and propagation pressure were both verified by numerical simulations and experiments. Therefore, the theoretical model can be used to analyze pipeline’s buckling deformation and contact between pipeline’s inner walls, which forms the basis for further research on three-dimensional buckling propagation.

References listed at the end of the paper:

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ABSTRACT: Imperfection sensitivity of cylindrical shells subjected to axial compressive load is investigated by means of nonlinear buckling analysis and post-buckling analysis. Nonlinear buckling analysis involves the determination of the equilibrium path (or load-deflection curve) up to the limit point load by using the Newton-Raphson approach, whereas post-buckling analysis involves the determination of the equilibrium path beyond the limit point and up to the collapse load by using the arc-length approach. Limit point loads evaluated from these two approaches for various imperfection magnitudes show an excellent agreement, which clearly confirms the numerical results obtained. Finally, the influence of L/D and R/t ratios on post-buckling behavior of isotropic and composite cylindrical shells is briefly highlighted.

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“Apparent strain of a pipe at plastic bending buckling state”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 37, No. 6, pp 1811-1818, November 2015
ABSTRACT: An expression for apparent strain of a pipe at plastic bending buckling status is proposed in the present paper. The material of the pipe is considered as a rigid-perfectly plastic one, and the cross section of the pipe during the pipe-bending process assumes to be elliptic gradually. The energy rate for the pure bending of the elliptic pipe is proposed firstly, and the energy rate of cross-sectional ovalizing of the pipe is derived
afterward. Furthermore, both the energy rates are combined to analyze the pipe bending buckling. As a result, an apparent strain expression of a pipe at the plastic bending buckling status is proposed. The predicted result of the new strain expression of pipe bending at buckling status is compared with the available test data and shows that the new formula is reasonable.

References listed at the end of the paper:

ABSTRACT: A parametric study on circular thin-walled pipes subjected to pure bending is performed. Both straight and curved pipes are considered. Ratio D/t, initial pipe curvature and internal pressure are the parameters varying in the analyses. The study is mainly FEA-based. It is found that negative curvatures (opposite to bending moment) considerably increase stiffness and buckling limit of the pipe when no internal pressure is acting and, similarly, positive curvatures decrease the stiffness and buckling limit. For internal pressurised pipes the effects of initial pipe curvature are less relevant. Results show that this phenomenon is in relationship with the cross-section deformation due to bending moment, which undergoes relevant ovalisation for no pressurised pipes and little ovalisation for pressurised pipes.

References listed at the end of the paper:


ABSTRACT: This paper presents results from a recent combined experimental-analytical study of the inelastic response and the sequence of events that lead to collapse of pipes bent under internal pressure. Experimental results from stainless steel 321 seamless tubes with D/t of 52 are reported. The tubes were loaded by pure bending at fixed values of pressure ranging from zero to a value that corresponds to 0.75 times the yield pressure. The moment-curvature response is governed by the inelastic characteristics of the material. Bending induces some ovalization to the tube cross section while, simultaneously, the internal pressure causes the circumference to grow. Following some inelastic deformation, small amplitude axial wrinkles appear on the compressed side of the tube, and their amplitude grows stably as bending progresses. Eventually, wrinkling localizes, causing catastrophic failure in the form of an outward bulge. Pressure increases the wavelength of the wrinkles as well as the curvature at collapse. The onset of wrinkling is established by a custom bifurcation buckling formulation. The evolution of wrinkling and its eventual localization are simulated using a FE shell model. The material is represented as an anisotropic elastic-plastic solid using the flow theory, while the models are assigned initial geometric imperfections that correspond to the wrinkling bifurcation mode. It will be shown
that all aspects of the observed behavior including the failure by localized bulging can be successful reproduced by the models developed.

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ABSTRACT: This paper deals with the combined effect of pressure and geometric imperfection on buckling of stressed thin films on a semi-infinite rigid substrate. Analytical approximate solutions are proposed by using the total potential energy of the system and the Rayleigh–Ritz’s method, and their stabilities are also determined. The present analytical approximate solutions agree very well with the numerical solutions obtained via the improved shooting method. The effect of pressure mismatch together with imperfection on the critical stress (above which the film buckles) and on the film-center deflection is characterized. It is found that, compared with the classical case of the Euler column buckling, the equilibrium solutions and critical stress of the film are strongly dependent on the linear combination of the pressure mismatch and imperfection amplitude.

References listed at the end of the paper:

ABSTRACT: This paper investigates the delamination buckling of an orthotropic film with compressive prestress bonded to an orthotropic substrate. The buckled film detached from the film/substrate structure is solved in the closed form except for the resultant force and bending moment at the ends of the buckled film, which are obtained by matching the solutions for the buckled film and the film/substrate structure in which the buckled part of the film is removed. Special attention is paid to the effects of parameters of orthotropic materials on delamination buckling based on a numerical analysis. The energy release rate and mode mixity induced by buckling are evaluated, and the growth and arrest of the interface crack under mixed loading induced by buckling are discussed based on the energy criterion.

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A. Shahrjerdi and B. Bahramibabamiri (Department of Mechanical Engineering, Malayer University, Malayer, Iran), “The effect of different geometrical imperfection of buckling of composite cylindrical shells subjected to axial loading”, International Journal of Mechanical and Materials Engineering, Vol. 10, No. 6, December 2015

ABSTRACT: The effects of geometric properties, lamina lay-up, amplitudes of imperfection and parametric research of the shape (square, circular) and the dimensions (axial and circumferential sizes, diameter) of the opening on the strength of the cylinders under compression were studied. The measurement of imperfections on the cylindrical surface is achieved using the interpolation method and Fourier series. The analysis indicates that the critical load is sensitive to the circumferential size of the opening. The function (critical load-circumferential size of the opening) is linear for large openings and independent of the geometrical imperfections of the shell. However, for small openings, it is necessary to take into account the coupling between the initial geometrical imperfections and the openings. The linear approach does not fit due to the importance of the evolution of the displacements near the openings. Also, it was shown that the buckling behaviour of thin composite cylindrical shells can be evaluated accurately via modelling to determine the imperfections and the material properties in FEM.

References listed at the end of the paper:

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ABSTRACT: Imperfection sensitivity of cylindrical shells subjected to axial compressive load is investigated by means of nonlinear buckling analysis and post-buckling analysis. Nonlinear buckling analysis involves the determination of the equilibrium path (or load-deflection curve) upto the limit point load by using the Newton-Raphson approach, whereas post-buckling analysis involves the determination of the equilibrium path beyond the limit point and upto the collapse load by using the arc-length approach. Limit point loads evaluated from these two approaches for various imperfection magnitudes show an excellent agreement, which clearly confirms the numerical results obtained. Finally, the influence of L/D and R/t ratios on post-buckling behavior of isotropic and composite cylindrical shells is briefly highlighted.

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excessively to a failure. Accordingly, the proposed model considered an imaginary patch plate on a long plate.

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Dynamic buckling response of long plates for the prediction of local plate buckling of corrugated core sandwich columns”, Journal of Applied Mechanics, Vol. 82, No. 11, 111008, September 2015 (12 pages)

ABSTRACT: An analytical model predicting the dynamic local buckling failure of plates with a large dimension in the longitudinal direction compressed at a constant rate was proposed. The model began with the hypothesis that the proposed analytical approach could be an alternative methodology to approximate the dynamic local plate buckling response of constituent plates of corrugated core sandwich columns. Prior to the model development, four preliminary finite-element (FE) simulations were conducted to observe the typical dynamic response of the sandwich columns having thin core web plates or thin face sheets. From the simulations, several wrinkles with a regular pattern were generated, and then one of the wrinkles grew excessively to a failure. Accordingly, the proposed model considered an imaginary patch plate on a long plate
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“Spiral welded tubes – imperfections, residual stresses, and buckling characteristics”, Eighth International Conference on Advances in Steel Structures, Lisbon, Portugal, July 22-24, 2015

ABSTRACT: Spiral Welded Tubes (SWTs) are manufactured from steel coil, which is de-coiled and levelled by using cold rolling. The edges of the plate material are bevelled and set for welding containing preheating, if required. The coil is then cold formed into a spiral with a series of rollers and welded into a continuous tube. The rolling equipment applies a significant force to the plate material during production that can increase geometric imperfections in the tube wall. At the spiral welds a high or low imperfection can exist and weld shrinkage could cause local imperfections. Internal residual stresses are the main drawback of SWTs compared with longitudinally welded tubes (LWTs). SWTs offer cost benefits when compared with other types of tubes and they have successfully been used for low-pressure applications, water supply, and structural components. The aim of this paper is to investigate the imperfections, residual stresses, and buckling characteristics of SWTs in comparison with LWTs.

References listed at the end of the paper:
The calculations were carried out with FEM using ABAQUS. The results show that silos with corrugated sheets are significantly more economical and less sensitive to initial geometric imperfections than silos with flat sheets.

References listed at the end of the paper:


ABSTRACT: This study examines the buckling of a single strip of material, modeled as a two-dimensional (2D) micropolar solid. The effects of material microstructure are incorporated by modeling the material using micropolar theory. By setting the micropolar constants to zero, the equations of classical elasticity are obtained and these results are compared to the buckling analysis performed by previous authors on elastic materials. In the limiting case, when the thickness of the strip becomes small in comparison to the overall length, the micropolar beam equations are developed. Because buckling analysis requires the consideration of geometric nonlinearity, nonlinear micropolar equations are derived using a variational procedure, which also results in variationally consistent boundary conditions. Due to the complexity of micropolar theory, its application has been limited to linear analysis with a few exceptions.

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ABSTRACT: The high-polymeric degree or molecular-weight of self-made polyethoxydisiloxane (PEDS) was successfully used to synthesize aerogels with several advantageous mechanical characteristics, compared with those based on conventional tetraethylorthosilicate (TEOS) aerogel preparation methods. The first advantage is their lower initial values of bulk modulus (K0), compared with those prepared via the two-step method; this is due to release of internal stress during the shrinkage of wet gel. Secondly, a collapse index n of -0.125 is obtained by the collapse law; this implies a new buckling destruction model. This is different from those prepared via the two-step method, and suggests that a hierarchical filament structure, formed by the connection of nano-particles, constitutes the solid skeleton of pores. In this paper, average aerogel pore sizes between 16.0 and 39.3 nm are analyzed by the combination of Mercury Intrusion Porosimetry (MIP) and Nitrogen Adsorption–Desorption (NAD). The microstructure and morphology of the aerogels are demonstrated by Transmission Electron Microscopy (TEM) and Field Emission Scan Electron Microscopy (FE-SEM).
M. Mohammadi and M. Fooladi Mahani (Department of Mechanical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran), “An analytical solution for buckling analysis of size-dependent rectangular micro-plates according to the modified strain gradient and couple stress theories”, Acta Mechanica, Vol. 226, No. 10, pp 3477–3493, October 2015

ABSTRACT: In this study, a size-dependent Kirchhoff plate model is developed for determining the critical buckling loads of rectangular micro-plates. Modified strain gradient theory with three length scale parameters is used. It should be noted that this theory is reduced to modified couple stress theory by setting two length scale parameters to zero. Using the variational approach and the principle of minimum total potential energy, the nonlinear form of the governing equations and all possible boundary conditions are determined. It is assumed that the micro-plate is simply supported on two opposite edges. The stability equations are solved analytically, and the critical buckling loads are obtained based on the modified strain gradient and modified couple stress theories. Also, the effects of length scale parameters, dimensions and loading states on the buckling loads are investigated in detail.

References listed at the end of the paper:

ABSTRACT: In this article, an analytical method for buckling analysis of thin functionally graded (FG) rectangular plates is presented. It is assumed that the material properties of the plate vary through the thickness of the plate as a power function. Based on the classical plate theory (Kirchhoff theory), the governing equations are obtained for functionally graded rectangular plates using the principle of minimum total potential energy. The resulting equations are decoupled and solved for rectangular plate with different loading conditions. It is assumed that the plate is simply supported along two opposite edges and has arbitrary boundary conditions along the other edges. The critical buckling loads are presented for a rectangular plate with different boundary conditions, various powers of FGM and some aspect ratios.

References listed at the end of the paper:


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“Buckling analysis of orthotropic rectangular plate resting on Pasternak elastic foundation under biaxial in-plane loading”, Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2015.1059528
ABSTRACT: In this study, buckling of rectangular orthotropic plates resting on Pasternak elastic foundation under biaxial in-plane loading by the power series method (the method of Frobenius) was analyzed. Similar to many studies, two opposite edges of loading is simply supported and two other edges is assumed clamped. In order to extract the characteristic equations of orthotropic rectangular plate under in-plane loading resting on a pasternak elastic foundation, the classical plate theory by considering the interaction between plate and foundation is used. The results showed that in the aspect ratio of less than 2, existing Pasternak foundation caused to increase the buckling load severely, but by increasing the aspect ratio, the effect of foundation is negligible. Applying the in-plane load in the y-direction caused to decrease the buckling load, but by increasing the aspect ratios the effect of the load is negligible.

Marcos A. Reyes-Martinez, Alfred J. Crosby and Alejandro L. Briseno (Polymer Science and Engineering, University of Massachusetts, Amherst, Massachusetts, USA), “Rubrene crystal field-effect mobility modulation via conducting channel wrinkling”, Nature Communications, Vol. 6, Article No. 7948, May 2015, DOI: 10.1038/ncomms7948
ABSTRACT: With the impending surge of flexible organic electronic technologies, it has become essential to understand how mechanical deformation affects the electrical performance of organic thin-film devices. Organic single crystals are ideal for the systematic study of strain effects on electrical properties without being concerned about grain boundaries and other defects. Here we investigate how the deformation affects the field-effect mobility of single crystals of the benchmark semiconductor rubrene. The wrinkling instability is used to apply local strains of different magnitudes along the conducting channel in field-effect transistors. We discover that the mobility changes as dictated by the net strain at the dielectric/semiconductor interface. We propose a model based on the plate bending theory to quantify the net strain in wrinkled transistors and predict the change in mobility. These contributions represent a significant step forward in structure–function relationships in organic semiconductors, critical for the development of the next generation of flexible electronic devices.
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“Assessment of stiffening type of the cutout in tubular wind turbine towers under artificial dynamic wind”, J.
ABSTRACT: The effectiveness of alternative stiffening types of the cutout provided near the base of tubular
steel wind turbine towers is assessed, taking into account the dynamic nature of wind loading. To that effect,
artificial wind load time histories are first obtained using the public domain aero-elastic code FAST. Finite
element models that have been previously validated by means of comparison with experimental results, are then
used to carry out fully nonlinear dynamic analyses and compare strength and overall structural performance.

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“Buckling behavior of bidirectional composite flat panels with delamination in hygrothermal field”, Acta
ABSTRACT: Hygrothermal influence on the buckling behavior of bidirectional glass/epoxy composite panels
having delaminations was studied numerically and verified by conducting several experiments. First-order shear
deformation theory was used to develop a finite element model for numerical predictions with an 8-noded
quadratic isoparametric element that takes care of the effects of delamination area and hygrothermal conditions
of composite panels. Verification of results of the numerical analysis was done by conducting several
experiments showing the effects of various parameters like temperature, moisture, area of delaminations,
orientations of fibers, stacking sequence and boundary conditions on the buckling characteristics of
bidirectional glass/epoxy composite panels. Experimental buckling loads were calculated using an INSTRON
8862 universal testing machine for hygrothermally treated composite panels having delaminations. It was
observed that there is a good comparison of predicted and experimental buckling loads. The effects of various
parameters on the buckling behavior of composite panels are presented. The buckling results can be utilized as a
tool for detection of delamination damage in composite plates subjected to hygrothermal environment.

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9. Pietropaoli E., Riccio A.: Finite element analysis of the stability (buckling and post-buckling) of composite laminated structures:
10. Fazzolari F.A., Banerjee J.R., Boscolo M.: Buckling of composite plate assemblies using higher order shear deformation theory —
ABSTRACT: In industrial applications structural efficiency is primary concern, this brings about the need of strong and lightweight materials. Due to their high specific strength, fibre reinforced polymers find wide application in these areas. Panels made of composite materials are widely used in aerospace structures.
automobile, civil, marine and biomedical industries because of their good mechanical properties, impact resistance, excellent damage tolerance and also low fabrication cost. In this Paper, buckling and post-buckling analysis was performed on composite stiffened panel to obtain the critical load and modes of failures, with different parameters like ply-orientation, different composite materials, and stiffeners and by changing the number of stiffeners was derived. To analyze the post buckling behaviour of composite stiffened panels the nonlinear finite element analysis is employed and substantial investigations are undertaken using finite element (FE) model. Effect of critical parameters on buckling behaviour is studied and parametric studies were conducted with analytical tool to understand the structural behaviour in the post buckling range.

References listed at the end of the paper:


ABSTRACT: This paper models the effect of material parameter randomness on the initial buckling load of rectangular, specially orthotropic, composite laminates. The basic formulation for stability analysis is based on classical laminate theory. A perturbation technique is used to obtain the solution of the governing equation. The effects of aspect ratio and change in standard deviation of the input parameters have been investigated for several laminate configurations. The solution has also been checked with the help of Monte Carlo simulation.

References listed at the end of the paper:
Changhong Cao (1), Alex Reiner (1), Chunhui Chung (1), Shuo-Hung Chang (2), Imin Kao (1), Robert V. Kukta (1) and Chad S. Korach (1)
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ABSTRACT: Carbon nanotube (CNT) arrays have shown the remarkable ability to react as foam-like structures and exhibit localized buckling coordinated within specific regions. Here, we report on the low-cycle compression of bulk vertically aligned CNT arrays to observe initiation and growth of the buckling as a function of compressive strain. A critical strain is found above which the buckling region length increased and below which it remained at or below the applied strain. As previously observed, the buckling region of the CNT array propagates from the surface where growth occurred, which, in the test specimen, is a free surface and later receives compressive contact by a polished silicon substrate. The results are corroborated with nanoindentation on the surfaces, which indicate a stiffening of the near surface with increasing applied strain. Observation and results of the buckling region nature are important for applications of nanotube arrays as energy absorbing cushions, tunable dampers, thermal contacts, or in sliding contact.

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ABSTRACT: The local buckling behavior of vertically aligned carbon nanotubes (VACNTs) has been investigated and interpreted in the view of a collective nanotube response by taking van der Waals interactions into account. To the best of our knowledge, this is the first report on the case of collective VACNT behavior regarding van der Waals force among nanotubes as a lateral support effect during the buckling process.
local buckling propagation and development of VACNTs were experimentally observed and theoretically analyzed by employing finite element modeling with lateral support from van der Waals interactions among nanotubes. Both experimental and theoretical analyses show that VACNTs buckled in the bottom region with many short waves and almost identical wavelengths, indicating a high mode buckling. Furthermore, the propagation and development mechanism of buckling waves follow the wave damping effect.

References listed at the end of the paper:
P. Hosseini Tehrani and I. Ferestadeh (School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran), “Studying energy absorption in tapered thick walled tubes”, Latin American Journal of Solids and Structures, Vol. 12, No. 1, January 2015

ABSTRACT: In many engineering structures different energy absorption systems may be used to improve crashworthiness capability of the system and to control damages that may occur in a system during an accident. Therefore, extensive research has been done on the energy-absorbing cells. In this paper, energy absorption in tapered thick walled tubes has been investigated. As a practical case, studies have been focused on the crush element of Siemens ER24PC locomotive. To investigate performance of this part at collision time, it has been modeled in Abaqus software and its collision characteristics have been evaluated. Considering that the crash element is folded at time of collision, an analytical approach has been presented for calculation of instantaneous folding force under axial load. Basis of this method is definition and analysis of main folding mechanism and calculation of average folding force. This method has been used for validation of the results of numerical solution. Since sheet thickness of the crash element is high and may be ruptured at time of collision, some damage models have been used for numerical simulations. One of the three damage models used in this paper is available in the software and coding has been done for two other damage models and desirable damage model has been specified by comparing results of numerical solution with results of laboratory test. In addition, authenticity of the desirable damage model has been studied through ECE R 66 standard. To improve crashworthiness characteristic some attempts, such as use of metal foam and creation of trigger in suitable situations to reduce maximum force resulting from collision, have been performed. Finally though different simulation optimal crush element has been introduced and its performance and efficiency have been evaluated.

ABSTRACT: The buckling of hybrid boron nitride–carbon nanotubes (BN–CNTs) with various BN compositions and locations of the BN domain is investigated using molecular dynamics. We find that BN–CNTs with large BN composition (>38%) only undergo local shell-like buckling in their BN domain. Although similar local shell-like buckling can occur in BN–CNTs with a relatively small BN composition, it can transfer to the global column-like buckling of the whole BN–CNT with increasing strains. The critical strains for local shell-like and global column-like buckling decrease with increasing BN composition. In addition, critical strains and buckling modes of the global column-like buckling of BN–CNTs also strongly depend on the location of their BN domain. As a possible application of the buckling of BN–CNTs, we demonstrate that the BN–CNT can serve as a water channel integrated with a local natural valve using the local buckling of its BN domain.


ABSTRACT: When a flexible pipe is subjected to high external hydraulic pressure, the innermost carcass layer serves to resist buckling and collapse. The maximum external pressure that the carcass layer can withstand before buckling collapse must be considered during pipe design. To study this problem, a strain energy equivalence method is proposed to transform a representative volume element (RVE) of the carcass layer, which has a complex geometry, into a homogeneous shell with an equivalent thickness. To obtain the strain energy, a finite element model of the RVE is developed, and the analytical equations for the homogeneous shell are derived for the same uniform-strain boundary conditions. Radial compression tests on three different carcass layer test pieces are performed to verify the safety and effectiveness of the proposed equivalence method. The strain energy equivalence method is found to give conservative results when compared to other equivalence approaches. The advantages of the method for designing a collapse-resistant carcass layer in engineering practice are also discussed.


ABSTRACT: Bases of asymptotic theory of beams, plates and shells are stated. The comparison with classic theory is conducted. New classes of thin bodies problems, for which hypotheses of classic theory are not applicable, are considered. By the asymptotic method effective solutions of these problems are obtained. The effectiveness of the asymptotic method for finding solutions of as static, as well as dynamic problems of beams, plates and shells is shown.

References listed at the end of the paper:

Under increasing compression, an unbuckled shell is in a metastable state which becomes increasingly precarious as the buckling load is approached. So to induce premature buckling a lateral disturbance will have to overcome a decreasing energy barrier which reaches zero at buckling. Two archetypal problems that exhibit a severe form of this behaviour are the axially-compressed cylindrical shell and the externally pressurized spherical shell. Focussing on the cylinder, a non-destructive technique was recently proposed to estimate the ‘shock sensitivity’ of a laboratory specimen using a lateral probe to measure the nonlinear load-deflection characteristic. If a symmetry-breaking bifurcation is encountered on the path, computer simulations showed how this can be suppressed by a controlled secondary probe. Here, we extend our understanding by assessing in general terms how a single control can capture remote saddle solutions: in particular how a symmetric probe could locate an asymmetric solution. Then, more specifically, we analyse the spherical shell with point and ring probes, to test the procedure under challenging conditions to assess its range of applicability. Rather than a bifurcation, the spherical shell offers the challenge of a de-stabilizing fold (limit point) under the rigid control of the probe.

References listed at the end of the paper:

ABSTRACT: Two buckling modes (out-of-surface and in-surface buckling) of micro/nanowires on elastomeric substrates are observed. Here, theoretical analysis and numerical simulations are presented to discover the critical factors that govern the competition between the two buckling modes. The aim is to fabricate buckled structures in selectable manner, instead of studying the buckling behavior of each individual buckling mode. The result shows the material properties have large influence on the critical buckling strain, but no significant influence on buckling competition behavior, the buckling mode is mainly determined by the micro/nanowires cross-section morphology. For cross-sections with equal moment of inertia in in-surface and normal-to-surface directions, in-surface buckling is always favorable. However, micro/nanowires with unequal moment of inertia,
e.g. ellipse, rectangle and trapezoid, are usually fabricated in practical micro/nanofabrication such as through electrospinning and etching, and their influence on buckling modes is investigated.

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“The influence of imperfections and nonlinearities on the failure and B2 stress index of thin-walled pipes”,
Journal of Pressure Vessel Technology, Vol. 137, No. 6, December 2015
ABSTRACT: The effects of imperfections and nonlinearities on the failure mode and the B2 stress index of thin-walled straight pipes are investigated with finite element (FE) analyses. The analyses were performed for pipes made of an ideal elastic–plastic material and the austenitic steel X6CrNiNb18-10. The B2 index is calculated from the instability bending moments obtained by limit load analyses. The effects of initial imperfections as well as the D/t-ratio and the yield stress on the B2 stress index are studied. As a first result, it is noted that thin-walled straight pipes and imperfections fail due to local plastic buckling. Further analyses show that the type of imperfections, the ovality, the D/t-ratio, and the yield stress have significant influences on the B2 index. The obtained B2 indices for thin-walled straight pipes with D/t > 40 and possible technical imperfections are considerably higher than 1.0. The results have been compared with those of other investigations.

ABSTRACT: Most common studies on the strength of plates under compressive longitudinal loading are related to plates having unrestrained edges which lead to a zero net load in the transverse direction. In ships, the framing system and the continuity of the plating in the transverse direction tend to induce rather different boundary conditions on the “unloaded” edges, which results in a completely different state of stresses when the external loads are applied. This is due to the surge of a significant level of induced membrane stresses in the direction perpendicular to loading. In this work, the behavior of long restrained plates under compressive axial loading is analyzed and compared with the one of plates having other boundary conditions. The finite element method is applied for the nonlinear analysis of the plates using a commercial package. Fifty-six cases are considered corresponding to different levels of plate slenderness which ranges between 0.35 and 3.46 covering the practical range of structural plates used in the shipbuilding industry. Various shapes of initial imperfections are considered in order to establish the minimum level of resistance. Also, the influence of the magnitude of the distortions associated to each mode is discussed. The study conducted to the establishment of the minimum compressive strength of restrained plates and it defines the expected range of strength’s variation due to the magnitude level of distortions. The biaxial state of stresses resulting from these boundary conditions is characterized and its dependence from the plate’s slenderness is quantified for the most common type of the hull plating.

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“Analytical solution for the axisymmetric buckling of cylindrical shells”, International Journal of Mechanics
ABSTRACT: Closed-form analytical solutions for thin shell buckling problem are useful in a wide range of analysis and design problems. In this paper, the profile of a cylindrical shell in the post-buckling regime of axisymmetric deformation is analysed, and the solution is shown to be a Jacobi elliptic sine function, for any load and axial deformation. The exact solution of the non-linear differential equation for the thin elastic shell profile holds for any deformation, up to the limit in which the shell is almost flattened by the applied load. Closed-form expressions are derived also for the load dependent axial deflection and stored energy. The analytical solution of the buckling loads and deformed profile are found to agree well with an equivalent numerical solution. Results show that an axially compressed cylindrical shell exhibits ideal behaviour for a safety shock energy absorber.

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Agnieszka Sabik and Ireneusz Kreja (Dept. of Structural Mechanics, Gdansk University of Technology, Poland), “Thermo-elastic nonlinear analysis of multilayered plates and shells”, Composite Structures, 04/2015, Vol. 130, pp 37-43, April 2015, DOI: 10.1016/j.compstruct.2015.04.024

ABSTRACT: Geometrically nonlinear FEM analysis of multilayered composite plates and shells is performed in order to resolve the stability problem of the structures being under the influence of temperature field. The Riks-Wempner-Ramm algorithm with a specially modified multi-choice unloading condition has been implemented in authors’ numerical code. As the representation of multilayered medium the Equivalent Single Layer approach with the First Order Shear Deformation kinematics is employed. The effectiveness of the proposed model is examined in numerical examples with reference solutions available in the literature. Presented study proves that the proposed approach can be very effective in the analysis of stability of thin-walled thermally loaded panels.

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ABSTRACT: The buckling of axially compressed beams resting on elastic foundation is considered, accounting for discontinuous (unbonded) contact between beam and subgrade which is the case of real structural response. Using Galerkin’s method a two-region contact/non-contact configuration was revealed as the only possible post-buckling deformation for both pinned – pinned and fixed – fixed boundary conditions, a fact strongly contradicting relevant results where continuous contact was assumed.

References listed at the end of the paper:


ABSTRACT: This paper considers the minimum buckling load and mode shape of a simply supported beam on an elastic foundation. Solutions are obtained by solving the eigenvalue problem delivered by a finite-element formulation and by using the analytical solutions involving (1) trials and (2) rounding of real numbers to integers as described by Hetényi [Hetényi, M. (1946). Beams on Elastic Foundations, University of Michigan Press, Ann Arbor, MI]. The comparison shows that the solution by rounding can lead to overestimation of the buckling load close to the transition zone between mode shapes. The paper explains the reason for the overestimation and offers a simple direct algorithm that always leads to the correct mode shape and minimum buckling load.


ABSTRACT: This paper concerns the efficiency study of the arc-length algorithm in the geometrically non-linear analysis of thermally loaded multilayered shells. The thermal loading is considered as the one-way thermo-mechanical coupling effect. Two implementations of the arc-length method are examined: the path-following technique available in NX-Nastran and the Riks-Wempner-Ramm algorithm adopted in the authors’ computer code SHLTH. It is shown that the appropriate unloading condition in each step of the analysis plays the crucial role in obtaining a proper solution. The algorithm offered in NX-Nastra tends to fail, whereas the authors’ code enables to find the solution in required temperature range.

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ABSTRACT: With the availability of user oriented software tools, dedicated architectures, such as the parallel computing platform and programming model CUDA (Compute Unified Device Architecture) released by NVIDIA, one of the main producers of graphics cards, and of improved, highly performing GPU (Graphics Processing Unit) boards, GPGPU (General Purpose programming on GPU) is attracting increasing interest in the engineering community, for the development of analysis tools suitable to be used in validation/verification and virtual reality applications. For their inherent explicit and decoupled structure, explicit dynamics finite element formulations appear to be particularly attractive for implementations on hybrid CPU/GPU or pure GPU architectures. The issue of an optimized, double-precision finite element GPU implementation of an explicit dynamics finite element solver for elastic shell problems in small strains and large displacements and rotations, using unstructured meshes, is here addressed. The conceptual difference between a GPU implementation directly adapted from a standard CPU approach and a new optimized formulation, specifically conceived for GPUs, is discussed and comparatively assessed. It is shown that a speedup factor of about 5 can be achieved by an optimized algorithm reformulation and careful memory management. A speedup of more than 40 is achieved with respect of state-of-the art commercial codes running on CPU, obtaining real-time simulations in some cases, on commodity hardware. When a last generation GPU board is used, it is shown that a problem with
more than 16 millions degrees of freedom can be solved in just few hours of computing time, opening the way to virtualization approaches for real large scale engineering problems.


ABSTRACT: In this paper, the geometric nonlinear bending response of channel-section beams of finite length is investigated by using energy methods. The basic assumptions used in the present study are that the total strain energy of a channel-section beam subjected to pure bending can be simplified into a two-stage analysis process. One is the local bending response of the web behaving as the plate; the other is the overall bending response as a beam with flattened section. Analytical solutions for both static and dynamic instabilities of channel section beams of finite length subjected to pure bending about its minor axis are derived by applying the minimum potential energy principle. To validate the analytical solution developed, geometric nonlinear finite element analyses are also conducted. Good agreement between the present solution and the FEA results is demonstrated. The effect of beam's length on the critical load is also discussed.


ABSTRACT: The present study deals with the dynamic stability behavior of laminated composite and sandwich plates subjected to in-plane static and periodic compressive loads based on a recently developed inverse hyperbolic zigzag theory by the authors. The present model satisfies the traction-free boundary conditions on the surfaces of the plate and interlaminar continuity conditions at the layer interfaces, thus obviating the need for a shear correction factor. An efficient Co continuous isoparametric serendipity element with seven field variables is employed for the usual discretization of the plate structure. The effect of span-thickness ratio, modular ratio, boundary conditions, static load factor, and thickness ratios are examined by solving a variety of numerical problems on laminated composite and sandwich structures. The principal instability regions of plate structures are obtained using Bolotin’s approach and are represented either in the nondimensional load amplitude-excitation frequency plane or load amplitude-load frequency plane. The evaluated results are compared with the available published results based on various deformation theories. The prediction of accurate results at the cost of less computational effort ensures the efficiency of the present models for a wide range of applications

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ABSTRACT: Corrugated tubes with sinusoidal patterns were studied to improve the energy absorption properties of traditional circular tubes and reduce the initial peak force. The effects of the radius-thickness ratio, wavelength, and amplitude of corrugated tubes under an axial impact were determined using the LS-DYNA. The numerical simulations show that tube deformation can be classified into three crushed modes, namely,
dynamic asymptotic buckling, dynamic plastic buckling, and transition buckling. The theoretical equation for dynamic plastic buckling was developed to predict the impact force using certain assumptions. The theoretical prediction results are consistent with the findings of the numerical simulations.

References listed at the end of the paper:
ABSTRACT: Weak formulations of mixed state equations of closed laminated cylindrical shells are presented in the Hamilton System. The Hamilton canonical equation of closed cylindrical shell is established. By means of applying the transfer matrix method and taking the advantage of Hamiltonian matrix in the calculation, a unified approach and three-dimensional thermoelastic solutions are obtained for the buckling analysis of closed thick laminated cylindrical shells. All equations of elasticity can be satisfied and all elastic constants can be taken into account. Numerical results are given to compare with those of FEM calculated using SAP5. The principle and method suggested here have clear physical concepts. The equations and boundary conditions proposed in this paper are weakened. The solutions and results given here may serve as a benchmark for other numerical procedures.

ABSTRACT: Background: Nowadays, because of construction and repair costs, maintenance of structures is indispensable. Several factors such as design and calculation errors, lack of proper installation, change structures application, fatigue, corrosion and events such as earthquake, fire and environmental conditions reduce their durability, which renew and restore to its original function is inevitable. One of the proper materials for strengthening is Carbon Fibre Reinforced Polymer (CFRP). This paper presents an investigation on the effect of CFRP for strengthening of short steel box-shaped members with initial horizontal and vertical deficiency. Thirteen specimens with variety of parameters such as length, width and position of deficiency, and strengthening techniques were investigated to study amount of CFRP and strengthening methods to reform the performance. Three-dimensional (3D) modeling and nonlinear static analysis method using ABAQUS software were utilized. The results of research on the use of CFRP fibers to strengthening of short steel box-shaped members with initial deficiency indicate, the fibres have significant effects on increasing load bearing capacity and ductility and, also prevent deficiency propagation.

T.-P. Chang (Dept. of Construction Engineering, National Kaohsiung First University of Science and Technology, Taiwan), “Nonlinear vibration of single-walled carbon nanotubes under magnetic field by stochastic finite element method”, International Journal of Structural Stability and Dynamics, August 2015, DOI: 10.1142/S0219455415500467
ABSTRACT: In the present study, we investigate the statistical nonlinear dynamic behaviors of a single-walled carbon nanotube (SWCNT) subjected to a longitudinal magnetic field by considering the effect of geometric nonlinearity. We consider both the Young's modulus of elasticity and mass density of the SWCNT as stochastic with respect to the position to actually characterize the random material properties of the SWCNT. In addition, we use the theory of nonlocal elasticity to investigate the small scale effect on the nonlinear vibration of the SWCNT. By using the Hamilton's principle, the nonlinear governing equations of the SWCNT subjected to a longitudinal magnetic field are derived. We utilize the stochastic finite element method along with the perturbation technique to compute the statistical response of the SWCNT. Some statistical dynamic response of the SWCNT, such as the mean values and standard deviations of the midpoint deflections, are computed and checked by the Monte Carlo simulation, besides, the effects of the small scale coefficients, magnetic field and the elastic stiffness of matrix on the statistical dynamic response of the SWCNT are studied and discussed.
ABSTRACT: The objective of this study was to evaluate three potential core alternatives for glass fiber reinforced polymer (GFRP) foam-core sandwich panels. The proposed system could reduce the initial production costs and the manufacturing difficulties while improving the system performance. Three different polyurethane foam configurations were considered for the inner core, and the most suitable system was recommended for further prototyping. These configurations consisted of high-density polyurethane foam (Type 1), a bidirectional gridwork of thin, interconnecting, GFRP webs that is in-filled with low-density polyurethane foam (Type 2), and trapezoidal-shaped, low-density polyurethane foam utilizing GFRP web layers (Type 3). The facings of the three cores consisted of three plies of bidirectional E-glass woven fabric within a compatible polyurethane resin. Several types of small-scale experimental investigations were conducted. The results from this study indicated that the Types 1 and 2 cores were very weak and flexible making their implementation in bridge deck panels less practical. The Type 3 core possessed a higher strength and stiffness than the other two types. Therefore, this type is recommended for the proposed sandwich system to serve as a candidate for further development. Additionally, a finite element model (FEM) was developed using software package ABAQUS for the Type 3 system to further investigate its structural behavior. This model was successfully compared to experimental data indicating its suitability for parametric analysis of panels and their design.

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ABSTRACT: There are vast possibilities in fibre architecture design of 3D woven reinforcement. This paper considers the application of Genetic Algorithm (GA) in 3D woven composites optimisation. A set of real and integral variables, representing 3D fibre architecture, are formulated into a mixed integer Genetic Algorithm. The objective function is evaluated through automation of the unit cell based finite element analysis, by using the open source pre-processor TexGen and the commercial solver ABAQUS. The mixed integer Genetic Algorithm is adapted to a micro-population, aiming to improve computational efficiency. The study uses statistical tests to quantify the performance of the Genetic Algorithm schemes and the choice of parameters. The proposed approach was applied to the optimisation of 3D woven composites for maximum buckling resistance for the case of a landing gear brace. This study demonstrated that the optimisation converged to the optimum design within 20 iterations, considering 300 out of 7000 permissible solutions. In terms of buckling performance, the optimum design performed twice as well as cross-ply laminated composites and at least 50% better than known orthogonal 3D woven composites.

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ABSTRACT: The paper investigates the effects of creep of the core material on the geometrically nonlinear behavior of sandwich panels with debond at one of the core–face interfaces within the framework of the high-order sandwich panel theory (HSAPT). The theoretical model accounts for the viscoelasticity of the core via an incremental exponential law that corresponds to the rheological generalized Maxwell model obtained from the expansion of the relaxation moduli into Prony series. The HSAPT structural modeling accounts for the deformability of the core in shear and through its thickness, as well as for the large displacements of the facesheets. An incremental time-stepping analysis is conducted, which accounts for the time variations of the stresses, deformations, and the geometrically nonlinear effects. The incremental governing equations and the stresses and deformations fields through the thickness of the core are derived, and the capabilities of the model are studied numerically. The results show that creep of the core leads to significant variations in the deformations and stresses over time, which when combined with the geometrically nonlinear effects of the debonded facesheet, can have an important influence on the performance of sandwich panels under sustained loads. It is shown that stress relaxation due to creep and/or contact may restrain the buckling of the debonded facesheet in some cases.

ABSTRACT: Not only straight pipes, but also the curved ones are used in an actual pipeline. In designing such a pipeline, it is important to know the buckling strength of the pipe under various kinds of loads. Especially, it is well known that the buckling moment will be reduced by increasing the pipe’s length. However, comprehensive studies for the buckling strength of straight and curved pipe under bending loads are still limited. In this research, the previous research for the buckling strength of pipe under bending moments was reviewed. It is well known that the cross-sectional oval deformation takes place and the buckling strength of pipe is reduced due to this deformation. Therefore, secondly, the buckling phenomenon for a straight pipe under a pure bending moment was investigated by nonlinear FEA, considering the effect of a cross-sectional oval deformation by changing the varying of pipes, that is, the length-to-diameter ratio \((L/D)\) varying from about 5 to 20 and the diameter-to-thickness ratio \((D/t)\) varying from about 50 to 200. Thirdly, the buckling phenomenon for curved
pipe was also investigated by changing the \( R/D \) from 50 to 200 where \( R \) is the curvature radius of curved pipe. From the results of the calculations for the straight pipe, the reduction rate of the buckling moment due to the oval deformation of pipe was clarified for various values of \( L/D \) and \( D/t \), not only in elastic buckling, but also in elasto-plastic buckling. For the curved pipe, it was explained that the buckling moment will be reduced by lowering the value of \( R/D \).

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“Buckling phenomenon for imperfect pipe under pure bending”, Journal of Marine Science and Technology, First online, 11 June 2015, pp 1-8

ABSTRACT: The buckling phenomenon for imperfect pipe under bending has been investigated by nonlinear FEA, considering the effect of a cross sectional oval deformation by changing the variables of pipes, that is, \( L/D \) varying from 2.5 to 20, \( D/t \) varying from 50 to 200, and imperfection (\( \delta_o/t \)) varying from 0.05 to 0.5. As well as the elastic buckling, the elasto-plastic buckling was investigated. From the calculation results, the followings were found. The reduction of buckling moment due to imperfection is larger in short pipe than in long pipe. The effect of imperfection for pipes with large values of \( D/t \) is larger than those with small values of \( D/t \) if \( L/D \) of both pipes is same. The effects of imperfection for elastic analysis are larger than elasto-plastic analysis. The buckling moment reduces more by the imperfection of buckling mode than by that of oval mode.

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Andrea Matteo de Leo, Alessandro Contento and Angelo Di Egidio (via G. Gronchi, 18, 67100, L’Aquila, Italy), “Semi-analytical approach for the study of linear static behaviour and buckling of shells with single constant curvature”, Continuum Mechanics and Thermodynamics, Vol. 27, No. 4, pp 767-785, September 2015

ABSTRACT: A model of linear, internally constrained shell with single, constant curvature is used to describe the behaviour of existing structures, such as barrel shells. A linear, elastic, isotropic material is considered. Observing that in the shell two families of mono-dimensional interacting beams can be recognized: straight longitudinal beams and transversal arches, a non-conventional semi-analytical approximate solution, which uses the method of separation of variables, is proposed. By using an integral procedure, reduced differential, ordinary equations, capable of describing the behaviour of the shell, are obtained. Both linear static behaviour and longitudinal buckling of the shell are investigated. The approximate solution proposed leads to results that match those of a finite element model and permits to give a description of shells similar to that of beams on elastic soil. With regard to the linear static behaviour of the shell, a “short” and a “long” characterization is proposed and original graphical abaci are obtained with the purpose of facilitating the classification. An extensive study is then performed in order to analyse the buckling of the shells.

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ABSTRACT: The elastic limit analysis for elliptical and circular tubes under lateral force is conducted in the present paper, and elastic–perfect plastic material model is employed. An analytical expression for describing the elastic limit load of elliptical and circular tubes under lateral force is obtained. It shows that the critical load for elliptical and circular tubes under lateral force increases with the plastic yielding strength of the tube material, the ratio of the wall thickness to radius, the wall thickness and the length of the tube, as well as the degree of deviation from circular tube monotonously. The experimental results from available literature for both steel and aluminum tubes are cited to verify the proposed expression, and it shows that the expression reflects the loading capacity of elliptical and circular tubes quite well, which indicates the proposed expression is a reasonable formula.

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ABSTRACT: This paper is focused on the buckling and the vibration analyses of microstructured struc-
tures, i.e., elements composed of repetitive structural cells. The relationship between the discrete and the
equivalent nonlocal continuum is specifically addressed from a numerical and a theoretical point of view. The
microstructured beam considered herein is modeled by some repetitive cells composed of finite rigid segments
and elastic rotational springs. The microstructure may come from the discreteness of the matter for small-
scale structures (such as for nanotechnology applications), but it can also be related to some larger scales as for civil
engineering applications. The buckling and vibration results of the discrete system are numerically obtained
from a discrete-element code, whereas the nonlocal-based results for the equivalent continuum can be

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analytically performed. It is shown that Eringen’s nonlocal elasticity coupled to the Euler-Bernoulli beam theory is relevant to capture the main-scale phenomena of such a microstructured continuum. The small-scale coefficient of the equivalent nonlocal continuum is identified from the specific microstructure features, namely, the length of each cell. However, the length scale calibration depends on the type of analysis, namely, static versus dynamic analysis. A perfect agreement is found for the microstructured beam with simply supported boundary conditions. The specific identification of the equivalent stiffness for modeling the equivalent clamped continuum is also discussed. The equivalent stiffness of the discrete system appears to be dependent on the static-dynamic analyses, but also on the boundary conditions applied to the overall system. Satisfactory results are also obtained for the comparison between the discrete and the equivalent continuum for other type of boundary conditions.

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ABSTRACT: This paper presents the treatment of elastically restrained ends for the axially loaded beam-buckling problem for the central finite difference beam model, the microstructured beam model, and Eringen’s nonlocal continuous beam model. The equivalence between the central finite difference beam model and the microstructured beam model is established herein, and these equivalent systems are regarded as belonging to one class of discrete systems since they become indistinguishable. Also, the continualized form of the discrete system is obtained by adopting the continualization method that is based on an exponential displacement function. Three approaches are then proposed for matching the discrete system with Eringen’s nonlocal continuous system for the beam-buckling problem. The approaches depend on the assumption made on the constancy/or varying Eringen’s small length scale coefficient $e_0$ as well as which one of the discrete or continuum system is taken as the reference system.

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ABSTRACT: We use the Mindlin plate theory and the finite element method to delineate the effect of fixing points on a transverse normal to the mid-surface of the plate on the localization of buckling modes in clamped–clamped rectangular plates made of linear elastic, homogeneous and either isotropic (monolithic) or orthotropic (fiber-reinforced composite) materials. The in-plane loads considered on the bounding edges are: (i) normal tractions on the length, (ii) normal tractions on the width, (iii) equal normal tractions on the length and the width (equal biaxial loading), (iv) shear (tangential), and (v) combined same normal and shear tractions on all sides. It is found that clamping points on a transverse normal passing through the mid-point of a line parallel to the short side increases the critical buckling load of plates of only low aspect ratios over that of the corresponding plates unconstrained at interior points. However, for plates of all aspect ratios (thickness/length) fixing points on a transverse normal divides it into two regions with negligible transverse deflections in only one of the two regions. Only for loads (i)–(iii) the dividing line is parallel to the short side of the plate. For both thin and thick isotropic plates the slope of the dividing line is found to monotonically increase with an increase in the aspect ratio of a plate until it reaches a saturation value. A parameter based on the modal strain energy is used to quantify the degree of localization of a buckling mode. For an isotropic plate the degree of localization is found to increase with the increase in the aspect ratio for load cases (i)–(iii) but is found to be moderate for load cases (iv) and (v). For an orthotropic layer the degree of localization with an increase in the aspect ratio of the plate increases more for the 90° lamina than that for the 0° and the 45° laminae. Also, the mode localization in the (45°, 45°) laminate is stronger than that in the (0°, 90°) laminate for the five load cases. However, moderate degree of mode localization is found in symmetric and anti-symmetric cross-ply and angle-ply laminates.

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ABSTRACT: This paper presents a comprehensive review of the various methods employed to study the static, dynamic and stability behavior of Functionally Graded Material (FGM) plates. Both analytical and numerical methods are considered. The review is carried out with an emphasis to present stress, vibration and buckling characteristics of FGM plates predicted using different theories proposed by several researchers without considering the detailed mathematical implication of various methodologies. The effect of variation of material properties through the thickness, type of load case, boundary conditions, edge ratio, side-to-thickness ratio and the effect of nonlinearity on the behavior of FGM plates are discussed. The main objective of this paper is to serve the interests of researchers and engineers already involved in the analysis and design of FGM structures.

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“Regular and chaotic oscillations of a Timoshenko beam subjected to mechanical and thermal loadings”,
Continuum Mechanics and Thermodynamics, Vol. 27, No. 4, pp 719-737, September 2015

ABSTRACT: Dynamics of a Timoshenko beam under an influence of mechanical and thermal loadings is analysed in this paper. Nonlinear geometrical terms and a nonuniform heat distribution are taken into account in the considered model. The mathematical model is represented by a set of partial differential equations (PDEs) which takes into account thermal and mechanical loadings. The problem is simplified to two PDEs and then reduced to ordinary differential equations (ODEs) by means of the Galerkin method taking into account three modes of a linear Timoshenko beam. Correctness of the analytical model is verified by a finite element method. Then, the nonlinear model is studied numerically by a continuation method or by a direct numerical integration of ODEs. An effect of the temperature distribution on the resonance near the first natural frequency and on stability of the solutions is presented. The increase of mechanical loading results in hardening of the resonance curve. Thermal loading may stabilise the beam dynamics when the temperature is decreased. The elevated temperature may transit dynamics from regular to chaotic oscillations.

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Xin Ren (1, 2), Jianhu Shen (1), Arash Ghaedizadeh (1), Hongqi Tian (2) and Yi Min Xie (1)
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“Experiments and parametric studies on 3D metallic auxetic metamaterials with tuneable mechanical properties”, Smart Materials and Structures, Vol. 24, 095016, August 2015
http://dx.doi.org/10.1088/0964-1726/24/9/095016
ABSTRACT: Auxetic metamaterials are synthetic materials with microstructures engineered to achieve negative Poisson's ratios. Auxetic metamaterials are of great interest because of their unusual properties and various potential applications. However, most of the previous research has been focused on auxetic behaviour of elastomers under elastic deformation. Inspired by our recent finding of the loss of auxetic behaviour in metallic auxetic metamaterials, a systematic experimental and numerical investigation has been carried out to explore the mechanism behind this phenomenon. Using an improved methodology of generating buckling-induced auxetic metamaterials, several samples of metallic auxetic metamaterials have been fabricated using a 3D printing technique. The experiments on those samples have revealed the special features of auxetic behaviour for metallic auxetic metamaterials and proved the effectiveness of our structural modification. Parametric studies have been performed through experimentally validated finite element models to explore the auxetic performance of the designed metallic metamaterials. It is found that the auxetic performance can be tuned by the geometry of microstructures, and the strength and stiffness can be tuned by the plasticity of the base material while maintaining the auxetic performance.

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ABSTRACT: Variations of manufacturing process parameters, environment aspects, and imperfections may significantly affect the quality and performance of stiffened shells. The reliability-based design optimization (RBDO) of stiffened shells, considering all these uncertainty factors simultaneously, is extremely time-consuming, even if the surrogate-based technology is used. Therefore, a hybrid bi-stage framework for RBDO of stiffened shells is presented to release the computational burden, where two main sources of uncertainties are considered: variations of material properties and geometric dimensions are described as random variables, while various forms of imperfections of stiffened shells are covered by the single perturbation load approach. The basic idea of the proposed method is to combine the efficiency of smeared stiffener method with the accuracy of finite element method, and then narrow the design window efficiently with little accuracy sacrifice. The adaptive chaos control method is used to ensure the robustness of the search process of the most probable target point. The numerical example illustrates the advantage of the proposed method over other RBDO approaches from the point of view of computational cost, accuracy and robustness of the result.

ABSTRACT: Under increasing compression, an unbuckled shell is in a metastable state which becomes increasingly precarious as the buckling load is approached. So to induce premature buckling a lateral disturbance will have to overcome a decreasing energy barrier which reaches zero at buckling. Two archetypal problems that exhibit a severe form of this behaviour are the axially-compressed cylindrical shell and the externally pressurized spherical shell. Focussing on the cylinder, a non-destructive technique was recently proposed to estimate the ‘shock sensitivity’ of a laboratory specimen using a lateral probe to measure the nonlinear load deflection characteristic. If a symmetry-breaking bifurcation is encountered on the path, computer simulations showed how this can be suppressed by a controlled secondary probe. Here, we extend our understanding by assessing in general terms how a single control can capture remote saddle solutions: in particular how a symmetric probe could locate an asymmetric solution. Then, more specifically, we analyse the spherical shell with point and ring probes, to test the procedure under challenging conditions to assess its range of applicability. Rather than a bifurcation, the spherical shell offers the challenge of a de-stabilizing fold (limit point) under the rigid control of the probe.


ABSTRACT: The purpose of this paper is to develop a general mathematical model for laminated curved structure of different geometries using higher-order shear deformation theory to evaluate in-plane and out of plane shear stress and strains correctly. Subsequently, the model has to be validated by comparing the responses with developed simulation model (ANSYS) as well as available published literature. It is also proposed to analyse thermal buckling load parameter of laminated structures using Green–Lagrange type non-linear strains for excess thermal distortion under uniform temperature loading. Laminated structures known for their flexibility as compared to conventional material and the deformation behaviour are greatly affected due to combined thermal/aerodynamic environment. The vibration/buckling behaviour of shell structures are very different than that of the plate structures due to their curvature effect. To model the exact behaviour of laminated structures mathematically, a general mathematical model is developed for laminated shell geometries. The responses are evaluated numerically using a finite element model-based computer code developed in MATLAB environment. Subsequently, a simulation model has been developed in ANSYS using ANSYS parametric design language code to evaluate the responses. Vibration and thermal buckling responses of laminated composite curved panels have been obtained based on proposed model through a customised computer code in MATLAB environment and ANSYS simulation model using ANSYS parametric design language code. The convergence behaviour are tested and compared with those available in published literature and ANSYS results. Finally, the investigation has been extended to examine the effect of different parameters (thickness ratios, curvature ratios, modular ratios, number of layers and support conditions) on the free vibration and thermal buckling responses of laminated curved structures.

PARTIAL ABSTRACT: We study the fabrication of thin polymeric shells based on the coating of a curved surface by a viscous fluid. Upon polymerization of the resulting thin film, a slender solid structure is delivered after demolding. This technique is extensively used, empirically, in manufacturing, where it is known as
rotational molding, as well as in the food industry, eg for chocolate-eggs. This problem is analogous to the Landau-Levich-Derjaguin coating of . . .


ABSTRACT: Thin spherical shells range from nanometer-sized viruses to space vehicles. A pressure differential between the inner and outer part of the shell can result in the buckling and catastrophic failure of the structure. We revisit this classic buckling problem, depressurizing thin elastic shells, which are arrested from within by a concentric spherical mandrel. As a result, buckling is constrained to occur within the gap between the two. Above a critical pressure, dimples appear sequentially on the surface of the shell to form a robust periodic pattern. We perform precision desktop experiments to construct the bifurcation diagram of the process, and explore a range of geometric and material properties. A scaling analysis enables us to rationalize the dependence of the size of the dimples on both the radius of the shell and the radial gap between the shell and the inner rigid mandrel. Moreover, we characterize the process of nucleation and progression of the dimpled pattern front. Particular emphasis is given to the patterns obtained in the strongly nonlinear post-buckling regime where a network of sharp ridges forms.


PARTIAL ABSTRACT: We introduce a new class of pre-stressed bilayer shells, whose surface morphology can be used to smoothly tune their optical transmittance by pneumatic actuation. Each sample is fabricated by pressurizing a disk made out of an optically clear silicone-based rubber to bulge it into a nearly hemispherical pre-strained shell. The surface of this shell is then taken as a substrate and coated with a thin layer of a polymer suspension with black micron-sized dye particles, which, upon curing, can make the samples opaque. The . . .

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ABSTRACT: A thin flat rectangular plate supported on its edges and subjected to in-plane loading exhibits stable post-buckling behaviour. However, the introduction of a nonlinear (softening) elastic foundation may cause the response to become unstable. Here the post-buckling of such a structure is investigated and several important phenomena are identified, including the transition of patterns from stripes to spots and back again. The interaction between these forms is of importance for understanding the possible post-buckling behaviours of this structural system. In addition, both periodic and some localized responses are found to exist as the dimensions of the plate are increased and this becomes relevant when the characteristic wavelengths of the buckle pattern are small compared to the size of the plate. Potential application of the model range from macroscopic industrial manufacturing of structural elements to the understanding of micro- and nano-scale deformations in materials.

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“Buckling of a spherical shell under external pressure and inward concentrated load: Asymptotic solution”, Mathematics and Mechanics of Solids, Published online before print, March 21, 2016,
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ABSTRACT: An asymptotic solution is suggested for a thin isotropic spherical shell subject to uniform external pressure and concentrated load. The pressure is the main load and a concentrated lateral load is considered as a perturbation that decreases buckling pressure. First, the post-buckling solution of the shell under uniform pressure is constructed. A known asymptotic result for large deflections is used for this purpose. In addition, an asymptotic approximation for small post-buckling deflections is obtained and matched with the solution for large deflections. The proposed solution is in good agreement with numerical results. An asymptotic formula is then derived, with the load-deflection diagrams analyzed for the case of combined load. Buckling load combinations are calculated as limiting points in the load-deflection diagrams. The sensitivity of the spherical shell to local perturbations under external pressure is analyzed. The suggested asymptotic result is validated by a finite element method using the ANSYS simulation software package.

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ABSTRACT: In the present work, in order to tackle the linear elastic buckling problem, we develop a shape optimization process based on a free-form optimization method to optimize a shell structure under out-of-plane and in-plane shape variations. The free-form optimization method is a node-based method in which mesh regularity can be maintained and shape design parameterization is not required. It has the advantages of sufficient efficiency for treating large-scale problems and the ability to realize a smooth shape. The buckling coefficient in buckling mode 1 is set as the objective function in the shape optimization problem. We consider repeated eigenvalues and volume constraint for the whole optimization process. Three numerical examples are presented in this work to illustrate the shape optimization algorithm and to show that it can increase the buckling strength substantially, especially under shape variation in the out-of-plane direction.

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ABSTRACT: The post-buckling behavior of elastic–plastic cylindrical shells under external pressure and twisting moment is unstable. The effect of stabilization of the post-buckling behavior is in most cases obtained by changing geometry of the structure. In this paper an alternative concept of modification of the post-buckling behavior is applied, namely modification of post-buckling path is achieved by application of additional loadings acting on the structure without changing the shape or sizes of the optimized element. Calculations are performed using ANSYS code for elastic–plastic shells of different length and thickness for the whole range of load from a pure external pressure to a pure twisting moment. It turned out that the active stabilizing force can always stabilize the post-buckling paths whereas the passive and ‘mixed’ variant of stabilizing loads are able to stabilize the post-buckling paths only for thicker elastic–plastic shells and for limited states of loading.


ABSTRACT: An investigation has been undertaken on the buckling strength of concrete arch dams in the form of thin shells of single and double curvature. When subjected to the hydrostatic pressure exerted by the retained water, the shell experiences predominantly compressive internal actions, which can result in buckling failure of the thin shell. There are many factors influencing the buckling strength of the arch dam. These include the shape of the valley, the geometry of the arch surface, the degree of bulging of the arch, shell-thickness variation and support conditions. The present study makes use of FEM modelling to determine the influence of key parameters on the critical buckling pressure of cylindrical and elliptic-paraboloidal arch dams. For cylindrical arch dams, design curves giving information on factors of safety against buckling are presented. By comparing the results for the elliptic paraboloid with those for the parabolic cylindrical arch, the benefits of double curvature are evaluated.

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this paper for a 9-noded co-rotational shell element, which utilises the Mixed Interpolation of Tensorial Components (MITC) method in the local system for overcoming locking effects. Several linear and nonlinear numerical examples of multi-layer shell structures with alternating stiff/soft lay-ups are used to illustrate the effectiveness and efficiency of the proposed modelling approach.

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ABSTRACT: The cross-sectional behaviour of laminated glass (LG) is characterised by a significant zigzag effect owing to the large stiffness mismatch between the glass and polymer layers. The approach incorporated in current glass design standards is based on the use of a monolithic model with an effective thickness, which suffers several sources of inaccuracy and limitations. In this paper, laminated shell elements with an alternating stiff/soft lay-up are enhanced and used to model LG structures, so as to accurately reproduce the through-thickness behaviour of LG with a minimal number of zigzag displacement parameters per node. In order to consider the influence of loading rate and temperature on the response of LG, a linear viscoelastic material model is adopted to simulate the polymer interlayer, which is formulated based on a recursive formula for stress calculation. Finally, several applications of the proposed modelling approach for two-ply and multi-ply LG structures are presented, considering typical deflection, stability and creep problems, where the benefits of the proposed approach are demonstrated through comparisons against monolithic shell models based on an effective thickness as well as 3D continuum models.

References listed at the end of the paper:


ABSTRACT: This paper proposes a kinematic model for sandwich plates and shells, utilising a novel zigzag function that is effective for symmetric and asymmetric cross-sections, and employing a piecewise through-thickness distribution of the transverse shear strain. The proposed model is extended to large displacement analysis using a co-rotational framework, where a 2D local shell system is proposed for the direct coupling of additional zigzag parameters. A 9-noded co-rotational shell element is developed based on the proposed approach, which utilises the MITC method for overcoming locking effects. Several linear/nonlinear analysis examples of sandwich structures demonstrate the effectiveness of the proposed approach.

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ABSTRACT: We demonstrate the existence of spurious modes in finite elements with incompatible modes when a geometrically nonlinear displacement analysis with small displacements and strains is performed. The spurious modes are a direct consequence of the incompatibility of the elements with displacement boundary conditions. We derive a critical compressive strain condition analytically, and show that the critical strain can be quite small, with small displacements, if the geometric aspect ratio of the elements is large but still practical. In numerical examples we give further insight and results in correspondence with the analytical theory, and demonstrate that spurious modes can be triggered in practical small strain analyses when using elements with incompatible modes.

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V.N. Paimushin [Kazan (Volga Region) Federal University, ul. Kremlyovskaya 18, Kazan, 420008, Russia], “Static and dynamic buckling modes of spherical shells subjected to external pressure”, Russian Mathematics, Vol. 60, No. 4, pp 37-46, April 2016, DOI: 10.3103/S1066369X1604006X
ABSTRACT: We investigate the possibilities for simplification of previously proposed refined linearized equations of perturbed motion to identify, by dynamic method, the buckling mode shapes of isotropic spherical shells undergoing external hydrodynamic pressure. In the analysis of classical flexural buckling shapes of spherical shells, it is shown that preserving of nonconservative parametric terms in governing equations of formulated problem, which are related with loading of the shell with follower pressure practically does not affect the value of critical load and the resulting buckling mode shapes in shell.

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ABSTRACT: In this research, buckling analysis of a two-dimensional, functionally graded, cylindrical shell that has been embedded in an outer elastic medium in the presence of combined axial and transverse loading based on third-order shear deformation shell theory is numerically investigated. Variations of the shell properties are considered to be continuous through length and thickness. Winkler–Pasternak foundation and simply supported boundary conditions have been applied. The problem has been solved using the generalized differential quadrature method. Geometrical, load, and foundation parameters beside functionally graded power indexes effects on the critical buckling load have been studied.

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ABSTRACT: The aim of this experimental research work is to investigate the effect of axial crack length on the buckling behavior of cracked cylindrical shells subjected to axial compression loading. The crack on the cylindrical strucutures is assumed to be a percentage of the axial length of the cylindrical shell structure. The magnitude of the crack length-to-cylinder axial length is varied between 0.05 and 0.15. Cylindrical specimens are made from mild steel with radius-to-thickness ratio ranging from 25 to 100. The axial length of the
specimens was assumed to be constant. Results indicate that the crack length strongly affect the buckling behavior of the axially compressed cylinder. Also, it was revealed that the buckling load of the cylindrical specimens with high value of radius-to-thickness ratio is more sensitive to the effect of change in crack length as compared to cylinder with low value of radius-to-thickness ratio.


ABSTRACT: In this paper, the buckling analysis of thin walled composite cylindrical shells with and without cutouts is investigated by applying axial load on Glass Fiber Reinforced Plastic (GFRP) shell. The effect of cutout not only introduces stress concentration but also significantly reduces the buckling strength. The column is fixed at one end and load is applied at the other end. The Static and Eigenvalue buckling analysis is done on shell model. The circular, elliptical and rectangle cutouts are considered on cylindrical shell. The buckling analysis is repeated in each case. The compressive stress, buckling load factor and lateral strain of each case for cylindrical shell is obtained from ANSYS software. The buckling load decreases for shell with cutout when compared to the value of the shell without a cutout. Stress and lateral strain increases for shell with cutout when compared to the shell without a cutout. The buckling load value is maximum in circular cutout and minimum in the rectangular cutout.

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Alireza Sadeghi (1), Mahmoudreza Hosseini Tabatabaci (2) and Ali Ghods (1)
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ABSTRACT: The buckling load make reduce the bearing in shells. This is one of the disadvantages of the shell. Key factors influencing the buckling load of the shell are the types of structures. In this paper, the effect of the ratio of radius to thickness ratio of length to thickness of the skin buckling load of laminated composite materials is investigated. It should be added, the shell is below the static water pressure. Therefore, the interaction effects of axial load and the static water pressure is also analyzed. It must be understood, to do this by a geometric nonlinear analysis. Also, the software ANSYS is used.

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Thorpe, Maria Anastasia. Deformation and buckling of isolated and interacting thin shells in an elastic medium. Degree: 2016, University of Manchester. URL: http://www.manchester.ac.uk/escholar/uk-ac-man-scw:294750
This thesis 'Deformation and buckling of isolated and interacting thin shells in an elastic medium', is submitted by Maria Thorpe to The University of Manchester for the degree of PhD in September 2015. This thesis aims to model the effects of interaction and buckling upon pairs of micro-shells embedded within an elastic medium under far field hydrostatic pressure. This analysis is motivated by the role shell buckling plays in the nonlinear nature of the pressure relative volume curve of elastomers containing micro-shells. Current models of the effective properties of these types of composites assume shells are in a dilute distribution within the host medium, and as such assume shells will buckle at the pressure of the associated isolated embedded shell model. For composites with a high volume fraction of micro-shells, or in poorly mixed composites, the dilute distribution model may provide a first approximation to the effective properties of the composite, however, interaction between shells must be considered to find a more accurate model. We begin the process of modelling the buckling of interacting embedded shells by considering the buckling of an isolated embedded thin spherical shell. For a host medium undergoing far field hydrostatic pressure we demonstrate the parameter ranges in which Jones et al. thin shell buckling theory agrees with the thin shell buckling theory of Fok and Allwright. We then use scalings to increase the range of validity of the thin shell approximation used in the Jones et al. theory to include composites with a high contrast between medium and shell materials. This enables more accurate predictions of buckling pressures of embedded shells under far field axially symmetric pressures to also be found, as is demonstrated for an embedded shell under far field axial compression. We model the linear elastic deformation of pairs of embedded micro-shells using the Boussinesq-Papkovich stress function method, before employing the thin shell linear analysis method developed in previous chapters to calculate the critical buckling pressure and buckling patterns of the pair of embedded shells.


ABSTRACT: The present work investigates stress analysis and buckling analysis of cylindrical shell. It had been wide applications in the industry especially in mechanical and nuclear applications.. etc. The most common type of failure which may be happen in this type of structure was the buckling when was subjected to
external hydrostatic pressure which represents the aim of this work. The buckling happen due to transfer major amount of strain energy into bending energy which leads to sudden failure in the structure. To avoid this type of failure the cylindrical shell must be stiffened by adding stiffeners rings along the shell from internal or external surface. In this work two types of stiffeners existed, longitudinal and circumferential stiffeners based on the direction of the installation on the shell surface. In this work the critical pressure due to buckling was calculated numerically by using ANSYS15 for both stiffened and un-stiffened cylinder for various location and installing types, strengthening of the cylinder causes a significant increase in buckling pressures than non reinforced cylinder. Also the deflection for stiffened cylinder is function to mode shape and increasing with increasing the mode number because when the mode is increased, the strength of cylinder is increased and this leads to lower deflection. Also the stress analysis due to buckling for different depths of sea water was done to find the critical depth which may be the stresses exceeded the elastic limit. And from stress analysis results, it is observed that there is not a huge difference in stresses between stiffened shell and un-stiffened shell in similar boundary and loading condition so the value of stresses in stiffened shell is a little lower compared to un-stiffened shell.

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Luis Miguel dos Santos Laim, “Experimental and numerical analysis on the structural behaviour of cold-formed steel beams subjected to fire”, Ph.D dissertation, Department of Civil Engineering, University of Coimbra, Portugal, 2013. ABSTRACT: The steel construction is increasingly an important technology for civil building. Actually, the steel industry is constantly in search of more and better uses for steel. The uses of hot-rolled, welded and cold-formed steel elements in the construction of buildings are ones of the solutions that can easily replace the traditional technology of construction. Indeed, cold-formed steel is one of which are becoming a very popular material in construction because they provide a high strength to weight ratio, are easy to produce, transport and assembly when compared to thicker hot-rolled steel members. Another advantage is the great variety of profiles available on the market which allow the building of different member cross-sections.
However, they may behave poorly under fire conditions, especially when they are unprotected in fire case, due to the combination of the high thermal conductivity of steel and section factor of these structural members (small wall thickness), both of which lead to a rapid rise of temperature in steel in fire situation. In addition, cold-formed steel members usually have complex buckling behaviour, involving local, distortional, global buckling and their interactions. Studies on fire performance of cold-formed steel members are still fairly rare, are mostly of a numerical nature and are based on the structural behaviour of single and short elements at elevated temperatures. Hence, this research work intended to study the behaviour of cold-formed galvanized steel beams under fire conditions, basing on the results of a large programme of experimental tests. Four-point bending tests on cold-formed steel C-, lipped I-, R- and 2R-section beams were performed, both under fire conditions, under flexural loading conditions and under simply supported boundary conditions (roller and pinned supports) with different restraining conditions, including no restraints, partial axial restraint to the thermal elongation of the beam (15 kN/mm) and partial rotational restraint at the beam supports (150 kN.m/rad). In other words, it was investigated the influence of the cross-sections, the axial restraining to the thermal elongation of the beam and the rotational stiffness of the beam supports. These beams, commonly used in CFS buildings, had a span of 3000 mm and were made of one or more cold-formed steel profiles (channel, U, and lipped channel, C, profiles), which were 2.5 mm thick, 43 mm wide and 250 mm tall for C sections and 255 mm for the U sections. On the other hand, as reference, four-point bending tests on the same type of beams at room temperature and under simply supported boundary conditions were also carried out to assess their ultimate bending strength and to compare with the failure modes. A numerical study was still performed by the finite element program ABAQUS. So a great number of numerical simulations aimed to carry out a parametric study outside the bounds of the original experimental tests, in other words, to find out the effect of thickness (from 1.5mm to 3.5mm) and height (from 200mm to 300mm) of the beam cross-sections, of the beam spans (from 2000mm to 5000mm) and of other values of axial (from zero to infinite) and rotational stiffness (from zero to 1200kN.m/rad) of the surrounding structure to the beam. Finally, the results of the experimental tests and the numerical simulations were the basis of an analytical study for the development of simplified calculation equations for fire design of cold-formed steel beams. The main conclusions of this research study were that the cold-formed steel beams commonly used in this kind of buildings may have a quite low fire resistance (less than 30 minutes), but high critical temperatures (higher than 350 oC - limitation enforced by Eurocode 3, Part 1.2) in most of the cases. On the other hand, the critical temperature may drop significantly (30% in some cases) with the axial restraint to thermal elongation of the beam. This decreasing is however minimized when the rotational restraint at beam supports is relevant comparing with rotational stiffness of the beam.

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ABSTRACT: Aluminium stiffened panels are the basic elements of many structures with requirements of high strength/weight ratio. They are used in a wide variety of applications such as airplane wings and fuselage, ships and off-shore structures. Friction Stir Welding (FSW) process has been used in the manufacturing of such structures as an alternative of other joining techniques, such as riveting or fusion welding processes, with many
advantages. The understanding of the effects of FSW processes in the structural behaviour of stiffened panels is a relevant research area, useful to avoid conservative design choices often motivated by an attempt to compensate for structural analysis uncertainties.

The present work focuses on the numerical simulation of FSW processes, aiming to predict its effects, and also on the numerical simulation of the longitudinal compression of aluminium stiffened panels, including these effects. The numerical model for FSW was firstly developed to simulate single plates’ joining and subsequently validated using data from experiments, also performed in the scope of this work. The validated model was afterwards adapted to simulate FSW operations on stiffened panels. Sensitivity analyses performed showed an insignificant variation in the results coming from models using distinct heat input distributions related to the geometry of the tool. On the contrary, both models showed significant sensitivity to the variations of the mechanical boundary conditions that simulate the clamping system, although the single plate model was seen to be more affected by this modelling parameter.

The simulations regarding the longitudinal compression of the panels included the study of the influence of each one of the welding effects (distortion, residual stresses and material softening) on the structural behaviour. The numerical modelling of these welding effects was performed adopting two different procedures: using the results from FSW numerical analyses; and using a simplified methodology based on the literature. Regarding the compression of the panels, other modelling details were also tested and compared, such as: the numerical solving methodology; the plastic behaviour definitions of the material and the welding effects on the transversal edges. All the mentioned welding effects were able to affect the panel behaviour and, namely, the collapse load. Finally, a complementary study on initial geometrical imperfection was performed using distinct deformed shapes obtained from eigenvalue analyses and applied with different magnitudes. The variation of the collapse load with the increase of the imperfection magnitude revealed to be dependent on the shape of that imperfection.

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Gary Han Chang, “Reduced order fluid-structure interaction models for thin shells with non-zero Gaussian curvatures to understand the response of aneurysms to flow”, Ph.D dissertation, Dept. of Mechanical and Industrial Engineering, University of Massachusetts Amherst, 2016

ABSTRACT: In this thesis, a reduced-order model is constructed to study the physiological flow and wall shear stress conditions for aneurysms. The method of local proper orthogonal decomposition (POD) is used to construct the reduced-order modes using a series of CFD results, which are subsequently improved using a QR-factorization technique to satisfy the various boundary conditions in physiological flow problems. This method can effectively construct a computationally efficient physiological model, which allows us to examine the fluid velocities and wall shear stress distributions over a range of different physiological flow parameters. Aneurysms are the dilation, bulging, or ballooning-out of part of the wall of a human artery. Repetitive forces on an existing aneurysm can lead either to its gradual expansion or to a devastating event of rupture. Traditionally, clinicians use the largest diameter as the sole parameter for standard risk stratification outside of clinical trials. However, there seems to be no safe small aneurysm size and a more accurate answer depends on the exact distributions of material and geometrical properties of the aneurysms. Aneurysms can have a very non-uniform distribution of thickness, modulus, and failure tension. We focus on the thins-shell fluid-structures interactions (FSI) with thickness inhomogeneity by studying the influence of one or multiple thin spots on the flow-induced instabilities of flexible shells of revolution with non-zero Gaussian curvatures. The results show that for shells with positive Gaussian curvatures conveying fluid, the existence of a thin spot results in a localized flow-induced buckling response of the shell in the neighborhood of the thin spot, and significantly reduces the critical flow velocity for buckling instability. For shells with negative Gaussian curvatures, the buckling response is extended along the shell’s characteristic lines and the critical flow velocity is only slightly reduced. Finally, the shell model with non-uniform thickness is combined with the ROM of hemodynamic loads. We show that based on a growth and remodeling (G&R) model, the rate of aneurysmal wall’s elastin degradation
can be predicted efficiently with various degrees of thickness inhomogeneity.

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ABSTRACT: The complex configurations of soft materials are vital for many biological systems because they allow them quickly response to environmental stimuli and therefore achieve some necessary living functions. Such stimulus-sensitive properties are ascribed to the large deformation resulted from the bending, folding and buckling and have attracted the scientists to explore their essences in a variety of scenarios relating to mechanical force, temperature, humidity, pH value, electricity, magnetism to van der Waals force. Up to date, some exciting achievements have been made and successfully applied to soft robot, sensor, nano-reactor and artificial organ. However, there are still many challenging problems to be well addressed in future. This research aims to investigate the bending, folding and buckling of soft materials via theoretical analysis, numerical simulation and experimental validation. The retractile behaviours of a spherical shell perforated by sophisticated apertures, attributed to the buckling-induced large deformation are studied. The buckling patterns observed in experiments are reproduced in computational modeling by imposing velocity-controlled loads and eigenmode affine geometric imperfection. It is found that the buckling behaviours are topologically sensitive with respect to the shape of dimple and the buckliball featured with rounded-square apertures has the maximal volume retraction ratio. Afterwards, a kirigami approach is used to fold a patterned planar sheet into a buckliball under a certain thermal stimulus. By minimizing the potential strain energy, we obtain a critical temperature, below which this bilayer sheet exhibits identical principal curvatures everywhere in the self-folding procedure and above which the buckling occurs. The applicability of the theoretical analysis to the self-folding of sheets with a diversity of patterns is verified by the finite element method. Finally, the opening and closure of pine cones is revealed, which is attributed to the self-bending of its scales. It undergoes three states of humidity-driven deformation in terms of Föppl–von Kármán plate theory. Both numerical simulation and experimental data support the theoretical analysis and indicate the longitudinal principal curvature and transverse principal curvature bifurcate at a critical humid value which relies on the thickness and shape of scales.

The findings in this dissertation are significant not only for understanding the principle of natural structures with stimuli-responsive properties, but also for offering a novel way to design and fabricate functional shape-morphing structures for a variety of applications.

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ABSTRACT: In this paper, a novel foam-filled double ellipse tube (F-DET) is proposed. First, the circle and ellipse tubes with three different configurations (hollow, foam-filled, double foam-filled) are investigated under axial and oblique impact by using the nonlinear finite element code LS-DYNA. The numerical results showed that the F-DET tube has the best crashworthiness performance than tubes with other configurations. Then to optimize the F-DET tube, the Kriging model about the radial rate $f$, thickness of wall $t$ and foam density $\rho_f$ is constructed. Based on the Kriging model, the multiobjective particle swarm optimization (MOPSO) algorithm is utilized to achieve the optimized F-DET tube, foam-filled ellipse (F-ET) tube and foam-filled double circle (F-DCT) tube on the maximizing specific energy absorption (SEA) and minimizing peak crush force (PCF) under multiple loading angles. It can be found that the F-DET tube has better crashworthiness performance than F-ET tube and F-DCT tube. This indicates F-DET tube can be a potential energy absorber under the multiple loading cases.


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ABSTRACT: Lightweight magnesium alloys and polyurethane foams have attracted much attention in the automotive industry due to their potential to reduce vehicle weight. This study conducted quasi-static/dynamic three-point bending tests to investigate the energy absorption characteristics and deformation behaviour of empty and polyurethane foam-filled magnesium alloy AZ31B thin-walled beams, and to make comparisons with mild steel DC04 beams. The results showed that both deformation/fracture modes and energy absorption capacity of the thin-walled beams subjected to bending loads depend on the strain rate and other parameters, such as the beam material’s strength and ductility, foam density and wall thickness. Both the DC04 beams and AZ31B extruded beams showed a positive effect of strain rate on the energy absorption capacity. A beam filled with a higher density foam achieves higher bending resistance, but fractures at a smaller deflection. The experiments demonstrated that AZ31B significantly outperforms DC04 in terms of energy absorption and specific energy absorption for the foam-filled beams, when the beams are subjected to bending loads at a deflection of 250 mm. However, this gain could be weakened when the performance is assessed at a larger fracture deflection because the foam-filled AZ31B beams tend to fracture at smaller deflections. For applications that require limited deformation, there is a possibility to develop lightweight auto-body structures such as rocker rails by substituting foam-filled AZ31B structures for mild steel structures, while maintaining or exceeding their current crashworthiness and safety.

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ABSTRACT: Auxetic materials are modern class of materials that have recently been gaining popularity within the research community due to their enhanced mechanical properties. Unlike conventional materials, they exhibit a negative Poisson's ratio when subjected to a uniaxial loading. This present research experimentally investigates the crush response and energy absorption performances of auxetic foam-filled square tubes under axial loading. For comparison, the crush response and energy absorption of empty and conventional foam-filled square tubes have also been examined with respect to deformation modes and force displacement curve. Standard compression tests were conducted on a series number of thin-walled tube samples. An additional compression test on conventional and auxetic foam has also been conducted to observe the behavior of foam itself. It is evident that the auxetic foam-filled square tubes are superior to empty and conventional foam-filled square tubes in terms of energy absorption capacity. It shows that such tube is preferable as an impact energy absorber due to their ability to withstand axial loads effectively. Furthermore, it is found that the load capacity increases as the crush length increases. The primary outcome of this study is design information for the use of auxetic foam-filled square tubes as energy absorbers where impact loading is expected particularly in crashworthiness applications.

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ABSTRACT: This present study investigates experimentally and numerically the crush response and energy absorption performances of auxetic foam-filled square tubes under quasi-static axial loading. Three different structures: empty, conventional and auxetic foam-filled square tubes have been compared and examined with respect to the deformation modes and load-displacement curves. Standard compression tests were conducted on the tubes to evaluate the influence of auxetic foam in the energy absorption of empty tubes. Moreover, results from computer simulation have also been supplemented to further examine the abovementioned effect. It is discovered that the auxetic foam-filled square tube is superior to empty and conventional foam-filled square tubes in terms of all studied crashworthiness indicators.

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ABSTRACT: As a class of widely observed materials in nature, hierarchical micro structures maybe of superior mechanical properties. In this study, we incorporate the concept of hierarchy into honeycomb structures for enhancing their crashworthiness performance. Hierarchical honeycombs are constructed by replacing every vertex of a regular hexagonal network with a smaller hexagon topology and repeating this process for
constructing fractal-appearing honeycombs with higher order of structural hierarchy. To examine the crashing characteristics the hierarchical honeycombs with the first-order and second-order structures were investigated under an out of the cross-sectional plane loading. A parametric study on structural variables ($\gamma_1$, $\gamma_2$) which are defined by $\gamma_i = L_i / L_0$ ($L_0$ is the edge length of regular honeycomb cell, $L_i$ is the edge length of $i$-th order hexagon in hierarchical honeycombs) and oblique-wall angles $\theta$ which is defined by the angle of oblique-wall edge to the vertical direction are undertaken with three different densities. A comparison between regular honeycombs and hierarchical honeycombs was conducted. The results showed that the out-of-plane energy absorption of the first-order hierarchical honeycombs with $0.04 \leq \gamma_1 \leq 0.2$ and the second-order hierarchical honeycombs with $0.15 \leq \gamma_1 \leq 0.2$ and $0.04 \leq \gamma_2 \leq 0.08$, as well as the hierarchical honeycombs with oblique-wall angle $\theta$ from $30^\circ$ to $50^\circ$ have better overall performance. Further, it was found that the specific energy absorptions (SEA) of the first-order hierarchy with $\gamma_1 = 0.08$ and the second-order hierarchy with $\gamma_1 = 0.20$, $\gamma_2 = 0.06$ were improved about $81.3\%$ and $185.7\%$, respectively. Moreover, their corresponding peak forces ($P_{\text{max}}$) do not increase much compared with the regular honeycomb under the same density, indicating that hierarchical honeycombs can be an ideal lightweight structure for designing crashworthy structures.

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ABSTRACT: Thermoplastic composites are likely to emerge as the preferred solution for meeting the high-volume production demands of passenger road vehicles. Substantial effort is currently being directed towards the development of new modelling techniques to reduce the extent of costly and time consuming physical testing. Developing a high-fidelity numerical model to predict the crush behaviour of composite laminates is dependent on the accurate measurement of material properties as well as a thorough understanding of damage mechanisms associated with crush events. This paper details the manufacture, testing and modelling of self-supporting corrugated-shaped thermoplastic composite specimens for crashworthiness assessment. These specimens demonstrated a $57.3\%$ higher specific energy absorption compared to identical specimen made from thermoset composites. The corresponding damage mechanisms were investigated in-situ using digital microscopy and post analysed using Scanning Electron Microscopy (SEM). Splaying and fragmentation modes were the primary failure modes involving fibre breakage, matrix cracking and delamination. A mesoscale composite damage model, with new non-linear shear constitutive laws, which combines a range of novel techniques to accurately capture the material response under crushing, is presented. The force-displacement curves, damage parameter maps and dissipated energy, obtained from the numerical analysis, are shown to be in a good qualitative and quantitative agreement with experimental results. The proposed approach could significantly reduce the extent of physical testing required in the development of crashworthy structures.

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ABSTRACT: An integrated design concept for crashworthy fuselage using sine-wave beam and strut is proposed and investigated. The finite element model of aircraft fuselage is built first. The structures above cabin floor, occupant and seat are simplified as two rigid blocks. The fuselage frame is redesigned, and the sine-wave beam is arranged under the frame. The impact dynamic performance of the aircraft with bottom sine-wave beam structure is studied and compared with that of conventional type. To obtain better crashworthiness performance, different rigidity of strut is combined with the sine-wave beam bottom structure. Numerical simulation result shows that the proposed sine-wave beam bottom structure could not only dissipate more proportion of impact kinetic energy but also reduce the initial peak acceleration. The structure and rigidity of strut have great influence on the crashworthiness performance. To give a better fuselage structure, both of the strut and bottom structure should be properly integrated and designed.

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ABSTRACT: This paper describes a test program on austenitic stainless steel beam-columns. Two types of section were investigated: cold-formed square hollow section and welded H section. Twelve material tensile coupon tests and four stub column tests were conducted to provide the material properties of the specimens. The overall initial geometric imperfections were measured. Ten beam-columns were tested between pin-ended conditions with sideway supports. Results from the tests, including the strengths, the load-deformation responses, and the failure modes were presented. The test strengths and the strengths of all the previous available test specimens were compared with the design strengths predicted using Eurocode (EN 1993-1-4:2006) and American code (SEI/ASCE 8-02). It is shown that the design strengths predicted by these two design codes are generally conservative, and the performance of the American code is better than that of the Eurocode. A modified design rule based on the American code was proposed. Comparison of the predicted strengths with the tests strengths shows that the proposed method offers improved accuracy and reduced scatter.

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ABSTRACT: Cold-formed steel members have been widely used in residential and commercial buildings as primary load bearing structural elements. They are often made of thin steel sheets and hence they are more susceptible to local buckling. The buckling behaviour of cold-formed steel compression members under fire conditions is not fully investigated yet and hence there is a lack of knowledge on the fire performance of cold-formed steel compression members. Current cold-formed steel design standards do not provide adequate design guidelines for the fire design of cold-formed steel compression members. Therefore a research project based on extensive experimental and numerical studies was undertaken to investigate the local buckling behaviour of light gauge cold-formed steel compression members under simulated fire conditions. First a series of 91 local buckling tests was conducted at ambient and uniform elevated temperatures up to 700 °C on cold-formed lipped and unlipped channels. Suitable finite element models were then developed to simulate the behaviour of tested
columns and were validated using test results. All the ultimate load capacity results for local buckling were compared with the predictions from the available design rules based on AS/NZS 4600, BS 5950 Part 5, Eurocode 3 Parts 1.2 and 1.3 and the direct strength method (DSM), based on which suitable recommendations have been made for the fire design of cold-formed steel compression members subject to local buckling at uniform elevated temperatures.

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“Dynamic axial crashing of tailor-welded blanks (TWBs) thin-walled structures with top-hat shaped section”, Advances in Engineering Software, Vol. 96, pp 70-82, June 2016, DOI: 10.1016/j.advengsoft.2016.02.003
ABSTRACT: In this paper, dynamic axial crashing analysis of tailor-welded blanks (TWBs) thin-walled structures with top-hat shaped section under front impact is presented. The crash tests are performed through a sled test in order to model a car-to-car front impact. The strain rate dependence of both high strength steels (DP590 and DP780) is considered to study its influence on acceleration and energy absorption involved into high speed impacting process. The FE model about the front dynamic crashing is conducted, and different weld line modeling types on the dynamic simulation results such as acceleration history are compared. It demonstrates that coincide node (CN) model is considered appropriate for simulating the dynamic impacting. Additionally, the effects of weld line locations and spotweld spacing are also performed. It may be concluded that the material and thickness properties of front end have certain influence on the crashworthiness performance of TWBs. The simulation results show that the acceleration curves of three TWB combinations are insensitive to spotweld spacing. A comprehensive analysis including the crash mode, the acceleration curves and the energy absorption is carried out for crashworthiness assessment. The obtained results can provide some insightful guide information and fundamental supports for light-weight and crashworthiness design of TWBs to a certain extent.

ABSTRACT: Large and small cylindrical shells have long been used as tanks and silos to store materials such as oil and its derivatives. The radius-to-thickness ratio of these shells is 500:2000; as a result, buckling collapse of these thin-walled structures is of major concern for designers. The present study examined inelastic buckling behavior of cylindrical shells near the base, known as elephant foot buckling. This form of buckling occurs under high internal pressure exerted simultaneously with axial compression. The buckling of cylindrical shells subjected to combined axial loads and internal pressure was experimentally studied and tested and a new method of strengthening steel cylindrical shells using fiber-reinforced polymer (FRP) composite materials is presented. The proposed method was studied by numerical methods using a nonlinear algorithm, and the results were evaluated for resistance to buckling of cylindrical shells. The results provide effective and useful information for use in retrofitting cylindrical shell tanks.
Wenfeng Du and Nasim Uddin, “Innovative composite structural insulated panels (CSIPs) folded shell structures for large-span roofs”, Materials and Structures, Vol. 50, No. 51, February 2017
DOI: 10.1617/s11527-016-0924-3

ABSTRACT: Composite structural insulated panels (CSIPs) have the potential to construct lighter large-span roof structures due to high strength-to-weight ratio. However, the drawback of large deflection severely limits their applications. Two effective methods improving the stiffness of CSIPs were investigated in this paper at first. One is the method of folding, which improves the moment of inertia of cross-section areas using the principle of folded panels. The other is the method of curving, which transforms structural bending moments into axial forces using the principle of arches. Then an innovative CSIPs folded shell structure was proposed by combining the advantages of above two methods together. The mechanical behaviors of the CSIPs folded shell structure were studied comparing with CSIPs folded panels and CSIPs thin shells. The static analysis results showed the maximum vertical displacement of the CSIPs folded shell structure under self-weight was 11.054 mm, which was much less than that of CSIPs folded panel (129.17 mm) and that of CSIPs thin shell (89.78 mm). The results of geometrical nonlinear analysis demonstrated that the CSIPs folded shell structure has 5 times larger nonlinear buckling load capacity than the CSIPs thin shell. CSIPs folded shell structures have excellent structural configurations and extensive application prospects in large-span roof structures.

References listed at the end of the paper:
ABSTRACT: In this paper, the buckling analysis of thin walled composite cylindrical shells with and without cutouts is investigated by applying axial load on Glass Fiber Reinforced Plastic (GFRP) shell. The effect of cutout not only introduces stress concentration but also significantly reduces the buckling strength. The column is fixed at one end and load is applied at the other end. The Static and Eigenvalue buckling analysis is done on shell model. The circular, elliptical and rectangle cutouts are considered on cylindrical shell. The buckling analysis is repeated in each case. The compressive stress, buckling load factor and lateral strain of each case for cylindrical shell is obtained from ANSYS software. The buckling load decreases for shell with cutout when compared to the value of the shell without a cutout. Stress and lateral strain increases for shell with cutout when compared to the shell without a cutout. The buckling load value is maximum in circular cutout and minimum in the rectangular cutout.

References listed at the end of the paper:


ABSTRACT: Curved micromechanical beams are a versatile platform for exploring multistable behavior, with potential applications in mechanical based logic elements and electrical and optical switches. Here we demonstrate bidirectional electrostatic actuation of a bistable, latched, micromechanical beam by the same electrode, which was used for the snap-through switching of the device. The release of the mechanically-latched beam is achieved by pre-loading the structure using a rising voltage applied to the electrode, followed by a sudden decrease of the voltage. This abrupt removal of the loading results in a transient response and dynamic snap-back of the beam.

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ABSTRACT: To get a strong, stiff and weight efficient cylindrical shell, a carbon fiber reinforced orthogrid-core sandwich cylinder was designed and fabricated. The core is made up of orthogonal grids and manufactured by interlocking method. The sandwich cylinder is fabricated by filament winding method. Free vibration test combining with theoretical analysis and numerical simulation was carried out to reveal the vibration responses and estimate the modulus of the wound laminate. Uniaxial compression test was performed to reveal the strength and failure mode. Without end flanges, laminate delamination at the end controls the peak load. Delamination of skins induces interfacial debonding and dimpling of inner skin finally. An engineering method based on the average strain at the peak load is proposed to predict the load capacity of the cylinder. Compared with stiffened cylinder, the orthogrid sandwich cylinder is stiffer and stronger. Meanwhile, its making process is simplified and the mechanical ability is comparable with other lattice-core sandwich cylinders.

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ABSTRACT: The nonlinear free vibration and postbuckling behaviors of multilayer functionally graded (FG) porous nanocomposite beams that are made of metal foams reinforced by graphene platelets (GPLs) are investigated in this paper. The internal pores and GPL nanofillers are uniformly dispersed within each layer but both porosity coefficient and GPL weight fraction change from layer to layer, resulting in position-dependent
elastic moduli, mass density and Poisson's ratio along the beam thickness. The mechanical property of closed-cell cellular solids is employed to obtain the relationship between coefficients of porosity and mass density. The effective material properties of the nanocomposite are determined based on the Halpin-Tsai micromechanics model for Young's modulus and the rule of mixture for mass density and Poisson's ratio. Timoshenko beam theory and von Kármán type nonlinearity are used to establish the differential governing equations that are solved by Ritz method and a direct iterative algorithm to obtain the nonlinear vibration frequencies and postbuckling equilibrium paths of the beams with different end supports. Special attention is given to the effects of varying porosity coefficients and GPL's weight fraction, dispersion pattern, geometry and size on the nonlinear behavior of the porous nanocomposite beam. It is found that the addition of a small amount of GPLs can remarkably reinforce the stiffness of the beam, and its nonlinear vibration and postbuckling performance is significantly influenced by the distribution patterns of both internal pores and GPL nanofillers.


ABSTRACT: The new Reference Resistance Design (RRD) method, recently developed by Rotter [1], for the manual dimensioning of metal shell structures effectively permits an analyst working with only a calculator or spreadsheet to take full advantage of the realism and accuracy of an advanced nonlinear finite element (FE) calculation. The method achieves this by reformulating the outcomes of a vast programme of parametric FE calculations in terms of six algebraic parameters and two resistances, each representing a physical aspect of the shell’s behaviour. The formidable challenge now is to establish these parameters and resistances for the most important shell geometries and load cases. The systems that have received by far the most research attention for RRD are that of a cylindrical shell under uniform axial compression and uniform bending. Their partial algebraic characterisations required thousands of finite element calculations to be performed across a four-dimensional parameter hyperspace (i.e. length, radius to thickness ratio, imperfection amplitude, linear strain hardening modulus). Handling so many nonlinear finite element models is time-consuming and the quantities of data generated can be overwhelming. This paper illustrates a computational strategy to deal with both issues that may help researchers establish sets of RRD parameters for other important shell systems with greater confidence and accuracy. The methodology involves full automation of model generation, submission, termination and processing with object-oriented scripting, illustrated using code and pseudocode fragments.

References listed at the end of the paper:
parallel-studio-xe.


ABSTRACT: The nonlinear axisymmetric post-buckling behavior of perfect thin spherical shells subject to external pressure and their asymmetric bifurcations are characterized providing results for a structure/loading combination with an exceptionally nonlinear buckling response. Immediately after the onset of buckling, the buckling mode localizes into a dimple at the poles. The relations among the pressure, the dimple amplitude and the change in volume of the shell are determined for large deflections. These results allow accurate evaluation of criteria such as the Maxwell condition for which the energy in the unbuckled and buckled states are the same and evaluation of the influences of pressure versus volume controlled loadings. Non-axisymmetric bifurcation from the axisymmetric state which occurs deep into the post-buckling regime in the form of multi-lobed dimples is also established and discussed.

References listed at the end of the paper:

Michael Rotter, “Shell buckling transformed: Mechanics, design processes and their inter-relation”, Stahlbau, Vol. 86, No. 4, pp 315-324, April 2017, DOI: 10.1002/stab.201710478 (Dedicated to Professor Herbert Schmidt on his 80th birthday)
ABSTRACT: This paper, in honour of Professor Herbert Schmidt, provides a brief description of two parallel but connected historical developments in the field of the buckling of thin metal shells, an area in which Professor Schmidt has made very significant contributions over the last four decades. The developments in shell buckling mechanics have been enormous over the last century, in addressing challenging practical problems and in changing from difficult mathematics to universal access for competent engineers. The second development has been in design calculations for practising engineers, moving from crude empiricism based on simple tests into a complete framework that can house all computational predictions in a structured manner, permitting very complex problems to be fully characterised. These two fields are quite separate, especially in the early part of the 20th century, and still lie somewhat apart, but the problems encountered in practical engineering continue to influence the development of shell buckling mechanics, whilst the conceptual framework for practical design is evolving to accommodate the most complex of findings in structural mechanics.

ABSTRACT: Thin-walled cylindrical shells are commonly used in numerous branches of industry. Since they are subjected to axial load, the most common cause of their failure is buckling. This paper provides numerical analysis and experimental verification of the buckling of the thin-walled aluminium alloy cylindrical shell with special regard to the influence of dent, positioned in the middle of the shell. Numerical simulation was performed using ANSYS 16.2, and experimental verification was performed by means of hydraulic press Armavir, PSU-50, which was used to subject the specimen to the increasing axial load until the occurrence of buckling. Comparing the results it was concluded that there is significant decrease of the buckling resistance if compared the values of the specimen with no dent, and the specimen with 2 mm deep dent. On the contrary, resistance of the 2 mm and 4 mm dented specimen is quite similar. Position and shape of the deformations occurred due to buckling are matching if experimental and numerical results are compared.
References listed at the end of the paper:

ABSTRACT: In this paper, seaming and seamless as well as short and long cylindrical shell buckling of aluminum 6063 which is under axial loading is taken into account. The used parts have equal mass and thickness and the seam is filled with argon method. An experimental test has been done by SANTAM-STM-250 device. Numerical analysis has been conducted by Abaqus Software, and precision of these models is measured by experimental results.

References listed at the end of the paper:

ABSTRACT: Buckling and post buckling of cylindrical shells under hydrostatic pressure is regarded as important issue in structure of submarines. These cylindrical shells have variable thickness due to construction process which effected by pressure of buckling and its destruction. In this paper, effects of changing thickness on buckling and destruction pressure under external hydrostatic pressure of a shell are studied. Results of buckling pressure of cylindrical shell have been obtained with theoretical relations and finite element method. Then, using machining process a sample of cylindrical shell with variable thickness has been produced. Buckling pressure and post buckling of the constructed sample have been obtained with the reservoir under closed-ended hydrostatic pressure. Changes of the test sample size have been considered with closed-ended testing apparatuses which are used for new evaluation of buckling. In this research, results of the pressure have been obtained in terms of the volume change. At the end, results of the finite element method have been compared with results of the analytical solutions and experimental data. Results show that the shell with variable thickness has buckling pressure close to shell bucking pressure with mean thickness.

References listed at the end of the paper:

ABSTRACT: We compute nonlinear force equilibrium solutions for a clamped thin cylindrical shell under axial compression. The equilibrium solutions are dynamically unstable and located on the stability boundary of the unbuckled state. A fully localized single dimple deformation is identified as the edge state—the attractor for the dynamics restricted to the stability boundary. Under variation of the axial load, the single dimple undergoes homoclinic snaking in the azimuthal direction, creating states with multiple dimples arranged around the central circumference. Once the circumference is completely filled with a ring of dimples, snaking in the axial direction leads to further growth of the dimple pattern. These fully nonlinear solutions embedded in the stability boundary of the unbuckled state constitute critical shape deformations. The solutions may thus be a step towards explaining when the buckling and subsequent collapse of an axially loaded cylinder shell is triggered.

References listed at the end of the paper:

ABSTRACT: Shells are among the most frequent structural components which are used in construction and industrial projects. Shell structures are composed of shell bearing elements and mainly used in oil and gas tanks, offshore marine platforms, silos, funnels, cooling towers, ship and aircraft body, etc. Despite the frequent use of steel cylindrical shells, their construction and assembling process has caused main problems. In these structures,
there is no possibility for the integrated construction due to their large shell extent and they are built using a number of welded curved panel parts; hence, some geometrical imperfections emerge. Most of these imperfections are caused by the process of welding, transportation, inappropriate rolling, as well as installation and implementation problems. These imperfections have a direct impact on the structural behavior of shells during the buckling and external compressive load. Since in most shell tanks during operation, there is high possibility for the suction (vacuum) state, compressive forces in their thin wall cause buckling and failure. In this research, the imperfections made in steel cylindrical tanks being constructed in one of the refinery site are introduced and evaluated using a field study. Relying on the statistical inference, they are classified and then, by studying the effective factors and origin in their generation, the common imperfections are identified. Later, the impact of common imperfections on the buckling behavior is experimentally evaluated under uniform external pressure. Then, nonlinear numerical analysis of the test specimens is performed. Finally, experimental results, finite element and analytical relations are compared.

References listed at the end of the paper:

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ABSTRACT: Shell structures are susceptible to various types of imperfections and damage such as cracking, corrosion, chemical attack and time-dependent material degradation, which may impair their structural integrity and affect their service life. The effects of cracks are important considerations in the design of cylindrical shell structures as they influence on load carrying capacity and safety. This present work is a finite element investigation on the vibration, buckling and fracture analysis of a cracked cylindrical shell subjected to a time varying rotating speed. The effects of crack length, orientation of crack and length-diameter ratio of the cylindrical shell are investigated under free-vibration and buckling. The fracture parameters like stress intensity factor and J-integral of the cracked shell are also studied considering the influence of crack length and crack orientation. Results reveal that the crack length and crack orientation can affect the vibration, buckling behaviour of the cylindrical shell significantly.

References listed at the end of the paper:


ABSTRACT: Shell structures are widely used in civil, mechanical, aerospace and marine engineering applications (e.g. offshore oil tanks, automotive industry, aircraft and submarines). Like other types of structures, they are susceptible to various types of defect and damage such as cracking, corrosion, chemical attack and time-dependent material degradation, which may impair their structural integrity and affect their service life. The presence of cracks in a cylindrical structure can considerably affect its behavior. The effects of these imperfections on load carrying capacity and safety are thus important considerations in the design of cylindrical shell structures. This present work presents a finite element study on the vibration, buckling and fracture behavior of a cracked cylindrical shell with clamped type supports and subject to a time varying rotating speed. Vibration, linear elastic buckling and fracture parameters of a cracked cylindrical shell with
time-varying rotating speed are analyzed. The effects of constant rotating speed, crack length and orientation of crack and length-diameter ratio of the cylindrical shell on the free-vibration and buckling behaviors are investigated.

Arash Ghaedizadeh, Jianhu Shen, Xin Ren and Yi Min Xie (Centre for Innovative Structures and Materials, School of Engineering, RMIT University, GPO Box 2476, Melbourne 3001, Australia), “Tuning the performance of metallic auxetic metamaterials by using buckling and plasticity”, Materials, Vol. 9, No. 1, 54, 2016, doi:10.3390/ma9010054

ABSTRACT: Metallic auxetic metamaterials are of great potential to be used in many applications because of their superior mechanical performance to elastomer-based auxetic materials. Due to the limited knowledge on this new type of materials under large plastic deformation, the implementation of such materials in practical applications remains elusive. In contrast to the elastomer-based metamaterials, metallic ones possess new features as a result of the nonlinear deformation of their metallic microstructures under large deformation. The loss of auxetic behavior in metallic metamaterials led us to carry out a numerical and experimental study to investigate the mechanism of the observed phenomenon. A general approach was proposed to tune the performance of auxetic metallic metamaterials undergoing large plastic deformation using buckling behavior and the plasticity of base material. Both experiments and finite element simulations were used to verify the effectiveness of the developed approach. By employing this approach, a 2D auxetic metamaterial was derived from a regular square lattice. Then, by altering the initial geometry of microstructure with the desired buckling pattern, the metallic metamaterials exhibit auxetic behavior with tuneable mechanical properties. A systematic parametric study using the validated finite element models was conducted to reveal the novel features of metallic auxetic metamaterials undergoing large plastic deformation. The results of this study provide a useful guideline for the design of 2D metallic auxetic metamaterials for various applications.


ABSTRACT: The buckling and layer failure characteristics of composite laminated cylinders subjected to hydrostatic pressure were investigated through finite element analysis for underwater vehicle application. The Tsai-Wu failure criteria were used as the failure criteria for the buckling analysis. A sensitivity analysis was conducted to research the influence of the number of elements on the critical buckling pressure. ANSYS, a finite element program, successfully predicted the buckling pressure with 5.3–27.8% (linear) and 0.3–22.5% (nonlinear) deviation from experimental results. The analysis results showed that the cylinders can carry more pressure after a slight decrease in pressure and recovery of the supporting load. For layer failure analysis, it was found that the failure that occurred in the 0° layer was more serious than that in the 90° layer within the neighboring layers at the inner layers (nos. 1–7) and outer layers (nos. 8–24).

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ABSTRACT: Micro-buckling of unidirectional fiber-reinforced composites is investigated in this paper by means of an explicit representation of a geometrically imperfect fiber within the context of kinematical and material non-linear behavior. Two types of fiber imperfections are considered: a helicoidal shape, identified as 3D imperfection; and a sinusoidal plane shape (2D imperfection). Both imperfection models are characterized by a maximum misalignment angle of the fiber with respect to the ideal or perfect configuration, as is usually considered in this field. A total of 816 cases were computed in terms of imperfection type (either 2D or 3D), fiber volume fraction, fiber arrangement (square or hexagonal array), orientation for 2D models, matrix yield stress, and misalignment angle. Two load cases, with constrained and unconstrained transverse strain, were considered. Assuming periodic boundary conditions, homogenization was carried out to obtain macroscopic stresses. Numerical results are compared with an analytical model available in the literature. The results show a high imperfection-sensitivity for small misalignment angles; on the other hand, the type of imperfection and the fiber arrangement do not have a large influence on the results. In addition, it was found that this problem is governed by fiber volume fraction and matrix yield stress only for small imperfections, whereas for large misalignment angles, a change in fiber volume fraction produces small changes in micro-buckling stress.

References listed at the end of the paper:
Loads. Results show that the FML layup has a significant effect on the buckling loads of FML cylindrical composite fiber orientation, stacking sequence of layers and geometric parameters. Afterward, the effects of FML parameters such as metal volume fraction (MVF), experimental and analytical data for buckling behavior of FML cylindrical shells in the literature, the proposed calculation and finite element approaches. The governing equations are derived based on the first-order shear deformation theory and solved by the Navier solution method. Also, the buckling load of a FML cylindrical shell is calculated using linear eigenvalue analysis in commercial finite element software, ABAQUS. Due to lack of experimental and analytical data for buckling behavior of FML cylindrical shells in the literature, the proposed model is simplified to the full-composite and full-metal cylindrical shells and buckling loads are compared with the available results. Afterwards, the effects of FML parameters such as metal volume fraction (MVF), composite fiber orientation, stacking sequence of layers and geometric parameters are studied on the buckling loads. Results show that the FML layup has a significant effect on the buckling loads ofFML cylindrical shells.
shells in comparison to the full-composite and full-metal shells. Results of this paper hopefully provide a useful guideline for engineers to design an efficient and economical structure.

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ABSTRACT: In this paper, non-linear dynamics analysis of functionally graded material (FGM) shell structures is investigated using the higher order solid-shell element based on the Enhanced Assumed Strain (EAS). With this element, a quadratic distribution of the shear stress through the thickness is considered in an enhancing part. Material properties of the shell structure are varied continuously in the thickness direction according to the general four-parameter power-law distribution in terms of the volume fractions of the constituents. Performance and accuracy of the present higher order solid-shell element are confirmed by comparing the numerical results obtained from finite element analyses with results from the literature.

References listed at the end of the paper:

ABSTRACT: We report the results of an experimental and numerical investigation into the buckling of thin elastic rings confined within containers of circular or regular polygonal cross section. The rings float on the surface of water held in the container and controlled removal of the fluid increases the confinement of the ring. The increased compressive forces can cause the ring to buckle into a variety of shapes. For the circular container, finite perturbations are required to induce buckling, whereas in polygonal containers the buckling occurs through a linear instability that is closely related to the canonical Euler column buckling. A model based on Kirchhoff–Love beam theory is developed and solved numerically, showing good agreement with the experiments and revealing that in polygons increasing the number of sides means that buckling occurs at reduced levels of confinement.

M. Gil-Oulbие, S.T. Farhan and D. Tyekolo, “Buckling analysis of functionally graded epitrochoidal shell
http://journals.rudn.ru/structural-mechanics/article/view/14617

ABSTRACT: В настоящей статье рассматривается устойчивость функционально-градиентных эпитрохоидальных оболочек под давлением и тепловой среды. Свойства материала принимаются как зависящие от температуры. Конечно-элементные решения получены с помощью программного комплекса ANSYS. Линейные задачи на собственные значения устойчивости решается с помощью блочного метода Ланцоша. Влияние различной геометрии и параметров материала на критическую температуру функционально-градиентных эпитрохоидальных оболочек под давлением и тепловой средой наглядно показано. В конце, изменение напряжений, перемещений, вращений и деформаций изучены и представлены.

Keywords: Functionally Graded Materials, Cyclic Shells, Epitrochoidal Shells, mechanical and thermal material properties, conservative, nonconservative, Stability, Instability, buckling analysis.

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Yaghoub Tadi Beni, Fahimeh Mehralian and Mehran Karimi Zeverdejani, “Size-dependent buckling analysis of different chirality SWCNT under combined axial and radial loading based on orthotropic model”, Materials Research Express, Vol. 4, No. 6, June 2017
ABSTRACT: In the present study, the size-dependent buckling behavior of carbon nanotubes (CNTs) is investigated on the basis of orthotropic shell model. Due to the nature of carbon nanotubes, their properties differ in various directions; therefore, they must be treated as anisotropic shells. Moreover, due to the small dimensions of CNTs, material length scale parameter must be included to predict the mechanical behavior of CNTs more accurately; accordingly this study is carried out on the basis of the new modified couple stress theory. CNT buckling affects the stability of nanocomposites and nanoactuators and small dimensions and different properties affect the CNT stability. In this article, using minimum potential energy principle, the equilibrium equations and boundary conditions are derived. Then, the buckling response of simply supported CNTs under combined loading is studied and the critical buckling load of the orthotropic CNT is calculated for various structural and geometrical conditions. Finally, the molecular dynamics (MD) simulation is performed to investigate the axial buckling behaviour of defective CNTs.


ABSTRACT: Perforated steel thin plates are commonly used in structural engineering. Due to their geometric characteristics, these panels can suffer the undesired buckling phenomenon. In this context, the present work associates the computational modeling and the constructal design method to evaluate the influence of the geometric configuration in the plate buckling behavior, using the exhaustive search method to determine which geometries conduct to superior mechanical behavior. To do so, numerical models are employed to solve elastic and elasto-plastic buckling of plates having a centered perforation. Different hole types (longitudinal oblong, transversal oblong, elliptical, rectangular, diamond, longitudinal hexagonal, or transversal hexagonal) with different shapes (variation of characteristics dimensions of each hole type) are analyzed. Limit curves to avoid buckling were obtained, as well as the definition of the geometries that can improve up to 107% the plate performance.


ABSTRACT: Composite lattice structures are shells that are reinforced by unidirectional helical and hoop ribs. Their main advantage over contemporary composite structures is their superior stiffness to mass ratio. However, their application in industry is still limited. In this paper, the lattice structure concept was applied for the case of a small business aircraft. Emphasis here is given at the initial stages of the design. More specifically, the buckling modes for bending loads were calculated by utilizing a continuum unit cell model which was correlated with finite element models for a cylindrical small fuselage structure and two scaled down versions.

References listed at the end of the paper:

ABSTRACT: Cell-generated mechanical forces drive many of the tissue movements and rearrangements that are required to transform simple populations of cells into the complex three-dimensional geometries of mature organs. However, mechanical forces do not need to arise from active cellular movements. Recent studies have illuminated the roles of passive forces that result from mechanical instabilities between epithelial tissues and their surroundings. These mechanical instabilities cause essentially one-dimensional epithelial tubes and two-dimensional epithelial sheets to buckle or wrinkle into complex topologies containing loops, folds, and undulations in organs as diverse as the brain, the intestine, and the lung. Here, I highlight examples of buckling and wrinkling morphogenesis, and suggest that this morphogenetic mechanism may be broadly responsible for sculpting organ form.

References listed at the end of the paper:


Ngoc Lieu Le, Dooli Kim and Suzana P. Nunes (King Abdullah University of Science and Technology (KAUST), Biological and Environmental Science and Engineering Division (BESE), Thuwal, Saudi Arabia), “Evolution of regular geometrical shapes in fiber lumens”, Scientific Reports, Vol. 7, Article number: 9171, August 2017, doi:10.1038/s41598-017-09134-z

ABSTRACT: The geometry of polymeric hollow fibers for hemodialysis or desalination is a key factor determining their performance. Deformations are frequently observed, but they are rather random. Here we were able to exactly control the shape evolution of the internal channels or lumens of polymeric hollow fibers, leading to polygonal geometries with increasing number of sides. The elasticity of the incipient channel skin and instabilities during fiber formation are affected by the internal coagulant fluid composition and flow rate; and highly influence the polygonal shape. We propose a holistic explanation by analyzing the thermodynamic, kinetic and rheological aspects involved in the skin formation and their synergy.


ABSTRACT: In this research work, an exact analytical solution for frequency characteristics of the free vibration of rotating functionally graded material (FGM) truncated conical shells reinforced by eccentric FGM stringers and rings has been investigated by the displacement function method. Material properties of shell and stiffeners are assumed to be graded in the thickness direction according to a simple power law distribution. The change of spacing between stringers is considered. Using the Donnell shell theory, Leckhinsky smeared stiffeners technique and taking into account the influences of centrifugal force and Coriolis acceleration the governing equations are derived. For stiffened FGM conical shells, it is difficult that free vibration equations are a couple set of three variable coefficient partial differential equations. By suitable transformations and applying Galerkin method, this difficulty is overcome in the paper. The sixth order polynomial equation for $\omega$ is obtained and it is used to analyze the frequency characteristics of rotating ES-FGM conical shells. Effects of stiffener, geometrics parameters, cone angle, vibration modes and rotating speed on frequency characteristics of the shell forward and backward wave are discussed in detail. The present approach proves to be reliable and accurate by comparing with published results available in the literature.

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Pham Minh Vuong and Dao Van Dung, “Nonlinear analysis on buckling and postbuckling of stiffened FGM imperfect cylindrical shells filled inside by elastic foundations in thermal environment using TSDT”, Latin

ABSTRACT: The main aim of this paper is to investigate analytically nonlinear buckling and post-buckling of functionally graded stiffened circular cylindrical shells filled inside by Pasternak two-parameter elastic foundations in thermal environments and under axial compression load and external pressure by analytical approach. Shells are reinforced by closely spaced rings and stringers. The material properties of shell and the stiffeners are assumed to be continuously graded in the thickness direction. Using the Reddy third order shear deformation shell theory, stress function method and Lekhnitskii smeared stiffeners technique, the governing equations are derived. The closed form to determine critical axial load and post-buckling load-deflection curves are obtained by Galerkin method. The effects of temperature, stiffener, foundation, material and dimensional parameters on the stability behavior of shells are shown. The accuracy of the presented method is affirmed by comparisons with well-known results in references. The results shown for thick cylindrical shells, the use of TSDT for determining their critical buckling load is necessary and more suitable.

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ABSTRACT: The mechanics of a fascicle insertion into the skin by a mosquito of the type *aedes aegypti* has been studied experimentally using high-speed video (HSV) imaging, and analytically using a mathematical model. The fascicle is a polymeric microneedle composed of a ductile material, chitin. It has been proposed that the mosquito applies a non-conservative follower force component in addition to the Euler compressive load in order to prevent buckling and penetrate the skin. In addition, the protective sheath surrounding the fascicle (labium) provides lateral support during insertion. The mechanics model presented approximates the fascicle as a slender column supported on an elastic foundation (labium) subjected to non-conservative (Beck) and
conservative Euler loads simultaneously at the end. Results show that the lateral support of the fascicle provided by the labium is essential for successful penetration by increasing the critical buckling load by a factor of 5. The non-conservative follower force application increases the buckling load by an additional 20% and may or may not be necessary for successful penetration. Experimental results showing the importance of the labium have been cited to validate the model predictions, in addition to the video observations presented in this work. This understanding may be useful in designing painless needle insertion systems as opposed to miniaturized hypodermic needles.


ABSTRACT: Thin walled tubes are often used for load-bearing structures, in nature and in engineering, because they offer good resistance to bending and torsion at relatively low weight. However, when loaded in bending they are prone to failure by buckling. It is difficult to predict the loading conditions which cause buckling, especially for tubes whose cross sections are not simple shapes. Insights into buckling prevention might be gained by studying this phenomenon in the exoskeletons of insects and other arthropods. We investigated the leg segments (tibiae) of five different insects: the locust (Schistocerca gergaria), American cockroach (Periplaneta americana), death's head cockroach (Blaberus discoidalis), stick insect (Parapachymorpha zomproi) and bumblebee (Bombus terrestris audax). These were tested to failure in cantilever bending and modelled using finite element analysis (FEA). The tibiae of the locust and the cockroaches were found to be approximately circular in shape. Their buckling loads were well predicted by linear elastic FEA, and also by one of the analytical solutions available in the literature for elastic buckling. The legs of the stick insect are also circular in cross section but have several prominent longitudinal ridges. We hypothesised that these ridges might protect the legs against buckling but we found that this was not the case: the loads necessary for elastic buckling were not reached in practice because yield occurred in the material, causing plastic buckling. The legs of bees have a non-circular cross section due to a pollen-carrying feature (the corbicula). We found that this did not significantly affect their resistance to buckling. Our results imply that buckling is the dominant failure mode in the tibia of insects; it likely to be a significant consideration for other arthropods and any organisms with stiff exoskeletons. The interactions displayed here between material properties and cross sectional geometry may provide insights for the biomimetic design of engineering structures using thin walled tubes.


ABSTRACT: This thesis deals with shell structures in shape of a cylinder and an arch. First a cylindrical shell is examined analytically and numerically to see how the shell behaves under meridional- and circumferential compression and torsion. Afterwards imperfections are implemented by using an eigenmode as initial geometry to see how this affects the buckling stress. It is seen that the imperfection reduces the buckling stress as expected and the larger the scaling factor of the eigenmode is the lower is the buckling stress. Afterwards, a study of shells in the shape of an arch is analysed in order to determine the optimal geometry when considering buckling and yielding. Here a circular, parabolic and catenary cross sectional geometry is analysed when exposed to an inside suction, self weight and line load on top of the arc. The results shows that the different shapes have a large influence on the buckling stress. It is also concluded that the support type is of importance since they might increase or decrease the stresses. Finally, imperfections are implemented in the arch and the
results show that the different types of imperfection have different influence on the buckling stress.

References listed at the end of the thesis:


Hyperphysics (2016). Moment of Inertia. URL: http://hyperphysics.phy-astr.gsu.edu/hbase/icyl.html. Downloaded: 30-03-2016.


ABSTRACT: A typical mechanical failure mode observed in slender percutaneous instruments, such as needles and guidewires, is buckling. Buckling is observed when the axial compressive force that is required to penetrate certain tissue types exceeds the critical load of the instrument and manifests itself by sudden lateral deflection of the instrument. In nature, several organisms are able to penetrate substrates without buckling while using apparatuses with diameters smaller than those of off-the-shelf available percutaneous needles and guidewires. In this study we reviewed the apparatuses and buckling prevention strategies employed by biological organisms to penetrate substrates such as wood and skin. A subdivision is made between buckling prevention strategies that focus on increasing the critical load of the penetration tool and strategies that focus on decreasing the
penetration load of the substrate. In total, 28 buckling prevention strategies were identified and categorized. Most organisms appear to be using a combination of buckling prevention strategies simultaneously. Integration and combination of these biological buckling prevention strategies in percutaneous instruments may contribute to increasing the success rate of percutaneous interventions.


ABSTRACT: This paper presents the effect of stiffeners on the free vibration response of delaminated composite shallow cylindrical shells employing the finite element method. An eight-noded isoparametric shell element based on the first-order shear deformation theory is combined with a three-noded isoparametric curved beam element in the present formulation. The stiffeners follow the nodal lines of the shell wherein the stiffness and mass of the stiffeners are lumped at the corresponding nodal points of the shell elements considering curvature and eccentricity. The generalized dynamic equilibrium equation is derived from Lagrange’s equation of motion, wherein Coriolis effect for moderate rotational speeds is neglected. The multi-point constraint algorithm has been used to model delamination at the desired locations wherein the compatibility of deformation and equilibrium of stress resultants are ensured at the delamination crack front. Numerical results are presented for cantilevered long, intermediate and short cylindrical shells as defined by Aas-Jakobsen’s parameters, and the influence of important parameters like location of delamination, twist angle, rotational speed, number of layers and eccentricity of the stiffeners is studied. The mode shapes for a typical composite un-stiffened and stiffened long cylindrical shell at different rotational speeds and twist angles are also presented.


ABSTRACT: We study a Brownian dynamics simulation model of a biopolymeric shell deformed by axial forces exerted at opposing poles. The model exhibits two distinct, linear force-extension regimes, with the response to small tensions governed by linear elasticity and the response to large tensions governed by an effective spring constant that scales with radius as \( R^{-0.25} \). When extended beyond the initial linear elastic regime, the shell undergoes a hysteretic, temperature-dependent buckling transition. We experimentally observe this buckling transition by stretching and imaging the lamina of isolated cell nuclei. Furthermore, the interior contents of the shell can alter mechanical response and buckling, which we show by simulating a model for the nucleus that quantitatively agrees with our micromanipulation experiments stretching individual nuclei.

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Fahimeh Mehralian, Yaghoub Tadi Beni and Yaser Kiani (Faculty of Engineering, Shahrekord University, Shahrekord, Iran), “Molecular dynamics study on the thermal buckling of carbon nanotubes in the presence of pre-load”, Materials Research Express, Vol. 4, No. 1, January 2017, https://doi.org/10.1088/2053-1591/aa576a

ABSTRACT: This paper presents a molecular dynamics (MD) study on the thermally induced buckling of pre-compressed carbon nanotubes (CNTs) using AIREBO interatomic potential. CNTs are compressed at a certain ratio of their critical buckling strain and then undergo a uniform temperature rise. In order to evaluate the chirality effects, armchair and zigzag CNTs are investigated. The results demonstrate that critical buckling temperature depends strongly on the geometrical parameters such as chirality, diameter and aspect ratio. The armchair CNTs, due to their bond configuration, show higher resistance to thermal buckling than zigzag ones. Moreover, the buckling mechanism is strongly affected by the length of CNTs. At small aspect ratios, radial limit load shell buckling occurs while by increase in aspect ratio above the critical one different behaviors emerge. Due to the strong thermal oscillation of carbon atoms, increase in temperature changes perfect nanotubes to defective ones.

S. Sahmani and A.M. Fattahi (Department of Mechanical Engineering, Bandar Anzali Branch, Islamic Azad University, Bandar Anzali, Iran), “An anisotropic calibrated nonlocal plate model for biaxial instability analysis of 3D metallic carbon nanosheets using molecular dynamics simulations”, Materials Research Express, Vol. 4, No. 6, June 2017, https://doi.org/10.1088/2053-1591/aa6bc0

ABSTRACT: Based upon an interlocking hexagonal arrangement of carbon atoms, it is possible to have a mechanically stable three-dimensional (3D) carbon structure including metallicity which provides a wide range of applications. In the present study, a novel calibrated size-dependent plate model using nonlocal continuum...
theory of elasticity with an exponential distribution of the shear deformation is constructed to anticipate accurately the nonlinear instability response of biaxially loaded 3D metallic carbon nanosheets. Explicit expressions for the size-dependent equilibrium curves are proposed via a two-stepped perturbation technique. After that, the critical biaxial buckling loads obtained by the developed nonlocal plate model are matched with those evaluated by some molecular dynamics (MD) simulations of biaxial instability of square 3D metallic carbon nanosheets to catch the proper value of nonlocal parameter. It is indicated that by using the proposed calibrated nonlocal plate model, the error in prediction of the biaxial instability behavior of 3D metallic carbon nanosheets reduces significantly.


ABSTRACT: This paper deals with the theoretical analysis of free vibration and biaxial buckling of magneto-electro-elastic (MEE) microplate resting on Kelvin–Voigt visco-Pasternak foundation and subjected to initial external electric and magnetic potentials, using modified strain gradient theory (MSGT). Kirchhoff plate model and Hamilton's principle are employed to extract the governing equations of motion. Governing equations were analytically solved to obtain clear closed-form expression for complex natural frequencies and buckling loads using Navier's approach. Numerical results are presented to reveal variations of natural frequency and buckling load ratio of MEE microplate against different amounts of the length scale parameter, initial external electric and magnetic potentials, aspect ratio, damping and transverse and shear stiffness parameters of the visco-Pasternak foundation, length to thickness ratio, microplate thickness and higher modes. Numerical results of this study illustrate that by increasing thickness-to-material length scale parameter ratio, both natural frequency and buckling load ratio predicted by MSGT and modified couple stress theory are reduced because the non-dimensional length scale parameter tends to decrease the stiffness of structures and make them more flexible. In addition, results show that initial external electric and initial external magnetic potentials have no considerable influence on the buckling load ratio and frequency of MEE microplate as the microplate thickness increases.

Jiyoon Nam, Bowook Seo, Youngjoo Lee, Dong-Ho Kim and Sungjin Jo, “Cross-buckled structures for stretchable and compressible thin film silicon solar cells”, Scientific Reports, Vol. 7, Article Number 7575, August 2017, doi:10.1038/s41598-017-08012-y

ABSTRACT: Increasing interests in stretchable electronic devices have resulted in vigorous research activities, most of which are focused on structural configurations. Diverse structural configurations are available for stretchability, including stiff-island, serpentine, and buckled structures. With easily deformable shapes and simple fabrication processes, buckled structures have the potential to realize stretchability. However, conventional buckled structures exhibit stretchability only in a single-axis direction. In the present study, a new type of cross-buckled structure, which can overcome the limitations of conventional buckled structures is developed. The stretchable thin film solar cells with the cross-buckled structure showed stable mechanical and electrical characteristics under both stretching and compressing conditions. The cross-buckled structure for stretchable electronic devices is expected to broaden the fields of wearable electronics, stretchable displays, and biocompatible applications.

ABSTRACT: We present a novel cellular metamaterial constructed from Origami building blocks based on Miura-ori fold. The proposed cellular metamaterial exhibits unusual properties some of which stemming from the inherent properties of its Origami building blocks, and others manifesting due to its unique geometrical construction and architecture. These properties include foldability with two fully-folded configurations, auxeticity (i.e., negative Poisson’s ratio), bistability, and self-locking of Origami building blocks to construct load-bearing cellular metamaterials. The kinematics and force response of the cellular metamaterial during folding were studied to investigate the underlying mechanisms resulting in its unique properties using analytical modeling and experiments.

References listed at the end of the paper:
ABSTRACT: Programmable stiff sheets with a single low-energy folding motion have been sought in fields ranging from the ancient art of origami to modern meta-materials research. Despite such attention, only two extreme classes of crease patterns are usually studied; special Miura-Ori-based zero-energy patterns, in which crease folding requires no sheet bending, and random patterns with high-energy folding, in which the sheet bends as much as creases fold. We present a physical approach that allows systematic exploration of the entire space of crease patterns as a function of the folding energy. Consequently, we uncover statistical results in origami, finding the entropy of crease patterns of given folding energy. Notably, we identify three classes of extreme classes of crease patterns ranging from the ancient art of origami to modern meta-materials research.

References listed at the end of the paper:

Eliseu Lucena Neto, Marcus Antonio Ferreira Araripe, Francisco Alex Correia Monteiro and Jose Antonio Hernandes (Instituto Tecnológico de Aeronáutica, 12228-900 São José dos Campos, SP, Brazil), An explicit consistent geometric stiffness matrix for the DKT element”, Latin American Journal of Solids and Structures, Vol. 14, No. 4, Rio de Janeiro, March 2017

ABSTRACT: A large number of references dealing with the geometric stiffness matrix of the DKT finite element exist in the literature, where nearly all of them adopt an inconsistent form. While such a matrix may be part of the element to treat nonlinear problems in general, it is of crucial importance for linearized buckling analysis. The present work seems to be the first to obtain an explicit expression for this matrix in a consistent way. Numerical results on linear buckling of plates assess the element performance either with the proposed explicit consistent matrix, or with the most commonly used inconsistent matrix.

References listed at the end of the paper:
ABSTRACT: Tiny concentrations of suspended particles may alter the behavior of an evaporating droplet remarkably, leading to partially viscous and partially elastic dynamical characteristics. This, in turn, may lead to some striking mechanical instabilities, such as buckling and rupture. Here, we report certain non-trivial implications of the consequent morpho-dynamics (macro to nano scales), when such an evaporating droplet is encapsulated in a confined environment. Compared to unconfined scenario, we report non-intuitive suppression of rupturing beyond a critical confinement. We attribute this to confinement-induced dramatic alteration in the evaporating flux, leading to distinctive spatio-temporal characteristics of the internal flow leading to preferential particle transport and subsequent morphological transitions. We present a regime map quantifying buckling-non-buckling pathways. These results may turn out to be of profound importance towards achieving desired morphological features of a colloidal droplet, by aptly tuning the confinement space, initial particle concentration, as well as the initial droplet volume.

ABSTRACT: Currently, lattice composite structures have many applications in aerospace industries. The present research analyzed the effect of an external skin consisting of a lattice’s cylindrical shell on the buckling strength of composite materials, both numerically and experimentally. Two classes of specimens, with and without external skins, were fabricated using the filament winding process. To find the buckling strength of the fabricated samples, tests were carried out. For validation of the experimental results, the finite element method was used to test the shells under the same testing conditions. The results of the experimental and numerical tests showed good agreement with one another, revealing that the lattice cylindrical shell specimen with the outer skin had a much higher buckling strength than the one without the outer skin (≈50%). The added weight of the outer skin was negligible compared to the overall weight of the lattice cylindrical shell, and the external skin had a tremendous positive effect on the buckling strength to weight ratio of the lattice composite structures.

References listed at the end of the paper:

Andrey Kosmrlj (1) and David R. Nelson (2)
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ABSTRACT: We explore how thermal fluctuations affect the mechanics of thin amorphous spherical shells. In flat membranes with a shear modulus, thermal fluctuations increase the bending rigidity and reduce the in-plane elastic moduli in a scale-dependent fashion. This is still true for spherical shells. However, the additional coupling between the shell curvature, the local in-plane stretching modes, and the local out-of-plane undulations leads to novel phenomena. In spherical shells, thermal fluctuations produce a radius-dependent negative effective surface tension, equivalent to applying an inward external pressure. By adapting renormalization group calculations to allow for a spherical background curvature, we show that while small spherical shells are stable, sufficiently large shells are crushed by this thermally generated “pressure.” Such shells can be stabilized
by an outward osmotic pressure, but the effective shell size grows nonlinearly with increasing outward pressure, with the same universal power-law exponent that characterizes the response of fluctuating flat membranes to a uniform tension.

References listed at the end of the paper:


ABSTRACT: This contribution provides simulated results of cross-sectional deformations observed in carbon nanotubes under high pressure. Molecular dynamics (MD) simulations were performed to explore radial buckling characteristics of multi-walled carbon nanotubes, and confirmed a variety of large-amplitude deformation modes. The energetically stable deformation mode turned out to be strongly dependent on the diameter of the innermost tube and the number of concentric walls. Critical buckling pressure obtained by MD simulations was compared with that estimated from a continuum elastic approximation, by which the validity of the continuum approximation was assessed.


[NOTE: “particle morphology” includes buckling.]

ABSTRACT: Powders of nanoparticles are volatile, i.e. easily disperse in air, which makes their handling difficult. Granulation of nanoparticle powders provides a solution to that issue, and it is generally performed by spray drying the nanoparticles that have been suspended in a liquid. Spray drying of a colloidal suspension consists of atomising the suspension into droplets by a fast flowing and hot gas. Once the droplets dried, the resulting dry grains/microparticles can be used in a wide range of applications – food, pharmaceutics, fillers, ceramics, etc. It is well known that the grains resulting from spray-drying may be spherical but may also exhibit other diverse morphologies. Although different influencing parameters have been identified, no clear overview can be found in the literature for the driving mechanisms of grain shaping. In the present work, we review the assumptions made in the literature to explain the different morphologies. We analyse the orders of magnitude of the different effects at stake and show that the grain shape does not result from a hydrodynamic instability but is determined by the drying stage. However, we emphasize that neither the drying time nor the associated Péclet number are critical parameters for the determination of shape morphology. In light of those results, we also review and discuss the single droplet experiments developed to mimic spray drying. Generalising our previous works, we further analyse how the control of morphology can be achieved by tuning the colloidal interactions in the suspension. We detail the model we have developed that relates the colloidal interaction potential to a critical pressure exerted by the solvent as it flows, and we provide a quantitative prediction of the grain shape. Finally, we offer perspectives with regard to spray drying of systems such as molecular solutions, widely performed in e.g. the pharmaceutical industry.
ABSTRACT: The present paper discusses reliability of dynamic buckling of single layer reticulated domes under dead and seismic loads. First, several domes with different safety factors for dead load are designed based on elasto-plastic buckling analysis. Second, the dynamic buckling loads obtained based on dynamic nonlinear analysis of these domes are analyzed aiming at formulating a mathematical expression for buckling loads in terms of related structural variables. Then, an equation for the dynamic buckling load is formulated explicitly in terms of the related variables. Third, concerning dynamic buckling under dead and seismic loads, a performance function for reliability is expressed in terms of seismic input acceleration intensity as action and buckling strength as resistance. Fourth, a trial is performed to evaluate an approximate value of reliability index using a performance function, then solved successively using AFOSM method, and the values of reliability index for reticulated domes using 50-year and 100-year reference periods are searched considering the related stochastic properties. Finally, the paper discusses the relationship between reliability index and safety factor for dead load in the two cases of reference period from a viewpoint of structural design for ordinary structures.


ABSTRACT: In this paper a physically based and deterministic design procedure for spherical shells under external pressure is introduced. Within the new design concept the membrane energy of a sphere is incrementally reduced by means of perturbation cutouts, until a bending energy dominate state is identified. The threshold between membrane energy state and bending energy state represents a robust plateau for the buckling pressure. A comprehensive numerical investigation was performed in order to study the influence of radius-to-thickness ratio (R/t) as well as the dome height-to-base radius ratio (H/r). The results verify that both geometric properties ratios significantly influence the lower-bound buckling pressure, especially if plastic buckling occurs. Improved shell buckling design factors are given in the form of an simple analytic equation. The corresponding threshold KDFs were validated with a large number of buckling experiments and deliver much higher KDFs than currently used empirical guidelines. Based on the new design criterion lower-bound estimation for the buckling pressure of a tori-spherical bulkhead and the inner dome of the cryogenic upper stage ESC-A from the European space launch-vehicle Ariane 5 are determined.

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Christopher R. Calladine, “Shell buckling, without ‘imperfections’”, Advances in Structural Engineering (a special issue in honor of Michael Rotter), SAGE, p 1-11, 2018, DOI: 10.1177/1369433217751585

ABSTRACT: The buckling behaviour of thin shell structures under load has been a persistent challenge to engineering designers and researchers over many decades. In this article I consider two unusual experimental studies on the buckling of thin-walled elastic cylindrical shells, each of which sheds intriguing light on the buckling phenomena. The classical theory of buckling of thin cylindrical shells under axial compression predicts that the buckling stress will be proportional to \( t/R \) – the ratio of thickness to radius – other things being equal. But collected results of experimental studies from many laboratories, when plotted on log–log scales, show clearly that the buckling stress is actually proportional to \( (t/R)^1.5 \), with the measured buckling stresses being scattered through a factor of about 4 for shells with \( R/t > 200 \). Such scatter is commonly judged to be in accord with Koiter’s theory of ‘imperfection sensitivity’. But that theory lays no claim to an understanding of the empirical 1.5-power law. I claim that a key to this situation is the experimental performance of some small-scale open-topped silicone rubber shells, buckling under their own weight, which clearly demonstrates a 1.5-power law, but with very little scatter. The buckling mode of these shells involves almost entirely inextensional deformation, with a single small dimple growing near the base, separated from the rest of the shell by a narrow boundary layer that accounts for almost all of the dimple’s elastic strain energy. A straightforward, simple analysis of the mechanics of the dimple is consistent with the experimental 1.5-power law. As noted above, experimental buckling loads of shells that are closed at both ends also show the empirical 1.5-power law, but now with significant statistical scatter. A second aim of the paper is to throw light on that phenomenon. I venture to attribute it to the effect of the boundary conditions of the shell. I adduce support for this view from experimental observations on the buckling of a shell with special, frictional end-fittings. That feature produces significantly higher collapse loads, and with much smaller scatter, than for corresponding shells with fixed boundaries; and it permits striking pre-buckled deformations to occur, of a kind not previously noted. It will be appreciated that neither of the two parts of this article depends on the widely accepted theory of imperfection-
sensitivity; hence my choice of title. It is a pleasure for me to submit this article to a special publication in honour of Michael Rotter, with whom I have discussed matters of this sort through three decades.

References listed at the end of the paper:

Wang Xiang, “Cellular cavity structure and its building technology for shell structure with thin sheet materials”, Ph.D dissertation, Darmstadt University, 2017
ABSTRACT: This research investigates a new structure concept and its building techniques for shell structures that can be built with thin sheet materials. Shell structures have been a desired structure type for both architects and structural engineers due to its efficient load-bearing behavior and also the elegant curved geometry. In the past decades, innovational structure concepts such as grid-shells and spatial framework structures have continuously pushed the development of shell structures towards a comprehensive type of structures which provides a better structural behavior of building materials.
This dissertation argues for a material-driven design methodology of the new shell structure design through a well-rounded revisit of the development of shells in the past decades. And a new type of industrial materials has been selected for the innovational structure concept of the novel type of shells.
The research is based on a comprehensive analysis of the materials’ application in the existing industrial and architectural design, as well as the theoretical analysis of the materials’ behavior and the corresponding fabrication techniques and structural consideration in designs. A novel structure concept is then generated with also the inspiration of the natural cellular structures.
The main focus of the architectural analysis is the design procedure of the cellular cavity structure, including the form-finding process, the structural consideration of the stability problem of thin materials, the possible simple fabrication with the materials form a planar sheet form. At the same time, a collaborative design process is also discussed to enable a better cooperation between both architects and engineers.
A novel shell was finally built as a demonstrator of such a structure concept. With a dome which reaches a span of 5 meters and a height of 2.5 meters and was built only with 1mm paperboard as major materials, the load-bearing capacity and the construction details of the cellular cavity structure is tested and evaluated.
Finally, through the comparison with the recent parallel research and the popular experimental shell designs in the past several years, the cellular cavity structure is positioned into a series of relevant research fields. With the analysis of the limitations of this research, future works are also defined for the improvement and future development of this Ph.D. research.

ABSTRACT: The performance of recently proposed flag-based energy harvesters is strongly limited by the chaotic response of flags to strong winds. From an experimental point of view, the detection of flag chaotic dynamics were scarce, based on the flapping amplitude and the maximal Lyapunov exponent. In practice, tracking the flapping amplitude is difficult and flawed in the large oscillation limit. Also, computing the maximal Lyapunov exponent from time series of limited size requires strong assumptions on the attractor geometry, without getting insurance of their reliability. For bypassing these issues, (1) we use a time series which takes into account the whole dynamic of the flag, by using the flapping moment which integrates its displacements, and (2) we apply an algorithm of detection of chaos based on recurring values in time series.

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Virot, E (1), Kreilos, T. (2), Schneider, T.M.(2) and Rubinstein, S.M. (1)
(1) John A. Paulson School of Engineering and Applied Science, Harvard University, Cambridge, MA, USA
(2) Emergent Complexity in Physical Systems Laboratory, Ecole Polytechnique, Lausanne, Switzerland
ABSTRACT: We measure the response of cylindrical shells to poking and identify a stability landscape, which fully characterizes the stability of perfect shells and imperfect ones in the case where a single defect dominates. We show that the landscape of stability is independent of the loading protocol and the poker geometry. Our results suggest that the complex stability of shells reduces to a low dimensional description. Tracking ridges and valleys of this landscape defines a natural phase-space coordinates for describing the stability of shells.
References listed at the end of the paper:
[14] Note that in the situations where during the buckling process several dimples are formed (more common at high axial loads), $D_{p}^S$ only indicates the depth of the dimple in the direction of the poker and the other dimples are not taken into account.
[15] For load-controlled compression, the shell is totally crushed when buckling is induced; thus, $D_{p}^S$ cannot be measured.
[17] A violent drop in the poking force is observed for axial loads of $F_0^A 1/4859$ or $F_0^A 1/41084$ N in Fig. 2(a). In these two cases the force drops to zero significantly faster than the axial loading rate. We did not observe any rate dependence of the mechanical response in the loading rate range that we tested (0.1 to 10 mm= min).

Van Vinh Nguyen, “Direct strength method for the design of cold-formed steel sections under localized loading”, Ph.D dissertation, Civil Engineering, The University of Sydney, 2017
ABSTRACT: The main objective of the thesis is the development of the Direct Strength Method (DSM) for the design of cold-formed steel sections under general localised loading. In order to calibrate the DSM equations, it is necessary to have three main input variables which are the buckling load, the yield load and the experimental data.
The first objective of this research is the development of the Finite Strip Method (FSM) theory for analysis of thin-walled sections under localised loading with general end boundary conditions to determine the buckling load as described in Chapters 3 and 4 of the thesis. The theory is included in Version 2.0 of the THIN-WALL-2 program which can be used for analysing structural members under generalised loading conditions as described in Chapter 5.
The second objective is the formulation of plastic mechanism models to estimate the yield load of thin-walled sections subjected to localised loading. In order to establish these models, observations are performed from
experiments to ascertain the failure modes of structural members under localised loading with different cross-sections, load cases and flange fastening conditions. From the data, new simple plastic mechanism models are built-up based on the concept of the balance between the internal energy of the structural member and the external energy of the applied loads to estimate the yield load as described in Chapter 6.

The third objective is collating the experimental data of thin-walled sections under localised loading. The data is collected from previous literature for different types of cross-sections: un-lipped plain-C, lipped plain-C, SupaCee and Dimond Hi-Span channel (DHS) sections subjected to all load cases. In addition, both flange fastened and unfastened conditions are assembled in the experimental database as described in Chapter 6.

From these three input variables, the DSM design equations are proposed for structural members under general localised loading. The method is a consistent and simplified model generalised for all localised load cases. It includes both an inelastic reserve component as observed in testing and a yield load component. Also, a reliability analysis calibration is performed to validate the accuracy of the DSM predictions with the collected experimental data as described in Chapter 7.

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SUMMARY: The thin walled structures are used in many area, such as aircraft, space vehicles, and missiles thanks to providing lower weight than the thicker structure. However, when the lower weight is providing, there can be some lost of the strength of the structure. One of the possible problem that coming with having thin walled structures is the buckling. The shell structures under compression load may have some deformation. The loading type which causes to the buckling may be the axial compression loading, torsional loading, bending loading, hydrostatic or external pressure. In this thesis, the consideration is only given to the axially compressed cylinders thanks to the most cylinders are under this type of loading and more sensitive the structures under that type of loading.

When the structure under compressive load, at a point, it suddenly start to buckle. This point is the critical point for that structure. At that point, the structure has the deformation. This deformed shape can still carry the loading but, of course, it is lower than the critical load value. The behavior, after buckling, called post buckling behavior. This implies that the buckled structure can be still used with the lower buckling strength.

The phenomena buckling is studied for decades. For the derive the critical buckling load under axially compressed cylinders, the stability theory is used and both energy and the Donnell approaches is provided in the thesis. As the result of the derivation, the critical stress value is $\frac{Et}{r} \sqrt{3(1 - \mu^2)}$. Since the stress value is the ratio of the force to area of the load applied. For the cylindrical shell structure, area that the load applied is $2\pi rt$. Therefore the buckling load formula is obtained as $2\pi \frac{Et^2}{\sqrt{3(1 - \mu^2)}}$.

Keep in mind that, this formula is only valid for the medium length cylinder. As it is seen form the critical load formula, it is highly depended to the thickness of the shell structure. The shorter cylinders are behaves plate like and longer cylinders behave like the Euler column. The length range of the cylinder is decided with the help of the Batdorf parameter.

After the theoretical part the analysis are presented. To be able to making numerical analysis, first of all the optimization of the some parameters should be made. Those parameters are mesh density, element type, constrain and load type etc. After the suitable parameters are chosen, the analyses are made and compared to the theoretical value. The computer program used the linear eigenvalue analysis for buckling prediction. The lowest eigenvalue is provides to calculate the critical eigenvalue. When it is multiplied with the applied load, the result is the critical load value.

For the verification of the numerical study, the obtained value is compared with the analytic solution. Also, some papers are found and the cylinders in those papers are modeled and the results are compared.

Then, the some addition properties are given to the cylinder to see the effect of them. These additions are used to increase the strength of the structure. For instance, the composite material is used in terms of aluminum. For the same mass, the composite material have higher critical value. When the effect of stringer and ring stiffened structure is investigated, it is realized that the effect of the ring is lower than the ring since the load is applied to the longitudinal direction. In addition, the shell cylinders are used as tank, for that reason, effect of the internal
pressure is investigated. As it is expected, the internal pressure provide higher critical load value.
After the investigation of the stiffeners, composite material, and internal pressure, the inertia relief load is applied to the same model. Inertia relief load is applied for simulating the free structures like spacecraft, aircraft, or rocket. This kind of load is applied for the static, dynamic, or buckling analysis. Obtained buckling shape is shown in the thesis. The critical value that is obtained is the critical thrust value, as the cylinder is considered as the rocket body. Obtained value is low but it is sourced from the lack of the internal pressure or some structural components like stiffeners.
After all the analysis are performed, to see the buckling behavior, an experimental study is performed. For the test specimens, the Coca-Cola can is used. The top and bottom side of the cans are cut off and the buckling test is performed with the two aluminum plate placed to the top and bottom side of the cylinder. Although there is a significant difference. It can be sourced because of the high sensitivity of the buckling. The load eccentricity has a great influence. Therefore, the analysis are made with the eccentric loading.

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NASA. (1965). Buckling of Thin-walled Circular Cylinders. National Aeronautics and Space Administration.

ABSTRACT: Material efficiency in modern tank constructions often is achieved by combining thin plates with
light and heavy ring stiffeners. While the plates are designed to resist hydrostatic pressure, the stiffeners are designed against wind and external pressure. Axial buckling may occur due to high roof loads and wind since very thin plates are prone to a loss of stability.

Test results in the 60s and 70s revealed that closely spaced ring-stiffeners may greatly enhance the axial buckling behavior, allowing for knock-down factors greater unity. However, until today, no design procedure is available allowing for adopting the beneficial effect of ring stiffeners under axial compression into practical design.

In this paper a design procedure is proposed that closes this gap in current design codes. One outcome of the conducted literature study revealed that test results of unstiffened shells may be more closely approximated and is shortly presented. The design procedure for ring-stiffened shells was then developed from lower bound curves deduced from categorized buckling tests.

The results of a parametrical study, that was conducted over a wide range of r/t-values, is presented. Imperfection depths up to 10t were examined using a stiffener spacing of one buckling half-wave. Especially highly slender stiffened cylinders benefit from ring-stiffening, showing up to 380% strength gains.

Imperfection depths proposed by the current design code were found to be too conservative.

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[1] Kremsmüller Industrieanlagenbau KG.
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Yang Zhou, Ilinca Stanciulescu, Thomas Eason and Michael Spottswood, “Fast approximations of dynamic stability boundaries of slender curved structures”, ABSTRACT: Curved beams and panels can often be found as structural components in aerospace, mechanical and civil engineering systems. When curved structures are subjected to dynamic loads, they are susceptible to dynamic instabilities especially dynamic snap-through buckling. The identification of the dynamic stability boundary that separate the non-snap and post-snap responses is hence necessary for the safe design of such structures, but typically requires extensive transient simulations that may lead to high computation cost. This paper proposes a scaling approach that reveals the similarities between dynamic snap-through boundaries of different structures. Such identified features can be directly used for fast approximations of dynamic stability boundaries of slender curved structures when their geometric parameters or boundary conditions are varied. The scaled dynamic stability boundaries of half-sine arches, parabolic arches and cylindrical panels are studied.

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ABSTRACT: Shells are important structural elements widely used in various engineering applications ranging from outer space to deep oceans such as rockets, aircrafts, missiles, submarines and automobiles etc. A huge amount of research efforts has been devoted to vibration analysis and dynamic behaviors of the shells. Furthermore, a large variety of shell theories and computational methods have been proposed and developed by researchers. For different cases different computational approaches have been used in literature to study the vibration characteristics of shells. This review is aimed to provide contemporarily relevant survey of papers on vibrational characteristics of shells and identification of various methods and approaches that have been used to study its vibration characteristics. Focus has been kept to important and prominent studies and its compilation in a single paper to help future researchers to identify relevant literature quickly and easily and also help them to apply these approaches to study vibration characteristics of other built up and coupled structures.

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ABSTRACT: The purpose of this paper is to establish the mathematical model on the elastic-plastic transitions occurring in the rotating spherical shells based on compressibility of materials. The paper investigates the elastic-plastic stresses and angular speed required to start yielding in rotating shells for compressible and incompressible materials. The paper is based on the non-linear transition theory of elastic-plastic shells given by B.R. Seth. The elastic-plastic transition obtained is treated as an asymptotic phenomenon at critical points & the solution obtained at these points generates stresses. The solution obtained does not require the use of semi-empirical yield condition like Tresca or Von Mises or other certain laws. Results are obtained numerically and depicted graphically. It has been observed that Rotating shells made of the incompressible material are on the safer side of the design as compared to rotating shells made of compressible material. The effect of density variation has been discussed numerically on the stresses. With the effect of density variation parameter, rotating spherical shells start yielding at the internal surface with the lower values of the angular speed for incompressible/compressible materials.

Abdullah Mahmoud, “Analysis and design of spirally welded thin-walled steel tapered cylindrical shells under bending with application to wind turbine towers”, PhD dissertation, Johns Hopkins University, Baltimore, 2017
ABSTRACT: An important obstacle restricting the growth of wind-generated energy is the production of taller towers for wind turbines that can harvest energy from the steadier, stronger winds at higher elevations. Currently, the need to transport wind turbine tower sections to the construction site constrains the diameter of the section, which then limits the height of the tower. This limitation can be avoided if the tower sections are made on-site, and one potential method for on-site manufacturing is automated spiral welding. This thesis, which focuses largely on computational modeling for design, is part of a larger research effort to advance the application of spirally welded tubes (SWTs) in wind tower structures. With the new manufacturing technique, a wider range of tower diameters and thicknesses, and potentially more optimal thin-walled sections can be employed. Thin-walled shells are one of the most advanced and efficient forms of large structures; however, their behavior can be unstable and extremely sensitive to imperfections. For decades, the structural design of such shell structures relied on elastic buckling “knockdown factors” obtained from experimental results, but with the expansion in the capabilities of computational modeling, today design is working to leverage the power of shell finite element models that are geometrically and materially nonlinear with imperfections included (i.e. “GMNIA” analysis models). This thesis explores the analysis and design of spirally welded tapered cylindrical steel shells and complements experimental results conducted as a companion to this effort within the larger SWT effort. The thesis includes an introduction and historical background on the development of research on thin shells; a summary of relevant experimental work completed in the literature and in the SWT project; careful examination of geometric imperfections in the world of shells in general and spirally welded shells in particular; provides a practical finite element modeling protocol for predicting the flexural strength and collapse behavior of thin-walled spirally welded tapered steel tubes; validates the proposed modeling protocols for GMNIA models with SWT test results; extends the results to provide standard “reference resistance” curves that can be used for future GMNIA analyses by structural designers; and highlights the application to an archetype 3MW wind turbine tower using both classical and new analysis-based.
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ABSTRACT: We investigate the elastic buckling of a triangular prism made of a soft elastomer. A face of the prism is bonded to a stiff slab that imposes an average axial compression. We observe two possible buckling modes which are localized along the free ridge. For ridge angles $\Phi$ below a critical value $\Phi^* \approx 90^\circ$, experiments reveal an extended sinusoidal mode, while for $\Phi$ above $\Phi^*$, we observe a series of creases progressively invading the lateral faces starting from the ridge. A numerical linear stability analysis is set up using the finite-element method and correctly predicts the sinusoidal mode for $\Phi < \Phi^*$, as well as the associated critical strain $\varepsilon^*(\Phi)$. The experimental transition at $\Phi^*$ is found to occur when this critical strain $\varepsilon^*(\Phi)$ attains the value $\varepsilon^*(\Phi^*) = 0.44$ corresponding to the threshold of the subcritical surface creasing instability. Previous analyses have focused on elastic crease patterns appearing on planar surfaces, where the role of scale invariance has been emphasized; our analysis of the elastic ridge provides a different perspective, and reveals that scale invariance is
not a sufficient condition for localization.


ABSTRACT: Inspired by the differential-growth-driven morphogenesis of leaves, flowers, and other tissues, there is increasing interest in artificial analogs of these shape-shifting thin sheets made of active materials that respond to environmental stimuli such as heat, light, and humidity. But how can we determine the growth patterns to achieve a given shape from another shape? We solve this geometric inverse problem of determining the growth factors and directions (the metric tensors) for a given isotropic elastic bilayer to grow into a target shape by posing and solving an elastic energy minimization problem. A mathematical equivalence between bilayers and curved monolayers simplifies the inverse problem considerably by providing algebraic expressions for the growth metric tensors in terms of those of the final shape. This approach also allows us to prove that we can grow any target surface from any reference surface using orthotropically growing bilayers. We demonstrate this by numerically simulating the growth of a flat sheet into a face, a cylindrical sheet into a flower, and a flat sheet into a complex canyon-like structure.

References listed at the end of the paper:

ABSTRACT: The rapid growth of the human cortex during development is accompanied by the folding of the brain into a highly convoluted structure\(^1\)–\(^3\). Recent studies have focused on the genetic and cellular regulation of cortical growth\(^4\)–\(^8\), but understanding the formation of the gyral and sulcal convolutions also requires consideration of the geometry and physical shaping of the growing brain\(^9\)–\(^15\). To study this, we use magnetic resonance images to build a 3D-printed layered gel mimic of the developing smooth fetal brain; when immersed in a solvent, the outer layer swells relative to the core, mimicking cortical growth. This relative growth puts the outer layer into mechanical compression and leads to sulci and gyri similar to those in fetal brains. Starting with the same initial geometry, we also build numerical simulations of the brain modelled as a soft tissue with a growing cortex, and show that this also produces the characteristic patterns of convolutions over a realistic developmental course. All together, our results show that although many molecular determinants control the tangential expansion of the cortex, the size, shape, placement and orientation of the folds arise through iterations and variations of an elementary mechanical instability modulated by early fetal brain geometry.

References listed at the end of the paper:


ABSTRACT: Predicting the large-amplitude deformations of thin elastic sheets is difficult due to the complications of self contact, geometric nonlinearity, and a multitude of low-lying energy states. We study a simple two-dimensional setting where an annular polymer sheet floating on an air-water interface is subjected to different tensions on the inner and outer rims. The sheet folds and wrinkles into many distinct morphologies that break axisymmetry. These states can be understood within a recent geometric approach for determining the gross shape of extremely bendable yet inextensible sheets by extremizing an appropriate area functional. Our analysis explains the remarkable feature that the observed buckling transitions between wrinkled and folded shapes are insensitive to the bending rigidity of the sheet.

ABSTRACT: In order to examine the accuracy of the enhanced double directors shell model for the functionally graded material (FGM) shell structures, a series of benchmark static tests are tackled using finite elements method. For implementing the discrete double directors shell model (DDDSM) within the Enhanced Strain Technique (EST), four parameters are used for enhancing the membrane strain. The vanishing of transverse shear strains on top and bottom faces is considered in a discrete form. The mechanical properties of
the shell structure are assumed to vary continuously in the thickness direction by a simple power-law
distribution in terms of the volume fractions of the constituents. A comparison with the exact solutions
presented by several authors for shell structures indicates that the present model accurately estimates the stress-
strain responses.

Abdessalem Hajlaoui, Abdessalem Jarraya, Mondher Wali and Fakhreddine Dammak, “A higher order shear
strain enhanced solid-shell element for laminated composite structures analysis”, in Multiphysics Modelling
and Simulation for Systems Design and Monitoring, pp 497-506, 2015, Springer
ABSTRACT: This paper presents a free from locking higher order solid-shell element based on the Enhanced
Assumed Strain (EAS) for laminated composite structures analysis. The transverse shear strain is divided into
two parts: the first one is independent of the thickness coordinate and formulated by the Assumed Natural Strain
(ANS) method; the second part is an enhancing part which ensures a quadratic distribution through the
thickness. This permit to remove the shear correction factors and improves the accuracy of transverse shear
stresses. Also, volumetric locking is completely avoided by using the optimal parameters in the EAS method.
Comparisons of numerical results with those extracted from literature show the performance of the developed
finite element.

A. Hajlaoui, E. Triki, A. Frikha and F. Dammak, “Non-linear dynamics analysis of multilayer composite shells
with enhanced solid-shell element”, in Advances in Acoustics and Vibration, pp 291-300, 2017, Springer
ABSTRACT: This paper presents the non linear dynamic response of multilayer composites with an enhanced
solid-shell element. The transverse shear and transverse normal locking are treated using the Assumed Natural
Strain formulation (ANS). For the enhanced part, one, three and five parameters are examined. Comparisons of
numerical results with those extracted from literature show the good performance of the developed formulation
in the isotropic case. The three enhancement choices give the same results in the multilayer composite case.

Amin Taraghi Osguei, Mohamad Taghi Ahmadian, Mohsen Asghari and Nicola Maria Pugno, “A shell model
for free vibration analysis of carbon nanoscroll”, Materials (MDPI), Vol. 10, p 387, 6 April 2017
ABSTRACT: Carbon nanoscroll (CNS) is a graphene sheet rolled into a spiral structure with great potential for
different applications in nanotechnology. In this paper, an equivalent open shell model is presented to study the
vibration behavior of a CNS with arbitrary boundary conditions. The equivalent parameters used for modeling
the carbon nanotubes are implemented to simulate the CNS. The interactions between the layers of CNS due to
van der Waals forces are included in the model. The uniformly distributed translational and torsional springs
along the boundaries are considered to achieve a unified solution for different boundary conditions. To study the
vibration characteristics of CNS, total energy including strain energy, kinetic energy, and van der Waals
energy are minimized using the Rayleigh-Ritz technique. The first-order shear deformation theory has been
utilized to model the shell. Chebyshev polynomials of first kind are used to obtain the eigenvalue matrices. The
natural frequencies and corresponding mode shapes of CNS in different boundary conditions are evaluated. The
effect of electric field in axial direction on the natural frequencies and mode shapes of CNS is investigated. The
results indicate that, as the electric field increases, the natural frequencies decrease.
References listed at the end of the paper:
Jorge Yarasca and J.L. Mantari, “N-objective genetic algorithm to obtain accurate equivalent single layer models with layerwise capabilities for challenging sandwich plates”, Aerospace Science and Technology, Vol. 70, pp 170-188, July 2017

ABSTRACT: This paper presents refined equivalent single layer plate theories develop by an effective N-objective optimization method, considering multiple displacements and stresses as output parameters. The refined plate theories reported belong to Best Theory Diagrams (BTDs), in which the minimum number of terms that have to be used to achieve a desired accuracy can be read. Maclaurin, high order zig-zag, trigonometric, exponential and hyperbolic terms are employed in order to investigate their influence on several static mechanical studies for sandwich plates. The used refined models are develop via the Unified Formulation developed by Carrera. The governing equations are derived from the Principle of Virtual Displacement (PVD), and Navier-type closed form solutions have been obtained in the case of simply supported plates subjected to binuisoidal transverse pressure. BTDs have been constructed using the Axiomatic/Asymptotic Method (AAM) and genetic algorithms (GA). The results are compared with the layer-wise solution in several benchmarks proposed in the literature. It is shown that the ESL plate models can accurately describe the displacement field and the mechanical stress fields predicted by a LW model with less computational effort, even for extreme theoretical cases. Furthermore, the method presented allows the user to analyze the influence of numerous test functions in a single run. The combined use of CUF, AAM and GA is a powerful tool to evaluate the accuracy of any structural theory.

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E. Viola, F. Tornabene, N. Fantuzzi, General higher-order shear deformation theories for the free vibration analysis of completely doubly-curved laminated shells and panels, Compos. Struct. 95 (2013) 639–666.


A.S. Sayyad, Y.M. Ghugal, On the free vibration analysis of laminated composite and sandwich plates: a review of recent
Jorge Yarasca, J.L. Mantari, Marco Petrolo and E. Carrera, “Multiobjective best theory diagrams for cross-ply
composite plates employing polynomial, zig-zag, trigonometric and exponential thickness expansions”.

Composite Structures, Vol. 176, pp 860-876, June 2017

ABSTRACT: This paper presents Best Theory Diagrams (BTDs) for plates considering all the displacement and stress components as objectives. The BTD is a diagram in which the minimum number of terms that have to be used to achieve the desired accuracy can be read. Maclaurin, zig-zag, trigonometric and exponential expansions are employed for the static analysis of cross-ply composite plates. The Equivalent Single Layer (ESL) approach is considered, and the Unified Formulation developed by Carrera is used. The governing equations are derived from the Principle of Virtual Displacement (PVD), and Navier-type closed form solutions are adopted. BTDs are obtained using the Axiomatic/Asymptotic Method (AAM) and genetic algorithms (GA). The results show that the BTD can be used as a tool to assess the accuracy and computational efficiency of any structural models and to draw guidelines to develop structural models. The inclusion of the multiobjective capability extends the BTD validity to the recognition of the role played by each output parameter in the refinement of a structural model.

References listed at the end of the paper:

ABSTRACT: The effects of the hydroelastic coupling on structures in contact with fluid are pronounced when composite materials are used due to the low composite density. This paper presents an analytical solution for the free vibration analysis of thick rectangular composite plates in contact with a bounded fluid. The plate displacement field is analyzed using Carrera Unified Formulation in order to consider displacement theories of arbitrary order. The displacement variables are approximated using the Ritz method. Analysis considering any of the classical boundary conditions is performed using suitable functions in the Ritz series. The fluid kinetic energy is obtained by considering an inviscid and incompressible fluid, and thus the velocity potential is applicable. The kinetic and potential energy of the plate are also obtained, and the energy functional is used to derive the eigenvalue problem. Validation is performed with results in the open literature and by using 3D finite element software. The influence of the fiber orientations on the natural frequencies is discussed, as well as the influence of the plate and fluid domain geometry. Certain natural frequencies are seen to be independent of the fluid domain depth, depending on the symmetric or antisymmetric nature of the normal mode.

References listed at the end of the paper:


References listed at the end of the paper:

http://dx.doi.org/10.1137/100804036.


ABSTRACT: A so far unavailable quasi-3D trigonometric shear deformation theory for the bending analysis of functionally graded plates is presented. This theory considers the thickness-stretching effect ($\epsilon_{zz}$ not = 0) by modeling the displacement field with just four unknowns and rich trigonometric shear strain shape functions. The principle of virtual works is used to derive the governing equations and boundary conditions. Results from this theory are compared with the CPT, first-order shear deformation theory (FSDT), and other quasi-3D HSDTs. In conclusion, this theory is more accurate than the CPT and FSDT and behaves as well as quasi-3D HSDTs having much less number of unknowns.

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ABSTRACT: This paper develops a coupling approach which integrates the meshfree method and isogeometric analysis (IGA) for static and free-vibration analyses of cracks in thin-shell structures. In this approach, the domain surrounding the cracks is represented by the meshfree method while the rest domain is meshed by IGA. The present approach is capable of preserving geometry exactness and high continuity of IGA. The local refinement is achieved by adding the nodes along the background cells in the meshfree domain. Moreover, the equivalent domain integral technique for three-dimensional problems is derived from the additional Kirchhoff-Love theory to compute the J-integral for the thin-shell model. The proposed approach is able to address the problems involving through-the-thickness cracks without using additional rotational degrees of freedom, which facilitates the enrichment strategy for crack tips. The crack tip enrichment effects and the stress distribution and displacements around the crack tips are investigated. Free vibrations of cracks in thin shells are also analyzed. Numerical examples are presented to demonstrate the accuracy and computational efficiency of the coupling approach.

References listed at the end of the paper:
ABSTRACT: An extended isogeometric thin shell analysis (XIGA) for the analysis of through-the-thickness cracks in thin shell structures is developed. The discretization is based on Non-Uniform Rational B-Splines (NURBS). The proposed XIGA formulation can reproduce the singular field near the crack tip and the discontinuities across the crack. It is based on the Kirchhoff-Love theory where C1-continuity of the displacement field is required. This condition is satisfied by the NURBS basis functions. Hence, the formulation eliminates the need of rotational degrees of freedom or the discretization of the director field facilitating the enrichment strategy. The performance and validity of the formulation is tested by several benchmark examples.

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ABSTRACT: NURBS-based isogeometric analysis was first extended to thin shell/membrane structures which allows for finite membrane stretching as well as large deflection and bending strain. The assumed non-linear kinematics employs the Kirchhoff–Love shell theory to describe the mechanical behaviour of thin to ultra-thin structures. The displacement fields are interpolated from the displacements of control points only, and no rotational degrees of freedom are used at control points. Due to the high order $C^k$ ($k \geq 1$) continuity of NURBS shape functions the Kirchhoff–Love theory can be seamlessly implemented. An explicit time integration scheme is used to compute the transient response of membrane structures to time-domain excitations, and a dynamic relaxation method is employed to obtain steady-state solutions. The versatility and good performance of the present formulation are demonstrated with the aid of a number of test cases, including a square membrane subjected to static pressure, the inflation of a spherical shell, the inflation of a square airbag in excitations, and a dynamic inflation of a rubber balloon. The mechanical contribution of the bending stiffness is also evaluated.

References listed at the end of the paper:
ABSTRACT: This thesis presents two new methods in finite elements and isogeometric analysis for structural analysis. The first method proposes an alternative alpha finite element method using triangular elements. In this method, the piecewise constant strain field of linear triangular finite element method models is enhanced by additional strain terms with an adjustable parameter $\alpha$, which results in an effectively softer stiffness formulation compared to a linear triangular element. In order to avoid the transverse shear locking of Reissner-Mindlin plates analysis the alpha finite element method is coupled with a discrete shear gap technique for triangular elements to significantly improve the accuracy of the standard triangular finite elements. The basic idea behind this element formulation is to approximate displacements and rotations as in the standard finite element method, but to construct the bending, geometrical and shear strains using node-based smoothing domains. Several numerical examples are presented and show that the alpha FEM gives a good agreement compared to several other methods in the literature. Second method, isogeometric analysis based on rational splines over hierarchical T-meshes (RHT-splines) is proposed. The RHT-splines are a generalization of Non-Uniform Rational B-splines (NURBS) over hierarchical T-meshes, which is a piecewise bicubic polynomial over a hierarchical T-mesh. The RHT-splines basis functions not only inherit all the properties of NURBS such as non-negativity, local support and partition of unity but also more importantly as the capability of joining geometric objects without gaps, preserving higher order continuity everywhere and allow local refinement and adaptivity. In order to drive the adaptive refinement, an efficient recovery-based error estimator is employed. For this problem an imaginary surface is defined. The imaginary surface is basically constructed by RHT-splines basis functions which is used for approximation and interpolation functions as well as the construction of the recovered stress components. Numerical investigations prove that the proposed method is capable to obtain results with higher accuracy and convergence rate than NURBS results.

References listed at the end of the dissertation:


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ABSTRACT: This paper presents an alternative alpha finite element method using triangular meshes (AaFEM) for static, free vibration and buckling analyses of laminated composite plates. In the AaFEM, an assumed strain field is carefully constructed by combining compatible strains and additional strains with an adjustable parameter $\alpha$ which can produce an effectively softer stiffness formulation compared to the linear triangular element. The stiffness matrices are obtained based on the strain smoothing technique over the smoothing domains and the constant strains on triangular sub-domains associated with the nodes of the elements. The discrete shear gap (DSG) method is incorporated into the AaFEM to eliminate transverse shear locking and an improved triangular element termed as AaDSG3 is proposed. Several numerical examples are then given to demonstrate the effectiveness of the AaDSG3.

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ABSTRACT: Isogeometric analysis (IGA) aims at simplifying the Computer Aided Design (CAD) and Computer Aided Engineering (CAE) pipeline by using the same functions to describe the geometry (CAD) and the unknown fields (Analysis). IGA can be based on a variety of CAD descriptions, the most widely used today being Non-Uniform Rational B-Splines (NURBS). In this paper, we investigate the suitability of NURBS-based isogeometric analysis within a third-order shear deformation theory for the simulation of the static, dynamic and buckling response of laminated composite plates. The method employs NURBS basis functions to both represent the geometry (exactly) and the unknown field variables. One of the main advantages of the present method is directly inherited from IGA, that is to easily increase the approximation order. To avoid using a shear correction factor, a third order shear deformation theory (TSDT) is introduced. It requires C1-continuity of generalized displacements and the NURBS basis functions are well suited for this requirement. Several numerical examples are used to demonstrate the performance of the present method compared with other published ones.

References listed at the end of the paper:


ABSTRACT: This paper presents a novel approach for isogeometric analysis of thin shells using polynomial splines over hierarchical T-meshes (PHT-splines). The method exploits the flexibility of T-meshes for local refinement. The main advantage of the PHT-splines in the context of thin shell theory is that it achieves C1 continuity, so the Kirchhoff–Love theory can be used in pristine form. No rotational degrees of freedom are needed. Numerical results show the excellent performance of the present method.

References listed at the end of the paper:
ABSTRACT: In this paper, a node-based smoothed finite element method (NS-FEM) using 3-node triangular elements is formulated for static, free vibration and buckling analyses of Reissner–Mindlin plates. The discrete weak form of the NS-FEM is obtained based on the strain smoothing technique over smoothing domains associated with the nodes of the elements. The discrete shear gap (DSG) method together with a stabilization technique is incorporated into the NS-FEM to eliminate transverse shear locking and to maintain stability of the present formulation. A so-called node-based smoothed stabilized discrete shear gap method (NS-DSG) is then proposed. Several numerical examples are used to illustrate the accuracy and effectiveness of the present method.

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ABSTRACT: A four-node quadrilateral shell element with smoothed membrane-bending based on Mindlin-Reissner theory is proposed. The element is a combination of a plate bending and membrane element. It is based on mixed interpolation where the bending and membrane stiffness matrices are calculated on the boundaries of the smoothing cells while the shear terms are approximated by independent interpolation functions in natural coordinates. The proposed element is robust, computationally inexpensive and free of locking. Since the integration is done on the element boundaries for the bending and membrane terms, the element is more accurate than the MITC4 element for distorted meshes. This will be demonstrated for several numerical examples.

References listed at the end of the paper:

ABSTRACT: Isogeometric finite element analysis has become a powerful alternative to standard finite elements due to their flexibility in handling complex geometries. One major drawback of NURBS based isogeometric finite elements is their less effectiveness of local refinement. In this study, we present an alternative to NURBS based isogeometric finite elements that allow for local refinement. The idea is based on polynomial splines and exploits the flexibility of T-meshes for local refinement. The shape functions satisfy important properties such as non-negativity, local support and partition of unity. We will demonstrate the efficiency of the proposed method by two numerical examples.

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ABSTRACT: An alternative alpha finite element method (αFEM) using triangular elements is proposed that significantly improves the accuracy of the standard triangular finite elements and provides a superconvergent solution in the energy norm for the static analysis of two-dimensional solid mechanics problems. In the αFEM, the piecewise constant strain field of linear triangular FEM models is enhanced by additional strain terms with an adjustable parameter \( \alpha \) which results in an effectively softer stiffness formulation compared to a linear triangular element. The element is further extended to the free and forced vibration analyses of solids. Several numerical examples show that the αFEM achieves high reliability compared to other existing elements in the literature.

References listed at the end of the paper:

ABSTRACT: A four-node quadrilateral shell element with smoothed membrane-bending based on Mindlin–Reissner theory is proposed. The element is a combination of a plate bending and membrane element. It is based on mixed interpolation where the bending and membrane stiffness matrices are calculated on the boundaries of the smoothing cells while the shear terms are approximated by independent interpolation functions in natural coordinates. The proposed element is robust, computationally inexpensive and free of locking. Since the integration is done on the element boundaries for the bending and membrane terms, the element is more accurate than the MITC4 element for distorted meshes. This will be demonstrated for several numerical examples.

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ABSTRACT: A cell-based smoothed discrete shear gap method (CS-FEM-DSG3) using three-node triangular
element was recently proposed for static, free vibration and buckling analyses of stiffened Mindlin plates. The CS-FEM-DSG3 element is a significant improvement of the original DSG3 element by using smoothing technique to soften the stiffness of the DSG3 element while it has still inherited the locking-free feature of the former. In this paper, the CS-FEM-DSG3 is further extended for the static and free vibration analyses of stiffened flat shells by combining the original plate element CS-FEM-DSG3 with Allman’s plane stress element and a linearly isotropic two-node stiffened beam element. The compatibility of displacement field of stiffeners and shell is applied at the contact positions. Numerical results of the proposed element are compared with those of some existing methods to demonstrate the accuracy and reliability of the proposed method.

References listed at the end of the paper:


ABSTRACT: The edge-based strain smoothing technique is combined with the three-node Mindlin plate element (MIN3) to give a so-called the edge-based smoothed three-node Mindlin plate element (ES-MIN3) for static and free vibration analyses of plates. In the formulation of the ES-MIN3, the MIN3 together with a shear stabilized technique is used to compute the strains and to avoid the shear locking. Then the strain smoothing technique on the smoothing domains associated with edges of elements is used to smooth the strains on the adjacent elements. This strain smoothing technique can provide proper softening effect, which will effectively relieve the stiff behavior of the MIN3 and thus improve significantly the accuracy of solutions. The numerical examples demonstrated that the ES-MIN3 is free of shear locking, passes the patch test and shows three superior properties such as: (1) be a strong competitor to others existing plate elements in the static analysis; (2) can give high accurate solutions in free vibration analysis; (3) can provide accurately the values of high frequencies of plates by using only coarse meshes.

References listed at the end of the paper:


ABSTRACT: The paper presents an extension of the Edge-based Smoothed Finite Element Method (ES-FEM-T3) using triangular elements for the dynamic response analysis of two-dimension fluid-solid interaction problems based on the pressure-displacement formulation. In the proposed method, both the displacement in the solid domain and the pressure in the fluid domain are smoothed by the gradient smoothing technique based on the smoothing domains associated with the edges of the triangular elements. Thanks to the softening effect of the gradient smoothing technique used in the ES-FEM-T3, the numerical solutions for the coupled systems by the ES-FEM-T3 are improved significantly compared to those by some other existing FEM methods.

References listed at the end of the paper:


ABSTRACT: A cell-based smoothed discrete shear gap method (CS-FEM-DSG3) was recently proposed and proven to be robust for free vibration analyses of Reissner-Mindlin shell. The method improves significantly the accuracy of the solution due to softening effect of the cell-based strain smoothing technique. In addition, due to using only three-node triangular elements generated automatically, the CS-FEM-DSG3 can be applied flexibly for arbitrary complicated geometric domains. However so far, the CS-FEM-DSG3 has been only developed for analyzing intact structures without possessing internal cracks. The paper hence tries to extend the CS-FEM-DSG3 for free vibration analysis of cracked Reissner-Mindlin shells by integrating the original CS-FEM-DSG3 with discontinuous and crack–tip singular enrichment functions of the extended finite element method (XFEM) to give a so-called extended cell-based smoothed discrete shear gap method (XCS-FEM-DSG3). The accuracy and reliability of the novel XCS-FEM-DSG3 for free vibration analysis of cracked Reissner-Mindlin shells are investigated through solving three numerical examples and comparing with commercial software ANSYS.

References listed at the end of the paper:


ABSTRACT: Nowadays, stiffened plates have been widely used in many branches of structural engineering such as aircraft, ships, bridges, buildings etc. In comparison with common bending plate structures, stiffened plates not only have larger bending stiffness but also use less amount of material. Hence, it usually has higher economic efficiency. However, to obtain high effectiveness in solving the design problems of the stiffened plate, the reliability-based optimization problems need to be established together with the ordinary numerical computing methods. Therefore, the paper presents an approach to establish and solve the reliability-based optimization problem for the stiffened Mindlin plate. To analyze the behavior of Mindlin plate, we use the recently proposed CS-DSG3 element. The random variables are chosen to be elastic modulus, density of mass and external force. The design variables are the thickness, the width and the height of the stiffened plate. The objective function can be the strain energy or the mass of the structure and subjected to the constraints of displacement or vibration frequency. The reliability-based optimization algorithm used in this paper is a three-step closed loop: 1) Estimating the random variables by the Reliability Index (RI) method; 2) Solving the optimization problem using Sequential Quadratic Programming (SQP) method; 3) Checking and estimating the reliability by the first-order reliability method (FORM) in which the limit state function is the limit of displacement or vibration frequency of the structure.
REFERENCES LISTED AT THE END OF THE PAPER:


ABSTRACT: A cell-based smoothed three-node Mindlin plate element (CS-MIN3) was recently proposed and proven to be robust for static and free vibration analyses of Mindlin plates. The method improves significantly the accuracy of the solution due to softening effect of the cell-based strain smoothing technique. In addition, it is very flexible to apply for arbitrary complicated geometric domains due to using only three-node triangular elements which can be easily generated automatically. However so far, the CS-MIN3 has been only developed for isotropic material and for analyzing intact structures without possessing internal cracks. The paper hence tries to extend the CS-MIN3 by integrating itself with functionally graded material (FGM) and enriched functions of the extended finite element method (XFEM) to give a so-called extended cell-based smoothed three-node Mindlin plate (XCS-MIN3) for free vibration analysis of cracked FGM plates. Three numerical examples with different conditions are solved and compared with previous published results to illustrate the accuracy and reliability of the XCS-MIN3 for free vibration analysis of cracked FGM plates.

REFERENCES LISTED AT THE END OF THE PAPER:


SUMMARY: Smart materials are material classes, which have several properties, such as coupling electrical and mechanical properties, changing properties from one surface to the other across the thickness, high strength and stiffness, moisture resistance, etc. Some of the most popular and common types of smart materials are as follows:

Piezoelectric materials are materials in which a voltage is produced when load/stress is applied and vice versa. Carbon nanotube-reinforced composites are a class of new materials, which are being developed to take advantage of electrical conductivity and the high tensile strength of carbon nanotube materials. Regarding mechanical properties, carbon nanotubes are the stiffest and strongest materials yet discovered in terms of elastic modulus and tensile strength. This strength leads to the covalent sp2 bonds formed between the individual carbon atoms.

Shape memory alloys (SMA) are materials that through stress changes (pseudo-elasticity) or temperature changes, large deformation can be produced and recovered. This is due to the martensitic phase change and induced elasticity at higher temperatures. And this phenomenon is called the shape memory effect.

The smart materials offer a considerable interest in many practical applications, such as micro-electromechanical systems (MEMS), automotive sensors, actuators, transducers, active damping devices and smart material systems, especially in the medical and aerospace industries. With these complex problems, i.e., coupling problems, Nano-structures, etc., it is very difficult or impossible to find exact solutions or analytical solutions by solving the partial differential equations (PDEs). Hence, approximated solutions or numerical solutions are considered to be the most suitable in order to analyze and simulate these problems.

For numerical methods, isogeometric analysis (IGA) has been recently proposed as a useful numerical method of computational analysis with the aim of integrating Finite Element Analysis (FEA) and Computer Aided Design (CAD) into one model. Data generated from CAD can be used directly for FEA. It means that the IGA uses Non-Uniform Rational B-Splines (NURBS), which are commonly used in CAD in order to describe both the geometry and the unknown variables for analyzed problems. Hence, the exact geometry is expressed in both design and mechanical analysis. Therefore, the process of re-meshing in IGA can be omitted. And an advantage of NURBS is its ability to easily control the continuity, as C^{p-1} continuity is obtained by using p-th order NURBS.

In this thesis, IGA is developed for analyzing and simulating smart plate structures. Four main contributions have been obtained from the results of the research as follows:

Firstly, a simple and effective formulation using IGA based on higher-order shear deformation theory (HSDT) is presented to investigate dynamic control of piezoelectric composite plates. There are two field variables, which need to be approximated, including mechanical displacement field and electrical potential field. In composite plates, the mechanical displacement field is approximated according to the HSDT model with five
degrees of freedom per each control point using isogeometric elements based on Non-Uniform Rational B-Spline (NURBS) basis functions. These achieve naturally any desired degree of continuity through the choice of the interpolation order, so that the method easily fulfils the C1-continuity requirement of the HSDT model. To simulate numerical results, NURBS with quadratic, cubic and quartic functions are considered. Besides, the electric potential is assumed to vary linearly through the thickness for each piezoelectric sublayer. Finally, governing equations of piezoelectric composite plates for static, free vibration analyses and dynamic control are expressed. In control section, a displacement and velocity feedback control algorithm is used for the active control of the static deflection and of the dynamic response of the plates through a closed-loop control with bonded or embedded distributed piezoelectric sensors (the bottom layer) and piezoelectric actuators (the top layer). The displacement feedback control is based on the actuator, and the velocity feedback control gives the velocity component. The accuracy and reliability of the proposed method is verified by comparing its numerical predictions with those of other available numerical approaches.

Secondly, IGA based on a generalized shear deformation theory for geometrically nonlinear transient analysis of smart piezoelectric functionally graded material (FGM) plates is developed. In this part, the electrical field is assumed to be independent on each layer and the mechanical displacements are approximated by the generalized higher order shear deformation theory. The nonlinear transient formulation for plates is formed with the total Lagrange approach based on the von Kármán strains. For nonlinear transient solution, Newmark’s method and Newton-Raphson method are used to find displacements, velocities and accelerations at each time step. Besides, thermo-piezoelectric effects are also considered. Temperature distributions of the bottom surface and top surface of piezoelectric FGM model are assumed to be constant. The temperature variation along the thickness is obtained by solving the one-dimensional steady state heat equation. The material properties vary through the thickness of FGM and are assumed to follow the rule of mixture. To consider the interactions among the constituents, the Mori-Tanaka scheme is used. For numerical results, many examples are investigated and compared to other available numerical methods to show the accuracy and effectiveness of the present method. The effects of volume fraction exponents on frequencies and displacements of the piezoelectric FGM plates are examined. And the effects of thermo-electro-mechanical loads on the behavior of the plates are also studied.

Thirdly, IGA based HSDT is proposed to investigate the static and dynamic vibration behavior of functionally graded carbon nanotube-reinforced composite plates. The material properties of functionally graded carbon nanotube-reinforced composites (FG-CNTRCs) are assumed to be graded through the thickness direction according to several linear distributions of the volume fraction of carbon nanotubes. Four distributions are considered UD (uniform), FG-V, FG-O and FG-X. For the FG-V type, the top surface of the CNTRC plate is CNT-rich. In FG-X, the top and the bottom surface of CNTRC plate are CNT-rich. And in case of FG-O, the CNT-rich zone is in the middle of the CNTRC plate. The displacements of the CNTRC plates are approximated according to the third-order shear deformation theory. Numerical results proved the high accuracy and reliability of the proposed method in comparison with other available numerical approaches. Fourthly, an efficient computational approach based on a generalized unconstrained approach in conjunction with IGA are proposed for dynamic control of smart piezoelectric composite plates. A new function for the unconstrained third order shear deformation theory (UHSDT) is introduced. In this theory, there are seven degrees of freedom per control point. Constant gains of the displacement feedback control and velocity feedback control are used in active control analysis in order to predict geometrically nonlinear transient response of the piezoelectric composite plates. An optimization procedure using genetic algorithm (GA) is considered to search optimal design for actuator input voltages. Various numerical examples are investigated to demonstrate the effectiveness of the proposed method.

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ABSTRACT: The cell-based strain smoothing technique is combined with the well-known three-node Mindlin plate element (MIN3) to give a so-called the cell-based smoothed MIN3 (CS-MIN3) for static and free vibration analyses of plates. In the process of formulating the system stiffness matrix of the CS-MIN3, each triangular element will be divided into three sub-triangles, and in each sub-triangle, the stabilized MIN3 is used to compute the strains and to avoid the transverse shear locking. Then the strain smoothing technique on whole the triangular element is used to smooth the strains on these three sub-triangles. The numerical examples demonstrated that the CS-MIN3 is free of shear locking, passes the patch test and shows four superior properties such as: (1) be a strong competitor to many existing three-node triangular plate elements in the static analysis, (2) can give high accurate solutions for problems with skew geometries in the static analysis, (3) can give high accurate solutions in free vibration analysis, (4) can provide accurately the values of high frequencies of plates by using only coarse meshes.

References listed at the end of the paper:

ABSTRACT: A n-sided polygonal cell-based smoothed finite element method (nCS-FEM) was recently proposed to analyze the elastic solid mechanics problems, in which the problem domain can be discretized by a set of polygons with an arbitrary number of sides. In this paper, the nCS-FEM is further extended to the free and forced vibration analyses of two-dimensional (2D) dynamic problems. A simple lump mass matrix is proposed and hence the complicated integrations related to computing the consistent mass matrix can be avoided in the nCS-FEM. Several numerical examples are investigated and the results found of the nCS-FEM agree well with exact solutions and with those of others FEM.

References listed at the end of the paper:
ABSTRACT: An edge-based smoothed finite element method (ES-FEM-T3) using triangular elements was recently proposed to improve the accuracy and convergence rate of the existing standard finite element method (FEM) for the solid mechanics analyses. In this paper, the ES-FEM-T3 is further extended to the dynamic analysis of 2D fluid–solid interaction problems based on the pressure-displacement formulation. In the present coupled method, both solid and fluid domain is discretized by triangular elements. In the fluid domain, the standard FEM is used, while in the solid domain, we use the ES-FEM-T3 in which the gradient smoothing technique based on the smoothing domains associated with the edges of triangles is used to smooth the gradient of displacement. This gradient smoothing technique can provide proper softening effect, and thus improve significantly the solution of coupled system. Some numerical examples have been presented to illustrate the effectiveness of the proposed coupled method compared with some existing methods for 2D fluid–solid interaction problems.

References listed at the end of the paper:


ABSTRACT: In this paper, a combined scheme of edge-based smoothed finite element method (ES-FEM) and node-based smoothed finite element method (NS-FEM) for triangular Reissner–Mindlin flat shells is developed to improve the accuracy of numerical results. The present method, named edge/node-based S-FEM (ENS-FEM), uses a gradient smoothing technique over smoothing domains based on a combination of ES-FEM and NS-FEM. A discrete shear gap technique is incorporated into ENS-FEM to avoid shear-locking phenomenon in Reissner–Mindlin flat shell elements. For all practical purpose, we propose an average combination (aENS-FEM) of ES-FEM and NS-FEM for shell structural problems. We compare numerical results obtained using aENS-FEM with other existing methods in the literature to show the effectiveness of the present method.

References listed at the end of the paper:


ABSTRACT: In this paper, a suitable and simple computational formulation based on Isogeometric Analysis (IGA) integrated with higher-order shear deformation theory (HSDT) is introduced for size-dependent buckling analysis of functionally graded material (FGM) nanoplates. The material properties of FGM based on the Mori–Tanaka schemes and the rule of mixture are used. The differential nonlocal equations are utilized to take into account size effects. The nonlocal governing equations are approximated according to IGA based on HSDT, which satisfies naturally the higher-order derivatives continuity requirement in weak form of FGM nanoplates. The effect of nonlocal approach on the behaviors of the FGM nanoplates with several volume fraction
exponents is investigated to show the reliability of the proposed method.


ABSTRACT: Isogeometric analysis (IGA) based on HSDT is used to simulate buckling analysis of nanoplates. The material properties of nanoplates based on the Mori–Tanaka schemes and the rule of mixture are utilized. The differential nonlocal equations with size effect are utilized. The nonlocal governing equations are approximated according to IGA, that satisfies naturally the higher-order derivatives continuity requirement in weak form of nanoplates. Several numerical results are presented to demonstrate the reliability of the proposed method.


ABSTRACT: A novel and effective formulation that combines the eXtended IsoGeometric Approach (XIGA) and Higher-order Shear Deformation Theory (HSDT) is proposed to study the free vibration of cracked plates. XIGA utilizes the Non-Uniform Rational B-Spline (NURBS) functions with their inherent arbitrary high order smoothness, which permit the C1 requirement of the HSDT model. Two numerical examples are provided to show excellent performance of the proposed method compared with other published solutions in the literature.

References listed at the end of the paper:


ABSTRACT: A cell-based smoothed discrete shear gap method (CS-FEM-DSG3) using triangular elements was recently proposed to improve the performance of the discrete shear gap method (DSG3) for static and dynamics analyses of Mindlin plates. In this paper, the CS-FEM-DSG3 is incorporated with spring systems for dynamic analyses of composite plates on the Pasternak foundation subjected to a moving mass. The composite plate-foundation system is modeled as a discretization of triangular plate elements supported by discrete springs at the nodal points representing the Pasternak foundation. The position of the moving mass with specified velocity on triangular elements at any time is defined, and then the moving mass is transformed into loads at nodes of elements. The accuracy and reliability of the proposed method is verified by comparing its numerical solutions with those of other available numerical results. A parametric examination is also conducted to determine the effects of various parameters on the dynamic response of the composite plates on the Pasternak foundation subjected to the moving mass.

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ABSTRACT: In this paper, equilibrium and stability equations of functionally graded material (FGM) plate under thermal environment are formulated based on isogeometric analysis (IGA) in combination with higher-order shear deformation theory (HSDT). The FGM plate is made by a mixture of two distinct components, for which material properties not only vary continuously through thickness according to a power-law distribution but also are assumed to be a function of temperature. Temperature field is assumed to be constant in any plane and uniform, linear and nonlinear through plate thickness, respectively. The governing equation is in nonlinear form based on von Karman assumption and thermal effect. A NURBS-based isogeometric finite element formulation is utilized to naturally fulfill the rigorous C1-continuity required by the present plate model. Influences of gradient indices, boundary conditions, temperature distributions, material properties, length-to-thickness ratios on the behaviour of FGM plate are discussed in details. Numerical results demonstrate excellent performance of the present approach.

References listed at the end of the paper:


ABSTRACT: The cell-based smoothed discrete shear gap method (CS-FEM-DSG3) using three-node triangular elements was recently proposed to improve the performance of the discrete shear gap method (DSG3) for static and free vibration analyses of isotropic Mindlin plates. In this paper, the CS-FEM-DSG3 is further extended for static and free vibration analyses and dynamic control of composite plates integrated with piezoelectric sensors and actuators. In the piezoelectric composite plates, the electric potential is assumed to be a linear function through the thickness of each piezoelectric sublayer. A displacement and velocity feedback control algorithm is used for active control of the static deflection and the dynamic response of the plates through closed loop control with bonded or embedded distributed piezoelectric sensors and actuators. The accuracy and reliability of the proposed method is verified by comparing its numerical solutions with those of other available numerical results.


ABSTRACT: Growing bacterial biofilms exhibit a number of surface morphologies, e.g., concentric wrinkles, radial ridges, and labyrinthine networks, depending on their physiological status and nutrient access. We explore the mechanisms underlying the emergence of these greatly different morphologies. Ginzburg-Landau kinetic method and Fourier spectral method are integrated to simulate the morphological evolution of bacterial biofilms. It is shown that the morphological instability of biofilms is triggered by the stresses induced by anisotropic and heterogeneous bacterial expansion, and involves the competition between membrane energy and bending energy. Local interfacial delamination further enriches the morphologies of biofilms. Phase diagrams are established to reveal how the anisotropy and spatial heterogeneity of growth modulate the surface patterns. The mechanics of three-dimensional microbial morphogenesis may also underpin self-organization in other development systems and provide a potential strategy for engineering microscopic structures from bacterial aggregates.


ABSTRACT: The control of surface wrinkling patterns at the microscale is a concern in many applications. In this letter, we regulate surface wrinkling patterns on a film–substrate system by introducing microbeads atop the film. Both experiments and theoretical analysis reveal the changes in surface wrinkles induced by microbeads. Under equibiaxial compression, the film–substrate system without microbeads bonded on its upper surface often buckles into global, uniform labyrinths, whereas the labyrinthine pattern locally gives way to radial stripes emanating from the microbeads. This
regulation of surface wrinkles depends on the sizes and spacing of microbeads. We combine the finite element method and the Fourier spectral method to explore the physical mechanisms underlying the phenomena. This study offers a viable technique for engineering surfaces with tunable functions.


ABSTRACT: Biofilm morphogenesis not only reflects the physiological state of bacteria but also serves as a strategy to sustain bacterial survival. In this paper, we take the Bacillus subtilis colony as a model system to explore the morphomechanics of growing biofilms confined in a defined geometry. We find that the growth-induced stresses may drive the occurrence of both surface wrinkling and interface delamination in the biofilm, leading to the formation of a labyrinthine network on its surface. The wrinkles are perpendicular to the boundary of the constraint region. The variation in the surface undulations is attributed to the spatial stress field, which is isotropic in the inner regime but anisotropic in the vicinity of the boundary. Our experiments show that the directional surface wrinkles can confer biofilms with anisotropic wetting properties. This study not only highlights the role of mechanics in sculpturing organisms within the morphogenetic context but also suggests a promising route toward desired surfaces at the interface between synthetic biology and materials sciences.


ABSTRACT: The global growth in wind energy suggests that wind farms will increasingly be deployed in seismically active regions, with large arrays of similarly designed structures potentially at risk of simultaneous failure under a major earthquake. Wind turbine support towers are often constructed as thin-walled metal shell structures, well known for their imperfection sensitivity, and are susceptible to sudden buckling failure under compressive axial loading. This study presents a comprehensive analysis of the seismic response of a 1.5-MW wind turbine steel support tower modelled as a near-cylindrical shell structure with realistic axisymmetric weld depression imperfections. A selection of 20 representative earthquake ground motion records, 10 ‘near-fault’ and 10 ‘far-field’, was applied and the aggregate seismic response explored using lateral drifts and total plastic energy dissipation during the earthquake as structural demand parameters. The tower was found to exhibit high stiffness, although global collapse may occur soon after the elastic limit is exceeded through the development of a highly unstable plastic hinge under seismic excitations. Realistic imperfections were found to have a significant effect on the intensities of ground accelerations at which damage initiates and on the failure location, but only a small effect on the vibration properties and the response prior to damage. Including vertical accelerations similarly had a limited effect on the elastic response, but potentially shifts the location of the plastic hinge to a more slender and, therefore, weaker part of the tower. The aggregate response was found to be significantly more damaging under near-fault earthquakes with pulse-like effects and large vertical accelerations than far-field earthquakes without these aspects.

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ABSTRACT: The length-dependent behaviour domains of thin elastic cylindrical shells under uniform bending have recently received significant research attention. Ovalization is known to affect very long cylinders that undergo significant cross-sectional flattening before failing by local buckling. This effect is restrained by the end boundary conditions in shorter cylinders, which instead fail by local buckling at moments close to the
classical analytical prediction. In very short cylinders, however, even this local buckling is restrained by the end boundary, and failure occurs instead through the development of a destabilizing meridional fold on the compressed side. Although this is a limit point instability under bending, ovalization does not play any role at all. This ‘very short’ length domain has only recently been explored for the first time with the aid of finite element modelling. A brief overview of the non-linear buckling behaviour of very short elastic cylinders under uniform bending is presented in this paper. Two types of edge rotational restraint are used to illustrate the influence of a varying support condition on the stability in this short length range. It is shown that short cylinders under bending do not suffer at all from local short-wave buckling. Additionally, when the meridional dimension of such cylinders becomes particularly short, the resulting numerical models may predict indefinite stiffening without a limit point, even when the shell is modelled using more complete 3D solid continuum finite elements. Idealized weld depressions, which are realistic representations of a systemic manufacturing defect, are used to demonstrate only a very mild sensitivity to geometric imperfections at such short lengths owing to a pre-buckling stress state dominated by local compatibility bending. The topic should be of interest to researchers studying shell problems dominated by local bending with computational tools and designers of multi-segment shells with very close segment spacing.

References listed at the end of the paper:
ABSTRACT: Efforts are ongoing to characterise a comprehensive resistance function for cylindrical shells under uniform bending, a ubiquitous structural system that finds application in load-bearing circular hollow sections, tubes, piles, pipelines, wind turbine support towers, chimneys and silos. A recent computational study by Rotter et al. (2014) demonstrated that nonlinear buckling of perfect elastic cylinders under bending is governed by four length-dependent domains – ‘short’, ‘medium’, ‘transitional’ and ‘long’ – depending on the relative influence of end boundary conditions and cross-section ovalisation. The study additionally transformed its resistance predictions into compact algebraic relationships for use as design equations within the recently-developed framework of Reference Resistance Design (RRD). This paper extends on the above to present a detailed computational investigation into the imperfection sensitivity of thin elastic cylindrical shells across the most important length domains, using automation to carry out the vast number of necessary finite element analyses. Geometric imperfections in three forms – the classical linear buckling eigenmode, an imposed cross-section ovalisation, and a realistic manufacturing ‘weld depression’ defect – are applied to demonstrate that imperfection sensitivity is strongly length-dependent but significantly less severe than for the closely-related load case of cylinders under uniform axial compression. The axisymmetric weld depression almost always controls as the most deleterious imperfection. The data is processed computationally to offer an accurate yet conservative lower-bound algebraic design characterisation of imperfection sensitivity for use within the RRD framework. The outcomes are relevant to researchers and designers of large metal shells under bending and will appeal to computational enthusiasts who are encouraged to adopt the automation methodology described herein to explore other structural systems.

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for Standardization (CEN), Brussels.
ABSTRACT: Liquid storage tanks are vulnerable to a wide variety of failures under severe seismic excitation. Among all failure modes shell buckling and anchor bolt failures are the most critical forms of damage. Sometimes combination of different modes intensifies or accelerates liquid storage tank’s damage. Although the effect of each different failure modes has been studied separately by a number of researchers, few studies may have considered combination of main failure modes concurrently. Hence, in this paper, a cylindrical steel tank has been selected in order to study multiple damages due to dynamic loadings on the tank. All anchor bolts and steel thin wall and reinforced concrete pedestal have been modeled counting material and geometric non-linearity. The methodology for finite element modeling of fluid-structure interaction has included applying the added-mass strategy, followed by performing the numerical analyses. A suite of ground motions has been selected and matched to the target spectrum. Afterwards, incremental dynamic analyses have been conducted to obtain fragility curve according to simultaneous modes of failure. The results have indicated that anchor bolt failures along with shell buckling significantly have contributed to more flexible behavior of the thin-walled steel tank and distribution of buckling to uppermiddle part of tank which might increase seismic effects on the tank. Also, the design of steel tanks needs more considerations beyond current codes in major earthquake prone zones.
WMPLA [5]. Validated by the buckling tests of a 5 m-diameter stiffened shell [6] and five 1-m-diameter unstiffened shells [7], WMPLA has showed significantly higher prediction accuracy in the actual buckling load than NASA SP-8007 and Single Perturbation Load Approach (SPLA).


ABSTRACT: Steel cylindrical shell structures are used in a large variety of civil engineering applications such as off-shore platforms, tanks, silos, wind turbine towers, etc. The local stability of such structures and their sensitivity to imperfections is a well-known problem. In current engineering practice the design method is based on the selection of an imperfection class for the shell and subsequently calculating a reduction factor, $\chi$, to the resistance of the shell. One such methodology is supplied by the EN1993–1–6; special conditions are given to pressurized tubes subjected to meridional compression. Past studies have focused on the stability of cylindrical shells with internal pressure. The stability problem of a long cylinder considering the internal pressure as a simple static load was addressed. Thus, the approaches considered the fluid as compressible. The purpose of the present work is to investigate numerically the potential benefit of using an incompressible fluid fully enclosed in a circular cylindrical shell. The constraint imposed by the presence of the liquid in the interior of a shell will be referred to as “hydraulic constraint”. As liquids are nearly incompressible, the buckling of a liquid-filled shell has to satisfy the condition that the integral of all the displacements normal to the shell surface is equal to the volume variation of the contained liquid. The volume variation of the shell interior has to be equal to the dilation of the shell due to liquid pressure increments associated to the onset of geometrical instability. Additionally, the weight of the contained liquid causes additional circumferential tension in the cases of vertically placed cylinders. The methodology followed is the numerical analysis of cylindrical shells by means of the ABAQUS Finite Element code and a comparison with the methods given in the Eurocode.


ABSTRACT: Carbon Fiber Reinforced Polymers (CFRPs) have been widely used in numerous applications where high specific stiffness and strength offer structural weight reduction and fuel efficiency. RVS (re-entry vehicle system) structural protection to the weapon system during re-entry. These kinds of structures are realized using filament winding process. In this paper mechanical characterization of CFRP with Carbon Nano-fiber has been prented. Studies are carried out to characterize the strength and Young’s modulus of the composite structure. Carbon Nano-fibers are among the greatly potential reinforcing additives for polymeric composites due to their high axial Young’s modulus, high aspect ratio, large surface area, and excellent thermal and electrical properties. Various studies can be found in the literature regarding the incorporation of CNFs in polymeric matrices and the final mechanical and/or electrical properties of these materials. To prove the technology a composite cylinder having size Length of 600mm, Diameter 300mm and thickness 1.5mm is considered for experimental study. In the present work a method has been developed to analyze composite shell using Layered 46. In addition, 3D layered analysis of composite cylinder with end metallic plates have been performed to predict the Buckling behavior of the Composite shell. Composite shell were fabricated & tested with buckling load condition to verify the design and analysis procedure. It has been observed that the experimental results are in close agreement with the finite element analysis results, also the design stresses were within safe limits. Based on test results, the Longitudinal Strength of CFRP with CNF is achieved 1860 MPa,
Young’s modulus is 118 GPa and improvement against CFRP with epoxy resin (LY556).

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Sen Lin, Yi Min Xie, Qing Li, Xiaodong Huang, Zhe Zhang, Guowei Ma and Shiwei Zhou, “Shell buckling: from morphogenesis of soft matter to prospective applications”, Bioinspiration & Biomimetics, Vol. 13, No. 5, July 2018, https://doi.org/10.1088/1748-3190/aacdd1

ABSTRACT: Being one of the commonest deformation modes for soft matter, shell buckling is the primary reason for the growth and nastic movement of many plants, as well as the formation of complex natural morphology. On-demand regulation of buckling-induced deformation associated with wrinkling, ruffling, folding, creasing and delaminating has profound implications for diverse scopes, which can be seen in its broad applications in microfabrication, 4D printing, actuator and drug delivery. This paper reviews the recent remarkable developments in the shell buckling of soft matter to explain the most representative natural morphogenesis from the perspectives of theoretical analysis in continuum mechanics, finite element analysis, and experimental validations. Imitation of buckling-induced shape transformation and its applications are also discussed for the innovations of sophisticated materials and devices in future.


ABSTRACT: This paper is the first to present the dynamic buckling behavior of spherical shell structures colliding with an obstacle block under the sea. The effect of deep water has been considered as a uniform external pressure by simplifying the effect of fluid–structure interaction. The calibrated numerical simulations were carried out via the explicit finite element package LS-DYNA using different parameters, including thickness, elastic modulus, external pressure, added mass, and velocity. The closed-form analytical formula of the static buckling criteria, including point load and external pressure, has been firstly established and verified. In addition, unprecedented parametric analyses of collision show that the dynamic buckling force (peak force), mean force, and dynamic force redistribution (skewness) during collisions are proportional to the velocity, thickness, elastic modulus, and added mass of the spherical shell structure. These linear relationships are independent of other parameters. Furthermore, it can be found that the max force during the collision is about 2.1 times that of the static buckling force calculated from the analytical formula. These novel insights can help structural engineers and designers determine whether buckling will happen in the application of submarines, subsea exploration, underwater domes, etc.

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ABSTRACT: We study the thermal buckling behavior of cylindrical shells reinforced with Functionally Graded (FG) wavy Carbon NanoTubes (CNTs), stiffened by stringers and rings, and subjected to a thermal loading. The equilibrium equations of the problem are built according to the Third-order Shear Deformation Theory (TSDT), whereas the stiffeners are modeled as Euler Bernoulli beams. Different types of FG distributions of wavy CNTs along the radial direction of the cylinder are herein considered, and temperature-dependent material properties are estimated via a micromechanical model, under the assumption of uniform distribution within the shell and through the thickness. A parametric investigation based on the Generalized Differential Quadrature (GDQ) method aims at investigating the effects of the aspect ratio and waviness index of CNTs on the thermal buckling of FG nanocomposite stiffened cylinders, reinforced with wavy single-walled CNTs. Some numerical examples are here provided in order to verify the accuracy of the proposed formulation and to investigate the effects of several parameters—including the volume fraction, the distribution pattern of wavy CNTs, and the cylinder thickness—on the thermal buckling behavior of the stiffened cylinders made of CNT-reinforced composite (CNTRC) material.

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Erik Johannes Giesen Loo, “Quantifying the Influence of Membrane Forces, Curvatures, and Imperfections on the Nonlinear Buckling Load of Thin-shells”, Master’s thesis, Dept. of Structural Mechanics, Civil Engineering
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ABSTRACT: Shells tend to be thin because their curvature enables them to carry distributed loads as membrane forces. The property of thinness stems from shells’ capacity to store membrane strain energy without much deformation. As a result, buckling failures often govern the design of shell structures. These buckling failures usually start locally, at a location where a combination of curvature and membrane forces is met. Moreover, shells tend to be imperfection-sensitive structures, that is, real-life shells (with initial geometric imperfections) usually cannot resist loads as high as the theoretically predicted critical buckling load. Advanced finite element analyses can accurately predict these so-called nonlinear buckling loads but require significant time and computation effort. On the other hand, current design equations are simple yet highly inaccurate and often penalize strength significantly. This treatise caters a Python script that executes nonlinear finite element analyses (using ANSYS Mechanical APDL) to generate a database of the nonlinear buckling loads of shell portions with varying membrane forces, curvatures and magnitudes of initial geometric imperfections. The aim, beyond the scope of this treatise, is to perform a parametric regression on said database to device design equation(s) that accurately predict the nonlinear buckling load of linear-elastic shell structures with initial geometric imperfections based merely on the linear elastic results of a geometrically perfect shell model.

References listed at the end of the paper:


ABSTRACT: In this paper, the dynamic plastic buckling of axisymmetric circular cylindrical shells subjected to axial impact is investigated. The von Mises yield criterion is used for the elastic-plastic cylindrical shell made of linear strain hardening material in order to derive the constitutive relations between stress and strain increments. Nonlinear dynamic circular cylindrical shell equations are solved with the finite difference method for three types of boundary conditions and two types loading. Two types of loading are stationary cylindrical shells impacted axially and traveling cylindrical shells impacted on a rigid wall. The growth and improvement of axial and lateral strains and buckling shapes of cylindrical shells are investigated for different boundary and loading conditions, from the viewpoint of stress wave propagation. It is found that the total length of cylindrical shell is affected by the plastic deformation when the plastic wave reaches unimpacted end. Also it is found that shortening and energy absorption are independent of loading and boundary conditions. The buckling shapes are affected by loading and boundary conditions; also peak loads at impacted and unimpacted ends are affected by loading conditions and are independent of boundary conditions. The presented theoretical results are compared with some experimental results and good agreement is obtained.


ABSTRACT: This research presents a study on mechanical buckling of thick-walled cylindrical shell made of functionally graded materials with ring supported under uniform axial and lateral loads. The mechanical properties of shell are variable along the thickness direction. First, the governing equations on the buckling of the FGM cylindrical shell supported with ring are established based on third-order shear deformation theory. Then, the governing characteristic equations were employed using energy method and by applying the Ritz technique. In the following with solving characteristic equations, the critical load buckling of the FGM thick-walled cylindrical shell supported with axial and lateral loads are calculated. The boundary conditions represented by end conditions of the FGM shell are the following: clamped-clamped and free-free. To verify the validity of the proposed analytical method the results of this research are compared with the results that came from using the finite element software. Finally, the effects of the different parameters such as thickness variations, boundary conditions, loading conditions and geometrical parameters of shell and ring on the buckling behavior of FGM thick-walled cylindrical shell are investigated. The results showed that by increasing the FGM volume fraction power in the shell structure, the critical buckling load increases and the location of the ring support has a significant effect on the critical buckling load. The results presented can be used as an important benchmark for researchers to validate their numerical and analytical methods.

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ABSTRACT: Cylindrical shells are often used in ship structures at deck plating with a camber, side shell plating at fo̧re and aft parts, and bilge structure part. It has been believed that such curved shells can be modelled fundamentally by a part of a cylinder under axial compression. From the estimations with the usage of cylinder models, it is known that, in general, curvature increases the buckling strength of a curved shell subjected to axial compression, and that curvature is also expected to increase the ultimate strength. We conduct series of elasto-plastic large deflection analyses in order to clarify the fundamentals in buckling and plastic collapse behaviour of cylindrical shells under axial compression. From the numerical results, we derive design formula for predicting the ultimate strength of cylindrical shell, based on a series of the nonlinear finite element calculations for all edges, simply supporting plating, varying the slenderness ratio, curvature and aspect ratio, as well as the following design formulae for predicting the ultimate strength of cylindrical shell. From a number of analysis results, fitting curve can be developed to use parameter of slenderness ratio with implementation of the method of least squares. The accuracy of design formulae for evaluating ultimate strength has been confirmed by comparing the calculated results with the FE-analysis results and it has a good agreement to predict their ultimate strength.

Dmytro Dizhur, Gye Simkin, Marta Glaretton, Giuseppe Loporcaro, Alessandro Palermo and Jason Ingham, “Performace of winery facilities during the 14 November 2016 Kaikoura Earthquake”, Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 2, pp 206-223, June 2017 ABSTRACT: In-field post-earthquake performance observations of winery facilities in the Marlborough region, New Zealand, were documented following the 14 November 2016 Kaikoura earthquake and subsequent aftershocks. Observations presented and discussed herein include land damage to vineyards and the performance of winery building facilities, legged and flat-bedded storage tanks, barrel racking systems, and catwalks. A range of winery facilities were instrumented with tri-axial accelerometers to capture seismic excitations during aftershocks, with the specific aim to instrument different storage tanks having varying capacities and support systems to better understand the dynamic performance and actual forces experienced up the height of the tanks during an earthquake, with preliminary results reported herein.

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classical theory of shells

Fundamental relations and equilibrium equations are derived for the thermal post-buckling analysis of eccentrically stiffened FG cylindrical shells surrounded by elastic foundation and subjected to thermal radial loading. A two-parameter elastic foundation is introduced based on the Winkler and Pasternak model. The shell is modeled by a two-parameter elastic foundation, and the stiffeners are assumed to be placed on the inner surface of the shell. The material properties of the shell and stiffeners are assumed to depend on the temperature. The Von-Karman nonlinear equations are derived based on the smeared stiffeners technique and the classical theory of shells according to the von-Karman nonlinear equations. By using the Galerkin method, the
thermal post-buckling response of eccentrically stiffened FG thin circular cylindrical shells is obtained. In order to validate the method, the obtained results are compared with available solutions and to continue, the effects of different parameters such as volume fraction exponent, number of stiffeners and elastic foundation parameters, on the thermal post-buckling response of eccentrically stiffened FG thin circular cylindrical shells are considered. Numerical results show that stiffeners and elastic foundation enhance the stability of the FG shells. Moreover, increasing the shell thickness, reducing the volume fraction index, increasing the number of stringer and ring stiffeners and applying stiffer elastic foundation lead to an increase in the thermal post-buckling response of stiffened FG circular cylindrical shells.

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ABSTRACT: Recently, the demand for Liquefied Natural Gas (LNG) as power-generating fuel has rapidly increased. On the other hand, the production of a new type of natural gas, due to the development of technologies for gas extraction from shale formations (referred to as “Shale Gas Revolution”), has been expanding mainly in the United States. Due to the increasing demand for this natural gas, the marine transport of LNG is expected to increase significantly. Currently, regarding the transport of American shale gas, which has attracted enormous attention, there are concerns such as restrictions on the dimensions of vessels after the expansion of the Panama Canal and long-distance transport across the Pacific Ocean. Therefore, it is important for LNG carriers to achieve a high level of safety and improve cargo loading space efficiency. Mitsubishi Heavy Industries, Ltd. (MHI) developed the 155 km$^3$ Sayaendo LNG carrier in 2011, and has delivered five vessels of the same model so far. In order to satisfy the needs of our customers, MHI has completed the development of an “Apple-Shaped Tank” that inherits the features of the existing MOSS spherical tank, which has enjoyed a great reputation for reliability. As of April 2016, MHI has received orders for eight new LNG carriers with apple-shaped tanks, and began the manufacturing of aluminum tanks in October 2015.

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ABSTRACT: The paper is concerned with the sensitivity analysis of structural responses in context of linear and non-linear stability phenomena like buckling and snapping. The structural analysis covering these stability phenomena is summarised. Design sensitivity information for a solid shell finite element is derived. The mixed formulation is based on the Hu-Washizu variational functional. Geometrical non-linearities are taken into account with linear elastic material behaviour. Sensitivities are derived analytically for responses of linear and non-linear buckling analysis with discrete finite element matrices. Numerical examples demonstrate the shape optimisation maximising the smallest eigenvalue of the linear buckling analysis and the directly computed critical load scales at bifurcation and limit points of non-linear buckling analysis, respectively. Analytically derived gradients are verified using the finite difference approach.

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Gil-Oulbe Mathieu, Ismael Taha Farhan and Dau Tyekolo (Peoples Friendship University of Russia, Moscow), “Buckling analysis of functionally graded epitrochoidal shells structures”, Structural Mechanics of Engineering Constructions and Buildings, No. 6, 2016
ABSTRACT: In the present article, stability of functionally graded epitrochoidal shells under pressure and thermal environment is examined. Material properties are taken as temperature dependent. Finite element solutions are obtained through commercially available tool ANSYS. The linear eigenvalue buckling problem is solved using Block Lanczos method. The effect of different geometry and material parameters on the critical buckling temperature of functionally graded Epitrochoidal Shells under pressure and thermal environment is demonstrated. Finally, the change of the stresses, displacements, rotations and stains were investigated and presented.

ABSTRACT: Superelastic conducting fibers with improved properties and functionalities are needed for diverse applications. Here we report the fabrication of highly stretchable (up to 1320%) sheath-core conducting fibers created by wrapping carbon nanotube sheets orientated in the fiber direction on stretched rubber fiber cores. The resulting structure exhibited distinct short- and long-period sheath buckling that occurred reversibly out of phase in the axial and belt directions, enabling a resistance change of less than 5% for a 1000% stretch. By including other rubber and carbon nanotube sheath layers, we demonstrated strain sensors generating an 860% capacitance change and electrically powered torsional muscles operating reversibly by a coupled tension-to-torsion actuation mechanism. Using theory, we quantitatively explain the complementary effects of an increase in muscle length and a large positive Poisson’s ratio on torsional actuation and electronic properties.

J. Zhang, Z. Liang, C.J. Han and H. Zhang (School of Mechatronic Engineering, Southwest Petroleum

ABSTRACT: Reverse fault movement is one of the threats for the structural integrity of buried oil-gas pipelines caused by earthquakes. Buckling behavior of the buried pipeline was investigated by finite element method. Effects of fault displacement, internal pressure, diameter-thick ratio, buried depth and friction coefficient on buckling behavior of the buried steel pipeline were discussed. The results show that internal pressure is the most important factor that affecting the pipeline buckling pattern. Buckling mode of non-pressure pipeline is collapse under reverse fault. Wrinkles appear on buried pressure pipeline when the internal pressure is more than 0.4Pmax. Four buckling locations appear on the buried pressure pipeline under bigger fault displacement. There is only one wrinkle on the three locations of the pipeline in the rising formation, but more wrinkles on the fourth location. Number of the wrinkle ridges and length of the wavy buckling increase with the increasing of friction coefficient. Number of buckling location decreases gradually with the decreasing of diameter-thick ratio. A protective device of buried pipeline was designed for preventing pipeline damage crossing fault area for its simple structure and convenient installation. Those results can be used to safety evaluation, maintenance and protection of buried pipelines crossing fault area.

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ABSTRACT: There are several methods for considering the interaction between compression and bending for slender steel members. This is covered by the interaction formula and the general method, currently. For stainless steel, the structural design standards have been developed largely in-line and refer to carbon steel design guidelines. The current stainless steel interaction formula of axial force and bending moment given in EN 1993-1-4 was derived on limited results available. On the other hand, the general method may be used without any change for stainless steel according to the Eurocode despite the non-linear stress-strain behaviour, which obviously could lead to some drawbacks. Hence, the main objective of this paper is to compare the analysis results with existing Eurocode design formulas, the general method and some formula taken from
experimental and parametric studies, showing their possible applicability, weaknesses and the need of further development. The conclusions are not applicable for stainless steel only, but they may be used for other non-linear materials such as aluminium alloys to some extent.

Matteo Pezzulla, Norbert Stoop, Mark P. Steranka, Abdikhalaq J. Bade and Douglas P. Holmes, “Curvature-induced instabilities of shells”, Physical Review Letters, June 2017, DOI: 10.1103/PhysRevLett.120.048002

ABSTRACT: Induced by proteins within the cell membrane or by differential growth, heating, or swelling, spontaneous curvatures can drastically affect the morphology of thin bodies and induce mechanical instabilities. Yet, the interaction of spontaneous curvature and geometric frustration in curved shells remains still poorly understood. Via a combination of precision experiments on elastomeric spherical bilayer shells, simulations, and theory, we show a spontaneous curvature-induced rotational symmetry-breaking as well as a snapping instability reminiscent of the Venus fly trap closure mechanism. The instabilities and their dependence on geometry are rationalized by reducing the spontaneous curvature to an effective mechanical load. This formulation reveals a combined pressure-like bulk term and a torque-like boundary term, allowing scaling predictions for the instabilities in excellent agreement with experiments and simulations. Moreover, the effective pressure analogy suggests a curvature-induced buckling in closed shells. We determine the critical buckling curvature via a linear stability analysis that accounts for the combination of residual membrane and bending stresses. The prominent role of geometry in our findings suggests the applicability of the results over a wide range of scales.

References listed at the end of the paper:


ABSTRACT: The laminated composite materials are widely used in almost every engineering field due to its high strength, stiffness, corrosion resistance, thermal insulation and many more. Laminated composite cylindrical shells are one the most common structures and depending on their usage they may face several loading condition. One of the most popular failures of these structures is buckling under axial compression. The application of cylindrical shells in variety of structures demands the creation of cutouts in shells, such as for access openings, pipeline passages etc. Hence there will be an invariable reduction in the strength due to the cutouts of the laminated composite cylindrical shell. The effect of cutout is that it not only introduces stress concentration but also significantly reduces buckling load. In present study, the nonlinear buckling analysis of laminated composite cylindrical shells under axial loading has been investigated. The analysis is carried out using ANSYS software. The results show how the imperfections like cutouts affect the buckling behavior of the shells.

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Michel Potier-Ferry (1), Foudil Mohri (1), Fan Xu (2), Noureddine Damil (3), Bouazza Braikat (3), Khadija Mhada (3), Heng Hu (4), Qun Huang (4) and Saeid Nezamabadi (5)
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ABSTRACT: The paper is concerned by multi-scale methods to describe instability pattern formation, especially the method of Fourier series with variable coefficients. In this respect, various numerical tools are available. For instance in the case of membrane models, shell finite element codes can predict the details of the wrinkles, but with difficulties due to the large number of unknowns and the existence of many solutions. Macroscopic models are also available, but they account only for the effect of wrinkling on membrane behavior. A Fourier-related method has been introduced in order to modelize the main features of the wrinkles, but by using partial differential equations only at a macroscopic level. Within this method, the solution is sought in the form of few terms of Fourier series whose coefficients vary more slowly than the oscillations. The recent progresses about this Fourier-related method are reviewed and discussed.

References listed at the end of the paper:

ABSTRACT: Curvature and mechanics are intimately connected for thin materials, and this coupling between geometry and physical properties is readily seen in folded structures from intestinal villi and pollen grains to wrinkled membranes and programmable metamaterials. While the well-known rules and mechanisms behind folding a flat surface have been used to create deployable structures and shape transformable materials, folding of curved shells is still not fundamentally understood. Shells naturally deform by simultaneously bending and stretching, and while this coupling gives them great stability for engineering applications, it makes folding a surface of arbitrary curvature a nontrivial task. Here we discuss the geometry of folding a creased shell, and demonstrate theoretically the conditions under which it may fold smoothly. When these conditions are violated we show, using experiments and simulations, that shells undergo rapid snapping motion to fold from one stable configuration to another. Although material asymmetry is a proven mechanism for creating this bifurcation of stability, for the case of a creased shell, the inherent geometry itself serves as a barrier to folding. We discuss here how two fundamental geometric concepts, creases and curvature, combine to allow rapid transitions from one stable state to another. Independent of material system and length scale, the design rule that we introduce here explains how to generate snapping transitions in arbitrary surfaces, thus facilitating the creation of programmable multistable materials with fast actuation capabilities.

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42 Niodson FI (1985) Shell Theory (Elsevier, Amsterdam)
44 Landau LD, Lifshitz EM (1959) Course of Theoretical Physics Vol 7: Theory and Elasticity (Pergamon, Oxford)


ABSTRACT: The wind turbine blade is a very important part of the rotor. Wind turbine provides an alternative way of generating energy from the power of wind. Extraction of energy depends on the design of blade. At windy places where the wind speeds are so high, sufficient amount of energy can be harnessed by making use of wind turbines. The blades of such turbines are so designed that they generate lift from wind and thus rotate. In this work, the wind turbine blade is modelled in CATIA V5 and analyzed for five different materials like Structural steel, Epoxy carbon, s-glass, E-glass, Aluminium alloy. Then the work explores the finite element analysis of a Wind Turbine Blade using ANSYS software. The aim of the analysis is to validate the strength of the blade and compare the above materials to select the best material for the wind turbine blade.

References listed at the end of the paper:

Hamed Farokhi, “Nonlinear behaviour of carbon nanotube resonators with applications in mass-sensors”, Ph.D dissertation, Dept. of Mechanical Engineering, McGill University, Montreal, April 2017

ABSTRACT: Recent technological advances have facilitated the development and fabrication of nanoelectromechanical systems (NEMS). NEMS are nano-scale devices consisting of integrated mechanical and electrical components designed to work in different environments for various purposes. A special class of NEMS devices are nanomechanical resonators which have received considerable attention from researchers around the world. Due to their small mass and size, nano resonators are capable of detecting the presence of even one very small particle, since the addition of the particle mass causes a shift in the resonance frequency of such devices. Carbon nanotubes (CNTs) have been considered as suitable candidates to be implemented in nano resonators, due to their small mass, high stiffness, small cross-section, and unique electrical properties. The performance of a nano resonator is directly related to its dynamical behaviour. The objective of this thesis is to perform a comprehensive investigation on the nonlinear behaviour of CNT resonators and to examine their
applications in mass detection. To this end, new nonlinear size-dependent continuum models are developed for doubly clamped and cantilevered CNT resonators taking into account the effects of small size, initial curvature, geometric imperfection, nonlinear damping, and geometrical and inertial nonlinearities; for a special case, the size-dependent continuum model is validated via molecular dynamics simulations. On the electrical part, new nonlinear models are proposed for the electrostatic load distribution in doubly clamped and cantilevered CNT resonators, taking into account the end effects caused due to the finite length; the proposed models are validated employing 3D finite element simulations.

Solving the complete nonlinear model developed for each case is a significantly complicated and challenging task, due to presence of various nonlinearities associated with the large-amplitude motion of the CNT resonator as well as the strong nonlinear coupling between the electrostatic load and the motion of the system. In this thesis, highly optimized and efficient discretization schemes as well as advanced numerical techniques are employed to investigate the nonlinear behaviour of the CNT resonator. The nonlinear static and dynamic responses of the CNT resonator are examined thoroughly, investigating the effect of various parameters, such as DC and AC voltages, length-scale parameter, nonlinear intrinsic damping, number of degrees of freedom, initial curvature, and geometric imperfections; it is shown that the DC voltage acts as a tuning parameter for the nonlinear behaviour of the system. More importantly, it is shown that when a realistic model is employed for the electrostatic load, via taking into account the end effects, the response of the system, in both static and dynamic regimes, changes significantly compared to the model available in the literature. Furthermore, the mass detection sensitivity of the cantilevered CNT resonator is examined in detail and methods are proposed for its enhancement.

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1867, 2013.

attached mass: molecular dynamics


prediction of intrinsic quality factors of nanoresonators,” Journal of Applied


Mostafa livani, Keramat Malekzadeh Fard and Saeed Shokrollahi, “Higher order flutter analysis of doubly curved sandwich panels with variable thickness under aerothemoelastic loading”, Structural Engineering and
ABSTRACT: In this study, the supersonic panel flutter of doubly curved composite sandwich panels with variable thickness is considered under aerothermoelastic loading. Considering different radii of curvatures of the faces in this paper, the thickness of the core is a function of plane coordinates \((x,y)\), which is unique. For the first time in the current model, the continuity conditions of the transverse shear stress, transverse normal stress and transverse normal stress gradient at the layer interfaces, as well as the conditions of zero transverse shear stresses on the upper and lower surfaces of the sandwich panel are satisfied. The formulation is based on an enhanced higher order sandwich panel theory and the vertical displacement component of the faces is assumed as a quadratic one, while a cubic pattern is used for the in-plane displacement components of the faces and the all displacement components of the core. The formulation is based on the von Kármán nonlinear approximation, the one-dimensional Fourier equation of the heat conduction along the thickness direction, and the first-order piston theory. The equations of motion and boundary conditions are derived using the Hamilton principle and the results are validated by the latest results published in the literature.

References listed at the end of the paper:


ABSTRACT: This thesis presents a study on vibration of an axially moving web following a curved path. The web is considered as a simply supported beam travelling axially on a curved guide that consists of a combination of linear and nonlinear elastic supports. The main objective of this work is to investigate the effect of the path curvature on the moving beam vibration and investigate the effect of different parameters on the system’s dynamic response. These parameters include axial speed, applied tension, degree of curvature of the path and stiffness of the path supports. The Galerkin decomposition with a first mode-shape of a straight a pinned-pinned basis function is utilized to realize a mathematical model that describes the static and dynamic behaviors of the axially moving curved beam. Numerical solutions of the developed model are obtained using a fourth-order Runge-Kutta algorithm under MATLAB environment. Fundamental frequencies are calculated results for axially moving curved beams and compared with those for axially moving straight beam. Amplitude-frequency curves are developed to study forced vibration of the axially moving curved beam under an external
force excitation. Poincaré sections and bifurcation diagrams are obtained for three cases: primary, sub-harmonic, and super-harmonic resonance excitations. It is found that the natural frequency of an axially moving beam travelling on a curved elastic support is higher than that of its axially moving straight beam for all considered cases of different path curvatures and different degrees of support stiffness. Forced vibrations of an axially moving beam on a curved elastic support are considered under harmonic excitation. Using the excitation amplitude as a controlling parameter over a wide range of variation, while keeping the excitation frequency fixed, it is found that the system exhibits many types of bifurcations, including period doubling bifurcation, period four bifurcation and many jumps. Compared to an axially moving beam resting on a straight elastic support, the axially moving curved beam showed earlier bifurcation and more swarming bifurcation diagram.


ABSTRACT: Previous research has shown that steel plate shear walls (SPSWs) are efficient lateral force-resisting systems against both wind and seismic loads. A properly designed SPSW can have high initial stiffness, strength, and energy absorption capacity as well as superior ductility. SPSWs have been commonly designed with unstiffened and stiffened infill plates based on economical and performance considerations. Recent introduction and application of corrugated plates with advantageous structural features has motivated the researchers to consider the employment of such elements in stiffened SPSWs with the aim of lowering the high construction cost of such high-performing systems. On this basis, this paper presents results from a numerical investigation of the hysteretic performance of SPSWs with trapezoidally corrugated infill plates. Finite element cyclic analyses are conducted on a series of flat- and corrugated-web SPSWs to examine the effects of web-plate thickness, corrugation angle, and number of corrugation half-waves on the hysteretic performance of such structural systems. Results of the parametric studies are indicative of effectiveness of increasing of the three aforementioned web-plate geometrical and corrugation parameters in improving the cyclic response and energy absorption capacity of SPSWs with trapezoidally corrugated infill plates. Increasing of the web-plate thickness and number of corrugation half-waves are found to be the most and the least effective in adjusting the hysteretic performance of such promising lateral force-resisting systems, respectively. Findings of this study also show that optimal selection of the web-plate thickness, corrugation angle, and number of corrugation half-waves along with proper design of the boundary frame members can result in high stiffness, strength, and cyclic performances of such corrugated-web SPSWs.

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AISC 341-10 (2010), Seismic Provisions for Structural Steel Buildings, American Institute of Steel Construction; Chicago, IL, USA.
ANSYS 11.0 (2007), ANSYS 11.0 Documentation, ANSYS Inc.
Eurocode (2003), Design of Steel Structures. Part 1.5: Plated Structural elements, European Committee for Standardization; Brussels, Belgium.


ABSTRACT: In this article, we investigate the buckling analysis of plates that are made of functionally graded materials (FGMs) resting on two-parameter Pasternak’s foundations under thermal loads. Three different thermal loads were considered, i.e., uniform temperature rise (UTR), linear and non-linear temperature distributions (LTD and NTD) through the thickness. The mechanical and thermal properties of functionally graded material (FGM) vary continuously along the plate thickness according to a simple power law distribution. Employing an analytical approach, the five coupled governing stability equations, which are derived based on first-order shear deformation plate theory, are converted into two uncoupled partial differential equations (PDEs). Considering the Levy-type solution, these two PDEs are reduced to two ordinary differential equations (ODEs) with variable coefficients. Then, the ODEs are solved using an exact analytical solution, which is called the power series Frobenius method. The appropriate convergence study and comparison with previously published related articles was employed to verify the accuracy of the proposed method. After such verifications, the effects of parameters such as the plate aspect ratio, side-to-thickness ratio, gradient index, and elastic foundation stiffnesses on the critical buckling temperature difference are illustrated and explained. The critical buckling temperatures of functionally graded rectangular plates with six various boundary conditions are reported for the first time and can serve as benchmark results for researchers to validate their numerical and analytical methods in the future.

References listed at the end of the paper:
This paper presents an analytical investigation on the buckling analysis of symmetric sandwich plates with functionally graded material (FGM) face sheets resting on an elastic foundation based on the first-order shear deformation plate theory (FSDT) and subjected to mechanical, thermal and thermo-mechanical loads. The material properties of FGM face sheets are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. An analytical approach is used to reduce the governing equations of stability and then solved using an analytical solution which is named as power series Frobenius method for symmetric sandwich plates with six different boundary conditions. A detailed numerical study is carried out to examine the influence of the plate aspect ratio, side-to-thickness ratio, loading type, sandwich plate type, volume fraction index, elastic foundation coefficients and boundary conditions on the buckling response of FGM sandwich plates. This has not been done before and serves to fill the gap of knowledge in this area.


ABSTRACT: This paper presents an analytical investigation on the buckling analysis of symmetric sandwich plates with functionally graded material (FGM) face sheets resting on an elastic foundation based on the first-order shear deformation plate theory (FSDT) and subjected to mechanical, thermal and thermo-mechanical loads. The material properties of FGM face sheets are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. An analytical approach is used to reduce the governing equations of stability and then solved using an analytical solution which is named as power series Frobenius method for symmetric sandwich plates with six different boundary conditions. A detailed numerical study is carried out to examine the influence of the plate aspect ratio, side-to-thickness ratio, loading type, sandwich plate type, volume fraction index, elastic foundation coefficients and boundary conditions on the buckling response of FGM sandwich plates. This has not been done before and serves to fill the gap of knowledge in this area.

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Solids Struct 42:5243–5258
29. Boucherba B, Houari MSA, Tounsi A (2013) Thermomechanical bending response of FGM thick plates resting on Winkler-

ABSTRACT: In this paper, nonlinear vibration and post-buckling analysis of beams made of functionally graded materials (FGMs) resting on nonlinear elastic foundation subjected to thermo-mechanical loading are studied. The thermo-mechanical material properties of the beams are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents, and to be temperature-dependent. The assumption of a small strain, moderate deformation is used. Based on Euler-Bernoulli beam theory and von-Karman geometric nonlinearity, the integral partial differential equation of motion is derived. Then this PDE problem which has quadratic and cubic nonlinearities is simplified into an ODE problem by using the Galerkin method. Finally, the governing equation is solved analytically using the variational iteration method (VIM). Some new results for the nonlinear natural frequencies and buckling load of the FG beams such as the influences of thermal effect, the effect of vibration amplitude, elastic coefficients of foundation, axial force, end supports and material inhomogeneity are presented for future references. Results show that the thermal loading has a significant effect on the vibration and post-buckling response of FG beams. References listed at the end of the paper:


PARTIAL SUMMARY: The main objective of this thesis is to study thermo-mechanical responses and free vibration of plates and shells composed of FGM composites. To this end, methodology used in this thesis is organized as follows.

Firstly, theoretical formulations for free vibration, static and thermal analyses of FGMs are developed based on 3-D elasticity theory and 2-D plate theories. The main approach in formulations based on 3-D elasticity theory is to combine the the equilibrium equations with the stress-strain and strain-displacement relations to derive the governing equations in term of the displacement components. This approach is called Navier method. In case of 2-D theories, the displacements are expanded in terms of thickness and transverse displacement is independent of the transverse coordinate. This causes coupled governing equations to be independent of transverse
displacement. For the first time, thermo-elastic governing equations for a 2-D FGM panel based on third-order-shear deformation theory are derived.

Secondly, for modelisation of variation of volume fraction or fiber orientation, classic form of power-law distribution is introduced. Then, as one of the contributions of this thesis, 1-D and 2-D generalized power-law distributions are presented. By using generalized power-law distribution, it is possible to study the effects of the various kinds of material profiles including symmetric, asymmetric, sigmoidal and classic on mechanical behaviour of FGM structures. To compute effective material properties of composites, rule of mixture and Mori-Tanaka method are used. In case of nanocomposites, Eshelby-Mori-Tanaka method is employed to determine the effective material properties of composites reinforced by various type of carbon nanotubes dispersion.

Thirdly, owing to the complexity of governing equations with variable coefficients initiated from non-homogeneity, it is very rigorous to obtain the exact solutions. Due to non-linear variation of material properties, seeking a powerful numerical method is highly desirable. In this thesis, generalized differential quadrature method (GDQM) is adopted to solve coupled governing differential equations. The 1-D and 2-D GDQM are applied to various problems consisting of thermal, vibration, and static analyses of FGMs. By solving free vibration, static, and thermal problems and by comparing the results with those of other methodologies, accuracy, convergency and efficiency of the methodology are asserted. Less computational efforts of the proposed approach for FGMs problems with respect to other available methods have been found. According to contributions of the thesis into FGMs, significant motivations and findings can be categorized into three parts as follows: 1) 1-D FG fiber-reinforced composites, 2) 2-D FGM composites, and 3) FG carbon nanotubes-reinforced composites.

References listed at the end of the dissertation:


T. Gomshima, K. Miyao: Transient thermal stresses in a plate with a hole due to rotating heat source. J Therm Stresses, 13, 43–


[105] M. Nemat-Alla, N. Noda, Study of an edge crack problem in a semi-infinite functionally graded medium with two


ABSTRACT: This study investigated influences of vacancy defects on buckling behaviors of open-tip carbon nanocones (CNCs) by molecular dynamics simulations. Effects of vacancy location and temperature on the buckling behaviors were examined in the study. Some interesting findings were attained from the investigations. It was noticed that the CNC with an upper vacancy has comparable degradation in the critical strain and in the critical load with the CNC with a middle vacancy, whereas the CNC with a lower vacancy has lower degradation in the antibuckling ability than the above two CNCs. The antibuckling ability of the CNCs reduces with the growth of the temperature. This temperature effect is more apparent in the perfect CNC than in the vacancy-defect CNCs. It was also observed that the degradation in the antibuckling ability is obvious at a lower temperature, but it decreases as the temperature grows. Besides, all the CNCs (including the perfect and the vacancy-defect CNCs) exhibited a shrinking/swelling buckling mode shape at the studied temperatures. Existence of the vacancies did not alter the buckling mode shape of the CNCs.

References listed at the end of the paper:

ABSTRACT: An analytical algorithm is proposed for studying the stability of a cylindrical shell subjected to nonuniform external pressure. The algorithm is based on a perturbation procedure and Pade approximants. Unlike the commonly used perturbation method, this approach is not limited by the smallness of the perturbation parameter. The approximate formulas obtained are sufficiently accurate and can be used in engineering practice.

References listed at the end of the paper:


James G.A. Croll (Emeritus Professor of Civil Engineering, University College London), “Validation and Design Use of Analytic Lower Bounds for the Unstable Postbuckling of Shells: Experimental, Analytical and

ABSTRACT: Because they so often exhibit extreme forms of nonlinear mode coupling in their imperfection-sensitive response, the buckling design of shells is often thought to require either massive computational power or vast accumulations of test data, or both. Nothing could be further from the truth. Virtually all the information required to predict lower bounds to the imperfection-sensitive buckling loads, for the vast majority of shells, is conveniently contained within a reanalysis of the stiffness (or energy) components characterizing the linearized, classical critical load (eigenvalue) analysis. This chapter briefly outlines the philosophical basis for the "reduced stiffness method," refers to its capacity to predict lower bounds to the scatter of past test results, and illustrates its more recent validation through carefully controlled numerical experiments. It also demonstrates how the understanding of the relative importance of the various energy components within each of the prospective buckling modes provides a powerful guide as to the best choice of rib stiffening or fibre reinforcement to enhance the buckling performance. Although attention is focused on the elastic buckling behaviour, it will be indicated how a simple extension of the reduced stiffness method also allows prediction of lower bounds to elastic-plastic buckling loads of shells.

References listed at the end of the paper:


Lin S1, Xie YM2, Li Q3, Huang X4, Zhang Z5, Ma G6, Zhou S7
1 School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin, Tianjin, CHINA.
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ABSTRACT: Being one of the commonest deformation modes for soft matters, shell buckling is the primary reason for the growth and nastic movement of many plants, as well as the formation of complex natural morphology. On-demand regulation of buckling-induced deformation associated with wrinkling, ruffling, folding, creasing and delaminating has profound implications for diverse scopes, which can be seen in its broad
applications in microfabrication, 4D printing, actuator and drug delivery. This paper reviews the recent remarkable developments in the shell buckling of soft matters to explain the most representative natural morphogenesis from the perspectives of theoretical analysis in continuum mechanics, finite element analysis, and experimental validations. Imitation of buckling-induced shape transformation and its applications are also discussed for the innovations of sophisticated materials and devices in future.

Jun Young Chung, Ashkan Vaziri and Lakshminarayanan Mahadevan, “Reprogrammable Braille on an elastic shell”, Proceedings of the National Academy of Sciences, Vol. 115, No. 29, 201722342, July 2018

ABSTRACT: We describe a minimal realization of reversibly programmable matter in the form of a featureless smooth elastic plate that has the capacity to store information in a Braille-like format as a sequence of stable discrete dimples. Simple experiments with cylindrical and spherical shells show that we can control the number, location, and the temporal order of these dimples, which can be written and erased at will. Theoretical analysis of the governing equations in a specialized setting and numerical simulations of the complete equations allow us to characterize the phase diagram for the formation of these localized elastic states, elastic bits (e-bits), consistent with our observations. Given that the inherent bistability and hysteresis in these low-dimensional systems arise exclusively due to the geometrical-scale separation, independent of material properties or absolute scale, our results might serve as alternate approaches to small-scale mechanical memories.


ABSTRACT: It is widely acknowledged that tracking the postbuckling response of structures made from thin plates can be problematical. Such difficulty is associated with highly nonlinear effects, including mode jumping, imperfection sensitivity, and their combined interactions. Two widely used techniques that are currently used involve path following and asymptotic expansion. The former is often implemented in commercial finite element codes but can prove unreliable at representing branch switching. The latter is a relatively quick technique due to its recursive nature but is only reliable in the vicinity of bifurcations. Due to the overall complex nonlinearity, analytical closed-form solutions do not exist for path following and exist rarely for quadratic asymptotic expansions where simple forms have been adopted. This paper presents an analytical-based approach that enables the efficient optimal design of “moderately deep” nonlinear postbuckling behavior of laminated composite plates under uniaxial or biaxial loading. It provides a closed-form solution that more reliably reflects a deeper postbuckling response than the state of the art. Subsequently, highly efficient postbuckling optimization is attributed to the newly derived closed-form solution and a recent two-level optimization framework.

References listed at the end of the paper:


Join the world’s experts in structural stability at CIMS 2016 and have your voice heard in the conversation to advance our understanding of the complex interactive stability problems associated with thin-walled and slender structures. The seventh international conference on Coupled Instabilities in Metal Structures, CIMS 2016, will be held at the Royal Sonesta Hotel, Baltimore, Maryland, USA. The conference is being organized by the Cold-Formed Steel Research Consortium and its Director Ben Schafer from Johns Hopkins University. Also join Dr. Schafer and his colleagues at the Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures 2016 immediately following the CIMS 2016 conference at the Royal Sonesta Hotel.

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SEMC 2016: The Sixth International Conference on Structural Engineering, Mechanics and Computation, 5-7 September 2016, Cape Town, South Africa

Special Session: SS07: Design, Modeling and Analysis of Thin Shell Structures, organized by Krzysztof Magnucki, Poznan University of Technology, Poland

SUMMARY: The purpose of this special session of SEMC 2016 will be to share and exchange the latest knowledge concerning the design and analysis of thin shell structures. The session will cover analytical, numerical and experimental investigations. While the focus will be on stability problems of shells in both the critical and post-critical range, other related subjects will be equally welcome. Contributions are invited on the following topics: Analytical and numerical modeling of the pre-buckling state; Numerical simulations of post-buckling behaviour of shells; Control of buckling and post-buckling behavior; New shell applications; Nonconventional shell forms.

The “Thin-Walled Structures” papers that involve instability in some form are almost numberless. There are numerous other similar papers in other journals not covered in the following list, papers in journals such as Engineering Structures, Journal of Constructional Steel Research, Journal of Composites, International Journal of Solids and Structures, International Journal of Impact Engineering, International Journal of Mechanical Sciences, etc., etc. I cannot possibly include citations of all of them. By far most of the “buckling” papers in Thin-Walled Structures involve shear walls and beam-columns with thin-walled cross sections. I have not included them previously at this website because they are not, in the strictest sense, “shell structures”. However, the physics and mathematics governing their behavior is entirely analogous to that governing shell buckling and post-buckling.

H.E. Estekanchi and M. Alembagheri (Department of Civil Engineering, Sharif University of Technology (SUT), P.O Box 11155-9313, Tehran, Iran), “Seismic analysis of steel liquid storage tanks by Endurance Time method”, Thin-Walled Structures, Vol. 50, pp 14-23, January 2012, DOI: 10.1016/j.tws.2011.08.015
ABSTRACT: Endurance Time (ET) method is a time history based method for seismic evaluation of structures using intensifying dynamic excitation as the loading function. In this paper, application of this method in the analysis of steel tanks has been investigated. A methodology for practical application of ET method in seismic assessment of storage tanks has been presented. This methodology has been applied in three-dimensional nonlinear analysis of a particular anchored steel tank using Finite Element method, and results are compared with conventional codified design procedures. Results of the analyses indicate reasonable accuracy of the proposed method in estimation of seismic responses of steel tanks and its applicability in enhancing the design process of steel tanks considering various sources of complicated behavior. Comparative study of seismic response of the tank in anchored and unanchored states utilizing ground motions has been presented. Advantages and limitations of the procedure have also been discussed.


ABSTRACT: This paper presents a detailed investigation into lateral-torsional stability of aluminium extruded I section beams under pure bending. Forty aluminium members of two different alloys 6061-T6 and 6063-T5, representing weak hardening and strong hardening alloys respectively, were tested. Stress–strain relationships were determined by tensile tests with 8 coupons cut from extruded flanges and web. Widths of flanges and lengths of members were herein taken as primary parameters to study lateral-torsional stability of the beams. With rigid lateral-torsional restraint on beam ends, lateral-torsional buckling resistances and load-rotation
relationships were obtained by continuous loading. Comparison of numerical predictions with test results indicated that accurate and reliable replication could be achieved by the described finite element (FE) models. By means of measured material behaviour and geometric properties, the corresponding provisions in Eurocode 9 (CEN 2007) and a design method previously proposed by the authors were evaluated by the test results. It was demonstrated that the proposed calculation method could provide cross-section lateral-torsional buckling resistances that are much closer to the test results than design strengths on the basis of the Eurocode 9 provisions are. Therefore, the proposed design method could be an alternative way of predicting the lateraltorsional buckling resistances of aluminium alloy I-beams.

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DOI: 10.1016/j.tws.2011.10.001
ABSTRACT: The aluminum tubular structure with hat-shaped cross-section was axially compressed under the dynamic condition. The crush strength was larger for the bonded structure than that for the riveted one. The crush strength level was remarkably dominated by the plastic deformation behavior at the double-walled flange. The method to initiate the first plastic buckling lobe was demonstrated, where the inertia force in the early stage of impact was exploited. The method uses the solid block attached to the structural wall causing the wall bending force. It successfully worked without changing the energy absorption performance of the structure.

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ABSTRACT: This paper presents numerical investigation and design of concrete-filled aluminum circular hollow section (CHS) columns. A non-linear finite element model is developed and verified against experimental results. An extensive parametric study was carried out to study the effects of cross-section geometries and material properties on the concrete-filled aluminum CHS column strengths. A total of 192 numerical data is presented in this study. The aluminum CHS tubes of normal strength material (T5) and high strength material (T6) using three different nominal concrete cylinder strengths of 40, 70 and 100 MPa were investigated. The nominal outer diameter-to-thickness (D/t) ratio of the sections ranged from 10 to 160. The test and numerical results of the concrete-filled aluminum CHS columns were compared with the design strengths to evaluate the reliability of the design rules in the American and Australian/New Zealand specifications for aluminum and concrete structures. Furthermore, the composite column design equations are proposed in this study. The proposed design equations consider the benefits of composite action between the aluminum CHS tube and the concrete infill. It is shown that the proposed design equations accurately predicted the strengths of the concrete-filled aluminum CHS columns.

ABSTRACT: The influence of roof on the natural frequencies and the modes of fixed roof, ground supported, liquid storage tanks is presented in this paper. Attention is given to partially filled tanks with the same heights of 12.19 m and the aspect ratios (H/R) of 2, 1.52, and 1.33. The bottom of tanks is considered to be anchored to the foundation. The effect of the roof, along with the liquid height, on dynamic properties is investigated. For this purpose, each tank is modeled in 4 liquid levels, equal to 1.80, 4.80, 8.50, and 10.90 m and in two various roof conditions: with roof (WR) and open top (OT). The finite element package ANSYS is used to model the tank–liquid systems. Tank roof and wall are meshed by shell elements and the liquid is modeled using fluid finite elements. The fluid–structure interaction is taken into account by coupling the nodes at the interface of the fluid and the shell in the radial direction. Results of ambient vibration tests are used to verify the numerical procedure in which good agreement is observed between the numerical and the experimental modal parameters. It is found that the influence of roof on natural frequencies of axial and vertical modes is negligible whereas its effect on the natural frequencies of circumferential modes is significant. It is also concluded that at low liquid levels, equal to 1.80 and 4.80 m, the tank roof does affect the axial modes of the tallest and medium height tanks while, at all of the considered liquid heights and aspect ratios, the tank roof affects the circumferential mode shapes; this confirms the idea that the roof does restrain the tank top against radial deformations.

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ABSTRACT: Cold-formed steel sections are often used as wall studs or floor joists; such sections often include web holes for ease of installation of the services. Cold-formed steel design codes, however, do not consider the effect of such web holes. In this paper, a combination of experimental tests and non-linear elasto-plastic finite element analyses are used to investigate the effect of such holes on web crippling under interior-two-flange (ITF) loading conditions; the cases of both flange fastened and flange unfastened are considered. A good agreement between the experimental tests and finite element analyses was obtained. The finite element model was then used for the purposes of a parametric study on the effect of different sizes and position of holes in the web. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the depth of the web, and the ratio of the distance from the edge of the bearing to the flat depth of web. Design recommendations in the form of web crippling strength reduction factors are proposed, that are conservative to both the experimental and finite element results.


ABSTRACT: Over the years the finite strip method (FSM) has proved to be an invaluable tool in the study of buckling modes in thin-walled structural members. This paper presents a formulation of the FSM, which is able
to predict the buckling stresses of initially perfectly straight thin-walled inelastic members under uniform compression. Plasticity is accounted for by means of plastic flow equations. Previous short-comings of plastic flow theory with respect to the modeling of buckling problems are overcome by deriving an expression for the inelastic shear stiffness from second order considerations.

Dragan D. Milasinovic (University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, 24000 Subotica, Serbia), “Harmonic coupled finite strip method applied on buckling-mode interaction analysis of composite thin-walled wide-flange columns”, Thin-Walled Structures, Vol. 50, pp 95-105, January 2012
DOI: 10.1016/j.tws.2011.08.011

ABSTRACT: This paper presents an investigation of bifurcation buckling, buckling-mode interaction and post-buckling equilibrium of composite thin-walled wide-flange columns. The non-linear harmonic coupled finite strip method is used. As far as linear analysis is concerned, it takes advantage of the orthogonality properties of harmonic functions in the stiffness matrices formulation. However, in the case of geometric non-linear analysis all harmonics are coupled. In thin-walled sections the finite strips include the local and global buckling modes. When critical local and global stresses are close, new bifurcations appear due to buckling-mode interaction and failure stresses may be lower than both predictions. In this work, the existence of buckling-mode interaction is verified in H-section columns made of fiber reinforced plastic using the viscoelastic rheological–dynamical modulus and non-linear harmonic coupled finite strip method. Numerical examples showing the theoretical considerations are presented and agree with the experimental data.


ABSTRACT: For thin-walled beams, the classic theory for flexural and torsional analysis of open and closed cross-sections can be generalized by including distortional displacements. In a companion paper it is shown that using a novel semi-discretization process, it is possible to determine specific distortional displacement fields which decouple the reduced order differential equations. In this process the cross section is discretized into finite cross-section elements, and the natural distortional modes as well as the related axial variations are found as solutions to the established coupled fourth order homogeneous differential equations of GBT. In this paper the non-homogeneous distortional differential equations of GBT are formulated using this novel semi-discretization process. Transforming these non-homogeneous distortional differential equations into the natural eigenmode space by using the distortional modal matrix found for the homogeneous system, we get the uncoupled set of differential equations including the distributed loads. This uncoupling is very important in GBT, since the shear stiffness contribution from St. Venant torsional shear stress as well as “Bredt's shear flow” cannot be neglected nor approximated by the combination of axial stiffness and transverse stiffness, especially for closed cross sections. The full analytical solutions of these linear non-homogeneous differential equations are given, including four illustrative examples, which illustrate the strength of this novel approach to GBT. This new approach is a considerable theoretical achievement, since it without approximation gives the full analytical solution for a given discretization of the cross section including distributed loading. The boundary conditions considered in the examples of this paper are restricted to built in ends, which are needed for future displacement formulation of an exact first-order distortional beam element.
Thamarajah Anapayan and Mahen Mahendran (Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Improved design rules for hollow flange sections subject to lateral distortional buckling”, Thin-Walled Structures, Vol. 50, pp 128-140, January 2012 DOI: 10.1016/j.tws.2011.09.004

ABSTRACT: The LiteSteel Beam (LSB) is a new hollow flange section with a unique geometry consisting of torsionally rigid rectangular hollow flanges and a relatively slender web. It is subjected to lateral distortional buckling when used as flexural members, which reduces its member moment capacity. An investigation into the flexural behaviour of LSBs using experiments and numerical analyses led to the development of new design rules for LSBs subject to lateral distortional buckling. However, the comparison of moment capacity results with the new design rules showed that they were conservative for some LSB sections while slightly unconservative for others due to the effects of section geometry. It is also unknown whether these design rules are applicable to other hollow flange sections such as hollow flange beams (HFB). This paper presents the details of a study into the lateral distortional buckling behaviour of hollow flange sections such as LSBs, HFBs and their variations. A geometrical parameter defined as the ratio of flange torsional rigidity to the major axis flexural rigidity of the web ($GJ/El_{web}$) was found to be a critical parameter in evaluating the lateral distortional buckling behaviour and moment capacities of hollow flange sections. New design rules were therefore developed using a member slenderness parameter modified by $K$, where $K$ is a function of $GJ/El_{web}$. The new design rules based on the modified slenderness parameter were found to be accurate in calculating the moment capacities of not only LSBs and HFBs, but also other types of Hollow Flange Sections.


ABSTRACT: This paper presents a development of the finite strip method based on the shallow shell theory of Marguerre. Most of existing semi-analytical finite strips are based on the plate theories of Kirchhoff and of Mindlin. As it is showed in the paper, the plate theories can be considered as the particular cases of the shallow shell theory. Numerical results show the efficiency of the finite strip based on the shallow shell theory in the buckling analysis of prismatic structures which have curved corners.


ABSTRACT: Cracking damage in a stiffened panel is likely to have a deleterious effect on its ultimate strength and collapse characteristics. The present study examines this problem for a crack with different configurations and increasing length inserted in a stiffened plate. The cracks are positioned normal to the direction of the prescribed axial compression and crack propagation is not considered. A key feature of this work is the role of crack closure on the structural response. The ultimate strength reduction and collapse response are reported for stiffened plates of varying aspect ratio. Finally, an FE modeling approach is presented, which has the potential to extend this investigation to multi-bay panels at a reasonable computational cost.

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ABSTRACT: Perforated and slotted tubes are widely used as liners in oil and gas industry to facilitate the collection of products from reservoirs, and prevent sand migration to wellbore, which in return could cause product contamination and affect functionality of the pumps. The objective of this research is to establish the critical axial load of perforated E-glass/epoxy tubes using numerical and experimental methods. Firstly, in an experimental attempt, a total of six sets of composite tubes (three sets with perforations and three sets of intact (non perforated) tubes), having two different thicknesses and diameters, were fabricated and tested under axial compression. The reduction in the critical load and axial stiffness of the composite tubes was investigated experimentally. Secondly, a comprehensive numerical investigation was carried out, using the finite element method (FEM), to simulate the instability response of the intact and perforated composite tubes under compressive axial loading. The effect of various parameters such as the tube diameter, size, number of perforation and wall thickness were investigated in the current research. Good correlation is obtained between the experimental and numerical results. According to the results, the intact and perforated tubes showed similar instability mode shapes under the axial loading. However, the critical load and global stiffness of the perforated tubes were considerably reduced.

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ABSTRACT: In this study, the bending characteristics of thin-walled (D/t=30) tubular beams with fixed supports are systematically investigated for different beam lengths and diameters. Bending behavior of the beam is simulated using the finite element method, in which elasto–plastic material, large-deformation and contact are included. Stress distribution is monitored by FE analyses during bending simulation. Also, load carrying and energy absorption capacities of the tubular beams having different geometrical combinations are compared with each other. The results of finite element (FE) analyses indicate that the deformation characteristics and load carrying capacities of the beam strongly depend on the diameter. From the load–displacement curve, three distinct regions were observed and the associated deformation characteristics were identified. There is a noticeable correlation between the energy absorption and transition displacements for the ranges of geometric parameters covered in this study. It is concluded that the presented simulation results can provide significant contribution to the design of side-door impact beams and passive safety research.

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ABSTRACT: Cured-in-place plastic pipe linings are widely used in the rehabilitation of deteriorated rigid pipelines. Generally, the thickness of the pipe lining is assumed to be constant for simplification during the previous analysis. However, the thickness of the pipe lining may be a variable due to corrosive liquids or gases in service. This paper develops an analytical solution for the elastic buckling of cylindrical pipe linings with variable thickness subjected to external hydrostatic pressure. In addition to the analytical solution based on the
minimum potential energy theory, a numerical analysis using the finite element method (FEM) is also performed for comparison. The FEM results agree well with the analytical solutions. Both the FEM results and the analytical solutions are discussed and compared with the models presented by other authors. When the thickness of pipe lining is constant, our analytical solutions can be simplified to Glock's typical solutions.


ABSTRACT: The failure mechanism of expanded metal tubes under axial crushing is addressed herein. Experimental results have shown that when collapsing the tubes, the expanded metal cells closes until the plastic moment in all nodes along the mid-section of the tubes is attained exhibiting a plastic collapse mechanism. From this deformed configuration, a simple analytical expression is developed for the ultimate strength of the tube based on a rigid-plastic analysis of a frame-like structure. In addition, the energy absorption capacity of the tubes is also calculated. Theoretical predictions for both strength and energy are in good agreement with experimental results taken from the literature. Thereafter, a numerical study was conducted in order to investigate the validation of the theoretical model depending on the expanded metal cell geometry. It is found that the load-displacement response and failure mechanism of the tubes depend upon the aspect ratio of the expanded metal cell.

Nirosha Dolamune Kankanamge and Mahen Mahendran (Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, Australia), “Behaviour and design of cold-formed steel beams subject to lateral-torsional buckling”, Thin-Walled Structures, Vol. 51, pp 25-38, February 2012

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ABSTRACT: Cold-formed steel beams are increasingly used as floor joists and bearers in buildings. Their behaviour and moment capacities are influenced by lateral–torsional buckling when they are not laterally restrained adequately. Past research on lateral–torsional buckling has concentrated on hot-rolled steel beams. Hence a numerical study was undertaken to investigate the lateral–torsional buckling behaviour of simply supported cold-formed steel lipped channel beams subjected to uniform bending. For this purpose a finite element model was developed using ABAQUS and its accuracy was verified using available numerical and experimental results. It was then used in a detailed parametric study to simulate the lateral–torsional buckling behaviour and capacity of cold-formed steel beams under varying conditions. The moment capacity results were compared with the predictions from the current design rules in many cold-formed steel codes and suitable recommendations were made. European design rules were found to be conservative while Australian/New Zealand and North American design rules were unconservative. Hence the moment capacity design equations in these codes were modified in this paper based on the available finite element analysis results. This paper presents the details of the parametric study, recommendations to current design rules and the new design rules proposed in this research for lateral–torsional buckling of cold-formed steel lipped channel beams.

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ABSTRACT: Shear wall systems are one of the most commonly used lateral-load resisting systems in high-rise buildings. The composite steel plate shear wall (CSPSW) systems have strong points, such as high bearing capacity, good ductility and energy dissipation capacity, which have been increasingly used as lateral load-resisting system in steel buildings. This paper describes the experimental work related to the tests of steel plate shear wall (SPSW) system and CSPSW system. Two 1/3 scaled specimens were fabricated and tested. The tested shear wall system consisted of concrete-filled circular hollow section (CHS) steel columns, steel beams, and SPSW or CSPSW. The experimental results were summarized and discussed, which showed that both SPSW system and CSPSW system possessed good ductility and energy dissipation capacity. For SPSW system, the primary mechanism for resisting storey shear arising from lateral loads came from the post-buckling inclined tension field that forms for thin-walled steel plate. For CSPSW system, the reinforced-concrete (RC) panels attached on both sides of steel plates were able to ensure the composite action by preventing the overall buckling of steel plate. Compared with SPSW system, the bearing capacity and energy dissipation capacity of CSPSW system increased evidently.

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ABSTRACT: This paper presents distorting buckling solutions for semi-discretized thin-walled columns using the coupled differential equations of a generalized beam theory (GBT). In two related papers recently published by the authors a novel semi-discretization approach to GBT has been presented. The cross section is discretized and analytical solutions are sought for the variation along the beam. With this new approach the general GBT equations for identification of a full set of deformation modes corresponding to both homogeneous and non-homogenous equations are formulated and solved. Thereby giving the (complex) deformation modes of GBT which decouple the state space equations corresponding to the reduced order differential equations. In this paper the developed semi-discretization approach to generalized beam theory (GBT) is extended to include the geometrical stiffness terms, which are needed for column buckling analysis and identification of buckling modes. The extension is based on an initial stress approach by addition of the related potential energy terms. The potential energy of a single deformation mode is formulated based on a discretization of the cross section. Through variations in the potential energy and the introduction of the constraints related to beam theory this leads to a modified set of coupled homogeneous differential equations of GBT with initial stress for identification of distortional displacement modes. In this paper we seek instability solutions using these GBT initial stress equations for simply supported columns with constrained transverse displacements at the end sections and a constant axial initial stress. Based on the known boundary conditions the reduced order differential equations are solved by using the trigonometric solution functions and solving the related eigenvalue problem. This gives the buckling mode shapes and the associated eigenvalues corresponding to the bifurcation load factors. Thus the buckling modes are found directly by the analytical solution of the coupled GBT-equations without modal decomposition. Illustrative examples showing global column buckling, distortional buckling and local buckling are given and it is shown how the novel approach may be used to develop signature curves and elastic buckling curves. In order to assess the accuracy of the method some of the results are compared to results found using the commercial FE program Abaqus as well as the conventional GBT and FSM methods using the software packages GBTUL and CUFSM.

ABSTRACT: Experimental investigations were conducted to evaluate the lateral seismic characteristics of light-weight knee-braced cold-formed steel structures. In all, four full-scale $2.4 \times 2.4 \text{ m}^2$ specimens with different configurations were tested under a standard cyclic loading regime. This paper focuses on the specimens' maximum lateral load capacity and deformation behavior and provides a rational estimate of the seismic response modification factor, $R$, of knee-braced walls. The study also looks at the failure modes of the system and investigates the main factors contributing to the ductile response of CFS walls. That is in order to suggest improvements so that the shear steel walls respond plastically with a significant drift and without any risk of brittle failure, such as connection failure or stud buckling. A discussion on the calculated response factors in comparison to those suggested in the relevant codes of practice is also presented.

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“Static analysis of thick laminated shells with different boundary conditions using GDQ”, Thin-Walled Structures, Vol. 51, pp 76-81, February 2012, DOI: 10.1016/j.tws.2011.11.004

ABSTRACT: Equilibrium equations and the associated boundary conditions for doubly curved, relatively deep and thick composite shells are shown. Two First Order Shear Deformation theories (FSDTs) are used. The first one uses plate stiffness parameters for thick shells and the other includes the effect of curvature in the calculation of stiffness parameters. Equilibrium equations are put together with the equations of stress resultants to arrive at a system of seventeen first order differential equations. These equations are solved numerically with the aid of General Differential Quadrature (GDQ) method for isotropic, cross-ply, angle-ply and general lay-up cylindrical shells with six types of different boundary conditions using above mentioned theories. Results obtained using both theories are compared with the available results in literature and those obtained using a three-dimensional (3D) analysis to test the accuracy of the shell theories presented here.


ABSTRACT: In this paper, the collapse behavior of corrugated cross section beams subjected to three-point bending is studied by using the finite element method (FEM). In order to estimate the energy absorption characteristics of the beam, it is essential to estimate the relation between load and deflection in the process of the beam collapse after the peak load. It is found that in the collapse process of the beam the load is decreased by flattening of the cross section of the beam, and that the flattened shape can be quantitatively expressed in terms of the curvature radius of the plane of the top and bottom of the cross section. Based on the energy balance that external work is equated to the flattening deformation energy of the cross section, a new method is proposed for predicting the relation between load and deflection. The validity of the presented method is verified through a comparison with numerical results of FEM analysis under various conditions.

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ABSTRACT: This paper presents three methodologies to predict the load carrying capacity of cold formed steel rack columns via nonlinear finite element analysis (FEA). The column lengths are chosen in the range where the main failure is due to distortional buckling. It is demonstrated that for this range, to derive an accurate prediction of the ultimate load is more complex than for lengths where the main failure is local or global. The nonlinear analysis is carried out introducing an initial geometric imperfection on the upright. The three methodologies presented here allow for different imperfection shapes. The first one uses the critical mode shape (the first buckling mode). The second corresponds to an iterative methodology in which the shape that leads to the lowest ultimate load is used. These two first methodologies use exclusively the finite element method (FEM). The third one combines the finite element analysis with the generalised beam theory (GBT) in order to determine the modal participation of the FEM buckling mode and generate a particular combined geometric imperfection. To validate the predicted loads, the results of the three methodologies are compared with values obtained in experimental tests.


ABSTRACT: In this paper, we proposed a strategy to improve energy absorption efficiency of thin-walled columns by introducing extra non-convex corners in the cross section. Several profiles of non-convex multi-corner thin-walled columns obtained through this strategy are presented and their energy absorption capacities under axial crush are investigated analytically and numerically. Explicit formulations for predicting the mean crushing force of non-convex multi-corner thin-walled columns are derived based on the theory of Super Folding Element method, and the predicting results of these formulations have good agreement with the numerical simulation performed by explicit non-linear finite element method. The comparisons of the non-convex columns with square column show that the non-convex multi-corner thin-walled columns have higher energy absorption capacity.

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ABSTRACT: This paper presents the formulation and validation of a geometrically and physically ($J_2$ plasticity) non-linear Generalised Beam Theory formulation, intended to calculate accurate non-linear elastoplastic equilibrium paths of thin-walled metal bars and associated collapse loads. This formulation extends previous work (Gonçalves and Camotim, 2011) [1] by including the geometrically non-linear effects. The plate-like bending strains are assumed to be small (as in all GBT formulations), but the membrane strains are calculated exactly. Both stress-based and stress resultant-based GBT approaches are developed and implemented in a 3-node beam finite element. The stress-based formulation is generally more accurate, but the
stress resultant-based formulation makes it possible to avoid numeric integration in the through-thickness direction of the walls. In order to show the potential of the proposed formulation and resulting finite element, several numerical results are presented and discussed. For validation purposes, these results are compared with those obtained with standard 2D-solid and shell finite element analyses.

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ABSTRACT: The quasi-static axial buckling response of super-elastic NiTi thin-walled cylindrical shells has been investigated. The results show that the main buckling pattern is the non-axisymmetric mode with various circumferential patterns depending on the geometry of a specimen. The specific energy is strongly related to the geometry and the buckling mode of a specimen. The austenite–martenite phase transition is concentrated in the buckling area to form so-called phase transition hinges. The buckling behavior of a specimen is significantly related to the phase transition and phase transition hinges. After unloading a NiTi specimen can recover to its initial shape, which differs from an elastic–plastic specimen.

ABSTRACT: This paper presents an analytical solution of skin wrinkling for sandwich polymer matrix composite panels in a combined thermal–mechanical condition. The thermal gradient in the transverse direction is induced by one-sided fire exposure, and the mechanical load is the in-plane compression. Due to low thermal conductivities of polymer matrix composites, the thermal gradient exists for a long period of time. The material properties of polymer matrix composites are degraded as temperature rises. These behaviors induce mechanical properties' gradients along the transverse direction. The general solution for the wrinkling load in the thermal–mechanical loading condition is investigated. The solution is characterized in terms of two non-dimensional parameters that represent material properties and dimensional lengths of the skin and the core. The wrinkling load is presented for fairly complete ranges of the two non-dimensional parameters. The wrinkling load is also derived from Winkler model for non-homogeneous materials. An example of thermal-mechanical simulation to design the wrinkling load-bearing capacity of a panel exposed to fire is given.

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ABSTRACT: An analytical approach was considered to study the buckling and the behavior of an inflatable orthotropic beam subjected to uniform compression loads under different boundary conditions. In order to assess the stability of inflatable structures, it is necessary to evaluate the critical load of the inflatable components in their pressurized configurations. First, a 3D inflatable orthotropic beam model based on the Timoshenko's kinematics was briefly introduced: the nonlinearities (finite rotation, follower forces) were included in this model. The nonlinear equilibrium equations were derived from the total Lagrangian form of the virtual work principle: the linearized equations were then obtained. By solving these linearized equations, an analytical expression of the critical buckling load was obtained. This critical buckling load was investigated through several load cases with several boundary conditions. The discrepancy due to the orthotropic character between the present model and the isotropic models found in the literature was evaluated, as well as the influence of the inflation pressure and the fabric mechanical properties on the value of critical load. The buckling mode shapes were also determined. To check the limit of validity of the results, the wrinkling load was also presented in every case.

Jia-Hui Zhang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong), “Compression tests of cold-formed steel I-shaped open sections with edge and web stiffeners”, Thin-Walled Structures, Vol. 52, pp 1-11, March 2012, DOI: 10.1016/j.tws.2011.11.006

ABSTRACT: A series of column tests on cold-formed steel I-shaped open sections with edge and web stiffeners has been conducted. The test specimens were firstly brake-pressed from high strength zinc-coated steel sheets and then two of the same members were connected back-to-back by self-tapping screws to form an I-shaped section with edge and web stiffeners. The members had the nominal thicknesses of 0.48, 1.0 and 1.2 mm. The column length of the test specimens varied from 300 to 3200 mm with an increment of approximately 600 mm. The column specimens were compressed between fixed ends. Tensile coupon tests were also conducted to obtain the material properties at both flat and corner portions of the sections. Initial local and overall geometric imperfections were measured. The columns were failed by local, distortional, flexural buckling and the interaction of these buckling modes. The failure modes and ultimate strengths of the column specimens were presented. The direct strength method in the North American Specification and the Australian/New Zealand Standard was used to calculate the design strengths of the I-shaped open section columns. The appropriateness of the direct strength method for I-shaped open sections with edge and web stiffeners was evaluated. In addition, the reliability of the direct strength method for the I-shaped open sections was evaluated using reliability analysis. It is shown that the direct strength method can be used for cold-formed steel I-shaped open sections with edge and web stiffeners.

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ABSTRACT: A welded built-up square tube is made by flare welding 4 thin steel plates, which are bent to form L-shape. When it is used for a CFST column, the ribs placed at the center of concrete and steel tube width prevent local buckling and the tube confines concrete to improve its structural load capacity. In this study to introduce how to build welded built-up square columns and to evaluate the structural capacities of welded built-
up square steel tubes and CFST columns, 15 full-size specimens were fabricated for structural test with various types of steel tubes (welded built-up square tube and generic steel tube), width–thickness ratio ($B/t=50$, 58 and 67) and concrete strength ($f_c=10$ MPa and 40 MPa) to verify sectional efficiency and structural superiority inherent in welded built-up square columns.


ABSTRACT: The behaviour of thin steel plates fall into three general classes, unstiffened (no edge-stiffener), stiffened (adequate sized edge-stiffener) and partially stiffened (inadequate sized edge-stiffener). When used in cold-formed steel sections they may elastically buckle when subjected to either uniform compression or stress gradient. There are thus six possible combinations of element class and loading condition. All except the class of partially stiffened elements under stress gradient has been investigated experimentally, and design equations developed. This paper presents experiments of edge-stiffened plates under stress gradient, where the edge-stiffener size was increased from zero to a size sufficient to create a stiffened element. Edge-stiffener types investigated are simple lips and complex lips. Design solutions for partially stiffened elements under stress gradient using the effective width concept are presented. A generalised effective width design model is developed to account for all classes of elements under any loading condition.

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ABSTRACT: Tubular structures play an important role in energy absorbing components and structural members requiring high strength-to-weight ratio. The theory of buckling of circular, square and rectangular tubes is relatively well established in the literature. The study of buckling of triangular tubes, however, has received much less attention. In this paper, an analytical solution for the elastic buckling of isosceles triangular tubes was obtained by considering the buckling characteristics of individual walls of the triangular tube with appropriate edge conditions. The results from this analytical solution were compared with previously published work in the literature and finite element simulations. The comparison revealed good agreement between these results.


ABSTRACT: This paper discusses the nonlinear analysis of normal and high strength cellular steel beams under combined buckling modes. A nonlinear 3-D finite element model has been developed, which accounted for the initial geometric imperfection, residual stresses and material nonlinearities of flange and web portions of cellular steel beams. The nonlinear finite element model was verified against tests on cellular steel beams having different lengths, different cross-sections, different loading conditions and different failure modes. Failure loads, load–mid-span deflection relationships and failure modes of cellular steel beams were predicted
from the finite element analysis. An extensive parametric study involving one hundred and twenty cellular steel beams was performed using the verified finite element model to study the effects of the change in cross-section geometries, beam length and steel strength on the strength and buckling behaviour of cellular steel beams. The results of the parametric study has shown that cellular steel beams failing due to combined web distortional and web-post buckling modes exhibited a considerable decrease in the failure loads. It is also shown that the use of high strength steel offers a considerable increase in the failure loads of less slender cellular steel beams. The failure loads predicted from the finite element model were compared with that predicted from Australian Standards for steel beams under lateral torsional buckling. It is shown that the Specification predictions are generally conservative for normal strength cellular steel beams failing by lateral torsional buckling, unconservative for cellular steel beams failing by combined web distortional and web-post buckling and quite conservative for high strength cellular steel beams failing by lateral torsional buckling.


ABSTRACT: This paper reports the results of a numerical investigation aimed at providing fresh insight on the mechanics underlying the buckling and (mostly) post-buckling behaviour of short-to-intermediate equal-leg thin-walled angle steel columns exhibiting fixed and pinned (but with the secondary warping prevented) end supports. Although most of the numerical results presented and discussed were obtained through Abaqus shell finite element analyses, the paper also includes some GBT-based critical stresses and buckling mode shapes, whose interpretation help clarify the distinction between local and global buckling. The shell finite element results displayed consist of (i) elastic post-buckling equilibrium paths and (ii) curves and diagrams providing the evolution, along a given path, of the column deformed configurations and normal stress distributions.

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ABSTRACT: This paper presents computational modeling and results of steel storage tanks under heat induced by an adjacent fire. In this research, modeling is restricted to the structural behavior of the tank, with emphasis on thermal buckling of the shell. Two tanks that buckled under a huge fire in Bayamón, Puerto Rico in 2009, are investigated in detail: a small tank with a self-supported conical roof, and a large tank in which the conical roof is supported by a set of rafters and columns. For a tank that is empty, the results show that a relatively low temperature is enough to produce static buckling of the shell. In pre-buckling states, the cylindrical shell has thermal expansion; at the critical state the displacements reverse and inwards displacements are observed at advanced post-buckling states. Parametric studies are performed to understand the influence of the shell thickness, the level of fluid stored in the tank, the area affected by fire in the circumferential direction, and the temperature gradient through the thickness. The buckling modes are compared with real deflection of tanks that were affected by fire.
ABSTRACT: This work presents a consistent geometrically exact finite element formulation of the thin-walled anisotropic beam theory. The present formulation is thought to address problems of composite beams with nonlinear behavior. The constitutive formulation is based on the relations of composite laminates and thus the cross sectional stiffness matrix is obtained analytically. The variational formulation is written in terms of generalized strains, which are parametrized with the director field and its derivatives. The generalized strains and generalized beam forces are obtained by introducing a transformation that maps generalized components into physical components. A consistent tangent stiffness matrix is obtained by parametrizing the finite rotations with the total rotation vector; its derivation is greatly simplified by obtaining the derivatives of the director field via interpolation of nodal triads. Several numerical examples are presented to show the accuracy of the formulation and also its frame invariance and path independence.

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ABSTRACT: In the paper an alternative for horizontal cylindrical tank is presented. The proposed solution has the form of a barrelled tank in which the classical cylindrical shell is replaced by the barrelled one. The geometry of this shape is described. The buckling behaviour of the horizontal barrelled shell filled with liquid is analysed. The liquid level and the negative internal pressure which appear during emptying of the tank are also taken into consideration. On the basis of numerical analyses number of plots as well as analytical formulae are elaborated as a tool for design of barrelled tank with respect of stability criterion. Analyses are made on three families of barrelled shells of different capacities. In each family the capacity and length are constant. Advantages of barrelled tanks in comparison with cylindrical one are discussed.

ABSTRACT: This work deals with the buckling behavior of large scale oil tanks with a conical roof subjected to harmonic settlement. Firstly, the buckling behavior and the critical harmonic settlement of the tank with the conical roof for different wave numbers are analyzed. The results show that buckling occurs on the roof when the wave number is small, while it changes to the shell when the wave number is large. Also, for the original tank, the critical harmonic settlement decreases greatly for a small wave number, while the critical harmonic settlement decreases slightly for large wave numbers. Then, the parametric studies are conducted including the height-to-radius ratio, the radius-to-thickness ratio, the slope and the thickness of the conical roof. For the height-to-radius ratio, when the wave number is small, the critical harmonic settlement depends not only on the h/r ratio but also on the wave number. However, when the wave number is large, the critical harmonic settlement versus h/r ratio is monotonically increasing. For the radius-to-thickness ratio, for a small wave number, the critical harmonic settlement is not only related to the r/t ratio, but to the wave number as well.
However, for large wave numbers, the critical harmonic settlement versus $r/t$ ratio is monotonically decreasing. For the slope of the conical roof, when the wave number is small, in general, the critical harmonic settlement increases with the slope. However, when the wave number is large, the critical harmonic settlement is almost independent on the slope. For the thickness of the conical roof, for a small wave number, the critical harmonic settlement increases with the thickness of the conical roof. However, for large wave numbers, the critical harmonic settlement is almost independent on the thickness of the conical roof.


ABSTRACT: Dynamic pulse buckling of a single curvature composite shell under external pressure was examined using Lagrange's equation of motion and the Budiansky–Roth criterion. The predicted transient shell response compared very well with results from ABAQUS Implicit, and the predicted buckling loads also agreed with experiments on steel arches. Load duration determined whether the buckling was impulsive, dynamic or quasi-dynamic. Thicker composite shells were more likely to fail by first-ply failure rather than buckling. It was shown that the composite lay-up could be adjusted to increase the buckling resistance of the shell.

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ABSTRACT: Critical elastic buckling load of uniformly compressed isotropic plates perforated in equilateral triangular patterns was investigated using FEM. Stiffened and unstiffened square and rectangular elements with wide ranges of hole diameter-to-spacing ratio and plate slenderness were studied. The effect of perforations on the critical elastic buckling load was determined. Design formulas for predicting critical elastic buckling stress based on reduction coefficient approach and equivalent thickness approach were developed using multiple nonlinear regression analysis of FEM results. The obtained critical elastic buckling stress reductions and developed formulas were verified by comparison with results available in literature and with an extensive database of FEM results.


ABSTRACT: In this paper, finite element (FE) studies for LDSS (Lean Duplex Stainless Steel) hollow columns with square, L-, T-, and +-shaped cross sections (i.e., SHC, LHC, THC and +HC respectively) are presented using ABAQUS, to gain an understanding of the cross sectional shape effects. The LDSS hollow columns having equal material cross-sectional areas with thickness varying from 5 m to 20 mm were subjected to uniform axial compression. Short/Stocky columns with lengths ($\sim$1800 mm) of about three times the outer width of square were considered for the analyses. Based on the analyses, it has been found that for all the NRHCs (i.e., LHC, THC and +HC) considered, a nearly linear variation of $P_u$ with section thicknesses has been
observed, although the increase for SHC was relatively slower in thinner sections ($t<12.5$ mm). The % increase in $P_u$ with 300% increase in $t$ (from 5 m to 20 mm) has been found to be $\sim 1273\%$, $1252\%$, $1041\%$ and $679\%$, respectively, for square, L-, T-, and +-shaped sections. The gain in $P_u$ for LHC, THC and +HC sections as compared (expressed as $P_u/P_{u_{sq}}$) to SHC are in the range $120\%–150\%$, $130\%–170\%$, $140\%–230\%$, respectively. Ductility at ultimate load has been observed to be $\sim 0.1–0.6\%$ for SHC, LHC and THC (all thicknesses), and +HC ($t\leq10$ mm).


ABSTRACT: This paper presents an assessment of the influence of structural imperfections, namely, the residual stresses, on the ultimate load capacity of steel plate girders when subjected to patch loading. The basis of the research is a thorough comparison between numerical and experimental results as well as the recommendations for FE-modeling suggested by EN1993-1-5 (Annex C). A systematic exploit of a properly validated numerical model has been used in this study. Several residual stress patterns found in the literature have been implemented in numerical simulations of four different tests on girders subjected to patch loading. On such a basis, an appraisal of the influence of the structural imperfections on the ultimate load capacity of girders subjected to patch loading is presented.


ABSTRACT: Nonlinear free vibration analysis of prestressed circular cylindrical shells placed on Winkler/Pasternak foundation is investigated in the present paper. The nonlinearity is considered due to large deflections. Simultaneous effects of prestressed condition and elastic foundation on natural frequencies of the shells under various boundary conditions are examined extensively in this study. The nonlinear Sanders–Koiter shell theory is employed in order to derive strain–displacement relationships. The nonlinear classical Love's thin shell theory is also applied in some specific cases due to contrast the results. Beam modal functions are used to approximate spatial displacement field. The governing equations in linear state are solved by the Rayleigh–Ritz procedure. Perturbation methods are used to find the relationship between vibration amplitude and frequency in nonlinear state. Prestress state includes the effects of internal hydrostatic pressure and initial uniaxial tension. Results are compared with published theoretical and experimental data for some specific cases.


ABSTRACT: An approximate and simple method for rectangular orthotropic plates, loaded biaxially along two mutually perpendicular directions is presented. The theory is based on the energy method and it is free from difficult calculations such as those encountered when large deflection theory is used. Effects of initial imperfections are taken into account. The number and lengths of half-waves are assumed to be the same in the
post-buckling stage as at incipient buckling. The finite buckled shape in the post-buckling stage is taken to be the same as that during incipient buckling. The Von Mises yield criterion is employed to determine the upper bound solution of the plate. Interaction curves for square plates subjected to longitudinal and transverse stresses, applicable to three different boundary conditions, four edges simply supported or four edges clamped or two opposite edges clamped with the other two edges simply supported, are presented in a non-dimensional form. Results for plates having different values of plate slenderness \((b/t)\) and flexural rigidity ratios, \(D_2/D_1\), are given.

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ABSTRACT: Using the conventional cold-formed shapes in built-up assemblies (composed members, trusses, etc.) has allowed designers of light-steel framing to widen the applications of cold-formed steel (CFS) to structures of larger scale. Built-up elements, fastened by bolts, screws or welds are usually symmetrical, more stable and of higher capacity. However, they are not addressed in the various design codes for CFS structures. Additional flexibility is caused by slippage between the constituents of a composed member, especially if bolts are used as interconnectors and hole clearances are provided to ensure the ease of assembly. The paper presents experimental studies on the behaviour of double-Z built-up members (bolted). First, twelve members are tested in weak-axis bending, to evaluate the stiffness of the member for the axis of symmetry. Second, the overall behaviour is analysed in eight compression tests on slender members. The goal is to determine the actual failure mode and overall buckling capacity of these members.

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ABSTRACT: This paper presents experiments and theoretical analysis of 16 steel I-section beams strengthened using externally bonded CFRP under quasi-static large deformation 3-point bending. The main parameters examined in this paper were the section and member slenderness and the location of the CFRP plates. The member slenderness examined in this paper was in the range of \(L_e/r_p=40–92\). The section slenderness examined in this paper was in the range of \(b/t_f=6.25–16.67\). The CFRP plates were added either to the tension flange or both compression and tension flanges or even to the whole section including the web. An expression for the yield and plastic moments of the composite section were obtained by means of an equivalent thickness approach for the web and flange. The newly obtained strength results were compared against the present design rules in steel specifications. The CFRP increased the strength by up to 32% for compression and tension flange strengthening whereas the strength increased only by 15% for tension flange strengthening. The per cent increase in strength for short specimens was mostly affected by the section slenderness where the maximum gain was obtained for the semi-compact section. Plastic mechanism analysis was performed to predict the collapse curves. Good agreement was found between the theoretical and experimental post buckling load–deflection curves.
Shahin Nayyeri Amiri and Hayder A. Rasheed (Department of Civil Engineering, Kansas State University, Manhattan, KS 66506, USA), “Plastic buckling of thin hemispherical shell subjected to concentrated load at the apex”, Thin-Walled Structures Volume 53, April 2012, Pages 72–82, DOI: 10.1016/j.tws.2011.11.009

ABSTRACT: This study presents the analytical, numerical, and experimental results of thin hemispherical metal shells into the plastic buckling range illustrating the importance of geometry changes on the buckling load. The hemispherical shell is rigidly supported around the base circumference against horizontal and vertical translation and the load is vertically applied by a rigid cylindrical boss at the apex. Kinematics stages of initial buckling and subsequent propagation of plastic deformation for rigid-perfectly plastic shells are formulated on the basis of Drucker–Shield’s limited interaction yield condition. The effect of the radius of the boss, used to apply the loading, on the initial and subsequent collapse load is studied. In the numerical model, the material is assumed to be isotropic and linear elastic perfectly plastic without strain hardening obeying the Tresca or Von Mises yield criterion. Both axisymmetric and 3D models are implemented in the numerical work to verify the presence of non-symmetric deformation modes in the case of thin shells. In the end, the results of the analytical solution are compared and verified with the numerical results using ABAQUS software and experimental findings. Good agreement is observed between the load–deflection curves obtained using three different approaches. A secondary bifurcation point is detected in thin shells in which the deformation degenerates from symmetric to non-symmetric behavior. The bifurcation point depends on the (R/t0) ratio and the material parameters.

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ABSTRACT: This paper examined the potential of the lightweight bamboo–steel composite slab as a structural member. Six slab specimens were tested to study the flexural behavior of the composite slabs, which were composed of cold-formed thin-walled steel channel and bamboo plywood sheathings. Three types of connections to fabricate the composite slabs were investigated, which are simple adhesive connection, self-tapping screw enhanced connection, and stability improved connection with bamboo laths glued on the both sides of cold-formed steel channel. Results indicated that the specimens fabricated using the stability improved connection showed a remarkable increase in stiffness, capacity and stability, compared with the other two connections. The bamboo–steel composite slabs have the potential to replace concrete or wood slabs in low buildings.


ABSTRACT: High strength concrete filled steel tube (HSCFT) members have found wide applications. However, there are few reports on the test and model of their creep. This paper investigates the creep of axially loaded HSCFT columns by testing eight specimens for 380 day. A creep model, considering the state of triaxial stress and autogenous shrinkage of the high strength concrete core, has been proposed and validated against the test data. Parametric analysis demonstrates that there exists an obvious difference in the creep between HSCFT
columns and normal strength concrete filled steel tube columns, additionally, concrete composition influences the creep of HSCFT columns considerably.

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“Steel square hollow sections subjected to transverse blast loads”, Thin-Walled Structures, Vol. 53, pp 109-122, April 2012, DOI: 10.1016/j.tws.2012.01.007

ABSTRACT: Thin-walled steel hollow sections are used extensively in the construction, offshore, mining and security industries. Such members subjected to blast loads are of interest due to increased security demands and the occurrence of accidental or intentional explosive events. This paper reports an experimental and analytical investigation of steel square hollow sections subjected to transverse blast load, applied with explosive uniformly distributed along the length of the member. Three different section sizes were tested over three different lengths, and the members were fully clamped at their ends. The explosive loads were sufficient in magnitude to cause plastic deformation of the cross-section (local deformation), plastic flexural deformation of the overall member (global deformation), and tensile tearing at the supports. The energy dissipated in the local deformation is determined using rigid-plastic analysis and yield line mechanisms of the deformed cross-sections. The total input energy minus the energy dissipated in local deformation is assumed to be expended in flexural deformation. Analytical solutions using the energy consumed in flexural deformation are shown to produce bounded solutions of the transverse plastic deformation of the members. Finally, a semi-empirical solution is suggested that can be used to aid in design.

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“A design rule for web crippling of cold-formed steel lipped channel beams based on nonlinear FEA”, Thin-Walled Structures, Vol. 53, pp 123-130, April 2012, DOI: 10.1016/j.tws.2012.01.003

ABSTRACT: This paper presents the details of a research study conducted with the aim of developing an alternative design rule to predict the web crippling strength of cold-formed steel lipped channel beams. Current empirical web crippling design rules are perceived to be only accurate for the type of sections and the section dimensions that have been tested. A large number of experiments are often necessary to validate these design rules for a wider range of section types and dimensions, and these experiments are often expensive and impractical. Hence, a design rule which is based on a theoretical or numerical model has been attempted through this work. Four series of tests, replicating the four web crippling loading conditions namely: Interior-One-Flange (IOF), Interior-Two-Flange (ITF), End-One-Flange (EOF) and End-Two-Flange (ETF), were performed to predict the ultimate strength of one hundred and eight specimens. The test specimens were manufactured to include three distinct corner radii and two different web heights, and the specimens were tested using three different lengths of load bearing plates. Two additional loading scenarios which could arise due to the loading flange restraint namely—fixed-flange and free-flange were also examined. Finite element models were developed to numerically simulate the tests performed in the experimental investigations. Load-deformation curves were obtained from both the tests and FE models, and the FE models were validated using
the test results. The validation showed a close agreement of FE results with the test results which provided the confidence of using the FE model for a parametric study beyond the limits of the experiments. Based on the results of the parametric study, a design rule was developed which is much more flexible to adapt for new types of sections and ranges of dimensions.

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ABSTRACT: This paper presents experimental tests conducted to investigate the local buckling behavior of thin-walled tubular polygon steel columns. The experimental program consists of six stub columns with three different cross-sections, octagonal (eight-sided), dodecagonal (twelve-sided) and hexdecagonal (sixteen-sided), tested under concentric compression. For each cross-section, two values of the plate slenderness ratio (plate width-to-thickness ratio) are considered. Accurate measurements of geometrical imperfections are taken prior to the test. The experimental results show that the local buckling mode of failure depends on the type of the cross-section. Moreover, the plate slenderness ratio is the main factor controlling the local buckling capacity. Design equations provided in the ASCE 48-05, the EC3 and Migita and Fukumoto to predict the local buckling capacity of tubular polygons are evaluated against experimental results of 22 polygons tested under concentric compression available in the literature. Based on drawbacks observed in the design equations, the Loov’s equation developed on basis of the ultimate stress concept is adjusted with new fitting parameters to fit for tubular polygon columns. The accuracy of the new equation is evaluated through a comparison with the experimental results.

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ABSTRACT: This paper studies the behavior of very slender thin-walled concrete filled steel tubular (CFST) columns under axial compression. A finite element analysis (FEA) was developed to carry out the behavior of compressive columns. Initial out-of-straightness imperfection was discussed. Generally good agreement was obtained between the predicted and measured results. The FEA model was then used to perform mechanism analysis on very slender circular CFST columns. Parametric studies were carried out and the ultimate strengths from tested results and design codes were compared and discussed. The reliability analysis method was used to calibrate the existing design formulas given in DBJ/T13-51-2010, ANSI/AISC 360-05 and Eurocode 4.

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ABSTRACT: The crush behavior of polycrystalline metallic square tubes under quasi-static axial loading condition is investigated through a mesoscale crystal plasticity model embedded in an explicit finite element simulation code as a concurrent multiscale model. The boundary value problem is defined at the local continuum scale whereas the material behavior is modeled at the mesoscale through crystal plasticity defined in a representative volume element. The anisotropic behavior of the tubes emerges from the texture induced by the large plastic deformations created during the manufacturing process. In this work, this effect is modeled by considering the texture generated by deforming a single element model with an embedded polycrystalline aggregate of face center cubic (FCC) crystals under basic loading paths, including uniaxial tension, uniaxial compression, and simple shear. This initial texture is then used at each integration point in the explicit crush simulations of a square tube model made of an FCC aluminum alloy. As energy absorption is dominated by the plastic collapse mechanisms at the corner elements, the influence of the initial texture and its evolution during crush are found to be significant.

Ashkan Shahbazian and Yong Chang Wang (School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Pariser Building, Sackville Street, Manchester M13 9PL, United Kingdom), “Direct strength method for calculating distortional buckling capacity of cold-formed thin-walled steel columns with uniform and non-uniform elevated temperatures”, Thin-Walled Structures, Vol. 53, pp 188-199, April 2012 DOI: 10.1016/j.tws.2012.01.006

ABSTRACT: This paper assesses the applicability of the Direct Strength Method (DSM) to calculating the distortional buckling strength of cold-formed thin-walled (CF-TW) steel members with uniform and non-uniform elevated temperature distributions in the cross-section. The assessment was carried out by checking the DSM calculation results with numerical simulation results using the general finite element software ABAQUS which was further validated against ambient and uniform elevated temperature tests on short lipped channel sections, in addition to the author's previous validation studies for thin-walled steel columns with non-uniform temperature distributions. The validated numerical model has been used to generate an extensive database (453) of numerical results of load carrying capacity of CF-TW members with different uniform and non-uniform temperature distributions in the cross-sections, under different boundary and loading conditions and with different dimensions and lengths. It is concluded that the existing DSM distortional buckling curve for ambient temperature application is also applicable for columns with uniform temperature distributions in the cross-section, but is un-conservative for columns with non-uniform temperature distributions in the cross-section. This paper proposes a modification to the distortional buckling curve to enable DSM to deal with distortional buckling in columns with non-uniform temperature distributions.


ABSTRACT: An analytical investigation of the buckling/wrinkling behavior of GFRP webs in cell-core sandwiches subjected to combined in-plane shear and bending stresses is conducted. Web–core panels are modeled as long orthotropic plates stabilized by a relatively thick layer of elastic foam. The boundary condition
of the plate is defined according to the interaction between the webs and face sheets in the presence of the core material by applying a series of numerical analyses using the three-dimensional finite element modeling. Two approaches are adopted to predict the wrinkling behavior. The first is to predict the buckling/wrinkling of webs subjected to combined shear and bending loads using a mixed-mode interaction formula. In the second approach, the wrinkling behavior of web–core panels is treated as a biaxial compression–tension local buckling problem. The developed approaches are applied to predict the wrinkling loads of thin-walled webs in GFRP cell-core sandwich beams designed for the GFRP cell-core sandwich roof of the Novartis Campus Main Gate Building constructed in Switzerland.

Jianghong Xue (Department of Mechanics and Civil Engineering, Jinan University, Guangzhou, Guangdong 510632, China), “Local buckling in infinitely, long cylindrical shells subjected to uniform external pressure”, Thin-Walled Structures, Vol. 53, pp 211-216, April 2013, DOI: 10.1016/j.tws.2012.01.008
ABSTRACT: This paper presents a unique approach to analyze the buckling of an infinitely long cylindrical shell subjected to the external pressure. Buckling is considered to occur locally in the shell, spreading over a certain length along the longitudinal axis of the shell. A plausible function of the flexural displacement is created according to Timoshenko's ring solution of the transverse collapse mode. The governing equations based on Donnell–МУШТАРИ's shell theory are solved using Ritz method and the equilibrium conditions are educed. Numerical computations are performed for cases when shell thickness/radius ratios are 0.1, 0.05 and 0.03. In general, the pressure decreases sharply with a very slight increase of the normalized radial deflection just at the beginning of the initiation, then falls quite slowly till the two opposite points on the inner surface of the shell contact each other. It is found that the buckling pressure of the shell converges to the critical value given by Donnell–МУШТАРИ's shell theory and the span of the buckling mode in the longitudinal axis of the shell is independent of material properties. Solutions given in this paper can be used to address the problem of steady-state buckle propagation in the shells.

ABSTRACT: This paper proposes a new automotive box-beam crash absorber design with sinusoidal patterns embedded on the beam surfaces. Six different types of surface patterns were initially proposed and a total of 43 samples were simulated using the commercial pre-processor HyperCrash™ and the commercial explicit FEM solver RADIOSS™. The aim of the study is to improve energy absorption properties of the beams by controlling the wavelength of progressive buckle formations and obtaining denser collapse formations. It was found that the relief patterns could be used effectively to change the buckling modes and reduce the buckle wavelength. A maximum of 42 percent increase in the amount of total energy absorbed and an increase in the energy efficiency factor from 1.08 to 1.54 was observed moving from the reference model to the best design so far. This research may possibly pave new avenues in crash absorber design.

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ABSTRACT: This paper presents an improved finite element approach in which a node-based strain smoothing is merged into shear-locking-free triangular plate elements. The formulation uses only linear approximations and its implementation into finite element programs is quite simple and efficient. The method is then applied for static, free vibration and mechanical/thermal buckling problems of functionally graded material (FGM) plates. In the FGM plates, the material properties are assumed to vary across the thickness direction by a simple power rule of the volume fractions of the constituents. The behavior of FGM plates under mechanical and thermal loads is numerically analyzed in detail through a list of benchmark problems. The numerical results show high reliability and accuracy of the present method compared with other published solutions in the literature.

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ABSTRACT: This work deals with the structural behaviour and ultimate strength of fixed-ended cold-formed steel lipped channel columns experiencing local–distortional–global buckling mode interaction, due to the closeness between the critical buckling stresses associated with these three buckling mode types. After briefly addressing the column specimen geometry selection and showing a few numerical elastic post-buckling results, the paper reports the results of an experimental investigation involving a set of 12 columns with several cross-section dimensions and yield stresses, which is aimed at (i) providing experimental evidence of the occurrence of the triple mode interaction under consideration and (ii) quantifying its effect on the column deformed configuration evolution and failure load erosion (drop). Various aspects concerning the test set-up and procedure are described in some detail before presenting and discussing the obtained column experimental results, which basically consist of (i) measured cross-section dimensions, lengths and initial displacements (geometrical imperfections), (ii) stress–strain curves and yield stresses determined from tensile coupon tests, (iii) recorded non-linear equilibrium paths (applied load vs. various relevant displacements) and ultimate strength values, and (iv) observed deformed configurations and collapse mechanisms.

DOI: 10.1016/j.tws.2012.01.016

ABSTRACT: The SAFESA procedure is an idealisation error control process developed for linear static finite element (FE) analysis. This paper investigates the application of this process to non-linear problems. The post-buckled collapse of a stiffened panel in compression is used as the case study. The main part of the paper presents the critical analysis of important modelling assumptions, including the material model, boundary conditions and geometrical imperfections. Several potential error sources are identified and then investigated using the non-linear FE code ABAQUS. The outcome of the analysis is an improved FE model and a quantification of the idealisation error.
Farhad Khalili and Hossein Showkati (Civil Engineering Department, Urmia University, Urmia, Iran), “T-ring stiffened cone cylinder intersection under internal pressure”, Thin-Walled Structures, Vol. 54, pp 54-64, May 2012, DOI: 10.1016/j.tws.2012.01.015

ABSTRACT: Cone–cylinder junctions are vastly used in the industries such as oil refineries and aeronautics. They can be seen in pressure vessels and piping such as tanks' roofs and pipes' reducers. When cone–cylinder junctions are subjected to the internal pressure, compression stresses are established near the joining point of the cone to cylinder and make the junction susceptible to non-symmetric buckling failure or axisymmetric failure. As it is practical to increase the shell wall thickness locally near the point of intersection, sometimes it is more convenient to attach a ring-beam exactly to the point of intersection. Only limited work has been done on the T-ring stiffened cone–cylinder junctions under internal pressure. In this study, experimental behavior along with numerical analysis of T-ring stiffened cone–cylinder intersection under internal pressure has been dealt and experimental results such as buckling mode and load are presented here and compared with numerical results. It can be seen that by wise consideration and manipulated use of material properties and geometric imperfections in nonlinear analysis, buckling mode and load resulted from non-linear analysis are compatible with that of experimental results. Two classes of non-linear analyses have been carried out and compared with each other, then it was inferred that even though pattern of geometrical imperfection is effective in determination of buckling modes, but in these kinds of structures it is not necessarily used for the analysis of buckling loads. Finally experimental results were compared with design proposals. It is shown that these proposals can conservatively predict the failure loads.


ABSTRACT: Thin-walled tubes are a kind of popular design for the energy absorbing devices. However, when they are subjected to axial loading, there exists a large undesirable initial peak force, followed by fluctuation in the forcedisplacement curve. In this paper, the origami patterns are introduced to thin-walled tubes to minimize the initial peak and the subsequent fluctuations. Tubes of square, hexagonal and octagonal cross-sections with origami patterns are investigated by finite element analysis. Numerical results show that compared with the conventional tube, the patterned tubes exhibit a lower initial peak force and more uniform crushing load. The critical states are obtained under which the crushing mode follows the initial origami pattern. The parametric study shows the relationship between the pre-folding angle and the initial peak force as well as the mean crushing force for the tubes with different cross-sections. A prototype of the patterned tube is constructed and tested, showing much lower initial peak force and a smooth crushing process which agrees with the numerical results.

Yuner Huang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Material properties of cold-formed lean duplex stainless steel sections”, Thin-Walled Structures, Vol. 54, pp 72-81, May 2012, DOI: 10.1016/j.tws.2012.02.003

ABSTRACT: This paper presents the behaviour of cold-formed lean duplex stainless steel for six different sections, among which two are square hollow sections and four are rectangular hollow sections. The test specimens were cold-rolled from flat strips of lean duplex stainless steel. The material properties of high strength cold-formed lean duplex stainless steel square and rectangular hollow sections were determined. Tensile coupons in the flat portions and corners of each section were tested. Hence, the Young's moduli, 0.2% proof stresses, 1.0% proof stresses, tensile strengths, elongation at fracture and the Ramberg–Osgood parameter
of lean duplex material for each section were measured. The material properties of the complete cross-sections in the cold-worked state were also obtained from stub column tests. The initial local geometric imperfections of the six sections were measured, and the profiles of the local imperfections along cross-section were plotted for each section. Residual stresses were measured for section 150×50×2.5 using the method of sectioning. The membrane and bending residual stress distributions in the cross-section were obtained and plotted. Furthermore, finite element model of stub columns was developed and compared well with the test results. The stub column test strengths were also compared with the design strengths predicted by the American Specification, Australian/New Zealand Standard and European Code for stainless steel structures. Generally, the three specifications conservatively predicted the column strengths. The European Code provides the most conservative prediction.

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ABSTRACT: This paper describes the finite element method using ABAQUS to model the axial compressive behaviour of inclined, tapered and straight–tapered–straight (STS) concrete filled steel tubular stub (CFST) columns with square hollow sections. The accuracy of the numerical model was verified by comparing the numerical predictions with experimental study of the 200×200×3.75 RHS filled with C60 concrete with inclined angle of 0–9° and tapered angle of 0–4°. The results show that the compressive behaviours, load vs. strain relationship and failure mode predicted by the numerical simulations were agreeable with experimental results. After the validation, a parametric study was performed with 3 typical steel hollow sections (200×200×3.75 RHS, 300×300×6.3 RHS and 400×400×8.0 RHS) and extended the inclined angle and tapered angle to 0–15° and 0–12° respectively. The parametric study highlights some of the behaviour observed in test and extends the application range. In addition, reduction factor for calculating the axial capacity of this form of CFST columns are proposed.

Mohammad Reza Haidarali and David A. Nethercot (Civil and Environmental Engineering Department, Imperial College London SW7 2AZ, United Kingdom), “Local and distortional buckling of cold-formed steel beams with both edge and intermediate stiffeners in their compression flanges”, Thin-Walled Structures, Vol. 54, pp 106-112, May 2012, DOI: 10.1016/j.tws.2012.02.013
ABSTRACT: The true buckling behaviour of cold-formed steel beams with both edge and intermediate stiffeners in their compression flanges has been predicted with the aid of advanced numerical modelling. A series of nonlinear finite element analyses has been carried out to investigate the flexural behaviour of cold-formed Z sections with both edge and intermediate stiffeners in their flanges, when the failure is controlled by local and/or distortional buckling. The effect of the size and position of intermediate stiffeners as well as the effect of the edge stiffener/intermediate stiffener interaction on the buckling behaviour and ultimate strength of these sections has been studied. The knowledge gained from FE analyses was used to check the accuracy of the Eurocode design rules in predicting the ultimate strengths for these sections.
Young Bong Kwon and Gun Ho Seo (Department of Civil and Environmental Engineering, Yeungnam University, Gyongsan, Korea), “Prediction of the flexural strengths of welded H-sections with local buckling”, Thin-Walled Structures, Vol. 54, pp 126-139, May 2012, DOI: 10.1016/j.tws.2012.02.005

ABSTRACT: This paper describes the flexural strength of welded sections based on a series of flexural tests performed on H-sections fabricated from steel plates of thickness 6.0 mm with nominal yield stress of 315.0 MPa. Thin-walled flexural members undergo local, lateral-torsional or their interactive buckling according to the section geometries and lateral boundary conditions. Flexural members with the flanges or the web of large width-to-thickness ratios may undergo local buckling before lateral-torsional buckling and their interaction before the final collapse of the section. The local buckling has a negative effect on the flexural strength based on the lateral-torsional buckling. This phenomenon should be considered in the estimation of the nominal flexural strength of thin-walled flexural members. Welded H-section beams composed of the flanges and the web with various width-to-thickness ratios were tested to failure. The initial imperfections in local and lateral buckling mode, and residual stresses were included in the FE analyses. Simple design flexural strength formulas for the direct strength method (DSM) were proposed based on the test and FE results of welded sections to account for interaction between local and lateral-torsional buckling. The design strength curves were compared with the AISC specifications (2005), Eurocode3 (2003) and test results. The adequacy of the strength curve for the DSM was confirmed. A set of conclusions on the flexural strength and structural behavior of thin-walled welded H-sections was drawn from the experimental studies.


ABSTRACT: This paper presents an original method based on the Generalised Beam Theory (GBT) capable to decompose the elastic buckling modes from a shell finite element analysis (FEA) of an isotropic thin-walled member, into pure buckling modes of global, distorsional or local nature. The main novelty lies in using only the GBT cross-sectional deformation modes instead of member base mode shapes. The contribution of each pure buckling mode can be calculated, allowing a better understanding of the member post-buckling behaviour and strength reserve. Following the GBT classical assumptions, the membrane shear strains and transverse extensions are neglected. The modal participations obtained from FEA are in good agreement with the values calculated via classical GBT approach.


ABSTRACT: The objective of this work is to analyze the initial and post-collapse plate deflections based on measurement records of the experiments of three corroded box girders subjected to pure vertical bending loading inducing a compressive stress on deck. The effect of initial imperfections and corrosion degradation on the final post-collapse deformation shape has been investigated and a relationship between different loading responses, shape of initial imperfections and plate slenderness has been derived. Analyzing initial imperfections, plate slenderness and final post-collapse deformations, a slenderness criterion has been established to predict the post-collapse deformation shape.
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ABSTRACT: The effect of geometric imperfections on the buckling capacity of thin cylindrical shells subjected to uniform external pressure is investigated in this paper. Geometric surveys were conducted on small-scale thin cylinders in order to measure geometric imperfections of the shell surface. These imperfections were then modelled in the FE analysis and a geometrically nonlinear static analysis was carried out. The cylinders are tested to collapse in the laboratory and the results are compared to the results of the FE analysis. Both collapse pressure and postbuckling mode shape are accurately predicted by the FE analysis.

References listed at the end of the paper:
[22] Park T, Kyriakides S. On the collapse of dented cylinders under external pressure. International Journal of Mechanical Sciences
DOI: 10.1016/j.tws.2012.02.006

ABSTRACT: The ultimate strength of five narrow stiffened panels tested with two stiffeners under axial compression until collapse and beyond is determined by finite element analysis, and is compared with experimental results. Models with two half bays plus one full bays in the longitudinal direction are used in the finite element analysis. The material properties used in the finite element analysis have been evaluated by tensile tests. The initial geometrical imperfections also affect significantly the collapse behavior of the stiffened panels. Hence, the initial imperfections of the stiffened plates were measured before the experiment. The results of the FE analysis with measured and with equivalent initial imperfections are compared and conclusions are derived about the possible bias of the results when the initial imperfections are not measured.


ABSTRACT: To complement previous experimental studies on the performance of unprotected Elliptical Hollow Section (EHS) steel columns, under the hydrocarbon fire curve, a numerical analysis has been performed and outlined in this paper. A three-dimensional Finite Element Method (FEM) model has been developed and calibrated against 12 experiments, comprising of six unrestrained and six axially restrained EHS columns of two slenderness, $\lambda_z=40.1$ and $\lambda_z=50.8$. The EHS temperature profiles and axial displacements, measured under three different loading levels, ($\alpha_L=0.3, 0.45$ and 0.6) were utilised in the calibration process. The mechanical and thermal properties for carbon steel at elevated temperatures, detailed in the Eurocode standard EC3 Part 1–2, design of steel structures [1] have been applied. Axial displacement charts illustrate that a close agreement between the FEM model and the experiment results was achieved, while highlighting how critical the thermal expansion coefficient and geometric imperfection was during the calibration process. Ultimately, the paper will detail appropriate recommendations for the thermal analysis of unfilled Elliptical Hollow Section steel columns, of steel grade S355J2H, and provide the platform for comprehensive parametric fire investigations to commence.

ABSTRACT: Initial sizing procedures for aircraft stiffened panels that include the influence of welding fabrication residual process effects are missing. Herein, experimental and Finite Element analyses are coupled to generate knowledge to formulate an accurate and computationally efficient sizing procedure which will enable designers to routinely consider panel fabrication, via welding, accounting for the complex distortions and stresses induced by this manufacturing process. Validating experimental results demonstrate the need to consider welding induced material property degradation, residual stresses and distortions, as these can reduce static strength performance. However, results from fuselage and wing trade-studies, using the validated sizing procedure, establish that these potential reductions in strength performance may be overcome through local geometric tailoring during initial sizing, negating any weight penalty for the majority of design scenarios.


ABSTRACT: This paper presents a numerical and analytical study of the behavior of thin-walled plates connected by multiple bolts under shear. A validated finite element model has been used to perform a comprehensive set of parametric studies to investigate the effects of different design parameters on the connected plate behavior, including initial stiffness, ultimate resistance and maximum deformation at the ultimate resistance. The design parameters include edge and end distances, bolt spacing, number of bolts along and perpendicular to the loading direction and elongation limit of steel. It has been found that the existing methods for calculating the stiffness and ultimate resistance are directly applicable. The main focus of this paper is the maximum plate deformation at the ultimate plate resistance. Based on the parametric study results, it has been found that strain distributions around the bolt holes for different failure modes, as proposed by the authors for plate connected by a single bolt, are still applicable. However, it is necessary to modify the plate dimension ranges within which the different strain distributions apply to recognize the difference in failure modes for plates with different bolt arrangements.


ABSTRACT: In this paper global buckling (i.e., flexural, pure torsional, or flexural–torsional buckling) of thin-walled columns is discussed. The considered problem is the most basic one: the column is simply supported and subjected to a uniform concentric compressive force. The column's cross-section is an arbitrary open thin-walled cross-section. For the critical forces of this problem classical analytical solutions are known. In the presented research alternative formulae are derived on the basis of modeling the member as a set of flat plane elements (or strips). As it is found, the derivations can be carried out in various ways, among which eight
options are considered. The resulted critical force formulae are briefly discussed in this paper. Extensive numerical studies are also completed; these studies are summarized in a companion paper.

M.M. Alinia, Ghazaleh Soltanieh and Mozhdeh Amani (Department of Civil Engineering, Amirkabir University of Technology, 424 Hafez Avenue, Tehran 15875-4413, Iran), “Inelastic buckling behavior of stocky plates under interactive shear and in-plane bending”, Thin-Walled Structures, Vol. 55, pp 76-84, June 2012
DOI: 10.1016/j.tws.2012.03.007
ABSTRACT: Inelastic buckling and postbuckling behavior of stocky plates under combined shear and in-plane bending stresses are investigated and compared to slender plates. Aluminum and steel plates having various slenderness ratios are modeled and analyzed by means of (i) numerical nonlinear finite element method and (ii) theoretical p-Ritz energy method; and both results are compared to the classic interaction equation. It is observed that whereas in slender plates, elastic buckling occurs prior to the material's proportional limit load, stocky plates buckle in an inelastic way within the post-yield stage. In contrast to slender plates with considerable postbuckling reserves, the buckling of stocky plates is immediately followed by softening. In addition, it is shown that the classic interaction equation overestimates buckling loads; and therefore, a modified equation that can safely be applied to both stocky and slender plates is proposed.

Gongyao Gu, Yong Xia and Qing Zhou (State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China), “On the fracture possibility of thin-walled tubes under axial crushing”, Thin-Walled Structures, Vol. 55, pp 85-95, June 2012, DOI: 10.1016/j.tws.2012.03.005
ABSTRACT: Thin-walled tubes are widely used as energy absorption components in vehicle crashworthiness design where axial crushing is one of the most typical loading conditions. Lightweight materials such as high-strength steel, aluminum and magnesium have been applied for thin-walled tubes for weight reduction. Meanwhile, most of these lightweight materials are more brittle and easily fractured than traditional steel. Distribution and history of stress triaxiality and equivalent strain in the thin-walled tubes under axial crushing have been analyzed in this article with finite element simulation, as these two parameters of stress and strain states are commonly used for constructing fracture locus of materials. It is observed that both stress triaxiality and equivalent strain are transferring along the tube length like waves. Analysis results show that fracture is more likely to take place on the edge than the other positions of square thin-walled tubes. For identical axial crushing stroke, there is little difference of stress and strain states inside the square thin-walled tubes with initial impact velocity varying from 6 m/s to 24 m/s. Influence of geometrical parameters on the stress and strain states have also been analyzed, including the shape of cross-section corner, the wall thickness and the shape of cross-section, respectively. Analysis results in this article may offer references for design of thin-walled tubes and the necessary experimental characterization of mechanical properties for lightweight materials.

ABSTRACT: Small-deflection theory is used along with FE models to compute the equivalent elasticity parameters of sandwich structures. Eigenfrequency and eigenmode analyses, comparing the equivalent 2-D continua with full 3-D models, are utilized to determine how continuous connections and in-vacuo assumptions are influenced as real-world discontinuities and gas- or foam-filled cavities are included. It is found that discrete
connections between structural elements reduce stiffnesses and eigenfrequencies of the net structure substantially. The presence of gas or foam in the core cavities is observed to increase the overall damping of the dynamic panel response while also amplifying certain panel resonances.

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ABSTRACT: Concrete filled double skin steel tubular (CFDST) columns have some advantages when compared to conventional concrete filled steel tubular (CFST) columns, such as lighter self-weight and better cyclic performance. CFDST columns have the potential to be used in structures such as bridges, high-rise buildings, viaducts and electricity transmission towers. The inner and outer steel tubes will be subjected to preloads from upper structures and wet filled concrete. The initial stresses and extra deformations on steel tubes caused by these preloads would affect the capacity of the CFDST members. This paper thus discusses the behaviour of axially loaded CFDST columns with preload either on the outer tube alone or on both tubes. A general purpose finite element analysis (FEA) model is developed to predict the behaviour of CFDST columns with the steel tubes subjected to preload. The FEA model is verified using test results of CFDST columns without preload and those of CFST columns with preload. The influences of preload ratio, slenderness ratio, hollow ratio and material strength on axial strength are discussed. Finally, formulas are proposed for calculating the ultimate strength of CFDST columns with preload on steel tubes.

Amin Mohebkhah and Behrouz Chengeni (Structural Engineering Division, Faculty of Civil and Architectural Engineering, University of Malayer, Malayer, Iran), “Local-global interactive buckling of built-up I-beam sections”, Thin-Walled Structures, Vol. 56, pp 33-37, July 2012, DOI: 10.1016/j.tws.2012.03.018
ABSTRACT: According to the Specification for structural steel buildings (AISC-LRFD 360-10), the nominal flexural capacity of I-beam sections having compact webs and noncompact or slender flanges can be estimated as the lower value obtained for the limit states of lateral-torsional buckling (LTB) and compression flange local buckling (FLB). The main assumption behind the approach is that there is no interaction between LTB and FLB limit states and they can be considered as two independent phenomena. In this paper a three dimensional finite-element model using ABAQUS is developed for the inelastic nonlinear analysis of I-beams having noncompact or slender flanges. The model is used to investigate the applicability of the AISC-LRFD approach in estimating the moment capacity of locally buckled steel built-up I-beams with various flange slendernesses. It was found that as the distance between the global and local buckling capacities becomes larger, there would be an interaction between the FLB and LTB limit states; indicating a considerable post-local-buckling capacity for such cases.

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ABSTRACT: The results of 82 web crippling tests are presented, with 20 tests conducted on channel sections without web openings and 62 tests conducted on channel sections with web openings. The tests consider both end-two-flange and interior-two-flange loading conditions. In the case of the tests with web openings, the hole was located directly under the concentrated load. The concentrated load was applied through bearing plates; the effect of different bearing lengths is investigated. In addition, the cases of both flanges fastened and unfastened to the support is considered. A non-linear elasto-plastic finite element model is described, and the results compared against the laboratory test results; a good agreement was obtained in terms of both strength and failure modes.

ABSTRACT: An experimental study was undertaken to investigate the behaviour of 24 concrete-filled steel tube (CFST) columns, loaded concentrically in compression to failure. Variables in the tests include the length, diameter, strength of the steel tubes and the strength of the concrete. The large slenderness ratio caused all composite columns in Series 1 to fail by overall flexural buckling. Although overall flexural buckling was also experienced in the composite columns of Series 2 tests, the stockier columns failed by crushing of the concrete and yielding of the steel tube. A comparison of the experimental results with the loads predicted by the South African code (SANS 10162-1) and Eurocode 4 (EC4) shows that the codes are conservative by 8.4% and 13.6%, respectively, for Series 1 tests, and 10.5 and 20.2%, respectively, for Series 2 tests. A plot of the compressive load versus the vertical deflection shows the composite columns to be fairly ductile.

Jose Aguilera, Amr Shaat and Amir Fam (Department of Civil Engineering, Queen's University, Kingston, ON, Canada), “Strengthening T-joints of rectangular hollow steel sections against web buckling under brace axial compression using through-wall bolts”, Thin-Walled Structures, Vol. 56, pp 71-78, July 2012 DOI: 10.1016/j.tws.2012.03.013
ABSTRACT: The effectiveness of through-wall bolts is examined for strengthening T-joints of rectangular hollow steel sections. This is accomplished by controlling the web outward buckling of the chord under the brace axial load. The study examined the effect of the number and pattern of bolts, as well as the web height-to-wall thickness \((h/t)\) ratio of the chord, on strengthening effectiveness. Rectangular 203\(\times\)76\(\times\)(3.09, 4.5, and 5.92) mm chord members were tested. The number of 8 mm diameter steel bolts varied from a single bolt to 15 bolts of various distributions. Holes were first drilled in the vertical walls of the chord member, and then bolts were inserted through one wall and anchored at the other wall. The joint strength increased by 29% for chords with \((h/t)\) of 65. As \((h/t)\) ratio reduced to 45 and 35, the gains were only 6.2% and 3.1%, respectively. The number and distribution of bolts had little effect on their effectiveness.

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ABSTRACT: A parametric study of cold-formed steel sections with web openings subjected to web crippling was undertaken using finite element analysis, to investigate the effects of web holes and cross-section sizes on the web crippling strengths of channel sections subjected to web crippling under both interior-two-flange (ITF) and end-two-flange (ETF) loading conditions. In both loading conditions, the hole was centred beneath the bearing plate. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the flat depth of the web, and the ratio of the length of bearing plates to the flat depth of the web. In this paper, design recommendations in the form of web crippling strength reduction factors are proposed, that are conservative to both the experimental and finite element results.


ABSTRACT: In this paper, an extended numerical investigation is conducted to study the shear behavior of transversely stiffened hollow tubular flange plate girders (HTFPGs) using ABAQUS software. A comparison between the HTFPGs and plate girders with flat flange plates (IPGs) is first made considering the elastic-buckling and the post-buckling strength. The results indicated that the realistic support condition at the juncture of the web and flanges of HTFPGs is nearly fixed. The study is then extended to examine hybrid HTFPGs (HHTFPGs). The main goal of this extension was to examine the validity of the current EN 1993-1-5 provisions regarding both the shear resistance and the behavior trend of such hybrid girders. The validity of the other international design codes such as the AASHTO, AISC and BS 5950 were also checked. The results of the finite element (FE) models confirmed that using HHTFPGs provides economy as their strength could be utilised efficiently. In addition, it was found that the strengths obtained with EN 1993-1-5 provisions do reproduce suitably the trends obtained numerically, but their design equations were found to be extremely conservative. Moreover, the shear strength recently proposed for homogenous HTFPGs seemed to be slightly conservative for the case of HHTFPGs. Therefore, it was modified herein by taking the relative effect of the actual flange yield strength into account. This shear strength currently modified is found to represent the actual behavior of these girders better than the original and recently proposed EN 1993-1-5 shear strengths. Several remarks regarding the selection of optimum dimensions for the HTFPGs are also presented.

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ABSTRACT: This paper investigates the moment modification factors of an I-girder with trapezoidal web corrugations under moment gradient and various end restraint conditions. The moment modification factors are obtained by using the finite element method with beam elements and new general formulas of cross-section properties as well as a new warping constant of the I-girder with trapezoidal web corrugations. The theoretical results of moment modification factors are successfully verified by comparing them with the results from the commercial finite element software using shell elements. A series of finite element analyses with different
corrugation profiles and lengths are investigated. From the results, it is found that the present design of moment modification factor formulas cannot satisfactorily predict the buckling capacities of the I-girder with trapezoidal web corrugations under unequal end moments with various end restraint conditions. For the purpose of design, the closed-form expressions for the moment modification factors are proposed and successfully verified.

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ABSTRACT: The initial depression of shell skins is usually created through various panel processes such as rolling or welding. It is important to create some basic design regulations associated with the existing codes. A longitudinal imperfection caused by the continuous welding of a panel's edge to form a cone is the most important case in this context. The present paper discusses 14 laboratory specimens in 2 groups, labeled Shallow Conical Caps (SCC) and Deep Conical Caps (DCC), loaded under uniform hydrostatic pressure. The samples were modified to include either 1 or 2 line imperfections with amplitudes of 1t, 2t and 3t in depth (t the thickness of conical shell). The results presented here are in general agreement with international codes as well as theories concerning initial and overall buckling and collapse.


ABSTRACT: Energy absorption characteristics of regular polygonal columns and rhombic columns under quasi-static axial compression are investigated by using an INSTRON materials testing machine. The influence of central angle on deformation mode and mean crushing force of angle elements is studied. Numerical investigations are also carried out to study the crush resistance of polygonal columns and angle elements under quasi-static and dynamic axial compression. The numerical predicted crushing force and deformation mode of the polygonal columns are found to be in good agreement with the experimental results. In addition, based on the experiment observations, some discussion about the deformation mechanism of energy absorption is presented.

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ABSTRACT: Recently, tapered concrete-filled double skin steel tubular (CFDST) columns have been applied in electricity transmission towers in China. However, there is still lack of information on the behaviour of such kind of members. This paper thus carried out the investigation on axially loaded tapered CFDST stub columns. The parameters included the tapered angle and the sectional profile. A finite element analysis (FEA) model was developed to predict the behaviour of the tapered member as well. The results showed that the steel tubes and the sandwiched concrete could work together well despite the tapered angle. The failure mode of the tapered
CFDST stub column was similar to that of the straight one, and the failure occurred near the smallest section. The confinement effect of the tapered member was discussed by using the stress analysis. Finally, formulas were suggested for the calculation on the ultimate strength of the tapered CFDST stub column.

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ABSTRACT: Various types of composite members have been developed to utilize the combined advantages of existing reinforced concrete and steel structures, and to actively improve ductility and serviceability of structural members. One of them is the hybrid-type steel beam, in which the prestressing method is applied to a steel beam. Introducing prestress to the existing I-shaped steel beam, however, results in a very low prestress efficiency due to the large axial stiffness of the section. On the other hand, if corrugated webs are used, the prestress introduced to the main flexural-resistant elements—the upper and lower flanges—gets larger due to the accordion effect, so that it is very advantageous not only in terms of serviceability, but also of achieving the improved flexural strength. Most previous studies on steel members with corrugated webs, however, have focused on the shear buckling strength of the corrugated webs, and few studies have been conducted on the accordion effect of the corrugated webbed beam to which prestress is introduced. Therefore, this research proposed two rational and theoretical models to quantitatively estimate the accordion effect, which is induced by the introduction of prestress to corrugated webbed steel beams, and performed experiments on two steel beams with corrugated webs and one with typical wide flange section. The experimental results showed that the prestressing efficiency of steel beams with corrugated webs increased more significantly than that of the steel beam with a typical web, and it is verified that the proposed methods are very simple and provide good agreements with the experimental results.

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ABSTRACT: Thin cylindrical shells are the most prevalent and important structural component of vessels across the process industries. Such structures are prone to accidental buckling due to inadvertently induced vacuum. Minor deviations in the nominal geometry of the shell can affect the apparent initial buckling load. One common deviation is that the radius of the vessel is not constant but rather varies randomly with location on the shell. This paper presents extensive experimental data permitting a full statistical characterisation of defects of this nature. The data was obtained from detailed measurements of 39 replicate test vessels at the laboratory scale. Both amplitude and frequency content of this type of imperfection is quantified. Furthermore a methodology whereby the variation in radius is characterised as a two dimensional random field is outlined. An algorithm to generate realisations of this field is developed and the output is shown to be consistent with the measured results.

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ABSTRACT: Square concrete-filled steel tubes (CFSTs) are gaining increasing usage in modern construction practice, offering improved mechanical properties and increased material efficiency compared with the individual steel and core concrete components. However, the cross-section slenderness of the encasing steel is, although more inflexible than a comparable hollow steel tube, restrained due to local buckling. A number of innovative kinds of reinforcement stiffeners have been put forward particularly for the square CFSTs with slender sections of encasing steel. To investigate the mechanical effect of the reinforcement stiffeners and compare them with traditional ones in practice, four square CFSTs welded with various reinforcement stiffeners and one reference CFST have been tested, and are presented in this paper. The mechanical behaviors such as the resistance, ductility and failure modes investigated during the test were also studied in the theoretical research, which was carried out to predict and further summarize the comprehensive properties of the specimens. A numerical analysis program was written and verified with related scholars’ experimental data, and extensive parametric analysis was conducted to investigate the influencing parameters on mechanical properties. Design recommendation for the cross-section strength has been put forward based on the test results and previous research.


ABSTRACT: The structural behaviour of elliptical hollow sections has been examined in previous studies under several loading conditions, including pure compression, pure bending and combined uniaxial bending and compression. This paper examines the elastic buckling response of elliptical hollow sections under any linearly varying in-plane loading conditions, including the most general case of combined compression and biaxial bending. An analytical method to predict the elastic buckling stress has been derived and validated against finite element results. The predictive model first identifies the location of the initiation of local buckling based on the applied stress distribution and the section geometry. The critical radius of curvature corresponding to this point is then introduced into the classical formula for predicting the elastic local buckling stress of a circular shell. The obtained analytical results are compared with results generated by means of finite element analysis. The comparisons between the analytical and numerical predictions of elastic buckling stress reveal disparities of less than 2.5% for thin shells and, following an approximate allowance for the influence of shear, less than 7.5% for thick shells.

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ABSTRACT: The aim of the present paper is to investigate the effects of pitting corrosion on the ultimate capacity of mild steel rectangular plates under biaxial compression, extending earlier results of uniaxially loaded plates. A series of non-linear FEM analysis of plates with partial depth corrosion pits are carried out, changing geometrical attributes of both pits and plates, i.e., the radius, depth and location of pits and the slenderness of plates. Simulation results show that volume loss dominates the degradation of the compressive capacity of pitted mild steel plates as well as loading ratio. Plate slenderness has considerable effect on biaxial interaction curve shape. A regression analysis of FEM results is conducted leading to a closed form formula able to predict the remaining strength of pitting corroded plates, where both volume loss and plate slenderness are taken into account. The proposed formula will facilitate a quick estimation of the remaining strength of pitting corroded plates during lifetime ship design phase which is relevant to maintenance decision-making of aging ship structures and components.

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ABSTRACT: Aluminium tubular structural members may experience web crippling failure due to localise concentrated loads or reactions. This paper presents a test programme on strengthening of high strength aluminium tubular structural members using externally bonded carbon fibre-reinforced polymer (CFRP). A series of tests on CFRP strengthened aluminium square and rectangular hollow sections subjected to web crippling is presented. The web crippling tests were conducted under four loading conditions of End-Two-Flange, Interior-Two-Flange, End-One-Flange and Interior-One-Flange. A total of 48 web crippling tests was conducted in this study. The investigation was mainly focussed on the effects of web slenderness of aluminium tubular sections on CFRP strengthening against web crippling. The tests were performed on eight different sizes of square and rectangular hollow sections which covered a wide range of web slenderness (flat portion of web depth-to-thickness) ratio from 6.2 to 62.2. The test specimens were fabricated by extrusion from 6061-T6 heat-treated aluminium alloys. Material properties of the aluminium sections were obtained from tensile coupon tests. Most of the strengthened specimens were failed by debonding of CFRP plate from the aluminium tubes. Three main failure modes were observed in the tests, namely the adhesion, combination of adhesion and cohesion, and interlaminar failure of CFRP plate. The failure loads, failure modes and the load-web deformation behaviour of the aluminium sections are also presented. It was found that the web crippling capacity of aluminium sections are significantly increased due to CFRP strengthening, especially for those sections with large value of web slenderness ratio.

DOI: 10.1016/j.tws.2012.05.001

ABSTRACT: In this paper, strengthening effects of stiffeners on regular and arbitrarily stiffened plates are discussed in terms of the ultimate strength limit (USL) obtained through full nonlinear transient analysis. This study starts from the investigation of strengthening effects of regular stiffened plates which are subjected to uniaxial stress and then arbitrarily stiffened plates that are subjected to biaxial stress. The optimal height,
number, and arrangement of the stiffener that provide the best strengthening effect are revealed and it is also found that the strengthening effects of an arbitrarily oriented stiffener (or oblique stiffener) can be decoupled to two perpendicular regular stiffeners which are located in appropriate positions. Nonlinear buckling analyses were performed on the arbitrarily stiffened plates with one and two arbitrarily oriented stiffeners to verify this finding. The outcome of this paper can be further extended and applied to develop simplified semi-analytical models for buckling strength analysis of constructional plates.

A. Alavi Nia, Kh. Fallah Nejad, H. Badnava and H.R. Farhoudi (Mechanical Engineering Department, Bu-Ali Sina University, Hamedan, Iran), “Effects of buckling initiators on mechanical behavior of thin-walled square tubes subjected to oblique loading”, Thin-Walled Structures, Vol. 59, pp 87-96, October 2012
DOI: 10.1016/j.tws.2012.03.002
ABSTRACT: Thin-walled structures usually collapse in Eulerian buckling mode under oblique loads. Energy absorption capacity and crush force efficiency of the structure in this type of collapse are low. Collapse initiators are used to improve these properties. In this research, effect of collapse initiators on energy absorption characteristics of square tubes under oblique quasi-static loads is investigated both experimentally and numerically. Initiators are in the form of cuttings on the tube corners. Results show that collapse initiators in most of the specimens change deformation mode from general buckling to progressive buckling and decrease considerably the peak load; therefore increase crush force efficiency. Furthermore, effect of location and number of initiators is studied. There is good agreement between the numerical results and data from experiments.

C.G. Wang (1,2), Z.Y. Du (1,2) and H.F. Tan (1,2) (1) Center for Composite Materials, Harbin Institute of Technology, Harbin 150080, China (2) National Key Laboratory of Science and Technology on Advanced Composites in Special Environments, Harbin Institute of Technology, Harbin 150080, China “Initial wrinkling and its evolution of membrane inflated cone in bending”, Thin-Walled Structures, Vol. 59, pp 97-102, October 2012, DOI: 10.1016/j.tws.2012.05.007
ABSTRACT: The concept of the wrinkling factor is firstly presented to obtain the wrinkling condition. An extremum method is then proposed to predict the critical wrinkling load and the initial wrinkling location by searching the maximum of the wrinkling factor. Here the critical wrinkling load is defined as the ratio of the wrinkling moment versus the initial wrinkling location, which is different from previous definition. The nondimensional analyses show that the critical wrinkling load and the initial wrinkling location are both closely related to the taper ratio of the inflated cone. The critical taper ratio is 1.5 which corresponds to the highest load-carrying efficiency of the inflated cone in bending. The wrinkled region is finally predicted to deeply understand the wrinkling evolution in the bended membrane inflated cone. A series of wrinkling experiments on the inflated cone in bending are performed to verify the accuracy and the validation of the proposed method. The good agreements between the tests and the predictions give confidence to use the extremum method for wrinkling analysis of the inflated load-carrying structures.

Chang Qi, Shu Yang and Fangliang Dong, “Crushing analysis and multiobjective crashworthiness optimization of tapered square tubes under oblique impact loading”, Thin-Walled Structures, pp 103-119, October 2012
DOI: 10.1016/j.tws.2012.05.008
ABSTRACT: In this paper, a class of axisymmetric thin-walled square (ATS) tubes with two types of
geometries (straight and tapered) and two kinds of cross-sections (single-cell and multi-cell) are considered as energy absorbing components under oblique impact loading. The crash behavior of the four types of ATS tubes, namely single-cell straight (SCS), single-cell tapered (SCT), multi-cell straight (MCS) and multi-cell tapered (MCT), are first investigated by nonlinear finite element analysis through LS-DYNA. It is found that the MCT tube has the best crashworthiness performance under oblique impact regarding both specific energy absorption (SEA) and peak crushing force (PCF). Sampling designs of the MCT tube are created based on a four-level full factorial design of experiments (DoE) method. Parametric studies are performed using the DoE results to investigate the influences of the geometric parameters on the crash performance of such MCT tubes under oblique impact loading. In addition, multiobjective optimization design (MOD) of the MCT tube is performed by adopting multiobjective particle swarm optimization (MOPSO) algorithm to achieve maximum SEA capacity and minimum PCF with and without considering load angle uncertainty effect. During the MOD process, accurate surrogate models, more specifically, response surface (RS) models of SEA and PCF of the MCT tubes are established to reduce the computational cost of crash simulations by finite element method. It is found that the optimal designs of the MCT tubes are different under different load angles. It is also found that the weighting factors for different load angles are critical in the MOD of the MCT tubes with load angle uncertainty.


ABSTRACT: The post-buckling path for cylindrical shells under external pressure and twisting moment is unstable. The effect of stabilization in most cases is obtained by changing geometry of the structure. In this paper an alternative concept is applied, namely stabilization of the unstable post-buckling path is achieved by application of additional axial loads imposed to the ends of the structure without changing its shape and sizes. Three types of stabilizing forces were investigated: active forces applied to the structure or passive ones or combinations of both. Calculations were performed using ANSYS 11.0 code for elastic shells under different combinations of loadings.


ABSTRACT: Modern aircraft wings are thin-walled structures composed of ribs, spars and stiffened panels, where the top skin is subject to compressive forces in flight that can cause buckling instability. If these panels are machined from a single billet of metal then the initial buckling performance can be significantly improved by increasing the fillet radius along the line junction between the stiffener webs and skin. Typically thin-walled structures are usually modelled with two dimensional elements. To model the stiffened panel with fillets three dimensional elements are required. For the stiffened panel selected for the analysis the paper shows that the three dimensional model shows a substantial increase in skin initiated buckling if the fillet is taken account of. A 5 mm radius leads to an increase of 34% increase in local buckling load performance for a skin portion of breath to thickness ratio of 100. The associated overall buckling load increases by 1.8%. The mass penalty for a 5 mm radius is 5.1%. To avoid local and overall buckling interaction an accurate measure of both buckling loads is very important and may have impact for designers. The three dimensional models with no fillets show
very good agreement with the two dimensional models.

References listed at the end of the paper:


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ABSTRACT: For the cylindrical reticulated mega-structure, two types of cable-strut arrangements are presented. The basic static properties of the pretensioned reticulated mega-structures with different types of cable-strut arrangements are compared and the optimal one is then selected. The elastic static property and stability of the structure with the optimal cable-strut arrangement is comprehensively analyzed. And the indexes including the decrease in structural displacement, reduction in horizontal support reactions, uniformity of distribution of member forces, and the improvement of structural stability are compared with those of the corresponding non-pretensioned reticulated mega-structure. Also, the effect of values and distribution of the cable pretensions on structural stability is studied, and the influence of half-span loading on structural stability
is investigated. Results indicate that the static properties and stability of the structure can be most effectively improved for adoption of the crossover arrangement of the cables and struts according to the buckling shape of the non-pretensioned structure. Additionally, the ultimate load-carrying capacity of the structure with small ratio of rise to span can be more effectively improved when the pretension of the cables set in the mid-span is larger than that of the cables set on both sides of the structure.

M. Nithyadharan and V. Kalyanaraman (Department of Civil Engineering, IIT Madras, Chennai-600036, India), “Behaviour of cold-formed steel shear wall panels under monotonic and reversed cycled loading”, Thin-Walled Structures, Vol. 60, pp 12-23, November 2012, DOI: 10.1016/j.tws.2012.05.017

ABSTRACT: This paper presents the results of an experimental study on the behaviour and strength of the cold-formed steel shear wall panel (CFSSWP) with calcium silicate board as sheathing, when subjected to monotonically increasing and reversed cyclic in-plane shear deformation. These specimens were specifically designed to reach the strength as governed by the strength of the screw connection between the board and the CFS framing and avoid all other modes of failure, ahead of this. The main objectives of the experimental study are (a) to study the influence of board thicknesses and the distance of the screws from the nearest free edge of the board on the wall panel behaviour and strength; (b) to study the behaviour of different wall board configurations normally used in construction practice (c) to develop the values of the important parameters that determine the load-deformation behaviour of the wall panels under in-plane shear and (d) to determine the different limit states in the failure of the screws connecting the board and the CFS framing in such CFSSWP. In addition, a simplified design equation is proposed to evaluate the ultimate shear strength of CFSSWP based on the strength of the screw connection obtained from a sub assemblage shear strength test.

V. Jandaghi Shahi and J. Marzbanrad (School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran), “Analytical and experimental studies on quasi-static axial crush behavior of thin-walled tailor-made aluminum tubes”, Thin-Walled Structures, Vol. 60, pp 24-37, November 2012 DOI: 10.1016/j.tws.2012.05.015

ABSTRACT: In this paper, the crush behavior of segmented circular tubes, made of aluminum alloy 6061 and subjected to quasi-static axial loading, has been analytically and experimentally investigated. Crush behavior of these tubes was modeled by integrating available analytical models and superposition principle. In the certain overall length of segmented circular tubes, effects of changing the wall thickness and length of each segment on the energy absorption characteristics have been evaluated. One successful approach toward obtaining lightweight energy absorbers with high energy absorption capacity is the use of thin-walled Tailor-Made Tubes (TMTs). In these tubes, the thickness and mechanical properties of the wall vary along the length of the tube. Applying these tubes; crush force can be controlled by changing the length and thickness of each tube segment, improving the performance of energy absorbing systems. Results of this research showed that Tailor-made tubes have higher energy absorption capacity at identical crush lengths, and they can absorb more energy per unit weight compared to simple tubes with constant wall thickness and mechanical properties. Moreover, for the same specific energy absorption, the TMTs exhibit a considerable reduction in the magnitude of the mean and initial maximum crush forces. With the use of TMTs, the maximum crush force shifts to the end of the crush range, reducing the exerted deceleration on occupants and equipments. Comparing mean crush force and specific energy absorption obtained by analytical and experimental approaches, it was observed that combining current analytical models with superposition principle can prepare a set of analytical formulations to predict TMTs crush characteristics within an acceptable proximity.
DOI: 10.1016/j.tws.2012.07.015
ABSTRACT: This paper focuses on the buckling of cylindrical shells under axial compression with small arbitrary thickness variations in the axial direction. General asymptotic formula of the buckling load, which is in terms of the thickness variation parameter $\varepsilon$ up to arbitrary order, is first derived by the perturbation expansion. Then effects led by three patterns of thickness variations on the buckling of axially compressed cylindrical shells, which are axisymmetric modal, local and stepwise variable, are, respectively investigated. Buckling loads of thin shells with axisymmetric modal thickness variation obtained from general analyses coincide with the Koiter's results. Particularly, an analytical study on the buckling of cylindrical shells with stepwise variable thickness is carried out, because these thin-walled structures are widely used in actual engineering. In addition to the analytic investigation, numerical analyses and comparisons are also performed.

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ABSTRACT: The geometric non-linear analysis of imperfect composite laminates is presented based on the concept of the Semi-Energy finite strip method (FSM). The initial out-of-plane imperfection is assumed to be of the sinusoidal shape in the longitudinal direction, and of different shapes in the transverse direction. The validity and numerical efficiency of the developed semi-energy FSM is investigated by comparing the results with those obtained from a fairly conventional and well exploited finite strip technique, namely the Full-Energy FSM as well as the evaluated results from ANSYS.

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ABSTRACT: The use of the finite element method (FEM) for the design of composed, thin-walled, structural steel members is considered. The bolted double-Z frame member is an interesting and economical engineering solution, already used in practice [1]. However, the European recommendations for the design of steel structures do not consider built-up members from cold-formed steel profiles. Finite element analysis is used to capture the various buckling effects that shape the response of slender thin-walled members. From the finite element model, the importance of initial imperfections and stiffness of connections is identified. The experimentally validated model predictions show that a non-linear finite element analysis can predict the member behaviour, in terms of failure mode and ultimate load, yield line pattern, overall stiffness and local strain in the cold-formed profiles. To obtain a good prediction, overall and localised initial imperfections should be considered and included in the analysis.
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ABSTRACT: For the coupled static and dynamic buckling of thin walled beam subjected to various forces, such as axial force, uniform bending moment, and bending moment due to concentrated and distributed lateral forces, the spline finite element method is employed to obtain the dynamic stiffness matrix. Second order effects of the axial force and moment are considered. A doubly symmetric cantilever beam with uniform cross-section is investigated. Extensive static and dynamic interaction diagrams are plotted. The effects of warping rigidity, torsional rigidity, axial tension and compression on moment buckling, moment on axial buckling compression, higher buckling modes are discussed in detail. The spline finite element method is proved to be very efficient for the present problem and many interaction diagrams can be plotted easily. Some new results are presented. The methodology is based on finite element formulation and therefore it can be easily extended to analyze structural frames.

ABSTRACT: In case of hot-rolled or extruded profiles, the fillet corner shaping of the flange-to-web connection may highly increase the transverse load resistance. Real test illustrates the proneness of compact aluminium profiles to web crippling and the influence of the curved corner. Numerical model is developed and validated by the real test. Invoking non-linear numerical analysis, parametric study on simply supported girders subjected to interaction of transverse load and bending confirms the beneficial influence of the curved corners. Based on the results the author proposes a modification in the Eurocode formulation. The simulation results prove the validity of the proposed method.

Salvatore S. Ligaro and Riccardo Barsotti (Department of Civil Engineering, University of Pisa, Largo L. Lazzarino 1, 56126 Pisa, Italy), “Shear deformations in inflated cylindrical beams: An old model revisited”, Thin-Walled Structures, Vol. 60, pp 137-144, November 2012, DOI: 10.1016/j.tws.2012.07.004
ABSTRACT: The paper considers the effects of shear deformations on the load-displacement response of pressurized thin-walled circular-cylindrical beams subjected to lateral loads. A classical structural model, able to account for the inability of the wall's constituent material to withstand compressive stresses, is used to model the nonlinear behavior of partially wrinkled beams under simultaneous bending and shear. Particular attention is devoted to accurate determination of the shear stiffness within the wrinkled zones of the beam. The system of nonlinear equations governing the equilibrium of the inflated beams after the onset of the post-critical stage is amenable to numerical solution via standard incremental-iterative algorithms, as long as the wrinkling of the cross sections is small or moderate. Application of the proposed model to some well-documented problems drawn from the literature serves to illustrate the proposed algorithm's potential.
ABSTRACT: Recently worldwide cold formed steel buildings are recognized as viable alternatives to reinforced concrete buildings especially in seismic areas. This is because they are lightweight (easy to handle), fast constructed, energy efficient (green houses), economical, dimensionally stable and they do not need skilled worker. Under vertical loading the design principles of these buildings are well established and codified, however, under lateral loadings such as wind and earthquake loads efficiently design is needed. In this paper a new sheathing technique uses shotcreted ribbed steel sheets is proposed to improve the stability and increase the lateral load carrying capacities of the CFS walls in order to withstand earthquake and wind loads safely. The idea is to sheath the outer side of CFS structure external walls with thin ribbed steel sheets, then shotcreted the sheets with cement or gypsum mortars. To test the concept full size wall specimens were prepared in the laboratory and tested under monotonic vertical and lateral loads. Some of the specimens were sheathed with the traditional fiber cement boards or gypsum boards with mat reinforcement, while the others were sheathed with the proposed technique. Test results indicates that the lateral load carrying capacities of the walls sheathed with the proposed technique increases by about two times compared with the walls sheathed with traditional boards. And under ultimate loads they fail in local failure modes rather than overall buckling failure modes which commonly occur in the walls sheathed with traditional boards.


ABSTRACT: The current study assesses the enhancement in the buckling capacity of steel plates through bonding glass fibre reinforced polymer (GFRP) plates. Despite their low modulus of elasticity, GFRP plates are relatively thick and, therefore, can be efficient in magnifying the buckling capacity of the retrofitted steel plates. In this application, a heavy duty adhesive system that was tested in a previous experimental programme is employed to bond the steel and the GFRP plates. The current study is conducted numerically using a nonlinear shell element model to simulate the steel and GFRP plates and a special contact element to simulate the flexibility of the adhesive medium. The failure modes in the adhesive and the GFRP plates, based on real strength values, as well as the instability of the entire system are considered. A buckling magnification factor relating the capacity of the retrofitted system to the capacity of the corresponding bare steel plate is evaluated. The study considers two types of boundary conditions as well as two types of in-plane compatibility between the steel and GFRP plates. The effect of geometric imperfection is also studied. Both elastic and inelastic stability analyses are considered in this investigation.

Zhangming Wu, Paul M. Weaver, Gangadharan Raju and Byung Chul Kim, “Buckling analysis and optimisation of variable angle tow composite plates”, Thin-Walled Structures, Vol. 60, pp 163-172, November
ABSTRACT: Variable angle tow (VAT) placed composite laminates, where the fibre orientations continuously varying over the plane of each ply, generally exhibit variable stiffness properties. The stiffness tailoring of VAT plates through the design of fibre orientation distributions can substantially improve the buckling resistance, which is mainly due to the benign, non-uniform, in-plane load redistribution. In this work, a new mathematical definition is proposed to represent the general variation of fibre-orientation in the VAT plate. In this definition, the coefficients of polynomials are directly equal to the designed fibre angles at pre-selected control points. A Rayleigh-Ritz approach is used to determine the prebuckling loads distributions and critical buckling load of VAT plates. It provides a more efficient means to evaluate the buckling load of VAT laminates, compared with other numerical solutions. Subsequently, preliminary optimisation of VAT plates for maximum buckling load is done using the proposed definition of non-linear variation of fibre angles. Results obtained for simply supported square VAT plates are compared with optimal results reported in the literature. Finally, long VAT plates with one free edge and others simply supported are studied to demonstrate the viability of the proposed modelling strategy.

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ABSTRACT: This paper presents the optimisation of cold-formed steel open columns using the recently developed self-shape optimisation method that aims to discover new profile shapes. The strength of the cold-formed steel sections is calculated using the Direct Strength Method, and the rules developed in the present work to automatically determine the local and distortional elastic buckling stresses from the Finite Strip and constrained Finite Strip Methods are discussed. The rules are verified against conventional and optimum sections yielded in this research, and found to accurately predict the elastic buckling stresses. The optimisation method is applied to singly-symmetric (mono-symmetric) cold-formed steel columns, and the operators behind the method for the special case of singly-symmetric open profiles are introduced in this paper. “Optimum” cross-sections for simply supported columns, 1.2 mm thick, free to warp and subjected to a compressive axial load of 75 kN are presented for column lengths ranging from 1000 to 2500 mm. Results show that the optimum cross-sections are found in a relatively low number of generations, and typically shape to non-conventional “bean”, “oval” or rounded “Σ” sections. The algorithm optimises for distortional and global buckling, therefore likely subjecting the cross-sections to buckling interaction. A manual attempt to redraw the “optimum” cross-sections to include limitations of current manufacturing processes is made. Future developments of the method for practical applications are also discussed.

Mergen H. Ghayesh, Michael P. Paidoussis and Marco Amabili (Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada H3A 0C3), “Subcritical parametric response of an axially accelerating beam”, Thin-Walled Structures, Vol. 60, pp 185-193, November 2012
DOI: 10.1016/j.tws.2012.06.012

ABSTRACT: In this paper, the planar nonlinear dynamics of an axially accelerating beam in the subcritical speed regime is examined theoretically, via two different numerical techniques, employing a large enough number of modes in order to investigate modal interactions. The equation of motion is discretized via the Galerkin method which results in a set of coupled nonlinear ordinary differential equations (NODEs) with time-
dependent coefficients. The set of NODEs is solved by means of the pseudo-arclength continuation technique and some of the results are tested and verified via direct time integration of the NODEs. The analyses include the system tuned to a three-to-one internal resonance, as well as for the case where it is not. Results are illustrated through frequency–response diagrams, time traces, phase–plane portraits, and fast Fourier transforms (FFTs).

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ABSTRACT: For economical benefits, optimisation of mass-produced structural steel products has been widely researched. The objective is to minimise the quantity of material used without sacrificing the strength and practicality of the structural members. Current research focuses on optimising the main dimensions of conventional cross-sectional shapes but rarely considers discovering new optimum shapes. This paper introduces the concepts of a new optimisation method that enables the cross-section to self-shape to an optimum by using the evolution and adaptation benefits of Genetic Algorithm (GA). The feasibility and the accuracy of the method are verified by implementing it to optimise the section capacity of thin-walled profiles. Specifically, the profiles are optimised against simple parameters, for which analytical solutions are known, namely the optimisation of doubly-symmetric closed profiles. Results show that the cross-section accurately self-shapes to its optimum in a low number of generations. Factors influencing the convergence are presented in this paper. The method is extended to optimisation of cold-formed steel open section columns in the companion paper.

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DOI: 10.1016/j.tws.2012.06.016
ABSTRACT: In the present work buckling stresses of prismatic flat and stiffened shell structures are derived within the framework of the Kantorovich approach, making reference to both Von Karman and Koiter–Sanders theories, the latter exploiting the Green–Lagrange strain tensor which is needed if the expected buckling modes involve comparable in-plane and out-of-plane displacements. Additionally, in order to highlight the contribution of each nonlinear term of the Koiter–Sanders model, two further intermediate choices are also considered, namely an enhanced Von Karman model and a spurious model which collects selected terms from different theoretical approaches, generally adopted in literature with the aim of simplifying the numerical analyses. The obtained results show how in buckling problems where the weight of in-plane displacements cannot be neglected the Von Karman model tends to overestimate the critical load, while the three considered alternative models result substantially equivalent, at least from the practical standpoint.

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“Some thoughts on a surprising result concerning the lateral-torsional buckling of monosymmetric I-section beams”, Thin-Walled Structures, Vol. 60, pp 216-221, November 2012, DOI: 10.1016/j.tws.2012.06.015

ABSTRACT: This technical note addresses a surprising result concerning the lateral-torsional buckling of monosymmetric I-section beams: amongst all bending moment diagrams caused by any combination of applied end moments and transverse loads acting at the shear centre, the lowest critical moment does not necessarily correspond to uniform bending, which is at odds with the “intuitive expectation” of most engineers that such bending moment distribution is the most unfavourable with respect to lateral-torsional buckling. It is shown, by means of several illustrative examples, that this may not be the case for I-section beams with unequal flanges (monosymmetric cross-section – symmetry with respect to the minor axis). Moreover, the critical inspection of the terms (i) associated with the cross-section monosymmetry and (ii) appearing in the beam potential energy expression and differential equilibrium equation provides the mechanical/mathematical explanation for this surprising behavioural feature.

Feng Fan, Jiachuan Yan and Zhenggang Cao (School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China), “Elasto-plastic stability of single-layer reticulated domes with initial curvature of members”, Thin-Walled Structures, Vol. 60, pp 239-246, November 2012, DOI: 10.1016/j.tws.2012.01.012

ABSTRACT: Initial curvature of members is an inevitable geometrical imperfection for reticulated domes. To investigate the stability of single-layer domes with initial curvature of members, the multi-beam method was presented to simulate the initial curvature of members, and two modeling methods were adopted to introduce the initial curvature of members for reticulated domes by means of ANSYS. First, the random imperfection mode method was introduced according to the randomness of initial curvature of members. The example of a Kiewitt-8 dome was used to explain the method and investigate the influence of angle and amplitude random variables on the stability of reticulated domes. Second, the modified consistent imperfection mode method was obtained, which was an efficient method to evaluate the lowest buckling load of the structure with initial curvature of members. Based on this method, the Kiewitt-6 and Kiewitt-8 single-layer reticulated domes were taken as examples to analyze the stability of structures with initial curvature of members, and the influences of initial curvature of members on the ideal structure and the structure with nodes deviation were obtained quantitatively. The results show that, for the ideal structure and the structure with nodes deviation, initial curvature of members can decrease the buckling load of the structure obviously. Initial curvature of members can change the buckling mode and plasticity development of the structure. The influence of initial curvature of members on the elasto-plastic stability of single-layer reticulated domes cannot be neglected.

======== Begin list of papers in the Dec. 2012 special issue of Thin-Walled Structures =========

Dan Dubina and Viorel Ungureanu, “Recent research advances on thin-walled structures”, Special issue of the journal, Thin-Walled Structures, Vol. 61, pp 1-266, December 2012.

Papers included in this special issue:


ABSTRACT: This work aims at contributing towards understanding the structural response and predicting the ultimate strength of cold-formed steel lipped channel columns affected by local–distortional–global (LDG)
interaction. Initially, the most relevant aspects concerning the buckling and elastic–plastic post-buckling behaviours of fixed-ended lipped channel columns with nearly coincident local, distortional and global (flexural–torsional) buckling loads are briefly addressed. Then, the paper (i) summarises the most important test results obtained in a recently reported experimental investigation carried out at the Federal University of Rio de Janeiro, (ii) addresses their numerical simulation by means of Abaqus shell finite element analyses (SFEA) and (iii) presents the outcome of a fairly extensive numerical parametric study performed to obtain ultimate strength data concerning fixed-ended lipped channel columns experiencing LDG interaction. Finally, the ultimate strength “data bank” gathered, consisting of 12 experimental and 134 values, are used as the starting point to assess the performance (accuracy and safety) of design approaches, based on the currently available Direct Strength Method (DSM) strength curves and intended to estimate the failure loads of cold-formed steel lipped channel columns affected by the triple mode interaction under consideration.

J. Loughlan, N. Yidris, K. Jones, “The failure of thin-walled lipped channel compression members due to coupled local-distortional interactions and material yielding”, Thin-Walled Structures, Vol. 61, pp 14-21, DOI: 10.1016/j.tws.2012.03.025
ABSTRACT: This paper details appropriate finite element modelling strategies and procedures for the determination of the coupled local-distortional interactive response of thin-walled lipped channel sections. The modelling procedures are able to describe the complete loading history of the compression members from the onset of local buckling through post-local buckling behaviour leading to local-distortional interaction including material yielding and yield propagation to ultimate conditions and then to elasto-plastic unloading. The numerical simulations take due account of the influence of geometrical imperfections on the compressive ultimate failures of the sections and the results from the finite element models are shown to agree favourably with the ultimate loads and failure mechanisms from experimental tests on steel lipped channel sections exhibiting local-distortional interaction.

Cao Hung Pham, Gregory J. Hancock, “Elastic buckling of cold-formed channel sections in shear”, Thin-Walled Structures, Vol. 61, pp 22-26 DOI: 10.1016/j.tws.2012.05.004
ABSTRACT: The paper studies and provides solutions to the elastic buckling of whole channel sections including flanges and lips where the sections are loaded in pure shear parallel with the web. The elastic buckling analyses of thin-walled channel sections in pure shear have been implemented by means of the Spline Finite Strip Method (SFSM) to determine the elastic buckling loads (Vcr) of the sections. The shear buckling coefficients (kv) of the web for design of a section are back-calculated from the shear buckling loads. The main variables are the flange widths, member lengths and lip sizes. The boundary conditions at two end sections are simply supported. The results of the analyses plotted in the format of interaction charts are given as design guidelines for designers to predict the elastic buckling shear coefficient (kv) without using the Spline Finite Strip Method (SFSM) software. Typical buckling modes at different flange widths, member lengths and lip sizes are also included in this paper. The modes include local web and flange buckling, section distortional buckling and section twisting.

ABSTRACT: This paper presents and illustrates a GBT formulation to analyse the elastic localized web buckling of thin-walled steel beams under concentrated loads. The theme of localised web buckling is first introduced by describing the parameters that most influence the buckling behaviour of slender plates subjected to edge loads. After that, a GBT formulation to analyse the elastic localized web buckling of thin-walled steel beams under concentrated loads is presented: the GBT equations are derived and the determination of deformation modes is briefly addressed. Then, two illustrative examples are shown and validated by comparison with shell finite element results: (i) cold-formed steel plain channel beams with web crippling configurations and (ii) welded steel I-section beams with patch loading configurations. It is found that both pre-buckling longitudinal normal ($\sigma_{xx0}$) and shear ($\tau_{xs0}$) stresses have to be included in the buckling analyses of cold-formed steel beams with External One Flange (EOF) and Internal One Flange (IOF) configurations as well as welded steel beams with Patch Loading Test (PLT) configuration. Furthermore, the pre-buckling transverse normal ($\sigma_{ss0}$) stresses have to be included in the buckling analysis of cold-formed steel beams with External Two Flange (ETF) and Internal Two Flange (ITF) configurations as well as welded steel beams with Opposite Patch Loading Test (OPLT) configuration. In beams with EOF, IOF, PLT configurations, the GBT pre-buckling analysis should consider global and shear modes while the GBT buckling analysis may only consider local modes. In beams with ETF, ITF, OPLT configurations, the GBT pre-buckling analysis should consider transverse extension modes while the GBT buckling analysis may only consider local modes.


ABSTRACT: The decomposition of buckling modes of thin-walled members subjected to axial stresses is a topic of great practical interest which can be achieved using the generalised beam theory (GBT) or the constrained finite strip method (cFSM). However, the latter is not general enough to study prismatic members with arbitrary cross-sections and the objective of this paper is to extend the cFSM to allow the buckling modes decomposition for prismatic members with branches and/or closed parts. To define the combined GD buckling mode, two assumptions are used: (i) cylindrical plate bending and (ii) negligible in-plane transverse/shear strains. The corresponding constraint matrix, $R_{GD}$, is derived in a simple and general way. The methodology used to separate the global and distortional modes is similar to that used in the original cFSM while the derivation of the constraint matrix for local modes remains identical. Some examples are considered and the pure buckling curves are compared to the conventional FSM results. The conclusion is that the new cFSM has successfully computed the GD and the L modes of these sections.


ABSTRACT: A recently developed inelastic large displacement isoparametric spline finite strip method was used to investigate the inelastic stress distributions, load transfers and failure modes for a range of hole shapes, sizes and spacings. While such study is available for elastic material behaviour, the influence of yielding on the load transfers in and failure modes of perforated plates and sections is not well understood. This study considers perforated simply supported plates under compression and perforated C-section columns in compression failing by local buckling. Several inelastic material models were included in the study, including elastic perfectly-plastic and linear hardening models, and a model with nonlinear yielding and isotropic hardening. Comparisons are made with elastic analyses and conclusions are drawn about the influence of yielding and strain hardening
on the stress distributions, load transfers and failure modes of typical thin-walled metallic plates and structural sections.

Miquel Casafont, Magdalena Pastor, Jordi Bonada, Francesc Roure, Teoman Peköz, “Linear buckling analysis of perforated steel storage rack columns with the finite strip method”, Thin-Walled Structures, Vol. 61, 71-85, DOI: 10.1016/j.tws.2012.07.010

ABSTRACT: An investigation on the use of the Finite Strip Method (FSM) to calculate elastic buckling loads of perforated cold formed storage rack columns is presented. Nowadays, this calculation can be accurately performed by means of the Finite Element Method (FEM), because the effect of perforations can be explicitly considered in the analysis. However, the FSM is preferred in cold-formed steel design since it is implemented in much convenient and easy to use software. The problem with FSM is that holes cannot be easily modeled. In this paper, the concept of the reduced thickness of the perforated strip is applied to take into account their effect. A formulation is presented for the reduced thickness that has been calibrated with loads obtained in eigen-buckling FEM analyses. Its accuracy has been verified carrying out analyses on real rack columns with different end conditions.


ABSTRACT: This paper is the first part of a study devoted to interactive buckling of steel pallet racks compression members, carried out at the CEMSIG Research Centre http://cemsig.ct.upt.ro from “Politehnica” University of Timisoara; this part summarizes the experimental program 1 and 2. Upright members of two different cross-sections, with and without perforations, were tested according to the guidelines of European design code for pallet rack systems EN15512 [3], in order to determine the ultimate strength for specimens of length corresponding to local buckling, i.e. stub columns, and of length equal to the distance between two subsequent nodes of an upright frame, i.e. upright members. The last set of tests was devoted, mainly, to the observation of distortional buckling of upright members. However, depending on the cross-section dimensions, the length between two subsequent nodes can be often larger than distortional critical length. In such cases the test results correspond rather to the distortional–global interaction, than to pure distortion. Consequently, additional specimens having the length calibrated to correspond to distortional buckling and to interactive distortional-overall buckling range, respectively, were tested. Material tests and imperfection measurements were also performed.


ABSTRACT: Based on the results of experimental tests, presented in the first part of this paper, Part 1 — Experimental Investigations [1], and using the ECBL (Erosion of Critical Bifurcation Load) approach, in this second part the influence of imperfections on the erosion of critical bifurcation load in the coupling point, both for brut and perforated sections, subjected to uniform compression, is investigated using numerical analysis. A numerical sensitivity analysis is performed on the purpose to identify the most significant imperfections. The “theoretical” compression capacity of the tested members is calculated considering the significant imperfections and compared with the experimental results. The calibrated Finite Element (FE) model and the ECBL approach
are used to determine the buckling curves for studied sections. At the end, a numerical procedure is proposed in order to obtain the buckling curves for such a type of sections.

ABSTRACT: As more metallic alloys are introduced in engineering structures, the demand for the proper utilisation of their nonlinear stress–strain relationship is increasing. This paper discusses the inelastic buckling of members from such materials with a special focus on ferritic stainless steels. Here we introduce an alternative approach for the overall stability of members that considers material nonlinearity, namely the strain hardening parameter \( n \). The suitability of the new model is verified by regression analysis in comparison with the commonly used standard calculations. The analysis results show that the present approach could be applied successfully in flexural, flexural–torsional and lateral–torsional buckling.

Maria Kotelko, Radoslaw J. Mania, “Quasi-static and dynamic axial crushing of TWCF open-section members”, Thin-Walled Structures, Vol. 61, pp 115-120, DOI: 10.1016/j.tws.2012.03.026
ABSTRACT: The paper presents the results of theoretical and experimental investigations into an influence of strain rate (loading velocity) upon the structural behaviour of TWCF members, namely top hat section and plain channel section columns subjected to uniaxial uniform compression. Theoretical analysis was performed using the FE method and the analytical solution based on the plastic yield-line analysis. In both cases the plastic strain rate was taken into account. Experimental static and quasi-static tests were conducted with different loading velocities up to 600 mm/min. Results of numerical calculations together with tests results are shown in load-shortening diagrams. Failure patterns are also presented. Some conclusions concerning the influence of strain-rate upon the ultimate load and post-failure path of examined members are derived.

ABSTRACT: In this paper the bending-shear interaction of slender plates is studied. Six large tests were performed on longitudinally and transversally stiffened girders in the range of high bending moment and shear force. In longitudinal direction the web was stiffened with a trapezoidal stiffener positioned at the mid web depth for two girders and in the compression zone for the other four girders. The test procedure and test results are presented in details from the point of global behaviour and web buckling. The girders were divided in three groups; within each group one of the parameters was varied. Furthermore, a numerical model built in the general-purpose code ABAQUS is presented and verified against test results regarding initial stiffness, resistance and failure mode. In the last part of this paper the maximum load and the design resistance according to EN 1993-1-5 are compared and discussed. The design resistance was calculated with both options, according to the effective width method and the reduced stress method.

ABSTRACT: Due to its advantages corrugated steel plates are widely used in various applications. Engineers realized a potential application field in bridges, especially in composite bridges. When such a bridge is
incrementally launched, the girder is subjected to combined action of bending moment, shear and transverse forces, resulting in a complex stress field and interacting instability phenomena. The current paper focuses on the experimental and numerical investigation of the structural behaviour of the girders with corrugated webs under all of the above mentioned actions. 12 large scale test specimens are investigated under combined patch load and bending moment. Based on the experimental investigations a numerical model is developed and the structural behaviour of the girders with corrugated web is analysed under the complex loading situation due to combined bending moment, shear force and patch loading.

Tian Gao, Cristopher D. Moen, “Predicting rotational restraint provided to wall girts and roof purlins by through-fastened metal panels”, Thin-Walled Structures, Vol. 61, pp 145-153, DOI: 10.1016/j.tws.2012.06.005
ABSTRACT: This paper introduces mechanics-based expressions for predicting the rotational restraint provided by through-fastened metal panels to Z- and C-section girts or purlins. The analytical prediction equations include the effect of local panel deformation at a screw, and girt or purlin flange bending at a through-fastened connection. Finite element parameter studies are performed to quantify the local fastener pull-out stiffness for a common panel profile, and flange bending stiffness is determined with a cantilever beam model. Rotational restraint experiments are conducted to validate the prediction equations. The through-fastened connection stiffness is simulated in a finite strip elastic buckling analysis with a rotational spring to demonstrate how system effects can be included in design.

ABSTRACT: The paper is devoted to the analytical, numerical and experimental studies of the global and local buckling–wrinkling of the face sheets of sandwich beams and sandwich circular plates. A mathematical model of displacements, which includes a shear effect, is presented. The governing differential equations of sandwich plates are derived. The equations are analytically solved and the critical loads are obtained. Finite element models of the plates are formulated and the critical loads and buckling modes are calculated. Moreover, experimental investigations are carried out for the family of sandwich beam-plates. The values of the critical load obtained by the analytical, numerical (FEM), and experimental methods are compared.

ABSTRACT: Metal cylindrical storage structures of significant size, such as silos and vertical-axis tanks, are almost always constructed from many short cylindrical shells of different thickness as the stress resultants on the wall progressively increase towards the base. The resulting increases in thickness are always made in step changes using metal sheets of uniform thickness because of the availability of such source materials. The result is a shell with a stepped wall with multiple discrete steps in thickness. Such shells are very susceptible to buckling under external pressure when empty or partially filled, but the buckling mode may involve only part of the shell height due to the changes in shell thickness. These changes must therefore be accounted for within the design process. A new method of determining the critical buckling resistance of such shells was recently developed, and although it has been shown to be valid, the methodology for its application in practical design has not been set out or shown. This paper therefore briefly describes the new method and demonstrates the
manner in which it can be used to produce rapid, safe assessments of cylindrical shells with a wide range of patterns of wall thickness changes. The results are then suitable for direct introduction into such documents as the European standard on metal shells [1] and the ECCS Recommendations [2].


ABSTRACT: Modern procedures for the design of shell structures against buckling have their basis in analytical studies of axisymmetric shell geometries under the very simple load cases of uniform compression, external pressure and torsion. Studies of more complex but realistic stress states were based on prebuckling analyses using either membrane theory or linear bending theory because even these involved considerable mathematical complexity. As a result, only limited conclusions for practical design could be drawn and the effects of geometric nonlinearity could not be assessed. With recent advances in computing power and nonlinear finite element programs, it is now possible to undertake nonlinear analyses of complex load patterns that would have been very difficult to do only a decade or so ago. A number of practical load cases lead to a strip of pressure down one meridian, of which the best known ones are probably wind on tanks, eccentric discharge in silos, local thermal differentials, and partial fluid filling of a cylinder. This paper explores some of the rather unexpected stress patterns and modes of buckling that are predicted to develop in thin-walled cylindrical shells under such unsymmetrical strips of normal pressure. The results of a parametric study are presented to show the influence of the circumferential spread of the pressure strip on the structural behaviour. It is shown that the structural response to such loads may be very different, depending on whether the load acts inward or outward, and whether geometric nonlinearity and geometric imperfections are also included in the assessment.

References listed at the end of the paper:
successive reductions in the number of circumferential waves at every path jumping. In this paper, we traced experimental results have shown that after primary buckling, secondary buckling occurs accompanied by successive reductions in the number of circumferential waves at every path jumping. In this paper, we traced


ABSTRACT: In terms of the buckling problem related to elastic cylindrical shells under axial compression, experimental results have shown that after primary buckling, secondary buckling occurs accompanied by successive reductions in the number of circumferential waves at every path jumping. In this paper, we traced
this successive buckling of the elastic cylindrical shells using the latest general-purpose finite element technology with a static stabilizing method. The study accomplished a fully automatic and seamless simulation of successive path jumping in the deep post-buckling region and showed good agreement with Yamaki’s experimental results and Esslinger’s high-speed photography.

Carlos F. Estrada, Luis A. Godoy, Fernando G. Flores, “Buckling of vertical sandwich cylinders embedded in soil”, Thin-Walled Structures, Vol. 61, pp 188-195, DOI: 10.1016/j.tws.2012.05.010

ABSTRACT: Composite or sandwich materials have been used in the construction of pipelines for some time, but not for the construction of inspection cameras, which are buried vertical cylinders that connect the pipeline with the ground. This paper explores the buckling and post-buckling behavior of vertical sandwich shells under lateral pressure, considering typical dimensions of inspection cameras employed in the industry. The analysis is carried out using a finite element model including geometric nonlinearity, in which the shell and the soil are represented together with the contact zone between them. Parametric studies are reported to account for the influence of shell slenderness, imperfection amplitude and soil elasticity. Results are also compared with those obtained for a circular ring under similar lateral constraints. The results show that for a shell in rigid soil the critical loads are higher than in the case of elastic soil, but the sensitivity with respect to imperfections in the geometry is also high. Cylinders in an elastic soil, on the other hand, tend to have lower buckling loads and moderate imperfection sensitivity. Finally, a ring model leads to good approximations to buckling loads but does not adequately represent the post-buckling behavior of a shell in this problem.


ABSTRACT: Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns which consists of a layer of concrete sandwiched between an inner steel tube and an outer FRP tube. While a large amount of research has been conducted on the monotonic behavior of this novel form of columns, only a limited amount of work has been conducted on their behavior under cyclic loading. This paper presents the first ever study on the behavior of circular hybrid DSTCs under cyclic axial compression. Results from a series of stub column tests, where the hybrid DSTCs were subjected to cyclic axial compression, are first presented and discussed. The test results show that hybrid DSTCs are very ductile under cyclic axial compression, with the envelope axial load-strain curve being almost the same as the axial load-strain curve of a corresponding DSTC under monotonic compression. It is also shown that repeated unloading/reloading cycles have a cumulative effect on the permanent strain and the stress deterioration of the confined concrete in hybrid DSTCs. The experimental stress–strain curves of the confined concrete in hybrid DSTCs are then compared with predictions from two existing models: (1) a monotonic stress–strain model for the confined concrete in hybrid DSTCs; and (2) a cyclic stress–strain model for the concrete in FRP-confined solid columns. The comparison suggests that the combined use of the two models can give reasonably accurate predictions of the test results.

Lincy Pyl, Luc Schueremans, Willem Dierckx, Iveta Georgieva, “Fire safety analysis of a 3D frame structure based on a full-scale fire test”, Thin-Walled Structures, Vol. 61, pp 204-212, DOI: 10.1016/j.tws.2012.03.023

ABSTRACT: The topic of this paper is the fire safety analysis of 3D frame structures such as industrial halls. Cold-formed thin plated elements are used as structural components. The building, which is submitted to a full-
scale fire test, is introduced. A blind prediction analysis is performed using the finite element model SAFIR. The thermal response of the structural elements under both a standard fire and a natural fire corresponding to a fire load density of 625 MJ/m² and an opening factor 0.009 m^{1/2} is predicted. As expected, the temperature of the cold-formed sections follows more or less the gas temperature in the fire compartment due to the thin plates. The results of the predicted mechanical response are presented, giving a resistance of 27 min (standard fire) and 54 min (natural fire). The model is validated based on the results of the full-scale fire test, demonstrating a fire resistance of 62 min. Comparison with a simple 2.5D model is made and proved to provide results sufficiently accurate to make it applicable for daily design practice.

Niroscha Dolamune Kankanamge, Mahen Mahendran, “Behaviour and design of cold-formed steel beams subject to lateral-torsional buckling at elevated temperatures”, Thin-Walled Structures, Vol. 61, pp 213-228, DOI: 10.1016/j.tws.2012.05.009

ABSTRACT: Cold-formed steel beams are increasingly used as floor joists and bearers in buildings and often their behaviour and moment capacities are influenced by lateral–torsional buckling. With increasing usage of cold-formed steel beams their fire safety design has become an important issue. Fire design rules are commonly based on past research on hot-rolled steel beams. Hence a detailed parametric study was undertaken using validated finite element models to investigate the lateral–torsional buckling behaviour of simply supported cold-formed steel lipped channel beams subjected to uniform bending at uniform elevated temperatures. The moment capacity results were compared with the predictions from the available ambient temperature and fire design rules and suitable recommendations were made. European fire design rules were found to be over-conservative while the ambient temperature design rules could not be used based on single buckling curve. Hence a new design method was proposed that includes the important non-linear stress–strain characteristics observed for cold-formed steels at elevated temperatures. Comparison with numerical moment capacities demonstrated the accuracy of the new design method. This paper presents the details of the parametric study, comparisons with current design rules and the new design rules proposed in this research for lateral–torsional buckling of cold-formed steel lipped channel beams at elevated temperatures.

Wei Lu, Zhongcheng Ma, Pentti Mäkeläinen, Jyri Outinen, “Behaviour of shear connectors in cold-formed steel sheeting at ambient and elevated temperatures”, Thin-Walled Structures, Vol. 61, pp 229-238, DOI: 10.1016/j.tws.2012.04.008

ABSTRACT: Cold-formed profiled steel roof sheeting can be directly connected to the top chord of a steel truss through powder-actuated shot nails or self-tapping screws. The lap shear behaviours of both shot nailed and screwed connections are studied in this paper using both testing and FE analysis at ambient and elevated temperatures. The studies for screwed connections show four components of loading capacity, including bearing force between thin sheet and screw shank, frictional force between washer and thin sheet, frictional force between thin sheet and thick plate, and the bearing force by the tilting of thin sheet are identified and quantified. The studies for shot nailed connections show strong interactions among washer, shot nail, thin sheet and supporting plate. The protuberance feature developed during the nail driving process, which causes material in thick plate flowing upward, has a significant positive contribution to the loading capacity of the connection.

ABSTRACT: An experimental program of nine steel deck roof diaphragm specimens was carried out to assess their seismic characteristics. The dynamically loaded diaphragms were able to develop the shear strength but not the shear stiffness values calculated using current diaphragm design methods. Furthermore, the shear stiffness decreased with increasing excitation amplitude. Diaphragm ductility decreased with the use of thicker deck panels and when the deck was oriented parallel to the loading direction. Most of the damaged diaphragms could be repaired to recuperate their original strength. A seismic retrofit scheme was effective in increasing the shear strength and stiffness of an arc-spot weld/ button-punch diaphragm.

Luigi Fiorino, Ornella Iuorio, Vincenzo Macillo, Raffaele Landolfo, “Performance-based design of sheathed CFS buildings in seismic area”, Thin-Walled Structures, Vol. 61, pp 248-257, DOI: 10.1016/j.tws.2012.03.022
ABSTRACT: The widely recognized structural performance provided by cold-formed steel (CFS) systems together with high levels of prefabrication, safety, durability and sustainability are spreading the CFS construction systems all over the world. At the same time, the actual lack in European seismic design codes requires the development of specific design procedures for the application in seismic area. The seismic behaviour of CFS structures is characterized by the lateral response of shear walls. In particular, when the sheathing-design methodology is adopted, then the seismic behaviour is strongly influenced by the nonlinear response of sheathing-to-frame connections. In this paper a performance-based design methodology for the seismic design of sheathed CFS walls is proposed. The presented methodology is based on the results of an extensive parametric nonlinear dynamic study carried out on one story buildings by means of incremental dynamic analysis. Moreover, a multistep design procedure that allows all the main structural components to be defined in three steps is developed. In particular, a nonlinear dynamic (ND) nomograph for the assessment of the external screw spacing is presented in this work in order provide a new tool that upgrade the design procedure under investigation by the Authors in the last years. Finally the application of the proposed design methodology is verified through a case study.

ABSTRACT: The main aspects of theory, design, codification and application of 3D aluminium structures are examined, by emphasising the peculiar differences with steel, by referring to real cases. The main applications in the field of geodetic domes represent a challenging example of 3D aluminium structures. The theoretical and experimental results were used for setting-up Part 1.5 “Shell Structures” of Eurocode 9.

============= End of list of papers in the Dec. 2012 special issue of Thin-Walled Structures =============

Mahmoud R. Maheri and A. Abdollahi (Shiraz University, Iran), “The effects of long term uniform corrosion on the buckling of ground based steel tanks under seismic loading”, Thin-Walled Structures, Vol. 62, pp 1-9, January 2013, DOI: 10.1016/j.tws.2012.06.004
ABSTRACT: Material degradation due to corrosion significantly alters the seismic response of ground-based cylindrical steel storage tanks. A numerical study is conducted to investigate the effects of internal shell corrosion on the dynamic buckling of three cone roof ground-based, steel cylindrical tanks with height to diameter ratios \((H/D)\) of 0.40, 0.63 and 0.95, subjected to horizontal seismic base excitations. Internal corrosion is considered as a time dependent uniform thinning of the wall at the upper and the lower parts of the tank being in contact with, respectively, atmospheric oxygen and acid gases and residual water. Detailed numerical models
of the tank–liquid systems at different stages of corrosion degradation are subjected to two representing accelerograms and for each model the critical peak ground acceleration (PGA) for dynamic buckling of the shell and its associated mode of failure are evaluated. It is found that in all three tanks, the critical PGA is markedly reduced with thinning of the shell, irrespective of the type of ground input. The buckling mode of failure of the tanks also changed from an elastic diamond-shaped failure at the top of the shell to an elasto-plastic elephant foot type failure near the base, after 10 years for the shorter tanks ($H/D=0.4$ and 0.63) and after 15 years for the tallest tank. The effects of uniform corrosion degradation on the critical buckling load of the tanks were found to be such that after 20 years of thinning due to corrosion, the static loading alone was responsible for the elephant foot buckling of the shell.

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ABSTRACT: To study the collapse mode and energy absorption of triangular tubes, quasi-static axial compression experiments were carried out. Deformation curves and collapse modes were revealed by the experiments. Based on various combinations of the two basic folding elements, four potential collapse modes were proposed and compared to predict the mean crushing force of the tube theoretically. Numerical simulations were applied to suggest a fitted formula of the mean crushing force. Both the analytical and numerical predictions were compared with the experiments to build an effective method to predict the mean crushing force of the triangular tube.

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ABSTRACT: Corrugated steel plates have several advantages such as high resistance for shear without stiffeners, minimization of welding process, and high fatigue resistance. To take advantage of these benefits, several researchers have attempted to use corrugated steel plate as a web for I-girders. The flexural–torsional buckling is the major design aspect of such I-girders. However, the flexural–torsional buckling of the I-girder with corrugated steel webs still needs to be investigated especially for a real loading condition such as non-uniform bending. This paper investigated the flexural–torsional buckling strength of an I-girder with corrugated steel webs under linear moment gradient by using finite element analysis. From the results, it was found that the buckling behavior of the I-girder with corrugated steel webs differed depending on the number of periods of the
corrugation. Also, a simple equation for the moment gradient correction factor for the I-girder with corrugated steel webs was suggested. The inelastic flexural–torsional buckling strength of the I-girder with corrugated steel webs was then discussed based on current design equations for ordinary I-girders and inelastic finite element analysis considering initial imperfection and residual stresses.

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ABSTRACT: Semi-analytical elastic methods for stiffened plate analysis are computationally very efficient. In addition to eigenvalue analysis, such methods may also offer a viable approach for the prediction of ultimate strength limits (USLs) of the plates when combined with appropriate strength criteria. In this paper, existing strength criteria are discussed, and extended criteria proposed for plates with various stiffener arrangements and boundary conditions such as full out-of-plane supports along all edges or plates with a free or partially stiffened edge. The extended criteria reflect in a simplified manner the effect of redistribution of stresses due to the formation of local plastic regions at stiffeners, supporting edges and in the plate interior. The equilibrium path is traced using large deflection theory and the Rayleigh–Ritz approach on an incremental form. The approach is able to account for the reserve strength of slender plates in the postbuckling region. With the considered criteria included, good agreement is obtained with results from fully nonlinear finite element analyses for different support conditions and for a variety of plate and stiffener dimensions.

ABSTRACT: The elaborated method of eigenfunction expansion in elliptic coordinates is employed to obtain an exact time-domain series solution, involving products of angular and radial Mathieu functions, for the forced flexural vibrations of a thin elastic plate of elliptical planform. The plate is supported by a constant moduli two-parameter foundation, while elastically restrained against translation and rotation at its edge, and subjected to the combined action of uniform in-plane static edge forces and general arbitrary time-dependent transverse loads with arbitrary initial conditions. Numerical calculations are carried out for the displacement response of clamped or simply supported elliptical plates of selected aspect ratios in various practical loading configurations (i.e., an impulsive point load, a point force in circular motion, a uniformly distributed harmonic load, and a blast load), with or without an elastic foundation, while taking the effects of initial tension or compression below the buckling load into consideration. Limiting cases are considered and good agreements with available results as well as with the computations made by using a commercial finite element package are obtained.

Ali Chaaba (Moulay Ismail University, Mechanics and Integrated Engineering Research Team (M2I), National Higher School of Engineering (ENSAM), Marjane II, B.P. 4024, Meknès, Morocco), “Reliability assessment by
analytical calculation of the plastic collapse load of thin pressure vessels with strain hardening and large deformation”, Thin-Walled Structures, Vol. 62, pp 46-52, January 2013, DOI: 10.1016/j.tws.2012.08.001

ABSTRACT: The paper investigates the assessment of the capacity loading in terms of internal limit pressure of thin metallic vessels such as thin tubes and thin spheres. This assessment is dealt with, taking into consideration large deformations of the geometry as well as the most common rules for strain hardening modeling such as isotropic, kinematic or isotropic and kinematic combined. Analytical solutions are established for predicting plastic limit pressure evolution together with hardening variables.

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ABSTRACT: A type of cylindrical multi-cell column is proposed to improve energy absorption performance, which is inspired by the phenomenon that the circular tube is more efficient than the square tube in energy absorption. This type of structure shows high performance in energy absorption for its considerable number of corners on the cross section and the angles between neighbor flanges are in the optimal range as well as some more efficient cylindrical shells have been adopted. Numerical examples illustrate that cylindrical multi-cell column is more efficient than square column and square multi-cell column in energy absorption. In addition, a parametric study considering the effects of geometrical parameters on the structural crashworthiness has been carried out. And it is found that wall thickness, the number of cells alone the radial and circumferential directions have a distinct effect on the energy absorption.

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ABSTRACT: The present paper deals with the experimental and computational study of collapse of the metallic shells having combined tube–cone geometry subjected to axial compression between two parallel plates. The aim is to study the influence of the shell thickness and cone angle on its mode of deformation. Shells were having top one third length as tube and remaining bottom two third length as truncated cone having semi-apical angle about 23°. The other geometrical dimensions were almost same. Shells were tested in an INSTRON universal testing machine, to identify their modes of collapse and associated energy absorption capacity. In experiments it was found that the collapse process of all shells was initiated by development of an axisymmetric fold followed by a plastic zone of increasing length. An axisymmetric Finite Element computational model of collapse process is presented and analysed, using a non-linear FE code FORGE2 [13]. Six noded triangular elements were used to descretize the domain. The material of the shells was idealised as rigid visco-plastic. Experimental and computed results of the deformed shapes and their corresponding load-compression and energy–compression curves were compared to validate the computational model. Typical computed variations of nodal velocity distribution, equivalent strain rate, equivalent strain, hoop stress and principal stress are presented to help in predicting the mode of collapse. On the basis of the experiments and computed results development of the axisymmetric mode of collapse has been presented, analysed and discussed. Further the
A computational model is used to simulate the mode of collapse of specimens having lower semi-apical angles between 19° and 23° of the conical portion. It was found that the mode of collapse of combined geometry specimens mainly governed by the semi-apical angle of the truncated cone portion.

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ABSTRACT: In this paper, a theoretical and numerical model based on the power series method is investigated for the lateral buckling stability of tapered thin-walled beams with arbitrary cross sections and boundary conditions. Total potential energy is derived for an elastic behavior from strain energy and work of the applied loads. The effects of the initial stresses and load eccentricities are also considered in the study. The lateral-torsional equilibrium equations and the associated boundary conditions are obtained from the stationary condition. In presence of tapering, all stiffness coefficients are not constant. The power series approximation is then used to solve the fourth-order differential equations of tapered thin-walled beam with variable geometric parameters having generalized end conditions. Displacement components and cross section properties are expanded in terms of power series of a known degree. The lateral buckling loads are determined by solving the eigenvalue problem of the obtained algebraic system. Several numerical examples of tapered thin-walled beams are presented to investigate the accuracy and the efficiency of the method. The obtained results are compared with finite element solutions using Ansys software and other available numerical or analytical approaches. It is observed that suggested method can be applied to stability of beams with constant cross sections as well as tapered beams.

References listed at the end of the paper:

ABSTRACT: Uni-lateral buckling behavior of cylindrical panels on tensionless elastic foundation under axial compression is investigated through Rayleigh–Ritz method. Derivation of the equations is based on Kirchhoff–Love’s hypotheses. All the contributed researches on the uni-lateral buckling problem are limited to plates. Buckling curves are produced that indicate relationships between buckling load and geometrical parameters. It is concluded that increasing the surface of panel does not necessarily lead to an increase in the contact region between panel and foundation. Influences of geometrical parameters and foundation on the uni-lateral buckling behavior are examined. The results for flat panel are validated with available data.

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ABSTRACT: In this study, the buckling analysis of homogeneous and non-homogeneous orthotropic, thin walled truncated conical shells under axial load and in large deformation has been investigated. First, the
governing relations are derived using the large deformation theory with von Karman–Donnell-type of kinematic non-linearity. Then modified Donnell type stability and compatibility equations of non-homogeneous orthotropic thin-walled truncated conical shells in large deformation are obtained and solved analytically. Finally, influences of the non-homogeneity, orthotropy and the variation of the shell geometry on the non-linear axial buckling load are investigated. Comparing the results of this study with those in the literature validates the present analysis.


ABSTRACT: Due to the increased consumption of thin-walled structural elements there has been increasing focus and need for more detailed calculations as well as development of new approaches. In this paper a thin-walled beam element including distortion of the cross section is formulated. The formulation is based on a generalized beam theory (GBT), in which the classic Vlasov beam theory for analysis of open and closed thin-walled cross sections is generalized by including distortional displacements. The beam element formulation utilizes a semi-discretization approach in which the cross section is discretized into wall elements and the analytical solutions of the related GBT beam equations are used as displacement functions in the axial direction. Thus the beam element contains the semi-analytical solutions. In three related papers the authors have recently presented the semi-discretization approach and the analytical solution of the beam equations of GBT. In this approach a full set of deformation modes corresponding to the homogeneous GBT equations are found. The deformation modes of which some are complex decouple the state space equations corresponding to the reduced order differential equations of GBT and allow the determination of the analytical solutions. Solutions of the non-homogeneous GBT differential equations and the distortional buckling equations have also been found and analyzed. Thus, these related papers are not dealing with an element but dealing with analytical solutions to the coupled differential equations. To handle arbitrary boundary conditions as well as the possibility of adding concentrated loads as nodal loads the formulation of a beam element is needed. This paper presents the formulation of such a generalized one-dimensional semi-discretized thin-walled beam element including distortional contributions. It should be noticed that we are only dealing with a basic generalized beam theory and not an extended finite element formulation of an approximate beam element, which allows the addition of special (transverse extension and shear lag) modes. Illustrative examples showing the validity and the accuracy of the developed distortional semi-discretized thin-walled beam element are given and it is shown how the novel approach provides accurate results making it a good alternative to the traditional and time consuming FE calculations.

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ABSTRACT: A model of deformation of a metal hollow section beam under a uniform blast loading is developed in order to reveal the characteristic features of deformation and energy absorption of hollow section beams under such loading. It is established that as a typical structural component a hollow section distinguishes itself from its solid counterpart with two characteristic features of the response. First, a considerably larger kinetic energy is generated in the hollow section beam as the impulsive load is imparted on the upper flange of the beam having a significantly lower mass than the member. Second, a considerable proportion of the blast energy can be absorbed by the local collapse of the section. A two-phase analytical model is proposed. In the first phase, the local collapse of the thin-walled cross-section is determined by using an upper bound approach; and in the subsequent second phase, the global bending of the beam with the distorted section is analyzed by taking into account the effect of axial force. It is demonstrated that mass distribution in the hollow section is an important factor in determining the energy partitioning between the local deformation phase and global bending of the hollow beam. Reasonable agreement is obtained with the experimental data published in the literature [Jama HH, Nurick GN, Bambach MR, Grzebieta RH, Zhao XL, Steel square hollow sections subjected to transverse blast loads, Thin-Walled Structures 2012;53:109–122].

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ABSTRACT: Cold-formed stainless steel tubular structural members which may experience web crippling failure due to localised concentrated loads or reactions are investigated. A series of tests on fibre-reinforced polymer (FRP) strengthening of cold-formed stainless steel tubular structural members subjected to End-Two-Flange and Interior-Two-Flange loading conditions is presented. The strengthening only applied to a localise area of the members under concentrated load. A total of 58 web crippling tests were conducted. The investigation mainly focused on the effects of different surface treatment, different adhesive, and FRP for strengthening of stainless steel tubular sections against web crippling. The behaviour of stainless steel members strengthened by different widths of FRP plate against web crippling has been also investigated in this study. The test specimens consisted of ferritic stainless steel EN 1.4003 square and rectangular hollow sections. Two different surface treatments were considered. Furthermore, six different adhesives and six different FRPs were also considered in this study. The properties of adhesive and FRP as well as the bonding between the FRP and stainless steel tube have significant influence on the effectiveness of the strengthening. Most of the strengthened specimens were failed by debonding of FRP plates form the stainless steel tubes. Six different failure modes were observed in the tests, namely the adhesion, cohesion, combination of adhesion and cohesion, interlaminar failure of FRP plate, FRP delaminating failure and web crippling failure. The failure loads, failure modes, and the load-web deformation behaviour of the ferritic stainless steel sections are presented in this study. It was found that the web crippling capacity of ferritic stainless steel tubular sections may increase up to 51% using FRP strengthening.

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ABSTRACT: The objective of this paper is to explore the potential strength and serviceability implications of metallic foams, specifically steel foam, utilized as a thin-walled channel structural member. A typical advantage sought in the selection of a thin-walled member is minimal weight. However, the stability of the thin walls and the related limit states constrains the extent to which weight minimization may be utilized. As a material, steel foam (literally creating air voids in the steel microstructure) offers the potential to provide increased plate stiffness for a given weight and thus create even lighter thin-walled members and structures. In this work analytical material relationships are used to explore the structural potential for steel foam. First, the local buckling and yielding of an isolated steel foam plate is explored. Second, the local, distortional, and global buckling of a prototypical cold-formed steel channel using steel foam is examined. Finally, the strength and governing limit state of the channel as a function of relative density (i.e., the degree to which the material is foamed) is explored. The results show the key tradeoff made when foaming–stiffness per weight is increased, including stiffness related to member buckling modes; however, yield strength per weight decreases. Depending on the slenderness (in local, distortional, and global modes) of the member this tradeoff can be beneficial or detrimental.

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ABSTRACT: This paper presents the development and illustrates the application of a beam finite element based on the generalised beam theory (GBT) and intended to analyse the local, distortional and global post-buckling behaviour of thin-walled steel frames. After briefly reviewing the main concepts and procedures required to obtain the GBT system of non-linear equilibrium equations, the paper describes the steps involved in the numerical implementation (incremental-iterative strategy) of a non-linear beam finite element that incorporates the influence of the frame joint behaviour. Next, one uses evidence gathered from shell finite element simulations to establish kinematic constraint conditions ensuring displacement compatibility at frame joints connecting two non-aligned plain/lipped channel members. Finally, the application and capabilities of the proposed GBT-based beam finite element formulation are illustrated by presenting and discussing numerical results concerning the post-buckling behaviour of two “L-shaped” frames and a symmetric portal frame. For validation purposes, most GBT-based results are compared with values yielded by beam and shell finite element analyses carried out in the code ANSYS.

ABSTRACT: The nonlinear behaviour of fibre reinforced (FR) concrete-filled stainless steel tubular columns is discussed in this paper. A nonlinear 3-D finite element model was developed for the analysis of the composite columns. The pin-ended axially loaded composite columns had different lengths, which varied from stub to long columns. The nonlinear material properties of the composite column’s components comprising stainless steel
tube and FR concrete were incorporated in the model. The effect of FR concrete confinement and interface between the stainless steel tube and FR concrete infill was also considered allowing the bond behaviour to be modelled. In addition, the measured initial overall (out-of-straightness) geometric imperfection was carefully incorporated in the model. The finite element model has been validated against tests recently conducted by the author on FR concrete-filled stainless steel tubular columns. The composite column strengths, load–axial strain relationships and failure modes were predicted from the finite element analysis and compared well against that measured experimentally. Furthermore, the variables that influence the composite column behaviour and strength comprising different lengths, external diameter-to-plate thickness \((D/t)\) ratios and FR concrete strengths were investigated in a parametric study. The parametric study has shown that the increase in column strengths owing to the increase in concrete strength is more significant for the columns having \(L/D\) ratios less than 6 as well as for the columns having \(D/t\) ratios less than 50. The composite column strengths obtained from the finite element analysis were compared with the design strengths calculated using Eurocode 4 for composite columns. It is shown that the EC4, in most cases, accurately predicted the design strength for axially loaded FR concrete filled stainless steel tubular columns.


ABSTRACT: A new framework, EBF3PanelOpt, is being developed for design and optimization of complex, multifunctional, aircraft structural concepts like pressurized non-circular fuselage structures to be used in hybrid wing/body vehicles that are subjected to complex structural loading cases. This tool can be used to integrate materials and structural concepts to exploit emerging additive manufacturing processes that offer the ability to efficiently fabricate complex structural configurations. Commercial software packages, MD-Patran (geometry modeling and mesh generation), MD-Nastran (Finite Element Analysis), are integrated in the EBF3PanelOpt framework using Python programming environment to design stiffened panels with curvilinear stiffeners. Typically, these panels experience multiple loading conditions during the operations of these vehicles. EBF3PanelOpt has the capability to optimize flat/curved multi-sided panels with straight/curved edges having curvilinear, blade-type stiffeners under multiple loading conditions. The mass of the panel is minimized subjected to constraints on buckling, von Mises stress, and crippling or local failure of the stiffener using global optimization techniques or gradient based optimization techniques. The panel/stiffener geometry is parametrized using design variables that include variables for orientation and shape of the stiffeners, the thicknesses and height of the stiffeners, and the plate thickness. The plate can have uniform thickness or non-uniform thicknesses for the pockets created by the stiffeners. During optimization, constraints can be applied for each of the loading conditions by aggregating all the responses using Kreisselmeir–Steinhauser criteria or using worst response amongst all the responses or applying all the constraints. Initially, the flat rectangular panel is optimized for the single load-case to study the effectiveness of the panel thickness option. Then, the optimization of flat rectangular and cylindrical panels is carried out for three sample load cases of practical interest. This paper discusses the advantages and disadvantages of the proposed constraints' application.

ABSTRACT: This work addresses the buckling behavior of the open top tanks subjected to harmonic settlement. First of all, the buckling behavior and the critical harmonic settlement of an open top tank for various wave numbers are investigated. The results present that buckling occurs on the upper shell for a small wave number, while it changes to other places of the shell for large wave numbers. Also, with the wave number increasing, the buckling point is closer to the base of the shell. Besides, for the original tank, the critical harmonic settlement decreases greatly when the wave number is small, while the critical harmonic settlement decreases slightly when the wave number is large. Then, the parametric studies for the buckling behavior of the open top tank are conducted, composed of the height-to-radius \((h/r)\) ratio and the radius-to-thickness \((r/t)\) ratio. Regarding the \(h/r\) ratio, for a certain wave number, the critical harmonic settlement versus the \(h/r\) ratio is monotonically decreasing. Also, with the wave number increasing, the critical harmonic settlement decreases more and more slightly. Regarding the \(r/t\) ratio, for a certain wave number, the critical harmonic settlement versus the \(r/t\) ratio is monotonically decreasing. Moreover, with the increasing wave number, the critical harmonic settlement decreases more and more slightly. Finally, the buckling results of the open top tank are compared with that of the conical roof tank. The results illustrate that the open top tank can hold a larger harmonic settlement than the conical roof tank for no restraint from the roof for a small wave number. However, for large wave numbers, there is a small difference in settlement sustaining capacity for open top tanks and conical roof tanks.


ABSTRACT: A series of bending tests of thin-walled concrete-filled steel tubes (CFST) were presented in this study. A total of 4 specimens were tested, two square specimens and two rectangular specimens, with width to wall thickness ratio ranging from 50 to 100. The load–displacement curves, failure mode and ultimate capacity of test specimens were obtained. An analytical model was developed for the thin-walled CFSTs subjected to bending. Material properties of confined concrete, corner strength enhancement of cold-formed steel sections, residual stresses and plate local buckling were considered in the developed model. The proposed model was able to predict the behavior and strengths of test specimens with reasonable accuracy. In addition, the suitability of current AISC standard, Eurocode 4 and Han's model for thin-walled CFSTs subjected to bending was also evaluated.

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“In-plane ultimate compressive strengths of HPS deck panel system stiffened with U-shaped ribs”, Thin-Walled Structures, Vol., 63, pp 70–81, February 2013, DOI: 10.1016/j.tws.2012.10.001

ABSTRACT: The ultimate compressive strengths of deck plates stiffened longitudinally by U-shaped stiffeners have been investigated by the nonlinear finite element analysis (FEA). A total of 112 hypothetical models with various combinations of slenderness parameters for the deck plates and column slenderness parameters for the stiffeners were modeled and analyzed. Both conventional and high performance steels were considered in models following elasto-plastic strain hardening constitutive relationships. Initial geometric imperfections and residual stresses were also incorporated in the FEA. Numerical results from FEA have been compared to
compressive strengths from Eurocode 3 EN 1993-1-5, FHWA-TS-80–205, and other available formulas. Based on analysis results, new unified strength predictor equations have been developed for the stiffened plate systems with conventional steel and/or high performance steel (HPS). It has been found that use of Eurocode 3 EN 1993-1-5 and FHWA-TS-80–205 may lead to highly conservative design when large column slenderness parameters are encountered. The proposed equations have simple forms yet provide accurate strength predictions resulting in more economic design.

ABSTRACT: Free vibration analysis of laminated composite skew hypar shells are presented using a $C_0$ finite element (FE) formulation based on higher order shear deformation theory (HSDT). Effect of cross curvature is included in the formulation. The $C_0$ finite element formulation has been done quite efficiently to overcome the problem of $C_1$ continuity associated with the HSDT. The isoparametric FE used in the present model consists of nine nodes with seven nodal unknowns per node. Since there are no results available in the literature based on HSDT on the problem of free vibration of laminated composite skew hypar shells, present results are validated with the results available for laminated composite hypar shells without skew angle and with the results available for laminated composite skew plates. New results are presented by varying geometry, boundary conditions, ply orientations and skew angles.

ABSTRACT: This paper presents a finite element (FE) study on fixed-ended LDSS slender hollow columns with square (SHC), and non-rectangular hollow columns (NRHCs) viz., L- (LHC), T- (THC), and +- (+HC) shaped cross-sections subjected to pure axial compression using Abaqus software. SHC columns with thicknesses of 5.25 mm and 2.0 mm, which lie in Class 3 (stocky) and Class 4 (slender) sections, respectively, as per EN 1993-1-4 were considered in the study as referral sections. Variations in buckling strength with changes in the cross-sectional shapes were studied by considering NRHCs having equal material cross-sectional areas (or equal material consumption) as that of SHCs over a range of column lengths. The FE results of SHC and NRHCs were then compared with the design strengths predicted by the EN1993-1-4 and ASCE 8-02 specifications. Good agreements between the FE strengths and codal predictions have been observed, except for the ASCE 8-02 prediction of LHC where it over predicts the FE strengths. At both the slenderness regime (i.e., low and high slenderness values) of Class 3 sections and high slenderness regime of Class 4, all the sections exhibit similar structural capacities. Cross-sectional shape is found to become increasingly significant with decreasing member slenderness in Class 4 sections. In Class 3 sections, compared to SHC there is a nearly linear variation in strength (increased for +HC, similar behavior for THC and decreased for LHC) up to $\lambda^-$ about 2.0, then it stabilizes out. After, $\lambda^-$ about 2.0, $P_u$ for +HC showed about 30% higher; THC showed similar strength; and LHC showed about 20% lower than the corresponding value for SHC, indicating that +HC has an improved ultimate strength for all the ranges of $\lambda^-$. The strength enhancement as compared to that of SHC are about 10%, 50%, and 90% higher for LHC, THC, and +HC, respectively, for Class 4 sections. Based on the
reliability analyses it is recommended that both the codes can be adopted for all the design of fixed-ended LDSS columns except for LHC, wherein a suitable modification may be employed after systematic studies.


**ABSTRACT:** The nonlinear buckling and post-buckling behavior of functionally graded stiffened thin circular cylindrical shells subjected to external pressure are investigated by the analytical approach in this paper. The shells are reinforced by eccentrically rings and stringers attached to the inside and material properties of shell and stiffeners are assumed to be continuously graded in the thickness direction. Fundamental relations, equilibrium equations are derived based on the smeared stiffeners technique and the classical shell theory with the geometrical nonlinearity in von Karman sense. Approximate three-terms solution of deflection is more correctly chosen and explicit expression to finding critical load and post-buckling pressure-deflection curves are given by using the Galerkin's method. The numerical results show the effectiveness of stiffeners in enhancing the stability of shells.

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**ABSTRACT:** A concrete-filled stainless steel–carbon steel tubular (CFSCT) column is introduced as a new form of composite member in this paper, which is believed to achieve higher corrosion resistance, higher bearing capacity and lower cost by combination the advantages of stainless steel and concrete filled steel tube (CFST) structure. A series of compression test was carried out on this newly proposed composite column. A modified stress–strain model for concrete core was proposed and then three-dimensional nonlinear finite-element (FE) models were established and verified with the experimental results. Close agreement was achieved between the test and numerical results in terms of load–deformation responses. A parametric study, including tube thickness, diameter and yield strength of carbon steel tube was also conducted to give a clear insight on the performance such composite columns.

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**ABSTRACT:** Reinforced concrete (RC) shear-dominant walls can fail suddenly at lower ductility levels, which can lead to catastrophic damage. Accurate modeling of shear-dominant RC walls is therefore essential. In this paper, fiber beam elements, which are proven to be computationally very efficient, were developed to model the
behavior of thin-walled RC shear walls. Concrete and steel were considered as separate materials, and are combined at the section level to describe the behavior of the reinforced concrete member. Concrete was modeled as an orthotropic material in which the principal directions of total stresses were assumed to coincide with the principal directions of total strains, thus changing the directions continuously during the loading. The constitutive model follows the Softened Membrane Model (SMM) in which the compressive strength of concrete is reduced as a function of the lateral strain. The model was subsequently used to conduct a series of numerical studies to evaluate the effect of several parameters affecting the nonlinear behavior of the shear dominated wall. These parameters include the aspect ratio, the transverse reinforcement ratio, the axial force, and the concrete compressive strength. These studies resulted in several important conclusions regarding the global and local behavior of wall systems.


ABSTRACT: In deep and ultra-deep waters the diameter of trunk lines coupled with the hydrostatic pressure tends to lead to failure of the pipeline by external collapse. This failure mode is an instability phenomenon that is governed by the geometry of the pipeline and its material properties and takes place through a subtle combination of its properties. As such the exact limiting collapse pressure is very difficult to determine and twenty years of studies seem to have not managed to clarify entirely the matter. In the present paper the elastic-plastic collapse of test rings from UOE formed pipes under external uniform pressure is analysed both from an analytical and a computational viewpoint and the significance of the actual shape of the out of roundness and of the material inhomogeneity is examined in details. The work has been motivated by a number of accurate experimental tests recently performed on rings cut from UOE pipes and it is found that the material inhomogeneity can affect the collapse modes and produce an occasionally unforeseen reduction in the carrying capacity of the rings prompting a swing between the underlying collapsing modes. Importantly, it is shown that this behaviour can turn quite difficult to follow numerically, also by means of robust strategies such as Riks and improved arc-length. The features of the problem can help to give reason of some apparently anomalous experimental results.

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“Finite element investigation of the influence of material properties on the crushing characteristics of in-plane loaded composite sandwich panels”, Thin-Walled Structures, Vol. 63, pp 163-174, February 2013
DOI: 10.1016/j.tws.2012.09.011

ABSTRACT: In the present paper, the explicit finite element code LS-DYNA3D was used to investigate the influence of selected material properties in the crash energy absorption characteristics of composite sandwich panels subjected to in-plane compressive loading. The first step in this investigation was to simulate as accurate as possible representative tests corresponding to the collapse modes that occurred in a series of static edgewise compression tests performed in the National Technical University of Athens (NTUA) using various types of composite sandwich panels. These sandwich panels were candidate materials for use in the new type of composite front-end bumper of a transportation vehicle. Subsequent to the precise reproduction of the collapse
modes, a step-by-step approach was followed in order to examine the influence of selected faceplate and foam core material properties on the crash energy absorption characteristics of the in-plane loaded sandwich panels. More specifically, several series of finite element models were created, by altering the value of only one material parameter per time of the initial FEA models used for the simulation of the sandwich panels collapse modes. The results from the processing of these series of FEA models were used to create figures that graphically depict the influence of the material properties on the energy characteristics. Moreover, the simulation results were analysed in order to express by means of simple linear or polynomial functions the dependence of the crash energy absorption characteristics on the sandwich material parameters. The findings of this series of investigations were recorded aiming to be used as reference to the design of composite sandwich panels in various crashworthiness applications.

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ABSTRACT: Cold-formed steel structural members play a great role in modern steel structures due to their high strength and light weight. The behavior and strength of battened column members composed of slender angle sections are mainly governed by local buckling of angle legs or torsional buckling of the angle between batten plates. Moreover, local buckling depends on the interaction between the width–thickness ratio of angle leg, overall slenderness ratio of angle between batten plates and overall slenderness of column. Theoretical study has been carried out by a nonlinear material and geometrical finite element model. Numerous cases of slender battened column sections having different width–thickness angle leg ratios, overall slenderness ratios between batten plates and overall slenderness ratios are chosen in this study. Complete ultimate strength curves are drawn and different failure modes are studied by taking different member lengths, which produce local or torsional buckling of single angles between batten plates or overall buckling of the member. Empirical equations for the effect of shear deformation factor and the ultimate axial load capacities of members formed of battened slender angle sections are proposed. Strengths of axially loaded battened members predicted using finite element as well as the proposed empirical equations is compared with the design strengths obtained using North American and European codes. It is concluded that the design strengths predicted by North American and European codes are generally conservative, and these design rules have been shown to be reliable using reliability analysis.

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“Strengthening of steel members in compression by mortar-filled FRP tubes”, Thin-Walled Structures, Vol. 64, pp 1-12, March 2013, DOI: 10.1016/j.tws.2012.11.001

ABSTRACT: A strengthening approach to improve the buckling resistance of steel members in compression is introduced in this paper, where a mortar-filled FRP tube is sleeved outside the steel member and wrapped with
FRP fabrics at the ends of the tube. Through axial compression tests on 18 specimens with bi-axial symmetrical cross-section, the load–strain development and failure modes were obtained and improved load bearing capacity and ductility were evidenced. The effects of the cross-section of core steel, slenderness and FRP fabric layers wrapped at the ends of specimens were investigated. It was found that, after strengthening, the failure modes changed from steel yielding at the mid-height of the steel member due to global buckling to local damage at the steel end. As a result, the load bearing capacity increased by 44–215% and ductility increased by up to 877%. The segmentation model was developed for strengthened specimens, by which the calculated load bearing capacity agrees well with the experimental result.

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ABSTRACT: The dimpling process is a novel cold-roll forming process that can enhance the steel material and structural performance by plastically deforming the material surface prior to the section forming operation [1]. Owing to the complex and interrelated nonlinear changes in contact, geometry and material properties that occur in the process and section forming, there have been no existing methods to simulate the process and resultant dimpled products and validate through physical measurements. This paper describes a numerical modelling approach and results into the mechanical properties and structural behaviour of cold-formed dimpled steel. A series of mechanical tests including tensile, plate bending and column compression tests on cold-formed plain and dimpled steel material were conducted for evaluation of numerical results. A finite element approach to practically simulate the dimpling process and experimental tests was presented. True stress–strain data obtained from tests were incorporated into nonlinear simulations of dimpled steel sheets and sections. The simulation of the dimpling process revealed that during the process, various levels of plastic strain are developed throughout the thickness of the steel sheet; this could correlate to the increase in the strength of the dimpled steel as observed in experimental tests and simulations. The simulation of the mechanical tests of dimpled specimens predicted similar results to the experiments, in terms of mechanical properties and structural behaviour. Since the finite element approach was able to successfully represent mechanical properties and structural behaviour of dimpled steel, it can be a powerful method in analysis and design of dimpled steel material and completed sections.

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“Buckling analysis of stiffened plates subjected to non-uniform biaxial compressive loads using conventional and super finite elements”, Thin-Walled Structures, Vol. 64, pp 41-49, March 2013
DOI: 10.1016/j.tws.2012.12.004

ABSTRACT: This paper presents the buckling analysis of stiffened plates, using both conventional and super finite element methods. Mindlin plate and Timoshenko beam theories are utilized so as to formulate the plate and stiffeners, respectively. The arbitrary oriented stiffeners can be positioned anywhere within the plate element and are not limited to be placed on nodal lines. Therefore, any configuration of plate and stiffeners can be modeled. Furthermore, extensive boundary conditions as well as general in-plane loading conditions can be
considered using the proposed method. As the applied in-plane loads are not uniform, the buckling load is evaluated in two steps. First, the elasticity problem is solved to determine the stress distribution in prebuckling stage. Applying the principle of minimum potential energy, based on derived stress distribution, yields to the buckling equation of stiffened plates. Numerical examples are proposed to study the accuracy and efficiency of the developed super elements. Effects of various combinations of biaxial loads along with different boundary conditions on buckling characteristics of stiffened panels are also investigated.

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ABSTRACT: Cylindrical ground supported steel tanks are traditionally applied to store water and inflammable liquids due to their simple structural design, very good behavior under hydrostatic loads, low cost and easy construction. Despite these advantages, thin-walled steel tanks are sensitive to seismic loading. The aim of this work is the simplified, fast and direct optimum seismic design of these special structures, avoiding complicated computational methods such as the finite element or the boundary element methods. This objective is achieved using software developed in-house, where the optimum seismic design is achieved satisfying the stability of these structures under extreme seismic design loads according to the Eurocode 8 or the Greek seismic regulation provisions. The proposed method provides with the most economical dimensions for the tank and its foundation, for a predefined, design liquid volume. The proposed method can be considered as a basis for determining minimum cost seismic design of thin-walled steel tanks that satisfy the structural and stability requirements.

Xiushu Qu, Zhihua Chen and Guojun Sun (Structural Engineering, School of Civil Engineering, Tianjin University, Tianjin 300072, PR China), “Experimental study of rectangular CFST columns subjected to eccentric loading”, Thin-Walled Structures, Vol. 64, pp 83-93, March 2013, DOI: 10.1016/j.tws.2012.12.006
ABSTRACT: To study the behavior of rectangular CFST columns subjected to eccentric loading, a total of 17 rectangular CFST columns uniaxial and biaxial bending tests were carried out. Concrete compressive strength, steel strength, cross-sectional proportion and eccentricity were selected as the variables to be investigated. The relationship between the load and the lateral displacement at the mid-height of the columns in the directions of both the strong and weak axes and the relationships of load versus end shortening for each specimen were duly recorded. The influences of the constraining factor and eccentric ratio in relation to the strength and ductility indexes of the specimens were investigated. Moreover, in order to achieve the ultimate bearing capacity of the relative rectangular hollow sections with a load of the same eccentricity, the rectangular hollow section models were established by means of the FEM. The concrete contribution ratio necessary for the rectangular CFST columns to be able to resist the eccentric loading was obtained also through comparison of the simulated results and the test data. Finally, based on the definitions and conclusions obtained for the design strength of rectangular CFST columns relying on the “Technical specification for design of steel structure dwelling houses in Tianjin” code (DB 29-57-2003), a factor \( \beta \) was proposed to enhance the steel strength in order to take into account the concrete contribution to the resistance. The modified equation can subsequently provide improved understanding and a more accurate predictive ability or value.
ABSTRACT: Conventionally a pipeline resting on a prop tends to buckle upward under thermal loads, which is called upheaval pipeline buckling. To analyze the phenomenon, most previous studies have modeled the pipeline as a long heavy beam resting on a rigid seabed. However, the seabed may be very soft and uneven; consequently, the pipeline may penetrate into the seabed under thermal compressive forces and change its buckling mode. This study is concerned with the effect of seabed resistance on upheaval buckling of pipelines with prop imperfection. We find that the seabed resistance exerts a remarkable influence on the phenomenon of upheaval pipeline buckling.

ABSTRACT: This paper presents an energy-consistent beam theory and uses it to show the order deficiency, shear locking, and other problems of shear-deformable beam theories. The order of spatial differentiation of both Timoshenko's first-order shear-deformable beam theory and the Euler–Bernoulli beam theory is four, but Timoshenko's theory can account for shear deformation but the other cannot. However, Timoshenko's beam theory is shown to be order-deficient by two, and this order deficiency causes the shear locking problem in finite-element analysis of thin beams. Moreover, the use of one shear correction factor alone cannot fully account for the influence of shear warping on the total strain energy of composite beams. The Cosserat rod theory with Green–Lagrange strains is often used to model highly flexible beams because it can account for geometric nonlinearity and first-order shear deformation. Unfortunately, the use of first-order shear theory makes it order-deficient and is prone to shear locking problems. Moreover, it requires the use of three Rodrigues parameters or four Euler parameters for modeling large rotations, but these math-based variables may experience soft singularity (due to discontinuous spatial derivatives) and artificial strains. Furthermore, the use of Green–Lagrange strains to account for geometric nonlinearity is well known to be problematic. It is also shown that shearing- and bending-induced displacements are relative quantities and they cannot be used as nodal degrees of freedom in finite-element analysis.

ABSTRACT: The load-carrying behavior of cylindrical thin-walled shell structures under load pressure is strongly dependent on the nature and magnitude of the imperfections invariably caused by various manufacturing/welding processes. Weld-induced geometric imperfections have been reported to have especially detrimental effects on the buckling resistance of shells under uniform external pressure. Buckling and post buckling capacity of the shells depend considerably on the cross-sectional form and depth of the geometric imperfections. It also relies on the $H/R$ and $R/t$ ratios ($H$=height, $R$=radius, and $t$=thickness of a cylindrical shell). In the present study, we manufactured and tested a series of specimens having 4 $t$ and 8 $t$ magnitudes of
imperfections with different ratios of $H/R$ and $R/t$. The results of testing under different codes are compared. This study shows considerable reduction in the buckling resistance of the shells.

DOI: 10.1016/j.tws.2013.01.002
ABSTRACT: The paper presents an analysis of the optimal design of cold-formed beams with generalized open shapes under pure bending, uniformly distributed loads, concentrated loads and axial loads with constant bending moment. The optimization problem includes the cross section area as the first objective function and the deflection of a beam as the second one. The geometric parameters of cross sections are selected as design variables. The set of constraints includes global stability condition, selected forms of local stability conditions, strength condition and technological and constructional requirements in a form of geometric relations. The strength and stability conditions are formulated and analytically solved using mathematical equations. The optimization problem is formulated and solved with help of the Pareto concept of optimality. The numerical procedure, based on the Messac normalized constraint method, include discrete, continuous and discrete-continuous sets of design variables. Results of the numerical analysis for different loads of beams with monosymmetrical cross section shapes are presented in tables.

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“Effect of offset web holes on web crippling strength of cold-formed steel channel sections under end-two-flange loading condition”, Thin-Walled Structures, Vol. 65, pp 34-48, April 2013,
DOI: 10.1016/j.tws.2012.12.003
ABSTRACT: A combination of experiments and non-linear finite element analyses are used to investigate the effect of offset web holes on the web crippling strength of cold-formed steel channel sections under the end-two-flange (ETF) loading condition; the cases of both flanges fastened and unfastened to the support are considered. The web holes are located at the mid-depth of the sections, with a horizontal clear distance of the web holes to the near edge of the bearing plate. Finite element analysis results are compared against the laboratory test results; good agreement was obtained in terms of both strength and failure modes. A parametric study was then undertaken to investigate both the effect of the position of holes in the web and the cross-section sizes on the web crippling strength of the channel sections. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the depth of the web, and the ratio of the distance from the edge of the bearing to the flat depth of the web. Design recommendations in the form of web crippling strength reduction factors are proposed in this study.

M.F. Hassanein, O.F. Kharoob and A.M El Hadidy (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Lateral-torsional buckling of hollow tubular flange plate girders with slender stiffened webs”, Thin-Walled Structures, Vol. 65, pp 49-61, April 2013
DOI: 10.1016/j.tws.2013.01.006
ABSTRACT: This paper is concerned with the assessment of the lateral–torsional buckling (LTB) of hollow tubular flange plate girders (HTFPGs) with slender stiffened webs. Using the general purpose finite element package ABAQUS, 3-D finite element (FE) models for simply supported HTFPGs subjected to uniform bending are built. First, a preliminary analysis is conducted to compare the HTFPGs with their equivalent I-section plate girders with flat flanges (IPGs). The results indicate that the HTFPGs display larger load-carrying capacities and stiffnesses compared to IPGs especially in the elastic LTB range. In addition, it is found that the inelastic LTB dominates the failure mode for higher spans of HTFPGs compared to equivalent IPGs. Consequently, a parametric study for the HTFPGs is carried out considering two key parameters; namely the radius of gyration of the compression–flange and the section modulus. The results showed that using HTFPGs with less slender webs (i.e. with shorter webs) for medium-to-long spans optimizes the girders by reducing their weight. Additionally, to save the fabrication costs via reducing the weld lengths, it is more significant to increase the hollow tubular flange depth. It is as well found that the AISC and EC3 provide highly conservative predictions for the HTFPGs under bending. A modified AISC design method is, therefore, suggested to predict the flexural strength of the HTFPGs. The results predicted by the proposed method show better agreement with the FE strengths than the values predicted by the AISC and EC3.

ABSTRACT: The purpose of this work is to investigate the effect of top stiffening rings of open top tanks on the critical harmonic settlement. First, the buckling behavior of a tank with a top stiffening ring is provided and the results are compared with that of the model with no stiffening ring. The results show that the critical harmonic settlement for the tank with a top stiffening ring is lower than that for the tank with no top stiffening ring. Moreover, the top stiffening ring plays a significant role on the critical harmonic settlement when the wave number is small, but plays a minor role on that when the wave number is large. Then, the imperfection sensitivity analysis is conducted to identify whether the top stiffening ring can decrease the sensitivity of imperfection. Meanwhile, the worst imperfection form for tanks subjected to harmonic settlement is reported. The results present that the weld depression has the most adverse effect on the settlement carrying capacity of tanks. Moreover, it is indicated that the top stiffening ring cannot always decrease the sensitivity of the imperfection. The sensitivity plots are related to harmonic wave numbers, as well as imperfection forms. Finally, the effect of top stiffening rings with different structure parameters on the critical harmonic settlement is reported, including the length and the thickness of the top stiffening ring. For the length of the top stiffening ring, the critical harmonic settlement versus the wave number decreases more and more slightly with the increasing length of the top stiffening ring. For the thickness of the top stiffening ring, the critical harmonic settlement versus the wave number decreases more and more mildly with the thickness of the top stiffening ring on the increase.

Shanmuganathan Gunalan, Prakash Kolarkar and Mahen Mahendran (School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology), “Experimental study of load bearing cold-formed steel wall systems under fire conditions”, Thin-Walled Structures, Vol. 65, pp 72-92, April 2013, DOI: 10.1016/j.tws.2013.01.005
ABSTRACT: Light Gauge Steel Framing (LSF) walls made of cold-formed and thin-walled steel lipped channel studs with plasterboard linings on both sides are commonly used in commercial, industrial and residential buildings. However, there is limited data about their structural and thermal performance under fire
conditions while past research showed contradicting results about the benefits of using cavity insulation. A new composite wall panel was recently proposed to improve the fire resistance rating of LSF walls, where an insulation layer was used externally between the plasterboards on both sides of the wall frame instead of using it in the cavity. In this research 11 full scale tests were conducted on conventional load bearing steel stud walls with and without cavity insulation, and the new composite panel system to study their thermal and structural performance under standard fire conditions. These tests showed that the use of cavity insulation led to inferior fire performance of walls, and provided supporting research data. They demonstrated that the use of insulation externally in a composite panel enhanced the thermal and structural performance of LSF walls and increased their fire resistance rating. This paper presents the details of the LSF wall tests and the thermal and structural performance data and fire resistance rating of load-bearing wall assemblies lined with varying plasterboard-insulation configurations under two different load ratios. Fire test results including the time–temperature and deflection profiles are presented along with the failure times and modes.

Iman Dayyani, Masih Moore and Alireza Shahidi (Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran), “Unilateral buckling of point-restrained triangular plates”, Thin-Walled Structures, Vol. 66, pp 1-8, May 2013, DOI: 10.1016/j.tws.2013.01.007

ABSTRACT: In this paper the unilateral buckling behavior of point restrained triangular plates is studied. Firstly, the energy functional of a general triangular plate with elastic foundation is calculated. The Rayleigh–Ritz method for investigating the local buckling of unilaterally restrained triangular plates is applied. The displacement functions and restraining medium are modeled as polynomials and tensionless foundation respectively. The results are obtained for different boundary conditions, aspect ratios and various in-plane compressive and shear loadings. Confirming the validity of this investigation, convergence and comparison studies are undertaken. The comparisons show the efficiency and accuracy of the presented method.

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ABSTRACT: The collapse of thin-walled tubes under axial and oblique loading is frequently encountered in real crash events. The windowing and multi-cell methods are effective in improving tubes' energy absorbing performance. In this paper, a comparative study on the performance of windowed and multi-cell square tubes of the same weight under axial and oblique loading is conducted numerically. The results show that the multi-cell tube can achieve higher mean crushing force than the windowed tube but the windowed tube has lower initial peak force. The effectiveness of both methods reduces as the load angle increases. Moreover, the multi-cell and windowed tubes may have worse performance than the conventional tube if the former two collapse in global bending and the later in axial mode.

ABSTRACT: Thin-walled tubes made from metals or fibre–resin composites have been used widely as energy absorbers in structural crashworthiness applications. A relatively recent advent of composite energy absorbers are externally fibre-reinforced metal tubes, where fibres are bonded to the metal tube surface. Such composites take advantage of the favourable characteristics of each material, being the stable, ductile plastic collapse mechanism of the metal and the high strength to weight ratio of the fibre–resin composite. While several recent experimental and analytical studies have highlighted the substantial improvements in performance fibre strengthening provides, the potential use of such members as structural components in vehicles has yet to be explored. This paper presents a numerical study of the application of fibre strengthened steel tubes to the frontal crush tubes of two different passenger vehicles under frontal collisions. Substantial improvements in vehicle crash performance are demonstrated, as is the potential for vehicle light-weighting. Such components have the potential to contribute to improvements in fuel efficiency and emissions reductions in future passenger vehicle fleets.

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ABSTRACT: An analytical method is proposed to determine the dynamic response of 3-D rectangular fluid containers with four flexible walls, subjected to seismic ground motion. By applying Rayleigh–Ritz method using the vibration modes of flexible plates, fluid–structure interaction effects on the dynamic responses of fluid containers are considered. A mechanical model, which takes into account the deformability of the tank wall, is developed. The maximum seismic loading of the base at the tank and a section immediately above it can be predicted by this model. Accordingly, a 2-D simplified model is proposed to evaluate pressure distribution on the flexible tank wall.

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ABSTRACT: To simplify the waste concrete recycling process, the authors have proposed several new kinds of structural members containing demolished concrete with a distinctly larger size than conventional recycled aggregates. Previous researches and applications have preliminarily verified the suitability of these new environment-friendly structural members. The objective of the presented research is to provide new test data to study the seismic performance and to evaluate the strength and ductility of the thin-walled circular steel tubular column filled with demolished concrete blocks (DCBs) and fresh concrete (FC). Fifteen specimens, including 10 columns filled with DCBs and FC and 5 reference columns filled with FC alone, were tested under combined constant axial compression and reversed cyclic lateral loadings. Test variables are: replacement ratio of DCBs, thickness of steel tube, and axial load ratio. Based on the concept of combined strength of new and old concrete in steel tube, some design codes are employed to predict the lateral strength of the specimens. Research findings
indicate that: (1) the seismic performance of thin-walled circular steel tubular columns filled with DCBs and FC is similar to that of the reference columns filled with FC alone; (2) the lateral strength of the columns filled with DCBs and FC is slightly lower than that of the reference columns filled with FC alone; and (3) even though the diameter-to-thickness ratio is only 168, the ultimate drift ratio of such a specimen filled with DCBs and FC with an axial load ratio of 0.4 can reach 4%, showing good deformation capacity.

You-Fu Yang and Guo-Liang Ma (State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China), “Experimental behaviour of recycled aggregate concrete filled stainless steel tube stub columns and beams”, Thin-Walled Structures, Vol. 66, pp 62-75, May 2013 DOI: 10.1016/j.tws.2013.01.017

ABSTRACT: The behaviour of recycled aggregate concrete (RAC) filled stainless steel tube (RACFSST) stub columns and beams under short-term loadings was experimentally studied, and a total of 28 specimens, including 14 stub columns and 14 beams, were tested. The experimental investigations were carried out on circular and square specimens with recycled aggregate replacement ratio of 0, 25%, 50% and 75%, and both recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) were adopted in the tests. The main objectives of these tests were threefold: first, to describe a series of tests on new composite stub columns and beams; second, to investigate the effect of cross-section type and recycled aggregate replacement ratio on the compressive and flexural behaviour of RACFSST specimens; and finally, to evaluate the accuracy of the calculated bearing capacity, bending moment capacity and section flexural stiffness of the RACFSST specimens by using the design formulae in six codes related to the design of concrete filled carbon steel tube. The experimental results showed that the RACFSST stub columns and beams under short-term loadings had the stable load versus deformation responses and the good deformation-resistant ability, and the performance of core RAC was generally enhanced due to the confinement of the outer stainless steel tube.

Jian-guo Nie, Yu-hang Wang and Jian-sheng Fan (Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China), “Experimental research on concrete filled steel tube columns under combined compression-bending-torsion cyclic load”, Thin-Walled Structures, Vol. 67, pp 1-14, June 2013, DOI: 10.1016/j.tws.2013.01.013

ABSTRACT: Based on the force–displacement mixed control quasi-static test on eight CFST columns subjected to combined compression, bending and torsion cyclic load, the mechanical behavior of CFST columns with various section types, bending moment to torsion moment ratios and axial load levels was studied. The test results showed that the hysteretic curves of CFST columns under combined compression, flexure and torsion are plump due to the good seismic behavior and the ductility was also good. But for rectangular CFST columns with high bending moment to torsion moment ratio, the strength degradation was observed due to the local buckling of the steel plate at the bottom. The torsion capacity of CFST columns would be reduced by the bending moment. The plane section assumption of axial strain of CFST columns could be satisfied. The shear strain of the steel tube has good linear relationship with the rotation angle of the section when CFST columns subjected to combined compression, flexure and torsion. Based on the test results and literatures available, the mechanism of CFST columns was qualitatively analyzed.

Ali Ghadianiou and Shahrir Bin Abdullahk (Department of Mechanical and Materials Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia), “Crashworthiness design of

ABSTRACT: In low speed collisions, insurance cost is a factor which is taken into account as a design criterion to reduce structure damage and fixing cost. In this study, it is focused on the applied permanent damages of vehicle frontal door caused by pole impacts. In the side impact, the side door beam is responsible to absorb the most possible kinetic energy. Two significant parameters including material and geometry of a side door beam are discussed here to reduce permanent damage of the door. To study the effect of material as the first phase, six different sheets of material have been concerned to investigate the rigidity of the structure. For the second phase, geometry modification of the side door beam has been performed via creating new CAD-reinforcing ribs. Consequently, the strength in elasto-plastic mode, maximum deflection and plastic strain of the equipped system representing the permanent damage is obtained in order to achieve lower losses.

Hasan Gedikli (Karadeniz Technical University, Department of Mechanical Engineering, Trabzon 61080, Turkey), “Crashworthiness optimization of foam-filled tailor-welded tube using coupled finite element and smooth particle hydrodynamics method”, Thin-Walled Structures, Vol. 67, pp 34-48, June 2013

DOI: 10.1016/j.tws.2013.01.020

ABSTRACT: This paper has presented the optimal design for empty and foam-filled tailor welded tubes (TWTs). Specific energy absorption, peak force and crushing force efficiency (CFE) were used to determine energy absorbing capacity in empty and foam-filled tubes using both finite element and smooth particle hydrodynamics methods. Numerical results showed that SEA and peak force increased with increasing thickness of upper part and foam density while peak forces were significantly low in TWTs made from different materials. Moreover, CFE decreased with increasing thickness of upper part and with decreasing welding location whereas CFE slightly increased with increasing foam density.

Ming Song and ShiRong Ge (Institute of Rescue Technology and Equipment, School of Mechanical and Electrical Engineering, China University of Mining & Technology, Xuzhou 221116, China), “Dynamic response of composite shell under axial explosion impact load in tunnel”, Thin-Walled Structures, Vol. 67, pp 49-62, June 2013, DOI: 10.1016/j.tws.2013.02.009

ABSTRACT: This paper presents a study on the dynamic response of a capsule-shaped composite metallic shell under axial explosion impact load in a tunnel. The composite shell, which consists of a cylindrical shell and a semi-spherical shell on both ends, is analyzed by experimentation and simulation. The three-dimensional finite element models of the shell and tunnel were established using DYTRAN®, and the simulation and experiment results are highly consistent. The spread trend of shock wave around the shell is analyzed, thus the stress distribution and deformation trend on the composite shell given different shell thicknesses and fixed mode is obtained.


ABSTRACT: In this paper, the nonlinear vibrations of functionally graded (FGM) circular cylindrical shells are analysed. The Sanders–Koiter theory is applied to model the nonlinear dynamics of the system in the case of finite amplitude of vibration. The shell deformation is described in terms of longitudinal, circumferential and radial displacement fields. Simply supported, clamped and free boundary conditions are considered. The
displacement fields are expanded by means of a double mixed series based on Chebyshev orthogonal polynomials for the longitudinal variable and harmonic functions for the circumferential variable. Both driven and companion modes are considered; this allows the travelling-wave response of the shell to be modelled. The model is validated in the linear field by means of data retrieved from the pertinent literature. Numerical analyses are carried out in order to characterise the nonlinear response when the shell is subjected to a harmonic external load; a convergence analysis is carried out by considering a variety of axisymmetric and asymmetric modes. The present study is focused on determining the nonlinear character of the shell dynamics as the geometry (thickness, radius, length) and material properties (constituent volume fractions and configurations of the constituent materials) vary.

M.P. Kulatunga and M. Macdonald (School of Engineering & Built Environment, Glasgow Caledonian University, Cowcaddens Road, Glasgow, Glasgow G4 0BA, UK), “Investigation of cold-formed steel structural members with perforations of different arrangements subjected to compression loading”, Thin-Walled Structures, Vol. 67. Pp 78-87, June 2013, DOI: 10.1016/j.tws.2013.02.014

ABSTRACT: An investigation of cold-formed steel sections subjected to compression loading was undertaken using Finite Element Analysis to study the effects of perforation positions on the load capacity of column members of lipped channel cross-section. For this purpose, a finite element model was developed using ANSYS and its accuracy was verified using experimental and theoretical results. The study showed that the ultimate load of the lipped channels under compression varied greatly with the perforation position. Comparisons of the finite element results and the test results are also made with existing design specifications, and conclusions are drawn on the basis of the comparisons.


ABSTRACT: A new formulation of the Generalized Beam Theory (GBT) that coherently accounts for shear deformation is presented in this paper. In particular, a modified formulation of the kinematics early proposed by Silvestre and Camotim for shear deformable GBT is devised. The new formulation, which preserves the general format of the original GBT for flexural modes, introduces the shear deformation along the wall thickness direction besides that along the wall midline, so guaranteeing a coherent matching between bending and shear strain components of the beam. According to the new kinematics, a reviewed form of the cross-section analysis procedure is devised, based on a unique modal decomposition for both flexural and shear modes. Much attention is posed on the mechanical interpretation of the deformation parameters in the modal space. It is shown that, in the modal space, it is possible to clearly distinguish bending deflections from deflections due to shearing strains, and to recover classical beam degrees of freedom and standard beam theories as special cases. The effectiveness of the proposed approach is illustrated on two typical benchmark problems.

Sherif Saleh Safar (Cairo University, Giza 11835, Cairo, Egypt), “Shear strength of end web panels”, Thin-Walled Structures, Vol. 67, pp 101-109, June 2013, DOI: 10.1016/j.tws.2013.02.003

ABSTRACT: In most classical theories for post-buckled web panels under shear, it was assumed that tension-field action was anchored by flanges and adjacent web panels. Such an assumption led to the conclusion that post-buckling strength can only develop in intermediate web panels. Accordingly, the AISC specifications do not account for post-buckling strength in end web panels. In this paper, more than sixty full-scale plate girders
were modelled and analyzed by the finite element method to assess the shear strength of end web panels. An objective of this nonlinear large deflection numerical study was to clarify the effect of geometric properties of end web panels on their shear strength in the elastic and inelastic buckling ranges. Numerical results were verified by comparison to classical web buckling theory and experimental results published in literature. Unlike most post-buckling theories, it was shown that end web panels possessed post-buckling strength where diagonal tension stresses were equilibrated by compressive stresses in end-bearing stiffeners and portions of the web stiffened by flanges and stiffeners. Numerical results were used to establish new design rules for shear strength of end web panels including tension field action.


ABSTRACT: Inflatable tubes must be pressurized before they are able to resist to external loadings. While there are many studies dedicated to the behavior of inflated tubes under bending or twisting, few results are available on the inflating stage when the beam is only submitted to the internal pressure. In this paper, an exact solution is proposed for a cylindrical tube made of an orthotropic membrane, with the orthotropy axes parallel to the circumferential and longitudinal directions of the cylinder, and undergoing finite deformations under internal pressure. The solution of the problem amounts to solving a cubic equation and analytical relations are given for the inflated geometry as well as the resultant stresses in the membrane. Numerical results are shown to compare very well with those obtained from a finite element code.

Bin Cheng, Jianlei Wang and Chun Li (Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai, China), “Compression tests and numerical analysis of perforated plates containing slotted holes in steel pylons”, Thin-Walled Structures, Vol. 67, pp 129-143, June 2013, DOI: 10.1016/j.tws.2013.02.005

ABSTRACT: This paper presents experimental and numerical studies on the compression behaviors of perforated plates in steel pylons. Each rectangular plate considered has a centrically located slotted hole and is simply supported on four edges in the out-of-plane direction. In a experimental study, 15 specimens, i.e., four non-perforated plates and 11 perforated plates, are tested under uniaxial compression by the use of a self-balanced loading device. The elastic strain distribution, out-of-plane deformation, failure pattern, and ultimate strength are observed in the compression test. In the numerical analysis, finite element models are developed to predict the stress concentration factor and the ultimate strength of plates with various dimensions. The results of the finite element analyses are validated by the experimental data. The influences of non-dimensional parameters including plate slenderness ratio, plate aspect ratio, hole width/plate width as well as hole aspect ratio on the concerned predictions are illustrated on the basis of numerous parametric studies. The results of the studies indicate that slotted perforations make significant alterations in the compression behaviors of perforated plates, and those alterations vary with non-dimensional parameters of plates, holes or between them.

ABSTRACT: Alternative structural layouts for wind turbine blades are investigated with the aim of improving their design, minimizing weight and reducing the cost of wind energy. New concepts were identified using topology optimization techniques on a 45 m wind turbine blade. Additionally, non-dimensional structural shape factors were developed for non-symmetric sections under biaxial bending to evaluate structural concepts in terms of ability to maximize stiffness and minimize stress. The topology optimization evolves a structure which transforms along the length of the blade, changing from a design with spar caps at the maximum thickness and a trailing edge mass, to a design with offset spar caps toward the tip. The shape factors indicate that the trailing edge reinforcement and the offset spar cap topology are both more efficient at maximizing stiffness and minimizing stress. In summary, an alternative structural layout for a wind turbine blade has been found and structural shape factors have been developed, which can quantitatively assess the structural efficiency under asymmetric bending.

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ABSTRACT: The steel plate shear wall system has been used in a number of buildings as an innovative lateral force resistance system. Stiffened steel plate shear walls possess greater stability and energy absorption during dynamic loading, such as during seismic loading, when compared with unstiffened steel plate shear walls. Openings, however, often exist in the steel plate shear walls due to various functional requirements of the structure. These openings may negatively impact the overall capacity of the shear wall, necessitating additional stiffening. Therefore, an experimental research program was instituted to investigate the seismic behavior of stiffened steel plate shear walls, with and without openings. Strength, stiffness, ductility and energy absorption were evaluated based on the results of reversed cyclic loading tests on three specimens. Two of the test walls had openings, while one wall was constructed without any openings. The test program results showed that stiffened steel plate shear walls exhibit satisfactory seismic behavior, and, as expected, the strength and stiffness characteristics of the walls were reduced in walls with openings. In addition to the test program, an analytical study utilizing a beam–shell mixed Finite Element (FE) model of a single-story wall panel with boundary columns is made to determine the critical factors influencing the shear strength reduction of stiffened wall panels with the opening. Furthermore, extensive numerical calculation and parametric analysis are conducted to derive a simplified formula for the determination of the shear strength reduction coefficient. In addition, complex elasto–plastic FE models of the three specimens are developed to investigate in detail the lateral force resistance behavior of stiffened steel plate shear walls. Good agreement is observed between the experimental and numerical results. Finally, a design method for calculating the lateral resistance capacity, based on the test program and the FE model analysis, is recommended to be used for the routine design practice of stiffened steel plate shear walls.

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ABSTRACT: This work reports the results of a numerical investigation on the influence of the cross-section geometry and end support conditions on the post-buckling behaviour and Direct Strength Method (DSM) design of cold-formed steel columns buckling and failing in distortional modes. The columns analysed exhibit (i) four end support conditions, (ii) different cross-section shapes, dimensions and lengths, and (iii) several yield stresses. These features were carefully selected in order to ensure, as much as possible, that all columns (i) buckle and fail in “pure” distortional modes and (ii) cover a wide (distortional) slenderness range. The post-buckling equilibrium paths and ultimate loads presented and discussed were obtained through Ansys elastic and elastic-plastic shell finite element analyses. Moreover, the ultimate strength data acquired are used to show that, regardless of the column geometry, the current DSM distortional design curve is not able to predict adequately (safely and accurately) the ultimate loads of columns with other than fixed end supports. The paper also includes a preliminary assessment/proposal of the modifications that must be included into this DSM design curve in order to overcome the above limitation.

Ehab Ellobody (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “A consistent nonlinear approach for analyzing steel, cold-formed steel, stainless steel and composite columns at ambient and fire conditions”, Thin-Walled Structures, Vol. 68, pp 1-17, July 2013
DOI: 10.1016/j.tws.2013.02.016

ABSTRACT: This paper presents a consistent nonlinear 3-D finite element approach, adopted by the author over the last ten years, for analysing steel, cold-formed steel, stainless steel and composite columns at ambient and fire conditions. The main parameters affecting the finite element approach, which has accounted for the nonlinear material properties of the column cross-sections at ambient and elevated temperatures, initial local and overall geometric imperfections and residual stresses, are highlighted in this paper. The finite element approach could be easily extended to study columns constructed from other materials or built-up using different sections. This paper also presents up-to-date review for previously published experimental and numerical investigations highlighting the stability of the aforementioned columns at ambient and elevated temperatures. In addition, the paper highlights the design rules specified in current codes of practice for the columns. Furthermore, this paper presents, as examples, comparisons of finite element analysis results, previously reported by the author, with design values calculated using of current codes of practice. In overall, the paper aims to stress the fact that consistent, robust and efficient nonlinear 3-D finite element models could improve and assess the accuracy of design rules specified in current codes of practice at ambient and elevated temperatures. Also, better understanding of the structural performance of the columns in the cold condition is essential to analyse the column behaviour under severe fire conditions.


ABSTRACT: This study presents the effect of various geometrical parameters of circular single perforation on the critical/ultimate buckling load of a circular lean duplex stainless steel (LDSS) stub column loaded axially using finite element (FE) software, Abaqus. The effect of eccentricity (distance between the perforation centre and edge of column), hole diameter and column thickness are studied on the critical buckling load capacity. The decrease of buckling load when perforation size \((d/D)\) is increased from 0.02 to 0.20 is found to be 13.9%, 13.5%, 12.0%, 10.1%, 8%, respectively, for perforation eccentricities \((e/L)\) of 0.5, 0.4, 0.3, 0.2 and 0.1, indicating maximum reduction of buckling load when the perforation is located at mid-height (or \(e/L=0.5\)). For
lower values of \( d/D \) (say 0.02), there is no significant effect of perforation on the buckling load for all values of eccentricities considered. With 72% increase in thickness (from \( t=2.75 \)), the buckling load is found to increase by 5.0%, 4.2%, 3.2%, 1.2%, 0.3%, 0% for \( d/D=0.20, 0.12, 0.10, 0.08, 0.04, 0.02 \), respectively, with the rate of increase higher for higher \( d/D \) ratios.

A. Alavi Nia and M. Parsapour (Mechanical Engineering Department, Bu-Ali Sina University, Hamedan, Iran), “An investigation on the energy absorption characteristics of multi-cell square tubes”, Thin-Walled Structures, Vol. 68, pp 26-34, July 2013, DOI: 10.1016/j.tws.2013.01.010
ABSTRACT: Due to increasing applications of thin-walled structures, especially as energy absorber, considerable researches have been made about them. In this paper, firstly, behavior of simple and multi-cell square tubes with equal cells is studied analytically, experimentally and numerically. Then, it is shown that for 3×3 square tubes with unequal cells, adding the partitions at corners increases energy absorption capacity of the tubes. Furthermore, the Zhang’s formula for prediction of mean crushing load (MCL) is revised to inclusion of unequal cells square tubes; then, analytical and numerical results are validated with experiments. Finally, it is shown that the energy absorption capacity of the proposed new multi-cell square section is about 227% greater than that of simple section.

Qijie Ma and Peijun Wang (Civil Engineering Department, Shandong University, Jinan, Shandong Province 250061, China), “Simplified stability design method for the stiffened plate with slotted holes under uniform compression”, Thin-Walled Structures, Vol. 68, pp 35-41, July 2013, DOI: 10.1016/j.tws.2013.02.017
ABSTRACT: The elastic buckling and nonlinear post-local buckling behavior of a stiffened plate with slot holes is different to that of a solid plate. As results of systematic parameter studies, design equations for calculating the elastic buckling stress of a solid plate is modified for design a stiffened plate with slot holes. Numerical simulation shows that in the post-local buckling phase, the slots cause the membrane stress redistribution and help the non-slotted region developing into a much higher stress state, which may lead to the increase in the load bearing capacity of the slotted plate. Through studying the longitudinal stress distribution along the plate width, the effective width design equation for the solid plate is also modified to account for effects of the slots. Comparisons of the effective width factor obtained from the proposed equations, previous research results and the numerical simulation show that they agree well with each other.

ABSTRACT: Current stainless steel design standards are based on elastic, perfectly plastic material behaviour providing consistency with carbon steel design expressions, but often leading to overly conservative results, particularly in the case of stocky elements. More economic design rules in accordance with the actual material response of stainless steel, which shows a rounded stress–strain curve with significant strain hardening, are required. Hence, the continuous strength method (CSM) was developed. The CSM replaces the concept of cross-section classification with a cross-section deformation capacity and replaces the assumed elastic, perfectly plastic material model with one that allows for strain hardening. This paper summarises the evolution of the method and describes its recent simplified form, which is now suitable for code inclusion. Comparison of the predicted capacities with over 140 collected test results shows that the CSM offers improved accuracy and reduced scatter relative to the current design methods. The reliability of the approach has been demonstrated by
statistical analyses and the CSM is currently under consideration for inclusion in European and North American design standards for stainless steel structures.

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“Full-range analysis on square CFST stub columns and beams under loading and chloride corrosion”, Thin-Walled Structures, Vol. 68, pp 50-64, July 2013, DOI: 10.1016/j.tws.2013.03.003
ABSTRACT: This paper presents a finite element analysis (FEA) on concrete filled steel tubular (CFST) members with square sections under both loading and chloride corrosion, the established FEA model was verified by the experimental results presented in the companion paper (Han et al., 2012) [1]. The FEA model was then used to perform mechanism analysis on the CFST stub columns and beams subjected to both loading and chloride corrosion. Full-range analysis on the load versus deformation relations was carried out. Finally, simplified methods for calculating the strength of CFST stub column and beam under long-term loading and corrosion were illustrated based on the parameter analysis.

ABSTRACT: This paper presents finite element simulations of the crash behavior and the energy absorption characteristics of thin S-shaped longitudinal members with variable cross-sections made of different materials to investigate the design of optimized energy-absorbing members. Numerical studies are carried out by simulation via the explicit finite element code LS-DYNA [1] to determine the desired variables for the design of energy-absorbing members. The specific energy absorption (SEA), the weight of the members and the peak force responses during the frontal impact are the main measurements of the S-shaped members' performance. Several types of inner stiffening members are also investigated to determine the influence of the additional stiffness on the crash behavior.

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ABSTRACT: Filament winding and twice co-curing processes were applied to make advanced carbon fiber reinforced composite (CFRC) sandwich cylinder with lattice cores. Split metallic moulds were designed and adopted for easy demoulding after winding the lattice core. The cylinders were designed with a small tapering to assure tight contact between the lattice core and the inner skin. To avoid local failure at the end of the
cylinder, flange structures were placed continuously from the fibers of skins and lattices. Axial compression was carried out to reveal the mechanical behaviors of the fabricated sandwich cylinder. The experiment shows that the advanced making technology shows the promise of lattice sandwich cylinder (LSC) avoiding instability, local buckling, local cracking and debonding.

References listed at the end of the paper:


Yucheng Liu and Qingkui Wang (Department of Mechanical Engineering, University of Louisiana at Lafayette, Lafayette, LA 70503, USA), “Strengthening effects of stiffeners on arbitrarily stiffened and regularly stiffened plates subject to biaxial stress”, Thin-Walled Structures, Vol. 68, pp 85-91, July 2013
DOI: 10.1016/j.tws.2013.02.013
ABSTRACT: A hypothesis that when subject to biaxial stress, the strengthening effects of arbitrarily oriented stiffener can be approximated by those of regularly oriented stiffener is proved through several simulations and comparisons. It is also found that in an arbitrarily stiffened plate with multiple stiffeners, the orientation of the stiffeners does not apparently affect the plate's strength limit. Based on this find, any arbitrarily stiffened plate can be simplified as regularly stiffened plate, therefore can be analyzed through simplified semi-analytical models during buckling strength analysis. The proved hypothesis can also be explained from an existing analytical model for the arbitrarily oriented stiffener. Engineering simulation software ANSYS is used for modeling and analysis involved in this study.
ABSTRACT: Engineers are increasingly expected to consider dynamic loads in the design of structures due to increased security demands and as a result of accidental or intentional impact or explosive events, for example in the construction, infrastructure, offshore, mining, protective and security industries. Metal hollow section tubular columns are used extensively in such applications, however currently no blast design procedures exist for such sections. Recent experimental studies have shown that such sections often sustain substantial local deformations and/or collapse of the cross-section, in addition to global (overall) transverse displacement of the member, when subjected to transverse blast load. These studies investigated a limited range of boundary conditions and blast environments due to the limitations of laboratory testing. The present paper validates numerical models of these experiments, and then extends the numerical models to consider a broad range of geometric properties, boundary conditions and blast conditions typical to axial compression members. The numerical results are used to develop generalised design methods for metal hollow section columns subjected to transverse blast loads. The design model is unified with a recently developed model for tubular columns subjected to transverse impact, providing a generalised solution for the design of metal tubular columns for dynamic loads. Accounting for the development of local deformation of the cross-section is shown to be especially important in the blast design of such members.

Nicola L. Rizzi, Valerio Varano and Stefano Gabriele (Università degli Studi Roma Tre, Via C. Segre, 6 00146 Roma, Italy), “Initial postbuckling behavior of thin-walled frames under mode interaction”, Thin-Walled Structures, Vol. 68, pp 124-134, July 2013, DOI: 10.1016/j.tws.2013.03.004
ABSTRACT: An L frame made up by beam and column having channel cross sections, has been analyzed in a previous work by two of the authors [14]. Depending on the aspect ratio and the joint configuration, it has been proved that the structure can exhibit two simultaneous buckling modes. Here using the asymptotic theory of elastic bifurcation that takes into account mode interaction, the initial slope of the bifurcated paths has been determined. Three cases of joint configurations, which are the more common used in welded connections, have been considered. For each case three admissible bifurcated paths have been found. Two of them show a slope having the same order of magnitude of the ones found in the absence of mode interaction while the remaining exhibits a slope largely steepest. Selecting, for each joint case, the bifurcated path with the higher slope and between them the smallest one, it is found that it is associated to the path which bifurcates at the higher critical load. This means that the stiffer structure is also the less imperfection sensitive. Finally for each one of the cases studied, the effect of initial imperfection has been considered and the real load carrying capacity of the frames has been determined. Finally some results have been compared with those obtained using the FE code ABAQUS.

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“Experimental and theoretical investigation on torsional behavior of CFRP strengthened square hollow steel section”, Thin-Walled Structures, Vol. 68, pp 135-140, July 2013, DOI: 10.1016/j.tws.2013.03.008
ABSTRACT: Carbon fibre reinforced polymer (CFRP) has been used to strengthen steel members in bending and compression. There is a lack of understanding on behaviour of CFRP strengthened steel beams subject to torsion. This paper presents an experimental study on the behaviour of CFRP strengthened square hollow section (SHS) beams in pure torsion. A set of tests on CFRP strengthened steel specimens under torsion was carried out in which several different strengthening configurations were used. CFRP sheet wrapping consisted of different configurations including vertical, spiral, and reverse-spiral wrapping were used. The results showed that using CFRP could improve the elastic and plastic torsional strength of CFRP strengthened steel beam specimens. The number of layers of CFRP and the strengthening configurations were important factors for the improvement. Based on the measured values of the torsional moment at yielding and at ultimate, the corresponding twists, the torsional behavioural curves and the failure modes of the strengthened beam specimens, useful concluding remarks are presented.

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ABSTRACT: This paper describes a series of compression tests performed on welded rectangular hollow section (RHS) columns fabricated from 6.0-mm-thick steel plates with a nominal yield stress of 315 MPa. The ultimate strength and performance of the welded RHS compression members undergoing a nonlinear interaction between local buckling and overall buckling were investigated experimentally and theoretically. The compression test results indicated that the interaction between local buckling and overall buckling had a significant negative effect on the ultimate strength of the welded RHS columns. Design strength formulae for the direct strength method (DSM) for the welded RHS columns were proposed based on the compression test results. The study results confirmed that DSM based on the American Institute of Steel Construction (AISC) or Eurocode 3 (EC3) column curves can properly predict the ultimate strength of welded RHS columns when local buckling and overall buckling occur simultaneously or nearly simultaneously.

ABSTRACT: Multi-cell metal columns were found to be much more efficient in energy absorption than single-cell columns under axial compression. However, the experimental investigations and theoretical analyses of them are relatively few. In this paper, the quasi-static axial compression tests are carried out for multi-cell columns with different sections. The significant advantage of multi-cell sections over single cell in energy absorption efficiency is investigated and validated. Numerical simulations are also conducted to simulate the compression tests and the numerical results show a very good agreement with experiment. Theoretical analyses based on constitutive element method are proposed to predict the crush resistance of multi-cell columns and the theoretical predictions compare very well with the experimental and numerical results.

response of rectangular and square stiffened plates supported on two opposite edges”, Thin-Walled Structures, Vol. 68, pp 164-182, July 2013, DOI: 10.1016/j.tws.2013.03.007

ABSTRACT: Experimental drop weight impact tests have been performed to examine the dynamic response of small-scale stiffened plates struck laterally by a mass with a spherical indenter. The laboratory results are compared with numerical simulations. The plates stiffened with a flat bar or L profile are supported at two opposite edges and impacted at different velocities and locations along the span. The impact scenarios could represent incidents in marine structures, such as load actions due to dropped objects on decks. The experiments are conducted using a fully instrumented impact testing machine. The obtained force–displacement responses show a good agreement with the simulations performed by the LS-DYNA finite element solver. The finite element model includes defining the experimental boundary conditions so as to simulate small axial displacements of the specimen at the supports. This representation can be used to analyze the structural crashworthiness of similar marine structures under collision scenarios. The strain hardening of the material is defined using experimental data of quasi-static tension tests and the strain rate sensitivity is evaluated using standard coefficients of the Cowper–Symonds constitutive model. The results show that the plastic response of the specimens is highly sensitive to the amount of restraint provided at the supports. Furthermore, it is found that in most of the specimens the contribution of the stiffeners to the impact response is insignificant, since the ends of the stiffener are free at the unsupported edges and the specimens experience small axial displacements at the supports.

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ABSTRACT: A numerical study on the elastic buckling behaviour of simply supported cylindrically curved panels, with longitudinal edges unconstrained and loaded edges constrained, including the influence of curvature, aspect ratio and loading type (from pure compression to full in-plane bending) is presented in this paper. Subsequently, an extension of rules for internal plated members’ critical stress calculation from EN 1993-1-5 is proposed that takes into account the effect of curvature. The proposed approach, based on the numerical results, gives a safe but accurate estimate (lower bound) for the elastic critical stress.

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“Theoretical model and investigation of concrete filled stub columns under axial force-torsion combined action”, Thin-Walled Structures, Vol. 69, pp 1-9, August 2013, DOI: 10.1016/j.tws.2013.03.005

ABSTRACT: Concrete filled steel tube (CFST) columns are currently being widely used in the construction of modern buildings and bridges. In practice, the torsion effect will be often created in CFST columns when the horizontal earthquake happened. Based on geometrical, material constitutive and equilibrium equations, a theoretical model called laminated tubes model for analyzing the mechanical behavior of CFST columns under axial force–torsion combined action was proposed. The confined effect provided by the steel tube and the compression softening effect of the concrete could be considered in the proposed concrete material model. Based on the theoretical model, the non-linear analysis program was developed for obtaining the entire loading
history of CFST columns under axial force–torsion combined action. The predicted results have good agreement with test results. The torsion behavior of CFST columns was detailed discussed based on the theoretical model, and the simplified formulae for practical design are also proposed based on regression methods.

M.F. Hassanein and O.F. Kharoob (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Flexural strength of hollow tubular flange plate girders with slender stiffened webs under mid-span concentrated load”, Thin-Walled Structures, Vol. 69, pp 18-28, August 2013
DOI: 10.1016/j.tws.2013.03.016

ABSTRACT: A three-dimensional elastic finite element (FE) model, considering merely the geometric nonlinearity, is used in the first part of this paper to study the overall buckling resistance of hollow tubular flange plate girders (HTFPGs). Modeling is conducted using the general-purpose FE software package ABAQUS under mid-span concentrated loads. The developed model consists of the type and number of elements that allows capturing the different possible buckling mode patterns including local, interactive and lateral-torsional buckling. Finite element results revealed that, unlike the case of conventional beams with solid webs, the moment-gradient factor $C_b$ is significantly influenced by the girder geometry and slenderness. Hence, an equation representing the $C_b$ factor for the case of HTFPGs with slender stiffened webs is proposed. The paper extends to investigate the nonlinear flexural strengths of such girders. The results are compared to the AISC predictions. The original AISC predictions are found to be highly conservative using the code recommended $C_b$ value as well as the current proposed value. However, the suggested AISC strength (found in Hassanein et al., 2013 [1]) using $C_b=1.35$ is found to be the best among other values but it suffers from the discontinuity in the flexural strength-unbraced length relationship. Accordingly, a line representing the middle part of this relationship is currently assumed. Comparisons with FE results indicate that the currently proposed AISC method can fairly predict the flexural strength of the HTFPGs with slender stiffened webs.

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ABSTRACT: Cold-formed stainless steel members are widely used due to their high corrosion resistance and high resistance-to-weight ratio but their susceptibility to buckle implies that instability phenomena such as web crippling, where the web locally buckles due to concentrated transverse forces, must be considered. On the other hand, the emergent ferritic stainless steel has very low nickel content and therefore, they are cheaper and relatively price stable compared to austenitics and duplex. Their promising future has aimed to develop efficient design guidance and as a result, a new unified web crippling resistance expression based on numerical simulations and thereafter validated with experimental results has been proposed.

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ABSTRACT: Two kinds of tubular structures were axially compressed under impact condition, where type-A structure consisted of hat shaped part and flat plate and type-B consisted of two similar hat parts. They were constructed with adhesive. Sheet materials were A1050 and A5052. The crush strength was greater in type-B. Separation of bonded flange was almost suppressed in A1050 type-A and -B structures, though it was highly visible for A5052 structure, especially in type-A. Predicted deformation behavior with separation behavior of the bonded flange by finite element method well agreed with the corresponding experimental result.

Chih-Pong Wu, Yen-Cheng Chen and Shu-Ting Peng (Department of Civil Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC), “Buckling analysis of functionally graded material circular hollow cylinders under combined axial compression and external pressure”, Thin-Walled Structures, Vol. 69, pp 54-66, August 2013, DOI: 10.1016/j.tws.2013.04.002

ABSTRACT: The unified formulations of finite cylindrical layer methods (FCLMs) based on the Reissner mixed variational theorem (RMVT) and the principle of virtual displacements (PVD) are developed for the three-dimensional (3D) linear buckling analysis of simply-supported, multilayered functionally graded material (FGM) circular hollow cylinders and laminated composite ones under combined axial compression and external pressure. In this work, the material properties of the FGM layer are assumed to obey the power-law distributions of the volume fraction of the constituents through the thickness coordinate, and full kinematic nonlinearity is also considered. The accuracy and convergence of the RMVT- and PVD-based FCLMs are assessed by comparing their solutions with both the exact 3D and accurate two-dimensional (2D) solutions available in the literature. A parametric study for variations of the lowest critical load parameters with the material-property gradient index, the load intensity, and the orthotropic, length-to-radius, and radius-to-thickness ratios is carried out.

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ABSTRACT: A design method for continuous profiled decking based on post-elastic moment re-distribution is presented. This method is based on that permitted in EN 1993-1-3: Eurocode 3, and in this paper, its application to highly stiffened composite deck profiles is explored. The new aspect is the way in which the residual negative bending moment is established at high rotations using a non-linear moment–rotation stiffness relationship. Tests on three modern deck profiles of 80 mm depths are presented. It was found that the degree of redistribution of negative moment can be high, and so the stiffness coefficient used for deflection calculations should also reflect the degree of redistribution of moment that occurs at the serviceability limit state.


ABSTRACT: The deformed geometry often is the most important information for applications of highly flexible plates/shells, and a geometrically exact shell theory should be displacement-based in order to directly
and exactly describe any greatly deformed geometry. The main challenges of modeling a shell undergoing large deformation are how to describe its deformed reference plane and its differential element's large rotations and how to derive objective strains in terms of global displacements and rotations that contain both elastic straining and rigid-body movement. This paper presents a truly geometrically exact displacement-based shell theory without singularity problems. The theory fully accounts for geometric nonlinearities, all possible initial curvatures, and extensionality by using Jaumann strains and stresses, exact coordinate transformation, and orthogonal virtual rotations. Moreover, transverse shear deformations are accounted for by using a high-order shear deformation theory. The derived fully nonlinear strain–displacement relations enable geometrically exact forward analysis (obtaining the deformed geometry under a set of known loads) and inverse analysis (obtaining the required loads for a desired deformed geometry). Several numerical examples are used to demonstrate the accuracy and capabilities of the geometrically exact shell theory. Moreover, different theoretical and numerical problems of other geometrically nonlinear shell theories are shown to be mainly caused by the use of Mindlin plate theory to account for transverse shears, Green–Lagrange strains to account for geometric nonlinearities, and/or Euler and Rodrigues parameters to model large rotations.

ABSTRACT: This study presents detailed and rigorous numerical analysis for a parametric series of unstiffened aluminium plates typical of those used in lightweight ships and equivalent thin walled stiffened structures. The study is undertaken with a nonlinear finite element analysis procedure using ABAQUS. The strength behaviour of the plates under a progressively increasing longitudinal in-plane load are shown to be affected by a number of parameters including the alloy, geometric imperfection shape, heat affected zone distribution, level of heat softening and residual stress distribution. The comparative influences of these various factors, some of which are specific to welded aluminium structure, are explored to determine which must be accounted for in the development of a parametric series of design curves.

Kojiro Uenaka (Department of Civil Engineering, Kobe City College of Technology, Gakuenhigashimachi 8-3, Nishi, Kobe 6512194, Japan), “Concrete filled double skin circular tubular beams with large diameter-to-thickness ratio under shear”, Thin-Walled Structures, Vol. 70, pp 33-38, September 2013
DOI: 10.1016/j.tws.2013.04.009
ABSTRACT: Concrete filled double skin circular tubular (CFDST) members consist of double concentric circular steel tubes with concrete sandwiched between them. Having hollow cross-section, CFDST members are lighter than ordinary concrete filled steel tubular (CFT) members, which have solid cross-sections. Therefore, by alleviating seismic force against the foundation during earthquake, CFDST members can be effectively applied to seismic resistant structures such as a high raise bridge pier. The present study aims to investigate shear characteristics of deep CFDST beams experimentally through an asymmetric static four-point loading test. Two main parameters were selected, namely, the diameter-to-thickness and the inner-to-outer diameter ratios. The results showed that the shear resistance of CFDST gradually decreased as inner-to-outer diameter ratio increased. Methods to predict the shear resistance of deep CFDST beams are also provided. Additionally, stress histories of both tubes are discussed based upon their elasto-plastic stress behavior under plane stress condition.
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ABSTRACT: Gap between the steel tube and concrete core can be considered as a kind of initial concrete imperfection in concrete-filled steel tubular (CFST) structures. This paper performs a nonlinear analysis of CFST stub columns with a circumferential gap or spherical-cap gap under axial compression. A nonlinear finite element model is developed, where the nonlinear material behaviour and the effect of gap on the interface behaviour of the concrete and steel tube are included. Close agreement is achieved between the test and calculated results in terms of load-deformation response and ultimate strength. In light of the numerical results, the behaviour of CFST columns with a circumferential gap or spherical-cap gap is analysed. Parametric studies are then carried out to investigate the influence of different parameters on the ultimate strength of CFST stub columns with gaps. Finally, the maximum limit of the gap ratio is proposed for CFST stub columns with circumferential gaps, and a simplified formula is proposed to estimate the effect of spherical-cap gap on the ultimate strength of CFST stub columns as well.

Yang Zhao, Xiang Lei, Zhen Wang and Qing-shuai Cao (Space Structures Research Center, Zhejiang University, Hangzhou 310058, China), “Buckling behavior of floating-roof steel tanks under measured differential settlement”, Thin-Walled Structures, Vol. 70, pp 70-80, September 2013
DOI: 10.1016/j.tws.2013.04.015
ABSTRACT: Large vertical cylindrical steel tanks constructed on soft foundations may bring forth various types of settlement, which is well known as the uniform settlement, the planar tilt and the differential settlement. Measured settlements of steel tanks in several practical projects are first summarized according to the in-site surveying data, and two kinds of settlement patterns are clearly defined, which are referred to as the global differential settlement and the localized differential settlement. Two practical floating-roof steel tanks are taken as the illustrative examples of large steel tanks, which are marked TK-2020 with the height-to-radius ratio of 0.35 as the representatives of large volume tanks and TK-2090 with the height-to-radius ratio of 0.7 as representatives of smaller volume tanks in this paper. Buckling behaviors of the two illustrative tanks under the global and localized differential settlement are investigated using the general-purpose finite element computer package ABAQUS by means of the geometrical nonlinearity algorithm. It is shown that for tanks under global differential settlement, local buckling occurs first at the eave wind girder, followed by a stable post-buckling behavior, so that the local buckling of the wind girder can be taken as the serviceability limit state and the post-buckling strength can be utilized in structural design of tanks. Moreover, the behavior of tanks under localized differential settlement is related to the degree of localization. The buckling behavior in the case of a large circumferential central angle for localized settlement is similar to that under global differential settlement, while the effect of the localized settlement with a relatively small central angle is more obvious than that of the global differential settlement, and the snap-through buckling induced by localized settlement would govern the design.

M.F. Hassanein and O.F. Kharoob (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Shear capacity of stiffened plate girders with compression tubular flanges and slender webs”, Thin-Walled Structures, Vol. 70, pp 81-92, September 2013, DOI: 10.1016/j.tws.2013.04.013
ABSTRACT: In this paper, finite element (FE) investigation is conducted to study the shear behaviour of compression hollow tubular flange plate girders (CHTFPGs) using ABAQUS software. The compression and tension flanges are formed from tubular and flat plate, respectively. First, a comparison is made between the CHTFPGs and plate girders with flat flanges (IPGs). This comparison indicated that CHTFPGs provide higher strengths and consequently provide weight savings compared to IPGs. A parametric study is, then, carried out on simply supported CHTFPGs regarding the span length, the flange dimensions, and the thickness and the aspect ratio of the web. From this study, the key parameters affecting the behaviour and the strength of CHTFPGs are discussed. The shear strengths of the CHTFPGs are determined from the current FE models and then compared to the unfactored design strengths computed according to Eurocode 3. It is found that the predictions following the European specifications are conservative compared to the FE strengths. The FE strengths are also compared with the strength recently proposed by the current authors for girders with upper and lower tubular flanges (HTFPGs). The comparison indicates that the later strength is unconservative compared with the FE strengths. Accordingly, a design method is suggested to calculate the nominal shear strengths of the CHTFPGs based on their FE strengths and the strength results of additionally generated equivalent plate girders with upper and lower flat flanges (IPGs). The suggested design method is found to give more accurate predictions for the shear strengths of the CHTFPGs.

Hossein Khalilpasha and Faris Albermani (School of Civil Engineering, The University of Queensland, Australia), “Hyperbaric chamber test of subsea pipelines”, Thin-Walled Structures, Vol. 71, pp 1-6, October 2013, DOI: 10.1016/j.tws.2013.05.001

ABSTRACT: An experimental study of buckle propagation in subsea pipelines is presented in this paper. The experimental protocol consists of two types of experiments; hyperbaric chamber and ring squash tests. Intact and dented steel and aluminium pipes with different diameter-to-thickness ratio are used in these tests. The experimental results are presented and compared with available analytical and empirical solutions. The sensitivity of buckle initiation to initial geometric imperfection is evaluated. The evolution of hoop and longitudinal strain during buckle propagation is presented to show the extent of plastic deformations.

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“Design of thin wall structures for energy absorption applications: Enhancement of crashworthiness due to axial and oblique impact forces”, Thin-Walled Structures, Vol. 71, pp 7-17, October 2013
DOI: 10.1016/j.tws.2013.04.003

ABSTRACT: This paper describes a computationally aided design process of a thin wall structure subject to dynamic compression in both axial and oblique directions. Several different cross sectional shapes of thin walled structures subjected to direct and oblique loads were compared initially to obtain the cross section that fulfills the performance criteria. The selection was based on multi-criteria decision making (MCDM) process. The performance parameters used are the absorbed crash energy, crush force efficiency, ease of manufacture and cost. Once the cross section was selected, the design was further enhanced for better crash performances by investigating the effect of foam filling, increasing the wall thickness and by introducing a trigger mechanism.
The outcome of the design process was very encouraging as the new design was able to improve the crash performance by an average of 10%.


ABSTRACT: An exact dynamic stiffness element based on higher order shear deformation theory and extensive use of symbolic algebra is developed for the first time to carry out a buckling analysis of composite plate assemblies. The principle of minimum potential energy is applied to derive the governing differential equations and natural boundary conditions. Then by imposing the geometric boundary conditions in algebraic form the dynamic stiffness matrix, which includes contributions from both stiffness and initial pre-stress terms, is developed. The Wittrick–Williams algorithm is used as solution technique to compute the critical buckling loads and mode shapes for a range of laminated composite plates including stiffened plates. The effects of significant parameters such as thickness-to-length ratio, orthotropy ratio, number of layers, lay-up and stacking sequence and boundary conditions on the critical buckling loads and mode shapes are investigated. The accuracy of the method is demonstrated by comparing results whenever possible with those available in the literature.

Iman Shamim and Colin A. Rogers (Department of Civil Engineering & Applied Mechanics, McGill University, Macdonald Engineering Building, 817 Sherbrooke Street, Montreal, QC, Canada H3A 0C3), “Steel sheathed/CFS framed shear walls under dynamic loading: Numerical modeling and calibration”, Thin-Walled Structures, Vol. 71, pp 57-71, October 2013, DOI: 10.1016/j.tws.2013.05.007

ABSTRACT: This paper describes the numerical modelling using OpenSees of shear walls constructed of cold-formed steel (CFS) framing and flat steel sheathing. The first phase comprised non-linear models calibrated using existing reversed cyclic shear wall test data. The second phase involved more advanced models calibrated using data from dynamic shake table tests of single- and double-storey shear walls and additional ancillary component testing. These advanced models were able to accurately reproduce the shear strength and displacement time history and hysteretic response of the dynamically tested shear walls. The use of a building model that incorporates the second phase wall models is demonstrated for the evaluation of representative CFS framed structures using non-linear time history dynamic analyses.

Gregory J. Hancock and Cao Hung Pham (School of Civil Engineering, Building J05, The University of Sydney, NSW 2006, Australia), “Shear buckling of channel sections with simply supported ends using the semi-analytical finite strip method”, Thin-Walled Structures, Vol. 71, pp 72-80, October 2013

DOI: 10.1016/j.tws.2013.05.004

ABSTRACT: Buckling of thin-walled sections in pure shear has been recently investigated using the Semi-Analytical Finite Strip Method (SAFSM) to develop the “signature curve” for sections in shear. The method assumes that the buckle is part of an infinitely long section unrestrained against distortion at its ends. For sections restrained at finite lengths by transverse stiffeners or other similar constraints, the Spline Finite Strip Method (SFSM) has been used to determine the elastic buckling loads in pure shear. These loads are higher than those from the SAFSM due to the constraints. The SFSM requires considerable computation to achieve the buckling loads due to the large numbers of degrees of freedom of the system. In the 1980s, Anderson and
Williams developed a shear buckling analysis for sections in shear where the ends are simply supported based on the exact finite strip method. The current paper further develops the SAFSM buckling theory of Y.K. Cheung for sections in pure shear accounting for simply supported ends using the methodology of Anderson and Williams. The theory is applied to the buckling of plates of increasing length and channel sections in pure shear also for increasing length. The method requires increasing numbers of series terms as the sections become longer. Convergence studies with strip subdivision and number of series terms is provided in the paper.

Abolfazi Darvizeh, Mansour Darvizeh, Reza Ansari and Ata Meshkinzar (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Effect of low density, low strength polyurethane foam on the energy absorption characteristics of circumferentially grooved thick-walled circular tubes”, Thin-Walled Structures, Vol. 71, pp 81-90, October 2013, DOI: 10.1016/j.tws.2013.04.014
ABSTRACT: In this paper, analytical and experimental investigations are performed on the energy absorption characteristics of circumferentially grooved thick-walled circular tubes filled with low density and very low strength polyurethane foam typical of cushioning material. Thick-walled grooved tubes filled with low density foam are prepared for experiments. The results are also compared with the ones for the geometrically identical empty tubes. Employing the Taguchi method for designing the geometrical parameters of the specimens leads to a suitable range of groove length-to-wall thickness ratios to be covered. Based on the concept of energy dissipation through the circumferential plastic hinges during the successive folding of the specimens, an analytical approach is proposed. In addition, the amount of energy dissipated due to the interaction between tube metal and foam material is expressed by a conventional semi-empirical equation. A new constant, \( C_{av},Cav \), for low strength foam material is found by fitting the experimental data. The modified analytical model is in reasonable agreement with the experiments. This may indicate the validity of the proposed analytical model. The obtained results show that grooved thick-walled tubes filled with low strength foams can offer favorable energy absorption capacity and stability. Euler buckling is prevented due to the grooves and specific energy absorption is increased approximately twice that of the empty tubes. Structural effectiveness is increased nearly two times that of the empty tubes.

Tarek Sharaf and Amir Fam (Department of Civil Engineering, Queen’s University, Kingston, ON, Canada), “Analysis of large scale cladding sandwich panels composed of GFRP skins and ribs and polyurethane foam core”, Thin-Walled Structures, Vol. 71, pp 91-101, October 2013, DOI: 10.1016/j.tws.2013.05.006
ABSTRACT: This paper addresses the numerical modeling of lightweight sandwich panels intended for cladding of buildings. The proposed sandwich panels are composed of woven glass fiber reinforced polymer (GFRP) skins and ribs and soft polyurethane foam core, which provides excellent insulation. The panels are designed to resist wind loading. A robust 3D FE model was developed for the large scale panels (9145×2440×78 mm\(^3\)) tested under transverse loading. The model accounts for material nonlinearities; most pronounced in the soft polyurethane core and in the [0/90] GFRP ribs under shear, as well as geometric nonlinearities in the form of a reduction in panel thickness due to the soft core. The model captures both stability and material failure modes, essentially skin wrinkling and crushing in compression. It was then successfully validated using experimental results. Failure of the tension skin never occurred in this type of panels as compression skin wrinkling and crushing consistently governed. The cladding panel was shown to satisfy design code requirements in terms of strength and stiffness.
ABSTRACT: The buckling behavior of quadrilateral laminated thin-to-moderately thick plates composed of perfectly bonded carbon nanotube reinforced composite (CNTRC) layers is studied. The stability equations are derived using the adjacent equilibrium (Trefitz) buckling criterion and based on the first-order shear deformation theory (FSDT) of plates. Four different profiles of the single walled carbon nanotubes (SWCNTs) distribution through the thickness of layers are considered, which include their uniform distribution (UD), functionally graded (FG) symmetric and asymmetric distributions. The stability equations subjected to arbitrary boundary conditions are discretized by employing a mapping-differential quadrature technique. The formulation and method of solution are validated by showing their fast rate of convergence and performing comparison studies with the available results in the open literature wherever possible. In addition, analytical solution for the simply supported symmetric laminated rectangular plate with CNTRC layers is derived and excellent agreement of the numeric results with the analytical solution is exhibited. Then, the effects of volume fraction of carbon nanotubes (CNTs), geometrical shape parameters, thickness-to-length ratio, different kinds of CNTs distribution along the layers thickness and boundary conditions on the critical buckling load of the quadrilateral laminated plates are investigated.

ABSTRACT: The paper concerns the load capacity analysis of thermally loaded multilayered plates and shells. The multilayered body is treated as an equivalent single layer whose kinematics is consistent with the first-order shear deformation theory. The authors focus on the thermo-elastic stability problem of the thin-walled structures. The equilibrium paths are traced with the use of Riks–Wempner–Ramm algorithm. By making use of the Tsai–Wu hypothesis the material's strength examination is included in the study. The considered problems are resolved with the authors' program. The presented results confirm that proposed model can be very effective in the stability analysis of multilayered panels.

ABSTRACT: Expanded metal tubes have a great potential for energy absorbing applications. A study on the energy absorption capacity of axially compressed expanded metal tubes is conducted herein; the investigation is performed through nonlinear finite element analyses. At first, the numerical models are validated with experimental results, thereafter a parametric study is carried out in order to investigate the effects of the length-to-diameter ratio, on both the peak forces and the energy absorption capacity of the tubes. The numerical results are also compared with those obtained using a mechanical model found in the literature. Finally, it is found that peak loads and energy absorption capacity depends on the number of expanded metal cells in the cross-section. The results also show that, concentrical expanded tubes could be an effective mean to enhance energy absorption capacity.
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“Experimental investigation of channel-section composite profiles’ behavior with various sequences of plies subjected to static compression”, Thin-Walled Structures, Vol. 71, pp 147-154, October 2013
DOI: 10.1016/j.tws.2013.07.008

ABSTRACT: This paper deals with the buckling of thin-walled channel-section composite columns subjected to static compression. It was assumed that the columns were supported with articulated joints at both ends. For experimental testing, three series of specimens were manufactured with autoclaving technique. The specimens had identical dimensions but differed about ply sequence. The Hexcel's HexPly M12 carbon-epoxy prepreg was used in order to fabricate the channel-section profiles. During the stand tests minimal critical forces of the real structure and the corresponding buckling modes were determined with an application of electrical strain gauges. In addition, post-critical equilibrium paths for small overloads—150% of the critical load for the ideal structure—were determined. The experimental results were compared to the ones obtained numerically with the finite element method (FEM).

Luis Laim, Joao Paulo C. Rodrigues and Luis Simoes da Silva (ISISE, University of Coimbra, Portugal),
“Experimental and numerical analysis on the structural behaviour of cold-formed steel beams”, Thin-Walled Structures, Vol. 72, pp 1-13, November 2013, DOI: 10.1016/j.tws.2013.06.008

ABSTRACT: A research study on the structural behaviour of cold formed steel beams with C-, I-, R- and 2R-shaped cross-sections at ambient temperature is presented, based on the results of a large programme of experimental tests and numerical simulations. Firstly, several four-point bending tests were carried out in order to assess mainly the failure loads and failure modes of the beams. Secondly, a suitable finite element model was developed to compare with the experimental results, and finally, a parametric study was undertaken in order to investigate the influence of the thickness, height and length of the beams on its structural behaviour.


ABSTRACT: Carbon fiber reinforced polymer (CFRP) composites are considered to have high performance and potential for use in strengthening, retrofitting and for the rehabilitation of structural sections. In this paper, design procedures are proposed for the axial load capacity of cold formed steel lipped channel columns strengthened with carbon fiber reinforced polymer (CFRP). For the purpose of validation, the results are based on the proposed design equation from the North American specification for the design of cold-formed steel structural members (AISI-2007) and Euro code for cold-formed members and sheeting (EC3-EN1993-1-3:2006) are compared against the experimental test data. The test results showed that the capacity of the columns are close to the theoretical values predicted by the AISI-2007 and EC 3 provisions. Some tested specimens showed reduced capacity and premature failure due to peeling and debonding of the CFRP from the
Rahman Seifi and Ali Reza Kabiri (Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran), “Lateral load effects on buckling of cracked plates under tensile loading”, Thin-Walled Structures, Vol. 72, pp 37-47, November 2013, DOI: 10.1016/j.tws.2013.06.010
ABSTRACT: Fractured thin plates may be buckled locally due to applying the tensile loads in certain conditions. Sometimes the buckling mode can occur before fracturing or collapsing. Lateral loads can affect the buckling loads and modes. In thin cracked plates, compressive stress region near the crack or defect can be changed due to the lateral loads, so critical local buckling loads can be increased or decreased. Experimental and numerical study of the buckling load of plates with central crack under axial tensile loading is done. Effects of lateral load and constraint, relative crack length and its direction are investigated.

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“Numerical buckling analysis of an inflatable beam made of orthotropic technical textiles”, Thin-Walled Structures, Vol. 72, pp 61-75, November 2013, DOI: 10.1016/j.tws.2013.06.014
ABSTRACT: This paper is devoted to the linear eigen and nonlinear buckling analysis of an inflatable beam made of orthotropic technical textiles. The method of analysis is based on a 3D Timoshenko beam model with a homogeneous orthotropic woven fabric. The finite element model established here involves a three-noded Timoshenko beam element with $C^0$-type continuity for the transverse displacement and quadratic shape functions for the bending rotation and the axial displacement. In the linear buckling analysis, a mesh convergence test on the beam critical load was carried out by solving the linearized eigenvalue problem. The stiffness matrix in this case is generally assumed not to be a function of displacements, while in the nonlinear buckling problem, the tangent stiffness matrix includes the effect of changing the geometry as well as the effect of the stress stiffening. The nonlinear finite element solutions were investigated by using the straightforward Newton iteration with the adaptive load stepping for tracing the load–deflection response of the beam. To assess the effect of geometric nonlinearities and the inflation pressure on the stability behavior of inflatable beam: a simply supported beam was studied. The influence of the beam aspect ratios on the buckling load coefficient was also pointed out. To check the validity and the soundness of the results, a 3D thin-shell finite element model was used for comparison. For a further validation, the results were also compared with those from experiments at low inflation pressures.

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“Exploring the constancy of the global buckling load after a critical geometric imperfection level in thin-walled
ABSTRACT: Some of the knock-down factors applied in design of rocket launcher structures are based on design recommendations which rely on lower-bound curves from experimental data. The best known example is the NASA guideline SP 8007, published in 1965 and revised in 1968, which is applied for cylindrical structures in the space industry. This guideline is based on test data, computational methods and resources from the 1930–1960’s. At that time the application of less empirical methods for the design of actual cylindrical shells could not count with the current computational power, and the available methods led to quite large discrepancies between experiments and test observations. Significant improvement on the available analyses approaches and manufacturing techniques since 1960’s have not been taken into account in design processes using the NASA SP-8007, and many authors have recognized that for the current standards this guideline is leading to conservative structures. Another aspect for attention regarding application of the NASA SP-8007 for composite shells is that it does not consider the laminate stacking sequence. Moreover, physical observations regarding how does the imperfection sensitivity of unstiffened cylindrical shells change with the presence of an induced geometric imperfection have also suggested that the current applied design rules are too conservative. This conservativeness is confirmed by many tests carried out recently. This study presents an overview of the problem and a detailed description of the physical observations regarding the buckling mechanism of the thin shells under consideration. It is discussed how these observations can be used for less conservative, laminate dependent, knock-down factors accounting for geometric imperfections. The single perturbation load approach is studied in detail and a physically based definition for the minimum perturbation load ($P_1$) is given, paving the way for the development of semi-analytical methods to calculate this minimum perturbation load.

DOI: 10.1016/j.tws.2013.06.009
ABSTRACT: Through a programme of experiments, numerical modelling and parametric studies, the implications of allowing for strain-hardening in the design of laterally restrained steel beams is investigated with particular emphasis on the performance of the bracing elements. A total of twelve tests were performed on simply supported beams considering two basic scenarios: discrete rigid restraints and discrete elastic restraints of varying stiffness. In the latter case, the forces developed in the restraints were measured and compared to the design forces specified in EN 1993-1-1 (2005). Two different restraint spacings were considered in the tests to give non-dimensional lateral torsional slenderness values of 0.3 and 0.4 for the unrestrained lengths. In all tests, bending resistances in excess of the plastic moment capacity were observed, but for the considered restraint spacings, the resistances often fell short of that predicted by the deformation-based continuous strength method (CSM), which allows for strain-hardening. It was concluded that closer restraint spacing may be required to harness significant benefit from strain-hardening and to develop the full CSM bending resistance, though the forces generated in the restraints were within current code requirements.

ABSTRACT: This paper is concerned with an approximate method to predict the bending behaviour and ultimate strength of partially connected composite plate girders. Based on curvature compatibility, analytical
solution incorporating post-buckling effect in the webs and different degree of shear connection is presented herein. Slender girders with centrally placed square or circular web openings of various proportions are considered in the analysis. The obtained results are verified against the corresponding ones using the established finite element method. A satisfactory correlation between the findings establishes the accuracy of the proposed method to a certain extent. Results are presented in the form of ultimate strength and load-deflection response for girders with variations in shear connection stiffness.

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“Buckle interaction in deep subsea pipelines”, Thin-Walled Structures, Vol. 72, pp 113-120, November 2013
DOI: 10.1016/j.tws.2013.07.003
ABSTRACT: The paper investigates the interaction between propagation buckling and upheaval or lateral buckling in deep subsea pipelines. The upheaval and lateral buckling are two possible global buckling modes in long pipelines while the propagation buckling is a local mode that can quickly propagate and damage a long segment of a pipeline in deep water. A numerical study is conducted to simulate buckle interaction in deep subsea pipelines. The interaction produces a significant reduction in the buckle design capacity of the pipeline. This is further exasperated due to the inherent imperfection sensitivity of the problem.

Ingrit Lillemae, Heikki Remes and Jani Romanoff (Aalto University, School of Engineering, Department of Applied Mechanics, P.O. BOX 15300, FIN-00076 Aalto, Finland), “Influence of initial distortion on the structural stress in 3 mm thick stiffened panels”, Thin-Walled Structures, Vol. 73, pp 121-127, November 2013
DOI: 10.1016/j.tws.2013.07.001
ABSTRACT: This paper investigates the effect of initial distortion on the structural stress in 3 mm thick stiffened panels. The influence of initial distortion shape as well as magnitude is studied under axial tension and compression using geometrically non-linear finite element analysis. Different levels of structures are analyzed starting from the plate strips to an actual panel in order to understand how the structural response of thin initially distorted panel builds up. This way the difference between having initial distortion in one or two directions as well as the effect of boundary conditions becomes visible. The results reveal high non-linearity in the behavior of plate strip models and relatively linear behavior of actual plates and panel models in typical fatigue relevant ranges. This is due to support that the actual structures get from having initial distortion in two directions and from surrounding structures. In case of panels the most important effect on structural stresses near the transverse butt weld is the shape of the initial distortion. The second important is the magnitude of initial distortion and significantly less relevant is the straightening effect, i.e. decrease in structural to nominal stress ratio under loading.

Huihuan Ma, Feng Fan, Jie Zhong and Zhenggang Cao (Harbin Institute of Technology, 2619#, 202 Haihe Road, Nangang District, Harbin 150090, China), “Stability analysis of single-layer elliptical paraboloid lattice shells with semi-rigid joints”, Thin-Walled Structures, Vol. 72, pp 128-138, November 2013
DOI: 10.1016/j.tws.2013.06.020
ABSTRACT: Based on the bending stiffness of socket joints obtained through experiments, the finite element models of single-layer elliptical paraboloid latticed shells with the semi-rigid socket joints are established. Parametric analysis of the latticed shells is carried out using ANSYS. The parameters considered are bending
stiffness, ratio of rise to span, rotation-stiffness, ball size, asymmetric load distribution, tube section, support conditions and initial imperfections. The effects of the different parameters on the critical loads of the shells are thereby identified. Both geometric and material nonlinearity are considered during the analysis. Finally, formulae are derived for the calculation of critical loads of the shells under symmetric and asymmetric loading conditions. This will be useful for the design and application of single-layer latticed shells with semi-rigid joints.

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“Finite element model based on coupled refined high-order global-local theory for static analysis of electromechanical embedded shear-mode piezoelectric sandwich composite beams with various widths”, Thin-Walled Structures, Vol. 72, pp 139-163, November 2013, DOI: 10.1016/j.tws.2013.06.001

ABSTRACT: In this study, a new theory for the accurate simulation of the shear-mode behaviour of thin or thick piezoelectric sandwich composite beams is developed. The effects of transverse normal stress and transverse flexibility of layers are considered in the development of the proposed formulation. In order to increase the computational accuracy, all kinematic and stress continuity conditions are satisfied at layer interfaces. Moreover, for the first time, both the electrically induced strain components and the transverse flexibility are taken into account in the proposed formulation. Despite the fact that the number of unknown mechanical parameters in this theory is only one degree higher than the first order shear deformation theory, the accuracy is surprisingly more pronounced for the thicker beams.

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ABSTRACT: Glass fiber reinforced polymer (GFRP) pultruded profiles are being increasingly used in civil engineering applications. Although they offer several advantages over traditional materials, such as high strength, lightness and non-corrodibility, GFRP profiles present low elasticity and shear moduli, which together with their slender walls makes them very prone to buckling phenomena. Several previous studies addressed the global and local buckling behavior of GFRP pultruded members under concentric loading. However, little attention has been given to the effect of small eccentricities, which may arise from material geometrical imperfections or construction errors. This paper presents results of experimental and numerical investigations about the structural behavior of GFRP pultruded columns subjected to small eccentric loading about the major (strong) axis. To accomplish such goal, three series of 1.50 m long GFRP I-section (120×60×6 mm) columns were tested in compression applied with the three following eccentricity/height of the cross-section ratios: e/h=0.00, 0.15 and 0.30. It was found that such small eccentricities are of major importance for the behavior of GFRP pultruded columns. Although the initial axial stiffness of eccentrically loaded columns was similar to that of concentrically loaded ones, for increasing loads the stiffness considerably decreased due to bowing and second-order P–δ effects. Furthermore, results show that the load capacity of columns subjected to loads applied within the kern boundaries is reduced up to 40% at an approximately linear trend. Results obtained from
the experimental campaign were compared with analytical predictions and numerical simulations using (i) the finite element method (FEM) and (ii) the generalized beam theory (GBT). In general, a very good agreement was obtained between experimental data and analytical and numerical results.


ABSTRACT: This work presents a state-of-the-art report of the most recent developments concerning formulations, numerical implementations and applications of Generalised Beam Theory (GBT) to analyse the structural response of thin-walled steel members and frames. After a brief overview of the cross-section analysis, one addresses new findings dealing with the use of GBT to assess the (i) first-order behaviour of steel-concrete composite bridge decks, (ii) buckling and post-buckling behaviour of members and frames with arbitrary loading and support conditions, (iii) vibration behaviour of load-free and loaded open-section members and (iv) dynamic behaviour of members subjected to periodic and moving loads. In order to illustrate the unique features and show the potential of the GBT approach, several numerical results are presented and discussed. For validation purposes, most of these results are compared with values yielded by shell finite element analyses, performed in the codes ADINA, ABAQUS and ANSYS.

References listed at the end of the paper:

DOI: 10.1016/j.tws.2013.07.004
ABSTRACT: This paper presents the main steps and procedures involved in the development of a Generalised Beam Theory (GBT) formulation to perform dynamic analyses of thin-walled members subjected to initial perturbations or acting loads. It combines (i) the GBT modal discretisation of the cross-section deformation with (ii) the commonly adopted vibration mode superposition approach – this combination leads to an original “doubly modal” representation of the displacement field, which (i) provides deep insight into the mechanics involved in the dynamic response under consideration and, moreover, (ii) makes it possible to obtain accurate results with surprisingly low degree of freedom numbers. The application and potential of the formulation is illustrated by presenting and discussing numerical results concerning the dynamic responses of cold-formed steel lipped channel beam in several situations, namely (i) the damped oscillations following the release from a deformed configuration, (ii) the action of uniformly distributed loads with periodic (sinusoidal and square-wave) and impulsive (rectangular) time variations, and (iii) the effect of a point load moving along the span with constant speed. For validation purposes, the GBT-based results are compared with values yielded by Ansys shell finite element analyses – the total number of degrees of freedom involved in the GBT analyses was significantly lower.

M.C. Ray and R.C. Batra (Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, MC 0219 Blacksburg, VA 24061, USA), “Transient hydroelastic analysis of sandwich beams subjected to slamming in water”, Thin-Walled Structures, Vol. 72, pp 206-216, November 2013
DOI: 10.1016/j.tws.2013.06.002
ABSTRACT: This work deals with the transient hydroelastic analysis of a sandwich beam which represents a boat hull. The beam is subjected to slamming pressure while it enters into water with constant vertically downward velocity. A coupled hydroelastic finite element model is developed using higher order shear and normal deformation theories for the faces and the core of the beam and the velocity potential theory for the fluid. Transient responses of the beam for transverse deflection and stresses are studied. Dynamic failure analysis has been carried out to investigate the initiation and cause of the failure of the beam due to slamming load.

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“GBT-based assessment of the buckling behavior of cold-formed steel purlins restrained by sheeting”, Thin-Walled Structures, Vol. 72, pp 217-229, November 2013, DOI: 10.1016/j.tws.2013.06.005
ABSTRACT: This paper presents and discusses the results of a GBT-based numerical investigation concerning the local, distortional and global buckling behaviour of lipped channel and zed-section cold-formed steel purlins restrained by steel sheeting and subjected to an uplift loading. Strengthened (lapped) joints, commonly employed at internal supports to preclude the occurrence of local/distortional buckling phenomena, are also investigated and an illustrative application of the use of GBT to determine strengthening lengths is also presented. The sheeting restraint is modelled by means of elastic translational and rotational springs, located at the purlin upper flange, and the joint strengthening is modelled by doubling the cross-section wall thickness. For validation, the GBT-based results are compared with values yielded by Ansys shell finite element analyses.
Shanmuganathan Gunalan and Mahen Mahendran (School of Civil Engineering and Built Environment Science and Engineering Faculty, Queensland University of Technology, Brisbane QLD 4000, Australia), “Improved design rules for fixed ended cold-formed steel columns subject to flexural-torsional buckling”, Thin-Walled Structures, Vol. 73, pp 1-17, December 2013, DOI: 10.1016/j.tws.2013.06.013
ABSTRACT: This paper has presented the details of an investigation into the flexural and flexural–fl buckling behaviour of cold-formed structural steel columns with pinned and fixed ends. Current design rules for the member capacities of cold-formed steel columns are based on the same non-dimensional strength curve for both fixed and pinned-ended columns. This research has reviewed the accuracy of the current design rules in AS/NZS 4600 and the North American Specification in determining the member capacities of cold-formed steel columns using the results from detailed finite element analyses and an experimental study of lipped channel columns. It was found that the current Australian and American design rules accurately predicted the member capacities of pin ended lipped channel columns undergoing flexural and flexural torsional buckling. However, for fixed ended columns with warping fixity undergoing flexural–torsional buckling, it was found that the current design rules significantly underestimated the column capacities as they disregard the beneficial effect of warping fixity. This paper has therefore proposed improved design rules and verified their accuracy using finite element analysis and test results of cold-formed lipped channel columns made of three cross-sections and five different steel grades and thicknesses.

ABSTRACT: An arch often has elastic end restraints provided by the connected structures or elastic foundations. When the arch is subjected to an in-plane central concentrated load, the load produces combined non-uniform axial compressive and bending actions with complicated distributions along the arch length and these actions are significantly influenced by the stiffness of the end restraints. These combined axial compressive and bending actions increase with an increase of external loads and may reach the values, at which the arch suddenly deflects laterally and twists out of the plane of loading, and fails in a lateral–torsional buckling mode. Little research of the lateral–torsional buckling of such arches has been reported in the open literature. This paper derives the analytical solution for the elastic lateral–torsional buckling load of pin-ended circular arches with a thin-walled section and having in-plane elastic rotational end restraints under a central concentrated load, using the principle of stationary potential energy in conjunction with the Rayleigh–Ritz method. The analytical solution agrees with independent finite element results very well, which indicates that the analytical solution can provide accurate predictions for the lateral–torsional buckling loads of arches having in-plane rotational end restraints. The effects of the stiffness of rotational end restraints on the lateral–torsional buckling resistance of arches are investigated. It is found that the change of the stiffness of rotational end restraints has significant effects on the lateral–torsional buckling resistance of arches.

ABSTRACT: In this paper in-plane (membrane) shear deformations in thin-walled members are discussed. Unlike many earlier works on the effect of shear deformations, the actual work is based on shell model rather than beam model. Thus, the presented work has no intention to develop a new shear-deformable beam theory, by adding some assumed shear deformations to classical beam degrees of freedom, but the actual research considers the thin-walled member as a set of connected flat plates, the displacement field of which is determined by nodal displacements and shape functions. The goal here is to make a full and meaningful modal decomposition within the given displacement field, i.e., to determine sub-fields within the general displacement field so that deformations within the sub-fields would correspond to some desired buckling or deformation modes. The presented work is therefore the direct extension of constraint finite strip method (cFSM), however, this time having a special focus on the shear modes. Though the presented shear modes are initiated by cFSM, and the presentation utilizes the terminology of cFSM, it is to highlight here that the proposed modal decomposition of in-plane shear deformations is not limited to buckling analysis or to the finite strip method. Indeed, the proposed shear space decomposition can be used in any case when the analysed member is thin-walled, built up from flat plates, is modelled by shell-type elements, and the member is prismatic. Since the flexural behaviour of the plates is assumed to follow Kirchhoff thin plate theory, no out-of-plane shear is considered.

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ABSTRACT: The elaborate finite element model of Kiewitt-8 single-layer reticulated dome with span of 40 m subjected to eccentric blast loading was established and all the process from the detonation of the explosive charge to the demolition of reticulated dome structure was reproduced. The blast performance of reticulated dome was numerically studied and two approaches to improve the blast resistant capacity of reticulated dome were discussed. Response types of reticulated dome under eccentric blast loadings were defined. Partially reinforcement of reticulated dome is found to be an effective and economical way to improve its blast resistant capacity compared with fully reinforced reticulated dome. The pre-designed openings on the wall to release blast loading were studied, which provided some guidance on the blast resistant design of such structures.


ABSTRACT: An experimental–numerical investigation of the ballistic impact of 7.62×51 mm soft-core ball 9.5 g projectiles on aluminium tubes is presented in this paper. The tubes are made of Al-6061-T6 and simulate actual components of a helicopter tail rotor drive shaft. Several tests have been carried out: a real gun has been used to produce ordnance velocities and a dedicated support frame has been built to perform impact tests with an angle of obliquity (in order to reproduce the most critical damage on the component that is subjected to torsional service load). Initial and residual velocity of the bullets, shape and dimensions of the damage, and the residual stresses on the components, have been measured. Numerical models of the impact have been developed with the commercial Finite Element code ABAQUS/Explicit. The Johnson–Cook (JC) constitutive model and the Bao–Wierzbicki (BW) ductile fracture criterion have been calibrated for Al-6061-T6 and have been used for
the analyses. The effect of the bullet type on the damage has been investigated; therefore the ball bullet has been fully modelled (core and jacket) to highlight the effect and danger of this type of soft core bullet in case of impact against aluminium thin structures. Numerical models are in good agreement with the experimental results; more specifically they show a satisfactory capability to reproduce the residual velocity of the bullets and the failure mode, as well as the residual stress fields on the tubes near the damaged zone.

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ABSTRACT: The finite element simulation of structures subjected to post-buckling still faces computational limits, especially for large stiffened structures. Several solving strategies have already been proposed in response to this issue. Among them are the adaptive model reduction solving techniques which demonstrated their ability to drastically reduce the number of unknowns as well as to control the approximation error of solving non-linear problems like post-buckling. The challenges regarding these techniques are the computation of a reduced basis at lower cost, the use of an efficient adaptive procedure and the limitation of the number of call to the adaptive procedure. This paper proposes a Post-Buckling Adaptive Model Reduction (PBAMR) strategy, which requires only two initial Ritz vectors without compromising the accuracy of the simulation. This solving method is tested in the case of shear of a stiffened panel.

ABSTRACT: Adding complex sinusoidal patterns on wall surfaces has been recently suggested in literature as an effective innovation for improving energy dissipation of thin walled box beams during axial collapses. This paper studies the energy absorption efficiency and performance of patterned beams under pure bending. A numerical investigation is carried out using commercially available Marc Mentat solver and the investigation is also verified using existing analytical models. Five different types of patterns are tested. The result of adding patterns on individual and combination of walls and the effect of progressive triggering proposed previously in literature on the maximum bending moment of the beam is also studied. Results indicate that the beams with sinusoidal patterns are significantly better in energy absorption in deep bending collapse; an increase of about 53.49% at 0.6 rad is noted in the optimal case. The pattern types which had higher energy absorption in axial impact reflect the same trend in bending collapses. This research may further endorse the viability of using sinusoidal patterned beams in mainstream practical applications.

ABSTRACT: Trapezoidal sheeting of thin-walled steel is applied frequently for roofing and cladding. As such, it is loaded by a concentrated load (at the support) and a bending moment. A recently developed model to predict the sheeting’s failure behaviour leaves the question open whether mode jumping (the phenomenon where a plate dynamically changes its buckling mode during an increasing load) should be taken into account in the model. This article presents the analytical and finite element modelling of square and long plates, which, depending on the boundary conditions, may represent the compressed flange of trapezoidal sheeting. The analytical modelling is based on the combination of several displacement functions and using the principle of minimal potential energy. Hereafter the stability of each part of the resulting equilibrium curves is determined. A spin-off of the analytical model is an analytical expression for a current curve-fitted based prediction formula for the post/pre-buckling stiffness ratio by Rhodes. Furthermore, the accuracy range of a solution by Williams and Walker for the far-post buckling behaviour can be confirmed. The finite element modelling has been carried out by implicit dynamic, and explicit (dynamic) simulations. Both for the load levels and the buckling mode sequences, the analytical and finite element models give equivalent results. It is concluded that for the specific boundary conditions that represent the situation of a compressed flange for trapezoidal sheeting, it is very likely that mode jumping will not occur.

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ABSTRACT: This paper is focused on the lateral-torsional buckling of cracked or weakened elastic beams. The crack is modelled with a generalised elastic connection law, whose equivalent stiffness parameters can be derived from fracture mechanics considerations. The same type of generalised spring model can be used for beams with semi-rigid connections, typically in the fields of steel and timber engineering. As the basis for the present investigation, we consider a strip beam with fork end supports and exhibiting a single vertical edge crack, subjected to uniform bending in the plane of greatest flexural rigidity. We adopt both direct and variational approaches. In the former, conducted within the framework of the Kirchhoff–Clebsch theory, the effect of prebuckling curvature is taken into consideration. This effect is subsequently neglected in the variationally based analyses. First, the three-dimensional elastic connection law adopted is a direct extension of the planar case, which leads to a paradoxical conclusion: the critical moment is not affected by the presence of the crack, regardless of its location. It is shown that the above paradox is due to the non-conservative nature of the connection model adopted (in the sense that the connection law cannot be derived from a potential). Simple alternatives to this cracked-section constitutive law are proposed, based on conservative moment-rotation laws (quasi-tangential and semi-tangential) and consistent variational arguments. Only one of the proposed alternatives leads to a critical moment that depends on both the torsional and flexural stiffnesses of the spring modelling the cracked cross-section. The analyses are always conducted analytically, yielding closed-form characteristic equations for the buckling moments.
Poolanganthan Keerthan and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Experimental studies of the shear behaviour and strength of lipped channel beams with web openings”, Thin-Walled Structures, Vol. 73, pp 131-144, December 2013
DOI: 10.1016/j.tws.2013.06.018

ABSTRACT: Cold-formed steel members are increasingly used as primary structural elements in the building industries around the world due to the availability of thin and high strength steels and advanced cold-forming technologies. Cold-formed lipped channel beams (LCB) are commonly used as flexural members such as floor joists and bearers. However, their shear capacities are determined based on conservative design rules. Current practice in flooring systems is to include openings in the web element of floor joists or bearers so that building services can be located within them. Shear behaviour of LCBs with web openings is more complicated while their shear strengths are considerably reduced by the presence of web openings. However, limited research has been undertaken on the shear behaviour and strength of LCBs with web openings. Hence a detailed experimental study involving 40 shear tests was undertaken to investigate the shear behaviour and strength of LCBs with web openings. Simply supported test specimens of LCBs with aspect ratios of 1.0 and 1.5 were loaded at mid-span until failure. This paper presents the details of this experimental study and the results of their shear capacities and behavioural characteristics. Experimental results showed that the current design rules in cold-formed steel structures design codes are very conservative for the shear design of LCBs with web openings. Improved design equations have been proposed for the shear strength of LCBs with web openings based on the experimental results from this study.

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“Improved fire resistant performance of load bearing cold-formed steel interior and exterior wall systems”, Thin-Walled Structures, Vol. 73, pp 145-157, December 2013, DOI: 10.1016/j.tws.2013.07.017

ABSTRACT: In order to improve the fire performance of load-bearing CFS wall systems for applications in mid-rise buildings, different panels and external insulation were examined in this paper. Experiments on six full-scale CFS wall specimens were performed in which the insulation material of aluminum silicate wool was located outside the CFS frame and sandwiched between two layers of boards on the fire side instead of being placed in the cavity. Five types of panels were involved in the experiments, including gypsum plasterboard, bolivian magnesium board, oriented standard boards (OSB), autoclaved lightweight concrete (ALC) boards and rock wool boards. The results showed a noticeable reduction of heat transfer to the surface of steel stud and a considerable improvement of fire performance of CFS walls by using aluminum silicate wool as external insulation. For CFS walls with aluminum silicate wool as external insulation on fire side, gypsum plasterboard as face layer and bolivian magnesium board as base layer on both sides, different load ratios may result in different failure modes, and the fire resistant time can be more than 150 min when the load ratio was less than 0.65. It was also demonstrated that the fire performance of CFS wall systems lined with bolivian magnesium board or ALC boards were superior to those lined with gypsum plasterboard and OSB. Therefore, bolivian magnesium board may be recommended to replace gypsum plasterboards as the base layer and ALC board may be used to replace OSB as exterior wall panels of CFS wall systems for applications in mid-rise buildings.

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ABSTRACT: This paper presents a study of the failure behaviour of column-supported silos with flexible engaged steel columns, based on finite element analyses. For a wide range of silo and column geometries, the influence of all geometrical parameters to the failure behaviour will be demonstrated. An important finding is that the height over which the column is attached to the silo initially has a positive influence to the failure behaviour and the failure load, but proves to be disadvantageous from a certain critical height.

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ABSTRACT: This paper investigated the bending strength of girth-welded stainless steel circular hollow sections by numerical method. At first, finite element simulation of girth welding process was carried out to obtain the weld-induced residual stresses and deformations employing sequentially coupled three-dimensional thermo-mechanical finite element formulation. Then, nonlinear finite element analysis in which the moment versus end-rotation response, the ultimate moment resistance and the failure mode of the girth-welded circular hollow sections under pure bending were explored incorporating the residual stresses and depressions along with the initial global geometric imperfections was performed. Feasibility of adopting the current codified provisions (Eurocode 3) for stainless steel circular hollow sections in bending as the cross-section slenderness limit for girth-welded stainless steel circular hollow section flexural members was also examined. Results showed that the flexural behavior of girth-welded stainless steel circular hollow sections always involves local buckling near the girth weld on the compression side, which significantly affects the moment versus end-rotation behavior. Moreover, the results demonstrated that the Class 3 slenderness limit of 280ε^2 from Eurocode 3 for stainless steel circular hollow sections in flexure may be applied to girth-welded stainless steel circular hollow sections subjected to bending.


ABSTRACT: This paper presents a novel energy absorption structure known as the origami beam. It is made from a shallow curved thin-walled beam of square cross section whose surface is pre-folded according to an origami pattern. Numerical simulation of the quasi-static lateral collapse of the origami beam shows that two new collapse modes, referred to as the longitudinal folding mode and the mixed mode both of which feature
large magnitude of plastic deformation along the entire beam, can be triggered in the beam, leading to higher energy absorption and lower peak force than those of conventional ones.

ABSTRACT: Buckling and postbuckling behavior of metal plates is governed by their slenderness parameter. Using nonlinear finite element simulations, unstiffened mild carbon steel, stainless steel and aluminum plates under the action of axial compression are first classified into slender, moderate and stocky plates. Then the effects of initial imperfection amplitude on each plate type and material is studied via sensitivity analyses. The results show that the transition from slender to stocky plates, regardless of material type, occurs at the slenderness parameter of 2. Empirical equations for evaluating the buckling and postbuckling capacities of imperfect plates are drawn out. It is observed that the increase of imperfection amplitude decreases the buckling load of slender plates, but their postbuckling reserves and ultimate capacities are unaffected. In contrast, the ultimate strength of stocky plates is highly affected by initial imperfections.

Yuner Huang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Experimental and numerical investigation of cold-formed lean duplex stainless steel flexural members”, Thin-Walled Structures, Vol. 73, pp 216-228, December 2013 DOI: 10.1016/j.tws.2013.07.019
ABSTRACT: Experimental and numerical investigation of cold-formed lean duplex stainless steel flexural members is presented in this paper. The test specimens were cold-rolled from flat plates of lean duplex stainless steel with the nominal 0.2% proof stress of 450 MPa. Specimens of square and rectangular hollow sections subjected to both major and minor axes bending were tested. A finite element model has been created and verified against the test results using the material properties obtained from coupon tests. It is shown that the model can accurately predict the behaviour of lean duplex stainless steel flexural members. An extensive parametric study was carried out using the verified finite element model. The test and numerical results as well as the available data on lean duplex beams are compared with design strengths predicted by various existing design rules, such as the American Specification, Australian/New Zealand Standard, European Code and direct strength method for cold-formed stainless steel. Reliability analysis was performed to evaluate the reliability of the design rules. It is shown that these current design rules provide conservative predictions to the design strengths of lean duplex stainless steel flexural members. In this study, modified design rules on the American Specification, Australian/New Zealand Standard, European Code and direct strength method are proposed, which are shown to improve the accuracy of these design rules in a reliable manner.

Zuxing Pan, Yuansheng Cheng and Jun Liu (School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China), “A semi-analytical analysis of the elastic buckling of cracked thin plates under axial compression using actual non-uniform stress distribution”, Thin-Walled Structures, Vol. 73, pp 229-241, December 2013, DOI: 10.1016/j.tws.2013.08.007
ABSTRACT: An improved hybrid semi-analytical method for calculating elastic buckling load of a thin plate with a central straight through-thickness crack subject to axial compression is proposed. In the study, the actual non-uniform in-plane stress distribution is firstly conducted by using Muskhelishvili’s complex variable formulation in conjunction with boundary collocation method. A deflection shape function, satisfying not only
the outer boundary conditions but also the inner boundary conditions of the crack edges, is obtained by using domain decomposition method. Finally the buckling load of a cracked plate using Raleigh–Ritz energy method is calculated based on the actual in-plane stress distribution and the reasonable deflection shape function obtained. The effects of crack length, plate's aspect ratio are studied for thin plates with different boundary conditions. Results obtained from the proposed method are in good agreement with the existing numerical results and experimental ones. It is finally shown that the proposed method, based on a correct non-uniform in-plane stress distribution, is more accurate than the few existing analytical methods based on a uniform in-plane stress distribution.

Zhanming Qin, Yizhe Feng and Guiping Zhao (State Key Lab for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi’an Jiaotong University, No. 28 West Xianning Rd, Xi’an 710049, PR China), “Modal interactions of a geometrically nonlinear sandwich beam with transversely compressible core”, Thin-Walled Structures, Vol. 73, pp 242-251, December 2013, DOI: 10.1016/j.tws.2013.07.014
ABSTRACT: Modal interactions of a geometrically nonlinear sandwich beam with transversely compressible core in the presence of combination internal resonance are investigated. At first, a geometrically nonlinear, {2,1}-order theory is used to derived the equations of motion and the compatible boundary conditions of the beam. Then, Galerkin's weighted residual method and the multiscale approach are used to address the governing system. Next, modal interactions in the presence of combination internal resonance and subjected to primary-resonance excitation are investigated. Finally, the commercial code ABAQUS is used to validate the theoretical results we have obtained.

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ABSTRACT: Lean duplex stainless steel (EN 1.4162) has recently gained significant attention for its higher structural performance, similar corrosion resistance and lower cost compared to the austenitic steel. This paper presents the nonlinear finite element (FE) analysis, behaviour and design of circular lean duplex stainless steel–concrete–carbon steel double skin tubular (CFDST) short columns under compression. The finite element (FE) model for CFDST short columns is developed and validated by comparisons with experimental results available in the literature. The FE model is used to investigate the fundamental behaviour of axially loaded CFDST short columns with various parameters. The results show that the ultimate axial strength of CFDST short columns increases significantly with increasing the concrete compressive strength or with decreasing the hollow ratio. However, increasing the ratio of inner-to-outer thickness or increasing the yield strength of the inner carbon steel tube leads to insignificant increase in the ultimate axial strength of the short column. The accuracy of the design models given in ACI code and by Han et al. (2011) and of the modified continuous strength method (CSM) for CFDST short columns is examined against the FE and experimental results. It is demonstrated that the ACI code and Han et al. model provide conservative strength predictions of CFDST short columns, with a relatively high margin of safety. The ultimate axial strengths of CFDST short columns predicted by the CSM are unconservative. A new design model is proposed and shown to be a reliable predictor of the ultimate axial strength of CFDST short columns under axial loading.
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ABSTRACT: Compressive tests of the CFT stub columns with artificial notches in the steel tubes were conducted in this paper to investigate the effects of the material imperfections of steel tubes on mechanical performances of the CFT stub columns. The load–displacement responses, column strength and confining effects were discussed in detail. A parametric study, including the notch length, notch orientation, concrete strength and steel ratio, was also conducted. The results indicated that the notched CFT specimens had quite different failure modes from the intact CFT specimens. A notched CFT specimen might fail by cracking of the steel tube or closing of the notch, which was determined by the notch orientation. The results also showed that the notched CFT specimens had lower mechanical performance than those intact CFT specimens because the notch steel tube could not offer sufficient confining effect on the concrete core inside it. Based on the experimental results, an empirical equation for predicting the column strength of a notched CFT column was proposed.

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“Reduced numerical model to investigate the dynamic behaviour of honeycombs under mixed shear–compression loading”, Thin-Walled Structures, Vol. 73, pp 290-301, December 2013
DOI: 10.1016/j.tws.2013.08.016

ABSTRACT: Cellular materials such as aluminium honeycombs combine lightweight with an efficient crash energy absorption capability. They have a major role in a wide range of transport applications to reduce gas emission by the design of lighter structures but remaining safe in accident case. Many investigations on the honeycomb behaviour have been performed, under uni-axial compression loading and more recently under mixed shear–compression loading. The influence of the in-plane orientation has not been however considered. The objective is to develop a reduced numerical model able to investigate, with a reduced cost of calculations, the dynamic behaviour of honeycomb under mixed shear–compression loading and taking into account of the in-plane orientation angle. Reduced model based on the periodicity procedure is developed and its validity range is evaluated. The numerical results show that in terms of pressure–crush curve and collapse mechanisms, the reduced model is consistent with a complete FE model composed of 39 cells with a CPU-time gain efficiency about 97.17%. The reduced model is valid from a loading angle $\psi=0^\circ,\psi=0^\circ$ to a loading angle $\psi_{\text{limit}}$ contained between $\psi=30^\circ,\psi=30^\circ$ and $\psi=45^\circ,\psi=45^\circ$. The reduced model allows investigating in depth the influence of the in-plane orientation and the loading angles on the crush behaviour with minimum time calculations in accord with the validity range.

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ABSTRACT: In this study, the shear buckling behavior and shear failure mode of a locally corroded web were examined using nonlinear FE analysis, depending on the corroded web and web boundary conditions. Longitudinally corroded web panels and triangularly corroded webs were considered for quantitatively evaluating the shear buckling behaviors of the corroded web panel. For the longitudinally corroded web panels, the shear buckling strengths were only slightly reduced by about 9–16% depending on the corroded web conditions and web boundary conditions. Their diagonal tension field widened and became distorted with the pronounced shear-bent shape of the corroded web. In particular, in a web-flange separated boundary case, it is out-of-plane displacement and deformation exhibited different shear buckling modes, i.e., a diagonal tension field in its upper part and a large triangular lateral displacement in its lower part. On the other hand, the triangularly corroded web panels had only slight effect on the shear buckling resistance of the corroded web because this corroded model does not affect the diagonal tension field of web panel.

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ABSTRACT: The nonlinear rotational behaviour of bolted joints in the cold-formed steel purlin system is normally approximated to a linear theoretical model. Based on the experimental and numerical results, this paper employs a new method to obtain the nonlinear flexural rigidity of the sleeved connections for deflection analysis. Two equations are proposed to predict the moment resistance and the effective flexural rigidity ratio respectively, for the sleeved modified Z connections with different configurations. The nonlinear load-deflection behaviour of sleeved connections can then be predicted using these equations.


ABSTRACT: The influence of inner and outer reinforcements on the bending performance of a thin walled aluminum tube was investigated. Polymeric materials (PA6, PP) and glass/carbon fiber reinforced epoxy were considered to form the composite beam for the inner and outer reinforcement, respectively. The experimental results indicated that the outer reinforcement with a [0°/90°] fiber orientation layout increased the collapse load by a factor of 4.5 and 5.3. In the hybrid composite beam (HCB), load carrying capacity (LCC) increased a maximum of 14 times. Load carrying capacity of HCB is 2.5 times higher than the steel tube that is used in automotive industry.

Yang Zhao, Qing-shuai Cao and Liang Su (Space Structures Research Center, Zhejiang University, Hangzhou 310058, China), “Buckling design of large circular steel silos subject to wind pressure”, Thin-Walled Structures, Vol. 73, pp 337-349, December 2013, DOI: 10.1016/j.tws.2013.08.015
ABSTRACT: Large steel silos are typical kinds of thin-walled structure which are widely used for storing huge quantities of granular solids in industry and agriculture. In the present analyses, buckling design of large steel silo subject to wind pressure is demonstrated in accordance with Eurocode (EN1990, 1991, 1993) and the proposed combinational Load Case WE (wind and empty silo) and WF (wind and full silo). The finite element model is established by using the commercial general purpose computer package ANSYS. Five types of buckling analyses are carried out for the geometrically perfect and imperfect models with and without the consideration of the material plasticity, which are designated as LBA, GNA, GMNA, GNIA, and GMNIA in EN 1993 Part 1–6. The geometrical imperfections are known to have a large impact on the buckling behavior of steel silo structure, in which the magnitude and distribution of the weld depression during construction process is adopted to account for fabrication quality. The buckling behavior of a reference silo with a diameter of 40 m and an aspect ratio of 0.9 is first investigated, which shows that the buckling behaviors from Load Case WE and WF are much different. The material nonlinearity shows little influence on buckling resistance in Load Case WE, while the buckling resistance and buckling mode is much sensitive to weld imperfection. In Load Case WF, both material nonlinearity and geometrical nonlinearity effect is strong and detrimental to buckling behavior of steel silos, resulting in decrease of buckling resistance. The buckling deformation corresponding to the critical point in Load Case WE is governed by the circumferential compression which is generated in the windward region of the shells localized at the top part of silo wall. The buckling mode in Load Case WF takes the form of the well-known elephant-foot deformation at the bottom part of the shell wall, which is induced by the meridional compressive stress. It is also indicated from the parametric analyses that the buckling resistance of steel silo is closely correlative with the loading conditions involving the wind velocity, the patch load, and the geometrical parameters including the aspect ratio, the radius-to-thickness ratio, the type of wall thickness, and the wall openings.

M.R. Bambach (Transport and Road Safety (TARS), Faculty of Science, Old Main Building (K15), University of New South Wales, Sydney, NSW 2052, Australia), “Fibre composite strengthening of thin steel passenger vehicle roof structures”, Thin-Walled Structures, Vol. 74, pp 1-11, January 2014, DOI: 10.1016/j.tws.2013.09.018

ABSTRACT: There is an increasing pressure on vehicle manufacturers internationally to increase the strength of vehicle roofs, in response to the ongoing morbidity and mortality related to vehicle rollover crashes. Several countries are mandating increased roof strengths for future vehicle fleets, and this is occurring at the same time as increased regulations to reduce vehicle emissions. Thus light weight strengthening solutions are required to increase roof strengths while minimising structural mass. This paper presents the novel approach of strengthening vehicle roof structure components by bonding carbon fibres to the steel surface. Such fibre strengthening systems have been shown to provide substantial increases in force and energy resistance for steel tubes under both axial crushing and pure bending. The strengthening potential is assessed with a numerical study of two different passenger vehicles subjected to various roof crush test protocols. Numerical models of fibre composite strengthening systems are validated against experiments, then applied to numerical models of the vehicles. Substantial improvements in the roof strength, and correspondingly the vehicles' roof strength to weight ratio, are demonstrated with the fibre strengthening technique. Comparisons are made with models of strengthening the roof structure components by adding steel rather than fibre composite, and the implications with regards to vehicle light-weighting are discussed. It is shown that fibre composite strengthening of vehicle roof structures has the potential to contribute to higher roof strengths and/or light-weighting in future vehicle fleets.
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ABSTRACT: This paper aims to investigate the crushing behaviors of tailor-welded blank (TWB) thin-walled structures. A series of TWB high-strength steel (HSS) square tubes with different weld line locations is used to perform the crushing tests for evaluating the effects of different TWB parameters, such as weld line locations and material combinations, on crushing characteristics. These TWB specimens are fabricated through the laser welding process to ensure sufficiently narrow weld line. In the study, the center edge of TWB square specimens is not welded so that such special TWB structures have open cross section. The crushing test results exhibit excellent repeatability. The collapse modes and force–displacement relationships are compared with each other. It is found that the crushing behaviors of different material combinations are fairly significant for a given weld line location. Such key crushing characteristics as specific energy absorption (SEA), average crush force ($F_{avg}$), peak force ($F_{max}$) are also evaluated for understanding crashworthiness of these TWB structures. The experimental results provide us with some insightful guidance to crashworthiness design of TWB thin-walled HSS structures.

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ABSTRACT: This research is concentrated on the structural strength and behavior of cold-formed steel wall frame sheathed with calcium silicate board under shear load. Test specimens with two different thicknesses of sheathing were assembled, 9 mm and 12 mm, with one-side or two-side of attachment. Monotonic shear and cyclic loading tests are conducted on wall specimens utilizing two C sections connected back-to-back to be as chord studs and calcium silicate board sheathing on the exterior. Based on the test results, detailed discussions on the strength, stiffness, energy absorption, ductility ratio, and failure mode of cold-formed steel wall specimens are given. It is noted that the failure mostly occurred at the bottom track of wall specimens due to the large deformation or tearing failure of track. The wall strength is not affected by the change of sheathing's thickness significantly, but wall frames attached with two-side calcium silicate board sheathing provide higher resisting strength and stiffness than those attached with one-side sheathing. In this study, test results are also used to compare with the previous study that single chord stud was used in the assembly of wall frame. In addition, the suggested response modification factor of the wall sheathed with calcium silicate board is proposed for design purpose.

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ABSTRACT: A partially encased composite I-girder with flat or corrugated web has been proposed to improve the structural performance of continuous composite girder under hogging moment. The flexural behavior of such structure under two points symmetric loading has been experimentally and analytically investigated. Static flexural loading tests showed that the partially encased girder improved bending strength in comparison to steel I-girder, as local buckling of steel flange was restricted by encased concrete. Especially for the corrugated web girder, the ultimate bending strength was improved about 20%, and the ductility also increased about 3 times. In addition, the limitation of width-to-thickness ratios for steel and concrete-encased composite I-girders with corrugated web were suggested to prevent premature failure due to local buckling of compressive flange. Moreover, the analytical methods of flexural strength under service and ultimate state for partially encased composite girder were proposed and verified with experimental results. It was found that the analytical bending strengths agreed well with the experimental ones at both service and ultimate state, which means the proposed analytical equations can be applied in predicting flexural strength accurately for such encased composite girder with flat or corrugated web.

ABSTRACT: A linear model for beams with compact or thin-walled sections and heterogeneous anisotropic materials is presented. It is obtained by means of a Ritz–Galerkin approximation using independent descriptions of the stress and displacement fields. These are evaluated by a preliminary semi-analytic solution based on a finite element description of the cross section. A coherent definition of the deformations and stresses is obtained which includes both the generalized Saint Venànt solution for generic materials and some significant additional effects, due to out-of-plane warping and section distortions. The so-built 1-D model maintains the richness of the 3-D solution using a small number of variables.

ABSTRACT: The great majority of the studies in this area emphasise further the structural behaviour of cold-formed steel members by means of analytical approximation and purely numerical methods. In addition, they generally only take into account the structural behaviour of members with just one profile. On the contrary, this paper reports a series of flexural tests under fire conditions focused on cold-formed galvanised steel beams consisting on compound cold-formed steel profiles which are often used in floors and roofs of warehouses and industrial buildings. The main objective of this research was to assess the failure modes, the critical temperature and the critical time of the studied beams. Other important goals of this research work were also to investigate the influence of the cross-sections, the axial restraint to the thermal elongation of the beam and the rotational
stiffness of the beam supports. Finally, the results showed above all that the critical temperature of a cold-formed steel beam might be strongly affected by the axial restraint to the thermal elongation of the beam.

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ABSTRACT: This paper proposes a new approach for the evaluation of the conventional modes, i.e. rigid, distortional, local and Bredt shear-modes, to be used in the framework of the Generalised Beam Theory (GBT) for the analysis of thin-walled members. The new method identifies a set of conventional modes in a single step cross-sectional analysis and for any type of cross-section, i.e. open, closed and partially-closed ones. The algorithm differs from that of the classical GBT, which requires a two-step evaluation procedure, consisting of an initial choice of the vector basis and its successive orthogonalization. The method is based on a definition of a new quadratic functional, whose steady condition leads to an eigenvalue problem, and directly generates the sought orthogonal basis, here found using a finite-element approach. The accuracy of the proposed method is validated by means of two numerical examples, one dealing with a lipped C-section and one with a partially-closed profile. It is shown that the conventional modes derived with the proposed approach are identical to those determined with the classical two-step procedure, thus limiting the computational effort required in their identification.

ABSTRACT: In this paper, a procedure for a posteriori reconstruction of three-dimensional stresses in the finite element analysis of beams modelled within the framework of the Generalized Beam Theory is presented. The reconstruction is based on the enforcement of the pointwise three-dimensional equilibrium equations over the beam, interpreted as an assembly of thick plates, and on the use of the Recovery by Compatibility in Patches procedure. No corrections to meet the equilibrium boundary conditions on bottom/top wall faces are needed. Numerical results show that the proposed approach allows to effectively recover local stress profiles which match those of three-dimensional solid finite element models.

ABSTRACT: Energy must dissipate during a collision to prevent damage and injury. To reduce loss from collision, energy absorbers are used that dissipate energy upon deformation and folding to prevent damage to critical parts of a structure. In this paper, simple and multi-cell thin-walled tubes made from aluminum with triangular, square, hexagonal and octagonal sections were subjected to quasi-static loading. The experimental results were then compared with numerical simulations. The results showed that the energy absorption capacity
of multi-cell sections is greater than for that of simple sections. Also, hexagonal and octagonal sections in a multi-cell configuration absorbed the greatest amounts of energy per unit of mass.

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ABSTRACT: An experimental investigation of square concrete-filled thin-walled steel tube under local bearing forces is described, and the loads are applied by a steel bearing member (BM). A total of 20 specimens, including 12 concrete-filled steel tubular (CFST) members, 4 reference hollow structural section (HSS) members and 4 reference plain concrete (PC) members, were tested. The parameters considered in the tests included (1) type of BM: solid and hollow; (2) width ratio between BM and compression member: from 0.36 to 0.73; (3) wall thickness of the steel tube of the compression member: 2.6 mm and 3.7 mm, and (4) angle between BM and the compression member: 45° and 90°. It is found that, while being subjected to local bearing forces, square CFST has a higher bearing capacity and a better deformation-resistant ability, and the performance of a CFST member is better than that of the superposition of HSS and PC members. The calculated bearing capacities of square CFST under local bearing forces using the simplified design method in CIDECT design guide [9] and Feng and Young [12] are evaluated by comparison with the experimental results.

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ABSTRACT: The mechanical behaviour of welded structures can be significantly affected by the effects of the employed joining process. The main goal of this work is to assess the influence of the longitudinal residual stresses on the overall compressive performance of aluminium friction stir welded plates. Longitudinal residual stress distribution was measured by means of the contour method and introduced as initial condition into a finite element model of the compressed assembly. Also, the sensitivity of the plates to the magnitude of the initial geometrical imperfections was analysed. It can be inferred that both factors influence the plate's mechanical behaviour.

Mehran Sadri and Davood Younesian (Center of Excellence in Railway Transportation, School of Railway Engineering, Iran University of Science and Technology, Tehran 16846-13114, Iran), “Nonlinear free vibration analysis of a plate-cavity system”, Thin-Walled Structures, Vol. 74, pp 191-200, January 2014
DOI: 10.1016/j.tws.2013.09.023
ABSTRACT: Free vibration of a plate-cavity system is analytically studied in this paper. For this purpose, a rectangular enclosure composed of one flexible and five rigid walls are taken into account. The flexible wall is modeled by the Von-Karman plate theory and the Galerkin method is employed to derive interior acoustic pressure and subsequent equations of motion. Harmonic balance approach, variational iteration method (VIM) and direct integration method are employed to determine nonlinear natural frequencies of the coupled system. A
parametric study is then carried out and effects of different parameters on the value of frequency ratio are studied.

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ABSTRACT: A long, thin, inextensible cylindrical tube made of Hollomon's power-law material acted upon by a uniform normal pressure is considered. The nonlinear boundary value problem that governs the equilibrium states of such a tube is formulated as a differential system of equations. Perturbation solutions are obtained for the cases of small pressure values in the neighborhood of the critical buckling pressures. Numerical solutions based on a special initial value problem Matlab solver, Newton's and shooting methods are obtained. The results show that a high strength material tube deforms similarly to an elastic material tube for values of strain hardening exponent.

DOI: 10.1016/j.tws.2013.10.003

ABSTRACT: The fact that the buckling load of cylindrical shells depends on imperfections raised the idea of applying probabilistic design methods for these structures. Whether a probabilistically motivated design load may be regarded as a representative for a type of shell depends, among others, on the samples that build the data basis for the probabilistic methodology. In the current paper a methodology is presented that takes into account the samples size within a fast probabilistic design. The method presented leads to a lower design load, as the sample size decreases. The methodology is applied to a set of 33 beer cans, which have been measured and tested at the Delft University of Technology. The 33 cans are subdivided into groups which are then analyzed probabilistically in order to observe how the probabilistically motivated design load varies for different samples sizes. The results indicate that the method presented provides a useful tool for designers to ensure that a small data basis does not yield an unsafe probabilistic design.


ABSTRACT: The design of steel sheathed cold-formed steel (CFS) framed shear walls is not addressed in Canadian design standards. A program of displacement based loading tests was carried out on single-storey shear walls of various configurations to investigate their performance and to establish a comprehensive database of information. The walls, which were subjected to lateral loading and combined lateral plus gravity loading, differed in sheathing thickness, screw fastener detailing, framing thickness, aspect ratio and framing reinforcement. The performance under loading was directly related to the sheathing connection pattern;
however, when the framing elements were not blocked tension field forces resulted in significant damage to the chord studs. Details of the test program and general results are presented in this paper.

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ABSTRACT: In this paper, a novel layerwise theory based on first order shear deformation theory has been developed to evaluate the buckling load of delaminated composite plates with through-the-width and rectangular embedded delaminations. The Rayleigh–Ritz method has been adopted and displacement fields are obtained by incorporating polynomial series. Besides, contact constraints are imposed to the delaminated area using penalty method in order to prevent unacceptable penetration. The present layerwise theory provides a more realistic description of the kinematics of composite laminates when compared to equivalent single layer theories. This method is capable of predicting buckling response of thick delaminated composite plates.

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ABSTRACT: In the present paper, two independent functions of displacements along the z axis direction, i.e., the total lateral displacement w and the bending deflection φ, have been introduced within the first order shear deformation plate theory FSDT. The differential equations of motion and boundary conditions have been derived from Hamilton's principle employing the classical Mindlin approach. Modified conditions of two adjacent component plate interactions have been formulated. A plate model of the plate structure has been adopted to describe all possible buckling modes. The obtained equations are approximate since the shear locking is not ignored but the boundary layer effect is neglected. A method of the modal solution to the buckling problem within Koiter's asymptotic theory has been used. The calculations have been conducted for a few beam-columns of various shapes of cross-sections. The obtained results that account for transverse shear deformation have been compared to the results attained for the classical thin plate theory.

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ABSTRACT: Following recent investigations on the decomposition of elastic buckling modes into combinations of structurally meaningful deformation modes, this work presents a novel extension of the above procedure to elastic–plastic collapse mechanisms and highlights the relevant role that this concept may play in
the mechanical knowledge/interpretation of thin-walled member failures. In order to achieve the sought decomposition, a code based on a Generalised Beam Theory (GBT) formulation developed to perform first-order elastic–plastic analyses of thin-walled members is employed. Five illustrative examples are presented and discussed, and the results displayed, namely load-deflection curves, deformed configurations and stress contours, are validated through the comparison with values provided by shell finite element analyses. The most relevant modal results addressed consist of (i) load-deflection curves determined on the basis of pre-selected deformation mode sets, (ii) modal participation diagrams and (iii) modal amplitude functions. These results make it easy to characterise and interpret the mechanics associated with the thin-walled member elastic–plastic failures (as well as with the various loading stages), which may be of great importance in the improvement/development of existing/new design methods (e.g., yield-line theory, direct strength method).

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ABSTRACT: Shells are thin-walled structures whose stability and performance is governed by geometrical buckling. The buckling stability of shell structures has been investigated through numerous analytical and experimental studies. In an experimental investigation, it is quite important to determine the accurate buckling load of the structure as the critical load is usually masked by failure owing to large deformations as well as the effects of initial imperfections. On this basis, the main objective of this study is to evaluate the applicability of the Southwell, Massey, Modified, and Meck plotting methods in predicting the accurate critical buckling loads of conical shell structures with various geometrical properties. To this end, the buckling loads of several test specimens are determined through application of the aforementioned plotting methods as well as consideration of the test data for strain and displacement deformation variables, and compared with numerical and analytical predictions. Based on the findings of this study, agreement between the extrapolated and numerical as well as analytical results for buckling loads of the considered conical shell specimens is quite satisfactory, which is in turn indicative of applicability of the extrapolation techniques in experimental determination of buckling loads of shell structures. The applicability of extrapolation techniques in predicting the critical buckling load of conical shell structures is demonstrated. Southwell, Massey, and Modified Plots are successfully applied on strain and displacement data and reliable predictions are obtained for the critical buckling loads. The proportionality between strain and displacement deformation variables is demonstrated. The critical buckling loads of conical shells are satisfactorily predicted through application of Meck Plot method on strain and displacement data.

References listed at the end of the paper:
Hanfeng Yin (1,2), Guilin Wen (1,2), Zhibo Liu (2) and Qixiang Qing (2)
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“Crashworthiness optimization design for foam-filled multi-cell thin-walled structures”, Thin-Walled 
Structures, Vol. 75, pp 8-17, February 2014

ABSTRACT: Foam-filled thin-walled structure and multi-cell thin-walled structure both have recently gained 
attentions for their excellent energy absorption capacity. As an integrator of the above two kinds of thin-walled 
structures, foam-filled multi-cell thin-walled structure (FMTS) may have extremely excellent energy absorption 
capacity. This paper firstly investigates the energy absorption characteristics of FMTSs by nonlinear finite 
element analysis through LS-DYNA. Based on the numerical results, it can be found that the FMTS with nine 
cells has the most excellent crashworthiness characteristics in our considered cases. Thus, the FMTSs with cell 
number n=9 are then optimized by adopting a multi-objective particle swarm optimization (MOPSO) algorithm 
to achieve maximum specific energy absorption (SEA) capacity and minimum peak crushing force (PCF). 
During the process of multi-objective optimization design (MOD), four kinds of commonly used metamodels, 
namely polynomial response surface (PRS), radial basis function (RBF), Kriging (KRG) and support vector 
regression (SVR) for SEA and PCF, are established to reduce the computational cost of crash simulations by 
the finite element method. In order to choose the best metamodel for optimization, the accuracies of these four 
kinds of metamodels are compared by employing the error evaluation indicators of the relative error (RE) and 
the root mean square error (RMSE). The optimal design of FMTSs with nine cells is an extremely excellent 
energy absorber and can be used in the future vehicle body.

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“Improving strength, stiffness and ductility of CFDST columns by external confinement”, Thin-Walled
ABSTRACT: Concrete-filled double-skin tubular (CFDST) column is one of the most efficient forms of column construction in which the steel tubes provides both axial strength and confining pressure to enhance the strength and ductility of the in-filled concrete. Compared with confined reinforced concrete columns, CFDST columns had stronger and more uniform confining pressure provided to the in-filled concrete by the steel tubes, which reduces the steel congestion problem for better concrete placing quality. However, a major shortcoming of the CFDST columns is the imperfect interface bonding that occurred at the elastic stage that reduces the elastic strength and stiffness of columns. To improve the situation, it is proposed in this study to use external steel rings to restrict the dilation of outer steel tube of CFDST columns. For verification, a series of uni-axial compression test was performed on some CFDST columns with external steel rings. From the results, it was found that the elastic strength, elastic stiffness and ductility were enhanced by installing the steel rings as external confinement. Lastly, a theoretical model for predicting the axial strength of confined CFDST columns has been developed.

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ABSTRACT: A rotational resistant stiffness of the zed-purlins connection with sandwich panels is investigated. A simple finite element method model of the connection is proposed. The numerical analysis of the model performed by ABAQUS software, in physically linear and geometrically nonlinear ranges, leads to the rotational resistant stiffness sought. The numerical solution obtained is verified experimentally. Two variants of distribution of screws connecting the purlin with the sandwich panel are taken into investigation. A good agreement of both, theoretical and experimental, results should be noticed. Conclusion related to possible application in design practice is formulated.

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ABSTRACT: A new cold-formed steel corrugated shear wall seismic force resisting system has been recently
developed by Tipping Mar and Associates of Berkeley, California. The seismic performance quantification of buildings with the system requires non-linear dynamic analysis, where the shear wall – to reduce calculation demands – is modeled by cyclic strut element. The paper presents the model development and calibration to test results. In lack of monotonic test results, monotonic backbone curve is estimated by non-linear static analysis. Cyclic deterioration parameters are determined by genetic algorithm optimization method. Standard model that is applicable to the various shear wall configurations is developed.


ABSTRACT: Critical loads were determined experimentally from the condition of the local buckling of thin-walled bars with Z-section subjected to warping torsion. The experimental investigations were carried out using simply supported models, loaded with a concentrated torsional moment at the mid-span. A method of determining the so-called “local ordered deflection interval” was developed. In this interval, the modeled deflection of the component plates (walls) of a thin-walled bar with random wall geometrical imperfections is compliant with the local buckling mode. The “local ordered deflection interval” makes it possible to adjust the known experimental methods so that they could be used to determine critical torsional loads and local critical bimoments. Experimental investigations showed the occurrence of two local critical bimoments in bars with Z-section. The bimoments are different in their absolute values, depending on the sense (sign) of the torsional load. Experimentally determined critical loads were compared with theoretical results.

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ABSTRACT: State-of-the-art studies of the crushing of composite tubes reveal different factors affecting their crushworthiness. Of those factors, the geometrical property of the tube is of great interest. In the current study, four different categories of tube cross-sectional geometrical properties were tested under a quasi-static crushing scenario to investigate the best cross-section in terms of the crushing load and the energy-absorption capacities. A woven GFRP consisting of eight layers was used to manufacture the tubes. The results showed that reinforcing the circular tube with radial GFRP webs could improve both the load-carrying capacity and the specific energy-absorption capability. The stability of the crushing process is of great interest in automotive applications. It was found that introducing the geometrical reinforcement inside the tubes could have a positive effect on the stability of the crushing during the loading, the average crush load, and the crush-load efficiency.

ABSTRACT: A generalized Ritz based approach that accounts for pre-buckling bending deformations as well as geometric non-linearity to find the buckling load for thin cylindrical shells under uniform axial compression is proposed. The approach accommodates within a unified framework, based on a shell and spring restraint system, the entire range of boundary conditions: ranging from free boundaries to compliant boundaries. The classical kinematic boundary conditions are recovered as limiting cases. The method involves choice of a single trial function that is invariant with respect to boundary conditions. The proposed approach is validated using existing analytical results, where available, and numerical solutions, otherwise.


ABSTRACT: Results of a theoretical analysis of the local buckling in thin-walled bars with open cross-section subjected to warping torsion are presented. The local critical bimoment, which generates local buckling of a thin-walled bar and constitutes the limit of the applicability of the classical Vlasov theory, is defined. A method of determining local critical bimoment on the basis of critical warping stress is developed. It is shown that there are two different local critical bimoments with regard to absolute value for bars with an unsymmetrical cross-section depending on the sense of torsion load (sign of bimoment). However, for bars with bisymmetrical and monosymmetrical sections, the determined absolute values of local critical bimoments are equal to each other, irrespective of the sense of torsional load. Critical warping stresses, local critical bimoments and local buckling modes for selected cases of thin-walled bars with open cross-section are determined.

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ABSTRACT: Finite Element simulations and mechanical tests are undertaken to assess the impact of weld joint location on stiffened panel static strength. An upper wing cover panel, with a manufacturing process of welding multiple near-net-shape multi-stiffener extrusions with a final net-shape machining phase is investigated. The 7000 series aluminium alloy extrusions and skin bay longitudinal friction stir butt welds are examined. Geometric imperfections exhibit the greatest influence on panel collapse, thus for static strength design the selection of weld joint location should minimise imperfection generation. Moreover the analysis demonstrates limited impact on panel collapse strength when an optimised welding process is employed.


ABSTRACT: Because the deformed beam geometry often is the most important information for applications of highly flexible beams, a geometrically exact beam theory needs to be displacement-based in order to directly and exactly describe any greatly deformed geometry. Main challenges in geometrically exact beam modeling
are how to describe a beam's large reference-line deformation and cross-sectional rotations without singularity and how to derive objective directional strains in terms of global displacements and rotations that contain elastic deformation and rigid-body movement. By comparing with a geometrically exact displacement-based beam theory this paper shows that theoretical and numerical problems of other geometrically nonlinear beam theories are mainly caused by: (1) use of independent variables to account for bending-shear rotations, (2) use of problematic energy-based Green–Lagrange strains in order to have objective strain measures, and/or (3) use of strain-based formulations in order not to use problematic Green–Lagrange strains. The theoretical problems include inconsistent governing equations from energy- and momentum-based formulations, inexistence of material property matrices for the chosen strain and stress measures, and non-directional stresses. The numerical problems include shear locking in finite-element analysis, the need of internal nodes and hence more degrees of freedom in finite-element modeling, singularity of mathematics-based rotational variables, deformed geometry being obtained by approximate post-processing numerical integration, and difficult to match secondary (force) variables with deformed conditions.

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ABSTRACT: This paper presents an equation for the effective tangent moduli for steel axial members of hot-rolled I-shaped section subjected to various residual stress distributions. Because of the existence of residual stresses, the cross section yields gradually even when the member is subjected to uniform axial stresses. In the elasto-plastic stage, the structural response can be easily traced using rational tangent modulus of the member. In this study, the equations for rational tangent moduli for hot-rolled I-shaped steel members in the elasto-plastic stage were derived based on the general principle of force-equilibrium. For practical purpose, the equations for the tangent modulus were presented for conventional patterns of the residual stress distribution of hot-rolled I-shaped steel members. Through a series of material nonlinear analyses for steel axial members modeled by shell elements, the derived equations were numerically verified, and the presented equations were compared with the CRC tangent modulus equation, the most frequently used equation so far. The comparative study shows that the presented equations are extremely effective for accurately analyzing elasto-plastic behavior of the axially loaded members in a simple manner without using complex shell element models.

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ABSTRACT: To complement available design methods, this study develops a practical and economical approach to estimate shear strength of non-composite symmetric and asymmetric cellular beams, based on
failure by local web-post buckling. Influence of geometric web-post parameters on the buckling strength and mechanism, such as section size, opening depth ratio, spacing ratio and tee depth, are investigated with a validated finite element (FE) web-post model. The validation is against 13 cases reported in the literature, and 390 parametric web-post models are analyzed. Tee depth is found to be the key parameter distinguishing failure modes between buckling and Vierendeel bending. The buckling design equation is adopted based on a simple strut model. The observed stress distributions from simulations suggest half the web-post width for the effective strut width and half the length of a line segment tangent to neighboring openings as the strut length. Based on the simulation study, an effective length is proposed to incorporate the effects of restraint due to the tee section and the stress variation around the opening. The strut models of the upper and lower parts of the web-post are separately computed for their buckling shear strength according to BS EN 1993-1-1 and ANSI/AISC 360-10. The shear strength of each part is related to the web-post shear strength through the vertical shear area of the tee section. Accuracy of the proposed model is validated against existing experiments or their FE models. The new design equations facilitate safe and cost-effective design of cellular beams.

Yuner Huang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Experimental investigation of cold-formed lean duplex stainless steel beam-columns”, Thin-Walled Structures, Vol. 76, pp 105-117, March 2014, DOI: 10.1016/j.tws.2013.11.006
ABSTRACT: This paper describes a test program on cold-formed lean duplex stainless steel members in combined compression and minor axis bending. The test specimens were cold-rolled from flat strips of lean duplex stainless steel grade EN 1.4162. In this study, square and rectangular hollow sections were compressed at different eccentricities, in order to obtain a beam-column interaction curve for each series of tests. Initial overall geometric imperfections of the members were measured prior to testing. The ultimate loads and the failure modes of each specimen were obtained. The observed failure modes include local buckling, flexural buckling and interaction of local and flexural buckling. The test strengths obtained from this study and other available data were compared with the design strengths predicted by the American Specification, Australian/New Zealand Standard and European Code for stainless steel structures. It should be noted that these specifications do not cover the material of lean duplex stainless steel. Therefore, the suitability of the beam-column design rules in these specifications for lean duplex stainless steel is assessed in this study. Generally, these specifications are capable of predicting the beam-column strengths of the lean duplex stainless steel test specimens, and the design rules in the specifications are considered to be reliable. It is observed that the European Code generally provides quite conservative predictions for the beam-column specimens compared to the American Specification and Australian/New Zealand Standard predictions.

ABSTRACT: Nowadays stiffened aluminium panels have been widely used for marine applications such as building high speed vessels. The panels of high speed vessels are subjected to different in plane and out-of-plane loads. One of the most important out-of-plane loads is the impulse caused by bottom slamming. In the present study, the transient large deflection elastic-plastic responses of a number of stiffened aluminium panels subject to slamming impulsive loads are investigated. The impulsive loads are exerted on the finite element models of aluminium panels proposed by Ultimate Strength Committee of ISSC 2003. Several impact conditions are considered to study the influence of several structural factors such as heat affected zone (HAZ)
arrangement, boundary conditions, thickness of plating, number of transverse frames and in-plane fixation. Based on these studies, several design-oriented conclusions are issued. Moreover, this paper outlines the various aspects of the influence of the HAZ presence on the strength of the slam-loaded panels with respect to loading time ratio.

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ABSTRACT: This paper aims at finding the optimal folding of open cold formed steel cross sections under compression. Starting with a fixed coil width, a design point in the design space is defined by a vector of turn angles at a set of points along the coil width. Generalized Finite Strip Method (FSM) and Direct Strength Method (DSM) are combined to calculate the nominal compressive strength for a given cross section (a given design with a given set of turn angles). The design space is searched primarily via a stochastic search algorithm, Genetic Algorithm (GA). The near-optimal folding of the cross section is then fine-tuned through a few steps of the gradient descent optimization. To arrive at practical designs the optimization problem is augmented with constraints on the geometrical properties of the cross section. The optimal cross sections are found to have compressive capacities that are higher than the original designs by a factor of more than three in many cases. The shape of the optimal folding is shown to be greatly influenced by the choice of boundary condition. Strategies for identification of instability modes, a necessary first step to using DSM, are also discussed in detail.

Eduardo M.B. Campello and Leonardo B. Lago (Department of Structural and Geotechnical Engineering, Polytechnic School, University of São Paulo, P.O. Box 61548, 05424-970 São Paulo, Brazil), “Effect of higher order constitutive terms on the elastic buckling of thin-walled rods”, Thin-Walled Structures, Vol. 77, pp 8-16, April 2014, DOI: 10.1016/j.tws.2013.11.001
ABSTRACT: In this paper we revisit an elastic constitutive equation proposed in two previous works and extend it in order to include all higher-order terms on the deformations. Our purpose is to assess the influence of these terms on the elastic buckling of thin-walled rods. The resulting material model was incorporated into a geometrically exact rod formulation and implemented into a nonlinear finite element code. By means of simple numerical examples we show that the higher order terms may play a significant role on the values of the buckling loads and on the post-buckling behavior of thin-walled beams and columns.

ABSTRACT: This paper investigates the behavior of steel plate shear walls (SPSWs) with pre-compression from adjacent frame columns which is produced in the construction process. Firstly, some parameters used in analytical finite element models, such as the stiffness of frame beams and columns and the magnitude of the loads are discussed. Then, numbers of numerical examples are analyzed and show that the influence of pre-compression varies with the dimension of SPSWs. Also, the distribution and transferring of axial forces
between frame columns and SPSWs during loading are discussed. Finally, a reduction coefficient of shear-carrying capacity of SPSW due to pre-compression is proposed.

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ABSTRACT: This paper presents a non-linear finite element model (FEM) used to predict the behaviour of slender concrete filled steel tubular (CFST) columns with elliptical hollow sections subjected to axial compression. The accuracy of the FEM was validated by comparing the numerical prediction against experimental observation of eighteen elliptical CFST columns which carefully chosen to represent typical sectional sizes and member slenderness. The adaptability to apply the current design rules provided in Eurocode 4 for circular and rectangular CFST columns to elliptical CFST columns were discussed. A parametric study is carried out with various section sizes, lengths and concrete strength in order to cover a wider range of member cross-sections and slenderness which is currently used in practices to examine the important structural behaviour and design parameters, such as column imperfection, non-dimension slenderness and buckling reduction factor, etc. It is concluded that the design rules given in Eurocode 4 for circular and rectangular CFST columns may be adopted to calculate the axial buckling load of elliptical CFST columns although using the imperfection of length/300 specified in the Eurocode 4 might be over-conservative for elliptical CFST columns with lower non-dimensional slenderness.

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ABSTRACT: A numerical study on the post-buckling behaviour of simply supported short cylindrically curved panels, with longitudinal edges unconstrained and loaded edges constrained (internal element of a section), including the influence of curvature and loading type (pure compression and in-plane bending) is presented in this paper. Additional relevant parameters are identified and their influence on the ultimate strength of cylindrically curved panels is studied. Numerical results of the ultimate reduction factor from the parametric study are converted into geometry (width) reduction factors by an iterative routine. Subsequently, an extension of rules for internal plated members’ ultimate load calculation from EN 1993-1-5 is proposed based on the effective width concept. It is concluded that (except for stocky panels) the increase in the curvature parameter led to an increase on the cylindrically curved panel’s resistance and that the upper limit proposed by EN 1993-1-5 to the value of the curvature parameter is reasonable. Finally, a statistical study is performed that concludes that the proposed approach provides an accurate estimate of the ultimate load.
DOI: 10.1016/j.tws.2013.11.014

ABSTRACT: This paper investigates the local buckling strength of stainless steel beam webs, subjected to a stress gradient. Due to relatively low values of the proportional limit, stainless steels resist loads at stresses beyond the proportional limit. The design of such steels is therefore influenced by its inelastic buckling strength. To determine this strength, plasticity reduction factors are used in local buckling calculations to account for inelastic post-buckling behavior. Steels chosen for this study are AISI Type 304, 410 and Type 3CR12 stainless steels. Dimensions of the sections were selected to promote local buckling, and inhibit other forms of buckling, such as distortional and lateral-torsional buckling. The depth of the web was varied in order to study channels of different slenderness ratio. It was concluded in this investigation that an acceptable prediction of the local buckling strength of stainless steel beam webs may be obtained through the use of the effective width approach, using no plasticity reduction factor.

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“A statistical and experimental investigation into the accuracy of capacity reduction factor for cold-formed steel shear walls with steel sheathing”, Thin-Walled Structures, Vol. 77, pp 56-66, April 2014
DOI: 10.1016/j.tws.2013.11.016

ABSTRACT: Buildings constructed of cold-formed steel members are increasingly used in many countries. In recent years, cold-formed steel shear walls with steel sheathing were introduced as lateral force resisting systems. Design provisions of these structures require that the shear strength of shear walls with a height to width aspect ratio \( ({h/w}) \) greater than 2:1 be reduced by the factor \( 2w/h \) for satisfying allowable story drift limit. In this research, the accuracy of the factor is investigated using the results of previous tests and the tests performed by the researcher. Results show that the reduction factor \( (2w/h) \) is conservative. Thus, a relation is proposed for the reduction factor.

Ashkan Shahbazian and Yong Chang Wang (School of Mechanical, Aerospace and Civil Engineering, the University of Manchester, Pariser Building, Sackville Street, Manchester M13 9PL, United Kingdom), “A fire resistance design method for thin-walled steel studs in wall panel constructions exposed to parametric fires”, Thin-Walled Structures, Vol. 77, pp 67-76, April 2014, DOI: 10.1016/j.tws.2013.12.001

ABSTRACT: This paper investigates the applicability of a simple fire resistance design method for axially loaded thin-walled steel studs in wall panel assemblies when exposed to parametric fires from one side. The simple method includes calculations of cross-section temperatures and ultimate load carrying capacities at elevated temperatures. The simplified calculation method for heat transfer in the cross-section is based on dividing the cross-section into a number of segments. The thermal properties of these layers are based on weighted averages of the thermal properties of the components contained within. The structural capacity calculation method is based on the Direct Strength Method. Results from the design method are compared with the results from Finite Element simulations for heat transfer and structural analysis (236 models). The calculation results are in good agreement with the simulation results and the proposed method may be used in performance-based fire engineering design of such construction.

ABSTRACT: To rehabilitate damaged or sub-standard box girders, techniques utilising the lightweight, high strength and corrosion resistance of carbon fibres reinforced polymers (CFRP) composites have been proposed. This paper presents experimental results for two series of CFRP strengthened and rehabilitated model box girders under quasi-static large deformation 3-point bending. The first series represents strengthening 12 undegraded rectangular hollow section (RHS) beams from the manufacturer using externally wrapped CFRP sheets. The second series was for rehabilitation of 41 artificially degraded RHS beams strengthened using externally wrapped sheets or bonded plates. The main parameters examined in this paper were the section type, section and member slenderness and the type and number of the CFRP sheets. The flange and web slenderness examined in this paper was in the range of \( b/t = 20 \) to 66.67 and \( d/t_w = 20 \) to 75. The CFRP sheets were wrapped around the section in the transverse direction with a sufficient overlap. The results show that the combined flexural and bearing strength of the steel box girder can be significantly increased by adhesively bonding CFRP. Expressions for the bearing strength and plastic moment of the composite section were obtained by means of an equivalent thickness approach. The newly derived interaction equations were compared against the present design rules in steel specifications. The average gain in strength due to bonding the CFRP laminate was 65% and 19.9% for the strengthening and rehabilitations series, respectively. The percent increase in strength was mostly affected by the section slenderness where the maximum gain was obtained for the slender section.

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ABSTRACT: This paper presents a finite element analysis (FEA) of circular concrete filled steel tubular (CFST) members under local bearing forces applied either perpendicularly to the member or at an angle of 45°. The established FEA modeling was verified by the experimental results that have been published in an international journal. The FEA modeling was then used to perform analysis on the typical failure modes and full-range load-deformation relations of CFST subjected to local bearing forces. Finally, simplified formulae for calculating the strength of CFST under local bearing forces was presented. Practical guidance was also given to avoid premature local buckling of brace member and premature fracture of chord member.

Poologanathan Keerthan, David Hughes and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Experimental studies of hollow flange channel beams subject to combined bending and shear actions”, Thin-Walled Structures, Vol. 77, pp 120-140, April 2014, DOI: 10.1016/j.tws.2013.12.003

ABSTRACT: This paper presents the details of an experimental study of a cold-formed steel hollow flange channel beam known as LiteSteel beam (LSB) subject to combined bending and shear actions. The LSB sections are produced by a patented manufacturing process involving simultaneous cold-forming and electric resistance welding. Due to the geometry of the LSB, as well as its unique residual stress characteristics and initial geometric imperfections resultant of manufacturing processes, much of the existing research for common
cold-formed steel sections is not directly applicable to LSB. Experimental and numerical studies have been carried out to evaluate the behaviour and design of LSBs subject to pure bending actions and predominant shear actions. To date, however, no investigation has been conducted into the strength of LSB sections under combined bending and shear actions. Combined bending and shear is especially prevalent at the supports of continuous span and cantilever beams, where the interaction of high shear force and bending moment can reduce the capacity of a section to well below that for the same section subject only to pure shear or moment. Hence experimental studies were conducted to assess the combined bending and shear behaviour and strengths of LSBs. Eighteen tests were conducted and the results were compared with current AS/NZS 4600 and AS 4100 design rules. AS/NZS 4600 design rule based on circular interaction equation was shown to grossly underestimate the combined bending and shear capacities of LSBs and hence two lower bound design equations were proposed based on experimental results. Use of these equations will significantly improve the confidence and cost-effectiveness of designing LSBs for combined bending and shear actions.

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ABSTRACT: In this paper, a soft-computing based study aimed to estimate the available rotation capacity of cold-formed rectangular and square hollow section (RHS-SHS) steel beams is described and novel mathematical models based on neural network (NN) and genetic expression programming (GEP) are proposed. In order to develop the proposed formulations, a wide experimental database obtained from available studies in the literature has been considered. The data used in the NN and GEP models are arranged in a format of eight input parameters covering both geometrical and mechanical properties such as width, depth and wall thickness of cross section, inside corner radius, yield stress, ratio of modulus of elasticity to hardening modulus, ratio of the strain under initial hardening to yield strain and shear length. The accuracy of the proposed formulations is verified against the experimental data and the rates of efficiency and performance are compared with those provided by analytical semi-empirical formulation developed by some of the Authors in a previous study. The proposed prediction models proved that the NN and GEP methods have strong potential for predicting available rotation capacity of cold-formed RHS-SHS steel beams.


ABSTRACT: This paper focuses on the compressive strength of the concrete-filled double skin steel tubular (CFDST) short columns. Columns with external and internal circular carbon steel tubes are merely considered. First, this paper summarises previously developed formulas for predicting the compressive strength of the CFDST columns, along with the formula recently suggested by Yu et al. (2013) for solid and hollow circular concrete-filled tubular (CFST) columns. The various formulas for predicting compressive strength are then compared with test results. Test results are then organised and evaluated according to the relevant test specimen parameter; the diameter-to-thickness ratio (D/tD/te). It is found that the available tests do not cover the full range of the D/tD/te ratio. Hence, numerical nonlinear simulations, based on the finite element (FE) method
using the software package ABAQUS/Standard, are constructed to compensate for the shortage in the available results. Through comparison with test and FE results, a new design formula is suggested. Such formula is shown to be more accurate than available formulas for estimating the compressive strength of the CFDST short columns. This recommended design model requires relatively less calculation efforts, and provides less scattered predictions than those using the current design rules. At the end, an illustrative example for the calculation of the compressive strength of the CFDST columns using the currently proposed formula is provided.

DOI: 10.1016/j.tws.2013.09.026
ABSTRACT: Forced vibration response of laminated composite and sandwich shell is studied by using a 2D FE (finite element) model based on higher order zigzag theory (HOZT). This is the first finite element implementation of the HOZT to solve the forced vibration problem of shells incorporating all three radii of curvatures including the effect of cross curvature in the formulation using Sanders' approximations. The proposed finite element model satisfies the inter-laminar shear stress continuity at each layer interface in addition to higher order theory features, hence most suitable to model sandwich shells along with composite shells. The $C_0$ finite element formulation has been done to overcome the problem of $C_1$ continuity associated with the HOZT. The present model can also analyze shells with cross curvature like hypar shells besides normal curvature shells like cylindrical, spherical shells etc. The numerical studies show that the present 2D FE model is more accurate than existing FE models based on first and higher order theories for predicting results close to those obtained by 3D elasticity solutions for laminated composite and sandwich shallow shells. Many new results are presented by varying different parameters which should be useful for future research.

ABSTRACT: In this study, the thermal buckling behavior of a circular aluminum plate that results from thermal loading was investigated using a digital image correlation (DIC) technique. The aluminum plate was placed in a titanium ring and the structure was heated from room temperature 25 °C to 160 °C. Due to the differences in the coefficients of thermal expansion (CTEs) between aluminum and titanium, the aluminum plate buckles at a certain temperature. The buckling temperature was determined from the full-field deformation shape and temperature-displacement curve that were obtained using the DIC-based ARAMIS® software. In order to obtain an appropriate full-field deformation, a polarized light filter was used to reduce the out-of-plane displacement error, which is an unavoidable error in the experiment. Using this method, the standard deviation of the $z$ directional displacement was reduced from ±3.14 μm to ±2.70 μm. In addition, the results demonstrated that the measured buckling temperature was close to the theoretical buckling temperature of the circular plate in a simply supported boundary condition. In order to verify the proposed measurement method, a finite element analysis of the structure was performed using the ABAQUS software. The results of the DIC-based measurement and finite element analysis were in good agreement regarding the deformation curve tendency. The buckling temperature from the finite element method (FEM) was slightly larger than that from the
experimental results due to the initial imperfections of the aluminum specimen. These results provide a good method for studying thermal buckling for the design and analysis of engineering structures in diverse fields such as aerospace engineering, oil refineries, and nuclear engineering.

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ABSTRACT: The free vibration of inflatable beams was studied using the dynamic stiffness method. A 3D Timoshenko beam with a homogeneous orthotropic woven fabric (OWF) was considered. Using the usual total Lagrangian form of the virtual work principle, the model took the geometric nonlinearities and the inflation pressure follower force effect into account. The nonlinear equilibrium equations were then linearized around the prestressed reference configuration. The exact dynamic stiffness matrix was developed by directly solving the governing differential equations of a 3D loaded inflatable beam in a free vibration. The effects of the inflation pressure, fabric mechanical properties and the boundary conditions on the natural frequencies and mode shapes of the inflatable beams were demonstrated. The proposed model was validated favorably through its comparison with a 3D thin shell finite element model and an isotropic fabric model found in the literature.

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ABSTRACT: A fully geometrically nonlinear finite element (FE) model is developed using large rotation shell theory for static analysis of composite and piezoelectric laminated thin-walled structures. The proposed large rotation theory is based on the first-order shear deformation (FOSD) hypothesis. It has six independent kinematic parameters which are expressed by five mechanical nodal degrees of freedom (DOFs). Linear electromechanically coupled constitutive equations with a constant electric field distribution through the thickness of each smart material layer are considered. Eight-node quadrilateral plate/shell elements with five mechanical DOFs per node and one electrical DOF per smart material layer are employed in the FE modeling. The present large rotation FE model is implemented into static analysis of both composite and piezoelectric laminated plates and shells. The equilibrium equation is solved by Newton–Raphson algorithm with system matrices updated in every iteration. The results are compared with those presented in the literature and others calculated by various simplified nonlinear shell theories. They indicate that large rotation theory has to be considered for the calculation of displacements and sensor output voltages of smart structures undergoing large deflections, since other simplified nonlinear theories fail to predict the static response precisely in many cases.
P. Malekzadeh, M.R. Golbahar Haghighi and M. Shojaee (Department of Mechanical Engineering, School of Engineering, Persian Gulf University, Bushehr 7516913798, Iran), “Nonlinear free vibration of skew nanoplates with surface and small scale effects”, Thin-Walled Structures, Vol. 78, pp 48-56, May 2014
DOI: 10.1016/j.tws.2013.10.027

ABSTRACT: The nonlinear free flexural vibration of skew nanoplates is studied by considering the influences of free surface energy and size effect (small scale) simultaneously. The formulations are derived based on classical plate theory (CPT) in conjunction with nonlocal and surface elasticity theories using Hamilton's principle. Green's strain tensor together with von Kármán assumptions is employed to model the geometrical nonlinearity. The free surfaces are modeled as two-dimensional membranes adhering to the underlying bulk material without slipping. The solution algorithm is based on the transformation of the governing differential equation from the physical domain to a rectangular computational one, and discretization of the spatial derivatives by employing the differential quadrature method (DQM) as an efficient and accurate numerical tool. The effect of small scale parameter and surface effect together with the geometrical parameters and boundary conditions on the nonlinear frequency parameters of the skew nanoplates are studied.

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DOI: 10.1016/j.tws.2014.01.017

ABSTRACT: The axial crushing responses of bonded and brazed multi-layer 1050 H14 trapezoidal aluminum corrugated core (fin) sandwich structures, with and without aluminum interlayer sheets in 0°/0° and 0°/90° core orientations, were both experimentally and numerically investigated at quasi-static and dynamic strain rates. Multi-layering the core layers decreased the buckling stress and increased the densification strain. The experimental and simulation compression stress–strain curves showed reasonable agreements with each other. Two main crushing modes were observed experimentally and numerically: the progressive fin folding and the shearing interlayer aluminum sheets. Both, the simulation and experimental buckling and post-buckling stresses increased when the interlayer sheets were constraint laterally. The multi-layer samples without interlayer sheets in 0°/90° core orientation exhibited higher buckling stresses than the samples in 0°/0° core orientation. The increased buckling stress of 0°/0° oriented core samples without interlayer sheets at high strain rate was attributed to the micro-inertial effects which led to increased bending forces at higher impact velocities.

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ABSTRACT: The present study deals with the effects of moist environment on the natural frequencies of vibration of Glass/Epoxy woven fibre composite doubly curved panels with strip delamination using the finite element method (FEM). For modelling the delamination, multipoint constraint algorithm is incorporated in the analysis. The effects of boundary condition, delamination size and shape of panels on natural frequencies of
vibration are investigated in the moisture content range. The frequencies of vibration reduce with increase of moisture in delaminated curved panels. The reductions of frequencies are more prominent for higher degree of moisture concentrations and significantly affected by boundary conditions.

Ahmad Partovi Meran, Tuncer Toprak and Ata Mugan (Faculty of Mechanical Engineering, Istanbul Technical University, 34437 Gumussuyu, Istanbul, Turkey), “Numerical and experimental study of crashworthiness parameters of honeycomb structures”, Thin-Walled Structures, Vol. 78, pp 87-94, May 2014
ABSTRACT: Crashworthiness parameters of aluminum hexagonal honeycomb structures under impact loads are investigated by using finite element methods and conducting experiments. To validate the finite element models, numerical results are compared with experimental measurements and theoretical results reported in literature. In numerical simulations of honeycomb structures, out-of-plane loads are considered while the aluminum foil thickness, cell side size, cell expanding angle, impact velocity and mass are varying, and dynamic behavior and crashworthiness parameters are examined. It is observed that there are good agreements between numerical, experimental and theoretical results. Numerical simulations predict that crashworthiness parameters depend on cell specification and foil thickness of the honeycomb structure and are independent of impact mass and velocity.

ABSTRACT: This paper summarizes results from an experimental program that investigated the cyclic axial behavior and energy dissipation of cold-formed steel C—sections structural framing members. Fully characterized cyclic axial load—deformation response of individual members is necessary to facilitate performance-based design of cold-formed steel building systems. Specimen cross-section dimensions and lengths were selected to isolate specific buckling modes (i.e., local, distortional or global buckling). The cyclic loading protocol was adapted from FEMA 461 with target displacements based on elastic buckling properties. Cyclic response showed large post-buckling deformations, pinching, strength and stiffness degradation. Damage accumulated within one half-wave after buckling. The total hysteretic energy dissipated within the damaged half-wave decreased with increasing cross-section slenderness. More energy dissipation comes at the cost of less cumulative axial deformation before tensile rupture.

ABSTRACT: Vertical cylindrical tanks for fluid and bulk storage are generally with very thin wall so they are very susceptible to buckling under wind loads. One of the main challenges for designers is the scarcity of reliable wind loads on tanks. A particular case of wind loads on tanks may occur when a tank is situated at the corner of a group in tank farm or distribution station, since it is expected to be loaded by different wind pressures compared with those of an isolated tank. In this paper, a large number of wind tunnel tests are conducted to investigate the wind loads on vertical cylindrical open-topped tanks in group, with main focus on
the grouping effect of large cylindrical tanks with a very low aspect ratio. Three types of tank groups are covered in this study: two adjacent tanks including tandem, parallel and staggered configurations, three adjacent tanks in triangular array and four adjacent tanks in square array. The effects of spacing between tanks and wind attack angle on wind pressure distributions of both external and internal wall are investigated, and the difference of wind loads on tanks in a group compared with those on an isolated tank is discussed.

Kojiro Uenaka (Department of Civil Engineering, Kobe City College of Technology, Gakuenhigashimachi 8-3, Nishi, Kobe 6512194, Japan), “Experimental study on concrete filled elliptical/oval steel tubular stub columns under compression”, Thin-Walled Structures, Vol. 78, pp 131-137, May 2014, DOI: 10.1016/j.tws.2014.01.023
ABSTRACT: A concrete filled elliptical/oval steel tubular (CFEST) member consists of elliptical/oval steel tube and in-filled concrete. The CFEST member is a new type of steel–concrete composite member and is part of a family of concrete filled steel tubular members known as CFT. The present study aims to investigate, experimentally, the characteristics of CFEST stub columns under centric loading. The main test parameters selected are diameter-to-thickness and diameters ratios of elliptical/oval steel tube. From the results, local buckling of the elliptical/oval steel tube associated with shear failure of in-filled concrete could be observed. Axial loading capacity decreased as diameter-to-thickness ratio increased. Whereas, those capacities normalized by the summation of the individual strengths, namely the elliptical/oval steel tube and in-filled concrete strengths, are regulated in case the diameter-to-thickness ratio becomes larger. Finally, a method to predict the axial loading capacity induced by confinement effects of the in-filled concrete is proposed.

Anthony Deloge Ariyanayagam and Mahen Mahendran (School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Numerical modeling to load bearing light gauge steel frame wall systems exposed to realistic design fires”, Thin-Walled Structures, Vol. 78, pp 148-170, May 2014, DOI: 10.1016/j.tws.2014.01.003
ABSTRACT: Fire safety has become an important part in structural design due to the ever increasing loss of properties and lives during fires. Conventionally the fire rating of load bearing wall systems made of Light gauge Steel Frames (LSF) is determined using fire tests based on the standard time–temperature curve in ISO834 (ISO 834-1, 1999 [1]). However, modern commercial and residential buildings make use of thermoplastic materials, which mean considerably high fuel loads. Hence a detailed fire research study into the fire performance of LSF walls was undertaken using realistic design fire curves developed based on Eurocode parametric (ENV 1991-1-2, 2002 [2]) and Barnett's BFD (Barnett, 2002 [3]) curves using both full scale fire tests and numerical studies. It included LSF walls without cavity insulation, and the recently developed externally insulated composite panel system. This paper presents the details of finite element models developed to simulate the full scale fire tests of LSF wall panels under realistic design fires. Finite element models of LSF walls exposed to realistic design fires were developed, and analysed under both transient and steady state fire conditions using the measured stud time–temperature curves. Transient state analyses were performed to simulate fire test conditions while steady state analyses were performed to obtain the load ratio versus time and failure temperature curves of LSF walls. Details of the developed finite element models and the results including the axial deformation and lateral deflection versus time curves, and the stud failure modes and times are presented in this paper. Comparison with fire test results demonstrate the ability of developed finite element models to predict the performance and fire resistance ratings of LSF walls under realistic design fires.

ABSTRACT: This paper addresses the nonlinear vibration problem of simply supported functionally graded (FG) cylindrical shells with embedded piezoelectric layers. The governing differential equations of motion of the FG cylindrical shell are derived using the Lagrange equations under the assumption of the Donnell’s nonlinear shallow-shell theory. A semi analytical approach, wherein the displacement fields are expanded by means of a double mixed series based on linear mode shape functions for the longitudinal, circumferential and radial variables, is proposed to characterize the nonlinear response of the cylindrical shell. The large-amplitude response and amplitude frequency curves of the cylindrical shell are obtained by using the proposed approach. Finally, the effects of excitation force and applied voltage on the vibration behavior of the cylindrical shell are investigated.

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ABSTRACT: Closed-form equations to determine the local buckling critical stress of typical pultruded fiber reinforced polymer (FRP) sections – angles, I-shaped, channels and rectangular tubes – comprised of orthotropic thin walls subject to concentric compression are developed. Approximate deflected-shape functions addressing boundary conditions and compatibility of rotation between plate elements are chosen for each section having uniform thickness and material properties. The Rayleigh energy method is used to obtain equations for the local buckling critical stress. Results are compared with numerical analyses using the finite strip method (FSM) for isotropic and orthotropic sections with typical ranges of properties. Comparison is also made with the method recommended by current available standards and guidelines.

DOI: 10.1016/j.tws.2014.01.008

ABSTRACT: This paper investigates the strength and behaviour of concrete-filled double skin steel tubular (CFDST) slender columns under axial compression. The lean duplex stainless steel material (EN 1.4162) which has recently gained significant attention is considered herein as the external jacket of such columns. Finite element (FE) analyses of several CFDST columns are conducted. Careful consideration is taken in the modelling for the concrete behaviour, for which both of the compressive and the tensile behaviours and the nonlinear behaviour due to cracking are fully considered. The accuracy of the current FE models is ensured through the comparison with the existing columns in literature. A parametric study is then conducted to investigate the behaviour of such columns under different affecting factors; the slenderness ratio, the concrete confinement effect, the hollow ratio, the concrete compressive strength and the thickness ratio. The behavioural differences
between intermediate length and very long CFDST columns are carefully addressed. Analytically obtained ultimate strengths are compared with design strengths calculated by European and American specifications. European design strength is found to give better predictions compared to the American specifications. However, it is shown that both strengths cannot be used in design because they overestimate the ultimate strengths and thereby do not satisfy the safety requirements. Therefore, a modification is suggested to the European design model which is shown to be able to estimate the compressive resistance of the CFDST columns more accurately than other methods.

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ABSTRACT: In this study, based on the analytical model of circular plane plate with initial bending curvature under large deflection and conical shells theory, the energy method is proposed and a new analytical solution of the load deformation characteristic of the Belleville springs was obtained. Compared with experimental results, the analytical solution has higher precision than the traditional A-L algorithm solution and the FEA method, and the validity of energy method is verified. On this basis, the deformation energy is studied and the analytical solution is applied to the mono-freedom conservative system consisting of a single Belleville spring and mass. The natural frequency of the conservative system under free vibration is analyzed, followed by the discussion on two factors, the ratio of free height and width, the width of supporting surface, which affect load deformation characteristic of Belleville springs.

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“Strength design curves and an effective width formula for cold-formed steel columns with distortional buckling”, Thin-Walled Structures, Vol. 79, pp 62-70, June 2014, DOI: 10.1016/j.tws.2014.02.004
ABSTRACT: Distortional buckling mode of cold-formed steel thin-walled member is an unstable behavior, and in some cases it may govern the load-carrying capacity of the member. The source, evolution and performance of the formulas and test data for the two strength design curves developed by Hancock are studied, for predicting the load-carrying capacity in the distortional mode. A proposed strength design curve based on available test data and Hancock’s strength design curves are then compared with the current design methods, the Direct Strength Method and the Effective Width Method, which are incorporated in the “North American specification for the design of cold-formed steel structural members” (AISI-NAS: 2007), “cold-formed steel structures” (AS/NAS 4600: 2005), and the Chinese “Technical specification for low-rise cold-formed thin-walled steel buildings” (JGJ 227-2011). The results indicate that the current design standards adopted the two strength design curves for the DSM and EWM, but they have some differences at the partial extent. A novel formula is proposed for dealing with this problem. The range of applicability of the proposed strength equation is extended from that in AS/NZS 4600 and is shown to be more accurate than AS/NZS 4600 when compared with that in the NAS S100.
ABSTRACT: The use of thin-walled steel members has significantly increased in the last decades, especially in the field of logistics. Goods and products are frequently stored in pallet racks, i.e., in structural framed systems assembled from components manufactured from cold formed steel coils. The great convenience in using rack systems is, however, counterbalanced by a complex local and global structural behavior, often difficult to predict accurately. Owing to the light weight of the key structural components, rack design requires high engineering competence. A structural failure of these structures may result in a very great economic loss. Several research programs are currently in progress worldwide; their outcomes are expected to contribute significantly to the improvements of design rules. Standards, however, do not seem to cover adequately the modeling phase of the framed systems nor minimum requirements for the finite element (FE) analysis programs to be used for analysis. These two points are fundamental pre-requisites for guaranteeing an adequate safety level in design. A research project aimed at improving the reliability of the design rules for steel storage pallet racks and at developing suitable approaches for preliminary calculations is currently in progress. Main results of a numerical study carried out on typical medium-rise unbraced pallet racks are summarized here with the goal of investigating the key features of the warping influence on the structural frame behavior under monotonic loading; the seismic response of rack is considered in a separate paper.


ABSTRACT: Vertical cylindrical welded steel tanks are typical thin-walled structures which are very susceptible to buckling under wind load. This paper investigates the buckling behavior of open-topped steel tanks under wind load by finite element simulation. The analyses cover six common practical tanks with volumes of $2\times10^3$ m$^3$ to $100\times10^3$ m$^3$ and height-to-diameter ratios $H/D<1$. The linear elastic bifurcation analyses are first carried out to examine the general buckling behavior of tanks under wind load, together with comparison to that of tanks under uniform pressure and windward positive pressure (only loaded by positive wind pressure in the windward region). The results show that for larger tanks in practical engineering, the stability carrying capacity of wind load is relatively lower. It is also indicated that the buckling behavior of tanks under wind load is governed by the windward positive pressure while wind pressure in other region of tank essentially has no influence on the buckling performance. The geometrically nonlinear analyses are then conducted to investigate the more realistic buckling behavior of tanks under wind load. It is found that the buckling behaviors of perfect tanks and imperfect tanks are much different. The weld induced imperfection only has little influence on the wind buckling behavior while the classical buckling mode imperfection has significant influence, leading to a considerable reduction of wind buckling resistance. The influences of thickness reduction of cylindrical wall, liquid stored in the tank and wind girder on the buckling behavior are also examined. It shows that the thickness reduction of cylindrical wall considerably reduces the wind buckling resistance while sufficient liquid stored in the tank and wind girder significantly increase the wind buckling resistance.

ABSTRACT: An experimental study investigating the mechanical response of both empty and aluminum foam filled braided stainless steel tubes subjected to transverse loading is presented in this manuscript. Tube specimens were loaded using a custom built testing machine which operated at a constant velocity of 18.8 mm/s. The braided tubular specimens utilized in this study were round AISI 301 stainless steel tubes with a nominal wire diameter of 0.51 mm, external nominal diameter of 64.5 mm, and length of 330 mm. Four different foam core configurations were tested, with densities ranging from 248 kg/m³ to 493 kg/m³. Additionally, two different core geometries were considered, namely cylindrical and rectangular prism configurations. Both core geometries were constructed from circular and rectangular flat panel sections of larger metallic foam panels. Structural adhesive was used to bond the smaller sections of the foam panels together to generate the cylindrical and rectangular prism cores. Deformation mechanisms of these structures were identified through use of a high speed, high resolution camera. The applied transverse load resulted in significant tensile loads within the braided tube and further resulted in braid diameter reduction as well as crushing and pulverization of the metallic foam core. Failure of the circular foam filled braided tubes was observed to be a combination of foam core separation, foam pulverization, as well as braid tow failure resulting from tensile forces and to a lesser extent bending. Failure of rectangular foam filled braided tubes was generally consistent with the mechanisms associated with the cylindrical cores, with the exception of the foam core separation. Force/displacement behavior was dependent on foam core density prior to tow lockup. Energy absorption levels ranged from 2.37 kJ to 9.13 kJ for the core densities and geometries are considered within this investigation.

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ABSTRACT: In bridge construction, the use of stiffened plates for box-girder or steel beams is common day to day practice. The advantages of the stiffening from the economical and mechanical points of view are unanimously recognized. For curved steel panels, however, applications are more recent and the literature on their mechanical behaviour including the influence of stiffeners is therefore limited. Their design with actual finite element software is possible but significantly time-consuming and this reduces the number of parameters which can be investigated to optimise each panel. The present paper is thus dedicated to the development of a preliminary design formula for the determination of the ultimate strength of stiffened cylindrical steel panels. This approximate formula is developed with the help of a design of experiment method which has been adapted from the current statistical knowledge. This method is first presented, and its feasibility as well as its efficiency are illustrated through an application to the reference case of unstiffened curved panels. Then, the case of stiffened curved panels is investigated and a preliminary design formula is developed. The ease of use of this formula for preliminary design is finally illustrated in a cost optimisation problem.
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ABSTRACT: Flutter of cantilevered, functionally graded cylindrical shells under an end axial follower force is addressed. The material properties are assumed to be graded along the thickness direction according to a simple power law. Using the Hamilton principle, the governing equations of motion are derived based on the first-order shear deformation theory. The stability analysis is carried out using the extended Galerkin method and minimum flutter loads and corresponding circumferential mode numbers are obtained for different volume fractions, length-to-radius, and thicknesses-to-radius ratios. Two different configurations are considered for the FGM: one in which the metal phase is the outer layer and the ceramic phase is the inner one, and the other vice versa. Results indicate the ranges of major influence due to the volume fraction, and the combined effect of thickness and volume fraction on the flutter load. Also, the optimum and critical power parameters between zero and infinity for which the flutter loads are maximum and minimum are determined.

A. Mroz and R.J. Mania (Faculty of Mechanical Engineering, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland), “The complex influence of aluminium aging on the dynamic response of the thin-walled AL-6060 alloy profile”, Thin-Walled Structures, Vol. 79, pp 147-153, June 2014
DOI: 10.1016/j.tws.2014.02.008
ABSTRACT: This paper presents the results of dynamic stability analysis of pre-aged aluminium profiles subjected to dynamic impulse loading. As an example a rectangular compressing pulse is considered. The analysis deals with the open cross-section ‘channel profile’ and its section modifications where the material properties obtained in experimental testing are employed. Instead of static buckling to determine a critical load, usage of a criterion is necessary. Thus the application of dynamic buckling criterion is commented on according to presented results of computations. The influence of material aging on dynamic buckling load level is argued.

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ABSTRACT: In composite construction, rectangular hollow steel tubular slender beam-columns are subjected to preloads arising from construction loads and permanent loads of the upper floors before infilling of the wet concrete. The behavior of biaxially loaded thin-walled rectangular concrete-filled steel tubular (CFST) slender beam-columns with preloads on the steel tubes has not been studied experimentally and numerically. In this paper, a fiber element model developed for CFST slender beam-columns with preload effects is briefly described and verified by existing experimental results of uniaxially loaded CFST columns with preload effects. The fiber element model is used to investigate the behavior of biaxially loaded rectangular CFST slender beam-
columns accounting for the effects of preloads and local buckling. Parameters examined include local buckling, preload ratio, loading angle, depth-to-thickness ratio, column slenderness, loading eccentricity and steel yield strength. The results obtained indicate that the preloads on the steel tubes significantly reduce the stiffness and strength of CFST slender beam-columns with a maximum strength reduction of more than 15.8%. Based on the parametric studies, a design model is proposed for axially loaded rectangular CFST columns with preload effects. The fiber element and design models proposed allow for the structural designer to efficiently analyze and design CFST slender beam-columns subjected to preloads from the upper floors of a high-rise composite building during construction.

Young Bong Kwon and In Kyu Jeong (Department of Civil Engineering, Yeungnam University, Gyongsan 712-749, Republic of Korea), “Resistance of rectangular concrete-filled tubular (CFT) sections to the axial load and combined axial compression and bending”, Thin-Walled Structures, Vol. 79, pp 178-186, June 2014 DOI: 10.1016/j.tws.2014.02.019

ABSTRACT: This paper describes the development of the direct strength method (DSM) for concrete-filled tubular (CFT) sections. The axial and flexural strength of CFT sections with local buckling are proposed based on previous test results. Although Eurocode4 does not allow the use of slender steel skins for CFT sections, the limit of the width-to-thickness ratio for the steel skin has recently been extended to slender sections in AISC specifications. A simple formula for the axial and flexural strength of CFT sections for the DSM is proposed to account for the local buckling of a thin steel skin and for the enhanced compressive strength of concrete from the confining effect of the steel skin. The squash load predicted by the proposed formula is compared with test results and those predicted by AISC specifications and Eurocode4. A formula for strength interactions of CFT members under combined compression and flexure is proposed and is compared with test results. The comparison confirmed that the formula for axial and flexural strength and that for strength interactions can conservatively predict the resistance of CFT columns to the axial load and combined compression and bending.


ABSTRACT: Approximate finite strip eigen-buckling solutions are introduced for local, distortional, flexural, and flexural-torsional elastic buckling of a thin-walled metal column with perforation patterns. These methods are developed to support a calculation-based strength prediction approach for steel pallet rack columns employing the American Iron and Steel Institute’s Direct Strength Method, however they are generally posed and could also be useful in structural studies of thin-walled thermal or acoustical members made of steel, aluminum, or other metals. The critical elastic global buckling load including perforations is calculated by reducing the finite strip buckling load of the cross-section without perforations using the weighted average of the net and gross cross-sectional moment of inertia along the length of the member for flexural (Euler) buckling, and for flexural-torsional buckling, using the weighted average of both the torsional warping and St. Venant torsional constants. For local buckling, a Rayleigh–Ritz energy solution leads to a reduced thickness stiffened element equation that simulates the influence of decreased longitudinal and transverse plate bending stiffness caused by perforation patterns. The cross-section with these reduced thicknesses is input into a finite strip analysis program to calculate the critical elastic local buckling load. Local buckling at a perforation is also treated with a net section finite strip analysis. For distortional buckling, a reduced thickness equation is derived for the web of an open cross-section to simulate the reduction in its transverse bending stiffness caused by
perforation patterns. The approximate elastic buckling methods are validated with a database of 1282 thin shell finite element eigen-buckling models considering five common pallet rack cross-sections featuring web perforations that include 36 perforation dimension combinations and twelve perforation spacing combinations.

Yuanqi Li, Yinglei Li, Shukun Wang and Zuyan Shen (Department of Building Engineering, Tongji University, Shanghai 200092, China), “Ultimate load-carrying capacity of cold-formed thin-walled columns with built-up box and I section under axial compression”, Thin-Walled Structures, Vol. 79, pp 202-217, June 2014
DOI: 10.1016/j.tws.2014.02.003
ABSTRACT: The use of cold-formed thin-walled steel structures has increased in recent years, and some built-up section members are motivated and also widely used for their excellent structural behaviors. In this paper, a series of axially-compressed tests on built-up box section members composed of two C-section by self-drilling screws at flanges are conducted. The differences of global, local and distortional buckling behaviors between members with built-up and single sections are investigated at first. Then the effects of installation error and fastener spacing on ultimate load-carrying capacity of built-up members are analyzed. A strength estimation method for built-up members under axial compression is proposed based on the experimental investigation in this paper, as well as some existing experiments, and corresponding numerical analysis studies. Finally, the predicted capacity obtained by using the proposed strength estimation method is compared with experimental results and the nominal axial strength determined according to the AISI provisions, by which the suitability and accuracy of the proposed strength estimation method have been established.

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ABSTRACT: This paper formalizes the domain of all and only manufacturable open cold-formed steel (CFS) profiles aimed at improving their strength capability in the development of new products. A Genetic Algorithm is applied over this domain to get a set of best solutions from structural and constructive viewpoints. A basic review is carried out with regard to (i) Shape Grammar, (ii) Finite Strip Method-based elastic buckling analysis, (iii) Direct Strength Method-based structural strength computation and (iv) modified procedure of the Non-dominated Sorting Genetic Algorithm. CFS-manufacturing is defined as a language and its general grammar is presented. This grammar-based model responds to requisites of descriptive power, simplicity of implementation, and customization to specific needs. The CFS grammar has been implemented using scripting languages available in pre-existing CAD and CAE applications. Implementation includes generation, visualization, analysis and improvement capabilities. Results show that innovative shapes with improved strength could be generated from the finite set of allowable manufacturing grammar rules encoded by the grammar.

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ABSTRACT: An investigation was carried out into the influence of perforations of various shapes on the buckling behaviour of cold-formed column members of lipped channel cross-section. A finite element analysis using ANSYS, an experimental investigation, and design code predictions using the AISI Specification, British Standards (BS) and EU Standards, are employed to determine the buckling load capacity. An experimental investigation of the buckling behaviour of flat and fixed ended columns is presented, and the findings from this are used to validate finite element results, and compare with design code predictions. The numerical results of load vs. displacement behaviour are shown to be in good agreement with those reported from the tests. It is shown that the ultimate failure load of the lipped channels under compression varies greatly with the presence of perforations.

Tohid Ghanbari Ghazijahani, Hui Jiao and Damien Holloway (School of Engineering, University of Tasmania, Hobart, Australia), “Experimental study on damaged cylindrical shells under compression”, Thin-Walled Structures, Vol. 80, pp 12-21, July 2014, DOI: 10.1016/j.tws.2014.02.029
ABSTRACT: Sensitivity to initial imperfections under compressive loading has been extensively studied in shell structures. However, due to the existence of a wide range of imperfections with various shapes and amplitudes, the real behavior of such structures needs to be further investigated when they face with a damaged area. This study presents an experimental program in which buckling and failure response of damaged shell specimens are analyzed. The results of this study can be generalized for many kinds of cylindrical shells to full scale of applications with similar D/t ratios.

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ABSTRACT: An experimental study on stiffened plates subjected to combined action of in-plane load and lateral pressure is described in the paper. Details of the experiments and finite element analyses of the specimens tested are presented along with the results. Measurements of initial imperfection in the specimens have been made and included in the analyses. Results show that lateral load carrying capacity of stiffened plate drops with increase in axial load and vice-versa. It is found that plate slenderness ratio has significant influence on the ultimate load capacity of stiffened plates subjected to both in-plane load and lateral pressure. Increase of plate slenderness ratio results in a decrease of ultimate load capacity of stiffened plate. The accuracy of the finite element modelling is established by comparing the results with the corresponding experimental values.

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ABSTRACT: Due to the long stroke and stable reaction force, circular tubes under inversion are always adopted in the design of energy absorbers. Although a few studies were conducted, the existing theoretical predictions on the knuckle radius and the reaction force of the circular tube during its free inversion displayed large discrepancy from the experimental observations. In this paper, currently existing two-dimensional theoretical models of the free inversion tube are carefully reviewed. After realizing the defects of these models, Reddy’s model is improved by adopting the appropriate external work rate and material yield condition, for tubes made of rigid, perfectly plastic material. In order to validate the improved theoretical model, experiments of the free inversion of circular aluminum tubes, and finite element simulations of tubes made of the elastic, perfectly plastic material are all carried out. It is confirmed that compared with the experimental data and the FE simulations, the current model provides more accurate predictions on both the knuckle radius and the steady inversion load for the quasi-static free inversion of circular tubes.

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ABSTRACT: This paper presents a study to extend a previously developed theoretical model to predict the crushing behavior of hexagonal multi-cell thin-walled structures, e.g. honeycombs under quasi-static loading. The low speed compressive tests were conducted on three types of aluminum honeycomb panels. Based on the test data and existing theoretical models, a new analytical model was developed to predict its mean crushing strength. Some key parameters in this new model were determined with the finite element (FE) method. Then the predictions based on the new model were compared with the results reported in the published literature. It has been shown that the new model has a similar or better performance compared to its counterparts. Considering its concise expression, the newly developed model can be deemed as a convenient computational tool in engineering practice.

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ABSTRACT: In this study, compressive strength, modulus of elasticity and steel tensile coupon tests are performed to determine material properties. Sixteen hollow cold formed steel tubes and 48 concrete filled steel tube specimens are used for axial compression tests. The effects of width/thickness ratio (b/t), the compressive strength of concrete and geometrical shape of cross section parameters on ultimate loads, axial stress, ductility and buckling behavior are investigated. Circular, hexagonal, rectangular and square sections, 18.75, 30.00, 50.00, 100.00 b/t ratio values and 13, 26, 35 MPa concrete compressive strength values are chosen for the experimental procedure. Analytical models of specimens are developed using a finite element program (ABAQUS) and the results are compared. Circular specimens are the most effective samples according to both axial stress and ductility values. The concrete in tubes has experienced considerable amount of deformations
which is not expected from such a brittle material in certain cases. The results provide an innovative perspective on using cold formed steel and concrete together as a composite material.


ABSTRACT: Circular hollow steel sections are normally specified in truss and dome structures to take advantage of their efficiency in compression and the ease in which they can be curved to match the various radii of different domes. However, it is not easy to connect these members together or to other members. In order to connect them together or to other members the ends are sometimes squashed or flattened. Although the process of flattening does not reduce the area of the section, it does reduce the flexural stiffness of the section. The aim of this paper is to study the behaviour of circular hollow members with flattened edges, in compression. Variables in the tests include the diameter, thickness and length of the sections, and number of bolts in the connection. Two failure modes were observed and these are overall flexural buckling (OFB) of the member and excessive deformation of the transition zone (DTZ). The results from these tests are compared with the flexural compressive resistance formula in the South African steel code (SANS10162-1) and the European steel code (EN 1993-1-1), with a view of determining a simple formula for designing such members.

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ABSTRACT: A model of the dynamic response of a relatively long circular hollow section beam to a uniform blast modeled as an impulsive loading is developed in order to reveal the characteristic features of deformation and energy absorption of hollow section beams under such loading. A two-phase analytical model is proposed for a circular metallic hollow beam made of a strain-rate insensitive material. Both local and global deformations build up simultaneously during the first phase, and then only global bending occurs during the second phase. Because mainly large plastic deformations develop in the hollow section, the elastic deformations are neglected and a rigid-plastic method of analysis is applied. The responses of circular hollow beams with lengths between 600 and 1000 mm are analyzed for beam radii varying between 50 and 70 mm and wall thicknesses between 1.2 and 1.6 mm. The model predictions are verified by numerical simulations and reasonable agreement is observed with respect to the characteristic displacements and deformed section shape. The energy partitioning during the deformation process is briefly discussed.

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“Seismic performance and collapse prevention of concrete-filled thin-walled steel tubular arches”, Thin-Walled Structures, Vol. 80, pp 91-102, July 2014, DOI: 10.1016/j.tws.2014.03.005

ABSTRACT: The primary objective of this paper is to investigate the seismic behaviour of concrete-filled steel tubular (CFST) arches using incremental dynamic analysis (IDA). A nonlinear elastic–plastic finite element model is developed using OpenSees software and is verified with a shaking table test. Single-record IDA studies indicate that a CFST arch undergoes global dynamic instability when subjected to ground motions of increasing intensity levels. During this process, either dynamic elastic buckling or dynamic elastic–plastic buckling may occur. Dynamic strength, which is defined as the capacity for preventing global dynamic instabilities of CFST arches, is determined with a series of multi-record IDA calculations. A lower bound equation that takes into account the effect of slenderness ratio, axial compression ratio, and included angle is proposed for the prediction of the dynamic strength of CFST arches.

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“Mechanism investigation of welding induced buckling using inherent deformation method”, Thin-Walled Structures, Vol. 80, pp 113-119, July 2014, DOI: 10.1016/j.tws.2014.03.003

ABSTRACT: Due to the increasing use of thin plates in lightweight welded structure, welding induced buckling may occur in such thin plate welded structure. In this study, welding induced buckling of thin plate welded structure is investigated using the eigenvalue analysis and elastic Finite Element (FE) analysis based on inherent deformation theory, and the mechanism of welding induced buckling is clarified. Bead-on-plate welding is first examined. Measured out-of-plane welding distortion indicates that saddle type buckling is produced after cooling. Eigenvalue analysis shows the computed lowest buckling mode is the saddle type and the corresponding critical force is less than the applied tendon force evaluated by Thermal–Elastic–Plastic (TEP) Finite Element (FE) analysis beforehand. Using elastic Finite Element (FE) analysis in which all components of inherent deformation are used and also considering initial deflection, out-of-plane welding distortion is predicted with high accuracy compared with measurement. It is also concluded that tendon force (longitudinal inherent shrinkage) is the dominant reason of buckling and it determines the buckling mode, and initial deflection and inherent bending are considered to be disturbances which trigger buckling. Later, a thin plate stiffened welded structure with fillet welded joints is examined. Although welding did not induce buckling of plate fields in bending modes in the considered thin plate stiffened welded structure, the whole stiffened welded structure buckles in a twisting mode, while plate panels remain unbuckled. Eigenvalue analysis gives the twisting buckling mode as the lowest buckling mode. However, in stiffened welded structures, not only tendon force (longitudinal inherent shrinkage) but also transverse inherent shrinkage is responsible for buckling. The good agreement between computed and measured out-of-plane welding distortion shows that the elastic Finite Element (FE) analysis using inherent deformation theory is an advantage of the computational approach to predict welding distortion in large-scale and complex welded structure with enough computational accuracy.


ABSTRACT: To date, despite the significant development in the field of structural mechanics, there still remains a paradox in the solutions available for a classical shell buckling problem. The difference in strength between a cylindrical shell under uniform axial compression and that under pure bending is not quite well
investigated. This lack of research is reflected in the wide variations in the elastic bending strength and the slenderness limits given in current international design standards. The discrepancies in the available classical solutions and hence the design rules have initiated the current research. The main aim of this paper is to present a closed-form solution for the elastic buckling strength of unstiffened circular cylinders under pure bending using a new simplified energy approach employing the well-known Ritz method. Two types of analyses are presented for cylinders with large \((D/t>200)\) and medium \((100<D/t<200)\) diameter-to-thickness ratios. A unique testing rig was used to experimentally verify the new theory using a Moiré fringe film. The theoretical results are compared against the available and present test results and the existing classical solutions. The current design rules for thin-cylinders in international steel specifications are also compared, and the newly derived design curve is proposed which was found in a good agreement with the available test results.

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“Cold-formed steel lipped and plain angle columns with fixed ends”, Thin-Walled Structures, Vol. 80, pp 142-152, July 2014, DOI: 10.1016/j.tws.2014.03.001

ABSTRACT: The objective of this study is to explore the significant post-buckling reserve in global buckling that has been observed in tests on cold-formed steel angle columns, and to provide design guidance for locally slender cold-formed steel lipped and plain angle columns with fixed end boundary conditions. Global buckling modes are generally regarded to have no post-buckling reserve, and indeed all column design curves, including those used in North America for cold-formed steel columns limit the strength to 0.877\(P_{cre}\) (where \(P_{cre}\) is the global buckling load) or lower. However, tests conducted on cold-formed steel angles by Young (2004,2005) 1 and 2 demonstrate capacities significantly in excess of \(P_{cre}\) – an observation usually reserved for local-plate buckling modes, which due to transverse membrane resistance are known to have significant post-buckling reserve. In this work, specific attention is paid to the impact of end boundary conditions, with emphasis on warping (longitudinal) deformations. Utilizing nonlinear collapse analysis with shell finite element models, and existing testing, alternatives to current design methods are explored. New design procedures are recommended for strength prediction of cold-formed steel angle columns with fixed end boundary conditions.

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DOI: 10.1016/j.tws.2014.02.030

ABSTRACT: A homogeneous generalized yield criterion (HGYC) expressed by piecewise polynomial is given for angle section. The element bearing ratio (EBR), reference EBR, and uniformity of EBR are defined in term of the HGYC. Then, a HGYC based elastic modulus reduction method for limit analysis of thin-walled structures with angle steel is presented based on the modulus adjustment strategy established on the EBR and the conservation criterion of energy. The method proposed can overcome the disadvantage of the conventional elastic modulus adjustment procedure where the nonhomogeneous generalized yield criterion is employed and the proportional loading condition is not satisfied.
Noureddine Ferhoune (Doctorate at Civil Engineering, University Larbi Ben Mhidi Oum El Bouaghi, Algeria), “Experimental behaviour of cold-formed steel welded tube filled with concrete made of crushed crystallized slag subjected to eccentric load”, Thin-Walled Structures, Vol. 80, pp 159-166, July 2014
DOI: 10.1016/j.tws.2014.02.014
ABSTRACT: This paper presents results of tests conducted on thin welded rectangular steel stubs filled with concrete that gravel was substituted by 10 mm crushed crystallized slag stone. The studied section was made of two cold steel plates with U shape and welded with electric arc to form a steel box section. The cross-section dimensions were: 100×70×2 mm³. the main studied parameters were the stub height (200, 300, 400, 500 mm), the effect of the in filled concrete, the continued weld and the eccentric force. The tests were carried out 28 days after the date of casting. A total of 20 stubs were tested in a 50 tf machine up to failure, 4 stubs subjected to axial load compression and 16 stubs subjected to eccentric load compression along the minor and major rigidity axis. The aim of the study is to provide some evidences that the use of crushed slag could be integrated in the manufacturing of non-conventional concrete. All failure loads were predicted by using the Euro code 4 and the design method proposed by Z. Vrcelj and B. Uy. From test results, it was confirmed that the length of stubs and the eccentric load had a drastic effect on the load carrying capacity. The failure mode of composite stubs was a local buckling mode with all steel sides deformed outwards. The Euro code 4 loads predictions were generally in good agreement compared with experimental loads and on safe side. The loads results of design method proposed by Vrcelj and B. Uy were generally on safe side compared with experimental load except the columns subject to eccentric load with 400 mm and 500 mm height.

Guangjun Gao, Haipeng Dong and Hongqi Tian (Key Laboratory of Traffic Safety on Track of Ministry of Education, Central South University, Changsha 410075, China), “Collision performance of square tubes with diaphragms”, Thin-Walled Structures, Vol. 80, pp 167-177, July 2014, DOI: 10.1016/j.tws.2014.03.007
ABSTRACT: The energy absorption responses of conventional tubes and tubes with diaphragms are analysed here by means of finite element simulation. Numerical results show that tubes with diaphragms exhibit a relatively stable crushing process. The effect of imperfect energy absorption responses is also analysed, including the top shape of tubes and oblique loading. The strain rate affects the dynamic response of tubes with diaphragms. Four prototypes of these tubes were constructed and tested; however, sizeable differences were obtained between experimental results and the results of numerical simulation of the ideal structure in terms of process errors.

DOI: 10.1016/j.tws.2014.03.016
ABSTRACT: The buckling problem of a heterogeneous orthotropic truncated conical shell subjected to an axial load and surrounded by elastic media is analyzed based on the finite deformation theory. Using von-Karman nonlinearity, the governing equations of elastic buckling of heterogeneous orthotropic truncated conical shells surrounded by elastic media are derived. The governing equations are solved using superposition and Galerkin methods and obtained expressions for upper and lower critical axial loads. The influences of elastic foundations, heterogeneity, orthotropy and geometric characteristics on the upper and lower critical loads of conical shells with and without elastic foundations are studied in detail.
Olga Mijuskovic, Branislav Coric and Biljana Scepanovic (University of Montenegro, Faculty of Civil Engineering, Cetinjski put bb, 81000 Podgorica, Montenegro), “Exact stress functions implementation in stability analysis of plates with different boundary conditions under uniaxial and biaxial compression”, Thin-Walled Structures, Vol. 80, pp 192-206, July 2014, DOI: 10.1016/j.tws.2014.03.006

ABSTRACT: Analytical approach used for critical load determination is based on Ritz energy technique in which two factors are crucial for the accuracy of results. First factor is deflection function. Herein, double Fourier series are used to represent buckled shape of the plates under arbitrary external loads. The second and the most important factor is adoption of adequate realistic stress distribution within plate prior to buckling. Based on the Baker&Pavlović&Tahan and Pavlović&Liu investigations, exact stress distributions were introduced herein. In that way, with the adequate deflection functions and precise stress distribution, Ritz energy method can produce highly accurate results. Through several examples for the plates with different boundary conditions, for which available literature offers very few analytical solutions, accuracy of the presented analytical approach is proved. Results obtained by analytical approach are reaffirmed by numerical finite-element runs.

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DOI: 10.1016/j.tws.2014.03.004

ABSTRACT: This paper presents a comprehensive experimental and numerical investigation on the cyclic response of cold-formed steel columns with hollow rectangular sections. The present study examined the columns’ post-buckling strength and rigidity degradation, deformation and failure modes, ductility, and energy dissipation capacity. The cold-formed steel members exhibited stable hysteretic performance up to the point of local buckling with considerable degradation in strength and ductility. The energy dissipation mechanisms from the in-plane plastic behavior and out-of-plane elastic buckling deformation were identified. The influence of the height-to-width ratio and axial-compression ratio on energy-dissipation and failure mode was also investigated.

---------- Begin Vol. 81 of Thin-Walled Structures, August 2014, Special Issue ----------

Joseph Loughlan, David H. Nash and James Rhodes (Editors), Coupled Instabilities in Metal Structures, Special issue of Thin-Walled Structures, Vol. 81, pp 1-258, August 2014. The following papers appear in this volume of Thin-Walled Structures.

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ABSTRACT: The paper describes the recently ballots Direct Strength Method (DSM) of design for shear of the North American Specification for Cold-Formed Steel Structural Members NAS S100. The method requires the shear buckling load $V_{cr}$ of the complete section to be computed. Shear buckling examples of channel sections in pure shear using both the semi-analytical and spline finite strip buckling analyses are presented. Recent work on the buckling and strength of channel sections in pure shear with rectangular and triangular web stiffeners is also described.

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ABSTRACT: Space and aircraft industry demands for reduced development and operating costs. Structural weight reduction by exploitation of structural reserves in composite space and aerospace structures contributes to this aim, however, it requires accurate and experimentally validated stability analysis. Currently, the potential of composite light weight structures, which are prone to buckling, is not fully exploited as appropriate guidelines in the field of aerospace and space applications do not exist. This paper deals with the state-of-the-art advances and challenges related to coupled stability analysis of composite structures which show very complex stability behaviour. Two types of thin-walled light weight structures endangered by buckling will be considered; imperfection tolerant and imperfection sensitive structures. For both groups improved design guidelines for composites structures are still under development. This paper gives a short state-of-the-art and presents proposals for future design guidelines.

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ABSTRACT: In the case of an ideal structure, the theoretical equilibrium bifurcation point and the corresponding load, $N_{cr}$, are obtained at the intersection of the pre-critical (primary) force–displacement curve with the post-critical (secondary) curve. For a real structure, affected by a generic imperfection the bifurcation point does not appear anymore and, instead, the equilibrium limit point is the one characterizing the ultimate capacity, $N_u$, of the structure. The difference between $N_{cr}$ and $N_u$ represents the Erosion of the Critical Bifurcation Load (ECBL), due to the imperfections. This model applies in the instability mode interaction. The meaning of mode interaction inherently refers to the erosion of critical bifurcation load in case of interaction of
two (or more) buckling modes associated with the same, or nearly the same, critical load. A well-known example of such a mode interaction is the one resulting from the coupling of local or distortional buckling with overall buckling in the case of thin-walled cold-formed members. Van der Neut [1] stated the erosion due to coupling and imperfection effects is maximum in the local–global coupling point. The ECBL approach extracts its basic principle from this conclusion. This is a review paper of which purpose is to summarize the mode interaction problem and ECBL approach, presenting the last results obtained by the authors.

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ABSTRACT: This paper reports the main results of an ongoing numerical investigation aimed at (i) assessing the buckling, post-buckling, strength and collapse behaviour of thin-walled steel structural systems and (ii) developing an efficient direct approach to estimate the ultimate loading of such structural systems, which may fail in complex modes that combine local, distortional and global features. The results currently available, obtained from Generalised Beam Theory and Ansys shell finite element analyses, concern continuous beams and simple frames subjected to various transverse loadings applied at/along the shear centre axis and causing non-uniform bending. The possibility of developing a design approach, based on the application of the existing Direct Strength Method (DSM) strength curves, is explored for the structural systems under consideration. The quality of the corresponding failure loading estimates is assessed through the comparison with the values yielded by shell finite element simulations.

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DOI: 10.1016/j.tws.2013.08.013

ABSTRACT: The paper presents the case of plastic instability of I-shaped beams where the rotation capacity is a very important characteristic in order to assure the required ductility in plastic or seismic design. The failure of such beams can be due to the local plastic plate buckling of compression flange and local plate buckling of the web in flexural compression, produced in-plane or out-of-plane. In the same time the failure can occur by coupling of these two local buckling modes. In order to study the plastic buckling of beams and to determine the available rotation capacity which is required by the plastic or seismic design, the collapse plastic mechanism theory was developed and a specialized computer program DUCTROT-M was elaborated. The parametrical analysis reveals the paramount importance of the web to thickness ratio and furthermore the sensitivity in out-of-plane buckling of the European hot-rolled sections.

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“Behaviour, failure and DSM design of cold-formed steel beams: Influence of the load point of application”, Thin-Walled Structures, Vol. 81, pp 78-88, August 2014, DOI: 10.1016/j.tws.2013.07.007

ABSTRACT: This work presents and discusses the results of an ongoing numerical investigation on the buckling, post-buckling, collapse and design of cold-formed steel beams subjected to non-uniform bending due to transverse loadings acting away from the shear centre (either at the top or bottom flange). These results consist of (i) elastic buckling loads and modes, obtained through analyses based on Generalised Beam Theory (GBT), and (ii) elastic–plastic equilibrium paths and collapse loads, yielded by Ansys geometrically and materially non-linear shell finite element analyses. The numerical ultimate strength values are compared with their estimates provided by the current Direct Strength Method (DSM) strength curves and, on the basis of this comparison, it is possible to assess the merits of the DSM approach to design beams subjected to transverse loadings acting away from the shear centre – moreover, novel features that may improve the performance of this approach are identified.

M. Ahmer Wadee and Li Bai (Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK), “Cellular buckling in I-section struts”, Thin-Walled Structures, Vol. 81, pp 89-100, August 2014, DOI: 10.1016/j.tws.2013.08.009

ABSTRACT: An analytical model that describes the interactive buckling of a thin-walled I-section strut under pure compression based on variational principles is presented. A formulation combining the Rayleigh–Ritz method and continuous displacement functions is used to derive a system of differential and integral equilibrium equations for the structural component. Numerical continuation reveals progressive cellular buckling (or snaking) arising from the nonlinear interaction between the weakly stable global buckling mode and the strongly stable local buckling mode. The resulting behaviour is highly unstable and when the model is extended to include geometric imperfections it compares excellently with some recently published experiments.


ABSTRACT: The elastic Van der Neut column has been a very useful tool to enhance our understanding of local-flexural interaction buckling of columns. In particular, Van der Neut's work has (a) illuminated the basic mechanism behind interaction buckling and (b) demonstrated that local-flexural interaction buckling is a highly imperfection sensitive phenomenon. In this paper, a component of inelastic behaviour is added to the classical Van der Neut column and its influence on the column buckling curve and the imperfection sensitivity is investigated. Numerical calculations are carried out using a finite differences scheme which is first explained in detail. In general, plasticity gives rise to a second ‘plateau’ in the buckling curve, curtailing the column capacity at low column slenderness values. This plateau typically exhibits low to moderate imperfection sensitivity. However, for yield stresses of the order of the local buckling stress of the flanges, both plateaus merge to form an extended zone of very high imperfection sensitivity.

Dieter Ungermann, Sebastian Lubke and Bettina Brune (Dortmund University of Technology, Institute of Steel Construction, August-Schmidt-Street 6, 44227 Dortmund, Germany), “Tests and design approach for plain

ABSTRACT: Thin-walled plain channels are often subjected to coupled local and global flexural buckling. The objective of this paper is to verify and discuss the current design procedure of Eurocode 3 for plain channels in coupled instabilities. This paper deals with experimental investigations on plain channel stub columns subjected to local buckling only and long columns subjected to coupled local-flexural buckling. The test series consists of cold-formed and welded plain channels made of steel grade S355 and S460. Based on this experimental results modifications of the method of effective width (and thickness) as stated by Eurocode 3 Part 1-3 are discussed. Previously developed modified buckling coefficients, which take into account the rigidity of the connection of web and flange, are verified by comparative calculations. Additionally an approach for an approximation of effective stiffness for coupled instabilities is discussed as well.


ABSTRACT: The direct strength method (DSM) has been adopted by the NAS (2004) and AS/NZS 4600 (2005) for the design of cold-formed steel members. The method can be successfully applied to the design of welded and hot-rolled sections. This paper reviews the development of the DSM for welded steel structural members. The design strength formulae for welded section columns and beams for the DSM are provided based on the tests performed on welded H-section, C-section, circular and rectangular hollow section columns fabricated from steel plates whose nominal yield stress is 235 MPa or 315 MPa. The comparison between the design strength of welded sections predicted by the DSM and that estimated by existing specifications is provided. This paper verifies that the DSM which adopts the nominal axial strength and flexural strength in the AISC (2010) or EC3 (2004) can properly predict the ultimate strength of welded section columns and beams.

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“The local-overall flexural interaction of fixed-ended plain channel columns and the influence on behaviour of local conditions at the constituent plate ends”, Thin-Walled Structures, Vol. 81, pp 132-137, August 2014 DOI: 10.1016/j.tws.2014.02.028

ABSTRACT: This paper examines the effect of the local support conditions at the ends of the constituent plates of plain channel section columns when subjected to uniformly compressed loading. The buckling and post-buckling interactive response of the columns have been determined through the development of suitable finite element modelling strategies and solution procedures which take due account of the influence of material nonlinearity and geometrical imperfections. Uniformly compressed loading means, of course, fixed conditions at the column ends with respect to global rotations and the ends of the constituent plates of the cross-section can be treated as either locally rotationally constrained or locally rotationally free. These two conditions are shown to lead to quite different characteristic interactive responses of the columns due to amplitude modulation in the buckling mode for the rotationally constrained case.

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ABSTRACT: This paper presents and discusses numerical results, obtained through Ansys shell finite element analyses, dealing with the post-buckling behaviour (mostly elastic, but also elastic–plastic), ultimate strength and failure mode nature of fixed-ended and pin-ended thin-walled equal-leg angle steel columns with coincident critical flexural-torsional and minor-axis flexural buckling loads (i.e., experiencing very strong coupling effects between these two global instability phenomena) – for comparative purposes, columns that are buckling in pure flexural-torsional and flexural modes are also analysed. Since the main aim of the work is to investigate the column imperfection-sensitivity, the analyses concern otherwise identical columns containing initial geometrical imperfections with different shapes and amplitudes, combining the competing critical buckling modes – particular attention is paid to the sign of the minor-axis flexural component. The results reported consist of column (i) elastic equilibrium paths and the corresponding peak loads and deformed configurations and (ii) elastic–plastic collapse loads and mechanisms, making it possible to assess how they are influenced by the initial geometrical imperfections.

Mihai Nedelcu and Hortensiu L. Cucu (Faculty of Civil Engineering, Technical University of Cluj-Napoca, Str. C. Daicoviciu No. 15, 400020 Cluj-Napoca, Romania), “Buckling modes identification from FEA of thin-walled members using only GBT cross-sectional deformation modes”, Thin-Walled Structures, Vol. 81, pp 150-158, August 2014, DOI: 10.1016/j.tws.2013.06.007

ABSTRACT: This paper presents the latest developments of an original method based on Generalized Beam Theory (GBT) capable to identify the fundamental deformation modes of global, distorsional or local nature, in general buckling modes provided by the shell finite element analysis (FEA) of isotropic thin-walled members. This method has the advantage of using only the GBT cross-sectional deformation modes instead of the member base mode shapes. The participation of each fundamental buckling mode can be calculated, allowing an accurate and quantitative evaluation of the coupled instability. There are no restrictions regarding the element cross-sectional shape, loading and quite recently discovered, boundary conditions.

Mihai Nedelcu, Andrei Crisan, Viorel Ungureanu and Dan Dubina, “Analysis of storage rack members by using GBT and Shell FEA”, Proceedings of the ICTWS 2014, 7th International Conference on Thin-Walled Structures, ICTWS2014, Busan, Korea

ABSTRACT: This paper analyses the interactive buckling behaviour of compression members used for steel pallet racks. Recently, the proposed rack members were thoroughly analyzed at CEMSIG Research Centre of “Politehnica” University of Timisoara. Following the guidelines of EN15512, the authors of this study performed experimental and numerical testing on a large number of specimens with lengths carefully chosen in order to capture the lower critical loads related with pure Local, Distortional buckling and also with the interactive Distortional-Global buckling usually met in practice for this type of sections. The aim of the presented paper is to quantify the Local-Distortional-Global (L-D-G) modes participation in the linear buckling shapes, assessing with high precision if the methods used for choosing the members lengths for experimental analyses, are valid. For this reason, an original modal identification method, based on the Generalised Beam Theory (GBT), is applied, providing the pure modes participation in any general buckling shape produced by
shell Finite Element Analysis.

Mihai Nedelcu, Anca Popa, Hortensiu-Liviu Cucu and Nicolae Chira (Faculty of Civil Engineering, Technical University of Cluj-Napoca, Str. C. Daicoviciu No. 15, 400020 Cluj-Napoca, Romania), “Vibration mode decomposition from finite element analysis of thin-walled members with holes”, publisher not listed, June 2016

ABSTRACT: Perforated thin-walled steel members are often used in civil engineering as structural elements for residential buildings and storage racks systems. In this paper the local-plate, distortional and global vibration behavior of perforated thin-walled members subjected to various loading is studied. This investigation is carried out by means of a very recently developed method based on the Generalised Beam Theory capable to decompose the general vibration/buckling modes provided by the shell finite element analysis into pure deformation modes of global, distortional or local nature. There are no restrictions regarding the element cross-


ABSTRACT: This paper presents an experimental investigation into the behaviour of ultra light-gauge steel storage rack uprights subjected to compression. Two different types of members with varying lengths are tested and while the combined effects of local and distortional buckling are investigated, special attention is given to longer specimens that fail by flexural–torsional buckling in combination with local and distortional buckling. Deformations experienced during testing by all of the specimens were measured and observations regarding failure modes have been documented. In addition, the geometric imperfections of each member were measured before testing, as were the material properties of the cold-rolled sections and the virgin steel from which the sections were formed. This paper details the observed failure modes, the recorded ultimate strengths and the load-deflection responses. Design capacities calculated from AS/NZS 4084 (2012) [1], RMI (2012) [2] and EN 15512 (2009) [3] specifications are then evaluated and compared to the experimental results obtained. The evaluation of international specifications determined that EN 15512 (2009) [3] is more accurate in predicting ultimate loads of sections undergoing interactive buckling than both AS/NZS 4804 (2012) [1] and RMI (2012) [2].

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ABSTRACT: Global buckling behaviour, with or without interaction with distortional buckling, of storage rack members is evaluated by tests carried out according to EN 15512 (2009) [1] on compression and out-of-plane bending of upright frame modules. Based on test results for both single upright sections and frame modules, completed by numerical simulation, the present paper attempts to demonstrate that the design buckling strength of uprights can be conveniently estimated by single section tests, providing that the length of these members is calibrated for the distortional–global interaction mode.

Pedro B. Dinis (1), Ben Young (2) and Dinar Camotim (1)
ABSTRACT: Experimental and numerical results concerning the post-buckling behaviour and strength of fixed-ended cold-formed steel rack-section columns experiencing local–distortional (L–D) interaction are reported. The experimental results, obtained from tests carried out at The University of Hong Kong include initial imperfection measurements, equilibrium paths and failure loads/modes – they provide clear evidence of the above coupling phenomenon. After presenting and discussing a comparison between test results and the values yielded by the corresponding Abaqus shell finite element numerical simulations, the experimental failure loads are used to assess the quality of their estimates provided by design approaches based on the Direct Strength Method (DSM) that were recently developed exclusively for fixed-ended lipped channel columns affected by L–D interaction. The work also includes a comparison between the ultimate strength and DSM design of lipped channel and rack-section columns undergoing similar L–D interaction effects.

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ABSTRACT: The paper reports experimental and numerical results concerning the post-buckling behaviour, strength and failure of fixed-ended cold-formed steel web-stiffened lipped channel columns that buckle in distortional modes. The experimental results, obtained from the tests carried out at The University of Hong Kong, (i) include initial imperfection measurements, equilibrium paths and failure loads and modes, and (ii) provide evidence of the occurrence of flange-triggered local-distortional interaction. After presenting and discussing a comparison between some test results and the values yielded by the corresponding Abaqus shell finite element numerical simulations, the experimental failure loads obtained in this work, together with additional data reported in the literature, are used to assess whether the available Direct Strength Method (DSM) design approaches are capable of predicting them efficiently (safely and accurately). It is found that this is not the case, mainly because of the fact that the mechanics of the flange-triggered and web-triggered local-distortional interactions are quite different. Although fairly good failure load predictions are provided by a new DSM design approach proposed in this work, further research is required on the mechanics of local–distortional interaction in web-stiffened lipped channel columns.

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“Effects of modal coupling on the dynamics of parametrically and directly excited cylindrical shells”, Thin-Walled Structures, Vol. 81, pp 210-224, August 2014, DOI: 10.1016/j.tws.2013.08.004
ABSTRACT: Cylindrical shells exhibit a dense frequency spectrum, especially in the lowest frequency range. In addition, due to the circumferential symmetry, frequencies occur in pairs. So, in the vicinity of the lowest natural frequencies, several equal or nearly equal frequencies may occur, leading to multiple internal resonances. The aim of the present work is to investigate the dynamic behavior and stability of cylindrical shells under lateral and axial forcing with equal natural frequencies. The shell is modeled using the Donnell nonlinear shallow shell theory. A consistent modal solution for this problem is deduced and used to discretize the equations of motion by applying the Galerkin method. A parametric analysis is conducted to clarify the influence of the modal interaction among these nonlinear vibration modes on coexisting solutions, bifurcations, resonances curves and stability boundaries of the shell.

ABSTRACT: This paper examines the response of stiffened plates with plain flat outstands when subjected to in-plane shear loading in the form of applied in-plane shear displacement. The buckling and post-buckling failure capabilities of thin plates subjected to in-plane shear, can, of course, be improved through the introduction of stiffening elements whose flexural and torsional rigidities can contribute significantly towards a more stabilised structural system. This paper details appropriate suitable finite element modelling strategies and procedures to enable the determination of the post-buckled failure response of the stiffened shear panels and to highlight the significant influence of the stiffeners. The modelling procedures are able to describe the complete loading history of the stiffened panel structures from the onset of initial buckling through the elastic post-buckling phase of behaviour involving the considerable interaction between plate and stiffener and then through initial material yielding and yield propagation to ultimate conditions and elasto-plastic unloading.

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ABSTRACT: The sandwich panel roof supported by continuously connected thin-walled cold-formed Z-purlins with overlapping over intermediate supports is a practical case of very frequent use. Among the two possible directions of investigation mentioned in the code when studying torsional/distortional instability of Z-purlins (i.e. rotational stiffness and linear stiffness) the authors have chosen to look at the notional linear spring placed at the free flange of the purlin. The linear spring is defined by EN 1993-1-3 Annex A5, as an equivalent or alternative to the stabilizing rotational spring generated by the continuous connection of the sandwich panels to purlin upper flange. This type of approach, on authors' opinion, has the advantage to include into the experimental phase, the real imperfections, and support conditions characteristic to such roof systems, having a very important impact on purlin stability behaviour. A description of the proposed full scale arrangement and experimental conditions, plus values of obtained results are given in the paper.

ABSTRACT: Stowell's solution [1] for the buckling behaviour of flange elements in compression was premised on the assumption that the element was fixed against flexural rotations at the ends, a condition representing relatively thick elements for which the thickness dimension is adequate to prevent rotations. This paper presents a solution similar to Stowell's which is applicable to pin-ended flange elements. Aspects not considered in Stowell's work, such as the use of elliptic functions to describe the gradual change of mode shape from sinusoidal to essentially linear, and the gradual and asymptotic changes in axial rigidity in the post-buckling range are described in the paper. The paper also presents comparisons between the behaviour of pin-ended and fixed-ended flange elements. Finally, simple strength equations for flange elements in uniform compression based on the first yield criterion are derived.

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“Experimental and numerical study of circular, stainless thin tube energy absorber under axial impact by a control rod”, Thin-Walled Structures, Vol. 82, pp 24-32, September 2014, DOI: 10.1016/j.tws.2014.03.020

ABSTRACT: In this study, several crashworthiness parameters of a circular, thin tube energy-absorbing structure, which is used in a high-temperature, gas-cooled reactor (HTR), are studied experimentally and numerically at various tube thicknesses, temperatures and impact velocities. The average crushing force is fundamentally dependent on strain hardening, strain rate hardening, and, particularly, temperature softening of the material. The peak forces during buckling are significantly affected by the local strain rate in the material and exhibit a decreasing trend in sequentially formed folds. Reducing the tube thickness is an effective method to weaken the average crushing force, but it does not weaken the maximum crushing force. Additionally, the stress concentration at the edge of the backplate–graphite contact surface is evaluated in detail to ensure the structural security of the energy absorber.

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“Experimental study on local buckling of axially compressed steel stub columns at elevated temperatures”, Thin-Walled Structures, Vol. 82, pp 33-45, September 2014, DOI: 10.1016/j.tws.2014.03.015

ABSTRACT: There are few design provisions in codes and standards on local buckling of steel columns under fire conditions. To examine the local stability of steel stub columns at elevated temperatures, 12 stub columns were tested under simultaneous application of load and fire conditions. The test variables included Grade (type) of steel, buckling resistance, temperature and load levels. During fire tests, cross sectional temperatures, axial displacement, buckling deflection, and local buckling failure modes of flange and web of stub columns were recorded at various temperatures. Data from the tests is utilized to evaluate buckling resistance of flange and web both at room and elevated temperatures by applying the ultimate strain method and curve inflexion point
method. Results from fire tests are utilized to validate a finite element model developed for tracing local buckling of steel columns at elevated temperatures. Results from fire tests and finite element analysis show that failure mode of columns at room and elevated temperatures follow similar pattern but the load bearing capacity of Q460 steel columns degrade much more rapidly under fire conditions than that of Q235 steel columns. Further, Eurocode 3 provisions for local buckling produce non-conservative results in certain situations.

Mihai Nedelcu (Faculty of Civil Engineering, Technical University of Cluj-Napoca, Str. C. Daicoviciu nr 15, 400020 Cluj-Napoca, Romania), “Buckling mode identification of perforated thin-walled members by using GBT and shell FEA”, Thin-Walled Structures, Vol. 82, pp 67-81, September 2014, DOI: 10.1016/j.tws.2014.04.005
ABSTRACT: The paper presents an original method based on the Generalised Beam Theory (GBT) whereby the general buckling modes, provided by the shell Finite Element Analysis (SFEA) of perforated thin-walled members, are expressed in terms of the fundamental (pure) buckling types (global, distortional and local). The contribution of each pure buckling mode to a coupled instability can be quantified, allowing a better understanding of the member buckling behaviour and post-buckling strength reserve. The main advantage of this method lies in using only the GBT cross-sectional pure deformation modes instead of member pure modal shapes. There are no restrictions regarding the element cross-sectional shape, loading and boundary conditions.

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“Semi-analytical models for the post-buckling analysis and ultimate strength prediction of isotropic and orthotropic plates under uniaxial compression with the unloaded edges free from stresses”, Thin-Walled Structures, Vol. 82, pp 82-94, September 2014, DOI: 10.1016/j.tws.2014.04.003
ABSTRACT: This paper introduces two semi-analytical models developed for the nonlinear analysis of stability of isotropic and orthotropic plates under uniaxial compression. The possibility of considering fully free in-plane displacements at longitudinal edges (or unloaded edges) is the innovation of these models over existing models, where these displacements are always assumed constrained to remain straight. Contributions for the large deflection theory of plates related to the derivation of analytical solutions for the Airy stress function which satisfy Marguerre’s equations for isotropic and orthotropic plates are presented. Namely, the extension of the Coan and Urbana solution for isotropic plates in order to consider all the terms of the unknown amplitudes of the out-of-plane displacements and the derivation of a solution for orthotropic plates. Comparisons between the semi-analytical model and nonlinear finite element model results are presented in order to discuss the effect of in-plane displacement boundary conditions on behaviour and strength of plates similar to bottom flanges used in steel box girder bridges. This study shows that the semi-analytical models have a clear potential to provide accurate solutions, requiring only a short computer time. It is also shown that the in-plane displacement boundary conditions for the unloaded edges significantly influence the behaviour and strength of plates and this problem cannot be neglected in the definition of the design rules.

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ABSTRACT: A new type of spot-weld double-hat section with symmetrically distributed tilt flanges (STFD-HAT) is introduced in this paper to improve the crushing performance, especially crushing stability. LS-DYNA code has been employed here to analyze the effect of several parameters on the collapse modes of STFD-HAT sections under axial dynamic impact loading condition. Some variables, such as tilt angle, size of core cross-section and thickness of sheet shell, have been proved to be effective in controlling the collapse mode and crushing performance of STFD-HAT sections by analysis on energy absorption and RSS of result curves. Compared with traditional double-hat sections, the STFD-HAT sections with reasonable designed profiles can effectively improve the crushing resistances and stabilities, especially, the bending mode.

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“Effect of reinforcement stiffeners on square concrete-filled steel tubular columns subjected to axial compressive load”, Thin-Walled Structures, Vol. 82, pp 132-144, September 2015, DOI: 10.1016/j.tws.2014.04.009
ABSTRACT: Eight stiffened square concrete-filled steel tubular (CFST) stub columns with slender sections of encasing steel and two non-stiffened counterparts were tested subjected to axial compressive load. Four types of reinforcement stiffeners and steel tensile strips were introduced to postpone local buckling of steel tubes, in which the tensile strip was first used as stiffener in CFSTs. The stiffening mechanism, failure modes of concrete and steel tubes, strength and ductility of stiffened square CFSTs were also studied during the experimental research. A numerical modeling program was developed and verified against the experimental data. The program incorporates the effect of the stiffeners on postponing local buckling of the tube and the tube confinement on concrete core. Extensive parametric analysis was also conducted to examine the influencing parameters on mechanical properties of stiffened square CFSTs.

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“Theoretical prediction and crashworthiness optimization of multi-cell triangular tubes”, Thin-Walled Structures, Vol. 82, pp 183-195, September 2014, DOI: 10.1016/j.tws.2014.03.019
ABSTRACT: The triangular tubes with multi-cell were first studied on the aspects of theoretical prediction and crashworthiness optimization design under the impact loading. The tubes’ profiles were divided into 2-, 3-, T-shapes, 4-, and 6-panel angle elements. The Simplified Super Folding Element theory was utilized to estimate the energy dissipation of angle elements. Based on the estimation, theoretical expressions of the mean crushing force were developed for three types of tubes under dynamic loading. When taking the inertia effects into account, the dynamic enhancement coefficient was also considered. In the process of multiobjective crashworthiness optimization, Deb and Gupta method was utilized to find out the knee points from the Pareto solutions space. Finally, the theoretical prediction showed an excellent coincidence with the numerical optimal results, and also validated the efficiency of the crashworthiness optimization design method based on surrogate models.

S. Koczubiej and C. Cichon (Faculty of Management and Computer Modelling, Kielce University of Technology, Al. Tysiclecia Państwa Polskiego 7, 25-314 Kielce, Poland), “Global static and stability analysis of thin-walled structures with open cross-section using FE shell-beam models”, Thin-Walled Structures, Vol. 82, pp 196-211, September 2014, DOI: 10.1016/j.tws.2014.04.014

ABSTRACT: The finite shell-beam models for static and global stability analysis of thin-walled structures with open cross-section are proposed. The discretization using thin-walled beam elements is connected with the space discretization of some parts of the frame. The space joint element, formulated using only translational degrees of freedom on cross-sections connecting the joint with the thin-walled beams and the so-called transition elements, defined between the beam and the shell nodes are used for consistent coupling beams and shell parts.

Zhen-hua Ji and De-yu Wang (State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China), “Influence of load shape on dynamic response of cross-stiffened deck subjected to in-plane impact”, Thin-Walled Structures, Vol. 82, pp 212-220, September 2014, DOI: 10.1016/j.tws.2014.04.007

ABSTRACT: Under severe sagging condition or wave slamming, ship deck is dynamically loaded in nature with impact type load. Based on the nonlinear explicit finite element method, the paper aims at studying influence of load shape on dynamic response of a cross-stiffened deck subjected to in-plane impact, accounting for strain rate effect, strain hardening, and potential contact of compressive components. Axial residual displacement of the impacted end is selected as main detected dynamic response of the deck. Four parameters depicting load shape are considered; they are impact duration, peak load, the decaying type after reaching the peak load (here refers to second order derivative of the load), ratio between rise time of the load and total impact duration. The first three load shape parameters, impact duration, peak load and decaying type, are related to impulse. The longer the impact duration, the larger the peak load, the slower the decaying of the load, which can result in the larger impulse. The larger the impulse is, the larger the dynamic response of the impacted deck is, on the condition that the impact duration is finite with the order of milliseconds. While the fourth load shape parameter, ratio of rise time and impact duration, although it is not related to impulse, it is also an important influential factor on dynamic response of the impacted deck. The smaller the ratio is, the larger the dynamic response of the impacted deck is; if the impact duration is longer, the effect is more significant. So the parameter, ratio of rise time and impact duration, deserves more concern in future research.
P. Malekzadeh and A.R. Zarei (Department of Mechanical Engineering, School of Engineering, Persian Gulf University, Bushehr 7516913798, Iran), “Free vibration of quadrilateral laminated plates with carbon nanotube reinforced composite layers”, Thin-Walled Structures, Vol. 82, pp 221-232, September 2014
DOI: 10.1016/j.tws.2014.04.016

ABSTRACT: The free vibration behavior of quadrilateral laminated thin-to-moderately thick plates with carbon nanotube reinforced composite (CNTRC) layers is studied. The governing equations are based on the first-order shear deformation theory (FSDT). The solution procedure is based on transforming the governing differential equations from an arbitrary straight-sided physical domain to a regular computational one, and discretization of the spatial derivatives by employing the differential quadrature method (DQM) as an efficient and accurate numerical tool. Four different profiles of single walled carbon nanotubes (SWCNTs) distribution through the thickness of layers are considered, which are uniformly distributed (UD) and three others are functionally graded (FG) distributions. The fast rate of convergence of the presented approach is numerically demonstrated and to show its high accuracy, wherever possible comparison studies with the available results in the open literature are performed. Then, the effects of volume fraction of carbon nanotubes (CNTs), geometrical shape parameters, thickness-to-length and aspect ratios, different kinds of CNTs distribution along the layers thickness and different boundary conditions on the natural frequencies of laminated plates are studied.

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ABSTRACT: The structural configuration and method of analysis of the single-layer inverted catenary cylindrical reticulated shell are introduced in this paper, and the elastic as well as elastic–plastic stability of this kind of reticulated shell is then investigated. The stability of the structures with different types of grid patterns is compared, and the reasonable grid pattern is hence recommended. The structural buckling mode and ultimate load–carrying capacity are studied in detail by parametric analysis. Influence of various factors on structural ultimate load is investigated, and the fitting formula of ultimate load is thus presented. Comparison analysis between the inverted catenary and circular cylindrical reticulated shells is also carried out. The work will provide guidance in theory for practical applications of this kind of structure.

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ABSTRACT: In this paper, a numerical method is presented for the free vibration and stability analyses of tapered thin-walled beams with arbitrary open cross sections. The proposed method takes the flexural–torsional coupling effect of tapered thin-walled beams with arbitrary open cross sections into account. The total potential energy is derived for an elastic behavior from the strain energy, the kinetic energy and work of the loads applied on the cross section contour. Free vibration is considered in the presence of harmonic excitations. The effects of the initial stresses and load eccentricities are also considered in stability analysis. The governing equilibrium
equations, motion equations and the associated boundary conditions are derived from the stationary condition. As in the presence of tapering, stiffness quantities are not constant; therefore, the power series approximation is used to solve the fourth-order differential equations. Displacement components and cross-section properties are expanded in terms of power series of a known degree. Then, the shape functions are obtained by deriving the deformation shape of tapered thin-walled member as power series form. Finally, stiffness and mass matrices are carried out by means of the principle of virtual work along the member’s axis. In order to measure the accuracy and check the validity of this method, the natural frequencies and buckling loads of non-prismatic thin-walled beams with web and flange tapering and various boundary conditions are obtained and compared to the results of finite element analysis using Ansys software and those of other available numerical and analytical ones. It can be seen that the results of present study are in a good agreement with other available theoretical and analytical methods.

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“Quasi-static response and multi-objective crashworthiness optimization of oblong tube under lateral loading”, Thin-Walled Structures, Vol. 82, pp 262-277, September 2014, DOI: 10.1016/j.tws.2014.03.012
ABSTRACT: This paper addresses the energy absorption responses and crashworthiness optimization of thin-walled oblong tubes under quasi-static lateral loading. The oblong tubes were experimentally compressed using three various forms of indenters named as the flat plate, cylindrical and a point load indenter. The oblong tubes were subjected to inclined and vertical constraints to increase the energy absorption capacity of these structures. The variation in responses due to these indenters and external constraints were demonstrated. Various indicators which describe the effectiveness of energy absorbing systems were used as a marker to compare the various systems. It was found that unconstrained oblong tube (FIU) exhibited an almost ideal response when a flat plate indenter was used. The design information for such oblong tubes as energy absorbers can be generated through performing parametric study. To this end, the response surface methodology (RSM) for the design of experiments (DOE) was employed along with finite element modeling (FEM) to explore the effects of geometrical parameters on the responses of oblong tubes and to construct models for the specific energy absorption capacity (SEA) and collapse load \( F \) as functions of geometrical parameters. The FE model of the oblong tube was constructed and experimentally calibrated. In addition, based on the developed models of the SEA and \( F \), multi-objective optimization design (MOD) of the oblong tube system is carried out by adopting a desirability approach to achieve maximum SEA capacity and minimum \( F \). It is found that the optimal design of FIU can be achieved if the tube diameter and tube width are set at their minimum limits and the maximum tube thickness is chosen.

Mohamed Elchalakani (Higher Colleges of Technology, Dubai Men’s College, PO Box 15825, Dubai, UAE), “Plastic collapse analysis of CFRP strengthened and rehabilitated degraded steel welded RHS beams subjected to combined bending and bearing”, Thin-Walled Structures, Vol. 82, pp 278-295, September 2014
DOI: 10.1016/j.tws.2014.05.002
ABSTRACT: Innovative techniques using the lightweight, high strength and corrosion resistance of carbon fibres reinforced polymers (CFRP) composites have been proposed in a recent paper by the author. The present paper presents plastic mechanism analyses of CFRP strengthened and rehabilitated rectangular hollow sections (RHS) under quasi-static large deformation 3-point bending. The strengthening series was for un-degraded RHS beams from the manufacturer reinforced using externally wrapped CFRP sheets. The rehabilitation series was
for artificially degraded RHS beams repaired using externally wrapped sheets or bonded plates. The main parameters examined in this paper were the section type, section and member slenderness and the type and number of the CFRP sheets. Three different phases of plastic deformation were observed during the test, namely, denting, denting and bending, and structural collapse. Two methods were used to model the large plastic deformation measured during plastic collapse of the composite RHS beams, namely, equilibrium and energy methods of analysis. It was found that the predicted collapse curves using the equilibrium approach were in good agreement with the measured curves for the bare and composite specimens examined in the strengthening and rehabilitation series, particularly for the latter series. This may be caused by a number of factors such as the specimens in the rehabilitations series were comparatively longer and had larger bearing width. The energy theory was found to have deficiencies represented in the simplified linear polygon shape adopted for the mechanism geometry, and adopting the plastic 1/2-wave length used for I-sections, as well as the use of a simplified formulae to describe the relationship between the local denting displacement and global bending rotation angle for the three phases of deformation observed during the test.

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“Multiobjective crashworthiness optimization of hollow and conical tubes for multiple load cases”, Thin-Walled Structures, Vol. 82, pp 331-342, September 2014, DOI: 10.1016/j.tws.2014.05.006

ABSTRACT: Much attention of current design analysis and optimization of crashworthy structures have been largely paid to the scenarios with single load case in literature. Nevertheless the designed structures may often have to be operated in other load conditions, thus raising a critical issue of optimality. This paper aims to understand and optimize the dynamic responses and energy absorption of foam-filled conical thin-walled tubes under oblique impact loading conditions by using multiobjective optimization method. The crashworthiness criteria, namely specific energy absorption (SEA) and crushing force efficiency (CFE), are related to loading parameters and design variables by using D-optimal design of experiments (DoE) and Kriging model. To obtain the optimal Pareto solutions of hollow and foam-filled conical tubes, design optimization is first performed under different loading case (DLC) using multiobjective particle swarm optimization (MOPSO) algorithm separately. The optimal designs indicate that hollow tube has better crashing performance than the foam-filled tube under relatively high impacting velocity and great loading angle. To combine multiple load cases (MLC) for multiobjective optimization, a double weight factor technique is then adopted. It is found that the optimal foam-filled tube has better crashing performance than empty conical tube under any of overall oblique loading cases concerned. The study gains insights in deriving multiobjective optimization for multiple load cases, providing a guideline for design of energy absorber under multiple oblique loading.

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ABSTRACT: The objective of this paper is to develop a design method for stainless steel columns subjected to flexural buckling. In this method, the strength curve for every type of stainless steel in common use is generated by using the base strength curves and a slenderness conversion formula. A validated finite element model is employed to generate the strength curves for different types of stainless steels. According to the strain hardening exponent $n$ in the Ramberg-Osgood material model, cluster analysis is conducted to separate these strength curves into two groups. In each group, one type of material parameter is selected as the base material and the corresponding strength curve is expressed in the form of a modified Perry formula that serves as the base strength curve. A slenderness conversion formula is derived for any two stainless steel columns with the same section type and boundary conditions, but with different types of stainless steel. Based on the base strength curves and the slenderness conversion formula, the strength curve for every type of stainless steel in common use can be generated. The predictions of the proposed method show a good agreement with the results of the finite element analysis.

Petr Hradil and Asko Talja (VTT, Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland), “Numeric verification of stainless steel overall buckling curves”, Thin-Walled Structures, Vol. 83, pp 52-58, October 2014, DOI: 10.1016/j.tws.2014.01.011

ABSTRACT: The introduction of new material grades or fabrication methods in engineering structures always raises concerns about the validity of current design rules, especially those based on earlier material or member testing. One of the fundamental structural checks is the overall stability of beams and columns. In this paper, a series of virtual buckling tests is calculated and compared to the Eurocode buckling curves. The main focus is on the applicability of ferritic steels that generally have different stress–strain behaviour than austenitic or duplex grades.

Yuner Huang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Structural performance of cold-formed lean duplex stainless steel columns”, Thin-Walled Structures, Vol. 83, pp 59-69, October 2014, DOI: 10.1016/j.tws.2014.01.006

ABSTRACT: The structural performance of cold-formed lean duplex stainless steel columns was investigated. A wide range of finite element analysis on square and rectangular hollow sections and other available data, with a total number of 259 specimens, were considered. An accurate finite element model has been created to simulate the pin-ended cold-formed lean duplex stainless steel columns. Extensive parametric study was carried out using the validated finite element model. The column strengths predicted from the parametric study together with the available data are compared with the design strengths calculated from various existing design rules for cold-formed stainless steel structures. It is shown that the existing design rules, except for the ASCE Specification as well as the stub column and full area approach, are conservative. Modifications are proposed for the AS/NZS Standard, EC3 Code, and direct strength method. Reliability analysis was performed to assess the existing and modified design rules. It is also shown that the modified design rules are able to provide a more accurate and reliable predictions for lean duplex stainless steel columns. In this study, it is suggested that the modified design rules in the AS/NZS Standard and the modified direct strength method to be used in designing cold-formed lean duplex stainless steel columns.

Shenggang Fan, Fang Liu, Baofeng Zheng, Ganping Shu and Yuelin Tao (School of Civil Engineering, Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Sipailou 2, Zip: 210096, Nanjing, China), “Experimental study on bearing capacity of stainless steel lipped C section stub columns”, Thin-Walled Structures, Vol. 83, pp 70-84, October 2014,
ABSTRACT: This paper studies the failure mechanism and the bearing capacity of stainless steel lipped C section stub columns under axial and eccentric compression. A series of tests were performed on S30408 stainless steel, including 16 mechanical property tests, 10 axially loaded and 28 eccentrically loaded stub column tests. Flat and corner coupon tests were conducted to investigate the anisotropy, the hardening index and the stress–strain behavior of stainless steel. Stub column tests were carried out to obtain the load–displacement curves, the bearing carrying capacity and the section strain variation. Comparison of test results with code predictions indicates that the design strengths are lower than the experimental strengths, and that the deviation between test and predicted results reduces as the section plate slenderness coefficient increases.

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ABSTRACT: When compared with carbon steel, stainless steel exhibits a more pronounced non-linearity and no well-defined yield plateau, as well as appealing features such as aesthetics, higher corrosion resistance and lower life cycle cost. Due to its considerably high ductility/strength and cost, stainless steel structural solutions tend to be adopted mostly for slender/light structures, thus rendering the assessment of their structural behaviour rather complex, chiefly because of the high susceptibility to instability phenomena. The first objective of this paper is to present the main concepts and procedures involved in the development of a geometrically and materially non-linear Generalised Beam Theory (GBT) formulation and numerical implementation (code), intended to analyse the behaviour and collapse of thin-walled members made of materials with a highly non-linear stress–strain curve (e.g., stainless steel or aluminium). The second objective is to validate and illustrate the application of the proposed GBT formulation, by comparing its results (equilibrium paths, ultimate loads, deformed configurations, displacement profiles and stress distributions) with those provided by shell finite element analyses of two lean duplex square hollow section (SHS) columns previously investigated, both experimentally and numerically, by Theofanous and Gardner (Eng Struct 2009; 31(12): 3047–3058.). The stainless steel material behaviour is modelled as non-linear isotropic and the GBT analysis includes initial geometrical imperfections, but neglects corner strength enhancements and membrane residual stresses. It is shown that the GBT unique modal nature makes it possible to acquire in-depth knowledge concerning the mechanics of the column behaviour, by providing “structural x-rays” of the (elastic or elastic–plastic) equilibrium configurations: modal participation diagrams showing the quantitative contributions of the global, local, warping shear and transverse extension deformation modes - moreover, this feature makes it possible to exclude, from future similar GBT analyses, those deformation modes found to play a negligible role in the mechanics of the behaviour under scrutiny, thus further reducing the number of degrees of freedom involved in a GBT analysis, i.e., increasing its computational efficiency.

References listed at the end of the paper:

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“Stub column tests on stainless steel built-up sections”, Thin-Walled Structures, Vol. 83, pp 103-114, October 2014, DOI: 10.1016/j.tws.2014.01.007

ABSTRACT: This paper presents twenty-eight stub columns tests on stainless steel built-up sections. The test specimens, including I-sections, square hollow sections (SHS) and rectangular hollow sections (RHS), were fabricated by shielded metal arc welding (SMAW) from hot-rolled plates of nominal thicknesses 6 mm and 10 mm. The twenty-eight stub columns, of two stainless steel alloys (austenitic EN 1.4301 and duplex EN 1.4462), were tested in pure axial compression. Both tensile and compressive material properties were obtained by means of coupon tests in three directions – longitudinal, diagonal and transverse to the rolling direction. Geometric imperfection measurements for each specimen were conducted by means of a calibrated electric guideway, and residual stress distributions in the built-up sections were determined by means of the sectioning method. The test strengths were used to evaluate the design strengths predicted by EN 1993-1-4, the Continuous Strength Method (CSM) and the direct strength method (DSM). It was demonstrated that the predicted strengths from EN 1993-1-4 provisions were generally conservative, while both the CSM and the DSM predicted values were closer to the test strengths.

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ABSTRACT: An experimental study of stainless steel continuous beams not susceptible to lateral torsional buckling is reported in this paper and the applicability of plastic design methods to such structures is considered. A total of 18 two-span continuous beams were tested. Three cross-section types – cold-formed square hollow sections (SHS), cold-formed rectangular hollow sections (RHS) and welded I-sections, and two material grades – austenitic EN 1.4301/1.4307 and lean duplex EN 1.4162, were considered. The geometric and material properties of the continuous beam test specimens were carefully recorded and supplemented by tests on simply supported specimens of the same cross-sections. The test specimens covered a wide range of cross-section slendernesses and two different loading positions were adopted. The experimental results were used to assess the degree of moment redistribution in indeterminate stainless steel structures and the applicability of both conventional and novel plastic design methods, including an extension of the continuous strength method (CSM). Comparisons indicated that conventional plastic design is applicable to stainless steel structures, while greater efficiency can be achieved by considering strain-hardening through the CSM.

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ABSTRACT: The present investigation studies the overall stability bearing capacities of stainless steel welded I-section beams. Experimental tests of 8 specimens have been conducted. In addition, complementary finite element (FE) models, which have been validated by the test results, are adopted to calculate the overall stability bearing capacities of the beams. Based on the results of FE analyses and experimental tests, as well as the comparisons of design standards for buckling reduction factor calculations of stainless steel structural components, two calculation methods for buckling reduction factors of welded I-section beams are proposed. One is the modification of Chinese code for design of steel structures, and the other is regressed by the FE analysis results. Both methods are conservative and have simple formulations for engineering design.

P. Malekzadeh and M. Daraie (Department of Mechanical Engineering, Persian Gulf University, Bushehr 7516913798, Iran), “Dynamic analysis of functionally graded truncated conical shells subjected to asymmetric moving loads”, Thin-Walled Structures, Vol. 84, pp 1-13, November 2014, DOI: 10.1016/j.tws.2014.05.007
ABSTRACT: The dynamic behavior of functionally graded (FG) truncated conical shells subjected to asymmetric internal ring-shaped moving loads is studied. The material properties are assumed to have continuous variations in the shell thickness direction. The equations of motion are derived based on the first-order shear deformation theory (FSDT) using Hamilton’s principle. The finite element method (FEM) together with Newmark’s time integration scheme is employed to discretize the equations of motion in the spatial and temporal domain, respectively. The formulation and method of solution are validated by studying their convergence behavior and carrying out the comparison studies in the limit cases with existing solutions in the literature. Then, the influences of material graded index, radius-to-length ratio, semi-vertex angle, thickness, boundary conditions and moving load velocity on the dynamic behavior of the FG truncated conical shells are
studied. In addition, the difference between the responses of the FG shells under symmetric and asymmetric loadings is compared.

Ahmad Amiri Rad and Danial Panahandeh-Shahraki (Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran), “Buckling of cracked functionally graded plates under tension”, Thin-Walled Structures, Vol. 84, pp 26-33, November 2014, DOI: 10.1016/j.tws.2014.05.005

ABSTRACT: Buckling of functionally graded plates under tension has not been investigated so far. In this paper critical buckling load of functionally graded plates containing a crack has been obtained using classical plate theory through the finite element method. Displacement in vicinity of crack tips has been approximated using previous solutions related to bending of cracked plates. Effect on buckling of plate under uni-axial and bi-axial tension of different parameters, such as plate dimensions and material properties, are studied. Results show that the critical load decreases as material gradient index increases, while bi-axial loading leads to higher critical loads compared to uni-axial case.

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“Web crippling failure using quasi-static FE models”, Thin-Walled Structures, Vol. 84, pp 34-49, November 2014, DOI: 10.1016/j.tws.2014.05.003

ABSTRACT: This paper presents an investigation on the use of quasi-static analyses with explicit integration to evaluate the web crippling behaviour of cold-formed steel beams. Web crippling failure occurs due to the application of transverse concentrated loads, which can be applied statically or dynamically. In the majority of the examples found in the literature, the web crippling phenomenon has been investigated by means of purely static shell finite element (SFE) models with implicit integration. In this work, the ABAQUS code was employed to implement SFE models aimed at replicating an experimental test and quasi-static analyses with an explicit integration scheme were adopted. First, a brief literature review on the topic of the numerical investigation of web crippling of cold-formed steel members is presented. Then, the paper addresses the characterisation of the quasi-static analysis concept with particular emphasis on the control of dynamic effects and the SFE model of a lipped channel beam under External Two Flange (ETF) loading is described. Several conventional parameters of standard SFE analysis, such as the SFE type, mesh selection, steel model, hardening effects due to cold-forming, residual stresses, initial imperfections and support conditions are explained, as well as additional specifications pertaining to the adoption of quasi-static analyses, such as the load rate, mass scaling, contact and friction, smoothed amplitude curves and inhibition of inertia (noise) effects. Finally, the results obtained are presented in the context of the ETF case, including load–displacement curves, curves of kinetic-to-internal energy ratio vs. displacement and beam deformed shapes (failure modes). It is concluded that explicit analysis leads to rigorous simulations of experimental test results, in terms of ultimate load, post-collapse load–deflection curve and failure mechanism. The failure mode obtained with the quasi-static analysis provides a better approximation of the one observed experimentally than its non-linear static analysis counterpart. Indeed, the failure mechanism emerges considerably more clearly when the quasi-static analysis is adopted.
Tohid Ghanbari Ghazijahani, Hui Jiao and Damien Holloway (School of Engineering and ICT, University of Tasmania, Hobart, Australia), “Experiments on dented cylindrical shells under peripheral pressure”, Thin-Walled Structures, Vol. 84, pp 50-58, November 2014, DOI: 10.1016/j.tws.2014.05.012

**ABSTRACT:** In spite of numerous papers in the literature on the buckling behavior of cylindrical shell structures, the effect of local large imperfections caused by physical contacts has not been exhaustively examined yet. To this end, this paper reports on an experimental program on the buckling and post-buckling response of thin cylindrical shells with local dent imperfections under uniform external pressure. The results of this study can be used in practical structures with similar geometric features, i.e. $D/t$ ratio.

Fei Xu, Ju Chen and Wei-liang Jin (Department of Civil Engineering, Zhejiang University, China), “Experimental investigation of thin-walled concrete-filled tube columns with reinforced lattice angle”, Thin-Walled Structures, Vol. 84, pp 59-67, November 2014, DOI: 10.1016/j.tws.2014.05.015

**ABSTRACT:** Experimental investigation of thin-walled concrete-filled steel tube columns with reinforced lattice angle was conducted in this study. The lattice angle was designed to reinforce the concrete-filled steel tube columns by increasing the percentage of steel cross-sectional area. Column specimens having different lengths ranged from 500 mm to 3500 mm were tested. The behavior and strengths of concrete-filled steel tube columns with lattice angle were investigated. In addition, concrete-filled steel tube columns having the same size but without reinforced lattice angle were also tested for comparison. Material properties of the concrete and steel used in the test specimens were measured. The test strengths are compared with the design strengths calculated using the AISC Specification and Eurocode for the design of composite structural members. A new design method was also proposed for the concrete-filled steel tube columns with reinforced lattice angle. It is shown that the design predictions from the proposed method agree with test results well.

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“Post-local-buckling of fiber-reinforced plastic composite structural shapes using discrete plate analysis”, Thin-Walled Structures, Pp 68-77, November 2014, DOI: 10.1016/j.tws.2014.05.008

**ABSTRACT:** In this paper, post-buckling of rectangular composite plates rotationally restrained at the longitudinal unloaded edges and subjected to end shortening strain at the simply-supported loaded edges is analyzed using the first-order shear deformation plate theory-based spline finite strip method, and its application to post-local-buckling of fiber-reinforced plastic (FRP) composite structural shapes is illustrated with discrete plate analysis. Two cases of elastically- and rotationally-restrained plates are analyzed using the spline finite strip method: rotationally-restrained along both the unloaded boundary edges (RR) and one rotationally-restrained and the other free along the unloaded edges (RF). The two cases of rotationally-restrained plates (i.e., the RR and RF plates) are further treated as the discrete plates of closed and open section FRP shapes, and by considering the effect of elastic restraints at the joint connections of flanges and webs, post-local-buckling of various FRP shapes under end shortening is studied. The numerical comparisons with the finite element modeling demonstrate that the proposed discrete plate analysis technique and spline finite strip method can be used as an efficient and valid tool for post-local-buckling analysis of FRP shapes.
Elsayed B. Machaly, Sherif S. Safar and Mostafa A. Amer (Cairo University, Giza, Egypt), “Numerical investigation on ultimate shear strength of steel plate shear walls”, Thin-Walled Structures, Vol. 84, pp 78-90, November 2014, DOI: 10.1016/j.tws.2014.05.013

ABSTRACT: Ultimate shear strength of steel plate shear walls, SPSW, was conventionally computed as the sum of base shear supported by in-fill plate and boundary frame elements. The base shear supported by the in-fill plate was computed assuming that it was fully yielded after buckling whereas the base shear supported by the boundary frame elements was computed by plastic analysis assuming uniform yielding mechanism. In this paper the ultimate shear strength of SPSW was investigated by the finite element method. A detailed three-dimensional finite element model was established using ANSYS software at which the in-fill plate and the boundary frame elements were modeled using finite strain iso-parametric shell elements. The analysis included material and geometric non-linearities. Numerical results obtained from cyclic and pushover loading of SPSWs were verified by comparison to test results published in the literature. A comprehensive parametric analysis was conducted to assess the effect of geometric and material parameters of the wall on its ultimate shear strength. Discrepancies between numerical results and conventional theory were attributed to interaction of in-fill plate and boundary frame elements at ultimate load. When the flexural rigidity of boundary frame elements decreased, the in-fill plate did not achieve full yield strength. On the other hand, the base shear supported by boundary frame elements increased when thicker in-fill plates were utilized. Numerical results were used to update the theoretical expression of ultimate shear strength of SPSWs. The proposed expression was assessed by comparison to test results published in the literature.

Vaibhav Mittal, Tanusree Chakraborty and Vasant Matsagar (Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi 110016, India), “Dynamic analysis of liquid storage tank under blast using coupled Euler-Lagrange formulation”, Thin-Walled Structures, Vol. 84, pp 91-111, November 2014, DOI: 10.1016/j.tws.2014.06.004

ABSTRACT: A growing number of terror attacks all over the world have become a threat to the human civilization. In the last two decades, bomb blasts in crowded business areas, underground railway stations and busy roads have taken numerous lives and destroyed properties in different parts of the world. However, blast response of many important civil infrastructures has still not been well understood due to the complexities in their material behavior, loading and higher nonlinearities. One such example of important civil infrastructure is liquid storage tanks which are undividable parts of any society for storage of water, milk, liquid petroleum, chemicals in industries etc. Blast loading on liquid storage structures may lead to disaster due to water and milk crisis, health hazard owing to the spread of chemicals and fire hazard due to the spread of liquid fuel. Hence, understanding the dynamic behavior of liquid storage structures under blast loading through numerical simulations is of utmost importance. In the present study, three dimensional (3D) finite element (FE) simulations of a steel water storage tank for different tank aspect ratios, percentages of water stored in the tank, tank wall thicknesses, boundary conditions at the bottom of the tank and magnitudes of blast loading have been performed using the FE software Abaqus. The coupled Euler–Lagrange (CEL) formulation in Abaqus has been adopted herein which has the advantage of considering the coupling of structural mechanics and fluid mechanics fundamental equations. The maximum hoop stress and shear stress in the tank wall, the water sloshing heights in tanks and the energy response of the tanks have been studied. It is observed that stresses and liquid sloshing heights in the tank increase with decreasing scaled distance of the explosive material and increasing aspect ratio, i.e. height to radius ratio.

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“Eccentric low-velocity impact analysis of transversely graded plates with Winkler-type elastic foundations and fully or partially supported edges”, Thin-Walled Structures, Vol. 84, pp 112-122, November 2014
DOI: 10.1016/j.tws.2014.05.011

ABSTRACT: Impact analysis of plates with either elastic foundations or partially supported edges has not been accomplished, even for the homogeneous isotropic plates. In the present paper, eccentric low-velocity impact analysis of a functionally graded plate with fully/partially supported edges and a Winkler-type elastic foundation is performed. In contrast to the available researches, stiffness of the underneath layers is also taken into account in determination of the apparent stiffness of the contact region, employing Mori–Tanaka micromechanics-based model instead of the traditional rule of mixtures. The governing equations are derived based on the principle of minimum total potential energy and the first-order shear-deformation plate theory. Some of the included novelties are: modification of the contact law, incorporation of effects of the elastic foundation, considering the material heterogeneity and partially supporting the edges, and proposing various semi-analytical and (Galerkin-type) numerical solutions. Numerical time integration schemes are used to trace time variations of the responses. A sensitivity analysis is performed to investigate influences of the specifications of the plate and the indenter, the eccentricity, and the supporting length ratio on time histories of the indentation and contact force.

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DOI: 10.1016/j.tws.2014.06.002

ABSTRACT: In this paper the generalization of the constrained finite strip method (cFSM) is provided. cFSM is an extension of the semi-analytical finite strip method (FSM), where carefully defined constraints are applied to enforce the thin-walled member to deform in accordance with desired deformations, e.g., to buckle in flexural, lateral-torsional, distortional, or local buckling mode. This paper is a companion to [1], where the method is introduced and where the primary modes are defined, i.e., modes that are associated with minimal cross-section discretization, when nodal lines are located at folds and ends only. In this paper the so-called secondary modes are defined, i.e., those with no displacements at folds and edges, which thus exist only if flat plates are discretized into multiple strips. Moreover, some practical aspects are also discussed, including how the individual base vector of the deformation spaces can be defined in a practically useful and meaningful manner. The applicability of the method is demonstrated by numerical examples.

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“Effective width method to account for the local buckling of thin plates at elevated temperatures”, Thin-Walled Structures, Vol. 84, pp 134-149, November 2014, DOI: 10.1016/j.tws.2014.06.003

ABSTRACT: The local buckling of thin steel plates exposed to fire is investigated using a finite element model. The reduction of strength and stiffness that occurs at elevated temperatures needs to be taken into account in the design, as it increases the susceptibility to local buckling of the plates thus affecting their load carrying capacity. The obtained results show that the current existing design method of Eurocode 3 to take into consideration the local buckling in the calculation of the ultimate strength of steel thin plates at elevated temperatures needs to be improved. These methods are based on the same principles as for normal temperature but using for the design yield strength of steel, at elevated temperatures, the 0.2% proof strength of the steel instead of its strength at 2% total strain as for the cases where the local buckling is not limiting the ultimate strength of the plates. This consideration, however, leads to an inconsistency if cross-sections are composed simultaneous of plates susceptible and not to local buckling. To address this issue, new expressions for calculating the effective width of internal compressed elements (webs) and outstand elements (flanges) are proposed, which have been derived from the actual expressions of the Part 1.5 of the Eurocode 3 and validated against numerical results. It is also demonstrated that it is not necessary to use for the yield stress at elevated temperatures the 0.2% proof strength of the steel instead of the yield stress at 2% total strain, given that the necessary allowances are considered in these new expressions, thus leading to a more economic design.

Sandor Adany and Benjamin W. Schafer, “Generalized constrained finite strip method for thin-walled members with arbitrary cross-section: Primary modes”, Thin-Walled Structures, Vol. 84, pp 150-169, November 2014 DOI: 10.1016/j.tws.2014.06.001

ABSTRACT: In this paper the generalization of the constrained finite strip method (cFSM) is discussed. cFSM is a special version of the semi-analytical finite strip method (FSM), where carefully defined constraints are applied which enforce the thin-walled member to deform in accordance with specific mechanics, e.g., to allow buckling only in flexural, lateral–torsional, or a distortional mode. In the original cFSM only open cross-section members are handled, here the method is extended to cover any flat-walled member, including those with closed cross-sections or cross-sections with open and closed parts. Moreover, in the original cFSM only 4 deformation classes are defined, here the deformation field is decomposed into additional, mechanically meaningful, sub-fields. Formal mechanical criteria are given for the deformation classes, and implementation of the criteria regardless of cross-section topology is illustrated. In this paper, the primary deformation classes are presented in detail. Primary deformations are associated with minimal cross-section discretization, i.e. nodal lines located at folds and ends only. This paper is accompanied by a companion, where secondary modes and additional practical aspects in the selection of base vectors for the deformation classes are discussed. With the proposed modifications the powerful cFSM capabilities of buckling mode decomposition and identification are extended to essentially arbitrary thin-walled cross-sections.

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“Quasi-static axial compression of concentric expanded metal tubes”, Thin-Walled Structures, Vol. 84, pp 170-176, November 2014, DOI: 10.1016/j.tws.2014.06.012
ABSTRACT: Previous studies have demonstrated that the failure mechanism and energy absorption capacity of expanded metal tubes strongly depends on the orientation of the cells. This paper presents an experimental investigation on the collapse of concentric expanded metal tubes subjected to quasi-static axial compression. Square tubes with two different cell orientations are tested to failure, and the energy absorption characteristics are calculated. The results show that the combination of cell geometries lead to a complex buckling mode interaction, which enhances the energy absorption capacity of expanded metal tubes.

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ABSTRACT: This paper addresses the free vibration behaviour of single-cell thin-walled tubes with regular convex polygonal cross-section (RCPS) and provides an extensive analysis of the resulting natural frequencies and associated vibration mode shapes. A semi-analytical approach is adopted, which is based on the generalised beam theory (GBT) specialisation for RCPS recently proposed by Gonçalves and Camotim (2013) and subsequently employed to obtain insightful conclusions concerning the buckling behaviour of RCPS tubes (Gonçalves and Camotim (2013) 2 and 3). This approach makes it possible to obtain closed-form analytical solutions and also acquire in-depth knowledge concerning the mechanics of the vibration problem, through the well-known GBT modal decomposition features. Attention is paid to local (plate-like), extensional, torsional and distortional vibration modes, as well as their interaction.

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ABSTRACT: This paper examines the design and load-carrying capacity of fixed-ended web-stiffened lipped channel columns eroded by mode interaction behaviour combined with distortional and local deformations. Initially, the paper presents the results of an experimental investigation of compressive tests on web-stiffened lipped channel columns fabricated from cold-formed mild steel with a thickness of 1.50 mm, which is aimed at determining their failure load-carrying capacity; the experimental investigation also aims to provide experimental evidence of the occurrence of such coupling phenomena concerning distortional and local modes, namely, local-distortional interaction and distortional-local interactive failures. Then, the paper examines the ultimate strength data of experimental columns, both reported in this paper and collected from the literature, and concludes that the current direct strength method (DSM) provides very unsafe predictions concerning such a detrimental interaction nature. Next, two DSM-based design approaches, namely, the nominal strength against local-distortional (NLD) and distortional-local (NDL) procedures, are presented and evaluated on the basis of all available experimental ultimate strength data. Finally, proposals and design considerations based on the
DSM-shape for the thin-walled cold-formed steel sections, which fail in mixed modes of distortional and local buckling, are presented.

Riccardo Barsotti and Salvatore S. Ligaro (Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino 1, 56126 Pisa, Italy), “Numerical analysis of partly wrinkled cylindrical inflated beams under bending and shear”, Thin-Walled Structures, Vol. 84, pp 204-213, November 2014
DOI: 10.1016/j.tws.2014.06.009

ABSTRACT: This paper is aimed at assessing the nonlinear elastic response of an inflatable cylindrical beam through a simple mechanical model recently proposed by the authors for studying the equilibrium configurations of highly pressurised elastic membranes with general shapes. The attention is focused on beams loaded at mid-span with two different constraints, corresponding to simply-supported ends and built-in ends. The geometrical nonlinearities due to both the cross-sectional ovalization and wrinkling are carefully considered. In particular, the wrinkling of the membrane, clearly visible for load values much lower than the collapse load, is taken into account by means of an equivalent physical non-linearity. A two-states constitutive law for the material is assumed: when a fibre is stretched (the active state), its response is elastic, while when the fibre is contracted, no compressive force can be engendered in it (the passive state). The evolution of the cross-sectional ovalization, the size of the wrinkled regions and the magnitude of longitudinal and transverse stresses in the membrane are accurately determined for increasing levels of loads, up to collapse. The numerical results for the corresponding values of load and internal pressure, obtained through an expressly developed incremental-iterative algorithm, are compared with the experimental ones available in the literature.

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“Experimental investigation on flexural behavior of concrete-filled pentagonal flange beam under concentrated loading”, Thin-Walled Structures, Vol. 84, pp 214-225, November 2014, DOI: 10.1016/j.tws.2014.06.008

ABSTRACT: The flexural behavior of simply supported concrete-filled pentagonal flange beams (CFPBs) under mid-span loading is experimentally and numerically investigated. There are two CFPFB specimens tested to failure under static load condition to determine the beam flexural capacity. One of the test specimens is designed with a pair of transverse stiffener at mid-span while the other is without any stiffener to resist the load. Both the test specimens have identical geometrical and material properties. From the experimental results, the flexural capacity of the specimen with stiffener is found to be 10% higher than that of the specimen without stiffener. The failure behavior shows the importance of transverse stiffener to enhance the ultimate flexural capacity and to avoid the localized web distortion of the beam. In the numerical study based on finite element (FE) analysis, the concrete and steel materials are modeled using the eight-node solid and four-node shell element respectively. A comparison of the ultimate capacity of the CFPFBs with and without stiffener reveals that the FE models simulate very well the flexural behavior of the test specimens and the difference of maximum load is found to be less than 10%.

Carlos A. Gurgos (1), Rossana C. Jaca (1), Jorge L. Lassig (1) and Luis A. Godoy (2,3) (1) Engineering School, Universidad Nacional del Comahue, Neuquén, Argentina
“Wind buckling of tanks with conical roof considering shielding by another tank”, Thin-Walled Structures, Vol. 94, pp 226-240, November 2014, DOI: 10.1016/j.tws.2014.06.007

ABSTRACT: Oil storage tanks are usually arranged in groups in tank farms, and this configuration may affect their buckling and postbuckling strength under wind loads. The assessment of wind action on tank structures is performed in this work by means of wind tunnel experiments to evaluate the pattern of pressure distribution for a tank which is shielded by another tank under various configurations and separation between them. The experimental results show significant changes in pressures due to shielding effects. In a second stage the structural response under the pressures previously evaluated is performed by finite element analysis using both linear bifurcation and geometrically nonlinear analysis. Results of two-tank interaction are compared with those of an isolated tank. Based on the results, it is concluded that the changes in wind pressures due to group effects induce changes in buckling loads and in the associated deflected patterns.

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ABSTRACT: Based on the vibro-acoustical model, an effective new approach to nondestructively predict the elastic critical hydrostatic pressure of a submerged elliptical cylindrical shell is presented in this paper. Based on the Goldenveizer–Novozhilov thin shell theory, the vibration equations considering hydrostatic pressures of outer fluid are written in the form of a matrix differential equation which is obtained by using the transfer matrix of the state vector of the shell. The fluid-loading term is represented as the form of Mathieu function. The data of the fundamental natural frequencies of the various elliptical cylindrical shells with different hydrostatic pressure and boundary conditions are obtained by solving the frequency equation using Lagrange interpolation method. The curve of the fundamental natural frequency squared versus hydrostatic pressure is drawn, which is approximately straight line. The elastic critical hydrostatic pressure is therefore obtained while the fundamental natural frequency is assumed to be zero according to the curve. The results obtained by the present approach show good agreement with published results.

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“Axial crushing and optimal design of square tubes with graded thickness”, Thin-Walled Structures, Vol. 84, pp 263-274, November 2014, DOI: 10.1016/j.tws.2014.07.004

ABSTRACT: Introducing thickness gradient in cross-section is a quite promising approach to increase the energy absorption efficiency and crashworthiness performance of thin-walled structures. This paper addresses
the deformation mode and energy absorption of square tubes with graded thickness during axial loading. Experimental study is firstly carried out for square tubes with two types of thickness distributions and numerical analyses are then conducted to simulate the experiment. Both experimental and numerical results show that the introduction of graded thickness in cross-section can lead to up to 30–35% increase in energy absorption efficiency (specific energy absorption) without the increase of the initial peak force. In addition, structural optimization of the cross-section of a square tube with graded thickness is solved by response surface method and the optimization results validate that increasing the material in the corner regions can indeed increase the energy absorption efficiency of a square tube.


ABSTRACT: The potentiality of cold-formed steel structures (CFS) in terms of lightness, rapid on-site erection and high structural performance is spreading the use of the technology in the most industrialized countries. In particular, the overall recognized capability to assure a good structural response in high seismic areas is allowing the adoption in some of the most conservative communities. On the other hand, despite the many ongoing research in different countries, the current seismic design codes are often inadequate if compared to the evolutionary process. In this context, the new British Force School (BFS) represents one of the first cold-formed steel structures realized in Italy and, therefore, it required a long and complex verification process. Indeed, the seismic performance at the global and local scale had to be verified during the construction phase. This paper focuses on the evaluation of lateral response of the sheathed cold-formed steel (SCFS) shear walls, which represent the seismic resisting system of this structural typology through the presentation and discussion of the experimental campaign carried out to support the design.

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“Elastic distortional buckling of doubly symmetric steel I-section beams with slender webs”, Thin-Walled Structures, Vol. 84, pp 289-301, November 2014, DOI: 10.1016/j.tws.2014.05.010

ABSTRACT: Doubly symmetric steel I-section members with thin webs and stocky flanges have a tendency to buckle in a so-called distortional buckling mode, involving distortion of the web of the I-section in the plane of its cross-section. As this mode is more complicated than the local or global buckling, analytical expressions take empirical forms and vary in between different proposals. This paper has two main objectives. The first objective is to propose a complex finite strip method for distortional buckling analysis of I-section beams with slender webs and check the suitability for such analysis by comparing its accuracy with other methods and the second objective is to propose a simple method for predicting the distortional buckling loads of I-beams. The latter objective is superior to current methods with respect to the weight of the sections.

Niyazi Tanlak and Fazil O. Sonmez (Department of Mechanical Engineering, Bogazici University, Istanbul, Bebek 34342, Turkey), “Optimal shape design of thin-walled tubes under high-velocity axial impact loads”, Thin-Walled Structures, Vol. 84, pp 302-312, November 2014, DOI: 10.1016/j.tws.2014.07.003
ABSTRACT: In this study, the objective is to maximize the crashworthiness of thin-walled tubes under axial impact loads by shape optimization. As design variables, parameters defining the cross-sectional profile of the tube as well as parameters defining the longitudinal profile like the depths and lengths of the circumferential ribs and the taper angle are used. The methodology is applied to the design optimization of a crash-box supporting the bumper beam of a vehicle for the loading conditions in standard EuroNCAP crash tests. The crash event is simulated using explicit finite element method. While the crash-box is fully modeled, the structural response of the remaining parts during the test is taken into account by developing a lumped-parameter model. A hybrid search algorithm combining Genetic and Nelder & Mead algorithms is developed. The results indicate significant improvement in the crashworthiness over the benchmarks designs.


ABSTRACT: The main objectives of this study are to describe the compressive behavior and to determine the squash load of steel plate–concrete (SC) wall structures using ordinary and eco-oriented cement concrete. The major parameters in this research were the material of the concrete and width–thickness (B/t) ratio of surface steel plate. Six SC wall specimens were tested in compression in this test. In the three specimens, to reduce emissions of carbon dioxide (CO₂), some of the cement in weight was replaced by the Hwangtho (red clay) which is traditional and environmental material. The failure behavior, buckling behavior of the surface steel plate, the effective buckling length factors and plate buckling coefficient are discussed. Based on the test results, simplified rule was suggested to evaluate the buckling stress for surface steel plate. Several comparisons were made to evaluate the predicted strengths and test results.

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ABSTRACT: This paper extends previous work concerning the determination of cross-section deformation modes in thin-walled members with arbitrary polygonal cross-section, in the framework of Generalized Beam Theory (Gonçalves et al., 2010 [1]). In particular, the paper addresses the so-called “natural shear deformation modes” (i.e. the deformation modes that involve non-null membrane shear strains and are independent of the cross-section discretization employed), which are relevant for capturing the behaviour of thin-walled members with complex multi-cell cross-sections undergoing torsion and/or distortion. The contributions of the paper are (i) the derivation of fundamental properties of the shear modes, (ii) the proposal of an efficient mode extraction procedure and (iii) the development of analytical results for several particular cases. In order to illustrate the application of the proposed mode extraction procedure and demonstrate the validity of the derived properties, several cross-sections are analyzed, including complex multi-cell tubes.

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ABSTRACT: Thin-walled open section beams are carefully analysed by Vlasov’s theory of the sectorial areas. It allows to take into account their peculiar warping deformation which appears in the presence of torsional actions. This behaviour determines a further stress state along the axis of the element which is rarely considered in structural analyses. The aim of the present paper is the evaluation of the warping deformation of thin-walled open section beams subjected to torsion. Firstly, the analytical theory proposed by Vlasov is verified through an experimental test on a steel specimen defined by a U profile. Specific analyses are performed with the aim of a sophisticated optical device in order to assess the transverse distortion of the section. Then, the results obtained experimentally and confirmed by a Finite Element (FE) programme permit to validate a computer programme based on the analytical theory and devised to study the structural behaviour of high-rise buildings stiffened by thin-walled open section shear walls. In order to evaluate the effectiveness of the programme, an example which highlights the benefits provided by the present method compared to FE programme is carried out.


ABSTRACT: The buckling of cylindrical steel silos is caused by the wall friction force due to shearing between the silo fill and silo wall. The aim of this paper is to investigate the stability process in a silo composed of thin-walled isotropic plain rolled sheets using a static and dynamic finite element analysis by taking both the geometric and material non-linearity into account during eccentric discharge. Silo shells were subjected to axisymmetric and non-axisymmetric loads imposed by a bulk solid following Eurocode 1. The differences between the results of static and dynamic analyses were comprehensively discussed. The advantages of a dynamic approach were outlined.

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ABSTRACT: This paper numerically deals with the influence of cracks (in terms of length and location) on the ultimate compressive strength characteristics of unstiffened and stiffened plate elements used in thin-walled structures. The cracks were presumed to be through-thickness, having no contact between their faces and no propagation was allowed. A series of nonlinear finite element analyses was conducted using ANSYS commercial finite element code in which the Newton–Raphson method has been employed to solve the nonlinear governing equations. This study indicates that the length of cracks and especially its location can significantly affect the ultimate strength characteristics of unstiffened and stiffened plate elements subjected to axial compressive action.
“Computational modeling of flange crushing in cold-formed steel sections”, Thin-Walled Structures, Vol. 84, pp 393-405, November 2014, DOI: 10.1016/j.tws.2014.07.006

ABSTRACT: The computational modelling of the flange crushing phenomenon in cold-formed steel profiles is described in this paper, with particular emphasis to the development of shell finite element (SFE) models and performance of quasi-static analyses with an explicit integration scheme. Web crippling failure is widely recognised as the most relevant collapse mode of cold-formed steel members subjected to transverse concentrated loads. However, it has been experimentally and numerically observed that a somewhat different collapse mode may occur, due to the heavy stress concentrations stemming from the adoption of narrow bearing plates. This phenomenon, termed flange crushing, should not be confused with web crippling. Usually, the web crippling phenomenon is numerically investigated by means of non-linear static SFE models with an implicit integration scheme. In this study, SFE models are developed in ABAQUS code to study the flange crushing failure of a plain channel beam subjected to Internal Two Flange (ITF) loading conditions. These models are described in detail, as well as additional modelling concerns regarding quasi-static analyses and the explicit integration method. Different parameters are discussed in this article and the numerical results obtained are commented throughout. Such parameters include the (i) SFE type and mesh, (ii) load rate, mass scaling, adoption of smoothed displacement amplitude curves and control of inertial effects, (iii) contact and friction definitions, (iv) effects of forming cold-work and manufacturing process and (v) geometrical imperfections. Finally, the load–displacement response obtained with the quasi-static model and an equivalent non-linear static analysis are compared with the experimental test curves. It is concluded that very good results are achieved with the quasi-static approach, not only in terms of the ultimate load prediction, but also regarding the post-collapse load–deflection curve and the failure mechanism.


ABSTRACT: The full potential of carbon-fiber and aluminum-honeycomb sandwich panels and structures has been limited by the huge property mismatch between the high-stiffness carbon fiber and low-stiffness aluminum honeycomb. In this study, an orthogrid structure was added into the sandwich structure to raise the stiffness of soft honeycomb and therefore reduce the interfacial mismatch. The core then became an aluminum orthogrid structure filled with aluminum-honeycomb blocks. Three point bending tests were conducted to compare carbon fiber sandwiches with different types of core: (1) aluminum-honeycomb core; (2) aluminum-plate orthogrid core; and (3) aluminum-plate orthogrid core filled by aluminum-honeycomb blocks. The honeycomb filled orthogrid core sandwich was a bit heavier than the honeycomb or grid sandwich, but the critical load, specific
strength and energy absorption ability were all improved. The results indicated that the honeycomb filled orthogrid core sandwich with carbon fiber face sheet could provide improved structural properties for thin walled engineering structures.


ABSTRACT: In this article, behavior of honeycomb core against compressive force along cell axis was investigated. The samples were laterally compressed quasi-statically between rigid platens under displacement control. First, for some samples with different cell wall thicknesses and sizes, compressive strength was made by finite element using LSDYNA 971 program. It was determined that decreased cell size and increased cell wall thickness resulted in the increased compressive strength of the honeycomb. Afterwards, homogeneous and non-homogeneous methods were used for modeling the whole honeycomb and the relationship of sample modeling from smaller size to the original ones was stated.


ABSTRACT: This work presents a new formulation of the geometrically exact thin walled composite beam theory. The formulation assumes that the beam can undergo arbitrary kinematical changes while the strains remain small, thus compatibilizing the hypotheses of the strain measure and the constitutive law of the composite material. A key point of the formulation is the development of a pure small strain measure written solely in terms of scalar products of position and director vectors; the latter is accomplished through the obtention of a generalized small strain vector by decomposition of the deformation gradient. The resulting small strain measure is objective under rigid body motion. The finite element implementation of the proposed formulation is simpler than the finite strain theory implementation previously developed by the authors. Numerical experiments show that the present formulation is very accurate and computationally more efficient than the finite strain formulation, thus it is more convenient for most practical applications.

Helder D. Craveiro, Joao Paulo C. Rodrigues and Luis Laim (ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Coimbra, Portugal), “Cold-formed steel columns made with open cross-sections subjected to fire”, Thin-Walled Structures, Vol. 85, pp 1-14, December 2014

DOI: 10.1016/j.tws.2014.07.020

ABSTRACT: An experimental study on the fire behaviour of cold-formed steel lipped channel (C) and built-up I (2C) slender columns with restrained thermal elongation is presented. The studied parameters were the stiffness of the surrounding structure, type of cross-section, end support conditions and initial applied load level on the columns. The results showed that increasing the stiffness of the surrounding structure and initial applied load level for the semi-rigid support conditions and both cross-sections, lead to a significant reduction of the critical temperature whereas for the pin-ended support conditions the reduction is supposed to be smaller.
ABSTRACT: So far, the equations for buckling capacity of web panels focus on thin-walled beams with very strong flanges. In this paper, elastic buckling behavior of web panels of thin-walled beams with weak flanges is further studied, aiming at a buckling coefficient formula unifying the effect of both weak and strong flanges. A new parameter, the flange-to-web ratio of moment of inertia, is proposed to characterize the effect of flanges. Then, a semi-analytical method is applied to investigate the buckling behavior of simply supported web panels, in two cases, inclusive or exclusive of effect of the moment of inertia of flanges. It is revealed that elastic buckling load, in particular, the buckling coefficient of web panel is a function of two key parameters, web aspect ratio and flange-to-web ratio of moment of inertia. Meanwhile, a finite element analysis (FEA) model allowing for the sensitivity of boundary conditions is validated by comparing with the semi-analytical solution to the case exclusive of effect of the moments of inertia of flanges. Next, numerical results are utilized to illustrate the influence of the previous parameters, which verify the increase of buckling coefficient with flange-to-web ratio of moment of inertia or the decrease of buckling coefficient with web aspect ratio. Besides, it also verifies that for the same flange-to-web ratio of moment of inertia, the buckling behavior of square web panels is closer to the uniform shear buckling than other rectangular web panels. Finally, an accurate design formula is proposed to calculate bucking coefficient of web panel.

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DOI: 10.1016/j.tws.2014.08.001
ABSTRACT: This paper presents an investigation on the structural behavior of flattened expanded metal tubes subjected to axial crushing. At first, the study is carried out experimentally to investigate the effect of the angle formed between the expanded metal cell and the applied load. Secondly, the results are compared with experimental results for standard expanded metal sheets. Thereafter, numerical analyses are conducted by means of nonlinear finite element models, to investigate the enhancement in the energy absorption characteristics due to flattening of the expanded metal. Both results, experimental and numerical show a significant increase in energy absorbing capacity and mean force for the flattened tubes.
the effect of pore pressure on critical magnetic field of plate and the effect of important parameters of poroelastic material on buckling capacity are investigated. Also the compressibility of fluid and porosity on the buckling strength are being investigated.

DOI: 10.1016/j.tws.2014.08.003
ABSTRACT: To improve the behaviour of conventional T-shaped concrete-filled steel tubular (CFST) columns, multi-cell composite T-shaped concrete-filled steel tubular (MT-CFST) columns are proposed in this paper. Experimental study of 25MT-CFST columns, including 13 short specimens with various cross sections and material properties and 12 slender specimens with different slenderness ratios, subjected to axial loads was conducted. The failure modes, axial load–strain curves for short specimens and axial load–lateral deflection curves for slender specimens were investigated. The test results were compared with design approaches for conventional CFST columns presented in Eurocode 4, AISC specification, Australian standard AS51006, Chinese code CECS159, and Hong Kong steel code, and it was found that all the design codes underestimate the bearing capacity of both short and slender MT-CFST columns to some extent.

Liping Wang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong), “Design of cold-formed steel channels with stiffened webs subjected to bending”, Thin-Walled Structures, Vol. 85, pp 81-92, December 2014, DOI: 10.1016/j.tws.2014.08.002
ABSTRACT: The objectives of this study are to investigate the structural behaviour and evaluate the appropriateness of the current direct strength method on the design of cold-formed steel stiffened cross-sections subjected to bending. The stiffeners were employed to the web of plain channel and lipped channel sections to improve the flexural strength of cold-formed steel sections that are prone to local buckling and distortional buckling. An experimental investigation of simply supported beams with different stiffened channel sections has been conducted. The moment capacities and observed failure modes at ultimate loads were reported. A nonlinear finite element model was developed and verified against the test results in terms of strengths, failure modes and moment–curvature curves. The calibrated model was then adopted for an extensive parametric study to investigate the moment capacities and buckling modes of cold-formed steel beams with various geometries of stiffened sections. The strengths and failure modes of specimens obtained from experimental and numerical results were compared with design strengths predicted using the direct strength method specified in the North American Specification for cold-formed steel structures. The comparison shows that the design strengths predicted by the current direct strength method (DSM) are conservative for both local buckling and distortional buckling in this study. Hence, the DSM is modified to cover the new stiffened channel sections investigated in this study. A reliability analysis was also performed to assess the current and modified DSM.

DOI: 10.1016/j.tws.2014.07.021
ABSTRACT: The web crippling design guides are based on empirical adjustments of available test data. These equations differ from the basic concept underpinning most of the other instabilities, the so-called strength
curves. This investigation presents a new design approach for web crippling design of stainless steel hat sections based on strength curves controlled by slenderness-based functions $\chi (\lambda)$. The effects of web crippling on such cross-sections were studied numerically and the obtained results were used to derive the design expressions. Comparisons with tests and FE data, and with design guides show that the proposed design approach provides more accurate web crippling resistance.

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“Buckling measurement and numerical analysis of M-type ribs stiffened composite panel”, Thin-Walled Structures, Vol. 85, pp 117-124, December 2014, DOI: 10.1016/j.tws.2014.08.008

ABSTRACT: A combination of methods of strategy which combines optical measurements and numerical calculations was developed to study the buckling behavior and failure modes of composite panel with M-type stiffeners under compression. Utilizing the non-contact optical means for non-destructive testing, the full-field buckling deflections/evolution and compressive failure of the panel surface were systematically collected for mechanical analysis. Based on continuum mechanics modeling, the buckling and post-buckling behaviors of the composite panel were predicted and compared with the buckling shapes that are obtained from experiments. The numerical simulation methods and experimental test technique in the work provides a useful tool to study the compressive buckling behaviors of composite panel with M-type stiffeners.

Alessandra Genoese, Andrea Genoese, Antonio Bilotta and Giovanni Garcea (Dipartimento di Modellistica per l’Ingegneria, Università della Calabria, 87030 Rende (Cosenza), Italy), “Buckling analysis through a generalized beam model including section distortions”, Thin-Walled Structures, Vol. 85, pp 125-141, December 2014, DOI: 10.1016/j.tws.2014.08.012

ABSTRACT: A geometrically nonlinear beam model suitable for describing complex 3D effects due to non-uniform warpings including non-standard in-plane distortions of the cross-section is presented and applied to the buckling analysis of beams. Each section is endowed with a corotational frame where statics and kinematics are described using a refined linear elastic model which exploits a semi-analytical solution of the Cauchy continuum problem based on a FEM discretization of the cross-section. The stress field in this way is fully 3D, allowing both the exact recovery of the standard Saint Venant solution and the consideration of some additional relevant strain modes of the cross-section that are evaluated in a simple and effective way. Numerical results are presented and compared with 3D shell reference solutions obtained by using the commercial code ABAQUS.


ABSTRACT: A shear deformable thin-walled beam theory is developed for the analysis of steel beams reinforced with a GFRP plate to one of the flanges. Starting with the principle of stationary potential energy, the governing equilibrium equations and boundary conditions are formulated for the problem. The theory results in two sets of fully coupled systems of equilibrium equations. The first system describes the longitudinal-flexural response of the system and involves four generalized displacement fields and the second system governs the
lateral-torsional response and involves six generalized displacement fields. The resulting coupled systems are then solved numerically for practical problems. Detailed comparisons with three dimensional and shell solutions under ABAQUS show that the present theory provides reliable predictions for displacements and stresses. A comparison with results from a non-shear deformable theory illustrates the necessity of incorporating shear deformation effects in cases involving predominantly twisting responses.

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“FRP strengthening of lean duplex stainless steel hollow sections subjected to web crippling”, Thin-Walled Structures, Vol. 85, pp 183-200, December 2014, DOI: 10.1016/j.tws.2014.08.010

ABSTRACT: This paper presents the experimental and numerical investigations of lean duplex stainless steel hollow sections subjected to web crippling. The test specimens were strengthened with different fibre-reinforced polymer (FRP). The web crippling tests were conducted under end-two-flange, interior-two-flange, end-one-flange and interior-one-flange loading conditions. A series of web crippling tests was conducted. The investigation was focused on the effects of surface treatment, web slenderness, different adhesives and FRPs for the strengthening of lean duplex stainless steel hollow sections against web crippling. The lean duplex stainless steel type EN 1.4162 was used in the investigation. Two different surface treatments, three different adhesives and six different FRPs were investigated in this study. The tests were performed on five different sizes of square and rectangular hollow sections that covered a wide range of web slenderness ratio from 8.1 to 57.3. Three different failure modes were observed in the tests of the strengthened specimens, namely the adhesion, interlaminar failure of FRP plate and combination of adhesion and interlaminar failure of FRP plate. Finite element models have been developed and verified against the test results of the specimens subjected to two-flange loading conditions.

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ABSTRACT: Current design codes provide two design methods: allowable stress/strain design and limit state design. Design in the current pipework composite repair codes is based on the allowable design method and only two safety factors are applied to the ultimate strain of the composite layer and to the yield stress of steel. On the other hand, safety factors are applied to each of the load and resistance parameters in the limit state design method. The limit state design method is probabilistic based in which the safety factors are calibrated based on a target reliability index. In this study, an investigation into the reliability of rehabilitated pipelines is conducted. The limit state function is defined based on ASME PCC-2, and reliability analysis is conducted using the AFOSM method. Results show that ASME PCC-2 generally provides adequate safety although the level of safety is not uniform for different percentages of corrosion. Comparing the achieved results and the ISO 2394 target reliability indices, some resistance factors are proposed.
Poologanathan Keerthan, Mahen Mahendran and Edward Steau (Science and Engineering Faculty, Queensland University of Technology, Brisbane, Australia), “Experimental study of web crippling behaviour of hollow flange channel beams under two flange load cases”, Thin-Walled Structures, Vol. 85, pp 207-209, December 2014, DOI: 10.1016/j.tws.2014.08.011

ABSTRACT: This paper presents the details of an experimental study of a cold-formed steel hollow flange channel beam known as LiteSteel beam (LSB) subject to web crippling under End Two Flange (ETF) and Interior Two Flange (ITF) load cases. The LSB sections with two rectangular hollow flanges are made using a simultaneous cold-forming and electric resistance welding process. Due to the geometry of the LSB, and its unique residual stress characteristics and initial geometric imperfections, much of the existing research for common cold-formed steel sections is not directly applicable to LSB. Experimental and numerical studies have been carried out to evaluate the behaviour and design of LSBs subject to pure bending, predominant shear and combined actions. To date, however, no investigation has been conducted on the web crippling behaviour and strength of LSB sections. Hence an experimental study was conducted to investigate the web crippling behaviour and capacities of LSBs. Twenty-eight web crippling tests were conducted under ETF and ITF load cases, and the ultimate web crippling capacities were compared with the predictions from the design equations in AS/NZS 4600 and AISI S100. This comparison showed that AS/NZS 4600 and AISI S100 web crippling design equations are unconservative for LSB sections under ETF and ITF load cases. Hence new equations were proposed to determine the web crippling capacities of LSBs based on experimental results. Suitable design rules were also developed under the direct strength method (DSM) format.

DOI: 10.1016/j.tws.2014.08.021

ABSTRACT: This paper investigates the effect of long-duration blast loads on the structural response of aluminium cylindrical shell structures containing varying fluid levels. A detailed non-linear numerical model comprising remapped Lagrangian analysis examines localised plate buckling and deformation. The relative computational accuracy of an uncoupled numerical model developed in this paper is compared with experimental results obtained at one of the world’s most powerful air blast testing facilities. Evaluating structural response for blast loads with an extended dynamic pressure phase is exceptionally difficult using only Eulerian controlled CFD methods; due to domain constraints incorporating restrictive cell sizes engulfing the target structure before remapping. The further complexity of shock transmission through a structure damped by an internal fluid is examined experimentally. Fibre optic controlled instrumentation and high speed photography provide a vital insight towards coupled flow-field behaviour of the shell structure. Surface mounted pressure gauges on the cylindrical wall accurately record the pressure time history throughout the passage of the shock wave. This paper highlights the key influence on blast response due to varying internal fluid levels and the relative importance pertaining to a conservative design solution for varying operational states. Numerical modelling in this paper demonstrates the robust accuracy achievable for a remapped Lagrangian solution. The routine analytical assumption of uniform drag forces acting on the structural body was shown to be both misleading and inaccurate by comparison. This research will be of direct interest to both practitioners and researchers considering high power explosive blasts from sources such as hydrocarbon vapour cloud ignition.

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**ABSTRACT:** The postbuckling behaviour and load carrying capacity of thin-walled composite channel sections subjected to uniform compression are presented. An analysis of the influence of parameters of the composite manufacturing process on strength properties and load carrying capacity of the thin-walled structure made of this composite has been conducted. The microstructure characteristics of composites is presented and discussed. The postbuckling behaviour and load carrying capacity of thin-walled channel section columns subjected to compression have been determined with the finite element method. The ANSYS software has been employed.

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“Shape optimization of cold-formed steel columns with fabrication and geometric end-use constraints”, Thin-Walled Structures, Vol. 85, pp 271-290, December 2014, DOI: 10.1016/j.tws.2014.08.014

**ABSTRACT:** The objective of this paper is to present constrained optimization results for a cold-formed steel (CFS) cross-section shape with maximum axial capacity. In the authors’ previous work unconstrained shape optimization was performed via stochastic search and gradient-based algorithms. Unconstrained shape optimizations produced a significant capacity increase, more than 140%, above standard CFS cross-sections, but many of the solutions are highly unconventional and have potential limitations both with respect to end use (e.g. attaching boards for walls and floors) and cost of manufacturing. Column capacity is determined using the Direct Strength Method (DSM) which requires inputs for the local, distortional and global critical buckling loads. These critical loads are obtained using the finite strip method, as implemented in the open source software CUFSM, which allows essentially any potential cross-section to be evaluated. To advance the applicability of the optimized results, end-use constraints and manufacturing constraints on the number of rollers employed in forming were both successfully incorporated in the shape optimization presented in this paper, resulting in optimized cross-sections that are more practical and economical with only marginally decreased capacity (usually less than 10%) from the earlier unconstrained optimized solutions. The constraints are implemented within a simulated annealing (SA) algorithm for the optimization. Optimized sections from multiple runs show uniformity, partially indicating the robustness of the final optimized shapes. The implemented constrained shape optimization provides a thorough search with high computational efficiency. The optimized cross-sections from this research provide promising potential shapes for the development of new commercial product families, and the member-level optimization methodology can also be integrated into building optimization in the future.

ABSTRACT: In the structural design of the sandwich plate, the inner core plays a key role to have its maximum performance. A shaped pyramidal truss core is proposed in order to increase the strength and productivity of the sandwich core. In this paper, the design guidelines of the shaped pyramidal truss core, which is enhanced by forming a cross-section of an arc shape at the strut of the inner core, is described. The inner core is composed of a stiffened section and a transient section with a varying cross-section. The critical load for bifurcation in compressive instability is calculated using an analytical and FEM simulation. The analytical equation for the critical load of the shaped column is derived using the energy method. The various buckling modes (global, distortional, local) occur due to these effects. Therefore, complications induced by such effects must be taken into account in the design. Parametric studies for the stiffened core are conducted. The effect of geometric parameters is investigated for optimal design of the inner core and their influence have been discussed.

Jian-xing Yu, Zhen-zhou Sun, Xiao-xie Liu and Yu-xuan Zhai (State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China), “Ring-truss theory on offshore pipelines buckle propagation”, Thin-Walled Structures, Vol. 85, pp 313-323, December 2014
DOI: 10.1016/j.tws.2014.08.015
ABSTRACT: Buckle propagation is an essential concern in offshore pipeline design. Once the propagation occurs, it may cause unavoidable failure of an entire pipeline. With the consideration of both longitudinal and hoop deformation behavior of pipeline, a ring-truss theory was analytically established in this study. Laboratory experiments were conducted in full-scale hyperbaric chamber in order to verify the analytical equation. It was observed that the length of transition zone has great influence on determination of propagation pressure. Due to the difficulties of measurement during test process, the length of transition zone was obtained using the finite element simulation. The comparison of propagation pressure between the current study and published model shows that for small diameter to thickness ratio, the ring-truss model is the one that is closest to the actual situation.

ABSTRACT: The paper deals with buckling of short thin-walled lipped-channel columns, simply supported on both ends and subjected to uniformly distributed compressive load. The main objective of the study was to investigate the structure’s work in far post-buckling state and at collapse corresponding to the moment of the column’s stiffness loss. The following measuring devices and methods were applied: electrical strain gauges for strain measurements, a laser sensor to measure the displacements, and the Acoustic Emission method. Along with running the experimental tests, the non-linear stability of compressed composite columns was analyzed with the Finite Element Method. The numerical and experimental results showed good agreement.

DOI: 10.1016/j.tws.2014.09.003
ABSTRACT: In this present article, large amplitude free vibration behaviour of doubly curved composite shell panels have been analysed using the nonlinear finite element method. The nonlinear mathematical model is
derived using Green Lagrange type geometric nonlinearity in the framework of higher order shear deformation theory. In addition to that all the nonlinear higher order terms are included in the mathematical model to achieve more general case. The nonlinear governing equation of free vibrated curved panel is derived based on Hamilton’s principle and solved numerically by using the direct iterative method. The developed mathematical model has been validated by comparing the responses with those available numerical results. Finally, some new numerical experimentation (orthotropy ratio, stacking sequence, thickness ratio, amplitude ratio and support conditions) have been carried out to show the significance and the efficacy of the proposed mathematical model.

M. Shakouri and M.A. Kouchakzadeh (Department of Aerospace Engineering, Sharif University of Technology, Azadi Street, P.O. Box 11155-8639, Tehran, Iran), “Free vibration analysis of joined conical shells: Analytical and experimental study”, Thin-Walled Structures, Vol. 85, pp 350-358, December 2014 DOI: 10.1016/j.tws.2014.08.022

ABSTRACT: Natural frequencies and mode shapes of two joined isotropic conical shells are presented in this study. The joined conical shells can be considered as the general case for joined cylindrical–conical shells, joined cylinder–plates or cone–plates, conical and cylindrical shells with stepped thicknesses and also annular plates. Governing equations are obtained using thin-walled shallow shell theory of Donnell and Hamilton’s principle. The continuity conditions at the joining section of the cones are appropriate expressions among stress resultants and deformations. The equations are solved assuming trigonometric response in circumferential and series solution in meridional directions and all combinations of boundary conditions can be assumed in this method. The results are compared and validated with the available results in other investigations and also modal testing. The effects of semi-vertex angles and meridional lengths on the natural frequency and circumferential wave number of joined shells are investigated.


ABSTRACT: It has long been identified that stiffening of steel shells is one of the most effective ways of enhancing the capacity of these structures. Stiffeners largely in the form of welded elements have been employed to strengthen shell structures in which the stiffeners generally cover the whole length of the structure. In this research the effect of partial and full length stiffening of shells was studied in which the stiffeners were attached without welding to avoid the adverse effect of the residual stresses. Furthermore, local thickening of the shells by the same stiffening strips was investigated and the results were evaluated against the plain specimen. The effect of strengthening provided by local thickening was slightly less but comparable to that provided by the stiffeners.

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ABSTRACT: This present work aims to investigate the effect of debonds on the structural performance of adhesively bonded curved carbon fiber reinforced plastic (CFRP) panels under compressive loading environment. Representative curved panels are fabricated with a quasi-isotropic lay-up. Two types of specimens are prepared for the studies, one without debonds and the other with debonds of specified size, artificially introduced within the lap region. Pulsed thermography non-destructive technique is employed for the detection of debonds on the specimens. A set of experiments are conducted with displacement, strain and acoustic emission sensors to ascertain the performance of adhesively bonded joints under compression loading. Computational analyses are carried out using commercial finite element code MSC/NASTRAN to reproduce the experimental behavior and to aid in understanding the effect of closed debonds on the bonded joints. The computational model predictions are in good agreement with experimental observations. The effects of location of debond and panel curvatures are studied computationally incorporating debonds of different sizes. It is observed that debond location along the specimen length has significant effect and the buckling load reduces when the panel curvature increases for the same debond size.

Junyuan Zhang, Linan Wu, Guang Chen and Hao Zhou (State Key Laboratory of Automobile Simulation and Control, Jilin University, Changchun 130000, China), Bending collapse theory of thin-walled twelve right-angle section beams”, Thin-Walled Structures, Vol. 85, pp 377-387, December 2014, DOI: 10.1016/j.tws.2014.09.016

ABSTRACT: The present paper focuses on the bending collapse behavior of the twelve right-angle section (TTRS) beams. This paper presents the theoretical bending collapse mechanism of the TTRS beams around two axes based on the kinematic approach, and derives the expressions of the bending moments. The accuracy of the theoretical calculations are validated respectively by performing 36 groups finite element simulations including three kinds of materials, three different section dimensions and four different thicknesses. The results show that for $17.5 < c/h < 48.6$, the theoretical bending collapse mechanism of the TTRS beams presented in this paper can describe the collapse process accurately, and the moment–rotation curves calculated by theory show a good consistency with simulation results.

Recep Gumruk (Mechanical Engineering Department, Karadeniz Technical University, 61080 Trabzon, Turkey), “A numerical investigation of dynamic plastic buckling behaviour of thin-walled cylindrical structures with several geometries”, Thin-Walled Structures, Vol. 85, pp 388-397, December 2014 DOI: 10.1016/j.tws.2014.08.016

ABSTRACT: In this study dynamic buckling behaviors of an aluminum alloy cylindrical shell with axial linear variable thickness, discontinuity and conical shaped have been numerically investigated for high velocity impact by means of finite element method. The validation of finite element model was provided by the results of previous studies in literature. Throughout study commerce finite element package program LS-DYNA3D was used and all simulations were fulfilled as explicitly. According to results obtained, the minor changes in the geometry are able to convert the dynamic plastic buckling into dynamic progressive buckling behavior. This study indicates that which of the dynamic buckling or progressive buckling mechanism will be dominant is sensitive to geometrical properties for cylindrical aluminum alloy shells under the high velocity impact.


DOI: 10.1016/j.tws.2014.09.011
ABSTRACT: The residual ultimate strength of stiffened panels with locked cracks under axial compressive loading is analyzed. The influences of various geometrical characteristics of cracks and panels, such as the length and the orientation angle of cracks, are investigated by the nonlinear finite element analysis. The cracks are prevented from further propagation by holes with a diameter of 2 mm drilled at their tips. The finite element model has two bays in the longitudinal direction, employing periodical symmetrical boundary conditions at the ends of the loading edge. Beam tension test results are used to define the true stress–strain relationship of the material, which is used in the FE analyses to account for the nonlinear material property of steel.

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ABSTRACT: The majority of gravity pipes with a non-circular cross section have an egg-shaped profile and an inner surface that can be geometrically delineated by three interconnecting circles on each side of a vertical axis of symmetry. Renovation of these pipes can be undertaken at low cost and with minimal surface disruption by installation of a close-fitting polymeric liner, most commonly by the ‘cured-in-place pipe’ technique. There are two pre-existing methodologies for the structural design of such liners. Although these procedures have served the international wastewater industry well over an extended period, detailed consideration of both methods suggests that an improved methodology which is straightforward to apply and addresses all relevant issues in a consistent manner would be both technically and financially beneficial. Accordingly a new design method is here proposed, which is based on an assumed displacement distribution in a manner consistent with previous work on close-fitting liners of circular cross section. The new design procedure addresses all the relevant issues in a rational manner, and is readily implemented as a small computer software simulation mountable on any current generation personal computer.

DOI: 10.1016/j.tws.2014.09.012

ABSTRACT: A recently developed nonlinear analytical model for axially loaded thin-walled stringer-stiffened plates based on variational principles is extended to include local buckling of the main plate. Interaction between the weakly stable global buckling mode and the strongly stable local buckling mode is highlighted. Highly unstable post-buckling behaviour and a progressively changing wavelength in the local buckling mode profile are observed under increasing compressive deformation. The analytical model is compared against both physical experiments from the literature and finite element analysis conducted in the commercial code Abaqus; excellent agreement is found both in terms of the mechanical response and the predicted deflections.

Licai Yang, Ying Luo, Tian Qiu, Min Yang, Gaobin Zhou and Guofu Xie (National Key Laboratory of Reactor System Design Technology, Nuclear Power Institute of China, 25 South Section 3, 2nd Ring Road, Chengdu, Sichuang 610041, People’s Republic of China), “An analytical method for the buckling analysis of cylindrical

ABSTRACT: This article presents an analytical method for the buckling analysis of laterally pressured cylindrical shells with non-axisymmetric thickness variations. The previous results for thickness variations under external pressure are reviewed firstly. Then, a general analytical method that combines the perturbation method and Fourier series expansion is developed to derive buckling load formulas, which is in terms of thickness variation parameter up to arbitrary order. A classical non-axisymmetric thickness variation is discussed in detail by the presented analytical method. When non-axisymmetric modal thickness variation becomes axisymmetric, the buckling loads degenerate to the known results. Furthermore, the influence of circumferential modal thickness variation with mode corresponding to twice the circumferential buckling mode on the buckling of laterally pressured cylindrical shells is analytically investigated and the results show a great agreement with previous numerical ones by Gusic et al. Thus we confirm the presented method. In addition to theoretical analysis, calculations and comparisons are also performed. The general analytical method presented in the article can be utilized to determine the buckling loads of shells with general thickness variations.

DOI: 10.1016/j.tws.2014.09.019

ABSTRACT: Buckling behaviors of web-posts in a cellular steel beam at elevated temperatures in a fire were studied using the Finite Element Method (FEM) analysis and available analytical models. The buckling temperatures obtained by the analytical models differed greatly to those obtained from the FEM simulation. Among these analytical models, the buckling temperature obtained through the strut model based on BS5950-1 agreed with the FEM result the best. It is more reasonable to take the width of the compression stress band in the web-post as the effective width of the strut. Numerical parametric studies showed that the width of the compression stress band varied with the opening diameter, the opening distance and the web thickness. A simplified method was proposed to calculate the effective width of the strut. The accuracy of the strut model integrating the new effective width was validated against the FEM simulations. The obtained buckling temperature of the web-post using the modified strut model agreed well with the FEM simulation result.

Lei Zhu, Yan Zhao, Shuwen Li, Yuxing Huang and Liren Ban (School of Civil and Transportation Engineering, Beijing Higher Institution Engineering Research Center of Structural Engineering and New Materials, Beijing University of Civil Engineering and Architecture, Beijing, China), “Numerical analysis of the axial strength of CHS T-joints reinforced with external stiffeners”, Thin-Walled Structures, Vol. 85, pp 481-488, December 2014
DOI: 10.1016/j.tws.2014.09.018

ABSTRACT: This study reinforced circular hollow section (CHS) T-joints with external stiffeners and analyzed the axial strength of both the unreinforced and reinforced T-joints. The SHELL181 element in ANSYS was used to establish FE models of the T-joints. A comparison between the experimental results indicated that the numerical method could be used to compute the strength for the unreinforced and reinforced CHS T-joints. To further investigate the reinforcement effect of the external stiffeners, a numerical parametric study was conducted. The study then evaluated the variations in strength of differently sized stiffeners. It was found that the joint strength increased significantly as the size of the stiffener increased. The reinforcement effect is more dependent on the stiffener length than on the stiffener height, but it is reasonable to adopt stiffeners with equal lengths and heights since this shape is commonly-used in engineering projects.
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ABSTRACT: Most existing studies on single-layer spatial structures with semi-rigid joints were focused on spherical domes. The present paper analyzed the squared plan-form single-layer structures, examining the influence of joint-rigidity on the mechanical performances of the structures. An experiment has been conducted on a 5×6 m single-layer cylindrical reticulated shell with semi-rigid bolt-ball joints. The mechanical performance of the latticed shell is investigated in detail. Finite element analysis (FEA) model of the latticed shell is established taking material and geometric nonlinearities into account. The results show that the behavior determined using the FEA models correlates well with the experimentally observed behavior for the single-layer structures with semi-rigid joints.

DOI: 10.1016/j.tws.2014.09.004
ABSTRACT: The present paper deals with a dynamic interactive response of square FGM plates subjected to in-plane pulse loading. The structures are assumed to be simply supported along all edges. In order to obtain the equations of motion of individual plate, the classical laminate plate theory (CLPT) has been modified in such a way that it additionally accounts for all components of inertial forces. An effect of the imperfection sign (sense) influence on the dynamic response of plates made of functionally graded materials (FGMs) has been analyzed. In the case of the static problem, Koiter’s theory explains this sign (sense) sensitivity by an unsymmetrical stable equilibrium path of the FGM plate. The investigations deal with a comparison of the semi-analytical method (SAM) and the finite element method (FEM) applied to the dynamic postbuckling nonlinear analysis of thin-walled FG plated structures.

Hancock GJ, Pham CH., “Buckling analysis of thin-walled sections under localised loading using the semi-analytical finite strip method”, Thin-Walled Structures, Vol. 86, pp 35–46, January 2015,
DOI: 10.1016/j.tws.2014.09.017
ABSTRACT: Thin-walled sections under localised loading may lead to web crippling of the sections. This paper develops the Semi-Analytical Finite Strip Method (SAFSM) for thin-walled sections subject to localised loading to investigate web crippling phenomena. The method is benchmarked against analytical solutions, Finite Element Method (FEM) solutions, as well as Spline Finite Strip Method (SFSM) solutions. The paper summarises the SAFSM theory then applies it to the buckling of plates, and channel sections under localised loading. Multiple series terms in the longitudinal direction are used to compute the pre-buckling stresses in the plates and sections, and to perform the buckling analyses using these stresses. Solution convergence with increasing numbers of series terms is provided in the paper. The more localised the loading and buckling mode,
the more series terms are required for accurate solutions. The loading cases of Interior One Flange (IOF) and Interior Two Flange (ITF) are investigated in this paper using simply supported boundary conditions.


ABSTRACT: In practice, there is a wide variety of commercially available channel sections with complex shapes where the web is stiffened by adding longitudinal intermediate stiffeners. These stiffeners may improve the shear capacity of the channels. Recently, the Direct Strength Method (DSM) of design of cold-formed sections has been extended in the North American Specification for Cold-Formed Steel Structural Members (NAS S100:2012) to include shear based on research by the authors. The prequalified sections include flat webs and webs with small intermediate longitudinal stiffeners. To extend the range to larger intermediate stiffeners as occurs in practice, a series of predominantly shear tests of lipped channel sections with one web stiffener of different shapes and various sizes has been performed at the University of Sydney. Six different types of stiffened web channel sections were tested along with an additional reference plain section. All tests were conducted with straps screwed on the top flanges adjacent to the loading points. These straps provide torsion/distortion restraints which may enhance the shear capacities of the sections. The test failures were observed mainly in the combined bending and shear modes. Numerical simulations based on the Finite Element Method (FEM) using the software package ABAQUS/Standard are also performed to compare with and calibrate against the tests. The accurate results from the FEM models allow extension of the test data. Based on the reliable FEM models, a series of FEM modelling of predominantly shear tests for stiffened web channels has been performed without straps attached to the top flanges adjacent to loading points. The test and FEM results are subsequently plotted against the DSM interaction curves between bending and shear where the interaction is found to be significant. An extended range of DSM prequalified sections with longitudinally stiffened web channels in shear is proposed in this paper.


ABSTRACT: One of the most important advantages of steel plate shear wall (SPSW) is to create openings with different sizes and arbitrary locations on the infill plate depending on their application. In this research, the effects of two openings on the structural behavior of SPSWs were studied experimentally. Experimental testing was performed on three one-third scaled single-story SPSW specimens with two rectangular openings under quasi-static cyclic loading. The differences between the three perforated experimental specimens were the interval between two openings and their closeness to the frame columns. The structural parameters of perforated specimens were compared to the similar specimen without any opening. The experimental results were utilized (a) to compare the ultimate shear strength, stiffness and energy absorption of specimens; (b) to evaluate the performance of central, lateral, top and bottom panels; (c) to investigate the effect of distance between the openings and the columns on the formation of plastic hinges on the column flanges; (d) to study the behavior of stiffeners around the openings. Test results showed that the ultimate shear strength, stiffness and energy absorption were the same in all three perforated specimens and the interval between the two openings had no effect on these values. Moreover, existence of openings will lead to reduction in values of structural parameters.

ABSTRACT: To reduce the vulnerability of both civilian and military aircraft, it is essential to take the Hydrodynamic Ram (HRAM) pressure into account when designing their fuel tanks. In particular HRAM is especially dangerous for thin walled lightweight structures that cannot be armoured due to weight penalty reasons. Similarities in bubble behaviour between HRAM and underwater explosion situations were observed in recent high-speed tank penetration/water entry experiments. The present work concerns the application of a confined version of the Rayleigh–Plesset equation – which is classically used for bubble dynamics analysis (including underwater explosion) – to simulate a bubble created by an HRAM event induced by projectile penetration at ballistic speed in a confined geometry filled with a liquid. This equation is applied to a case of impact in a small closed tank. The initialisation of the model is based on experimental data and a conservation principle of the initial energy (of the projectile). To apply this equation, a relationship between the pressure applied on the structure and the structure deformation is needed. However it can only be obtained explicitly for spherical containers. The authors discuss the parameters needed in this equation and compare their calibrated values to theoretical ones calculated with analytical plates formulae.


ABSTRACT: We investigate the effects of warping on the dynamic stability of non-trivial equilibrium configurations for non-symmetric open thin-walled beams. We use a direct one-dimensional model coarsely describing warping; the rest of the kinematics is exact. Dynamic derives from the balance of power; constitutive relations are non-linear, hyper-elastic, and distinguish the roles of the centroids and shear centres; inertial actions account for warping, too. By centred finite differences, the warping inertial action is found ineffective on the natural angular frequencies. Then, we follow non-trivial equilibrium paths and investigate their Ljapounov stability, by examining the small superposed oscillations. Results for generic, non-symmetric cross-sections are presented and discussed, showing the effects of warping and of coupling constitutive coefficients.


ABSTRACT: The quasi-static and dynamic crushing response and the energy absorption characteristics of combined geometry shells composed of a hemispherical cap and a cylindrical segment were investigated both experimentally and numerically. The inelastic deformation of the shells initiated with the inversion of the hemisphere cap and followed by the axisymmetric or diamond folding of the cylindrical segment depending on the loading rate and dimensions. The fracture of the thinner specimens in dynamic tests was ascribed to the rise of the flow stress to the fracture stress with increasing strain rate. The hemisphere cap absorbed more energy at dynamic rates than at quasi-static rates, while it exhibited lower strain rate and inertia sensitivities than the
cylinder segment. For both the hemisphere cap and the cylinder segment, the inertial effect was shown to be more pronounced than strain rate effect at increasing impact velocities.


ABSTRACT: This paper addresses the energy absorption behaviour and crashworthiness optimisation of short length circular tubes under quasi-static lateral loading. Finite element (FE) models were developed using implicit FE code ANSYS to simulate the deformation behaviour and energy absorption of circular tube under lateral loading. These FE models were validated using experimental techniques to ensure that they can predict the responses of circular tube with sufficient accuracy. Response surface methodology (RSM) for design of experiments (DOE) was used in conjunction with finite element modelling to evaluate systematically the effects of geometrical parameters on the energy absorption responses of laterally crushed circular tubes. Statistical software package, design-expert, was used to apply the response surface methodology (RSM). The energy absorbing responses (specific energy absorbing capacity (SEA) and collapse load (F)) were modelled as functions of geometrical factors (tube diameter, tube thickness, and tube width). These developed functions allow predictions of the energy absorption response of laterally crushed tubes, based on their geometry parameters. Based on DOE results, parametric studies were conducted to generate design information on using the laterally crushed tubes in energy absorbing systems. Finally, the approach of multi-objective optimization design (MOD) was employed to find the optimal configuration of the proposed energy absorption structures. Design-expert software, which employs the desirability approach as optimization algorithm, was used for solving the MOD problem.


ABSTRACT: In this paper, an analytical simplified method for derivation of the average stress–average strain relationship of imperfect steel plates taking into account of both geometric and material nonlinearities is presented. The method utilizes the theory of elastic large deflection analysis of plates in the elastic region, and also the theory of rigid-perfectly plastic mechanism analysis of plates in the plastic region. The ultimate strength of the plate is predicted using an empirical formulation. The steel plates may be entirely un-corroded or both-sides randomly corroded. The algorithm can be easily implemented in methods for evaluation of ship hull girder ultimate strength as well as in the estimation of the ultimate capacity of offshore structures.

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ABSTRACT: This paper researches a type of absorber of kinetic collision energy that works on the principle of shrinking and splitting a tube of circular cross section. During collision, a seamless tube is thrust through a cone
bush, squeezing the tube. Energy is absorbed by the plastic deformation, and through the friction between the tube and the bush. After passing through the cone bush, the tube presses against a splitter, and further energy is lost to friction and plastic deformation during the splitting process. Grooves on the inner wall of the tube prevent uncontrolled longitudinal tearing of the wall during the splitting. This new combined method of energy absorption enables greater absorption power with compact dimensions. Scaled samples have been tested in the laboratory. The influence of geometry and manufacturing technology of the samples, as well as the benefits of using such an absorber, are presented and discussed in this paper. The results show that the combined absorber has approximately 60% higher absorption power than the shrinking absorber by itself.

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ABSTRACT: Buckling analysis of thin-walled functionally graded (FG) sandwich box beams is investigated. Material properties of the beam are assumed to be graded through the wall thickness. The Euler-Bernoulli beam theory for bending and the Vlasov theory for torsion are applied. The non-linear stability analysis is performed in framework of updated Lagrangian formulation. In order to insure the geometric potential of semitangential type for internal bending and torsion moments, the non-linear displacement field of thin-walled cross-section is adopted. Numerical results are obtained for FG sandwich box beams with simply–supported, clamped–free and clamped–clamped boundary conditions to investigate effects of the power-law index and skin-core-skin thickness ratios on the critical buckling loads and post-buckling responses. Numerical results show that the above-mentioned effects play very important role on the buckling analysis of sandwich box beams.

Rosario Montuori and Vincenzo Piluso (Department of Civil Engineering, University of Salerno, Salerno, Italy), “Analysis and modeling of CFG members: Moment curvature analysis”, Thin-Walled Structures, Vol. 86, pp 157-166, January 2015, DOI: 10.1016/j.tws.2014.10.010

ABSTRACT: The evaluation of the ultimate behaviour of Concrete Filled Tubular (CFT) members subjected to non-uniform bending moment is the main objective of this work. To this aim eight experimental tests have been performed at the Materials and Structures Laboratory of the Department of Civil Engineering of Salerno University. In particular, Square Hollow Section (SHS) CFT members have been investigated under monotonic loading conditions. The three point bending scheme is adopted for testing specimens, where an hydraulic actuator is used for the transmission of the transverse load at midspan under displacement control and an LVDT is used to measure the corresponding maximum transverse displacement. In addition, longitudinal deformations along the cross section perimeter have been measured by means of strain gauges, aiming to the experimental evaluation of moment–curvature relationship. This paper presents the structural details of the tested specimens and the corresponding experimental results. In addition, a fibre model able to predict the ultimate response of CFT members is also presented and compared with the experimental results. The presented fibre model accounts for all the effects influencing the ultimate behaviour of composite members, such as local buckling, confining effects on concrete, bi-axial stress state of the steel plate elements constituting the hollow profile and
hardening of its corners due to cold forming process. The comparison between experimental and numerical results shows a good agreement pointing out the accuracy of the proposed fibre model.


ABSTRACT: Lateral–torsional buckling (LTB) resistance of an I-beam depends on the minor axis moment of inertia of its compression flange and torsional rigidity of the section. A practical solution to increase lateral buckling of I-beams is to add two Delta stiffeners between the compression flange and web plates to form a hollow compression flange. Although these beams known as Delta hollow flange beams (DHFBs) have been introduced about half a century ago for bridge construction, however, their LTB behavior has not been investigated, yet. This paper develops a three dimensional finite-element model using ABAQUS for the inelastic nonlinear flexural–torsional analysis of DHFBs and uses it to investigate the effects of unbraced length and central off-shear center loading (located at center, top flange and bottom flange) on their moment gradient factor in different behavioral zones. It was found that the C b factor and moment resistance curve given by AISC-LRFD in Specification for structural steel buildings [2] are not accurate for intermediate (inelastic) and short plastic DHFBs leading to an unconservative design. Therefore, a modified moment resistance equation is proposed to be used instead of the code equation in inelastic zone for the investigated load cases in this paper.

Poologanathan Keerthan and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Experimental investigation and design of lipped channel beams in shear”, Thin-Walled Structures, Vol. 86, pp 174-184, January 2015, DOI: 10.1016/j.tws.2014.08.024

ABSTRACT: Cold-formed high strength steel members are increasingly used as primary load bearing components in low rise buildings. Lipped channel beam (LCB) is one of the most commonly used flexural members in these applications. In this research an experimental study was undertaken to investigate the shear behaviour and strengths of LCB sections. Simply supported test specimens of back to back LCBs with aspect ratios of 1.0 and 1.5 were loaded at mid-span until failure. Test specimens were chosen such that all three types of shear failure (shear yielding, inelastic and elastic shear buckling) occurred in the tests. The ultimate shear capacity results obtained from the tests were compared with the predictions from the current design rules in Australian/NewZealand and American cold-formed steel design standards. This comparison showed that these shear design rules are very conservative as they did not include the post-buckling strength observed in the shear tests and the higher shear buckling coefficient due to the additional fixity along the web-flange juncture. Improved shear design equations are proposed in this paper by including the above beneficial effects. Suitable lower bound design rules were also developed under the direct strength method format. This paper presents the details of this experimental study and the results including the improved design rules for the shear capacity of LCBs. It also includes the details of tests of LCBs subject to combined shear and flange distortion, and combined bending and shear actions, and proposes suitable design rules to predict the capacities in these cases.

ABSTRACT: This paper presents the multi objective optimization of foam-filled tubular tubes under pure axial and oblique impact loadings. In this work, the double circular tubes, whose bottom is the boundary condition, while at the top, is the impacted rigid wall; with respect to the axis of the tubes. The optimal crash parameter solutions, namely the minimum peak crushing force and the maximum specific energy absorption, are constructed by the Non-dominated Sorting Genetic Algorithm-II and the Radial Basis Function. Different configurations of structures, such as empty empty double tube (EET), foam filled empty double tube (FET), and foam filled foam filled double tube (FFT), are identified for their crashworthiness performance indicators. The results show that the optimal foam filled foam filled tube (FFT) had better crashworthiness than the others under pure axial loading. However, the foam filled empty tube (FET) was the best choice for structures under an oblique loading.

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ABSTRACT: The post-fire behaviour of slender reinforced concrete columns confined by circular steel tubes is investigated experimentally and numerically in this paper. Experiments were performed firstly to explore the fundamental behaviour of steel tube confined reinforced concrete (STCRC) slender columns after exposure to the ISO 834 standard fire, including the cooling phase. Temperature distributions, load versus lateral displacement curves, strains in the steel tube and failure modes were obtained and discussed. Next, a 3D finite element model was developed with the program ABAQUS using a sequentially coupled thermal-stress analysis. After validation of the FE model, parametric studies were carried out to identify the influence of key parameters on the load-bearing capacity and buckling reduction factor of slender STCRC columns. The considered parameters were the heating time, cross-sectional dimension, slenderness ratio, material strength, steel tube to concrete area ratio and reinforcement ratio. Finally, a simplified design method was proposed for predicting load-bearing capacity of STCRC slender columns after exposure to standard fires.

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“Experimental and finite element analysis research on cold-formed steel lipped channel beams under web crippling”, Thin-Walled Structures, Vol. 87, pp 41-52, February 2015, DOI: 10.1016/j.tws.2014.10.017
ABSTRACT: This article presents the results of an investigation into web crippling behavior of cold-formed steel lipped channel beams subjected to end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF), and interior-two-flange (ITF) loading conditions. A total of 48 cold-formed steel lipped channel beams with different boundary conditions, loading conditions, bearing lengths, and section heights were tested. The experimental scheme, failure modes, concentrated load-general vertical deformation and strain intensity distribution curves are presented in the article. The effect of boundary condition, loading condition, bearing length and section height on web crippling ultimate capacity and ductility of cold-formed steel lipped channel
beams was also studied. Results of these tests show that the effect of bearing length on the web crippling ultimate capacity in EOF and ETF loading conditions is more obvious than those in IOF and ITF loading conditions. When bearing length is 50, 100, and 150 mm, web crippling ultimate capacity of cold-formed steel lipped channel beams with web slenderness=78 reaches its peak. The middle web enters plasticity and form plastic hinge zone. The values of web crippling ultimate capacity in interior-flange loading conditions are larger than those in end-flange loading conditions. It is shown that the specimens in the interior-flange loading conditions have higher ultimate capacity, larger initial stiffness and better ductility than those of specimens in the end-flange loading conditions. Finite element analysis can simulate experimental failure mode and web crippling ultimate capacity. The calculation equations of web crippling ultimate capacity put forward in the article can accurately predict experimental value.

ABSTRACT: This paper presents a combined experimental, numerical and theoretical study on the transverse impact behavior for ultra lightweight cement composite (ULCC) filled steel pipe structures. The drop weight impact test investigates the impact behavior of the pipe specimens. The numerical simulation using the non-linear finite element software LS-DYNA agrees closely with the experimental data. Meanwhile, this study develops a theoretical method to predict the impact response for cement composite filled pipes. Compared to the experimental results, the theoretical method provides reasonable predictions on the impact force and the global displacement response for the cement composite filled pipe specimens.

ABSTRACT: In civil engineering, shell structures are widely used as liquid-containment vessels. Understanding how the shell responds to relevant loading conditions is important for the design of safe and economical liquid-containment shell structures. This paper reviews recent research on the strength, stability and vibration behaviour of liquid-containment shell structures, and traces the developments pertaining to the design of these facilities to withstand various loading and environmental effects such as liquid pressure, wind pressure, ground movement and thermal effects. Results of recent feasibility studies of non-conventional shell forms for liquid containment are also reported, and areas of focus for future research are suggested.

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“Elastic buckling of a sandwich beam with variable mechanical properties of the core”, Thin-Walled Structures, Vol. 87, pp 127-132, February 2015, DOI: 10.1016/j.tws.2014.11.014
ABSTRACT: This paper deals with the analytical and numerical studies of elastic buckling of a three-layered beam with metal foam core. Mechanical properties of the core are variable along the z-axis. There are two
schemes of displacement of the faces and core of the beam: a broken line hypothesis and a non-linear hypothesis. The mathematical models for both types of displacements are presented. The governing differential equations of the sandwich beam are derived. Numerical analysis of sandwich beams is conducted in ANSYS environment. The finite elements analysis has been performed using a linear elastic buckling model. The analysis with constant and variable Young’s modulus of the core of the beam is carried out. The values of the critical load obtained by the analytical and numerical (FEM) methods are compared.

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ABSTRACT: The paper studies the influence of internal pressure on circular thin-walled pipes (D/t>150)/(D/t>150) subjected to pure bending. Both straight pipes and curved pipes are analysed. Both yield and buckling failures are considered. It is shown that internal pressure decreases the limiting load for yield but increases the limiting load for buckling. The study is mainly FEA-based. A formula to predict critical moment given by linear buckling analysis is proposed. Comments on difference between linear and non-linear analysis results are given. It is shown that a pipe curvature opposite to the bending moment can increase the critical load. It is shown that cylindrical thin-walled shells have an optimal value of internal pressure to which limiting load for yield and critical buckling moment are equal, corresponding to an optimal use of material.

References listed at the end of the paper:

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ABSTRACT: Over the last several decades, various approaches to strengthening steel structures through the use of Carbon fibre reinforced polymer (CFRP) composites have been investigated; however, most of the studies have been focused on the steel tubes. This paper presents the feasibility analysis on the application of CFRP composite strips to strengthen the CFST column member under axial loading. CFRP strips having a width of 50 mm were used to confine the columns. The experimental parameters were the spacing between the CFRP strips (20 and 30 mm) and number of CFRP layers (one, two and three layers). All columns were tested under axial compression until failure. The experimental results revealed that bonding of CFRP composites effectively delayed the local buckling of the columns and also reduced the axial deformation by providing a confinement/restraining effect against the elastic deformation at both spacings. The confinement effect provided by CFRP composites was increased with the increase in the number of layers; however, the enhancement in buckling stress was not proportional. The load carrying capacity of the column increased with the application of CFRP strips, by up to 30% compared to the of un-strengthened column. From the test results it is suggested that the application of CFRP strips at a spacing of 20 mm or 30 mm is suitable for strengthening of a CFST circular column member; however, the application of strips at intervals of 30 mm recommended as an economical approach to strengthening compared to the 20 mm spacing. Finally, an analytical equation was proposed to predict the load carrying capacity of the CFRP strengthened CFST column, and the average difference between the calculated and experimental value was only ±5%.

G.M. El-Mahdy and M.M. El-Saadawy (Housing and Building National Research Center (HBRC), 87 El-Tahrir St., Dokki, Giza 11511, PO Box 1770, Cairo, Egypt), “Ultimate strength of singly symmetrical I-section steel beams with variable flange ratio”, Thin-Walled Structures, Vol. 87, pp 149-157, February 2015
DOI: 10.1016/j.tws.2014.11.016
ABSTRACT: Long steel beams in entrances of hotel lobbies and halls often support a masonry wall and are laterally unsupported. These beams do not reach their in-plane flexural capacity due to the occurrence of elastic or inelastic lateral–torsional buckling (LTB). Designers usually select doubly-symmetrical sections for these beams. In this paper the ratio of the compression flange size to the tension flange size is increasingly varied to obtain a higher resistance to lateral buckling of the compression flange. However, increasing the size of the compression flange and decreasing the size of the tension flange leads to the limiting case of a T-section which is weak in in-plane bending. Code provisions usually refer to generalized cases and special cases are always embedded in these and are not directly addressed. One of these special cases is the singly symmetric I-section. Special direct solutions for such problems are becoming more popular based on accurate inelastic ultimate load analysis. This paper develops a three dimensional finite element model, using ANSYS for the elastic and inelastic flexural–torsional buckling of I-beams, which is used to investigate the effect of varying the ratio of the flange sizes on the optimum performance of the beam. Slender webs are proposed and a study is made on the material of this web and the performance of its local and global buckling and its correlation to the total ultimate load of the beam system. The flange material consumption is kept constant and only the shares to the tension and compression flanges are varied to achieve the most economical system for design. The main goal of this research is to present a direct solution system that is simplified for the use of inexperienced designers, which provides the most economic system selection for design.

ABSTRACT: This paper deals with the development of novel procedures for the design of fixed-ended and pin-ended equal-leg angle columns with short-to-intermediate lengths, i.e., those buckling in flexural–torsional modes. Initially, numerical results concerning the buckling and post-buckling behaviour of the above angle columns are presented, (i) highlighting the main differences between the fixed-ended and pin-ended column responses, and (ii) evidencing the need for specific design procedures. Then, the paper gathers a large column ultimate strength data bank that includes (i) experimental values, collected from the available literature, and (ii) numerical values, obtained from Abaqus shell finite element analyses. The set of experimental results collected comprises 41 fixed-ended and 35 pin-ended columns, and the numerical results obtained concern 337 fixed-ended and 197 pin-ended columns – various cross-section dimensions, lengths and yield stresses are considered. Next, after reviewing the available methods to estimate the ultimate strength of angle columns, the paper develops new design approaches for fixed-ended and pin-ended columns, based on the direct strength method (DSM) – the mechanical reasoning behind the procedures proposed, which include the use of genuine flexural–torsional strength curves, is also provided. Finally, the paper closes with the assessment of the ultimate strength predictions yielded by the proposed DSM design procedures, through their comparison with the assembled experimental and numerical failure loads – it is shown that both the quality and reliability of these predictions are very good and slightly higher than those exhibited by the available design methods for angle columns.

DOI: 10.1016/j.tws.2014.11.008

ABSTRACT: There are considered thin periodic plates with moderately large deflections. To take into account the effect of the microstructure on behaviour of these plates the tolerance modelling method is applied, cf. Domagalski and Jedrysiak [2], Meccanica, 2012. This method makes it possible to derive model equations with constant coefficients involving terms dependent of the microstructure size. The paper contains an computational example of critical load calculations and postbuckling analysis.


ABSTRACT: To investigate the effect of corrosion on the axial capacity of steel bridge piles, a total of 13 H-shaped short columns were tested under monotonic axial load. The columns were machined to simulate different degrees and patterns of corrosion. The remaining axial capacity of the deteriorated members was assessed. To simulate the corrosion, webs and flanges were milled near the mid-height of the columns to reduce their thicknesses. The experimental results were compared to the axial capacities predicted by the design provisions of the American Institute of Steel Construction (AISC), American Association of State Highway and Transportation Officials (AASHTO), and American Iron and Steel Institute (AISI). The results of this study indicate that the degree of flange corrosion is the single factor that has the most significant effect on the column capacity. Other factors, including unsymmetry of the corrosion pattern or reduction of the flange width had a
minor influence on the capacity. The results also indicate that, among the design methods considered, the effective width method recommended by AISI provides the best prediction of the capacity of severely deteriorated steel columns.

Hong-Xia Shen (School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an 710055, PR China), “Behavior of high-strength steel welded rectangular section beam-columns with slender webs”, Thin-Walled Structures, Vol. 88, pp 16-27, March 2015, DOI: 10.1016/j.tws.2014.11.019

ABSTRACT: This paper develops a double nonlinear finite element model that can take account of both geometric and material imperfections. On verified the numerical model the behavior and ultimate carrying capacity of eccentrically loaded welded thin-webbed rectangular section columns made from high strength steel with a nominal yield stress of 460 MPa are analyzed, and further the influences of the slenderness ratio, web depth-to-thickness ratio, flange width-to-thickness ratio, and relative eccentricity ratio on the ultimate carrying capacity are investigated. On the basis of these, the simple calculation formulas, which use the gross cross-section properties, for predicting the in-plane maximum strength of high strength steel beam–columns with large depth-to-thickness ratios are proposed. It shows that the developed finite element model can simulate the local–overall interaction buckling behavior of the eccentrically loaded welded box-section compression members. A brittle failure characteristic is found with a relatively steeper drop just after the peak in the load–displacement curve. A nonlinear and complex stress distribution, in the longitudinal direction, when reaching the ultimate capacity, seriously deviates from an elastic stress distribution, on the basis of which, the effective width is determined. The non-dimensional ultimate bearing capacity is approximately linear with the slenderness, depth-to-thickness ratio and width-to-thickness ratio, respectively. The interaction curves between the axial force and flexural moment for the high-strength steel thin-webbed rectangular section beam–columns are nearly linear. After introducing a steel yield strength modification factor, the formula based on the edge fiber yielding criterion can precisely predict the local–overall interactive buckling strength of high strength steel beam–columns.


ABSTRACT: A series of tests on dodecagonal section double skin concrete-filled steel columns (DCS) were carried out in this study. Column specimens having different lengths ranged from 1000 mm to 3500 mm were tested. The behavior and strengths of dodecagonal section double skin concrete-filled steel columns were investigated. In addition, local bucking of inner and outer steel tubes were also investigated. Material properties of the concrete and steel used in the test specimens were measured. The test strengths are compared with the design strengths calculated using the proposed methods based on current AISC Specification and Eurocode for the design of composite structural members. The suitability of design method proposed by other researcher for circular section double skin concrete-filled steel columns for dodecagonal section specimens was also evaluated.

ABSTRACT: In order to prevent vehicle access to a protected area, vehicle barriers can be installed around the perimeter of the area. Bollards are commonly used as vehicle barriers. This is due to the fact that they can be readily blended with other architectural features and present fewer disturbances to a building’s functionality when compared to other barrier systems. Hollow steel tubes are used in a variety of barrier system applications where they are required to absorb deformation energy. Varying methods, such as finite element analysis or experimental observation, can be used to determine the collapse behaviour and energy absorption of these steel structures under lateral impact load. These methods have high accuracy but demand a significant amount of time and computational resources. Apart from experimental and numerical analyses, Yield Line Mechanism (YLM) is an approach that can provide the collapse response of sections. This is when a section fails and the YLM of failure forms at its localised plastic hinge point. The YLM analysis approach is commonly used to investigate the performance of thin-wall structures that have local failure mechanisms. This paper investigates the collapse behaviour and energy absorption capability of hollow steel tubes under large deformation due to lateral impact load. The YLM technique is applied using the energy method, and is based upon measured spatial plastic collapse mechanisms from experiments. Analytical solutions for the collapse curve and in-plane rotation capacity are developed, and are used to model the large deformation behaviour and energy absorption. The analytical results are shown to compare well with the experimental values. The YLM model is then used to verify the finite element model (FEM), and then the failure behaviour and energy absorption of hollow steel tubes under lateral impact load is investigated in more detail.

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ABSTRACT: The present paper focuses on the ultimate shear strength analysis of intact and cracked stiffened panels. Several potential parameters influencing the ultimate shear strength of intact panels are discussed, including the patterns and amplitudes of initial deflection, the slenderness and aspect ratios of the plates, and the boundary conditions defined by the torsional stiffness of support members. An empirical formula for the ultimate shear strength of intact stiffened panels is proposed based on parametric nonlinear finite element analyses in ANSYS. Furthermore, the ultimate shear strength characteristics of cracked stiffened panels are investigated in LS-DYNA with the implicit method. Three types of cracks are considered, namely vertical crack, horizontal crack and angular crack. A simplified method is put forward to calculate the equivalent crack length. And the formula for the ultimate shear strength of cracked stiffened panels is derived on the basis of the formula for intact stiffened panels.

Shutian Liu, Zeqi Tong, Zhiliang Tang, Yang Liu and Zonghua Zhang (State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116023, China), “Bionic design modification of non-convex multi-corner thin-walled columns for improving energy absorption through adding bulkheads”, Thin-Walled Structures, Vol. 88, pp 70-81, March 2015, DOI: 10.1016/j.tws.2014.11.006
ABSTRACT: Collapse analysis of the non-convex multi-corner thin-walled columns under axial loads illustrates that the non-compact expansion-contraction deformation mode of collapse may occur in some cases, which reduces greatly the energy absorption property of these structures. Inspired from the way by which the bamboo nodes and nodal diaphragms enhance the transverse strength of bamboo, the non-convex multi-corner thin-walled column is modified by adding bulkheads in the column for improving the energy absorption property, and a new excellent energy absorption structure named as the bionic non-convex multi-corner column (BI-NCMC) is proposed in this article, which is a non-convex multi-corner thin-walled column with bulkheads. The energy absorption of BI-NCMC has been investigated numerically. A progressive deformation mode has been achieved and this structure shows a higher energy absorption than a similar column without the bulkheads. The role of the bulkheads is to change the deformation mode from an expansion-contraction mode to a progressive mode, while the bulkheads themselves absorb little energy. The influences of parameters in the energy absorption of BI-NCMC are analyzed. It was found that the column with highest energy absorption efficiency is the one with the smallest number of bulkheads while still maintaining the progressive deformation mode.

Saeed Ebrahimi and Nader Vahdatazad (Department of Mechanical Engineering, Yazd University, Yazd, Iran), “Multiobjective optimization and sensitivity analysis of honeycomb sandwich cylindrical columns under axial crushing loads”, Thin-Walled Structures, Vol. 88, pp 90-104, March 2015, DOI: 10.1016/j.tws.2014.12.004

ABSTRACT: This paper firstly investigates the energy absorption characteristics of honeycomb sandwich cylindrical columns such as square, triangle, kagome and diamond core under axial crushing loads by nonlinear finite element analysis. The interaction effects between the honeycomb and column walls greatly improve the energy absorption efficiency. The response surface method with cubic basis functions is employed to formulate specific energy absorption and peak crushing force which reduces considerably the computational cost of crush simulations by finite element method. Both the single objective and multiobjective optimizations are performed for columns under axial crushing load with design variables inner, outer and core thickness. Models are optimized by multiobjective particle swarm optimization algorithm to achieve maximum specific energy absorption capacity and minimum peak crushing force. Furthermore, local and global sensitivity analyses are performed to assess the effect of design variable values on the specific energy absorption and peak crushing force functions in design domain.

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“Buckling and yielding behavior of unstiffened slender, moderate, and stocky low yield point steel plates”, Thin-Walled Structures, Vol. 88, pp 105-118, March 2015, DOI: 10.1016/j.tws.2014.11.022

ABSTRACT: Steel plates may be classified as slender, moderate, and stocky based on their distinctive behavior characterized by geometrical buckling and material yielding. Slender plates undergo elastic buckling first and then yield in the post-buckling stage, while stocky plates yield first and then undergo inelastic buckling. Moderate plates, on the other hand, buckle and yield simultaneously. The development of low yield point (LYP) steel enables the application of steel plates with improved buckling and energy absorption capacities as lateral force-resisting and energy dissipating elements in structures. On this basis, buckling and yielding behavior of LYP steel plates with various support and loading conditions is studied in this paper from the point of view of
their application in steel plate shear wall (SPSW) systems. The limiting thicknesses of standalone plates corresponding to concurrent geometrical buckling and material yielding are determined theoretically and verified through detailed numerical simulations. Effects of using LYP steel and plate aspect ratio parameter on the required limiting plate thickness as an effective parameter in seismic design of SPSW systems are investigated as well. In addition to the studies on the performance of plates with two and four restrained edges and also applicability of some extrapolation techniques for predicting the critical buckling load of moderate plates, detailed studies are performed on determination of the limiting plate thickness in code-designed SPSW systems. Based on the findings of this study, some practical recommendations are provided for efficient seismic design of SPSW systems with LYP steel infill plates.

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ABSTRACT: Nowadays, girders with corrugated webs are used in bridges as an efficient alternative to conventional girders with flat stiffened webs. Particularly in bridge girders with corrugated webs (BGCWs), the corrugated webs are the main elements for bearing the shear forces. Instead of prismatic BGCWs, tapered BGCWs are currently used mainly due to their structural efficiency, providing at the same time aesthetical appearance. Available literature shows that tapered BGCWs may be classified into four typologies. Among these typologies, Case I is the most common case appearing commonly near to the intermediate supports of continuous bridges. Accordingly, in this paper, the finite element (FE) method is employed to investigate the inelastic behavior of tapered BGCWs of Case I, following to the fundamental behavior of such girders published recently by the current authors. Previously validated 3-D nonlinear FE models are developed and used in this study. The paper seeks, first, at finding the validity limit of the previously proposed design strengths for the tapered BGCWs with respect to the girder’s initial imperfection. This is made by considering different initial imperfection amplitudes. Accordingly, it is found that the proposed equation is valid with initial imperfections of \( h_{w1}/200hw1/200 \); \( h_{w1}/hw1 \) is the height of the long vertical edge of the web panel. However, the accuracy increases for initial imperfections similar to the web thickness (\( t_{w1} \)) for cases of \( t_{w1}/200hw1/200 \). Then, it investigates the effect of the aspect ratio of the web panels, different flange inclination angles and flange slenderness ratios. Finally, the paper checks the authors’ previously proposed design model using the results of the generated parametric studies. Overall, the outcomes of this study are expected to provide more insight into the behavior of tapered BGCWs and enable accurate prediction of the shear capacity of this special type of BGCWs.

ABSTRACT: This paper presents a column curve formula capable of producing accurate strengths for extruded members of 6082-T6 aluminium-alloys failing by flexural buckling under axial compression. The formula uses the Perry-type curve. The material properties are expressed in terms of the Ramberg–Osgood parameters \( E \), \( f_{0.2} \), and \( n \), obtained from tensile coupon tests of the finished product. 30 specimens of 6082-T6 aluminium alloy, including 15 H-section and 15 rectangular hollow-sections were tested under axial load using a pin-ended condition. Numerical models were then developed using the FE software ANSYS, and were verified against the
experimental results. The coefficient of stability was determined and compared with the coefficients of stability from different codes such as American standard (American specification for aluminium structures), Eurocode 9 (European code for design of aluminium structures), GB50017-2003 (Chinese Code for design of steel structures) and GB50429-2007 (Chinese Code for the design of Aluminium Structures). The experiment column curve was then derived and compared with the curves of columns of different codes. Lastly a comparison between the present test results and the results of Rasmussen and Rondal (2000) [1] is presented.

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ABSTRACT: This article studies the influence of the bimoment on the buckling of thin-walled beams with open cross section subjected to axial loading. In the case of torsional and torsional-flexural buckling of thin-walled Z-section beam, it is shown that influence of the bimoment could be of importance in the assessment of buckling loads. In order to verify the accuracy and validity of this analysis, the obtained results are compared with those calculated by ANSYS software.

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ABSTRACT: Plastic deformation of structures absorbs substantial kinetic energy when impact occurs. Therefore, energy-absorbing components have been extensively used in structural designs to intentionally absorb a large portion of crash energy. On the other hand, high peak crushing force, especially with regard to mean crushing force, may lead to a certain extent and indicate the risk of structural integrity. Thus, maximizing energy absorption and minimizing peak to mean force ratio by seeking for the optimal design of these components are of great significance. Along with this analysis, the collapse behavior of square, hexagonal, and octagonal cross-sections as the baseline for designing a newly introduced 12-edge section for stable collapse with high energy absorption capacity was characterized. Inherent dissipation of the energy from severe deformations at the corners of a section under axial collapse formed the basis of this study, in which multi-cornered thin-walled sections was focused on. Sampling designs of the sections using design of experiments (DOE) based on Taguchi method along with CAE simulations was performed to evaluate the responses over a range of steels grades starting from low end mild steels to high end strength. The optimization process with the target of maximizing both specific energy absorption (SEA) and crush force efficiency (CFE), as the ratio of mean crushing load to peak load, was carried out by nonlinear finite element analysis through LS-DYNA. Based on single-objective and multi-objective optimizations, it was found that octagonal and 12-edge sections had the best crashworthiness performance in terms of maximum SEA and CFE.
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ABSTRACT: In this article, bitubal circular energy absorbers consist of two AL-6063-O tubes with unequal diameters placed coaxially and compressed under quasi-static axial load are studied experimentally. The effects of diameter and wall-thickness of each tube and the interaction between two tubes on the crashworthiness parameters are investigated in detail. In order to reduce the high value of peak load induced in the bitubal absorbers, two worthwhile solutions are proposed. The first one is to use two tubes with different lengths and the other one is to cut groove at the end portion of one of the tubes.

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ABSTRACT: 6082 is a relatively new alloy that currently provides the best combination of properties in 6xxx series alloys. A series of tests was conducted on the stability of heat-treated aluminium alloy 6082-T6 circular tube columns to check the reliability of buckling strength predictions of 6082-T6 alloy circular tube columns using current design rules. First, nine stub columns were tested to obtain stress–strain curves and three parameters of the Ramberg–Osgood expression (E, σ₀.2 and n). The experimental stress–strain curves were in good agreement with the Ramberg–Osgood expression, and the mean value of σ₀.2/n obtained from the tests was close to the Steinhardt assumption. Second, prior to column tests, the initial out-of-straightness of 15 circular tubes was accurately measured. Third, these 15 tubes, with five nominal slenderness ratios varying from 20.4 to 69.6, were tested between two pinned ends under axial compression to obtain failing modes and buckling strengths. Finally, the experimental buckling strengths were compared with the buckling strengths predicted by several current aluminium structure design codes, including the American Aluminium Design Manual (AA), Australian/New Zealand Standard 1664 (AS/NZS), and Eurocode 9 (EC9), as well as the general column curve formulation proposed by Rasmussen and Rondal [13]. These comparisons shows that the AA predictions are too conservative at small slenderness ratios, the AS/NZS predictions are unsafe at large slenderness ratios, the EC9 predictions are conservative, and the Rasmussen–Rondal formulation provides the closest and generally conservative strength predictions.

Chao Wu, Yu Bai and Xiao-Ling Zhao (Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia), “Improved bearing capacities of pultruded glass fibre reinforced polymer square hollow sections strengthened by thin-walled steel or CFRP”, Thin-Walled Structures, Vol. 89, pp 67-75, April 2015
DOI: 10.1016/j.tws.2014.12.006

ABSTRACT: Pultruded glass fibre reinforced polymer (GFRP) square hollow sections (SHS) are emerging as an alternative construction material in civil engineering. Different from thin-walled steel SHS, GFRP SHS is an orthotropic material and exhibits reduced capacity when concentrated bearing load is applied in the transverse to pultrusion direction. This paper examined two approaches to enhance the bearing capacity of the GFRP SHS, by using carbon fibre reinforced polymer (CFRP) sheets or thin-walled steel channel sections. Experimental studies were conducted on the strengthened pultruded GFRP SHS with two different dimensions. Two loading conditions, end-two-flange (ETF) and interior-two-flange (ITF), were applied to investigate the effect of
loading position on the bearing capacity of the GFRP SHS. Experimental results were discussed with relation to the failure modes and load–displacement responses. It was found that the bearing capacity of pultruded GFRP SHS was effectively improved by up to 70% after CFRP sheets strengthening, and by over 380% after steel strengthening. Finally, equations were proposed for calculation of the improved bearing capacities of pultruded GFRP SHS with either CFRP sheets strengthening or steel strengthening. A reasonable agreement was achieved between predicted capacities and the experimental results.

Jafar Rouzegar and Farhad Abad (Department of Mechanical and Aerospace Engineering, Shiraz University of Technology, Shiraz, P.O. Box-71555-313, Iran), “Free vibration analysis of FG plate with piezoelectric layers using four-variable refined plate theory”, Thin-Walled Structures, Vol. 89, pp 76-83, April 2015
DOI: 10.1016/j.tws.2014.12.010
ABSTRACT: This study presents an analytical solution for free vibration analysis of a functionally graded (FG) plate integrated with piezoelectric layers using four-variable refined plate theory. Equations of motion for simply supported rectangular plates are derived using Hamilton’s principle and Maxwell’s equation, and Navier method is employed for solution of equations. The obtained natural frequencies for different examples are compared with the results of other common plate theories. The results demonstrate the simplicity, accuracy and efficiency of presented formulation in vibration analysis of investigated problems.

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ABSTRACT: Unstiffened cylindrically curved panels constitute a common subset of shell structures and therefore share the advantages and disadvantages of such structural solution. One of the bigger disadvantages of shells is their sensitivity to imperfections that lower significantly their ultimate strength. At the European level, in the scope of plate design by FEM, imperfections are treated in EN 1993-1-5 (Annex C) and in shell structures designed by global numerical analysis using GMNIA, recommendations are given in EN 1993-1-6 (clause 8.7.2). Since curved panels are neither flat nor full revolution cylinders, rules for estimating equivalent geometric imperfections remain unclear. In order to tackle this problem, this paper introduces a numerical parametric study on the imperfection sensitivity of cylindrically curved panels. The effect of the amplitude and shape of initial geometric imperfections (together with different values of curvature and aspect ratio) on the ultimate strength of unstiffened cylindrically curved steel panels is studied, results are presented and conclusions are drawn.

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ABSTRACT: Sandwich structures with foldcores are regarded as a promising alternative to conventional honeycomb sandwich structures as lightweight structural materials. One of the proposed applications of foldcore sandwich structures is on the aircraft fuselage and the interstage of a rocket. While flat foldcore sandwich structures have been intensively studied in the literature, there lacks a general design tool to create foldcores for a given cylindrical sandwich structure and the mechanical properties of such structures have not been well investigated. In this paper, a geometrical design protocol for foldcores that will fit into the space between the external and internal walls of a given cylindrical sandwich structure is developed based on the vertex method. A parametric study on the mechanical properties of several selected cylindrical foldcore models and a honeycomb core model virtually tested in axial compression, internal pressure and radial crush using the finite element method is performed. It is shown that foldcores outperform the honeycomb core model in axial compression and radial crush but have lower radial stiffness when subjected to internal pressure. The design protocol together with the virtual test results can serve as a useful tool for researchers to design cylindrical foldcore sandwich structures for many potential applications including but not limited to aircraft fuselage, submarine shell and other pressurized cylinders.

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ABSTRACT: An investigation into the material response and local buckling behaviour of ferritic stainless steel structural cross-sections is presented in this paper. Particular attention is given to the strain hardening characteristics and ductility since these differ most markedly from the more common austenitic and duplex stainless steel grades. Based on collated stress-strain data on ferritic stainless steel, key aspects of the material model given in Annex C of EN 1993-1-4 [1] were evaluated and found to require adjustment. Proposed modifications are presented herein. The local buckling behaviour of ferritic stainless steel sections in compression and bending was examined numerically, using the finite element (FE) package ABAQUS. The studied section types were cold-formed square hollow sections (SHS), rectangular hollow sections (RHS) and channels, as well as welded I-sections. The models were first validated against experimental data collected from the literature, after which parametric studies were performed to generate data over a wide range of section geometries and slendernesses. The obtained numerical results, together with existing experimental data from the literature were used to assess the applicability of the slenderness limits and effective width formulae set out in EN 1993-1-4 [1] to ferritic stainless steel sections. The comparisons of the generated FE results for ferritic stainless steel with the design provisions of EN 1993-1-4 [1], highlighted, in line with other stainless steel grades, the inherent conservatism associated with the use of the 0.2% proof stress as the limiting design stress. To overcome this, the continuous strength method (CSM) was developed as an alternative design approach to exploit the deformation capacity and strain hardening potential of stocky cross-sections. An extension of the method to ferritic stainless steels, including the specification of a revised strain hardening slope for the CSM material model, is proposed herein. Comparisons with test and FE data showed that the CSM predictions are more accurate and consistent than existing provisions thus leading to significant material savings and hence more efficient structural design.
ABSTRACT: Mechanical and thermal post-buckling analysis is presented for FGM rectangular plates resting on nonlinear elastic foundations using the concept of physical neutral surface and high-order shear deformation theory, and investigations on post-buckling behavior of FGM rectangular plates with two opposite simply supported edges and other two opposite clamped edges are also new. Approximate solutions of FGM rectangular plates are given out using multi-term Ritz method, and influences played by different supported boundaries, foundation stiffnesses, thermal environmental conditions and volume fraction index are discussed in detail. It is worth noting that the effect of nonlinear elastic foundation is small at the pre-buckling and initial post-buckling state and is significant with increasing deflection at the deep post-buckling state. Especially, comparisons of post-buckling for FGM rectangular plates resting on nonlinear elastic foundations with movable simply supported edge subjected to compression acting on the geometric middle surface and the physical neutral surface are innovative, and may be helpful to clarify typical mistakes in literature.

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ABSTRACT: In this paper, the structural strength and stability of cold-formed steel lipped channel beam-columns under bi-axial moments and axial force are experimentally investigated. The results are employed to evaluate the reliability of the current North American cold-formed steel design standard, AISI-S100-12, for predicting the strength of beam-columns, by both the effective width method (EWM) and the direct strength method (DSM). Fifty-five 600S137-54 (AISI-S200-12 nomenclature) lipped channel beam-column sections with three different lengths: 305 mm (short), 610 mm (intermediate), and 1219 mm (long) are tested under combined bi-axial bending moments and axial force to characterize the failure modes and the member capacity. A loading rig specifically designed to apply eccentric axial load, in order to provide bi-axial bending and compression to the specimens, was developed and detailed herein. The experimental observations reveal that the failure modes are highly dependent on the stress distribution applied on the cross-section by the combined actions. The results show a considerable potential for improvement in current specification approaches which utilize a simple interaction equation, as this typically results in conservative strength predictions. The potential for further improvement of the current specification for predicting the strength of cold-formed steel beam-columns is discussed.

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ABSTRACT: To improve the efficiency of the numerical simulation of the crushing of a honeycomb structure, the equivalent solid model of an aluminium honeycomb core was established. Comparison between the numerical simulation results and experimental evidence revealed that the numerical model of the honeycomb structure was effectively verified as representative. Secondly, the response surfaces for the variation of specific energy absorption (SEA) with side length \( l \) and thickness \( t \) of the aluminium foil were constructed by surrogate models. Then the relationship between SEA variation and the length \( l \) and thickness \( t \) of the aluminium foil was investigated. Results indicated that SEA increased with increasing \( t \) and decreased with increasing \( l \). The optimum SEA and associated structural parameters (\( l=1.0 \) mm, and \( t=0.16 \) mm) of an aluminium honeycomb were obtained.

Jia-Hui Zhang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong), “Numerical investigation and design of cold-formed steel built-up open section columns with longitudinal stiffeners”, Thin-Walled Structures, Vol. 89, pp 178-191, April 2015


ABSTRACT: A built-up I-section with longitudinal stiffeners is expected to have better performance to resist against local and distortional buckling compared to conventional built-up I-section by simply connecting two plain channels back-to-back. This paper presents a non-linear finite element analysis to investigate the behaviour of cold-formed steel built-up open section columns with edge and web stiffeners. A finite element model was firstly developed and verified against tests of cold-formed steel built-up compression members, in which the initial geometric imperfections and material properties of the test specimens were included. Secondly, the verified finite element model was used for an extensive parametric study of fixed-ended cold-formed steel built-up open section columns. The parametric study was designed to investigate the effect of edge and web stiffeners in the built-up open sections. The finite element results together with the test results were compared with the design predictions calculated from the current design rules in the North American Specification and the Australian/New Zealand Standard. Furthermore, design rules of the current direct strength method were modified. It is shown that the design strengths predicted by the modified direct strength method are generally in good agreement with the ultimate loads of the built-up open section columns. In addition, the current design rules and the modified direct strength method were evaluated by reliability analysis.

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ABSTRACT: To research mechanical behaviour of square hollow section (SHS) brace-H-shaped steel chord T-joints under axial compression, eight different \( \beta \) joint specimens with different external stiffeners arrangements at the foot of SHS brace were tested under axial compression in brace. The axial compression force was applied to the top end of the SHS brace member, which was weld to the center of the chord member. The test procedures, joint failure modes, jack load–vertical displacement curves and jack load–strain intensity curves were presented in the paper. The effect of \( \beta \) (defined as the brace width to the flange of H-shaped steel chord
width ratio) and the external stiffeners at the foot of SHS brace on the mechanical behaviour of the T-joints was also studied. The corresponding finite element analysis was also performed and calibrated against the test results. An extensive parametric study was carried out to evaluate the effect of geometric parameters on mechanical behavior of the T-joints under axial compression. Results of these tests show that local buckling failure of brace member was the main failure mode observed during the tests. 45° oblique external stiffeners could not improve the ultimate capacity of unstiffened joints under axial compression, while 90°normal external stiffeners could effectively improve the ultimate capacity of unstiffened joints with large $\beta$, even decrease the ultimate capacity of unstiffened joints with small $\beta$. Increasing the thickness of stiffeners can slightly improve the ultimate axial compressive capacity of stiffened joints. It is shown that the design strengths predicted by the current design rules are conservative for the unstiffened test specimens. The joint strengths obtained from the parametric study were compared with the design strengths calculated using current Eurocode 3. It is shown from comparison that the current Eurocode 3 is dangerous for the SHS brace-H-shaped steel chord T-joints under axial compression. The new design equations were proposed for the SHS brace-H-shaped steel chord T-joints under axial compression, which were verified to be safe and accurate.

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ABSTRACT:
A shear deformable theory and a computationally efficient finite element are developed to determine the lateral torsional buckling capacity of beams with mono-symmetric I-sections under general loading. A closed-form solution is also derived for the case of a mono-symmetric simply supported beam under uniform bending moments. The finite element is then used to provide solutions for simply supported beams, cantilevers, and developing moment gradient factors for the case of linear moments. The formulation is shown to successfully capture interaction effects between axial loads and bending moments as well as the load height position effect. The validity of the element is verified through comparisons with other established numerical solutions.


ABSTRACT: Deformation and energy absorption studies with single, double and multi-wall square and circular tube structure with and without aluminum foam core are carried out for assessing its effectiveness in crashworthiness under the identical test conditions. Modeling and numerical simulation of aluminum foam filled square tubes under axial impact loading is presented. The foam-filled thin-walled square tubes are modeled as shell wherein, foam core is modeled by incorporating visco-elastic plastic foam model in Altair® RADIOSS™. It is observed that the multi-wall tube structure with foam core alters the deformation modes considerably and results in substantial increase in energy absorption capacity in comparison with the single and multi-wall tube without foam core. Moreover, the multi-wall tube foam filled structure shows mixed deformation modes due to the significant effect of stress wave propagation. This study will help automotive industry to design superior crashworthy components with multi-tube foam filled structures and will reduce the experimental trials by conducting the numerical simulations.
ABSTRACT: The paper deals with a solution of three-dimensional problems of natural vibrations and stability of loaded cylindrical shells with circular and arbitrary cross sections containing a quiescent ideal compressible fluid. A mathematical formulation of the problem has been developed based on the variational principle of virtual displacements taking into account the pre-stressed undeformed state caused by the action of static forces on the shell. The motion of potential compressible non-viscous fluid is described by a wave equation, which is transformed using the Bubnov–Galerkin method. The solution of the problem reduces to the computation of complex eigenvalues of a coupled system of two equations. Based on the developed finite element algorithm several numerical examples have been considered to analyze the influence of fluid levels, ratio of ellipse semi-axes, shell thickness and boundary conditions on the natural frequencies and vibration modes of circular and elliptical cylindrical shells loaded by mechanical forces. It has been found that the value of the external uniformly distributed pressure giving rise to instability does not depend on the level of fluid in the shell. The results allow us to conclude that the dynamic characteristics of the system are specified not only by the equivalent added mass of the fluid but also by hydroelastic interaction at the wetted surface.

ABSTRACT: The paper is devoted to the stability analysis of a five layer sandwich beam. The goal is to elaborate a mathematical model of this beam and to check the influence of the binding glue layers on the stability of this structure. The simply supported sandwich beam consists of five layers which are two metal faces, the metal foam core and two binding layers (the glue) between faces and the core. The mechanical properties vary through the thickness of the beam and depend on the material of each layer. The field of displacement for the flat cross section of the beam is defined. Based on Hamilton’s principle the system of three partial differential equations of motion is obtained. This system is approximately solved. The forms of unknown functions are assumed and the system of equations is reduced to a single ordinary differential equation of motion. The equation is then numerically processed. The results of solutions of the vibration problem analysis are shown in graphs and figures.

ABSTRACT: Foldcore is an origami-like structural sandwich core which is manufactured by folding a planar base material into a three dimensional structure. The manufacturing technology is open to a variety of base materials and also a range of unit cell geometries is feasible. This results in a wide spectrum of homogenized mechanical properties which can be achieved by foldcores. Aluminium was found to be a suitable base material for building high performance foldcores with high stiffness, strength and energy absorption capabilities. In this
study aluminium foldcores are built and tested in compression, shear, bending and impact. Simulation methods are developed and validated along these test series. Simulation shows good agreement to experiments and is therefore a good method for further foldcore developments.

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ABSTRACT: The numerical method was adopted in this paper to study the performance of water tank under blast loading. The established numerical model was verified by comparing with the test results and then utilized to study the effects of water on the response of water tank under blast loading. The numerical results showed that water can significantly reduce the response of water tank under blast loading through reducing the external work. As for the boundary reaction force, although the maximum boundary reaction force was increased by filling in water, the increase in maximum boundary reaction force was less significant as compared to the decrease in response. Besides, the positive duration of boundary reaction force was reduced by filling in water. The simply supported and axially restrained boundary conditions were compared to study their effects on the response of water tank. It was found that the blast resistant performance of axially restrained water tank could be significantly improved as compared to the simply supported water tank. This can be attributed to the increased internal energy and reduced external work by adopting the axially restrained boundary condition.

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ABSTRACT: This paper presents the details of experimental and numerical research study on web crippling property of aluminum tubular under concentrated web crippling loadings. A total of 48 aluminum square hollow sections with different boundary conditions, loading conditions, bearing lengths and section heights were tested. The experimental scheme, failure modes, load–displacement curves and strain intensity distribution curves were also presented. The investigation was focused on the effects of different boundary conditions, loading conditions, bearing lengths and web slenderness on web crippling ultimate capacity and ductility of aluminum square hollow sections. The results obtained from the experiments are shown that the effect of bearing length on the web crippling ultimate capacity under End-One-Flange (EOF) and End-Two-Flange (ETF) loading and boundary conditions is more obvious than those under Interior-One-Flange (IOF) and Interior-Two-Flange (ITF) boundary and loading conditions. The web crippling ultimate capacities under EOF and ETF loading conditions decreased as the slenderness ratio increased. As the bearing length was 150, the web crippling ultimate capacity under IOF and ITF loading conditions reached its peak when the value of the web slenderness was minimum. The web crippling ultimate capacities of aluminum tubular with bearing length=50 mm and 100 mm under IOF, ITF, EOF and ETF boundary and loading conditions decreased progressively. The web crippling ultimate capacity of aluminum tubular with bearing length=150 mm was approximately equal. Finite
element models were developed to numerically simulate the tests performed in the experimental investigations. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of aluminum tubular sections under four loading and boundary conditions.

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ABSTRACT: A semi-analytical model for the non-linear analysis of simply supported, unstiffened laminated composite cylinders and cones using the Ritz method and the Classical Laminated Plate Theory is proposed. A matrix notation is used to formulate the problem using Donnell’s and Sanders’ non-linear equations. The approximation functions proposed are capable to simulate the elephant’s foot effect, a common phenomenon and a common failure mode for cylindrical and conical structures under axial compression. Axial, torsion and pressure loads can be applied individually or combined, and solutions for linear static, linear buckling and non-linear buckling analyses are presented and verified using a commercial finite element software. The presented non-linear buckling analyses used perturbation loads to create the initial geometric imperfections, showing the capability of the method for arbitrary imperfection patterns. The linear stiffness matrices are integrated analytically and for the conical structures an approximation is proposed to overcome the non-integrable expressions.

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ABSTRACT: In this paper, a generalised complex finite strip method is proposed for buckling analysis of thin-walled cold-formed steel structures. The main advantage of this method over the ordinary finite strip method is that it can handle the shear effects due to the use of complex functions. In addition, distortional buckling as well as all other buckling modes of cold-formed steel sections like local and global modes can be investigated by the suggested complex finite strip method. A combination of general loading including bending, compression, shear and transverse compression forces is considered in the analytical model. For validation purposes, the results are compared with those obtained by the Generalized Beam Theory analysis. In order to illustrate the capabilities of
complex finite strip method in modelling the buckling behavior of cold-formed steel structures, a number of case studies with different applications are presented. The studies are on both stiffened and unstiffened cold-formed steel members.

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ABSTRACT: Cylindrical bolted steel tanks with H/D~1 can be made from very thin steel courses the thickness of which is determined by tension. The important issue is to stiffen the whole shell with intermediate stiffeners to prevent from stability loss in situations when the tank is empty and exposed to a strong wind. The FEM package Abaqus with nonlinear Riks algorithm was used for analysis. A parametric study programmed in python, internal Abaqus language was conducted to establish the influence of number and position of intermediate stiffeners on buckling resistance of the tank. After calculating nearly one thousands tasks, results were gathered with python script and compared with classic design recommendations proposed in Eurocode 3, DIN 18 800 Part 4 and AWWA D103-09. Simplified analytical approaches present in current standards are rather conservative and one may want to look for more sophisticated methods of analysis of tank shells presented in this paper for more economical design of such structures. From the comparison of the results obtained with different numerical strategies such as linear buckling analysis (LBA), geometrically nonlinear analysis of perfect (GNA) and imperfect (GNIA) structure a necessity of taking into account imperfections in GNA arises. Otherwise a capacity of the shell structure may be overestimated even over the value obtained from LBA.

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ABSTRACT: A novel methodology for imperfection sensitivity analysis is presented. Koiter’s perturbation method is used to calculate the imperfection paths emanating from mode interaction bifurcations, which occur on the post-buckling paths of the single modes. The Monte Carlo method is used to test a large number of modes and all possible interactions among them. The computational cost is low because of the efficiency of Koiter’s method. The demands of Koiter’s method for accurate evaluations of higher order derivatives of the potential energy are met by a mixed, corotational element.

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ABSTRACT: A comprehensive experimental programme has been carried out to investigate the local buckling and postbuckling strengths of aluminium alloy I-section stub columns. A total of 15 test specimens made of two heat-treated aluminium alloys (6061-T6 and 6063-T5) were fabricated by extrusion. The material properties were acquired by the tensile coupons cut directly from the extruded cross-sections. The local geometric imperfections in sections were accurately measured prior to the tests. The stub column specimens were tested under axial compression between two fixed end supports, during which the local plate buckling featured visibly for each test specimen before reaching the peak load. The critical local buckling strengths were determined from the measured out-of-plane deflections and surface strains corresponding to the plate elements, which were further compared with the theoretical and analytical values taking into account element interaction and material non-linearity. Based on the obtained experimental postbuckling strengths, the design provisions in current design standards, including the American, Australian/New Zealand, European and Chinese specifications, were all evaluated. It was revealed that the predicted compressive strengths from the four design standards were generally conservative, especially for the cross-sections made of aluminium alloys with pronounced strain hardening properties.

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ABSTRACT: In this work, finite element method is used to obtain elastic buckling loads and mode shapes of plates. The effect of four different in-plane boundary conditions on the elastic buckling load of simply supported plates subjected to in-plane uni-axial compressive loading is studied. Elastic buckling behavior of plates with cut-outs (circular and square with curved corners) is also studied to illustrate the effect of the size, shape and the eccentricity of the cut-out on buckling loads. Results of the study show that the in-plane boundary conditions affect the elastic buckling behavior of the plate to a significant extent. Aspect ratio influences both the mode shape and the elastic buckling load for perforated plates, whereas its influence is generally limited to mode shape only in case of a solid plate. Restraints on the in-plane movements of plate’s unloaded edges have different influence on the elastic buckling behavior of the plate when the position of cut-out is changed along the x-axis (loading direction) and along the y-axis (normal to loading direction) of the plate. Also, results show that a large cut-out in the vicinity of edges makes the plate unstable at a much lower load compared to the plate with no cut-out. It is envisioned that the results of this study may provide insight to predict buckling loads in practical scenarios.

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ABSTRACT: This paper deals with numerical procedure for the vibration analysis of rectangular plates and stiffened panels subjected to point excitation force and enforced displacement at boundaries. The procedure is based on the assumed mode method, where natural response is determined by solving an eigenvalue problem of a multi-degree-of-freedom system matrix equation derived by using Lagrange’s equation of motion. Mode superposition method is applied to calculate plate/stiffened panel frequency response. The Mindlin plate theory is adopted for a plate, while the effect of stiffeners having the properties of Timoshenko beams is taken into account by adding their potential and kinetic energies to the corresponding plate energies. The accuracy of the proposed procedure is justified by several numerical examples which include forced vibration analysis of plates and stiffened panels with different dimensions and framing sizes and orientations, having various combinations of boundary conditions. The results obtained by the developed in-house code are compared to those obtained by the finite element method (FEM) and experimental results from the relevant literature. The presented procedure is confirmed to be highly accurate.

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ABSTRACT: A minimum mass design study applicable to thin circular tube is performed for various modes of eccentric compressive loading. Axial crushing failure mode, frequently noticeable in uniform axial compressive loading of thin circular tube, does not appear in eccentric compression. Hence, other compressive failure modes, e.g., global buckling, yield and local buckling are studied with respect to non-dimensional load and geometric shape factors for a fixed-free condition. These modes are predominant in ductile engineering alloys. A failure mode map in terms of non-dimensional load and shape-factor for a given load-eccentricity are obtained and the prescription for minimum mass is given.

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ABSTRACT: This paper introduces an accurate and computationally efficient GBT-based finite element, specifically tailored to capture the materially non-linear behaviour of wide-flange steel and steel-concrete composite beams up to collapse. The element incorporates reinforced concrete cracking/crushing, shear lag effects and steel beam plasticity (including shear deformation of the steel web). A set of numerical examples is presented, showing that the proposed element is capable of capturing all relevant phenomena with a very small
computational cost. In addition, analytical solutions for elastic shear lag are derived and the GBT modal decomposition features are employed to extract valuable information concerning the effect of shear lag phenomena up to collapse. For validation and comparison purposes, results obtained with shell/brick finite element models are also presented.


ABSTRACT: This paper presents an alternative design procedure for lateral–torsional buckling of cantilever I-beams which aims to simplify the calculation of critical loads and design moments. In the first part of the study, a closed-form equation is proposed to determine elastic critical lateral–torsional buckling load. The accuracy of the equation is validated through ABAQUS which is a software suite for finite element analysis. The second part includes bending tests conducted on European IPE100 section cantilevers. The purpose of the experiments is to determine the failure modes and loads in order to obtain baseline data for the design curve and comparison with analytical results. Finally, a design procedure is presented for cantilever I-beams which considers elastic buckling, inelastic buckling and full plastic strength. Design moments calculated by the presented design procedure, Eurocode 3-2005 and AISC360-10 are compared. It is found that the design moments obtained by the presented design procedure are in good agreement with those obtained by the procedures introduced in mentioned codes.

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ABSTRACT: Oil storage tanks are short cylindrical shells fabricated with an external fixed roof or floating roof on the inside. Some features of the structure tend to be simplified in practice and research in order to perform stability and strength analyses using a much simpler model. This paper considers the structural consequences of such simplifications, including the substitution of a supporting structure of the roof or a wind girder by an equivalent thickness or by a fictitious boundary condition. Three load cases are investigated: thermal loads due to an adjacent fire, uniform external pressure, and wind pressure. Results of finite element analyses to evaluate bifurcation loads and modes are reported as estimates of buckling. Equivalent thickness models are derived by establishing equivalences in moment of inertia or sectional modulus of the components that are not represented in detail. The differences in buckling loads associated with equivalent thickness models depends on the load case considered, but range between 7-15% for a case studied with a fixed roof, with smaller differences (3%) for opened top tanks with wind girders. Substitution of a wind girder by a boundary condition, on the other hand, yields large errors under thermal loads exceeding 80% of buckling loads.

References listed at the end of the paper:
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ABSTRACT: Crash components in automobiles are probably subjected to multiple loading conditions in real life, such as axial crushing and lateral bending. Unlike most of the existing work that solely focuses on the pure axial crushing or lateral bending, this paper attempts to accommodate both by proposing a novel structure, namely foam-filled thin-wall tube with functionally lateral graded thickness (FLGT). From numerical study of FLGT structures, they are found to exhibit noticeable advantage over the corresponding traditional uniform thickness (UT) structures with the same weight under both axial crushing and lateral bending. Moreover, the gradient governing the varying thickness shows significant influence on the crashworthiness performance of FLGT. To seek for the optimal gradient, a multi-objective optimization is carried out using multi-objective particle swarm optimization (MOPSO) algorithm, where response surface models are established to formulate
the objectives functions, i.e. specific energy absorption (SEA) and peak impact force \(F_{\text{peak}}\). The optimization results show that the foam-filled structure with FLGT can produce more promising Pareto solutions than traditional UT counterparts. Therefore, the FLGT structure could have potential applications subjected to different loading conditions.

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“Internally nested circular tube system subjected to lateral impact loading”, Thin-Walled Structures, Vol. 91, pp 72-81, June 2015, DOI: 10.1016/j.tws.2015.02.014

ABSTRACT: The paper presents a theoretical, numerical and experimental investigation into the dynamic behavior of internally nested tube systems subjected to lateral impact loading. A theoretical model based on rigid, perfectly plastic material idealization is proposed, in which the effects of strain-hardening and strain-rate are considered. The analytical solutions to the crushing behavior of nested tube systems are obtained. Numerical simulations based on finite element method using the explicit code LS-DYNA and experiments are performed and the response of force and displacement versus time impacted by a drop hammer are compared with the theoretical predictions, resulting in good agreement.


ABSTRACT: Stainless steels are ideal for sustainable structural performances due to their excellent corrosion resistance, appropriate mechanical properties, aesthetic appearance and easy maintenance. However, the nonlinear behaviour and strain-hardening effects characterizing these materials make them different from carbon steel and some specific guidance is necessary. Although some investigations regarding the behaviour of stainless steel beam–columns subjected to combined compression and bending moment have already been published, most of them are based on the most commonly used austenitic and duplex grades. Hence, the work presented in this paper deals with the flexural buckling resistance of ferritic stainless steel RHS and SHS columns subjected to combined loading. The assessment of several design approaches codified in EN1993-1-4 and proposed in the literature has been conducted by comparing numerical results with the predicted ultimate capacities. The partial safety factor \(\gamma_{\text{ult}}\) currently coded in EN1993-1-4 has been found to provide unsafe ultimate flexural buckling resistance predictions and new coefficients for the \(k\) interaction factor for ferritic RHS and SHS elements are proposed.

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ABSTRACT: This paper presents the experimental and theoretical studies on square tubed reinforced-concrete (TRC) short columns under eccentric compression. The main parameters of the test specimens included
eccentricity and width-to-thickness ratio of the steel tube. The axial load versus lateral deformation curves, stresses in the steel tubes and the observed failure modes were discussed. The test results indicated that the eccentrically loaded specimens exhibited good ductile behavior with a bending failure mode. A new approach to determine the effective lateral confining pressure for TRC columns with square section was proposed. A numerical analysis model was developed to simulate the mechanical behaviors of square TRC short columns. Valuable attempts were made to describe the variation rules between the parameters in stress block method for tubed concrete and the magnitude of confinement. Furthermore, the axial force versus moment capacity interaction diagrams of square TRC columns were calculated.


ABSTRACT: Dynamic crushing and energy absorption characteristics of sandwich structures with combined geometry shell cores were investigated experimentally and numerically. The effect of strain rate on the crushing behavior was presented by the crushing tests at quasi-static, intermediate and high strain rate regimes. It was shown that absorbed energy increased with increasing impact velocity. The effect of confinement on crushing behavior was shown by conducting confined experiments at quasi-static and dynamic rates. Higher buckling loads at lower deformation were observed in confined quasi-static crushing due to additional lateral support and friction provided by confinement wall. By using fictitious numerical models with strain rate insensitive material models, the effect of inertia and strain rate on crushing were shown. It was observed that, increase in impact velocity caused increase in inertial effects and strain rate effects were nearly independent from the impact velocity. The effects of multilayering were also investigated numerically.

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ABSTRACT: This paper presents experimental and analytical studies on the behavior of square tubed SRC (TSRC) columns subjected to eccentric compression. Eight square TSRC columns were tested to investigate the effects of eccentricity ratio of the compression force, width-to-thickness ratio ($B/t$) of the steel tubes, and use of shear connector studs on the steel sections. The test results indicated that local buckling of the square tubes was delayed effectively since axial load was not directly applied on the steel tube. Buckling of the tube initially occurred when the load reached the ultimate value for the specimens with $B/t$ ratio of 100, and buckling occurred earlier for the specimens with $B/t$ ratio of 133 when the load reached 88% to 94% of the ultimate load. A nonlinear finite element (FE) model was developed using ABAQUS, in which the nonlinear material behavior and initial geometric imperfections were included. Good agreement was achieved between the predicted results using the proposed FE model and the test results. A modified Eurocode 4 design method was adopted to calculate the ultimate strength of square TSRC columns.

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ABSTRACT: Thin walled circular cylindrical shell structures are prone to buckle and very sensitive towards geometrical imperfections. The influence of imperfections on the load carrying capacity of shell structures, as they are applied in launcher vehicles is considered by reducing theoretical buckling loads with empirical knock down factors. In general, these knock down factors may lead to a conservative estimate of the load carrying capacity since a worst case scenario is considered. In order to exploit the lightweight design potential of a structure, theoretical approaches to account for geometrical imperfections may lead to more adequate buckling load predictions. Within this contribution different theoretical approaches to account for geometrical imperfections of isotropic shell structures subjected to axial compression are investigated, and the influence of these approaches on the buckling load obtained is studied.

ABSTRACT: Few researches have focused on elastoplastic mechanical performances of functionally graded plates and shells. In this paper, elastoplastic and plastic buckling behaviors of externally pressured cylindrical shells made from functionally graded materials are investigated by using Donnell shell theory. Either $J_2$ flow theory or $J_2$ deformation theory helps to found the constitutive relation of functionally graded materials. The material properties vary smoothly through the thickness, and a multi-linear hardening elastoplasticity is used in the analysis. The buckling governing equations are solved by Galerkin method, and the expression of the elastoplastic critical external pressure is given analytically. Numerical results from the present theory are derived by an iterative arithmetic developed in MATHEMATICA code. The theoretical critical loads of the present $J_2$ deformation theory are well verified by experimental and numerical results in literature. The elastic, elastoplastic, and plastic buckling regions of functionally graded cylindrical shells can be effectively distinguished by the present method, and various effects of the dimensional parameters, the power law exponent, and the elastoplastic material parameters are investigated.

ABSTRACT: This paper examines the effect of large local imperfections, known as dents, on the plastic buckling capacity of short steel tubes under axial compression. A total of 11 tests on such short columns were carried out. The specimens were indented through a separate process and the ultimate axial capacity was subsequently obtained through compression tests. Dent imperfections with various depths were introduced to different locations on the body of the specimens. Plastic buckling modes as well as the ultimate capacity of the specimens were thoroughly investigated. The adverse effect of such a local damage on the load carrying capacity was quantified for different values and types of imperfections.
ABSTRACT: In storage tanks, intermediate wind girders are used to prevent the buckling failure of tank wall caused by wind load. For the design of the intermediate wind girders, two key parameters must be determined: the size of intermediate wind girders and the spacing between the girders. In the code API650, the spacing is expressed as the maximum height of the unstiffened tank wall and the size is referred to the minimum section modulus. In this paper, the design approach for the maximum height of the unstiffened tank wall and the simplified mechanical model for the minimum section modulus adopted in API650 were presented to reveal the simplification regarding the magnitude and action zone of wind load and the negligence of the strengthening effects of the tank bottom. A 3D finite element model was built to study the wind pressure distribution around the tank and strengthening effects of the tank bottom. Optimal analysis to minimize the weight of the wind girders for a given wind load was performed numerically and formulas for the size and spacing of the wind girders according to the optimal results were given. Based on the optimal design proposed in this paper, the material consumed for the winder girders were significantly reduced.

ABSTRACT: The behaviour of square hollow section AA6060 aluminium profiles subjected to quasi-static axial crushing was investigated experimentally and numerically. The profiles were artificially aged to three different tempers (under-aged, peak-aged and over-aged) using two different cooling rates (water quench or air cooling) after the solution treatment, thus obtaining six different materials. The materials’ microstructures were characterized by scanning and transmission electron microscopy and mechanical testing was used to determine the stress–strain curves in uniaxial tension. Axial crushing tests were carried out on profiles made of the six different materials to study the influence of the heat treatment on the energy-absorbing capability of the profile. The nanometre-scale material model NaMo was employed to predict the stress–strain curves of the three water-quenched materials based on the chemical composition and the thermal history. A new feature was introduced in NaMo in order to account for the incubation period, which cannot be ignored for low-alloy materials such as the AA6060 alloy. The stress–strain curves predicted using the improved nano-scale material model showed good agreement with the experimental curves for the three tempers when the incubation period was considered. Using the predicted stress–strain curves in finite element simulations of axial crushing of the profiles, gave excellent predictions of the experimentally obtained force–deformation curves and thus the energy absorption. The results indicate that two-scale simulation based only on chemical composition and thermal history is now possible in designing AA6xxx structural components for safety applications.

ABSTRACT: Experimental investigation of built-up cold-formed steel section batten columns”, Thin-Walled Structures, Vol. 92, pp 137-145, July 2015, DOI: 10.1016/j.tws.2015.03.001
ABSTRACT: This paper presents an experimental investigation on behaviour and design of built-up cold-formed steel section batten columns. The built-up columns were pin-ended and consisted of two cold-formed steel channels placed back-to-back at varied spacing of intersection. The two channels were connected using batten plates, with varying longitudinal spacing. The cold-formed steel channel sections were manufactured by brake-pressing flat strips having a plate thickness of 2 mm. The built-up cold-formed steel section batten columns had different slenderness and geometries but had the same nominal length of 2200 mm. The column strengths, load–axial shortening, load–lateral displacement and load–axial strain relationships were measured in the tests. In addition, the failure modes and deformed shapes at failure were observed in the tests and reported in this paper. Overall, the built-up column tests provided valuable experimental data regarding the column behaviour that compensated the lack of information on this form of construction as well as used to develop nonlinear 3-D finite element models. The column strengths measured experimentally were compared against design strengths calculated using the North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel columns. Generally, it is shown that the specifications were unconservative for the built-up cold-formed steel section batten columns failing mainly by local buckling, while the specifications were conservative for the built-up columns failing mainly by elastic flexural buckling.

M.A. Eder and R.D. Bitschi (Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark), “A qualitative analytical investigation of geometrically nonlinear effects in wind turbine blade cross sections”, Thin-Walled Structures, Vol. 93, pp 1-9, August 2015, DOI: 10.1016/j.tws.2015.03.007

ABSTRACT: This paper analytically investigates the Brazier effect on asymmetric thin-walled sections subject to biaxial bending. In the latter case a torsional moment – in this paper referred to as Brazier torsion – is induced, which proved to be a vital part of the solution. By means of a generic cross section, that was inspired by a wind turbine blade, it is demonstrated that geometric nonlinear effects can induce an in-plane opening deformation in re-entrant corners that may decrease the fatigue life. The opening effect induces Mode-I stress intensity factors which exceed the threshold for fatigue crack growth at loads well below the load-carrying capacity of the beam. The findings in this paper are twofold: Firstly, the investigated analysis procedure can be integrated into the design process of wind turbine blade cross sections. Secondly, the proposed approach serves as a basis for computationally efficient numerical analysis approaches of structures that comprise complex geometry and anisotropic material behaviour – such as wind turbine rotor blades.

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“Dynamic instability of three-layered cylindrical shells containing an FGM interlayer”, Thin-Walled Structures, Vol. 93, pp 10-21, August 2015, DOI: 10.1016/j.tws.2015.03.006

ABSTRACT: In this study, the dynamic instability of three-layered cylindrical shells containing a functionally graded (FG) interlayer subjected to static and time dependent periodic axial compressive loads are investigated. The governing relations, modified Donnell type dynamic stability and deformation compatibility equations are derived. The governing equations are reduced Mathieu–Hill equation by using Galerkin’s method and the expressions for boundaries of unstable regions of three-layered cylindrical shell with an FG interlayer are found. Finally, the effects of variations of volume fractions of FG interlayer and shell characteristics on the magnitudes of boundaries of unstable regions are studied numerically.
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“Behaviour of circular concrete filled double skin tubes subjected to local bearing force”, Thin-Walled Structures, Vol. 93, pp 36-53, August 2015, DOI: 10.1016/j.tws.2015.03.004
ABSTRACT: This paper presents the behaviour of circular concrete filled double skin tubes (CFDST) subjected to local bearing forces. This is an extension of a previous work on concrete filled steel tubes (CFST). A series of tests were conducted where some key parameters were varied, including loading angle, hollow ratio, chord wall thickness, as well as brace to chord diameter ratio. A finite element analysis (FEA) modelling was established and verified by the test data. Comparative analysis was conducted between the full-range behaviour of CFDST and CFST under local bearing. It was found that the performance of CFDST is considerably affected by the interaction of the outer tube, inner tube and the sandwiched concrete, whilst its bearing capacity depends on the hollow ratio. Finally, based on the load-transfer mechanism analysis, simplified formulae for predicting the strength of CFDST under local bearing forces are presented. Reasonable agreement between the predicted and measured values is achieved.

ABSTRACT: In this paper the impact of a hollow elastic ellipsoidal thin shell with an elastic flat half space is analyzed. Due to the nonlinearity and complexity of the impact equation, classical numerical solutions cannot be employed. A closed-form solution for this problem is accomplished, using Hertzian theory [6] and the Vella’s analysis [17] in conjunction with the Newtonian method and a linearization scheme. The closed-form solution facilitates a parametric study of this problem. In next step, the closed-form analytical solution is validated by other research studies and explicit finite element method. Good agreement between the closed-form solution and other numerical results is observed. Based on the closed-form solution the maximum total deformation of the shell, the maximum transmitted force and the time duration of the contact were determined. The variations of the total deflection and the transmitted force as a function of the shell thickness and the different geometry of the shell were also determined. Finally it is concluded that the closed form equations are trustworthy and appropriate to investigate the impact of elastic ellipsoidal shells.

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“Effects of elastic-plastic behaviour on the axial crush response of square tubes”, Thin-Walled Structures, Vol. 93, pp 64-87, August 2015, DOI: 10.1016/j.tws.2015.02.023
ABSTRACT: Axial crushing of square tubes is widely studied for their energy absorption characteristics that are similar to automotive structural components. In this paper, the effects of the elastic–plastic behaviour of lightweight alloys on the steady state crush force, peak crush force, energy absorption and crush efficiency response of the axial crushing of square tubes are studied. Axial crush simulations are performed on square crush tubes where the yield stress and strain, ultimate tensile strength, hardening rate, and failure strain of the
material are varied. New definitions and analytical equations for crush efficiency and energy absorption are developed and calibrated with the axial crush simulations to develop a framework for optimal material selection for axial crush. This work shows that the yield stress increases the energy absorption, peak crush force and steady state crush force, while tending to decrease the crush efficiency. After sufficient increase in the hardening capabilities, positive gains are obtained in the crush efficiency when increasing the yield stress. The ultimate tensile strength, hardening rate and the yield stress of the material have a strong effect on improved energy absorption. Lightweight alloys with a low yield stress that have significant work hardening capabilities outperform materials with a high yield stress and very little work hardening in terms of energy absorption when a constraint is imposed on the peak crushing force.

DOI: 10.1016/j.tws.2015.03.012

ABSTRACT: The paper is devoted to a new shape of a shell of revolution with negative Gaussian curvature. The main part of the meridian of the shell is a plane curve of the Huygens tractrix. Geometrical properties of the middle surface of the shell of revolution are presented. The membrane state of stress for a family of shells with constant capacity and constant mass under uniform external pressure is analysed. The critical pressure, buckling modes and equilibrium paths for the family of shells are calculated with the use of the FEM (the ANSYS system). Results of the analytical and numerical investigations are presented in tables and figures. A stable post-critical behaviour of presented shells is pointed out which is not typical for most shell structures.

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“Selected problems concerning determination of the buckling load of channel section beams and columns”, Thin-Walled Structures, Vol. 93, pp 112-121, August 2015, DOI: 10.1016/j.tws.2015.03.009

ABSTRACT: The issue of buckling load determination in composite channel section beams subjected to pure bending and channel section columns subjected to uniform compression is considered. Some selected problems with determination of buckling load on the basis of the collected and processed experimental data are discussed. The data necessary to determine buckling load (applied load and the corresponding displacement, strains at chosen points of beam-columns and displacements in three perpendicular directions of all visible points of the considered beam-columns) were collected with a strain gauge system, an Aramis® 3D optical system and a universal testing machine. Buckling load was determined by means of the following well-known methods: the mean strain method, the method of straight-lines intersection on the graph of load vs. mean strains, the curve inflection point method, the load-square of deflection curve method and Koiter’s method. All results were obtained during the experimental investigations and the numerical FEM analysis of the channel section profile made of a GFRP laminate with the symmetrical eight-layer arrangement [45/-45/90/0]s. The profiles under consideration were subjected to compression or pure bending (four-point bending test). The rules for each methods of buckling load determination are proposed on the basis of the obtained results.
ABSTRACT: The paper presents 3D results on stability of thin-walled cylindrical metal silos made from isotropic rolled plates containing bulk solids. The behaviour of bulk solids was described with a hypoplastic constitutive model. Non-linear FE analyses with both geometric and material non-linearity were performed with a perfect and an imperfect silo shell wherein 3 different initial geometric imperfections were taken into account. The influence of a stored bulk solid (dry medium-dense cohesionless sand) during filling on the buckling strength of silos was compared with the strength of an empty silo and with the experimental results available in the literature. Our numerical results indicate a clear strengthening effect of the stored solid on the silo buckling strength as in the experiments, depending upon the wall thickness, wall loading way and imperfection type and amplitude.

ABSTRACT: This study investigates the effect of radial distance of concentric thin-walled tubes on their energy absorption capability through simulation by LS-Dyna finite element software and experimental tests. Concentric cylindrical tubes made of aluminum 1050 with different radii were exposed to axial dynamic and quasi-static loading and optimum radial distance in maximum energy absorption condition was obtained. In overall, 24 states for simulation and 8 states for experimental tests have been investigated. Dynamic loading has been applied in form of hitting of a 75 kg mass with speed of 8 m/s and quasi-static loading of the structures has been done with speed of 150 mm/min and elongated to 70% of the initial length of tubes. Comparison of results of the two concentric tubes and single-tube system with equal mass of structures showed that energy absorption of two-tube system is more than single-tube system. Furthermore, in concentric tubes’ system, in the state where the distance of both tubes has changed, the energy absorption is more than the state where the radius of the outer tube is constant and just the radius of the inner tube changes.

ABSTRACT: Nowadays, foam-filled multi-cell thin-walled structure (FMTS) has been widely used in the field of automotive due to their extraordinary energy absorption capacity and light weight. In this study, nine kinds of FMTSs with different cross-sectional configurations under lateral crushing load conditions were investigated using nonlinear finite element method through LS-DYNA. The complex proportional assessment (COPRAS) method was used to make clear which kind of FMTSs has the most excellent crashworthiness. According to this method, it can be found that FMTSs with 2, 3 and 9 cells are the top-3 excellent structures in our considered
cases. In order to improve the crashworthiness of the three FMTSs, they were optimized by metamodel-based multiobjective optimization method which was developed by employing polynomial regression (PR) metamodel and multiobjective particle swarm optimization (MOPSO) algorithm. In the optimization process, we aimed to achieve maximum value of specific energy absorption (SEA) and minimum value of maximum impact force (MIF). Based on the comparison of the Pareto fronts obtained by multiobjective optimization, we can find that FMTS with 9 cells (FTMT9) performs better than FMTSs with 2 and 3 cells. Thus, the optimal design of FMTS9 is exactly an excellent energy absorption candidate under lateral impact and can be used in the future vehicle body.

Junyuan Zhang, Hao Zhou, Linan Wu and Guang Chen (State Key Laboratory of Automobile Simulation and Control, Jilin University, Changchun 130000, China), “Bending collapse theory of thin-walled twelve right-angle section beams filled with aluminum foam”, Thin-Walled Structures, Vol. 94, pp 45-55, September 2015 DOI: 10.1016/j.tws.2015.03.024

ABSTRACT: This paper aims at studying the bending collapse behavior of the thin-walled twelve right-angle section (TTRS) beams filled with aluminum foam. This paper presents the theoretical bending characteristics of the TTRS-typed aluminum foam around two axes. Considering the contribution degree of thin-walled beam and aluminum foam in different angle range, the expressions of the bending moments are derived. The accuracy of the theoretical calculations are validated by performing 14 groups finite element simulations respectively including three kinds of aluminum foams with certain scope of plateau stress (1–12.5 MPa) and corresponding density (0.2–0.52 g/cm³). The results show that the bending collapse theory proposed in this paper can reflect the mechanical properties of the TTRS beams filled with aluminum foam accurately, and the moment–rotation curves calculated by theory are in good agreement with simulation results.

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“Multi-cornered thin-walled sheet metal members for enhanced crashworthiness and occupant protection”, Thin-Walled Structures, Vol. 94, pp 56-66, September 2015, DOI: 10.1016/j.tws.2015.03.029

ABSTRACT: Crash energy management in frontal crumple zone of the automotive body is one of the key elements for the design of automotive structure. Improving energy absorption characteristics reduces the magnitude of forces transferred to the occupant compartments. Here, a new strategy has been proposed to improve energy absorption efficiency of thin-walled columns by introducing extra stable corners in the cross-section. Several profiles of multi-corner thin-walled columns obtained through this strategy were presented and their crashworthiness capacities under axial crush loading were investigated analytically, experimentally, and numerically. First, explicit formulations for predicting the mean crushing force of multi-corner thin-walled columns were derived using the theory of super folding element (SFE). Predicted results of these formulations showed a good agreement with the results of quasi-static experiments and CAE simulations, which were performed by explicit non-linear finite element code through LS-DYNA. Based on this agreement, other significant crashworthiness assessment parameters were then investigated experimentally and numerically. Newly introduced 12-edge section with high energy absorption capacity was developed and its dominance was established through the responses in quasi-static experiments and CAE simulations. Finally, the foundational dominance of the 12-edge section was extended to the dynamic environment through a full vehicle crash test simulation to evaluate overall reduction in crashworthiness parameters which reflected occupant safety.
Interestingly, in the case of using 12-edge section as crush absorbers, specific energy absorption (SEA), dash intrusion and maximum occupant’s chest deceleration showed significant improvement, compared to the baseline design which used a rectangular section.

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ABSTRACT: Shells in textile reinforced concrete (TRC) can be made very thin thanks to their non-corroding reinforcement. Consequently, buckling becomes an important parameter. Because of the lack of data in literature, this paper presents the experimental and numerical analysis on the buckling behaviour of a TRC dome (2 m span, 0.2 m height, 3.7 mm thick), which is subjected to a uniform pressure load until it buckles. This experiment is simulated using the Riks method in Abaqus and implementing geometrical imperfections. The simulations correspond well to the experimental data and validate the model, which enables the prediction of buckling, necessary when designing thin TRC shells.

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ABSTRACT: A novel layerwise theory based on the first order shear deformation theory (FSDT) has been proposed to evaluate the buckling and post-buckling behavior of delaminated composite plates with multiple through-the-width delaminations. The Rayleigh–Ritz Method has been adopted and displacement fields are obtained by incorporating simple and complete polynomial series which result in much less computational cost. The proposed layerwise theory provides a more realistic description of the kinematics of composite laminates when compared to Equivalent Single Layer theories. Both local buckling of the delaminated sublaminates and global buckling of the whole plate can be handled. The method is capable of predicting response of thick delaminated composite plates. Presence of multiple delaminations can also be handled. In order to prevent unacceptable penetration, contact constraints are imposed on the delaminated area. The three dimensional finite element analysis is performed using ANSYS5.4 commercial software. The results show a very good agreement with those obtained by the analytical Model.

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ABSTRACT: Numerical simulation is carried out to investigate the crushing characteristics of a single cell in a fan-shaped deployable energy absorber (FDEA) under quasi-static axial loading. FDEA can effectively improve the crashworthiness behavior of aircrafts with the advantages of saving space and deploying actively. Hinges are added to the single cell to meet the need of fan-shaped deployment. The finite element model is established to study the effects of hinge’s parameters, including material properties such as Young’s modulus, yield strength and the tube thickness, on the single cell’s energy absorption characteristics. The relationship between the deployment angle and the specific energy absorption (SEA) of the single cell is also studied. The numerical results indicate that the energy absorption increases rapidly as yield strength and the hinge’s thickness increase, while it only has minor correlation with Young’s modulus of the material. Three different modes of the cell appear during its axial crushing as the deployment angle increases. Besides, experiments were conducted to observe the crushing mode of the straight single cell, and the results are compared with the numerical simulation results. Finally, a theoretical model of a straight single cell with hinges is proposed to predict the mean crushing force, which is in good agreement with the numerical simulation.

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ABSTRACT: This paper presents the numerical and analytical models to predict the response behaviour of Steel–Concrete–Steel (SCS) sandwich composite beams subjected to drop-weight impact loading. The sandwich composite beam has an ultra-lightweight concrete core of density 1440 kg/m³ sandwiched between two thin steel face plates which are interconnected by J-hook connectors. Explicit nonlinear finite element analysis was carried out and the results obtained are verified against the impact test data to establish its accuracy in predicting the permanent deformation, vertical displacement–time history and impact force–time history of the sandwich beams. The numerical analysis also shows that the J-hook connectors are subjected to tension force during impact in addition to shear force due to flexural action in the beam. This signifies the important role of J-hook connectors in preventing tensile separation of the steel face plates when subjected to impact load. An analytical approach based on energy balance model was also developed to predict the impact response of SCS sandwich beams. A good agreement was observed between the analytical solution and the experimental data indicating that the approach provides a reasonable and conservative estimation of the impact resistance of the sandwich beams.

Carlos Graciano (Universidad Nacional de Colombia, Facultad de Minas Sede Medellén, Departamento Departamento Ingeniería Civil, A.A. 75267 Medellín, Colombia), “Patch loading resistance of longitudinally stiffened girders – A systematic review”, Thin-Walled Structures, Vol. 95, pp 1-6, October 2015
DOI: 10.1016/j.tws.2015.06.007
ABSTRACT: At present, strength-curves approaches are used within European standards to deal with stability problems in steel structures. In this regard, three parameters require special attention; those are the yield load for plastic resistance, the resistance function depending on element slenderness and the buckling load. This paper presents a systematic review of current developments for the resistance of longitudinally stiffened girders to patch loading. Firstly, a historical overview of the mainstream within the field of patch loading is presented. At the end, an illustrative design example is presented in order to further discuss the improvements in the calculation of the resistance.

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ABSTRACT: Based on the Galerkin method, a semi-analytical solution for the shear buckling of composite laminated plates with all four edges elastically-restrained against rotation is presented. The considered laminated plates are loaded in pure shear or combined shear and compression. The deformation shape function is constructed through a unique weighting combination of vibration eigenfunctions of simply-supported and clamped conditions, and it is an effective method for solving the considered eigenvalue problem. A parametric study is conducted to evaluate the effect of the rotational restraint stiffness, plate aspect ratio, material orthotropy and anisotropy on the buckling behavior of the rotationally-restrained laminated plates under pure shear or combined shear and compression action. The semi-analytical solution presented can be used to analyze the restrained laminated plates under shear-dominated loading and applied to predict the web local buckling of thin-walled composite beams.

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ABSTRACT: This paper presents a combined experimental and numerical study on the behavior of both circular and square concrete-filled steel tube (CFT) stub columns under local compression. Twelve circular and eight square CFT stub columns were tested to study their bearing capacity and the key influential parameters. A 3D finite element model was established for simulation and parametric study to investigate the structural behavior of the stub columns. The numerical results agreed well with the experimental results. In addition, analytical formulas were proposed to calculate the load bearing capacity of CFT stub columns under local compression.
Stanislav Kitarovic, Jerolim Andric and Karlo Piric (University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lucica 5, 10000 Zagreb, Croatia), “Rational magnification of the plate elastic shear buckling strength”, Thin-Walled Structures, Vol. 94, pp 167-176, September 2015
DOI: 10.1016/j.tws.2015.04.016

ABSTRACT: Various feasible approaches to magnification of the plate elastic shear buckling strength are comprehensively investigated. Based on derived theoretical envelopes of the considered approaches, stiffening parallel to the longer plate edges is identified as the most effective approach to the considered problem. An accompanying analytical formulation, convenient for utilization in structural analysis and design of the plated structures, is approximated. Various recommendations and formulations relevant for determination of the rational stiffened plate design (with respect to the considered problem) are proposed. All derived conclusions and proposed formulations are based on results of the numerous rationally designed numerical simulations.

Mei Liu, Lulu Zhang, Peijun Wang and Yicun Chang (School of Civil Engineering, Shandong University, Jinan 250061, China), “Experimental investigation on local buckling behaviors of stiffened closed-section thin-walled aluminum alloy columns under compression”, Thin-Walled Structures, Vol. 94, pp 188-198, September 2015
DOI: 10.1016/j.tws.2015.04.012

ABSTRACT: Six aluminum alloy tensile coupon tests were carried out and stress–strain curves obtained from tests were compared with a Ramberg–Osgood model. Comparison showed that the Ramberg–Osgood model can precisely describe stress–strain relationship of 6063-T5 aluminum alloy. Totally, 10 axial compression tests on thin-walled aluminum alloy members with four stiffened closed-section were carried out. Local buckling occurred in all specimens eventually. The axial displacement, lateral deflection, strain development and failure modes of the tested specimens were recorded. A finite element method (FEM) model was presented to simulate local buckling behaviors of the tested columns under axial load. The ultimate strength, strain development and failure modes obtained from FEM agreed well with the test results. Current design codes on aluminum alloy structures, such as the American aluminum design manual (AA), the European code (EC9), Chinese design specifications for aluminum structures (GB50429), the North American Specification for the design of cold-formed steel structural members (AISI) and the direct strength method (DSM), were used to calculate the ultimate strength of the tested columns. Comparison showed that current design codes overestimated the ultimate strength of stiffened closed-section thin-walled aluminum alloy columns under axial compression loads.


ABSTRACT: This master thesis presents research into buckling of thin hyperboloid shells structures. This type of structure is typically applied as the large cooling towers at coal fired electricity plants. However, modelling cooling towers is not the objective of this research. The objective of this research is to understand the buckling behaviour of shells with negative Gaussian curvature, which cooling towers have. In previous research it was found that negatively curved shells are not very sensitive to imperfections and that the first buckling mode provides the most critical imperfection. This research starts from the assumption that a design formula can be derived for predicting the ultimate load of negatively curved shells. A step in this direction is understanding how hyperboloid shells buckle and determining what parameters influence the ultimate load. A finite element model was developed with suitable properties. The influence of the boundary conditions has been studied. The element size and the aspect ratio have been optimised. Various methods of adding imperfections have been considered. The buckling modes have been studied for a large range of curvatures. The influence of the
imperfection amplitude on the load displacement curve has been determined by geometrical nonlinear analysis and the arc length method. A parameter study has been performed of a large range of geometries. Varied are the radii of curvature, the thickness, the height of the hyperboloid. Also varied are Young’s modulus and Poisson’s ratio. In total 700 geometrical nonlinear analysis have been performed. The results have been stored in a large data base in Matlab. This includes the support reactions, membrane forces, moments and stresses at each load step. A series of Matlab scripts were developed to generate various graphs. The graphs were used to form a detailed understanding of the buckling behaviour of negatively curved shells and to identify remarkable features. A two-phased curve fitting method has been used is to obtain a formula for the ultimate buckling load and a formula for the peak membrane force of inward buckles. The main conclusion is that hyperboloid shells of significant curvature carry load in three ways: the outward buckles, the inward buckles and the material in-between. First the outward buckles fail then the inward buckles fail and finally the material between the buckles fails. A design method is proposed based on the local linear elastic stress state.

References listed at the end of the thesis:


ABSTRACT: Rectangular thin walled tubes are commonly used in front rail structures of automotive chassis, and are designed to absorb maximum amount of energy during frontal impact. With increasing emphasis over the last few decades on building lighter and faster vehicles by auto manufacturers, researchers are actively exploring opportunities to improve crashworthiness of vehicles by exploiting structural and material optimization approaches. In this paper, two new shapes, Pentagon and Cross, were studied for two materials, aluminum and steel, with the objective of improving the crashworthiness of automobiles without adding any additional weight (within the same type of material) to the chassis. The tubes were initially analyzed using finite element method. The performances of proposed tubes were compared with a rectangular cross-section tube by
comparing the average mean force (required to crush the tube under 35 mph impact velocity) and the total specific energy absorbed. A theoretical plastic analysis was carried out by evaluating the folding mechanisms of tubes for Pentagon and Cross shapes and an analytical model was developed that predicted the mean force necessary to crush the tubes. The numerical and theoretical analysis showed that for equivalent tube wall areas, the aluminum and steel Pentagon and Cross tubes absorbed 31–60% and 48–92% more energy than the rectangular tube. The outputs of proposed predictive theoretical model for the Pentagon and Cross tubes were compared reasonably well with the mean force values calculated through numerical method. An experimental study was conducted on cross tube samples machined from Aluminum AA6061–T6511 blocks with the purpose of validating numerical and theoretical approaches used in the present study. Experimental results for the mean force demonstrated a good correlation with numerical and theoretical approaches with approximately 1% and 6% variation, respectively. In addition, the deformation modes observed in the experiment matches reasonably well with the ones observed in the finite element analysis (FEA) simulations.

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ABSTRACT: A relaxation method is applied to estimate and predict a critical set of parameters responsible for stability loss (buckling) of spherical circle axially symmetric shells. The buckling phenomenon under static loading was investigated by solving the Cauchy problem for a set of ordinary differential equations and the Hausdorff metrics was applied while quantifying the data obtained within the novel approach.

References listed at the end of the paper: (Cannot cut and paste them)

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ABSTRACT: This paper discusses aspects related to the mechanics underlying the distortion of thin-walled members with symmetric and periodic open cross-section, such as those commonly employed in cold-formed steel construction. The Generalised Beam Theory (GBT) framework is employed to determine the cross-section distortional deformation modes and obtain insight into the problem under consideration. Besides reviewing the well known case of reflectional symmetry, the implications of rotational symmetry and periodicity through translation or glide reflection are examined. For each case, computationally efficient procedures to obtain the distortional modes are provided. Several examples are presented throughout the paper, in order to enable a better grasp of the concepts and procedures addressed.
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NSW, Australia
“Comparison of functionally-graded structures under multiple loading angles”, Thin-Walled Structures, Vol. 94,
ABSTRACT: This paper provides a comparative study on the crashworthiness of different functionally-graded
thin-wall tubes under multiple loading angles, which include hollow uniform thickness (H-UT), hollow
functionally graded thickness (H-FGT), foam-filled uniform thickness (F-UT) and foam-filled functionally
graded thickness (F-FGT) configurations. First, finite element analyses of these differently graded circular tubes
reveal that the F-FGT tube has the best crashworthiness under multiple loading angles. Second, parametric
study on the F-FGT tube indicates that the thickness gradient and variation range significantly influence its
crashworthiness. Third, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize the F-
FGT tube, in which the optimal thickness variation is sought for maximizing specific energy absorption (SEA)
and minimizing initial peak force (IPF) under multiple loading angles. The optimized F-FGT tube exhibits
better crashworthiness than other three equivalent tube configurations, indicating that the F-FGT tube can be a
potential energy absorber when oblique impact loading is inevitable.

Andrzej Szychowski (Faculty of Civil Engineering and Architecture, Kielce University of Technology, Al.
Tysiąclecia Państwa Polskiego 7, 25-323 Kielce, Poland), “Stability of cantilever walls of steel thin-walled bars
with open cross-section”, Thin-Walled Structures, Vol. 94, pp 348-358, September 2015
DOI: 10.1016/j.tws.2015.04.029
ABSTRACT: In thin-walled bars with open cross-section, built from flat walls, cases are found in which, the
cantilever wall, elastically restrained in the web, is compressed, and at the same time, longitudinal variation in
stresses along its length occurs. Such a wall can be analyzed as a cantilever thin plate, elastically restrained
against rotation on the longitudinal supported edge. The paper presents the results of investigations into the
stability of elastically restrained cantilever plates for varied stress intensity in the longitudinal direction. Graphs
of plate buckling coefficients ($k$) were determined and approximation formulas were derived for technically
crucial stress distributions and different degrees of the plate edge elastic restraint. The impact of longitudinal
stress variation and of the degree of elastic restraint on the plate buckling modes was analyzed.

Sajjad Tohidi and Yasser Sharifi (Department of Civil Engineering, Vali-e-Asr University of Rafsanjan, Iran),
“Neural networks for inelastic distortional buckling capacity assessment of steel I-beams”, Thin-Walled
ABSTRACT: An Artificial Neural Network (ANN) model is developed as a reliable modeling method for
simulating and predicting the ultimate moment capacities for intermediate doubly-symmetric steel I-beams. The
training and testing data for neural network are generated using Finite Element Analysis (FEA). In other word,
an extensive numerical study was also undertaken to investigate the distortional buckling behavior of simply
supported compact steel I-beams. A series of nonlinear elasto-plastic FE analyses have been carried out to
simulate the distortional buckling behavior of doubly-symmetric steel I-beams, and the effects of six
independent parameters as input in a lateral-distortional buckling mode has been investigated. Moreover, unlike
the existing design codes the model considers the effect of web distortions in a lateral-distortional buckling
mode. Then a new formula based on the ANNs has been proposed to predict the member moment capacities of
steel I-beams subjected to distortional buckling. The attempt was done to evaluate a practical formula
considering all parameters which may affect distortional capacity. Then, a comparison has been made between
the proposed formula and the predictions from the current design rules in some structural steel codes. The
results show that the proposed formula is more accurate and applicable than existing design codes. Finally, a
sensitivity analysis using Garson’s algorithm has been also developed to determine the importance of each input
parameters.
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ABSTRACT: Experimental studies on the behaviour of concrete filled double-skin steel tube (CFDST) subjected to local bearing forces are presented in this paper. Sixteen specimens were prepared and tested with the included angle between bearing member (BM) and compression member of 45° and 90°, whilst both the inner and outer steel tubes of the CFDST specimens are square hollow sections (SHS). The main parameters in the tests were: 1) outside width ratio between BM and compression member: from 0.4 to 0.6; 2) hollow ratio of CFDST: from 0 to 0.6; 3) wall thickness of outer steel tube: 3.05 mm and 3.95 mm; and 4) cross-section of BM: solid and hollow. The failure pattern, load versus deformation curve, bearing capacity and corresponding deformation at bearing capacity of the tested specimens are presented and analyzed. The experimental results show that, while subjected to local bearing forces, CFDST specimens have a high bearing capacity and a good deformation-resistant ability. The calculated bearing capacities of CFDST under local bearing forces using the proposed formulae in the paper are evaluated by comparison with the experimental results.

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ABSTRACT: Steel moment frame buildings face severe collapse potentials when subjected to earthquakes beyond the design level. Reliable numerical modeling of steel moment frames is significant to assess the critical parameters affecting collapse behavior. A fiber-element model is presented to evaluate post-local buckling behavior for steel structures. A constitutive relationship was defined for material properties taking into account of post-local buckling degradation in strength and stiffness. The model is compared with quasi-static test databases related to H-shaped steel, circular and rectangular hollow steel section (HSS) members. Three parameters, including strength, associated deflection and post-peak degradation were reasonably simulated. Significant strength degradation was triggered by the local buckling in the thin-walled HSS beam–columns. The numerical model well presented the collapse of a steel moment frame tested by E-Defense shaking table. The results show that the thin-walled square HSS column components induced low-ductile collapse behavior due to the prior local buckling at the bottom storey. The proposed fiber-element model provides a simple alternative method for predicting deterioration and collapse of steel frames under extreme earthquakes.

Qingsong Li, Xiao Guo, Qiang Qing and Jinghai Gong (Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China), “Dynamic deflation assessment of an air inflated membrane structure”, Thin-Walled Structures, Vol. 94, pp 446-456, September 2015, DOI: 10.1016/j.tws.2015.05.008
ABSTRACT: As a critical safety performance index, the emergency evacuation capacity of air inflated membrane structures subjected to accidental deflation deserves in-depth study. Although conventional static
analysis can be applied to predict its potential collapsed shapes, it cannot provide details of collapse behavior and the internal air state variation. Dynamic analysis is recommended. The focus of this paper is to apply the Control Volume method to deflation simulation of a large-scale air inflated arch frame, which is designed for a temporary pavilion, and to validate numerical analysis results by full-scale testing. Through a series of preliminary studies on air inflated single arches, practical analytical parameters and solutions are concluded regarding proper numerical modeling, pre-stressing, and precision controlling. A full-scale frame is then modeled and simulated. Results appear to agree with experimental tests of the corresponding real-life structure with minor differences in collapse behavior and deflation duration time. Several general guidelines for design and deflation simulation analysis are proposed as a result of research. Feasible measures to ensure emergency evacuation capacity of the air inflated arch frame are adopted in the design based on results of this dynamic assessment.

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ABSTRACT: Buckling collapse of thin-walled structures under compression is one of the critical type of failures. These structures also may be locally buckled under tensile load with special conditions. In this paper, compressive and tensile buckling of thin cracked cylindrical panels are investigated. Effects of various factors such as the position, length and direction of crack, length, width and thickness of the panel and boundary conditions on the compressive and tensile buckling loads are determined. The results show that the dimensions of panels have lowest while characteristics of crack and closing to edges have greatest effects on the buckling load.

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“Buckling and post-buckling behaviour of elastic seven-layered cylindrical shells – FEM study”, Thin-Walled Structures, Vol. 94, pp 478-484, September 2015, DOI: 10.1016/j.tws.2015.05.017
ABSTRACT: The paper is devoted to buckling and post-buckling problems of an elastic seven-layered cylindrical shell under uniformly distributed pressure. The shell is an untypical sandwich structure composed of main corrugated core and two three-layer faces. Numerical FEM model for the shell has been elaborated. The calculations have been performed with the use of the ANSYS code for elastic shells of different dimensions. The linear and non-linear analyses of the shells have been performed with the use of the finite elements method. Critical pressure and equilibrium paths for the family of seven-layered shells subjected to uniformly distributed external pressure are calculated. The influence of corrugation pitch of main core and the length of the shell on the critical pressure has been determined. The results of these investigations are presented on the graphs.

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ABSTRACT: The thermal wrinkling behavior of thin membranes is investigated in this paper. Wrinkles often occur at multiple length scales where induced compressive stresses are located during thermal loading. In the present study, the method of double scale Fourier series is used to deduce the macroscopic membrane wrinkling equations. The obtained equations account for the global and local wrinkling modes. Numerical examples are conducted to assess the validity of the approach developed. The present membrane’s model needs only few degrees of freedom to recover more accurately the post-buckling equilibrium curves and the wrinkling shapes. Different parameters such as membrane’s aspect ratio, wave number, and pre-stressed membranes are discussed from a numerical point of view and the properties of the wrinkles (critical load, wavelength, size, and location) are presented.

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“Ship structural integrity using new stiffened plates”, Thin-Walled Structures, Vol. 94, pp 545-561, September 2015, DOI: 10.1016/j.tws.2015.05.018

ABSTRACT: The objective of the present paper is to use novel longitudinal Y (Hat+Conventional) stiffener profiles instead of the conventional stiffener profiles. That helps obtaining more safety margin (the ultimate strength minus the applied compression stress) to weight ratio. Using the hat section (closed section) gives more torsional rigidity and more effective plate allowing an increase of the stiffener spacing, hence a reduction in the number of stiffeners. During the replacement process the following constraints are taken into account: the weight of the stiffened bottom and deck panels, and the unstiffened plate width using the Y-stiffener profiles are less than those of panels with the original conventional stiffeners, whereas the section modulus of the Y-stiffener with the attached effective plate is larger than that of the original conventional stiffener. The safety margin of bottom and deck panels with Y-stiffeners is to be more than that of panels with the original conventional stiffeners. The ultimate strength of stiffened panels with either longitudinal conventional or Y-stiffener profiles were calculated according to the International Association of Classification Societies-Common Structural Rules for double hull oil tanker based on the following failure modes: unstiffened plate buckling, stiffener beam-column buckling, and stiffener torsional/flexural buckling (tripping). The attached effective plate for the Y-stiffener was calculated according to Eurocode. The Y-stiffener is a built-up section and the simplest production method is to weld the lower end of the web of a conventional stiffener to the top of the hat part. The conventional stiffener as a part of the Y-stiffener is fabricated according to the ratios stated in the International Association of Classification Societies-Common Structural Rules, while the hat part of the Y-stiffener is made by a hot-rolling process with inclination angle of the two webs of the hat taken as 30°, 45°, 60°, and 90°.

H. Ramezannezhad Azarboni, M. Darvizeh, A. Darvizeh and R. Ansari (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Nonlinear dynamic buckling of imperfect
rectangular plates with different boundary conditions subjected to various pulse functions using the Galerkin method”, Thin-Walled Structures, Vol. 94, pp 577-584, September 2015, DOI: 10.1016/j.tws.2015.04.002

ABSTRACT: In this paper, the nonlinear dynamic pulse buckling of imperfect rectangular plate subjected to sinusoidal, exponential, damping and rectangular pulse functions with six different boundary conditions is investigated. In order to solve the large deformation equations of plate, Galerkin method together with trigonometric mode shape functions is applied. Also, the nonlinear coupled time integration of the governing equation of plate is a solved employing fourth-order Runge–Kutta method. The effects of boundary conditions, pulse functions, initial imperfection, force pulse amplitude and geometrical parameters of the shock spectrum of a plate and deflection histories of plate for impulsive, dynamic and quasi-periodic force loads are studied. In this study, the effects of boundary conditions, pulse functions, initial imperfection, force pulse amplitude and geometric parameter in nonlinear dynamic response are investigated. According to the results for impulsive loading, the displacement response reaches its peak after shock duration and in the dynamic and quasi-static pulse loading, the maximum response of plate occurs during and before shock duration. Moreover, with increasing the loading amplitude, length of the plate and initial imperfection, the maximum displacement of plate increases. Different boundary conditions and various pulse functions have significant influence on the dynamic response of the plate. By increasing the restriction in supports, the resistance ability against deformation and stability of plate increases.

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“General distortional buckling formulae for both fixed-ended and pinned-ended C-section columns”, Thin-Walled Structures, Vol. 94, pp 603-611, September 2015, DOI: 10.1016/j.tws.2015.04.032

ABSTRACT: This paper presents general explicit analytical formulae to provide distortional critical stress estimates for cold-formed steel C-section columns subjected to uniform compression. These formulae are derived by employing the Lau and Hancock model and by introducing a new factor for considering the web rotational restraint reduced by web bending. The results obtained from the general explicit analytical formulae are compared with the numerical results obtained from the computer programs CUFSM or/and GBTUL. For pinned-ended columns, these values are also compared with those yielded by the formulae developed by Lau and Hancock, Schafer, and Silvestre and Camotim. In particular, the distortional critical stress of fixed-ended C-section columns is validated by comparing the corresponding ultimate load based on Schafer’s DSM expressions with numerical results from the research literature. The formulae derived here are validated and their application, accuracy and capabilities are illustrated by these comparisons and validations.

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“Behaviour and strength of hollow flange channel sections under torsion and bending”, Thin-Walled Structures, Vol. 94, pp 612-623, September 2015, DOI: 10.1016/j.tws.2015.05.013

ABSTRACT: Hollow flange channel section is a cold-formed high-strength and thin-walled steel section with a unique shape including two rectangular hollow flanges and a slender web. Due to its mono-symmetric
characteristics, it will also be subjected to torsion when subjected to transverse loads in practical applications. Past research on steel beams subject to torsion has concentrated on open sections while very few steel design standards give suitable design rules for torsion design. Since the hollow flange channel section is different from conventional open sections, its torsional behaviour remains unknown to researchers. Therefore the elastic behaviour of hollow flange channel sections subject to uniform and non-uniform torsion, and combined torsion and bending was investigated using the solutions of appropriate differential equilibrium equations. The section torsion shear flow, warping normal stress distribution, and section constants including torsion constant and warping constant were obtained. The results were compared with those from finite element analyses that verified the accuracy of analytical solutions. Parametric studies were undertaken for simply supported beams subject to a uniformly distributed torque and a uniformly distributed transverse load applied away from the shear centre. This paper presents the details of this research into the elastic behaviour and strength of hollow flange channel sections subject to torsion and bending and the results.

Soren Randrup Henrichsan, Esben Lindgaard and Erik Lund (Department of Mechanical and Manufacturing Engineering, Aalborg University (AAU), Fibigerstræde 16, 9220 Aalborg East, Denmark), “Robust buckling optimization of laminated composite structures using discrete material optimization considering “worst” shape imperfections”, Thin-Walled Structures, Vol. 94, pp 624-635, September 2015, DOI: 10.1016/j.tws.2015.05.004

ABSTRACT: Robust buckling optimal design of laminated composite structures is conducted in this work. Optimal designs are obtained by considering geometric imperfections in the optimization procedure. Discrete Material Optimization is applied to obtain optimal laminate designs. The optimal geometric imperfection is represented by the “worst” shape imperfection. The two optimization problems are combined through the recurrence optimization. Hereby the imperfection sensitivity of the considered structures can be studied. The recurrence optimization is demonstrated through a U-profile and a cylindrical panel example. The imperfection sensitivity of the optimized structure decreases during the recurrence optimization for both examples, hence robust buckling optimal structures are designed.


ABSTRACT: A computational parametric finite element analysis was carried out, investigating closely spaced cellular beams with double concentric transverse stiffeners. An unstiffened perforated beam section was initially designed and validated against existing finite element analysis results found in the literature. Then, thirty-one models were studied, while altering the spacing between the web openings, the web thicknesses, and the stiffener thicknesses. The results showed that Vierendeel shearing failure occurred more frequently for very closely spaced sections. However, as the spacing increased, the contribution of the stiffener to strength of the section was decreased, and out-of-plane buckling failure occurred more often. A maximum distance for the spacing between the openings was suggested in order to optimally use the derived formulae. At last, a design model was proposed, where for very closely spaced openings the compressive stresses were given by the Vierendeel moment capacity, while for the maximum distance of the spacing between the openings studied, the compressive stresses were given by a strut analogy, as found in BS5950-1.

ABSTRACT: A deep doubly curved shell element is developed for free vibration analysis of general shells of revolution. The mid-surface of the shell may have an arbitrary shape as well as a variable thickness, and the shell can be closed circumferentially or not. For both the circumferential and meridian directions of the shell element, Lagrange polynomials are used to interpolate the displacement variables. Stringer stiffeners are modeled as discrete curved beams to investigate the free vibration of stiffened shells. The frequencies are compared with the published data, and new examples of axisymmetric shells with positive and negative Gaussian curvature are presented.

M. Capuzzi, A. Pirrera and P.M. Weaver (Advanced Composites Centre for Innovation and Science, Department of Aerospace Engineering, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK), “Structural design of a novel aeroelastically tailored wind turbine blade”, Thin-Walled Structures, Vol. 95, pp 7-15, October 2015, DOI: 10.1016/j.tws.2015.06.006

ABSTRACT: The structural design for a recently presented aeroelastically-tailored wind turbine blade is produced. Variable elastic twist has been shown to improve performance in response to load variation across different wind conditions. This load variation is exploited as a source of passive structural morphing. Therefore, the angle of attack varies along the blade and adjusts to different operating conditions, hence improving both energy harvesting and gust load alleviation capability, below and above rated wind speed, respectively. The twist variation is achieved by purposefully designing spatially varying bend–twist coupling into the structure via tow steering and using a curved blade planform. This process enables the blade sections to twist appropriately while bending flapwise. To prove the feasibility of the proposed adaptive behaviour, a complete blade structure is analysed by using refined finite element models, with structural stability and strength constraints imposed under realistic load cases. Nonlinear structural effects are analysed as well as modal dynamic features. In addition, the weight penalty due to aeroelastic tailoring is assessed using structural optimisation studies.

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“A new method to investigate the energy absorption characteristics of thin-walled metal circular tube using finite element analysis”, Thin-Walled Structures, Vol. 95, pp 24-30, October 2015 DOI: 10.1016/j.tws.2015.06.001

ABSTRACT: A numerical study is made to investigate the energy absorbing rule of thin-walled metal circular tube made of three different materials (steel, copper, aluminum) by using response surface methodology (RSM). At the same time, the application prospect of RSM in terms of the research on the energy absorption rule of energy absorption structure can be explored. The test result shows that, the compression process of thin-walled metal circular tube can be divided into three stages: elastic stage, yielding plateau stage, compact stage; To get the greatest value of average plateau force (APF), a tube with a shorter height and thicker wall should be adopted; To get the greatest length energy absorption (LEA), a tube with thicker wall should be adopted and the ratio of its height and diameter should be as big as possible; To get the greatest specific energy absorption
(SEA), a tube with a thicker wall should be adopted and the ratio between its height and diameter should be as big as possible. Thus, it can be seen that, RSM is an advanced experiment design method, and it can be widely used in the research on the energy absorption characteristics of thin-walled metal circular tube and has a promising application prospect in the development of new energy absorbing material and structure.

Yan-lin Guo, Bo-hao Zhang, Si-yuan Zhao, Chao Dou and Yong-Lin Pi (Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China), “Ultimate resistance design of shuttle-shaped steel tubular latticed columns”, ASCE Journal of Structural Engineering, Vol. 140, 04014076, October 2014
ABSTRACT: As a new type of nonprismatic built-up columns, the shuttle-shaped steel tubular latticed (SSTL) column is widely used in engineering structures. However, there are no methods available to test its ultimate resistance design and little research about its behavior. This article investigates the elastic buckling behavior of three-tube SSTL columns only with horizontal web members and subject to an axial load, and it is found that the SSTL column may buckle in a symmetric flexure-dominated mode or an antisymmetric shear-dominated mode, depending on distributions of sectional flexural stiffness and shear stiffness along the column length. The formulas for predicting elastic buckling loads are derived by accounting for the effects of sectional shear deformations. With the elastic buckling loads obtained, formulas for the effective slenderness and the normalized effective slenderness are proposed. The resistance design procedure for SSTL columns only with horizontal web members is developed in association with Chinese code GB50017 and Eurocode 3. Comparisons with finite element results demonstrate the proposed procedure can provide reasonably accurate predictions for the resistances of SSTL columns.

Jing-Zhong Tong and Yan-Lin Guo (Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China), “Elastic buckling behavior of steel trapezoidal corrugated shear walls with vertical stiffeners”, Thin-Walled Structures, Vol. 95, pp 31-39, October 2015, DOI: 10.1016/j.tws.2015.06.005
ABSTRACT: This paper investigates the elastic buckling behavior of steel trapezoidal corrugated shear walls (STCSWs) with vertical stiffeners. On the basis of an orthotropic plate model, by utilizing the theorem of minimum potential energy and the Ritz method, the buckling loads of stiffened STCSWs can be precisely calculated using MATLAB. Then, a value of transition rigidity of stiffener is suggested and, hence formulas of elastic buckling coefficients of stiffened STCSWs are proposed. Finally, the verification of proposed formulas using a FE model shows that the formulas are validated and applicable in estimating the elastic buckling loads of stiffened STCSWs.

Yangqing Dou and Yucheng Liu (Department of Mechanical Engineering, Mississippi State University, Mississippi State, MS 39762, USA), “Computational investigation of lateral impact behavior of pressurized pipelines and influence of internal pressure”, Thin-Walled Structures, Vol. 95, pp 40-47, October 2015
DOI: 10.1016/j.tws.2015.06.012
ABSTRACT: This paper presents a computational study to examine lateral impact behavior of pressurized pipelines and to determine influence of internal pressure on the pipelines on their impact behaviors. A total of more than 300 numerical simulations were carried out on mild steel pipe models with different internal pressure levels and were struck at the mid-span and at the one quarter span positions. These numerical simulations of the impact tests were performed using 3D dynamic nonlinear finite element analysis (FEA) through LS-DYNA,
where both geometrical and material nonlinearities were considered. The computational results for the first time systematically revealed the effects of internal pressure, impact position, and outside diameter on the lateral impact behavior of the pipeline models. The outcomes of this study will have potential benefits on research of safety and reliability of civil pipelines and development of advanced pipeline materials.

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“Axial crushing analysis of empty and foam-filled brass bitubular cylinder tubes”, Thin-Walled Structures, Vol. 95, pp 60-72, October 2015, DOI: 10.1016/j.tws.2015.05.019
ABSTRACT: To reduce loss from collision, energy absorbers are used which dissipate energy upon deformation and folding in order to prevent damage to critical parts of a structure. In this study, the empty and polyurethane foam-filled bitubular tubes made from brass with circular section were subjected to quasi-static axial compression loading. Nonlinear dynamic finite element analyses are carried out to investigate the details concerning crushing process by using explicit finite element code ABAQUS. Satisfactory agreements are achieved between the finite element and the experimental results. The validated finite element model was then used for the parametric studies, in order to determine the effect of the empty and filler tube geometry parameters (i.e. wall thickness, semi-apical angle) and loading parameters (i.e. impact mass, impact velocity) on the Dynamic Amplification Factor. The results highlight the advantages of using the brass bitubular circular tubes as energy absorber.

Weiqiang Wang, M. Neaz Sheikh and Muhammad N.S. Hadi (School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW 2522, Australia), “Behaviour of perforated GFRP tubes under axial compression”, Thin-Walled Structures, Vol. 95, pp 88-100, October 2015,
DOI: 10.1016/j.tws.2015.06.019
ABSTRACT: This study investigates the influences of various parameters on the behaviour of perforated Glass Fibre Reinforced Polymer (GFRP) tubes under axial compression. A total of 15 GFRP tubes with and without perforations were tested under axial compression. All the GFRP tubes were divided into two groups: 12 tubes with 89 mm outer diameter and 6 mm wall thickness and 3 tubes with 183 mm outer diameter and 8 mm wall thickness. The influences of hole diameter, vertical hole spacing, tube diameter, perforation pattern, transverse hole spacing, and hole reinforcement on the axial compressive behaviour of perforated GFRP tubes were experimentally investigated. Considerable decreases in the axial stiffness, axial critical load, and axial deformation capacity of perforated GFRP tubes have been observed. The hole diameter, tube diameter, perforation pattern, and transverse hole spacing significantly influence the axial compressive behaviour of perforated GFRP tubes. However, the influences of vertical hole spacing and hole reinforcement have been observed not significant. Design-oriented equations for the prediction of the axial stiffness, axial critical load and axial deformation capacity of perforated GFRP tubes under axial compression have been proposed. The proposed equations have been found to be in good agreement with experimental results and can be used for the reliable design of perforated GFRP tubes.

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ABSTRACT: Multi-cell tubes have been drawn increasing attention for their excellent energy-absorbing ability. However, the effect of cell number and oblique loads on crashing behaviors has seldom been studied to date. In this paper, a group of multi-cell tubes with different cell numbers were comprehensively investigated under both axial and oblique loads. The finite element models were first established and then validated by experimental tests. The simulation results showed that the increase in cell number can be beneficial to the energy absorption (EA) but detrimental due to increase in peak force (F_{max}) under axial load. When the oblique loads were taken into account, the tubes could undergo global bending, which is an inefficient deformation mode. By applying complex proportional assessment (COPRAS) method, the 7x7 tube was selected as the best based on multi-criteria under multiple loading angles. Then the Kriging modeling technique and multiobjective particle optimization (MOPSO) algorithm were integrated to address the optimization problems, where EA and F_{max} were taken as objectives and tube sizes as design variables. The results demonstrated that different loading angles have different requirements on cell allocation and optimizations of multiple load cases (MLC) can yield better solutions in a weighted average fashion, whereas the optimization for separate single load cases (SLC) could result in inferior performance under other load cases.

Xi Zhang, Kim J.R. Rasmussen and Hao Zhang (School of Civil Engineering, The University of Sydney, Australia), Beam-element-based analysis of locally and/or distortional buckled members: Application”, Thin-Walled Structures, Vol. 95, pp 127-137, October 2015, DOI: 10.1016/j.tws.2015.06.021

ABSTRACT: The companion paper [1] presents a theory to account for the effects of local and/or distortional buckling in a seven degrees of freedom beam finite element analysis. The theory considers the effect of local and/or distortional buckling as a reduction in tangent rigidities, and determines the reduced tangent rigidities by an a priori post-local or post-distortional buckling analysis of a short length of section. In this paper, the presented method is incorporated into the open source software package OpenSees which was previously modified to account for warping effects [2]. The accuracy of the method is validated by comparison with shell element results for beams, columns and frames.

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“Study on distortional buckling performance of cold-formed thin-walled steel flexural members with stiffeners in the flange”, Thin-Walled Structures, Vol. 95, pp 161-169, October 2015, DOI: 10.1016/j.tws.2015.07.006

ABSTRACT: This paper presents a finite strip program CUFSM used to calculate and analyze the elastic distortional buckling of cold-formed thin-walled steel flexural members with stiffeners in the flange, which has different sectional geometric parameters. According to the classical buckling stress formula, the distortional buckling coefficient of the flange can be calculated so as to analyze the influence of changed sectional geometric parameters on it. On this basis, this study provides a simplified formula of distortional buckling stress to calculate 40 members with different sections which are selected from the Technical Code of Cold-Formed
Thin-Wall Steel Structures of China but not contained in this paper. Compared with the analysis results of CUFSM, it shows that the two simplified formulas have quite high accuracy and wide applicability for general members provided by the specification. So it is suggested that they can be used for engineering design and standard revision.

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“On nonlinear thermal buckling analysis of cylindrical shells”, Thin-Walled Structures, Vol. 95, pp 170-182, October 2015, DOI: 10.1016/j.tws.2015.06.013
ABSTRACT: In this article, the nonlinear buckling behavior of imperfect cylinders made of isotropic, composite and functionally graded materials is studied. A continuum-based semi-analytical finite element formulation is introduced to study the nonlinear behavior of cylinders under thermal loads. A method is proposed to implement the initial geometric imperfection of the cylinder by transformation of structure due to deformation gradients. The influences of geometrical parameters, different materials and imperfection factors are investigated on pre- and post-buckling paths. A comparison is made between the classical von Kármán-based and continuum-based approaches to ensure the validation of the results and to study the applicability of the von-Kármán approximation.

Nicola Tondini and Andrea Morbioli (Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano 77, Trento 38123, Italy), “Cross-sectional flexural capacity of cold-formed laterally-restrained steel rectangular hollow flange beams”, Thin-Walled Structures, Vol. 95, pp 196-207, October 2015, DOI: 10.1016/j.tws.2015.06.018
ABSTRACT: This paper presents the results of a comprehensive experimental-numerical study aimed at determining the flexural performance of cold-formed laterally-restrained steel rectangular hollow flange beams (RHFBs). Two RHFBs of different dimensions were considered as representative of typical secondary beams in small steel-framed houses. Results of the experimental study that consisted of (i) material characterisation and (ii) tests on full-scale specimens are thoroughly presented. Moreover, a numerical work was performed in order to develop a model able to reproduce the experimental outcomes and used to expand the available findings over a wider slenderness range through parametric studies.

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“Design of progressively folding thin-walled tubular components using compliant mechanism synthesis”, Thin-Walled Structures, Vol. 95, pp 208-220, October 2015, DOI: 10.1016/j.tws.2015.06.010
ABSTRACT: This work introduces a design method for the progressive collapse of thin-walled tubular components under axial and oblique impacts. The proposed design method follows the principles of topometry optimization for compliant mechanism design in which the output port location and direction determine the folding (collapse) mode. In this work, the output ports are located near the impact end with a direction that is
perpendicular to the component's longitudinal axis. The topometry optimization is achieved with the use of hybrid cellular automata for thin-wall structures. The result is a complex enforced buckle zone design that acts as a triggering mechanism to (a) initiate a specific collapse mode from the impact end, (b) stabilize the collapse process, and (c) reduce the peak force. The enforced buckle zone in the end portion of the tube also helps to avoid or delay the onset of global bending during an oblique impact with load angles higher than a critical value, which otherwise adversely affects the structure's capacity for load-carrying and energy absorption. The proposed design method has the potential to dramatically improve thin-walled component crashworthiness.

M.F. Hassanein (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Fundamental behaviour of concrete-filled pentagonal flange plate girders under shear”, Thin-Walled Structures, Vol. 95, pp 221-230, October 2015, DOI: 10.1016/j.tws.2015.07.003
ABSTRACT: Hollow tubular flange plate girders are found to possess higher flexural and shear strengths over those of I-section plate girders with flat flanges. Recently, concrete-filled pentagonal flange girders (CFPFGs) have been suggested in literature to increase the out-of-plane flexural strength of the girders. The geometrical configuration of the section is assumed identical to that of the girder with the rectangular concrete-filled flanges, but the flange depth-to-width ratio is designed to be larger in order to reduce the local buckling of the web. In this paper, the fundamental shear behaviour of these CFPFGs with slender stiffened webs is investigated. Nonlinear three-dimensional finite element (FE) analyses using ABAQUS are employed to conduct parametric studies, having first validated the models against available experimental data. For comparison purposes and to examine the effect of the infill concrete, steel pentagonal flange girders (SPTGs) are also generated. It is found that CFPFGs and SPFGs with the same dimensions have similar buckling shapes but with different loads with the buckling load of the CFPFG being higher than that of the corresponding SPFG. In the post-buckling stage, the width of the inclined tension field becomes greater in the CFPFGs relative to that of the SPFGs. This highlights the influence of the infill concrete which increases the stiffness of the upper flanges, and hence allows the webs to carry additional shear loads compared to SPFGs. Several affecting parameters are, additionally, examined and important conclusions are remarked. The FE strengths are compared with the design strength of the webs following the EN 1993-1-5, indicating that it can conservatively be used with the SFPFGs. On the other hand, it becomes highly conservative for the CFPFGs.

DOI: 10.1016/j.tws.2015.07.012
ABSTRACT: Optimization of a simply supported cylindrical shell stiffened by inner rings is considered in this paper. The shell is loaded by external pressure. The first critical buckling load is maximized. A material volume and a slope of a post-critical path are assumed as optimization constraints. The inner rings are made from the material obtained from the shell by decreasing its thickness. This way the volume of the material remain constant. The structure is modelled and solved by the finite element method (FEM). The linear and nonlinear stability analyses are done in the ANSYS software. An effect of geometric imperfections on a shape of equilibrium path is discussed. The optimization was performed numerically using the modified particle swarm optimization method (MPSO). The results are compared with a reference cylindrical shell with no rings. The single ring placed in the middle of the shell is good enough for stabilization of a post-buckling path for a shorter shell, regardless of its thickness. It is necessary to use three rings optimally distributed along the shell length, for a longer shell. The additional optimization profit was obtained by varying internal diameters of the rings.
The proposed concept of shell stiffening by inner rings eliminates a major disadvantage of smooth cylindrical shells, namely an unstable post-buckling path.

Genshu Tong, Yixiao Feng and Lei Zhang (Department of Civil Engineering, Zhejiang University, Hangzhou 310058, PR China), “A unified analysis for distortional and lateral buckling of C-purlins in flexure”, Thin-Walled Structures, Vol. 95, pp 244-254, October 2015, DOI: 10.1016/j.tws.2015.07.001

ABSTRACT: This paper developed a unified model for the distortional and lateral buckling of cold-formed C-purlins subjected to bending in the plane of symmetry. It can study not only the distortional buckling, but also the global lateral buckling. Different from Hancock's model, the new model includes two interactive springs between lateral and rotational restraints provided by the web to the flange-lip section. A closed-form solution is acquired by the Ritz method. And the elastic buckling coefficients of 20 purlin sections predicted by the solution are compared with those from Finite Element Method (FEM), showing excellent agreement between them. Comparison is also provided with Hancock's method. The closed form solutions are also substituted into the Direct Strength Method to obtain nominal flexure strength of the purlins, and it is found that the proposed model predicted almost the same strength as the software Schafer's CUFSM with differences less than 1%. A good correlation is observed between test results and the proposed method.

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“The energy absorption of bamboo under dynamic axial loading”, Thin-Walled Structures, Vol. 95, pp 255-261, October 2015, DOI: 10.1016/j.tws.2015.06.017

ABSTRACT: The energy absorption characteristics and material parameters of the bamboo species Phyllostachys pubescens are studied by drop-weight and dynamic tensile tests. The dynamic tensile test shows that 1-year-old bamboo has the greatest tensile strength (251 MPa), which is 1.85 times that of a 2A12 aluminium alloy. The drop-weight test shows that the energy absorption of nodal samples is greater than that of the internode samples, and the specific energy absorption (SEA) values of the nodal and internode samples are 11.85 kJ/kg and 9.78 kJ/kg, respectively. The SEA of nodal samples is close to that of aluminium alloy and steel tube, and the SEA of the internode samples is close to that of copper tube. The energy absorption increases with increasing moisture content and decreases with growth age. Analyses show that the bamboo nodes and the vascular bundle are the main factors affecting bamboo energy absorption. The results indicate that bamboo is a tubular structure with excellent mechanical and energy absorption properties.

Edward Steau, Mahen Mahendran and Poologanathan Keerthan (Science and Engineering Faculty Queensland University of Technology, Brisbane, Australia), “Web crippling tests of rivet fastened rectangular hollow flange channel beams under two flange load cases”, Thin-Walled Structures, Vol. 95, pp 262-275, October 2015 DOI: 10.1016/j.tws.2015.06.008

ABSTRACT: Recent research on hollow flange beams has led to the development of an innovative rectangular hollow flange channel beam (RHFCB) for use in floor systems. The new RHFCB is a mono-symmetric structural section made by intermittently rivet fastening two torsionally rigid closed rectangular hollow flanges to a web plate element, which allows section optimisation by selecting appropriate combinations of web and
flange widths and thicknesses. However, the current design rules for cold-formed steel sections are not directly applicable to rivet fastened RHFCBs. To date, no investigation has been conducted on their web crippling behaviour and strengths. Hence an experimental study was conducted to investigate the web crippling behaviour and capacities of rivet fastened RHFCBs under End Two Flange (ETF) and Interior Two Flange (ITF) load cases. It showed that RHFCBs failed by web crippling, flange crushing and their combinations. Comparison of ultimate web crippling capacities with the predictions from the design equations in AS/NZS 4600 and AISI S100 showed that the current design equations are unconservative for rivet fastened RHFCB sections under ETF and ITF load cases. Hence new equations were proposed to determine the web crippling capacities of rivet fastened RHFCBs. These equations can also be used to predict the capacities of RHFCBs subject to combined web crippling and flange crushing conservatively. However, new capacity equations were proposed in the case of flange crushing failures that occurred in thinner flanges with smaller bearing lengths.


ABSTRACT: The axial crushing of circular structures with rectangular insert was investigated. Literature available experimental data were used to validate the numerical models of the structures investigated. Results are compared in order to set up the simulation layout. To increase the efficiency of the simulation process a software module was developed and some explanations related to the generation of the numerical model are provided. Based on the theoretical models of the symmetric crushing of circular tubes and the model developed to investigate multi-cell square thin-walled structures a formula for the evaluation of the mean crushing force for the proposed structure was derived. Results obtained from the experiments and different numerical simulations of structures with different number of cells, different thicknesses and main dimensions were evaluated and compared with theoretical results. The theoretical model predicted the mean crushing force with and error of 20% in case of structures with a reduced number of cells (four cells) or with a very thin insert while for structures with a higher number of cells or thicker insert (comparable with the thickness of the tube) the predicted value is within 5% range. Some plots based on the theoretical model are presented and can provide the start point for an optimisation process.

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ABSTRACT: Many shell structures used in modern technology consist of regular shell parts joined together along their common boundaries. We review different theoretical, numerical, and experimental approaches to modelling, analyses and design of the compound shell structures with junctions. Several alternative forms of boundary, continuity and jump conditions at the singular midsurface curves modelling the shell junction are reviewed. We also analyse the results obtained for special shell structures containing the cylinder–cylinder intersections, cone–, sphere–, and plate–cylinder junctions, tubular joints as well as other special types of junctions appearing in complex multi-shell structures.

ABSTRACT: The paper deals with stability of steel cylindrical silos composed of corrugated walls and vertical open-sectional stringers. Comprehensive three-dimensional finite element analyses were carried out with perfect slender, semi-slender and squat silos by means of a linear buckling approach. Corrugated walls were simulated as an equivalent orthotropic shell and vertical open-sectional stringers as beam elements. The FE results were compared with the Eurocode approach. In addition, comprehensive FE computations for axially compressed cylindrical shells composed of an orthotropic shell and stringers were carried out. An improvement of standard formulae was proposed.

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ABSTRACT: The literature lacks exhaustive study on CFDST hybrid columns circumscribed by FRP layers. Extended FEM analysis was carried out on 70 real-scale models with varying parameters including the material and number of FRP layers, concrete strength, length-to-diameter ratio (specific length), and hollow section ratio. Carbon fibers proved stronger than glass fibers, leading to higher ultimate stress associated with lower strain. Specimens with high specific lengths suffered from steel premature buckling, thus stiffened with steel plates. Specimens with various hollow section ratios were finally compared, showing an increase range of 70% between the maximum (0.75) and minimum (0.25) ratios.

A.R. Vosoughi and M.R. Nikoo (Department of Civil and Environmental Engineering, School of Engineering Shiraz University, Shiraz, Iran), “Maximum fundamental frequency and thermal buckling temperature of laminated composite plates by a new hybrid multi-objective optimization technique”, Thin-Walled Structures, Vol. 95, pp 408-415, October 2015, DOI: 10.1016/j.tws.2015.07.014

ABSTRACT: In this paper, a hybrid method for simultaneously maximizing fundamental natural frequency and thermal buckling temperature of laminated composite plates is developed. This method is a new combination of the differential quadrature method (DQM), non-dominated sorting genetic algorithm II (NSGA-II) and Young bargaining model. The governing equations are obtained within the framework of the first-order shear deformation theory (FSDT) of plates and are discretized using the DQM. Then, the DQM is linked with the NSGA-II optimization model and the trade-off between the objectives with respect to fibers orientations is obtained. Finally, by applying Young bargaining model the best fibers orientations which maximize the objectives of laminated composite plates with different boundary conditions, thickness-to-length and aspect ratios are obtained.

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ABSTRACT: The blast performance of water tank with an innovative energy absorbing support was studied to reduce the support reaction force and mitigate the damage on the water tank. The aluminum foam was adopted as the energy absorbing material, since it has high energy absorbing potential during crush plateau and safety backup zone after the compaction strain. Finite element model considering fluid and structural interaction in which the water is modeled using the Eulerian formulation and the steel tank by Lagrangian formulation is proposed. The proposed numerical model of water tank was verified by comparing the predicted results with the test results obtained from dynamic pressure tests on steel tanks filled with water. The numerical results showed that the support reaction force depends on the density and yield strength of the aluminum foams and the reaction force could be reduced significantly if softer aluminum foam was chosen. The total displacement of the water tank was increased by up to 38% due to the increase in deformation of the energy absorbing foam. The aluminum foam was proposed to absorb the blast energy and reduce the damage on the water tank. However, more damage on the water tank was observed when a very low density aluminum foam support was used. This was attributed to the increased external work done by blast loading which was higher than the energy absorbed by the aluminum foam support.

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ABSTRACT: The optimal design of cold-formed steel columns is addressed in this paper, with two objectives: maximize the local-global buckling strength and maximize the distortional buckling strength. The design variables of the problem are the angles of orientation of cross-section wall elements—the thickness and width of the steel sheet that forms the cross-section are fixed. The elastic local, distortional and global buckling loads are determined using Finite Strip Method (CUFFSM) and the strength of cold-formed steel columns (with given length) is calculated using the Direct Strength Method (DSM). The bi-objective optimization problem is solved using the Direct MultiSearch (DMS) method, which does not use any derivatives of the objective functions. Trade-off Pareto optimal fronts are obtained separately for symmetric and anti-symmetric cross-section shapes. The results are analyzed and further discussed, and some interesting conclusions about the individual strengths (local-global and distortional) are found.

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ABSTRACT: This paper is based on an investigation into the performance of cold-formed C-channels stiffened with cover plates and subjected to pure bending and primarily shear condition tests. Cover plates with three different thicknesses (1.6, 2 and 2.4 mm) were installed at top flanges only as it would be the predicted location for local and distortional buckling. The local and distortional buckling capacities were evaluated via Direct Strength Method, DSM, in accordance with AISI 2007. The accuracy of the interaction equation between the required flexural strength, $M$, and the required shear strength, $V$, prescribed by AISI 2007 was also investigated in this paper. A nonlinear finite element model was developed and verified against the test results in terms of maximum strength and buckling failure modes. The results explicitly showed that by attaching the cover plate on top flanges, the non-dimensional slenderness decreased resulted in improved buckling capacities, where the nominal flexural moment of sections, $M_n$, were close to the plastic moment, $M_p$. Besides, it was concluded that the interaction equation between $M$ and $V$ predicted by AISI was conservative for sections with small non-dimensional slenderness values.


ABSTRACT: The toroidal shell with stiffened ribs is a new-style structure in ocean engineering especially in underwater engineering. This paper attempts to provide a simple theoretical method to obtain the stress solution of toroidal shell with ribs for its strength assessment. Firstly according to the structural property of toroidal shell with ribs and theory of curve-beam, a simple model for toroidal shell with ribs has been developed; then coupled with theory of thin-shell and elastic beam, its stress and deformation have been solved and can be expressed into analytic formulas; lastly by finite element method (FEM) and model experiment method, this simple theoretical solution has been verified to be reasonable and quite accurate. Thus this simple theoretical solution could be applied for analysis and design of pressure equipment in such toroidal structure type.

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ABSTRACT: Thermoplastic polymers such as HDPE are nowadays widely used as lining materials for oil and gas pipelines. However, during maintenance or unexpected service stoppages, these liners can undergo external pressure induced buckling collapse. The objective of this work is to assess the mechanical response of HDPE liners undergoing buckling collapse by means of Finite element modeling (FEM) simulations on Abaqus 6.10. To accomplish this, an advanced constitutive model, namely the Three Network Model (TNM) was employed. In order to determine the input parameters for the model, a series of tensile and compressive uniaxial tests were conducted. The suitability of the model for this particular application was assessed by contrasting the simulation and the experimental results of a diametral compression test. The complex strain rate and pressure dependent mechanical response of HDPE liners was analyzed by modeling the buckling collapse dynamic event as an increasing volume of fluid entering the gap cavity between liner and host pipe. The model predictions allowed
establishing a mathematical relationship between the depressurization velocity of the tubes and the resulting collapse pressure. These relations can be used to improve the current design guidelines for plastic liners.

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“Strength and stiffness requirements for intermediate ring stiffeners on discretely supported cylindrical shells, Thin-Walled Structures, Vol. 96, pp 64-74, November 2015, DOI: 10.1016/j.tws.2015.08.004
ABSTRACT: Silos in the form of a cylindrical metal shell are often supported on a ring beam which rests on discrete column supports. This support condition produces a circumferential non-uniformity in the axial membrane stresses in the silo shell. One way of reducing the non-uniformity of these stresses is to use a very stiff ring beam which partially or fully redistributes the stresses from the local support into uniform stresses in the shell. A better alternative is to use a combination of a flexible ring beam and an intermediate ring stiffener. Recent research by the authors has identified the ideal location of the intermediate ring stiffener to provide circumferentially uniform axial membrane stresses above the stiffener. To be fully effective, this intermediate ring should locally prevent both radial and circumferential displacements in the shell. This paper explores the strength and stiffness requirements for this intermediate ring stiffener. Pursuant to this goal, the cylindrical shell below the intermediate ring stiffener is analysed using the membrane theory of shells and the reactions produced by the stiffener on the shell are identified. These reactions are then applied to the intermediate ring stiffener. Vlasov’s curved beam theory is used to derive closed form expressions for the variation of the stress resultants around the circumference to obtain a strength design criterion for the stiffener. A stiffness criterion is then developed by considering the ratio of the circumferential stiffness of the cylindrical shell to that of the intermediate ring stiffener. The circumferential displacements of the ring and the shell are found for the loading condition previously obtained to determine the required strength. A simple algebraic expression is developed for this intermediate ring stiffness criterion. These analytical studies are then compared with complementary finite element analyses that are used to identify a suitable value for the intermediate ring stiffness ratio for practical design.

Cenk Kilicasian (Department of Mechanical Engineering, Faculty of Engineering, Adnan Menderes University, Aydın, Turkey), “Numerical crushing analysis of aluminum foam-filled corrugated single- and double-circular tubes subjected to axial impact loading”, Thin-Walled Structures, Vol. 96, pp 82-94, November 2015
DOI: 10.1016/j.tws.2015.08.009
ABSTRACT: In this paper, aluminum foam-filling method was applied to corrugated tubes numerically, offering a novel structure that may have excellent energy absorption capacity. The study aims to provide a comparative study on the crushing responses of aluminum foam-filled corrugated single- and double-tubes with different corrugation lengths. The effects of geometric parameters like radius and wall thickness of inner tube in double-tubes on the energy absorption were also discussed. Dynamic crushing simulations were performed on finite element software LS-DYNA at impact velocity of 16.7 m/s (corresponding to 60 km/h). The comparisons revealed that tubes with corrugations experienced progressive and concertina type of deformation and tubes with smaller corrugation length showed smooth force–displacement curve with low initial peak force. SEA of foam-filled corrugated double-tubes was found to be superior to foam-filled straight tubes.

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ABSTRACT: This study concentrates on a comparison between steel plate and stiffened panels subject to localised corrosion. A finite element analysis is used to investigate the effect of random corrosion on the compressive strength capacity of marine structural units. Variables include the extent of corrosion; slenderness ratio and aspect ratio. A corrosion prediction model is incorporated to determine the thickness reduction with time. Corrosion-induced volume loss results in a greater reduction of ultimate strength for slender plates compared to stiffened panels, up to 45%, showing the structural element selection can strongly influence the accuracy of the estimated corrosion damage effect.


ABSTRACT: This paper investigates the effect of cross-section thickness, flat length and curvature of end parts, on the load capacity of fixed ended LDSS (Lean Duplex Stainless Steel) flat oval stub columns, using the commercial finite element software, Abaqus. Based on the FE analyses, it has been found that sections with semicircular elements provided the maximum load capacity, and for flatters, the rate of decrement in load capacity is seen to be small. The effect of flat length on the load capacity, for thinner sections, is found to be relatively insignificant, however for thicker sections, an increase in load capacity is observed, with the slope of increment getting relatively higher as the thickness increases. Strength gain per unit increase in area by 1) increasing thickness, increases with increasing curvature radius and decreases with increasing flat length; 2) increasing flat length, increases with increasing thickness; while the decrease in strength per unit decrease in area by increasing curvature radius decreases with increasing thickness. The FE results have been compared with ASCE 8-02, AS/NZS 4673, EN 1993-1-4, DSM, CSM predictions, and it has been found that ASDM, DSM and CSM are applicable for the design of flat oval LDSS columns.

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“Counter-intuitive collapse of single-layer reticulated domes subject to interior blast loading”, Thin-Walled Structures, Vol. 96, pp 130-138, November 2015, DOI: 10.1016/j.tws.2015.08.001

ABSTRACT: A commercial finite element package, LS-DYNA, was employed to simulate the response of a single-layer reticulated dome to an interior blast. The dome, which was initially stressed by static preloading, encountered an interesting phenomenon namely counter-intuitive collapse, which was found during the blast analysis. The Johnson–Cook constitutive model for mild steel was used to identify different failure modes of the dome for more than 2430 samples. A seemingly counter-intuitive collapse was identified due to dynamic instability. This unusual collapse was explained using total potential curves, and the critical blast load was defined. The effect of different static preloads, which is the other determination factor of counter-intuitive collapse, was investigated. A relationship between collapse and static/dynamic loads was also obtained. The
results indicate that single-layer reticulated domes, with large initial stresses, may collapse at lower dynamic loads than expected.

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ABSTRACT: This paper presents an analytical approach to investigate the nonlinear stability analysis of eccentrically stiffened thin FGM cylindrical panels on elastic foundations subjected to mechanical loads, thermal loads and the combination of these loads. The material properties are assumed to be temperature-dependent and graded in the thickness direction according to a simple power law distribution. Governing equations are derived basing on the classical shell theory incorporating von Karman–Donnell type nonlinearity, initial geometrical imperfection, the Lekhnitsky smeared stiffeners technique and Pasternak type elastic foundations. Explicit relations of load–deflection curves for FGM cylindrical panels are determined by applying stress function and Galerkin method. The effects of material and geometrical properties, imperfection, elastic foundations and stiffeners on the buckling and postbuckling of the FGM panels are discussed in detail. The obtained results are validated by comparing with those in the literature.

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ABSTRACT: Two major requirements for crush analysis of thin-walled cylindrical tubes are being lightweight and having good crashworthiness. Thin-walled cylindrical tubes, which are either empty or foam filled, can potentially be used in all vehicles and moving parts such as road vehicles, trains, aircrafts, ships, lifts and machinery to protect passengers and the structure itself during impact. This paper discusses an idea of utilizing the initiator on the foam-filled thin-walled circular tubes with stiffened annular rings to increase the specific energy absorption (SEA) and prevent the sudden force applied to the main part of the automotive and its occupants. Effect of initiator, at the top of the foam-filled aluminum tube, different densities of rigid polyurethane foam, and number of annular rings under axial compression were described through energy absorption, crush force efficiency (CFE), and mass of structure. In order to verify the numerical results, a series of quasi-static axial compression tests was performed, and both load–displacement curves and deformation mechanism of the structure were analyzed. The results of multi-criteria decision analysis (MCDA), by incorporating numerical and experimental data, showed that in the considered material and geometry, the design with an initiator, four rings tube, and higher density of foam have superior performance in terms of energy absorption, CFE, and mass. More debate on effect of initiator would help to reach the simultaneous improved crashworthiness structure and lightweight design with greater degree of accuracy in the hope of reducing the occupant injury in a collision.
DOI: 10.1016/j.tws.2015.08.010
ABSTRACT: This paper presents a rational procedure for implementing geometric imperfections into inelastic large displacement (“advanced”) analysis. The procedure uses a statistical approach that considers the reliability of the structural strength of a selection of well-documented tests of thin-walled members and frames. The aim of the study is to derive a statistical procedure for implementing imperfections in shell-element based advanced analyses and to determine an appropriate interval of half-wavelengths and number of eigenmodes to incorporate when modeling geometric imperfections. To achieve this, a analysis of strength as a function of imperfection spectra for 20 storage rack uprights and 56 frame members was conducted using finite element analysis (FEA). All FEA models were calibrated against completed experimental results. Based on the results, practical recommendations for modelling cross-sectional and member imperfections in advanced analysis for individual uprights and storage rack frames are provided.

ABSTRACT: Steel girders with corrugated webs are increasingly used in the field of bridges, especially in case of composite bridges. During launching of a bridge structure the girder can be subjected by the combination of bending moment (M), shear (V) and transverse forces (F) which result in a complex stress field in the girder and in an interacting stability problem. Previous research activities related to the corrugated web girders showed that the structural behavior of the girders with corrugated webs differ from the conventional I-girders, especially in the stress distribution of the flanges and the web. On the other hand the stability behavior of the corrugated web girders are also different from the flat web girders due to the corrugation profile therefore the interaction equations developed for conventional I-girders cannot be used for corrugated web girders. There is a lack of investigations analyzing the effect of the complex loading situation for corrugated web girders, therefore the current paper focuses on the investigation of the structural behavior under all of the aforementioned actions and their combinations. Based on the previous and current investigations design interaction equation is developed for the combined M–V–F loading situation.

Kun Xie, Meixia Chen, Naiqi Deng and Wenchao Jai (School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China), “Free and forced vibration of submerged ring-stiffened conical shells with arbitrary boundary conditions”, Thin-Walled Structures, Vol. 96, pp 240-255, November 2015, DOI: 10.1016/j.tws.2015.08.013
ABSTRACT: An analytic approach is presented to analyze free and forced vibration of submerged ring-stiffened conical shell with arbitrary boundary conditions at low frequencies. According to the junctions of shell-stiffener, the shell is firstly divided into multiple substructures, e.g. conical segments and stiffeners. To take into account fluid loading, conical segments are divided into more narrow strips and those strips are approximately considered as local cylindrical shells. Then, Flügge theory is used to describe the motion of conical strips and displacement functions are expressed as power series. Instead of utilizing smeared out method, ring stiffeners are treated as discrete members and the equations of motion of annular plate, rather than curve beam, are adopted to describe the motion of stiffeners with rectangular cross-section. Lastly, boundary
conditions and continuity conditions of adjacent substructures are used to assemble the final governing equation. Comparisons of free and forced vibration results of present method and those in literature and/or calculated by finite element method show the validity of present method. The effects of boundary conditions, ring stiffeners and fluid loading on free vibration are studied. The effects of external point force and fluid loading on forced vibration are also discussed.

Nan Hu and Rigoberto Burgueño (Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA), “Elastic postbuckling response of axially-loaded cylindrical shells with seeded geometric imperfection design”, Thin-Walled Structures, Vol. 96, pp 256-268, November 2015, DOI: 10.1016/j.tws.2015.08.014

ABSTRACT: Elastic instabilities (such as buckling) have been recognized as a promising phenomenon to design smart materials and mechanical systems. Thin-walled cylindrical shells under axial compression can attain multiple bifurcation points in their postbuckling regime due to the natural transverse deformation restraint provided by their geometry; but harnessing such behavior for smart purposes is lacking extensive study due to its notoriously high imperfection sensitivity. In this paper, the concept of seeded geometric imperfection (SGI) design is proposed to modify and control the elastic postbuckling behavior of cylindrical shells. Eigenvalue-based mode shapes were used as basic geometric forms to generate a seeded imperfection. Prototyped SGI cylindrical shells were fabricated through 3D printing and tested under loading–unloading cycles. Numerical and experimental results suggest that the SGI cylindrical shells are less sensitive to initial imperfections and load variation than uniform ones. Cylindrical shells with seeded geometry can be potentially used in the design of smart devices and mechanical systems such as energy harvesters and self-powered sensors.

Adel Elsabbagh (Group for Advanced Research in Dynamic Systems, Design and Production Engineering Department, Ain Shams University, 1 Elsarayat Street, Abbasya, Cairo 11517, Egypt), “Nonlinear finite element model for the analysis of axisymmetric inflatable beams”, Thin-Walled Structures, Vol. 96, pp 307-313, November 2015, DOI: 10.1016/j.tws.2015.08.021

ABSTRACT: Inflatable structures are already being used for decades now especially in aerospace applications. The Inflatoplane and inflatable space habitats are just examples. On the other hand, the modeling and simulation techniques of inflatable structures are lacking far behind. Most of the available models are concerned with cylindrical beams. In this paper, a nonlinear Finite Element model for axisymmetric inflatable structures is developed using beam elements. The model is validated by comparing its predictions to two cases of cylindrical beams in the literature. The model is then utilized to predict the effect of two parameters on the wrinkling load of the beam. Results show that the wrinkling load is proportional to the square root of the inflation pressure. For the beam radius, it is proportional to the cube of the radius at small radii but then the relation is linear afterwards. The model is also used to predict the performance of an inflated truncated cone as a function of the inflation pressure and the root radius. The proposed nonlinear Finite Element model is a step towards analyzing real-life inflatable structures.

ABSTRACT: This paper focuses on understanding the effect of disbonds on stability aspects of adhesively bonded aluminum structures. In order to utilize that a numerical methodology was developed and it consisted of a parametric finite element model that coupled non-linear buckling analysis with calculation of the critical strain energy release rate on the disbonds tip. The structure under investigation was representative of those used in aerospace industry, an aluminum plate with 4 adhesively bonded J-profile stiffeners subjected to compression loading. Disbonds of several sizes were located in different positions along the second stiffener. A critical disbond size observed after which the compression load capacity of the structure decreased significantly. Moreover, the position of the disbond played a critical role both on the buckling load and the buckling mode and as a consequence, the mechanisms that triggered the disbond onset.

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ABSTRACT: In this paper, the mechanical behaviors and failure mechanism of steel-reinforced concrete-filled steel tubular (SRCFST) columns were numerically investigated with the software of ABAQUS/standard solver. Existing experimental results were employed to verify the validity of the finite element models of SRCFST columns. A total of 22 specimens were numerically studied to examine the effect of steel tube ratio ($\alpha_t$), section steel ratio ($\alpha_s$), concrete strength ($f_{ct}$), yield strength of steel tube ($f_{yt}$) and yield strength of section steel ($f_{ys}$) on the mechanical behaviors and ultimate resistance of the SRCFST columns under axial compression. The model in Eurocode 4 significantly underestimated the load bearing capacity of SRCFST columns, and a new model was then proposed to predict the strength of the SRCFST columns. Based on the comparison between the calculation results from the proposed model and experimental results, the proposed model can provide reliable prediction of the ultimate load carrying capacity for the SRCFST columns.

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ABSTRACT: External confinement in the form of steel rings, tie bars, spirals and FRP wraps has been widely adopted for strengthening concrete-filled-steel-tube (CFST) columns. Previous experimental and theoretical studies have proved that it can improve the strength, elastic stiffness, ductility and interface bonding of CFST columns. However, in real engineering practise, CFST columns need to be strengthened are usually under pre-compressed axial load. The stress-lagging effect between the CFST columns and external confinement due to pre-loading has not yet been justified. In this paper, external confinement in the form of circular steel jacket is proposed to improve the uni-axial behaviour of CFST columns with and without pre-compressed axial load. An experimental study, consisting of 5 hollow-steel-tubes and 10 thin-walled CFST columns was conducted to examine the effectiveness of the proposed strengthening scheme. The main parameters were the concrete cylinder strength, jacket spacing and pre-compressed axial load level. Test results revealed that the steel jacket could improve the uni-axial behaviour of CFST columns and the stress-lagging could degrade this beneficial
effect. In addition, a theoretical model developed by the authors previously was adopted to predict the uni-axial behaviour of the strengthening columns. Very good agreement has been obtained between the theoretical and experimental results.

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“Mechanical performances of concrete-silled steel tubular stub columns with round ends under axial loading”,
Thin-Walled Structures, Vol. 97, pp 22-34, December 2015, DOI: 10.1016/j.tws.2015.07.021

ABSTRACT: An experimental study of 22 concrete-filled round-ended steel tubular (CFRT) stub columns under axial compression is conducted compared with 4 circular concrete-filled steel tubular (CFT) stub columns. The influences of width–thickness ratio, concrete strength, steel yield strength and wall-thickness of steel tube on the ultimate bearing capacity of the CFRT columns are discussed. The 3D finite element (FE) model is also developed to analyze the behavior of the CFRT columns under axial compression. From the results, local buckling of the round-ended steel tube associated with shear failure of in-filled concrete could be observed. With the increasing width–thickness ratio, the corresponding load–strain curves have a shorter elastic–plastic stage. The parametric studies indicate that the concrete strength, tube thickness and width–thickness ratio of the steel tube also have a great effect on the ultimate bearing capacity. The numerical results also show that the confinement effect of the stub columns decreases with the increasing width–thickness ratio. A practical calculation formula for the bearing capacity of the CFRT stub columns is proposed, which is well in agreement with the experimental results.

J. Blachut (The University of Liverpool, School of Engineering, Liverpool L69 3GH, UK), “Locally flattened or dented domes under external pressure”, Thin-Walled Structures, Vol. 97, pp 44-52, December 2015
DOI: 10.1016/j.tws.2015.08.022

ABSTRACT: The paper provides comparisons of sensitivity of buckling pressures to initial shape imperfections, for the case of externally pressurised steel domes. A priori defined deviations from perfect shape include: Legendre polynomials, increased-radius patch, and localised inward dimple. The latter is created by a concentrated force acting radially. In this case the effects of spring back and/or annealing of the dented patch and the surrounding area on the load carrying capacity are assessed. Some of the elastic solutions related to the lower-bound approach are compared with the available experimental data.

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ABSTRACT: Steel plate shear wall (SPSW) systems have dual characteristics, the frame and infill wall action. The connection flexibility of frame joint not only changes the force and moment distribution, but also increases the lateral displacement and weakens the overall stability in SPSW structure. This paper presents the influence of hinged, rigid and semi-rigid connection joints on the behavior of SPSW structures. The bearing capacity, energy dissipation mechanism, failure mode, stress and deformation development process of the semi-rigid composite frame with steel plate shear walls under different stiffener forms were studied using experimental tests and finite element analysis. It was observed that with stiffeners the specimen yield load increased about 20% on the elastic stage, the ultimate bearing capacity of the diagonal stiffener was about 5% larger than the cross stiffener on the plastic stage, but the overall failure modes were basically the same. Additionally, the quantitative indications of the effect of joint stiffness on load carrying capacity were presented.

Francesco Tornabene (1), Nicholas Fantuzzi (1), Michele Bacciocchi (1) and Rossana Dimitri (2) (1) DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy (2) Department of Innovation Engineering, University of Salento, Via per Monteroni, 73100 Lecce, Italy “Free vibrations of composite oval and elliptic cylinders by the generalized differential quadrature method”, Thin-Walled Structures, Vol. 97, pp 114-129, December 2015, DOI: 10.1016/j.tws.2015.08.023

ABSTRACT: We use the generalized differential quadrature method (GDQ) and shell theories of different order to study free vibrations of laminated cylinders of oval and elliptic cross-sections. In the GDQ method partial derivatives of a function at a point are expressed as weighted sums of values of the function at several neighboring points. Thus, strong forms of equations of motion are analyzed. It is found that the computed frequencies rapidly converge with an increase in the number of grid points along the oval or elliptic circumference defining the cross-section of the mid-surface of the cylinder. For a clamped-free elliptic cylinder the converged frequencies match well with the corresponding experimental ones available in the literature. Furthermore, the lowest ten frequencies computed with either an equivalent single layer theory or a layer wise theory of first order and using shear correction factor are accurate.

Mahmoud Zohrabi, Abbas Niknejad and Sima Ziaee (Mechanical Engineering Department, Yasouj University, P.O. Box: 75914-353, Yasouj, Iran), “A novel method for enhancing energy absorption capability by thin-walled sections during the flattening process”, Thin-Walled Structures, Vol. 97, pp 140-153, December 2015 DOI: 10.1016/j.tws.2015.09.013

ABSTRACT: This article introduces a novel method to enhance energy absorption capability of thin-walled sections subjected to the quasi-static lateral loading by performing the saw cutting process on simple closed sections with rectangular columns and shaping them into open sections. For this purpose, some simple closed-sectional columns with square and rectangular cross-sections of aluminum were prepared and used to produce different types of open sections with different geometries and lip lengths through the saw cutting process on a face of the columns. Different paths were selected and performed for the saw cutting to obtain six types of square open section and five types of rectangular open sections with different forms of lips. Lateral compression tests between two rigid platens were employed to obtain variations of lateral load and absorbed energy versus lateral displacement and to calculate specific absorbed energy by thin-walled open sections during the flattening process. For each type of rectangular open sections, two similar specimens were prepared and one of them was compressed along the shorter edge and the other one was tested along the longer edge of the cross-section. Also, as benchmarks, some simple specimens with closed section were compressed in the lateral direction to compare their results with energy absorption capacity by the corresponding open sections. Experimental results show that in all types of square and rectangular open-sections, lip length has significant effects on energy absorption
capability by the structure; and there is an optimum value for lip length of open section and the column with optimized length of the lips has the maximum absorbed energy. Furthermore, experiments reveal that rectangular open sections which are laterally compressed along their shorter edges absorb higher energy, in compression with the corresponding loaded specimens along the longer edges. Results show that maximum absorbed energy/mass belongs to a square open section of type A with rectangular lips and it is 2.68 times of the corresponding value of the similar closed section, as a valuable result.

Hsuan-Teh Hu and Pei-Jen Chen (Department of Civil Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC), “Maximization of fundamental frequencies of axially compressed laminated truncated conical shells against fiber orientation”, Thin-Walled Structures, Vol. 97, pp 154-170, December 2015
DOI: 10.1016/j.tws.2015.09.004
ABSTRACT: Free vibration analyses of laminated truncated conical shells subjected to axial compressive forces are carried out by employing the Abaqus finite element program. The fundamental frequencies of these truncated conical shells with a given material system are then maximized with respect to fiber orientations by using the golden section method. Through parametric studies, the influences of the end condition, shell length, shell radius ratio and the compressive force on the maximum fundamental frequencies, the associated optimal fiber orientations and the associated vibration modes are demonstrated and discussed.

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ABSTRACT: In practical applications, the load bearing capability of slender plates can be affected by the existence of flaws resulting from a number of material deterioration (corrosion, fatigue, etc.). In the present work, a numerical analysis on the residual strength and post-buckling behavior of flawed shear panels using FE method is performed. Using a continuum damage mechanics model, the possibility for a ductile crack to grow under loading is considered. This approach allows us to investigate the role of crack growth in materials with different capabilities to accommodate plastic deformations at the crack tip, as well as geometry effect on the material crack resistance, due to loss of constraint. The effect on the buckling load, ultimate load and postbuckling response of shear panels varying both geometry characteristics and materials (such as initial crack length, slenderness ratio, panel boundary conditions, material properties, etc..) is investigated. Results indicate that crack growth can play a relevant role in the response of shear panels, especially for those materials in which ductile tearing can occur in the early stages of loading. The damage mechanics model used in this work offered the possibility to simulate the occurrence of ductile crack growth based on material properties, without the need of arbitrary assumptions on the crack advance process.

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ABSTRACT: While plate girders with perforated web are commonly used in ships, aircraft applications for their high efficiency. In spite of numerous papers in the literatures on plate girders with perforated web subjected to web crippling, the ultimate capacity load of plate girders with perforated web subjected to plate buckling has not been exhaustively examined. In this study, experimental and numerical studies are performed to investigate the failure behavior of plate girders with perforated web under axial compression and bending moment, which is the typical action pattern arising from cargo weight and water pressure together with hull girder motions in ships and ship-shaped offshore structures. Six specimens with one oval hole are tested to investigate the failure modes and ultimate load capacities of plate girders with perforated web. Test results show that computational model can predict the failure behavior of plate girders with perforated web, and an extensive numerical study is conducted to investigate the influence of hole location. It showed that hole location have more influence on ultimate capacity load of plate girders when hole close to the middle of the web, particularly. Based on the experimental and numerical investigations, an influence curve is proposed to account for effects of hole location.

DOI: 10.1016/j.tws.2015.09.014

ABSTRACT: In this study, forced vibration behavior of thin-walled composite circular cylindrical shells is investigated using the spline finite strip method (spline FSM). Spline FSM is one of the versions of finite element method (FEM) employing a special element called finite strip. The shells considered in this study are assumed to be thin; therefore, the classical bending theory of shells and Sanders–Koiter's strain–displacement relation are used in the theoretical formulation of developed method. Time-history response of shells concerning arbitrary type of forces, boundary conditions and damping effects are obtained using developed spline FSM. To check the validity of results a comparison has been performed with the results obtained by conventional finite element method using ANSYS software. As far as the time history response of cylindrical shells is available the natural frequencies are extracted using Fast Fourier Transform (FFT) approach. The evaluated natural frequencies of composite shells are then compared with those obtained from an eigenvalue analysis. The comparison of results revealed the fact that developed spline FSM is an accurate tool that can be used in transient and harmonic analyses of composite laminated cylindrical shells.

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ABSTRACT: This paper presents a finite element model of square and diamond bird-beak SHS T-joints under axial compression, which was verified by the corresponding test results. The parametric study was carried out to
reveal the failure modes and plasticity propagation of square and diamond bird-beak SHS T-joints. The effects of SHS brace to SHS chord width ratio ($\beta$), SHS chord width to 2 times thickness ratio ($\gamma$), and SHS brace to SHS chord thickness ratio ($\tau$) on the ultimate strengths of square and diamond bird-beak SHS T-joints were evaluated. The typical failure modes of square bird-beak SHS T-joints were obtained from the finite element analysis, which included Brace End Buckling (BEB) and Chord Face Failure (CF). The typical failure modes of diamond bird-beak SHS T-joints were obtained from the finite element analysis, which included Brace Bending (BB), Brace End Buckling (BEB)+Chord Face Failure (CF), Chord Face Failure (CF). The bird-beak T-joints with $\tau=0.6–0.8$ was recommend in the paper. The design equations are proposed by using multiple linear regression for square and diamond bird-beak SHS T-joints under axial compression based on the current design rules of traditional SHS T-joints given in the CIDECT. It is shown from the comparison that the joint strengths of square and diamond bird-beak SHS T-joints calculated using the proposed design equations agreed well with the finite element analysis results, which means the proposed design equations are verified to be accurate.


ABSTRACT: The behaviour and ultimate strength of locally damaged plate panels is investigated in this study. The damage is in the form of a local imperfection and represents a dent that could be caused by a fall or strike of an object. Panels are made of nine identical plates – three plates transversally and three longitudinally – and only one of the plates is damaged. The influence of several parameters has been studied to establish their interaction with the presence of the local dent. The main focus, is however the influence of the adjacent intact plates. The large panel is compared with smaller transverse model made of three plates and with a single plate model in order to evaluate the effects of adjacent plates and define the minimum size of the model necessary to obtain proper results.


ABSTRACT: This paper presents an analytical study to investigate the effect of flange–web interaction on local buckling of welded steel I-sections subjected to bending. An inelastic local buckling stability model is presented that accounts for all the geometric and material variables of the problem. The deformation theory of plasticity was used to describe the behavior of steel beyond the elastic limit. The model results were verified through comparison with finite element model results and published experimental ones. A parametric study was conducted to investigate the effect of flange–web interaction on the width to thickness limits. Using the parametric study results, new width to thickness limits were proposed in which all the parameters of the section are reflected.

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ABSTRACT: Thirty-one tests under low velocity drop weight impact were carried out to examine the residual failure modes and the time history of the impact forces, global deformations and strains of concrete filled double steel tubular (CFDST) members in this paper. The parameters varied in the testing program include the column type (straight and tapered), the boundary conditions (simply supported and fixed), the axial load level and the impact energy. The results showed that all CFDST members behaved in a ductile manner and the residual deformation consisted of local deformation at the impact section, as well as the overall bending deformation. Compared to hollow double steel tubes, the CFDST members under the same applied impact energy demonstrate superior impact behavior in terms of higher energy absorbed, smaller global deformation and local deformation due to the interaction of the sandwich concrete and double skin steel tubes. The influence of key parameters on the dynamic resistance ability of CFDST is discussed.


ABSTRACT: This paper deals with the nonlinear thermal stability of composite plate with embedded and through-the-width delaminations under uniform temperature rise. The formulation is established within the framework of the higher order shear deformation theory by taking into account the von Karman geometrical nonlinearity. The thermomechanical properties of the laminates are assumed to be temperature-dependent. The nonlinear equilibrium equations derived by the minimum total potential energy principle, are solved using the Rayleigh–Ritz method along with the Newton–Raphson iterative procedure. For modeling the embedded and through-the-width delaminations, the plate is divided into a number of smaller regions. The proposed model is capable of analyzing both local buckling of the delaminated base laminate and sublamine as well as the global buckling of the plate. Numerical results are presented to provide an insight into effects of delamination type, size of delamination and boundary condition on the critical buckling temperature difference, buckling mode and postbuckling behavior of the composite plate. It is found that presence of delamination leads to substantial reduction in the load carrying capacity of the composite plate. Furthermore, the results reveal that the buckling mode could be changed depending on the delamination area.

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ABSTRACT: At elevated temperature, behaviour of Class 1 to 3 open cross-section beams have been investigated experimentally and numerically, whereas for slender Class 4 sections only few experimental data have been collected. Due to the economic assumptions of members with Class 4 cross section and general validity of the existing design rules, further investigation is desired. This paper presents tests and numerical simulation of welded slender (Class 4) I-section beams at elevated temperature. The design of the test set-up, as well as progress of the experiments is presented. Detailed information about the geometrical data, measured geometrical imperfections, temperature, load and actual mechanical properties were collected. The tests were
subsequently used for a FE model validation. The described research allows better understanding to the fire behaviour of steel members of Class 4 cross-section beams.

Jaroslav Vacha, Petr Kyzlik, Ioan Both and Frantisek Wald (Czech Technical University in Prague, Department of Steel and Timber Structures, Prague, Czech Republic), “Beams with corrugated web at elevated temperature, experimental results”, Thin-Walled Structures, Vol. 98, Part A, pp 19-28, January 2016
DOI: 10.1016/j.tws.2015.02.026
ABSTRACT: The paper is focused on presenting the thermal and mechanical response of sinusoidal corrugated web beams subjected to high temperatures. Two tests were performed to monitor the behavior of isolated elements and composite slabs designed with corrugated web beams. Different aspect ratio beams exposed to standard fire temperatures and one beam subjected also to mechanical load were tested in the first experiment. The second study was conducted on a real-scale building compartment designed using corrugated web beams–concrete slab composite floor. The results obtained from experimental works reveal the real temperature distribution in the steel profile and the fire performance of sinusoidal corrugated web beams.

DOI: 10.1016/j.tws.2015.02.028
ABSTRACT: Web-post buckling behaviors of fully and partially protected cellular steel beams at elevated temperatures in a fire were investigated through verified finite element models. The partially protected cellular steel beam represented a protected cellular steel beam with the hole edge left unprotected. The temperature distribution in the web-post was non-uniform, even for the unprotected CSB and the fully protected CSB. The fire resistance time of a CSB increased linearly with the increase in fire coating thickness. However, for the partially protected cellular steel beam, the temperature gradient in the web-post becomes greater with the increase in the fire protection thickness. And with the increase in the fire protection thickness, the increment in the fire resistance time decreased. Additional thermal stress occurred due to the non-uniform thermal strain in the web-post. When web-post buckled, the principle compression stress in the web-post decreased suddenly. The stress at the center of the web-post could change from compression to tension due to the membrane action caused by the large buckling deformation.

ABSTRACT: This paper presents the results of a wide-ranging experimental research carried on the flexural behaviour of cold-formed steel beams subjected to fire. The main purpose of this work was to evaluate the influence of different cross-sections, especially of compound cold-formed steel sections, the axial restraint to the thermal elongation of the beam and the rotational stiffness of the beam supports. The results showed above all that the critical temperature of a cold-formed steel beam might be strongly affected by the stiffness of the surrounding structure depending on the relation between its stiffness and the stiffness of the beam.
ABSTRACT: This paper presents critical factors that influence the onset of local buckling in steel beams when exposed to fire conditions. A three-dimensional nonlinear finite element model, capable of accounting for critical factors that influence local instability in fire exposed steel beams is developed. This model is applied to investigate the effect of beam-slab interaction, strength properties (Grade) of steel, and presence of fire insulation on the onset of local instability, and resulting capacity degradation in fire exposed steel beams. Results from numerical simulations are utilized to evaluate failure of beams under different limit states including flexure, shear, sectional instability and deflection. These results infer that web instability can occur at early stages of fire loading, leading to faster degradation of shear capacity and premature failure of steel beams before attaining flexural capacity. Also, results from the analysis indicate that the contribution of concrete slab to shear capacity can counterbalance the adverse effect of web local instability to a certain degree. Overall, neglecting the effect of fire-induced web local instability can lead to unconservative design in steel beams or girder subjected to high shear loading and/or local instabilities.

ABSTRACT: The large deflection behaviours of axially restrained corrugated web steel beam (CWSB) at elevated temperatures were investigated using a finite element method. The web of studied CWSB adopted commonly used trapezoidal shape. The applicability of finite element model presented was validated against test results on the restrained flat web steel beam (FWSB) in a fire. Studied parameters of CWSB included the load ratio, the axial restraint stiffness ratio, the span-depth ratio, the corrugation shape of the web, the web thickness and the flange thickness. The evolutions of the vertical deflection, the axial force and the bending moment at mid-span of the CWSB with the elevated temperatures were presented. For the axial stiffness of a CWSB was smaller than that of a FWSB with the same dimension, the compressive force due to the restrained thermal elongation in a CWSB at elevated temperatures was lower than that in a FWSB. In addition, the CWSB went into the catenary action phase at a lower temperature compared with the FWSB with the same load and axial restraint stiffness ratio. The corrugation shape and the thickness of the web had very little influences on the catenary action behaviour of the restrained CWSB at elevated temperatures. Parameters that greatly affected behaviours of CWSB at elevated temperatures were the load ratio, the axial restraint stiffness ratio, and the span-depth ratio. With the increase in load ratio, the temperature at which the restrained CWSB went into catenary action phase decreased. The axial restraint stiffness and the span-depth ratio did not affect the temperature at which the restrained CWSB went into catenary action phase. However, with the increase in the axial restraint stiffness, the maximum axial force that the CWSB experienced increased and the temperature at which the maximum axial force was reached decreased. With the increase in the span-depth ratio, the maximum axial force the CWSB experienced and the temperature at which the maximum axial force was reached decreased.

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“Distortional failure and DSM design of cold-formed steel lipped channel beams under elevated temperatures”, Thin-Walled Structures, Vol. 98, Part A, pp 75-93, January 2016, DOI: 10.1016/j.tws.2015.06.004

ABSTRACT: The aim of this paper is to report an ongoing shell finite element investigation on the distortional post-buckling behaviour, ultimate strength and DSM design of cold-formed steel single-span lipped channel beams under elevated temperatures due to fire conditions. The beam ultimate strengths are computed by means of a steady-state loading strategy that consists of applying an increasing major-axis uniform bending moment to a beam under a uniform and constant (elevated) temperature distribution, until failure is reached. The steel constitutive law at elevated temperatures is simulated by means of the stress–strain–temperature models prescribed in EC3-1.2 for cold-formed steel. The materially and geometrically non-linear response of the cold-formed lipped channel beam is determined through ANSYS shell finite element analyses that incorporate critical-mode (distortional) initial geometrical imperfections. Finally, since there are no specific rules to predict the bending strength of cold-formed steel beams failing in distortional modes at elevated temperatures, the above failure moments and temperatures are used to establish preliminary guidelines for the design of cold-formed steel lipped channel beams under fire conditions. The approach followed is based on the Direct Strength Method (DSM) and has been already employed by other researchers – the currently available design/strength equations/curves, developed for ambient temperature, are modified to account for the appropriate Young’s modulus and yield stress reductions due to the temperature increase. The results presented in the paper provide solid numerical evidence that the currently codified DSM distortional strength curve is not appropriate to predict beam failure moments at elevated temperatures. This is because it either (i) does not account for the material non-linearity due to the elevated temperature (low-to-moderate slenderness range) or (ii) is already inadequate to predict room temperature failure moments (unsafe estimates obtained in the high slenderness range).

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ABSTRACT: When subjected to elevated temperatures, steel displays a reduction in both strength and stiffness, its yield plateau vanishes and its response becomes increasingly nonlinear with pronounced strain hardening. For steel sections subjected to compressive stresses, the extent to which strain hardening can be exploited (i.e. the strain at which failure occurs) depends on the susceptibility to local buckling. This is reflected in the European guidance for structural fire design EN1993-1-2 [1], which specifies different effective yield strengths for different cross-section classes. Given the continuous rounded nature of the stress–strain curve of structural steel at elevated temperatures, this approach seems overly simplistic and improved accuracy can be obtained if strain-based approaches are employed [2]. Similar observations have been previously made for structural stainless steel design at ambient temperatures and the continuous strength method (CSM) was developed as a rational means to exploit strain hardening at room temperature. This paper extends the CSM to the structural fire design of steel cross-sections. The accuracy of the method is verified by comparing the ultimate capacity predictions with test results extracted from the literature. It is shown that the CSM offers more accurate ultimate capacity predictions than current design methods throughout the full temperature range that steel structures are likely to be exposed to during a fire. Moreover due to its strain-based nature, the proposed methodology can readily account for the effect of restrained thermal expansion on the structural response at cross-sectional level. References listed at the end of the paper:
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CUFSM: conventional and constrained finite strip methods. Proceedings of the 20th International Speciality Conference on Cold-Formed Steel Structures, St. Louis, MO. November 2010.

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ABSTRACT: Thermal gradients often occur in fire exposed structures. This paper considers thermal gradients over the cross-section of steel columns. By means of finite element simulations, the paper demonstrates that these gradients reduce the flexural buckling resistance of the columns. This is due to the eccentricity in the column created by the temperature gradient. Design equations in modern standards provide a gross approximation of the load bearing resistance of such columns in which the eccentricity is ignored and in order to compensate for this the yield stress and modulus of elasticity are to be determined at maximum temperature. Based on an in-depth analysis of the results of the finite element simulations, this paper provides an alternative design model which much better agrees with the actual behaviour of a fire exposed column.

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ABSTRACT: This paper presents the results of a numerical and analytical study of the load–deflection behaviour of thin-walled bolted plates under bolt shear at elevated temperatures. This paper first presents validation of the numerical simulation results against the high temperature tests carried out by Hirashima and Uesugi. The validated numerical model was then used to conduct an extensive series of parametric studies, in which the connection temperatures, material properties, geometries were changed, to generate a database of results to check the applicability of an analytical model previously developed by the authors for evaluating the load–deflection behaviour of this type of connection at ambient temperature. The results of this comparison indicate that the ambient temperature model can be applied to the elevated temperature condition if the ambient temperature mechanical properties of steel (Young’s modulus, yield stress, elongation) are replaced by those at elevated temperatures.

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ABSTRACT: Based on the prior experimental studies on the 6 square hollow section stainless steel columns without axial constraints in fire, the fire resistance performance of stainless steel columns under axial compression was investigated in this paper. The numerical simulation and analysis of the performance of stainless steel columns relative to fire resistance were conducted by the finite element software ABAQUS. The effects of various parameters on the fire resistance performance of the stainless steel columns were studied, focusing on the initial defect amplitude, the load ratio and the length of the stainless steel columns. Referring to the structural fire design methods of stainless steel in the European Code (EN 1993-1-2) and the Euro Inox/SCI Design Manual, the new formulae for ultimate bearing capacity at elevated temperatures were fitted for the axially compressed stainless steel columns. The comparison of fitting results with test results and code results indicates that the fitting formulae are highly accurate and can predict the capacity and critical temperature of the axially compressed stainless steel columns in fire.

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ABSTRACT: To study the bearing capacity and failure mechanism of a square stainless steel column in fire, a series of tests were performed on S30408 stainless steel, including 6 material mechanical property tests at room temperature, 16 material mechanical property tests at elevated temperature and fire experiments on 8 square sections of stainless steel columns. Steady tests at elevated temperature were performed to investigate the mechanical properties of stainless steel. The stress–strain curve, elastic modulus, yield strength and the
reduction factor of the ultimate strength of stainless steel at elevated temperature were determined, and the test results were compared with the European Codes. The experiments studied the properties of the square section stainless steel columns without axial constraints in fire, which were compressed axially and eccentrically. The failure phenomenon, heating curve, deformation curve and critical temperature of the specimens were obtained. The effects of the load ratio, section dimension and eccentricity on the critical temperature and fire-resistance performance of the stainless steel column were examined. The test results show that load ratio and eccentricity are the key factors for critical temperature and fire-resistance performance of the stainless steel column without axial constraints.


ABSTRACT: Failure modes of the thin-walled aluminum alloy column with irregular shaped cross section at ambient temperature and elevated temperatures in a fire were studied using a verified finite element model. The studied failure modes included the sectional yielding, interaction of local buckling and sectional yielding, interaction of local and global buckling, and global buckling. The finite element model was verified by experimental results from the ultimate strength, the failure modes and the failure deformation. Deformation shape along the column failed by different failure modes was presented. Stresses development at the middle span section was greatly affected by the failure modes. Ultimate strengths of a series of aluminum alloy columns with different length, cross section dimension were analyzed by the finite element analysis and current design codes at different temperatures in a fire. The current design codes greatly underestimated the ultimate strength of the thin-walled aluminum alloy column with irregular shaped cross section. Design method provided by EN1999-1-2 can give an accurate prediction of the ultimate strength of a short thin-walled aluminum alloy column with irregular shaped cross section at temperatures lower than 250 °C. A modification to the design method in EN1999-1-2 was proposed for predicting the ultimate strength of the aluminum alloy column with length longer than 500 mm and at temperatures higher than 250 °C. Ultimate strength predicted by the modified equation agreed well with finite element analysis results.

Lei Zhu, Shuo Han, Qiming Song, Limeng Ma, Yue Wei and Shuwen Li (School of Civil and Transportation Engineering, Beijing Higher Institution Engineering Research Center of Structural Engineering and New Materials, Beijing University of Civil Engineering and Architecture, Beijing, China), “Experimental study of the axial compressive strength of CHS T-joints reinforced with external stiffening rings”, Thin-Walled Structures, Vol. 98, Part B, pp 245-251, January 2016, DOI: 10.1016/j.tws.2015.09.029

ABSTRACT: This paper studies circular hollow section (CHS) T-joints by conducting experiments on the comparative axial compressive strength of unreinforced and reinforced T-joints. Three pairs of unreinforced and reinforced T-joints, a total of six specimens with the ratio of brace to chord diameter equal to 0.26, 0.51, and 0.74 respectively, were tested to determine their compressive load capacity. The specimen parameters, experimental setup, and test results are presented. The failure modes of the unreinforced and reinforced T-joints were compared. The unreinforced joints failed due to chord plastification, while the reinforced joints failed due to chord bending. The experiment indicated that the external stiffening ring significantly increased the axial compressive strength of the T-joints. Every reinforced joint behaved like a beam when loaded by concentrated force at the brace end; the strength of the reinforced joint can be predicted by calculating the plastic bending moment at the crown section.
Lu Wang, Weiqing Liu, Yuan Fang, Li Wan and Ruili Huo (College of Civil Engineering, Nanjing Tech University, Nanjing 211816, China), “Axial crush behavior and energy absorption capability of foam-filled GFRP tubes manufactured through vacuum assisted resin infusion process”, Thin-Walled Structures, Vol. 98, Part B, pp 263-273, January 2016, DOI: 10.1016/j.tws.2015.10.004

ABSTRACT: Foam-filled circular metallic tube has been widely used in safety design of automobile, spacecraft recovery and so on due to its advantage of high energy absorption. But poor chemical stability and easily oxidized of metal materials seriously threaten the durability and safety of the traditional metallic tube. The application of fiber reinforcement polymer (FRP) can effectively address these issues. In this paper, a simple and innovative foam-filled GFRP tube, fabricated by vacuum assisted resin infusion process, is proposed to enhance the durability and improve the energy absorption capacity. An experimental study was conducted to validate the effectiveness of this kind of absorber for increasing the energy absorption capacity. Meanwhile, the influences of GFRP skin thickness, diameter of tube, foam density and fiber orientation angle of GFRP mat on failure mode, initial stiffness, stroke efficiency and specific energy absorption were also investigated. An analytical model, considered the confinement effect on foam core and local buckling of GFRP skin, was also developed to predict the ultimate peak strength of foam-filled GFRP tubes. The experimental and analytical results were shown to be well matched.

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ABSTRACT: This paper presents a finite element model of circular hollow section (CHS) brace-to-H-shaped chord T-joints under axial compression, which was verified by the corresponding test results. The parametric study was carried out to reveal the failure modes and plasticity propagation of tubular joints. The effects of CHS brace diameter to H-shaped chord flange width ratio (\(\beta\)), H-shaped chord flange width to thickness ratio (2\(\gamma\)), and CHS brace to H-shaped chord flange thickness ratio (\(\tau\)) on the ultimate strengths of tubular joints were evaluated. The typical failure modes were obtained from the finite element analysis, which include local buckling failure of CHS brace (LBFB), local buckling failure of flange and web of H-shaped chord (LBFF+LBFW), and local buckling failure of CHS brace and H-shaped chord flange (LBFB+LBFF). The validity range of main geometric parameters was recommended to be \(\beta \geq 0.7\), \(2\gamma = 20–30\), and \(\tau = 0.25–0.5\). The design equations are proposed by using multiple linear regression for CHS brace-to-H-shaped chord T-joints under axial compression based on the current design rules given in the Eurocode 3. Current Eurocode 3 is dangerous for predicting the ultimate strengths of CHS brace-to-H-shaped chord T-joints under axial compression. It is shown from the comparison that the joint strengths calculated using the proposed design equations agreed well with the finite element analysis results, which means the proposed design equations are verified to be accurate.

ABSTRACT: The paper describes the derivation of a beam finite element method which enables the effects of local and/or distortional buckling deformations to be accounted for. The development of local/distortional buckling reduces the rigidity of the section against axial straining, minor and major axis flexure, as well as twisting. The reduction in rigidity can be determined by an analysis performed prior to the frame analysis, in which tangent rigidities ((\(EA_t\)), (\(EI_z\)), (\(EI_y\)), (\(EI_w\))) and other tangential stiffness terms are obtained for increasing values of generalised strains (\(\varepsilon\), \(\kappa_z\), \(\kappa_y\), \(\kappa_w\)). The paper sets out the tangential stiffness matrix for a locally/distortional buckled element and discusses in detail the determination of tangent rigidities. The companion paper [1] shows that close agreement can be obtained between the beam analysis which incorporates reduced rigidities and analysis using full shell finite element discretisation. The paper is limited in scope to doubly-symmetric open sections.

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ABSTRACT: The behavior of thin-walled dodecagonal section double skin concrete-filled steel tubes under bending was studied in this paper. Both experimental investigation and finite element analysis (FEA) were carried out. A total of 7 specimens were tested with the beam length of 2000 mm. The width to thickness ratio of the outer steel tube ranged from 75 to 133. The load–displacement curves, failure mode and ultimate capacity of test specimens were obtained. A finite element model was developed for the thin-walled dodecagonal section double skin concrete-filled steel tube subjected to bending. The FEA results were verified against the test results and parametric study was conducted using the verified model. In addition, the suitability of Han's method, Uenaka's method and proposed method for thin-walled circular section double skin concrete-filled steel tubes subjected to bending was also evaluated.

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"Stability improvement of thin isotropic cylindrical shells with partially filled soft elastic core subjected to external pressure", Thin-Walled Structures, Vol. 98, Part B, pp 301-311, January 2016

DOI: 10.1016/j.tws.2015.09.028

ABSTRACT: Improvement of stability of thin isotropic shell in the presence of soft elastic filler has been investigated. Critical buckling loads for empty and filled cylinder have been studied both experimentally and theoretically using FE analysis. Various percentage of cross sectional filling are examined as a parametric variation. Nonlinear analysis with proper geometric imperfection modeling is carried out to represent correct behavior of soft elastic filler. The experimental results and FE analysis corroborate well to establish this improvement in buckling strength. It is observed that critical buckling load of the cylinder subjected to external pressure improves up to an extent of five times depending upon percentage of filling. It is concluded that improved strength can be utilized for more efficient design of thin tubular shells.

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“Quasi-static, impact and energy absorption of internally nested tubes subjected to lateral loading”, Thin-Walled Structures, Vol. 98, Part B, pp 337-350, January 2016, DOI: 10.1016/j.tws.2015.11.001

ABSTRACT: This paper presents the responses of nested tube systems under quasi-static and dynamic lateral loading. Nested systems in the form of short internally stacked tubes were proposed as energy absorbing structures for applications that have limited crush zones. Three configurations of nested tube systems were experimentally analysed in this paper. The crush behaviour and energy absorbing responses of these systems under various loading conditions were presented and discussed. It was found that the quasi-static and dynamic responses of the nested systems were comparable under an experimental velocity of v=4.5 m/sec. This is due to insignificant strain rate and inertia effects of the nested systems under the applied velocity. The performance indicators, which describe the effectiveness of energy absorbing systems, were calculated to compare the various nested systems and the best system was identified. Furthermore, the effects of geometrical and loading parameters on the responses of the best nested tube system were explored via performing parametric analysis. The parametric study was performed using validated finite element models. The outcome of this parametric study was full detailed design guidelines for such nested tube energy absorbing structures.


ABSTRACT: This paper deals with the ultimate strength, post-buckling behaviour and design of cold-formed steel lipped channel beams affected by local-distortional buckling mode interaction, subjected to uniform bending of the major axis. The cross-sectional dimensions and length of the beams were chosen to have almost equal local and distortional critical buckling stresses by using the $G_{BTUL\beta}^2$ and CUFSM software. The beams are analysed under pinned with warping free end conditions. 12 sections were selected for this study. The selected sections satisfy the geometric limitations for pre-qualified sections in AISI-S100:2007. Elastic buckling and non-linear finite element analyses were carried out using ABAQUS. The results were compared with corresponding results from experiments available in the literature. The numerical parametric study of 60 analyses of different geometries and yield stress values was undertaken. Based on the comparison of ultimate strengths obtained from the finite element analysis and Direct Strength Method (DSM), a design equation is proposed for lipped channel sections which have their elastic local and distortional buckling moments nearly equal.

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ABSTRACT: This paper proposes a new approach to predict the web crippling failure load of cold-formed steel beams under External Two Flange (ETF) loading using the Direct Strength Method (DSM). After the description of the existing test data, Eurocode 3 (Comité Européen de Normalisation (CEN), 2006) [1] and the North-American Specification (American Iron and Steel Institute (AISI), 2012) [2] are used to predict the corresponding web crippling failure loads and the accuracy of such predictions is briefly assessed. In order to obtain additional information on the web crippling behaviour of each test specimen, non-linear numerical simulations are performed. Since the calibration of the DSM-based design expressions requires the previous calculation of (i) elastic buckling loads and (ii) plastic strengths/loads, two procedures are presented to achieve these goals. While the buckling loads are determined using the GBTWEB software, specifically developed for this purpose, the plastic loads are calculated by means of analytical expressions based on yield-line models. By adopting a non-linear regression procedure, the coefficients of a DSM-based formula are determined on the basis of the set of 128 experimental results available and the corresponding buckling and plastic load values. In spite of the different cross-sections, fastening conditions and test set ups considered in the calibration procedure, it is possible to establish a clear relationship between the web crippling slenderness and the nominal-to-plastic load ratio. Finally, it is shown that the developed/proposed DSM-based formula for ETF web crippling design yields reliable predictions, since they are associated with a LRFD (Load and Resistance Factor Design) resistance factor $\phi = 0.81$, which is located within the range of values currently adopted in the 2012 NAS (American Iron and Steel Institute (AISI), 2012) [2].


ABSTRACT: Buckling of flexurally anisotropic composite plates under combined loading is considered. The purpose of the paper is to develop approaches for predicting buckling loads for the plates, basing on buckling analysis results for separate loadings. Theoretical aspects of the problem are explored. The derivatives of the buckling interaction curves are analytically derived. The finite predicting formulae are proposed. The Galerkin-type numerical method for combined loading buckling analysis is developed. The method is based on buckling modes of separate loadings. Numerical examples are discussed. Convergence of the method is shown. Influence of the flexural anisotropy on the buckling behavior is demonstrated.


ABSTRACT: Shell buckling experiments are mostly conducted in a displacement controlled manner, that is the displacement at the loaded shell edge is increased and the load applied is measured as reaction force. The corresponding boundary conditions are realized by potting the shell edges. Real shell structures, such as primary structures of space launcher vehicles, are loaded in a load controlled manner and boundary conditions are defined by the adjacent structures and stiffening rings. Within this contribution, the discrepancy between boundary conditions and load introduction of full-scale built-in and sub-scale experimental shell structures of space launcher vehicles is studied numerically. For this purpose, dynamic explicit load controlled buckling analyses were performed using theoretical boundary conditions to idealize built-in conditions in an extreme manner and taking localized perturbations, such as those due to a single perturbation load, geometrical dimple imperfections and circular unreinforced cut outs, into account. The results are compared to displacement...
controlled shell buckling predictions in which boundary conditions commonly used within shell buckling experiments of sub-scale structures are taken into account.

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ABSTRACT: This paper presents an analytical solution for calculating the critical buckling load of simply supported cellular columns when they buckle about the major axis. The solution takes into account the influence of web shear deformation on the buckling of cellular columns and is derived using the stationary principle of potential energy. The formula derived for calculating the critical buckling load is validated using finite element analysis results. It is shown from the present analytical solution that the web shear deformation can significantly reduce the buckling resistance of cellular columns. The influence of the shear deformation on the critical buckling load increases with the cross-section area of the tee section and the radius of circular holes but decreases with the length and the web thickness of the cellular column.

ABSTRACT: The present paper deals with a dynamic interactive response of FG beam-columns subjected to in-plane pulse loading when the shear lag phenomenon and distortional deformations are taken into account. The structures are assumed to be simply supported at the ends. In order to obtain the equations of motion of individual plates, the classical laminate plate theory (CLPT) has been modified in such a way that it additionally accounts for all components of inertial forces. Thin-walled trapezoidal FGM beam-columns are considered. A dynamic interaction of the global mode with the lowest primary local buckling mode and the secondary local mode has been analysed. Attention has been drawn to some unexpected aspects related to the fact that a two- and three-modal approach has been assumed in the analysis of dynamic interactive buckling.

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ABSTRACT: This paper presents a comparative study and a 3D finite element (FE) model of square stirrup-confined concrete-filled steel tubular (stirrup-confined CFT) stub columns. The FE results agreed well with the experimental results. The results indicated that: (1) The ultimate load-bearing capacity of CFT stub columns with internal studs was no improvement; (2) All three forms of stirrup confinement effectively reduced local buckling of the steel tube, and the cross ties was optimal, followed by spiral stirrups; (3) With the same overall
steel ratio, the behavior of the square stirrup-confined CFT stub columns was considerably higher than in the square CFT stub columns.

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ABSTRACT: In general, the calculation of ultimate load capacity (UL) of a concrete-filled steel tubular (CFST) column is based on the assumption that the load is resisted by both the steel tube and the concrete core simultaneously as a composite member. However, steel tubes of CFST columns are preloaded due to self-weight, wet concrete weight as well as temporary construction loads before the composite action is formed. There is still no consensus on how the preload affects the loading resistance of CFST columns and how to quantify the effect of preload on the ultimate strength.

The paper reported an experimental study on circular CFST columns subjected to preload. The testing results showed that the preloading effect increased with the increase of slenderness, decreased the ultimate load capacity and increased the deformation significantly at high preloading ratio, but did not have much influence on the ultimate load capacity at light preload. Then, a parametric analysis of coupled effects of preloading ratio with other parameters, such as slenderness ratio, eccentric ratio, as well as material properties, is presented. Finally, a simplified method is proposed to predict the ultimate load capacity of CFST columns with preload. The preloading reduction factor of simplified methods of UL based on regressive analysis can be used to evaluate the UL of CFST columns with preload after verified by overall comparison of total preloading tests.

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ABSTRACT: The structural strength and stability of cold-formed steel Zee-section beam-columns including 22 structural Zee-sections at a length of 305 mm and 21 at a length of 1219 mm were tested under several load combinations of biaxial bending moments and axial force. This testing on Zee-section beam-column specimens complements an earlier test series on lipped channel specimens and provides an exploration of the impact of the principal axis configuration and the differing location of shear center for Zee-sections as relative to their location in lipped channels. The short length specimens are intended to mobilize local buckling and avoid distortional and global buckling, while the long length specimens are intended to mobilize other buckling modes such as distortional and local-global buckling. The combined axial force and biaxial bending moments were applied via a special test rig designed to apply axial load with eccentricities. The results were used to evaluate the current AISI-S100-12 specification for beam-column strength prediction via both effective width and direct strength methods. Both methods employ a simple linear interaction equation for strength prediction of the members under combined actions. The experimental results showed a considerable prospective for
improvement in the current specification approach by providing more optimized and realistic results in design considering the actual stress resulted from combined actions on the cross-section. Accordingly, the potentials for further improvements of the direct strength design method for cold-formed steel beam-columns are discussed.

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ABSTRACT: This paper describes a series of shear tests of plate girders fabricated from steel plates with a nominal yield stress of 235 MPa for the web and 315 MPa for flanges. The ultimate shear strength and performance of end web panels with a single double-sided transverse stiffener at support of plate girders undergoing a significant tension field action were investigated experimentally and theoretically. According to shear test results, post-buckling strength in the shear buckling mode has a significant effect on the ultimate shear strength of end web panels of plate girders. Design shear strength formulae for the direct strength method (DSM) for end web panels of plate girders were developed based on shear test results. The results verify that DSM shear curves can accurately predict the ultimate shear strength of web panels of plate girders showing a significant post-buckling behavior in the shear buckling mode.

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ABSTRACT: Steel–concrete–steel (SCS) sandwich wall infilled with ultra-lightweight cement composite has been developed and proposed for applications in offshore and building constructions. A new form of J-hook connector is introduced to connect the external plates to improve the composite action between the steel face plates and cement composite core to form an integrated unit which is capable of resisting extreme loads. This research experimentally investigates the structural behaviour of SCS sandwich composite wall based on a series of combined compression and uniaxial bending tests on short SCS sandwich composite wall with interlocking J-hook connectors. From the tests, it is found that the SCS sandwich wall exhibits good ductility behaviour with a bending failure mode. Nonlinear finite element (FE) model is also developed to simulate the mechanical behaviour of sandwich wall in terms of ultimate strength and load-deflection curves. Analytical studies show that the N–M interaction model based on Eurocode 4 may over-predict the combined resistance of the SCS sandwich walls subjected to eccentric compression. Therefore, a new approach is proposed to evaluate the resistance of sandwich wall. The axial force versus moment capacity interaction diagrams of sandwich wall are calculated. The validation against the test and FE results shows a reasonable and conservative estimation on the combined resistance of SCS sandwich wall.

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ABSTRACT: This paper presents a finite element (FE) model, which is validated and developed to simulate the axial load behavior of an existing experimental composite wall consisting of double-skinned profiled steel sheet (PSS) in-filled with normal concrete. This type of wall is designed to resist the axial load in the composite structure buildings. The performance of three FE models, namely, PSS only, in-filled concrete only and full composite wall system (two PSS in-filled with concrete) are accurately compared with an existing experimental test. Then, the validated FE models are utilized to perform comprehensive parametric studies which presented information about the effect of the ECFS thickness, number of the ECFS, and ECFS shapes on the load resisting behavior of the composite wall. After comparing all FE models with Euro Code 4 (EC4), the results showed reasonable degree of accuracy.

ABSTRACT: Crush behavior of different arrangements of multi-tubes filled by functionally graded foams (FGF) are evaluated in this study. Our study shows that the energy absorption of FGF filled multi-tubes is higher than their equivalent multi-tubes filled by uniform foams. Also, the results show that the type of function employed for grading foam has significant effect on their crush response. In this study, multi-objective optimization was carried out using geometrical average and multi-design objective (MDO) methods. The results give new design ideas under axial loading to improve energy absorption performance of FGF foam-filled tubes.

ABSTRACT: The cylinder had been wide applications in the industry especially in mechanical and nuclear applications. The most common type of failure which may be happen in this type of structure was the buckling when was subjected to external hydrostatic pressure which represents the aim of this work. The buckling happen due to transfer major amount of strain energy into bending energy which leads to sudden failure in the structure at load less than the yield point. To avoid this type of failure the cylindrical shell stiffened by adding a stiffeners ring along the shell from internal or external surface. In this work two types of stiffeners existed, longitudinal and circumferential stiffeners based on the direction of the installation on the shell surface.

ABSTRACT: Dynamics of contact free (levitated) drying of nanofluid droplets is ubiquitous in many application domains ranging from spray drying to pharmaceutics. Controlling the final morphology (macro to micro scales) of the dried out sample poses some serious challenges. Evaporation of solvent and agglomeration of particles leads to porous shell formation in acoustically levitated nanosilica droplets. The capillary pressure...
due to evaporation across the menisci at the nanoscale pores causes buckling of the shell which leads to ring and bowl shaped final structures. Acoustics plays a crucial role in flattening of droplets which is a prerequisite for initiation of buckling in the shell. Introduction of mixed nanocolloids (sodium dodecyl sulfate + nanosilica) reduces evaporation rate, disrupts formation of porous shell, and enhances mechanical strength of the shell, all of which restricts the process of buckling. Although buckling is completely arrested in such surfactant added droplets, controlled external heating using laser enhances evaporation through the pores in the shell due to thermally induced structural changes and rearrangement of SDS aggregates which reinitializes buckling in such droplets. Furthermore, inclusion of anilinium hydrochloride into the nanoparticle laden droplets produces ions which adsorb and modify the morphology of sodium dodecyl sulfate crystals and reinitializes buckling in the shell (irrespective of external heating conditions). The kinetics of buckling is determined by the combined effect of morphology of the colloidal particles, particle/aggregate diffusion rate within the droplet, and the rate of evaporation of water. The buckling dynamics leads to cavity formation which grows subsequently to yield final structures with drastically different morphological features. The cavity growth is controlled by evaporation through the nanoscale pores and exhibits a universal trend irrespective of heating rate and nanoparticle type.

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Asmani, M.; Kermel, C.; Leriche, A.; Ourak, M. Influence of porosity on Young’s modulus and Poisson’s ratio in alumina
Joseph D. Paulsen (1,2), Evan Hohifeld (1), Hunter King (1), Jiangshui Huang (1,2), Zhanlong Qiu (1), Thomas P. Russell (2), Narayanan Menon (1), Dominic Vella (3) and Benny Davidovitch (1)
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“Curvature-induced stiffness and the spatial variation of wavelength in wrinkled sheets”, Proceedings of the National Academy of Sciences of the United States of America (PNAS), Vol. 113, No. 5, February 2016
ABSTRACT: Wrinkle patterns in compressed thin sheets are ubiquitous in nature and technology, from the furrows on our foreheads to crinkly plant leaves, from ripples on plastic-wrapped objects to the protein film on milk. The current understanding of an elementary descriptor of wrinkles—their wavelength—is restricted to deformations that are parallel, spatially uniform, and nearly planar. However, most naturally occurring wrinkles do not satisfy these stipulations. Here we present a scheme that quantitatively explains the wrinkle wavelength beyond such idealized situations. We propose a local law that incorporates both mechanical and geometrical effects on the spatial variation of wrinkle wavelength. Our experiments on thin polymer films provide strong evidence for its validity. Understanding how wavelength depends on the properties of the sheet and the underlying liquid or elastic subphase is crucial for applications where wrinkles are used to sculpt surface topography, to measure properties of the sheet, or to infer forces applied to a film.

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ABSTRACT: Crashworthiness performance of conical tubes with various thickness distributions are investigated in the present work. Specimens are fabricated by tube shrinking process and axial crushing tests are carried out to study their energy absorption characteristics. The potential and benefit of tube shrinking to improve crashworthiness performance of tubes are analyzed. Both thickness increase and material hardening during tube shrinking lead to up to 120% increase in energy absorption with even less structural mass. Although the peak force of tubes is increased after shrinking, the load uniformity is still improved due to larger increase in mean crushing force. Numerical simulations are also conducted for tubes with quadratic thickness distributions. The material hardening during fabrication is included and the numerical results compare well with experiment. In addition, crashworthiness optimization of conical tubes with nonlinear thickness distribution is performed by surrogate method. Influences of relevant thickness parameters on performance of the structure are analyzed.

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ABSTRACT: This research work investigated the axial crushing behavior of a circular aluminum extrusion in alloy AA6063-T5 internally reinforced with a glass–fiber structure and filled with polymeric foam. The components were experimentally tested under quasi-static and impact loading conditions supported by a material testing campaign. Energy absorption, crush force efficiency and specific energy absorption were experimentally measured in order to assess the performance of a design proposal. Besides, the interaction effects between the different materials have been analyzed in depth and compared to the results for aluminum foam filled extrusions available in the literature. The confinement effect of the foam on the glass fiber plates has been found to have a very remarkable contribution to the energy absorption levels of the component, whereas a negligible foam–extrusion interaction was observed due to the gaps in the initial geometry of the specimen. The investigated component showed an overall good performance: the absorbed energy increased by almost 100% compared to an empty extrusion, the specific energy absorption was reduced by approximately 15% and the crush force efficiency was increased from 0.41 to 0.83.

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ABSTRACT: Several recent developments have shown that introducing sinusoidal patterns on square section automotive crash absorber beams increased the energy absorption. This paper studies the behaviour of patterned circular tubes when used as crash absorbers. The effect of varying parameters of radial and longitudinal geometrical pattern frequency on internal energy absorption and energy absorption effectiveness factor is also studied in this work. Different types of patterns were simulated in axial impacts in which two geometrical pattern frequencies (radial and longitudinal) are multiplied. A numerical investigation was carried out using the commercially available LS-DYNA™ solver. The investigation was verified using existing analytical models. Results indicate that the circular sinusoidal patterned tubes behave better in energy absorption in axial impact. However, circular tubes have an altogether different collapse mode therefore the pattern formation has to be modified and optimized differently as compared to square beams. A new set of patterns named as CBC patterns is proposed in the study which increased the energy absorption of circular tubes significantly. An increase of about 36.86% in energy absorption is noted and energy absorbing efficiency factor is escalated from 2.23 to 3.05 in the best case. This research may further endorse the feasibility of using sinusoidal patterned tubes in mainstream engineering applications.

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ABSTRACT: This study presents the buckling analysis of radially loaded solid circular plate made of porous material. Properties of the porous plate, where pores are assumed to be saturated with fluid, vary across its thickness. The boundary condition of the plate is assumed to be clamped and the plate is assumed to be geometrically perfect. The higher order shear deformation plate theory (HSDT) is employed to derive the governing equations. The equilibrium and stability equations, derived through the variational formulation and based on the Sanders non-linear strain–displacement relation, are used to determine the prebuckling forces and critical buckling loads. The results are compared with the buckling loads of circular plates made of porous material and reported in the literature based on the classical plate theory (CPT) and the first order shear deformation plate theory (FSDT).

ABSTRACT: In this paper, simplified mechanical models for the design of the top wind girder of large storage tanks adopted in the codes SH3046 and API650 were presented to show their differences regarding the wind load magnitude and action zone. Finite element models for the tanks were built to study the strengthening effects of the bottom constraints. It is found that for a large storage tank with a small ratio of height to diameter, the strengthening effects of the bottom constraints are significant and should not be ignored. If based on two-dimensional models without considering the strengthening effects of the bottom constraints, the strength design of the top wind girder according to the present codes of SH3046 or API650 is too conservative.

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ABSTRACT: The research investigates the axial splitting of E-glass/vinylester and E-glass/polyester composite columns with identical perimeters but different cross sections on polygonal aluminum dies, and the elimination of restrictions on the initial slit in the classical splitting process. A novel technique for the construction of mandrels using polystyrene foam is developed. Composite columns are produced by winding the fiber fabric layers around the mandrels using coarse and fine E-glass woven fibers. The deformation modes and energy absorption behavior of columns during the long stroke of the splitting process are compared. The effects of the initial slits, various cross sections, side lengths, number of fiber fabric layers, resin type, fiber fabric type and angle of polygon dies on the splitting and curling of the structures are investigated. The results of this study reveal that alternating cross sections of columns may affect deformation modes and energy absorption parameters.
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ABSTRACT: Vertical connecting plates exist in the panel zones of spatial moment frames, which are used to link beam webs in the perpendicular direction. However, current provisions take no consideration of their effect on the panel zone shear stability. This paper aims to evaluate the effect of vertical connecting plates on panel zone shear stability through experimental studies on cruciform beam-to-column subassemblages with/without connecting plates under cyclic loading. The connecting plates are found to be effective in mitigating the shear buckling potential of the panel zone and thus improving the hysteresis behavior of slender panel zones. Based on current seismic provisions, a modified approach for evaluating the panel zone shear stability through its equivalent width-thickness ratio is proposed and proved to be appropriate and on the conservative side.

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ABSTRACT: This paper considers local buckling of perforated square aluminium plates. Plates of various slenderness with simply supported edges and subjected to uniaxial compression are studied using the finite element method. Different perforation patterns are investigated, from a single circular hole to 25 circular holes distributed over the plate. A number of aluminium alloys are considered and compared to steel grade A36. Results show that the resistance of the plates containing a single central cut-out is higher than that of plates with more holes and of equal total cut-out size. A further refinement beyond 5 holes does not influence the resistance.

ABSTRACT: Lateral buckling is a main failure mode controlling the strength of C- and Z-section purlins under wind suction, as the compressive flange of cross-section is laterally free in this case. The lateral buckling of roof purlins is different from the normally considered simply supported beams, because the top flange of cross-section of these purlins is laterally restrained due to the bracing of the above roof sheeting. To reveal the lateral buckling of C- and Z-section purlins with their top flanges horizontally restrained, two representative buckling theories for the lateral buckling of thin-walled beams, the traditional buckling theory and a new theory recently proposed by the authors of this paper, are adopted in this study. Comparisons made in this study indicate that the total potentials derived from these two theories have different expressions for the considered purlins. Subsequently, the finite element (FE) analysis using the shell element modeling is adopted to examine the buckling loads of purlins based on these two buckling theories, which indicates that the buckling theory
proposed by the authors of this paper is more reasonable for this problem. Simple solutions are also proposed for buckling loads of C- and Z-section purlins with their top flange horizontally restrained, and very good agreements are achieved in the comparisons between the predictions of the proposed solutions and FE results.

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DOI: 10.1016/j.tws.2015.11.022
ABSTRACT: This paper presents a combined experimental, numerical, and theoretical study on the mechanical behaviors of track-shaped concrete-filled steel tubular (SCFRT) stub columns stiffened by rebars under compressive load. A total of 18 track-shaped concrete-filled steel tubular specimens including 12 specimens stiffened by rebars and 6 non-stiffened counterparts are tested, with consideration of parameters including flakiness ratio, concrete strength, and stiffeners. Failure pattern, bearing capacity, and ductility are all analyzed and discussed based on the experimental results. The numerical simulation by finite element (FE) software ABAQUS is also conducted. Based on both experimental and numerical results, theoretical formula to predict the load-bearing capacity of SCFRT stub columns subjected to axial compression loading is established according to the superposition principle of ultimate load-bearing capacity with rational simplification. The proposed theoretical method provides accurate predictions on the load bearing capacity by comparing with experimental results from 18 groups of specimens.

ABSTRACT: To facilitate accurate but conservative design of cellular beams for resistance against lateral–torsional buckling (LTB), this study proposes rational design guidelines based on General method of EC3. The inelastic LTB resistance was the subject of parametric studies using nonlinear finite elements, covering various loading configurations and geometric parameters of practical cellular beams. End moment and shear loadings were considered. The design resistance is slightly conservative in cases with complete LTB behavior that is generally found with non-dimensional slenderness exceeding 2.50. With short beams and shear loads LTB failure may interact with the local failures web-post buckling and web distortional buckling. However, combinations of LTB and Vierendeel failure were not observed. Concentrated stresses in the flange occur with short beams and moment loads, and these can degrade the LTB resistance. Due to interactions of the local failures in short beams, the design resistance requires a correction to ensure it is conservative. The key parameters affecting resistance include load configuration, section ratio, spacing ratio, and slenderness. All these parameters reflect shear effects, but section ratio and slenderness significantly influence the accuracy of the design results. Therefore, a correction factor based on these parameters is proposed, such that improves the EC3 accuracy by minimizing overestimation. The proposed LTB resistance design approach remains mostly conservative relative to both FE simulations and experimental results.

ABSTRACT: We present a detailed asymptotic analysis of the point indentation of an unpressurized, spherical elastic shell. Previous analyses of this classic problem have assumed that for sufficiently large indentation depths, such a shell deforms by ‘mirror buckling’ — a portion of the shell inverts to become a spherical cap with equal but opposite curvature to the undeformed shell. The energy of deformation is then localized in a ridge in which the deformed and undeformed portions of the shell join together, commonly referred to as Pogorelov’s ridge. Rather than using an energy formulation, we revisit this problem from the point of view of the shallow shell equations and perform an asymptotic analysis that exploits the largeness of the indentation depth. This reveals first that the stress profile associated with mirror buckling is singular as the indenter is approached. This consequence of point indentation means that mirror buckling must be modified to incorporate the shell's bending stiffness close to the indenter and gives rise to an intricate asymptotic structure with seven different spatial regions. This is in contrast with the three regions (mirror-buckled, ridge and undeformed) that are usually assumed and yields new insight into the large compressive hoop stress that ultimately causes the secondary buckling of the shell.

References listed at the end of the paper:

ABSTRACT: Buckling is characterized by a sudden failure of a structural member subjected to high compressive stress and it is a structural instability leading to a failure mode. One of the major design criteria of thin shell structures that experience compressive loads is that the buckling load limit. Therefore it is important to know about the Buckling loads. The buckling load of thin shell structures are dominantly affected by the geometrical imperfections present in the cylindrical shell which are very difficult to alleviate during manufacturing process. In this paper, two types of geometrical imperfection patterns are considered for cylindrical shells with and without dent. Analysis for all the cases is carried out and results are compared with theoretical results with ANSYS results .It is found that buckling strength of plain cylindrical shell is different compare to cylindrical shell having dents.

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ABSTRACT: Buckling analysis is of fundamental importance for the design and sizing of aerospace structures. These structures, which are essentially reinforced-shells, are commonly modelled by combining, via fictitious links, one-dimensional (1D/beam) and two-dimensional (2D/shell) finite elements that are implemented in commercial codes. This approach, however, introduces various physical and geometrical inconsistencies. For example, the out-of-plane warping of the stringers and the transverse normal stress in the panel are not considered. In the present paper, a geometrically exact higher-order beam model able to correctly characterize the three-dimensional strain/stress field is proposed for the accurate buckling analysis of reinforced aerospace structures. The proposed theory is based on the Carrera Unified Formulation (CUF), which, by employing a recursive index notation, allows to write the governing equations and the related finite element arrays of arbitrarily refined beam models in a very compact and unified manner. In fact, according to CUF, the three-
dimensional displacement field is expressed as a generic expansion of the primary mechanical variables by arbitrary functions of the cross-section coordinates. Namely, in this work, higher-order Lagrange polynomials are employed to formulate advanced beam theories in a hierarchical manner. The proposed models are referred to as Component-Wise (CW) because Lagrange polynomials are used to model the displacement variables in each structural component (i.e., stringers, panels, ribs, etc.) at the cross-sectional level. In a finite element framework, this means that different components are modelled using the same 1D finite element. By using the principle of virtual displacements and by considering the complete 3D stress field in formulating the geometrical stiffness, linearized buckling analysis of metallic, composite and reinforced panels as well as complex aerospace structures assemblies are investigated by CW models. Critical loads are also found as zero-frequency modes from vibration analysis of pre-stressed structures. Various boundary conditions and loadings are considered, including compression, combined traction/compression, and bending loads. The results, which are compared to those from the literature and commercial FEM tools, provide good confidence and widely demonstrate the high accuracy and numerical efficiency of the CW models when applied to buckling.

http://tuprints.ulb.tu-darmstadt.de/id/eprint/5288

ABSTRACT: Modern composite materials and lightweight construction elements are increasingly replacing classic materials in practical applications of mechanical and civil engineering. Their high prevalence creates a demand for calculation methods which can accurately describe the mechanical behavior of a composite structure, while at the same time preserving moderate requirements in terms of numerical cost. Modeling the full microstructure of a composite by means of the classical finite element method quickly exceeds the capabilities of today’s hardware. The resulting equation systems would be extremely large and unsuitable for solution due to their enormous calculation times and memory requirements. Homogenization methods have been developed as a remedy to this issue, in which the complex microstructure is replaced by a homogeneous material using averaged mechanical properties that are determined via experiments or by analytical or numerical investigation. However, classical homogenization methods usually fail as soon as nonlinear system behavior is introduced and the effective properties, which are presumed to be constant, begin to change during the course of a simulation. In this work, a coupled global-local method will be presented specifically for sandwich panels with axially stiffened or honeycomb cores. Herein, a global model, in which the complete structure is discretized with standard shell elements, is coupled with multiple local models, describing the microstructure of the sandwich throughout the full thickness coordinate and using shell elements for discretization as well. The local formulation is implemented by means of a constitutive law for the global model, so that one local boundary value problem is evaluated in each integration point of the global structure. By reevaluating the local models in every iteration step in a nonlinear simulation, physical and geometrical nonlinearity can be described. For instance, it will be shown in numerical examples that elasto-plastic material behavior and pre- and postcritical buckling behavior can be described, contrary to most classical homogenization methods. Next to the derivation of theoretical fundamentals and the introduction of the coupled method as well as several numerical examples, additional chapters are detailing some issues concerning mesh generation and the implementation of a high-bandwidth data interface between global and local models.

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ABSTRACT: Various manufacturing techniques exist to produce double-curvature shells, including injection, rotational and blow molding, as well as dip coating. However, these industrial processes are typically geared for mass production and are not directly applicable to laboratory research settings, where adaptable, inexpensive and predictable prototyping tools are desirable. Here, we study the rapid fabrication of hemispherical elastic shells by coating a curved surface with a polymer solution that yields a nearly uniform shell, upon polymerization of the resulting thin film. We experimentally characterize how the curing of the polymer affects its drainage dynamics and eventually selects the shell thickness. The coating process is then rationalized through a theoretical analysis that predicts the final thickness, in quantitative agreement with experiments and numerical simulations of the lubrication flow field. This robust fabrication framework should be invaluable for future studies on the mechanics of thin elastic shells and their intrinsic geometric nonlinearities.

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ABSTRACT: The non-linear dynamic analysis of continuous systems, such as thin plates and shells, is a problem of relevance in many engineering fields. The finite element method is the most used approach for nonlinear dynamic analyses of these structures. However, the computational effort is very high. As an alternative to complex numerical approaches, analytical methods using simplified models can be successfully used to understand the main nonlinear features of the problem and may constitute efficient tools in the initial design stages. For plates and shells, the derivation of efficient reduced order models is in fact essential due to the complex nonlinear response of these structures. The usual procedure is to reduce the partial differential equations of motion of the continuous system to an approximate system of time-dependent ordinary differential equations of motion, which are in turn solved by numerical methods or, approximately, by perturbation procedures. However, the use of inappropriate modal expansions usually leads to misleading results or may require a rather large number of terms. The aim of the present work is to show how the application of a perturbation analysis together with the Galerkin method can be used to derive precise low order models for plates and shells, by capturing the influence of modal couplings and interactions.

References listed at the end of the paper:

ABSTRACT: The stiffened panels are often forming less thin wall. Consequently, the dynamic buckling is a major challenge to be addressed in the quest to increase the strength-to-weight ratio. Stiffened are subjected to various loading conditions can be static or dynamic, as they may suffer from degradation of the material and initial geometric distortions due to the welding assembly process used. Buckling of structures subject to sudden dynamic impulse load can be analyzed without detour to the approach based on the equations of motion. In this approach, which can be easily adapted to the methods of calculation using the finite element method, the motion equations are solved for various values of the parameters defining the loading. The value of the load parameter for which there is a big change in the response then defines the critical load according Budiansky and Roth criterion.

In this work, dynamic buckling of stiffened panels is analyzed numerically through a nonlinear incremental formulation using explicit time integration procedure under Abaqus software package. The dynamic buckling state is recovered from the curve giving the end-shortening as function of time when the structure is subjected to a compressive rectangular pulse loading applied parallel ally to the stiffeners direction. Fixing the pulse duration and the initial distortion magnitude as well as the ratio of material degradation in the heat affected zone, the dynamic buckling load was identified for each given configuration. This process has enabled the derivation of a response surface model which was used with Monte Carlo method to determine reliability of the stiffened panel with regards to the dynamic buckling state.

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7. C. Bisagni, Dynamic buckling of fiber composite shells under impulsive axial compression, Thin-Walled Structures, 43 (2005), pp. 499–514
Sergio Pellegrino (Graduate Aerospace Laboratories, California Institute of Technology, 91125, Pasadena, CA, USA), “Folding and deployment of thin shell structures”, Chapter in Extremely Deformable Structures, pp 179-267, 2015, DOI: 10.1007/978-3-7091-1877-1_5, Vol. 562 of the series: CISM International Centre for Mechanical Sciences, Davide Bigoni, Editor, published by Springer Vienna

ABSTRACT: Thin shells made of high modulus material are widely used as lightweight deployable space structures. The focus of this chapter is the most basic deployable thin shell structure, namely a straight, transversely curved strip known as a tape spring. Following a review of the materials used for the construction of deployable thin shell structures, including constitutive models and failure criteria developed specifically for this type of structures, this chapter provides an introduction to the mechanics of tape springs and tape spring hinges. Finite element techniques to model deployable structures containing tape springs are presented and the ability of these models to accurately simulate experimentally observed behavior is demonstrated. These tools can be used to design structures able to achieve specific behaviors. As an example, the design of a two-hinge boom that can be wrapped around a small spacecraft without any damage, and can dynamically deploy and smoothly latch into the deployed configuration is presented.


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ABSTRACT: Stiffened panels are basic building blocks of weight sensitive structures. Design of laminated composite stiffened panels is more involved and requires the use of an optimization approach, which needs a computationally efficient analysis tool. This paper deals with the development of an analytical and computationally efficient analysis tool using artificial neural networks (ANN) for predicting the buckling load of laminated composite stiffened panels subjected to in-plane shear loading. The database for training and testing is prepared using finite element analysis. Studies are carried out by changing the panel orthotropy ratio, stiffener depth, pitch length (number of stiffeners). Using the database, key parameters are identified and a
neural network is trained. The results show that the trained neural network can predict the shear buckling load of laminated composite stiffened panels accurately and will be very useful in optimization applications where computational efficiency is paramount.

ABSTRACT: Thin-walled tubes are widely used as energy absorption components. In this study, two different origami patterns were introduced to circular tubes. The influence of the origami patterns on the energy absorption capacity and the deformation mechanism of tubes under uniaxial loading were investigated both numerically and experimentally. The results showed that the initial peak force of origami tubes would be significantly reduced, while the energy absorption capacity could be improved or maintained. Brass tubes with and without origami patterns were fabricated using 3D printing and were tested to validate the finite element models.

ABSTRACT: The paper presents a theory of inelastic column buckling which is consistent with the principles of plastic flow theory. The theory accounts for flexural, torsional and flexural-torsional modes. While the use of the tangent modulus to describe inelastic flexural buckling has been common place for a long time, efforts to comprehensively unite the torsional and flexural-torsional modes with the principles of plastic flow theory have so far been hampered by the ‘plastic buckling paradox’. New theoretical developments presented in this paper provide a way to achieve this goal. The solution hinges on the derivation of the inelastic shear stiffness while considering an infinitesimal solid element embedded within the column at a stage immediately past the point of buckling. The proposed inelastic column theory is verified against selected experimental data pertaining to aluminium and stainless steel columns of various cross-sections. Particular attention is paid to the torsional buckling problem of the inelastic cruciform section column.

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ABSTRACT: The transverse impact on a pipeline caused by a dropped anchor is among the main factors resulting in submarine pipeline failure. The impact could cause leakage of the pipeline, resulting in a huge environmental disaster and heavy economic losses. To investigate the deformations of a pipeline impacted by dropped anchors, a three-dimensional numerical method, known as the local Galerkin discretization method for shell structures, is developed under the condition of a rigid bed. The method has the advantages of higher-order
resolution and low computational cost. Small-scale model experiments were then carried out. Different bed conditions were considered, including rigid ground and ground covered by sandy soil. The dent depths of the pipes after the impacts were measured to study the pipeline deformations. The dent depths estimated by the local Galerkin discretization method were compared with the results of the experiment, which showed good consistency. The Galerkin numerical simulation method can also be applied to other pipe impact situations.

Luis A. Godoy (Institute for Advanced Studies in Engineering and Technology, Science and Technology Research Council (CONICET) and Universidad Nacional de Córdoba, FCEFyN, PO Box 916, Correo Central, Córdoba 5000, Argentina), “Buckling of vertical oil storage steel tanks: Review of static buckling studies”, Thin-Walled Structures, Vol. 103, pp 1-21, June 2016, DOI: 10.1016/j.tws.2016.01.026

ABSTRACT: Research on the structural behavior and buckling of vertical, aboveground tanks employed to store oil and fuels have significantly increased during the past two decades. Interest in this shell form is related not just to the cost of the infrastructure, but also because failures in cases of accidents or natural disasters may cause huge economic, environmental and social losses. This review concentrates on buckling problems of such tanks under static or quasi-static loads, including uniform pressure, wind, settlement of foundation, and fire. In all cases, buckling is considered as a static process. Attention is given to the load definition in each case, followed by buckling studies under previously defined pressures or temperatures. The structural configuration of tanks is first described in order to understand what is specific about this structural form. Next, the theoretical framework for stability and buckling is briefly described to place each contribution in a wider context. Each loading case is first explained, experiments or case-studies are briefly described, and computational analytical modeling is reviewed; finally, efforts towards improving design are mentioned. Most papers published in the literature have been motivated by wind effects on tanks, but the review shows that other areas, such as thermal buckling under an adjacent fire, are currently receiving increasing attention.

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ABSTRACT: This paper presents an analytical solution to predict the nonlinear forced vibrations of elastic thin-walled cylindrical shells under suddenly applied loads. Interest in this problem is motivated by effects due to explosions on fluid-storage metal tanks. The model is based on the energy criterion due to Lagrange, in which the kinematic nonlinear relations are assumed using Donnell's simplified shell theory. Solution is achieved as a series summation in terms of trigonometric functions in the axial and circumferential directions, whereas the degrees of freedom depend on time. A blast load is assumed to represent effects due to explosions on the shell as time-dependent pressures with a given circumferential distribution (a cosine square distribution in terms of the central angle). The procedure is validated by comparison with a nonlinear finite element model under the same load conditions. The influence of load level and shell geometry on the transient response is investigated by mean of parametric studies. Good accuracy is found in the results for the range of shells which are representative of horizontal, fuel storage tanks in the oil industry.

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DOI: 10.1016/S0263-8231(99)00029-4

ABSTRACT: Starting from an Airy stress function in plane strain a new solution is presented for the buckling of plates on elastic foundations with in-plane loading. Saint Venant's Principle is shown to play an important part in plate buckling behaviour when ‘deep’ foundations are present. Results are compared with those from Winkler's and Pasternak's models and they demonstrate that, provided certain restrictions are satisfied, the latter can give reasonably accurate results.


ABSTRACT: To date, despite the significant development in the field of structural mechanics, there still remains a paradox in the solutions available for a classical shell buckling problem. The difference in strength between a cylindrical shell under uniform axial compression and that under pure bending is not quite well investigated. This lack of research is reflected in the wide variations in the elastic bending strength given in current international design standards. This paper presents a theoretical treatment of the stability of unstiffened thin cylinders under pure flexure. The results of the theory are in good agreement with experimental findings. The theoretical results confirm the classical 40% increase in bending strength over axial strength. The current design rules for thin-cylinders are compared, and a newly derived design method is proposed.

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ABSTRACT: An efficient technique of Carbon Fiber Reinforced Polymer (CFRP) application was proposed to promote joint capacity of general tubular K-joints fabricated from Circular Hollow Section (CHS) members. Using this technique, in order to understand the static performance of CFRP-strengthened CHS joints, a systematic investigation was carried out by means of both experiments and finite element method. Three CHS gap K-joints strengthened with CFRP sheets were tested under static axial force in braces, whilst one additional joint was served as reference joint without CFRP. The results of failure modes, deformation, Mises stress, strain intensity and load-bearing capacity of the joints were presented and compared. A series of finite element models were developed and validated for the joints with and without CFRP reinforcement. A parametric study was conducted to evaluate the effect of variables (length, layers and mechanical properties of CFRP) on load-bearing capacity. The research results revealed that the proposed technique of CFRP installation was efficient to promote performance of in-service CHS gap K-joints. Moreover, the layer of CFRP sheets has significant effect on load-bearing capacity, but the effect was negligible for either length or mechanical properties of CFRP sheets. Finally, formulas were proposed for calculating ultimate load-bearing capacity of CHS gap K-joints with CFRP composites, and their calculation results matched well with the experimental and numerical results respectively.

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ABSTRACT: In this study, the crashworthiness behavior of the tapered multi-cell tubes is theoretically and numerically investigated. The side wall tapering and the cross section dividing into the cells are used in order to improve the energy absorption of the thin walled structure. In order to estimate the non-constant mean crush load of the tapered multi-cell tubes, incorporating the theoretical relations on the energy absorption of the simple multi-cell and tapered single-cell tubes, in conjunction with numerical results, would lead to the development of the analytical formula. The analytical formula is based on the mean crush load calculation of the equivalent segmented simple multi-cell tubes. In order to prepare a realistic finite element model, the elastic–plastic-damage material assumption is introduced into the numerical simulation. The numerical predictions of the mean crush load are consisted with experimental data in literature. The results reveal that the increase of the taper angle, the wall thickness and the number of cells in the cross section would enrich the crashworthiness capacity of the structure. The results indicate that the crashworthiness improvement rate of the structure with number of cells in the cross section is decreased in such a way that the variation of the energy absorption efficiency in the thin walled structure with the 8×8, 9×9 and 10×10 cells in the cross section would
be negligible. The transition wall thickness in which the crashworthiness of the tapered multi-cell structure transits from thin to thick walled behavior are determined.

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“Finite element limit load analysis of thin-walled structures by ANSYS (implicit), LS-DYNA (explicit) and in combination”, Thin-Walled Structures, Vol. 41, Nos 2-3, pp 227-244, February 2003,
DOI: 10.1016/S0263-8231(02)00089-7
ABSTRACT: After discussing general properties of implicit FE analysis using ANSYS and explicit analysis using LS-DYNA it is shown when and how quasi-static limit load analyses can be performed by a transient analysis using explicit time integration. Then we focus on the remaining benefits of implicit analysis and how a proper combination of ANSYS and LS-DYNA can be used to prepare the transient analysis by common preprocessing and static analysis steps. Aspects of discretization, solution control, consideration of imperfections and methods of checking the results are outlined.

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“Theoretical prediction and optimization of multi-cell hexagonal tubes under axial crashing”, Thin-Walled Structures, Vol. 102, pp 111-121, May 2016, DOI: 10.1016/j.tws.2016.01.023
ABSTRACT: In this paper, the analytical formulas of mean crashing force for four different hexagonal tubes with multiple cells were first derived based on the Simplified Super Folding Element (SSFE) theory through several typical constituent elements: corner element, three-panel angular element I and three-panel angular element II. The numerical simulations of hexagonal multi-cell configurations were then correlated with the derived analytical solutions. Finally, both analytical formulas and finite element analysis (FEA) based surrogate models were employed to optimize the cross-sectional dimensions of the hexagonal tubes. From the optimization results, web-to-web (W2W) is the most efficient configuration in improving the crashing behavior, while corner-to-corner (C2C) is the worst of these four configurations. Importantly, the Pareto fronts obtained from the analytical formulas agree well with those from the FEA based surrogate models. As a result, analytical formulas could be recommended in crashworthiness optimization for the sake of computational efficiency.

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“Application of high strength and ultra-high strength steel tubes in long hybrid compressive members: Experimental and numerical investigation”, Thin-Walled Structures, Vol. 102, pp 273-285, May 2016,
DOI: 10.1016/j.tws.2016.02.002
ABSTRACT: With the increasing application of high strength steel material in industries, there is a high potentiality for taking advantage of the exceptional load-bearing capacities of this material in construction
practice. In the present study, an innovative application for high and ultra-high strength steel material is proposed which enhances the overall behavior of structural elements. The high strength and ultra-high strength steel with nominal tensile strengths of 750 MPa and 1250 MPa, respectively, are proposed to be utilized as tube elements welded to corners of mild steel plates shaping an innovative hybrid section. This section takes advantage of the combined material properties of the two constituting elements in terms of strength, local buckling behavior and ductility. Large-scale tests and numerical analysis have been conducted to compare the behavior of the proposed sections against conventional welded sections. The effect of heat on the material properties of the hybrid section has also been considered. These effects are included in the finite element modeling of innovative columns where numerical outputs have been verified accordingly.

Tao Tang, Weigang Zhang, Hanfeng Yin and Han Wang (State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, Hunan University, Changsha, Hunan 410082, PR China), “Crushing analysis of thin-walled beams with various section geometries under lateral impact”, Thin-Walled Structures, Vol. 102, pp 43-57, May 2016, DOI: 10.1016/j.tws.2016.01.017

ABSTRACT: Due to the advantages of light weight and excellent energy absorption capacity, thin-walled beams are widely used as strengthen parts or energy absorbers in vehicle body. Thus, the collapse behaviors and mechanical properties of thin-walled beams under the static and dynamic loadings have drawn great attentions of the researchers. In vehicle side crash accident, the contact parts of the vehicle usually deformed in bending mode. Thus, it is significantly important to investigate the bending collapse behaviors of these parts. In this study, the bending behaviors of several thin-walled beams with simple cross section subjected to lateral impact were investigated using analytical and numerical methods. The crashworthiness parameters such as energy absorption ($EA$), average crash force ($F_{avg}$), peak crash force ($F_{max}$) and crash force efficiency ($CFE$) were employed to evaluate the bending resistant property. In order to study how geometry shapes affect the bending performance, the main geometry parameters such as radius/radius ratio of circular/elliptical section, side length ratio of rectangular section, height and base angle of hat section were chosen as the design parameters. After investigating the beams with simple cross sections, some new beams with complex cross sections were constructed by combing these simple beams or adding reinforce ribs to these simple beams. Then, the bending performance of these new beams was studied by numerical simulation and compared with original section beams. Result shows that the section type b performs better in $SEA$ and $CFE$ than original simple section beams. It also can be concluded that adding ribs can greatly improve the bending resistant performance for circular, rectangular and hat section beams, and the vertical ribs can achieve the best reinforce effect for the circular and rectangular section beams.

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ABSTRACT: This paper presents a novel thin-walled tube design with a pre-folded kite-shape rigid origami pattern as an energy absorption device. Numerical simulation of the quasi-static axial crushing of the new device shows that a smooth and high reaction force curve can be achieved in comparison with those of conventional square tubes, with an increase of 29.2% in specific energy absorption and a reduction of 56.5% in initial peak force being obtained in the optimum case. A theoretical study of the energy absorption of the new device has also been conducted, which matches reasonably well with the numerical results.
ABSTRACT: Thin-walled tubes are widely used as energy absorbers. In this study, we evaluated the energy absorbing behavior of empty and aluminum metal foam-filled tubes with different taper angles (0°, 5°, 10°, and 15°) by using the Finite Element Method (FEM)/Smooth Particle Hydrodynamics (SPH) with the Feed forward Neural Network (FNN). Within the scope of the study, tubes composed of AL6061 and AISI1018 materials were designed by using three different weld locations (L0/L=0.25, L0/L=0.50, and L0/L=0.75). In the welded tubes, the thickness of the lower part (AISI1018) was held constant (1.5 mm), while the thickness of the upper part (AL6061) and the foam density of the filler material were variable (0.5–2.5 mm and 100–800 kg/m³, respectively). Based on the analysis of the study results, it was determined that empty and foam-filled tubes with a 5° taper angle exhibited the best energy absorbing behavior. In addition, we also determined the optimum upper part thickness and foam density for obtaining the minimum peak force (Fpeak) and maximum specific energy absorption (SEA) values.

Francesco Tornabene, Nicholas Fantuzzi and Michele Bacciocchi (DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy), “Higher-order structural theories for the static analysis of doubly-curved laminated composite panels reinforced by curvilinear fibers”, Thin-Walled Structures, Vol. 102, pp 222-245, May 2016, DOI: 10.1016/j.tws.2016.01.029
ABSTRACT: The main aim of this paper is the evaluation of the through-the-thickness profiles of strain, stress and displacement components of several doubly-curved panels reinforced by curvilinear fibers. The placement of the reinforcing phase along curved paths allows to obtain mechanical properties which change point by point and affects the static behavior of shell structures. Some numerical applications based on both higher-order Equivalent Single Layer (ESL) and Layer-Wise (LW) theories are shown in order to underline the curvilinear fiber influence on the static analysis. The structural model, which is based on the so-called Carrera Unified Formulation (CUF), is completely general and can deal easily with variable stiffness shells. An appropriate recovery procedure based on the three-dimensional elasticity equations in principal curvilinear coordinates is presented to compute strains and stresses. The equation system which governs the static problem under consideration is solved numerically through the Generalized Differential Quadrature (GDQ) method. The same numerical technique is employed to evaluate the geometrical parameters needed for the characterization of the shell reference surface, according to the differential geometry.

W. Hamouche, C. Maurini, A. Vincenti and S. Vidoli (Institut Jean Le Rond d’Alembert, Sorbonne Universités, UPMC Univ Paris 06, CNRS, UMR 7190, 4 place Jussieu, 75005, Paris, France), “Basic criteria to design and produce multistable shells”, Meccanica, pp 1-16, First online 02 February 2016, DOI: 10.1007/s11012-016-0375-5
ABSTRACT: A shell can have multiple stable equilibria either if its initial curvature is sufficiently high or if a suitably strong pre-stress is applied. Under the hypotheses of a thin and shallow shell, we derive closed form results for the critical values of curvatures and pre-stresses leading to bistability and tristability. These analytical expressions allow to easily provide guidelines to build shells with different stability properties.

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Ten papers on wrinkling given at the American Physical Society (APS) meeting on March 16, 2016 in Baltimore, Maryland, in Session P40: More Geometry and Dynamics: Wrinkling, Folding, Snapping, etc.:

Michael Imburgia and Alfred Crosby (University of Massachusetts, Amherst, MA, USA) “Rolling wrinkles on elastic substrates”, Abstract ID BAPS.2016.MAR.P40.1

ABSTRACT: The mechanics of rolling contact between an elastomer layer and a thin film present unique opportunities for taking advantage of elastic instabilities, such as surface wrinkling, to create patterned surfaces. Here we present a plate-to-roll(P2R) geometry to laminate a thin film onto an elastomer layer in order to induce surface wrinkling. First, a poly(dimethylsiloxane)(PDMS) layer is draped around a roller and pressed into contact with a poly(styrene)(PS) film supported on a plate. Once rolling begins, the PS film preferentially laminates onto the PDMS layer. During this process, the deformation of the PDMS layer can induce wrinkling when the contact load exceeds a critical value. Wrinkle feature size consists of amplitudes of $0.2-4 \mu m$ and wavelengths of $15-20 \mu m$. Wrinkle amplitude can be controlled by contact load and roller curvature, as well as the mechanical properties and thickness of the film and elastomer. We develop semi-empirical equations to describe the effect of contact load and roller curvature on the wrinkle aspect ratio. Finite-element modeling of
an elastomer layer in rolling contact with a rigid plate is used to support experimental results. Using these models, wrinkle-based technologies such as optoelectronics and enhanced adhesives can be envisioned.

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“Poking around: how indentation reveals wrinkly isometries”, Abstract ID BAPS.2016.MAR.P40.2

ABSTRACT: When deforming extremely thin objects, deformation via stretching is relatively expensive. It is therefore natural to seek deformations that preserve lengths, or isometries. Two common examples of such isometries in mechanics are the ‘d’-cone (for a plate) and ‘mirror buckling’ (for a shell). I will show two examples for which the presence of a weak tension means that these isometries are not obtained experimentally. Instead, the systems in question wrinkle and tend to new ‘wrinkly isometries’: isometries that are only available to a wrinkled object.


ABSTRACT: A thin film confined to a liquid interface responds to uniaxial compression by wrinkling, and then by folding, that has been solved exactly before self-contact. Here, we address the mechanics of large folds, i.e., folds that absorb a length much larger than the wrinkle wavelength. With scaling arguments and numerical simulations, we show that the antisymmetric fold is energetically favorable and can absorb any excess length at zero pressure. Then, motivated by puzzles arising in the comparison of this simple model to experiments on lipid monolayers or capillary rafts, we discuss how to incorporate film weight, self-adhesion, or energy dissipation.

References listed at the end of the paper:
Joseph D. Paulsen (1), Vincent Demery (2), K. Bugra Toga (3), Zhanlong Qiu (4), Benny Davidovitch (4), Thomas P Russell (4) and Narayanan Menon (4)

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“Geometry-driven folding transitions in floating thin films”, Abstract ID BAPS.2016.MAR.P40.3

ABSTRACT: When a thin elastic sheet is compressed, it forms wrinkles to gather excess material, while deforming the fluid or solid substrate by only a small amount. Upon further compression, the sheet may fold, in order to lower the mechanical energy of the system. Here we demonstrate a folding transition that is independent of the mechanical properties of the sheet. We study the deformations of a thin polymer film that has an annular shape, floating on a planar air-water interface. By controlling the concentration of a surfactant outside the film, we vary the tension pulling on the outer boundary of the annulus. The sheet spontaneously folds at a threshold ratio of inner to outer surface tension that depends on the geometry of the sheet, but is independent of its bending rigidity. Our results are consistent with a simple geometric principle: the sheet adopts the unstretched shape that minimizes the interfacial energy of the exposed liquid. Finally, we consider the application of this geometric principle to the folding of a floating indented film.


ABSTRACT: Thin spherical shells range from nanometer-sized viruses to space vehicles. A pressure differential between the inner and outer part of the shell can result in the buckling and catastrophic failure of the structure. We revisit this classic buckling problem, depressurizing thin elastic shells, which are arrested from within by a concentric spherical mandrel. As a result, buckling is constrained to occur within the gap between the two. Above a critical pressure, dimples appear sequentially on the surface of the shell to form a robust periodic pattern. We perform precision desktop experiments to construct the bifurcation diagram of the process, and explore a range of geometric and material properties. A scaling analysis enables us to rationalize the dependence of the size of the dimples on both the radius of the shell and the radial gap between the shell and the inner rigid mandrel. Moreover, we characterize the process of nucleation and progression of the dimpled pattern front. Particular emphasis is given to the patterns obtained in the strongly nonlinear post-buckling regime where a network of sharp ridges forms.


ABSTRACT: We revisit the classic problem of buckling of spherical elastic shells under pressure loading, with an emphasis on determining the role that engineered imperfections have on the critical buckling pressure. Since
the 1960s numerous theoretical and computational studies have addressed this canonical problem in engineering mechanics, but there is a striking lack of precision experiments to corroborate these predictions. We perform an experimental investigation where thin shells of nearly uniform thickness are fabricated by the coating of hemispherical molds with a polymer solution, which upon curing yields the elastic structure. Moreover, our manufacturing technique allows us to introduce a single dimple-like defect with controllable geometric properties. By systematically varying the amplitude of this defect (smaller than the thickness of the shell) we study the effect that these imperfections have on the buckling strength of our spherical shells. Small deviations from the spherical geometry result in large reductions in the buckling pressure and our experimental results agree well with the existing theories. We then perform a broader exploration for other classes of defects, for which theoretical predictions are yet to be developed.

Sarah Selden, Arthur Evans, Nakul Bende, Ryan Hayward, Christian Santangelo (University of Massachusetts – Amherst), “Stress localization in elastic shells”, Abstract ID BAPS.2016.MAR.P40.6
ABSTRACT: Upon indentation, thin shells react by localizing strain energy in polygonal structures as opposed to a uniform axisymmetric distribution. While the formation of these localized structures are well-characterized for perfect shells, a change in shell thickness or the introduction of a crease fundamentally changes the nature of the shell deformation. We perform finite element simulations, in tandem with experiments to explore the effect of different shell geometries on the energy landscape. We find that the crease induces a new symmetry-breaking localization that does not appear in perfect shells, and we explore the deformation characteristics of the creased shell over a wide range of crease radii, and crease orientations.

Salem Al Mosleh and Christian Santangelo (University of Massachusetts – Amherst), “Regularizing rigidifying curves to understand the low-energy deformations of thin shells”, Abstract ID BAPS.2016.MAR.P40.7
ABSTRACT: It is much harder to stretch a piece of paper than bend it. We exploit this fact to simplify the elastic energy of a thin shell. We accomplish this by extending the linear isometric displacements, displacements that do not cause stretching to lowest order, to low energy Nambu-Goldstone modes. This approach fails in an interesting way in the vicinity of “rigidifying curves,” curves with zero normal curvature, because half of the linear isometries are divergent there. We use a renormalization group methods to show that nonlinearities in the strain regularize these divergences. We explore the relationship between these modes and folding along curves of zero normal curvature.

Michael Gomez, Derek E. Moulton and Dominic Vella (Mathematical Institute, University of Oxford), “Hunting for ghosts in elastic snap-through”, Abstract ID BAPS.2016.MAR.P40.8
ABSTRACT: Elastic ‘snap-through’ is a striking instability often seen when an elastic system loses bistability, e.g. due to a change in geometry or external loading. The switch from one state to another is generally rapid and hence is used to generate fast motions in biology and engineering. While the onset of instability has been well studied, the dynamics of the transition itself remain much less well understood. For example, the dynamics exhibited by children’s jumping popper toys, or the leaves of the Venus flytrap plant, are much slower than would be expected based on a naïve estimate of the elastic timescales. To explain this discrepancy, the natural conclusion has been drawn that some other effect, such as viscoelasticity, must play a role. We demonstrate here that purely elastic systems may show similar ‘slow’ dynamics during snap-through. This behaviour is due to a remnant (or ‘ghost’) of the snap-through bifurcation underlying the instability, analogously to bottleneck phenomena in 1-D dynamical systems. This slowness is a generic consequence of being close to bifurcation — it does not require dissipation. We obtain scaling laws for the length of the delay and compare these to numerical simulations and experiments on real samples.
Yiwei Sun, Benny Davidovitch and Gregory Grason (University of Massachusetts – Amherst), “Wrinkling instability induced by imposed Gaussian curvature in the zero-tension limit”, Abstract ID BAPS.2016.MAR.P40.9
ABSTRACT: The adhesion of thin stiff films onto spherical substrates introduces compressive stresses, which cause the laminated film to buckle out of plane. Previous studies addressed the emerging wrinkle pattern in the limit of zero bending modulus and the presence of surface tension at the boundary, and found the radius of the inner unwrinkled zone scales with the tension. Here we study another fundamental limit: finite bending modulus and zero exerted tension. In this limit, subtlety will arise from the fact that the singular expansion, which previous studies relied on, becomes ill-defined. To reveal the morphology in the zero-tension limit, we employ numerical simulations based on bead-bond model. Surprisingly, we find that the scaling law for the radius of the unwrinkled zone can be generalized from the finite tension to the zero tension limit, by applying a bending modulus dependent term to the tension dominated scale. The simulation results also highlight the residual compressive hoop stress, which is scaled by bending modulus in the absence of tension. The findings suggest the existence of a new, yet unstudied process, by which the deformed shape of the sheet approaches isometry as the bending modulus vanishes, in the absence of boundary loads.

Nicholas Nechitaiilo (Naval Surface Warfare Center, Dahlgren, Virginia), “Unpredictable motion and post-chaotic self-organization of flexible structures”, Abstract ID BAPS.2016.MAR.P40.10
ABSTRACT: Two physical phenomena, “reverse buckling” and “post-chaotic self-organization”, were discovered by the author of this paper. The phenomena were analyzed using Newton’s mechanics, Euler bifurcation and buckling theory, and Poincare’s theory of chaotic motion when “prediction becomes impossible.” However, our experimental and theoretical findings revealed a more complex nonlinear physics with some predictability of final states. Geometric and material nonlinearities in flexible plates, beams and shells lead to transient chaos and unexpected final shapes. In one experiment, an axisymmetric transverse pressure pulse was applied to a circular metal membrane. It buckled, lost axial symmetry and formed a folded six-corner star. In another test, an impulsively stretched rod buckled and obtained a final shape similar to that of a rod under static axial compression. “Reputable” finite element and finite difference codes could not reliably predict deformation of an aluminum beam under a transverse pressure pulse. The anomalous responses were observed in a narrow region of the load amplitude and duration. These were described by simple analytical equations. Similar phenomena were seen in nonlinear equations of motion representing various non-mechanical systems.

ABSTRACT: In this paper a hexahedral solid-shell element with in-plane reduced integration is developed. The element is intended to the analysis of thin/thick elastic–plastic shells with moderate to large strains. Developed within the framework of a total Lagrangian formulation, the element uses as strain measure the logarithm of the right stretch tensor \( \mathbf{F} \) obtained from a modified right Cauchy–Green tensor \( \mathbf{C} \). The modifications, in order to remove transverse shear, Poisson and volumetric locking, are three: a) a classical assumed mixed shear strain approximation for and b) an assumed strain approximation for the in-plane components and c) an enhanced assumed strain for the through the thickness normal component (one additional degree of freedom). The first five components of are interpolated to the integration points from values at the center of the top and bottom faces. An arbitrary number of integration points is used in the transverse direction and a stabilization scheme is used to avoid spurious modes due to the in-plane sub integration. Several examples are presented that show the locking-free behavior and the very good performance of the presented element for the analysis of shells with
geometric and material nonlinearities, including quasi-incompressible elastic and elastic–plastic with incompressible plastic flow models.


ABSTRACT: A recent paper (Healey et al., J. Nonlin. Sci., 2013, 23, 777-805.) predicted the disappearance of the stretch-induced wrinkled pattern of thin, clamped, elastic sheets by numerical simulation of the Foppl-von Karman equations extended to the finite in-plane strain regime. It has also been revealed that for some aspect ratios of the rectangular domain wrinkles do not occur at all regardless of the applied extension. To verify these predictions we carried out experiments on thin (20 µm thick adhesive covered), previously prestressed elastomer sheets with different aspect ratios under displacement controlled pull tests. On one hand the the adjustment of the material properties during prestressing is highly advantageous as in targeted strain regime the film becomes substantially linearly elastic (which is far not the case without prestress). On the other hand a significant, non-ignorable orthotropy develops during this first extension. To enable quantitative comparisons we abandoned the assumption about material isotropy inherent in the original model and derived the governing equations for an orthotropic medium. In this way we found good agreement between numerical simulations and experimental data. Analysis of the negativity of the second Piola-Kirchhoff stress tensor revealed that the critical stretch for a bifurcation point at which the wrinkles disappear must be finite for any aspect ratio. On the contrary there is no such a bound for the aspect ratio as a bifurcation parameter. Physically this manifests as complicated wrinkled patterns with more than one highly wrinkled zones on the surface in case of elongated rectangles. These arrangements have been found both numerically and experimentally. These findings also support the new, finite strain model, since the Foppl-von Karman equations based on infinitesimal strains do not exhibit such a behavior.

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Noureddine Damil, Michel Potier-Ferry, Heng Hu. New nonlinear multiscale models for wrinkled membranes. 2013. <hal-00823921>, Comptes Rendus Mecanique, Vol 341, No. 8, pp 616-624, August 2013, Elsevier

ABSTRACT: A new macroscopic approach to modelise membrane wrinkling is presented. Most of the studies of the literature about membrane behaviour are macroscopic and phenomenological, the influence of wrinkles being accounted by non-linear constitutive laws without compressive stiffness. The present method is multiscale and it permits to predict the wavelength and the spatial distribution of wrinkling amplitude. It belongs to the family of Landau-Ginzburg bifurcation equations and especially it relies on the technique of Fourier series with slowly varying coefficients. The result is a new family of macroscopic membrane models that are deduced from Föppl-Von Karman plate equations. Numerical solutions are presented giving the size of the wrinkles as a function of the applied compressive and tensile stresses.

Xu, F., Potier-Ferry, M., Belouettar, S., Cong, Y., “3D finite element modeling for instabilities in thin films on soft substrates”, Int. J. Solids Struct. 51, 3619–3632., October 2014, DOI: 10.1016/j.ijsolstr.2014.06.023

ABSTRACT: Spatial pattern formation in stiff thin films on compliant substrates is investigated based on a nonlinear 3D finite element model. Typical post-bifurcation patterns include 1D sinusoidal, checkerboard and herringbone shapes, with possible spatial modulations, boundary effects and localizations. The post-buckling behavior often leads to intricate response curves with several secondary bifurcations that were rarely studied and only in the case of periodic cells. The proposed finite element procedure allows accurately describing these bifurcation portraits by taking into account the effect of boundary conditions. It relies on the Asymptotic Numerical Method (ANM) that offers considerable advantages to get a robust path-following technique and to detect multiple bifurcations. The occurrence and evolution of sinusoidal, checkerboard and herringbone patterns will be highlighted.

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ABSTRACT: A wrinkling-based method is proposed to create various surface micropatterns regulated by a hardened skin layer with a periodic stiffness distribution on a soft material. It is shown that the surface patterns generated by this technique are controlled by three fundamental surface deformation modes that involve sinusoidal wrinkling, Euler buckling, and rigid rotation of the skin. Systematic experiments and a phase diagram validate the efficacy and robustness of the proposed method.


ABSTRACT: Numerically accurate simulation of the mechanical behavior of thin flexible structures is important in application areas ranging from engineering design to animation special effects. Subdivision surfaces provide a unique opportunity to integrate geometric modeling with concurrent finite element analysis of thin flexible structures. Their mechanics are governed by the so-called thin-shell equations. We present a concise treatment of thin-shell equations including dynamic behavior, scalable material models, and the treatment of collisions (detection as well as response). The resulting energy minimization problem is non-linear and in turn able to capture effects of far more realism than linear models. We demonstrate these claims with a number of simulations which exhibit characteristic effects of real world experiments.

References listed at the end of the report:
unlike mesh refinement, basis refinement never creates incompatible meshes. Our contributions are (a) a basic principle of our approach is to refine basis functions, not elements. Our method is naturally compatible: simple, general method for adaptive refinement which applies uniformly in all these settings and others. The basic principle of our approach is to refine basis functions, not elements. Our method is naturally compatible: unlike mesh refinement, basis refinement never creates incompatible meshes. Our contributions are (a)
minimal mathematical framework, with (b) associated algorithms for basis refinement; furthermore, we (c) describe the mapping of popular methods (finite-elements, wavelets, splines and subdivision) onto this framework, and (d) demonstrate working implementations of basis refinement with applications in graphics, engineering, and medicine.

Our approach is based on compactly supported refinable functions. We refine by augmenting the basis with narrowly-supported functions, not by splitting mesh elements in isolation. This removes a number of implementation headaches associated with element-splitting and is a general technique independent of domain dimension, element type (e.g., triangle, quad, tetrahedron, hexahedron), and basis function order (piecewise linear, quadratic, cubic, etc.). The (un-)refinement algorithms are simple and require little in terms of data structure support. Many popular discretizations, including classical finite-elements, wavelets and multi-wavelets, splines and subdivision schemes may be viewed as refinable function spaces, thus they are encompassed by our approach. Our first contribution is the specification of a minimal mathematical framework, at its heart a sequence of nested approximation spaces. By construction, the bases for these spaces consist of refinable functions. From an approximation theory point of view this is a rather trivial statement; however it has a number of very important and highly practical consequences. Our adaptive solver framework requires only that the basis functions used be refinable. It makes no assumptions as to (a) the dimension of the domain; (b) the tesselation of the domain, i.e., the domain elements be they triangles, quadrilaterals, tetrahedra, hexahedra, or more general domains; (c) the approximation smoothness or accuracy; and (d) the support diameter of the basis functions. The specification of the nested spaces structure is sufficiently weak to accommodate many practical settings, while strong enough to satisfy the necessary conditions of our theorems and algorithms.

Our second contribution is to show that basis refinement can be implemented by a small set of simple algorithms. Our method requires efficient data structures and algorithms to (a) keep track of interactions between basis functions (i.e., to find the non-zero entries in the stiffness matrix), and (b) manage a tesselation of the domain suitable for evaluation of the associated integrals (i.e., to evaluate the entries of the stiffness matrix). We provide a specification for these requirements, develop the relevant theorems and proofs, and invoke these theorems to produce concrete, provably-correct pseudo-code. The resulting algorithms, while capturing the full generality (in dimension, tesselation, smoothness, etc.) of our method, are surprisingly simple.

Our third contribution is the mapping of finite-elements, wavelets and multi-wavelets, splines and subdivision schemes onto our nested spaces framework. No single discretization fits all applications. In our survey of classical and recently-popularized discretizations we demonstrate that our unifying algorithms for basis refinement encompass a very broad range of problems.

Our fourth contribution is a set of concrete, compelling examples based on our implementation of basis refinement. Adaptive basis refinement may be profitably applied in solving partial differential equations (PDEs) useful in many application domains, including simulation, animation, modeling, rendering, surgery, biomechanics, and computer vision. Our examples span thin shells (fourth order elliptic PDE using a Loop subdivision discretization), volume deformation and stress analysis using linear elasticity (second order PDE using linear-tetrahedral and trilinear-hexahedral finite elements respectively) and a subproblem of electrocardiography (the generalized Laplace equation using linear tetrahedral finite elements).


ABSTRACT: Current formulations of adaptive finite element mesh refinement seem simple enough, but their implementations prove to be a formidable task. We offer an alternative point of departure which yields equivalent adapted approximation spaces wherever the traditional mesh refinement is applicable, but our method proves to be significantly simpler to implement. At the same time it is much more powerful in that it is
general (no special tricks are required for different types of finite elements), and applicable for some newer approximations where traditional mesh refinement concepts are not of much help, for instance on subdivision surfaces.


ABSTRACT: Many computer graphics applications require high-intensity numerical simulation. We show that such computations can be performed efficiently on the GPU, which we regard as a full function streaming processor with high floating-point performance. We implemented two basic, broadly useful, computational kernels: a sparse matrix conjugate gradient solver and a regular-grid multigrid solver. Real time applications ranging from mesh smoothing and parameterization to fluid solvers and solid mechanics can greatly benefit from these, evidence our example applications of geometric flow and fluid simulation running on NVIDIA's GeForce FX.


ABSTRACT: In this paper we introduce a discrete shell model describing the behavior of thin flexible structures, such as hats, leaves, and aluminum cans, which are characterized by a curved undeformed configuration. Previously such models required complex continuum mechanics formulations and correspondingly complex algorithms. We show that a simple shell model can be derived geometrically for triangle meshes and implemented quickly by modifying a standard cloth simulator. Our technique convincingly simulates a variety of curved objects with materials ranging from paper to metal, as we demonstrate with several examples including a comparison of a real and simulated falling hat.

References listed at the end of the paper:

Yotam Gingold, Adrian Secord, Jefferson Y. Han, Eitan Grinspun and Denis Zorin, “A discrete model for inelastic deformation of thin shells”, (publisher not given in the pdf file), August 2004
ABSTRACT: We introduce a method for simulating the inelastic deformation of thin shells: we model plasticity and fracture of curved, deformable objects such as light bulbs, egg-shells and bowls. Our novel approach uses triangle meshes yet evolves fracture lines unrestricted to mesh edges. We present a novel measure of bending strain expressed in terms of surface invariants such as lengths and angles. We also demonstrate simple techniques to improve the robustness of standard timestepping as well as collision-response algorithms.

Eitan Grinspun (Columbia University), “A discrete model of thin shells”, Proceeding SIGGRAPH ’05 ACM SIGGRAPH 2005 Courses, Article No. 4, 2005
ABSTRACT: We present a discrete model for the behavior of thin flexible structures, such as hats, leaves, and aluminum cans, which are characterized by a curved undeformed configuration. Previously such models required complex continuum mechanics formulations and correspondingly complex algorithms. We show that a simple shell model can be derived geometrically for triangle meshes and implemented quickly by modifying a standard cloth simulator. Our technique convincingly simulates a variety of curved objects with materials ranging from paper to metal, as we demonstrate with several examples including a comparison of a real and simulated falling hat. This chapter is based on the paper by Grinspun, Hirani, Desbrun, and Schröder which appeared in the Proceedings of the Symposium for Computer Animation 2003 [Grinspun et al. 2003].

ABSTRACT: We introduce a way of simulating the creation of simple Origami (paper folding). The Origami is created in a thin shell simulation that realistically models the behavior and physical properties of paper. We
demonstrate how to fold and crease the simulated paper wherever the user desires. This work employs cutting-edge advances in the field of discrete shell modeling to meet the challenge of simulating Origami. We found that the discrete shell model is capable of creating simple Origami that does not involve paper to paper collisions. For more advanced origami, however, some kind of collision detection and resolution scheme is required. Further research is necessary to implement collision handling while maintaining a practical simulation speed.


ABSTRACT: Hinge-based bending models are widely used in the physically-based animation of cloth, thin plates and shells. We propose a hinge-based model that is simpler to implement, more efficient to compute, and offers a greater number of effective material parameters than existing models. Our formulation builds on two mathematical observations: (a) the bending energy of curved flexible surfaces can be expressed as a cubic polynomial if the surface does not stretch; (b) a general class of anisotropic materials---those that are orthotropic---is captured by appropriate choice of a single stiffness per hinge. Our contribution impacts a general range of surface animation applications, from isotropic cloth and thin plates to orthotropic fracturing thin shells.


ABSTRACT: We combine the often opposing forces of artistic freedom and mathematical determinism to enrich a given animation or simulation of a surface with physically based detail. We present a process called tracking, which takes as input a rough animation or simulation and enhances it with physically simulated detail. Building on the foundation of constrained Lagrangian mechanics, we propose weak-form constraints for tracking the input motion. This method allows the artist to choose where to add details such as characteristic wrinkles and folds of various thin shell materials and dynamical effects of physical forces. We demonstrate multiple applications ranging from enhancing an artist's animated character to guiding a simulated inanimate object.


ABSTRACT: We present a method for simulating highly detailed cutting and fracturing of thin shells using low-resolution simulation meshes. Instead of refining or remeshing the underlying simulation domain to resolve complex cut paths, we adapt the extended finite element method (XFEM) and enrich our approximation by customdesigned basis functions, while keeping the simulation mesh unchanged. The enrichment functions are stored in enrichment textures, which allows for fracture and cutting discontinuities at a resolution much finer than the underlying mesh, similar to image textures for increased visual resolution. Furthermore, we propose harmonic enrichment functions to handle multiple, intersecting, arbitrarily shaped, progressive cuts per element in a simple and unified framework. Our underlying shell simulation is based on discontinuous Galerkin (DG) FEM, which relaxes the restrictive requirement of C^1 continuous basis functions and thus allows for simpler, C^0 continuous XFEM enrichment functions.

ABSTRACT: In this paper, we derive a variational integrator for certain highly oscillatory problems in mechanics. To do this, we take a new approach to the splitting of fast and slow potential forces: rather than splitting these forces at the level of the differential equations or the Hamiltonian, we split the two potentials with respect to the Lagrangian action integral. By using a different quadrature rule to approximate the contribution of each potential to the action, we arrive at a geometric integrator that is implicit in the fast force and explicit in the slow force. This can allow for significantly longer time steps to be taken (compared to standard explicit methods, such as Störmer/Verlet) at the cost of only a linear solve rather than a full nonlinear solve. We also analyze the stability of this method, in particular proving that it eliminates the linear resonance instabilities that can arise with explicit multiple-time-stepping methods. Next, we perform some numerical experiments, studying the behavior of this integrator for two test problems: a system of coupled linear oscillators, for which we compare the stability of this method against the resonance behavior of the r-RESPA method, and slow energy exchange in the Fermi–Pasta–Ulam (FPU) problem, which couples fast linear oscillators with slow nonlinear oscillators. Finally, we prove that this integrator accurately preserves the slow energy exchange between the fast oscillatory components, which explains the numerical behavior observed for the FPU problem.


ABSTRACT: We develop an accurate, unified treatment of elastica. Following the method of resultant-based formulation to its logical extreme, we derive a higher-order integration rule, or elaston, measuring stretching, shearing, bending, and twisting along any axis. The theory and accompanying implementation do not distinguish between forms of different dimension (solids, shells, rods), nor between manifold regions and non-manifold junctions. Consequently, a single code accurately models a diverse range of elastoplastic behaviors, including buckling, writhing, cutting and merging. Emphasis on convergence to the continuum sets us apart from early unification efforts.

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“Discrete Viscous Sheets”, (an on-line pdf file, no date or publisher given; most recent reference is 2011)

ABSTRACT: We present the first reduced-dimensional technique to simulate the dynamics of thin sheets of viscous incompressible liquid in three dimensions. Beginning from a discrete Lagrangian model for elastic thin shells, we apply the Stokes-Rayleigh analogy to derive a simple yet consistent model for viscous forces. We incorporate nonlinear surface tension forces with a formulation based on minimizing discrete surface area, and preserve the quality of triangular mesh elements through local remeshing operations. Simultaneously, we track and evolve the thickness of each triangle to exactly conserve liquid volume. This approach enables the simulation of extremely thin sheets of viscous liquids, which are difficult to animate with existing volumetric approaches. We demonstrate our method with examples of several characteristic viscous sheet behaviors, including stretching, buckling, sagging, and wrinkling.

References listed at the end of the paper:


ABSTRACT: We propose an interactive, optimization-in-the-loop tool for designing inflatable structures. Given a target shape, the user draws a network of seams defining desired segment boundaries in 3D. Our method computes optimally-shaped flat panels for the segments, such that the inflated structure is as close as possible to the target while satisfying the desired seam positions. Our approach is underpinned by physics-based pattern optimization, accurate coarse-scale simulation using tension field theory, and a specialized constraint-
optimization method. Our system is fast enough to warrant interactive exploration of different seam layouts, including internal connections, and their effects on the inflated shape. We demonstrate the resulting design process on a varied set of simulation examples, some of which we have fabricated, demonstrating excellent agreement with the design intent.

Yinxiao Li, Yonghao Yue, Danfei Xu, Eitan Grinspun and Peter K. Allen (Dept. of Computer Science, Columbia University, NY, USA), “Folding deformable objects using predictive simulation and trajectory optimization”, International Conference on Intelligent Robots and Systems (IROS), 2015
DOI: 10.1109/IROS.2015.7354231
ABSTRACT: Robotic manipulation of deformable objects remains a challenging task. One such task is folding a garment autonomously. Given start and end folding positions, what is an optimal trajectory to move the robotic arm to fold a garment? Certain trajectories will cause the garment to move, creating wrinkles, and gaps, other trajectories will fail altogether. We present a novel solution to find an optimal trajectory that avoids such problematic scenarios. The trajectory is optimized by minimizing a quadratic objective function in an off-line simulator, which includes material properties of the garment and frictional force on the table. The function measures the dissimilarity between a user folded shape and the folded garment in simulation, which is then used as an error measurement to create an optimal trajectory. We demonstrate that our two-arm robot can follow the optimized trajectories, achieving accurate and efficient manipulations of deformable objects.

Yinxiao Li, Danfei Xu, Yonghao Yue, Yan Wang, Shih-Fu Chang, Eitan Grinspun and Peter K. Allen (Dept. of Computer Science, Columbia University, NY, USA), “Regrasping and unfolding of garments using predictive thin shell modeling”, IEEE International Conference on Robotics and Automation (ICRA), May 2015
DOI: 10.1109/ICRA.2015.7139370
ABSTRACT: Deformable objects such as garments are highly unstructured, making them difficult to recognize and manipulate. In this paper, we propose a novel method to teach a two-arm robot to efficiently track the states of a garment from an unknown state to a known state by iterative regrasping. The problem is formulated as a constrained weighted evaluation metric for evaluating the two desired grasping points during regrasping, which can also be used for a convergence criterion. The result is then adopted as an estimation to initialize a regrasping, which is then considered as a new state for evaluation. The process stops when the predicted thin shell conclusively agrees with reconstruction. We show experimental results for regrasping a number of different garments including sweater, knitwear, pants, and leggings, etc.

ABSTRACT: This thesis focuses on the task of dexterous manipulation of deformable objects, and in particular, clothing and garments. The task of manipulating deformable objects such as clothing can be broken down into a series of sub-tasks: (1) perceive and pick up garment, and then identify garment and recognize its pose; (2) using a manipulation strategy, regrasp the object to put it into a canonical state; (3) scan the surface of the object to find wrinkles, and use an iron to remove the wrinkles; (4) starting from the wrinkle-free state, fold the garment according to pre-planned sequence of manipulations with optimized trajectories; In this thesis, we will address all the phases of this process. A key contribution of the work is innovative use of simulation. We use offline simulation results to predict states of deformable objects (i.e. cloth, fabric, clothing) that are then recognized by a robotic vision/grasping system to correctly pick up and manipulate these objects. The
recognition will use the simulation engine to deform the models in real time to find correct matches. The simulation will also be used to find the optimized trajectories for the manipulation of the garments, such as the garment folding.

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“Wrinkling, creasing, and folding in fiber-reinforced soft tissues”, Extreme Mechanics Letters, available online

4 November 2015, DOI: 10.1016/j.eml.2015.10.005

ABSTRACT: Many biological tissues develop elaborate folds during growth and development. The onset of this folding is often understood in relation to the creasing and wrinkling of a thin elastic layer that grows whilst attached to a large elastic foundation. In reality, many biological tissues are reinforced by fibers and so are intrinsically anisotropic. However, the correlation between the fiber directions and the pattern formed during growth is not well understood. Here, we consider the stability of a two-layer tissue composed of a thin hyperelastic strip adhered to an elastic half-space in which are embedded elastic fibers. The combined object is subject to a uniform compression and, at a critical value of this compression, buckles out of the plane — it wrinkles. We characterize the wrinkle wavelength at onset as a function of the fiber orientation both computationally and analytically and show that the onset of surface instability can be either promoted or inhibited as the fiber stiffness increases, depending on the fiber angle. However, we find that the structure of the resulting folds is approximately independent of the fiber orientation. We also explore numerically the formation of large creases in fiber-reinforced tissue in the post-buckling regime.

References listed at the end of the paper:
Cem Sonat, Cem Topkaya and J. Michael Rotter, “Buckling of cylindrical metal shells on discretely supported ring beams”, Thin-Walled Structures, Vol. 93, August 2015, DOI: 10.1016/j.tws.2015.03.003

ABSTRACT: Silos in the form of cylindrical metal shells are usually supported on evenly spaced columns in applications where an access space is needed for the discharge of contained solids. In large silos a ring beam is used to distribute the column forces into the shell. The presence of discrete supports results in a circumferential non-uniformity of axial stresses in the shell. This non-uniformity leads to high local stresses that must be considered in assessing the possibility of shell buckling. Design standards provide recommendations for the buckling of shells under uniform axial compression, but are largely silent concerning stress peaks that may vary in width. Designers must resort either to onerous finite element analyses that include both geometric and material nonlinearities with imperfections (GMNIA) or trust to their own judgment. This paper presents a parametric study to develop resistance or capacity curves which can be used directly in design without the need for complicated analysis. The proposed design method uses only hand calculations apart from a simple linear finite element analysis to determine the degree of non-uniformity in the axial stresses.

ABSTRACT: The design of thin shell structures against buckling has a long and tricky history. The sensitivity of elastic buckling loads to geometric imperfections and the challenges in relating research findings to practical construction have required extensive research work over many decades. The wide range of geometries, construction forms and loading conditions has also led to many distinct solutions to individual situations. But recent innovations have enabled a new all-embracing perspective to be developed, which gives great potential for addressing new problems in a systematic manner. The new method of Reference Resistance Design provides a hand calculation process that can address all shell buckling and collapse situations, with particular attention to unsymmetrical and local loading conditions, including imperfections, geometric nonlinearity, plasticity and strain hardening all within a consistent framework.


E. Hotala, L. Skotny, M Kusnierek and J. Boniecka, “Experimental investigations on the resistance of vertical stiffeners of steel silos shells made of corrugated sheets”

L. Skotny, E. Hotala and J. Boniecka, “Load-bearing capacity of discretely supported steel silos shells with skirts”

N. Strunghoner and S. Stehr, “Postbuckling behaviour of open thin-walled shells made of stainless steel”

K. Rejowski and P. Iwicki, “Simplified stability analysis of steel cylindrical silos with corrugated walls and vertical columns”

J. Dudkiewicz and R. Ignatowicz, “Problems of designing tubular shell galleries”

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“Flexural elastic buckling stress of light gauge built-up member”

R. Studzinski and M. Czaja (Institute of Structural Engineering, Poznan University of Technology, Poznan, Poland), “Distortional lateral torsional buckling of open and closed steel cross-sections”


ABSTRACT: In the present investigation, the buckling of generally laminated conical shells with various boundary conditions subjected to axial pressure is studied using an analytical approach. The governing equations are obtained using classical shell theory with Donnell assumptions in strain–deformation relations and the principle of minimum potential energy. The differential equations are solved using trigonometric functions in circumferential and power series in longitudinal directions. All types of boundary conditions can be applied in this method. The results are compared and validated with the results available in the literature, and good agreement is observed. Finally, the effects of the length, semi-vertex angle, and lamination sequences on the buckling load and mode shapes of generally laminated conical shells are presented.

References listed at the end of the paper:
Youngjin Chung, “Buckling of composite conical shells under combined axial compression, external pressure, and bending”, Ph.D dissertation, New Jersey Institute of Technology (NJIT) 2001

ABSTRACT: (Cannot easily cut and paste)

M. Shakouri, H. Sharghi and M.A. Kouchakzadeh (Department of Aerospace Engineering, Sharif University of Technology, P.O. Box 11155-8639, Tehran, Iran), “Torsional buckling of generally laminated conical shell”, Meccanica, First online 11 April 2016, pp 1-11, DOI: 10.1007/s11012-016-0429-8

ABSTRACT: Buckling of generally laminated conical shells under uniform torsion with simply-supported boundary conditions is investigated. The Donnell type strain displacement relations are used to obtain potential strain energy of the shell and membrane stability equation is applied to acquire the external work done by torsion. The Ritz method is used to solve the governing equations and critical buckling loads are obtained. The accuracy of the results is validated in comparison of with other investigations and finite element method. The effects of lamination sequence, semi-vertex angle and length to radius ratio of the cone are evaluated and mode shapes are presented for two types of lamination sequences. To find a design criterion, effects of lamination angles and semi-vertex angle for two types of lamination sequence on torsional buckling of conical shells are investigated.

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30. Chung Y (2001) Buckling of composite conical shells under combined axial compression, external pressure, and bending. New Jersey Institute of Technology, Department of Mechanical Engineering

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ABSTRACT: We present a numerical technique to model the buckling of a rolled thin sheet. It consists in coupling, within the Arlequin framework, a three dimensional model based on 8-nodes tri-linear hexahedron, used in the sheet part located upstream the roll bite, and a well-suited finite element shell model, in the roll bite downstream sheet part, in order to cope with buckling phenomena. The resulting nonlinear problem is solved by the Asymptotic Numerical Method (ANM) that is efficient to capture buckling instabilities. The originalities of the paper are: first in an Arlequin procedure with moving meshes and second in an efficient application to a thin sheet rolling process. The suggested algorithm is applied to very thin sheet rolling scenarios involving “edges-waves” and “center-waves” defects. The obtained results show the effectiveness of our global approach.

References listed at the end of the paper:

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“Torsional buckling of generally laminated conical shell”, Meccanica, pp 1-11, First online 11 April 2016, DOI: 10.1007/s11012-016-0429-8

ABSTRACT: Buckling of generally laminated conical shells under uniform torsion with simply-supported boundary conditions is investigated. The Donnell type strain displacement relations are used to obtain potential strain energy of the shell and membrane stability equation is applied to acquire the external work done by torsion. The Ritz method is used to solve the governing equations and critical buckling loads are obtained. The accuracy of the results is validated in comparison of with other investigations and finite element method. The effects of laminate sequence, semi-vertex angle and length to radius ratio of the cone are evaluated and mode shapes are presented for two types of laminate sequences. To find a design criterion, effects of laminate angles and semi-vertex angle for two types of lamination sequence on torsional buckling of conical shells are investigated.

References listed at the end of the paper:
31. Chung Y (2001) Buckling of composite conical shells under combined axial compression, external pressure, and bending. New Jersey Institute of Technology, Department of Mechanical Engineering
ABSTRACT: The edges of torn plastic sheets and growing leaves often display hierarchical buckling patterns. We show that this complex morphology i) emerges even in zero strain configurations, and ii) is driven by a competition between the two principal curvatures, rather than between bending and stretching. We identify the key role of branch point (or “monkey saddle”) singularities in generating complex wrinkling patterns in isometric immersions, and show how they arise naturally from minimizing the elastic energy.

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ABSTRACT: In this work the critical pressure due to buckling was calculated numerically by using ANSYS for both stiffened and un-stiffened cylinder for various locations and installing types, strengthening of the cylinder causes a more significant increase in buckling pressures than non reinforced cylinder. The optimum design of structure was done by using the ANSYS program; in this step the number of design variables 21 DVs. These variables are Independent variables that directly affect. The design variables represented the thickness of the cylinder and (height and width of 10 stiffeners). State variables (SVs), these variables are dependent variables that change as a result of changing the DVs and are necessary to constrain the design. The objective function is the one variable in the optimization that needs to be minimized. In this case the state variable is critical pressure (CP) and the objective function is the total (volume) of the structure. The optimum weight of the structure with
reasonable required conditions for multi types of structure was found. The result shows the best location of stiffener at internal side with circumferential direction. In this case the critical pressure can be increased about 18.6% and the total weight of the structure decreases to 15.8%.

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Belegundu, 2005, Optimization concepts and applications in engineering.
Nguyen Thi Phuong, 2002, "Buckling analysis of eccentrically stiffened functionally graded circular cylindrical thin shells under mechanical load" University of Transport Technology, 54.
Qasim, H.B., 2003, "Optimization flexural design of linearly and non linearly elastic spinning rocket structure " University of Baghdad.
Ruud Selker, 2013, "Local buckling collapse of marine pipelines" Delft University of Technology Faculty of Mechanical.
ABSTRACT: Through a programme of experiments, numerical modelling and parametric studies, the implications of allowing for strain-hardening in the design of partially restrained steel beams are investigated. A total of fourteen tests were performed on simply supported beams that were partially restrained against lateral torsional buckling. Four different restraint spacings were considered in the tests to give non-dimensional lateral torsional slenderness values of 0.1, 0.2, 0.3 and 0.4 for the unrestrained lengths. In all tests, bending resistances in excess of the plastic moment capacity were observed, but in order to attain the levels of resistance predicted by the continuous strength method (CSM), which allows for strain-hardening, closer restraint spacing than the minimum specified by EN 1993-1-1 (2005) is required. Using additional data generated as part of an analytical and numerical study, as well as test data collected from the literature, a basic design approach was presented that incorporated a limiting lateral torsional slenderness for the CSM of 0.2, as well as a simple transition function from bending resistances predicted by plastic theory to those predicted by the CSM.


ABSTRACT: This work investigates the buckling behavior of circular sandwich plates with tapered cores and functionally graded carbon nanotube (FG-CNT) reinforced composite face sheets under uniform radial compression based on the first order shear deformation plate theory. The sandwich plate is assumed to be constituted of a pure polymer core and two FG-CNT reinforced composite layers with constant thickness whose material properties are assumed to be graded through the thickness direction. Different distributions of multi walled CNTs (MWCNTs) in the thickness direction of face sheets are introduced. Effective properties of materials are estimated through the modified form of rule of mixture. In order to determine the distribution of the prebuckling load along the radius, the membrane equation is solved using the shooting method. Subsequently, employing the pseudospectral method, the stability equations are numerically solved to evaluate the critical buckling load. Parametric studies are conducted for various types of CNTs distributions and geometrical parameters under different boundary conditions. The results show that the buckling behavior is significantly influenced by the CNTs distributions, the thickness variation profile, the aspect ratio and the face sheet-to-core thickness ratio. Some conclusions are drawn on the parametric studies with respect to the buckling characteristics.

Wangyu Liu, Zhenqiong Lin, Ningling Wang and Xiaolin Deng (School of Mechanical and Automotive Engineering, South China University of Technology, 381 Wushan Road, Tianhe District, Guangzhou 510641, People's Republic of China), “Dynamic performances of thin-walled tubes with star-shaped cross section under axial impact”, Thin-Walled Structures, Vol. 100, pp 25-37, March 2016, DOI: 10.1016/j.tws.2015.11.016

ABSTRACT: Under axial loading, the thin-walled structures will experience severe plastic collapse at the corners. The presented paper focuses on the axial dynamic performances of the thin wall tubes with star-shaped cross sections (S-tube). Firstly, the impact tests of the Aluminum S-tube samples are performed to confirm the accuracy of numerical simulation. Then, a mode classification chart is given based on simulations with tubes of various dimensions. It is found that the slenderness of tube plays an important role in the deformation mode. Besides, the relationship between the deformation mode and energy absorbing performance are discussed.
through FE method. The specific energy absorption (SEA) of S-tube is slightly better than the polygon tube (P-tube) due to the fact that the deformation mode of S-tube with longer fold length hinders the potential capability of multi-corner tube. Finally, a new design combining the characteristics of S-tube and traditional polygon tube (P-tube) is proposed. The numerical result shows that SEA of the new design is 40% higher than that of P-tube.


ABSTRACT: In aged steel bridges, an area of local damage may be created in girders nearby the bearing region due to corrosion. The existence of local corrosion damage in the plate girder end can reduce the load-carrying capacity of bridge. A three-layer Back-Propagation neural network (BPNN) has been developed to predict the residual buckling strength of such damaged members. In this paper, train, test and validation sets of the neural network were obtained by using the finite element software ABAQUS. The accuracy of the nonlinear finite element method (FEM) to evaluate the residual bearing capacities of damaged beams is discussed. Buckling and post-buckling behavior of plate girders ends were quantitatively evaluated from nonlinear finite element analyses (FEA) model varying the corrosion scenario. A parametric study is achieved based on FE and an empirical equation is proposed based on BPNN to estimate the residual bearing capacity of deteriorated steel plate girder by local corrosion damage. The obtained results show that the prediction of the residual bearing capacity of the locally corroded steel plate girder ends is accurate and effective.

Yuanzheng Zhao, Ximei Zhai and Lijuan Sun (School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, PR China), “Test and design method for the buckling behaviors of 6082-T6 aluminum alloy columns with box-type and L-type sections under eccentric compression”, Thin-Walled Structures, Vol. 100, pp 62-80, March 2016, DOI: 10.1016/j.tws.2015.12.010

ABSTRACT: In this study, a detailed experimental investigation of 29 extruded columns with box-type and L-type sections made of 6082-T6 aluminum alloy, was carried out to study the stability behavior of these columns when subjected to eccentric loads. Finite element (FE) models of all tested columns under eccentric loads were developed using the ABAQUS software package. The precision and utility of these FE models were verified by experimental data. Both the stability bearing capacity and deformation performance were evaluated. Using the proposed FE models, an extensive parametric study was performed to investigate the effects of section dimensions, slenderness ratio, and eccentricity on the stability bearing capacity of the eccentrically loaded columns. The test and parametric study results were compared to the design capacity predictions in the current Eurocode 9 and the Chinese Code for the Design of Aluminum Structures, GB 50429. It was found that the predicted stability bearing capacities in the two design codes was generally conservative for the eccentrically loaded columns made of 6082-T6 aluminum alloy. Several parameters of the design formulae from the Chinese Code were modified to predict the ultimate strength of 6082-T6 aluminum alloy columns more accurately.


ABSTRACT: The buckling analysis of thin rectangular plates under locally distributed compressive edge stresses is a challenging problem if the point discrete methods are to be used. To obtain accurate buckling stress,
one of the important factors is that the in-plane stress distributions within the plate prior to buckling should be accurate enough. Although it is possible to get analytical solutions for the in-plane stress distributions, but the expressions are very complicated since a stress-diffusion phenomenon exists. The differential quadrature method (DQM), being a point discrete method, has been successfully used in a variety of fields including the buckling analysis of thin rectangular plates under nonlinearly distributed edge compressions. However, it is rare to employ the DQM directly to solve problems of rectangular plates under locally distributed or point loads. To solve the challenging problem by using the DQM, novel formulations are presented in this paper. The locally distributed stress is first work-equivalently to point loads at all inner grid points on the loaded edge, then the normal stress boundary condition is numerically integrated before being discretized in terms of the differential quadrature. In this way accurate in-plane stress distributions can be obtained by the DQM without any difficulties. Buckling analysis of rectangular plates under either uniaxial or biaxial locally distributed compressive stresses is successfully performed. The accuracy of the DQ data is validated by comparing them with existing analytical solutions and finite element data. It is demonstrated that the compactness and computational efficiency of the DQM are retained. Accurate buckling loads are presented for rectangular plates with nine combinations of boundary conditions, various aspect ratios and load ratios. Some new results are also provided for references.

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ABSTRACT: In this paper, a novel foam-filled ellipse tube (FET) is proposed and compared with other hollow and foam-filled tubes with different cross-sections under multiple loading angles, which include square, circle and rectangle. First, finite element analyses of these tubes reveal that the FET tube has the best crashworthiness under multiple loading angles. Second, design of experiments (DOE) was used to analyze the parameters that radial rate \( f \), thickness of wall \( t \) and foam density \( \rho_f \). Third, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize the FET tube, in which the optimal parameter variation is sought for maximizing specific energy absorption (SEA) and minimizing peak crush force (PCF) under multiple loading angles. The optimized FET tube exhibits better crashworthiness than the origin FET tube and other tubes with different cross-section, indicating that the FET tube can be a potential energy absorber especially under oblique impact loading.

Abbas Niknejad and Pourya Heidari Orojloo (Mechanical Engineering Department, Yasouj University, P.O. Box 75914-353, Yasouj, Iran), “A novel nested system of tubes with special cross-section as the energy absorber”, Thin-Walled Structures, Vol. 100, pp 113-123, March 2016, DOI: 10.1016/j.tws.2015.12.009

ABSTRACT: The present article introduces a new thin-walled specimen with longitudinal grooved section as an energy absorber during the flattening process. On the other hand, this paper examines lateral compression process and energy absorption behavior of grooved sections with special cross-section between two rigid platens. Influences of presence of polyurethane foam-filler and nesting the section by aluminum or brazen tube are studied on energy absorption capability by the structure under the lateral loading in the quasi-static condition. For this aim, seven groups of specimens are prepared and in each group, five similar specimens are tested with different loading angles of 0°, 30°, 45°, 60° and 90°, respect to the central line of two grooves of thin-walled section. Effects of presence of foam-filler into the grooved section of single samples and into inner
aluminum or brazen tube of nested systems, effects of material type and wall thickness of inner tube of nested grooved sections, and influences of loading angle are investigated on energy absorption behavior and deformation mode of the structures during the flattening process. Based on experimental measurements and between all the tested specimens, the present research work suggest a grooved section with special cross-section that has been nested by an inner polyurethane foam-filled aluminum tube as the best energy absorber during the lateral compression. Finally, results of the present work are compared with represented results of some previous published works by other researchers to find out advantages of the introduced novel nested system of the present article.

Hui-Shen Shen and Hai Wang (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China), “Postbuckling of pressure-loaded FGM doubly curved panels resting on elastic foundations in thermal environments”, Thin-Walled Structures, Vol. 100, pp 124-133 DOI: 10.1016/j.tws.2015.11.015

ABSTRACT: Modeling and analysis for the postbuckling of FGM doubly curved panels resting on elastic foundations and subjected to lateral pressure under heat conduction are presented. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. The temperature-dependent material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction based on Mori–Tanaka micromechanics model. The formulations are based on a higher order shear deformation theory with von Kármán strain–displacement relationships. The panel-foundation interaction and thermal effects are also included. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach. The effects of volume fraction index, temperature variation, the panel geometric parameters as well as foundation stiffness on the postbuckling behavior of FGM doubly curved panels are discussed in detail.

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ABSTRACT: Stiffened plates are the most common structural units used in different structural applications ranging from buildings and bridges to ships and offshore structures. The present paper aiming at investigating the influence of using Y-stiffeners profile instead of conventional stiffeners on the load carrying capacity of ship deck panels under vertical hull girder bending moment. ANSYS (Release 15.0) nonlinear finite element software was used to verify the ultimate strength results obtained from applying the International Association Classification Societies-Common Structural Rules (IACS-CSR) on both conventional and novel deck panels. The developed numerical model with conventional stiffeners profile was validated in a good agreement with a benchmark study results included in the International Ship Structures Committee (ISSC). Furthermore, both analytical and numerical simulation results were in good agreement that demonstrates the capability of using IACS-CSR for designing the new stiffeners profile in practical applications. In comparison with the conventional stiffeners profile, the proposed Y-stiffeners resulted in a considerable increase in the panel safety margin to weight (area) ratio and higher ultimate strength. Moreover, the numerical simulations provided that
implementing the Y-stiffeners profile can also rise the first yielding stress point of the structural response with nearly the same strain absorption in comparison with T-stiffeners profile.


ABSTRACT: Cold-formed steel members are used as structural members in a wide range of applications because of their simpler fabrications and high strength-to-weight ratios. Though high width-to-thickness ratio of such sections make them vulnerable to local buckling under compressive stresses, past studies have shown that these members possess inelastic reserve strengths at the ultimate stage under flexural loading. This study explore the influence of width-to-thickness ratio, lip lengths and depth-to-width (aspect) ratio on the ultimate flexural strengths of cold-formed channel sections bending about their minor axes. Finite element (FE) analyses have been conducted on 216 numbers of channel sections with varying geometric properties to investigate their ultimate resistance and mode of failure under flexural loading. The ultimate flexural strengths of these sections are theoretically predicted using the current code provisions and are compared with the exact values obtained from FE analyses. An experimental investigation has also been performed on five specimens of channel sections with and without lips to validate the FE analyses results. Based on the analysis and experimental results, the limiting values of lip lengths, aspect ratios, and width-to-thickness ratios of channel sections are discussed.

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ABSTRACT: Foldcore sandwich structures have aroused considerable research interests in recent years as a promising alternative to honeycomb sandwich structures. While metallic, aramid and CFRP foldcores have been extensively studied, foldcores made of thermoplastic materials have not been well investigated. This paper presents an experimental and numerical study on thermoplastic foldcores. A manufacturing process involving folding with dies and shape-setting by heat-treatment was established. Both PET and PEEK foldcore specimens were successfully manufactured using this process and tested in compression. An explicit FE modeling protocol of PEEK foldcores were developed and validated with the test results. Furthermore, a parametric study on the weight-specific mechanical properties of various PEEK foldcore models subjected to virtual compression and in-plane shears was performed, through which the relationships between the mechanical properties and the geometric parameters were established. Finally, the mechanical properties of a PEEK model and its aramid counterpart with the same geometry were compared. It was shown that the PEEK foldcore has comparable or even better energy absorption performances than the aramid one.


ABSTRACT: The effect of heat treatment on the dynamic crushing and energy absorption behavior of combined geometry shell cores (hemisphere and cylinder) of sandwich structures were investigated both
experimentally and numerically. The applied heat treatment on the combined geometry shell cores relieved the stress caused by deep drawing, diminishing the peak transmitted forces. The verified numerical models of the as-received and heat-treated combined geometry shells were used to model blast loading of various sandwich configurations and the additional sandwich configurations of reversing the cylindrical side of the cores to the impacted side. Both the applied heat-treatment and the reversing process decreased the magnitude of the force transmitted to the protected structure. The applied heat treatment increased the arrival time of blast force wave to the protected structure, while the reversing resulted in opposite.

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DOI: 10.1016/j.tws.2015.11.013
ABSTRACT: This paper compares two distinct approaches for obtaining the cross-section deformation modes of thin-walled members with deformable cross-section, namely the method of Generalized Eigenvectors (GE) and the Generalized Beam Theory (GBT). First, both approaches are reviewed, emphasizing their differences and similarities, as well as their resulting semi-analytical solutions. Then, the GE/GBT deformation modes for four selected cross-sections are calculated and examined in detail. Subsequently, attention is turned to the efficiency and accuracy of the GE/GBT mode sets in typical benchmark problems, namely the calculation of the global–local–distortional first-order and buckling (bifurcation) behaviors of bars with the previously analyzed cross-sections. It is concluded that GE and GBT, both based on the method of separation of variables, yield accurate results although they use different structural models and mode selection strategies. Therefore they offer complementary advantages, which are put forward in the paper.

DOI: 10.1016/j.tws.2015.12.011
ABSTRACT: Concrete-filled steel tubes (CFTs) exhibit superior performance under static and dynamic loads, due to composite action. Factors, such as the thickness of the steel tube and the concrete core condition, have a significant effect on the structural behaviour of CFT columns, particularly in the post-yield behaviour. Studies show that if the concrete core is reinforced with steel bars, the new composite member has better characteristics compared to CFT columns. In this study, the axial compressive behaviour of reinforced concrete-filled steel tube (RCFT) columns using spirally reinforced concrete (SRCFT) was investigated and compared with CFTs. The main variation was the pitch spacing of the spiral shear reinforcement. Fifteen specimens, including three CFTs and twelve SRCFTs, were tested in five groups. The test results indicated that a SRCFT column has much better post-yield behaviour than a CFT column. A reduction in the pitch spacing rate further improves the post-yield behaviour of the SRCFTs. A comparison of the measured strength of the specimens with corresponding
values predicted by two international codes (ACI 318-11 and EC4-1994) shows a good prediction of EC4 and a conservative estimation of ACI.

Hamidreza Yazdani Sarvestani (Concordia Centre for Composites, Dept. of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec, Canada), “Buckling analysis of curved nanotube structures based on the nonlocal shell theory”, International Journal for Multiscale Computational Engineering, Vol. 14, No. 1, 2016, DOI: 10.1615/IntJMultCompEng.2015014848
ABSTRACT: In reality, nanotubes are not straight. In the present work, the buckling behavior of curved single-walled nanotubes (SWNTs), double-walled nanotubes (DWNTs) and multi-walled nanotubes (MWNTs) under axial compression is studied. The buckling analysis for the curved nanotube structures is performed by applying a nonlocal shell theory based on the constitutive relations of Eringen. The governing equations of curved SWNTs, DWNTs and MWNTs are developed. Solutions are obtained using Fourier series expansion. The effects of the curved nanotube length, bend angle, diameter and nonlocal parameter on the buckling loads are investigated. The numerical results indicate that the nonlocal parameter is important for the buckling analysis of curved nanotube structures.

ABSTRACT: European future space launchers are planned to be more cost-efficient and made from advanced materials which are expected to reduce weight and costs. Most structures are very thin-walled and imperfection sensitive. Buckling is therefore in most cases the critical design criterion. Currently such structures are still designed by the NASA SP 8007 which dates from 1968. This guideline is very conservative and recent results show that alternative design approaches may lead to lighter structures by up to 20%. Independent of the design approach a validation by experiments is absolutely necessary. Buckling experiments are the standard procedure, however, during the experiment the first damage may be material failure and not buckling, even if buckling was predicted. In this case the validation of the design method for buckling is not sufficient. There is therefore a high need for non-destructive methods, to obtain the buckling load of such imperfection sensitive thin-walled structures by an alternative way. The Vibration Correlation Technique (VCT) is the most promising method which allows determining the buckling load or real boundary conditions for different types of structures without reaching the instability point. This method proved to be successful for plates with simple boundary conditions. For curved shells or complex boundary conditions this technique is still under development. However, considering unstiffened cylindrical shells loaded in compression a promising approach [1], using VCT, to predict realistic buckling loads, was already developed. This approach was successfully validated for this type of structures.
The PhD work starts with benchmarking to study the limits of the current approaches. Next the empirical approach for typical scaled space structures using real boundary conditions shall be extended. The new concept will be finally validated by test results. The final project result is a new approach for the calculation of the buckling load imperfection sensitive space structures using the non-destructive method Vibration Correlation Technique.
Zhou, Fan, Chen, Zhiping, Fan, Haigui and Huang, Song (Institute of Process Equipment, Department of Chemical and Biological Engineering, Zhejiang University, Hangzhou, China), “Analytical study on the buckling of cylindrical shells with stepwise variable thickness subjected to uniform external pressure”, Mechanics of Advanced Materials and Structures, Vol. 23, No. 10, pp 1207-1215, October 2016, DOI: 10.1080/15376494.2015.1068401

ABSTRACT: This article focuses on the buckling of cylindrical shells with stepwise variable thickness subjected to uniform external pressure. First, combining the method of separation of variables, perturbation method, and Fourier series expansion, an analytical method for the buckling analysis of cylindrical shells with axisymmetric thickness variation subjected to external pressure is established. The method is verified by comparing with the previous results. Then, the stepwise variable thickness of cylindrical shells is described exactly by the arc tangent function. Finally, using the presented method, a general formula for the critical buckling load of cylindrical shells with stepwise variable thickness subjected to uniform external pressure is derived. This general formula is compared and discussed with some empirical formulae in the current design standards. This study lays a theoretical foundation for the calculation of the buckling load of cylindrical shells with stepwise variable thickness subjected to uniform external pressure. Moreover, it provides a reference and guidance for the further revision of related standards.


ABSTRACT: Natural Draft Cooling Towers (NDCTs) are extremely thin shell structures, clearly sensitive to instability failure. After the Ferrybridge-disaster in 1965, world-wide research efforts started to investigate the reasons for these collapses, including the possibility of instabilities. The paper will elucidate the different stability verification concepts for NDCTs over the last 40 years, starting with early experiments. This is followed by improvements of semi-experimental (local) methods, succeeded by modern stability verifications based on FE analysis techniques. The important question of influence of geometric imperfections on the instability of NDCTs is also addressed. Finally the paper offers the Eurocode-derivation for an appropriate factor of buckling safety.


ABSTRACT: Two advanced composite tow-steered shells, one with tow overlaps and another without overlaps, were previously designed, fabricated and tested in end compression, both without cutouts, and with small and large cutouts. In each case, good agreement was observed between experimental buckling loads and supporting linear bifurcation buckling analyses. However, previous buckling tests and analyses have shown historically poor correlation, perhaps due to the presence of geometric imperfections that serve as failure initiators. For the tow-steered shells, their circumferential variation in axial stiffness may have suppressed this sensitivity to imperfections, leading to the agreement noted between tests and analyses. To investigate this further, a numerical investigation was performed in this study using geometric imperfections measured from both shells. Finite element models of both shells were analyzed first without, and then, with measured imperfections that
were then, superposed in different orientations around the shell longitudinal axis. Small variations in both the axial prebuckling stiffness and global buckling load were observed for the range of imperfections studied here, which suggests that the tow steering, and resulting circumferentially varying axial stiffness, may result in the test-analysis correlation observed for these shells.

Zheng Jia and Teng Li, “Failure Mechanics of a Wrinkling Thin Film Anode on a Substrate under Cyclic Charging and Discharging”, Extreme Mechanics Letters, accepted, 2016 (DOI: doi:10.1016/j.eml.2016.03.006) ABSTRACT: Recent experiments show that a thin film anode on a compliant substrate can significantly mitigate mechanical degradation and capacity fading of lithium-ion and sodium-ion batteries in service. The enhanced cycle performance of such a substrate-supported thin film anode is attributed to the wrinkling-induced stress relaxation. While the experimental evidence is suggestive, there lacks a systematic mechanistic study of the wrinkling of the substrate-supported thin film anode and its influence on anode cycle performance. We report a comprehensive study of the charging/discharging induced wrinkling formation and subsequent morphologic evolution of a substrate-supported thin film anode, using theoretical analysis and finite element simulations. We reveal that necking bands may form near wrinkling troughs or peaks and further develop to cause fragmentation of the anode over charging/discharging cycles, a failure mode not reported in existing literature. The density and distribution of the wrinkling-associated necking bands in the substrate-supported thin film anode supported can be regulated by the substrate stiffness.

Mohammad Anwar-Us-Saadat, Mahmud Ashraf and Shameem Ahmed (School of Engineering and Information Technology, The University of New South Wales, Canberra, ACT 2610, Australia), “Behaviour and design of stainless steel slender cross-sections subjected to combined loading”, Thin-Walled Structures, Vol. 104, pp 225-237, July 2016, DOI: 10.1016/j.tws.2016.03.020 ABSTRACT: The Continuous Strength Method (CSM) is a recently developed strain based design technique that produces accurate predictions for cross-section resistances for stocky sections against individual and combined actions. This paper numerically investigates the behaviour slender stainless steel cross-sections subjected to combined loading i.e. compression plus bending. Generated numerical results and available test results were used to develop CSM formulations to tackle the conservatism shown by the current international codes in predicting resistances of slender sections. Keeping the basic design philosophy in line with the current CSM design technique, interaction equations are re-calibrated herein for slender stainless steel hollow sections.

Lu Yang (1), Menghan Zhao (1), Dongchen Zu (2), Fan Shang (1), Huanxin Yuan (3), Yuanqing Wang (4) and Yong Zhang (2) (1) The College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, PR China (2) Beijing Jiaotong University, Beijing 100044, PR China (3) School of Civil Engineering, Wuhan University, Wuhan 430072, PR China (4) Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China “Flexural buckling behavior of welded stainless steel box-section columns”, Thin-Walled Structures, Vol. 104, pp 185-197, July 2016, DOI: 10.1016/j.tws.2016.03.014 ABSTRACT: Flexural buckling behavior of stainless steel columns has been widely investigated and discussed. However, a barely explored area is that of welded-section members. In this paper, twelve full-scale columns buckling tests have been conducted for both austenitic and duplex welded stainless steel box-section members.
Specimen cross-sections and lengths have been selected to cover a wide range of geometries, varying between non-dimensional slenderness of 0.5 and 2.0. Measurements of material properties, residual stress and initial geometric imperfection have been also conducted. Relevant numerical simulation has been performed, accuracy of which is verified by comparing with the test results. The test results have been used to assess the applicability of the EN 1993-1-4, ASCE 8-02 and AS/NZS for stainless steel welded-sections. It shows that current design method predicts the buckling resistance of welded stainless steel box-section generally conservative thus improvement could be anticipated.

DOI: 10.1016/j.tws.2016.03.004
ABSTRACT: A numerical parametric investigation into the response of axially and rotationally restrained compound cold-formed steel beams in fire has been carried out. A suitable finite element model was validated against experimental fire tests. Some parameters that could have influence on the behaviour of these beams were evaluated, such as the section geometry, initial applied load, slenderness and influence of the axial and rotational restraints. The results showed that the critical temperature of axially restrained beams may drop significantly (reaching a 50% reduction) and, beyond a certain value of axial or rotational restraint it may be no longer possible to change its fire resistance. Furthermore, it was still concluded that the methods established in EN1993-1.2:2004 are not appropriate for the fire design of these beams (reaching relative differences in the order of 20% and some predictions can be unsafe).

Andre Reis, Nuno Lopes and Paulo Vila Real (RISCO – University of Aveiro, Department of Civil Engineering, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal), “Shear-bending interaction in steel plate girders subjected to elevated temperatures”, Thin-Walled Structures, Vol. 104, pp 34-43, July 2016
DOI: 10.1016/j.tws.2016.03.005
ABSTRACT: The purpose of the current study is to analyse the behaviour of steel plate girders with rigid and non-rigid end posts subjected to elevated temperatures, with the aim of assessing the interaction between shear and bending in case of fire. The intentional low stiffness of the flanges may precipitate the failure of these plate girders, making the interaction between shear and bending an important phenomenon which is also analysed in this work. A parametric numerical study was performed involving a wide range of cross-section’s dimensions, plate girders’ aspect ratios and steel grades. Plate girders were numerically tested at both normal and elevated temperature, considering three different uniform temperatures 350 °C, 500 °C and 600 °C. The influence of the geometrical imperfections, as well as the residual stresses, was taken into account. Finally, the numerical results were compared to the EC3 prescriptions for shear buckling and shear–bending interaction safety verifications, adapted to fire situation by the direct application of the reduction factors for the stress-strain relationship of steel at elevated temperatures.

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“Unconstrained shape optimization of singly-symmetric and open cold-formed steel beams and beam-columns”, Thin-Walled Structures, Vol. 104, pp 54-61, July 2016, DOI: 10.1016/j.tws.2016.03.007
ABSTRACT: This study aims to optimise the cross-sectional shape of singly-symmetric, open-section and simply-supported cold-formed steel (CFS) beams and beam-columns. No manufacturing or assembly constraints are considered. The previously developed augmented Lagrangian Genetic Algorithm (GA), referred to as the “self-shape” optimisation algorithm, is used herein. Fully restrained and unrestrained beams against lateral deflection and twist, as well as unrestrained beam-columns are optimised. Various combinations of axial compressive load and bending moment are analysed for the beam-columns. The Direct Strength Method (DSM) is used to evaluate the nominal member compressive and bending capacities. The accuracy of the automated rules, developed in the literature to determine the elastic local and distortional axial buckling stresses from Finite Strip signature curves, is verified herein to estimate the elastic bending buckling stresses. The optimised cross-sectional shapes are presented for all cases and the evolution of the unrestrained shapes from pure axial compression to pure bending is discussed.

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ABSTRACT: The nonlinear dynamic responses of symmetric laminated composite beams subjected to combined in-plane and lateral loadings are studied in this paper. The composite laminates are modelled using the full layerwise theory (FLWT) based on the advanced first order shear deformation theory (AFSDT). The nonlinear governing differential equations of the laminated composite beams are derived using Hamilton's principle. The partial discretization based on Galerkin method is used to obtain the nonlinear ordinary differential equations (ODEs); in addition, the obtained nonlinear ODEs are solved numerically using step-by-step Newmark-Beta algorithm. In this study, the effects of two different cross-ply lay-up sequences and in-plane loading on the dynamic responses of composite beams are investigated. Moreover, the normal and interlaminar shear stress distributions are obtained. The results of present study are compared with the results of Partial Layerwise theory (PLWT) and validated with the exist results in this field of subject. Furthermore, the obtained results are compared with those obtained from finite element method (FEM) of analysis, which are in good agreement. Beside these, the number of used degrees of freedom in the present method is remarkably less than the FEM, leading to a significant computational cost reduction. Moreover, because of using FLWT, the present method is capable of predicting through the thickness normal stress and strain distributions.

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“Optimal design of composite thin-walled beams using simulated annealing”, Thin-Walled Structures, Vol. 104, pp 71-81, July 2016, DOI: 10.1016/j.tws.2016.03.001

ABSTRACT: In this paper, a problem formulation and solution methodology for optimal design of thin-walled composite beams is presented. The aim is to maximize the buckling load capacity and minimize the weight of the beam. For this purpose, a theoretical model is developed for the analysis of thin-walled composite beams
under a state of arbitrary initial stresses. In order to find the optimal solution, Simulated Annealing method is implemented. Design variables are taken as the stacking sequences of laminate and the dimensions of the cross-section. The space of feasible solutions is constrained by strength, displacements, global and local buckling and geometric conditions.

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ABSTRACT: This paper presents a numerical investigation on the behaviour and design of lean duplex stainless steel (LDSS) lipped channel columns subjected to axial compression. Numerical models were developed using general purpose finite element (FE) package ABAQUS, and have been verified using experimental data available in the literature. Developed FE models included material nonlinearities as well as initial geometric imperfections. A comprehensive parametric study has been carried out covering a wide range of slenderness with different cross section geometries for the considered lipped channel columns. Column resistances obtained from the numerical study were used to assess the performance of the current Direct Strength Method (DSM) guidelines when applied for cold-formed LDSS columns; obtained comparisons showed considerable conservatism. A modified design method for LDSS lipped channels is proposed herein following DSM techniques, which provides considerably more accurate predictions for the considered cold-formed columns. Reliability of the proposed design equations is also presented showing a good agreement with both experimentally and numerically obtained results.


ABSTRACT: Elastic lateral-torsional buckling (LTB) is a common failure mode of large span beams. In this phenomenon the beam becomes unstable along the unbraced length. This instability of beams can be identified by out-of-plane deflection and twisting. Using discrete torsional braces is one of the ways to prevent LTB. In this paper the LTB strength and bracing stiffness requirements of monosymmetric I-beams with discrete torsional braces, under pure bending condition is investigated. First, an analytical solution for an unlimited number of braces is presented by using an energy approach. Then the results of the proposed equations are compared with the results of a 1-D finite element analysis and the equivalent continuous brace stiffness concept. The comparison shows that the proposed equations are in good agreement with the finite element analysis. A parametric study is carried out for various dimensions and geometrical properties of cross sections. The results show that using the monosymmetric I-sections with larger compression flange is the more economical solution. Finally, the effects of linear moment gradient conditions and the cross sectional distortion on the LTB strength and bracing stiffness requirement are investigated.

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ABSTRACT: The behavior of thin-walled dodecagonal section double skin concrete-filled steel tubular beam-columns was investigated in this paper. A series of tests were carried out on specimens having the length of 2000 mm. Both outer and inner tubes of test specimens were cold-formed steel dodecagonal hollow sections (DHS). The diameters of outer and inner steel tubes of test specimens were 400 mm and 240 mm, respectively. Each test specimen was tested to failure, and the behavior under loading was recorded. Finite element model was developed using ABAQUS and verified against the test results. Parametric study was conducted using the verified finite element model. The suitability of current design methods was evaluated.

ABSTRACT: A comparative evaluation of limit moments based on small displacement and collapse moments based on large displacement for structurally distorted throughwall circumferentially cracked pipe bends, under in-plane closing bending were carried out using finite element analysis. The moments were obtained employing the twice-elastic-slope method. Results indicate the influence of thinning is minimal whereas the effects of ovality on both limit and collapse moments for the cases considered are significant and therefore thinning need not be considered in the analysis. Moreover determination of collapse moments is preferred when ovality is incorporated in the analysis of pipe bends with the geometries considered.

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ABSTRACT: Large-scale inflatable structures have become a viable alternative for sealing and isolating segments of large-diameter conduits or tunnel sections to prevent the propagation of flooding, noxious gases or smoke. In such applications, the inflatable structure is prepared for placement, either permanently or temporary, and left ready for deployment, inflation, and pressurization when needed. Once deployed and in operation, the level of sealing effectiveness depends on the ability of the inflatable structure to deploy and self-accommodate, without human intervention, to the intricacies of the perimeter of the conduit being sealed. This work presents finite element evaluations of the deployment and inflation of a full-scale inflatable plug placed within a tunnel section. Folding sequences and controlled deployment techniques developed experimentally served as the basis for the development of finite element models that can simulate different stages of folding, placement, initial deployment and full inflation of the structure. The good level of correlation between experimental and simulation results in terms of deployment dynamics, levels of contact as well as number and position of zones with no contact in the confining perimeter, demonstrate that the proposed modeling strategy can be used as a predicting tool of the behavior of a large-scale inflatable structure for a given confining environment.

ABSTRACT: The generalized coupled thermoelasticity based on the Lord–Shulman (L-S) theory is employed to study the transient thermoelastic behavior of rotating functionally graded (FG) truncated conical shells subjected to thermal shock with different boundary conditions. Material properties are assumed to be graded in the thickness direction, which can vary according to a simple power law distribution. The governing equations together with related boundary conditions are discretized using a mapping-differential quadrature method (DQM) and Newmark time integration scheme in the spatial and temporal domains, respectively. The formulation and method of the solution are validated by showing their fast rate of convergence and comparison with available data in the open literature. Then, the effects of the material graded index, the angular velocity, semi-vertex angle together with other geometrical parameters on the thermal behavior of the rotating FG truncated conical shells under thermal shock, including temperature change, displacement and stress components are investigated.

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ABSTRACT: The eccentrically stiffened Ceramic-FGM-Metal layer toroidal shell segments which applied for heat-resistant, lightweight structures in aerospace, mechanical, and medical industry and so forth are the new structures. Thus, the nonlinear vibration of eccentrically stiffened (ES) Ceramic-FGM-Metal (C-FGM-M) layer toroidal shell segments surrounded by an elastic medium in thermal environment is investigated in this paper. Based on the classical shell theory with the geometrical nonlinear in von Karman-Donnell sense, Stein and McElman assumption and the smeared stiffeners technique, the governing equations of motion of ES-C-FGM-M layer toroidal shell segments are derived. The dynamical characteristics of shells as natural frequencies, nonlinear frequency-amplitude relation, and nonlinear dynamic responses are considered. Furthermore, the effects of characteristics of geometrical ratios, ceramic layer, elastic foundation, pre-loaded axial compression and temperature on the dynamical behavior of shells are studied.

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ABSTRACT: This paper presents a closed form solution for the analysis and design of composite steel concrete (SC) shear wall systems subjected to pure out-of-plane loads with partial interaction theory. This method takes into account the flexibility of connection between plate and concrete. SC walls under out-of-plane loads can be considered a slab under distributed loads; therefore, for obtaining the formulation of these systems, a strip
beam-slab is considered. These walls are subjected to soil pressure when used in deep excavations, water hydraulic pressure when used as marine structures, and ice moving pressure when used in offshore structures etc. For providing the interaction between steel and concrete, shear connectors and, for calculating the out-of-plane loadings, classic methods are utilized. The existence of concrete in composite shear walls not only prevents the steel plate from buckling, but also plays an important role in out-of-plane resistance. To investigate the effect of concrete on the behavior of these SC shear walls, two cases are considered in this study: shear walls with and without concrete. To validate the accuracy of the proposed method, a number of shear walls were modeled and analyzed by ABAQUS software and compared with the results from theoretical formulations. Results indicate that the proposed interaction theory is well capable of predicting the deformation and stress distribution of the composite shear walls.

ABSTRACT: Shear deformable finite element method is employed here to investigate the stability characteristics of isotropic and composite shear panels. The effects of in-plane boundary conditions (non-uniform pre-buckling stresses and development of a compression strip) and out-of-plane restraints against bending / torsion of the edges on the shear buckling loads of isotropic rectangular plates are examined at the beginning. Buckling loads of laminated composite plates are studied with an attempt to correlate the fiber orientation with the compression strip. Limited parametric study has been conducted to examine the postbuckling behavior of perfect, imperfect and eccentrically loaded thin rectangular plates with various practical boundary conditions.

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“In-plane behavior of cold-formed thin-walled beam-columns with lipped channel section”, Thin-Walled Structures, Vol. 105, pp 1-15, August 2016, DOI: 10.1016/j.tws.2016.03.021
ABSTRACT: This paper is mainly concerned with the in-plane behavior of cold-formed steel beam-column with lipped channel section. The tested members are classified into three series by loading types, including: axial compression and major axis bending (X), axial compression and minor axis bending (lips in tension, Y1), and axial compression and minor axis bending (lips in compression, Y2). A numerical model is developed and verified by the experimental results. The elastic local buckling loads and second-order effects are discussed based on results of test, numerical analysis and design methods. Comparing with test results in this paper, numerical analysis overestimates the elastic local buckling loads and the actual second-order effect is more severe than the prediction by current design methods. Finally, the comparison between test strength and predicted strength obtained by AISI specification indicates that the interaction equation can provide conservative strength prediction for beam-column.

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ABSTRACT: This paper presents an experimental investigation on local buckling behavior of extruded 6000 series alloy I-shaped aluminium alloy beams. A total of 10 specimens with a wide range of width-to-thickness ratios (4.4–15.0 of flange, 42.9–73.1 of web) of component plates were divided into two types: one with stiffeners at mid-span, and the other without intermediate stiffeners. Failure modes, ultimate loading capacities, load-deformation responses and load-strain curves of the specimens were studied. Local buckling occurred in the top flange and web of six specimens without intermediate stiffeners, and shear local buckling occurred in the other four specimens with intermediate stiffeners though which developed a tension field. A finite element model was developed and validated against the test results, which was used for parametric analysis of 24 specimens. The investigation focused on the effects of the intermediate stiffeners and width-to-thickness ratio on the buckling strength of the aluminium alloy beams. It was found that component plates with small width-to-thickness ratios could make material function to its fullest potential; And there was a significant increase in the post-buckling strength; Eurocode 9 underestimated the loading capacity of the specimens to be safe. For the specimens with thin (width-to-thickness ratio more than 40) web, the standards should be especially enhanced. Calculation results of the finite element model consist well with the experimental results.

Jafar Rouzegar and Mohammad Karimi (Department of Mechanical and Aerospace Engineering, Shiraz University of Technology, P.O. Box 71555-313, Shiraz, Iran), “Numerical and experimental study of axial splitting of circular tubular structures”, Thin-Walled Structures, Vol. 105, pp 57-70, August 2016
DOI: 10.1016/j.tws.2016.03.027
ABSTRACT: Among the different energy absorption mechanisms, axial splitting/curling is known as an efficient method due to its large stroke to length ratio. This paper presents a finite element model for numerical simulation of splitting of circular brazen tubes. Surface-based cohesive technique is employed for modeling fracture and cracks growth. The required material parameters are extracted from stress-strain diagram of simple tensile test. Some experimental tests were performed to validate the numerical results. For implementation of experimental procedure, the specimens were prepared by cutting the commercial brazen tube and some edge notches were created on one end side of tubes. The specimens were axially compressed between a rigid plate on top and a conical die at the bottom using Zwick universal testing machine. Good agreements were found between numerical simulations and experimental tests. The effects of several parameters such as number and length of initial notches, diameters and thickness of tubes and vertex angle of dies on energy absorption capacity of specimens are investigated, numerically.

DOI: 10.1016/j.tws.2016.04.012
ABSTRACT: In this paper a novel shell finite element is introduced, specifically proposed for constrained shell finite element analysis. The proposed element is derived from the finite strips used in the semi-analytical finite strip method. The new finite element shares the most fundamental feature of the finite strips, namely: transverse and longitudinal directions are distinguished. Moreover, the new element keeps the transverse interpolation
functions of finite strips, however, the longitudinal interpolation functions are changed from trigonometric functions (or function series) to classic polynomials. It is found that the proper selection of the polynomial longitudinal interpolation functions makes it possible to perform modal decomposition similarly as in the constrained finite strip method (cFSM). This requires an unusual combination of otherwise well-known shape functions. If the so-constructed shell finite elements are used to model a thin-walled member, (hence, with using discretization in both the transverse and the longitudinal directions,) modal decomposition can be done essentially identically as in cFSM, whilst the practical applicability of the method is significantly extended (e.g., various restraints, holes, certain cross-section changes can easily be handled). In this paper the focus is on the derivation of the novel shell finite element. Constraining capability is illustrated by some basic examples. Practical application of the novel element will be presented in subsequent papers.


ABSTRACT: The need for strengthening steel structures is as important as it is for concrete structures, or any other aging structure. Strengthening concrete structures by externally bonding thin composite materials in the form of laminates or strips has proven to be an efficient way for enhancing the flexural, shear, and axial strength of deficient elements. Use of external bonding of thin composite material to strengthen steel structures can also be found in literature. This paper presents another effective strengthening technique in which pultruded GFRP sections are bonded to shear deficient regions to enhance the local buckling resistance of thin walled steel structures. Three steel beams with different web thicknesses were tested experimentally with and without GFRP stiffeners to study the efficiency of the new technique; Strengthening-By-Stiffening or SBS. The ultimate shear capacities of the beams were enhanced by a minimum of 30% when one stiffener was used on a beam with a square panel and a maximum of 40% for beams with larger rectangular panel with two stiffeners (one on each side). The initial global stiffness was also enhanced between 5% and 41% for the strengthened beams as a result of the externally bonding the GFRP stiffeners. Unlike the one stiffener configuration which experienced a major load drop at high load levels, the post yielding behavior of the two stiffener configuration exhibited a sustainable load capacity around the peak load without any major load drop. Strain reading from the top and bottom flanges at the loading point revealed that a sway frame mechanism became the main shear resisting mechanism after the critical panel buckled due to shear.

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ABSTRACT: Within the framework of the nonlinear 6-parameter shell theory with the drilling rotation and asymmetric stress measures, the modifications of Tsai-Wu and Hashin laminate failure initiation criteria are proposed. These improvements enable to perform first ply failure estimations taking into account the non-symmetric stress measures. In order to check the validity of the proposed criteria, finite element analyses are performed with the use of the Authors’ program and the Abaqus package. It is shown that the classical forms of the well known failure hypotheses can predict different stress capacity of structure, if the stress measures do not preserve the symmetry condition.
ABSTRACT: This paper presents 18 tests conducted on short, medium and long circular Concrete Filled Steel Tube (CFST) columns. To explore the impact of column parameters and confinement effect three $L/D$ ratios, two $D/t$ ratios, two steel qualities and three concrete classes were employed. Some specimens have properties within application limits of EC4 and AISC 360-10 whereas others have properties beyond the application limits. Since new, large and efficient structures require adoption of high strength materials, it is compulsory to push the limits of design specifications. It is shown that 56 MPa and 66 MPa concretes provide very smooth and ductile load-shortening curves which imply high deformation capacity of such concrete classes. Brittle nature of 107 MPa concrete is shown by very sharp transitions from pre-peak to post-peak region and sudden discharge of loading in load-shortening curves. Additionally, 239 experimental data were collected from literature to assess EC4 and AISC 360-10 predictions within application limits and beyond application limits. Instead of focusing on a narrow region of configurations, this paper examines the performance of prediction methods on short, medium and long CFST columns. EC4 predictions indicate much better agreement with the test results. However AISC 360-10 predictions are conservative for all combinations of parameters. The application limits of EC4 can be widened to cover solutions of columns with broader properties. Confinement effect should be handled elaborately in AISC 360-10 formulations. $L/D$ and relative slenderness are key parameters and have direct impact on column behaviour. However $D/t$ does not have direct impact on column behaviour.

ABSTRACT: Two models for completing structural analyses of cured fabric-reinforced composites that link back to a forming simulation are investigated. The objective of each model is to seamlessly use the predicted geometries of the textile plies to generate a finite element model of the cured structure. The first is a beam-shell model, where beam elements represent the fibers and shell elements represent the matrix. The beams are imported directly from the forming model to capture the deformed fabric geometry. The second approach is a double-orthotropic shell model where two shells, each representing a set of fibers, i.e. warp or weft, are superimposed. The material orientation in each shell is aligned with the respective fiber directions. To investigate the capabilities of the models for unidirectional-fiber reinforced composite plates with multiple fiber orientations and loading configurations, the two models are compared to classical laminate theory (CLT). To explore the models’ ability to represent a plain-weave textile reinforced composite plate with various shear angles in the fabric reinforcements, the two proposed models are compared to experimental data. The double orthotropic shell model is found to be a better option for linking the mechanical behavior of the formed composite back to the simulation of the manufacturing process than the beam-shell model.

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ABSTRACT: The paper proposes a novel type of stiffener designed to bear bending loads by exploiting internal pressure effects. The stiffener is made of two adjacent thin-walled pipes \((r/t \geq 50)(r/t \geq 50)\) jointed with a connecting strip. Such a structure is shown to have higher performance against buckling failure compared to a single pipe and its geometry allows for good exploitation of internal pressurisation. The study is conducted by using the FEA software ANSYS and the analysis technique is the linear perturbation buckling analysis. Internal pressure ranges from 0 to 1.4 MPa. The buckling mechanisms are observed for a set of models with different values of length, wall thickness and geometric variation of the cross-section. It is shown that two different buckling modes can take place. However, for a given geometry, the level of pressure can alter the behaviour and lead to one mode rather than the other one. Potential of the presented structure is maximised by the use of high performance materials and a possible aerospace engineering application is presented.

ABSTRACT: The 2010 AISC flexural strength of I-shaped beams with slender flange was proposed based on Johnson (1985)’s experimental plate bucking coefficient \((k_c)\). However, our close examination revealed that most of I-beam specimens tested by Johnson to derive \(k_c\) had section configuration of slender web and noncompact flange, indicating the inappropriateness of the test database itself and probable underestimation of web restraint effect in the AISC codification. In this paper, the effect of web slenderness on the elastic flange local buckling is analytically investigated using the mixed variational approach, and more accurate but still practical formula is proposed.

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ABSTRACT: Thin-walled structures are widely used as energy absorbing devices for their proven advantages on lightweight and crashworthiness. However, conventional thin-walled structures often exhibit unstable collapse modes and excessive initial peak crushing force (IPCF) followed by undesirable fluctuation in force-displacement curves under impact loading. This paper introduces a novel tubal configuration, namely sinusoidal corrugation tube (SCT), to control the collapse mode, and minimize the IPCF and fluctuations. Through validating the finite element (FE) models established, the effects of wavelength, amplitude, thickness and diameter of SCTs on collapse mode and energy absorption were investigated. The results showed that SCTs can make the deformation mode more controllable and predictable, which can be transformed from a mixed mode to a ring mode by simply changing the wavelength and amplitude. Compared with the traditional straight circular tube, the IPCF is reduced appreciably. Furthermore, SCTs have lower fluctuation in the force–displacement curves than traditional straight circular tubes. Finally, a multiobjective optimization is conducted to obtain the optimized SCT configuration for maximizing specific energy absorption (SEA), minimizing IPCF under the
constraint of fluctuation criterion. The optimal SCTs are of even more superior crashworthiness and great potential as an energy absorber.

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ABSTRACT: In this paper, we present an original work for the examination of the stability of thin-walled beams with open section subject to arbitrary loads. It is based on a 3D nonlinear model where the equilibrium and material constitutive equations are established without any assumption on the torsion angle amplitude which leads to strong nonlinearity. In a recently published article [1], we compared this model without simplification to three others models with cubic, quadratic and linear simplifications. The efficiency of the model is confirmed from benchmark solutions. For this reason, we propose in this work to use this model without simplification in the presence of external forces. When these external forces are eccentric they make the nonlinear problem very difficult to solve because the tangent stiffness matrix depends on the load. In presence of arbitrary loads and large torsion context, the right hand side of the equilibrium equations is highly nonlinear and contributes to the tangent stiffness matrix. For this purpose, we use a continuation algorithm based on the Asymptotic Numerical Method ANM, recently published by the authors in [2]. The ANM is a computational tool for solving nonlinear equations numerically; this is achieved by associating the finite element method and a Taylor series expansions technique without any correction and iteration steps. By this way, we compute a large part of the branch by inverting only one stiffness matrix. The efficiency of the present extended model is tested on original applications of open sections thin-walled beams under arbitrary and eccentric loads. A comparison of the obtained results with those computed by Abaqus industrial code is presented.

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“Numerical investigation and direct strength design of cold-formed steel lipped channel columns experiencing local-distortional-global interaction”, Thin-Walled Structures, Vol. 105, pp 231-247, August 2016, DOI: 10.1016/j.tws.2016.03.025

ABSTRACT: This paper reports the results of a numerical investigation concerning the relevance and Direct Strength Method (DSM) prediction of the ultimate strength erosion caused by local-distortional-global (LDG) interaction in cold-formed steel fixed-ended lipped channel columns. The geometries of the columns analysed (cross-section dimensions and lengths) were carefully selected to ensure that the three competing critical buckling loads are not more than 20% apart, thus guaranteeing a fairly high level of LDG coupling, and ordered in all the various possible sequences. In order to cover a wide slenderness range, several yield stresses are considered, falling below, in-between and above the lowest and highest critical buckling stresses. After providing a brief description of the column selection procedure, which is based on buckling analyses performed with Generalised Beam Theory (GBT), the methodology adopted to identify the most detrimental initial geometrical imperfection shape (in the sense it minimises the column strength) is addressed – it employs
Koiter's asymptotic method along with a Monte Carlo simulation. Then, columns containing those initial geometrical imperfections are compressed up to failure, by means of Abaqus shell finite element analyses (SFEA), making it possible to acquire in-depth knowledge on the behaviour of lipped channel columns undergoing LDG interaction and gather considerable failure load data. Finally, the last part of the paper is devoted to the DSM prediction of those failure loads and uses the obtained “data bank” to assess whether the available design approaches are able to handle adequately the ultimate strength erosion caused by the triple interaction phenomenon under investigation – if this is not the case, new design curves must be developed.

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“On the strength and DSM design of cold-formed steel web/flange-stiffened lipped channel columns buckling and failing in distortional modes”, Thin-Walled Structures, Vol. 105, pp 248-265, August 2016, DOI: 10.1016/j.tws.2016.03.023

ABSTRACT: Results recently reported by Kumar and Kalyanaraman [1] suggest that the presence of web and flange V-shaped intermediate stiffeners in cold-formed steel lipped channel columns may alter considerably their distortional buckling, post-buckling and collapse behaviours. The objective of this work is to assess the validity of this assertion, constituting a significant break from the existing knowledge, which is widely accepted by the technical/scientific community working with cold-formed steel structures. In particular, it may even imply that the application of the Direct Strength Method (DSM) to web/flange-stiffened lipped channel columns requires the consideration of a different (higher) distortional strength curve. In order to carry out the above assessment, this work reports a thorough numerical investigation aimed at studying the peculiarities of the distortional buckling, post-buckling and collapse behaviours of (web/flange) stiffened cold-formed steel lipped channel columns. The first step consists of selecting column geometries associated with “pure” distortional buckling and failure modes, which is ensured by having local and global critical buckling loads much higher than their distortional counterparts – this task is carried out by means of sequences of “trial-and-error” buckling analyses, performed with the GBTul code. Then, it is necessary to address the mechanical characterisation of the distortional critical buckling modes in the stiffened columns, a task much more involved than in plain lipped channel columns (and by no means trivial). This is done through the in-depth inspection of the results provided by the aforementioned GBT buckling analyses. Next, an Ansys shell finite element model is employed to perform geometrically and materially non-linear analyses of the selected stiffened lipped channel columns. The numerical results obtained (equilibrium paths, failure loads and deformed configurations) are presented and discussed, in order to assess the influence of the V-shaped intermediate stiffeners. Finally, on the basis of the ultimate strength data obtained and also the experimental and numerical failure loads reported in [1], the paper presents some considerations concerning the application of the current DSM strength curve to the design of (web/flange) stiffened lipped channel columns failing in distortional modes – in particular, some conclusions are drawn concerning the need to develop a new DSM distortional design curve to handle columns with this cross-section shape.

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ABSTRACT: This paper reports an experimental campaign on the buckling behaviour of compressed single and built-up cold-formed steel columns. Four types of cross-sections were tested, namely, one single, one open built-up and two closed built-up, considering two end-support conditions, pin-ended and fix-ended. The obtained results were compared with the design predictions of EN1993-1-3:2004 and AISI S100-07. For pin-ended lipped channel columns the design predictions are in good agreement with the experimental results, however for the fix-ended columns the predictions may be conservative. For built-up columns was found that increasing the number of profiles may lead to unsafe design predictions.

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“Buckling of steel tanks under measured settlement based on Poisson curve prediction model”, Thin-Walled Structures, Vol. 106, pp 284-293, September 2016, DOI: 10.1016/j.tws.2016.05.009

ABSTRACT: Buckling behavior of large steel tanks under measured settlement has been researched and analyzed in this paper. The settlement prediction model based on Poisson curve is established by applying least square principle and Lagrange quadratic interpolation. Settlement of each measuring point at any time can be obtained applying this prediction model. The discrete settlement data at any time beneath the tank wall is transformed into global settlement expression distributed in the circumferential direction by using the method of Fourier series expansion. Settlement variation with time beneath the tank wall is predicted accurately then. Based on the predicted settlement beneath the tank wall at any time, bucking behavior of the tank is researched by numerical simulation method and the critical buckling time of the tank is predicted. Hydrostatic pressures are applied to inner surface of the tank wall to research the buckling behavior of the tank with different liquid storage. The present method is applied to a fixed roof tank and result shows that the tank wall presents stable linear variation under settlement in initial stage. As time and settlement increase, a typical snap-through buckling occurs to the tank wall, which indicates that the buckling analysis method presented in this paper can be used to predict the buckling behavior of the tank effectively. Buckling behavior analysis of a floating roof tank with the same size and under the same settlement with the fixed roof tank is also made. It indicates that compared to the buckling of fixed roof tanks, the radial displacement on the top of the floating roof tank wall is regarded as the controlling factor to determine the tank failure.

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ABSTRACT: A conical shell frustum with flat circular top is called dished shell. These type of shell find application in many aerospace and rocket industries. These type shells undergo a special type of buckling phenomenon similar to arches and spherical caps, which needs to be studied in detail. In the present study, an Eigen value buckling analysis of dished shallow shell is attempted. Two types of dished shallow shells are chosen: with a stiff top, and with a flexible top. Finite element analysis is done to find out the effect of various geometrical parameters such as shell thickness, height, top flat region radius and various boundary conditions on the mode shape and critical buckling load under uniform external pressure. It is found that mode shape and
critical buckling pressure changes with variation in geometrical parameters of shells. It is also observed that shells having stiff central flat circular region show different harmonics in conical region for different modes of deformation and the values of critical pressure for different modes are very close to each other. However, for dished shallow shells with flexible top critical buckling pressures are significantly different for various modes except conjugate ones. The numerical analysis results for dished shell with flexible top and fixed boundary condition is compared with analytical solutions of an equivalent spherical cap and for stiff top condition with analytical solutions of an externally pressurized conical frustum. The information obtained from this study, can be used for design improvement and failure mode analysis of dished shells.


ABSTRACT: A recently developed analytical model for a perfect I-section strut experiencing a nonlinear interaction between local buckling and global buckling about the strong axis is enhanced and subsequently extended. The initial enhancement is achieved by devising a simplified and calibrated model that provides an improved prediction of the local buckling load. A purely numerical model is then constructed within the commercial finite element (FE) software Abaqus for validation purposes and excellent comparisons are observed, demonstrating that the analytical model is considerably improved on previous work. The model for interactive buckling is then developed subsequently to include the effects of global and local geometric imperfections, which are introduced individually and in combination. The strut is found to be sensitive to all considered shapes of imperfection and the combined imperfection case correlates excellently with an equivalent FE model, particularly in the neighbourhood of the secondary instability that leads to mode interaction. This demonstrates that the enhanced analytical model predicts the actual load carrying capacity and the structural mechanics accurately.


ABSTRACT: In the present study, the buckling of laminated composite curved panels embedded with Shape Memory Alloy (SMA) fibers under different geometrical conditions was studied. The buckling load of curved panels subjected to axial, lateral and mixed loads was analyzed. Different distributions of SMA fibers were considered. The optimized reinforcement of curved panel using SMA fibers based on different opening angles was studied. The sensitivity analysis was performed to investigate the effect of the variables of fiber distribution function on critical buckling load of the panel. The results indicate that by increasing the radius, the buckling load for both axial and lateral loadings decreases, while the share of SMA fibers on buckling load increases. The result shows the possibility of buckling load enhancement by optimized distribution of SMA fibers in both flat and curved panels. In addition, sensitivity analysis shows that critical buckling is very sensitive to the coefficient of higher non-uniform distributions.

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ABSTRACT: In this paper, the effects of the yield surface curvature and anisotropy constants on the predicted crush response of aluminum tubes are investigated. The yield function proposed by Plunkett et al. (2008) with two linear transformations is employed in the commercial finite element software LS-DYNA to predict the crush response of the aluminum alloy AA5754-O circular tubes. This yield function represents anisotropy of aluminum alloys accurately by simultaneously capturing the variation of both the yield stress and the R-value with orientation. Dynamic crush simulations of tubes are performed using this yield function with four different yield surface shapes. The same sets of experimental uniaxial yield stresses and R-values along with various sample orientations are considered for determining the anisotropy coefficients of the yield function for each case (the coefficients are different even though the input experimental data is the same). Simulations of axial crush show that the yield surface shape affects the collapse mode and predicted energy absorption characteristics of the crush tube. The analysis shows that the deformation is predominately controlled by balanced biaxial deformation. However, characterization of both the plane strain and pure shear points on the yield surface for energy absorption are also important. The shape and the area of the yield function govern the loading condition, which dictates the deformation and energy absorption. The results demonstrate the importance of the shape of the yield surface in axial crush simulations of structural components using aluminum.

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ABSTRACT: The residual stresses and strains in cold-formed steel members are a result of the manufacturing process. It has been shown that the variation of residual stresses through the thickness of cold-formed steel members is not linear. In this study a numerical algorithm is developed to calculate the through-thickness variation of residual stresses and strains. The algorithm calculates the stresses and strains by viewing the manufacturing process as a combination of elasto-plastic bending and springback in a wide plate under plane strain conditions. In order to calculate the plastic deformations, the Prandtl-Reuss flow rule associated with von Mises yield criterion is used. With regard to satisfying the boundary conditions on the surface, the bisection method is used to find the location of the neutral axis. The results obtained via the proposed algorithm are verified with the available closed formed solutions, finite element analysis results and experimental measurements. A parametric study is performed to evaluate the effect of the coil radius and cross-sectional and material properties on the residual stresses and strains. It is shown that, while in the corner regions the most important parameter is the corner radius, it is the coil radius and yield stress that play a significant role in the variation of residual stresses and strains in the flat regions.

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ABSTRACT: This paper introduces manufacturing constraints into a recently developed evolutionary algorithm for shape optimisation of CFS profiles. The algorithm is referred to as “self-shape optimisation” and uses Genetic Algorithm (GA) together with the Augmented Lagrangian (AL) method to avoid ill-conditioned problems. Simple manufacturing rules derived from the limitations of current cold-forming processes, i.e. a limited ability to form continuously curved surfaces without discrete bends, are described in the paper and incorporated into the algorithm. The Hough transform is used to detect straight lines and transform arbitrarily drawn cross-sections into manufacturable ones. Firstly, the algorithm is verified against a known optimisation problem and found to accurately converge to a manufacturable optimum solution. Secondly, the algorithm is applied to singly-symmetric CFS columns each of which is subject to an axial compressive load of 75kN and has a uniform wall thickness of 1.2 mm. The strength of the columns is evaluated by the Direct Strength Method (DSM) and all buckling modes are considered. Various column lengths (from 500 mm to 3000 mm) and numbers of roll-forming bends were investigated. The optimised cross-sections are presented and discussed.

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ABSTRACT: The paper deals with local buckling of the compressed flanges of cold-formed thin-walled channel beams subjected to pure bending or axially compressed columns. Arbitrarily shaped flanges of open cross-sections and the web-flange interactions are taken into account. Buckling deformation of a beam flange is described by displacement related to torsion of the flange about the line of its connection with the web. Total potential energy of the flange is a base for the fundamental differential equation of the critical stress of local buckling. The differential equation is derived by means of the stationary total energy principle. The critical buckling stress corresponding to a number of the buckling half-wave matches to the minimum eigenvalue of the equation. Numerical examples dealing with single, double bend and lipped flanges are included. The analytical results are compared with the finite element method outcomes. Some conclusions are formulated, too.


ABSTRACT: The present paper is focused on the analysis of the collapse mode of circular tubes with multi-cell insert under oblique loads. The material assigned to the structures is AA6061-O thus the material strain rate sensitivity can be neglected. An analytical solution for the evaluation of the crushing force is proposed. Results obtained from extensive numerical simulation were used in order to validate the analytical solution. The
analysis of buckling and bending behaviour of the structure gives an estimate of the load that produces the collapse of the structure. This set of analytical equations can be used to predict the behaviour of the structure under oblique load. Results obtained from the numerical simulation are compared with the results of the parametric analysis in order to validate the procedure. In case of designing structures starting from the capable load, the available configurations were investigated using the set of analytical equations. A good agreement was found between the analytical results and numerical simulations. The proposed model can be applied to evaluate structures under oblique impact as the analytical equations can be easily solved providing a start for the investigation of these complex structures.

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“Structural behavior of hybrid FRP pultruded beams: Experimental, numerical and analytical studies”, Thin-Walled Structures, Vol. 106, pp 201-217, September 2016, DOI: 10.1016/j.tws.2016.05.004
ABSTRACT: This paper presents experimental, numerical and analytical studies on the flexural behavior of I-section hybrid fiber reinforced polymer (FRP) beams made of glass fibers (GF) and carbon fibers (CF) pultruded together and embedded in a polyester matrix. A reference profile (all-GFRP) and five series of hybrid C-GFRP profiles, with different types and architectures of CF reinforcement were tested under four-point bending to assess their structural response up to failure. The experimental results confirmed the effectiveness of hybridization in increasing the bending stiffness of pultruded beams. The experimental tests were simulated using finite element models with Hashin damage criterion to study the material progressive failure and delamination. Numerical results showed a good agreement with the experimental data both in terms of loading path and ultimate load. The design approaches of the Italian Guide and American Pre-Standard were assessed, the former being more accurate and conservative than the latter.

S.A. Jalali and M. Banazadeh (Department of Civil and Environmental Engineering, Amirkabir University of Technology, Hafez shomali street, Tehran, Iran), “Development of a new deteriorating hysteresis model for seismic collapse assessment of thin steel plate shear walls”, Thin-Walled Structures, Vol. 106, pp 244-257, September 2016, DOI: 10.1016/j.tws.2016.05.008
ABSTRACT: A new hysteresis model is developed for thin Steel Plate Shear Wall (SPSW) systems which incorporates cyclic and in-cycle deteriorations. The model is implemented into the OpenSees software and is validated against a number of experimental evidences. Seismic response sensitivity of SPSW system to the hysteretic model characteristics is evaluated, afterwards, using three code-conforming SPSWs with different heights. The 15 variant models developed for each frame using different combinations of deterioration parameters are subjected to incremental dynamic analysis. The sensitivity of the derived median collapse capacities, expressed in $S_a(T_s)$ terms, to the “cyclic” and “in-cycle” deterioration parameters are finally assessed.

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“Experimental and numerical investigations on double-skin CHS tubular X-joints under axial compression”, Thin-Walled Structures, Vol. 106, pp 268-283, September 2016, DOI: 10.1016/j.tws.2016.05.007

ABSTRACT: This paper presents the experimental and numerical investigations on double-skin circular hollow section (CHS) tubular X-joints under axial compression, in which PVC pipes were used as the internal members. A total of 22 X-joints with different brace to chord diameter ratio ($\beta$), hollow ratio of chord ($\phi$) and shapes of internal members was tested, in which two traditional CHS tubular X-joints and two grouted CHS tubular X-joints were tested for comparison. The joint strengths, failure modes, load-deformation curves, load-strain distribution curves and ultimate capacity evaluation of all specimens are reported. The effects of brace to chord diameter ratio ($\beta$), hollow ratio of chord ($\phi$) and shapes of internal members on the structural behaviour of double-skin CHS tubular X-joints under axial compression were evaluated. It is shown from the comparison that the ultimate strength, initial stiffness and ductility of double-skin CHS tubular X-joints benefit from the increase of brace to chord diameter ratio ($\beta$). Furthermore, the double-skin CHS tubular X-joints with large hollow ratio of chord ($\phi$) show good ductility. On the other hand, the ultimate strengths of double-skin tubular X-joints significantly increased by grouting the chord member. The ultimate strength and initial stiffness of double-skin tubular X-joints with small hollow ratio of chord ($\phi$) are close to their grouted counterparts. However, the ultimate strength and initial stiffness of double-skin CHS tubular X-joints with large hollow ratio of chord ($\phi$) are much smaller than their grouted counterparts. The corresponding finite element analysis was performed and calibrated against the test results. The design equations are proposed based on the test and numerical results for double-skin CHS tubular X-joints, which were verified to be more accurate.

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ABSTRACT: Previous studies on stainless steel tubular section beam-columns have revealed shortcomings in established codified design methods. These shortcomings stem principally from inaccurate predictions of the bending and column buckling end points of the design interaction curves, where the bending moment end points are tied to the elastic or plastic moment capacities without considering strain hardening, while the column buckling end points are often over-predicted. Inaccuracies also arise due to the adopted interaction factors, which do not fully capture the structural response of the stainless steel members under combined loading. These observations prompted the present research, which is aimed at developing more efficient design rules for stainless steel tubular section beam-columns. In the presented design proposals, the deformation-based continuous strength method (CSM), allowing for strain hardening, was used to determine the bending moment capacities (i.e. the bending end points), while the column buckling strengths (i.e. the column end points) were calculated according to recently proposed buckling curves. Based on these more accurate end points, new interaction factors were derived following a comprehensive numerical simulation programme. The accuracy of the new proposals was assessed through comparisons against over 3000 experimental and numerical results. Compared to the current design standards, the new proposal yields a higher level of accuracy and consistency in the prediction of stainless steel square and rectangular hollow section (SHS and RHS) beam-column strengths. Use of the proposed interaction factors but with the Eurocode bending moment capacities and revised column buckling strengths as the end points was also assessed and shown to result in more accurate and less scattered strength predictions than the current Eurocode provisions. The reliability of the proposals has been confirmed by means of statistical analyses according to EN 1990, demonstrating its suitability for incorporation into future revisions of international design codes for stainless steel structures.
DOI: 10.1016/j.tws.2016.04.007

ABSTRACT: It is vital to be able to rapidly assess damaged ship structures. This ensures the safety of personnel and facilitation of the most effective repair or recovery. Interframe progressive collapse analysis has been used as a method for rapid assessment for vessels but its suitability for application to damaged vessels has been questioned, due to the limited failure modes assessed and modelling assumptions required when implementing the method. To reduce the cost and increase the effectiveness of the recovery of a damaged vessel, it will be important to more accurately assess the structure by determining the correct failure mode. This paper presents a study on the use of progressive collapse analysis to model damaged box girders which assesses the structure across multiple frame boundaries. The study shows that while progressive collapse analysis can be applied in the assessment of damaged box girders, implementing the newly proposed assessment allows greater accuracy in the calculation of the collapse strength through capture of the true mode of failure. This new method will allow the effects of the damage on surrounding structure to be captured which can influence the deflection shapes that will lead to collapse of the structure.

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ABSTRACT: The article presents a methodology for the study of shell structure strength and stability. The basis of the study is a geometrically nonlinear mathematical model, which takes into account the transverse shifts and orthotropy of material. The model is presented in dimensionless parameters in the form of the total energy potential functional and can be used for different types of shells of revolution. The model is studied by using an algorithm based on the Ritz method and the method of solution continuation according to the best parameter (MSCBP), which allows for obtaining the values of the upper and lower critical loads and examining the supercritical behavior of designs. In accordance with an algorithm, the computer program has been developed and a comprehensive study of the strength and stability of shallow shells (which are square in plane), cylindrical, and conical panels has been explored. The load loss of strength and buckling load values have been obtained, and their relationship to one another has been demonstrated.

DOI: 10.1016/j.tws.2016.05.023

ABSTRACT: Steel cylindrical tanks are formed by very thin-walled shells and as typical thin-walled structures, they are very sensitive to buckling under external pressures, especially when they are empty or at low liquid level. Results of numerical investigations on the effects of spiral stairway on the buckling behavior of ground based steel cylindrical liquid storage tanks subjected to both wind and vacuum pressures are presented. It is concluded that by choosing appropriate circumferential position for stairway, considering regional prevailing wind direction, designers can use the noticeable amount of added strength arising from stairway as a safety
margin. In other words, it seems that the spiral stairway acts as an oblique stiffener on the tank wall. Contrary to the case of wind loading, the stairway has negligible effect on buckling resistance of tanks under vacuum pressure. However, it changes the buckling modes of tank significantly under vacuum loading.


ABSTRACT: Cross sections of modern bridges are generally build with stiffened plated elements. The verification methods given in Eurocode EN 1993-1-5, to obtain the ultimate buckling resistance of plated structures, result in a time consuming procedure. In addition, the methods are mainly based on the elasticity theory and reduction factors from e.g. experiments are needed. Therefore, an alternative approach to obtain the ultimate resistance of unstiffened and stiffened plates is used. The method is based on a strain-dependent and geometric nonlinear yield-line theory including imperfections. This theory makes it possible to approximate the decreasing part of the load–deflection curve of such stability sensitive structures. The ultimate resistance, as maximum of the load–deflection curve, is approximated by a defined limit value. Therefore, the use of additional reduction factors is not necessary. Collapse mechanisms, which have been determined with the Finite Element Method (FEM) beforehand, are needed in order to apply the yield-line theory.

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ABSTRACT: This study deals with vibration and stability analyses of a rectangular plate with a side crack based on classical thin plate theory using the famous Ritz method with admissible functions that are constructed by the moving least square (MLS) method with enriched basis functions. The enriched basis functions consist of regular polynomial functions along with crack functions that appropriately describe the stress singularities at the crack tip and show the discontinuities of displacement or slope crossing the crack. Comprehensive convergence studies on the stress intensity factor, buckling loads and vibration frequencies of a cracked rectangular plate under uniform loading at its two opposite edges are carried out and demonstrate the accuracy and efficiency of the presented approach by comparing the present results with previously published ones. Finally, the present approach is applied to investigate the effects of location, length and orientation of side cracks on the buckling loads, vibration frequencies and mode shapes of cracked rectangular plates. The in-plane boundary conditions are normal traction prescribed along two opposite edges and free along the other edges. Two out-of-plane boundary condition combinations are considered. One is simply supported along all the edges, and the other is simply supported along the two loaded edges and free along the other edges.

S.A.M. Ghannadpur and M. Barekati (New Technologies and Engineering Department, Shahid Beheshti University, G.C, Tehran, Iran), “Initial imperfection effects on post-buckling response of laminated plates under
ABSTRACT: The effects of initial imperfection on postbuckling behaviour of laminated plates subject to end shortening strain are investigated in this paper. Different boundary conditions and lay-up configurations are considered and classical laminated plate theory is used for developing the equilibrium equations. The equilibrium equations are solved directly by substituting the displacement fields with equivalent finite double Chebyshev polynomials. This technique allows imposing different combinations of boundary conditions on all edges of composite laminated plates. The final nonlinear system of equations is obtained by discretizing both equilibrium equations and boundary conditions with finite Chebyshev polynomials. Nonlinear terms caused by the product of variables are linearized by using quadratic extrapolation technique to solve the system of equations. Since number of equations is always more than the number of unknown parameters, the least squares technique is used to solve the system of equations. Some results for angle-ply and cross-ply composite plates with different boundary conditions are computed and compared with those available in the literature, wherever possible.

DOI: 10.1016/j.tws.2016.04.023

ABSTRACT: The Steel reinforced concrete-filled fiber reinforced polymer (FRP) tubular column is proposed as a new form of composite column to obtain higher mechanical performance. This paper presents experimental and numerical studies of axially loaded steel reinforced concrete-filled GFRP tubular columns. Ten steel reinforced concrete-filled GFRP tubular columns and two concrete filled GFRP tubular columns are tested. The specimens fail by the rupture of the GFRP tubes under hoop tension and only outward buckling can be observed because of the presence of the concrete core and steel section. Also, the crushed concrete core and buckling of steel section could be observed after removing of the FRP tube. The results indicate steel reinforced concrete-filled GFRP tubular columns have higher specimen stiffness, strength and deformability than concrete filled GFRP tubular columns. A parametric study, including steel ratio and concrete strength, is also carried out.

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ABSTRACT: In the present study, flattening deformation of rectangular tubes (thickness: t, width of the bottom wall: C1, width of the sidewall: C2) in bending was investigated using the finite element method. It is found that the flattening ratio μ2 can be expressed by a sole function of nondimensional curvature xgC12/t (xg: the bending curvature of the tube's central axis) independent of tube thickness in elastic bending; and in plastic bending, the relation between flattening ratio μ2 and xgC12/t is influenced by the tube thickness and the material parameters of yield stress and strain hardening, however, these effects are very small. A mechanical model is proposed to analyze the cross-sectional flattening of a rectangular tube in bending. In the analysis of flattening in plastic bending, it is essential to determine moduli Eg and Ep, the coefficients relating the stress and strain in the axial direction and relating the bending moment and curvature in circumferential direction, respectively. Based on the investigation carried out on the results of FEM, it seems that a simple approximation using a combination of $E_t$
and $E$, gives a solution with a reasonable accuracy. Moreover, when the tube is short, the cross-sectional flattening is also blocked in the middle part. The ratio of decrease of flattening ratio $A_\mu/A_\mu$ can be approximately expressed as a function of nondimensional length ratio $\xi$ 

\[ \xi = \frac{L}{C_1(3+C_2/C_1)} \]

$L$: tube length) alone. Also, based on the fact that the ratio between the flattening ratios of short and long tubes in plastic bending is almost the same as that in elastic bending, a formula for evaluation of the flattening ratio $\mu_2$ in plastic bending of a tube with finite length is proposed.


ABSTRACT: Imperfection sensitivity is essential for mechanical behavior of biopolymer shells [such as ultrasound contrast agents (UCAs) and spherical viruses] characterized by high geometric heterogeneity. In this work, an imperfection sensitivity analysis is conducted based on a refined shell model recently developed for spherical biopolymer shells of high structural heterogeneity and thickness nonuniformity. The influence of related parameters (including the ratio of radius to average shell thickness, the ratio of transverse shear modulus to in-plane shear modulus, and the ratio of effective bending thickness to average shell thickness) on imperfection sensitivity is examined for pressured buckling. Our results show that the ratio of effective bending thickness to average shell thickness has a major effect on the imperfection sensitivity, while the effect of the ratio of transverse shear modulus to in-plane shear modulus is usually negligible. For example, with physically realistic parameters for typical imperfect spherical biopolymer shells, the present model predicts that actual maximum external pressure could be reduced to as low as 60% of that of a perfect UCA spherical shell or 55%–65% of that of a perfect spherical virus shell, respectively. The moderate imperfection sensitivity of spherical biopolymer shells with physically realistic imperfection is largely attributed to the fact that biopolymer shells are relatively thicker (defined by smaller radius-to-thickness ratio) and therefore practically realistic imperfection amplitude normalized by thickness is very small as compared to that of classical elastic thin shells which have much larger radius-to-thickness ratio.


ABSTRACT: in this paper, free vibration of FGM thin cylindrical shells under non uniform linear and nonlinear internal pressure is investigated and the impact of non-uniform internal pressure on free vibrations and natural frequencies have been analyzed. The boundary conditions used in this study were two simple supported and in order to derive the equations, the theory of sanders thin shells and Rayleigh-Ritz method is used. The effect of various parameters on natural frequencies and free vibrations of shells under internal pressure, such as linear and nonlinear pressure profile, material, thickness to radius and the ratio of length to diameter have been investigated. Additionally, the effect of internal pressure on the natural frequencies profile, in different longitudinal modes and environment has been derived. The results of this study validated by data in the literature and ABAQUS software that reflects the accuracy and can be used as a reference for future designers and researchers.

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ABSTRACT: in this paper, free vibration of FGM thin cylindrical shells under non uniform linear and nonlinear internal pressure is investigated and the impact of non-uniform internal pressure on free vibrations and natural frequencies have been analyzed. The boundary conditions used in this study were two simple supported and in order to derive the equations, the theory of sanders thin shells and Rayleigh-Ritz method is used. The effect of various parameters on natural frequencies and free vibrations of shells under internal pressure, such as linear and nonlinear pressure profile, material, thickness to radius and the ratio of length to diameter have been investigated. Additionally, the effect of internal pressure on the natural frequencies profile, in different longitudinal modes and environment has been derived. The results of this study validated by data in the literature and ABAQUS software that reflects the accuracy and can be used as a reference for future designers and researchers.
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ABSTRACT: A review of papers that investigate the static and dynamic coupled buckling and post-buckling behaviour of thin-walled structures is carried out. The problem of static coupled buckling is sufficiently well-recognized. The analysis of dynamic interactive buckling is limited in practice to columns, single plates and shells. The applications of finite element method (FEM) or/and analytical-numerical method (ANM) to solve interaction buckling problems are on-going. In Poland, the team of scientists from the Department of Strength of Materials, Lodz University of Technology and co-workers developed the analytical-numerical method. This method allows to determine static buckling stresses, natural frequencies, coefficients of the equation describing the post-buckling equilibrium path and dynamic response of the plate structure subjected to compression load and/or bending moment. Using the dynamic buckling criteria, it is possible to determine the dynamic critical load. They presented a lot of interesting results for problems of the static and dynamic coupled buckling of thin-walled plate structures with complex shapes of cross-sections, including an interaction of component plates. The most important advantage of presented analytical-numerical method is that it enables to describe all buckling modes and the post-buckling behaviours of thin-walled columns made of different materials. Thin isotropic, orthotropic or laminate structures were considered.

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ABSTRACT: Grid-shells are lightweight structures used to cover long spans with few load-bearing material, as they excel for lightness, elegance and transparency. In this paper we analyze the stability of hex-dominant free-form grid-shells, generated with the Statics Aware Voronoi Remeshing scheme introduced in Pietroni et al. (2015). This is a novel hex-dominant, organic-like and non uniform remeshing pattern that manages to take into account the statics of the underlying surface. We show how this pattern is particularly suitable for free-form grid-shells, providing good performance in terms of both aesthetics and structural behavior. To reach this goal, we select a set of four contemporary architectural surfaces and we establish a systematic comparative analysis between Statics Aware Voronoi Grid-Shells and equivalent state of the art triangular and quadrilateral grid-shells. For each dataset and for each grid-shell topology, imperfection sensitivity analyses are carried out and the worst response diagrams compared. It turns out that, in spite of the intrinsic weakness of the hexagonal topology, free-form Statics Aware Voronoi Grid-Shells are much more effective than their state-of-the-art quadrilateral counterparts.

References listed at the end of the paper:

[35] Schneider W. Stimulating equivalent geometric imperfections for the numerical buckling strength verification of axially


ABSTRACT: In this article the effect of circular cutout size, fiber orientation, and reinforcer edge size on buckling behavior of composite plates is investigated by experimental and numerical. Samples have clamped boundary conditions on L-shaped edges and free on other two sides. In the experimental method, the E-glass/epoxy L-shaped samples with and without circular cutout is applied in three different lay-up under uniaxial compression. Then the buckling and failure loads will be recognized. In the second method, according to numerical method (Ansys 10), the effect of reinforcer edge size changing and size of circular cutout on composite plate buckling in four different lay-ups with the same experimental materials properties is investigated. The results show that there is the optimum height for reinforcer edge during different conditions that increasing this size just causes the extra weight and cost and does not have a good effect on buckling load.


ABSTRACT: In this article, according to the thin shell theory of Flugge as well as using a new mathematical procedure, the linear buckling of waffle cylindrical shell under axial load is investigated. Skin and grids are composed of the same isotropic material and the classical boundary conditions of clamped and simply supported are considered. Firstly, using a new mathematical modeling, the structural stiffness matrix of skin and grids is obtained. Then, the equilibrium equations of the shell are derived based on the new stiffness matrix. Finally, these equations are solved using differential quadrature method. The results are compared by the finite element analyses. Comparative results reveal that the present procedure is very stable and accurate. Also, the effects of various geometrical parameters on the linear buckling loads are presented.

ABSTRACT: The main purpose of this study is to investigate nonlinear buckling analysis of Functionally Graded (FG) cylindrical shells under uniform axial compressive loads by dynamic relaxation (DR) method. The mechanical properties of shell vary continuously throughout the thickness direction according to the power-law, exponential function and the Mori-Tanaka distribution. The Poisson’s ratio of the FG cylindrical shell is constant for power-law and exponential function. But in the Mori-Tanaka distribution variations of Poisson's ratio is determined as a function of the thickness direction. The incremental form of nonlinear formulations are based on first order shear deformation theory (FSDT) and large deflection von Karman equations. The DR method combined with the finite difference discretization technique is employed to solve the equilibrium equations. Some comparison study is carried out to compare the current solution with the results reported in the literature and the ones obtained by the Abaqus finite element software for the isotropic cylindrical shells. Finally, numerical results are presented for critical buckling load with various boundary conditions, grading indices, radius-to-thickness ratio, length-to-radius ratio and variation of Poisson’s ratio.


ABSTRACT: The conceptual ideas behind isogeometric analysis (IGA) are aimed at unifying computer aided design (CAD) and finite element analysis (FEA). Isogeometric analysis employs the non-uniform rational B-spline functions (NURBS) used for the geometric description of a structure to approximate its physical response in an isoparametric sense. Due to the tensor product property of multi-variate NURBS, it is difficult to represent complex topological shapes with a single NURBS patch. Multiple, often non-conforming patches are needed to tackle increasing complexity of the geometry. To further facilitate the modeling of complex shapes and geometric features trimming technology is widely used in CAD software, however, the trimmed domain is only visually unseen and the trimming features can not be utilized directly for the analysis. To overcome these difficulties, extra efforts are needed to make isogeometric methods adapted to engineering related cases. Thin-walled structures, such as plates and shells, excel in optimal load-carrying behavior and are of major importance in the design of aerospace components and the automotive engineering. Isogeometric analysis is an ideal candidate for the modeling and simulation of shell structures, especially for rotation-free Kirchhoff-Love type shells, which profit from the exact description of the geometry and from the higher continuity properties of NURBS. Furthermore, it favorably supports continuity requirements for flexible through-the-thickness design of laminate composites. Laminated composite materials are increasingly used in the aerospace industry this asks for reliable and computationally efficient lamina theories. The classical lamination theory belongs to the class of equivalent-single-layer methods (ESL), it is computationally efficient but often fails to capture the 3D stress state accurately. The demand for an accurate 3D stress state within laminates is mainly driven by the need to identify and to evaluate potential damage of lamina structures. While a full 3D layerwise (LW) model is computationally expensive, a combined approach considering both concepts, ESL and LW, seems to be a natural choice to tackle the computational costs of increasing model size and model complexity. In this thesis, a layerwise method for laminated composite structures is proposed in the framework of isogeometric analysis. A highly accurate prediction of the state of stress for thick and moderately thick laminate composite shells including transverse normal and shear stresses is demonstrated. The layerwise theory is successfully extended to linear buckling analysis of delaminated composites where a contact formulation is added to eliminate physically inadmissible buckling states which may result from overlapping plies. Furthermore, a Nitsche type formulation
is introduced to enforce both weakly, essential boundary conditions and multi-patch coupling constraints for trimmed and non-conforming isogeometric rotation-free Kirchhoff-Love shell patches. The proposed formulation is variationally consistent and excels in a high level of stability and accuracy. A built-in stabilization, used to ensure coercivity of the formulation, prevents ill-conditioning of the physical problem. The inherent trimming problem is tackled with a fictitious domain extension for the trimming domain following the principles of the finite cell method to facilitate the workflow for geometrically complex structures in engineering practice. Computational efficiency is significantly increased with a blended coupling, taking continuum-like shell elements and thin shells elements, according to the theory of Kirchhoff-Love, into account. The blended approach provides access to the full 3D state of stress within selected subdomains while preserving the computational efficiency of the overall analysis.

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“Nonlinear structural behaviour and design formulae for calculating the ultimate strength of stiffened curved plates under axial compression”, Thin-Walled Structures, Vol. 107, pp 1-17, October 2016  
ABSTRACT: Cylindrically curved and stiffened plates are often used in ship and offshore structures. For example, they can be found in the cambered decks, fore and aft side shells and circular bilge parts of ships. A number of studies have investigated curved plates in which the buckling/ultimate strength is increased according to the curvature under various loading scenarios and design formulas. However, information regarding the nonlinear structural behaviour and design formulas for calculating the ultimate strength of the stiffened curved plates is currently limited. In this paper, a series of finite element analyses are performed on stiffened curved plates with varying geometric parameters. The existing curvatures are also analysed to clarify the effects of these parameters on the buckling/post-buckling characteristics and collapse behaviour under axial compression. The results are used to derive closed-form expressions to predict the ultimate compressive strength of curved stiffened plates for marine applications.

DOI: 10.1016/j.tws.2016.05.016  
ABSTRACT: This paper presents and analytical study to investigate the local buckling behaviour of structural steel I-section columns at elevated temperatures. An inelastic stability model is developed that accounts for the reduction in stiffness and strength of the steel when subjected to elevated temperatures. Using the model, a comprehensive parametric study is conducted to investigate the effect of each of the parameters of the column. Based on the results of the parametric study, expressions for the local buckling capacity of steel I-section columns are given in which all the parameters are reflected including the interaction between the flange and the web.

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ABSTRACT: A series of axial compression tests was conducted to investigate the compressive behaviour of cold-formed steel stub columns with relatively thick walls (6 mm and 10 mm, respectively). Four different inner-stiffener arrangements were considered. Tensile coupons were cut from different parts of the square hollow section (SHS) sections to obtain a full picture of the enhanced material properties due to the cold-forming process. A finite element model was also developed and employed to provide a numerical perspective of the behaviour of the SHS columns. The applicability of two code-specified methods for the calculation of the strength of thin-walled cold-formed SHS columns for the present thick-walled cases is examined. The comparison shows that the AISI (and similarly AS/NZS) method tends to overestimate the sectional strength for the unstiffened and partially stiffened 6-mm thick columns, but predicts generally well (with slight underestimate) in the cases of well-stiffened 6-mm columns and all the 10-mm thick columns. The GB method, on the other hand, appears to predict well for all cases where the stiffening effect was less significant, but underestimates the sectional strength in the well-stiffened cases.

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“Effect of forcing frequency on nonlinear dynamic pulse buckling of imperfect rectangular plates with different boundary conditions”, Thin-Walled Structures, Vol. 107, pp 57-65, October 2016
DOI: 10.1016/j.tws.2016.06.001
ABSTRACT: The present study was aimed to investigate the influence of forcing frequency on nonlinear dynamic pulse buckling of imperfect rectangular plates with six different boundary conditions. The Galerkin's approximate method on the basis of polynomial and trigonometric mode shape functions is used to reduce the governing nonlinear partial differential equations to ordinary nonlinear differential equations. Moreover a numerical study of these governing equations is accomplished by Runge Kutta integration methods. The convergence of the polynomial and trigonometric mod shape functions are investigated to compute the dynamic response of plate. The effects of frequency of impulse loading and boundary conditions on the deflection histories of plate are studied. The dynamic response of plate subjected to impulsive loading with different forcing frequency is compared to results obtained by exponential impulsive loading. The results show that, by increasing the forcing frequency of impulsive loading, the maximum displacement of plate increases and converge with lower values to response of plate subjected to exponential impulse. Moreover, different boundary conditions and various pulse functions have significant influence on the dynamic response of the plate.

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ABSTRACT: Built-up sections are widely used in cold-formed thin-walled steel frames. This paper mainly investigates the in-plane behaviour of built-up box beams with nested C section and U section under pure bending about strong and weak axis. The four-point bending test was conducted on a total of 7 groups of specimens, including built-up box sections (CU) and individual sections (C, U). A finite element model is developed and verified by the test results for further parametric analysis. The stress distribution at mid-span cross-section shows that the components in built-up box beams can resist the bending moment together. For built-up box beams bending about strong axis, the reasonability of the capacity superposition method and equivalent method is assessed by the discussion on test results and numerical analysis results. The equivalent box section is suggested to calculate the flexural strength of built-up box beams bending about weak axis. Finally, the comparison between predicted and actual flexural strength indicates that this simplification of the proposed method can slightly underestimate the flexural strength.

Mousa Khalifa Ahmed (Department of Mathematics, Faculty of Science at Qena, South Valley University, Egypt), “Buckling behavior of a radially loaded corrugated orthotropic thin-elliptic cylindrical shell on an elastic foundation”, Thin-Walled Structures, Vol. 107, pp 90-100, October 2016 DOI: 10.1016/j.tws.2016.06.006
ABSTRACT: This paper is aimed to investigate how the corrugation parameters and the Winkler foundation affect the buckling behavior of isotropic and orthotropic thin-elliptic cylindrical shells with cosine-shaped meridian subjected to radial loads. The buckling three-dimensional equations of the shell are amended by including the Winkler foundation modulus based on the Flügge thin shell theory and Fourier's approach is used to deform the displacement fields as trigonometric functions in the longitudinal direction of shell. Using the transfer matrix of the shell, the governing equations of buckling can be written in a matrix differential equation of variable coefficients as a one-dimensional boundary-value problem that is solved numerically as an initial-value problem by the Romberg integration approach. The proposed model is adopted to determine the basic loads and the corresponding buckling deformations for the symmetrical and antisymmetrical modes of buckling. The sensitivity of the buckling behavior and bending deformations to the corrugation parameters, Winkler foundation moduli, ellipticity and orthotropy of the shell structure is studied for different type-modes of buckling. The obtained results indicate that this design model allows us to find out how the local properties of the shell and its stiffness in existence of an elastic foundation are related and would serve as benchmarks for future works in this important area.

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“A new nonlinear model for studying a sandwich panel with thin composite faces and elastic-plastic core”, Thin-Walled Structures, Vol. 107, pp 119-137, October 2016, DOI: 10.1016/j.tws.2016.06.012
ABSTRACT: In this paper elastic–plastic behavior of a sandwich beam with a transversely flexible core and thin faces is investigated. The elastic–plastic behavior of the core is described by a bilinear constitutive relation
of the shear stress. The governing equations for linear and nonlinear regions are derived using higher order sandwich panel theory. The governing equations are solved by finite element method based on the Galerkin weighted residual method. Since the limits of the plastic regions spread through the solution, an iterative procedure is employed to obtain reliable results. Three different boundary conditions including simply supported, clamped and three point bending configurations are studied. The results are compared with the available results in literatures and a good agreement can be seen. The results reveal that as the bilinear ratio decreases the maximum of the shear stress decreases and the plastic region extends. Comparing different boundary conditions shows that by increasing the constraint of the edges, the maximum of shear stress decreases. In addition, the plastic regions spreads by decreasing bilinear ratio and the maximum growth is belonged to clamped configuration.

A. Alavi Nia and S. Chahardoli (Mechanical Engineering Department, Bu-Ali Sina University, Hamedan, Iran), “Optimizing the layout of nested three-tube structures in quasi-static axial collapse”, Thin-Walled Structures, Vol. 107, pp 169-181, October 2016, DOI: 10.1016/j.tws.2016.06.010

ABSTRACT: In this study, energy absorption characteristics of aluminum nested three-tube structures as one of the types of thin-wall energy absorbers were experimentally and numerically examined and some optimal conditions were presented for such structures. In so doing, after determining the type of alloy and stress-strain curves of the tubes, four samples were analyzed under quasi-static collapse. The structures were simulated using finite element software LS-Dyna and the results were compared with data from experimental tests. There was good agreement between experimental and numerical results. After comparing multi-tubular structures with single conventional structures, it was indicated that these structures have a higher capacity to absorb energy. Then, with considering different height and thickness for the structures, the optimal value of these quantities was determined and it was shown that through optimizing three-tube structures, the maximum collapse force can be as low as possible and energy absorption capacity can be hold high. Finally, by optimizing the results with response surface method using Minitab software, samples with optimal performance in the process of collapse were obtained.


ABSTRACT: In this study, the design and optimization of a multi-layer configuration of hexagonal metal honeycomb energy absorber is performed using the genetic algorithm. It is assumed that the body structure with a predefined velocity impacts with barrier and the design objectives are to absorb whole kinetic energy besides limiting impact shock force. The response surfaces of honeycomb impact characteristics are extracted using finite element approach and then a honeycomb energy absorber is sized for case of a presumed impact problem. A multi-objective optimization technique is adopted to maximize the energy absorption capacity and to minimize the impact shock level while minimizing the total absorber size. A factorial design of experiment and response surface method is utilized to solve the optimization problem. The geometric specifications of honeycomb panels including the cell size, foil thickness, height and absorber face area for each layer of honeycomb panel are assumed as the design variables. Some optimization problems are handled and the optimized designs are compared to those from the literature wherever available.

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ABSTRACT: In this paper, an accurate and computationally efficient Generalised Beam Theory (GBT) finite element is proposed, which makes it possible to calculate buckling (bifurcation) loads of steel–concrete composite beams subjected to negative (hogging) bending. Two types of buckling modes are considered, namely (i) local (plate-like) buckling of the web, possibly involving a torsional rotation of the lower flange, and (ii) distortional buckling, combining a lateral displacement/rotation of the lower flange with cross-section transverse bending. The determination of the buckling loads is performed in two stages: (i) a geometrically linear pre-buckling analysis is first carried out, accounting for shear lag and concrete cracking effects, and (ii) an eigenvalue buckling analysis is subsequently performed, using the calculated pre-buckling stresses and allowing for cross-section in-plane and out-of-plane (warping) deformation. The intrinsic versatility of the GBT approach, allowing the incorporation of a relatively wide range of assumptions, is used to obtain a finite element with a reasonably small number of DOFs and, in particular, able to comply with the principles of the “inverted U-frame” model prescribed in Eurocode 4 [1]. Several numerical examples are presented, to illustrate the application of the proposed GBT-based finite element and provide clear evidence of its capabilities and potential.

Gang Li, Lichao Zhan and Hao Li (State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116023, China), “An analytical solution to lateral buckling control of subsea pipelines by distributed buoyancy sections”, Thin-Walled Structures, Vol. 107, pp 221-230, October 2016, DOI: 10.1016/j.tws.2016.06.003
ABSTRACT: Lateral buckling is the primary buckling form of the subsea pipelines. A promising recent practice is to the distributed buoyancy sections to control the lateral buckling of subsea pipeline. In this study, an analytical solution is deduced for the lateral buckling of the pipeline with buoyancy sections in the entire design region. However, numerical difficulty was encountered during the solution of the design equations. To overcome this difficulty, we adopt a response surface method (RSM) for the solution of nonlinear equation system. A strategy of multi-response-surface is proposed by dividing the entire design region into several partial domains and establishing different kinds of response surfaces for each region. A framework for lateral buckling control of subsea pipelines using distributed buoyancy sections is presented. Several illustrative examples demonstrate that the proposed method has a high efficiency and accuracy in solving the problem of the lateral buckling control.

DOI: 10.1016/j.tws.2016.06.014
ABSTRACT: This paper presents a method to perform generalized beam theory buckling analysis on thin-walled structural members with holes. Generalized beam theory (GBT) is an ideal tool for analyzing thin-walled structures because it can directly compute buckling mode participation in an eigen-buckling analysis. The GBT extension to members with holes is made by treating a thin-walled structural member as an assembly of
prismatic sub-members, and compatibility constraints on the GBT modal amplitudes are introduced to connect these sub-members. GBT shear modes with nonlinear warping deformation are included in both first order and buckling analyses to account for the nonlinear normal stress distribution in the vicinity of a hole. GBT buckling mode shapes are verified with shell finite element analysis (SFEA) in three examples that highlight the potential for quantitatively documenting buckling modes initiated by the presence of holes.

R. Rajabiehfard, A. Darvizeh, M. Darvizeh, R. Ansari, M. Alitavoli and H. Sadeghi (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Theoretical and experimental analysis of elastic-plastic cylindrical shells under two types of axial impacts”, Thin-Walled Structures, Vol. 107, pp 315-326, October 2016, DOI: 10.1016/j.tws.2015.12.014

ABSTRACT: In this paper, the dynamic buckling of axisymmetric circular cylindrical shells subjected to axial impact is investigated theoretically and experimentally. The von Mises yield criterion is used for the elastic–plastic cylindrical shell made of linear strain hardening material in order to derive the constitutive relations between stress and strain increments. Nonlinear dynamic circular cylindrical shell equations are solved with using finite difference method for two types of loading which are stationary cylindrical shells impacted axially and traveling cylindrical shells impacted against a rigid wall. Experimental tests for two types of loading are performed by gas gun. Theoretical and experimental results for cylindrical shells under axial impact for different loading conditions are reported and it is found that there is a good agreement between them.

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ABSTRACT: This paper deals with flange vertical buckling of an I-shaped steel girder having the practical section dimension. On flange vertical buckling, Basler et al. presented a formula to verify the occurrence of flange vertical buckling of an I-shaped steel girder by using the width-thickness ratio of the web plate. Two authors of the current paper carried out an experimental test on the hybrid steel girders, and in the test, unexpected vertical buckling was observed in the experimental test. With above background, the authors conducted the numerical studies on flange vertical buckling of the I-shaped hybrid steel girders having smaller section dimensions than practical based on the experimental model. Through these studies, the authors pointed out that occurrence of flange vertical buckling is owing to the thickness of flange and web plate and not to the width-thickness ratio. This fact suggests that a new collapse model is required to establish the procedure for verification of flange vertical buckling. In the current paper, the spring constant should have the new collapse model, the value determined by the Timoshenko's model. This paper shows the points that should be considered when creating the new collapse model.


ABSTRACT: The buckling and post-buckling behaviour of thin-walled Fibre Metal Laminate (FML) profiles subjected to axial loading is discussed. Study concerns open cross-section profiles which consist of alternating
thin layers of aluminium and fibre-reinforced unidirectional prepreg. Laboratory tested specimens were manufactured by autoclaving technique. Depending on fibres alignment, various 3/2-layer stacking were considered and subjected to axial compression in buckling tests. Carrying out an experiment allowed one to determine buckling load and equilibrium paths in buckling and post-buckling state. The results of substantial experimental investigations were compared with FML panel/columns modelling in FEA and with analytically examined based on Koiter's asymptotic theory. In conducted experiments the careful design of simply support boundary conditions of loaded edges of thin-walled columns is examined and discussed. Detailed analysis was also performed to assess the influence of the various fibres alignment on the specimen buckling and post-buckling response.

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ABSTRACT: This paper presents a first-order Generalised Beam Theory (GBT) formulation for naturally curved thin-walled members with deformable cross-section, whose undeformed axis is a circular arc with no pre-twist. First, the strain-displacement relations for naturally curved thin-walled members are derived and it is shown how the classic GBT assumptions concerning the strains can be incorporated, namely: (i) Kirchhoff's thin-plate assumption, (ii) Vlasov's null membrane shear strain assumption and (iii) the null membrane transverse extension assumption. The equilibrium equations are obtained in terms of GBT modal matrices and stress resultants. It is demonstrated that, for the so-called “rigid-body” deformation modes (extension, bending and torsion), the GBT equations coincide with those of the Winkler (in-plane case) and Vlasov (out-of-plane case) theories. A standard displacement-based GBT finite element is used to solve a set of representative illustrative examples involving complex local-global deformation. It is shown that the proposed GBT formulation leads to extremely accurate results with a reduced number of DOF and that the GBT modal solution provides an in-depth insight into the structural behaviour of naturally curved members.

Shameem Ahmed, Mahmud Ashraf and Mohammad Anwar-Us-Saadat (School of Engineering and Information Technology, The University of New South Wales at the Australian Defence Force Academy, Northcott Drive, Canberra, ACT 2600, Australia), “The continuous strength method for slender stainless steel cross-sections”, Thin-Walled Structures, Vol. 107, pp 362-376, October 2016, DOI: 10.1016/j.tws.2016.06.023

ABSTRACT: This paper extends the scope of the Continuous Strength Method (CSM), which has recently been proposed for stocky sections, to include slender stainless steel sections. A new parameter called the Equivalent Elastic Deformation Capacity is introduced to tackle the significant post-buckling deformation observed in slender sections. A comprehensive finite element study was carried out to supplement limited number of available test results. Obtained FE results and available test evidences were used to propose design guidelines for compression and bending. The performance of the proposed technique was compared against EC3 guidelines, which showed good agreement with test and FE results with an acceptable level of reliability.
Mariusz Urbaniak, Jacek Swiniarski, Pawel Czapski and Tomasz Kubiak (Department of Strength of Materials, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland), “Experimental investigations of thin-walled GFRP beams subjected to pure bending”, Thin-Walled Structures, Vol. 107, pp 397-404, October 2016, DOI: 10.1016/j.tws.2016.06.022

ABSTRACT: The results of the experimental buckling and postbuckling behaviour analysis of thin-walled, square cross-section tubes subjected to pure bending are presented. The beams under investigation were manufactured from a glass fibre reinforced polymer unidirectional prepreg tape in an autoclaving procedure. The experimental results for six different layups of the eight-layer laminate were considered. In order to collect all necessary data, strain gauges and an ARAMIS Digital Image Correlation (DIC) system produced by the GOM company were employed. The strain gauges measured strains at one point, whereas the DIC system was able to generate maps of displacement fields. On the basis of the data from an Instron universal testing machine, it was possible to determine buckling loads and equilibrium paths in order to compare the results. Moreover, grips designed especially for pure bending tests are presented.

Pham Toan Thang, Tan-Tien Nguyen and Jaehong Lee (Department of Architectural Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea), “Nonlinear static analysis of thin curved panels with FG coatings under combined axial compression and external pressure”, Thin-Walled Structures, Vol. 107, pp 405-414, October 2016, DOI: 10.1016/j.tws.2016.06.007

ABSTRACT: The buckling behavior of thin curved panel with functionally graded (FG) coatings under combined axial compression and external pressure is investigated in the present work based on nonlinear analysis. The governing equations are developed using the classical (Kirchoff) shell theory (CST) with von Karman-type of nonlinearity and combining with initial geometrical imperfection. An Airy stress function and Galerkin's technique are applied to obtain closed-form expression of critical buckling loads and load-deflection relations. Besides, a detailed parametric study is conducted to verify and perform the effects of gradual law, thickness of the ceramic layer, imperfection parameter, aspect ratio of the panel including arc length-to-thickness and axial length-to-radius ratios as well as mechanical loading on the nonlinear buckling behavior of the imperfect thin curved panel with FG coatings.

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ABSTRACT: The dynamic buckling of stiffened plates considering the elastically restrained edges subjected to in-plane impact loading is investigated. Navier's double Fourier series is selected as deflection function, then the large-deflection plate equations are solved by the Galerkin method and four-order Runge-Kutta method is used to solve the motion equations. An instance presented in the published literature has validated the correctness of the method. The method is extended to the research of the dynamic response of the stiffened plate with elastically restrained boundary condition. The results show the rotational restraint stiffness usually ignored by previous researchers plays an important role in dynamic response of the stiffened plate under in-plane impact loading, and the influence degree of rotational restraint stiffness on dynamic buckling loads and dynamic response increase along with the initial imperfection and pulse duration. In order to accurately evaluate the dynamic buckling load, a new simple buckling criterion is presented in the paper and proven effective.
ABSTRACT: This paper presents a combined experimental, numerical and theoretical study on the mechanical performances of octagonal CFT stub columns subjected to axial compressive loading. Eight specimens of axial compression tests have been carried out aiming at investigating the effects of the concrete strength and steel ratio on the mechanical and deformed behavior of octagonal CFT stub columns. 3D finite element modelling was established for parametric studies to probe into the composite action between the steel tube and the core concrete of the octagonal CFT stub column. In addition, a practical formula has been proposed to predict the ultimate bearing capacity of the octagonal CFT stub column with the confinement coefficient of 1.5, which is an amplification coefficient of the vertical bearing capacity of steel tube considering the composite action between the core concrete and the steel tube.

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“Influences of different internal stiffeners on energy absorption behavior of square sections during the flattening process”, Thin-Walled Structures, Vol. 107, pp 462-472, October 2016, DOI: 10.1016/j.tws.2016.07.006
ABSTRACT: The present article introduces some novel patterns of internal blades as the stiffener into thin-walled square aluminum sections to enhance energy absorption behavior of reinforced structures under the lateral loading by the experimental methods. To prepare the specimens, a thin-walled square columns made of aluminum with external cross-sectional dimensions of 34.4 mm×34.4 mm were prepared and cut to the constant nominal length of 40 mm. Then, some internal blades with thickness of 1.25 mm were prepared and after the shaping process, the formed blades were positioned into the square specimens by the point-welding. The manufactured specimens were positioned between two rigid platens and the quasi-static lateral load was performed on the specimens and the samples were laterally compressed in the flattening process. Furthermore, a simple square specimen without any stiffener was used in the lateral compressed test and its energy absorption capacity and specific absorbed energy were measured as the benchmark. The experiments show that by reinforcing the thin-walled square section with the internal blades, a new structure is achieved that can absorb the kinetic energy up to 2.99 times of the simple square section of the benchmark. In addition, according to the results, it is found that absorbed energy/mass ratio of the best reinforced specimen is 1.92 times of the benchmark.

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ABSTRACT: Four groups of axial compression tests on hexagonal CFT stub columns have been carried out aiming to investigate the effects of the concrete strength and steel ratio on the behaviour of hexagonal CFT stub columns. Studies on parametric analysis and composite action between core concrete and steel tube have been carried out using FE modelling which had been benchmarked using the test data. Based on the essential data obtained in this paper, the ratio of axial stress-yield strength of steel tube was determined at the ultimate state.
The stress contour of core concrete was simplified to an unconfined area without constraint and a confined area with uniform constraint imposed by hexagonal steel tube. Eventually, a practical design equation of the ultimate bearing capacity of hexagonal CFT stub columns was proposed based on the superposition principle. An excellent agreement between the proposed equation and the experimental results was observed, with an average ratio of predicted to measured capacity of 1.08 and a standard deviation of 0.05.

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ABSTRACT: In this paper, the theoretical and practical formulas of initial stiffness of welded hollow spherical joints were presented, and the elastic and elastoplastic critical displacements and rotations were obtained respectively. A mechanical model considering the stiffness characteristics of joints was proposed, the criterion of eccentric states and bearing stages was established to analyse the influence on the stability of single-layer latticed domes. Results indicate that the practical initial stiffness formulas proposed fit well with the theoretical solutions. The mechanical model can accurately simulate the stiffness characteristics and bearing stages of joints in the failure process of structure. Compared with the experimental results, the average error of mechanical model for the initial slope of load-rotation curve is 8%, and the average error for the ultimate bearing capacity is 7%. The stiffness degeneration of the joints in the plastic stage may cause a significant reduction in stability capacity of the structure. The stability reduction factors of K6 and Geodesic domes are between 0.7 and 1.0, and the stability reduction factors of K8-lamella domes are between 0.65 and 1.0.

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ABSTRACT: The compressive behaviour of Concrete-Filled Double-Skin tubular (CFDST) sections consisting of corrugated plates is investigated numerically in this study. Finite element simulations are employed to decipher more details on the compressive behaviour of numerous archetypes with different geometries and material properties. The results of these simulations reveal how the ultimate static compressive capacity of the intended sections may be affected by changing the geometric and material properties. Different cross-section shapes, dimensions and heights within the practical range are considered for the proposed archetypes. In addition, a wide range of concrete compressive strength values are assigned to the concrete infill of the archetypes. The ultimate axial capacity of almost all the intended CFDST archetypes is mainly dominated by concrete compressive strength. In conjunction with numerical simulations, different design formulations are also employed to predict the ultimate axial load-bearing capacity of CFDST sections.

ABSTRACT: In this paper, the effects of introducing lateral circular cutouts on crash performances of tapered thin-walled tubes are explored within a simulation-driven surrogate-based multi-objective optimization framework. The crash performances of the tubes are measured using the crush force efficiency (CFE) and the specific energy absorption (SEA) criteria, which are computed using the finite element analysis code LS-DYNA. Surrogate-based optimization approach is followed to find out that optimum values of the wall thickness, the taper angle, the cutout diameter and the numbers of cutouts in horizontal and vertical directions to maximize CFE and SEA. Four different surrogate models are used: polynomial response surfaces, radial basis functions, and Kriging models with zeroth- and first-order trend models. It is found that the optimum CFE of the tubes with lateral circular cutouts is 27.4% larger than the optimum CFE of the tubes without cutouts. It is also found that the optimum SEA of the tubes with lateral circular cutouts is 26.4% larger than the optimum SEA of the tubes without cutouts. It is observed that the optimum SEA design has slightly reduced wall thickness, significantly reduced taper angle, significantly increased cutout diameter, increased number of cutouts in horizontal direction and slightly reduced number of cutouts in vertical direction compared to the optimum CFE design. In addition, multi-objective optimization of the tubes is performed by maximizing a composite objective function that provides a compromise between CFE and SEA. It is found that the CFE dominates the behavior of composite objective function.


ABSTRACT: An experimental research on the fire behaviour of compressed cold-formed steel columns with closed built-up cross-sections and restrained thermal elongation is presented. Several parameters were assessed, including the influence of loading level, boundary conditions, restraint to thermal elongation imposed by the surrounding structure and cross-sectional shape. The investigation suggests that an increase in the non-dimensional axial restraint ratio and column load levels lead to a decrease in critical temperatures. Furthermore, the 350 °C critical temperature limit predicted in the EN 1993-1-3:2005 may be too simplistic and conservative for fire design of this type of columns.


ABSTRACT: The weighted extended B-spline method (Höllig, 2003) is applied to bending and buckling problems of plates with different shapes and stiffener arrangements. The discrete equations are obtained from the energy contributions of the different components constituting the system by means of the Rayleigh-Ritz approach. The pre-buckling or plane stress is computed by means of Airy's stress function. A boundary data extension algorithm for the weighted extended B-spline method is derived in order to solve for inhomogeneous Dirichlet boundary conditions. A series of benchmark tests is performed touching various aspects influencing the accuracy of the method.
Caiqi Zhao, Weidong Zheng, Jun Ma and Yangjian Zhao (Key Laboratory of Concrete and Prestressed Concrete Structure, Ministry of Education, School of Civil Engineering, Southeast University, Nanjing 210096, China), “The lateral compressive buckling performance of aluminum honeycomb panels for long-span hollow core roofs”, Materials, Vol. 9, 444, 2016, DOI: 10.3390/ma9060444

ABSTRACT: To solve the problem of critical buckling in the structural analysis and design of the new long-span hollow core roof architecture proposed in this paper (referred to as a “honeycomb panel structural system” (HSSS)), lateral compression tests and finite element analyses were employed in this study to examine the lateral compressive buckling performance of this new type of honeycomb panel with different length-to-thickness ratios. The results led to two main conclusions: (1) Under the experimental conditions that were used, honeycomb panels with the same planar dimensions but different thicknesses had the same compressive stiffness immediately before buckling, while the lateral compressive buckling load-bearing capacity initially increased rapidly with an increasing honeycomb core thickness and then approached the same limiting value; (2) The compressive stiffnesses of test pieces with the same thickness but different lengths were different, while the maximum lateral compressive buckling loads were very similar. Overall instability failure is prone to occur in long and flexible honeycomb panels. In addition, the errors between the lateral compressive buckling loads from the experiment and the finite element simulations are within 6%, which demonstrates the effectiveness of the nonlinear finite element analysis and provides a theoretical basis for future analysis and design for this new type of spatial structure.

References listed at the end of the paper:

ABSTRACT: This paper investigates the collapse by buckling of hollow polyvinylchloride profiles with various cross sections. The presentation identifies the modes of deformation and the critical buckling loads and investigates the possibility of developing innovative mechanical joining processes built upon the formation of bellow shapes (wrinkles) by radial outward flow. The methodology draws from the fundamentals of material characterization and plastic buckling by compression between flat parallel platens to the experimental and finite element analysis of the formation of wrinkles by compression in a semi-closed tool. Results show that the formation of wrinkles in hollow polyvinylchloride profiles at room temperature is limited to geometric features within a compact range. The connection of hollow polyvinylchloride profiles to polycarbonate sheets is given as examples of application of wrinkles in mechanical joining.

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ABSTRACT: The energy-absorbing structure of a crashworthy railway vehicle was designed by combining the characteristics of thin-walled metal structures and aluminum honeycomb structures: finite element models of collisions involving energy-absorbing structures were built in ANSYS/LS-DYNA. In these models, the thin-walled metal structure was modeled as a plastic kinematic hardening material, and the honeycomb structure was modeled as an equivalent solid model with orthotropic–anisotropic mechanical properties. The analysis showed that the safe velocity standard for rail vehicle collisions was improved from 25 km/h to 45 km/h by using a combined energy-absorbing structure; its energy absorption exceeded the sum of the energy absorbed by the thin-walled metal structure and honeycomb structure when loaded separately, because of the interaction effects of thin-walled metal structure and aluminum honeycomb structure. For an aluminum honeycomb to the same specification, the composite structure showed the highest SEA when using a thin-walled metal structure composed of bi-grooved tubes, followed by that using single-groove tubes: that with a straight-walled structure had the lowest SEA.


ABSTRACT: There exists inevitably various geometric imperfections in offshore pipelines in the manufacturing process. In deep waters, the pipes have to withstand high external hydrostatic pressure, in general, which is a dominant parameter for the design of such structures. A 2D theoretical formulation is presented to predict the collapse pressure of elastic–plastic tubes with arbitrary initial geometric imperfections represented by the ovality and wall thickness variations. In addition, numerical simulations are also carried out using a 3D finite-element model within the framework of ABAQUS. Close agreement between the results validates the effectiveness of this theoretical method. Then, the theoretical model is applied to study the effects of some important parameters such as diameter-to-thickness ratio, initial ovality, wall thickness variations and material properties, etc., on the collapse pressure of the pipes. Based upon extensive parametric studies, a few significant conclusions are drawn, which aim to provide the theoretical basis for design of offshore pipelines with various initial geometric imperfections and material properties.


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ABSTRACT: The seamless steel pipes inevitably incorporate various initial geometric imperfections introduced in the manufacturing process. The offshore pipelines close to the touch-down point in the sagbend have to withstand the combined actions of axial tension, bending and external pressure during deepwater installation. In this paper, a two-dimensional (2D) theoretical formulation is further developed to investigate the asymmetric buckling behaviour of offshore pipelines with arbitrary initial geometric imperfections under complicated loading conditions. In addition, numerical simulations based on a 3D finite-element model of the imperfect tube using the software ABAQUS are carried out. Close agreement between the results demonstrates the effectiveness and practicality of this theoretical method. The theoretical model is then employed to study the effects of some important influencing factors such as initial geometric imperfections represented by initial ovality and wall eccentricity, ovality orientation, material properties represented by effective yield stress and
strain-hardening parameter, diameter-to-thickness ratio, axial tension, and load cases on the buckling behaviour of the imperfect tubes. Based on extensive parametric studies, some significant conclusions were drawn.


PARTIAL INTRODUCTION: Pipelines and risers are among the most important equipment in subsea oil and gas exploration. As the offshore activities go into deeper water, they are inevitable to suffer high hydrostatic pressure as well as bending and tension during installation and operation. Considering the fact that it is uneconomical or even difficult to repair pipelines in deep sea, failure is not allowed to occur. Collapse could be the most important design factor under high external pressure. Collapse of circular shells under single or combined loads has been widely investigated in the past few decades. Timoshenko and Gere studied the elastic collapse of infinite long tube under external pressure and derived the Eigenvalue buckling solution of perfect shell. As to the tube with initial ovality, they suggested the collapse pressure to be the one to cause initial yielding. The collapse pressure determined in this way is always smaller than the real value and should serve as a conservative estimation, but it shows that the collapse pressure is strongly influenced by initial imperfection. Timoshenko’s results are limited to infinite long shells, the boundary conditions of which were neglected. Pinna and Ronalds examined the eigenvalue buckling solution of shorter shells under external pressure and gave an equation applicable to various boundary conditions. For deep-water pipelines, the pipelines’ diameter-to-thickness ratio (D/t) is lower and material plasticity will influence the collapse behavior. Yeh and Kyriakides studied the collapse of infinite long pipeline under external pressure with initial ovality and wall thickness variation. They showed that D/t, material property and initial ovality (Δk) affected collapse pressure significantly and wall thickness variation had a smaller effect, while yield anisotropy could affect collapse pressure positively or negatively. Based on finite element analyses, He et al. gave a simple equation to predict the collapse pressure of thick-walled pipelines. Offshore pipelines can experience combined external pressure, tension and bending. The behavior on collapse response and the collapse loads were found to be influenced by loading path and hardening rule as well as material . . .

References listed at the end of the paper:


ABSTRACT: (none given)


ABSTRACT: (none given)


ABSTRACT: (none given)


ABSTRACT: The paper presents the results from a combined experimental and analytic study on the collapse of long, thick-walled tubes subjected to external pressure and axial tension. The experiments involved tubes of
diameter-to-thickness ratio (Dm/t) 10 to 40. Collapse envelopes were obtained for two different pressure-tension loading paths. Collapse tests involving initially ovalized tubes were also carried out. The collapse strength predicted with a two-dimensional elasto-plastic model applying J2 flow rule was in good agreement with the experiments. The results show that the collapse strength under combined loading is strongly influenced by initial ovality and that the shape of the stress-strain curve has a significant influence on the tension-pressure collapse envelope.


ABSTRACT: A simplified method is proposed to predict the creep collapse behavior of a long tube subjected to external pressure. The shape of the cross section of a tube is assumed to be quasi-elliptical characterized by a single variable, often called as shape factor in the literature. The growth of the displacement field is represented by the change of shape factor which is governed by an ordinary differential equation. A general class of creep constitutive equations can be employed with an accompanying elasticity whose effect is crucial under higher external pressure. Plane strain condition is assumed. Nonlinearity of stress distribution through the wall of the tube is allowed according to the creep constitutive equation in general, while the strain distribution is assumed to be linear. The method is applied to the analyses of heat tubes, which are typical for heat exchangers of high-temperature gas-cooled reactors, and is compared with the computer solution by the finite element method based on a finite deformation theory, as well as solutions by other simplified methods.


ABSTRACT: This paper presents an analysis of the cross-sectional collapse of a cylinder of finite length loaded simultaneously by an axial tension (which may be zero) and external pressure. The calculation is based on Sanders’ nonlinear shell equations with plasticity introduced via the concept of effective stress from a uniaxial tension test. The finite cylinder is an appropriate model of oil well casing as it undergoes quality control testing in the steel mill where the edges of the cylinder are usually fixed in the case of nonzero axial load and free in the case of zero axial load. However, in field application, the length: diameter ratio of casing is such that the cylinder may be considered infinite. Guidelines contained herein permit prediction of the collapse resistance of field casing from the results of mill tests performed on short samples.


ABSTRACT: Experimental and theoretical results are presented for the collapse pressure of long straight slightly oval Inconel tubes under external pressure with dimensions used in heat exchangers for nuclear power plants. Since the tubes are in the thick-walled category, plastic effects are significant. Plastic limit analysis methods are utilized to obtain an expression for the collapse pressure which is exact for the idealized tube and which correlates well with the test data. The expected imperfection sensitivity is displayed by the significant drop of the collapse pressure for small increases in ovality.

ABSTRACT: Collapse tests were performed on one-in. dia steel tubes with flats milled on the exterior to simulate worn casing. External pressure and axial load were applied to the tubs having a range of wall thickness, yield strength, and degree of wear. Empirical correlation of the data and comparison with elastic collapse calculations indicate the percentage reduction in collapse pressure due to wear. This reduction is predictable within upper and lower bounds. While the milled external flat may not accurately simulate severe internal wear, the correlation is adequate for less than severe wear to give an indication of remaining strength.

References listed at the end of the paper:

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DOI: 10.1016/j.tws.2015.12.021

ABSTRACT: Cold-formed steel (CFS) cross-sections can be optimised to increase their load carrying capacity, leading to more efficient and economical structural systems. This paper aims to provide a methodology that would enable the development of optimised CFS beam sections with maximum flexural strength for practical applications. The optimised sections are designed to comply with the Eurocode 3 (EC3) geometrical requirements as well as with a number of manufacturing and practical constraints. The flexural strengths of the sections are determined based on the effective width method adopted in EC3, while the optimisation process is performed using the Particle Swarm Optimisation (PSO) method. To allow for the development of a new ‘folded-flange’ cross-section, the effective width method in EC3 is extended to deal with the possible occurrence of multiple distortional buckling modes. In total, ten different CFS channel cross-section prototypes are considered in the optimisation process. The flexural strengths of the optimised sections are verified using detailed nonlinear finite element (FE) analysis. The results indicate that the optimised folded-flange section provides a bending capacity which is up to 57% higher than standard optimised shapes with the same amount of material.

References listed at the end of the paper:
ABSTRACT: Latest development in material and manufacturing technologies make it possible to increase the strength level gives potential for considerable weight reduction and a cost-effective way to produce energy efficient products. Following the recently introduced hollow corrugated columns, this paper presents an advanced innovative hollow corrugated column by incorporating ultra high-strength (UHS) steel tubes. The superior performance of the proposed column under compressive loading is investigated in the present work. UHS tubes used at the corners have yield stress of 1250 MPa. Three different corrugated plates are introduced and fabricated so that the effect of corrugation geometry parameters such as angle of inclination and height of corrugation get experimentally investigated. Along with experiments, an
advanced finite element model is developed for predicting the behaviour of proposed columns and validated by experimental results. The geometric imperfection, material and geometric nonlinearities, and heat affected zone generated due to welding are included in the FE analysis. The results prove the high capacity and ductility of the proposed innovative columns under compression compared to the accumulated capacity of the individual components. Finally, the proposed high-strength columns are compared with the conventional columns in terms of weight and manufacturing costs.

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ABSTRACT: The problem of elastic stability of rectangular plates with different boundary conditions under wheel and patch loading is analyzed using Ritz energy technique. Basic analytical model with two specific types of boundary conditions, designed to simulate standard experimental sample, is tested. High quality of presented analytical results, proved through comparison with data obtained by numerical methods, is due to introduction of the exact stress functions of Mathieu's theory of elasticity and adequate deflection functions. Hence, the conditions for analyzing the advanced models with different levels of complexity and for realization of comprehensive parametric study are created for these load types.


ABSTRACT: In the field of structural engineering the design of cost efficient structures is highly important. This led to the development of cold-formed steel structures (CFS). An advanced CFS structure is introduced in this paper, which uses a special type of polystyrene aggregate concrete (PAC) as bracing material. This material has beneficial insulating and fire protection properties, which makes it a reasonable choice for residential buildings. An experimental program was performed, to gain information on the flexural and axial behaviour of PAC-braced CFS elements and panels. Both unbraced and braced members were tested to gain information on increment of load-bearing capacity. Several different element sizes were used to be able to investigate the different stability failure modes (i.e. local, distortional and global). Results showed that PAC was able to restrain the global and distortional buckling modes of steel elements, thus providing “full bracing” in most practical cases. These results are introduced in two papers (Part I and II), detailing the failure modes, load increments and the effect of composite action. In this paper – Part I – the background and the results of bending tests are presented, and the experiments on the compression elements are detailed in Part II.


ABSTRACT: In the field of structural engineering the design of cost efficient structures is highly important. This led to the development of cold-formed steel structures (CFS). An advanced CFS structure is introduced in
this paper, which uses a special type of polystyrene aggregate concrete (PAC) as bracing material. This material has beneficial insulating and fire protection properties, which makes it a reasonable choice for residential buildings. An experimental programme was performed, to gain information on the flexural and axial behaviour of PAC-encased CFS elements and panels. Both unbraced and braced members were tested to gain information on increment of load-bearing capacity. Several different element sizes were used to be able to investigate the different stability failure modes (i.e. local, distortional and global). Results showed that PAC was able to restrain the global and distortional buckling modes of steel elements, thus providing “full bracing” in most practical cases. These results are introduced in two papers (Part I and II), detailing the failure modes, load increments and the effect of composite action. In this paper – Part II – the background and the results of compression tests are presented, and the bending experiments are detailed in Part I.


ABSTRACT: Sandwich panels with uni-directional stiffeners in the core are lightweight structures. When the voids between the stiffeners are empty, the global bending of the panel is accompanied by the secondary bending of the faces between the stiffeners. This study investigates the effect of the secondary bending on local buckling of the sandwich panel. Web-core steel sandwich panel is analyzed with finite element method using shell elements. The panel is studied under uni-axial loading in the direction of the stiffeners. The results show that the local buckling strength is higher at the unloaded edges where the secondary bending deformation is larger. This has a positive effect on the strength of the panel since it postpones the reduction of the load-carrying capacity. Local buckling occurs first in the center of the panel. The buckles have a typical shape with the wave-length significantly smaller than the width of the face plate between the stiffeners.

References listed at the end of the paper:


ABSTRACT: A web–core steel sandwich panel is a lightweight structure where thin plates are welded together by laser-welding technique. The plates form a T-joint which has in the center a weld thinner than the plates themselves. Thus the rotational stiffness of the joint is not infinite. The paper investigates the influence of T-joint rotational stiffness on the lowest natural vibration frequency of the panel. The methods used in the study have different kinematic assumptions. Equivalent single-layer (ESL) theory is used to obtain the frequency of the global vibration. The local vibrations are predicted using an isolated part of the panel, the I-beam model. In addition, three-dimensional model of a sandwich panel is analyzed. Finite element method (FEM) and analytical solution are used to obtain the frequencies. First-order shear deformation theory (FSDT) is used. The joint is considered through its rotational stiffness whose quantitative values are presented in the literature. Four different cross-sections with industrial relevancy are considered. The rotational stiffness of the T-joint affects the transverse shear stiffness of the panels. The results show up to 22% reduction of the fundamental frequency when compared with the case of the rigid joint for the global vibration mode. The effect on local vibrations is up to 11% in the case of asymmetric rotation in the T-joint and is otherwise insignificant. The study furthermore outlined the limitations of the ESL approach for assessment of natural frequencies in web–core sandwich panels depending on the vibration mode shape. The results show that the rotational stiffness of the T-joint has to be considered in the conceptual design of these structures.

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ABSTRACT: This paper presents an investigation of the behavior of CFDST members under low velocity lateral impact using ABAQUS, where nonlinear material behavior and strain rates of steel and concrete are included. The finite element analysis (FEA) models of CFDST members are described and verified using existing experimental results. Strain and stress states of concrete and steel tube in CFDST members are analyzed over the full loading range, followed by a parametric study investigating the influence of impact height, hollow ratio, nominal steel ratio, diameter-to-thickness ratio of inner steel tube and strength of materials on the impact force and global residual lateral deformation. Furthermore, the dynamic increase factor (DIF) of
CFDST members under lateral impact is proposed, and the influence of the confinement factor on the dynamic increase factor (DIF) is analyzed. The results show that when the confinement factor is larger than 1.03, the dynamic increase factor needs to be considered to accurately estimate the dynamic resistance capacity of CFDST members subjected to lateral impact.

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ABSTRACT: We combine the isogeometric analysis, the level set and a simple first-order shear deformation theory (S-FSDT) to form a new effective and accurate approach for simulating free vibration and buckling problems of laminated composite plates with cutouts. The problem domain is discretized using non-uniform rational B-spline (NURBS) basis functions, which are utilized for geometry and field variables approximation. In S-FSDT, the shear locking effect is no longer valid and more interestingly, low computational cost is saved because of having fewer unknowns. The trimmed NURBS surface often used in existing approaches, which has some disadvantages in describing the geometrical structure with internal cutouts due to the tensor product of the NURBS basis functions, is no longer required in the present formulation, and the level set method (LSM) is employed to describe the cutouts instead. More interestingly, the numerical integration in the developed method is performed only inside the physical domain. All those features make the method effective in modeling cutouts with complicated shapes. Numerical examples are presented to show the performance of the method. The results obtained are validated against reference solutions showing a good agreement and performance.


ABSTRACT: This work reports the results of a numerical (Abaqus shell finite element analysis) investigation on the influence of local–distortional (L–D) interaction in the ultimate strength and design of fixed-ended cold-formed steel web-stiffened lipped channel columns, hereafter termed “WSLC columns”. These results concern columns with various geometries and yield stresses, ensuring a wide variety of combined ratios between (i) the distortional and local critical buckling stresses, and (ii) the yield stress and the higher of the above two buckling stresses. The objectives of the work are two-fold: (i) acquire in-depth knowledge on the mechanics underlying the L–D interaction in the WSLC columns analysed, all selected to ensure that local buckling is triggered by the flanges, and also (ii) provide a first contribution towards the efficient Direct Strength Method (DSM) design of these columns. The results presented and discussed concern the (i) post-buckling behaviour (elastic and elastic-plastic), (ii) ultimate strength and (iii) failure mechanisms of WSLC columns undergoing L–D interaction. Special attention is paid to the comparison between the ultimate strength erosion, stemming from L–D interaction, exhibited by web-stiffened and plain lipped channel columns (the latter were studied earlier by the
authors). The paper closes with some considerations about the impact of the findings reported in this work on the design of cold-formed steel columns experiencing different levels of L–D interaction.

Haigui Fan, Zhiping Chen, Jian Cheng, Song Huang, Wenzhuo Feng and Lige Liu (Institute of Process Equipment, Department of Chemical and Biological Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang 310027, PR China), “Analytical research on dynamic buckling of thin cylindrical shells with thickness variation under axial pressure”, Thin-Walled Structures, Vol. 101, pp 213-221 DOI: 10.1016/j.tws.2016.01.009
ABSTRACT: This paper focuses on the dynamic buckling of thin cylindrical shells with arbitrary axisymmetric thickness variation under time dependent axial pressure. Based on the derivation of stability and compatibility equations of variable thickness cylindrical shells under dynamic external pressure by Aksogan and Sofiyev, the corresponding stability and compatibility equations of thin cylindrical shells with arbitrary axisymmetric thickness variation under dynamic axial pressure are obtained and expressed in nondimensional form. Combining the small parameter perturbation method, Fourier series expansion and the Sachenkov–Baktieva method, analytical formulas of the critical buckling load of thin cylindrical shells with arbitrary axisymmetric thickness variation under axial pressure that varies as a power function of time are obtained. Two cases of thickness variation are introduced to research the critical dynamic buckling load with the present formulas. Effects of thickness variation parameters and loading speed of dynamic axial pressure on the critical buckling load are discussed. The method is also applied to determine the critical dynamic buckling load of thin cylindrical shells with a classical cosine form thickness variation. Results reveal that the thickness variation and pressure parameters play a major role in dictating the buckling capacity of thin cylindrical shells under dynamic axial pressure.

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ABSTRACT: In natural environment, many biological structures are tubular and exhibit excellent mechanical properties that can reduce self-weight effectively and transport more water and nutrients, such as bamboo. In this paper, the structure of bamboo was introduced to increase the axial and lateral energy absorption of thin-walled tubes by using bionic design method. Energy absorption ability of bamboo was tested by drop-weight experiments. The results showed that the energy absorption was excellent due to the gradient distribution of vascular bundles, nodes and density. These advantages of the bamboo make it possible to design of bionic structure which composed of 1 bionic node and 3 bionic inner tubes with 18, 9 and 4 bionic elements in each inner tube. Numerical examples of bionic structures under axial/lateral impacts were solved with nonlinear finite element method (FEM). The results indicated that the bionic design enhances the specific energy absorption (SEA) of tubes. Thus, the bionic structure is exactly excellent energy absorption under lateral/axial impact and can be used in the future.

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ABSTRACT: A comprehensive experimental and numerical investigation into the structural performance of stainless steel circular hollow sections (CHS) under combined compression and bending moment has been performed and is fully reported in the present paper and its companion paper. The experimental programme employed four CHS sizes made of austenitic stainless steel, and included material tensile coupon tests, four stub column tests and twenty combined loading tests. The initial loading eccentricities for the combined loading tests were varied to provide a wide range of bending moment-to-axial load ratios. In conjunction with the testing programme, a numerical modelling programme was performed to simulate the experiments. The developed FE models were shown to be capable of replicating the key test results, full experimental curves including the post-ultimate range and deformed failure modes. Upon validation of the FE models, a series of parametric studies were conducted in the companion paper, aiming at extending the current test data pool over a range of cross-section sizes and combinations of loading. The experimental data, together with the generated parametric study results, were analysed and employed to evaluate the applicability of the codified provisions given in the European code, American specification and Australia/New Zealand standard for design of CHS under combined loading. Improved design rules were also sought through extension of the deformation-based continuous strength method (CSM) to the case of stainless steel CHS under combined loading.

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ABSTRACT: This paper reports the second part of the study on the structural behaviour of stainless steel circular hollow sections subjected to combined axial load and bending moment. A series of numerical parametric studies is presented, using the validated finite element (FE) models from the companion paper, with the aim of generating further structural performance data over a wider range of stainless steel grades, cross-section slendernesses and combinations of loading. The considered parameters include the outer cross-section diameter, the ratio of outer cross-section diameter to thickness and the initial loading eccentricity. Both the experimentally and numerically derived section capacities were compared with the strength predictions determined from the current European code, the American specification and the Australian/New Zealand standard for design of CHS under combined loading. Improved design rules were also sought through extension of the deformation-based continuous strength method (CSM) to the case of stainless steel CHS under combined loading. Comparisons between the proposals and the test and FE results indicate a high level of accuracy and consistency in the predictions. The reliability of the proposed approach was confirmed by means of statistical analyses according to EN 1990.

ABSTRACT: Vibration characteristics of moderately thick doubly curved functionally graded composite panels reinforced by carbon nanotube are analyzed. Here, special cases of doubly curved shell panels such as spherical, cylindrical and hyperbolic paraboloid panels and five different distributions of carbon nanotubes through the thickness direction are considered. By utilizing the modified rule of mixture, mechanical properties are estimated. The equations of motion are derived via the first-order shear deformation theory, and non-dimensional frequencies are obtained by the use of Galerkin’s method. The suggested model is justified by a good agreement between the results given by present model and available data in the literature. The influences of volume fraction of carbon nanotubes, thickness ratio, aspect ratio, curvature ratio, and shallowness ratio on the frequencies of moderately thick doubly curved nanocomposite shell panels are also examined. Furthermore, the effect of various boundary conditions on the frequency analysis of doubly curved nanocomposite panels is studied, and the corresponding mode shapes are depicted.

References listed at the end of the paper:

In this research, the buckling analysis of orthotropic rectangular plate resting on Pasternak elastic foundation was studied, using Frobenius exact solution method. The plate is subjected to biaxial in-plane loading under axial compression. According to Levy solution, the buckling equation is reduced to an ordinary differential equation. Frobenius method is exploited in the governing equation, and the eigenvalue equation is obtained, imposing the boundary conditions on the other two sides. By solving the eigenvalue equation, the dimensionless critical buckling loads are determined. The accuracy of presented results is validated by comparing with available results in previous studies and also finite element method. Furthermore, the influences of some parameters such as aspect ratio, the ratio of elasticity modulus of the plate in two in-plane directions, the type of non-uniform loading in two states of uniaxial and
biaxial loadings, various combinations of boundary conditions, lateral and shear stiffness coefficients of elastic foundation are examined on critical buckling.

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23. Winkler E (1867) Die Lehre von der Elasticitaet und Festigkeit. Prag, Dominicus

ABSTRACT: Composite thin-walled shell structures are widely used now in design of high-speed air-space vehicles (ASVs) moving in dense layers of the atmosphere, for example, re-entry vehicles descending from the Earth’s orbit. The purpose of this chapter is to investigate thermal stresses caused by internal heat-mass-transfer processes in thin-walled multilayer shell structures of ablative composite materials under intensive heating. As an example, computations are conducted for cylindrical composite shells under high temperatures. It is shown that in composite shells under intensive nonstationary heating to the pyrolysis temperatures of the material, considerable thermal stresses appear: both normal through-thickness and tangential stresses occur even without external mechanical loads. The danger of these thermal stresses is estimated (when they reach the ultimate strength of the composite and the composite structure is destroyed). Three types of failure of a composite shell under high-temperature heating are described: cracking of the heated surface of the composite, delamination of the composite and appearance of several delaminations with loss of their stability.

References listed at the end of the paper:


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“Stabilization of carbon dioxide (CO2) bubbles in micrometer-diameter aqueous droplets and the formation of hollow microparticles”, Lab on a Chip (Miniaturisation for chemistry, physics, biology, materials science and bioengineering), No. 9, 2016
ABSTRACT: We report an approach to stabilize carbon dioxide (CO2) gas bubbles encapsulated in micrometer-diameter aqueous drops when water in the aqueous drops is evaporated. CO2-in-water-in-oil double emulsion drops are generated using microfluidic approaches and evaporation is conducted in the presence of sodium dodecyl sulfate (SDS), poly(vinyl alcohol) (PVA) and/or graphene oxide (GO) particles dispersed in the aqueous phase of the double emulsion drops. We examine the roles of the bubble-to-drop size ratio, PVA and GO concentration in the stabilization of CO2 bubbles upon water evaporation and show that thin-shell particles with encapsulated CO2 bubbles can be obtained under optimized conditions. The developed approach offers a new strategy to study CO2 dissolution and stability on the microscale and the synthesis of novel gas-core microparticles.

ABSTRACT: The paper presents results of a study on thin-walled structures modelling representative fragments of aircraft fuselages subjected to bending and torsion. The type of the considered load and deformation corresponds to the state of such structures under in-flight conditions. The subject of the study were structures made of composite materials. Adopted assumptions include admissibility of post-buckling deformation in the operating load regime. Results of experimental studies are presented together with nonlinear numerical analyses carried out with the use of the finite elements method applied to a number of variant structures provided with various types of skin stiffening elements. Operating properties of the examined structures have been compared on the grounds of adopted criteria.

References listed at the end of the paper:

ABSTRACT: In this article, nonlinear vibration and dynamic response of imperfect functionally graded materials (FGM) thick double-curved shallow shells resting on elastic foundations are investigated using Reddy's third-order shear deformation shell theory in thermal environments. Material properties are assumed to be temperature dependent and graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The FGM shells are subjected to mechanical, damping, and thermal loads. The Galerkin method and fourth-order Runge–Kutta method are used to calculate natural frequencies, nonlinear frequency–amplitude relation, and dynamic response of the shells. In numerical results, the effects of geometrical parameters, material properties, imperfections, shear deformation, the elastic foundations, mechanical, thermal and damping loads on the nonlinear dynamic response, and nonlinear vibration of FGM double-curved shallow shells are investigated. Accuracy of the present formulation is shown by comparing the results of numerical examples with the ones available in literature.


ABSTRACT: This paper presents a first proposal to investigate the nonlinear dynamic response of imperfect symmetric thin sigmoid-functionally graded material (S-FGM) plate resting on an elastic foundation and subjected to mechanical loads. The formulations use classical plate theory taking into account geometrical nonlinearity, initial geometrical imperfection of the S-FGM plate and stress function. The volume fractions of metal and ceramic are applied by sigmoid-law distribution (S-FGM) with metal-ceramic-metal layers. The nonlinear equations are solved by the Runge-Kutta and Bubnov-Galerkin methods using stress function. The obtained results show the effects of material, imperfection and elastic foundations on the dynamical response of S-FGM plate.


ABSTRACT: In this paper, we study the nonlinear dynamic response of higher order shear deformable sandwich functionally graded circular cylindrical shells with outer surface-bonded piezoelectric actuator on elastic foundations subjected to thermo-electro-mechanical and damping loads. The sigmoid functionally graded material shells are made of the metal–ceramic–metal layers with temperature-dependent material properties. The governing equations are established based on Reddy’s third-order shear deformation theory using the stress function, the Galerkin method and the fourth-order Runge–Kutta method. Numerical results are given to demonstrate the influence of geometrical parameters, material properties, imperfection, elastic foundations, and thermo-electro-mechanical and damping loads on the nonlinear dynamic response of the shells. Accuracy of the present formulation is shown by comparing the results of numerical examples with the ones available in literature.

ABSTRACT: The postbuckling and delamination growth for delaminated piezoelectric elastoplastic laminated beams under hygrothermal conditions are investigated. By considering hygrothermal environments, transverse shear deformation, geometrical nonlinearity and piezoelectric effect, the incremental nonlinear equilibrium equations of the piezoelectric elastoplastic laminated beams with delamination are obtained. The finite difference method and iterative method are adopted to solve the equations. Based on these, the delamination growth for the piezoelectric elastoplastic laminated beams is studied using J-integral theory. In the numerical examples, the effects of hygrothermal environments, transverse shear deformation, geometrical nonlinearity and piezoelectricity on the postbuckling behavior and delamination growth for the delaminated piezoelectric elastoplastic laminated beams are discussed in detail.

DOI: 10.1007/s11012-015-0320-z

ABSTRACT: In this paper, considering the small scale effect, the linear free vibration in pre/post-buckled states and nonlinear dynamic stability of lipid tubules with in-plane movable ends are studied. The small scale effect is characterized by nonlocal elasticity theory. The vibration in pre/post-buckled regions is solved by the differential quadrature method (DQM), and the nonlinear dynamic stability is solved by incremental harmonic balance method (IHBM). In numerical results, the effects of small scale parameter, types of lipid tubule on vibration in pre/post-buckled states and nonlinear dynamic stability are discussed.

Jun Zhong, Yiming Fu, Detao Wan and Yingli Li, “Nonlinear bending and vibration of functionally graded tubes resting on elastic foundations in thermal environment based on a refined beam model”, Applied Mathematical Modelling, March 2016, DOI: 10.1016/j.apm.2016.03.031

ABSTRACT: This paper studies the nonlinear bending and vibration problems of functionally graded tubes with temperature-dependent material properties based on a refined beam model. The tubes are exposed to a uniform distributed temperature field and are placed on elastic foundation. The refined beam model for tubes can satisfy the stress boundary conditions on inner and outer surfaces. The governing equations of nonlinear bending and vibration for the functionally graded tubes are derived by using Hamilton's principle and are solved by introducing a two-step perturbation technique. Some comparisons for bending and vibration are presented to validate the correctness of present beam model and solution method. In numerical results, the effects of transverse shear deformation, the volume fraction, inner radius and elastic foundation stiffness as well as the temperature on the natural frequency, amplitude-frequency responses and nonlinear bending responses are discussed.

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ABSTRACT: This paper details an analytical study on the contact buckling problem of infinite profiled skin sheets in unilateral contact with Winkler foundations. The profiled sheets are modelled as thin orthotropic plates resting on tensionless Winkler foundations. The buckling behaviour of the plates can be expressed through a group of nonlinear partial differential equations for both the contact and non-contact parts of the plate. The governing equations are further modified to a group of ordinary differential equations after representing the lateral plate buckling mode through an appropriate displacement function. Thus the system is simplified as a one-dimensional mathematical model. After solving the governing equations of the one-dimensional model, contact buckling coefficients of the system and the related buckling modes are obtained. Fitted formulae for the contact buckling coefficients in terms of relative foundation stiffness and skin profile parameters are also developed. The analytical solutions are verified through a series of finite element (FE) models set up in ABAQUS software. Finally, a practical design example is given to show the efficiency of the developed analytical method.

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ABSTRACT: In this paper, the local buckling behaviour of profiled skin sheets resting on tensionless elastic Winkler foundations under in-plane shear loadings is studied. The profiled sheets are modelled as thin orthotropic plates with the buckling behaviour being expressed through a group of nonlinear partial differential equations. For very long plates with both ends clamped, the buckling mode is composed of a series of periodically repeating buckling waves and hence an infinite plate model with only one buckle wave is effective to predict the buckling behaviour. The infinite orthotropic plate is further simplified to a one-dimensional mechanical model by assuming a lateral buckling mode function. After solving the governing equations of the one-dimensional model in both contact and non-contact regions, shear buckling coefficients of the system and the related buckling modes are obtained. Fitted formulae for the contact shear buckling coefficients in terms of relative foundation stiffness and skin profile parameters are developed. The analytical solutions are verified through examining extreme cases from previous studies and a series of finite element (FE) models in ABAQUS. Finally, a practical example is given to show the efficiency of the developed method.


ABSTRACT: The aim of the present work is twofold. The first is to present a study on nonlinear thermal stability of perfect/imperfect circular size-dependent functionally graded plates according to modified couple stress theory. The second, concurrent aim is to address snap-through phenomenon in the thermally preloaded plates due to concentrated/uniform lateral loads. Ritz finite element method is implemented into generalized form of Hamilton’s principle to construct the matrix representation of nonlinear governing equations. Under certain circumstances, bifurcation type instability may occur in which case a direct displacement control scheme is utilized. In other cases, the response is unique and stable to which any standard load control strategy seems appropriate and thus Newton-Raphson method is selected. Standard load control strategies, however, fail to
trace nonlinear equilibrium paths through limit points and path following methods must be employed in snap-through problems. Being more popular among the existing path following solution methods, cylindrical arc-length method is adopted. Two types of thermal loading as well as two cases of boundary conditions are considered. Moreover, various parametric studies are conducted to assess the influence of involved parameters.

DOI: 10.1016/j.euromechsol.2016.04.002
ABSTRACT: In this paper, computationally efficient multiscale modelling considering material and geometric nonlinearities is employed for the first time to investigate the dynamic response of single layer graphene sheets under harmonic excitation. The constitutive relation at continuum level is derived from a strain energy density function as Tersoff–Brenner atomic interaction potential per unit area of a unit cell through Cauchy–Born rule. The governing equation of motion obtained using Hamilton's principle is solved using Newmark's direct time integration and shooting techniques to obtain steady state periodic response. The effects of material and geometric nonlinearities, size of the graphene sheet, boundary conditions, damping and loading parameters on the natural frequencies/response characteristics are investigated. The dynamic response depicts hardening nonlinearity with the dominant effect of geometric nonlinearity compared to material nonlinearity.

DOI: 10.6052/0459-1879-15-222
ABSTRACT: Dynamic buckling instability of the supercavitating vehicle has the characteristics of being hidden, sudden and dangerous. The researches of unstable region and instability amplitude are very important. The supercavitating vehicle was assumed as a thin-walled cylindrical shell with an axial periodic load. Considering the nonlinear geometric equation, physical equation and equilibrium equation, the nonlinear dynamic buckling differential equations were developed firstly, and then the nonlinear displacement expressions were given. After that, with the help of Galerkin variational method and Bolotin method, the dynamic buckling differential equation was transformed to Mathieu equation with periodic coefficients and nonlinear terms. At last, the nonlinear Mathieu equation was solved and the expressions of the stationary state vibration amplitudes in the 1st order and the 2nd order unstable region were obtained. The nonlinear parametric resonance curves of supercavitating vehicle were obtained, and the influences of the speed, load ratio coefficient, load frequency of axial load and the vibration mode to the resonance were analyzed. The researches laid theoretical foundation for the dynamic buckling reliability analysis based on parametric resonance of a thin-walled cylindrical shell and dynamic optimum design based on parametric resonance reliability.

ABSTRACT: The present paper is focused on the development of an accurate computational method, based on the Finite Element (FE) approximation, for predicting the collapse behavior of thin-walled polygonal steel
beams subject to bending. The numerical model has been created using the software ABAQUS, and has been validated with experimental data obtained from the literature, concerning rectangular hollow section (RHS) in the four-point-bending situation. The model has been improved by means of a thorough study of material hardening, imperfections and residual stresses. The computational results of the analyses have been compared with the design procedures provided by Eurocode 3 (effective cross-section method and reduced stress method), in order to check their suitability.

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Yu Zhang, Bin He, Li-Ke Yao and Jin Long (Dept. of Mechanics, Nanjing Tech University, Nanjing, China), “Buckling analysis of thin-walled members via semi-analytical finite strip transfer matrix method”, Advances in Mechanical Engineering, Vol. 8, No. 5, May 2016, DOI: 10.1177/1687814016650341

ABSTRACT: Slender thin-walled members are main components of modern engineering structures, whose buckling behavior has been studied widely. In this article, thin-walled members with simply supported loaded edges can be discretized in the cross-section by semi-analytical finite strip technology. Then, the control equations of the strip elements will be rewritten as the transfer equations by transfer matrix method. This new method, named as semi-analytical finite strip transfer matrix method, expands the advantages of semi-analytical finite strip method and transfer matrix method. This method requires no global stiffness matrix, reduces the size of matrix, and improves the computational efficiency. Compared with finite element method’s results of three different cross-sections under axial force, the method is proved to be reliable and effective.

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24. Hancock GJ, Pham CH., Buckling analysis of thin-walled sections under localised loading using the semi-analytical finite strip method. Thin Wall Struct 2015; 86: 35–46.

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ABSTRACT: Several mechanical properties can be affected by the occurrence of residual stresses due to curing, and their effects are more pronounced in laminated composites. The effect of the thermal residual stresses on the buckling and post-buckling properties of perimetraly reinforced laminated composites is experimentally characterized. Carbon/epoxy laminates were prepared using two different techniques. One group of laminates was prepared by co-curing the reinforcement at 177 °C. The second group of laminates was prepared by secondary bonding of the reinforcement to the laminate at room temperature (22°C).

Topogrammetry equipment was utilized in order to determine the buckling and post-buckling properties of these two groups of laminates. A numerical model was achieved using commercial software for comparison with the experimental results. Suitable accuracy was observed when comparing experimental and numerical results. The co-cured laminates developed considerably higher critical load for buckling values than those obtained for laminates produced with secondary bonding at room temperature. The experimental and numerical results of this study demonstrate the importance of curing-induced thermal residual stresses on the mechanical behavior of laminate composites.

References listed at the end of the paper:


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ABSTRACT: The impact of buckling containment features on the stability of thin-gauge fuselage, metallic stiffened panels has previously been demonstrated. With the continuing developments in manufacturing technology, such as welding, extrusion, machining, and additive layer manufacture, understanding the benefits of additional panel design features on heavier applications, such as wing panels, is timely. This compression testing of thick-gauge panels with and without buckling containment features has been undertaken to verify buckling and collapse behaviors and validate sizing methods. The experimental results demonstrated individual panel mass savings on the order of 9%, and wing cover design studies demonstrated mass savings on the order of 4 to 13%, dependent on aircraft size and material choice.

ABSTRACT: This paper examines the buckling of short mild steel cylindrical shells subjected to axial compression. Cylinders were joined together using Metal Inert Gas (MIG) welding process with radius-to-thickness ratio, $R/t$, ranging from 25 to 100. The axial length of the specimens were assumed to be 111.8 mm. Past result on axially compressed cylinder machined using Computer Numerically Controlled (CNC) machining is compared with fresh experimental results on MIG manufactured axially compressed cylinder. The paper contains a comparison between theoretical predictions, ABAQUS FE results and experimental data for axially compressed cylinder. Details about material testing and collapse test are provided. As compared to the CNC machined specimen, results indicates that there is a good agreement between theoretical prediction, ABAQUS FE results and experimental data for MIG manufactured cylinder with radius-to-thickness ratio, $R/t$ ranging from 25 to 100, with difference ranging between $-7\%$ and $+2\%$.


ABSTRACT: Stiffened composite panels are primary structural components in ship, aircraft and aerospace vehicles. The main objective of this study is to investigate the behavior of Glass fiber reinforced Polymer (GFRP) composite panels with stiffener runout condition and different stiffener configurations such as blade, T and Hat under axial compression. A special fixture was designed and fabricated for the compressive testing of GFRP composite stiffened panels. Fabricated specimens were tested until failure and the effect of different stiffener configurations on the load–deformation behavior is compared. Digital image correlation (DIC) was used to measure the deformations and strains on the GFRP composite panels. Test results indicated that T-stiffeners performed well with higher failure load and stiffness as compared to other stiffeners. DIC results show that the presence of stiffeners reduced the out-of-plane displacement in the stiffened panels. As the load level increases, damage initiates and propagates. The surface strain and displacement are sensitive to damages and it can alter their distribution. This could be captured using DIC technique as the damage distribution takes place. The T-stiffeners were found to be effective in resisting bending strains and produced more uniform distribution of compressive strain compared to other stiffener configuration.

References listed at the end of the paper:


ABSTRACT: A Rayleigh-Ritz approach for the analysis of buckling and post-buckling behavior of cracked composite stiffened plates is presented. The structure is modeled as the assembly of plate elements modeled by the first order shear deformation theory and taking geometric nonlinearities into account through the von Karman’s theory assumptions. Continuity along the plate elements connected edges and the enforcement of rigid and elastic restraints of the plate boundaries are obtained by using penalty techniques, which also allow to straightforwardly implement efficient crack modeling strategies. General symmetric and unsymmetric stacking sequences are considered and numerical procedures have been developed and used to validate the present solution by comparison with FEA results. Original results are presented for post-buckling solution of multilayered stiffened plates with through-the-thickness cracks, showing the effects of large displacements on the cracked plate post-buckling behavior.

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ABSTRACT: Space launcher vehicle structures are designed as thin walled cylindrical and conical structures which are prone to buckling and are sensitive towards geometrical imperfections. Small deviations in dimensions, which still are within manufacturing tolerances, may lead to a tremendous decrease in load carrying capacity. Thus, imperfections have to be considered during the design phase and this is commonly done using empirical knock down factors. Besides this approach, imperfections can be considered by applying numerical or analytical structural models. Composite materials are used to exploit the light weight potential of unstiffened thin walled structures. For this type of shell structure, the buckling load of the geometrically perfect shell and the imperfection sensitivity are significantly influenced by the laminate stacking sequence. In this paper, the influence of the laminate stacking sequence of composite shells with rotational symmetric imperfections on the buckling behavior is studied and laminate stacking sequences leading to the highest buckling loads of an imperfect shell structure are identified. These stacking sequences are evaluated further by applying non-rotational symmetric imperfections and localized imperfections and the stacking sequences leading to optimum designs of the geometrical perfect shell structure are considered as reference structures.

Linus Friedrich, Pawel Lyssakow, Garth Pearce, Martin Ruess, Chiara Bisagni and Kai-Uwe Schroder, “On the structural design of imperfection sensitive laminated composite shell structures subjected to axial compression”, ECCOMAS Congress 2016, VII European Congress on Computational Methods in Applied Sciences
ABSTRACT: Shell structures are used as primary structures of space launch vehicles. These structures are thin-walled and are thus prone to buckling when loaded in compression. Because of the imperfection sensitivity of these structures, small deviations of the real shell from the theoretically perfect shell may result in a tremendous decrease in load carrying capacity. For this reason, geometrical imperfections need to be taken into account. When designing unstiffened composite shells, the laminate stacking sequence influences both, the buckling load of the geometrically perfect shell and the imperfection sensitivity of the shell. Consequently, to derive laminate stacking sequences that maximize the buckling load of real shell structures, geometrical imperfections need to be taken into account already in an early design phase. In this paper, two laminate stacking sequences that were derived to maximize the buckling load of the geometrically perfect and imperfect shell structure are studied using stochastic methods. To this end, combination of non-rotational symmetric imperfections derived from measured data and variations of the ply orientation are studied in a stochastic analysis on basis of Monte Carlo simulations. The results of this study will be used to evaluate the influence of the stacking sequence as one of the essential properties dominating the structural response of geometrically imperfect laminate composite shell structures.

References listed at the end of the paper:

ABSTRACT: Due to high strength and stiffness-to-weight ratio of composite materials, they are increasingly being used in different industries in the last decades. Cylindrical composite shells are one the most common structures and depending on their usage they may face several loading condition. One of the most popular failures of these structures is buckling under axial compression. Different types of stiffeners can be added to improve the buckling resistance of these structures. Moreover, these cylinders may have some opening because of several reasons such as weight reduction, make access to inner part, and attach other equipment. Existence of an opening affects the buckling behavior of composite shells, and they should be considered in designing these structures. Circular cutout is one the most common opening. In this paper, by employing commercial finite element package ABAQUS, a numerical study is carried out to investigate the effect of cutout size on the axial buckling response of unstiffened and stiffened composite shell. The presented model is verified in comparison with the experimental and numerical results available in the literatures. The results show that the perfect unstiffened shell always fails in global mode but the failure mode of the stiffened one depends on the skin thickness. The results also indicate that for the perfect shell, the maximum improvement in buckling load according to adding stiffening ribs befalls in the case that the combination of global buckling and local skin buckling occurs. Although the influence of existence of an opening on the buckling behavior of composite shells is generally similar but there are some differences. For example, increasing the cutout size in simple shell always decreases the critical load; however, in the stiffened cylinder the buckling load may increase. The results also illustrate that the stiffened shell always have higher critical load than the unstiffened ones. Even thought, for some sizes of the cutout the difference between the buckling load of the stiffened and unstiffened shell tends to zero.

References listed at the end of the paper:
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ABSTRACT: The study intends to investigate the large amplitude vibration of functionally graded material (FGM) orthotropic cylindrical shells interacting with the nonlinear Winkler elastic foundation in the framework of the Donnell's shell theory. To derivation of basic equations of FGM orthotropic cylindrical shells interacting with the nonlinear elastic foundation is used von-Karman type geometric nonlinearity. The superposition and Galerkin methods are used to convert the above equations into a nonlinear ordinary differential equation. The frequency-amplitude characteristics of functionally graded (FG) orthotropic cylindrical shell interacting with the nonlinear elastic foundation are obtained using the semi-inverse method. The accuracy of the current study is verified by comparing it other solutions available in the literature. Moreover, some new results are also presented for the nonlinear frequency parameters of the cylindrical shells to study the effects of the nonlinear elastic foundation, vibration amplitude, FG orthotropic profiles and shell characteristics.


ABSTRACT: The Koiter-Newton approach is a reduced-basis method for nonlinear structural analyses. The method combines Koiter's approach as a predictor step and the Newton arc-length technique as a corrector step to trace the entire load–displacement equilibrium path of a structure in a step by step manner. This computationally highly efficient and accurate solution method has recently demonstrated a superior performance in nonlinear analyses compared to standard techniques. In this paper we propose an extension to buckling imperfection sensitivity analyses exploiting the method’s stability and reliability. We present two different modeling techniques for imperfection loads that both profit from the Koiter–Newton approach reducing the initial computation steps to a small fraction thereof. We introduce von Kármán kinematics which neglect some nonlinear terms of the Green strain–displacement relations to further increase the computational efficiency of the analysis by an essential reduction of the computation effort required to obtain higher order derivatives of the strain energy. Using various numerical examples and benchmark tests we demonstrate the overall high quality and performance of the proposed method.

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“Combined effects of elastic foundations and shear stresses on the stability behavior of functionally graded truncated conical shells subjected to uniform external pressures”, Thin-Walled Structures, Vol. 102, pp 68-79, May 2016, DOI: 10.1016/j.tws.2016.01.010
ABSTRACT: According to the framework of the Donnell's shell theory, the stability behavior of functionally graded (FG) truncated conical shell interacting with two-parameter elastic foundations within the shear deformation theory (SDT) is investigated. The major goal of this research was to obtain a closed form of the solution for critical external pressures associated with the problem outlined above. The basic equations of FG truncated conical shell shells subjected to the external pressures are derived within the SDT. By using the Galerkin method to resulting basic equations are obtained the expressions for critical hydrostatic and lateral pressures of FG truncated conical shell interacting with two-parameter elastic foundations within the SDT. In particular, similar expressions within the classical shell theory (CST) are obtained, also. Comparison the current results and those available in the literature demonstrates the availability and accuracy of solutions. Finally, the calculation and presentation of the effects of many parameters included in the analysis conclude the goals to be reached in the study.


ABSTRACT: An extended formulation of the Coupled Beam Theory (CBT) developed by the authors is employed in order to calculate the ultimate strength of composite ships taking into account of the effect of the superstructure. A nonlinear finite element method is applied for solving the equilibrium equations. Behaviour of the stiffened composite panels in tension and compression is modelled by using progressive failure method. Both hull and superstructure of the ship are modelled using beam elements. Connection between beam elements representing hull and superstructure is made using specially developed spring box elements. Accuracy of the extended method is demonstrated using an available experimental result and also the results of finite element analysis. Also, a set of composite ships having different lengths of superstructure is generated and analysed. Efficiency of the composite superstructure in contribution to the ultimate bending strength of the composite ships is finally evaluated.

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ABSTRACT: This study considered the hydrostatic buckling failure of a noncircular composite liner with an arched invert installed in the sewer pipe. An equation was derived for the buckling of the invert liner, and its application procedure was proposed. A finite-element method was successfully employed for nonlinear and contact analyses of the buckling behaviour and the physical contact phenomena of different sewer culverts. Generally, the composite liner fails in a single-lobe buckling at the invert with the deflection similar to that observed onsite. The proposed theoretical solution was verified through numerical analysis; the critical pressure and buckling mode results showed good agreement.

ABSTRACT: Uprights in storage racks being predominantly subjected to axial compression are also subjected to bending moments, hence acting as beam-columns by nature. The design of uprights is currently based on experimental or high-end computational methods, but analysis based-design involves lesser design office effort enabling development of innovative and optimized sections. The major challenges in this design are perforation, buckling interaction and combined loading. Although recent attempts use Direct Strength Method (DSM) to determine the nominal strength of uprights, experimental evidence on beam-column behavior of uprights that validate analytical equations are scarce. With this background, 16 experiments were carried out on uprights subjected to axial or biaxial compression, considering biaxial compression for constant and linearly varying moments. Interaction of distortional mode with global modes is evident from the experiments, which is generally ignored in DSM. In this paper, DSM is briefly explained and the choice of appropriate yielding moment is exemplified. The experimental results are presented in terms of DSM for both Linear Interaction (LI – from current code of practice) and Nonlinear Interaction (NLI – from literature). The results show that NLI may lead to unconservative design for eccentrically loaded specimens with linearly varying moments.

Arash Sahraei and Magdi Mohareb (Department of Civil Engineering, University of Ottawa, Ottawa, ON, Canada K1N 6N5), “Upper and lower bound solutions for lateral-torsional buckling of doubly symmetric members”, Thin-Walled Structures, Vol. 102, pp 180-196, May 2016, DOI: 10.1016/j.tws.2016.01.015

ABSTRACT: A family of three finite elements is developed for the lateral-torsional buckling analysis of thin-walled members with doubly symmetric cross-sections. The elements are based on a recently derived variational principle which incorporates shear deformation effects in conjunction with a special interpolation scheme ensuring C1 continuity. One of the elements is developed such that it consistently converges from above while another element is intended to consistently converge from below. The third element exhibits fast convergence characteristics compared to other elements but cannot be guaranteed to provide either an upper or a lower bound solution. The formulation incorporates the ability to enforce any set of linear multi-point kinematic constraints. The validity of the solution is established through comparisons with other well-established numerical solutions. The elements are then used to solve practical problems involving simply supported beams, cantilevers and continuous beams under a variety of loading conditions including concentrated loads, linear bending moments and uniformly distributed loads. The effect of lateral and torsional restraints and the location of lateral restraint along the section height on lateral-torsional buckling capacity of beams are also examined through examples.

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ABSTRACT: The effect of moment gradient on the buckling moment resistance of I-beams can be taken into account by the use of an equivalent moment-gradient factor $C_g$. The $C_g$ factors given by the previous researchers have been derived from elastic lateral-torsional buckling (LTB) analysis of compact I-beams. However,
according to the available literature it is not known whether these factors can be applied to the LTB analysis of inelastic slender-web plate girders (SWPGs). The aim of this paper is to investigate the nonlinear LTB analysis of unstiffened SWPGs subjected to central loading. To this end, a 3D finite-element model using ABAQUS is developed for the inelastic nonlinear flexural-torsional analysis of SWPGs and used to evaluate the unbraced length and load-height effects (located at center, top flange and bottom flange) on their moment-gradient factor. It was found that the $C_b$ factor given by AISC in Specification for structural steel buildings is generally unconservative for the elastic and inelastic SWPGs under the considered point load cases. Also, it was observed that the moment resistance versus unbraced length ($M-L$) relationships for the elastic SWPGs are not significantly affected by the applied load height.


ABSTRACT: Anti-sag bar is frequently adopted to enhance the lateral stiffness of cold-formed steel purlins. In existing studies, the anti-sag bar is normally treated as the rigid lateral restraint of cold-formed steel purlins, while according to the previous study of the authors', the local deformation of purlin web near the location connecting the anti-sag bar may significantly reduce the efficiency of anti-sag bar for providing the lateral restraint to cold-formed steel purlins. The lateral buckling of C-section purlins with one anti-sag bar at their middle span section is investigated in this paper, where the effective stiffness of the anti-sag bar taking into account the local deformation of purlin web is adopted. Two representative total potentials for the lateral buckling of C-section purlins are discussed with the differences between highlighted. Based on the proposed total potential, a hand-calculation solution for the lateral buckling load of C-section purlins is developed. The total potential and the solution for buckling load proposed in this study are verified by comparing their results with those from the finite element (FE) analysis using the shell element modeling of ANSYS or the FE program developed. The influences of the key parameters on the lateral buckling load of the C-section purlins are discussed in the parametric study.

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ABSTRACT: Tension field theory has traditionally been used to determine the ultimate postbuckling shear strength of steel plates. More than a dozen theories have been proposed in the last nine decades to describe and predict this phenomenon, and all are based on the tensile response of the web plate, referred to as tension field action. Alternatively, in this paper a compression approach for determining the ultimate postbuckling shear strength is studied. First, an experimentally-validated finite element model is used to examine the mechanics of plate shear buckling. The response is shown to be similar to axially compressed plates, but in this case the axial compression is acting on a diagonal. Then a physical model and formulation based on the compressive strength of the plate is developed for predicting the ultimate postbuckling shear strength of a plate. For common design parameters of most bridge and building structures, this compression approach produces strengths that are closer to experimental and finite element results than the best and commonly accepted formulation based on tension field action. Overall, the results of this study show that a compression approach to predicting the postbuckling shear capacity of plates is an honest representation of shear buckling mechanics and has good correlation to
extensive experimental results, where in many cases improved correlation is seen compared to formulations based on tension field action.


ABSTRACT: In the framework of the INDUSE project, which aims at innovative design methodologies for the seismic design of industrial equipment and piping systems, case studies have been carried out, performing static and dynamic seismic analyses for two existing steel pipeline systems including steel supporting structures, situated in an area of moderate seismic activity:

a) A long aboveground 10" ammonia transmission line situated on sleepers with a vertical expansion loop and ending with a fixed point. The system may be typical for long distance above ground pipelines and for pipelines on jetties.

b) A 20" gas transmission pipeline at the interface of a buried pipeline section and an above ground piping section, including a branch connection, a vertical spring support structure and a fixed point, e.g. a tank nozzle. This system is typical for many plant piping systems.

The calculations were made using commercially available software. Both simplified static equivalent (‘uniform load method’) calculations as well as dynamic calculations were made in accordance with American (ASCE-7) and European (EN1998 and EN13480) earthquake design standards to identify differences in approach, differences in resulting seismic response spectra and differences in calculated results. The dynamic and static calculations were made with Caesar II software.

The results of the calculations are presented. Conclusions and recommendations are given with respect to:

- The differences between existing earthquake design codes.
- The validity of the use of the "static equivalent (uniform load) method".
- The need to include guidelines for design and modeling in the next revisions of existing seismic design standards for (above ground) industrial piping systems.

References listed at the end of the paper:

[10] ROHR2, Pipe Stress Analysis Static and Dynamic Analysis (http://www.rohr2.com/)

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ABSTRACT: The present investigation refers to the bending capacity of spiral-welded steel tubes. The first part of this investigation presents the results of a full-scale experimental program, aiming to investigate the structural behavior of large-diameter spiral-welded steel tubes under bending. A companion paper (Part II) is also published, which further studies the behavior of these elements numerically, using finite element simulations. The testing program presented in Part I consists of thirteen 42-inch-diameter spiral-welded steel tubes with D/t ranging between 65 and 120. Some of the tubular specimens contain girth welds and coil connection welds, which are shown to penalize the ultimate bending capacity of the tubes. Extensive measurements of initial imperfections and material properties are performed for each tubular specimen. The material properties of the specimens are investigated through both uniaxial tensile and compression coupon tests. A series of large-scale four-point bending tests is performed to determine the structural behavior of the tubes, resulting in local buckling failure of the tubes under consideration. The bending behavior of the thirteen specimens is documented extensively. The study offers information with regard to the ultimate bending resistance of the specimens. In addition, the full moment–curvature equilibrium path is presented, supplemented by measurements on the development of cross sectional ovalisation and tube wall wrinkling during the bending tests.

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ABSTRACT: In the second part of this investigation, numerical simulations are conducted using nonlinear finite element simulations, to define the bending strength and deformation capacity of large-diameter spiral-welded steel tubes. Under bending loading, the principal failure mode of those tubes is local buckling (wrinkling) of the tube wall, as shown experimentally in the companion paper (Part I) in a series of tests on 42-inch-diameter tubes (Van Es et al., 2015) [1], and this failure mode is explicitly simulated. Initially, a special-purpose numerical simulation of the cold bending process is conducted to calculate the corresponding residual stresses. Subsequently, a comparison with the test data on 42-inch-diameter tubes reported in Part I is conducted, using the actual material properties and initial geometric imperfections obtained from the tested specimens, as well as the residual stresses computed by the numerical process. Finally, a parametric investigation is performed on the influence of material properties, geometric initial imperfections and residual stresses on local buckling of spiral-welded tubes.

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ABSTRACT: The Koiter–Newton method is a reduced order modeling technique which allows us to trace efficiently the entire equilibrium path of a non-linear structural analysis. In the framework of buckling the method is capable to handle snap-back and snap-through phenomena but may fail to predict reliably bifurcation branches along the equilibrium path. In this contribution we extend the original Koiter–Newton approach with a reliable and accurate bifurcation indicator which is based on an eigenanalysis of the reduced order tangent stiffness matrix. The proposed indicator has a negligible numerical effort since all computations refer to the reduced order model which is typically of very small dimension. The extension allows the identification of bifurcation points and a tracing of corresponding bifurcation branches in each sector of the equilibrium path. The performance of the method in terms of reliability, accuracy and computational effort is demonstrated with several examples.


ABSTRACT: The objective of this paper is to numerically analyze the buckling of reinforced structures (stiffened plate) cracked under compressive stress by considering the evolution of cracks and its orientation. Numerical modeling and calculation by the finite element method, estimated the critical load for compression panel. The work presented in the article was inspired by several publications that related to this field. Brighenti (2005) have studied the behavior of elastic buckling of rectangular cracked thin plate for different boundaries conditions. Following these calculations, a calibration function was derived to estimate the load ratio $\varepsilon$ to the compression function of the crack length and its inclination. We found that the variation of the critical stress is proportional to the crack dimensions. In buckling, a transverse crack is more stable than a longitudinal crack.


ABSTRACT: This paper focuses on the elastic buckling strength of typical stiffened panels under bi-axial compression. Three levels of assumptions for stiffeners are investigated: (1) Vlasov assumption; (2) stiffeners’ web plate assumed deformable; (3) both stiffeners’ web and flange plates assumed deformable. The bi-axial buckling strengths for deck and bottom stiffened panels in typical merchant ships are obtained by minimum potential energy principle, and the results are compared with corresponding finite element analysis results. It shows that Vlasov assumption should be corrected, while the other two assumptions yield similar satisfactory results. Sensitivity analysis is made for scantlings of the stiffened panel. Above three assumptions all exhibit high efficiency.


ABSTRACT: This paper describes three tests on small scale, transversely stiffened plate girder. The objective of the test was to observe collapse mechanism and to study post buckling behavior i.e. in particular to investigate the behavior of the transverse web stiffeners. A problem was selected to choose the dimensions and loads of the
plate girder and design can be solved according to clauses of Indian Standers 800-2007. Model analysis technique was used to reduce the dimensions and loads of actual structure. Accordingly three small scale plate girder models were constructed with varying number of stiffeners and with constant dimensions of web, flange and stiffeners. The main objective of this experimental study was to study post buckling behavior. The observation given should facilitate future development of improved method of stiffeners.

References listed at the end of the paper:

Rasmus Tamstorf, “Large scale simulation of cloth and hair with contact”, Ph.D dissertation No. 23223, ETH, Switzerland, 2016

ABSTRACT: The goal of this thesis is to develop new methods for robust and scalable simulation of thin objects with contact. This work is motivated by applications in cloth and hair simulation in feature film production, but the results are also applicable in other domains such as in the garment industry, in biology, and in mechanical engineering. The contributions focus primarily on physically correct contact response and efficient implementation thereof. While collision detection has been studied extensively, collision response remains a challenging problem. This is due in part to the fact that contact constraints are both nonlinear, non-convex, and non-smooth. Furthermore, the response is inherently coupled to the underlying dynamics, which is often neglected in existing methods. We first develop the necessary details for implementation of the dynamics of orthotropic thin shells undergoing large deformations. This derivation is based on fundamental invariants and symmetry considerations from continuum mechanics and leads to a simple and efficient extension of existing membrane models. We also show how the analytical derivatives for the discrete shell bending model can be computed efficiently to facilitate implicit integration. The next part of the thesis is based on the observation that nonlinear compliance is critical for collision response involving thin objects. This is illustrated with rods (hair), which exhibit the same fundamental problem as shells, but are cheaper to simulate. Taking the nonlinearity into account, we show that simulations can be run with time steps that are 2-3 orders of magnitude larger than with existing methods. Based on this observation, we construct a solver that locally adapts the nonlinear treatment based on the current configuration to ensure stable simulations. We then validate our approach by running simulations with thousands of hairs and millions of contacts. Hair simulation is generally simpler than cloth
because the rods can be partitioned into contact groups that can each be handled separately. For shells, all degrees of freedom are inherently coupled, which leads to much larger systems of equations that have to be solved. In pursuit of solving these larger systems of equations, the last part of the thesis investigates the use of algebraic multigrid methods. The first key observation here is that standard multigrid methods (both geometric and algebraic) fail to perform well for thin shell equations even in the absence of contact. To address this difficulty, we introduce the smoothed aggregation method to cloth simulation. This is an algebraic multigrid method designed specifically for vector valued problems. Used as a preconditioner for CG, smoothed aggregation provides substantial speedups for medium and large size problems compared to a diagonally preconditioned CG method. Compared to geometric multigrid methods, it provides both better convergence rates and increased flexibility. Due to the algebraic nature of the method, it can be used for irregular meshes as well as with adaptive tessellations, which is not practical with geometric multigrid methods.

References listed at the end of the thesis:
doi:10.1109/PCCGA.2003.1238266.


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divide the whole bending process into three stages: low-curvature stage, mixed-curvature stage and high-curvature stage. Ripples are generated on the CNT surfaces before the formation of kinks. Compared to single-

ABSTRACT: This paper elucidates the buckling behavior of carbon nanotubes (CNTs) under bending. CNTs

are modeled as continuous thin-wall circular tubes, and their buckling is governed by equations that take into account of the sectional Brazier effect and non-uniform structural deformation. The CNT governing equations (fourth-order ordinary differential equations with integral conditions) are solved by introducing a

continuation algorithm. In addition, the buckling behavior of CNTs under bending is simulated with objective molecular dynamics (OMD). The atomistic simulations are used to verify the continuum results. We show that there exist low- and high-strain phases during the bending process of CNTs, and the transition in between may divide the whole bending process into three stages: low-curvature stage, mixed-curvature stage and high-curvature stage. Ripples are generated on the CNT surfaces before the formation of kinks. Compared to single-

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ABSTRACT: This paper elucidates the buckling behavior of carbon nanotubes (CNTs) under bending. CNTs are modeled as continuous thin-wall circular tubes, and their buckling is governed by equations that take into account of the sectional Brazier effect and non-uniform structural deformation. The CNT governing equations (fourth-order ordinary differential equations with integral conditions) are solved by introducing a continuation algorithm. In addition, the buckling behavior of CNTs under bending is simulated with objective molecular dynamics (OMD). The atomistic simulations are used to verify the continuum results. We show that there exist low- and high-strain phases during the bending process of CNTs, and the transition in between may divide the whole bending process into three stages: low-curvature stage, mixed-curvature stage and high-curvature stage. Ripples are generated on the CNT surfaces before the formation of kinks. Compared to single-


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ABSTRACT: This paper elucidates the buckling behavior of carbon nanotubes (CNTs) under bending. CNTs are modeled as continuous thin-wall circular tubes, and their buckling is governed by equations that take into account of the sectional Brazier effect and non-uniform structural deformation. The CNT governing equations (fourth-order ordinary differential equations with integral conditions) are solved by introducing a continuation algorithm. In addition, the buckling behavior of CNTs under bending is simulated with objective molecular dynamics (OMD). The atomistic simulations are used to verify the continuum results. We show that there exist low- and high-strain phases during the bending process of CNTs, and the transition in between may divide the whole bending process into three stages: low-curvature stage, mixed-curvature stage and high-curvature stage. Ripples are generated on the CNT surfaces before the formation of kinks. Compared to single-
walled CNTs (SWCNTs), hydrogen-filled CNTs have a longer mixed-strain stage owing to the presence of internal pressure, and are therefore more inclined to exhibit a ripple morphology. Our results offer better understanding of the buckling behavior of CNTs, and may open up new opportunities for the design and applications of novel CNT-based nanoelectronics.

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DOI: 10.1016/j.jmgm.2016.02.001

ABSTRACT: In the present paper, an analytical solution based on a molecular mechanics model is developed to evaluate the elastic critical axial buckling strain of chiral multi-walled carbon nanotubes (MWCNTs). To this end, the total potential energy of the system is calculated with the consideration of the both bond stretching and bond angular variations. Density functional theory (DFT) in the form of generalized gradient approximation (GGA) is implemented to evaluate force constants used in the molecular mechanics model. After that, based on the principle of molecular mechanics, explicit expressions are proposed to obtain elastic surface Young’s modulus and Poisson’s ratio of the single-walled carbon nanotubes corresponding to different types of chirality. Selected numerical results are presented to indicate the influence of the type of chirality, tube diameter, and number of tube walls in detailed. An excellent agreement is found between the present numerical results and those found in the literature which confirms the validity as well as the accuracy of the present closed-form solution. It is found that the value of critical axial buckling strain exhibit significant dependency on the type of chirality and number of tube walls.

References listed at the end of the paper:
and analytical approaches for linear buckling response are presented by using the layer trunks. The material properties of the shells are assumed to vary continuously in the radial direction. Relations distributed material properties under the axial load and lateral pressure based on the experimental study of palm trunks. The material properties of the shells are assumed to vary continuously in the radial direction. Relations and analytical approaches for linear buckling response are presented by using the layer-wise shell theory. The


ABSTRACT: This paper aims at the elastic buckling of multilayered thin-walled conical shells with power-law distributed material properties under the axial load and lateral pressure based on the experimental study of palm trunks. The material properties of the shells are assumed to vary continuously in the radial direction. Relations and analytical approaches for linear buckling response are presented by using the layer-wise shell theory. The
buckling behaviors of the conical shells subjected to axial and transverse loads are investigated. Parametric study in geometry (relative thickness, relative stiffness and cone angle) is performed to enhance the overall buckling resistance and minimize the weight. Numerical results show the possibility to achieve larger load-carrying capacity by simultaneously optimizing the material and geometric parameters based on the structure of palm trunks.

References listed at the end of the paper:
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ABSTRACT: The nonlinear analysis with an analytical approach on dynamic torsional buckling of stiffened functionally graded thin toroidal shell segments is investigated. The shell is reinforced by inside stiffeners and surrounded by elastic foundations in a thermal environment and under a time-dependent torsional load. The governing equations are derived based on the Donnell shell theory with the von Kármán geometrical nonlinearity, the Stein and McElman assumption, the smeared stiffeners technique, and the Galerkin method. A deflection function with three terms is chosen. The thermal parameters of the uniform temperature rise and nonlinear temperature conduction law are found in an explicit form. A closed-form expression for determining the static critical torsional load is obtained. A critical dynamic torsional load is found by the fourth-order Runge-Kutta method and the Budiansky-Roth criterion. The effects of stiffeners, foundations, material, and dimension parameters on dynamic responses of shells are considered.

References listed at the end of the article:

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DOI: 10.1007/s10778-016-0752-8

ABSTRACT: A procedure for analytical solution of the problem of the stability and post-buckling behavior of orthotropic cylindrical shells under external pressure or axial compression with allowance for transverse shears is developed. The shells are geometrically imperfect due to the presence of a local deflection. The problem is solved by analyzing the interaction of the modes that represent the critical loads of the perfect shell and using the Byskov–Hutchinson method. Equilibrium curves for both shells are plotted using the method of continuous loading.

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Jian Li, Guangjun Gao, Haipeng Dong, Suchao Xie and Weiyuan Guan (Key Laboratory of Traffic Safety on Track of Ministry of Education, School of Traffic & Transportation Engineering, Central South University, Changsha 410075, China), “Study on the energy absorption of the expanding-splitting circular tube by experimental investigations and numerical simulations”, Thin-Walled Structures, Vol. 103, pp 105-114, June 2016, DOI: 10.1016/j.tws.2016.01.031

ABSTRACT: This paper presents experimental and numerical investigations of a new type of combined energy absorber which working on the principle of expanding and splitting of the circular steel tube. In the first phase of deformation the tube is expanded by the cylinder part of the die. Second phase of deformation characterizes splitting of the expanded part of the tube into strips along the initial sawcuts by the cone part of the die. The strips bend outwards with certain radius to the end of the second phase. Quasi static compression test shows that this type of energy absorber is completely feasible and the combined absorber has 95.34% higher maximal force in compare with absorber which uses only expansion process of deformation. Using this system of deformation, the total energy absorption is obtained by the three mechanisms: elastic–plastic bending of the tube, splitting of the tube wall and friction between the tube and the die. The effect of friction coefficient is studied by simulation, it is found that the effect on friction energy is significant but negligible on splitting energy and plastic energy.

Hossein Nassiraei, Mohammad Ali Lotfollahi-Yaghin and Hamid Ahmadi (Faculty of Civil Engineering, University of Tabriz, Tabriz 5166616471, Iran), “Static strength of offshore tubular T/Y-joints reinforced with collar plate subjected to tensile brace loading”, Thin-Walled Structures, Vol. 103, pp 141-156, June 2016 DOI: 10.1016/j.tws.2016.02.010

ABSTRACT: This paper studies the static strength of circular hollow section (CHS) T/Y-joints reinforced with collar plates subjected to axial tension load. The SOLID186 in ANSYS was utilized to establish the finite element (FE) models of the T/Y-joints. Validation of the FE model with experimental data showed that the present FE model can accurately predict the ultimate strength, initial stiffness and failure modes of collar plate reinforced and unreinforced tubular joints. Afterwards, 210 FE models were generated and analyzed to investigate the effect of joint geometry and collar plate size on the ultimate strength, failure mechanisms, and initial stiffness through a parametric study. Results indicated that the ultimate strength of the collar plate reinforced T- and Y-joints under brace tension can be up to 200% and 180% to that of the strength of the corresponding unreinforced joint, respectively. Also, The strengthening influence of the collar plate length and collar plate thickness on the ultimate capacity becomes more significant when one of these parameters is big. Moreover, the comparison between failure modes of reinforced and unreinforced joints showed that the collar plate can significantly improve the failure mechanisms. Also, the collar plate can significantly increase the initial stiffness. Despite this significant difference between the ultimate strength, failure mode, and initial stiffness of unreinforced and collar plate reinforced T- and Y-joints under brace tension, investigations on these types of reinforced joints have been limited to very few T-joint tests. Also, no design equation is available to determine the ultimate strength of T- and Y-joints reinforced with collar plates. Therefore, the geometrically parametric study was followed by the nonlinear regression analysis to develop an ultimate strength parametric formula for the static design of collar plate reinforced T/Y-joints under brace tension.
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ABSTRACT: A concept of hybrid-stiffness stiffened shell is proposed based on sub-panel elements to achieve a simultaneous buckling pattern, which can provide enhanced design flexibility to fully explore the load-carrying capacity of structures. Then, a novel hybrid model is established to improve the computational efficiency of post-buckling analysis for stiffened shells, where the Numerical Implementation of Asymptotic Homogenization Method is utilized to smear out the stiffeners. On this basis, an integrated optimization framework of sub-panel configurations and weld lands for stiffened shells is presented. Illustrative examples with single and multiple cutouts demonstrate the effectiveness of the proposed framework based on the concept of hybrid-stiffness stiffened shell.

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“Experimental investigation of cold-formed steel channels with slotted webs in shear”, Thin-Walled Structures, Vol. 102, pp 30-42, May 2016, DOI: 10.1016/j.tws.2016.01.012
ABSTRACT: This paper presents results of an experimental investigation on shear strength of cold-formed steel channels with slotted webs. Fifteen specimens with slotted webs and ten specimens with solid webs were tested in three-point bending. The channel web slots studied in this work caused 50% to 71% reduction in the ultimate shear strength, which depended on the profile thickness and depth. Tentative equations for the shear capacity of slotted channels with and without tension field action were proposed. The equations that include tension field action showed a good agreement with the test results, which indicates that the slotted channels exhibited post-buckling strength due to tension field action.

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ABSTRACT: This paper presents finite element models of cold-formed steel channels with solid and slotted webs subjected to shear. The models were created in ANSYS and validated against test data. The effects of boundary conditions on the elastic shear buckling load and the ultimate shear strength were numerically investigated on the models with the test setup and realistic boundary conditions. The obtained results showed that the elastic shear buckling loads and the ultimate shear strengths of the slotted channels were affected considerably more by the boundary conditions when compared with the solid channels. Therefore, the actual boundary conditions should be considered in further parametric studies of the slotted channels.

ABSTRACT: Liquid tanks in the form of truncated cones are commonly used for liquid storage in North America and in other locations. This paper is a part of an extensive research program aimed to develop a comprehensive design procedure for liquid-filled steel conical tanks under seismic loading. Because of the inclination of the walls of conical tanks, the vertical component of the ground motion excitation has a significant effect on conical tanks compared to the case of cylindrical tanks. To the best of the authors' knowledge, the current study is the first to focus on the assessment of the capacity of steel conical tanks under the vertical component of a seismic excitation. The study is carried out numerically using an in-house finite element model by conducting nonlinear static pushover analysis under a load distribution simulating hydrodynamic pressure associated with vertical ground excitations. The numerical model accounts for the effects of geometric and material nonlinearities as well as initial geometric imperfections. Charts are developed to estimate the capacity of steel conical tanks to resist vertical ground excitations based on yielding and buckling criteria for different imperfection levels. The developed charts are used to estimate the capacities of a number of steel conical tanks which are then compared to the hydrodynamic loading associated with various seismic zones.


ABSTRACT: Steel conical tanks are widely used for liquid storage around the world and especially in North America. A number of those tanks collapsed in the last decades at different places as a result of instability of the steel shells. Despite being widely used, no specific design procedure is available for conical tanks under dynamic conditions. Most of the previous studies related to steel conical tanks focused on calculating the acting forces due to a seismic event. This study however, focuses on evaluating the capacity of conical tanks under hydrodynamic pressure resulting from horizontal ground excitation using non-linear static pushover analysis. The capacity is then compared to the seismic demand obtained using a previously developed mechanical model found in the literature for different seismic zones. This paper is a part of a larger study aiming to provide a simplified design procedure for steel conical tanks when subjected to earthquakes. The study is conducted numerically using a non-linear finite element model that accounts for the effects of large deformations and geometric imperfections on the stability of steel conical tanks.


ABSTRACT: Liquid tanks in the form of truncated steel cones are commonly used for liquid storage in North America and in other locations. The main cause of failure, for conical steel tanks in particular, which was identified in most of the failure cases, is the buckling of the tank’s shell at locations of maximum compressive stress. Being constructed of steel, geometric imperfections in the conical tank walls will exist and their amplitude will be dependent on the quality controls applied by the builder. Such geometric imperfections play an important role in defining the buckling capacity of shell structures in general. Some studies found in the
literature assessed the effect of geometric imperfections on the buckling capacity of steel tanks. However, most of these studies focused on hydrostatic pressure and not on hydrodynamic pressure that is induced on the tank walls when the tank base is subjected to either horizontal or vertical ground excitations. In this study, an expression for the critical imperfection wave length is obtained and the effect of the geometric imperfections’ amplitude on the buckling capacity of conical steel tanks is assessed numerically under hydrodynamic pressure due to horizontal and vertical ground excitations. The study is conducted numerically through non-linear static pushover analysis using an in-house finite element model that accounts for the geometric and material nonlinear effects.


ABSTRACT: In this paper, the problem of linear elastic buckling of a simply supported rectangular plate, with a single circular cutout, subjected to uniform uniaxial edge compression is considered. The design objective is the maximization of the buckling load by determining the optimal location of the cutout. To accomplish that, a MATLAB routine coupled with finite element computation in ANSYS is employed. The study shows that the position of the center of the circular hole for the maximum buckling load remains always on the longitudinal centerline of the plate. However, the optimal center positions along this longitudinal axis for a given cutout size have great dependence on the aspect ratio of the plates. These optimal positions are reported for various values of plate aspect ratios and cutout sizes. These results are important from a design perspective and will be useful for design purposes in the future.

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ABSTRACT: This paper addresses the determination of deformation modes for curved thin-walled cross-sections through the polygonal approximation of the cross-section mid-line, in the framework of Generalised Beam Theory (GBT). A new GBT cross-section analysis procedure is proposed, which discretises the geometry independently of the number of cross-section DOFs considered to obtain the deformation modes. This procedure is more efficient than the classic GBT one, since curved geometries may be accurately described without increasing the number of deformation modes. In particular, polygonal sections with rounded corners can be easily handled. For illustrative purposes, the procedure is applied to several cross-sections with curved walls and it is shown that it leads to accurate results with coarse cross-section DOF discretisations.

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ABSTRACT: This paper focuses on the crushing collapse theory of externally fiber-reinforced twelve right-angle section (TTRS) tubes based on the kinematic approach. This paper presents the crushing energy dissipation mechanism of metal TTRS tubes and derives the expression of mean crushing force. Considering the contribution of the composite-metal wall and the final crushing deformation, which affected by the accumulation of the composite after failure, the expression describing the mean crushing force for externally fiber-reinforced TTRS tubes is presented. The accuracy of the theoretical predictions is validated by finite element simulations, including four different metal wall thicknesses and three different amounts of composite plies. The results indicate that the mean crushing forces calculated by the proposed theory show a good consistency with the simulation results.


ABSTRACT: This paper demonstrates the computational advantages of combining shell-like stress resultant elastoplasticity with geometrically exact thin-walled beam finite elements. The material model employed follows the Ilyushin criterion for shell-type stress resultants, making it possible to bypass computationally expensive through-thickness numeric integration and enforce specific stress resultants to zero, leading to a particularly simple form of the return mapping algorithm and of the consistent constitutive tangent. This constitutive model is included in a geometrically exact two-node beam finite element which allows for torsion-related warping and Wagner effects. The accuracy of the proposed approach is assessed in several numerical examples.


ABSTRACT: In ship hull structures, bilge part is often composed of unstiffened radiused plating, for which the harmonized CSR stipulates required scantlings, locations of the longitudinals adjacent to the bilge radius, and so on. In recent years, under the increased demand for rational structural design, larger radius than ever is sought, expecting reduction of hull steel weight and welding lengths, thus contributing to the reduction of production cost of structures. However, structural problems arising from the larger bilge radius and associated structural arrangement around the bilge shell are not yet sufficiently identified. In these circumstances, the authors developed theoretical formulae, assuming radiused plating connected to continuous stiffened flat plating with regular stiffener spacing. The results of the theoretical calculations are compared with the results of finite element analysis, and it was found that the derived theoretical formulae well explain the complicated phenomena of the curved shell plating connected to the flat stiffened panels. Utilizing the derived theoretical formulae, parametric studies were carried out with regard to the radius of the bilge shell plating, the distance between the position where the curvature of the bilge plate starts and the adjacent longitudinal, and so on. As a result of the calculations, it was found that large bilge radius exceeding current usual practice is feasible, on the condition that the location of the longitudinals is well controlled to reduce bending stresses on the shell plate, and the buckling strength is satisfied. In such case, the stipulation in the harmonized CSR is not always rational, and the authors propose modified structural design methodologies around the unstiffened bilge shell plating.
ABSTRACT: Buckling is a critical failure phenomenon for structures, and represents a threat for thin shells subjected to compressive forces. The global buckling load, for a conical structure, depends on the geometry and material properties of the shell, on the stacking sequence, on the type of applied load and on the initial geometric imperfections. Geometric imperfections, occurring inevitably during manufacturing and assembly of thin-walled composite structures, produce a reduction in the carrying load capability with respect to the design value. This is the reason why investigating these defects is of major concern in order to avoid over-conservative design structures. In this paper, the buckling behavior a conical structure with 45° semi-vertical angle is numerically investigated. The initial imperfections are taken into account by using different strategies. At first, the Single Perturbation Load Approach (SPLA), which accounts for defects in the form of a lateral load, normal to the surface, has been adopted. Then, the actual measured defects have been applied to the structure by using the Real Measured Mid-Surface Imperfections (MSI) approach. Investigations on cylindrical shells using the first strategy have already shown the occurrence of a particular phenomenon called “local snap-through”, which represents a preliminary loss of stiffness. In order to better understand this phenomenon for conical shells, both the aforementioned techniques have been used to provide an exhaustive overview of the imperfections sensitteness in conical composite shells. This study is related to part of the work performed in the frame of the European Union (EU) project DESICOS.

References listed at the end of the paper:

ABSTRACT: The damage tolerance of delaminated composite panels under compressive load is usually numerically evaluated by means of computationally expensive non-linear approaches. In this study, an alternative numerical linear approach, able to mimic the delamination propagation initiation, is proposed. With the aim to exploit its benefits, in terms of computational costs reduction, the proposed linear methodology has been used in this study in conjunction with an optimization analysis to assess the damage tolerance of stiffened composite panels with an impact induced delamination under compression. Indeed, the optimization was aimed to find the minimum delamination growth initiation load for a delaminated stiffened panel with variable delamination size and position, providing indications on the damage tolerance capability of the stiffened panel with an arbitrary positioned and sized delamination induced (as an example) by a low energy impact.

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Linear Buckling Testing on Cylindrical Aluminium Structures – Experimental Investigation

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ABSTRACT: In this paper, cylindrical aluminium structures are tested for examination of buckling phenomenon. Testing of the material structures are accomplished by comparison made on the basis of linearity and non-linearity. The computation of various parameters viz. displacement, external work done, energy loss, and total energy consumed are being performed to evaluate the performance and optimal operating conditions of the aluminium structure. The results are visualized with ABAQUS CAE software. It is observed that non-linear buckling is found superior in terms of structural deformations and energy loss as compared to linear buckling. This non-linear buckling has proved to be an eminent technique to reduce the adverse effects of the buckling phenomenon prominent in aluminium structures.
References listed at the end of the paper:

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ABSTRACT: In the framework of a general stability theory for three-dimensional bodies the buckling analysis is carried out for the nonlinearly elastic three-layer cylindrical tube subjected to axial compression under internal or external pressure. It is assumed that the middle layer (core) of the tube is made of metal or polymer foam, and to describe its behavior the model of micropolar continuum is used. Such approach allows to study in detail the influence of foam microstructure on the deformation stability, which is especially important when the macroscopic dimensions of the tube are comparable with the average size of the foam cells. The inner and outer layers (coatings) of the tube are assumed to be made of the classic non-polar materials. Applying linearization the neutral equilibrium equations have been derived, which describe the perturbed state of the cylindrical sandwich tube. By solving these equations numerically for some specific materials, the critical curves and corresponding buckling modes have been found and the stability regions have been constructed in the planes of loading parameters (relative axial compression and internal or external pressure). Using the obtained results, the influence of coatings properties, as well as the overall size of the tube, on the loss of stability has been analyzed.

References listed at the end of the paper:
ABSTRACT: We revisit the consistently linearized path-following method that can be applied in the nonlinear finite element analysis of solids and structures in order to compute a solution path. Within this framework, two constraint equations are considered: a quadratic one (that includes as special cases popular spherical and cylindrical forms of constraint equation), and another one that constrains only one degree-of-freedom (DOF), the critical DOF. In both cases, the constrained DOFs may vary from one solution increment to another. The former constraint equation is successful in analysing geometrically nonlinear and/or standard inelastic problems with snap-throughs, snap-backs and bifurcation points. However, it cannot handle problems with the material softening that are computed e.g. by the embedded-discontinuity finite elements. This kind of problems can be solved by using the latter constraint equation. The plusses and minuses of the both presented constraint equations are discussed and illustrated on a set of numerical examples. Some of the examples also include direct computation of critical points and branch switching. The direct computation of the critical points is performed in the framework of the path-following method by using yet another constraint function, which is eigenvector-free and suited to detect critical points.

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ABSTRACT: This paper presents a free vibration analysis of functionally graded materials nano-plate resting on Winkler–Pasternak elastic foundations based on two-variable refined plate theories including the porosities effect. The small-scale effects are introduced using the nonlocal elasticity theory with a new shear deformation function. The governing equations are obtained through the Hamilton’s principle. The effect of material property, porosities, various boundary conditions and elastic foundation stiffnesses on free vibration functionally graded materials nanoplate are also presented and discussed in detail. The present solutions are compared with those obtained by other researchers. The results are in a good agreement with those in the literature.

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ABSTRACT: Carbon is one of the most important materials extensively used in industry and our daily life. Crystalline carbon materials such as carbon nanotubes and graphene possess ultrahigh strength and toughness. In contrast, amorphous carbon is known to be very brittle and can sustain little compressive deformation. Inspired by biological shells and honeycomb-like cellular structures in nature, we introduce a class of hybrid structural designs and demonstrate that amorphous porous carbon nanospheres with a thin outer shell can simultaneously achieve high strength and sustain large deformation. The amorphous carbon nanospheres were synthesized via a low-cost, scalable and structure-controllable ultrasonic spray pyrolysis approach using energetic carbon precursors. In situ compression experiments on individual nanospheres show that the amorphous carbon nanospheres with an optimized structure can sustain beyond 50% compressive strain. Both experiments and finite element analyses reveal that the buckling deformation of the outer spherical shell dominates the improvement of strength while the collapse of inner nanoscale pores driven by twisting, rotation, buckling and bending of pore walls contributes to the large deformation.

ABSTRACT: The effect of welding residual stress on the buckling behavior of storage tanks subjected to the harmonic settlement was simulated using the shell-to-solid coupling method. In the numerical model of tanks coupled with the welding residual stress, the welding joint and its adjacent zone were modeled using the solid submodel and the zone far away from the welding joint was built by the shell submodel. Effects of welding parameters (e.g., welding velocities and welding passes) on the buckling behavior of tanks were analyzed systematically. Results indicate that the buckling strength of tanks is enhanced due to the welding residual stress. Comparatively, a slow welding velocity presents a more remarkable strengthening effect than the fast welding velocity due to a larger axial residual stress produced at the welding joint. Nevertheless, no significant difference between the double-side welding and the one-side welding for buckling strength enhancement is observed for the cases studied. This indicates that the current design method causes a conservative design without considering the welding residual stress.
ABSTRACT: Panels and plates are an important structural element in many engineering applications, such as aircraft skin panels, ship hulls, and civil shell structures. These structures, particularly when their boundaries are in some way constrained, exhibit highly nonlinear behavior (e.g. spring hardening) even for relatively small deformations due to induced axial loading. An extreme, but highly important, example is dynamic snap-through buckling of curved or post-buckled thin panels. This phenomena is well represented in the literature, both for plates and for the simplified case of curved beams. The majority of the experimental studies, especially for panels, have been carried out using either wind tunnels or acoustic drivers to generate transverse loading. While this is directly applicable to real-world scenarios, say aircraft panel loading, it does not permit direct control of the loads that are applied. In this work, we instead apply loads to a thermally buckled panel using an electrodynamic shaker. This, along with the use of digital image correlation to capture the full field dynamic response allows for a complete picture of the complex characteristics of dynamic snap-through.

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Seyed A. Ahmadi and Hadi Pourshahsavari (Dept. of Mechanical Engineering, Babol University of Technology, Babol, Iran), “Three-dimensional thermal buckling analysis of functionally graded cylindrical panels using differential quadrature method (DQM)”, Journal of Theoretical and Applied Mechanics, Vol. 54, No. 1, pp 135-147, 2016, DOI: 10.15632/jtam-pl.54.1.135

ABSTRACT: Thermal buckling analysis of functionally graded cylindrical panels subjected to various conditions is discussed in this paper. Buckling governing equations are solved using the differential quadrature method. It is assumed that the mechanical properties of the panel are graded through thickness according to a power function of the thickness variable. The panel is assumed to be under the action of three types of thermal loading including uniform temperature rise and variable temperature rise in the axial and radial direction. In the present study, the effects of power law index, panel angle, different thermal load conditions and geometric parameters on the buckling behavior of functionally graded curved panels are studied. The results obtained through the present method are compared to the finite element solutions and the reported results in the literature. A desirable compatibility is concluded.

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4. Breivik N.L., 1997, Thermal and mechanical response of curved composite panels, Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of doctor of Philosophy in engineering mechanics
ABSTRACT: Due to their light weights and high load carrying capacities, composite structures are widely used in various industrial applications especially in aerospace industry. Strength to weight ratio is known to be as one of the most critical design parameters in these structures. In this paper, geometrical parameters of composite lattice structures are optimized to obtain the desired strength to weight ratio using finite element method, neural networks and ABC algorithm. At first, the finite element model is validated by experimental results and neural network is employed as the fitness function. The ABC algorithm is also applied to achieve the optimized strength to weight ratio. The results obtained from PSO algorithm on the basis of neural network have shown reasonable agreement with those of the finite element simulation. Increasing the thickness of the outer shell causes the structural strength-to-weight ratio to rise by 50 percent. The next effective parameter is reduction of rib angle which provides an increase of 30 percent in strength-to-weight ratio. Although Stiffeners (ribs) have a major role in load carrying, increasing the rib thickness causes the structural weight to rise. Thus compared with the two previous parameters, they do not have a significant effect on the strength of structures.

References listed at the end of the paper:

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ABSTRACT: This paper investigates nonlinear bending and buckling behaviours of composite plates characterized by a thickness variation. Layer interfaces are described as functions of inplane coordinates. Top and bottom surfaces of the plate are symmetric about the midplane and the plate could be considered as a flat surface in analysis along with thickness parameters which vary over the plate. The variable thickness at a certain position in the midplane is modeled by a set of control points (or thickness-parameters) through NURBS
(Non-Uniform Rational B-Spline) basic functions. The knot parameter space which is referred in modelling geometry and approximating displacement variables is employed for approximating thickness, simultaneously. The use of quadratic NURBS functions results in $C^1$ continuity of modeling variable thickness and analyzing solutions. Thin to moderately thick laminates in bound of first-order shear deformation theory (FSDT) are taken into account. Strain-displacement relations in sense of von Karman theory are employed for large deformation. Riks method is used for geometrically nonlinear analysis. The weak form is approximated numerically by the isogeometric analysis (IGA), which has been found to be a robust, stable and realistic numerical tool. Numerical results confirm the reliability and capacity of the propose method.

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DOI: 10.1134/S1810232816020053
ABSTRACT: Perforated steel plates are structural components widely employed in engineering. In several applications these panels are subjected to axial compressive load, being undesired the occurrence of buckling. The present work associates the computational modeling and the constructive design method to obtain geometries, which maximizes the mechanical behavior for these components. A numerical model was used to tackle with elastic and elasto-plastic buckling. Square and rectangular plates with centered elliptical cutouts were considered and several hole volume fractions and ratios between the ellipse axes ($H_o/L_o$) were taken into account. Stress limit improvements around 100% were achieved depending only on the cutout shape.

References listed at the end of the paper:


ABSTRACT: Additive manufacturing (AM) permits the fabrication of functionally optimized components with high geometrical complexity. The opportunity of using porous infill as an integrated part of the manufacturing process is an example of a unique AM feature. Automated design methods are still incapable of fully exploiting this design freedom. In this work, we show how the so-called coating approach to topology optimization provides a means for designing infill-based components that possess a strongly improved buckling load and, as a result, improved structural stability. The suggested approach thereby addresses an important inadequacy of the standard minimum compliance topology optimization approach, in which buckling is rarely accounted for; rather, a satisfactory buckling load is usually assured through a post-processing step that may lead to sub-optimal components. The present work compares the standard and coating approaches to topology optimization for the MBB beam benchmark case. The optimized structures are additively manufactured using a filamentary technique. This experimental study validates the numerical model used in the coating approach. Depending on the properties of the infill material, the buckling load may be more than four times higher than that of solid structures optimized under the same conditions.

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ABSTRACT: Understanding how a tiny dilute evaporative colloidal spray droplet gets transformed into a microgranule with a characteristic morphology is crucial from scientific as well as technological points of view. In the present work, it is demonstrated that the morphology and the size distribution of the microcapsules can be tuned simply by adjusting the drying temperature. Shape and size of the capsules are quantified at four different
drying temperatures. It is shown that the morphology transits gradually from sphere to toroid with increasing temperature keeping the average volume-fraction of the correlated nanoparticles nearly unaffected for the synthesized granules. A plausible mechanism for the chronological pathway of such morphological transformation is illustrated. Computer simulation corroborates the experimentally observed morphological transition. The variation in hollowness and buckling tendency of the capsules are elucidated by scattering and imaging techniques.


ABSTRACT: In this paper, nonlinear vibration of a single-walled carbon nanotube (SWCNT) with simply supported ends is investigated based on von Karman's geometric nonlinearity and nonlocal shell theory. The SWCNT is designated as an individual shell, and the Donnell's formulations of a cylindrical shell are used to obtain the governing equations. The Galerkin's procedure is used to discretized partial differential equations (PDEs) into the ordinary differential equations (ODEs) of motion, and the method of averaging is applied to obtain an analytical solution of the nonlinear vibration of (10,0), (20,0), and (30,0) zigzag SWCNTs. The effects of the nonlocal parameters, nonlinear parameters, different aspect ratios, and different circumferential wave numbers are investigated. The results of the classical and the nonlocal models are compared with different nonlocal elasticity constants (e0a). It is shown that the nonlocal parameter predicts different resonant frequencies in comparison to the local models. The softening and/or hardening nonlinear behaviors of the CNTs may change against the nonlocal parameters. Hence, considering the geometrical nonlinearity and the nonlocal elasticity effects, the dynamical models of the SWCNTs predict their vibration behaviors accurately and should not be ignored during theoretical modeling.

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ABSTRACT: In this paper, size-dependent effect of an embedded magneto-electro-elastic (MEE) nanoshell subjected to thermo-electro-magnetic loadings on free vibration behavior is investigated. Also, the surrounding elastic medium has been considered as the model of Winkler characterized by the spring. The size-dependent MEE nanoshell is investigated on the basis of the modified couple stress theory. Taking attention to the first-order shear deformation theory (FSDT), the modeled nanoshell and its equations of motion are derived using principle of minimum potential energy. The accuracy of the presented model is validated with some cases in the literature. Finally, using the Navier-type method, an analytical solution of governing equations for vibration behavior of simply supported MEE cylindrical nanoshell under combined loadings is presented and the effects of material length scale parameter, temperature changes, external electric potential, external magnetic potential, circumferential wave numbers, constant of spring, shear correction factor and length-to-radius ratio of the nanoshell on natural frequency are identified. Since there has been no research about size-dependent analysis MEE cylindrical nanoshell under combined loadings based on FSDT, numerical results are presented to be served as benchmarks for future analysis of MEE nanoshells using the modified couple stress theory.

References listed at the end of the paper:


cells. In addition, one may use the discrete buckling solutions to calibrate the small-length scale coefficient $e_0$ in the Eringen’s nonlocal column model. It was found that $e_0$ values varied from 0.289 to 0.373 with respect to increasing selfweight for clamped-free column case, from 0.289 to 0.276 for the pinned-pinned column case, and from 0.289 to 0.281 for the clamped-clamped column case.

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ABSTRACT: In the present work, thermo-electro-mechanical buckling behavior of functionally graded piezoelectric (FGP) nanobeams is investigated based on higher-order shear deformation beam theory. The FGP nanobeam is subjected to four types of thermal loading including uniform, linear, and sinusoidal temperature rise as well as heat conduction through the beam thickness. Thermo-electro-mechanical properties of FGP nanobeam are supposed to change continuously in the thickness direction based on power-law model. To consider the influences of small-scale sizes, Eringen’s nonlocal elasticity theory is adopted. Applying Hamilton’s principle, the nonlocal governing equations of an FGP nanobeam in thermal environments are obtained and are solved using Navier-type analytical solution. The significance of various parameters, such as thermal loadings, external electric voltage, power-law index, nonlocal parameter, and slenderness ratio on thermal buckling response of size-dependent FGP nanobeams is investigated.


ABSTRACT: In this paper, wave propagation analysis of an inhomogeneous functionally graded (FG) nanoplate subjected to nonlinear thermal loading is investigated by the means of nonlocal strain gradient theory. The model introduces a nonlocal stress field parameter and a length scale parameter to capture the size effect. Shear deformation effects are taken into account by using a four-variable refined shear deformation plate theory. Nonlinear thermal loading relation is derived by solving a heat conduction problem through the thickness of the nanoplate. Material properties are assumed to be temperature-dependent and change gradually through the thickness via Mori–Tanaka model. The governing equations are developed employing Hamilton's principle. The results of present work are validated by comparing to those of previous works. The effects of various parameters such as nonlocal parameter, length scale parameter, gradient index and temperature distribution on the wave dispersion characteristics of size-dependent nanoplates have been studied.

Topi Korhonen, “Modeling the Mechanical Behavior of Carbon Nanostructures”, Ph.D. dissertation, Dept. of Mathematics and Science, Physics, University of Jyväskylä

ABSTRACT: Low-dimensional nanostructures are expected to have vast number of applications in the future. Particularly large amount of research has been invested in the atom-thick carbon membrane called graphene, which has become popular due to its unique electronic and mechanical properties. This thesis presents studies of the mechanical and electromechanical properties of several different types of graphene nanostructures. In addition, short detours are performed in order to study the elasticity of gold nano-structures and topology effects
in graphene nanoribbons. The research is performed by using several different simulation methods. In simulations the system parameters and environment can be chosen at will, giving large amount of control over the studied phenomena. This control, and the access to different system parameters, can give insight into system properties that are hard to deduce from experiments alone. The reliability of the simulations depends on the used methods that are thus chosen according to the level of desired accuracy. Large-scale deformations of graphene nanostructures are studied by classical force field methods. We present and explain edge rippling due to compression at graphene nanospiral perimeters when the nanospiral is elongated above a certain threshold. Further insight into the elastic behavior of these nanospirals is obtained by continuum elasticity modeling. For graphene nanoribbons we explain two previous experimental observations, an abrupt buckling under in-plane bending and the stability of curved graphene nanoribbon geometry on a smooth substrate. Buckling is predicted by simple model and is found to be due to the compression at the inner edge of the curved graphene nanoribbon. The stability of the curved geometry is shown to be due to registry effects between the graphene nanoribbon and the substrate, and the buckling to be a mechanism that releases the excess compression from the graphene nanoribbon edge. Moreover, intricate interlayer sliding patterns under peeling of multilayer graphene stacks are discussed and we show that such stacks are likely to recover after the peeling force is released. Via electronic structure calculations we find a connection between the graphene nano-spiral elongation and electronic structure and show that for graphene nanospirals the interlayer interactions play major part in the electronic structure near the structural equilibrium. Moreover, for graphene nanoribbons we study the effect of M"obius topology by using the revised periodic boundary conditions in a novel way. By the introduced method we are able to impose M"obius topology into flat graphene nanoribbons enabling the study of the role of the topology alone. We conclude that the topology affects only graphene nanoribbons with small length-to-width ratios. Finally we consider the temperature dependence of the bending rigidity of a two-dimensional gold nanostructure realizable in suitably sized graphene pores. The underlying motivation for most of the performed studies is the connection between the mechanical deformations and the electronic structure, which is discussed qualitatively even for large systems, where explicit electronic structure calculations are not possible.

Hongli Chen, Youming Zhang, Baile Zhang and Lei Gao, “Optical bistability in a nonlinear-shell-coated metallic nanoparticle”, Scientific Reports, Vol. 6, Article Number 21741, 2016, DOI: 10.1038/srep21741

ABSTRACT: We provide a self-consistent mean field approximation in the framework of Mie scattering theory to study the optical bistability of a metallic nanoparticle coated with a nonlinear shell. We demonstrate that the nanoparticle coated with a weakly nonlinear shell exhibits optical bistability in a broad range of incident optical intensity. This optical bistability critically relies on the geometry of the shell-coated nanoparticle, especially the fractional volume of the metallic core. The incident wavelength can also affect the optical bistability. Through an optimization-like process, we find a design with broader bistable region and lower threshold field by adjusting the size of the nonlinear shell, the fractional volume of the metallic core, and the incident wavelength. These results may find potential applications in optical bistable devices such as all-optical switches, optical transistors and optical memories.


ABSTRACT: The aim of this paper is to analyse the influence of the nonlinear modal coupling on the nonlinear vibrations of a simply supported cylindrical panel excited by a time dependent transversal load. The cylindrical panel is modeled by the Donnell nonlinear shallow shell theory and the lateral displacement field is based on a
perturbation procedure. The axial and circumferential displacement are described in terms of the obtained lateral displacement, generating a precise low-dimensional model that satisfies all transversal boundary conditions. The discretized equations of motion in time domain are determined by applying the standard Galerkin method. Various numerical techniques are employed to obtain the cylindrical panel resonance curves, bifurcation scenario and basins of attraction. The results show the influence of geometry and the nonlinear modal coupling on the nonlinear response of the cylindrical panel.


ABSTRACT: The numerical structural analysis schemes are extensively developed by progress of modern computer processing power. One of these approximate approaches is called "dynamic relaxation (DR) method." This technique explicitly solves the simultaneous system of equations. For analyzing the static structures, the DR strategy transfers the governing equations to the dynamic space. By adding the fictitious damping and mass to the static equilibrium equations, the corresponding artificial dynamic system is achieved. The static equilibrium path is required in order to investigate the structural stability behavior. This path shows the relationship between the loads and the displacements. In this way, the critical points and buckling loads of the non-linear structures can be obtained. The corresponding load to the first limit point is known as buckling limit load. For estimating the buckling load, the variable load factor is used in the DR process. A new procedure for finding the load factor is presented by imposing the work increment of the external forces to zero. The proposed formula only requires the fictitious parameters of the DR scheme. To prove the efficiency and robustness of the suggested algorithm, various geometric non-linear analyses are performed. The obtained results demonstrate that the new method can successfully estimate the buckling limit load of structures.

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ABSTRACT: Purpose – The purpose of this paper is to study the nonlinear dynamic analysis of triangular and quadrilateral membrane elements with in-plane drilling rotational degree of freedom.
Design/methodology/approach – The nonlinear analysis is carried out using the updated co-rotational Lagrangian description. In this purpose, in-plane co-rotational formulation that considers the in-plane drilling rotation is developed and presented for triangular and quadrilateral elements, and a tangent stiffness matrix is derived. Furthermore, a simple and effective in-plane mass matrix that takes into account the in-plane rotational inertia, which permit true representation of in-plane vibrational modes is adopted for dynamic analysis, which is carried out using the Newmark direct time integration method.
Findings – The proposed numerical tests show that the presented elements exhibit very good performances and could return true in-plane rotational vibrational modes. Also, when using a well-chosen co-rotational formulation these elements shows good results for nonlinear static and dynamic analysis. Originality/value – Publications that describe geometrical nonlinearity of the in-plane behaviour of membrane element with rotational dof are few, and often they are based on the total Lagrangian formulation or on the rate form. Also these elements, at the author knowledge, have not been extended to the nonlinear dynamic analysis. Thus, an appropriate extension of triangular and quadrilateral membrane elements with drilling rotation to nonlinear dynamic analysis is required.
ABSTRACT: We present formulations for compressible and incompressible hyperelastic thin shells which can use general 3D constitutive models. The necessary plane stress condition is enforced analytically for incompressible materials and iteratively for compressible materials. The thickness stretch is statically condensed and the shell kinematics are completely described by the first and second fundamental forms of the midsurface. We use C1-continuous isogeometric discretizations to build the numerical models. Numerical tests, including structural dynamics simulations of a bioprosthetic heart valve, show the good performance and applicability of the presented methods.

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ABSTRACT: We model in closed form a proven bistable shell made from a magnetic rubber composite material. In particular, we incorporate a non-axisymmetrical displacement field, and we capture the nonlinear coupling between the actuated shape and the magnetic flux distribution around the shell. We are able to verify the bistable nature of the shell and we explore its eversion during magnetic actuation. We show that axisymmetrical eversion is natural for a perfect shell but that non-axisymmetrical eversion rapidly emerges under very small initial imperfections, as observed in experiments and in a computational analysis. We confirm the non-uniform shapes of shell and we study the stability of eversion by considering how the landscape of total potential and magnetic energies of the system changes during actuation.

References listed at the end of the paper:

ABSTRACT: Micropolar thin shallow shells are considered, the elastic deflections are comparable to their thickness and at the same time are small in relation to the basic size, at the same time as the small angles of relation of the normal to the middle surface before deformation, and their free rotations. Thus, in the deformation tensor and bending-torsion tensor takes into account not only linear but also the nonlinear terms in the gradients of displacements. The hypothesis method is developed and on this base static applied theory of micropolar elastic flexible shallow shells are constructed. Some practical problems are solved.

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Samvel Sargsyan (Department of Physics and Mathematics, Gyumri State Pedagogical Institute, Gyumri, Armenia), “Geometrically nonlinear theory of statics and dynamics of micropolar elastic thin plates and sloping shells”, ZIV ICTAM, Montreal, Canada, 21-26 August, 2016

ABSTRACT: General geometrically nonlinear theory of statics and dynamics of single and multilayered micropolar elastic thin plates and sloping shells is introduced in this paper. Variation approach is developed for the constructed theory and specific problems of statics, stability and vibration for rectangular and circular plates and sloping shells are studied, specific properties of micropolar material are revealed.

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Kai Luo, Chang Liu, Qiang Tian and Haiyan Hu (Beijing Institute of Technology, MOE, Key Laboratory of Dynamics and Control), “Nonlinear static and dynamic analysis of hyper-elastic thin shells via the absolute nodal coordinate formulation”, Nonlinear Dynamics, Vol. 85, No. 2, pp 949-971, 2016

DOI: 10.1007/s11071-016-2735-z

ABSTRACT: A new hyper-elastic thin shell finite element of absolute nodal coordinate formulation (ANCF) is proposed based on the Kirchhoff–Love theory. Under the condition of plane stress, a two-dimensional compressible neo-Hookean constitutive model and a two-dimensional incompressible Mooney–Rivlin constitutive model for the thin shell element of ANCF are derived. Based on the continuum mechanics, the efficient analytical formulations of the internal forces and their Jacobians of the shell element are also deduced. Then, a computation methodology for performing the nonlinear static analysis including buckling analysis of hyper-elastic thin shells is proposed. To accurately track the load–displacement equilibrium path in the analysis, the arc-length method is used to solve the nonlinear algebraic equations. The dynamics of the thin shells made of different hyper-elastic materials is also comparatively studied by using the generalized-alpha algorithm.
Finally, six case studies are given to validate the proposed hyper-elastic thin shell element and computation methodology. The influence of different constitutive models on the static and dynamic responses of thin shells is revealed.

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ABSTRACT: Based on nonlinear dynamic theory of thin shells and the basic large deflection equations of the shallow reticulated spherical thin shells, regarding large deflection as the initial deflection, the basic nonlinear dynamic equations are established by using the modified iteration method to obtain the analytical solution of quadratic approximation under the boundary conditions of clamped edges. The tension is obtained according to the displacement model that satisfies the same boundary conditions. The equation of the balanced surface is obtained by set the first variation of the dynamic potential to be zero. Then, the systems of equations of the corresponding bifurcation point set are given in terms of catastrophic theory and the whole stability of the shallow thin spherical shells is discussed. In addition, the sketch map of the corresponding bifurcation point set of the balanced surface is also given in this paper.

Alexis Kordolemis and Paul M. Weaver (ACCIS, Dept. of Aerospace Engineering, University of Bristol, UK), “Axially loaded pretwisted nonlinear thin plates: A strain gradient analogy”, XXIV ICTAM, 21-26 August, 2016, Montreal, Canada
ABSTRACT: In the present work a pre-twisted thin plate subjected to axial loading is analysed. The analysis is conducted within the framework of linear elasticity assuming that the plate undergoes large deformations associated with small strains, i.e. the generalised Hookes law is utilised. The problem is attacked under different conceptual perspectives. First, a classical structural theory is employed where the effect of warping of the non-circular cross section of the plate is introduced. Adopting an energy variational statement the governing partial differential equation is explicitly derived. Secondly, the problem is formulated in terms of second gradient elasticity theory involving only one material length parameter, in addition to the two classical Lame constants. It is shown, by the analogy, that the material length parameter can be expressed on physical ground through the geometrical aspects of the plate and the loading providing a thorough insight of the role of micro-structure.

PARTIAL ABSTRACT: Paper folding is found across cultures for both aesthetic and functional purposes, with its most widely recognized exponent being the ancient art form of origami. More recently, there has been an upsurge of interest for translating origami designs into mathematics, natural sciences, engineering, and architecture. Across these different fields, origami is becoming a fountain of inspiration for new reconfigurable and multifunctional materials and structures. However, the use of origami designs as engineering elements is typically compromised by . . .

PARTIAL ABSTRACT: We explore the natural tendency of fluid interfaces to destabilize into pattern forming instabilities in order to create new fabrication pathways for structured materials. Specifically, we harness the Rayleigh-Taylor instability in thin elastomeric films (PDMS) that evolve into regular drop arrays, which are eventually frozen in time as the polymer cures. Tuning the properties of the polymer enables us to tailor the fabricated shapes. Upon curing, the resulting structures can be peeled off from the substrate for a variety of applications. For ...

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ABSTRACT: We study the effect of a dimplelike geometric imperfection on the critical buckling load of spherical elastic shells under pressure loading. This investigation combines precision experiments, finite element modeling, and numerical solutions of a reduced shell theory, all of which are found to be in excellent quantitative agreement. In the experiments, the geometry and magnitude of the defect can be designed and precisely fabricated through a customizable rapid prototyping technique. Our primary focus is on predictively describing the imperfection sensitivity of the shell to provide a quantitative relation between its knockdown factor and the amplitude of the defect. In addition, we find that the buckling pressure becomes independent of the amplitude of the defect beyond a critical value. The level and onset of this plateau are quantified systematically and found to be affected by a single geometric parameter that depends on both the radius-to-thickness ratio of the shell and the angular width of the defect. To the best of our knowledge, this is the first time that experimental results on the knockdown factors of imperfect spherical shells have been accurately predicted, through both finite element modeling and shell theory solutions.

References listed at the end of the paper:


ABSTRACT: This paper intended to explore the aspects of pipe bending for composites material. In current industries such as oil and gas, petro-chemical, and aerospace needs very high quality bended pipes without any defects. There are many different methods for pipe bending. The pipes and tubes can bend in one of several methods depending on what requirement is to use the bend pipes and tubes. So the comparison between pipe bending methods needs to be an identified. In pipe bending process several defects occurs such as Ovality, wrinkling, and wall thinning and thickening. Purpose of this study is to comparing the available methods and finding out the suitable outcomes for the given circumstances.

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ABSTRACT: Nowadays composite pipelines are being widely used in the offshore oil and gas industry. However, composite pipelines are often subjected to combined bending and tension during the reeling process and offshore installations, which may lead to elliptical buckling due to the Brazier effect and material failure. The mechanical behaviour of reinforced thermoplastic pipe (RTP) under combined bending and tension is hence a significant parameter for the design of composite pipelines, and it was thoroughly investigated in this paper. Based on the nonlinear ring theory, mechanical behaviour of RTP under combined bending and tension was analysed. The formulations are based on the principle of virtual work and are solved by a numerical solution. To verify the accuracy of the theoretical formulations, an ABAQUS model was employed to simulate the buckling response of RTP under combined bending and tension. The results obtained by the theoretical method and ABAQUS simulation show excellent consistency. Furthermore, a series of sensitivity analyses were presented to highlight the influencing parameters under combined bending and tension. The proposed method will be helpful for RTP's engineering applications.

ABSTRACT: The collapse and buckling behaviors of reinforced thermoplastic pipe (RTP) under external pressure are studied in this paper. A theoretical model which includes axial and shear deformation is applied based on the model initially proposed by Kyriakides and his coworkers. Simulation of the reinforced layers of RTP is simplified using equivalent stiffness method. The load-displacement relation of RTP under external pressure is obtained based on the theoretical model. A three-dimensional (3D) finite element model (FEM) is also built to simulate the response of RTP using the software ABAQUS. Numerical simulation results from ABAQUS are similar to those from the theoretical model. Besides, external pressure tests for RTP are carried out and the test results are compared with the analyzed results. Finally, factors that influence the external pressure capacity are also studied.

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ABSTRACT: Flexible pipes can be used as risers, jumpers, and flowlines that may be subject to axial forces and out-of-plane bending motion due to operational and environmental loading conditions. The tensile armor
wires provide axial stiffness to resist these loads. Antibirdcaging tape is used to provide circumferential support and prevent a loss of stability for the tension armor wires, in the radial direction. The antibirdcaging tape may be damaged where a condition known as “wet annulus” occurs that may result in the radial buckling (i.e., birdcaging mechanism) of the tensile armor wires. A three-dimensional continuum finite element (FE) model of a 4 in. flexible pipe is developed using ABAQUS/IMPLICIT software package. As a verification case, the radial buckling response is compared with similar but limited experimental work available in the public domain. The modeling procedures represent an improvement over past studies through the increased number of layers and elements to model contact interactions and failure mechanisms. A limited parameter study highlighted the importance of key factors influencing the radial buckling mechanism that includes external pressure, internal pressure, and damage, related to the percentage of wet annulus. The importance of radial contact pressure and shear stress between layers was also identified. The outcomes may be used to improve guidance in the engineering analysis and design of flexible pipelines and to support the improvement of recommended practices.


ABSTRACT: A study is presented of the post-buckling behaviour and imperfection sensitivity of complete spherical shells subject to uniform external pressure. The study builds on and extends the major contribution to spherical shell buckling by Koiter in the 1960s. Numerical results are presented for the axisymmetric large deflection behaviour of perfect spheres followed by an extensive analysis of the role axisymmetric imperfections play in reducing the buckling pressure. Several types of middle surface imperfections are considered including dimple-shaped undulations and sinusoidal-shaped equatorial undulations. Buckling occurs either as the attainment of a maximum pressure in the axisymmetric state or as a non-axisymmetric bifurcation from the axisymmetric state. Several new findings emerge: the abrupt mode localization that occurs immediately after the onset of buckling, the existence of an apparent lower limit to the buckling pressure for realistically large imperfections, and comparable reductions of the buckling pressure for dimple and sinusoidal equatorial imperfections.

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ABSTRACT: The Eurocode 3 concerning thin-walled steel members divides members subjected to compression into four classes, considering their ductility. The representatives of the class C4 are short bars, for which the load-capacity corresponds to the maximum compression stresses less than the yield stress. There are bars prone to local buckling in the elastic range and they do not have a real post-elastic capacity. The failure at ultimate stage of such members, either in compression or bending, always occurs by forming a local plastic mechanism. This fact suggests the possibility to use the local plastic mechanism to characterise the ultimate strength of such members. The present paper is based on previous studies and some latest investigations of the
authors, as well as the literature collected data. It represents an attempt to study the plastic mechanisms for members in eccentric compression about minor axis and the evolution of plastic mechanisms, considering several types of lipped channel sections.

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“Fatigue life of postbuckled structures with indentation damage”, ECCM17: 17th European Conference on Composite Materials, Munich, Germany, 26-30 June 2016

ABSTRACT: The fatigue life of composite stiffened panels with indentation damage was investigated experimentally using single stringer compression specimens. Indentation damage was induced on one of the two flanges of each stringer. The experiments were conducted using advanced instrumentation, including digital image correlation, passive thermography, and in-situ ultrasonic scanning. Specimens with initial indentation damage lengths of 32 mm to 56 mm were tested quasi-statically and in fatigue, and the effects of cyclic load amplitude and damage size were studied. A means of comparison of the damage propagation rates and collapse loads based on a stress intensity measure and the Paris law is proposed.
References listed at the end of the paper:


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ABSTRACT: Thin-walled steel tube/bamboo-plywood composite hollow columns (SBCCs) have excellent physical and mechanical properties. The simple cross section of this composite makes it simple to process and suitable for industrial production. In this paper, axial and eccentric compression tests were conducted on 21 specimens to study the failure characteristics and maximum bearing capacity of this composite. The test results showed that compressive failure in an SBCC is primarily characterized by damage from glue failure in the matrix interface at the end of the column, internal damage of the bamboo-plywood material, damage from glue failure on the tension side in the middle of the column, and buckling damage to the plywood material on the compressive side. The maximum bearing capacity of the SBCC generally increased with the net cross-sectional area of the bamboo and decreased with the slenderness ratio and eccentricity. The hollow ratio reduced the slenderness ratio of the test specimens with the same net cross-sectional area of the bamboo and increased the critical compressive load, which significantly improved the compressive load capacity, as was reflected in the slenderness ratio. Finally, a model was formulated based on a non-linear regression analysis of the experimental data. The model was used to determine the allowable compressive capacity of an SBCC to provide guidance for engineering applications.

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ABSTRACT: Experimental and numerical investigations on three large diameter concrete-filled high strength steel tubular (CFHSST) stub columns under axial compression were performed. The three large size steel tubes had the same dimension in the test. The outer diameter was approximately 550 mm, the length was approximately 1000 mm, and the thickness was approximately 16 mm. The steel tubes were made of high strength steel Q550 and filled with C30 concrete. A 40,000 kN press machine was adopted to apply the required axial compression to the three specimens. It was found that the load-displacement curves of the three concrete-filled high strength circular steel tubular stub columns were notably close to each other, and the ultimate capacities were approximately 30,000 kN. Finite element analysis (FEA) was performed to analyze the stub columns, and the FEA results are consistent with the experimental results. The formulas from three types of design codes were used to calculate the column loading capacity, and the calculation results were compared with the experimental results. The results were close to the experimental results. The EC4 design code gives the most accurate estimations, with discrepancy less than 4% being observed.

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ABSTRACT: This paper demonstrates the importance of including non-linearities in the design of textile reinforced concrete (TRC) shells. By two cases, the influence on the buckling load of considering geometrical non-linearity and material non-linearity, but also of considering geometrical imperfections is examined. For stiff shells mainly in compression, the buckling load is significantly reduced by including imperfections, analogue to observations with steel reinforced concrete shells. For shells with a low stiffness, experiencing large deformations, a non-linear analysis is essential and the buckling load is mainly reduced by considering material non-linearity. Conclusively, the shape and boundary conditions of thin TRC shells indicate which parameters should be taken into account in their design.

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“Two-level optimization for a new family of cold-formed steel lipped channel sections against local and distortional buckling”, Thin-Walled Structures, Vol. 108, pp 64-74, November 2016
DOI: 10.1016/j.tws.2016.07.004
ABSTRACT: The objective of this paper is to provide the development of a new algorithm that produces a family of minimal weight cold-formed steel lipped channels with the smallest number of individual cross-sections (family size) that are still capable of covering the current engineering design demands as commonly found in light steel framing. Current research in cold-formed steel optimization has largely sought optimal cross-sections for single members under a single applied action. In this paper, the optimization effort is extended to a broad set of axial (P) and bending (M) demands. A two-level optimization framework is
proposed: level one focuses on member optimization of the P-M demand space as derived from current commercially available lipped channel sections in the United States; while level two focuses on the selection of a new family of optimal lipped channel sections that have the same efficiency in covering the design space, but utilize a minimal family size. As the focus of the effort is on the two-level optimization the cross-section optimization is simplified in this case to lipped channels against local and distortional buckling only; however the adopted algorithms are readily extensible. The results show that a new family of shapes with only 12 sections can achieve the same or better performance as the 108 sections commercially available in the United States. The developed family of shapes provides a direct demonstration of the potential for optimization to improve cold-formed steel manufacturing. In the future, the first-level member optimization will include new cross-section shapes, e.g., sigma sections, as well as global buckling, and will be performed along with the second family-level optimization to demonstrate additional potential benefits.

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“Influence of imperfection distributions for cylindrical stiffened shells with weld lands”, Thin-Walled Structures, Vol. 93, pp 177-187, August 2015, DOI: 10.1016/j.tws.2015.03.017
ABSTRACT: The influence of imperfection distributions considering manufacturing characteristics on the buckling response of stiffened shells has not been satisfactorily understood. Stiffened shells with three types of weld lands were established, including axial weld lands, circumferential and sequential axial weld lands, as well as staggered axial weld lands. As a concept of equivalent imperfection, dimple-shape imperfections produced by perturbation loads were adopted to substitute the measured imperfections, in order to reduce experimental and computational costs. Firstly, the influence of imperfection positions on the collapse load was examined for single perturbation load. Then, the influence of imperfection distributions was investigated for multiple perturbation load based on Monte Carlo Simulation. Finally, detailed comparison of three types of weld lands was made from the point-of-view of load-carrying capacity and imperfection sensitivity. Results can provide general instructions about imperfection-critical areas for axially compressed stiffened shells, which are particularly crucial for the manufacturing process.

ABSTRACT: This paper presents a theoretical study on both local and post-local buckling behaviors of partially encased composite (PEC) columns, made with thin-walled, welded H-shapes and concrete encasement between flanges; transverse links are welded between flange tips to reinforce the section. Nonlinear finite element analysis (FEA) was conducted to predict buckling behaviors and strengths of steel shapes. Finite element models were verified through a comparison of FEA results with experimental results. A parametric study was then performed using validated FEA models to investigate the effect of several parameters on the buckling behavior of PEC columns. The residual stress of steel shapes, which is introduced through welding process, was discussed in detail. Based on the parametric study, a series of expressions was developed for predicting critical strength, post-buckling strength, as well as the entire stress-strain relationship of steel shapes in PEC columns under concentric loading.
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Abstract: This paper presents an experimental study on concrete-filled circular tubes that consisted of seawater and sea sand concrete (SWSSC), stainless steel (SS) tube, carbon fibre reinforced polymer (CFRP) tube, and basalt fibre reinforced polymer (BFRP) tube. A total of 38 stub columns, which included 12 hollow section tubes, 12 fully SWSSC-filled tubes and 14 SWSSC-filled double-skin tubes, with four combinations of inner and outer tubes, were tested under axial compression. Tensile coupon tests and “disk-split” tests were conducted to obtain the material properties of SS, CFRP and BFRP. Ultimate strain of SWSSC-filled tubes and stress-strain curves of the confined concrete were characterised in the study. The effects of some key parameters (e.g., tube diameter-to-thickness ratio, cross-section types, outer tube types, and inner tube types) on the confinement effects were also discussed. Comparisons were made among CFRP, BFRP and glass fibre reinforced polymer (GFRP) in terms of confinement to SWSSC. The capacity prediction formulae previously proposed by the authors for SWSSC filled GFRP tubes were found to be reasonable for estimating the load carrying capacity of SWSSC filled CFRP and BFRP tubes.

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Abstract: The blast response behaviors of curved Steel-Concrete-Steel (SCS) sandwich shells were investigated using nonlinear finite element method. The accuracy of the numerical model was verified against the available field blast test results. The numerical results showed that shear connectors played a vital role in bonding the face plates and concrete core and therefore improving the blast resistant capacity of curved SCS sandwich shell. In addition, different failure modes for the curved SCS sandwich shell under close- and far-field blast loading were observed, i.e., separation of rear plate from concrete core and buckling of face plates for the shell under close- and far-field blast loading, respectively. The effects of rise height (or rise to span ratio) and rear to front plate thickness ratio on the blast responses of curved SCS sandwich shells were also studied. Numerical results showed that the damage of curved SCS sandwich shell could be reduced by increasing rise height and rear to front plate thickness ratio. Moreover, the energy absorption efficiency of concrete core also showed increase with increasing rear to front plate thickness ratio.

Partial Abstract: An imperfection sensitivity analysis of thin-walled cold-formed steel members in compression is presented. The members under investigation are perforated steel pallet racks in compression of different lengths. The analysis is based on a finite element implementation of the Koiter method coupled with Monte Carlo simulation. It is based on an intensive experimental study carried out at the Politehnica University of Timisoara, which showed a strong interaction of the buckling mode with a significant reduction in the load ...

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ABSTRACT: The imperfection sensitivity of the postbuckling behaviour of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) beams subjected to axial compression is investigated based on the first-order shear deformation beam theory with a von Kármán geometric nonlinearity. The material properties of FG-CNTRC are assumed to vary in the beam thickness direction and are estimated according to the extended rule of mixture. The differential quadrature method is employed to discretize the governing differential equations and the modified Newton-Raphson iterative technique is used to obtain the postbuckling equilibrium paths of FG-CNTRC beams with various imperfections. Parametric studies are carried out to examine the effects of imperfection modes, half-wave number, location, and amplitude on the postbuckling response of beams. The influences of CNT distribution pattern and volume fraction, boundary conditions, and slenderness ratio are also discussed. Numerical results in graphical form show that the postbuckling behaviour is highly sensitive to the imperfection amplitude. The imperfection mode and its half-wave number also moderately affect the imperfection sensitivity of the postbuckling response, whereas the effects of other parameters are much less pronounced.


ABSTRACT: Influence of non-uniform heating on critical buckling temperature of an aluminium beam has been investigated experimentally with the help of a novel experimental set-up developed in-house. Non-linear finite element analysis, considering the initial geometric imperfection, has been carried out to compare the experimentally obtained typical load-deflection curve. The linear critical buckling temperature predicted numerically are validated with analytical solutions. Experimental results revealed that critical buckling temperature of the non-uniformly heated beam greatly differs from the uniformly heated beam. It is also observed that the location of heat source and resulting non-uniform temperature variation influences the critical buckling temperature significantly.

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ABSTRACT: This paper has studied on the nonlinear buckling and postbuckling of a eccentrically stiffened functionally graded thin elliptical cylindrical shells surrounded on elastic foundations in thermal environment. Material properties are graded in the thickness direction according to a Sigmoid power law distribution (s-FGM) in terms of the volume fractions of constituents with metal - ceramic - metal layers. The elliptical cylindrical shells have stiffeners in two directions (longitudinal and transversal) on the external surface and inside surface surrounded on elastic foundations. The typical point in the study is both elliptical cylindrical shells and stiffeners having temperature-dependent properties are deformed under temperature simultaneously, leading to the equation to determine buckling thermal loads with both sides that are dependent on temperature, so the iterative algorithms are proposed to numerical technique in this case. The equilibrium and compatibility equations for the moderately elliptical cylindrical shells are derived by using the classical shell theory (CST) taking ito account both geometrical nonlinearity in von Karman sense and initial geometrical imperfection. By applying the Galerkin method and using a stress function, the effects of material and geometrical properties, temperature-dependent material properties, elastic foundations and stiffeners on the buckling and postbuckling loading capacity of eccentrically stiffened FGM elliptical cylindrical shells in thermal environments are studied simultaneously for first time.

S. Pirmohammad and S. Esmaeili Marzdasthi (Department of Mechanical Engineering, Faculty of Engineering, University of Mohaghegh Ardabili, Ardabil 179, Iran), “Crushing behavior of new designed multi-cell members subjected to axial and oblique quasi-static loads”, Thin-Walled Structures, Vol. 108, pp 291-304, November 2016, DOI: 10.1016/j.tws.2016.08.023

ABSTRACT: A new design of multi-cell devices was proposed in this paper, and evaluated in terms of crashworthiness capability under quasi-static axial and oblique (9°, 18° and 27°) loading. The structures studied in the present paper were single and multi-cell members made up of two straight columns with the same shape of cross-section connected together by several ribs. They included several sectional configurations such as triangle, square, hexagon and circle with different scales (i.e. 0, 0.25, 0.5, 0.75 and 1). Finite element code LS-DYNA was used to simulate the crashworthiness behavior of the proposed members under quasi-static loads. Several crashworthiness indicators including SEA, $F_{max}$ and CFE were obtained at different crushing angles for all the columns, and a powerful decision making method known as COPRAS was then implemented to choose the best energy absorber with the criteria of having higher specific energy absorption and lower initial peak force. From the COPRAS calculations, the multi-cell members with inner tube and scale number of 0.5 were selected as the better energy absorbers, and the column with circular cross-section was also found to be the best energy absorbing device.

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ABSTRACT: An experimental program including study has been conducted to investigate buckling behavior of 7A04 high-strength (HS) aluminum alloy columns under axial compression, in which 42 L-shaped extruded specimens were designed and tested. The specimens involved two sections and seven slenderness ratios varying from 15 to 100. The test results were compared with design results in accordance with American Aluminum Design Manual, GB 50429-2007 and Eurocode 9. A finite element (FE) model of the tested specimens under axial compression has been developed by using general finite element software ANSYS, and was verified by using the test results reported herein and other experimental results presented in the literature. By using this FE model, an extensive body of parametric analyses were conducted to clarify the effects of width-to-thickness ratio of angle legs, initial imperfections and material strengths on the buckling resistance of the 7A04 angle columns. Based on the test and FE analyses results, a modified design method was proposed for predicting the buckling resistance of 7A04 high-strength aluminum alloy columns more accurately.

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ABSTRACT: This paper presents the experimental results of axial compression tests on concrete-filled bimetallic tubes (CFBT). The cross section of the bimetallic tube is composed of an outer layer made of stainless steel and an inner layer made of carbon steel. A total of 12 specimens with a circular cross section were tested under axial compression. The test parameters included the thickness of the stainless steel tube layer ($t_{ss} = 0.6–1.36$ mm) and the compressive strength of the infilled concrete ($f_{cu} = 21.1–42.8$ MPa). Test results showed that, the two layers of the bimetallic tube worked well together, and the CFBT specimens exhibited ductile characteristics. The influence of the parameters on the failure mode, load versus deformation relationship, axial compressive strength, and strain development of the tested specimens were investigated. Finally, the feasibility of three existing design codes for predicting the axial compressive strength of CFBT under axial compression was evaluated.

Amir R. Shokrzadeh and Mohammad R. Sohrabi (Department of Civil Engineering, University of Sistan and Baluchestan, P.O. Box 98155-987, Zahedan, Sistan and Baluchestan, Iran), “Buckling of ground based steel tanks subjected to wind and vacuum pressures considering uniform internal and external corrosion”, Thin-Walled Structures, Vol. 108, pp 333-350, November 2016, DOI: 10.1016/j.tws.2016.09.007

ABSTRACT: Corrosion is one of the significant degradation processes, which occurs in aboveground oil storage tanks. A numerical study is performed to investigate the effects of internal and external corrosion on the buckling behavior of three steel cylindrical tanks with different height to diameter ratios, subjected to both wind and vacuum pressures. Internal corrosion is considered as a time dependent uniform thinning of the roof plate, roof supporting structure and upper part of the wall. Furthermore, the corrosion of the wall at the lower parts of the tank being in contact with residual water and sludge is analyzed. At the same manner, completely external corrosion of the roof and wall plates is considered in numerical analysis. It is found that the buckling load is markedly reduced with thinning of the shell for upper part and whole corrosion cases, irrespective of the loading
In addition, the buckled regions of the tanks are suddenly displaced toward the top of the shell during upper part corrosion process. Contrary to upper and whole corrosion cases, the critical load of tanks is only marginally affected by the corrosion of lower part of the wall. In the last part of this research, the analytical investigation results of a tank (TK-2047) that failed during discharge process in an oil plant are reported.

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ABSTRACT: Concrete-filled double-skin steel tubes (CFDSTs) find increasing use as bridge piers and building columns. This paper treats the impact response of such columns using numerical simulations. The modelling techniques are validated using experimental results to establish the capability of the numerical model to capture the impact response and failure modes of the column. The validated numerical model was used to carry out a parametric study on the effects of several structure-related parameters on the impact response of the CFDST columns. The findings of this paper can be used to develop appropriate design information for CFDST columns under lateral impact loading.

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ABSTRACT: The Single Perturbation Load Approach (SPLA) is a promising deterministic procedure on the basis of mechanical considerations to determine reasonable design loads for cylindrical shells in axial compression. In this paper, two main issues are identified that should be understood better in order to appreciate the potential and the limits of application of the SPLA. Firstly, the question whether a single perturbation load in general represents a “worst case” imperfection is addressed. Secondly, the influence of the stiffness properties of the shell on the quality of the SPLA predictions is studied. Finally, an indicator is suggested which identifies, based on the cylinder stiffness properties, whether the SPLA is conservative for a considered shell or not.

Ali Rezaiefar and Khaled Galal (Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Québec, Canada H3G 1M8), “Structural design of stiffened plates of industrial duct walls with relatively long panels undergoing large deformations”, Thin-Walled Structures, Vol. 108, pp 406-415, November 2016, DOI: 10.1016/j.tws.2016.08.028

ABSTRACT: Structural design of stiffened plates of the walls of rectangular-sectioned industrial ducts is currently based on the strip method that follows the linear flexural beam theory. The current design method assumes that the displacements generated in the plate are small and the membrane forces that generate in the plate are negligible. This paper addresses the current design method and discrepancies associated with it to present a new design approach that takes into account the effects of large displacements on the load-
deformation and load-stress behavior of stiffened plates. Two different sets of formulas are presented based on Finite Element analysis of rectangular plates with relatively long aspect ratios that estimate the maximum stress and deformation in the typical and edge panels of stiffened plates. These formulas are then used to establish design equations for stiffened plates. Based on the findings of this paper, a reduction of 30–40% in the plate thickness could be achieved if the new design approach is selected over the conventional design method.

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ABSTRACT: This paper investigates the free vibrations of a shell made of n cone segments joined together. The governing equations of the conical shell were obtained by applying the Sanders shell theory and the Hamilton principle. Then, these governing equations are solved by using the power series method and considering a displacement field which is harmonic function about the time and the circumferential coordinate. Using the boundary conditions of the two ends of the shell and the continuity conditions at the interface section of shell segments, and solving the eigenvalue problem, the natural frequencies and the mode shapes are obtained. Very good agreements exist between the analytical results of the present study and the available results in the literature. Also, a shell made of three cone segments is fabricated and experimentally tested. The analytical and experimental results are coincident very well. Finally, some examples are solved in order to study the effects of geometrical parameters as cone angles on modal parameters. Also, as a practical example, natural frequencies of a bell are determined using the formulation presented.

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“Imperfection-insensitive design of stiffened conical shells based on equivalent multiple perturbation load approach”, Composite Structures, Vol. 136, pp 405-413, February 2016, DOI: 10.1016/j.compstruct.2015.10.022

ABSTRACT: Stiffened conical shells in launch vehicles are very sensitive to various forms of imperfections. As a type of equivalent imperfections, several perturbation load approaches are used to investigate the influence of dimple-shape imperfections on the load-carrying capacity of stiffened conical shells. Firstly, the effect of axial location of dimple is examined by single perturbation load approach (SPLA), since the stiffness of stiffened conical shells varies along axial direction. Then, worst multiple perturbation load approach (WMPLA) is employed to find the lower bound of the collapse load of stiffened conical shells, and also provides the knowledge to determine the number of dimples in the multiple perturbation load approach (MPLA). After that, the optimization of stiffened conical shells for imperfection-insensitive design is carried out, where the equivalent MPLA is adopted during the optimization process to reduce the computational cost. Illustrative example indicates that stiffened conical shells exhibit more complicated imperfection sensitivity compared to cylindrical shells, and the proposed optimization framework can find an imperfection-insensitive design under structural weight constraint in an efficient manner.

ABSTRACT: A thin linearly elastic shell made of heterogeneous anisotropic material is studied. The general anisotropy described by 21 elastic moduli is examined. The material may be functionally graduated or multi-layered. The asymptotic expansions in powers of the relative shell thickness of the three-dimensional elasticity equations are used to deliver the two-dimensional shell model. In the zeroth-order approximation the model of 8th differential order is obtained. The asymptotic precision of this model is the same as the precision of the classic Kirchhoff–Love model for isotropic shell. Influence of the elastic moduli variation in the thickness direction is examined. As an example the Donnell system for shallow shells is presented, and this system is used to discuss the free transversal shell vibrations spectrum.

References listed at the end of the paper:
ABSTRACT: Stiffened shells in launch vehicles are very sensitive to various forms of imperfections. In this study, the imperfection sensitivity of a 4.5 m diam isogrid stiffened shell under axial compression is investigated. The measured imperfection, NASA SP-8007 and several types of assumed imperfections, including eigenmode-shape imperfection and dimple-shape imperfections (produced by the single perturbation load approach (SPLA) and worst multiple perturbation load approach (WMPLA)), are introduced into FE model to predict the knockdown factors (KDFs), respectively. Then, the buckling test of this full-scale stiffened shell under axial compression is carried out to validate the above numerical approaches. It can be found that the KDF predicted by the WMPLA is very close to the test results, while the ones predicted by eigenmode-shape imperfection and NASA SP-8007 are extremely conservative. Besides, the measured imperfection and other assumed imperfections are proven to be risky, because these methods overestimate the actual load-carrying capacity. Finally, it can be concluded that the WMPLA is a potential and efficient approach to predict KDFs in the design stages for future launch vehicles.

References listed at the end of the paper:


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ABSTRACT: By employing refined beam theories, free vibration analysis and tailoring of laminated composite box structures are discussed in this work. Higher-order models are implemented utilizing the Carrera Unified Formulation (CUF), according to which the mechanical variables are expressed in terms of arbitrary expansion of the generalized unknowns. The proposed 1D models have only pure displacement variables, are geometrically consistent and have component-wise capabilities because Lagrange polynomials are used in the framework of CUF to formulate refined kinematics theories. Moreover, since the finite element method is used to interpolate the generalized unknowns, arbitrary anisotropy, geometry and boundary/loading conditions can be considered with no loss of generality. The resulting methodology is exploited to analyse single- and multi-bay composite laminated box beams for aerospace applications. Particular emphasis is given to the parametric study and tailoring of the lamination scheme versus free vibration characteristics for various box structures. Also, the effects of cut-offs are investigated. The numerical results are compared to those from the literature and commercial finite element software tools. The study widely demonstrates the high computational efficiency and the refined capabilities of the proposed CUF-based models, which can be considered as ideal candidates for the detailed tailoring of aerospace composite structures and, possibly, for future implementation into an optimization procedure.

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ABSTRACT: The current slenderness limits in international design codes are often based on certain rotation capacities obtained from plastic bending tests of Concrete Filled Tubes (CFT). In the past, a plastic slenderness limit of $\lambda_s=188$ was obtained by the first author based on a fracture rotation limit of the steel tube. However, such limit may be questionable being brittle and insufficient for plastic design of CFT members, sub-assemblies and frames where adequate strain/deformation ductility is required. The main aims of this paper are to present (i) a new method to determine new ductile slenderness limits suitable for plastic design of structures based on the measured strains in plastic bending tests on CFT; (ii) a closed-form solution for the elastic and inelastic buckling strains of CFT under pure bending using a new simplified energy approach employing the well-known Ritz method. The critical strains obtained from such analysis were used to derive new slenderness limits for CFT; and (iii) finite element modelling of CFT and compare the experimental and numerical moment-rotation responses. The effect of concrete filling on the post-buckling strength of restrained tubes is quantified. The current design rules for unrestrained Circular Hollow Sections (CHS) in steel specifications are also compared with the restrained strength obtained from the tests. Two new compact and yield slenderness limits were derived based on the strength corresponds to the appearance of the plastic ripples during the test. The experimentally obtained and the theoretically derived slenderness limits are compared against the available limits in the design codes and standards. The newly derived compact limit of $\lambda_c=79$ was found in a good agreement with $\lambda_c=72$ specified for CFT in the ANSI/AISC 360-10 specification. However, the new yield limit of $\lambda_y=150$ was found considerably lower than $\lambda_y=254$ for CFT specified in the ANSI/AISC 360-10.

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ABSTRACT: This study aims to find the best cross-sectional shapes of thin-walled columns enduring an oblique impact loading for crashworthiness. For approximating to the shape, spline polynomials are used with four key-points benefitting from the double symmetry of the cross section. Crashworthiness is defined by using a multi-objective function. By using Latin hypercubes design of experiment methodology, the design space is sampled. Based on the finite elements analyses, the objective functions are approximated by adopting radial basis function network. The corresponding Pareto front is found by Non-dominated Sorting Genetic Algorithm II. It is found that plus-sign-like cross-sections have better performance than benchmarks for all objectives.

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ABSTRACT: Industrial steel storage pallets racks represent one of the most economical solutions for storing goods and products when space is limited. This well-recognized convenience is however counter-balanced by a structural response that is generally complex to predict, especially under earthquakes. The design procedures adopted worldwide do not seem to take adequately into account for the key features associated with these structures. From the engineering point of view, racks are designed as moment-resisting steel frames but of an unconventional type because they are characterized by an extensive use of thin-walled cold-formed members.
Furthermore, the overall dynamic response is often greatly affected by a non-negligible deterioration of the joint behavior due to large excursions in the plastic range, with the direct consequence that the load carrying capacity is reduced. In this paper, the well-established non-linear time-history (NLTH) method of analysis is combined with the low-cycle fatigue (LCF) damage approach in order to (1) investigate the damage distribution, (2) assess the residual fatigue life and (3) estimate the effective load-carrying capacity after an earthquake. In particular, key open problems related to the seismic design of racks are identified and the NLTH-LCF procedure is introduced and discussed. Finally, attention is focused on a practical case study related to a medium-rise doubly-entry pallet rack. Reference is made to two recent Italian earthquakes and two models have been adopted to reproduce the cyclic joint behavior of beam-to-column joints allowing for a direct appraisal of its influence on the overall rack response.

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ABSTRACT: The stiffness of the supports has an influence on the buckling modes and buckling loads of the arch. This paper investigates the in-plane nonlinear behavior and stability of shallow circular arches with elastic horizontal supports that are uniformly subjected to a radial load by the principle of virtual work. The three limiting shallowness values and the critical flexibility of the elastic horizontal supports are derived to differentiate the buckling mode. As the flexibilities of the elastic horizontal supports of an arch increase, the buckling load of the arch decreases, and the central radial displacement increases. And the buckling mode of the arch would then be changed from asymmetric bifurcation buckling to asymmetric bifurcation buckling after the occurrence of snap-through buckling. Then, snap-through buckling occurs, and finally, there is no buckling. Then the parameters including rise-to-span ratio($f/L$) and load type are further investigated. An experimental model is designed to verify the analytical results. Finally, a design method for a shallow circular arch with elastic horizontal supports is proposed with the requirement of the elastic-plastic buckling load carrying capacity and the maximum horizontal displacement of the supports for engineering reference.

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ABSTRACT: The purpose of this work is to provide a more complete framework for the development of short-term thermoplastic models to improve the design of liners subjected to external pressure. A device to perform short-term physical collapse buckling tests on HDPE liners to emulate in-service behavior under controlled conditions was designed and constructed. Tests were performed to explore the effect of temperature (in the range of 0–60 °C) on the buckling parameters of a HDPE pipe confined in a steel host pipe. The constitutive model for this material was calibrated from compression and tensile tests, performed at various strain rates and temperatures. The Three Network viscoplastic material constitutive model was adopted to reproduce material behavior. Full 3D FEM simulations of collapse buckling tests were conducted and validated against
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ABSTRACT: This paper describes a test program on a wide range of aluminium alloy circular hollow section (CHS) columns with circular openings. A total of 27 specimens including 18 perforated CHS columns and 9 CHS columns were tested with uniform axial compression force applied to the pin-ended columns, which were fabricated by extrusion of CHSs using 6061-T6 and 6063-T5 heat-treated aluminium alloys. The influence of the column slenderness ratio, the plate slenderness ratio, the opening size ratio and the number of openings on the strength and behaviour of aluminium alloy CHS columns were carefully evaluated. The ultimate strengths, failure modes, load versus axial shortening curves and strain distributions along the circular openings of test specimens were all obtained from the experimental investigation. The test strengths of aluminium alloy CHS columns were compared with the design strengths predicted using the design rules given in the current design specifications. Furthermore, the test strengths of aluminium alloy CHS columns with circular openings were also compared with the design strengths calculated using the current design rules for perforated cold-formed steel structural members, which were derived based on the effective diameter method and effective area method. It is shown from the comparison that the design rules given in American Design Manual (AA) and Australian/New Zealand Standard (AS/NZS) for limit state design of aluminium alloy structural members are generally appropriate but with comparatively high scatter of predictions; whereas the design rules given in Chinese Code are generally appropriate for the design of aluminium alloy CHS columns. In addition, the current design rules for perforated cold-formed steel structural members based on the effective area method are generally more accurate than those based on the effective diameter method for the design of aluminium alloy CHS columns with circular openings.

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ABSTRACT: Tailor welded blanks (TWB) have been widely applied in automobile industry. This paper firstly conducts experimental tests to investigate the crashworthiness of three different types of TWB hat-shaped structures. Their combinations provide three representative TWB configurations: namely the same material grade with different wall thicknesses; different grades with the same thickness, different material grades with different thicknesses, respectively. Secondly, the finite element (FE) models corresponding to each of the samples are established to perform crashworthiness analysis. It is exhibited that the FE simulations are in good agreement with the experimental tests. Thirdly, the surrogate models are constructed to approximate the
crashworthiness responses of these TWB structures. Fourthly, a sensitivity analysis is conducted to explore the effects of the weld line location, wall thickness and material properties for each segment of TWB structures subject to crashing load. The results showed that the wall thickness is most sensitive to the crashworthiness of TWB structures. Finally, reliability based design optimization is carried out by taking into account the uncertainties in the TWB configuration. The results demonstrate that the optimized TWB tubes are capable to improve energy absorption as well as enhance the reliability, potentially being an ideal structure for crashworthiness.

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ABSTRACT: An analytical model is presented for vibration of a thin orthotropic plate containing two perpendicular continuous line surface cracks located at the centre of the plate in the presence of thermal environment. Also new configuration of two perpendicular cracks as internal cracks, located along the thickness of the plate is studied by considering appropriate crack compliance coefficients based on line-spring model. Equilibrium principle based on Classical Plate Theory is used to derive the equations of motion for cracked plate, wherein the crack terms are formulated using the line spring model. The moments due to thermal environment are neglected in the results and only uniform heating of the cracked plate is considered. The solution for natural frequencies of cracked plate is obtained by Galerkin’s method. A relation for thermal buckling phenomenon for the cracked plate is also formulated. The influence of the lengths of the two cracks and their location along the thickness of the plate on critical buckling temperature and first mode natural frequency is demonstrated. The geometrically linear frequency response relation for cracked plate is formulated using the method of multiple scales. It is thus concluded that the presence of the two cracks affect the critical buckling temperature and natural frequencies.

ABSTRACT: Crush response of Variable Thickness Distribution (VTD) tubes subjected to oblique loading are investigated for external inversion process. Crashworthiness performance and benefits of VTD tubes compared with their Uniform Thickness (UT) equivalents. Furthermore, in order to find detail verification about crush process of VTD tubes, at first Finite element (FE) models established and then validated by experimental tests to ensure that they can accurately predict the responses of VTD inversion tubes. Our study shows that tube thickness distribution, die radius, and coefficient of friction between die and tube have great influence on the responses of VTD tubes inversion. The results demonstrated that different loading angles have different requirements on geometries of VTD inversion tubes. The outcome of this paper gives new design ideas to improve crashworthiness performance of inversion tubes under oblique loads.

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ABSTRACT: In this study, the dynamic behavior of uniform thickness, stepped thickness and functionally graded thickness tubes under axial impact are investigated experimentally and numerically. A striking mass has been used to impact tubes. Experimental tests are performed by using gas gun and numerical results are obtained by FE simulation. The effect of thickness distribution on shortening, energy absorption, axial force and buckling shape of tubes are investigated. It is found that a change in thickness distribution of tube can convert the buckling shape from buckling with mild folds to progressive buckling and vice versa. In addition, it is found that stepped thickness tube can be an approximate of functionally graded thickness tube which in this case almost, their behavior is identical. This study reveals that stepped thickness and functionally graded thickness tubes in comparison with uniform thickness tube absorb the same energy with more shortening and less peak load or less mean load; thus, they are better energy absorption specimens. With comparing experimental and numerical results, it is found that there is a good agreement between them.
ABSTRACT: This paper presents an experimental study on thin steel plates strengthened by CFRP layers under shear loading. A series of laboratory tests were conducted on scaled one-story steel shear panel models with hinge type connections under cyclic quasi-static loading. One of the specimens is un-stiffened and selected as a reference sample of three others specimens. Steel infill plates are strengthened by CFRP layers with different numbers of layers and orientations. The results indicate that the strengthening of thin steel plate by CFRP layers increases ultimate strength, secant stiffness and energy absorption. Comparisons are made between the performance of CFRP and GFRP strengthened steel plates under cyclic shear loads. It was shown that both materials were effective at increasing stiffness and strength of the system. The increased ratio is similar for both FRPs when two layers are applied. However, adding additional two layers of CFRP does not provide extra benefit in terms of stiffness and energy absorption although there is still benefit for ultimate strength.

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ABSTRACT: Natural and rocking frequencies of liquid-filled unanchored cylindrical steel tanks are determined using an analytical approach. In the proposed simplified mechanical model, the bottom plate of the tank is replaced by equivalent rotational and vertical springs. To evaluate natural frequencies, potential and kinetic energies of the liquid-filled tank are utilized and the eigen equation is solved by applying the Lagrange method and Ritz-type mode shapes for elastically supported cylindrical shells. Formulas are also derived to determine the rocking frequency based on a rotational rigid body motion and results are verified with available experimental data. Also, effect of the increase in kinetic energy of the tank during rocking motion on the natural frequencies of the tank is explored. To investigate the effects of tank geometrical aspect ratios on the structural responses, three models with height to diameter ratios of 0.4 (squat tank), 0.63 (medium tank) and 0.9 (slender tank) are considered. The results obtained using the proposed simplified mechanical model indicate that the method is capable of determining the rocking frequency of unanchored steel liquid-filled tanks with acceptable accuracy. Also, it is shown that at the onset of rocking mode, the fundamental natural frequency of the tank decreases considerably.

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“Shape optimization of manufacturable and usable cold-formed steel singly-symmetric and open columns”, Thin-Walled Structures, Vol. 109, pp 271-284, December 2016, DOI: 10.1016/j.tws.2016.10.004
ABSTRACT: This paper aims at incorporating manufacturing and assembly features into a shape optimisation algorithm for cold-formed steel (CFS) profiles. Genetic algorithm (GA) is used as the search algorithm and is combined with the augmented Lagrangian constraint-handling method to avoid ill-conditioning. Manufacturable cross-sections are arbitrarily drawn in the initial generation and subsequently treated as an integral part of the GA. The assembly features considered in the study reflect the ones commonly encountered in the construction industry. They include fastening elements (horizontal flange and vertical web) and allowances for utilities, and are treated as constraints. The algorithm is applied to simply-supported singly-symmetric, free-to-warp open section columns with various numbers of manufacturing bends. Three assembly cases for half sections are investigated: (a) a horizontal flange, (b) a horizontal flange and a vertical web, and (c) a horizontal flange and a
vertical web with a utility clearance. A two-step optimisation process is used to optimise the columns: (i) the optimum positions of the fastening elements (horizontal flange and vertical web) are determined first and (ii) the cross-sectional shapes are then optimised. The optimised columns are discussed and compared to the unconstrained optimised columns and the conventional lipped Cee-sections. The results demonstrate the robustness and efficiency of the algorithm.

W. Patangtalo, S. Aimmanee and S. Chutima (Advanced Materials and Structures Laboratory (AMASS), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi (KMUTT), ThungKhru, Bangkok 10140, Thailand), “A unified analysis of isotropic and composite Belleville springs”, Thin-Walled Structures, Vol. 109, pp 285-295, December 2016
DOI: 10.1016/j.tws.2016.09.023
ABSTRACT: This article discusses a method developed for predicting the deformation behavior of a Belleville spring under axial loading by using the minimum potential energy principle. Strain energy and work done of the Belleville spring are formulated based on the classical thin shell theory in a conical coordinate system. The von Kármán and Reissner approximations to the nonlinear strain-displacement relations take the geometrical effects of the moderately and very large axial deflection into consideration, respectively. The Ritz method is used to solve for the deformation and force characteristics of isotropic springs and the solutions are compared with the seminal equation of Almen and Laszlo, experiments, and finite element analyses. The present energy model can capture the effect of a geometric parameter that has been missing from the formulation of Almen and Laszlo. The comparison shows that the developed method gives very good agreement with the results from the testing and finite-element method, whereas in most cases, owing to their limited assumptions, Almen and Laszlo's equation overpredicts the applied load at a given deflection. This energy model is also applicable for composite Belleville springs with orthotropic material properties. A load factor and a orthotropic factor are defined to readily analyze load-deflection relationship of the composite springs based on the existing relationship of the isotropic elastic spring.

ABSTRACT: The present paper deals with an influence of the distortional-lateral buckling mode on the interactive buckling of thin-walled short channels with imperfections subjected to the bending moment when the shear lag phenomenon and distortional deformations are taken into account. A plate model (2D) is adopted for the channel section. The structure is assumed to be simply supported at the ends. A method of the modal solution to the coupled buckling problem within the Koiter's asymptotic theory, using the semi-analytical method (SAM) and the transition matrix method, was applied. The calculations and experimental preliminary tests were carried out for short channels.

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ABSTRACT: High-strength steel members are susceptible to local buckling. Rectangular concrete-filled tubular (CFT) columns could make full use of high-strength steel by restraining its buckling inward. This paper reports an experimental investigation of rectangular CFT columns using high-strength steel. Three current design codes are evaluated with the experiments both from this study and the previous literature. It indicates that EC4, AISC 360 and GB50936 tend to be unsafe incorporating high-strength steel and high aspect \((h/b)\) ratio. Design recommendations of the width-to-thickness \((h/t)\) ratio are proposed to account for the different \(h/b\) ratio effects for rectangular CFT columns.


ABSTRACT: A recent analytical model describing the post-buckling behaviour of an I-section strut experiencing strong axis global–local buckling interaction is extended to investigate the effects of modifying the strut geometry. Using a combination of analytical and finite element (FE) methods, the global and local slendernesses are varied parametrically, in turn, to determine the geometries leading to regions of interactive behaviour. The effect of stress relieved initial global imperfections are also investigated. It is observed that the strut can exhibit one of five distinct post-buckling behaviours, the geometries for which are identified. The strut can exhibit global buckling only, local buckling only, global–local buckling interaction with either the global or local mode being triggered first or the most severe case where both global and local buckling modes are triggered simultaneously. The strut is found to be highly sensitive to initial imperfections in the interactive region; the implications for imperfection sensitivity on the design and the practical use of such components are discussed.

Hanfeng Yin (1,2), Youye Xiao (1,2), Guilin Wen (1,2), Nianfei Gan (1), Can Chen (2) and Jinie Dai (2) (1) State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, PR China (2) Key Laboratory of Advanced Design and Simulation Techniques for Special Equipment, Ministry of Education, Hunan University, Changsha, Hunan 410082, PR China


ABSTRACT: Bio-inspired design has drawn increased attention in recent years for the excellent structural properties of biological system. In our recent work, a bionic thin-walled structure (BTS), which was inspired from the structural characteristic of horsetail, was found to have excellent crashworthiness (Yin et al., 2015) [1]. In order to further improve the crashworthiness of the BTS, a foam-filled bionic thin-walled structure (FBTS) was investigated using the software LS-DYNA in this study. And, the FBTS was optimized by a multi-objective deterministic optimization (MDO) method. The MDO result indicates that the FBTS performed better than the corresponding traditional structure. However, the deterministic optimal design is likely to become unacceptable when considering the uncertainties of design parameters. To solve this problem, a multi-objective robust optimization (MRO) method which employs ensemble metamodel, NSGA-II, “3-sigma” robust design and Monte Carlo simulation (MCS) was developed. Then, the FBTS was optimized by this MRO method. The comparison of the Pareto fronts of the MDO and MRO shows that the robust optimal FBTS is more reliable.
than the deterministic optimal FBTS. The robust optimal FBTS not only has excellent crashworthiness but also has high reliability. Therefore, the robust optimal FBTS is a kind of excellent and reliable energy absorber in impact engineering.

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“Effective width method for distortional buckling design of cold-formed lipped channel sections”, Thin_Walled Structures, Vol. 109, pp 344-351, December 2016, DOI: 10.1016/j.tws.2016.10.010
ABSTRACT: The aim of this paper is to improve the effective width method for distortional buckling strength of cold-formed steel lipped channel members using the energy method and the large deflection theory based on nonlinear post-buckling strength analysis of the partially stiffened element. The accuracy of the proposed method was verified using the finite element method. Comparison on post-distortional buckling strength is conducted between the energy method and the effective width method in the Chinese code Technical code of cold-formed thin-walled steel structures (GB50018–2002). The compared results show that the energy method is very efficient and the effective width method formula in Chinese code can be used to calculate the post-distortional buckling strength. Then, The half-wave length, elastic buckling stress of distortional buckling and the corresponding stability coefficient of partially stiffened elements are developed based on the energy method. With comparison on the calculated results of elastic buckling stress using the proposed method and the Finite Strip Method, suitability and good precision of the developed method are illuminated. Finally, a uniform formula for the stability coefficient of partially stiffened elements considering both local and distortional buckling effect is established. Comparison with experimental results and calculated results predicted with North America specification indicates that the proposed method is reasonable and has a high accuracy and reliability for the distortional buckling load carrying capacities of cold-formed lipped channel members.

ABSTRACT: The dynamic axial and oblique crushing of circular tubes with externally press-fitted ring around the outer tube surface was investigated numerically using the Abaqus/explicit finite element simulation tool. The study shows how the reinforcement of ring strips fitted around the tube surface have the potential of improving the energy absorption capacity. Crashworthiness parameters such as the mean and peak crushing force, Crush Force Efficiency and specific energy absorption were evaluated for different tube profiles. Effect of slenderness ratio and tube thickness on the collapsed mode and crashworthiness parameters were examined by increasing the number of rings around the tube surface with different ring thicknesses. New collapsed modes were obtained as the ringed circular steel tubes were subjected to dynamic axial and oblique compression. The results obtained from the ringed tubes showed a reasonable percentage increase in the total energy absorption as compared to the conventional circular tubes without rings.

Tohid Mirzabaie Mostofi, Hashem Babaei and Majid Alitavoli (Department of Mechanical Engineering, Engineering Faculty, University of Guilan, PO Box 3756-41635, Rasht, Iran), “Theoretical analysis on the
DOI: 10.1016/j.tws.2016.10.009

ABSTRACT: This paper presents an approximate theoretical analysis of inelastic behaviour of fully clamped thin quadrangular plates subjected to two different distributions of impulsive loading. The presented analysis has been developed based on plastic work of plate and kinetic energy in which it assumes that the plate behaves rigid perfectly plastic. The rigid plastic analysis uses an interaction yield surface based on reasonable assumption that only membrane force considers for plastic flow and employs the Cowper-Symonds equation to cater for material strain rate effect. In this study, the applied load is estimated by assuming the initial velocity field of flat plate based on the boundary conditions of plate and geometry of explosive charge setup. Obtained models predict final deflection of the quadrangular plate loaded by uniformly and localized loading. The proposed solution permits consideration of characteristic influence of the load and material on the response of plate. It is observed that the present theoretical models are in good agreements with experimental results and also in comparison with other approximate solution, the present models are found to be simpler and in better agreements with experimental values.

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ABSTRACT: Circular tube filled with cellular materials becomes a fairly attractive structural option in energy absorbing devices, such as crash box and front rail in vehicle. This paper introduces a novel configuration, namely double functionally graded (DFG) structure, which comprises of a functionally graded honeycomb filler in a functionally graded thickness (FGT) tube. Based on the validated finite element (FE) models, a comparative study on the DFG tube, single functionally graded (SFG) tube, and traditional uniform honeycomb filled uniform thickness (H-UT) tube were carried out to explore the crashing behaviors of different structures under multiple load cases. It is found that as crushing displacement increases, DFG structure exhibits superior capacity of energy absorption over other configurations and this trend is positively related to the impact angles. In addition, the comparisons of deformation modes and critical crushing angles clearly indicate that the DFG structure is of better and more stable crashing characteristics, being a crashworthy structure. Following the configurational comparison, further parametric studies on the DFG structures were conducted to explore the effects of tubal thickness range and honeycomb thickness range on the crashworthiness. It is found that the tube thickness range is more important to crashworthiness, which provides a basis for structural optimization.

End of many papers published in the journal, Thin-Walled Structures (2012-2016).

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ABSTRACT: Exploiting the capabilities of the DUCTROT-M computer program, a comparison between cross-section ductility classes, recommended in codes, and member ductility classes, proposed in technical literature, is performed, showing very important differences. A numerical analysis was carried out examining the main influencing factors such as collapse modes, fabrication details (welding, hot-rolling, connection details), material properties, geometrical beam dimensions and type of action. Because the out-of-plane mechanism produces very high ductility degradation during a cycling earthquake, the first purpose of the study is to determine the measures to eliminate this mechanism mode. For the welded beams, geometrical proportion of the flange and web thickness is the key, while for hot-rolled beams, the constructional detailing of the joint. The contribution of the junction between flange and web that increases the rotation capacity was revealed. Consequently, rolled and welded sections possess different available ductility, but this effect does not reflected to the current Eurocodes

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ABSTRACT: This paper is a development of the [1], presenting the new improvements in determining the rotation capacity of wide-flange beams. It deals with the available rotation capacity of steel beams, using the local plastic mechanism methodology. For these purposes, a more advanced software was elaborated at the “Politehnica” University of Timisoara, namely DUCTROT-M, substituting the old DUCTROT-96 computer program presented in [1]. The new version considers two different forms the in-plane and out-of-plane plastic mechanisms, as well as the application of gradient or quasi-constant moments. A CD-ROM containing the free DUCTROT-M computer program can be finding in Appendix of [2] or free on the site [3]. Thus, the present paper is focused on the phenomenological aspects of the utilized plastic collapse mechanisms, while the companion paper [4] is devoted to applications in design practice exploiting the new capabilities of the aforementioned current software version.

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“Compression tests of cold-formed plain and dimpled steel columns”, Journal of Con
ABSTRACT: This paper presents compression tests of cold-formed plain and dimpled steel columns. A series of compression and tensile tests were conducted on plain and dimpled steel of different geometries. For each group of geometries the source of material for both the plain and dimpled steel columns was taken from a single coil. Within each group the sections were fabricated either by press-braking or cold-rolled forming. The buckling and ultimate strength of the columns was investigated. The change in strength of the dimpled columns resulting from the cold working associated with the dimpling process was also considered. This paper contains the results obtained when comparing the test strengths of short plain and dimpled steel columns using a compression test. In outlining the work the test setup and testing procedure will be described. Enhancements in buckling and ultimate strengths were observed in the dimpled steel columns—caused by the cold-work of the material during the dimpling process. The results showed that the buckling and ultimate strengths of dimpled steel columns were up to 33% and 26% greater than plain steel columns, respectively.

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ABSTRACT: The use of curved panels for the construction of steel bridges becomes more and more popular. Their design is however made difficult by a lack of specifications, especially in European Standards. The present study aims thus at developing a method for predicting the ultimate strength of cylindrical unstiffened curved panels subjected to uniform axial compression. The methodology used in this study is based on the formal procedure recommended by Eurocode 3 for all types of stability verifications. A series of numerical simulations is first carried out to identify the fundamental characteristics of curved panels' elasto-plastic behaviour. Then on the basis of these numerical results, semi-empirical formulae for predicting the elastic buckling and ultimate strength are derived and illustrated on a practical example.

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ABSTRACT: Core concrete subjected to confinement effect from steel tube is the main advantage of concrete filled steel tubular (CFST) column under compression. However, this beneficial composite action could be weakened even destroyed by debonding, which is almost unavoidable as a common phenomenon in CFST structures and has not been considered satisfactorily by current design codes. In this paper, the influence of debonding on circular CFST stub columns was investigated experimentally and numerically. The main experimental parameters were the debonding arc-length ratio, the confinement factor and the load mode. Meanwhile, the finite element models were implemented using the ABAQUS finite element software, of which the validity and accuracy were verified by test results. Utilising the finite element model, the parametric analysis was carried out to study the influence of the following parameters on the ultimate load capacity of
debonding specimens: debonding arc-length ratio, debonding thickness and confinement factor. Based on the results of parametric analysis, a simplified calculation formula was proposed to calculate the ultimate load capacity of circular CFST stub columns with debonding.

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ABSTRACT: More than 400 concrete-filled steel tubular (CFST) arch bridges have been constructed worldwide so far. However, design codes or guidance for the in-plane strength design of CFST arches are yet to be developed. In current design practice, the philosophy for the in-plane strength design of reinforced and prestressed concrete arches is widely adopted for CFST arches. For this, the CFST arches are considered under central or eccentric axial compression and are treated similarly to CFST columns, and the classical buckling load of CFST columns is used as the reference elastic buckling load of CFST arches. However, under transverse loading, the in-plane elastic buckling behaviour of CFST arches, particularly shallow CFST arches, is very different from that of CFST columns under axial compression. In addition, different from CFST columns under central or eccentric axial compression, CFST arches are subjected to significant nonlinear bending actions and transverse deformations prior to buckling and these will influence the strength of CFST arches greatly. Therefore, it is doubtful if the current method for in-plane strength design of CFST arches can provide correct strength predictions. In this paper, a method for the in-plane strength design of CFST circular arches, which is consistent with the current major design codes for steel structures, is developed by considering both geometric and material nonlinearities. A design equation for the in-plane strength capacity of CFST arches under uniform compression, and a lower-bound design equation for the in-plane strength check of CFST arches under combined actions of bending and compression are proposed.

Tharmarajah Anapayan and Mahen Mahendran (Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Numerical modeling and design of LiteSteel Beams subject to lateral buckling”, Journal of Constructional Steel Research, Vol. 70, pp 51-64, March 2012 https://doi.org/10.1016/j.jcsr.2011.08.016
ABSTRACT: The LiteSteel Beam (LSB) is a new hollow flange channel section developed using a patented dual electric resistance welding and cold-forming process. It has a unique geometry consisting of torsionally rigid rectangular hollow flanges and a slender web, and is commonly used as flexural members. However, the LSB flexural members are subjected to a relatively new lateral distortional buckling mode, which reduces their moment capacities. Unlike lateral torsional buckling, the lateral distortional buckling of LSBs is characterised by simultaneous lateral deflection, twist and cross sectional change due to web distortion. Therefore a detailed investigation into the lateral buckling behaviour of LSB flexural members was undertaken using experiments and finite element analyses. This paper presents the details of suitable finite element models developed to simulate the behaviour and capacity of LSB flexural members subject to lateral buckling. The models included all significant effects that influence the ultimate moment capacities of such members, including material inelasticity, lateral distortional buckling deformations, web distortion, residual stresses, and geometric imperfections. Comparison of elastic buckling and ultimate moment capacity results with predictions from other numerical analyses and available buckling moment equations, and experimental results showed that the
developed finite element models accurately predict the behaviour and moment capacities of LSBs. The validated model was then used in a detailed parametric study that produced accurate moment capacity data for all the LSB sections and improved design rules for LSB flexural members subject to lateral distortional buckling.

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ABSTRACT: Various methods can be used to investigate buckling phenomena in a steel compression member. Among these methods, experimental formulas, semi-empirical formulas, closed-form solutions and classic methods based on differential equations as well as numerical methods based on finite elements are most commonly used. All of these methods have associated complexities. Thus, it is very difficult to perform a comprehensive parametric study on the buckling phenomenon of a compression member using these methods. The simplicity of the mathematical concepts used in ANNs (artificial neural networks) and their ability to model complex problems have led to the popularity of ANNs. After the learning step of an ANN, a function can be determined as a relationship between the input variables and output parameters, which is a load–displacement relationship in this article. It is then possible to perform an extensive parametric study on the buckling behavior of a compression member. In this research, the network can also extract the critical load–slenderness relationship. Using this network, it is possible to conduct an accurate study on the effects of various parameters at the critical load as well as to evaluate the sensitivity of the critical load to each variable used in the ANN training.

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ABSTRACT: Recently developed cold-formed LiteSteel Beam (LSB) sections have found increasing popularity in residential, industrial and commercial buildings due to their light weight and cost-effectiveness. Another beneficial characteristic is that they allow torsionally rigid rectangular flanges to be combined with economical fabrication processes. Currently, there is significant interest in the use of LSB sections as flexural members in floor joist systems. When used as floor joists, these sections require openings in the web to provide access for inspection and other services. At present, however, there is no design method available that provides accurate predictions of the moment capacities of LSBs with web openings. This paper presents the results of an investigation of the buckling and ultimate strength behaviour of LSB flexural members with web openings. A detailed finite element analysis (FEA)-based parametric study was conducted with the aim of developing appropriate design rules and making recommendations for the safe design of LSB floor joists. The results include the required moment capacity curves for LSB sections with a range of web opening combinations and spans and the development of appropriate design rules for the prediction of the ultimate moment capacities of LSBs with web openings.
ABSTRACT: In recent decades, steel plate shear walls have come to be considered as a convenient system for resisting lateral loads due to earthquakes and wind, especially in tall buildings, because of their ductile and energy absorption behaviors. The existence of openings affects the seismic behavior and performance of steel plate shear walls. In the present research, the effects of opening dimensions as well as slenderness factors of plates on the seismic behavior of steel plate shear walls are studied experimentally. Eight 1:6 scaled test specimens, with two plate thicknesses and four different circular opening ratios at the center of the panel, have been manufactured and were tested under the effects of cyclic hysteresis loading at the thin-walled structures research laboratory of Urmia University, Urmia, Iran. The hole was put in the center of the panel because this is the most detrimental location in view of the panel tension field action. The obtained results signify a stable and desired behavior of steel plate shear walls for large displacements of up to 6% drift. The creation of openings decreases the initial stiffness and strength of the system, and increasing the opening diameter will intensify this matter. The obtained ductility of specimens shows the stable functioning of a system in the nonlinear range. Although the stable cyclic behavior of specimens in the nonlinear range causes mostly a dissipation of energy during the loading of samples, but existence of an opening at the center of the panel causes a noticeable decrease in energy absorption of the system.

ABSTRACT: The purpose of this study is to derive an equation to evaluate the elastic buckling strength of thin plates under flexural shear and axial forces. Well-known evaluation methods consider bending as constant bending. However, under flexural shear, bending will not be constant bending. Moreover, currently used methods do not properly distinguish between bending stress and shear stress. This is because these variables are not always independent of each other. The validity of these methods has, therefore, not been adequately verified. In this study, we investigate the validity of these methods, and for cases in which bending cannot be regarded as constant bending, we propose a new method.

ABSTRACT: This paper is an attempt to study the performance of concrete filled steel tubular (CFST) members with square sections under both loading and chloride corrosion. A total of 28 specimens, including 17 stub columns and 11 beams, were tested. The main parameters were loading ratio (from 0 to 0.75) during corrosion, as well as corrosion condition (no corrosion, and fully or half immersed into corrosive solution,
According to the test, the effects of both loading and corrosion on the behaviour of CFST and reference hollow steel tubular members were analyzed. Comparisons between the predicted ultimate strength by using the existing codes of DBJ/T13-51-2010 and EC4-2004 and the testing results were proposed.

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ABSTRACT: This paper presents the numerical simulation and design of cold-formed steel oval hollow section columns. An accurate finite element model was developed to simulate the fixed-ended column tests of oval hollow sections. The material non-linearities obtained from tensile coupon tests as well as the initial local and overall geometric imperfections were incorporated in the finite element model. Convergence study was performed to obtain the optimized mesh size. A parametric study consisted of 100 columns was conducted using the verified numerical model. The failure modes of material yielding, local buckling and flexural buckling as well as interaction of local and flexural buckling were found in this study. The experimental column strengths and numerical results predicted by the parametric study were compared with the design strengths calculated using the current North American, Australian/New Zealand and European specifications for cold-formed steel structures. In addition, the direct strength method, which was developed for cold-formed steel members for certain cross-sections but not cover oval hollow sections, was used in this study. The reliability of these design rules was evaluated using reliability analysis.

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ABSTRACT: The experimental behaviour of concrete filled double-skin steel tube (CFDST) sections subjected to partial compression is reported in this paper. Fourteen specimens with outer and inner steel tubes of circular hollow section (CHS) and fifteen specimens with outer and inner steel tubes of square hollow section (SHS) were tested. The test parameters included: 1) hollow ratio, 2) top endplate thickness, and 3) partial compression area ratio. The test results indicated that the CFDST columns under partial compression behaved in a ductile manner. The partial compressive behaviour and the failure modes of partially loaded CFDST stub columns were significantly affected by the parameters investigated. Finally, a simplified model for predicting the bearing capacity of partially loaded CFDST sections is proposed.

ABSTRACT: The buckling behavior of a new ductile bracing concept for steel structures is examined. The system makes use of cast components introduced at the ends and the center of the brace to produce a special
bracing detail with reliable strength, stiffness and deformation capacity. The system takes advantage of the versatility in geometry offered by the casting process to create configurations that eliminate non-ductile failure modes in favor of stable inelastic deformation capacity. This paper presents analytical research performed to determine the buckling strength and buckling direction of the bracing element based on the geometries of the cast components. Limiting geometries are determined for the cast components to control the buckling direction. Design formulas for buckling strength are proposed.

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ABSTRACT: At present, Harmathy creep model is used in most fire resistance analysis, which explicitly consider creep. Harmathy creep model only predicts creep strains with acceptable accuracy for the case of constant stresses, but becomes invalid for the case of variable stresses. For the case of axially restrained steel columns subjected to fire, the fire induced stresses vary considerably and rapidly with time and temperature. In this paper, the effect of creep on the buckling behavior of axially restrained steel columns in real fires has been investigated. A creep model in ANSYS, which is capable of predicting creep strain regardless of any coupling between time and either stress or temperature of steel, is used to predict creep strains. The results for buckling temperatures and axial deformations, predicted with and without considering creep in numerical simulations, are compared. Both fast and slow fires are considered. The study found that for axially restrained steel columns in slow fires, considering creep gives higher buckling temperatures than those not considering creep; and for axially restrained steel columns in fast fires, considering creep might give higher or lower buckling temperatures than those not considering creep.

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ABSTRACT: Local buckling in floor beams has been one of the important observations in several fire events in steel buildings such as World Trade Center Tower 7 and large-scale fire experiments such as Cardington building test in U.K. Utilizing three dimensional finite element methods for complex geometry and nonlinear behavior of such connections, local buckling of the web followed by the buckling of the lower flange is observed to occur in early stages of fire, which causes instability to the floor system, and a significant reduction in the connection strength. The observations also suggest that the maximum compression in the floor beam is limited to the buckling capacity of the web and flanges near the connection. This paper contributes to such knowledge by investigating the local buckling of floor beams for different connection types at elevated temperatures using nonlinear finite element models. Moment connections are found to be more resistant to local buckling when compared to the shear connections. The results are also compared to the AISC design equation for plate buckling under ambient and elevated temperatures. Compared to the finite element analyses of this
study, it is observed that at ambient temperature the AISC curve conservatively captures the buckling capacity of webs and flanges; at higher temperatures, AISC overestimates the capacity.


ABSTRACT: Circular holes are commonly found on the web of cold-formed steel (CFS) flexural members for piping, electric-wiring, plumbing, or installing lateral bracing, etc. Traditional holes on CFS members are flat bunched without edge lips. A new generation of CFS C-section flexural members with edge stiffened holes was recently developed by the industry. However, research on the new generation C-section members is underdeveloped and available test results are limited. This paper presents finite element analyses to study on the stability of cold-formed steel thin plates and typical C-section members when edge stiffened circular holes are placed on those plates or members. Based on the elastic buckling analyses, the optimized profiles of the holes are obtained and then applied to standard C-section flexural members. The post-buckling finite element analysis is utilized to determine the flexural strength of those members. The results indicate that the stiffened holes can significantly improve the flexural strength of CFS C-sections. New design provisions are proposed to accurately predict the flexural strength of the new generation C-section flexural members with the optimized hole profiles.

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ABSTRACT: EC3–EN 1993-1-1 provides several methodologies for the stability verification of members and frames. When dealing with the verification of non-uniform members in general, with tapered cross-section, irregular distribution of restraints, non-linear axis, castellated, etc., the code mentions the possibility of carrying out a verification based on 2nd order theory; however, several difficulties are noted when doing so, in particular when the benefit of plasticity should be taken into consideration. Other than this, there are yet no guidelines on how to apply standardized, easily reproducible rules as those contained in Section 6.3.1 to 6.3.3 of the code to non-uniform members. As a result, practical safety verifications for these members are often carried out using conservative assumptions, not accounting for the advantages non-uniform members provide. In this paper, firstly, available approaches for the stability verification of non-uniform members are discussed. An Ayrton–Perry formulation is then derived for the case of non-uniform columns. Finally, and followed by a numerical parametric study covering a range of slenderness, cross-sections and fabrication process, a design proposal is made for the relevant case of in-plane flexural buckling of linearly tapered columns subject to constant axial force. The proposal is consistent with current rules for uniform columns provided in EC3-1-1, i.e., clause 6.3.1.

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ABSTRACT: The concrete filled steel tubular (CFST) members become very popular in the construction industry and, at the same time, aging of structures and member deterioration are often reported. The actions like implementation of new materials and strengthening techniques become essential to combat this problem. This research work aimed to investigate the structural improvements of CFST sections with normal strength concrete externally bonded with fibre reinforced polymer (FRP) composites. For this study, compact mild steel tubes were used with the main variable being FRP characteristics. Carbon fibre reinforced polymer (CFRP) fabrics were used as horizontal strips (lateral ties) with several other parameters such as the number of layers, width and spacing of strips. Among thirty specimens, twenty seven were externally bonded with 50 mm width of CFRP strips with a spacing of 20 mm, 30 mm and 40 mm and the remaining three specimens were unbonded. Experiments were undertaken until column failure to fully understand the influence of FRP characteristics on the compressive behaviour of square CFST sections including their failure modes, axial stress–strain behaviour, and load carrying capacity. From the test results, it was found that the external bonding of CFRP strips provides external confinement pressure effectively and delays the local buckling of steel tube and also improves the load carrying capacity further. Finally, an analytical model was proposed herein for predicting the axial load carrying capacity of strengthened CFST sections under compression.

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ABSTRACT: This paper is concerned with the eccentric load behavior of L-shaped concrete-filled steel tubular (CFT) stub columns with binding bars. Eight specimens with binding bars and one without binding bars were tested to examine the effects of horizontal spacing and diameter of binding bars, load eccentricity ratio, and load angle on the failure modes, bearing capacity and ductility of L-shaped CFT stub columns. Experimental results demonstrate that the local buckling of the steel tube can be postponed by setting binding bars, and the bearing capacity and curvature ductility of the L-shaped CFT stub columns are at most 1.04 and 3.31 times those without binding bars, respectively, and the plane section assumption can also be satisfied. Based on a modified stress–strain relationship of confined concrete, the fiber element analysis is applied to predict the bearing capacity of the specimens, and the predicted results agree well with the experimental ones. Then the parametric studies using the proposed theoretical model are carried out to further study the fundamental behavior of eccentrically loaded L-shaped CFT stub columns with various steel yield strengths, sectional steel ratios, cube strengths of concrete, confinement coefficients of binding bars, sectional aspect ratios and load angles. Finally, simplified interaction formulas are put forward to predict the $M_x/M_x'$–$M_y/M_y'$ curves for the L-shaped CFT stub columns with or without binding bars subjected to biaxial eccentric load, and the theoretical results predicted by the simplified formulas agree well with those predicted by the fiber element analysis program.


ABSTRACT: For shear, the design of sections for strength is usually governed by the web plate subjected to shear force and undergoing shear buckling, or yielding in shear or a combination of the two. For webs with relatively high depth-to-thickness ratios, the shear stress distribution in the web after buckling changes and
significant post-buckling strength may occur as a result of the development of a diagonal tension which is called “Tension Field Action” (TFA). Recently, the full set of shear test results for the plain lipped C- and SupaCee® sections performed at the University of Sydney shows that the post-buckling strength was attributed to TFA which was provided by the increased transverse restraints created by bolted connections attached to loading stiffeners over the full depth of the web panel at the supports and loading point. This improved the post-buckling strengths of the web in shear. Firstly, the results of finite element nonlinear simulations are compared with tests where bolted connections not over the full depth of the web panel were used to validate the FE method. Then the range of test data described previously is extended using finite element models, by reducing the bolting at support and loading points in the test data to provide further guidance on the availability of TFA in particular. Design equations are provided for Tension Field Action.

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ABSTRACT: This manuscript summarizes recent work to determine if the LRFD resistance factor for cold-formed steel compression members can be increased above its current value of 0.85. An experimental database of 675 concentrically loaded columns with plain and lipped C-sections, plain and lipped Z-sections, hat sections and angle sections, including members with holes, was compiled. The predicted strength of each specimen was calculated with the American Iron and Steel Institute's Main Specification and the Direct Strength Method, with the Direct Strength Method making more accurate strength predictions, especially for columns with partially effective cross sections. The LRFD resistance factor, calculated with a first order second moment reliability approach, was consistent with that currently specified in the code for both the Main Specification and the Direct Strength Method. Capacity predictions of columns failing by the distortional buckling limit state were more accurate than columns failing by global buckling or local–global buckling interaction. The test-to-predicted strength ratios for single angle columns were highly variable, with capacity predictions becoming excessively conservative with increasing global slenderness.

ABSTRACT: This paper reports an investigation aimed at developing a Direct Strength Method (DSM) approach to estimate the ultimate strength of lipped channel columns affected by local/distortional buckling mode interaction. Following a brief presentation of a few relevant aspects concerning the shell finite element analysis of the geometrically and materially non-linear behaviour of thin-walled members, one illustrates the methodology adopted to obtain a lipped channel column ultimate load “data bank” intended to be used in the development and assessment of a DSM design approach. Next, the current DSM expressions to predict the load-carrying capacity of columns failing in local and distortional modes are briefly reviewed, devoting special attention to an approach that takes into account the above mode interaction. Then, the results of a parametric study, carried out by means of the code Abaqus, are presented and discussed — this study involves the evaluation of the “exact” ultimate loads of 276 lipped channel columns with various geometries and two
boundary conditions (pinned and fixed end supports), all exhibiting local/distortional interaction. Finally, these ultimate strength data are compared with the estimates provided by the available DSM expressions and, on the basis of this comparison, one identifies several features that a DSM approach successfully accounting for local/distortional interaction must incorporate.

Mohammad Reza Haidarali and David A. Nethercot (Civil and Environmental Engineering Department, Imperial College London, SW7 2AZ, United Kingdom), “Local and distortional buckling of cold-formed steel beams with edge-stiffened flanges”, Journal of Constructional Steel Research, Vol. 73, pp 31-42, June 2012 https://doi.org/10.1016/j.jcsr.2012.01.006
ABSTRACT: The economic use of cold-formed steel members means that buckling and the possible loss of effectiveness it produces are important features of design. The prediction of the true buckling behaviour of cold-formed steel beams accounting for all governing features such as geometrical imperfections, material nonlinearity, postbuckling etc. has been possible with the development of advanced numerical modelling. The FE models developed in previous research have been used in this paper to investigate the effect of edge stiffeners (lips) and their interaction with compression flanges on the postbuckling of laterally restrained cold-formed Z-section beams. Depending on the lip size-to-flange width ratio and angle of inclination of the edge stiffener, the cross-sectional bending resistance varied and transitions between local, distortional and combined local/distortional buckling were observed. The suitability of the design treatments available in Eurocode 3 (EC3) for local and distortional buckling of cold-formed Z-section beams was assessed. Overall, the EC3 predictions for cross-sectional bending resistances were unconservative. Some shortcomings were identified and some suggestions for improvements were made. This included improvements in plate buckling factors for edge-stiffened compression flanges.

ABSTRACT: Concrete filled steel tubular columns have been extensively used in modern construction owing to that they utilise the most favourable properties of both constituent materials. It has been recognized that concrete filled tubular columns provide excellent structural properties such as high load bearing capacity, ductility, large energy-absorption capacity and good structural fire behaviour. This paper presents the structural fire behaviour of a series of concrete filled steel tubular stub columns with four typical column sectional shapes in standard fire. The selected concrete filled steel tube stub columns are divided into three groups by equal section strength at ambient temperature, equal steel cross sectional areas and equal concrete core cross sectional areas. The temperature distribution, critical temperature and fire exposing time etc. of selected composite columns are extracted by numerical simulations using commercial FE package ABAQUS. Based on the analysis and comparison of typical parameters, the effect of column sectional shapes on member temperature distribution and structural fire behaviour are discussed. It shows concrete steel tubular column with circular section possesses the best structural fire behaviour, followed by columns with elliptical, square and rectangular sections. Based on this research study, a simplified equation for the design of concrete filled columns at elevated temperature is proposed.

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ABSTRACT: In this research, 18 laced built-up columns with various geometric specifications were analyzed under different levels of axial load and cyclic lateral load using the finite element method. This research was performed as a continuation of the experimental investigation on the cyclic behavior of the laced columns. This study evaluated the effects of column's geometrical parameters and various levels of axial loads on the cyclic behavior of laced columns. A compression of the results shows that there is generally good agreement between the experimental and analytical results. The analytical results showed that as the axial load increased, the ductility of the laced columns decreased significantly. Further, at high levels of axial load (i.e., loads higher than 50% of the columns' compressive capacity), ductility was very poor. It was found that during lateral loading there is a bending moment in addition to the axial force in the lacing bars and the main chords, which affects the columns' behavior. The slenderness ratio of the main chords between the connecters and the shape of the cross-section of the lacing bars (i.e., bending strength of the lacing bars) are the main geometrical parameters affecting the laced columns' ductility.

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ABSTRACT: A series of tests on curved concrete filled steel tubular (CCFST) built-up members subjected to axial compression is described in this paper. Twenty specimens, including 18 CCFST built-up members and 2 curved hollow tubular built-up columns, were tested to investigate the influence of variations in the tube shape (circular and square), initial curvature ratio ($\beta_r$, from 0 to 7.4%), nominal slenderness ratio ($\lambda_n$, from 9.9 to 18.9), section pattern (two main components, three main components and four main components), as well as brace pattern (battened and laced) on the performance of such composite built-up members. The experimental results showed that the ultimate strength and stiffness of CCFST built-up specimens decreased with increasing $\beta_r$ or $\lambda_n$. Different load-bearing capacities and failure modes were obtained for the battened and laced built-up members. A simplified method using an equivalent slenderness ratio was suggested to calculate the strength of CCFST built-up members under axial compression.

Overall buckling behavior of 460 MPa high strength steel columns: Experimental investigation and design method”, Journal of Constructional Steel Research, Vol. 74, pp 140-150, July 2012
https://doi.org/10.1016/j.jcsr.2012.02.013
ABSTRACT: Overall buckling behavior of compression columns is one of the most important research subjects in steel structures, especially for high strength steel which has been increasingly applied in recent years. An
experimental investigation was carried out to study the overall buckling behavior of 460 MPa high strength steel compression members. Totally twelve columns including welded box and I-sections were comprised. The initial imperfections such as the residual stress, initial bending and loading eccentricity were all measured. Based on experimental results the buckling deformation and capacity were investigated. A finite element model was established and further validated by comparing with the test data in both present study and other previous researches, in which initial imperfections were taken into account. A large number of columns with various section dimensions and lengths were calculated by using the validated model, and their buckling capacities were compared with design values according to different steel structures specifications. It was found that the nondimensional buckling strength of such 460 MPa high strength steel columns were significantly improved compared to normal strength steel columns, and corresponding column curves and design formulae were suggested.

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ABSTRACT: In current Eurocode, the buckling temperature of steel columns can be calculated by either using an analytical approach or using a simple closed-form equation. This paper investigates the accuracy and limitations of those two calculation approaches. Test data on steel columns at elevated temperature reported in literature are used for comparison. The two approaches are found to give acceptable prediction for tests with moderate utilization factor, and unacceptable prediction for tests with either high utilization factor ($\mu_0 > 0.83$) or low utilization factor ($\mu_0 < 0.16$). The professional factor for the simple equation has a mean of 0.949 and a COV of 0.016, and can be best described by an extreme value distribution. The professional factor for the analytical approach has a mean of 1.018 and a COV of 0.013, and can be well described by either a normal, gamma or lognormal distribution.

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ABSTRACT: This paper experimentally investigated the behavior of a special shaped column composed of concrete-filled steel tubes (SCFST column) subjected to a constant axial load and a cyclically varying flexural load. The effects of both the axial compression ratio and the length to width ratio on the behavior (stiffness, strength, ductility, and energy dissipation) of SCFST columns were studied. The asymmetry character of the column was studied. The connection plate was an important member transferring shear force. The mono columns of SCFST columns worked together well and the seismic behavior of SCFST columns was good. An increase of the axial compression ratio increased the stiffness with a decrease of energy dissipation ability, ductility, and bearing capacity. On the other hand, an increase of the length to width ratio led to an increase of
energy dissipation ability and ductility and a decrease of stiffness and bearing capacity. Furthermore, a finite element analysis was also carried out to simulate the behavior of SCFST columns and the test results agreed with the results of finite element analysis.


ABSTRACT: In this paper, the buckling behavior of girth-welded circular steel tubes subjected to bending was investigated by numerical method. Finite element (FE) simulation of the girth welding process was first performed to obtain weld-induced residual stress and deformation employing sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. Elastoplastic large-deformation analysis in which the failure mode, the ultimate moment capacity and the moment versus end-rotation behavior of girth-welded circular steel tubes under pure bending were explored incorporating weld-induced geometric imperfection and residual stress was next carried out. Results showed that the flexural behavior of girth-welded circular steel tubes always involves local buckling near the girth weld on the compression side, which significantly affects the moment versus end-rotation response.

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ABSTRACT: Steel plate shear walls are lateral load resisting systems, especially against earthquake excitation. They are constructed with or without stiffeners. In contrary to stiffened steel plate shear walls, there are many theoretical and experimental studies on these systems without stiffeners and different analytical methods have been presented for them which are mostly applicable to very thin steel plates shear walls. In this research, two one story similar steel plate shear walls with and without stiffeners and one of their surrounding frames were tested and the behavior of them was studied. The results showed that, installation of stiffeners improved the behavior of the steel plate shear walls. It caused 26% increase in energy dissipation capacity and 51.1% increase in the shear stiffness of steel plate while its effect on the steel plate shear strength was minor. In addition, the Plate-Frame interaction theory (PFI) was verified by using the experimental results and the test results showed that, this theory has good capability for predicting the shear load – displacement curve behavior of steel shear walls with or without stiffeners.

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ABSTRACT: A new study was carried out and presented herein, on the optimisation of novel elliptically-based web opening shapes which enhance the structural behaviour of the perforated beams as well as lead to economic design in terms of both manufacture and usage. The finite element (FE) model used in the study was validated against experimental work conducted by the authors and the results of the comprehensive study are presented in
this research paper. For ease of comparison, the yield patterns and deflected shapes of the perforated beams are presented at three ‘characteristic’ load level points. Finally, shear–moment interaction FEM curves are presented for six novel web opening shapes to allow for easy use of the empirical design formulas that have previously been proposed by the authors in a complementary research paper. An overall study of many standard and non-standard web opening shapes, it was shown that perforated beams with vertical and inclined classic elliptical web openings (3:4 width to depth ratio) behave more effectively compared to perforated beams with conventional circular and hexagonal web openings, mainly in terms of stress distribution and local deflection. Therefore, perforated steel beams with large novel elliptically-based web openings with short critical opening length at the top and bottom tee-section as well as straight-line edges are presented for first time and examined in the current research programme.

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“Slenderness limits for cold-formed channel sections in bending by experimental methods”, Journal of Constructional Steel Research, Vol. 76, pp 75-82, September 2012

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ABSTRACT: Inelastic design methods allow for larger application of loads on sections than elastic design methods, due to the redistribution of yield stress through the depth of the section. Sections that can reach the full plastic capacity and maintain it for sufficient rotation are considered applicable for plastic mechanism design, resulting in more economical structural solutions. Cold-formed steel channel sections are used extensively in portal frame structures in agricultural and light industrial/commercial applications, structures well suited to plastic design, however may currently only be designed elastically. To address this limitation in design standards, experimental and numerical analyses on the inelastic bending capacity of cold-formed channel sections are performed, and design rules to account for such behaviour are developed. Design rules are prepared using the hot-rolled steel specification methodology of classifying a section as compact, non-compact or slender (according to the Australian Standards) and Classes 1, 2, 3 and 4 (according to the European Standards). Proposals for the Australian standard are shown to provide accurate and reliable capacity predictions for cold-formed steel channel sections whose bending capacity exceeds the elastic limit.

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ABSTRACT: It is clear from former researches on reinforced concrete filled tubular steel (RCFT) columns that RCFT columns have better performance than concrete filled steel tubular (CFT) columns. The enhancements may be mainly due to the improvements in performance of the concrete core because of the confinement pressure imposed by both steel tube and reinforcement. To clarify the effect of confinement on concrete core and propose evaluation equation for axial compressive strength of RCFT columns, numerical analyses of RCFT columns are conducted by matching the numerical results with experimental results via parametric study. According to the results of the analyses, effect of confinement on concrete and effect of stress state on steel tube of RCFT columns are discussed, as a result, a non-conventional method for evaluating the confinement effect.
which is concerned with load-sharing ratio of RCFT columns is proposed, and the evaluation equation for axial compressive strength of RCFT columns is obtained and validated through the experimental data.

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ABSTRACT: This paper presents an experimental investigation of axially and eccentrically loaded plain and fibre reinforced (FR) concrete-filled stainless steel circular tubular columns. The composite columns were pin-ended subjected to axial and eccentric loads. The stainless steel tubes were relatively slender having a diameter-to-plate thickness ratio of 50. The composite columns had different lengths varied from 3D to 12D. The column ultimate loads, load–axial shortening relationships, load–strain relationships, load–mid-height lateral deflection relationships and failure modes of the concrete-filled stainless steel circular tubular columns were measured from the tests. The study has shown that FR concrete-filled stainless steel tubular columns offer a considerable increase in column ductility compared with plain concrete-filled tubular columns. The test ultimate loads were compared with the design ultimate loads calculated using the Eurocode 4 for composite columns. Generally, it has been shown that the EC4 accurately predicted the ultimate loads of axially loaded concrete-filled stainless steel circular tubular columns, but were quite conservative for predicting the ultimate loads of the eccentrically loaded columns. It has also been shown that the conservatism of the EC4 predictions is increased as the eccentricity is increased. The test results provide useful information regarding the behaviour of FR concrete-filled stainless steel columns.

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ABSTRACT: This paper investigates the influence of weld rotation stiffness on the global bifurcation buckling strength of laser-welded web-core sandwich plates. The study is carried out using two methods, the first is the equivalent single-layer theory approach solved analytically for simply supported plates and numerically for clamped plates. First-order shear deformation theory is used. The second method is the three-dimensional model of a sandwich plate solved with finite element method. Both approaches consider the weld through its rotation stiffness. The weld rotation stiffness affects the transverse shear stiffness. Plates are loaded in the web plate direction. Four different cross-sections are considered. Weld stiffness is taken from experimental results presented in the literature. The results show a maximum of 24% decrease in buckling strength. The strength was affected more in plates with high reduction of transverse shear stiffness and high bending stiffness. Furthermore, clamped plates were influenced more than simply supported. The intersection between buckling modes shifted towards higher aspect ratios, in the maximum case by 24%. The results show the importance of considering the deforming weld in buckling analysis.

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ABSTRACT: This paper presents a study on the flattening behaviour of angle section beams subjected to pure bending. Analytical solutions for both static and dynamic instabilities of angle section beams subjected to pure bending about its weak axis are derived using energy methods. The results show that the dynamic instability of angle section beams under the action of a sudden step moment occurs at a moment about 71% of the corresponding static moment, but the deformations of the longitudinal curvature and flattening at the critical dynamic state are almost twice of those corresponding to the static instability case.

ABSTRACT: In order to understand the influence of member buckling on the stability of reticulated shells, a key problem of how to distinguish the member buckling for reticulated shell structures was pointed out, and judgment methods of member buckling were obtained. Using a Kiewitt-8 dome as an example, the buckling characteristic and propagation rule of member buckling were studied. Meanwhile, a reticulated dome model tested was analyzed and compared by using the finite element software ANSYS. Judgment results of member buckling and the influence of member buckling on the structure were obtained. The judgment results accorded well with the test. Then taking the member buckling into consideration, the effect of material nonlinearity, initial geometrical imperfections, and member size on the stability of the members and the reticulated shell structures were investigated. The results show that the methods adopted can judge the member buckling for reticulated shell structures effectively; the member buckling and its propagation can affect the stability of the structure directly.

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ABSTRACT: The filling of circular hollow sections (CHS) with concrete is a good solution for strengthening columns since such procedure increase their load bearing capacity at room and high temperatures. However, in the event of a fire, restraining to thermal elongation may change their mechanical behavior. This paper presents the results of a large series of fire resistance tests on CHS columns with restrained thermal elongation. Parameters such as the slenderness of the column, its load level, the stiffness of the surrounding structure, the percentage of steel reinforcement and the degree of concrete filling inside the column, were tested. The results obtained show that the critical time of the columns was less than 46 min. The use of a concrete ring around the internal surface of the column's wall is of no advantage in terms of its behavior under fire conditions because this concrete ring suffers extensive spalling and cracking due to overheating of the steel tube. The main failure mode of the columns was global buckling. However in several cases local buckling also occurred.

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ABSTRACT: Web crippling failure of ferritic stainless steel tubular structural members could be found due to localised concentrated loads or reactions. This paper reports experimental and numerical investigation on strengthening of ferritic stainless steel tubular members using externally bonded high modulus carbon fibre-reinforced polymer (CFRP) plate. The CFRP plate strengthening is only applied to a small localise area subjected to concentrated load. A series of tests on CFRP strengthened ferritic stainless steel square and rectangular hollow sections subjected to web crippling was conducted. The web crippling tests were conducted under four loading conditions of end-two-flange (ETF), interior-two-flange (ITF), end-one-flange (EOF) and interior-one-flange (IOF). A total of 37 web crippling tests was conducted in this study. The investigation was mainly focused on the effects of web slenderness of ferritic stainless steel tubular sections on CFRP strengthening against web crippling. The tests were performed on five different sizes of square and rectangular hollow sections. The ferritic stainless steel type EN 1.4003 test specimens were used in this study. Tensile coupon tests were conducted to determine the material properties of the ferritic stainless steel specimens. Most of the strengthened specimens were failed by debonding of CFRP plate from the ferritic stainless steel tubes. Two different failure modes were observed in the tests of the strengthened specimens, namely the adhesion failure as well as the combination of adhesion and cohesion failure. Finite element models have been developed and verified against the test results. The failure loads, failure modes and the load-web deformation behaviour of the ferritic stainless steel sections are also presented.

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ABSTRACT: Castellated beams are widely used as flexural members in steel construction. The economical and structural advantages of these elements have prompted many researchers to investigate the failure behavior of such structures. Despite numerous reported researches on the buckling stability of castellated beams, no experimental study is found on lateral–torsional buckling of these elements with elastic bracing. In this paper, the experimental study of nine full-scale castellated beams is reported with the aim of investigation of the performance as well as effect of elastic bracing on the buckling stability of these structural elements. In addition to the presentation of the experimental observations and findings, the current test results are compared with the results of other reported experimental, analytical and numerical studies. Ultimately, the experimental findings and results are evaluated by considering the AISC 360–05 code requirements and predictions.

ABSTRACT: The nonlinear behavior of steel plate shear walls (SPSWs) with stiffened large rectangular openings used as windows or doors in buildings is studied. A number of SPSWs with and without openings are numerically analyzed, and the results are utilized (a) to characterize the behavior of SPSWs with the openings, (b) to study the effects of various opening features as well as size of local boundary elements (LBE) around the opening and thickness of infill plates on either side of the opening and (c) to investigate the changes in the system strength, stiffness and ductility due to the introduction of the openings. Results show that the procedure addressed by AISC Design Guide 20 for design of beams above and below the opening level is not perfect. Use of thicker or thinner infill plates or weaker profiles for the LBE can alter the yielding sequence in the system. Notably, the type, location and geometry of stiffened openings are not influential themselves on the system strength, although different LBE sizes required for different openings may have some effects. The introduction of stiffened openings in different SPSWs increases both the ultimate strength and stiffness, while somewhat decreases the ductility ratio.

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ABSTRACT: A new type of partially encased composite I-girder with corrugated steel web has been proposed to improve the structural performance of continuous girders under hogging moment. The shear behavior of such partially encased composite I-girders under anti-symmetric loading has been experimentally and analytically investigated. Experimental results show that the partially encased composite girders has superior shear strength compared to steel I-girders, since shear bucking of steel web is restricted by concrete encasement. The shear stiffness of the composite section is based on the total summation of corrugated web and concrete encasement with average thickness before cracking, and the ratio of shear resistance shared by the steel web and the concrete encasement depends on their shear stiffness. In addition, predicted shear strength of the partially encased composite girder with corrugated web is proposed according to the experimental failure mode and strain distribution. The analytical shear stiffness and shear resistance ratio at the elastic stage are verified by experimental results. And the calculated shear strength for steel and composite girders agree well with the experimental results. The comparison shows that the proposed analytical methods can be applied in predicting elastic shear stiffness and design shear strength for such partially encased composite girders with corrugated web.

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ABSTRACT: Computational modelling of the buckling strength of cold-formed steel members as influenced by initial geometric imperfections is studied. The geometric imperfections are represented by the member
eigenmode shapes. Along with the classical measure — the amplitude of imperfections, an energy measure defined by the square root of the elastic strain energy hypothetically required to distort the originally perfect structural element into the considered imperfect shape is used. Based on the measures, two approaches for the choice of the most unfavourable imperfections are suggested. Normalising imperfections by the amplitude, the energy measure is calculated as indicative parameter of imperfection significance. Vice versa, when adopting normalisation by the energy measure, the amplitude is used as a supporting parameter. The suggestions are illustrated on calculating the strength of an axially compressed steel lipped channel column with eigenmodes exhibiting local-distortional interactions. For eigenvalue and geometrically and materially non-linear strength calculations, the FEM codes MSC.NASTRAN and COSMOS/M are employed.

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ABSTRACT: Nine square concrete-filled box column (CFBC) specimens were fabricated and tested under monotonic axial loading. The loading tests were simulated with the commercial finite element program ABAQUS. The feasibility of the finite element models was verified. Based on tests and FEM simulation results, the following conclusions can be made. The development procedure of the concrete confinement mechanism of CFBCs was identified. After concrete crushing occurs, concrete confinement provided by the horizontal arch action starts to become noticeable. After buckling of the column wall, vertical arch action, which provides additional concrete confinement, is developed. Horizontal arch action acting together with vertical arch action provides significant confinement for the concrete to gain and recover its strength. A larger width-to-thickness ratio of the column wall results in the earlier development of vertical arch action. From the concrete confinement mechanism, there will be a strength drop and a strength recovery in the concrete component of the load versus axial strain curve. As a result of these findings, Mander's concrete confinement model and Sakino's concrete analytical model were not able to reasonably predict the stress–strain behavior of the concrete inside CFBCs.

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ABSTRACT: An experimental study was performed for batten columns subjected to combination of constant axial compression and reversed cyclic lateral loads to evaluate their cyclic response, available ductility and post failure behavior under seismic conditions. To determine and evaluate the available ductility of batten columns, the backbone curves have been developed using experimental hysteresis curves of columns. The effect of different parameters such as axial compression, distance between battens and distance between chords on the available ductility of batten columns have further been studied. The results reveal that the available ductility of batten columns is considerably low compared with solid web columns. The failure mode of batten columns is
the combination of local and overall buckling of their bottom chords. The geometrical specifications of batten columns have no considerable and uniform effect on their available ductility. Moreover, it is shown that the backbone curves of batten columns are basically different from solid web columns.

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ABSTRACT: Over the past two decades, fiber-reinforced polymer (FRP) composites have gradually gained wide acceptance in civil engineering applications due to their unique advantages including their high strength-to-weight ratio and excellent corrosion resistance. In particular, many possibilities of using FRP in the strengthening and construction of concrete structures have been explored. More recently, the use of FRP to strengthen existing steel structures has received much attention. This paper starts with a critical discussion of the use of FRP in the strengthening of steel structures where the advantages of FRP are appropriately exploited. The paper then provides a critical review and interpretation of existing research on FRP-strengthened steel structures. Topics covered by the review include steel surface preparation for adhesive bonding, selection of a suitable adhesive, bond behavior between FRP and steel and its appropriate modeling, flexural strengthening of steel beams, fatigue strengthening of steel structures, strengthening of thin-walled steel structures against local buckling, and strengthening of hollow or concrete-filled steel tubes through external FRP confinement. The paper concludes with comments on future research needs.


ABSTRACT: In this paper, the nonlinear behavior of the composite steel plate shear walls, in which steel infill plates was strengthened by the fiber reinforced polymers (FRP), is experimentally investigated. Tests are designed to evaluate the effect of Glass-FRP layers, the number of GFRP layers and the orientation of GFRP layers on the stiffness, shear strength, cumulative dissipated energy and other major seismic parameters in the composite steel plate shear walls. Experimental models are scaled as one-story steel shear panel models with hinge type connections as boundaries at four corners. In the first test, unstiffened steel infill plate is used for the testing as a reference test. However, in the next four tests, strengthened steel infill plates were used with different numbers and orientation of GFRP layers. Each test was performed under fully reversed cyclic quasi-static loading in the elastic and inelastic response zones of the specimens, in compliance with the ATC-24 (1992) test protocol. The experimental results indicated that by strengthening the infill steel plates yield by laminates strength, ultimate shear strength and cumulative dissipated energy can be significantly increased. The paper therefore presents the background, procedure and set-up used as well as the test results.
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ABSTRACT: In the hogging bending moment region, continuous composite beams are subjected to the ultimate limit state of lateral-torsional buckling, which depends on web stiffness as well as concrete slab and shear connection stiffnesses. These three stiffnesses compose the rotational stiffness of composite beams. Eurocode 4 defines this stiffness in composite beams with plane webs, but there are no conclusive studies on the stiffness of composite beams with sinusoidal-web profiles. This paper presents a formulation to evaluate the rotational stiffness of composite beams with sinusoidal-web steel profiles presented based on (a) test results for four representative prototypes of the inverted U-frame model, (b) the development and calibration of a numerical model using the ANSYS commercial finite element software, and (c) the computational processing of sixty-eight numerical models. In these models, the researchers attempted to vary all the parameters that could influence the rotational stiffness, such as web height and thickness, slab size and type (concrete or composite), number of shear connectors in the cross-section and longitudinal spacing of connectors.

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ABSTRACT: Openings in steel plate shear walls (SPSWs) in buildings are provided for architectural reasons as well as for access requirements. Despite the reduction of stiffness and strength in panels with an opening being well-understood, further studies are essential in order to determine both the mechanism and the degree of this degradation, as well as its dependency on the location and the size of the opening. To accomplish this aim, a non-linear finite element analysis is used in this paper to study the behaviour of both stiffened and unstiffened SPSWs with a single rectangular opening. The size and location of the opening are varied from model to model in order to determine their influences on the stiffness and strength of the system. Based on the results obtained, the strength and stiffness degradation of unstiffened panels are affected adversely by the location of the opening. In contrast, the re-location of an opening of a specific size within the panel area in stiffened panels does not appear to influence this degradation, so that the stiffness and strength deterioration are not a function of the location of the opening. As expected, both stiffened and unstiffened panels experience a progressive reduction in their stiffness and strength with an increase of the size of the opening. It is demonstrated further that with an increase in the opening ratio (width to height), the energy absorbed by the system arising from seismic loading considerations in both stiffened and unstiffened SPSWs show a linearly decreasing trend; this trend being less stiff for stiffened panels. Unstiffened SPSWs with a central opening experience the least energy absorption. It is also shown that the absorption of energy is substantially higher in stiffened panels when compared with their otherwise identical, but unstiffened, counterparts.

ABSTRACT: Based on the quasi-static test on eight CFST columns subjected to pure torsion and compression–torsion cyclic load, the torsion behavior of CFST columns with various section types, steel ratios and axial load levels was studied. The test results showed that the hysteretic curves of CFST columns under pure torsion and low compression–torsion cyclic load are very plump, which indicate that CFST columns have good seismic capacity. The unloading stiffness of CFST columns was equal to the initial elastic stiffness. The torsion capacity of CFST columns could be improved by the low compressive load, and the ductility was also good. But the torsion capacity of CFST columns would be reduced by the high compressive load. When CFST columns subjected to pure torsion, spiral diagonal compressive struts will be created in the in-filled concrete, and the axial components of the diagonal compressive force of the in-filled concrete was equal to the axial tensile force of the steel tube in order to satisfy the axial load equilibrium condition on the section, so the axial strain will be produced in the steel tube. The shear strain has good linear relationship with the rotation angle of the section when CFST columns subjected to pure torsion and compression–torsion combined action. Based on the test results and literatures available, the torsion mechanism of CFST columns was preliminarily analyzed.

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ABSTRACT: One of the key requirements for the desirable mechanical behavior of buckling restrained braces (BRBs) under severe earthquake loading is to prevent global buckling until the brace member reaches sufficient plastic deformation and ductility. This paper presents finite element analysis results of the proposed all-steel buckling restrained braces. The proposed BRBs have identical core sections but different buckling restraining mechanisms (BRMs). The objective of the analysis is to conduct a parametric study of BRBs with different amounts of gap (between the core and the BRM) and initial imperfections to investigate the global buckling behavior of the brace. The results of the analysis showed that BRM flexural stiffness could significantly affect the global buckling behavior of a brace, regardless of the size of the gap. In addition, a minimum ratio of the Euler buckling load of the restraining member to the yield strength of the core, $P_e/P_y$, is suggested for design purposes. This ratio is the principal parameter that controls the global buckling of BRBs.

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ABSTRACT: Shear behavior of partially encased composite I-girders with corrugated web has been investigated analytically and numerically in this paper. A 3-D finite element model with geometric and material
nonlinearity is established and verified by the experiments. Subsequently, a parametric study is carried out to examine the effects of geometric and material properties on the shear behavior which includes corrugation, height, thickness, connection degree between steel web and concrete encasement. It is found that the ultimate shear strength of steel I-girders is improved with increases in the thickness, height and yield strength of corrugated web, while the ultimate shear strength of partially encased composite I-girders increases with the thickness, yield strength of corrugated web and the thickness, compressive strength of concrete encasement. However, the stud stiffness has little influence on the ultimate shear strength. Moreover, the concrete encasement improves the shear strength of steel I-girders, the degree of improvement increases with the thickness and compressive strength of the concrete, but decreases drastically with the thickness of corrugated web. Therefore, it is suggested that concrete should be poured on the corrugated web with thin thickness or low yield strength to prevent buckling occurrence before yielding of steel web. Finally, shear strength prediction equations are proposed and verified by numerical results. The calculated shear strength agree well with the numerical results for steel I-girders before and after composite with concrete, which indicates that the proposed analytical equations can be applied to predict the shear strength of such partially encased composite girders with corrugated web.


ABSTRACT: A full scale experimental investigation into the strength and behaviour of prestressed stayed columns in compression has been conducted. Results, including full load versus end-shortening curves, for a total of 18 test specimens are presented. Two critical modes of buckling — symmetric and antisymmetric — with interactive post-buckling are demonstrated experimentally and the imperfection sensitivity of the stayed columns is investigated. Interactive buckling is observed primarily when the individual buckling loads of the antisymmetric and symmetric modes are close or when the antisymmetric mode is critical. Analysis of the results reveals that increased prestress leads to an increased load-carrying capacity when instability occurs in the symmetric mode, but the reverse trend is found when the antisymmetric mode is critical.


ABSTRACT: Despite growing interest in the use of stainless steel in construction and the development of a number of national and regional design codes, stainless steel is often still regarded as only suitable for specialised applications. This is partly due to the high initial material cost associated with the most commonly adopted austenitic grades. The initial material cost of stainless steel is largely controlled by the alloy content, in particular the level of nickel, which is around 8%–10% for the common austenitic grades. A recently developed grade, known as lean duplex stainless steel (EN 1.4162), has a far lower nickel content, around 1.5%, and hence lower cost. Despite the low nickel content, it possesses higher strength than the common austenitic stainless steels, along with good corrosion resistance and high temperature properties and adequate weldability and fracture toughness. The structural performance of lean duplex stainless steel remains relatively unexplored to date with only a few studies having been performed. For this reason, an experimental and analytical research programme investigating the structural characteristics of lean duplex stainless steel was initiated. The present paper summarises the laboratory tests performed on lean duplex stainless steel welded I-sections. The experiments include material testing, stub column tests and 3-point and 4-point bending tests. The experimental
data were supplemented by results generated by means of a comprehensive numerical investigation including parametric studies covering a wide range of cross-sections. The obtained experimental and numerical results, together with the results of previous tests performed on lean duplex stainless steel cold-formed hollow sections are reported and used to assess the applicability of existing cross-section classification limits and the continuous strength method (CSM) to lean duplex stainless steel. Furthermore, the structural performance of lean duplex stainless steel was compared to the more commonly used stainless steel grades. Finally, based on the obtained results, design recommendations suitable for incorporation into Eurocode 3: Part 1.4 are proposed.


ABSTRACT: This paper presents a study on the performance of concrete-filled double skin composite tube columns (CFDSCT) under axially compressive loads using both experimental and numerical methods. The CFDSCT column investigated consists of an octagonal steel tube as its outer skin layer, a circle PVC-U pipe as its inner skin layer, and high strength concrete filled in between the two layers. Influences of concrete strength, radius-to-thickness ratio, hollow section ratio, and slenderness ratio on the ultimate axial compressive capacity of the CFDSCT column are examined. It is found that the ultimate axial compressive capacity of the CFDSCT column increases with the strength of concrete, but decreases with either increased radius-to-thickness ratio or increased hollow section ratio. Based on the findings from the present experimental and numerical studies, a design formula for predicting the ultimate load of the CFDSCT column is proposed.

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This paper presents a numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections in compression. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. The model was then used for an extensive parametric study to investigate the interaction effects of constituent plate elements on Class 3 slenderness limit and section capacities of cold-formed high strength stainless steel square and rectangular hollow sections in compression. The numerical investigation shows that the interaction effects of constituent plate elements on cross-section response are quite obvious particularly for slender sections. The design provisions on Class 3 slenderness limit and effective width equations specified in the EC3 Code and proposed by Gardner and Theofanous are suitable for square hollow sections, but not for rectangular hollow sections since they do not take into consideration of interaction effects of constituent plate element. Hence, the new Class 3 slenderness limit and the section capacity design equations based on the whole cross-section response are proposed in this study, which carefully consider the interaction effects of constituent plate elements.

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ABSTRACT: This paper presents the failure pattern, ultimate static strength and detailed behavior of un-stiffened T and Y tubular joints under axial brace compressive loading using finite element method performed by ABAQUS software package. Properties of the un-stiffened tubular joints were extracted from the available experimental-based tubular joint database. Utilizing the Modified Riks Method in numerical analyses led to an accurate simulation of joint behavior and also helped to investigate its correct failure pattern. The modes of failure observed throughout the numerical analysis were local bending of the chord member, ovalization and plastic failure of the chord. The results obtained from the numerical modeling revealed the critical areas on the joint surface with respect to ovalization, deflections and stresses. Also, the ultimate strength predicted by the numerical analysis was compared and validated with available experiment results. Despite the fact that much research has been conducted on tubular joints which have mostly focused on the estimation of ultimate strength or stress concentration factors rather than detail study of joint behavior, the present detail investigation has provided a thorough understanding of joint behavior under axial compressive loads. Such an in-depth and detail tubular joint investigation has been rarely reported in the open literature.

Shan-shan Cheng, Boksun Kim and Long-yuan Li (School of Marine Science and Engineering, Plymouth University, Plymouth PL4 8AA, United Kingdom), “Lateral–torsional buckling of cold-formed channel sections subject to combined compression and bending”, Journal of Constructional Steel Research, Vol. 80, pp 174-180, January 2013

ABSTRACT: This paper presents an analytical study of the flexural buckling and lateral–torsional buckling of cold-formed steel channel section beams subject to combined compression and bending about their major and minor axes. For channel section beams a bending about the minor axis creates a non-symmetric pre-buckling stress distribution, which has a significant influence on the lateral–torsional buckling of the beams. This kind of feature has not been discussed in the existing literature. The focus of this present study is the interaction between the compression load and the bending moments about the major and minor axes. It has been found that for a section subject to combined compression and the major-axis bending the bending moment will decrease the critical compression load, although the critical value of the largest compressive stress in the section actually increases with the applied bending moment. However, for a section subject to combined compression and the minor-axis bending the effect of the bending moment on the critical compression load depends on the direction of bending applied. For bending that creates a compressive stress in the lips the bending moment will reduce the critical compression load. However, for bending that creates a compressive stress in the web the bending moment has almost no influence on the critical compression load.


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ABSTRACT: The effects of concrete, plaster and polystyrene precast cover panels on the buckling and postbuckling behaviors of slender steel plates subjected to in-plane shear loads are investigated. Precast cover panels are principally used for acoustic and thermal insulation in structural members such as steel plate shear walls. These cover panels, in unison; provide lateral constraints to the buckling induced out-of-plane deformations of plates. Parametric studies on the effects of material and thickness of cover panels on nonlinear behavior of plates under shear loads are performed via finite element simulations. The results show that bilateral cover panels can considerably influence the buckling mode shapes and ultimate loads of slender plates. In addition, cover panels which possess sufficient flexural rigidity, force plates to enter their full plastic state and dissipate their associated maximum energy.

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ABSTRACT: This paper reports an investigation into the impact performance of concrete filled steel tubular (CFST) members. A series of tests were carried out to obtain the failure modes and the time history of the impact forces for the composite components under lateral impact. The testing parameters include the axial load level on CFST specimens, constraining factor and the impact energy. A finite element analysis (FEA) model was developed, in which the strain rate effects of steel and concrete materials, interaction between the steel tube and the core concrete, as well as the confinement effect of the outer steel tube provided to the core concrete were considered. The test data were then used to verify the accuracy of the FEA model and generally a good agreement was achieved. A full-range analysis on the impact behavior of CFST member was performed by using the FEA model.


ABSTRACT: During bridge erection employing the incremental launching method, plate girders are subjected to a combined loading situation. Due to the support reaction, the thin webs are withstanding concentrated loads, and due to the self weight of the launching nose and the span between the piers the web is also under the action of bending and shear force. This paper is aimed at investigating the nonlinear behavior of unstiffened girder webs subjected to combined loading (concentrated loading, bending and shear) by using the finite element method. Firstly, the numerical models are validated against experimental results taken from the literature. Secondly, each individual resistance is calculated in order to normalize the applied loads. Thereafter, a parametric analysis is conducted looking at the interaction between the three types of loading, and a combined failure mode is identified. Finally, the results shows limits in the resistance when all three loads are applied.

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ABSTRACT: A numerical study of the strength and behaviour of reinforced coped beams is presented in this paper. Nonlinear finite element analysis was conducted to predict the structural behaviour and strength of the test specimens examined in a different research study by the authors. The finite element analytical results generally agreed well with the test results. Subsequently, a parametric study using the validated FE models was conducted to further examine the effects of various parameters on the strength and behaviour of reinforced coped beams. For all cases examined in the study, none of the reinforced coped beams experienced flexural failure at the coped section. The parametric results show that for the same beam section, the strength of the reinforced coped beams decreases with increasing cope depth to beam depth ratio (d_c/D), irrespective of the cope length to beam depth ratio (c/D) and types of stiffener. In addition, the strength of the beams generally decreases with increasing c/D ratio. It was also found that for the cope details examined in the study, coped beam sections with a web depth-to-thickness ratio (d/t_w) less than or equal to 52.7 and reinforced by a pair of longitudinal stiffeners are able to develop either the plastic moment capacity of the full beam section near the loading position or the shear yield capacity of the coped section. For a coped beam section with a larger d/t_w ratio, a stiffener arrangement consisting of longitudinal and transverse stiffeners is recommended.

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ABSTRACT: The objective of the current research is to present ultimate load carrying capacities and finite element analysis of optimally designed steel cellular beams under loading conditions. The tests have been carried out on twelve full-scale non-composite cellular beams. There are three different types of NPI_CB_240, NPI_CB_260 and NPI_CB_280 I-section beams, and four tests have been conducted for each specimen. These optimally designed beams which have beginning span lengths of 3000 mm are subjected to point load acting in the middle of upper flange. The design method for the beams is the harmony search method and the design constraints are implemented from BS 5950 provisions. The last part of the study focuses on performing a numerical study on steel cellular beams by utilizing finite element analysis. The finite element method has been used to simulate the experimental work by using finite element modeling to verify the test results and to investigate the nonlinear behavior of failure modes such as web-post buckling and Vierendeel bending of steel cellular beams.

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ABSTRACT: A review is made of the treatment of cross-sectional classification in four major current design specifications (Eurocode, AISC, AIJ and Chinese Codes) including both the non-seismic and seismic cases. Three rules, namely ‘individual plate rule’, ‘limited load pattern rule’ and ‘monotonic rule’ are present in most of the specifications but these rules neglect the effect of some important interactive behavior. A review of the research base, paying particular attention to interactive effects and design criteria under complex load patterns, provides sufficient evidence for the conclusion that web–flange interaction, the axial force ratio, different bending axes and cyclic loading are significant features that influence cross-sectional behavior but have received little consideration. Thus, the necessity for current specifications to improve those rules has been highlighted. Finally the paper assesses the needs for future research to effect the significant improvements that would appear to be necessary for classifying cross-sections.

Poologanathan Keerthan and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Suitable stiffening systems for LiteSteel beams with web openings subjected to shear”, Journal of Constructional Steel Research, Vol. 80, pp 412-428, January 2013 https://doi.org/10.1016/j.jcsr.2012.08.004

ABSTRACT: LiteSteel beam (LSB) is a new cold-formed steel hollow flange channel section produced using a simultaneous cold-forming and dual electric resistance welding process. It is commonly used as floor joists and bearers with web openings in residential, industrial and commercial buildings. Their shear strengths are considerably reduced when web openings are included for the purpose of locating building services. A cost-effective method of eliminating the detrimental effects of a large web opening is to attach suitable stiffeners around the web openings of LSBs. Experimental and numerical studies were undertaken to investigate the shear behavior and strength of LSBs with circular web openings reinforced using plate, stud, transverse and sleeve stiffeners with varying sizes and thicknesses. Both welding and varying screw-fastening arrangements were used to attach these stiffeners to the web of LSBs. Finite element models of LSBs with stiffened web openings in shear were developed to simulate their shear behavior and strength of LSBs. They were then validated by comparing the results with experimental test results and used in a detailed parametric study. These studies have shown that plate stiffeners were the most suitable, however, their use based on the current American standards was found to be inadequate. Suitable screw-fastened plate stiffener arrangements with optimum thicknesses have been proposed for LSBs with web openings to restore their original shear capacity. This paper presents the details of the numerical study and the results.

Farid Abed, Mohammad AlHamaydeh and Suliman Abdalla (Department of Civil Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates), “Experimental and numerical investigations of the compressive behavior of concrete filled steel tubes (CFSTs)”, Journal of Constructional Steel Research, Vol. 80, pp 429-439, January 2013, https://doi.org/10.1016/j.jcsr.2012.10.005

ABSTRACT: This paper presents an experimental study to investigate the compressive behavior of circular concrete filled steel tubes (CFSTs) when subjected to pure axial loading at a low rate of 0.6 kN/s. CFSTs of three different diameter-to-thickness (D/t) ratios of 54, 32, and 20 are considered in this study filled with two concrete's compressive strengths of 44 MPa and 60 MPa. The measured compressive axial capacities are compared to their corresponding theoretical values predicted by four different international codes and standards: the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI 318), the Australian Standard (AS), and Eurocode 4. Result comparisons also included some suggested equations found in the literature. It was found that the effect of (D/t) ratio on the compressive behavior of the CFST specimens is greater than the effect of the other factors. The underestimation of the axial capacities calculated by most of
these codes reduces as the D/t ratio increases as verified by the experimental results. A nonlinear finite element (FE) numerical model using the commercial software package ABAQUS is also developed and verified using the presented experimental results.

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“Effect of confinement on steel-concrete composite light-weight load-bearing wall panels under compression”,  

https://doi.org/10.1016/j.jcsr.2012.10.008

ABSTRACT: The strength of composite wall panel depends on plain concrete strength, degree of confinement and the composite action of steel and concrete acting together. This paper presents details of an experimental study on the effect of confinement on axial capacity and behaviour of steel-foamed concrete composite panels. Five small scale load tests are carried out on wall panels with different configuration of studs and sheet edge boundary conditions. Light weight foamed concrete (LFC) is used as infill material and the interaction between sheeting and concrete is achieved by using through–through studs. The loading is primarily distributed over the concrete surface, so as to avoid early/brittle local buckling of sheet under direct compressive loading of wall panel. Failure modes such as vertical separation and diagonal shear failure of concrete are observed and the axial resistance of wall is found to increase with the degree of confinement provided by studs and sheet edge conditions. Also the controlled lateral deformations of confined concrete by steel sheeting due to interconnecting studs exhibited ductile deformations after the post peak behaviour. Based on the failure modes obtained from the tests, a new method is proposed to determine the axial resistance of composite walls.

Giuseppe Brando and Gianfranco De Matteis (Department of Engineering and Geology, University “G d’Annunzio” of Chieti-Pescara, Italy), “Buckling resistance of perforated steel angle members”,  

ABSTRACT: The detrimental effect due to perforations on the buckling resistance of perforated hot-rolled steel L-shaped members in compression is evaluated in the current paper. FEM numerical models are used in order to carry out buckling and non-linear analyses with the aim of detecting both the critical and the collapse load of the studied elements in case of one or more holes. The obtained results show that, although the critical load is not strongly influenced by the presence of holes, the load bearing capacity, when members are characterized by middle–low slenderness, could be significantly diminished when drillings of common sizes are applied on one of the two section legs, meaning that current methods given by the codes are not fully conservative. As a consequence, specific stability curves are determined and proposed as useful alternative design procedure.

Jahid Zeghiche (Department of Civil Engineering, Al-Baha University, Saudi Arabia), “Further tests on thin steel and composite fabricated stubs”,  

ABSTRACT: Results for tests conducted on thin cold fabricated steel–concrete stubs are presented. The studied sections were made of two cold formed U shaped steel plates welded to form a steel box or an I shaped steel section. The steel cross section dimensions were: 100 × 70 × 2 mm. The main studied parameters were: the stub height, the welding fillet nature and its location, the steel cross section shape, and the in filled concrete and its age. A total of 48 stubs were tested, 22 were empty and 26 were filled with concrete. The concrete was made of
crushed slag from blast furnace as a natural gravel substitute. All failure loads were predicted numerically using Abacus program and by Euro-codes EC3 and EC4 for steel and composite stubs respectively. From the test results it was confirmed that the length and the discontinuous welding fillet for empty stubs had a drastic effect on the load carrying capacity and the failure mode was mainly a premature local buckling mode. Test results showed that I shaped steel stubs had a higher compression load carrying capacity with a lower load decrease rate compared to fabricated rectangular steel stubs with height over 200 mm. Providing rectangular steel stubs with continuous welding on mid-depth improved the load carrying capacity for both rectangular empty steel and composite stubs. Regarding the concrete age effect, test results obtained from testing composite stubs after 3 years of concrete casting date, showed enhanced performance. Both numerical and test results were in good agreement whereas EC3 and EC4 predictions were not conservative.

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ABSTRACT: Research on earthquake-induced collapse simulation has a great practical significance for super-tall buildings. Although mega-braced frame-core tube buildings are one of the common high-rise structural systems in high seismic intensity regions, the failure mode and collapse mechanism of such a building under earthquake events are rarely studied. This paper thus aims to investigate the collapse behavior of a super-tall mega-braced frame-core tube building (H = 550 m) to be built in China in the high risk seismic zone with the maximum spectral acceleration of 0.9 g (g represents the gravity acceleration). A finite element (FE) model of this building is constructed based on the fiber-beam and multi-layer shell models. The dynamic characteristics of the building are analyzed and the earthquake-induced collapse simulation is performed. Finally, the failure mode and mechanism of earthquake-induced collapse are discussed in some detail. This study will serve as a reference for the collapse-resistance design of super-tall buildings of similar type.

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ABSTRACT: New type of cellular beams with sinusoidal shape of openings shows a specific behavior in comparison with the standard circular openings. Full scale tests were realized on three beams representing various dimensions of the openings. The aim was to observe the failure modes of these beams and to obtain the ultimate values of strength. The specimens were heavily gauged to clearly identify the local failure modes of the opening zone. Two specific failure modes were observed. For the opening with large height, the failure is reached by the formation of four plastic hinges at the corners of the critical section (Vierendeel bending). This mode is similar to that of the rectangular opening. Whereas with the small opening, failure arises by the local instability of the compressed out stand panel in the sinusoidal parts of the opening. A numerical model is developed and calibrated on the basis of the experimental results. The numerical model is used to analyze with more details the behavior of the critical opening including the stress distribution in its different parts. The
experimental results provided useful qualitative and quantitative information to understand the behavior of the cellular beams with sinusoidal openings. The numerical model showed a good accuracy in the prediction of the experimental results. It can be used as a tool to generate complementary results to develop an analytical model.

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ABSTRACT: Using the recently proposed Finite Particle Method (FPM), we present the post-buckling analysis of space trusses considering both geometric and material nonlinearities and member fracture. The FPM models the space truss with finite separated particles. Since every particle is considered to be in dynamic equilibrium, the static and dynamic analysis can be unified to the same procedure. Particles are free to separate from each other with FPM, which is advantageous in the simulation of member fracture. Fictitious motion procedures are developed in the particle internal force calculations to handle strong geometric nonlinearity without iterative correction and stiffness matrix calculation. The material nonlinearity is accounted for by tracing a complete stress–strain relationship including elastic and inelastic buckling, yielding, post-buckling, unloading and reloading. The fracture criterion and fracture model of the FPM are developed to simulate member fracture. Phenomena of multi-snap-through and dynamic fracture during the post-buckling range of two classic space trusses are obtained using present method. Corresponding results are verified by comparisons of numerical simulation results and energy conservation studies.

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ABSTRACT: This paper presents some new developments in structural stability analysis. A novel Trefftz-type finite element and efficient algorithms are proposed for calculating numerically exact solutions for frame structures. New shape functions are constructed by using general solutions of the homogeneous governing equation and an exact Trefftz element is formulated. An iterative algorithm based on conventional eigenvalue extraction method is then proposed, with which very accurate solutions can be obtained efficiently by using coarse finite element meshes. Further, an efficient method based on the new element matrices and Rayleigh's quotient is developed for a posteriori error estimation and solution improvement. Numerical examples are presented to demonstrate the effectiveness of the proposed element and algorithms. Finally, concluding remarks are made including those on the further extension of the approach.

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ABSTRACT: Concrete-filled stainless steel tubes can be considered as a new type of composite construction technique. The characteristics of stainless steel are quite different from those of mild steel in terms of strength, ductility, corrosion resistance and maintenance costs. This paper presents the behaviour of hollow and concrete-filled stainless steel tubular columns under static and impact loading. An experimental test series has been carried out at the University of Wollongong and the University of Western Sydney to investigate the performance of stainless steel hollow and concrete-filled steel tubular (CFST) columns under static and impact loads. This paper presents the results of the first test series, where stainless steel was used and no axial load was applied. The effects of a combined axial and transverse impact loads as well as the location of the impact loading have been considered in a subsequent series. Finite element modelling was carried out to predict the behaviour of composite columns under a lateral static or impact load using ABAQUS to simulate the static and impact experiments. The comparison of the experimental results with numerical results is the main objective of this paper. Moreover, the behaviour of hollow tubes under impact loading is compared with that of the in-filled sections. This paper also compared results of hollow and CFST stainless steel columns with those of mild steel columns under both static and impact loading. Generally, the stainless steel specimens showed improved energy-dissipating characteristics compared with their mild steel counterparts, especially when concrete was used to fill the hollow tubes.

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ABSTRACT: Tests are reported on composite slabs with trapezoidal sheeting and longitudinal reinforcing bars above the troughs. The contribution from this reinforcement to resistance to longitudinal shear is found to be substantial. Analyses of the results lead to a design method that allows for it. It may not be possible to take full advantage in the design of this extra resistance, because the predicted deflection in service may then become excessive. An appendix gives an elastic–plastic model that accurately predicts the deflection of the slabs just before failure. A list of the principal nomenclature is included.

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ABSTRACT: The strength and stability of steel columns that have suffered localized damage are investigated through analytical and computational means. An analytical model based on the Rayleigh–Ritz technique is
employed in conjunction with detailed finite element models that were validated using available experimental results. A parametric study is performed using the finite element models to assess the effect of location of damage, extent of damage, role of initial imperfection, as well as asymmetric damage on the stability of a steel column. Design guidelines utilizing commercial software typically found in a design office are presented to provide a practical technique for approximating the results obtained using the analytical and computational models. Analytical and simulation results show that localized flange loss in a steel column could lead to a severe reduction in its axial resistance.

ABSTRACT: This paper describes a test program on cold-formed lean duplex stainless steel columns compressed between pinned ends. Two square hollow sections and four rectangular hollow sections were tested at different column lengths. The material properties of the test specimens were obtained from tensile coupon tests and stub column tests. The test specimens were cold-rolled from flat strips of lean duplex stainless steel (EN1.4162). The column specimens were concentrically loaded between pinned ends. The ultimate loads and the failure modes of each column are presented. The American, Australian/New Zealand and European specifications for stainless steel structures are assessed by comparing the column test strengths and available data in the literatures with the design strengths. It should be noted that these specifications do not cover the material of lean duplex stainless steel. A reliability analysis was carried out to assess the current design rules of stainless steel for lean duplex material. Generally, the specifications are able to predict the strengths of the tested columns. The design approach of using full cross-section area and material properties obtained by stub column tests for all classes of sections including slender sections was recommended. This recommended design approach does not require section classification and calculation of effective area, and provides a more accurate and less scattered prediction than those using the current design rules.

ABSTRACT: Concrete-filled-steel-tube (CFST) columns have been widely adopted for column construction of tall buildings due to its superior strength and ductility performance contributed by the composite action. However, this beneficial composite action cannot be fully developed at early elastic stage as steel dilates more than concrete and thereby causing imperfect interface bonding, which reduces the elastic strength and stiffness. To resolve the problem, confinement in the form of tie bars is proposed in this study to restrict the elastic lateral dilation of concrete. For verification, 30 CFST columns of various dimensions cast with normal- (NSC) or high-strength concrete (HSC) and installed with tie bars were tested under uni-axial compression in this study. From the results, it was evident that: (1) tie-confined CFST columns had uni-axial strength larger than those of unconfined CFST columns. (2) Tie bars can increase slightly the elastic stiffness of the CFST columns. (3) Tie bars can restrict effectively the lateral dilation of CFST columns. (4) The failure modes of tie-confined NSCFST and HSCFST columns were the local buckling at the ends and formation of longitudinal steel cracks initiated at bolt holes. Lastly, based on the test results, analytical model taking into account the confining effects of steel tube have been developed to predict the uni-axial strength of tie-confined CFST columns.
A very efficient type of wind turbine tower is the tubular steel tower configured as a cantilever cylindrical or conical shell, which is used considerably nowadays. A typical feature of such towers is the presence of a manhole cutout near the bottom. This cutout is of considerable dimensions and lowers significantly the tower strength including stress concentrations and increased danger of local buckling. Therefore, it is common to stiffen the region around the cutout aiming at compensating for this loss of strength. In this paper the most common types of stiffening are investigated by means of nonlinear finite element analyses calibrated via experimental testing and the efficiency of each type is highlighted. It is found that simple stiffening types consisting of either a peripheral frame or two vertical stringers and a ring are particularly efficient and can be used instead of more complex ones. Rules for dimensioning of the stiffeners are also proposed.

In this study, shear loading tests on plate girder specimens were conducted to evaluate the shear behaviors of locally corroded web panels, including their critical shear buckling loads and shear strengths. The shear failure modes were also examined with regard to the corrosion damage in the web panels. For the shear loading tests, a total of five plate girder specimens were fabricated to consider different corrosion heights and mean corrosion depths of a corroded web base on the corrosion pattern of the web of a plate girder bridge. The critical shear buckling loads and shear buckling strengths recorded in the shear loading tests were evaluated and compared with design specifications. From the test results, the steel plate girder with a corroded panel was observed to have a larger shear failure region (tensile field band) than that with the un-corroded web panel, with the failure region of the former moving in the direction of the lower web panel. The shear buckling strength of the former decreased by up to 10% over that of the latter owing to the decrease in the shear resistance as a result of the decreased web thickness.

Concrete filled steel tubular (CFST) members are subjected to local bearing forces in a large number of truss and lattice structures. Previous research has focused on rectangular CFST members under such loading condition. There is a lack of understanding on circular CFST members subjected to local bearing force. This paper intends to fill the knowledge gap in this area. A series of tests were conducted on circular CFST, unfilled circular hollow section (CHS) steel tube and plain concrete specimens loaded with local bearing force. The load was applied either perpendicularly to the member or at an angle of 45°. A deformation limit was adopted to define the ultimate strength of the specimen since the load verse deformation curve exhibits a ductile
behavior. The effects of important parameters were investigated based on the test results. Finally, design formulae were developed to predict the ultimate strength of circular CFST members under local bearing forces.

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ABSTRACT: The tapered concrete-filled double skin steel tubular (CFDST) columns have been used in transmission towers with potential for other types of composite frame structures. However, the behavior of the tapered CFDST column under eccentric compression has not yet been studied, which will hinder the employment of such members. This paper reports an investigation on eccentrically loaded tapered CFDST columns with different load eccentricities. The numerical investigation was also carried out by using the finite element model to predict the behavior of the tapered member. Comparisons were made between the tapered and straight members on the strength and stress distribution. The stability of the tapered column was studied through numerical calculation. Finally, the load carrying capacity of the tapered CFDST column under eccentric compression was predicted using the concept of “equivalent column”.

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ABSTRACT: Jacket-type offshore platforms play an important role in oil and gas industries in shallow and intermediate water depths such as Persian Gulf region. Such important structures need accurate considerations in analysis, design and assessment procedures. In this paper, nonlinear response of jacket-type platforms against extreme waves is examined utilizing sensitivity analyses. Results of this paper can reduce the number of random variables and consequently the computational effort in reliability analysis of jacket platforms, noticeably. Effects of foundation modeling have been neglected in majority of researches on the response of jacket platforms against wave loads. As nonlinear response of the pile foundation is one of the most important sources of potential nonlinearity in the response of offshore platforms, in this study, a powerful model which is able to consider Pile–Soil–Structure Interaction (PSSI) is employed. Therefore, PSSI parameters as well as other parameters such as uncertainties in the prediction of the wave force on jacket structure and uncertainties in structural model are utilized in sensitivity analyses. In this research, pushover methods as well as an advanced approach named “Incremental Wave Analysis (IWA)” are employed. Consequently, collapse prevention limit state of jacket platforms is investigated through different outcomes of pushover and IWA methods including Reserve Strength Ratio, ultimate capacity, collapse displacement and Collapse Wave Height indicators. In order to consider the effects of correlation between random variables, a robust method of sensitivity analysis named correlation coefficient approach is also employed.

O. Curadelli (Laboratory of Experimental Dynamic, National University of Cuyo, CONICET, Centro Universitario - Parque Gral. San Martín - (5501) Mendoza, Argentina), “Equivalent linear stochastic seismic

ABSTRACT: Seismic performance of cylindrical liquid storage tanks base-isolated by bilinear bearings is investigated. The paper displays a stochastic parametrical study in which three design parameters, namely isolation period, yield strength and viscous damping ratio, characterizing the isolation system are taken into consideration. The earthquake excitation, modeled as a stationary random process, is characterized by a power spectral density function calculated via a compatible seismic design spectrum. The stochastic response of the base-isolated cylindrical tanks is obtained by the convolution between the frequency response function of the system and the input power spectrum. To determine effective damping and stiffness coefficients corresponding to the equivalent linear system a statistical linearization scheme was used. For the purpose of evaluating the seismic behavior under different conditions, two liquid levels (aspect ratios) and soil types (soft and stiff soil) were considered. Thus, the study demonstrates the influence of each characteristic parameter of the isolation system and soil conditions on the response of cylindrical base-isolated tanks and principally allows visualizing the seismic performance that can be achieved through the selection of those parameters under certain soil conditions. Further, it is confirmed that soft soil conditions amplify the overall response of the system specially the base and sloshing displacements, as well as the normalized base shear to a lesser extent.

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ABSTRACT: This paper describes a material test programme carried out as part of an extensive study into the prediction of strength enhancements in cold-formed structural sections. The experiments cover a wide range of cross-section geometries – twelve Square Hollow Sections (SHS), five Rectangular Hollow Sections (RHS) and one Circular Hollow Section (CHS), and materials – austenitic (EN 1.4301, 1.4571 and 1.4404), ferritic (EN 1.4509 and 1.4003), duplex (EN 1.4462) and lean duplex (EN 1.4162) stainless steel and grade S355J2H carbon steel. The experimental techniques implemented, the generated data and the analysis methods employed are fully described. The results from the current test programme were combined with existing measured stress–strain data on cold-formed sections from the literature and following a consistent analysis of the combined data set, revised values for Young's modulus E and the Ramberg–Osgood material model parameters n, n’0.2,a and n’0.2,1.0 are recommended. A comparison between the recommended values and the codified values provided in AS/NZS 4673 (2001) [1], SEI/ASCE-8 (2002) [2] and EN 1993-1-4 (2006) [3] is also presented. The test results are also used in a companion paper Rossi et al. (submitted for publication) [4] for developing suitable predictive models to determine the strength enhancements in cold-formed structural sections that arise during the manufacturing processes.

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ABSTRACT: Cold-formed structural sections are manufactured at ambient temperature and hence undergo plastic deformations, which result in an increase in yield stress and a reduction in ductility. This paper begins
with a comparative study of existing models to predict this strength increase. Modifications to the existing models are then made, and an improved model is presented and statistically verified. Tensile coupon data from existing testing programmes have been gathered to supplement those generated in the companion paper [1] and used to assess the predictive models. A series of structural section types, both cold-rolled and press-braked, and a range of structural materials, including various grades of stainless steel and carbon steel, have been considered. The proposed model is shown to offer improved mean predictions of measured strength enhancements over existing approaches, is simple to use in structural calculations and is applicable to any metallic structural sections. It is envisaged that the proposed model will be incorporated in future revisions of Eurocode 3 [2,3].

Mina Seif and Therese McAllister (National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 8611, Gaithersburg, MD 20899, USA), “Stability of wide flange structural steel columns at elevated temperatures”, Journal of Constructional Steel Research, Vol. 84, pp 17-26, May 2013
https://doi.org/10.1016/j.jcsr.2013.02.002
ABSTRACT: There is a lack of understanding of how structural systems perform under realistic, uncontrolled fires. Fire protection of steel structures is usually provided through prescriptive requirements. The development of performance-based standards and tools requires explicit consideration of fire effects on structural components and systems. This paper presents a parametric study employing nonlinear material and geometric finite element analyses to model the response of wide flange steel column sections at elevated temperatures. The parametric study varied the axial load and cross-sectional slenderness of three lengths of column sections. The column sections were uniformly heated until they exhibited either inelastic or elastic buckling failure. Typically, cross-sectional slenderness is addressed through limiting the element (flange/web) width to thickness ratio, so only member buckling occurs. However, as members are heated, the modulus of elasticity and the yield strength are reduced, which (in effect) results in slender elements at elevated temperatures. Computational results illustrate the relationship between local slenderness in the web and/or flanges and the local and global buckling modes under varying load and temperature conditions.

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ABSTRACT: The behavior of lean duplex stainless steel plate girders (LDIPGs) with slender unstiffened webs is studied in this paper. Firstly, shell finite element models are validated using experimental test results available in the literature. Secondly, these models are used to investigate the behavior of LDIPGs subjected to uniform bending. Parametric studies for the LDIPGs are carefully designed based on three parameters: the radius of gyration of the compression flange ($r_T$), the section modulus ($S_x$), and the unbraced length ($L_b$). The results showed that LDIPGs with higher $r_T$ but similar $S_x$ values can attain higher flexural strengths compared to their yield strengths because of the higher torsional rigidity of the flanges and stockier webs. On the other hand, by increasing the $S_x$ value of the girder but keeping fixed the $r_T$ values, the moment carried by the girder is found relatively to decrease with the simultaneous increase in the amount of steel. Finally, the numerical results are compared with predictions given by design standards. It is found that the EC3 provides conservative bending predictions. Accordingly, the imperfection factor associated to buckling curve ($c$) is recommended to be used in the scope of the design method provided by EN 1993-1-4.
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ABSTRACT: A new approach to develop seismic response factors for the design of structural systems has recently been developed by the Applied Technology Council and published in the FEMA P-695 document. The FEMA P-695 assessment methodology provides a comprehensive and objective approach to evaluate the performance factors based on non-linear structural analysis, while considering the uncertainties in design requirements, supporting test data, and the non-linear model. The goal of the methodology is to ensure that buildings designed with the selected performance factor have an acceptably low likelihood of structural collapse under extreme (rare) earthquake ground motions. The methodology is based on the design and assessment of representative archetypical building designs, whose collapse performance is evaluated through a series of non-linear static and dynamic analyses using numerical models that are calibrated to experimental test data. This methodology is applied to evaluate the seismic performance factors for a newly proposed lightweight steel shear wall seismic force resisting system, developed by Tipping Mar and Associates of Berkeley, California. The system consists of a steel corrugated sheet shear wall for use in mid-size residential and commercial structures. The calibration of the non-linear analysis model parameters to experimental data uses genetic algorithms. The system archetypes evaluated in this study are shown to meet the FEMA P-695 acceptance criteria for a seismic response modification factor of $R$ equal to 4.

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ABSTRACT: In this paper, the geometric nonlinear bending response of angle-section beams of finite length is investigated by using energy methods. The basic assumptions used in the present study are that the total strain energy of an angle-section beam subjected to pure bending can be simplified into a two-stage process. One is the bending response of the two legs behaving as the plate; the other is the overall bending response as a beam with flattened section. The nonlinear bending response is derived by applying the minimum potential energy principle and the corresponding static and dynamic critical moments associated with the section flattening-induced buckling are determined. To validate the analytical solution developed, geometric nonlinear finite element analyses are also conducted. Good agreement between the present solution and the FEA results is demonstrated.

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ABSTRACT: Shear strength of trapezoidal corrugated steel webs is an important issue for the design of box girder bridges with trapezoidal corrugated steel webs. Eight H-shape steel girders with trapezoidal corrugated webs are firstly tested to investigate the shear behavior of webs. An extensive parametric study based on the linear elastic buckling analysis is then conducted to derive the simplified formula for calculating the elastic shear buckling strength of trapezoidal corrugated steel webs considering three different shear buckling modes. The proposed formula can give more satisfactory results for predicting the elastic shear buckling strength than some available formulae provided in the literature when compared with the numerical results. Furthermore, the nonlinear buckling analysis is conducted to intensively investigate the shear strength associated with initial geometric imperfections, and the formulae of the shear strength are proposed. Good agreements can be observed between the results calculated using the proposed prediction formula in this paper and the experimental results, and a design formula is also recommended for the routine shear design of trapezoidal corrugated steel webs.

ABSTRACT: Results of four full-scale tests on plate girders stiffened with transverse and longitudinal stiffeners subjected to interaction of high bending moment and shear force are presented and discussed. In longitudinal direction the web was stiffened with open or closed stiffeners positioned in the compression zone. Detailed information on initial geometric imperfection and residual stresses is given. The experimental results were used to verify numerical model. The resistance is compared against reduced stress method and effective width method given in EN 1993-1-5.

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ABSTRACT: Nowadays, steel coupling beams are used as an efficient alternative to reinforced concrete (RC) coupling beams. Particularly in the coupled shear walls system, coupling beams are the main members for dissipating seismic energy. In this paper, for the first time the application of corrugated plates as the web of steel coupling beams (rather than flat web and its stiffeners) is studied as a proposition for improving seismic behavior of such beams. The study addresses the linear elastic buckling analysis and non-linear analysis of steel coupling beams with flat and corrugated webs using finite element technique for which ANSYS software is employed. 160 models have been studied, considering parameters such as shape of web plate (flat and three corrugated types, including trapezoidal, curved, and zigzag), web thickness, number of corrugations, and
corrugation angle. The finite element results are validated through comparison with the experimental results of a common steel coupling beam, tested by other researchers. In addition to the advantages of eliminating web stiffeners, results of this study show that the application of corrugated web with the proposed geometric criteria makes it possible to achieve further rotation capacity in comparison with common steel coupling beams.

Finally, a design approach for corrugated web of steel coupling beams, accompanied by a practical example, is presented.

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ABSTRACT: Experimental and numerical investigations into the behaviour of elliptical hollow section beam-columns under axial compression and uniaxial bending have been performed and described in this paper. A large-scale experimental programme, comprising a total of 10 tensile coupon tests and 24 beam-column tests, was carried out. The beam-column tests included 6 pure compression tests, 3 buckling about the major axis and 3 about the minor axis, and 18 eccentric compression tests, 9 inducing compression plus bending about the major axis and 9 inducing compression plus bending about the minor axis. All tested elliptical hollow sections were EHS 150 × 75 × 5, and three member lengths of 1 m, 2 m and 3 m were considered. The test results have been supplemented by numerically generated results based on validated FE models to assess the influence of member slenderness and cross-sectional aspect ratio. On the basis of the experimental and numerical findings, design rules covering instabilities in hot-finished EHS beam-columns have been assessed and verified by statistical analysis. The limiting length concept has also been extended to EHS beam-columns.


ABSTRACT: This paper proposes an innovative structural wall, named “the steel tube–double steel plate–concrete composite wall”, which is suited for use in high-rise buildings. The composite wall consists of concrete filled steel tubular (CFST) boundary elements and a double “skin” composite wall web where two steel plates are connected by tie bolts with space between them filled with concrete. The seismic behavior of the composite walls was examined through a series of experiments in which five slender rectangular wall specimens were subjected to axial forces and lateral cyclic loading. The specimens failed in a flexural mode, characterized by local buckling of the steel tubes and plates, fracture of the steel tubes, and concrete crushing at the wall base. The extent of the CFST boundary element was found to significantly affect the deformation and energy dissipation capacities of the walls. The area ratio of steel plates had a minimal effect on the deformation capacity of the slender walls. The addition of circular steel tubes embedded in the CFST boundary elements obviously increased the lateral load-carrying capacity of the walls. When the CFST boundary element's extent was 0.2 times the wall's sectional depth and the test axial force ratio was no more than 0.25, the walls had a yield drift ratio of over 0.005 and an ultimate drift ratio of around 0.03. Simplified formulas used to evaluate the flexure strength of the composite walls were proposed. The evaluated results had good agreement with the test results, with errors no greater than 10%.
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ABSTRACT: To investigate the static behavior of laced columns, 18 tests were conducted on sample columns constructed from pairs of u-section profiles with various lengths and various distances between the main chords, all with an initial imperfection. To study the behavior of built-up columns in the plane parallel to the lacing planes, the test set-up was arranged in such a way that buckling occurred in this plane. There was generally good agreement between the test results and the theoretical results for the elastic critical loads. The SSRC method overestimated the results with a high error, whereas Engesser's method was more conservative, with a minor error. Bleich's method and Paul's method both led to results with moderate error. The compressive capacity of the sample columns, obtained by the tests, were compared to those obtained by the Ayrton–Perry and capacity curves methods, of which the first gave conservative results and the second led to the results being slightly overestimated. The experimental results showed that the amount of initial imperfection has a significant effect on reducing the compressive capacity of the samples.

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ABSTRACT: This paper presents an experimental study on the deformation behavior of pre-compression free-spanned steel tubular members under lateral loads due to an indenter. The tests were carried out on six similar pipes with an outer diameter of 139.9 mm, a length of 2400 mm and a thickness of 2.55 mm, which are presented and discussed. The strains and deformations were determined in the local load-effected zone, and the effect of different magnitudes of compression pre-loading on the strength of samples against lateral load was investigated. The main advantage of the current investigation compared with those carried out previously and reported in literature is that both the pre-loading axial compression force and local load applied statically by an indenter are included experimentally in the study. From the results of the tests, it can be concluded that pre-loading has a marked effect on the lateral strength and deformation behavior of the pipes. Furthermore, finite element analyses for geometrically identical specimens are presented, and the analytical solutions are compared to the experimental results.

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ABSTRACT: High-yield strength steel-plated structures represent competitive solutions when used in steel and steel–concrete composite bridges. Nevertheless, further modifications may still be introduced at the design stage in the case of slender sections, in order to minimize the number of their stiffeners and thereby economize on manufacturing costs. Eurocode 3 “Design of steel structures” specifies design methodologies for slender plates subjected to compression and for stiffeners. Moreover, the use of Finite Element Method (FEM) software is fast becoming an alternative analytical method for the design of complete structures or structural elements, as it offers a more realistic approach. This paper makes recommendations for FEM assessments of plated sections in bridges that take the initial imperfections, geometric imperfections and residual stresses of the sections into account, in order to arrive at realistic results.

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ABSTRACT: It is a well established fact that the behaviour of columns as part of a structure is affected by the end restraints. The main aim of the current study is to develop a criterion of stability capable of predicting an impending failure by elastic buckling of a column of a structure. The rigidities at the ends of a column element are modelled using rotational and translational springs, which have been considered by taking into account their coupling effects. The role of the springs is to model the nodal restraints of any column of a given structure. This formulation offers significant practical advantages in the elastic buckling analysis of such structures. This approach is performed through a relationship to several parameters, such as the non-dimensional rotational and translational restraint indices and the effective length factor K. The approach was applied in analysing the elastic buckling of a number of structures and good results were obtained, thus justifying its reliability. In determining the effective length factor K, a marked difference was noted between the results obtained using the Eurocode approach and that proposed by the current study, particularly in the case of non-braced structures.

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ABSTRACT: This paper presents the experimental results and observation of elliptical concrete filled tube (CFT) columns subjected to axial compressive load. A total of twenty-six elliptical CFT specimens including both stub and slender composite columns are tested to failure to investigate the axial compressive behaviour. Various column lengths, sectional sizes and infill concrete strength are used to quantify the influence of member geometry and constituent material properties on the structural behaviour of elliptical CFT columns. As there is no design guidance currently available in any Code of Practice, this study provides a review of the current design rules for concrete filled circular hollow sections in Eurocode 4 (EC4). New equations based on the Eurocode 4 provisions for concrete filled circular hollow sections were proposed and used to predict the capacities of elliptical CFT columns.
References listed at the end of the paper:

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ABSTRACT: In this paper an analytical model is presented to describe the lateral–torsional buckling behaviour of steel web tapered tee-section cantilevers when subjected to a uniformly distributed load and/or a concentrated load at the free end. To validate the present analytical solutions finite element analyses using ANSYS software are also presented. Good agreement between the analytical and numerical solutions is demonstrated. Using the present analytical solutions, the interactive buckling of the tip point and uniformly distributed loads is investigated and a parametric study is carried out to examine the influence of section dimensions on the critical
buckling loads. It is found that web tapering can increase or decrease the critical lateral–torsional buckling loads, depending on the flange width of the beam. For a beam with a wide flange (width/depth = 0.96) the critical buckling load is increased by 2% by web tapering, whereas for a beam with a narrow flange (width/depth = 0.19) web tapering reduces the buckling load up to10% and 6% for the tip point loading and the uniformly distributed load respectively.

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ABSTRACT: Thin-walled cylindrical shells are extensively used in numerous kinds of industrial applications under different cases of load combination. Nonetheless, quite few are the experimental researches that point out the real behavior of cylindrical shells under pure bending and external pressure. In the present experimental study, the buckling behavior of long cylindrical steel shells was investigated under combined bending and uniform peripheral pressure. Relevant FE simulations were also carried out and the results were compared with the experiments. The study shows that the theoretical outcomes predicted by nonlinear finite element analyses agree acceptably with the experimental results in terms of bucking load and modes of deformation. Furthermore, it was found that the initial sectional out of circularity developed by bending (especially higher values) considerably influences the buckling capacity of such shells under uniform external pressure. Ultimately, an interaction formula was proposed to generalize the interaction behavior of the test results within the range of this study.

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ABSTRACT: A cable-braced grid shell is a new type of single-layer latticed shell suitable for glass roofs. Compared with traditional single-layer latticed shells, this new type of shell has a unique mesh shape, mesh form and surface shape. The lamella cylinder cable-braced grid shell is the single-layer latticed structure, and therefore, stability is a key design factor. These shells are also sensitive to initial imperfections, and thus, the influence of initial imperfections on stability should be considered. Therefore, in this paper, a lamella cylinder cable-braced grid shell with imperfections is used to develop formulas to describe the buckling load based on the continuum analogy. The major contributions of this paper include the formula for the linear buckling load of a lamella cylinder cable-braced grid shell with imperfections, which is deduced based on the continuum analogy. Then, the equivalent rigidity for a lamella mesh is determined. Last, the formula for the linear buckling load is verified by numerical examples, the errors are analyzed, and a corresponding correction factor is provided.
https://doi.org/10.1016/j.jcsr.2013.05.016
ABSTRACT: The paper deals with the resistance of longitudinally stiffened plate girders subjected to moment–shear interaction. Based on a verified numerical model an extensive numerical parametric study was performed. Altogether 630 girders were analysed and the results were used for reliability analysis of resistance models. Five different resistance models were considered and the corresponding partial safety factors were determined. The resistance models were: moment–shear (M–V) interaction model from EN 1993-1-5, modified M–V interaction model, gross cross-section bending resistance model and two additional resistance models that present combination of the first three resistance models. It was shown that M–V interaction can be covered using EN 1993-1-5 M–V interaction resistance model with partial safety factor 1.1 or with only bending resistance check of gross cross-section taking partial safety factor equal to 1.1.

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“Experimental investigation of the overall buckling behaviour of 960 MPa high strength steel columns”, Journal of Constructional Steel Research, Vol. 88, pp 256-266, September 2013,
https://doi.org/10.1016/j.jcsr.2013.05.015
ABSTRACT: Investigations of the mechanical performance of high strength steel structures have become a research hotspot in civil and structural engineering, and existing experimental studies of their overall buckling behaviour have hitherto focused mainly on columns fabricated from either 460 MPa or 690 MPa steels. The present study describes an experimental programme including six pin-ended 960 MPa steel columns under axial compression. Both welded I- and box-section specimens are considered. The initial geometric imperfections and cross-sectional residual stresses are reported, with the axial loading, deformation and the strain distributions at the mid-length section being monitored during the testing. The buckling mode is clarified, and the buckling capacity is compared with design results according to current national design codes. Based on the experimental results, a finite element model is described and validated, and then used to perform a large number of parametric studies, considering different cross-sectional dimensions and column slendernesses. It is found that all specimens failed by overall flexural buckling, and the corresponding column curves in current design codes underestimate the dimensionless buckling strength of 960 MPa steel columns. Higher and more adequate column curves are suggested for such columns, and new column curves are proposed based on a non-linear fitting of the parametric results.

Xin Cheng, Yiyi Chen and Lingli Pan (State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China), “Experimental study on steel beam–columns composed of slender H-sections under cyclic bending”, Journal of Constructional Steel Research, Vol. 88, pp 279-288, September 2013
https://doi.org/10.1016/j.jcsr.2013.05.020
ABSTRACT: This paper presents an experimental study of six H-section steel beam–columns with large width-to-thickness ratios subjected to combined constant axial force and cyclic bending moment about the strong-axis.
Considering different categories of cross-sections, various width-to-thickness ratios of the flange and web of the specimens were selected, and a reliable structural testing system was employed. The test results showed that, for all the specimens, local buckling was the dominating failure mode. Due to their relatively large width-to-thickness ratios of the flange and web, the H-section specimens exhibited limited resisting strength but certain plastic deformation capacity as well as energy dissipation capacity, encouraging employment of such members in seismic areas. It was also found that the flange width-to-thickness ratio and the axial force ratio have significant effects on the hysteretic behavior. In addition, a modified plastic effective width method for ultimate strength was proposed.

https://doi.org/10.1016/j.jcsr.2013.06.004

ABSTRACT: Current design approaches to assess the lateral torsional buckling capacity of steel beams in fire are based on the assumption of uniform steel temperature. This paper investigates the effect of temperature gradients on the lateral torsional buckling behavior of steel wide flange (W) beams in fire conditions. The effects of localized fires and the temperature gradients they produce in steel beams were studied. Laterally unrestrained beams of various dimensions were subjected to a range of load ratios. The location of the localized fire was varied to provide different heating conditions. The standard ISO834 fire, and a uniform temperature condition in which the steel temperature was ramped linearly were used for comparison. The study shows that temperature gradients within a steel W-beam may have a detrimental effect on the lateral torsional buckling capacity of the beams in fire. The critical temperature, defined as the maximum temperature in a steel beam at which the beam undergoes lateral torsional buckling, in real fires may be hundreds of degrees lower than that in the standard ISO834 fire. The critical temperature in real fires may also be lower than that in the uniform heating condition. Design approaches based on the standard ISO834 fire or uniform steel temperature assumption may give unconservative results if the potential real fires are localized fires.

Shanmuganathan Gunalan and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Development of improved fire design rules for cold-formed steel wall systems”, Journal of Constructional Steel Research, Vol. 88, pp 339-362, September 2013
https://doi.org/10.1016/j.jcsr.2013.05.021

ABSTRACT: Traditionally the fire resistance rating of LSF wall systems is based on approximate prescriptive methods developed using limited fire tests. Therefore a detailed research study into the performance of load bearing LSF wall systems under standard fire conditions was undertaken to develop improved fire design rules. It used the extensive fire performance results of eight different LSF wall systems from a series of full scale fire tests and numerical studies for this purpose. The use of previous fire design rules developed for LSF walls subjected to non-uniform elevated temperature distributions based on AISI design manual and Eurocode3 Parts 1.2 and 1.3 was investigated first. New simplified fire design rules based on AS/NZS 4600, North American Specification and Eurocode 3 Part 1.3 were then proposed in this study with suitable allowances for the interaction effects of compression and bending actions. The importance of considering thermal bowing, magnified thermal bowing and neutral axis shift in the fire design was also investigated. A spreadsheet based design tool was developed based on the new design rules to predict the failure load ratio versus time and temperature curves for varying LSF wall configurations. The accuracy of the proposed design rules was verified using the test and FEA results for different wall configurations, steel grades, thicknesses and load ratios. This
paper presents the details and results of this study including the improved fire design rules for predicting the load capacity of LSF wall studs and the failure times of LSF walls under standard fire conditions.


ABSTRACT: One of the advantages of Steel Plate Shear Walls (SPSWs) is the easiness of openings application in infill plate. The openings are sometimes required for passing utilities, architectural purposes, and/or structural reasons. However, the recent researches on perforated steel plate shear walls have shown that the shear strength and stiffness of an un-stiffened steel shear wall decrease due to perforation of the infill plate. Hence, this paper presents a special combination of diagonal stiffeners with a central perforation. The seismic behavior of the new system is experimentally investigated and compared to the solid infill plate models. Experimental testing is performed on three $\frac{1}{2}$ scaled single-story SPSW specimens under cyclic quasi-static loading. One of the specimens is un-stiffened and the two others are diagonally stiffened, which in one of them, a circular opening with the diameter of $\frac{1}{8}$ depth of the panel is cutout from the wall center. It is observed that by means of the proposed stiffening method the shear strength of the perforated shear walls is achieved close to the un-stiffened wall with the solid panel, and the seismic behavior of the system is considerably improved. Test results show that the ductility ratio of the specially perforated specimen is about 14% greater than the un-stiffened specimen. A formula is developed and verified for the estimation of the shear strength of a perforated and diagonally stiffened SPSW. There are good agreements between the experimental outcomes and the theoretical predictions.

Bo-Hao Zhang, Yan-Lin Guo and Chao Dou (Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China), “Ultimate bearing capacity of asymmetrically double tapered steel columns with tubular cross-section”, Journal of Constructional Steel Research, Vol. 89, pp 52-62, October 2013 https://doi.org/10.1016/j.jcsr.2013.06.010

ABSTRACT: As a new kind of non-uniform member, the asymmetrically double tapered column with tubular cross-section is composed of two tapered parts with different lengths. This kind of column is more effective and economic to resist combination of axial load and transverse load, with both its ends hinged and transverse load applied at the largest cross-section. Some classic non-uniform members such as stepped or tapered members have been investigated thoroughly, but there is not any available design method for asymmetrically double tapered columns so far. In this study, the elastic buckling behaviors of asymmetrically double tapered columns with solid circular and tubular cross-section are studied respectively. Bessel functions and fitting processes are used to derive explicit formulas of the critical load. Subsequently, the ultimate bearing capacity of asymmetrically double tapered tubular columns subject to axial load is studied. And the results obtained by the design formula proposed herein correlate well with these obtained by using finite element numerical analysis. Finally, a P–M interaction formula for predicting in-plane strength of double tapered tubular columns under axial load and uniaxial bending is suggested. Employment of a detailed nonlinear finite element analysis demonstrates the accuracy of the interaction formula.

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ABSTRACT: This paper presents a combined study of theoretical solutions and experimental tests on the deformation processes of non-contact, point contact, line contact and secondary buckling of the sleeved column. In this study, a mechanical model based on the second order equilibrium differential equations with small deflection is developed, and two types of sleeved column are fabricated and tested using six specimens. And in the tests, it is observed that the ultimate axial load capacity and ductility of the sleeved column are substantially increased, and the axial load capacity will be reduced due to the small slenderness ratio of the inner core, large stiffness of the sleeved column and the large gap between the inner core and the sleeve. Furthermore, the study investigates the effects of the stiffness ratio of the inner core to the sleeve on the column's buckling mode transition process. Finally, a discussion on the comparison between the analytical results by the proposed mechanical model and the tested results is also presented.

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ABSTRACT: Due to the passive confinement provided by the steel jacket for the concrete core, the behaviour of the concrete in a concrete-filled steel tubular (CFST) column is always very challenging to be accurately modelled. Although considerable efforts have been made in the past to develop finite element (FE) models for CFST columns, these models may not be suitable to be used in some cases, especially when considering the fast development and utilisation of high-strength concrete and/or thin-walled steel tubes in recent times. A wide range of experimental data is collected in this paper and used to develop refined FE models to simulate CFST stub columns under axial compression. The simulation is based on the concrete damaged plasticity material model, where a new strain hardening/softening function is developed for confined concrete and new models are introduced for a few material parameters used in the concrete model. The prediction accuracy from the current model is compared with that of an existing FE model, which has been well established and widely used by many researchers. The comparison indicates that the new model is more versatile and accurate to be used in modelling CFST stub columns, even when high-strength concrete and/or thin-walled tubes are used.

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ABSTRACT: Eurocode 3 provides several methods for the stability verification of members and frames. However, several inconsistencies and difficulties have been noticed in the case of non-uniform members regarding in what concerns stability verification. In this paper, the case of web-tapered beams is studied. In a first step, available methods for stability verification of web-tapered beams are discussed. A second order
analytical model based on an Ayrton–Perry approach is then derived for the case of tapered beams with uniform bending moment and further extended to other bending moment distributions. Several consistent simplifications are carried out in order to build a simple but coherent design model for the stability verification of tapered beams subject to linear bending moment distributions and to parabolic bending moment. More than 3000 numerical simulations are carried out for calibration and analysis of the results. Throughout the paper, specific issues such as the presence of shear or the codified imperfections for welded cross-sections are brought in and taken into account. Finally, it is noted that the proposed model is consistent with recently proposed design models for the stability verification of prismatic beams.


ABSTRACT: This paper investigates the nonlinear behaviour of eccentrically loaded fibre reinforced (FR) concrete-filled stainless steel tubular composite columns. A nonlinear 3-D finite element model for the axially loaded composite columns, recently reported by the author, was extended to study the structural performance of the eccentrically loaded composite columns. The columns were pin-ended subjected to an eccentric load acting along one axis. The model accounted for the inelastic behaviour of the composite column components, effect of FR concrete confinement and interface between the stainless steel section and concrete. The measured initial local and overall geometric imperfections were carefully incorporated in the model. The finite element model has been validated against tests previously reported by the author. Furthermore, the variables that influence the eccentrically loaded composite column behaviour and strength comprising different eccentricities, different column slenderness and different concrete strengths were investigated in an extensive parametric study comprising 72 columns. The composite column strengths and moment resistances predicted from the finite element analysis were compared with the design composite column strengths and moment resistances calculated using the Eurocode 4. The study has shown that finite element modelling could effectively assess the accuracy of the design rules in current codes of practice.


ABSTRACT: The finite strip method employs simple polynomial functions to describe the transverse variations of the displacements and continuous harmonic series functions or discontinuous spline functions to describe the longitudinal variation of the strip displacements. While the Semi-Analytical Finite Strip Method (SAFSM) generally uses the longitudinal harmonic series to satisfy the boundary conditions at the longitudinal ends and to give compatibility between strips, the Spline Finite Strip Method (SFSM) employs local spline functions in the longitudinal direction to account for different boundary conditions. The Semi-Analytical Finite Strip Method (SAFSM) has been widely used in computer software (THIN-WALL, CUFSM) to develop the signature curves of the buckling stress versus buckling half-wavelength for a thin-walled section under compression or bending to allow identification of buckling modes. Recently, a complex mathematical technique has been applied in the SAFSM theory to allow for the case of shear. This paper provides the analysis and comparison between the new SAFSM development for shear and the SFSM for whole plain channel sections including flanges and lips where the sections are loaded in pure shear parallel to the web. The main variables are the flange widths and lip sizes. The SAFSM is limited to a single half-wavelength whereas the SFSM can include multiple buckles as seen in
the well-known garland curve. The paper demonstrates the potential for coupling between multiple short half-wavelength modes in shear and longer single half-wavelength as may occur in distortional buckling.

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ABSTRACT: This paper presents a series of tests on concrete filled double skin steel tubular (CFDST) members subjected to pure torsion. Two types of combinations are included, i.e., CFDST section with circular hollow section (CHS) as both inner and outer tubes, and section with CHS as the inner tube and square hollow section (SHS) as the outer tube. Finite element method was used to analyze typical failure mode and complete torque–rotation curve of the specimens, as well as interaction between the steel tubes and the sandwiched concrete of CFDSTs. It was found that the results calculated by finite element method show reasonable agreement with those of the test results. Six important parameters influencing the torque versus torsional rotation curves are identified, i.e. nominal steel ratio, yield strength of outer steel tubes and inner steel tubes, concrete cube compressive strength, width to thickness ratio of inner steel tubes and hollow section ratio. Finally, design formulas are proposed for calculating torsional capacities of CFDSTs.

Suliman Abdalla, Farid Abed and Mohammad AlHamaydeh (Department of Civil Engineering, American University of Sharjah, P.O. Box 26666 Sharjah, United Arab Emirates), “Behavior of CFSTs and CCFSTs under quasi-static axial compression”, Journal of Constructional Steel Research, Vol. 90, pp 235-244, November 2013, https://doi.org/10.1016/j.jcsr.2013.08.007
ABSTRACT: The behavior of circular Concrete Filled Steel Tubes (CFST) and Confined Concrete Filled Steel Tubes (CCFST) with Glass Fiber-Reinforced Polymers (GFRP) wrapping sheets subject to concentric compressive quasi-static loads is investigated in this paper. Thirty five CFST and CCFST specimens were tested to investigate the effect of different parameters on their behavior. Two concrete compressive strengths of 44 MPa and 60 MPa combined with three diameter-to-thickness (D/t) ratios of 54, 32, and 20 were considered. It was found that the dominant failure mode of the CCFST specimens is the explosive rupture of the GFRP wraps at the specimen's mid-height region. Even though the strain hardening region is as apparent in the CCFST specimen as its CFST benchmark, the CCFST section's axial load-carrying and ductility capacities have considerably increased due to the GFRP additional confinement.

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ABSTRACT: The buckling of columns is the classic problem in structural stability. It has been studied by many researchers over a large number of years, and it is well known that the severity of the buckling response can be greatly amplified by initial geometric imperfections in the column shape. The current paper presents and discusses the effects of imperfection shape, orientation and magnitude on the buckling behavior of columns. Analyses are conducted for elastic columns with overall initial imperfections in the form of out-of-straightness and sway displacements, as well as local imperfections that, for instance, model constructional and material defects. Traditionally, the initial imperfections are modeled with the first buckling mode with a size selected according to fabrication tolerances. This approach will not necessarily provide a lower limit to the column pre-buckling stiffness and strength. These assertions are supported by numerical results for imperfection-sensitive columns. The influence of end restraint on column strength is also studied since columns in actual frameworks are connected to other structural members such that their ends are restrained.

[No “buckling” papers in the December 2013 issue of Vol. 91]

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ABSTRACT: This paper describes an investigation into a metallic energy dissipater designed for earthquake risk mitigation of civil structures. It is called the Perforated Yielding Shear Panel Device (PYSPD). It comprises of a thin perforated diaphragm plate welded inside a short length square hollow section. The device is to be connected in the lateral load resisting system of a structure with the diaphragm plate being in the plane of the building frame. It is a displacement-based device in which energy is dissipated through plastic shear deformation of its perforated diaphragm plate. The PYSPD is a modified version of the previously tested Yielding Shear Panel Device (YSPD). Perforations on the diaphragm plate alleviate demand on supporting elements which reduces undesirable local deformations near the connections. As a result more stable force-displacement hysteresis is obtained. Three patterns of perforations are studied. Finite element models confirm that diagonal tension field develops under shearing action but stress patterns are affected by perforations. Two plate slenderness and three perforation patterns combinations were tested experimentally. Under quasi-static condition, devices with certain plate slenderness produced stable and repeatable force-displacement hysteresis, and achieved large energy dissipation capability. Compared to un-perforated specimens, perforations reduce elastic stiffness and yield strength. Under design displacement it produced a stable hysteretic behavior and endured code requirements against low-cycle fatigue.

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ABSTRACT: In recent years, stainless steel circular hollow section members have gained more widespread usage as load bearing constituents in construction due to their combination of corrosion resistance, aesthetic appearance and structural efficiency. This paper investigated the compressive strength of girth-welded stainless steel circular hollow section stub columns by numerical method. At first, finite element simulation of the girth welding process was carried out to obtain the weld-induced imperfections such as residual stresses and deformations employing sequentially coupled three-dimensional thermo-mechanical finite element formulation. Then, nonlinear finite element analysis in which the failure mode, the ultimate load-carrying capacity and the full load-displacement response of the girth-welded circular hollow section stub columns were explored taking the residual stresses and distortions together with the initial global geometric imperfections into consideration was conducted. Seven finite element models with different diameter-to-thickness ratios were developed in order to examine the effects that the diameter-to-thickness ratio has on the compressive strength. Results have shown that the weld-induced imperfections should be taken into account in accurate assessment of the compression behavior of girth-welded stainless steel CHS stub columns.

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ABSTRACT: This paper presents a set of new test data for high strength concrete filled steel tubular (CFST) members subjected to transverse impact. A total of 12 circular CFST specimens and reference hollow steel tubes were tested in a drop hammer rig. The cube strength of the concrete used for the CFST members is up to 75 MPa. A finite element analysis (FEA) model is established to predict the impact behaviour of high strength CFST members, and the accuracy of which is then verified by the presented test results. Full-range analyses of the behaviour of CFST members under impact loading are then carried out using the FEA model to produce the force state, internal force distribution, and flexural capacity. Finally, a simplified model is obtained based on a parametric analysis to calculate the flexural capacity of CFST members under impact load.

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ABSTRACT: The majority of the existing literature on castellated members is focused on beams. Very little work has been done on the stability of castellated columns although they have been increasingly used in buildings in recent years. This paper presents a new analytical solution for calculating the critical buckling load
of simply supported castellated columns when they buckle about the major axis. This analytical solution takes into account the influence of web shear deformations on the buckling of castellated columns and is derived using the stationary principle of potential energy. The formula derived for calculating the critical buckling load is demonstrated for a wide range of section dimensions using the data obtained from finite element analyses published by others. It was found that the influence of web shear deformations on the critical buckling loads of castellated columns increased with the cross-sectional area of a tee section and the depth of web opening, but decreased with the length and the web thickness of the column. It is shown that the inclusion of web shear deformations significantly reduces the buckling resistance of castellated columns. Neglecting the web shear deformations could overestimate the critical buckling load by up to 25%, even if a reduced second moment of area is used.

Pengcheng Li, Minger Wu and Pengju Xing (Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China), “Novel cable-stiffened single-layer latticed shells and their stabilities”, Journal of Constructional Steel Research, Vol. 92, pp 114-121, January 2014
https://doi.org/10.1016/j.jcsr.2013.10.008
ABSTRACT: The cable-stiffened single-layer latticed shell is a new structural system that aims to enhance the stability of the single-layer latticed shell. This paper compares the stability of a cable-stiffened single-layer latticed shell with that of a single-layer latticed shell using a numerical analysis to investigate the stability behaviour of the new structure. In the analysis, the following influential parameters have been taken into account: (1) layouts of the cables; (2) joint types; (3) pretension in the cables; and (4) cross-sections of the cables. The results indicate that the buckling load of single-layer latticed shells is improved significantly by the introduction of the cables. For the cable-stiffened single-layer latticed shells with different layouts of cables, both the pretension in the cables and the cross-sections of the cables have a considerable effect on their stabilities. Meanwhile, the numerical analysis also indicates that although joint types have a remarkable effect on the stability of a single-layer latticed shell, the effect on the corresponding cable-stiffened single-layer latticed shell is limited.

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ABSTRACT: The effects of cyclic local buckling on the behavior of concrete-filled steel tubular (CFST) slender beam-columns under cyclic loading were approximately considered in existing analytical methods by modifying the stress–strain curve for the steel tube in compression. These methods, however, cannot simulate the progressive cyclic local buckling of the steel tubes. This paper presents a new efficient numerical model for predicting the cyclic performance of high strength rectangular CFST slender beam-columns accounting for the effects of progressive cyclic local buckling of steel tube walls under stress gradients. Uniaxial cyclic constitutive laws for the concrete core and steel tubes are incorporated in the fiber element formulation. The effects of initial geometric imperfections, high strength materials and second order are also included in the nonlinear analysis of CFST slender beam-columns under constant axial load and cyclically varying lateral loading. The Müller's method is adopted to solve nonlinear equilibrium equations. The accuracy of the
A numerical model is examined by comparisons of computer solutions with experimental results available in the published literature. A parametric study is conducted to investigate the effects of cyclic local buckling, column slenderness ratio, depth-to-thickness ratio, concrete compressive strength and steel yield strength on the cyclic responses of CFST slender beam-columns. It is shown that the numerical model developed predicts well the experimentally observed cyclic lateral load–deflection characteristics of CFST slender beam-columns. The numerical results presented reflect the cyclic local and global buckling behavior of thin-walled high strength rectangular CFST slender beam-columns, which have not been reported in the literature.

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ABSTRACT: In contrast to the classical Engesser method of solving the buckling problem for laced columns in terms of an “equivalent” solid bar, the buckling problem of a column with a fir-shaped lattice is formulated as a stability problem of a statically indeterminate system of elastic bars. Solving this problem by conventional methods consists of the determination of a smallest eigenvalue for the linear algebraic system of a high order which depends upon the number of the column joints. The present approach requires analyzing only the fourth-order system for columns with any degree of static indeterminacy. The stability analysis is reduced to numerical solution of a two-point boundary value problem for a system of recurrence relations between deformation parameters of column cross-sections passing through the column joints. The critical force and the modified slenderness ratio for column with any number of panels and the fixed inclination of lattice diagonals are represented as a function of the lattice rigidity parameter. The obtained values of Euler's critical force are essentially higher than those obtained with Engesser's model. The distinctive feature which is similar to the Boobnov phenomenon occurs for the column with a fir-shaped lattice: the column loses stability so that joint cross-sections are not displaced and the chord panels are buckled as a simply-supported bar. This type of buckling is possible when the lattice rigidity exceeds a specific limit. The plots of the modified slenderness ratio as a function of the lattice rigidity can be applied in designing steel-laced columns with a fir-shaped lattice.

ABSTRACT: Concrete-encased CFST is a type of steel-concrete composite construction, and has an increasing trend in being used in high-rise building and bridge structures in China. This paper studies the behavior of concrete-encased concrete filled steel tube (CFST) stub columns under axial compression. A finite element analysis (FEA) modeling is developed to analyze the behavior of the composite columns. The material nonlinearity and the interaction between concrete and steel tube are considered. A set of test data are used to verify the FEA modeling. Full range analysis on the load versus deformation relations of the concrete-encased CFST stub columns is presented. The interactions between the outer concrete and the steel tube of CFST, as well as the core concrete and the steel tube of CFST are investigated. The differences of concrete-encased CFST columns, conventional CFST and RC columns are analyzed. A parametric study is then carried out by using the FEA modeling. Finally, simplified formulas are suggested for predicting the ultimate strength of the composite stub columns.

**ABSTRACT:** The paper presents results of experimental investigations of stability and limit load of cold-formed thin-walled channel beams with non-standard flanges subjected to pure bending. Critical and limit loads were determined using a strength testing machine. Obtained results were compared with analytical solutions. The influence of non-standard flanges on the critical load and limit load was shown as well.

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**ABSTRACT:** Summarized herein is a study that explored single span, horizontally curved, plate girders having a yield stress of 50 ksi (345 MPa) to investigate their flexural behavior as a function of the position of a single longitudinal stiffener at various locations along the depth of the web. The studies were conducted using ABAQUS [1] with the girder cross-sections under high vertical bending moment and low shear. As a result of these studies, recommendations are made for positioning longitudinal stiffeners on horizontally curved webs that complement existing criteria for straight plate girders in bending. The study shows that, for the high flexure situations and girder specimens that were examined: (1) the optimal position for longitudinal stiffeners on a horizontally curved web does not appear to differ appreciably from that for a straight web as recommended in the AASHTO LRFD Bridge Design Specifications [2]; and (2) horizontal curvature can contribute to enhancing web stability, and, in certain instances, curvature may mitigate the need to use longitudinal stiffeners to help increase cross-section flexural strength.

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**ABSTRACT:** The behavior and design of steel columns subjected to thermal gradients due to fire loading were evaluated numerically and experimentally. The numerical (FEM) modeling approach was verified using experimental data from large-scale tests. The FEM modeling approach was used to conduct parametric studies to evaluate the effects of different heating configurations on steel column strength, and failure behavior at elevated temperatures. The analyses were conducted by coupling transient heat transfer analysis with implicit dynamic stress analysis. Columns subjected to four sided heating configuration had uniform temperature distributions through the cross-section. The columns were subjected to non-uniform (partial) heating to produce thermal gradients through the cross-section. The analysis results indicated that the column strength and failure behavior depended on the column slenderness, axial loading, and heating configuration. Failure modes included flexural buckling about the weak axis, flexural buckling about the strong axis, and flexural-torsional buckling. The analysis results also indicated that columns subjected to uniform heating had significantly higher heat influx. In most cases, columns subjected to non-uniform heating failed at lower average temperatures than
columns subjected to uniform heating. However, the columns subjected to uniform heating reached their failure temperatures faster than the columns subjected to non-uniform heating due to the higher heat influx. The exceptions were very slender columns subjected to axial loads greater than 50% of their ambient load capacity. The results from the parametric studies were used to develop design equations for wide flange steel columns subjected to non-uniform heating resulting in thermal gradients through the cross-section.

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ABSTRACT: A series of tests were conducted on curved concrete filled steel tubular (CCFST) trusses with curved CFST chords and hollow braces subjected to bending. A total of 8 specimens, including 4 CCFST trusses, 2 straight CFST trusses (referred to as CFST trusses) and 2 curved hollow tubular trusses were tested to study the effect of the rise-to-span ratio and infill concrete on the flexural performance of CCFST trusses. Different failure modes were observed: bending failure for CFST trusses, bending-shear failure for CCFST trusses and local buckling failure for hollow tubular trusses. The experimental result showed that the stiffness and load-carrying capacity of CCFST trusses were larger than those of CFST trusses, but the CCFST trusses experienced a joint failure with relatively low ductility. Meanwhile, the infill concrete provided support to the steel tubular chords and increased the stiffness, load-carrying capacity and ductility. A finite element analysis (FEA) model of the CCFST trusses was developed and verified by the test results. The model was then used to investigate the mechanical behaviour of the truss by full range analysis. A simplified model was proposed to predict the elastic stiffness considering both the flexural and the shear deformation. The load-carrying capacity of the CCFST structure was also discussed.

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ABSTRACT: Concrete-filled steel tubes (CFTs) are widely used as columns in many structural systems. In CFTs, inward buckling deformations of the steel tube are prevented by the concrete core, but degradation in steel confinement, strength and ductility can still result from outward local buckling. To overcome this deficiency of CFTs, CFTs can be confined with fibre-reinforced polymer (FRP) wraps to suppress outward local buckling deformations. This paper is concerned with the behaviour and modelling of FRP-confined concrete-filled steel tubular columns subjected to cyclic axial compression. Results from two series of cyclic axial compression tests on CCFTs are presented and discussed. A cyclic stress–strain model for confined concrete in CCFTs is also proposed and is shown to compare well with the test results. The proposed stress–strain model can be employed in the modelling of CCFTs under seismic loadings in future studies.
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ABSTRACT: Hollow structural sections (HSS) are desirable for utilization in structural applications due to their inherent flexural, compression, and torsional properties. These sections are highly efficient, but have been underutilized in cyclic bending applications due to a lack of understanding of their behavior under these loads. To address the limited experimental data and determine potential limiting parameters for the use of HSS in seismic bending applications, a finite element model (FEM) considering experimentally measured material properties, section geometry, and geometric imperfections has been calibrated and validated to experimental findings. A parametric study is conducted on 133 different standard HSS beam members of sizes ranging from HSS 152 × 50.8 × 4.8 to HSS 508 × 305 × 15.9. To provide insight into the parameters that limit stable hysteretic behavior, the decrease in the overall maximum moment capacity with cycling at a given rotation level, rotational capacity at a given degradation of the moment capacity, and decrease of the secant stiffness with cycling are considered. The findings provide information about the interdependence of the width–thickness and depth–thickness ratios on the cyclic bending behavior of HSS. Linear regression analyses provide a relationship between the width–thickness and depth–thickness ratios and member performance from which equations for predicting the degradation of moment capacity and rotational capacity can be defined.

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“A new model based on evolutionary computing for predicting ultimate pure bending of steel circular tubes”, Journal of Constructional Steel Research, Vol. 94, pp 84-90, March 2014,
https://doi.org/10.1016/j.jcsr.2013.11.011

ABSTRACT: In this study, the feasibility of using evolutionary computing for modelling ultimate pure bending of steel circular tubes was investigated. The behaviour of steel circular tubes under pure bending is complex and highly non-linear, and the literature has a number of solutions, most of which are difficult to use in routine design practice as they do not provide a closed-form solution. This work presents a new approach, based on evolutionary polynomial regression (EPR), for developing a simple and easy-to-use formula for prediction of ultimate pure bending of steel circular tubes. The EPR model was calibrated and verified using a large database that was obtained from the literature and comprises a series of 104 pure bending tests conducted on fabricated and cold-formed tubes. The predicted ultimate pure bending of steel circular tubes using this model can be obtained from a number of inputs including the tube thickness, tube diameter, steel yield strength and modulus of elasticity of steel. A sensitivity analysis was carried out on the developed EPR model to investigate the model generalisation ability (or robustness) and relative importance of model inputs to its output. Predictions from the EPR model were compared with those obtained from artificial neural network (ANN) models previously developed by the authors, as well as most available codes and standards. The results indicate that the EPR model is capable of predicting the ultimate pure bending of steel circular tubes with a high degree of accuracy and outperforms most available codes and standards. The results also indicate that the performance of the EPR model agrees well with that of the previously developed ANN models. It was also shown that the EPR model was able to learn the complex relationship between the ultimate pure bending and most influencing factors, and render this knowledge in the form of a simple and transparent function that can be readily used by practising engineers. The advantages of the proposed EPR technique over the ANN approach were also addressed.

ABSTRACT: Cyclic loading tests for the panel buckling-restrained brace (panel BRB) comprising an unbounded steel plate brace encased in a panel were carried out to investigate constructional details of a novel type light-weight assembled steel panel and to study reinforcement forms to improve the punching shear capacity of reinforced concrete panel. The effects of unbonded materials and gaps between the panel and the brace, reinforcements in concrete panels and weight of panels on the hysteretic behavior of panel BRBs, were mainly examined. Tests reveal that, compared with additional steel bars and ties, perforated steel channels used as reinforcements along the entire length of brace can prevent concrete panels from failure by punching shear. Residual flexural deformations appeared in some braces due to the gaps. The maximum axial compressive strength of each specimen significantly exceeds its yield strength due to strain hardening and frictional action. Lubricating greases in the steel panel BRBs are helpful to reduce the frictional action and to achieve satisfied hysteretic responses. All specimens achieved great ductility and energy dissipation capacity. The concrete panel in one specimen failed by punching shear and the other specimens failed due to tensile fracture of the braces. The weight of the assembled steel panel is about 30% that of the concrete panel and the hysteretic behavior of the steel panel BRBs matches that of the concrete panel BRBs. The panels that can be assembled and disassembled would be advantageous in inspecting and replacing the braces, as well as in reusing the panels.

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ABSTRACT: The behaviour of unstiffened steel plate shear walls with circular perforations in the infill plates is examined. A shear strength model of the infill plate with multiple circular openings is proposed based on a strip model. Eight perforation patterns in a single storey steel plate shear wall of two different aspect ratios were analyzed using a geometric and material non-linear finite element model to assess the proposed shear strength model. A comparison between the nonlinear pushover analysis and the proposed shear strength equation shows excellent agreement. The proposed model is used to design the boundary columns of three sample four-storey perforated shear walls. A comparison between the predicted design forces in the boundary columns for the selected shear walls with the forces obtained from nonlinear seismic analyses demonstrates the accuracy of the proposed simple model to predict the design forces in the columns.

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ABSTRACT: The objective of this paper is to demonstrate how element (e.g., flange) local slenderness may be used to predict element strain capacity, and in turn, the element strain capacity may be used to predict member rotational capacity in structural steel members. Member plastic hinge rotation capacity has an important role in the design of steel structures, and while implicit understanding of the rotation capacity has sufficed in the past, as inelastic direct analysis methods are adopted in conventional as well as seismic design more explicit treatments are needed. Accordingly, a comprehensive series of material and geometric shell finite element collapse analyses are performed in ABAQUS on component elements (plates). The finite element analysis confirms the hypothesis that local slenderness of an element is intimately connected to the element's strain capacity. Utilizing element strain capacity to determine member rotational ductility demonstrates the importance of additional factors, such as depth-to-length and shape factor of the member in predicting the rotational capacity. The proposed method assumes Euler–Bernoulli beam theory, ignores interaction between local and lateral–torsional buckling, and presumes the flange (not the web) controls the section strain capacity. The analyses are compared to existing code provisions for both conventional and seismic design and recommendations for potential improvements are made.

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ABSTRACT: The use of very high strength materials is currently being researched as a way to reduce material use and improve sustainability. In this investigation a total of 32 specimens were fabricated using very high strength (VHS) steel tubes and plates to form stub columns. The VHS-plate fabricated stub columns were tested under axial compression. The specimens comprised 20 fabricated square sections and 12 fabricated triangular sections. The VHS steel tubes used have a nominal yield stress of 1350 MPa and a nominal ultimate tensile strength of 1500 MPa. Mild steel plates and high strength steel plates were used to connect the VHS tubes at the vertices thereby forming square and triangular cross sections. Normal strength concrete with a standard concrete strength grade of 32 MPa was used as concrete in-fill. Finite element models are developed to simulate the behaviour of the VHS-plate stub columns. The finite element models predicted the load–deformation behaviour of the fabricated columns well with the peak strength and post-peak behaviour similar to the experimental results. A parametric study was also carried out to determine the effect of concrete strength, facet plate yield strength and facet plate width to wall thickness ratio. The parametric study shows that there is benefit in concrete confinement through the use of higher strength steel facet plates. This paper also proposes a method for determining the axial compression capacity of fabricated VHS-plate stub columns. The predicted peak strength from the proposed design method is in good agreement with the test results.

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ABSTRACT: This paper reports on a study of local inelastic buckling in square hollow section columns with large plastic rotations. The study was conducted as part of the validation of a proposed design method for discontinuous columns in braced frames in which plastic rotations in the columns are used to limit the moments in the columns. The study included both testing of full-scale columns and a parametric study by finite element analysis. The results demonstrate that current codes permit cross section slenderness in plastic sections which are likely to lead to premature buckling in structures using plastic (inelastic) design if the rotations are large. Design limits are proposed for square hollow sections relating cross-section slenderness to column end rotations.

ABSTRACT: Cross-section classification is a significant concept in the design of flexural steel members as it addresses the susceptibility of a cross-section to local buckling and defines its appropriate design resistance. The present study employs experimentally verified nonlinear finite element modeling techniques to investigate the section classification based on member ductility. Attention is given to the interaction between local and lateral buckling of I-sections and their influence on inelastic flexural ductility for the members subjected to a constant moment. In fact, the section ductility concept is employed in most of the current steel design codes where section behavior is governed by the buckling of flange or web plates for which independent limitations are imposed. This assumption is unreasonable because, obviously, the flange is restrained by the web and the web is restrained by the flanges, so the interaction between the two local buckling modes must be considered. Furthermore at the member level, there are some additional factors that influence the ductility, and as a consequence of these factors, it seems that the above behavioral classes should be substituted by the concept of member behavioral classes. This paper proposes a classification of flexural members based on rotation capacity at the member level for the latest version of the Chinese steel design code which takes into account interaction between local and local–overall buckling modes.

ABSTRACT: This paper explores the mechanical behaviour of innovative fabricated stub columns, during ambient and elevated temperature conditions, under axial loads. The fabricated columns utilise very high strength (VHS) steel tubes welded to the corners of square and triangular conventional mild steel columns, of a 500 mm length. The nominal dimensions of the very high strength steel tubes used were 31.8 mm and 38.1 mm diameters with 2.3 mm and 1.6 mm thicknesses respectively, whilst the mild steel plates had widths of 120 mm and 400 mm and a 3 mm thickness. Individual mild steel and VHS tubes were also tested under elevated temperatures. Under ambient temperature, the testing consisted of applying an axial force to the columns to determine the ultimate capacities of the fabricated sections. The experimental tests at elevated temperatures
consisted of loading the specimens to 70% of the corresponding ultimate capacity, and increasing the furnace temperature in accordance with the ISO 834 curve, until failure was achieved. When the applied axial load is set to be the same at elevated temperatures, the fabricated VHS steel columns significantly outperformed the conventional mild steel columns. However, when degree of utilisation is set to be the same, the VHS specimens demonstrated a small reduction in strength compared to the corresponding mild steel columns. Moreover, numerical analysis was performed to verify the experimental results whilst a good agreement was achieved between the experimental results with those obtained from finite element modelling.

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ABSTRACT: This paper presents a set of new strength equations for box girder flanges stiffened with open ribs subjected to uniaxial compression. Tee type and flat-plate type cross-section ribs were considered in the isolated stiffened plate systems that were studied. A total of eighty four hypothetical compression flange panels were modeled with wide ranges of slenderness parameters and then were investigated by nonlinear finite element analysis (FEA). The dimensions of the FEA models were carefully determined to satisfy the major requirements for stiffened flange systems and the longitudinal stiffeners were designed such that stiffener local buckling did not govern the failure of the stiffened flanges. Both conventional and high performance steels (HPS) were investigated in the analysis models by utilizing multi-linear constitutive relationships. Initial imperfections and residual stresses were also considered in the analysis. New design equations to predict the in-plane compressive strengths of the stiffened flanges are proposed based on the FEA results and compared with other design equations specified in Eurocode 3, the Federal Highway Administration (FHWA) design specifications, and the Japanese Road Association (JRA) specifications, and equations previously proposed by other researchers. It has been found that the equations provided in the above design codes underestimate the strengths determined from the HPS models, which may result in an inefficiently conservative strength design.

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ABSTRACT: This paper describes the influence of surface transverse geometric imperfections called corrugations on the local stability of cold-formed elements. Such elements are used to construct self-supported arch buildings and roofs. The authors of the paper compare the results obtained from analytical investigation based on Eurocode 3 formulas, from linear and nonlinear numerical stability analyses and experimental investigation. Two types of thin-walled elements are considered: a panel with smooth walls and panels with corrugations on their surfaces. Finally the conclusions are made which can be useful for design purposes.
ABSTRACT: When an eccentrically braced frame (EBF) is subjected to a severe seismic event, large axial force and bending moments are produced in the beam outside of the link. Designers face significant difficulties in meeting the capacity design requirement to keep these beams elastic. On the other hand, previous research suggests that controlled yielding in the beams is not detrimental to EBF performance as long as stability of the beam is maintained. A computational study was undertaken to investigate the stability of cyclically loaded EBFs. A total of 51 EBF sub-assemblage models, none of which satisfies the capacity design requirement, were selected and investigated through three-dimensional, nonlinear finite element analysis. The results indicate that the link overstrength factor should be a function of the link length for performing capacity design of the beam outside of the link. This is because flexure yielding links, which are more problematic to beam stability, tend to develop smaller overstrength compared to shear yielding links. Furthermore, designs with demand-to-capacity ratios greater than unity were found to be viable provided that the stability of the beam is maintained by making use of a slenderness limit developed herein.

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https://doi.org/10.1016/j.jcsr.2014.01.007
ABSTRACT: This paper presents experimental data for cold-formed stainless steel lipped channel beams featuring distortional–global interaction buckling. Three stainless steel alloys were employed in the tests, namely austenitic S30401, ferritic S44330 and lean duplex S32101. Coupon tests were carried out to determine the mechanical properties of the virgin sheet material as well as the work-hardened corner material of the press-braked sections. Geometric imperfections were measured for each specimen prior to testing. A total of 32 specimens were tested under four-point bending, six of which were tested with lateral bracing in order to determine the section capacity. The remaining 26 specimens, with spans ranging from 1.8 m to 4.0 m, were tested in a specially devised test set-up. The set-up featured a dual-actuator gravity simulator, flexible load-applying frames and idealized end support conditions, all of which contributed to minimizing uncertainties in the tests, thereby affording benchmark tests for analytical and numerical studies. Interaction buckling was observed in all tests of unbraced members.

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ABSTRACT: The paper presents a detailed finite element (FE) model intended for studying the distortional–global interaction buckling behaviour of thin-walled stainless steel beams. The model incorporated actual
measured material properties of three stainless steel alloys (austenitic S30401, ferritic S44330 and lean duplex S32101), as well as measured initial geometric imperfections. The model was verified against the experimental data presented in the companion paper [1]. A parametric study was then carried out using the calibrated model to augment the ultimate strength database. The accuracy of the Australian/New Zealand (AS/NZS 4673 [2]), American (SEI/ASCE-8 [3]) and European (Eurocode3, Part1-4 [4]) standards for stainless steel structures was evaluated using the available data. It was found that the current Australian/New Zealand and American design codes do not contain rules for checking distortional buckling strength nor do they account for distortional–global interaction buckling effects. The European standard accounts for distortional buckling effects by reducing the effective area of flange stiffeners using an effective thickness method, and covers the effect of distortional–global interaction by using the effective cross-section for overall buckling strength checks. The European code was therefore more conservative than the other two standards. Following the principles of the Australian and American design codes for cold-formed steel structures, additional provisions for checking distortional buckling strength were suggested to improve the current Australian/New Zealand and American stainless steel design codes. Variants of the proposed provisions to account for distortional–global interaction were also examined which resulted in generally better predictions than those of the European code. However, the distortional–global interaction effect was found to vary with the section slenderness, and none of the design provisions performed consistently better than others.

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ABSTRACT: This paper investigates the behaviour of hollow and concrete filled steel (CFST) mild and stainless steel columns subjected to transverse static and impact loading with a pre-compressive axial load. Transverse load was applied at the mid or quarter point of the columns. A total of three test series were carried out recently at the University of Western Sydney and the University of Wollongong to obtain the performance of mild and stainless steel hollow and CFST columns subjected to lateral static as well as impact loading with or without pre-compressive load. The test results reported in this paper are from the third test series, where both axial and lateral loads were applied to the columns. This paper also investigates the finite element (FE) modelling of hollow and CFST mild and stainless steel columns due to static and impact loads. Three-dimensional nonlinear FE models were developed using ABAQUS, where nonlinear material behaviour, enhanced strength corner properties of steel, pre-compressive loads were all included to simulate the static and impact experiments. The main objective of this paper is to compare the performance of experimental results with numerical results for mild and stainless steel hollow and CFST columns. Moreover, the behaviour of infilled tubes under impact loading is also compared with that of hollow sections. Close agreement is achieved between the experimental and finite element results in terms of load–deflection response and ultimate strength. This paper also compares the results of hollow and CFST stainless steel columns with those of mild steel columns due to both static and impact loading. Generally, the stainless steel specimens showed higher strength and improved energy-dissipating characteristics compared with the mild steel columns.
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ABSTRACT: Owing to technological reasons the silos are frequently supported in a discrete way, usually by column heads. This kind of support causes a significant accumulation of compression meridional stresses in a cylindrical shell in support regions, which may lead to local buckling. The problem of determining shell resistance over the support region for different shapes of ribs constitutes a current research issue. One of highly preferred methods of strengthening this zone is the use of short ribs interconnected with a circumferential ring. Both the results of tests on the resistance of such shells and numerical analysis allowing to determine the course of this research are presented in this study. It has been demonstrated that the global resistance of the stiffened shells supported discretely is always much smaller from that in similar shells supported uniformly around the perimeter.

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ABSTRACT: In this paper, the flexural-torsional buckling and free vibration of tapered thin-walled beam-columns with arbitrary cross-section shape are extensively investigated. The governing equilibrium equations and motion equations are obtained from the stationary condition of the potential energy. The strain energy is derived in presence of initial stresses. In the work of the applied forces, effects of load eccentricities from shear and centroid centerlines are taken into account. Free vibration is considered in presence of harmonic excitations. In presence of arbitrary boundary conditions and variable cross-section properties, a semi-analytical approach based on power series method is adopted in solution. According to this method, displacements and geometric constants are approximated by polynomial functions up to a certain order, where accurate results are reached. The flexural-torsional buckling loads or natural frequencies are determined by solving an eigenvalue problem. In order to measure the accuracy and to check the validity of the present method, several examples including flexural-torsional behavior and free vibration analysis of non-prismatic thin-walled members with web and flange tapering and various boundary conditions are considered. The obtained results are compared to the finite element simulations and other available solutions.

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ABSTRACT: Stability of axially loaded steel columns with square hollow sections at elevated temperatures is studied herein. At present the Eurocode model for checking buckling capacity of columns in fire has been developed on the similar basis as for ambient conditions. It is shown that due to the effect of complex non-linear
behavior the standard design model is not always adequate and in certain situations prediction of buckling capacity of columns according to the common design formulas may even reach results on the unsafe side. The main focus of this work is the performance of an analytical model against advanced numerical methods. For this purpose extensive numerical study was performed using non-linear FE method. Based on the results obtained with advanced calculation models of column behavior at elevated temperatures an analytical model has been proposed and verified. The proposed model accounts for variable non-linear stiffness properties, which have significant effect on the buckling capacity of axially loaded columns in fire. The advantage of the method is the format, which is convenient for incorporation into common design algorithms.

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ABSTRACT: There are two primary collapse scenarios for single-layer latticed shells subjected to severe earthquake action: dynamic instability and strength failure. Of these, dynamic instability is the collapse scenario that must be avoided. First, taking the minimization of the standard deviation of the well-formedness as the optimization objective and the member sections as the optimization variables, an optimization model representing collapse scenarios for single-layer spherical shells is established. This optimization model also accounts for the displacement and stress constraints. Second, a genetic simulated annealing algorithm (GASA) is proposed by combining a genetic algorithm (GA) and a simulated annealing algorithm (SA). Finally, partial and overall optimizations are performed for a single-layer spherical shell that collapses due to instability under earthquake action. The results show that the optimized structure is subject to ideal strength failure under earthquake action with clear warning signs prior to collapse. In addition, the GASA performs better than the GA for optimization. Therefore, it is concluded that the optimization model and method presented in this paper can be used to perform collapse scenario optimization for single-layer spherical shells subjected to earthquake action.

Mikko Saliminen and Markku Heinisuo (Research Centre of Metal Structures, Tampere University of Technology), “Numerical analysis of thin steel plates loaded in shear at non-uniform elevated temperatures”, Journal of Constructional Steel Research, Vol. 97, pp 105-113, June 2014
https://doi.org/10.1016/j.jcsr.2014.02.002

ABSTRACT: The shear resistance of thin steel plate consists of three components: shear buckling, tension field and contribution of the flanges. This paper considers the first two. The shear resistance of steel plate at elevated temperatures is known when temperature is constant. However, in many practical applications temperature distribution across the plate is non-uniform. This paper presents the results of a finite element (FE) analysis of 12 steel plates at 18 non-uniform temperatures. A design method for predicting the shear resistance of thin steel plate at non-uniform elevated temperatures is also proposed. The basic idea of the method is to reduce the design strength of the plate based on so-called reference temperature, which is hotter than the average temperature but colder than the maximum temperature of the plate.
Poologanathan Keerthan and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Improved shear design rules for lipped channel beams with web openings”, Journal of Constructional Steel Research, Vol. 97, pp 127-142, June 2014
https://doi.org/10.1016/j.jcsr.2014.01.011

ABSTRACT: Cold-formed steel Lipped Channel Beams (LCB) with web openings are commonly used as floor joists and bearers in building structures. The shear behaviour of these LCBs with web openings is complicated and their shear capacities are considerably reduced by the presence of web openings. However, limited research has been undertaken on the shear behaviour and strength of LCBs with web openings. Hence a detailed numerical study was undertaken to investigate the shear behaviour and strength of LCBs with unreinforced circular web openings. Finite element models of simply supported LCBs under a mid-span load with aspect ratios of 1.0 and 1.5 were developed and validated by comparing their results with test results. They were then used in a detailed parametric study to investigate the effects of various influential parameters. Experimental and numerical results showed that the current design rules in cold-formed steel structures design codes are very conservative. Improved design equations were therefore proposed for the shear strength of LCBs with web openings based on both experimental and numerical results. This paper presents the details of finite element modelling of LCBs with unreinforced circular web openings, validation of finite element models, and the development of improved shear design rules. The proposed shear design rules in this paper can be considered for inclusion in the future versions of cold-formed steel design codes.

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ABSTRACT: This paper is an attempt to study the behavior of axially loaded concrete filled steel tubular (CFST) stub columns with special-shaped cross-sections, i.e. triangular, fan-shaped, D-shaped, 1/4 circular and semi-circular. A total of forty-four specimens including CFST stub columns and reference hollow steel tubular stub columns were tested. The effects of the changing steel tube wall thickness and the infill of concrete on the behavior of the composite columns were investigated. The results showed that the tested special-shaped CFST stub columns behaved in a ductile manner, and the composite columns showed an outward local buckling model near the middle section. Generally, the failure modes of these five kinds of special-shaped specimens were similar to those of the square CFST stub columns. Finally, simplified model for predicting the cross-sectional strength of the special-shaped CFST sections was discussed and proposed.

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ABSTRACT: This paper presents an experimental comparison between concrete-filled square steel tubular stub columns confined by internal loop or spiral stirrups, traditional square concrete-filled steel tubular stub columns (CFT), and inner stiffened square concrete-filled steel tubular stub columns. In total 11 specimens were
prepared and loaded concentrically in compression to failure. From the experimental results, the superior mechanical performance of stirrup-confined CFT to stiffened CFT was first demonstrated and the effects of different configurations of confinement (such as internal stiffeners, hoops and stirrups) on the ultimate load-bearing capacity were clarified. ABAQUS was used to establish 3D finite element models for the CFT and stirrup-confined CFT stub columns under axial compression, in order to understand the contribution made by loop or spiral stirrup confinement to the improvement of overall mechanical performance. Further, a simplified approach was developed to estimate the ultimate bearing capacity of stirrup-confined CFT stub columns, with consideration of the confinement effects offered by both square steel tube and stirrups. The predicted results showed satisfactory agreement with the experimental and numerical results.

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ABSTRACT: Steel structural members and frames always indicate imperfections to various degrees. These include initial out-of-straightness and initial out-of-plumb due to manufacturing and erection tolerances. In general, the shape and magnitude of geometric imperfections may have a significant influence on the response of a structure, and hence need to be modelled accurately when determining the load carrying capacity of a steel frame by advanced structural analysis. Most conveniently, geometric imperfections can be introduced in structural models as scaled eigenmodes obtained a priori from an elastic buckling analysis. However, it remains unanswered how many eigenmodes need to be incorporated and how to choose the scaling factors of each mode. This paper presents a study of how the strength of steel frames varies with the number and magnitudes of eigenmodes. Frames with random geometric imperfections are produced using the statistics of measurements of out-of-plumb and member imperfections, and analysed using advanced geometric and material nonlinear analysis. The imperfections are then resolved into eigenmodes and a second set of advanced analysis is carried out using a finite number of modes to represent the imperfections. Conclusions are drawn about the appropriate number and magnitudes of eigenmodes to use in advanced structural analyses of steel frames.

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ABSTRACT: When member buckling and joint fractures are considered in the numerical analyses of single layer lattice shells, the relationship curve between peak ground acceleration of the earthquake and the maximum nodal displacement, and the time–history curve of maximum nodal displacement, are erratic and unpredictable. Therefore, with such considerations, the current approach to determine dynamic damage of single layer lattice shells by comparing peak ground acceleration of the earthquake with critical ground acceleration derived from incremental dynamic analysis is inappropriate. An improved structure dynamic damage criterion is proposed for single layer lattice shells in this paper, which reviews the balance status of structure dynamic resistance against the earthquake action, and the structure damage time can be predicted by the occurrence of non-convergent solution to the structural nonlinear dynamic equilibrium equations in the iterative process from the mathematical point of view. Numerical examples are presented to illustrate the simplicity and practicality of the
proposed criterion. This criterion serves clear physical meaning and is of considerable potential applicability in analyzing single layer lattice shell structures. Results of parametric analyses of single layer lattice shells under severe earthquake actions indicate that the structure dynamic damage is not determined by material strength failure. For single layer spherical lattice shell, it is determined by structural instability resulted from member buckling; and for single layer cylindrical lattice shell, it is determined by the combined effect of structural instability and the change of structural topology that resulted from member buckling and joint fractures respectively. When member buckling and joint fractures are considered in the numerical analyses of single layer lattice shells, the relationship curve between peak ground acceleration of the earthquake and the maximum nodal displacement, and the time–history curve of maximum nodal displacement, are erratic and unpredictable. Therefore, with such considerations, the current approach to determine dynamic damage of single layer lattice shells by comparing peak ground acceleration of the earthquake with critical ground acceleration derived from incremental dynamic analysis is inappropriate. An improved structure dynamic damage criterion is proposed for single layer lattice shells in this paper, which reviews the balance status of structure dynamic resistance against the earthquake action, and the structure damage time can be predicted by the occurrence of non-convergent solution to the structural nonlinear dynamic equilibrium equations in the iterative process from the mathematical point of view. Numerical examples are presented to illustrate the simplicity and practicality of the proposed criterion. This criterion serves clear physical meaning and is of considerable potential applicability in analyzing single layer lattice shell structures. Results of parametric analyses of single layer lattice shells under severe earthquake actions indicate that the structure dynamic damage is not determined by material strength failure. For single layer spherical lattice shell, it is determined by structural instability resulted from member buckling; and for single layer cylindrical lattice shell, it is determined by the combined effect of structural instability and the change of structural topology that resulted from member buckling and joint fractures respectively.

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ABSTRACT: This paper presents a series of test results of elliptical concrete filled steel tubular (CFST) beams and columns to explore their performance under bending and compression. A total of twenty-six specimens were tested, including eight beams under pure bending and eighteen columns under the combination of bending and compression. The main parameters were the shear span to depth ratio for beams, the slenderness ratio and the load eccentricity for columns. The test results showed that the CFST beams and columns with elliptical sections behaved in ductile manners and were similar to the CFST members with circular sections. Finally, simplified models for predicting the bending strength, the initial and serviceability-level section bending stiffness of the elliptical CFST beams, as well as the axial and eccentric compressive strength of the composite columns were discussed.

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ABSTRACT: In comparison to steel sections made from normal strength steel (NSS), those fabricated from high strength steel (HSS) can be thinner and lighter because of the improvement of the steel yield strength. This results in higher width-to-thickness ratios of the component plates and makes local buckling more critical for members in compression. Axial compression experiments were performed on steel stub columns made from Q460 steel (with nominal yield strength greater than 460 MPa), including four box section members and nine I-section members. A finite element model was developed with accurate simulation of initial imperfections. The modeling results were verified by experiments and a parametric analysis was conducted based on the validated modeling. In comparing the ultimate stress calculated by design methods in different codes with the experimental and numerical results, it was found that for the component plates of box section members, the design methods overestimated the ultimate stress of local buckling, so that the result was not safe enough. For the flanges of I-section members, the design methods underestimated the ultimate stress, especially for cases with relatively higher width-to-thickness ratio.

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“Experimental study on column buckling of 420 MPa high strength steel welded circular tubes”, Journal of Constructional Steel Research, Vol. 100, pp 71-81, September 2014
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ABSTRACT: This paper investigates the column buckling performance of welded circular tubes made of 420 MPa high strength steel (HSS). 24 axial compression column tests on specimens with a nominal diameter of 273 mm and thickness of 6 mm were conducted. Initial geometric imperfections including out-of-straightness and loading eccentricity were measured. Experimental results in terms of buckling modes and load-carrying capacities are presented and discussed in detail. Non-linear finite element (FE) models were developed which captured the experimental observations satisfactorily. Based on the validated FE models, further parametric analyses incorporating 60 HSS numerically generated welded circular tubular columns with various section sizes were carried out. The resulting FE and experimental results were compared with the existing column design curves in Chinese, European and American codes. Numerical results showed that the design resistances calculated based on design curve a in both GB50017-2003 and Eurocode 3 and the design formula in the ANSI/AISC 360-10 could be adopted. In addition, to further improve the design efficiency, a column design curve based on Eurocode 3 formulation with a new imperfection factor of 0.17 was proposed for the design of such HSS welded tubular columns.

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In order to have a better understanding of the failure mechanism of a single-layer reticulated dome under seismic load, parametric analyses through increment dynamic analysis (IDA) are conducted on the dome. The results of the analyses indicate that the limit load of the structure significantly increases together with the plastic development with the decreasing rise–span ratio, roof mass and initial defects prior to the failure to collapse. The plastic development reduces and the structural ductility gets worse as the cross-section area of a structural member decreases. The failure of a single-layer reticulated dome under a strong seismic load is due to the failure in dynamic strength resulting from the excessive damage of material. A structural damage model which can estimate different degrees of damage of the dome is defined. Then, the fragility curves of the different values of the structural damage model with the corresponding different degrees of damage under seismic records are obtained through IDA analysis which can be used for seismic performance evaluation and risk assessment for its loss or fatality acceptability. A theoretical guidance is thus provided for the engineering application of this kind of structure.

ABSTRACT: This paper is aimed at investigating the elastic buckling of longitudinally stiffened plate girder subjected to patch loading. At first, buckling coefficients are computed by means of linear buckling analysis using the finite element method. Thereafter, a first order factorial design is performed to weigh the geometrical parameters on the buckling coefficient. Finally, a second order model is obtained to predict the buckling coefficient for longitudinally stiffened plate girders. A significant improvement, within the range of geometric parameters investigated herein, is achieved when compared to similar formulae found in the literature.

ABSTRACT: Hybrid structures which innovatively and reasonably combine two different materials in longitudinal direction have been applied world-wide, such as hybrid girder, hybrid pylon and hybrid arch skewback. The hybrid structure segment generally consists of steel stiffened segment, concrete strengthened segment and hybrid joint. In order to investigate ultimate capacity and buckling mode of steel stiffened segment in hybrid structure, model tests on five different specimens have been carried out. The test results indicated that embedded T-reinforcing stiffeners had the best axial stiffness, while the out-plane stiffness, ultimate capacity and local stress concentration of circumscribed π-reinforcing stiffeners were best among the three traditional reinforcing stiffeners. Besides, the methods of extending reinforcing stiffener web and adding diaphragms on the end of reinforcing stiffeners not only obviously improved both axial and out-plane stiffness but also increased ultimate capacity and reduced local stress concentration. Five three-dimensional finite element (FE) models of steel stiffened segments considering initial imperfections and residual stress were established.
Theoretical analysis based on the principle of stationary potential energy was carried out. The reduced parameters based on FE analysis results were consistent with those from tests and theoretical analysis and tended to be conservative at a safety level. The presented overall investigation may provide reference for the design and construction of stiffened steel segment in hybrid structure.

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ABSTRACT: Experiments show that the ultimate compressive strength of stainless steel is much higher than its tensile strength. The full-range two-stage constitutive model for stainless steels assumes that stainless steels follow the same stress–strain behavior in compression and tension, which may underestimate the compressive strength of stainless steel tubes. This paper presents a fiber element model incorporating the recently developed full-range three-stage stress–strain relationships based on experimentally observed behavior for stainless steels for the nonlinear analysis of circular concrete-filled stainless steel tubular (CFSST) short columns under axial compression. The fiber element model accounts for the concrete confinement effects provided by the stainless steel tube. Comparisons of computer solutions with experimental results published in the literature are made to examine the accuracy of the fiber element model and material constitutive models for stainless steels. Parametric studies are conducted to study the effects of various parameters on the behavior of circular CFSST short columns. A design model based on Liang and Fragomeni's design formula is proposed for circular CFSST short columns and validated against results obtained by experiments, fiber element analyses, ACI-318 codes and Eurocode 4. The fiber element model incorporating the three-stage stress–strain relationships for stainless steels is shown to simulate well the axial load–strain behavior of circular CFSST short columns. The proposed design model gives good predictions of the experimental and numerical ultimate axial loads of CFSST columns. It appears that ACI-318 codes and Eurocode 4 significantly underestimate the ultimate axial strengths of CFSST short columns.


ABSTRACT: The objective of the present study is the experimental and numerical investigation of the in-plane response of scaled Z-laced built-up columns under axial loading applied at the ends with significant eccentricities. The magnitude and direction of eccentricity, the profile of the chords and the density of the lacing are varied, in order to address their effect on the columns' capacity. Next, the corresponding numerical modeling of the experiments is presented in detail by describing the numerical models, types of finite elements and methods of analyses. The numerical analyses include the effects of initial geometric imperfections and thermally induced residual stresses. The numerical results showed a very good agreement with the experimental ones. The effect of end concentrated moments reduced significantly the axial capacity of the specimens.
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ABSTRACT: A circular concrete-filled steel tube (CFST) has several advantages compared with the conventional reinforced concrete member or hollow steel tube, since the tri-axial state of compression of the concrete infill increases its strength and strain capacity. Extensive studies have been conducted on the CFST and several researchers suggested empirical and theoretical formulas to predict the confinement effect and confined compressive strength of the concrete infill of the CFST. However, the previously proposed equations vary significantly because of the nature of complexity and uncertainty of the tri-axial stress state in the concrete infill. This study presented an alternative method to determine the confinement effect of the concrete infill and the axial load capacity of the stub CFST by using fuzzy logic. The focus was made on the accurate estimation of the confinement effect of the CFST by using a fuzzy-based model that makes it possible to evaluate the interaction between various parameters that affect the confinement effect. The proposed fuzzy-based model for the confinement effect and axial load capacity of the stub CFST was compared with current design codes and the results of previous studies. It was found that the proposed fuzzy-based model provides a good prediction of the confinement effect and axial load capacity of the stub CFST. Finally, the design chart to estimate the confinement effect of the stub CFST was provided for practical design purpose.

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ABSTRACT: This paper proposes the use of existing European buckling curves to check the resistance of heavy wide flange quenched and self-tempered (QST) sections made from high-strength steel, failing by flexural buckling. The buckling curves are evaluated according to the statistical procedure given in Annex D of EN 1990 using finite element analyses. The residual stress model as described in a related paper was used to define the initial stress state of the column in the finite element model. A large database was created containing the ratio between the elastic–plastic buckling resistance obtained from finite element analysis and the buckling resistance obtained from the proposed buckling curve for a wide set of column configurations from which a partial factor $\gamma_{rd}$ was deduced. Two different section types were investigated: the stocky HD and more slender HL type, featuring a height-to-width ratio ($h/b$) of approximately 1.23 and 2.35, respectively. Based on the criterion that the partial (safety) factor $\gamma_{rd}$ should not exceed 1.05 it is suggested to check the buckling response of a heavy HD section according to buckling curve “a” or “b” when failing by strong-axis or weak-axis buckling, respectively. HL sections are to be designed according to buckling curve “d” for strong-axis buckling and buckling curve “b” for weak-axis buckling.
ABSTRACT: This paper describes the blast loading trials on steel tubular members with and without concrete infill. The standoff distances considered in this trial were selected to demonstrate the response of these steel sections to contact and very close-range detonations of high explosive (HE). The main objective of the trials was to investigate the effects of contact and near-field explosions on steel square tubular members and to demonstrate the effect of standoff variations on the mode of response and failure of steel square sections. The experimental data collected during these trials can be used for verification of theoretical and numerical models of response of steel tubular columns subjected to contact and close-range blasts. Due to difficulties with collecting quantitative data (displacements, blast pressures, etc.) in the close proximity of a detonating HE charge, analysis of the steel tubes in this paper is confined mostly to qualitative assessment based on visual observations of the structural damage and limited numerical simulations of the blast–structure interaction using LS-DYNA aimed at clarifying some important phenomena that were not available to be obtained directly from the explosive tests. A new simplified approach to predicting the dynamic response of square tubular steel members subjected to the near-field airblast loading is proposed. The comparison of the analytically predicted dynamic response parameters of the concrete-filled steel tubular members with the experimental data shows very good agreement with the predicted failure mechanism and level of damage of the structural element.

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ABSTRACT: The performance of concrete-encased CFST column under combined compression and bending is studied in this paper. A finite element analysis (FEA) model is developed to analyse the behaviour of the composite column, and generally good agreement is achieved between the measured and predicted results in terms of the failure mode, the load-deformation relation and the ultimate load. Typical failure modes, full-range response of load-lateral deflection relation, loading distributions of the inner CFST and the outer RC components, the contact stress between the steel tube and the concrete of the composite columns are analysed. The influence of slenderness ratio and loading paths on the composite columns are also investigated. Influence of parameters, such as the strength of concrete and steel, steel ratio of CFST, longitudinal bar ratio and diameter of CFST on the sectional capacity of the concrete-encased CSFT columns is analysed based on the FEA model. A simplified model is proposed to calculate the sectional capacity of concrete-encased CFST columns under combined compression and bending.

P. Sharafi, Lip H. The and Muhammad N.S. Hadi (School of Civil, Mining & Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia), “Shape optimization of thin-walled steel

ABSTRACT: This paper presents an intuitive procedure for the shape and sizing optimizations of open and closed thin-walled steel sections using the graph theory. The goal is to find shapes of optimum mass and strength (bi-objectives). The shape optimization of open sections is treated as a multi-objective all-pairs shortest path problem, while that of closed sections is treated as a multi-objective minimum mean cycle problem. The sizing optimization of a predetermined shape is treated as a multi-objective single-pair shortest path problem. Multi-colony ant algorithms are formulated for solving the optimization problems. The verification and numerical examples involving the shape optimizations of open and closed thin-walled steel sections and the sizing optimization of trapezoidal roof sheeting are presented.


ABSTRACT: The strength of a web-core steel sandwich plate is potentially reduced in a corrosive environment. This study is dedicated to the influence of a reduction in the thickness of the plates as a result of general corrosion on sandwich plate buckling strength and first-fibre failure. Two scenarios are investigated in which corrosion reduces the thickness of (a) the outer sides of the face plates and (b) all surfaces, including the core. The laser weld between the face sheets and the core is assumed to be intact. The assumptions are made on the basis of earlier experimental findings. Critical buckling and geometric non-linear analysis are carried out with the finite element method, with the kinematics being represented using two approaches: (1) equivalent single-layer with first-order shear deformation theory, and (2) a three-dimensional model of the actual geometry of the structure, modelled using shell and connector elements. The former is used to identify the effect of corrosion on the stiffness coefficients and, consequently, the buckling strength. The latter is used for verification and for stress prediction during post-buckling. A rapid decrease in the buckling strength was found for corrosion affecting the outer sides of the sandwich plate. The decrease in the buckling strength doubled in the case of the diffusion of moisture (water) into the core. The shear-induced secondary bending of the faces was found to affect the first-fibre yield.


ABSTRACT: Steel plate girders with slender webs are particularly susceptible to severe damage when subjected to high temperatures due to fire. Using nonlinear finite element (FE) models, this study examines the buckling strength of steel plate girder webs subject to fire temperatures. The models were validated with experimental results presented by other researchers, and the validation study resulted in recommendations for appropriate FE representations of material properties and boundary conditions. The elastic shear buckling stress ($\tau_{cr}$) and ultimate shear buckling stress ($\tau_u$) was then studied for web plates with various span-to-depth ($a/D$) ratios and a range of temperatures representing fire conditions. The results of this parametric study were compared to predictions given by the Basler–Thürlimann (BT) closed-form solution, which was originally developed to predict $\tau_u$ at ambient temperature. Various representations of the elevated temperature stress, at the
time of $\tau_{u}$, were used in the BT solution and compared to the FE results. It was found that the BT solution provides adequate predictions of $\tau_{u}$ at elevated temperatures with appropriate substitutions for the yield stress.

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“Comparative study on the behaviour of Buckling Restrained Braced frames at fire”, Journal of Constructional Steel Research, Vol. 102, pp 1-12, November 2014, https://doi.org/10.1016/j.jcsr.2014.06.003
ABSTRACT: In this paper, the use of Buckling Restrained Brace systems (BRBs) in preventing the progressive collapse of the structural frame against fire is investigated using the stiffness reduction technique. Four-storey steel structures fitted with different bracing configurations were modelled using the Vulcan programme. For comparative purpose, the efficiency of BRBs in preventing the progressive collapse of the structure is compared with the Ordinary Concentrically Brace systems (OCBs) in the presence of edge and central bay fire exposures. In order to consider the effect of bracing member stiffness on the collapse prevention of the frame and to provide a comprehensive scheme of progressive collapse mechanism under fire condition, several cross sections of BRBs under different fire scenarios are considered. The results indicate that BRBs provide a higher global collapse temperature for the frame, owing to a greater stiffness and more symmetrical performance offered as compared to OCBs, and thus providing better progressive collapse resistance. Moreover, it is observed that BRBs are stiff enough to redistribute the sustained load by heated columns to adjacent members without any buckling occurrence in the bracing member, maintaining the stability of the whole frame through both heating and cooling phases of fire.

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ABSTRACT: The local elastic shear buckling strength of trapezoidal corrugated steel webs is investigated using finite element (FE) and theoretical analyses. The local elastic shear buckling strength is represented by the local elastic shear buckling coefficient, which is obtained from FE analysis. Although inelastic buckling will control the shear strength of most practical corrugated webs, the local elastic shear buckling coefficient is an important parameter in the shear strength calculation. This study shows that the fold width ratio, defined as the longitudinal fold width over the inclined fold width, has a significant influence on the local elastic shear buckling strength as the fold width ratio varies from 1.0 to 2.0. It is shown that the commonly-used local elastic shear buckling coefficient underestimates the local shear buckling strength by a considerable margin when the fold width ratio is greater than 1.0. It is also shown that the local elastic shear buckling coefficient is sensitive to the fold height-to-width aspect ratio, the fold width-to-thickness ratio, and the web corrugation angle, but is insensitive to the flange-thickness-to-web-thickness ratio when it varies from 5 to 15. Based on regression of FE analysis results, a formula is proposed to improve the calculation of the local shear buckling strength, in which parameters such as fold width ratio, fold aspect ratio, fold width-to-thickness ratio, and corrugation angle are taken into account.
ABSTRACT: Experimental and numerical studies into the structural behaviour of reinforced concrete columns confined by circular steel tubes after exposure to standard fire conditions are presented. These elements differ from conventional concrete-filled steel tubular (CFST) columns in that breaks in continuity are present at the member ends, which limit the longitudinal stresses in the steel and maximise the level of confinement afforded to the concrete through the generation of hoop stresses in the tube. The temperature distributions in the specimens were measured during the heating and cooling phases, while the load–displacement relationships and longitudinal and transverse strains in the steel tube were recorded during the subsequent compressive tests. 3D finite element (FE) models were also developed using the program ABAQUS to investigate the post-fire performance of circular steel tube confined reinforced concrete (CSTCRC) columns, including both heat transfer and stress analyses. The FE models were used to identify the influences of key parameters on the residual capacity of CSTCRC columns, following exposure to the ISO-834 standard fire. The considered parameters included heating time, cross-sectional dimensions, strength of the materials, steel tube to concrete area ratio and ratio of reinforcement. Finally, a design method was proposed for predicting the residual load bearing capacity and compressive stiffness of CSTCRC columns after standard fire exposure.

ABSTRACT: Equal-leg single angle section (SAS) members were analyzed for flexural loading patterns along the geometric axis. Uniform, triangular, double-curvature and parabolic bending moment were produced using loading patterns over the span of member. Variations in orientation as well as in local and global slenderness ratio were considered to plot normalized moment rotation curves. Both material and geometrical nonlinearities with imperfections in member were also incorporated. These curves were compared with the existing provisions of AISC specification to verify the validity of the upper limit on $C_b$, which accounts for the effect of loading patterns on the elastic critical buckling moment of SAS members. Design specifications of Indian Standard (IS 800: 2007) for lateral-torsional buckling (LTB) of doubly and mono-symmetric sections were used to develop the design guidelines for limit state of LTB of SAS members. Moment capacity curves from proposed guidelines were compared with the AISC specification and were found to be safe and conservative.

ABSTRACT: Experimental and numerical studies into the structural behaviour of reinforced concrete columns confined by circular steel tubes after exposure to standard fire conditions are presented. These elements differ from conventional concrete-filled steel tubular (CFST) columns in that breaks in continuity are present at the member ends, which limit the longitudinal stresses in the steel and maximise the level of confinement afforded to the concrete through the generation of hoop stresses in the tube. The temperature distributions in the specimens were measured during the heating and cooling phases, while the load–displacement relationships and longitudinal and transverse strains in the steel tube were recorded during the subsequent compressive tests. 3D finite element (FE) models were also developed using the program ABAQUS to investigate the post-fire performance of circular steel tube confined reinforced concrete (CSTCRC) columns, including both heat transfer and stress analyses. The FE models were used to identify the influences of key parameters on the residual capacity of CSTCRC columns, following exposure to the ISO-834 standard fire. The considered parameters included heating time, cross-sectional dimensions, strength of the materials, steel tube to concrete area ratio and ratio of reinforcement. Finally, a design method was proposed for predicting the residual load bearing capacity and compressive stiffness of CSTCRC columns after standard fire exposure.

ABSTRACT: Coped (notched) steel beams are widely used in steel frame structures. A state-of-the-art review on local failures of coped steel beams is presented with the main aim of providing a clear insight into the up-to-date research outcomes and design approaches on the issues of local web buckling, block shear, and fatigue. With a comprehensive review of the available research database, the rationale behind the current design treatments for these failure modes is evaluated. For the design of local web buckling for coped beams with bolted end connections, adopting the lowest value of the resistances governed by elastic local web buckling, flexural yielding, and shear yielding can be safe. A reduction factor of 0.9 on the design local web buckling resistance may be applied for the case of welded connections due to the possible interactive effect of block shear. Use of the AISC–LRFD equations is suggested for the block shear design of coped beams with single-line bolted connections, and both the AISC–LRFD and the CSA-S16-09 equations are suitable for the case of double-line bolted connections. For coped beams with welded connections, the use of a reduced $U_t$ of 0.7 in the CSA-S16-09 equations is recommended. For fatigue design, use of a new category curve modified from the relevant equations in AISC–LRFD is proposed in this paper to ensure a safe and consistent design. Illustrative design examples are presented based on the recommended design methods. The expected future work is also outlined.

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ABSTRACT: In this paper, an accurate finite element model which accounts for the effects of initial local imperfections and residual stresses is developed for the nonlinear analysis of high strength steel box columns infilled with high strength concrete. The inelastic behaviour of the steel box and the concrete core is modelled using an elastic–plastic model with linear hardening and a concrete damaged plasticity model, respectively. In addition, an extensive numerical analysis based on a wide range of width-to-thickness ratios, yield stresses of steel tubes and compressive strengths of concrete core was also carried out to propose a new empirical equation for estimating the confining pressure on the concrete. The predictions of ultimate strengths, behaviour and failure modes are compared with experimental results to verify the accuracy of the present model. Parameter studies indicate that both the Eurocode EC4 and Australian Standard AS 5100 approaches can be safely extended to predict the ultimate strength of concrete-filled steel columns with high strength materials.

ABSTRACT: The design force demands on the columns of steel plate shear walls tend to be very large. Several methods have been proposed to reduce the moments and axial forces on the columns, while still achieving good system performance. One such method is to reduce the strength of the infill plate by perforating it using a regular pattern of circular holes. The diameter of the holes selected and their center-to-center spacing control the decrease in lateral shear strength of the system. An appropriate performance-based design method is proposed and used to study the suitability of the perforated system. The results of a variety of finite element models showed that although introducing the perforations into the infill plates reduces the lateral strength of the system, the net demand on the columns can in some cases actually increase. The perforated system behavior is also sensitive to the pattern of holes selected; a small change in the arrangement of the holes can have a significant effect on the moment demand on the columns. Also, the flexibility of the beam-to-column connections influences the sensitivity of the column design forces to the pattern of holes selected and affects the column demands considerably.

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ABSTRACT: This paper studies the behavior of circular concrete filled steel tubular (CFST) stub columns under sustained load and chloride corrosion. A total of 17 specimens, including 11 stub CFST columns and 6 reference hollow steel tubes, were tested. The main parameters are loading ratios (0, 0.3 and 0.6) and corrosion conditions (no-corrosion, fully-immersed and half-immersed in corrosion environment). It was found that corrosion could have significant influence on the ultimate strength of both CFST and hollow steel tubular stub columns. Compared with the hollow steel tubes, the composite actions in CFST specimens can effectively lighten the effect. A finite element analysis (FEA) model was developed to take out full-range analysis on the behavior of CFST stub columns under long-term loading and corrosion, including failure modes, load–displacement relationship, load distribution in the composite section, and the interaction between the steel tube and its core concrete. Parametric studies were carried out to study the main factors that may influence the residual axial strength of CFST stub columns under long-term loading and corrosion. Based on the parametric analysis, a simplified model for the residual axial strength ratio of CFST stub column was suggested.
References listed at the end of the paper:
ABSTRACT: This paper focuses on the reinforcing methods used for improving the compression behaviors of perforated box-section walls as provided in the anchorage zones of steel pylons to hold the cables. The rectangular plates investigated each have single-row continuous elliptical holes and are simply supported on four edges in the out-of-plane direction. Two types of reinforcing stiffeners named flat stiffener (FS) and longitudinal stiffener (LS) are considered. Uniaxial compression tests are first conducted for 46 specimens, of which 10 are unreinforced plates and 36 are reinforced plates. The mechanical behaviors such as stress concentration, out-of-plane deformation, failure pattern, and elasto-plastic ultimate strength are experimentally investigated. Finite element models are further developed to predict the ultimate strengths of plates with various dimensions. The FE results are validated by the test data. The influences of non-dimensional parameters including plate aspect ratio, hole spacing, hole width, stiffener slenderness ratio, as well as stiffener thickness on the ultimate strengths are illustrated on the basis of numerous parametric studies. Comparison of reinforcing efficiency shows that the continuous longitudinal stiffener is the best reinforcing method for such perforated plates. The simplified formulations used for estimating the compression strengths of reinforced plates are finally proposed.

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ABSTRACT: In bridge construction, the use of stiffened plates for box-girder or steel beams is common day to day practice. The advantages of the stiffening from the economical and mechanical points of view are unanimously recognized. For curved steel panels, however, applications are more recent and the literature on their mechanical behaviour including the influence of stiffeners is therefore limited. Their design with commercial finite element software is significantly time-consuming, which reduces the number of parameters which can be investigated in an optimization procedure. The present paper is thus dedicated to the study of the behaviour of stiffened curved panels under uniform longitudinal compression. It addresses the linear buckling and the ultimate strength which are both influenced by the coupled effects of curvature and stiffening. It finally proposes a design methodology based on that for stiffened flat plates adopted by European Standards and a column-like behaviour.
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ABSTRACT: Composite shear walls are becoming popular in high-rise buildings for their high load-carrying and deformation capacities. The deformation capacity of composite shear walls is a key response characteristic for seismic resistance, and depends on a complex interaction of geometric and material properties, which needs to be explored. Based on a fiber section analysis approach using refined material constitutive models, an analysis program was developed to analyze the moment–curvature behavior of concrete-filled steel plate composite shear walls. The accuracy of the program was verified against available test results. A parametric study was then performed on 6379 configurations to study the effect of variables such as axial compression ratio, concrete strength, steel content ratio, and boundary element concrete confinement on the deformation capacity of the concrete-filled steel plate composite wall cross sections. The results were analyzed to develop simplified formulas based on geometric and material inputs for calculating the ultimate curvature which was defined as the curvature associated with a 15% loss in moment capacity. The formulas for calculating the ultimate curvature can be further used to calculate the drift capacities and ductility of composite shear walls.

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ABSTRACT: The structural behaviour of steel tied-arch bridges is determined by the introduction of a large compressive force. As a consequence, slender steel arches are highly sensitive to in-plane as well as out-of-plane buckling. At present, no specific buckling curves for out-of-plane buckling exist for non-linear or curved elements in the international codes and calculation methods. Hence, the buckling curves for straight columns, as determined by ECCS, are used, which leads to considerable inaccuracies in the assessment of the critical buckling load for arch bridges. This paper presents two practical calculation methods to design for the buckling behaviour of slender steel arch bridges. The first one follows the calculation method of the Eurocode, but proposes some augmented empirical formulas for the buckling length of the arches. This allows for a better representation of the out-of-plane stiffness of the arch cross section and of the wind bracings between both arches. In addition a second method is proposed, based on the use of simplified finite element models to determine the relative slenderness of the structure. Both methods are validated using results from very detailed three dimensional finite element models. Finite element models of several tied-arch bridges have been created. These models include variations of the bridge length, dimensions of the arch cross-section, boundary condition, and load type. The conclusion of these calculations is that for both of the proposed methods a higher buckling curve can be used than proposed by the code, thus resulting in a more slender bridge design.

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ABSTRACT: This study elucidates experimentally and analytically the axial compressive load-carrying capacity and behavior of square composite steel and concrete columns confined by multiple interlocking spirals. The variables of the specimens included type of the lateral reinforcement (rectilinear hoops and multiple spirals), spacing of the lateral reinforcement, and shape of the structural steel section (cruciform and box-shaped). Specimens were tested under monotonically increased axial load. The test results demonstrated that the composite columns with multiple spirals achieved great axial load-carrying capacity and deformability because of the excellent concrete confinement attributed to the multiple interlocking spirals and the structural steel section. Smaller spacing of the spirals and larger area of the highly confined concrete in the composite columns resulted in the better strength and ductility of the columns. An analytical model was proposed to calculate the load–displacement relations of the specimens, and the model predicted well the behavior of the specimens. The effectiveness of the multiple interlocking spirals in the square composite columns was evident via this study.

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ABSTRACT: This paper studies the behavior and capacity of stainless steel lipped C-section stub columns under axial compression. A total of 10 tests were conducted on stub columns to investigate the failure mechanism and mode, the load–displacement curves, the section strain variation and the capacity. A comparison of the test results with code predictions indicates that the design strengths are lower than the experimental strengths and that the deviation between the test and predicted results decreases as the section plate slenderness coefficient increases. A finite element model is built to conduct parametric studies on the influential factors of member strength. Finally, based on the finite element analysis of 98 stub column specimens, a direct strength equation for stainless steel lipped C-section stub columns is proposed.

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ABSTRACT: If steel structures are subjected to the combination of bending, shear and patch loading, the interacting stability behaviour in the design should be taken into consideration. The combined loading situation can often occur in case of bridge girders during launching, therefore the determination of the load carrying capacity under the combined loading situation is an important aspect of the bridge design. In the current version of EN1993-1-5 [1] there is no standard design method to take the interaction of these three effects into account.
and there are a very small number of previous investigations in the literature about this topic. The current paper focuses on the investigation of the interaction behaviour of longitudinally unstiffened steel I-girders under the combination of bending, shear and patch loading. The companion paper (Part II) Kövesdi et al., 2014 [25] deals with the M–V–F interaction behaviour of girders with longitudinal stiffeners. Based on a verified numerical model, the load carrying capacities are determined on various girder geometries for various loading situations, and the applicable interaction equation is investigated in the current paper.

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ABSTRACT: During launching of a bridge structure large bending moment, shear and transverse forces can often occur at the same time in the same cross section which can result in governing situations for the design. In case of these structures the interacting stability behaviour should be taken into consideration. Bridge structures have usually longitudinal stiffeners on the web, therefore the determination of the load carrying capacity of girders with longitudinally stiffened webs under the combined loading situation is an important aspect of bridge design. In the current version of EN 1993-1-5 [1] there is no standard design method to take the interaction of these three effects into account and there are a very small number of previous investigations in literature dealing with this topic. The companion paper (Part I) [27] deals with the M–V–F interaction behaviour of girders without longitudinal stiffeners. The current paper focuses on the interaction behaviour of longitudinally stiffened steel I-girders subjected to bending, shear and transverse force (patch loading). Numerical model is developed to investigate the combined effect of these three internal forces on the load carrying capacity. Based on the numerical parametric study design interaction equation is proposed to consider the M–V–F interaction behaviour of girders with longitudinal stiffeners in the design.

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ABSTRACT: This paper presents a numerical investigation on the buckling behaviour of plasterboard protected CFS channel-section beams subjected to uniformly distributed loads when exposed to fire on its one side. The work involves three phases, namely heat transfer analysis, pre-buckling analysis and buckling analysis. The heat transfer analysis is accomplished using two-dimensional finite element analysis methods, from which the temperature fields of the channel-section beams are obtained. The pre-buckling analysis is completed using the Bernoulli bending theory of beams with considering the effects of temperature on strain and mechanical properties. The buckling analysis is performed using combined finite strip analysis and classical Fourier series solutions, in which the mechanical properties are considered to be temperature dependent. The results show that there are significant temperature variations in web, fire exposed flange and lip. Also, it is found that the
buckling behaviour of the beam with temperature variation in its section is quite different from that of the beam with a constant uniform temperature in its section.

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ABSTRACT: This paper presents the long-term structural behaviour analysis and stability assessment carried out on concrete-filled steel tubular (CFST) circular arches. Linear and non-linear analyses are herein conducted for pin-ended and fixed arches subjected to a central concentrated load. Accounting for the significant effects from creep and shrinkage in concrete core, in-plane deformations, internal forces and in-plane buckling loads are evaluated analytically and the adequacy is validated against the finite element results. The comparison of the results obtained by linear and non-linear analyses exhibits significantly different change scopes in deformation and loading capacity. For the sake of structural safety, non-linear analysis is found to be more reliable in long-term behaviour analysis and stability assessment for CFST arches. Hence, non-linear buckling analysis should be employed in assessing the long-term serviceability limit state of pin-ended and fixed CFST shallow arches in design practice, although linear buckling analysis is capable of predicting the in-plane buckling loads for pin-ended CFST deep arches.

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ABSTRACT: In order to facilitate the constructability and meanwhile ensure desirable seismic behavior, an innovative type of replaceable steel truss coupling beam with a buckling restrained web was conceived and studied. The buckling restrained steel web is designed and detailed as a fuse and a damper of the beam in which all inelastic deformations and damage are concentrated. Bolted connections between steel webs and beam chords, as well as pin connections between beam chords and adjacent reinforced concrete shear walls, are employed to minimize the post-event repair/replacement difficulties and expenses. To evaluate the seismic behavior, three large scale coupling beam specimens were constructed and tested under cyclic loadings. The effects of some configurations of the steel webs including welded edge stiffeners and slits on the seismic behavior were highlighted. The test results indicate that all three specimens failed in a ductile manner with a concentration of inelastic deformations and damage are concentrated. Bolted connections between steel webs and beam chords, as well as pin connections between beam chords and adjacent reinforced concrete shear walls, are employed to minimize the post-event repair/replacement difficulties and expenses. To evaluate the seismic behavior, three large scale coupling beam specimens were constructed and tested under cyclic loadings. The effects of some configurations of the steel webs including welded edge stiffeners and slits on the seismic behavior were highlighted. The test results indicate that all three specimens failed in a ductile manner with a concentration of inelastic deformation at steel webs and thus exhibited desirable deformation and energy absorption capacities. The strength and stiffness of the proposed coupling beam can be enhanced by welding edge stiffeners to steel webs while the steel web with slits is susceptible to suffer significant buckling of flexural links, resulting in a relatively lower strength and ductility of the beam. To predict the load carrying capacity of the proposed coupling beam, a modified strip model to account for the beneficial effects of the buckling–
bracing provided by precast reinforced concrete panels was developed. The analytical results were compared with the experimental results.

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ABSTRACT: Flexible giant crane boom is a statically indeterminate mixed structure equipped in giant boom cranes. It has a soaring complex geometry consisting of a giant combined boom and a flexible luffing structure, and the overall plastic instability is apt to happen under large hoisting, gravity and wind loads. As dually (geometrically and materially) nonlinear buckling analysis for flexible giant crane booms has not been well studied in literature, a detailed investigation is presented in this paper. Prior to carrying out a dually nonlinear buckling analysis, this paper first undertakes a geometric buckling analysis for a better understanding of the buckling behavior. A method of applying temporary constraints is proposed to prevent the non-convergence issue caused by boom tilting. The incremental load method, the incremental displacement method, and the Newton–Raphson method are applied to evaluate the complete load–deflection response and the accurate critical load. Numerical analyses using the proposed method agree well with the conventional Arc-Length method and the survey results of a crane boom collapse accident. Results show that material nonlinearity is a remarkable factor that weakens the overall stability of the structure. The plastic development of the structure happens mainly in chord members of standard sections. The $P − \Delta$ effect of gravity load on the structure determines the first fracture position in the boom. The methodology developed in this paper can be easily extended for the development and applications of other performance-based approaches for enhancing the stability of flexible giant crane booms.

M.T. Hanna (Structure and Metallic Construction Institute, Housing and Building National Research Center, HBRC, 87-El-Tahreer Street, Dokki, P.O. Box 1770, Egypt), “Failure loads of web panels loaded in pure shear”, Journal of Constructional Steel Research, Vol. 105, pp 39-48, February 2015
DOI: 10.1016/j.jcsr.2014.10.021
ABSTRACT: The effect of tension field action on the ultimate shear strength of web panels has been considered using different approaches. These approaches lead to wide range of predicted shear capacities especially for slender web panels that have large web width–thickness ratios. Therefore, this study aims to investigate the actual behavior of web panels loaded in pure shear. Nonlinear analysis has been conducted using three-dimensional finite element model of plate girder web panels. The study covers a wide range of web width–thickness ratios, web-panel aspect ratios as well as flange bending stiffness. Results show that both short as well as long web panels have substantial post local buckling capacities. However, this additional capacity decreases by increasing the web panel aspect ratios. Moreover, the diagonal tension field is often formed off the web panel diagonal. In addition there is no remarkable effect of the flange bending stiffness on the ultimate shear strength. Based on the numerical results an empirical equation is proposed. Finally comparison has been done with AAHSTO, AISC, and Eurocode-3 as well as different theories.
DOI: 10.1016/j.jcsr.2014.11.003
ABSTRACT: The evenly spaced circular web openings in I-section cellular beams have an advantageous effect on the material use if these beams are loaded in strong-axis bending. However, not all aspects of the behaviour of such beams have been studied adequately, such as the lateral–torsional buckling failure. For the latter failure mode, the existing design approaches conflict. Furthermore, the detrimental effect of the modification of the residual stresses by the production process, as recently demonstrated by the authors in previous work, was never taken into account. In this paper, the lateral–torsional buckling behaviour of cellular beams is investigated using a numerical model that was validated based on experimental results. In this model, the effect of the modified residual stress pattern was aptly taken into account. Using the results of the parametric study, a preliminary design approach was proposed. This approach is based on the currently existing European guidelines for the calculation of the lateral–torsional buckling resistance of I-section beams, but with a modified calculation of the cross-sectional properties and a modified buckling curve selection.

DOI: 10.1016/j.jcsr.2014.10.020
ABSTRACT: A considerable volume of literature is found regarding the effect of an opening in thin cylindrical shells under different loading. Among these, quite a few of the references are directly related to the cutouts along the length of the shells in the form of entrance doors. The main focus of this study is the tubes with door-shaped cutouts under axial loading. Different buckling modes as well as the effect of geometric parameters of a cutout were examined in this study. A stiffening method was also used to decrease the effect of the cutout on the capacity of such structures.

DOI: 10.1016/j.jcsr.2014.10.024
ABSTRACT: The contact interaction between the core and external restraining members is a vital factor that affects the overall performance of buckling-restrained braces (BRBs) significantly. In this study, refined finite element (FE) model was employed to evaluate the contact force between the core and external restraining members and to investigate the BRB performance. Moreover, the influences of strength and stiffness of external restraining member, core length, and other geometric parameters on the BRB performance were also studied. On the basis of numerical results obtained in the study, the recommended values of core width-to-thickness ratio, core thickness and gap were proposed. By considering the core plasticity and the lateral restraint of external restraining member, some formulas for predicting the half-wave length of core buckling as well as contact force were also proposed while the core buckled in multi-wave form. These formulas were numerically verified and could be references in the design of BRB.
DOI: 10.1016/j.jcsr.2014.11.011

ABSTRACT: A new type of buckling-restrained braces (BRBs), called core-separated buckling-restrained braces (CSBRBs) is presented and investigated in this study. The CSBRBs are composed of two chord members and one or several continuous web plates that connect those members longitudinally. This core-separated section improves bending stiffness, thus resulting in lightness and convenience in fabrication and erection compared with conventional BRBs. The elastic buckling performance of CSBRBs is initially investigated because such performance depends directly on the restrain ratios, which should be specified in the design of all types of BRBs. The critical loads of pin-ended and fix-ended CSBRBs are then obtained based on the equilibrium method and verified by finite element (FE) elastic buckling analysis, respectively. Subsequently, the relationship between axial compression and core compressive strain of CSBRBs with different restrain ratios is studied by using FE elasto-plastic analysis. These research achievements provide the foundation for further investigations and applications for CSBRBs.

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ABSTRACT: This paper presents results from experimental and numerical studies on the fire performance of typical steel girders used in bridges. As part of experimental studies three steel–concrete composite girders were tested under simultaneous loading and fire exposure. Test variables included: load level, web slenderness, and spacing of stiffeners. Results from fire tests indicate that typical steel girders can experience failure under standard fire conditions in about 30–35 min. The time to failure and mode of failure in fire exposed steel girders is highly influenced by web slenderness, spacing of stiffeners, and type of fire exposure. Steel bridge girders fail through flexural yielding when web slenderness is around 50; however failure mode changes to web shear buckling when web slenderness in girders exceed 100. Data from fire tests is utilized to validate a finite element based numerical model for tracing the response of steel bridge girders exposed to fire. Results from numerical analysis show that the proposed finite element model is capable of tracing the response of steel bridge girders under simultaneous loading and fire conditions.

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ABSTRACT: Accidental loadings due to blast or impact may easily cause failure of the elements exposed or located in the vicinity of the hazard; therefore, assessment of the structural over strength is critical for structural engineers to ensure a certain level of security and validate alternative unloading paths. The importance of the
ductility of connections has been highlighted for the robustness evaluation of structures in FEMA's report “Connection performance under impact loads… needs to be analytically understood and quantified for improved design capabilities and performance as critical components in structural frames”. The design of moment-resisting steel joints under monotonic loading is based on the “component method” (Eurocode 3, Part 1.8). This method requires the accurate characterisation of each active component; T-stub model is used to describe the main components providing ductility to the joint due to its high deformation capacity. However, connection ductility capacity characterisation remains problematic, usually requiring the development of challenging finite-element models. In this paper, the T-stub evaluation is supplemented with dynamic increase factors to predict the response of T-stubs subject to rapidly applied dynamic loads. Firstly, based on the methodology established in the Eurocode, Part 1.8, a “dynamic” design resistance is calculated; secondly, by exploring and improving an analytical procedure available in the literature, its whole non-linear behaviour is described. The analytical results are compared with 3D FE predictions and experimental results. This “modified analytical procedure” was demonstrated to be able to describe the force-displacement response of the T-stub model for both static and dynamic situations with relevant accuracy.

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ABSTRACT: To study the collapse mechanism and energy absorbing ability in lateral compression, metallic isosceles triangular tubes were designed and fabricated, with the base angle varying from 30°, 45°, 60° to 75°. According to the experiments, it is found that three typical crushing modes and two critical base angles characterize the lateral crushing behaviors of the isosceles triangular tubes. Tubes with base angle smaller than 45.6° are crushed without obvious fold. Tubes with base angle greater than 72.6° have side-wall contact at the buckling center before forming a new shortened triangle and being folded. With the base angle between these two critical values, tubes behave the same as the equilateral triangular tube. Triangular tubes have unified energy absorbing mechanism, including six plastic hinges and one traveling plastic hinge. The mean crushing force of the tube was well predicted based on plastic analysis, supplying criterion for material selection in designing anti-impact structures.

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ABSTRACT: Fabricated sections are a convenient option for structures or structural elements in demand of very high strength capacities for which conventional hot-rolled and cold-formed elements with limited sizes are inadequate. When it comes to the design of compressive members, buckling is a critical design provision. In this paper the compressive and buckling behavior of an innovative long column is described. The proposed innovative fabricated columns consist of mild steel plates which are welded to mild steel tubes at corners. Experimental tests are conducted on one, two and three-meter columns whilst a robust finite element model is also developed which is validated against the results obtained from the experiments. Detailed focus is brought to the effect of fabrication imperfections, type of welding and residual stresses on the behavior of the proposed long hollow columns in test result analysis and the finite element modeling. The examined innovative column specimens are shown to exhibit superior compressive behavior since the interaction between section’s plates and tubes leads to a significant increase in both strength and ductility. In addition to the structural benefit, the production cost of these columns is estimated which also justifies its advantage compared to the equivalent welded box sections in an economic point of view.


ABSTRACT: The AISC 360-10 Specification categorizes circular concrete filled steel tube (CFT) members as compact, noncompact or slender depending on the slenderness ratio (diameter-to-thickness \(D/t\) ratio) of the steel tube walls. International design codes typically focus on the design of compact circular CFT members with relatively small slenderness \((D/t)\) ratios, and the behavior and design of noncompact and slender circular CFT members is not addressed directly. This paper presents the basis of the current AISC Specification (AISC 360-10) for the design of noncompact and slender circular CFT members under axial compression, flexure, and combined axial and flexural loading. An experimental database of tests conducted on noncompact and slender circular CFT members is compiled, and used to establish the conservatism of the design equations in the AISC Specification. Detailed 3D finite element method (FEM) models are developed for circular CFT members, and benchmarked using the database of experimental results. The benchmarked models are used to conduct parametric studies to address gaps in the experimental database, and further verify the conservatism of the design equations. The AISC 360-10 Specification is recommended for the design of noncompact and slender circular CFT members. Additionally, the numerical models developed and benchmarked for circular CFT members are recommended for future investigations.

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ABSTRACT: This paper presents an assessment on the current yield slenderness limits under axial compression for cold-formed and built-up high strength carbon and stainless steel hollow sections. The definition of high strength steel in this paper refers to the materials with nominal yield strength or 0.2% proof stress which is greater than 700 MPa (Eurocode 3: Part 1-12) for carbon steel and greater than 480 MPa (Eurocode 3: Part 1-4)
for stainless steel. A total of 147 stub column experimental results was compiled and assessed. Companion 46 finite element simulations were performed in this study and the results concurred with the experimental observations. The structural performance data showed that the current slenderness limits adopted in Eurocode 3, American and Australian Standards for both carbon and stainless steel under axial compression can be safely adopted for the high strength steel counterparts. New slenderness parameters and limits were also proposed to improve the design efficiency.

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ABSTRACT: Steel shear panel dampers (SPDs) have been widely used in structural seismic design. The low cycle fatigue damage for SPD often occurs close to the welded stiffener, significantly weakening the fatigue performance of the damper. A novel steel shear panel damper called a buckling restrained shear panel damper (BRSPD) is proposed in this paper. A BRSPD has two main parts, an energy dissipation plate and two restraining plates. No stiffener is welded to the energy dissipation plate. The two restraining plates clamp the energy dissipation plate with bolts on both sides to prevent out-of-plane buckling. Quasi-static tests of five specimens were carried out to investigate the performance of the BRSPDs. The test focused on the stiffness and strength of the restraining plates and the gaps between them and the energy dissipation plate. The tests showed that the restraining plates with adequate stiffness and strength can effectively restrain the out-of-plane buckling of the energy dissipation plate. Numerical analysis of the BRSPD was conducted using the general finite element program, ABAQUS, to supplement the test results. A design method for the restraining plates and the bolts is suggested based on the test and analysis results.

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ABSTRACT: For a concrete-filled double skin steel tubular (CFDST) column in practice, during the construction stage, both the inner and the outer hollow tubes are subjected to the constructional load; during the service stage, the whole composite cross-section is mainly subjected to compression. If it is used in offshore structures, the outer steel tube is subjected to chloride corrosion as well. However, the information is still limited on the structural behavior of CFDST columns under the combination of preload on hollow tubes, the sustained load on the composite cross-section and chloride corrosion on the outer tube. In this study, a finite element analysis (FEA) model is developed to predict the structural behavior of CFDST stub columns with considerations of these factors, where the long-term effect for concrete under sustained load is applied. The experimental work is also conducted for CFDST stub columns subjected to corresponding loading protocols, and the test results are used to calibrate the numerical model. Discussions are made on the differences of specimens with and without considerations of these factors. It has been found that, the results from the verified FEA model have generally good agreement with measured results in all loading stages. The corrosion of outer
steel tube leads to a large reduction of column strength, and the influences of the preload and long-term sustained load can be tentatively estimated by multiplying different coefficients together.

ABSTRACT: A component-based model is developed to predict the dynamic response of bolted-angle connections, such as web cleat connections and top and seat with web angle (TSWA) connections subjected to sudden column removal scenario. This model considers the behaviour of bolted-angles under large tension forces. A failure criterion determined from the test results is introduced into the model for the bolted-angle component to predict the connection resistance. The hysterical behaviour of each component under cyclic loads is also included for ensuring dynamic analysis. The proposed component-based connection models with detailed springs as well as their constitutive laws are implemented within a self-developed finite element programme FEMDYA to validate the model against both static and dynamic test results. A comparison study showed the capabilities of the component-based model in predicting the connection performance. Based on the failure criterion of the connection component, an accurate simulation of the fracture of the connections is conducted. Subsequently, the component model is incorporated directly into two types of 4-storey steel frames to simulate catenary action developed due to the loss of support to a middle column. The analysis results indicate that a value of up to 2.9 should be used as the dynamic increase factor for structures with web cleat connections when incorporating the dynamic effects into the nonlinear static load resistances. It is also shown that the ultimate load capacity of unbraced structure is much smaller than the one in the braced frame due to horizontal movements of adjacent columns under catenary action.

H.L. Hsu and Z.-C. Li (Department of Civil Engineering, National Central University, Chung-Li 32054, Taiwan), “Seismic performance of steel frames with controlled buckling mechanisms in knee braces”, Journal of Constructional Steel Research, Vol. 107, pp 50-60, April 2015, DOI: 10.1016/j.jcsr.2015.01.010
ABSTRACT: This study experimentally evaluates the seismic performance of knee braced moment resisting frame (KBRF) systems. A series of cyclic load tests were performed on the special moment resisting frame (SMRF) and KBRF systems with in-plane and out-of-plane controlled buckling mechanisms in the knee braces. It was found from the test results that the strength and energy dissipation capacity of the KBRFs was significantly enhanced regardless of whether the knee braces buckled in the in-plane or out-of-plane direction. Further test result comparisons demonstrated that the allowable drift at which the knee braces reached the buckling stage was higher for KBRF frames equipped with in-plane buckling braces. It is therefore suggested that braces with in-plane buckling modes be adopted for greater earthquake resistance in KBRF frame structure designs.

Bin Wu and Yang Mei (Key lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin 150090, China and School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China), “Buckling mechanism of steel core of buckling-restrained braces”, Journal of Constructional Steel Research, Vol. 107, pp 61-69, April 2015, DOI: 10.1016/j.jcsr.2015.01.012
ABSTRACT: This paper investigates the buckling mechanism of the steel core of buckling-restrained braces. The development of buckling mode is revealed with increasing axial load. The formulae of the maximum
contact force and the maximum bending moment of the restraining member are obtained. The analytical results are validated by the finite element analysis. Compared to the results by conventional analysis, the number of contact points or buckling waves is much less; for hinged ends, the contact force for the lower mode is the identical while the contact force for higher modes is 1/4 lower; for fixed ends, the contact force is half of the conventional method.

ABSTRACT: This paper presents an analytical investigation of the local buckling of steel I-sections strengthened with bonded Fiber Reinforced Polymer (FRP) plates to improve their local buckling capacity. An analytical stability model is presented that considers the section as being composed of a group of plates that are linked together. The non-strengthened parts of the section were modeled as isotropic plates while each of the strengthened ones was dealt with as a sandwich composite plate that was modeled as an orthotropic material. A parametric study is presented to investigate the effect of each of the parameters of the problem including the strengthening scheme, the section geometry, and the properties of the strengthening material.

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ABSTRACT: Concrete filled steel tubular columns (CFSTCs) are finding increasing use in modern construction practice throughout the world. The efficiency of CFSTCs can be further improved if high-strength materials are used. High-strength steel provides attractive alternatives to normal-strength steel for multi-storey and high-rise construction applications. This paper presents an extensive experimental investigation into the axial load behaviour of square composite columns incorporating compact high-strength steel plates. The test parameters include the concrete strength ($f'_c = 21–55$ N/mm$^2$), depth-to-thickness ratios in the range of 16–40, as well as length-to-depth ratios in the range of 2.60–2.85. Furthermore, a simplified confining pressure versus depth-to-thickness ratio model, appropriate confined concrete constitutive models, and an accurate finite element model which incorporates the effects of initial local imperfections and residual stresses has been developed using the commercial program ABAQUS. The predictions of the behaviour, ultimate strengths, and failure modes are compared with the experimental results to verify the accuracy of the models developed. Additionally, comparisons with the prediction of axial load capacity by using the Australian Standards, Eurocode 4, and American Institute of Steel Construction code provisions for composite columns are also carried out.

ABSTRACT: Reinforced concrete filled steel tubes (RCFSTs) are commonly used for bridge substructures in high seismic regions where the steel tube is used as a permanent casing which eases construction. Concrete
confinement is provided by the steel tube, increasing the compressive strength and strain capacity. Tests were performed on twelve large scale RCFSTs, seven of the tests focused on varying D/t ratio and the remaining five focused on varying internal reinforcement. The tubes were subjected to reversed cyclic four-point bending with a constant moment region centered in the pile. The large scale specimens consisted of outer diameters of 20 to 24 in. (508 to 610 mm) and diameter-to-thickness ratios between 33 and 192. Strain limit states for the onset of tube wall local buckling and fracture are developed, as is an expression for equivalent viscous damping for direct displacement-based design. The impact of the tubes on confinement and analysis methods is also discussed.

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ABSTRACT: This research investigated the behavior of a composite shear wall system consisting of two skins of profiled steel sheeting and an infill of concrete under in-plane monotonic loading. Three sets of double skin composite wall (DSCW) specimens with overall wall dimensions of 1626 mm high by 720 mm wide were tested. Steel sheet–concrete connections were provided by intermediate fasteners along the height and width of the wall to generate composite action. Two types of concrete namely self-consolidating concrete (SCC) and highly ductile engineered cementitious composite (ECC) as well as cold formed profiled steel sheet having same geometry but with two different yield strengths were incorporated to investigate their influence on the composite wall behavior. Analytical models for the shear resistance of the composite wall were developed based on existing models taking into account the shear capacity of steel sheet, concrete core and steel sheet–concrete interaction. The advantage of using ECC over SCC was exhibited through more ductile wall behavior and energy absorbing capacity. The benefit of using mild over high strength steel was also demonstrated through more ductile failure. The steel–concrete intermediate fasteners along the height and width of the wall provided sufficient steel–concrete composite action to prevent early elastic buckling of the profiled steel sheets. Experimental and analytical shear resistance of composite walls showed very good agreement. The proposed analytical models can be used for the prediction of shear resistance of composite walls with reasonable accuracy.

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“Seismic behaviors of steel plate shear wall structures with construction details and materials”, Journal of Constructional Steel Research, Vol. 107, pp 194-210, April 2015, DOI: 10.1016/j.jcsr.2015.01.007

ABSTRACT: In order to have a systematic and comprehensive comparison of seismic behaviors of steel plate shear wall structures with different construction details, a numerical method was proposed, which was proved accurately to predict the performance of structures with published quasi-static tests. Then, eight typical steel shear wall models with different structural construction details were established. Also an advanced stiffened low yield point steel plate shear wall was proposed to avoid excessive out-of-plane deformation. The seismic
behaviors of above nine shear wall models were fully compared and analyzed, and key issues, such as energy-dissipating capacity, ductility, out-of-plane deformation and the effect of tension field on the columns were discussed in depth. The results showed that: in high-intensity seismic area, load-carrying capacity, hysteretic behaviors, failure modes, seismic ductility and economic performance should be taken into account comprehensively to choose the appropriate form of steel plate shear wall structure; the proposed low yield point steel plate shear wall with T type stiffened ribs could most effectively improve the energy dissipation capacity and ductility, and lessen the impact of tension field on the columns, besides, it had better load-carrying capacity and smallest out-of-plane deformation. This method provided a good way for improving the seismic behaviors of steel shear wall structures.

DOI: 10.1016/j.jcsr.2015.02.003
ABSTRACT: An experimental study of the inelastic lateral torsional buckling of coped beams with simply supported ends is presented in this paper. Six full scale coped steel I-beam tests were conducted. The test parameters include the aspect ratio of cope length to beam depth at coped region as well as the ratio of cope depth to beam depth. The results of experimental tests were compared with finite element model results. The test results showed that a reduction in the inelastic buckling load due to coping could reach more than 60% of the uncoped buckling capacity. A group of twelve finite element models for steel coped beams is investigated. A comparison between uncoped models and coped models with different geometrical parameters is performed. The finite element results showed that both the cope length and cope depth have a significant influence on the lateral torsional buckling capacity. A parametric study of coped beams with stiffeners at coped region is reported in this paper. Based on the results of coped beams strengthened with either horizontal or vertical stiffeners, it is found that for cope depth to beam depth (d_c/D) ≥ 0.25; both horizontal and vertical stiffeners are required to prevent local web buckling at the coped region.

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ABSTRACT: One potential means for designing steel structures for progressive collapse resistance is to include considerations of catenary action in order to efficiently and economically allow beams to be designed to resist increased levels of load relative to what is currently considered in practice. However, the current inventory of typical girder-to-column connections limits the capability of girders to achieve their peak post-flexural capacities. Given this limitation, a finite element analysis (FEA) parametric study of steel girders containing idealized connections was conducted to better understand connection demands in this situation. The results are compared to existing FEA and experimental work documented in available literature and combinations of tensile force, moment, and rotation at various levels of applied vertical load are generated, which can inform benchmarks that future connections could be designed to provide in order for steel beams to provide capacities intermediate to their flexural and full catenary capacities, i.e., partial catenary action. A relatively simple metric for normalizing rotation data from disparate girder designs is also introduced and recommended for
consideration in any future connection rotation demand benchmarks. The influences of residual stresses and geometric imperfections on the FEA results are also discussed.

DOI: 10.1016/j.jcsr.2015.02.005
ABSTRACT: The usage of stainless steel in construction has been increasing owing to its corrosion resistance, aesthetic appearance and favourable mechanical properties. The most common stainless steel grades used for structural applications are austenitic steels. The main drawback of these grades relies on their nickel content (around 8–10%), resulting in a relatively high initial material cost. Other stainless steel grades with lower nickel content such as the ferritic steels offer the benefits of stainless steels in terms of functional qualities and design but within a limited cost frame. Hence, ferritic stainless steels may be a viable alternative for structural applications. Given the fact that little experimental information on ferritic stainless steels is currently available, the purpose of this investigation is to report a series of material and cross-section tests on ferritic grade EN 1.4003 (similar to 3Cr12) stainless steel square and rectangular hollow sections to enable a better understanding of their material response and structural performance. Four different cross-section geometries have been tested under pure compression and in-plane bending. Measurements of geometric imperfections and material properties are also presented. The obtained test results are used to assess the adequacy of the slenderness limits and effective width formula given in EN 1993-1-4 to ferritic stainless steels, those proposed by Gardner and Theofanous and Zhou et al. design approach.

ABSTRACT: This paper presents a stiffness reduction approach utilising Linear Buckling Analysis (LBA) with developed stiffness reduction functions for the lateral–torsional buckling (LTB) assessment of steel beams. A stiffness reduction expression is developed for the LTB assessment of beams subjected to uniform bending and modified for the consideration of moment gradient effects on the development of plasticity. The proposed stiffness reduction method considers the influence of imperfections and plasticity on the response through the reduction of the Young’s modulus $E$ and shear modulus $G$ and obviates the need of using LTB buckling curves in design. The accuracy and practicality of the method are illustrated for regular, irregular, single and multi-span beams. In all of the considered cases, the proposed method is verified against the results obtained through nonlinear finite element modelling.

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“Resistance of steel cross-sections with local buckling at elevated temperatures”, Journal of Constructional Steel Research, Vol. 109, pp 101-114, June 2015, DOI: 10.1016/j.jcsr.2015.03.005
ABSTRACT: In this work, the resistance of slender I-shaped cross-sections, where local buckling has a predominant role in the ultimate capacity, is investigated at elevated temperatures. A numerical study considering several cross-sections submitted to compression or bending about the major-axis is performed using a finite element analysis software. The results are compared with the existing formulae available in Part 1.2 of Eurocode 3 showing that they need to be improved. For Class 3 cross-sections, it is observed that the existing rules lead to unsafe results because local buckling occurs at elevated temperatures prior to the development of the elastic bending resistance or the gross cross-section compression resistance. For Class 4 cross-sections, the results show that these rules are not adequate because it is recommended for the design yield strength of steel the use of the 0.2% proof strength even if the cross-section has plates not prone to local buckling. A new methodology to account for the local buckling in steel I-sections at elevated temperatures is presented based on the expressions previously developed by the authors to calculate the effective width of thin plates at elevated temperatures. According to this new methodology, an effective cross-section is calculated for Class 3 and Class 4 cross-sections and the yield strength at 2% total strain is used for Class 4 cross-sections as recommended by Eurocode 3 for the other section classes. Finally, it is demonstrated that this methodology leads to good results when compared against numerical and experimental results.

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ABSTRACT: This paper discusses nonlinear behaviour and design of built-up cold-formed steel section battened columns. The built-up columns were pin-ended and consisted of two cold-formed steel channels placed back-to-back and were connected using batten plates. Nonlinear 3-D finite element models were developed to simulate the structural performance of the axially loaded columns. The nonlinear material properties of flat and corner portions of the channels, initial geometric imperfections, actual geometries and boundary conditions were carefully considered in the models. The finite element models were verified against tests, recently
conducted and reported by the authors, on the same form of construction. The column strengths, failure modes, deformed shapes at failure, load-lateral displacement and load-axial strain relationships were predicted from the finite element analyses and compared well against the test results. In addition, the validated finite element models were used to perform an extensive parametric study investigating different parameters affecting the behaviour of the columns comprising different slenderness, column lengths, cross-section geometries, steel strengths, spacing between channels and different batten plates spacing. Furthermore, the column strengths predicted in the parametric study were compared with design strengths calculated using the North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel columns.

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ABSTRACT: This paper presents an experimental and numerical study on the ultimate strength of steel–concrete composite beams subjected to the combined effects of sagging (or positive) bending and axial compression. Six full-scale composite beams were tested experimentally under sagging bending and increasing levels of axial compression. A nonlinear finite element model was also developed and found to be capable of accurately predicting the nonlinear response and the combined strength of the tested composite beams. The numerical model was then used to carry out a series of parametric analyses on a range of composite sections commonly used in practice. It was found that the sagging moment resistance of a composite beam is not reduced under low-to-moderate axial compression, while it significantly deteriorates under high axial compression. Sectional rigid plastic analyses confirmed the experimental results. The moment–axial force interaction does not change significantly between full and partial shear connection. Based on the experimental and numerical results, a sagging moment–axial compression interaction law is proposed which will allow for a more efficient design of composite beams.

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ABSTRACT: This paper presents the results of experimental and theoretical investigations on a novel form of pierced double skin composite wall (DSCW) system consisting of two skins of profiled steel sheeting with an in-fill of concrete. Nineteen composite walls are tested to failure under axial loading. The test variables include: types of profiled steel sheeting, types of load transfer device, size/orientation of opening/holes, wall height and types of strength enhancement devices around holes. The effects of each of these variables on axial load–deformation response, axial strength, steel–sheet concrete interaction, failure modes (including concrete core cracking and steel sheet buckling) and stress–strain development are critically evaluated. Strengthening of hole boundaries is found to be essential in enhancing the axial strength of the walls. The performance of strength enhancement devices installed in the walls is found satisfactory based on axial strength–deformation characteristics and failure modes of walls. Theoretical model for the prediction of axial strength of both pierced and non-pierced composite walls is developed taking into consideration the reduction of concrete capacity due
to profiling and buckling of steel sheeting. The performance of the model is validated through comparisons with experimental results.

ABSTRACT: Previous investigations have revealed the unsafety of the current calculation methods in Eurocode 4 for evaluating the fire resistance of concrete-filled steel tubular (CFST) columns, which has given place to a movement in Europe for correcting the existing methods and developing new design rules. In order to support the development of new guidance, further experimental research is needed, especially concerning slender columns and large eccentricities. In this paper, the results of a series of fire tests on slender CFST columns of different section shape (circular and square) subjected to large eccentricities are presented. The influence of the cross-section shape, load eccentricity and percentage of reinforcement on the response of these columns at elevated temperatures is studied in this paper, focusing on the effect of large eccentricities combined with high slenderness. On the basis of the experimental results, the current design rules in Eurocode 4 are assessed, and a previous calculation method developed by the authors is also evaluated.

ABSTRACT: This paper presents a new analytical expression for computing the web shear buckling stress with partial flange rotational restraints. The derived expression is suitable to be used in practice for hand calculation and avoids excessive efforts required to perform numerical analysis using finite element or finite strip methods. The material savings resulting from using the proposed design expression are also illustrated. Current design provisions ignore the flange rotational restraints effect in determining the web shear buckling stress for box sections. A comparison is made with AISI, CSA-S16, Eurocode 3 and AASHTO provisions for the limiting conditions. It is also shown that the shear buckling stress may vary by 40% with the current design expressions. Numerical validation of the proposed expression with semi-analytical finite strip method is also presented. The influence of the flange geometric properties on the web buckling stress is also highlighted.

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ABSTRACT: Thin-walled cylindrical shells are widely used as industrial structural members. Owing to low transverse strength, these structures are highly susceptible to the buckling phenomenon when they are exposed to external pressure. Many strengthening methods have been utilized in order to increase the buckling capacity of such structures among which is employing stiffeners in different forms connected to the surface of these structures. This study is aimed at a new approach for strengthening in which vertical corrugations were introduced on 11 cylindrical shell specimens under uniform external pressure. The results showed a considerable increase in the buckling capacity of such structures.
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“Biaxially loaded high-strength concrete-filled steel tubular slender beam-columns, Part II: Parameter Study”,

ABSTRACT: Biaxially loaded high strength rectangular concrete-filled steel tubular (CFST) slender beam-columns with large depth-to-thickness ratios, which may undergo local and global interaction buckling, have received very little attention. This paper presents the verification of a multiscale numerical model described in a companion paper and an extensive parametric study on the performance of high strength thin-walled rectangular CFST slender beam-columns under biaxial loads. Comparisons of computer solutions with existing experimental results are made to examine the accuracy of the multiscale numerical model developed. The effects of the concrete compressive strength, loading eccentricity, depth-to-thickness ratio and columns slenderness on the ultimate axial strength, steel contribution ratio, concrete contribution ratio and strength reduction factor of CFST slender beam-columns under biaxial bending are investigated by using the numerical model. Comparative results demonstrate that the multiscale numerical model is capable of accurately predicting the ultimate strength and deflection behavior of CFST slender beam-columns under biaxial loads. Benchmark numerical results presented in this paper provide a better understanding of the local and global interaction buckling behavior of high strength thin-walled CFST slender beam-columns and are useful for the development of composite design codes.

Ke Cao, Yao-Jie Guo and De-Wei Zeng (School of Civil Engineering, Wuhan University, Wuhan 430072, Hubei, China), “Buckling behavior of large-section and 420 MPa high-strength angle steel columns”, Journal of Constructional Steel Research, Vol. 111, pp 11-20, August 2015, DOI: 10.1016/j.jcsr.2015.03.014

ABSTRACT: Large-section and high-strength angle steel (LHS) columns have been increasingly used in steel structures in recent years, however existing corresponding design methods were mostly based on studies of mild carbon steels with normal-size sections. In order to investigate the buckling behavior of LHS columns, an experimental study, involving 90 Q420 (420 MPa) specimens under axial compression was conducted. The experimental buckling strengths were compared with corresponding design values in current specifications. Non-linear finite element (FE) models considering residual stress, actually measured geometric imperfections and stress–strain curves obtained from tension coupon tests were developed and validated, and then used to perform an extensive parametric study. Effects of hardening progress in Q420 stress–strain curves were investigated and discussed. Theoretical dimensionless buckling strengths for slenderness from 30 to 120 were obtained through FE analysis and then compared with current design column curves. It is concluded that, the degree of conservative of current codes decreased when slenderness increased, and none of the compared curves was in good agreement with theoretical results, while design curves in GB 50017-2003 and Eurocode3 can be used conservatively. Finally, based on the parametric studies a new column curve was proposed to predict the buckling strengths of LHS columns.

ABSTRACT: Flange edge stiffeners increase the ultimate moment capacity of cold-formed channel sections. At the same time, they cause complexity to the buckling failure mode of the section. There is a lack of experimental research on the failure mode of sections with a partially stiffened element, such as channel sections with edge stiffeners, in which a distortional buckling mode can be observed. The focus of recent studies is mainly on the behaviour of the whole section as one member under bending without any concern about the relationship between the web and flange ratio. In this study, an extensive experimental analysis of 42 cold-formed channel sections was used to explore the failure behaviour of cold-formed channel sections under pure bending. The sections were made from cold-formed G450 steel with a nominal thickness of 1.6 mm. The results of the pure bending experimental investigations are used to describe the relationship between the web and flange ratio and the failure deformations. It is also shown that the current international cold-formed steel specifications over-predict the buckling coefficient of partially stiffened elements with high aspect ratio values. The experimental results are used to propose revisions to current international cold-formed steel specifications.


ABSTRACT: This paper presents results from numerical studies on the behavior of fire exposed steel beams by taking into consideration temperature-induced sectional instabilities. A three-dimensional nonlinear finite element model is developed to evaluate the response of fire exposed steel beams under both flexural and shear effects. This model is applied to investigate the effect of sectional slenderness on the onset of local instability and capacity degradation in steel beams exposed to fire. Results from finite element analyses are utilized to evaluate failure of beams under different limit states including flexure, shear, sectional instability and deflection criteria. These results show that under certain loading scenarios and sectional configurations, shear capacity in steel beams can degrade at a higher pace than that of moment capacity. In addition, results from numerical studies infer that room temperature classification of steel beams based on local stability, can change with fire exposure time; a compact section at ambient conditions can transform to a non-compact/slender section under high temperature effects. This can induce temperature-induced local buckling in steel sections and lead to failure prior to attainment of failure under flexural yield and/or shear limit state.

Huu-Tai Thai, Brian Uy and Mahbub Khan (Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia), “A modified stress-strain model accounting for the local buckling of thin-walled stub columns under axial compression”, Journal of Constructional Steel Research, Vol. 111, pp 57-69, August 2015

DOI: 10.1016/j.jcsr.2015.04.002

ABSTRACT: A novel stress–strain model accounting for elastic and inelastic local buckling of thin-walled steel plates was proposed in this paper based on an energy method. The proposed model was then implemented in a fibre force-based beam-column element for the advanced analysis of thin-walled and concrete-filled steel stub columns under axial compression. Both geometric and material nonlinearities are included in the fibre model. The obtained results were compared with independent experimental results and those predicted by ABAQUS using shell and solid elements. As shown in the numerical examples, the proposed stress–strain models can reasonably predict the ultimate strength and local and post-local buckling behaviour of thin-walled and concrete-filled steel stub columns under axial compression.
ABSTRACT: The local–overall interactive buckling behaviour of welded stainless steel I-section columns was experimentally and numerically examined in this study. A total of ten test specimens were fabricated from hot-rolled stainless steel plates and axially loaded between two pin-ended supports. The specimens failed by local–overall interactive buckling about the minor axis. Prior to the member testing, material properties, residual stresses and initial local and global geometric imperfections were all accurately determined. Detailed finite element (FE) models, capable of simulating the interactive buckling behaviour and predicting the ultimate capacity of welded stainless steel I-section columns, were validated against the obtained test results. The validated FE models were subsequently used to carry out systematic parametric studies, exploring the influences of the key input parameters, including the welding residual stresses, initial geometric imperfections, material properties and slenderness ratios. The generated test and numerical results were then used to assess the accuracy of a series of existing design methods: Eurocode 3 Part 1.4 and the design proposal of Rasmussen and Rondal, both of which employ the effective width concept, and the two separate design proposals of Becque et al. in the EN 1993-1-4 and AS/NZS 4673 formats and the proposal of Huang and Young, all of which are based on the direct strength method (DSM). Based upon the assembled data points, two separate design curves are proposed herein for austenitic and duplex stainless steels, which have been demonstrated to offer very accurate strength predictions for welded stainless steel I-section columns undergoing interactive buckling.

ABSTRACT: Steel short columns are used in building structures. The heating conditions in real building fires are non-uniform. The structural fire design approaches in the Eurocode are based on uniform heating conditions. This paper presents a numerical investigation on the behavior of steel short columns subjected to a localized fire. The effect of non-uniform heating condition on the failure temperature of axially loaded steel short columns is studied. Failure temperature is defined here as the maximum temperature in a steel column at failure (e.g. the onset of buckling or squashing). Simple thermal models were used to calculate the temperature of steel short columns in localized fire conditions. Sequentially coupled thermal–mechanical simulations were conducted. The study finds that the failure temperature of steel short columns in a localized fire is much higher than that of columns with a uniform temperature. The failure temperature in a localized fire might be slightly lower (within 20 °C) than that in the standard ISO 834 fire. The Eurocode design equations give conservative results of the failure temperature for steel short columns subjected to localized fires.
ABSTRACT: The Vierendeel mechanism involves three interacting drivers, namely the axial force, the shear force, and the Vierendeel bending moment. This study proposes an alternative design method to check for the Vierendeel failure of non-composite symmetric cellular beams, or steel beams with circular or elongated circular openings. The method is based on a quadratic nonlinear failure criterion, using normalized driving forces, their simplified actions, and an approximate critical section location and angle. Accuracy of the method is assessed with 20 literature curated experiments. In addition, based on a parametric simulation study, the normalized moment-shear-interaction curves obtained from the proposed method agree well with these curves from finite elements (FE). Compared with the FE shear loads at failure, the designed shear loads calculated based on the member resistances recommended in both BS EN 1993-1-1 and ANSI/AISC 360-10 are conservative. However, for steel beams with elongated circular openings, using the resistances based on the BS EN 1993-1-1, the proposed design improves the accuracy by about 16% on an average relative to the SCI P355 method. In relation to other currently available design approaches, the proposed method is a simpler alternative for the Vierendeel bending check. No nonlinear reduction of the web thickness, to account for high shear, is required. Furthermore, the method simultaneously addresses the combined global bending from flexure, shear and Vierendeel. The proposed method thus facilitates safe and cost-effective design of beams with openings.


ABSTRACT: Cut-outs or openings are inevitable part of steel structural systems since they are required as access ports for mechanical and electrical systems or to reduce the amount of material that is used. When such perforated plates experience compression loads, they may buckle or show instability due to axial compression. In this study, the buckling of perforated square and rectangular plates subjected to in-plane compressive edge loading is investigated using the finite element method. To analyze the behavior of the plates the following four edge loading cases were applied; concentrated edge loading, asymmetric partial loading at the opposite edges, partial loading at the center of the opposite edges and partial loading at the two ends of the opposite edges. The plate aspect ratio, the length and location of the edge loading and diameter of the circular hole are taken as the variables that have a buckling effect on the behavior of the plate. The results show that the square plates are highly sensitive to buckling when the loading at the center of the plates.

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ABSTRACT: This paper presents theoretical and experimental investigations on the local stability of compression flanges of H-beams with corrugated webs. Firstly, a simplified model of the flange plate considering the rotational restraint from webs is established. A formula for calculating the critical buckling stress of flanges is deduced. After verifying the proposed theoretical model against finite element analyses using ANSYS, parametric studies are carried out to investigate the influence of the tension flange, beam length and corrugated web on the resistance of compression flanges against local buckling. Secondly, experiments are carried out on three groups of corrugated web beams. The finite element modeling of the test specimens is validated against the available experimental results of their ultimate load-bearing capacity. The influence of the initial geometric imperfection of compression flanges and residual stresses on the critical buckling stress of compression flanges are studied using the FE model. It is concluded that initial imperfections may reduce the critical buckling stress by 28% while residual stresses may lead to a reduction of 14%. Finally, a correction factor of 70% is suggested for the critical outstand-to-thickness ratio of flanges to account for these two effects on the stability of steel beams with corrugated webs.

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ABSTRACT: In order to investigate the effects of aspect ratio, curvature, and slenderness on the shear behavior of flat and curved plates, a parametric study is conducted. The simulations were performed by ABAQUS software. Theoretical relations were used to verify the validity of the out-coming numerical results. Comparing the results obtained from the FEM analysis with those from AASHTO, it is observed that the AASHTO shear strength of plates with aspect ratios less than 1.71 is non-conservatively more than the FEM results. For instance, in a flat plate with an aspect ratio of one, the difference between these two values is close to 8%. On the contrary, as the aspect ratio increases, the values of shear strength obtained from AASHTO are less than those derived from FEM. The difference of these two values reaches up to 11% in the case of plates with larger values of curvature. This study reveals that the curvature is a parameter which severely affects the shear behavior of plates. It is suggested that for a proper estimation of the elastic shear behavior of curved plates, this parameter must be taken into account. It is also observed that decreasing the slenderness results in lower effect of the curvature on the shear strength. Unlike the elastic range, in the plastic range of slenderness parameter, the shear strength of flat and curved plates could be considered equal.

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ABSTRACT: The strength of a battened beam-column composed of four slender cold formed angles is mainly governed by the local buckling of its elements as well as the overall buckling of the column. The local buckling mode is mainly affected by local slenderness ratio of one angle (between batten plates). Overall buckling mode is mainly affected by overall member slenderness ratio as well as angle legs width to thickness ratio. Members'
failure modes occur by local buckling and yielding at short lengths, and by local flexural buckling at intermediate and flexural at long lengths. In the present study, the behavior of bi-axially loaded battened beam-columns composed of four equal cold formed slender angles is investigated. A nonlinear finite element model was developed to study the effect of the aforementioned factors on the ultimate capacity of members. Geometrical and material nonlinearities were considered in the model. A parametric study was performed on a group of battened beam-columns with variable angle legs having different outstanding leg width–thickness ratios, angle local slenderness ratios, and column overall slenderness ratios. The axial–bending interaction curves are presented for short, medium and long beam-columns having two different square cross sections. These interaction curves were compared with different code rules. These design rules have been shown to be reliable using reliability analysis.

A. Aalberg (Norwegian University of Science and Technology, Department of Structural Engineering, Richard Birkelandssveg 1a, N-7491 Trondheim, Norway), “Experimental and numerical parametric study on the capacity of coped beam ends”, Journal of Constructional Steel Research, Vol. 113, pp 146-155, October 2015
DOI: 10.1016/j.jcsr.2015.06.004

ABSTRACT: Here, the reaction force capacity of I-section steel beam ends with top flange copes was investigated experimentally and numerically, with a focus on local web buckling. An experimental test series was carried out on unstiffened top coped beam ends that were subjected to reaction forces under the bottom flange. Experimental results are given for beam ends with five sizes of cope and for a reference beam without a cope. The investigated beam section was a standard IPE 300 in steel grade S355. The test results were compared with existing design models for coped beams and with models primarily developed for triangular stiffener brackets. A new design formula is proposed for top coped beams supported at the bottom flange, which allows the capacity to be determined as a function of capacity of uncoped beam end with a reduction based on the size of the cope. Finite element models were verified against the experiments and used to extend the experimental data and investigate parameters affecting the web buckling resistance, such as web slenderness and the restraints provided by connection devices.

P.M. Stylianidis and D.A. Nethercot (Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, United Kingdom), “Modelling of connection behaviour for progressive collapse analysis”, Journal of Constructional Steel Research, Vol. 113, pp 169-184, October 2015, DOI: 10.1016/j.jcsr.2015.06.008

ABSTRACT: The structural robustness of frame structures depends to a considerable extent on the ability of the connections between the main structural elements to transmit the sorts of loading generated following an initial structural damage while delivering the deformations needed to arrest progressive collapse through dissipation of the collapse energy. Therefore, connection performance is, arguably, the most important feature of the problem and accurate modelling of the connection behaviour under the sorts of conditions experienced during progressive collapse is an essential component for any realistic analysis. Based on the component method principles of EC3 and EC4, a mechanical approach for describing the behaviour of bare steel and composite connections for use in progressive collapse analyses is developed herein. Explicit expressions covering the full range of loading – including interaction between the connection bending moments and beam axial load – and problem variables likely to be encountered in practice are derived. Those expressions can be applied in a step-by-step consideration for tracing connection nonlinear behaviour up to failure. The model is carefully validated against both available tests and results obtained from rigorous numerical analyses.
ABSTRACT: Experiments on concrete-filled elliptical hollow section beam-columns have been conducted to examine their fundamental structural behaviour. A total of 27 specimens were tested — 3 stub columns and 24 longer members of varying slenderness. Seven of the tested specimens also contained steel reinforcement. The specimens were loaded in compression, either concentrically or with different major or minor axis eccentricities. Measurements of the applied load, the strains at mid-height, the axial displacement and the lateral deflection at mid-height were recorded. Plots of load against the lateral deflection at mid-height and load against axial displacement are presented for the specimens, along with values of strength index and ductility index. Comparisons have been made between the test results and the provisions of the European Standard EN 1994-1-1:2004 for determining the ultimate load of concrete-filled circular and rectangular hollow section columns. It was found that the predicted resistances are safe for use in the design of concrete-filled elliptical hollow section columns either with or without reinforcement, and loaded either concentrically or eccentrically.

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ABSTRACT: This paper studied the impact of various structural parameters on the length of damage zones of steel box girder under cyclic load using elasto-plastic FE model and proposed an empirical equation to estimate the length of the seismic damage zone. To verify this empirical equation, a multi-scale model as well as a fiber model of a half-through steel arch bridge of 130 m span was created. Pushover analysis and nonlinear seismic time-history analysis were performed using these two models. The results from the numerical analysis of this arch bridge indicate that the majority of seismic damages of this bridge occur near the joints and connections. The multi-scale model shows a good performance in predicting both of the displacement response and the propagation of seismic damage zones. Main structural components of the structure are less likely to experience low-cycle fatigue failure. Fiber model can accurately estimate the global displacement response and the general distribution of plastic regions across the entire bridge, but it cannot give detail information about the size of plastic zones.

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ABSTRACT: Based on the concepts of beam string structure and reticulated mega-structure, a new type of string cylindrical reticulated mega-structure is proposed and five cable–strut arrangement schemes are presented. The optimal scheme is obtained by comprehensive comparison in the structural static property and stability. For the structure with the optimal cable–strut arrangement scheme, large-scale parametric analyses are carried out to investigate the variation laws of various indices such as the structural deflection, member internal force, ultimate stability capacity, and their decreasing or increasing rates compared with the results of the
structure without cable–strut system. The rational values of various parameters, such as the ratio of rise to span, height of latticed 3D beams, strut length, and the cable pretension, are thus recommended. Additionally, the influence of half-span loading on structural stability is investigated. Results indicate that the structural static property and stability can be effectively improved by adopting the optimal cable–strut arrangement scheme, in which, the cable–strut units are symmetrically set within the full span except the two side large grids of the latticed 3D arches and the cables between the struts of the adjacent units cross each other. Also, the sensitivity of structural stability to the asymmetry of load distribution declines for adoption of the pretensioned cable–strut system.

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ABSTRACT: Conventional buckling restrained braces used in concentrically braced frames are expected to yield in both tension and compression without significant degradation of capacity under severe seismic ground motions. On the other hand, a new short core buckling restrained brace system could be introduced as an alternative for a conventional full core BRB. In a short core BRB (SCBRB), the core element is built shorter than usual. Therefore, for a given story drift, the core accepts bigger axial strains compared to a conventional (full core) BRB. A short core BRB seems to be easily fabricated, inspected, and replaced after a severe earthquake. The purpose of this study is to show how this type of buckling restrained braces is feasible. Reducing the core length in a buckling restrained brace may result in a shorter encasing member, decrease in frictional forces acting at the core and buckling restraining mechanism interface, and, as a consequence, reduction of the compression strength adjustment factor in the brace. This paper numerically investigates the seismic behavior of short core buckling restrained braced frames. The minimum core length of BRB is determined by considering the low cycle fatigue life of the core plate and the maximum anticipated strain demand under standard loading protocol. Nonlinear time history analyses were also performed on four and ten story prototype buildings equipped with full core (conventional BRBs) and short core BRBs and the story drifts were compared. The results showed that the SCBRB system is partially able to reduce the story and residual story drifts in the braced frames. In addition, SCBRBs sustain large plastic deformations without crossing the low cycle fatigue life borders or instability of the encasing system. However, the economic and practical aspects of using SCBRB seem to be more distinct in comparison to its mechanical characteristics.

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ABSTRACT: The so-called Reverse Channel connection has been conceived for the purpose of accommodating the thermal expansion of beams so that premature failure due to thermal buckling is avoided. The connection is made of a channel-shaped element, welded along the tips of its flanges onto the face of a hollow section
column; an endplate welded on the beam is bolted onto the web of the channel. In a fire situation, the thermal expansion of a reverse-channel supported beam causes extensive bending deformation of the connection, therefore preventing the development of significant axial stress in the beam. Furthermore, this connection offers a high rotational capacity, if designed properly, which is beneficial in a fire situation where excessive deflections of beams can be expected. This paper aims to provide analytical stiffness assessment tools for reverse channel connections in compression and tension under uniform temperatures. The proposed analytical models are compared to results of Finite Element simulations, which in turn have been benchmarked with experiments. In addition, a comprehensive parametric study is conducted in order to identify all influencing factors on the initial stiffness response: reverse channel geometry and thickness, plate thickness, bolt position, and bolt diameter. Correction factors that account for 3D effects and bolt size are presented and discussed. The obtained expressions for the reverse channel stiffness are found to provide an accuracy that is acceptable for structural applications and can, therefore, be used as a design tool.

ABSTRACT: This paper reports the experimental behavior of plain and steel fiber concrete-filled stainless steel tubular columns under biaxial bending and axial compression. In the experimental study, the length-to-diameter ratios of the stainless steel tubes were 12, 15, and 20. The effects of the main test parameters of concrete compressive strength, cross-section, load eccentricity, steel fiber material and slenderness on the structural behavior of plain and steel fiber concrete-filled stainless steel tubular columns were examined. The ultimate strength capacities, load–deflection relations, and load–axial strain behavior were observed in the tests. The plain and steel fiber concrete-filled tube columns have been analyzed with a theoretical method based on the nonlinear behavior of the materials. The experimental and theoretical biaxial load–deflection diagrams have been obtained and compared in the study. The experimental results have exposed significant knowledge to describe the behavior of plain and steel fiber concrete-filled stainless steel tubular columns.

ABSTRACT: In the construction of single layer domes and vaulted structures manufactured ball-node type connections are widely used. These ball-nodes deform due to the action of a three-dimensional state of stress while offering their resistance. These deformations result in a loss of connection stiffness, which influences the overall stability of these domes, and is usually ignored in the analysis. This work presents an investigation on the effect of ball-node deformations in the inelastic post-buckling behavior of domes and vaulted structures. A model for the load-deformation properties of the ball-nodes has been proposed in this study, in the lines of EC3-8. This connection flexibility model is integrated into a corotated–updated Lagrangian finite element formulation. Results for single layer domes and a braced barrel vault are presented. Although the present investigation deals with ball nodes only, the computational framework is still relevant for other type of connections of space structures, with modifications.

ABSTRACT: A new composite element comprising rectangular steel tubular sections filled with timber and confined with carbon fiber reinforced polymer (CFRP) was investigated in this study. Several tests were conducted on different specimens with varying geometrical conditions and the impact of each material was studied on the structural behavior of these members under axial compression. The timber infill was found to significantly improve the capacity by preventing local inward buckling. This effect was further enhanced when the short columns were confined with sufficient layers of CFRP to prevent local outward buckling. In both cases the strength increase (up to 75%) was substantially greater than the corresponding weight increase (up to 44%).

Dabin Yang, Bing Guo, Chuanchao Chong and Chunyang Liu (School of Civil Engineering, Shandong Jianzhu University, Fengming Road, Jinan 250101, China), “Modeling and structural behavior of cable-stiffened single-layer latticed domes of hexagonal meshes”, Journal of Constructional Steel Research, Vol. 114, pp 237-246, November 2015, DOI: 10.1016/j.jcsr.2015.08.003

ABSTRACT: As an effective structural system, the cable-stiffened single-layer latticed shell of quadrangular meshes have been extensively studied and used in many projects. This paper proposes the cable-stiffened single-layer latticed shell of hexagonal meshes. In order to reveal its working mechanism and evaluate its structural mechanical behavior, a geometrical modeling method for single-layer latticed dome of hexagonal meshes is presented firstly, then two planar hexagonal structures with and without cables are comparably analyzed, where the structural in-plane stiffness are compared and the influences of cable section and cable pretension on in-plane stiffness are studied, and the structural working mechanism of cable-stiffened hexagonal structure is presented. Last, three pairs of domes of hexagonal meshes with and without cables are numerically created and comparably analyzed, where the following structural behaviors are compared: (1) member strength and stability; (2) stiffness; (3) static stability. The results indicate that all the structural behaviors of single-layer latticed domes of hexagonal meshes are significantly improved by the introduction of the prestressed cables.

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ABSTRACT: Corrugated steel plate and simple steel plate shear wall construction is a widely accepted and efficient lateral force resisting construction. The widespread use is motivated by the large initial stiffness, high level of energy absorption, and ability to accommodate openings. There is a dearth of information regarding the detailed nonlinear, inelastic behavior of corrugated steel plate shear walls, particularly walls with openings. Presented here are the results of a detailed, numerical parametric study comparing corrugated steel plate and simple steel plate shear walls, with and without openings. Parameters studied are plate thickness, angle of corrugation, opening size, and opening placement. Behaviors of interest for comparison are initial stiffness, ultimate strength, energy absorption, force–displacement relationship. The present study results indicate that the use of trapezoidal corrugated steel shear walls increases initial lateral stiffness, increases energy absorption and
increases ductility while it reduces ultimate strength. In addition, the corrugated steel plate shear wall postpones the ultimate strength and degradation point relative to a corresponding unstiffened simple steel plate shear wall, which is a desirable characteristic for seismic resistance. An ultimate strength prediction procedure for corrugated steel plate shear walls with optimized rectangular opening position is developed and proposed.

Ai-Rong Liu, Yong-Hui Huang, Ji-Yang Fu, Qi-Cai Yu and Rui Rao (Guangzhou University-Tamkang University Joint Research Center for Engineering Structure Disaster Prevention and Control, Guangzhou University, Guangzhou 510006, China), “Experimental research on stable ultimate bearing capacity of leaning-type arch rib systems”, Journal of Constructional Steel Research, Vol. 114, pp 281-292, November 2015 DOI: 10.1016/j.jcsr.2015.08.011

ABSTRACT: The stability of a leaning arch structural system was investigated experimentally in this study. Scaled models of five structural systems including a single arch, a parallel arch, and leaning arch systems with a 10, 20, and 30-degree inclined angles between the main and the stabilizing arches were constructed. Each of these models was tested under five point loads spaced equally along the arch. Results show that adding stabilizing arches increased arch's lateral stability as well as its ultimate bearing capacity. Comparing against the single arch the parallel arch, 10-degree, 20-degree, and 30-degree arch system had 14.3%, 15.6%, 13.7%, and 12.9% increase in ultimate bearing capacity, respectively. As the inclined angle of the leaning arch increased, the failure mode changed from out-of-plane buckling to in-plane buckling. Out-of-plane buckling failure was observed in the single arch, parallel arch, and 10-degree arch system, while in-plane buckling failure was observed in the 20-degree and 30-degree arch rib system. Among the five models tested, the 10-degree leaning arch system had the highest ultimate bearing capacity.

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ABSTRACT: Since the establishment of the Eurocode design provisions for structural stainless steel, a considerable amount of both statistical material data and experimental results on structural elements has been generated. In light of this, the current partial resistance factors recommended in EN 1993-1-4 for the design of stainless steel elements are re-evaluated. First, following an analysis of material data from key stainless steel producers, representative values of the over-strength and the coefficient of variation (COV) of the material yield strength and ultimate tensile strength were established. For yield strength, over-strength values and COVs of 1.3 and 0.060 for austenitic, 1.1 and 0.030 for duplex and 1.2 and 0.045 for ferritic stainless steels were determined. For the ultimate tensile strength, an over-strength value of 1.1 was found to be suitable for all stainless steel grades, and COV values of 0.035 for the austenitic and duplex grades and 0.05 for the ferritic grade were proposed. For the variability of the geometric properties, a COV value of 0.05 was recommended. Analysis of available experimental results based on the First Order Reliability Method (FORM), set out in EN 1990 Annex D, and utilising the derived statistical material parameters, revealed that the current recommended partial resistance factors in EN 1993-1-4 ($\gamma_{M0} = \gamma_{M1} = 1.1$ and $\gamma_{M2} = 1.25$) cannot generally be reduced, and in some cases, modified design resistance equations are required, if the current safety factors are to be maintained.

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ABSTRACT: This paper presents the finite element analyses made which determine the inelastic buckling capacity of monosymmetric stepped I-beams under uniform bending. The stepped beams analyzed have non-compact flanges and varying degree of symmetry about the x-axis. Beams with degree of symmetry, $\rho$, of 0.1 to 0.9 with an interval of 0.2 are investigated for this study. Both doubly stepped and singly stepped beam configurations are analyzed. To determine the inelastic buckling strength of the beams, nonlinear analysis is performed using the finite element program ABAQUS. Different design standards such as AISC, AS4100 and EN1993 are then used to compare the strengths of prismatic and stepped beams. The results from the comparisons are also used to check the accuracy of the values obtained from finite element analysis. The results showed that finite element analysis can be a very useful tool in determining the inelastic buckling capacity of stepped beams. Also, the comparisons for the stepped beams analyzed with stepped length parameter $\alpha$ of 0.25, 0.333 and 0.5, with increase in flange thickness of about 20–80% and no increase in flange width, showed that there is about a 10% increase in the buckling strength when the beams are stepped. The new stepped beam correction factor, $C_{nfist}$, is then introduced to take into account the increase in strength when the beams are stepped.


ABSTRACT: The paper presents 3D numerical analysis results on the effect of bulk solid on strength and stability of metal cylindrical silos with corrugated walls (without stiffeners) during filling. The behaviour of two bulk solids (dry sand and wheat) was described with a hypoplastic constitutive model. Non-linear FE analyses with both geometric and material non-linearity were performed. The numerical results were compared with the Eurocode formulae. The strengthening effect of the stored solid, wall thickness, solid granular hardness, initial void ratio of solid and wall friction angle on buckling strength was investigated. The major contribution of the paper is the quantitative estimation of the effect of the bulk solid stiffness on the silo stability and wall stresses.

Liping Wang and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong), “Beam tests of cold-formed steel built-up sections with web perforations”, Journal of Constructional Steel Research, Vol. 115, pp 18-33, December 2015, DOI: 10.1016/j.jcsr.2015.08.001

ABSTRACT: The aim of this study is to investigate the flexural behavior, including the ultimate moment capacities and failure modes, of built-up cold-formed steel members with circular web holes. A total of 43 beams having ten cross-section sizes with different hole diameters were tested under four-point bending. The built-up sections were assembled by self-tapping screws from either two plain channels or lipped channels. Reduction of moment capacities and localized failure due to the presence of holes in the web plates of beams was observed in the tests. It is shown from the test results that when the hole diameter-to-web depth ratio ($d_h/h_n$) is 0.5, the influence of the holes on the moment capacities of beams is very small, however this is not the case when $d_h/h_n$ further increases up to 0.7. Different approaches of determining the critical elastic local and distortional buckling moments including the influence of holes for the built-up open and closed sections were
compared and discussed, and appropriate approach for built-up sections was recommended. The current direct strength method (DSM) was extended for the design of cold-formed steel built-up sections with holes in this study. The design strengths predicted by the DSM were compared with the test results. It is shown that the DSM formulae in the North American Specification are capable for predicting the design strengths of the built-up open and closed section beams with holes, using the critical elastic local and distortional buckling moments including the influence of holes determined by the recommended approaches in this study.

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ABSTRACT: The study described in this paper investigated the effects of a mega-thrust subduction earthquake on the seismic performance of moderately ductile concentrically braced frame multi-storey office buildings (MD–CBF) located on Site Class C in Victoria, B.C., Canada. Using data from the 2011 $M_w$9 Tohoku subduction earthquake in Japan and worldwide crustal earthquakes, nonlinear dynamic analyses were performed on detailed numerical models developed in the OpenSees framework. It was found that the effect of Trifunac duration on the nonlinear seismic response of 4-storey, 8-storey and 12-storey MD–CBF office buildings is particularly significant in terms of the strain accumulated in the fibers of hollow structural section braces causing low-cycle fatigue fracture. In addition, assessment of the likelihood of collapse safety of the studied multi-storey MD–CBF buildings found that the collapse margin ratio ($CMR$) value and the adjusted collapse margin ratio ($ACMR$) value are approximately 150% greater under the crustal record set than under the subduction record set. Among the three buildings studied, only the 12-storey MD–CBF building subjected to the subduction record set failed to meet the collapse safety criterion of $ACMR > ACMR_{10\%}$. Consequently, the $CMR$ value needs to be increased by strengthening the structural system. Therefore, particular attention should be given when designing MD–CBF multi-storey buildings located in the proximity of subduction fault, such as buildings in Victoria that lie within the Cascadia subduction zone.


ABSTRACT: This paper is on the numerical analysis of concrete filled Buckling Restrained Braces (BRBs), which are typically used as diagonal bracing members of steel braced frames designed for dissipative behavior and lateral load resistance under seismic action. BRBs are typically composed of a slender steel core which is continuously supported by a concrete casing against buckling. The complex behavior of the BRB devices is usually studied by experimental tests. The numerical analysis is rarely applied, it requires advanced tools, such as modeling of cyclic steel plasticity with combined hardening, cyclic concrete behavior, plastic buckling, contact and friction. In the paper a novel Chaboche based cyclic steel material model is presented, which is developed in ANSYS finite element environment. The model is able to describe all the important features of the cyclic behavior of structural steel, including low cyclic fatigue capacity. The William–Warnke model is used for the concrete material with combined kinematic hardening. The computational model has a special focus on
the contact/friction phenomena between the steel core and supporting concrete. The structure and approximations of the numerical models, the calculation of model parameters on the basis of its own test results are detailed. The features of the behavior are demonstrated by the application of the developed 3D solid Buckling Restrained Brace model.

ABSTRACT: The objective of this paper is to provide a simplified method for predicting the bending stiffness of thin-walled cold-formed steel members subject to elastic (or inelastic) local or distortional buckling. In thin-walled cold-formed steel members for serviceability and consideration of deformations (second-order effects) it is important to account for the loss of cross-section bending stiffness due to the use of slender elements and/or yielding. Although existing design specifications provide some guidance on how to predict the stiffness, limited information is available for cross-sections subject to distortional buckling or undergoing inelastic local and/or distortional buckling. Existing tests and shell finite element analysis on cold-formed steel beams failing in local or distortional buckling are used as the basis for the study conducted herein. Stiffness of the conducted tests and finite element models is compared with predictions based on the Effective Width Method and Direct Strength Method. Relationships between local and distortional cross-section slenderness and the observed and predicted secant stiffness up to the peak load are examined. New design expressions to predict cold-formed steel member bending stiffness depending on cross-section slenderness are presented. The new methods are proposed for adoption in cold-formed steel specifications.

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ABSTRACT: In this paper, the possible progressive collapse mechanisms of planar steel frames when one column failed under elevated temperature was studied through extensive case studies. An explicit dynamic solver was adopted, which could continue beyond local element buckling. The effects of analysis parameters such as mesh size and loading speed were investigated. And the numerical model was validated against experimental data and analysis results of other researchers. The investigated parameters included beam cross-sectional size, load ratio and location of heated column. Three progressive collapse mechanisms were found, namely, cantilever beam mechanism, pull-in force induced mechanism and high load ratio member failure mechanism, of which the last one is a new discovery. To evaluate progressive collapse of planar steel frames under fire, the cantilever beam mechanism and the pull-in force induced mechanism should be checked when the outer columns are heated, and the pull-in force induced mechanism and the high load ratio member failure mechanism need to be checked when the inner columns are heated. And the most adverse fire scenarios of a planar steel moment frame are when one of the following columns is heated: first floor column of the outmost, second and third outmost column lines or top floor column of the outmost, second and third outmost column lines.
Sivakumar Kesawan and Mahen Mahendran (School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Fire tests of load-bearing LSF walls made of hollow flange channel sections”, Journal of Constructional Steel Research, Vol. 115, pp 191-205, December 2015, DOI: 10.1016/j.jcsr.2015.07.020

ABSTRACT: Fire resistant and load bearing Light gauge Steel Frame (LSF) wall systems are generally made of cold-formed steel stud sections lined with gypsum plasterboards. Structural stability of these steel frames at elevated temperatures is important for the load bearing LSF walls for survival during fire events. The studs in these frames are usually Lipped Channel Section (LCS) studs. However, there are other more structurally efficient stud sections such as the hollow flange section studs, which can be effectively used in LSF walls. However, lack of fire research on these sections has inhibited their usage in LSF walls. This paper proposes the use of hollow flange channel (HFC) section studs in LSF walls with a view to increase their fire resistant ratings (FRR). In this study, five full scale fire tests of LSF walls made of welded hollow flange channel section studs were conducted under standard fire conditions. Three different wall configurations and three load ratios were considered in these tests. This paper presents the details of fire tests and their results including the time-temperature profiles of plasterboard and steel stud surfaces, lateral displacement and axial deformation profiles, failure modes and failure temperatures. It also presents the effects of using different wall configurations and load ratios on the FRR of LSF walls. Comparison of the fire performance of LSF walls made of welded HFC section studs with those made of conventional LCS studs demonstrated the superior fire performance through the use of welded HFC section studs.


ABSTRACT: This paper analyzes the geometrical nonlinear elastic instability for slender lattice-boom structures of crawler cranes. To reduce the dimension of equilibrium equations, the slender lattice-boom structure is divided into several substructures and an element-independent co-rotational substructure element is formulated. Including the discretization of gravity, a static condensation procedure for the co-rotational substructure element is implemented. In consideration of movable boundaries of the lattice-boom structure, the tensile forces of luffing cables related to the guyed mast rotation are given for the equilibrium equations. After that, accurate tangent stiffness matrices are formulated by taking the derivative of the general nodal forces with respect to the structural displacements and the guyed mast angle. To improve the computational efficiency of instability analysis under multiple loading conditions, a new method for identifying the instability loads of the slender lattice-boom structures is presented, based on the equilibrium equations in rate form. Two numerical examples show the availability and efficiency of the method.


ABSTRACT: Special concentrically braced frames (SCBFs) are commonly used to resist lateral forces in the structures located in high-seismic regions. Steel braces of SCBFs are expected to undergo large inelastic axial deformations in order to provide an adequate level of structural ductility and hysteretic energy dissipation under
cyclic loading. The energy dissipation capacity and ductility of SCBFs largely depend on the slenderness ratio and width-to-thickness ratio of braces. The main objective of this study is to find an optimum range of these parameters for braces of hollow circular steel (HCS) sections in order to achieve the enhanced seismic performance of SCBFs. A finite element (FE) study has been conducted on a wide range of values of these parameters using a software package ABAQUS. The FE models account for the inelastic hysteretic characteristics and the fracture behaviour of braces. The results of simulation models matched very well with the past experimental results with respect to the performance points, namely, global buckling, local buckling, fracture initiation, and complete fracture. Finally, a relationship has been established between the slenderness ratio and the width-to-thickness of HCS braces based on the simulation results.

Varathananthan Jatheeshan and Mahen Mahendran (School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Numerical study of LSF floors made of hollow flange channels in fire”, Journal of Constructional Steel Research, Vol. 115, pp 236-251, December 2015, DOI: 10.1016/j.jcsr.2015.08.021

ABSTRACT: Light gauge steel frame (LSF) floor systems are generally made of lipped channel section joists and lined with gypsum plasterboards to provide adequate fire resistance rating under fire conditions. Recently a new LSF floor system made of welded hollow flange channel (HFC) section was developed and its fire performance was investigated using full scale fire tests. The new floor systems gave higher fire resistance ratings in comparison to conventional LSF floor systems. To avoid expensive and time consuming full scale fire tests, finite element analyses were also performed to simulate the fire performance of LSF floors made of HFC joists using both steady and transient state methods. This paper presents the details of the developed finite element models of HFC joists to simulate the structural fire performance of the LSF floor systems under standard fire conditions. Finite element analyses were performed using the measured time–temperature profiles of the failed joists from the fire tests, and their failure times, temperatures and modes, and deflection versus time curves were obtained. The developed finite element models successfully predicted the structural performance of LSF floors made of HFC joists under fire conditions. They were able to simulate the complex behaviour of thin cold-formed steel joists subjected to non-uniform temperature distributions, and local buckling and yielding effects. This study also confirmed the superior fire performance of the newly developed LSF floors made of HFC joists.

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ABSTRACT: This paper presents an efficient mathematical model for studying the global buckling behavior of concrete-filled steel tubular (CFST) columns with compliant interfaces. The present mathematical model is used to evaluate exact critical buckling loads and modes of CFST columns for the first time. The results prove that the presence of finite interface compliance may significantly reduce the critical buckling load of CFST columns. A good agreement between analytical and experimental buckling loads of circular CFST columns is obtained if at least one among longitudinal and radial interfacial stiffnesses is high. The design methods compared in the paper give conservative results in comparison with the experimental results and analytical results for almost
perfectly bonded layers. The parametric study reveals that critical buckling loads of CFST columns are very much affected by the diameter-to-depth ratio and concrete elastic modulus. Moreover, a material nonlinearity has a pronounced effect for short CFST columns, and a negligible effect for slender ones.

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“Shear buckling experiments of web panel with pitting and through-thickness corrosion damage”, Journal of Constructional Steel Research, Vol. 115, pp 290-302, December 2015, DOI: 10.1016/j.jcsr.2015.08.032

ABSTRACT: This study considered the shear buckling behavior of a web panel with pitting and through-thickness corrosion damage in the diagonal tension field. Shear loading tests were conducted on three large-scale specimens under different corrosion damage conditions to compare their shear buckling behaviors. To consider corrosion damage, artificial pitting holes and artificial rectangular sectional damage were induced in the lower web panel of each specimen. Finite element (FE) analysis was also performed to evaluate the shear buckling strength and post-shear buckling behavior. From shear buckling test results, the specimen with artificial pitting corrosion damage exhibited similar shear buckling behavior to the specimen without corrosion damage. However, for the shear buckling specimen with artificial rectangular sectional damage, its shear buckling behavior and shear failure mode changed with a slightly distorted diagonal tension band, and its shear buckling strength and critical buckling load significantly decreased relative to the shear buckling specimen with pitting corrosion. Therefore, the region of corrosion damage should be examined with the corrosion level of the web panel because corrosion pitting or section loss of the web panel can affect the shear buckling behavior when it extends to the critical corrosion damage level in the diagonal tension field.

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ABSTRACT: A concept of using curved steel–concrete–steel (SCS) sandwich structure as the ice-resistant wall has been proposed for Arctic oil and gas drilling platform. In the developed curved SCS sandwich structure, ultra-lightweight cement composite (ULCC) and overlapped headed studs were used as the core material and bonding measures at the steel-concrete interface, respectively. In this paper, quasi-static tests on ten curved SCS sandwich beams have been carried out to investigate their ultimate strength behaviors under patch loading that considers the critical local ice-contact pressure. The test results reported the failure mode and shear resistances of structures, studied the influences of thickness of the steel skin shell, curvature, spacing of the connectors, depth of the cross section, strength of core materials, and boundary conditions on the ultimate strength behavior of the curved SCS sandwich beam. Extensive discussions and analysis were also carried out to provide information for the development of the analytical models. Analytical models were developed through modifying design code provisions. These innovative modifications in the analytical models included redefining the inclination angle of shear failure surface, redefining the effective depth of the section, considering the influence
of the thickness of steel skin, and developing analytical models on tensile resistance of the overlapped headed studs. The accuracy of the predictions by the analytical models was checked by the test data. All these efforts were made to provide better predictions on the shear resistance of the curved SCS sandwich beam.

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ABSTRACT: This paper proposes a design method for evaluating the fire resistance of circular hollow section (CHS) tubular K-joints subjected to axial loading based on a critical temperature method. In this method, a tubular K-joint is considered to be safe when the joint temperature is lower than a critical temperature. Through finite element (FE) analyses, it is proved that the temperature development of a steel tube in fire condition can be taken safely as the temperature development of a tubular K-joint with a chord same as the steel tube. Afterwards, an extensive parametric study is carried out to investigate the effect of geometric parameters including $\beta$, $\gamma$ and $\theta$ on the critical temperature of tubular K-joints. It is found that the critical temperature for a tubular K-joint without initial chord stress is merely related to the degree of utilization, and the effect of geometric parameters on such critical temperature can be ignored. The results also show that the critical temperature of a tubular K-joint subjected to balanced axial loads can be calculated on the basis of the equation for predicting the critical temperature of a steel member specified in Eurocode 3 (part 1-2). Moreover, the influence of the chord stress on the critical temperature is investigated through the numerical results of 30 FE models. The results show that the relationship between the critical temperature and the chord stress can be simplified as a parabolic curve for designed purpose.

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ABSTRACT: This paper presents an experimental investigation on lightweight concrete-filled circular and elliptical hollow sections under axial compression at cross-section level. The elliptical hollow section (EHS) was cold-formed from the hot-rolled circular hollow section (CHS). Experimental findings, including failure mode, load-deformation history and load carrying capacity, from the 24 stub column tests were compared and reported. Comparisons in particular between the parent hot-rolled CHS and cold-formed EHS were made and stub column results have indicated the cold-forming process decreases both the load carrying capacity and the ductility. Design rules based on European standards were also assessed and assessments have shown that the existing rules can be adopted for the design of lightweight concrete-filled hot-rolled CHS while a simple superposition model can be used for the design of lightweight concrete-filled cold-formed EHS.
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ABSTRACT: Conventional concentric braces buckle under compressive loading. To overcome this limitation, the Buckling-Restrained Braces (BRBs) were introduced in the mid 70s. They typically consist of a low-yield steel core and a restraining mechanism. In order to achieve enhanced understanding of the design parameters that have the most impact on the BRB inelastic behavior and failure mechanisms, comprehensive experimental efforts are typically needed. When such experimental programs are unfeasible or impractical, other investigative means are valuable. The presented paper explores the most influential BRB design parameters as well as the common failure modes observed. This is achieved through detailed nonlinear Finite Element Analysis (FEA). The FEA is carried out using the commercial software ABAQUS taking into consideration both material and geometric nonlinearities. The FE model is meticulously verified against experimental tests reported in the literature and good correlation is observed. The verified FE model is further utilized to perform a deterministic sensitivity analysis and simulate different failure scenarios for BRBs under cyclic loading. It is found that among the different failure modes, necking of the steel core is potentially the most serious. It could trigger significant internal damage to the BRB upon subsequent compressive load reversal leading to failure of the entire brace through significant internal damage or global buckling.


ABSTRACT: The paper describes a series of pin-ended compression tests and numerical analysis of channels with complex edge stiffeners and two different types of web stiffeners. In the tests, axial compression and eccentric compression loading were imposed respectively on 18 and 12 specimens. The stability capacity, buckling mode and deformation behavior of these specimens were studied. It was found that the longitudinal intermediate stiffeners could reduce the web width-to-thickness ratio effectively and enhance the stability capacity of members subjected to axial loading or eccentric loading with the eccentricity close to the web side. Compared with channels with complex edge stiffeners under the same condition, the ultimate load-carrying capacity of Σ shape section members and members with V type web stiffeners was increased by 65% and 50%, respectively. But distortional buckling of the complex section member was the governing failure modes of the specimens. Tests were then simulated by finite element analysis. The numerical analysis results show good agreement with experimental results. Furthermore, parametric study on a total of 144 samples was conducted to obtain the optimal web sub-element proportion for Σ cross-section columns.


ABSTRACT: An implicit finite element model based on the generalized beam theory (GBT) is developed to simulate the fire behavior of restrained steel beams. The model considers both material and geometric
nonlinearities. A bilinear stress–strain curve is used to represent the material behavior at elevated temperatures. The GBT cross-section deformation modes are utilized to construct the mid-surface displacements of each wall, where the longitudinal variations of the mode amplitudes are approximated by the cubic B-splines. The bending related displacements are established by using assumptions of the Kirchhoff's plate theory. The Green–Lagrangian strain tensor is employed to represent the deformation at each quadrature point, and therefore the geometric nonlinearity can be included. A weak-form of the nonlinear equilibrium equations is derived by the Principle of Virtual Work and is solved by employing an implicit iterative procedure. The current model can capture local deformation because higher-order cross-section deformation modes are used. The fidelity of the developed GBT formulation has been evaluated by comparing the predictions with three benchmark results available in the literature, and case studies have been performed. It is found that the local buckling can influence the overall behavior of beams in fire, which is different to the finding of the conventional beam-element-based analysis. The current GBT approach is an alternative to the shell finite element formulation, but exhibits higher computational efficiency.

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ABSTRACT: The effect of distortional deformation on the elastic lateral buckling of thin-walled box beam elements under combined bending and axial forces is investigated in this paper. For the purpose, an analytical model is developed for the stability of laterally unrestrained box beams according to higher order theory. Ritz and Galerkin's methods are applied in order to discretize the governing equilibrium equations and then the buckling loads are obtained by requiring the singularity of the tangential stiffness matrix. The different solutions are discussed and then compared to the finite element simulation using Abaqus software where shell elements are used in the mesh process. The numerical results reveal that classical stability solutions as those adopted in Eurocode 3 overestimate the real lateral buckling resistance of thin-walled box beam members, particularly for the ones with high ratios between the height and the thickness of the cross-section. Numerical study of incidence of compressive forces on lateral buckling resistance of thin-walled box beam is investigated.

ABSTRACT: The ultimate shear capacity of steel plate girders may be influenced by shear buckling, an important and common instability phenomenon occurring in plate girders with slender webs. The transverse loads and consequent shear effort applied on such beams have a large impact on the webs, leading to the possible collapse by shear buckling. In a fire situation, the buckling phenomena in these structural elements are amplified due to the reduction of the steel mechanical properties caused by the elevated temperatures. Recently, there has been an increase in the use of those plate girders, arising from the search for more economical and competitive solutions. However, no specific rules for shear buckling verification in case of fire are given in Eurocode 3 (EC3). After the validation of the numerical models against experimental tests from the literature,
an extended number of geometrically and materially nonlinear numerical analyses including imperfections (GMNIA) have been performed dealing with the evaluation of the effect of rigid and non-rigid end posts on the ultimate shear capacity of steel plate girders under fire. The obtained numerical results are compared with the specifications of EC3 for the design at normal temperature adapted to elevated temperatures. These specifications are non-conservative and, for this reason, a new design proposal harmonized with the EC3 principles is presented in order to evaluate the ultimate shear capacity of steel plate girders in fire situation.

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ABSTRACT: This paper presents a novel buckling-restrained steel plate shear wall with inclined slots called slotted SPSW to be used as an energy dissipation device for earthquake resistance. In the slotted SPSW, a steel plate with inclined slotted holes is sandwiched in between two external concrete panels which provide lateral restraint to achieve stable energy dissipation under cyclic reversal loading. Theoretical analysis and finite element monotonic pushover analyses are conducted to investigate the stability of slotted SPSWs. Global buckling and local buckling resistances of slotted SPSWs are determined. Some key parameters, such as the gap between steel plate and concrete panels, bolt spacing, width of steel strips, and steel panel slenderness, are investigated through numerical analyses. The shear force and lateral drift behavior of the slotted SPSW is found to be affected by the physical gap between the concrete panels and inner steel plate. The minimum concrete panel thickness for providing the effective lateral restraint to prevent buckling failure of the inner steel plate is determined based on the bolt spacing.

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ABSTRACT: Experimental and numerical studies of ferritic stainless steel beam-columns have been carried out and are described in this paper. Two cross-section sizes were considered in the physical testing: square hollow section (SHS) 60 × 60 × 3 and rectangular hollow section (RHS) 100 × 40 × 2, both of grade EN 1.4003 stainless steel. The experimental programme comprised material tensile coupon tests, geometric imperfection measurements, four stub column tests, two four-point bending tests, two axially-loaded column tests and ten beam-column tests. The initial eccentricities for the beam-column tests were varied to provide a wide range of bending moment-to-axial load ratios. All the test results were then employed for the validation of finite element (FE) models, by means of which a series of parametric studies was conducted to generate further structural performance data. The obtained test and FE results were utilized to evaluate the accuracy of the capacity predictions according to the current European code, American specification and Australian/New Zealand Standard, together with other recent proposals, for the design of stainless steel beam-columns. Overall, the
Australian/New Zealand Standard was found to offer the most suitable design provisions, though further improvements remain possible.

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ABSTRACT: In this study, the analytical study of concrete stiffened steel plate shear wall (CSPSW) with a reinforced concrete panel on one side and with gap between the concrete panel and steel frame is conducted. CSPSWs have a variety of infill steel plate and reinforced concrete panel thicknesses. The results show that the behavior of CSPSWs and corresponding steel plate shear walls (SPSWs) is utterly disparate. The infill steel plate of SPSW resists lateral load by development of tension fields, as the infill steel plate initiates elastic buckling. However, in CSPSW, the elastic buckling of the infill steel plate is prevented by the introduction of the reinforced concrete panel; hence, the infill steel plate carries out lateral load by pure shear yield. Moreover, during the lateral load, CSPSW undergoes four stages: initial elastic stiffness, shear yield stiffness, post-shear yielding stiffness, and pre-failure stiffness. The reinforced concrete panel thickness has a remarkable and direct influence upon the shear capacity and the ultimate strength of the CSPSW; furthermore, it is dependent upon the thickness of infill steel plate. Increasing the concrete panel thickness up to a specific value, the shear capacity and the ultimate strength enhance; however, while increasing it beyond that, the shear capacity and the ultimate shear strength of CSPSW remain constant. CSPSW provides a higher initial elastic stiffness, greater shear capacity, and higher ultimate strength as compared to its corresponding SPSW. The ductility ratio and energy absorption of CSPSW is improved owing to introduction of reinforced concrete panel as well.

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ABSTRACT: Web crippling failure of hot-rolled channel steel sections could be found due to localized concentrated loads or brace reactions. This paper reports the results of an investigation into web crippling behavior of channel sections subjected to end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF) and interior-two-flange (ITF) loading conditions. A total of 48 channel section tests subjected to web crippling were conducted. The investigation was mainly focused on the effects of bearing length and web slenderness ratio of channel sections on ultimate capacity against web crippling. The tests were performed on four different sizes of channel sections. The results obtained from these tests show that as the bearing length increases, the web crippling ultimate capacity increases significantly. When the bearing length was 50 and 100 mm, the web crippling ultimate capacity of channel sections with web slenderness ratio \((h/t) = 18\) reached its peak. When the bearing length was 150 mm, the web crippling ultimate capacity of channel sections with web slenderness ratio \((h/t) = 12.55\) reached its peak. The web crippling ultimate capacity of channel sections with web slenderness ratio \((h/t) = 24.67\) reached the minimum value. Plastic deformation developed near the
mid-height of the web, and that a plastic hinge zone formed in the ultimate limit state. Finite element models have been developed and verified against the test results. The calculation equations of web crippling ultimate capacity put forward in the paper can accurately predict experimental value.

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“DSM for ultimate strength of bolted moment-connections between cold-formed steel channel members”, Journal of Constructional Steel Research, Vol. 117, pp 196-203, February 2016,
DOI: 10.1016/j.jcsr.2015.10.005
ABSTRACT: Experimental tests have previously shown that the strength of bolted moment-connections between cold-formed steel channel members, where the connections are formed through an array of bolts in the web, is dependent on the length of the bolt-group. This reduced strength has been observed in tests on portal frame joints as well as overlapped purlin joints. For a long bolt-group length, an upper bound would be the full in-plane major axis moment-capacity of the section, which can be predicted using the conventional Direct Strength Method (DSM). For a short bolt-group length, in the order of the depth of the section, a reasonable lower bound to the reduced strength can be predicted by using the DSM, modified to include the effect of the bimoment at the connection. In this paper, a parametric study is performed covering sections of different values of slenderness.

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ABSTRACT: This paper points out an accurate buckling model for determining the flexural effective length of a steel column subjected to intermediate gravity loads, for applications in the 2D second-order elastic analysis based design procedure. The proposed buckling model has “notional” horizontal restraints where equivalent horizontal forces have been applied, and can be readily programmed into a structural analysis/design software. Thirty columns having various end restraints and subjected to concentrated gravity loads within their unsupported lengths are analysed to demonstrate the merits of the proposed buckling model. It is shown that, in most of the cases analysed, the proposed buckling model leads to more liberal column capacities compared to the use of the unity effective length factor or the buckling model described in the European drive-in rack design code. The more liberal capacities are very close to the ultimate loads determined through second-order plastic-zone analysis.

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ABSTRACT: Numerical investigation of cold-formed normal and high strength stainless steel square and rectangular hollow sections subjected to major axis bending is presented in this paper. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. The material properties of the flat and corner portions of the specimen sections were carefully incorporated. It was shown that the finite element model closely predicted the failure modes, ultimate moments and deflections of the tested specimens. The model was then used for an extensive parametric study to investigate the interaction effects of constituent plate elements on Class 3 and 2 slenderness limits and cross-section moment capacities of cold-formed stainless steel square and rectangular hollow sections in bending. The numerical strengths predicted from this study together with the experimental results were compared with the theoretical elastic and plastic bending moments. It was shown that the element interaction surely influences the flexural behavior of cold-formed stainless steel square and rectangular hollow sections especially for slender cross-sections. The design provisions on Class 3 and 2 slenderness limits and effective width equations specified in ASCE Specification, EC3 Code and proposed by Gardner and Theofanous are not suitable for square and rectangular hollow sections in bending since they did not take into consideration interaction effects of constituent plate elements. Hence, the new Class 3 and Class 2 slenderness limits and the cross-section moment capacity design equations are proposed in this study based on the whole cross-section response, which carefully consider the interaction effects of constituent plate elements.

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ABSTRACT: This paper presents an innovative “collapse prevention” system for seismic resistant design in new construction and existing buildings. The collapse prevention system consists of a collapse inhibiting mechanism, such as a pair of slack cables or loose linkages, working in tandem with the main lateral-force resisting system and engaging the gravity framing to avert collapse. In this holistic design approach, the main lateral-force resisting system and gravity framing are used to provide adequate performance under low to moderate level ground motions, and the collapse inhibiting mechanism is deployed as a back-up to provide life safety under extreme ground motions. The collapse inhibiting mechanism may be augmented with energy dissipation devices (small viscous fluid or visco-elastic solid dampers) to enhance performance under wind or small seismic events. Analytical performance of archetypical 1-story, 2-story, 4-story, and 8-story steel-frame buildings employing collapse prevention systems indicate that collapse prevention systems substantially reduce the probability of collapse during Maximum Considered Earthquake (MCE) ground motions, depending on the building and collapse inhibiting mechanism deployed. Seismic hazard data suggests that collapse prevention systems would provide a 1% or less risk of collapse in 50 years in many locations, mostly in the central and eastern United States.

Guan Quan, Shan-Shan Huang and Ian Burgess (Department of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, United Kingdom), “Component-based model of buckling panels of steel beams at elevated temperatures”, Journal of Constructional Steel Research, Vol. 118, pp 91-104, March 2016, DOI: 10.1016/j.jcsr.2015.10.024
ABSTRACT: Both bottom-flange buckling and beam-web shear buckling have been observed in many full-scale fire tests in the vicinity of beam-to-column connections. These phenomena can influence the load
redistribution within the adjacent connections and the global structural behaviour, detrimentally affecting the structural overall fire resistance. However, existing models for bottom-flange buckling overestimate the structural resistance when the beam is slender. In this work, a new analytical model has been created to predict both of these types of buckling behaviour in steel beams in the vicinity of beam-to-column connections at elevated temperatures. The model considers the individual effects of both buckling modes, as well as their interaction. It is capable of predicting the force–deflection relationship of the buckling zone from the initial elastic loading stage to run-away failure. The new analytical model has been compared with the existing Dharma's model and a range of 3D finite element simulations created using the ABAQUS software. Comparisons have shown that the proposed method gives better predictions than Dharma's model. A component-based model of the buckling zone has been created on the basis of this new analysis. The component-based model can provide sufficient accuracy, and will be implemented in the software Vulcan for performance-based global structural fire analysis.

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ABSTRACT: This paper presents an investigation on concrete-filled stainless steel tubular (CFSST) columns in fire and after fire exposure. A total of 12 specimens were tested, including 6 CFSST columns exposed to fire and another 6 CFSST columns subjected to sequential ambient temperature loading, fire exposure with constant applied load and post-fire loading phases. A photogrammetric method was employed during the test to capture the initial imperfections of the CFSST columns and strain developments of the stainless steel tubes in fire. The main variables explored in the test program include: (a) cross-section type (circular, square); (b) axial load level (0.28–0.48); and (c) presence of reinforcement or not. A three-dimensional finite element (FE) model was developed by introducing the measured initial imperfections and load eccentricities. The comparison of the FE predictions and the tests performed showed a reasonable agreement. To further simplify the FE analysis, the initial geometric imperfection of a column may be simulated in the model as the first buckling mode shape of the column multiplied by an amplification factor. The simplified model was verified by comparison with test results.


ABSTRACT: This work assesses the ultimate strength of experimentally tested steel plates with a large central elongated circular opening, subjected to uni-axial compressive load. A series of experimental tests have been carried out on plates that were part of a real structure, which represents a scaled midship section of single hull tanker ship, tested in a corrosive environment in direct contact with seawater. One elongated circular opening shape with different sizes is analyzed and the effect of the opening size on the ultimate strength is investigated. The force–displacements relationships are presented and the dissipated energy is analyzed. Stress–strain relationships, resilience and toughness have been evaluated. The collapse modes are discussed and the ultimate strength has been compared with recently published studies showing a good agreement in the trend.
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ABSTRACT: Using high-strength (HS) materials in steel–concrete composite beams is an efficient approach to reduce the self-weight and to improve the sustainability benefits of such members. Due to a lack of precise knowledge of the ductility of composite beams beyond their first yield as a result of the non-linear response of their constituent materials, a comprehensive investigation is reported herein to quantify the available rotation capacity of composite beams using HS materials when subjected to sagging bending. An advanced three-dimensional finite element model is utilised to calculate the end rotation of single-point-loaded simply-supported composite beams. The model has demonstrated to be adequate and reliable in terms of predicting the flexural strength and load–deflection response by comparisons with numerous experimental results reported elsewhere. As many as 1380 beams with various strengths of steel and concrete as well as a wide range of the degree of shear connection and geometries are modelled, and both solid slabs and composite slabs using profiled steel decking are incorporated. Analyses of this body of data indicate that the depth of the neutral axis is the most essential parameter for determining the available sagging rotation capacity, of which an increased value leads to a lower rotation capacity. The yield strength of the steel also has noticeable effects with higher values resulting in poorer rotation performance. The available rotation capacity is also sensitive to the span-to-depth ratio of the beams. In addition, the effects of varying cross-sectional geometries, different patterns of shear connector distributions as well as of geometric imperfections and residual stresses are clarified, which are shown to be slight and can therefore be ignored. Finally, a non-linear empirical equation is developed to predict the available rotation capacity of composite beams using HS materials, which covers the range of numerical data with satisfactory consistency. The outcomes provide an important basis for evaluating the ductility of composite beams by comparing with the required rotation capacity.

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ABSTRACT: Circular hollow sections (CHS) are widely used in a range of structural engineering applications. Their design is covered by all major design codes, which currently use elastic, perfectly-elastic plastic material models and cross-section classification to determine cross-section compressive and flexural resistances. Experimental data for stocky sections show that this can result in overly conservative estimates of cross-section capacity. The continuous strength method (CSM) has been developed to reflect better the observed behaviour of structural sections of different metallic materials. The method is deformation based and allows for the rational exploitation of strain hardening. In this paper, the CSM is extended to cover the design of non-slender and slender structural steel, stainless steel and aluminium CHS, underpinned by and validated against 342 stub column and bending test results. Comparisons with the test results show that, overall, the CSM on average offers more accurate and less scattered predictions of axial and flexural capacities than existing design methods.
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ABSTRACT: Cylindrical steel silos are often supported by discrete supports or columns to be able to provide a hopper and to facilitate emptying operations beneath the cylindrical barrel. The simplest mean of support for a light silo is by the use of engaged columns, without the use of unnecessarily expensive ring stiffeners. Such engaged columns gradually introduce the support load into the silo wall by shear, spreading the stresses in circumferential direction. In general, the highest axial compressive stress concentrations can be found in the shell wall in the vicinity of the top of the engaged column, resulting in failure due to excessive yielding and/or local instability. The study aims to identify the optimal combination of dimensions of an engaged column (i.e. the height, the widths in circumferential and radial direction and the thickness) to obtain a failure load as high as possible with as little material in the column as possible. An important condition is the requirement that the columns must withstand a higher load than the silo wall itself. In other words, failure should occur in the vicinity of the terminations of the columns (and not in the column itself). All results and conclusions are based on numerical finite element analyses.

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ABSTRACT: In the present paper, the static strength of steel collar plate reinforced tubular T/Y-joints is numerically investigated. A finite element (FE) model was developed and the results were verified against the experimental data. Afterwards, a set of 168 FE models of collar plate reinforced T/Y-joints was generated and analyzed under axially compressive loads. The effect of plate size and joint geometry on the ultimate strength and failure mechanism of the joints were investigated through a parametric study. Results showed that the ultimate strength of a collar plate reinforced T/Y-joint can be up to 270% of the strength of the corresponding unreinforced joint. Despite this significant difference between the static strength of unreinforced and collar plate reinforced T/Y-joints, studies on this type of reinforced joints have been limited to very few T-joint tests. Also, no design equation is available to determine the ultimate strength of T/Y-joints reinforced with collar plates. Hence, after the parametric study, a new equation is proposed, through nonlinear regression analysis, for determining the ultimate strength of collar plate reinforced T/Y-joints under axially compressive loads.

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ABSTRACT: All-steel buckling restrained braces (BRBs) are a newly developed variation of ordinary BRBs with enhanced characteristics in terms of weight and curing of the mortar core. Finite element (FE) models of all-steel BRBs with varied geometries were subjected to cyclic analyses in this study. The satisfactory brace
geometries that minimized instability of the core section while maximizing energy dissipation capacity were then identified. Bilinear FE-derived back-bone curves of the selected BRBs were subsequently used in the representative truss elements to retrofit three 4-, 8-, and 12-story frames. The advantages of these braces were highlighted by drawing performance comparisons against ordinary braces. Nonlinear static and dynamic responses of the frames with all-steel BRBs were also assessed in terms of parameters such as maximum inelastic deformation demand.

ABSTRACT: (cannot cut and paste)

ABSTRACT: High strength steels (HSSs) are increasingly applied in structural engineering due to their benefits in terms of mechanical performance and economy. Compared with normal strength steel (NSS) axial compression members, HSS members possess more critical local buckling behavior since its component plates may be designed as being more slender, and different mechanical properties of HSS, in terms of increased yield strength and reduced ductility, may result in different local buckling behaviors. In this paper, finite element (FE) analysis is performed to investigate the local buckling behavior of welded box section and I-section stub columns under axial compression with both NSS and HSS being incorporated, where initial geometric imperfections and welding-induced residual stresses are accurately simulated. Through this work, variation rules of post-buckling ultimate stress and local buckling stress of the axial compression members with steel yield strength and width-to-thickness ratio are clarified. By comparing the FE analysis results and existing test results with the corresponding design methods in ANSI/AISC 360-10, Eurocode 3 and GB 50017-2003, it is confirmed that the design methods for the local buckling behavior of welded box section and I-section stub columns under axial compression need to be modified. New design formulas are proposed to take the influence of the steel strength into consideration.

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ABSTRACT: Concrete-filled steel tube-enhanced steel plate-reinforced concrete (CFST-SPRC) shear walls have been proposed for use in super high-rise buildings. This paper presents an experimental study of CFST-
SPRC shear walls that aims to evaluate their seismic behavior. Three CFST-SPRC shear wall specimens with varying steel plate thicknesses and concrete strengths were tested under constant axial force and reversed cyclic loading. All of the specimens experienced a progression of failure from web concrete cracking, to local buckling of the steel tube plates, to fracturing of the vertical welds at the corners. One specimen exhibited brittle failure at the end of testing due to the sudden crushing of web concrete. Stable and full hysteretic behavior was developed by the shear wall specimens, indicating a capability for stable energy dissipation. The ultimate drift ratios were around 1.7% for all of the specimens. The flexural and shear deformations of the shear walls, and the base rotation caused by local deformations in the foundation beam, all provided a negligible contribution to the total lateral displacement. The proportions of the flexural displacement, shear displacement and rotational displacement to the total displacement were around 0.6, 0.2 and 0.2, respectively, for all specimens throughout the loading process. Simplified design methods were proposed for evaluating the load-carrying capacities of CFST-SPRC shear walls. The proposed method provided reasonable but conservative estimations for the test shear wall specimens.

Toi Limazie and Shiming Chen (School of Civil Engineering, Tongji University, Shanghai 200092, China), “FE modeling and numerical investigation of shallow cellular composite floor beams”, Journal of Constructional Steel Research, Vol. 119, pp 190-201, March 2016, DOI: 10.1016/j.jcsr.2015.12.022

ABSTRACT: The behavior of shallow cellular composite floor beam is normally governed by the shear transfer mechanism at the contact interface between the concrete slab and the encased steel beam, thus by the influence of the two materials. A detailed finite element modeling approach in investigating the structural behavior of shallow cellular composite floor beam is presented. The shear bound at the contact interface between the concrete slab and the steel beam is simulated by using the contact modeling and considering the adhesion, the friction and the local compression at all the contact zones. Both the material and geometric nonlinearities are considered in the FE modeling of the shallow cellular composite beams. The FEA results are calibrated and validated against the test results and the comparisons indicated that the FE analysis procedures with the contact modeling agree well with the test results, and can accurately predict the flexural behavior and the load bearing capacity of the composite slim floor beam. An extensive parametric study is further conducted to investigate all the likely influences of the parameters such as geometric dimensions and the web openings size and spacing on the structural performance of the shallow cellular composite floor beam.


ABSTRACT: The in-plane shear strength of steel-plate composite (SC) walls is governed by the onset of Von Mises yielding in the steel faceplates. This paper uses a mechanics based model (MBM) to present the fundamental in-plane shear force–shear strain ($V$–$\gamma$) response of SC walls. The MBM accounts for concrete cracking due to principal tensile stresses, and the post-cracking orthotropic composite behavior of SC walls subjected to pure in-plane shear forces. This fundamental behavior of SC walls is illustrated using the results from a large-scale in-plane shear test of an SC wall specimen (with flange walls), and compared to the predictions from the MBM. The paper also includes a comprehensive experimental database of all in-plane shear tests conducted in Japan, S. Korea, and US. The database consists of 26 SC wall tests with a wide range of parameters for the wall thickness, reinforcement ratio, aspect ratio, and the presence (or absence) of axial stress. The experimental results are used to identify the key parameter influencing the in-plane shear strength of SC walls, which is shown to be the steel faceplate reinforcement ratio. The design code equations used in
engineering practice around the world are used to predict the in-plane shear strength of all 26 SC wall specimens in the database. The conservatism and accuracy of the code predictions of strength are evaluated by comparing them with experimental results, and reliability analysis are performed to estimate the associated strength reduction ($\phi$) factors.

Kojiro Uenaka (Department of Civil Engineering, Kobe City College of Technology, Gakuenhigashimachi 8-3, Nishi, Kobe 6512194, Japan), “CFDST stub columns having outer circular and inner square sections under compression”, Journal of Constructional Steel Research, Vol. 120, pp 1-7, April 2016 DOI: 10.1016/j.jcsr.2015.12.005

ABSTRACT: Concrete filled double skin steel tubular (CFDST) members, having a hollow section consisting of two concentric steel tubes and filled concrete between the two walls of the tubes, are lighter than the ordinary concrete filled steel tubular (CFT) members, which have solid cross-sections. Therefore, the CFDST members can work effectively as seismic resistant structures such as bridges high piers during earthquake. The present study aims to investigate experimentally centric loading characteristics of the CFDST stub column consisting of an outer circular steel tube and an inner square steel tube with in-filled concrete between the double walls, which are abbreviated as CS-CFDST. The two selected testing parameters are the outer tube's diameter-to-thickness ratio and inner width to outer diameter ratio. From the results, observed failure modes were divided into two groups: local buckling associated with shear failure of in-filled concrete and local buckling of the double tubes. These failure modes were affected by inner width to outer diameter ratio. Axial load capacities were also determined by the above described failure modes. Additionally, elasto-plastic biaxial stress behavior of both tubes under plane stress condition is also mentioned. Methods to predict the axial load capacities of CS-CFDST stub columns are also provided.

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ABSTRACT: Recent studies (Issa-El-Khoury, 2010; Issa-El-Khoury et al., 2015), demonstrated the beneficial influence that horizontal curvature could have with respect to longitudinal stiffener requirements for thin webs in bridge plate girders when those webs are subjected to pure bending. These studies showed that, when longitudinal stiffeners are required in a slender web, curvature did not drastically alter optimal stiffener placement requirements from what is currently recommended for similarly proportioned straight webs (American Association of State Highway and Transportation Officials (AASHTO), 2007), and, more importantly, there were certain instances where curvature enhanced web stability to eliminate the need for longitudinal stiffeners. However, it is recognized that, in most cases, curved plate girder webs are not subjected to either pure bending or pure shear but a combination of the two. Therefore, an extension of previously published findings to examine the response of curved, plate girder webs under a combination of bending and shear was necessary to validate or refute the pure bending findings. Those studies are summarized herein and they demonstrated that, for the ranges of parameters that were examined and when acted on by bending and shear, placing longitudinal stiffeners either $D/3$ or $D/4$ below the top flange, with $D$ being the web depth, were optimal identified positions and that, at lower radii and in similar fashion to previously reported findings in pure bending, benefit realized from placing longitudinal stiffeners was offset by the effects of web curvature.
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ABSTRACT: This paper presents a comparative study on fire models to predict the performance of an axially loaded square hollow steel (SHS) column exposed to a localized fire. A simple fire model based on the classic fire plume theory and a sophisticated computational fluid dynamics (CFD) model named Fire Dynamics Simulator (FDS) were investigated and used to predict the heat fluxes from the localized fire to the column. Thermo-mechanical analyses using finite element software were conducted to obtain the temperature and structural responses of the column exposed to the predicted heat fluxes. A total of 22 cases were considered and the variable parameters included heat release rate, fire source diameter, location of the fire source and load ratio. The steel temperatures predicted using the simple fire model were higher than those predicted using the sophisticated fire model. The buckling temperatures predicted using the simple fire model were generally lower than those predicted using the sophisticated fire model, and the average difference of the predicted buckling temperatures was within 40 °C. Buckling temperature is defined here as the maximum temperature in a steel column on onset of buckling. Comparing with the sophisticated fire model, the simple fire model is computationally efficient and yields conservative results, which may be used in structural fire engineering design.

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ABSTRACT: The local buckling of steel plates in rectangular concrete-filled steel tubular (CFT) columns subjected to eccentric compression is investigated based on the energy method. The formulas for elastic local buckling stress of the steel plates in rectangular CFT columns under eccentric compression are derived, assuming that the unloaded edges of the steel plate are elastically restrained against rotation, whereas the loaded edges are clamped. Subsequently, the formulas are calibrated with the experimental results and compared with calculated results by the empirical method, which exhibit good agreement. Then, these formulas are applied to investigate the local buckling behavior of steel plates in eccentrically loaded rectangular CFT columns. It is found that the local buckling stress of steel plates in eccentrically loaded rectangular CFT columns is significantly influenced by the stress gradient coefficients and width–thickness ratios while it is slightly influenced by cross-sectional aspect ratios (D/B). Finally, the reasonable ranges for width–thickness ratios (B/t) and depth–thickness ratios (D/t) at various stress gradient coefficients corresponding to different cross-sectional aspect ratios are suggested for the steel plates in eccentrically loaded rectangular CFT columns. Furthermore, the appropriate relationship for the thickness of the steel plates at various stress gradient coefficients is suggested for the design of rectangular CFT columns under eccentric compression.
Experimental behavior of innovative T-shaped composite shear walls under in-plane cyclic loading

ABSTRACT: In this paper, an innovative structural wall, named bundled lipped channel-concrete (BLC-C) T-shaped composite wall, is proposed. The flange of the proposed wall consists of a cold-formed square hollow section (SHS) in the center and two cold-formed (CF) lipped channels at each side. The web of the wall is formed by connecting several lipped channels through complete joint penetration (CJP) weld. The concrete was filled into the compartments enclosed by the steel channels and tubes. Five full-scale specimens were tested under constant axial load subjected to cyclic lateral load. The variables studied in the experiments include the wall configuration, cross section of wall, steel sheet thickness, axial force ratio, and the presence of shear studs. The specimens exhibited ductile manner and experienced stable hysteresis behavior, failed in the sequence of local buckling of the wall at the base of the wall web, compressive crushing of concrete at the base of the wall web, and the fracture propagation at the boundary of the wall. The seismic behavior of the specimens was evaluated in terms of strength, stiffness, deformation, ductility, and energy dissipation capacity. The results indicate that the axial force ratio and the wall configuration detail have significant impact on the entire hysteresis behavior, while the shear studs delay the occurrence of fracture and failure.

A full-scale experiment of a lattice telecommunication tower under breaking load

ABSTRACT: The main aim of this paper is to present results of a full-scale pushover test of a 40 meter telecommunication tower under breaking load. A detailed description of the studied tower has been presented with emphasis on the geometrical imperfections of the selected members of the structure. The results of the experiment consisting of the axial forces in the tower's members, as well as the displacements of the observed nodes as a function of external load have been presented. A comparison of a wind load based on the current standards with the load based on the experimental breaking force has been discussed for a typical set of telecommunication equipment. The main conclusion was that the structure's overall carrying capacity depended on the buckling resistance of the legs. Additionally, theoretical buckling resistances (based on standards) of the tower's legs made with round solid bars were smaller than the experimental axial forces in compression.

The remaining load-bearing capacity of corroded steel angle compression members

ABSTRACT: The paper presents a study on the buckling of corroded equal-leg angle-section members. The remaining load-bearing capacity and the prospective behaviour modes are analysed by experimental and
numerical research. The diversity of the corrosion is taken into consideration in the analysis; the corrosion is modelled by thickness reduction. Compressive buckling tests, finite element and analytical studies are completed to analyse the modified buckling behaviour and the ultimate load. On the basis of the results simplified design method is developed for the prediction of remaining compressive resistance.

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ABSTRACT: The analytical behavior of concrete-encased CFST (concrete-filled steel tube) columns under cyclic lateral loading is reported in this paper. A finite element analysis (FEA) model is developed to investigate the cyclic behavior of such composite column. Comparisons are made between measured and predicted results on failure modes, load versus displacement relationships and ultimate strength. It is found that the proposed FEA model can reproduce the experimental results with good accuracy. The full-range load-displacement relationships, the contact stress between steel tube and concrete and the axial load distribution among different components are analyzed using the verified FEA model. The cyclic behavior of concrete-encased CFST is compared with that of conventional CFST and reinforced concrete (RC) columns. The parametric analysis is conducted to investigate influences of various parameters on the moment-curvature ($M-\phi$) envelope curves. The parameters include the material strength, the steel ratio of inner CFST, the longitudinal reinforcement ratio, the stirrup characteristic value, the tube diameter to cross-sectional width ratio ($D/B$) and the axial load level. Finally, a simplified hysteretic model for the $M-\phi$ relationship of concrete-encased CFST column is proposed.

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DOI: 10.1016/j.jcsr.2015.10.014
ABSTRACT: This paper presents results from experiments performed on cold-formed high strength steel circular and polygonal sections. The test specimens were conceived to provide necessary information for development of tubular towers for wind turbines. A total of 32 high strength steel specimens were tested under uniaxial compression. Various thicknesses, openings and geometric imperfections were studied. Sixteen specimens without opening and sixteen specimens with opening were tested under axial compression in order to investigate influences of opening on the resistances. Tensile tests of coupon specimens taken from flat part, circular part and corner part were used to investigate basic properties of high strength steel material S650 and to evaluate influence of corner on the material strength and ductility. Initial geometric imperfections of the specimens were determined by using a 3D laser scanning method. The coupon test results were used to calibrate the ductile damage material models for modelling of fracture. Results from the experiments are fully described in this paper.

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ABSTRACT: Experimental and numerical investigations have been conducted on cellular beams with sinusoidal openings. They showed specific failure modes, in comparison with common opening shapes, mainly the local buckling of the panels around the opening. Detailed analysis of the stress distribution around the openings allowed understanding the behavior of those beams at ultimate limit state with the aim to develop a specific analytical model. The direct application of existing analytical approaches to beams with sinusoidal openings showed that the predictions need to be improved. Indeed, in order to obtain an accurate prediction of the buckling strength of the web sinusoidal parts, the analytical model is modified. In this paper, an analytical approach is proposed, based on the existing methods for multiple openings and on the plate buckling theory. A formula for the calculation of the critical stress coefficient is proposed and a simple method is described to take into account the additional strength provided by the intermediate web-post to the adjacent web panel. This approach considers simple equivalent rectangular plates. The analytical model is validated against finite element results regarding the values of critical stress coefficient obtained through an Eulerian calculation. Then, the ultimate strengths of cellular beams with sinusoidal openings are evaluated through a comparative study with FEM for different parent beam profiles and opening shapes.

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ABSTRACT: High strength steels, considered in the context of the structural Eurocodes, as steels with a yield strength over 460 MPa, are gaining increasing attention from structural engineers and researchers owing to their potential to enable lighter and more economic structures. This paper focuses on the bending strength of hot-finished high strength steel (HSS) square and rectangular hollow sections; the results of detailed experimental and numerical studies are presented and structural design rules for HSS cross-sections are proposed. A total of 22 in-plane bending tests, in three-point bending and four-point bending configurations, on HSS sections in grades S460 and S690 were conducted. The experimental results were replicated by means of non-linear finite element modelling. Upon validation of the finite element models, parametric studies were performed to assess the structural response of HSS sections over a wider range of cross-section slenderness, cross-section aspect ratio and moment gradient. The experimental results combined with the obtained numerical results were used to assess the suitability of the current European (EN 1993-1-1 and EN 1993-1-12) cross-section classification limits for HSS structural components. The reliability of the proposed cross-section classification limits was verified by means of the EN 1990 — Annex D method.

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ABSTRACT: A parametric study is presented to quantify essential factors influencing cyclic behavior of a steel buckling-controlled brace (BCB) with a tube carrying axial load surrounded by an outer tube to control buckling of the load-bearing tube. A small-scale experiment helped observe overall cyclic behavior, and develop finite-element models for numerical simulations. The model-based simulations identified the interaction of the friction, gap and thickness ratio between the two tubes as the essential factor. The paper concludes that (1) the gap is a sensitive parameter influencing local and global buckling. The smaller the gap, the less likely the local and global buckling will occur, but the more participation of the outer tube in load bearing due to adverse interaction between the two tubes; (2) Friction between the two tubes is a very delicate factor because its impact on the cyclic behavior of BCB varies depending on thickness ratio and friction; (3) Thickness ratio of the two tubes decides the effectiveness of controlling buckling. The thickness ratio of 1.0 is sufficient to control global buckling, but a larger than 1.0 ratio is needed to control both local and global buckling; (4) Interaction among the gap, friction and thickness ratio is strong, and shall be considered in design; and (5) Optimal performance results from a system with smallest gap possible, low friction, and heavier outer tube. Some less optimal but lower costly design combinations may have moderate gaps and various outer tube sizes to control brace buckling within targeted drift limits in performance-based design.

Yue Yang, Jingbo Liu and Jiansheng Fan (Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China), “Buckling behavior of double-skin composite walls: An experimental and modeling study”, Journal of Constructional Steel Research, Vol. 121, pp 126-135, June 2016, DOI: 10.1016/j.jcsr.2016.01.019

ABSTRACT: Double-skin composite (DSC) panels can offer high strength and robustness while improving the convenience of construction, with great potential for application in high rise buildings and nuclear power plants. In DSC panels, the stability of the outer surface steel plates are governed by the constraints of the in-fill concrete and the discrete shear connectors, i.e., the ratio of connector spacing (B) and surface steel plate thickness (t). In this paper, tests were performed on 10 specimens to assess the buckling behavior of DSC panels. The arrangement of the shear studs and the B/t ratio were varied in the tests. The results show that the arrangement and spacing of the shear studs can considerably influence the buckling shapes and loading capacity of the steel plates. Three-dimensional finite element (FE) models were developed to simulate the behavior of DSC panels subject to compression, and the FE results were found to be in good agreement with the observed buckling behavior during tests. A theoretical model based on Euler's equation was also proposed to predict the buckling stress of steel plates, and it showed reasonable agreement with the experimental measurements and FE results. The formula proposed in this paper can be used for determining the number or spacing of shear studs in DSC walls.

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ABSTRACT: Bridge fires are becoming an increasing concern, and for steel plate girder bridges in particular, web shear buckling is one of the failure mechanisms that can make it necessary to replace the girder after the fire is extinguished. The objective of this study is to evaluate the web shear buckling response of two
experimental plate girder specimens subject to fire conditions, and also to determine how complex computational models must be to accurately characterize the web shear buckling response of steel plate girders subjected to fire. Three parameters are evaluated: boundary conditions representing the flange, representation of thermal gradients, and composite action with the slab. To meet this objective, finite element models with varying parameters are compared to each other and to experimental results. Results show that the presence of a composite slab significantly increases the shear capacity of the plate girder. The presence of thermal gradients makes finite element modeling of the flange more sensitive to the results compared to a uniform temperature distribution. Modeling the girder with a uniform temperature equal to the temperature of the web leads to similar results as modeling with thermal gradients.

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ABSTRACT: Nonlinear finite element models of through beam connection to concrete filled circular steel tube (CFCST) column with three types of connection failures (column, beam and joint shear failures) under monotonic loading were proposed by ABAQUS programme. The connection detail composed of a steel I-beam which is completely passed through the circular steel tube column and welded to it by fillet or full penetration weld and the tube is then filled with concrete. The connection parameters investigated included different ratios of column-to-beam flexural strength, fillet or full penetration weld to connect the beam to the tube, using rebar inside of the column and effect of beam web and concrete core inside the joint. Buckling analysis, concrete damage, weld fractured and tube tearing were defined in the model. Good agreement was achieved between the model and existing test results in terms of the beam tip force—storey drift relationship, joint distortion and joint shear strain. As a result, the models could correctly predict the linear, nonlinear and post-failure behaviours of the connection. In addition, other parameters of the connection were investigated for the specimens. Finally, the effect of column axial load level for the connection behaviour in the three types of failures was investigated as a parametric study.


ABSTRACT: Traditional definition of the effective width of steel-concrete composite beam is based on a certain beam section. Section-based effective width changes from one section to another along the beam span. Therefore, effective width for deflection calculation of composite beam should be evaluated based on an element, rather than a specific section. This paper firstly presents the development of two theoretical models for composite beams. One is shear-lag slip beam model (SSM), which takes into consideration both slip effects and shear-lag effects. The other is slip beam model (SLM), which only considers the interface slip between steel beam and concrete slab. Validation of the theoretical models is performed through comparison of the theoretical predictions with the results obtained from more complex finite element simulations. Based on the theoretical models, an element-based definition of effective width for deflection analysis of composite beams is proposed.
Parametric studies are performed to find out the most important parameters influencing effective width. It is demonstrated that the effective width is mostly related to the width of the concrete slab, the span of the beam and the thickness of the floor slab. Simplified design formulas for computing the effective width are proposed. Comparisons between the results of the simplified formulas and the test results indicate the accuracy of the proposed formulas.

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ABSTRACT: Shear buckling behaviors of web-post in a Castellated Steel Beam (CSB) with hexagonal web openings under vertical shear were investigated using finite element method. Through treating the upper part of the web-post as a free body under horizontal shear force, whose shear buckling strength can be calculated by the thin-plate shear buckling theory, design equations for the vertical shear buckling strength of the web-post were proposed. Parameters that affected the vertical shear buckling strength of the web-post were studied, which were the opening height to web thickness ratio $h_o/t_w$, the web-post width to web thickness ratio $e/t_w$, the web height of Tee-section above the opening to the web thickness $h_f/t_w$ and the incline angle of the opening edge $\alpha$. After obtaining the vertical shear buckling strength of a CSB through finite element model, the shear buckling coefficient $k$ can be obtained through inverse analysis. Research results showed that $k$ decreased non-linearly with the increase in $e/t_w$ and $h_f/t_w$ and it increased linearly with the increase in $\alpha$ and $h_o/t_w$. Practical calculating method for $k$ was proposed based on parameter analysis results. The vertical shear buckling strength of the web-post calculated using the proposed shear buckling coefficient $k$ agreed well with that obtained from the finite element simulation. For the proposed method was based on the elastic buckling of the web-post, it overestimated the shear buckling strength when the web-post buckled in the elastic–plastic state.

Mohammed H. Serror, Emad M. Hassan and Sherif A. Mourad (Department of structural engineering, Faculty of engineering, Cairo University, Egypt), “Experimental study on the rotation capacity of cold-formed steel beams”, Journal of Constructional Steel Research, Vol. 121, pp 216-228, June 2016
DOI: 10.1016/j.jcsr.2016.02.005
ABSTRACT: The rotation capacity of cold-formed steel (CFS) beams has been evaluated through experimental investigation. Studies on different structural levels have been performed. At the element level, different profile slenderness ratios have been considered, and different section shapes have been investigated by increasing the number of flange bends: C-section and curved-section, which represents an infinite number of flange bends. At the connection level, a web bolted moment resistant type of connection using through plate has been adopted. In web bolted connections without out-of-plane stiffeners, premature web buckling results in early loss of strength. Hence, out-of-plane stiffeners have been examined to delay web and flange buckling and to produce relatively high moment strength and ductility. The experimental results have been compared with numerical results obtained by the authors in another paper work. The results revealed that increasing the number of flange bends will not in all cases enhance the behavior. Meanwhile, the use of out-of-plane stiffeners can increase the seismic energy dissipation, the moment strength and the ductility, when compared with the case without stiffeners.

ABSTRACT: Submarine pipelines are important and influential structures in marine engineering because they transport important, useful, and common fuels around the world. The pipeline structure is affected by different environmental forces from the surrounding conditions such as the external uniform hydrostatic pressure, hydrodynamic pressure, seismic forces, installation forces, free span forces, and forces scouring the pipeline. These conditions cause the pipeline to express complicated behavior. Local buckling and buckling propagation along the pipeline are common examples of collapses under these conditions and loadings, which can destroy thousands of meters of pipeline. These post-buckling phenomena cause great damage and losses to the oil and gas industries and to the environment; the imposed costs for the repair and protection of pipelines and mitigation of environmental problems are high. The use of ring-stiffeners is one way of increasing the buckling capacity of a pipeline in order to prevent and control the buckling propagation in pipelines. In this study, the buckling and post-buckling behaviors of ring-stiffened pipelines were investigated at a small scale through experiments and the finite element method (FEM). Two different ring-stiffeners were attached to the specimens. Only the uniform hydrostatic pressure was considered as the main loading; the axial stress was neglected in this study. The buckling modes, lateral displacement of the pipeline, ring tilt, formation of yielding lines, and torsion of yielding lines were examined. The results indicated that increasing the number of ring-stiffeners greatly increases the buckling capacity and lateral displacement of the pipeline. The buckling modes were changed, the post-buckling region was shortened, and torsion in the yielding lines and tilting in the ring-stiffeners clearly appeared in the tests. The results of this study were compared with those of recent research and reliable guidelines and standards.

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ABSTRACT: To evaluate hysteretic performance of welded Q690D high-strength steel H-section columns, cyclic loading test and numerical simulation were carried out. Firstly, cyclic loading test was performed on two H-section Q690D HSS welded columns with nominal axial compression ratio of 0.35. The observed failure mode is elastic–plastic local buckling of component plates. Hysteretic curves and skeleton curves of the test specimens show that the tested columns have a good energy dissipation capacity. Then, a finite element model was developed to simulate the hysteretic behavior of Q690D beam-columns and verified through comparison of numerical and experimental results. It is found that residual stresses are of ignorable influence on the ultimate bearing capacity of beam-columns. With the verified finite element model, extensive parametric analyses were conducted to investigate the effects of component plate slenderness ratio, column slenderness ratio and axial force ratio on the hysteretic performance of the Q690D H-section columns. Based on the observation and analyses of the experimental and numerical hysteretic curves, a trilinear moment-curvature hysteretic model for welded Q690D steel H-section column was proposed.

Zhengyi Kong and Seung-Eock Kim (Dept. of Civil and Environmental Engineering, Sejong University, 98 Gunja-dong, Gwangjin-ku, Seoul 143-747, South Korea), “Numerical estimation of the initial stiffness and
ABSTRACT: Single-web angle connections bolted to the beam web and the column flange are studied to investigate the effect of the thickness, length, and material properties of the angles, number of bolts, and gage distances of the fasteners on their moment–rotation behavior. ABAQUS software is used to analyze the nonlinear behavior of a single-web angle connection. Identical geometric and material properties with Lipson's test are utilized to verify the finite element models. A simpler and more accurate equation for the initial stiffness is suggested, and good agreement between the proposed model and Lipson's test data is demonstrated. The type of collapse mechanisms for single-web connection is established. The ultimate moment capacity modified from Kishi and Chen's equation is also proposed, and it agrees well with Lipson's test data.

ABSTRACT: The intermittently rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new cold-formed hollow section proposed as an alternative to welded hollow flange beams. It is a monosymmetric channel section made by intermittently rivet fastening two torsionally rigid rectangular hollow flanges to a web plate. This process enables the end users to choose an effective combination of different web and flange plate sizes to achieve optimum design capacities. Recent research studies focused mainly on the shear behaviour of the most commonly used lipped channel beam and welded hollow flange beam sections. However, the shear behaviour of rivet fastened RHFCB has not been investigated. Therefore a detailed experimental study involving 24 shear tests was undertaken to investigate the shear behaviour and capacities of rivet fastened RHFCBs. Simply supported test specimens of RHFCB with aspect ratios of 1.0 and 1.5 were loaded at mid-span until failure. Comparison of experimental shear capacities with corresponding predictions from the current Australian cold-formed steel design rules showed that the current design rules are very conservative for the shear design of rivet fastened RHFCBs. Significant improvements to web shear buckling occurred due to the presence of rectangular hollow flanges while considerable post-buckling strength was also observed. Such enhancements to the shear behaviour and capacity were achieved with a rivet spacing of 100 mm. Improved design rules were proposed for rivet fastened RHFCBs based on the current shear design equations in AISI S100 and the direct strength method. This paper presents the details of this experimental investigation and the results.

ABSTRACT: The concrete-encased column base investigated in this paper is composed of an inner base plate column base partially encased by an outer reinforced concrete (RC) component. The seismic behavior of the column base for hexagonal concrete-filled steel tube (CFST) along the strong axis is studied experimentally. Twelve composite specimens are tested under constant axial loading and cyclic lateral loading applied on the hexagonal CFST columns. The test parameters are the height of the outer RC component, with or without shear studs outside the tube and the axial load level on the hexagonal CFST column. Two typical failure modes are observed in the test, and the experimental results show that the concrete-encased column bases exhibit a high strength with good ductility and high energy dissipation capacity. The damage modes of the outer RC
component are investigated, and the load transfer mechanism of the concrete-encased column base is analyzed. The load versus displacement relation, strain development, lateral deflection distribution and bottom rotation are compared for specimens under different failure modes. Further analysis is conducted to investigate the effects of parameters on various seismic performance indexes, such as the elastic stiffness, the maximum strength, the ductility coefficient, the strength and stiffness degradation, and the equivalent viscous damping ratio. Finally, a simplified strength model of the concrete-encased column base for hexagonal CFST is also proposed.


ABSTRACT: This paper describes an investigation on the critical temperatures of slender cross-sections according to Eurocode 3 design. Slender cross-sections are prone to local buckling, which, as the name implies, is characterized by a local failure that occurs in the presence of compressive stresses and prevents the cross-sections from developing their full plastic bending resistance or axial compression resistance, which leads to the reduction of the load bearing capacity. Eurocode 3 classifies these cross-sections as Class 4, the highest class, and suggests a default critical temperature of 350 °C irrespective of the load level conditions. This study demonstrates that this temperature is too conservative especially if different degrees of utilization of the cross-section are taken into account. The establishment of a default critical temperature is invaluable from a practical standpoint and, therefore, it is the purpose of this work to recommend and validate new default critical temperatures for Class 4 cross-sections subject to compression and bending about the major axis for different reduction factors for the design load level under fire conditions, based on an extensive numerical investigation. From this study, it is observed that the critical temperatures for such cross-sections are within the range of 400 °C and 600 °C for the usual load levels and, based on that, new default critical temperatures are suggested.


ABSTRACT: Girders with corrugated steel web is likely used in bridges as well as in building structures due to its numerous favourable properties. It is known from previous investigations that due to the web corrugation the normal and shear stress distribution in the flange and web plates of the corrugated web girders are different from the stress distribution in the conventional I-girders. The shear force in the corrugated web plate results in an additional transverse bending moment in the flanges, which indicates additional normal stresses. Previous investigations analysed this modified normal stress field and calculation methods were proposed to determine the maximum normal stresses. But there is a lack of investigations analysing the effect of the additional normal stresses on the bending resistance of the corrugated web girders. Different proposals can be found in the international literature to take this effect in the in-plane-bending resistance into account. This paper focuses on the determination of the transverse bending moment and its effect on the load carrying capacity of girders with trapezoidally corrugated webs.

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ABSTRACT: This paper presents a numerical and experimental study of double angle members connected by batten plates under concentric and eccentric axial compression. The number of batten plates is varied to study the influence on the nominal axial strength. Numerical analyses are able to accurately predict the behavior and strength found in the experiments, except for long columns under eccentric axial compression where the composite section failed in major-axis flexural buckling. Two design hypotheses are compared to the results obtained: (i) non-composite action (no interaction between angles), with only local, flexural, and flexural-torsional buckling considered; and (ii) composite action (full interaction between angles), and the only considering local and minor-axis flexural buckling of the pair of angles. The two design hypotheses ignore load eccentricity. Numerical and experimental results for angles connected by bolted batten plates fall in between the design curves defined by methods (i) and (ii), while angles connected by welded batten plates have greater strength than the design curve defined by method (ii). The use of batten plates significantly increases the strength of the system, especially for members under eccentric compression. However, the strength remains constant after a certain number of batten plates are connected, and after a minimum batten plate width is reached.

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ABSTRACT: In the paper, an analytical and experimental study aimed at supporting new design criteria for the exploitation of steel circular hollow columns made of HSS and subjected to exceptional loads, like earthquakes is presented. In fact, there is an increasing interest in the use of hollow sections of High Strength Steels (HSS). The ambitious targets are to enhance the structural performance of concentrically braced steel frame buildings with tubular columns, and to reduce weight and, at the same time, construction costs. The paper initially describes an experimental study of the seismic behaviour of substructures representing a concentric braced frame of a prototype structure: a steel building with concentric bracings for offices, meetings or exhibitions. The prototype structure was designed in accordance with the capacity design criterion, i.e. by assuming that breaking of connections and buckling of beams and columns must be preceded by yielding of the diagonals in tension. The brace-beam-to-column joints represent the critical component. The objective of the test programme was to characterize the connection behaviour under monotonic, cyclic and random loads. In detail, five tests were carried out on specimens with standard braces and two tests on specimens with weakened braces. Experimental results are shown as force-interstorey drift ratio diagrams. Then, a numerical calibration of a model of these joints was successfully accomplished. After the calibration of the numerical models, in order to evaluate the global response under seismic loading, a numerical analysis of the reference building was
performed with the OpenSees programme. Both pushover and dynamic nonlinear time-history analyses were carried out. Experimental and numerical results show that performance-based design approaches can be reasonably extended to concentrically braced frames (CBFs) with high strength tubular steel columns.

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ABSTRACT: In recent years, steel-concrete composite shear walls have been widely used in enormous high-rise buildings. This paper demonstrates nonlinear numerical studies on composite steel-concrete shear walls affecting cyclic loading. Five types of three-dimensional finite element model is developed using ABAQUS emphasizing constitutive material modeling and element type to represent the real physical behavior of complex shear wall structures. Modeling details of structural components, contact conditions between steel and concrete, associated boundary conditions, and constitutive relationships for the cyclic loading are explained. Load versus displacement curves, peak load, and hysteretic characteristics are verified with experimental data. Present study investigates important parameters such as concrete failure, hysteresis response, out of plan displacement, frame drift, and dissipated energy. The findings revealed that steel frame with concrete, on one side of shear plate, had better dissipation energy function compared with other types. Comparing the results, it was clearly observed that the lateral stiffness of the system isn't affected by changing the distance between connectors and concrete cover thicknesses. Numerical results show that shear steel plate buckling was reduced by increasing concrete thickness, and energy dissipation increased by reducing connectors' distance.

Pengchen Li and Minger Wu (Department of Structural Engineering, Tongji University, 1239 Siping Road, Shanghai, 200092, China), “Parametric study of cable-stiffened single-layer cylindrical latticed shells with different supporting conditions”, Journal of Constructional Steel Research, Vol. 121, pp 457-467, June 2016 DOI: 10.1016/j.jcsr.2016.03.028
ABSTRACT: Numerical investigations to the stability behaviour of novel cable-stiffened single-layer cylindrical latticed shells with different supporting conditions are presented. It is shown that the governing imperfection distribution that should be adopted within finite element analysis to capture the actual load carrying capacity does not always follow the lowest buckling mode for the type of element and assumptions implemented in the current study, which distinguishes it from the existed specification. The principle to determine the governing imperfection distribution is proposed in this study, this is followed by parametric analysis which aims to investigate the stability behaviour of cable-stiffened single-layer cylindrical latticed shell systematically. The parametric analysis shows that the stability behaviour of ordinary cylindrical latticed shell can be considerably enhanced by the pre-tensioned cable-stiffened system. It should be stressed that the introduction of cable-stiffened system decreases the sensitivity of the stability behaviour of ordinary cylindrical latticed shell to joint types, this would enable engineers to adopt scissor-type joints to cylindrical latticed shells. The effects of other parameters on the stability behaviour of cable-stiffened single-layer cylindrical latticed are also presented in this current work.

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ABSTRACT: Most finite element models of actual projects developed using general finite element software are rigid or hinge connected. These models are inconsistent with the actual situations of most actual projects that are semirigid jointed. The double element method was adopted to estimate the influence of joint stiffness on the mechanical behavior of suspend-dome structures. First, the accuracy of this method was validated. This approach was adopted to analyze the influence of joint stiffness on the mechanical behavior of the overall structure. Buckling, modal, and dynamic response analyses were conducted. The effect of joint stiffness on the buckling capacity of suspend-dome and single-layer latticed shell was derived and compared. The influence of joint stiffness on the characteristics of natural vibration was also determined. Finally, seismic response analysis was conducted to estimate the influence of joint stiffness on structural dynamic response. Results indicate that rigid connected finite element models may be unreliable to calculate dynamic response during the design phase.

Xi Zhang, Kim J.R. Rasmussen and Hao Zhang (School of Civil Engineering, The University of Sydney, Australia), “Second-order effects in locally and/or distortionally buckled frames and design based on beam element analysis”, Journal of Constructional Steel Research, Vol. 122, pp 57-69, July 2016 DOI: 10.1016/j.jcsr.2016.01.022

ABSTRACT: In the design of steel portal frames, second order effects are usually accounted for by using a second order elastic analysis to calculate the deformations and internal actions of the frame. In this analysis, one-dimensional beam elements are employed irrespective of whether the cross-sections of members are slender or non-sleender. However, frames composed of members with slender cross-sections may buckle in local and/or distortional modes before reaching the ultimate limit state. In this case, the flexural rigidity of the frame is reduced when local/distortional buckling occurs, and as a result it undergoes larger sway deflections than had local/distortional buckling not occurred. The additional second order moments thus caused by local/distortional bucking are not accounted for in current design provisions. In this paper, the additional second-order effects caused by the development of local/distortional buckling are studied by comparing numerically determined ultimate capacities with design capacities. The numerical ultimate strengths are based on previously calibrated geometric and material nonlinear shell finite element models, and the design capacities are determined using the Australian Standard for Cold-formed Steel Structures AS/NZS 4600. A simplified approach to account for local/distortional buckling in beam-element-based design is also proposed. The focus is on portal frames subject to in-plane sway failure.


ABSTRACT: Applying optimisation techniques to the design of cold-formed steel (CFS) sections can lead to more economical and efficient design solutions. However, a crucial factor in such an optimisation is to arrive at a solution which is practical and fits within the constraints of the fabrication and construction industries.
Targeting this objective, a comprehensive investigation was conducted on the practical optimisation of CFS beams using a Particle Swarm Optimisation (PSO) method. Six different CFS channel section prototypes were selected and then optimised with respect to their flexural strength, determined according to the effective width based provisions of Eurocode 3 (EC3) part 1–3. Comparing the capacities of the optimised sections to those of the original channel sections with the same amount of structural material, significant improvements were obtained. The accuracy of the optimisation procedure was assessed using experimentally validated nonlinear Finite Element (FE) analyses accounting for the effect of imperfections. The results indicated that, using the same amount of material, the optimum sections offered up to 25% and 75% more flexural strength for laterally braced and unbraced CFS beams, respectively, while they also satisfied predefined manufacturing and design constraints. Therefore, the proposed optimisation methodology has the potential to prove useful in practical design applications.

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ABSTRACT: In the current work, a probabilistic assessment method of a steel framed building under abrupt removal of a column due to catastrophic events is developed. A multi-story steel framed model taking into account the influence of catenary effect has been analyzed. Uncertainties in the structural variables are incorporated in the probabilistic simulation approach. Based on the changes of component internal energy, the progressive collapse sensitivity to abrupt removal of a column has been investigated. Besides, a simplified beam damage model is proposed to analyze the energies absorbed and dissipated by structural beams under large deflections. In addition, the correlation incorporating catenary action between bending moment and axial force in a beam during the whole deformation development process is studied. With the methodologies adopted for progressive collapse assessment under removal of a column, a deterministic method has been developed, framed within the Advanced First Order Reliability Method (AFORM). A robustness index (RI) is proposed to evaluate the structural robustness performance based on the acceptable probability of global failure and structural collapse probability.

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ABSTRACT: Analytical and numerical investigations of the stability of prestressed stayed columns with three crossarms branching laterally and symmetrically are presented. It is shown that modal symmetry is broken automatically if the critical mode is antisymmetric, which distinguishes it from the stayed columns studied hitherto. The governing imperfection distribution that should be adopted within finite element analysis to capture the actual load-carrying capacity is also obtained. The findings suggest that when the critical buckling mode is symmetric, the governing imperfection distribution should also be symmetric. Conversely, if the critical buckling mode is antisymmetric, a symmetric imperfection distribution or an asymmetric imperfection distribution may be adopted as the most severe imperfection distribution depending on the system
characteristics. This would enable designers to determine an accurate prediction of the actual strength through nonlinear finite element analysis.

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ABSTRACT: In this study six Cold-Formed Steel shear wall (CFS) with one and two side steel sheeting are tested under reversed cyclic loading. Besides, thirteen numerical models are simulated, using nonlinear finite element method, and analyzed under monotonic pushover loading. The studied parameters are the comparison of one and two side steel sheeting, the nominal thickness of steel sheet and boundary elements, and height to width aspect ratios of the wall. The performance of tested specimens is investigated in terms of lateral load-story drift response, failure modes and ultimate strength of shear walls. Based on AISI S213 the available strength of two-sided steel-sheathed walls is cumulative but the results of the experimental study show that the capacity of two-sided steel-sheathed walls is more than twice of one side steel sheathed if the boundary elements are strong enough to sustain imposed forces. Overall, the performance of CFS shear walls is highly depending on the ratio of boundary element thickness to steel sheet thickness. According to numerical models, there is a linear relationship between the nominal sheet thickness and the ratio of ultimate strength to nominal frame thickness.

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ABSTRACT: Columns in real buildings are normally axially and rotationally restrained by adjacent members. This paper investigates the dynamic performance of axially and rotationally restrained steel columns under fire via parametric analysis. Investigated parameters include the axial restraint stiffness, rotational restraint stiffness, column slenderness and load ratio. An explicit dynamic solver is employed to analyse the considered columns up to total failure. The numerical model is validated through comparing the results against those of a plane steel frame model which has been verified by means of experimental and analytical work. The results of the column model match well with those of the whole model of steel frame. Results show that the behaviour of restrained steel columns under fire may be quasi-static up to total failure or be with severe dynamic effects during buckling, depending on the restraint condition, load ratio and column slenderness. It is found that static analysis may significantly underestimate the maximum displacement for the case of dynamic buckling of columns under fire, and the maximum displacement of that case may even be larger than the final displacement of gradually removing the heated column. Axial restraint stiffness, rotational restraint stiffness and load ratio have significant effects on both the critical temperature and the initiation of dynamic effects. In this regard, dynamic buckling tends to occur with small axial and rotational restraint stiffness and a large load ratio. However, the performance of columns is found to be relatively insensitive to rotational stiffness ratio beyond a specific threshold value.
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ABSTRACT: The paper presents an investigation on welded stainless steel I-section columns. In total, 22 experiments on welded I-section columns, including members buckling about major and minor axis, for both austenitic and duplex stainless steel columns were carried out. Specimen cross-sections and lengths were carefully selected to cover a wide range of geometries and non-dimensional slenderness. Measurements were taken on geometry, global initial geometric imperfection, residual stresses and material properties. The experimental results have been supplemented by the finite element simulation. The resulting structural performance data have been used to assess the applicability of the current design provisions from EN 1993-1-4, ASCE 8-02 and AS/NZS 4673 for the design of stainless steel welded-I sections. Results showed that the design provisions from EN 1993-1-4 and AS/NZS 4673 can be conservatively adopted while the ASCE 8-02 provision shows scattered predictions.

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ABSTRACT: In this study, the slenderness limits for flanges and webs were examined to rationally evaluate the flange local buckling (FLB) strength of longitudinally stiffened I-girders. It is known that the bending resistance of a plate girder greatly increases when the web is longitudinally stiffened. This additional strength can be attributed to the fact that the stiffened web provides improved restraint to the rotation of the compression flanges as well as web bend-buckling strength. This study conducted a series of numerical analyses and it was found that the American Association of State Highway and Transportation Officials’ (AASHTO’s) load and resistance factor design (LRFD) requirements provide highly conservative estimates of the FLB strength of longitudinally stiffened plate girders, especially in noncompact sections. The reason is that the buckling coefficient and corresponding slenderness limit for a noncompact flange is determined based on the bending resistance of an unstiffened girder. Therefore, this study conducted a series of eigenvalue analyses in which the slenderness ratios of flanges and webs were considered. As a result, a buckling coefficient equation that reasonably reflects the interaction of the stiffened web and flange was derived. Based on the results of the analyses, this study proposed modified slenderness limits for the noncompact web and noncompact flange of a stiffened girder. It was verified that the bending resistance of longitudinally stiffened girders could be rationally estimated on the basis of the AASHTO LRFD specifications only by replacing the slenderness limits with the proposed formulas.
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ABSTRACT: Prediction of the column strength, associated with buckling and material yielding, is vital in a successful design. In this paper, a completely numerical analysis technique is employed for simulating the compressive behavior of Q690 high-strength steel columns with box- and H-sections, and its accuracy is verified by the experimental results as presented in the part 1 of the companion papers. To this, the curved Pointwise-Equilibrating-Polynomial (PEP) is introduced for representing the column deformations with an explicit simulation on the member initial imperfection. Further, the refined plastic hinge model combined with the use of sectional yield surfaces is employed to reflect inelastic yielding at the critical location. A cross-sectional analysis approach allowing for residual stresses modeling is also incorporated into the numerical method. Sequentially, a parametric study is conducted extensively for the Q690 high-strength steel welded columns. At last, the buckling curves from Chinese (GB 50017-2003), European (Eurocode 3), and American (ANSI/AISC 360-10) codes are examined, and some recommendations for design of Q690 high-strength steel columns are presented.


ABSTRACT: Progressive collapse analysis is used to evaluate robustness of buildings against unexpected extreme events and is a highly nonlinear dynamic problem. Motivated by the need for realistic and yet reasonably fast analysis, a “middle-way” approach for efficient progressive collapse analysis (ePCA) is explained in this paper, accounting for column buckling, semi-rigid connection and membrane action of slab. The accuracy of ePCA is validated by comparing with experimental results available in the literature. Application of ePCA on realistic building systems shows that robustness can be improved cost-effectively by introducing minor changes to the steel connection and slab reinforcement. The computational efficiency of this method enables incorporation of robustness design in building system in the early stage of design process. It can also be useful for researchers to more efficiently evaluate the behavior of different structural systems.

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ABSTRACT: The behaviour of laterally restrained steel beam-columns with slender cross-sections (Class 4) where local buckling occurs under fire situation is numerically investigated. Although recommendations are given in Eurocode to address the local buckling for the case of fire, few studies address its influence at elevated
temperatures, and more particularly its influence on the load bearing capacity of laterally restrained beam-columns, which represents an unknown safety level for the Eurocode procedures. As a primary objective of this study, the level of accuracy and safety of simplified methods of Eurocode 3 is studied based on extensive numerical investigation of several member lengths, different bending moment distributions and load ratios for various cross-sections and considering different heating temperatures. Local and global geometrical imperfections as well as residual stresses have been included in the numerical simulations. It is concluded that the Eurocode procedures lack consistency and the capacity of laterally restrained beams-columns is overestimated in many cases due to local buckling. Therefore, modifications to the current design methodology are proposed in this study leading to better estimation of the overall capacity of the laterally restrained beam-columns in case of fire, and finally, improved safety and consistency is achieved.


ABSTRACT: The paper presents an experimental investigation into the structural performance of cold-formed steel pitched portal frames subject to local and distortional buckling prior to global sway failure. The columns and rafters were constructed from back-to-back lipped channel sections, and the apex and eave joints comprised brackets bolted to both the webs and flanges of the channel sections. Three frames were tested, subjected to different combinations of horizontal and vertical loads. In all tests, lateral and torsional restraints effectively constrained the frames to deform in their own plane. Local buckling developed at a relatively early stage of loading while distortional buckling occurred when the loads were near ultimate. The occurrence of local and distortional buckling reduced the horizontal stiffness and ultimate load significantly. Failure occurred when a spatial plastic hinge formed at the top of the columns in the vicinity of the eave joints. Component tests, including tests on tension coupons and apex and eave joints, were also conducted to obtain the material and connection properties of the frames. A critical appraisal is made of the accuracy of existing design guidelines to predict the ultimate strength of the frames tested experimentally, including the interactive effect of local, distortional and overall sway buckling.

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ABSTRACT: In recent years, there has been a growing interest towards the use of corrugated infill plates as an alternative to flat infill plates in steel plate shear wall (SPSW) systems. Corrugated plates offer various advantages over flat plates including higher energy dissipation capacity, ductility, out-of-plane stiffness, and improved buckling stability. On the other hand, perforation of the web-plate can allow the utility passage through SPSW and also can alleviate the problem of large panel force over-strength due to larger web-plate thickness. Considering the structural and architectural features of corrugated- and perforated-web SPSWs
further research is required in order to obtain a better understanding of the structural and seismic performances of such efficient lateral force-resisting systems. On this basis, this paper investigates the cyclic behavior and energy absorption capabilities of SPSWs with trapezoidally-corrugated and centrally-perforated infill plates. To this end, numerous finite element models with various geometrical properties are developed and analyzed under cyclic loading. Results and findings of this study are indicative of effectiveness of the web-plate thickness, corrugation angle, and opening size on the hysteretic performance of corrugated- and perforated-web steel shear wall systems. Optimal and proper selection of the aforementioned geometrical parameters can result in SPSW systems with desirable structural behavior and seismic performance.

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ABSTRACT: With the increasing application of high-strength steel over the past years, the urgent problem is to determine buckling curves in current codes for design of axial compression columns fabricated by high-strength steel. The current design curves cannot cover the high-strength steel columns due to that the available curves were based on research of mild carbon steels. To study the overall buckling behavior of high-strength steel columns, an experimental investigation on the ultimate bearing capacity of weld box and H columns with a nominal yield stress of 690 MPa subjected to axial compression was carried out. Twelve columns with slenderness ratios ranging from 30 to 70 were comprised in the experiment. The geometrical dimensions and initial geometrical imperfection involving initial deflection and loading eccentricity were measured. The buckling deformation and bearing capacity of the columns were studied on the basis of the test results. By comparing the experimental results with the buckling curves stipulated in GB50017-2003, Eurocode 3, and ANSI/AISC 360-10, it is found that the current design curves underestimate the ultimate strength of the axially loaded box and H columns welded by 690 MPa high-strength steel plates. The curves “a” in the corresponding codes such as GB50017-2003 and Eurocode 3 are found to be suitable for the welded 690 MPa high-strength steel box- and H-columns buckling about minor axis. The test results are intended to assess the accuracy of the numerical method presented in Part 2 of the paper.

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ABSTRACT: Lattice transmission towers are critical components of power infrastructures. Collapse of a transmission tower may cause major economic and social impacts. The present study aims to evaluate the progressive collapse vulnerability of a lattice tower in a 400 kV power transmission line. The load increase factors (IF) after an instantaneous element removal are determined for application in static analyses and for design purpose. The capacity-to-demand ratios (C/D) are proposed to identify critical members after different removal scenarios. This proposed parameter is examined by comparison with Overload Factor (OF) from pushdown analysis. In addition, the pushdown analysis is used to determine the remaining capacity of the
structure after removing an element. It is found that tower may resist progressive collapse because of the possible alternative load paths. It is also observed that the studied structure has less susceptibility to progressive collapse in scenarios of element removal at higher elevations.

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ABSTRACT: The paper presents the main results obtained downstream experimental and numerical study on steel perforated shear panels. Primarily, the response of the studied devices determined by cyclic tests is analysed. It is evidenced that the hysteretic performance of steel perforated shear panels might be detrimentally influenced by pinching effects and softening due to cumulated damage produced by lateral-torsion buckling that may arises when the plate portions delimited by contiguous perforations are excessively slender. Based on tests results, a suitable analytical formulation for the prediction of the strength at several shear demands, accounting for the influence of the above detrimental effects, is provided. Also, a parametric study based on a FEM numerical model calibrated on the basis of the experimental tests is developed. Two main goals are achieved: i) to establish the influence of the main geometric parameters on the panel hysteretic response, with particular regard to the pinching effects provoked by buckling phenomena; ii) to determine analytical formulations able to give back the ratio between the “pinching” strength and the maximum strength, the former being the force corresponding to a null shear strain in a cycle. Therefore a useful predictive tool for defining the optimal perforation geometry to be adopted as a function of the expected shear demand is provided.


ABSTRACT: Various advantages of hysteretic energy dissipating devices (HEDDs) have been recognized and their applications are getting popular. In parallel with this, current seismic codes prescrie a design procedure for structures employing HEDDs. According to one of seismic codes, ASCE/SEI 7, the minimum seismic base shear resisted by its seismic force-resisting systems (SFRSs) shall not be < 75% of the total seismic base shear which is carried by a structure. This minimum base shear requirement for SFRSs is implicitly intended to provide safety in the event of malfunction of HEDDs. Although there are rigorous requirements for damped structures, further studies are still required to investigation of the collapse capacities of damped structures which have increasingly paid attention to earthquake engineering communities. In order to address this, this study carried out incremental dynamic analyses to evaluate the collapse performance of the 3- and 6-story prototype steel special moment-resisting frames (SMRFs) with and without HEDDs of which the strength capacities are different. The analysis results show that the collapse margin ratios of the prototype frames depend on the amount of base shear carried by their HEDDs and uncertainties on design requirements. The prototype structures with larger seismic base shear carried by HEDDs result in small variation in collapse capacity distribution and satisfy the minimum collapse margin ratio regardless of uncertainties on design requirements.
DOI: 10.1016/j.jcsr.2016.04.028
ABSTRACT: It is common practice in the steel construction industry to restrain members that largely in flexure and torsion using a combination of angle cleats, connected at the top flange, and fly-bracings. This system is complicated and expensive, especially when used to restrain channels in bending. This paper investigates experimentally the use of angle cleats, connected to the webs of both the purlin and the channels, as a restraining system. Pairs of channels were subjected to a two point loading system in order to simulate a distributed load. Variable in the tests include the unbraced length between the two-point loads and the size of the channels. Failure of the channels occurred by lateral torsional buckling and catastrophic distortional buckling of the intermediate unbraced length. Tests showed that the purlin-cleat restraining system is able to resist lateral torsional buckling of the channels, and that this system can be used without any fly bracing. Distortional buckling was the final failure mode, and it occurred at moments less than the predicted lateral torsional buckling moment of resistance. Distortional buckling is more critical in frames with shorter unbraced lengths and thicker channels.

Wu Xu, Lin-Hai Han and Wei Li (Department of Civil Engineering, Tsinghua University, Beijing, 100084, China), “Performance of hexagonal CFST members under axial compression and bending”, Journal of Constructional Steel Research, Vol. 123, pp 162-175, August 2016
DOI: 10.1016/j.jcsr.2016.04.026
ABSTRACT: The compressive and flexural behavior of the hexagonal concrete-filled steel tubular (CFST) members is investigated in this study. Tests are carried out on the specimens under axial compression and bending. The parameter of the experimental work is the steel ratio of the cross section, and the hollow tubular members are designed for comparison. The failure modes, load versus deformation relations and strain developments are studied. A finite element analysis (FEA) model is established and verified with the test results. The FEA model is then used to conduct the full range analysis on the load versus deformation relation, internal force distribution and stress development. The parametric study on the compressive and flexural behavior is conducted to investigate the effects of various parameters, e.g. the steel ratio, the steel yield strength and the concrete strength. Simplified models are proposed to calculate the ultimate compressive and flexural strength. It is found that the ultimate compressive strength of hexagonal CFST stub columns could be calculated accurately referring to the equations of rectangular CFST columns in DBJ/T13-51-2010 and EC4, and the plastic stress distribution method and the fiber model method achieve good predictions of the ultimate flexural strength of the hexagonal CFST beams.

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DOI: 10.1016/j.jcsr.2016.05.003
ABSTRACT: A novel buckling-restrained brace comprising three circular steel tubes with different diameters is proposed. The three tubes overlap, and the inner and outer tubes restrain the out-of-plane deformation of the middle tube. Slotted holes are arranged on the middle tube. This BRB has a much larger energy dissipation area
and can be conveniently fabricated. The size and number of slotted holes on the middle tube were adopted as test parameters. Five different specimens were tested by using quasi-static cyclic loading schemes to investigate the strength, deformation capacity, hysteretic behavior and failure mode of the new buckling-restrained brace. Nonlinear finite element analyses using ABAQUS were carried out in detail to explain the load-deflection hysteresis curves and modes of failure obtained in all five experiments. According to the tests and finite element analyses results, the structure of the novel buckling-restrained brace is reasonable and effective. When the opening-hole ratio is 0.2 and 2 × 2 slotted holes are arranged on the middle tube, the buckling-restrained brace exhibits excellent performance in terms of its deformation capacity and low-cycle fatigue behavior. The hysteresis curves of the braces are stable and saturated, and correspond to an equivalent ratio of critical viscous damping of 0.40 at the loading amplitude of 1/100L.

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ABSTRACT: Concrete-filled steel tubular (CFT) columns are widely used as columns in many structural systems and a common failure mode of such tubular columns is inelastic outward local buckling near a column end. The use of fibre-reinforced polymer (FRP) jackets/wraps for the suppression of such local buckling has recently been proposed and has been proven to possess excellent potential in both retrofit/strengthening and new construction. This paper presents the results of an experimental study into the behaviour of large-scale FRP-confined CFT (CCFT) columns under combined axial compression and lateral loading. The test parameters included the stiffness of the FRP jacket and the loading scenario. The test results showed that the FRP jacket can effectively delay or even prevent outward local buckling at the end of a cantilevered CFT column, leading to significantly improved structural performance under combined constant axial compression and cyclic lateral loading. Compared to monotonic lateral loading, cyclic lateral loading was found to introduce more severe localized deformation near the column end and may lead to earlier FRP rupture within that region.

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ABSTRACT: Local and distortional buckling reduces the flexural and warping rigidities of steel frames. As a result, the sway buckling load of locally unstable unbraced frames is reduced and sway deflections increase at a faster rate than corresponding locally stable unbraced frames. This leads to greater second order moments and potentially premature collapse, since commonly, unbraced steel frames are designed using elastic analyses (2nd order or 1st order with moment amplification) which assume unreduced values of the flexural and warping rigidities. This paper investigates the effects of second order moments induced by local and/or distortional buckling of the uprights of steel storage rack frames. Using results from the accompanying experimental investigation, calibrated FE models are used to predict the strength of steel storage rack frames with increasingly slender cross-sections. The FE strengths are compared to design strength predictions and
conclusions are drawn about the extent to which current specifications are able to accommodate second order moments generated by local and/or distortional buckling.


ABSTRACT: This paper presents an experimental investigation into locally unstable ultra-light-gauge steel storage rack frames that are prone to flexural-torsional buckling. The aim of the research was to understand how local instabilities and interactive buckling affect the strength of ultra-light gauge frames and to create reliable data through a controlled experimental investigation. A total of twelve full scale tests were conducted in the Civil Engineering Structures Laboratory at the University of Sydney. Prior to testing, the geometric imperfections of each member were measured, as were the material properties of the cold-rolled sections and the virgin steel from which the sections were formed. The cross-sectional deformations, ultimate loads and observations regarding failure modes were accurately captured and documented. The tests were also successful in capturing the post-ultimate response of the frames as well as the rotational stiffness of the beam-to-upright connections. Results from nominally identical tests were in good agreement. The tests provide comprehensive data for assessing the effects of interactive buckling and the extent to which cross-sectional deformations amplify the second-order deformations in locally unstable storage rack frames.


ABSTRACT: Cellular and castellated members are usually produced by performing cutting and rewelding operations on a hot-rolled I-section member. As illustrated in previous work, these operations will influence the residual stresses present in the members in a manner which is detrimental for the flexural buckling resistance. Up to now, this has not been considered in the limited amount of literature concerning the flexural buckling resistance of these members. In this paper, the weak-axis flexural buckling resistance is examined, taking into account the influence of the modified residual stress pattern and the modified geometry of cellular and castellated members. Therefore, the critical buckling load and the buckling resistance of simply supported cellular and castellated members were investigated numerically. In the numerical model, a modified residual stress pattern was introduced, based on earlier measurements. As the amount of measurements was relatively limited, the results of these simulations should be considered as preliminary results, in attendance of a confirmation of the utilized residual stress pattern. The results of the simulations illustrate the detrimental influence of the expected residual stress pattern modification on the buckling resistance. By comparing the results with the European buckling curves, preliminary best fit curves could be selected. This comparison was executed with a 2T approach, in which all cross-sectional properties are calculated for the 2T section at the centre of the opening.

ABSTRACT: High-strength steel (HSS) is gaining widespread acceptance in contemporary engineering structures, with grades of up to 690 MPa being included in many design standards. However, although strength grades well in excess of 690 MPa are possible with modern metallurgical processes, these are not compliant with most design codes of practice. HSS is advantageous when strength, rather than stiffness, predominates the structural response. When this is the case, HSS is very useful in reducing the self-weight of the structure, as many be needed in structural modification, or in contriving a design that minimises the carbon footprint of the structure. Research on the flexural-torsional buckling of steel structures is extremely abundant in the literature, and guidance in codes is very comprehensive. It is known that the resistance to flexural-torsional buckling depends on the interaction of (i) elastic buckling; (ii) yielding and post-yielding and (iii) residual stresses. Current design curves are based on the elastic buckling resistance, which is modified to account for the yield and post-yield response of structural steel and the residual stresses in the cross-section. However, HSS with yield stresses exceeding 690 MPa have somewhat different yield and post-yield characteristics and significantly different patterns of residual stresses when compared with structural steel. This paper uses ABAQUS software to investigate the flexural-torsional buckling strength of HSS I-section beams, by incorporating the stress-strain curves and residual stresses measured experimentally and reported in the literature. With a similar methodology to structural steel members, the interaction of elastic buckling at the member level with the material characteristics at the cross-sectional level is investigated and a strength design formulation is proposed.

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ABSTRACT: This paper investigates the structural behaviour of Steel-Concrete-Steel (SCS) sandwich wall which consists of two external steel plates infilled with ultra-lightweight cementitious composite material. A series of compression tests consists of a wide range of parameters have been carried out on the SCS sandwich walls of different heights forming short and slender wall. The test results show that the SCS sandwich walls with J-hook connectors exhibit comparable behaviour in compressive resistance and post-peak unloading behaviour to the ones with the overlapped headed studs. The interlocking J-hook connectors play an important role in providing composite action between the steel plates and the cementitious core, and preventing or delaying the local buckling of the external steel plates. The test results are compared against the predictions by Eurocode 4 and AISC 360 methods for composite columns. It is found that the Eurocode 4 and AISC 360 methods could over-predict the compressive resistance of sandwich wall subjected to compression. A modified method is then proposed, which takes into account the effect of interlocking J-hook connectors in providing lateral restraints to the external steel plates. The predictions show a reasonable correlation with the test results. Nonlinear finite element model has been established to predict the load-displacement curves, maximum resistance and failure modes of the sandwich walls. Both the experimental and finite element results confirm that the proposed analytical formulae are conservative for design of SCS sandwich composite walls with J-hook connectors.

Mohamed Elchalakani (The School of Civil, Environmental and Mining Engineering at the Faculty of engineering, computing and mathematics, the University of Western Australia, Australia), “Rehabilitation of

ABSTRACT: This paper presents experimental results for a series of rehabilitated corroded steel Circular hollow Sections (CHS) under quasi-static large deformation 3-point bending and direct indentation using Carbon Fibre Reinforced Polymers (CFRP). The main parameters examined were the amount of corrosion penetration in the wall thickness, its extent along the pipe, the type and number of the CFRP sheets. The corrosion in the wall thickness was artificially induced 360° around the circumference by machining. Four different severity of corrosion were examined of 20%, 40%, 60%, and 80%. The testing program included the rehabilitation of 12 artificially degraded CHS with limited corrosion repaired using externally wrapped CFRP sheets. The extent of corrosion along the pipeline was in the range of $L_c / D_n = 1.0$ to $3.0$, where $L_c$ is the length of corrosion and $D_n$ is the nominal diameter of the CHS. The external diameter-to-thickness ratio examined in this paper was in the range of $D_0 / t_s = 20.3$ to $93.6$. The CFRP sheets were wrapped around the section in the longitudinal and transverse direction with a sufficient overlap. The percent increase in strength was mostly affected by the corrosion level where the maximum gain was 282% obtained for the most severe 80% corrosion. The average increase in the load carrying capacity was 97%. Two new lower bound design equations based on the bare and composite section properties were developed to predict the strength of the bare and repaired CHS using CFRP under combined bending and bearing.

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ABSTRACT: An equivalent brace model is developed to evaluate the nonlinear behavior of a novel partially connected buckling-restrained steel plate shear wall (BRSPSW) subjected to seismic loading. The high-order buckling modes of the equivalent brace under compression are taken into account meanwhile a hysteresis model is proposed to describe the stress–strain relationship of the equivalent brace. A nonlinear finite element (FE) method is employed to establish the validity of the partially connected BRSPSWs with the equivalent braces under monotonic, cyclic and seismic loads. A comparison with the FE results shows that the equivalent brace model with the proposed hysteresis properties can reasonably predict the shear resistance, hysteretic and seismic behaviors of the novel partially connected BRSPSWs. The effect of initial imperfection on the buckling responses of the restrained steel plate is also investigated. Nonlinear push-over analyses show that the increase of the initial imperfection essentially triggers the buckling mode of the restrained steel plate from high order to low order.

Xiaoyi Lan, Fan Wang, Chen Ning, Xiaofeng Xu, Xiaorong Pan and Xhifeng Luo (State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China), “Strength of internally ring-stiffened tubular DT-joints subjected to brace axial loading”, Journal of Constructional Steel Research, Vol. 125, pp 88-94, October 2016, DOI: 10.1016/j.jcsr.2016.06.012
ABSTRACT: This paper presents the results of numerical and theoretical studies to obtain static strength equations for internally ring-stiffened circular hollow section (CHS) tubular DT-joints. An extensive study of 1264 unstiffened and ring-stiffened DT-joints subjected to brace axial compression or tension was conducted. The numerical analysis shows that failure mechanism of crown- and saddle-stiffened DT-joints under brace axial loading is formation of plastic hinges in the stiffener and chord wall yielding near the brace-chord intersection. Based on the identified failure mechanism, theoretical models and corresponding equations for predicting the stiffener strength in crown- and saddle-stiffened DT-joints subjected to brace axial compression or tension were proposed. The accuracy of the proposed stiffener strength equations was evaluated by an error analysis. A chord stress function was proposed to consider chord axial stress effect on the stiffened DT-joint strength. In conjunction with existing unstiffened DT-joint strength formulae and considering chord axial stress effect, a strength equation for crown- and saddle-stiffened DT-joints subjected to brace axial loading was proposed.


ABSTRACT: This paper presents the derivation of a new design formulation for the representation of the buckling strength of steel beam-columns, which follows the format and basic principles of novel and increasingly popular international design methods, such as the Direct Strength Method DSM (Schafer, 2008)–used predominantly in North America for the design of cold-formed steel members – and the General Method GM – included in the Eurocode EN 1993-1-1 (EN 1993-1-1, 2005) section 6.3.4 as an alternative way of designing generic steel members and structural systems. The paper focuses on the in-plane buckling strength of double-symmetric hot-rolled, tubular and welded sections, with compact sections; this focus on an otherwise well-understood problem allows for a clearer focus on the key aspects which need to be accounted for in a DSM/GM type representation of beam-column strength. In particular, a generalized definition of slenderness (in line with the DSM philosophy) and a generalized imperfection term, which accounts for the ratio between bending and compression loading, ii. the effect of non-uniform bending moment diagrams, iii. the deterioration of the achievable plastic cross-sectional utilization due to loss of rigidity by yielding in slender members and iv. the interaction between buckling modes, in this case local and global buckling. The paper proposes a coherent, innovative design formulation which accounts for all of these effects and compares the outcome of the new strength predictions with numerical (non-linear FEM) and traditional Eurocode results.

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“Cyclic tests of all-steel web-restrained buckling-restrained brace subassemblages”, Journal of Constructional Steel Research, Vol. 125, pp 164-172, October 2016, DOI: 10.1016/j.jcsr.2016.06.007
ABSTRACT: In this study, cyclic tests of a buckling-restrained brace (BRB) subassemblage with an all-steel web-restrained brace (WRB) were conducted to investigate hysteretic behavior under combined axial and rotational demands. Four full-scale WRB frame subassemblages were subjected to the quasi-static displacement protocol used for BRB qualification described in the AISC 341–10 Seismic Provisions for Steel Buildings. Three different sizes of steel core plates were examined. One specimen used a nominal 7.9-mm thick by 152-mm wide plate, two WRB specimens used a nominal 12.7-mm thick by 152-mm wide plate, and one specimen used a nominal 12.7-mm thick by 229-mm wide plate. All specimens successfully completed the cyclic testing up to 2% story drift without experiencing brace instability, brace end connection failure, or rupture. Specimens with a 12.7-mm thick core plate survived additional cycles at 1.5% story drift before rupture. The test results also showed that the maximum compression forces were less than 1.3 times the maximum tension forces for each cycle corresponding to a deformation greater than the yield displacement, demonstrating that compression overstrength of the WRB was comparable with typical BRBs.

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ABSTRACT: This paper presents a numerical study on the inelastic local web buckling behaviour of top flange coped beams with welded end connections. The modelling strategy based on the finite element (FE) method was validated and calibrated using the test results obtained in previous experimental work. Subsequently, a comprehensive parametric study using the validated FE model was carried out to carefully examine the effects of various parameters on the inelastic buckling strength and behaviour of practical coped beams with a welded end plate connection. Evident inelastic buckling behaviour was observed in most of the FE models, except for those with web slenderness \(\frac{d}{t}\) equal to 56.3 and cope length to reduced beam depth ratio \(\frac{c}{h_0}\) equal to 1.0. The influence of initial geometric imperfection on the buckling strength and response was also investigated in detail. Based on the parametric study results, a design approach according to the ‘plate shear buckling model’ was proposed to evaluate the inelastic buckling strength of coped beams. It was shown that the proposed approach provided better predictions of the FE results when compared with those of the current design strategy.

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ABSTRACT: The most common wind tower structure, a tapered tubular steel monopole, is currently limited to heights of ~ 80 m due to transportation constraints which arise because tower sections are manufactured at centralized plants and transported to site for assembly. The need to transport the sections imposes a limit on their size, whereby maximum tower diameters are dictated by bridge clearances rather than by structural
efficiency. New manufacturing innovations, based on automated spiral welding, may enable on-site production of wind towers, thereby precluding transportation limits and permitting the manufacture of taller towers, which can harvest the steadier, stronger winds at higher elevations. Taller towers, however, are expected to have cross-sections with slenderness that is uncommon in structural engineering (i.e., diameter-to-thickness ratios up to ~500) and much larger than those of conventionally manufactured towers (i.e., diameter-to-thickness ratios up to ~300). Tubular structures with highly slender cross-sections are imperfection-sensitive, and the welding process is known to influence imperfections. To account for this sensitivity, slender tubes are usually designed based on empirical knockdown factors, however there are few experiments of tubes in flexure with slenderness as high as what is expected for spirally welded wind towers, and there are no experiments on tubes within this slenderness range and manufactured with spiral welding. This paper reviews the state-of-the-art for designing spirally welded tubes as wind towers and identifies deficiencies. Relevant experimental and analytical research is summarized and research needs to efficiently design tapered spirally welded steel tubes as wind towers are identified.

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ABSTRACT: This paper is the second part of the study on the cold-formed high strength steel circular and polygonal sections intended to be used in tubular wind towers. Results from 32 numerical finite element analysis (FEA) models were compared with and calibrated against results of the tests on 32 corresponding specimens. The FEA results agreed well with the experimental results in terms of resistances and load-displacement curves. Further investigations on the numerical models were performed. Yield stress used in the FEA significantly affected the resistances of the numerical models. Using 0.2% proof stress led to higher resistance than the experimental results. Corners significantly influenced buckling behaviour in the polygonal section models. Analyses of an oval opening in the tubular specimens showed that peak stresses around the opening were considerably higher in the polygonal section models than in the circular section models. Finally, investigation of sensitivity to geometrical imperfections indicated that failure modes of numerical models with geometrical imperfections according to EC3 significantly differed from those of tested specimens and numerical models with geometrical imperfections obtained from the 3D scans.

ABSTRACT: This paper describes a study that led to the development of an FE model for the advanced analysis of storage rack frames. The FE model is shell element-based and incorporates geometric imperfections and the semi-rigid behaviour of the pallet beam-to-upright connections. The procedure to model geometric imperfections shifts the nodes of the model according to the superimposed shapes of pure buckling modes and covers frame, member and sectional type of imperfections. The semi-rigid behaviour of connections is implemented in the model by a point-based moment-rotation relation at the intersections between members. Furthermore, the study discusses the appropriate moment-rotation curve from the available component tests to
add to the model. The strength and deflection results of failure analysis are then validated against the results of four full-scale tests and the statistics of model uncertainty are obtained. Finally, strength predictions are obtained for two illustrative storage rack frames.


ABSTRACT: Steel Plate Shear Walls (SPSWs) are innovative systems able to confer to either new or existing structures a significant capacity to resist earthquake and wind loads. Many tests have shown that these devices may exhibit high strength, initial stiffness and ductility, as well as an excellent ability to dissipate energy. When full SPSWs are used as bracing devices of buildings, they may induce excessive stresses in the surrounding main structure where they are inserted, so to require the adoption of large cross-section profiles. For this reason, perforated steel panels, which are weakened by holes aiming at limiting the actions transmitted to the surrounding frame members, represent a valid alternative to full panels. In this work, aiming at showing the advantages of such devices, a FEM model of perforated panels has been calibrated on the basis of recent experimental tests. Subsequently, a parametric FEM analysis on different series of perforated panels, by changing the number and diameter of the holes, the plate thickness and the metal material, has been carried out. Finally, the achieved numerical results have been used to set up an analytical tool to correctly estimate the strength and stiffness of perforated metal shear panels.


ABSTRACT: Large deflection behaviors of restrained corrugated web steel beams (CWSBs) with both non-uniform temperature distribution (NUTD) and uniform temperature distribution (UTD) across the section in a fire were investigated using finite element model (FEM). The corrugated web adopted a commonly used trapezoidal shape. The applicability of FEM was validated against available test results on restrained flat web steel beams (FWSB) in a fire. Studied parameters included load ratio, axial restraint stiffness ratio, span–depth ratio, thickness of the flange and web and the incline angle of trapezoidal shape. Evolution curves of the vertical deflection, the axial force, the catenary action moment and the axial force provided by the corrugated web of restraint CWSB were presented. Due to the reduced axial stiffness of a CWSB, the axial compressive force in a restrained CWSB was much smaller than that in a FWSB. The vertical deflection of a CWSB with NUTD was larger than that with UTD at first for the bowing caused by temperature gradient across section. And it was smaller in catenary action stage, for the top flange of CWSB with NUTD having much greater yield strength and Young's modulus. At the catenary action stage, the axial tension in the top flange of the restrained CWSB with NUTD was higher than that in the bottom flange, which could cause a negative internal bending moment. Catenary temperature of a restrained CWSB with NUTD was a little higher than that with UTD. But failure temperature of a restrained CWSB with NUTD was much lower than that with UTD. For the negligible axial stiffness in corrugated web, variations of web corrugation parameters have little influence on large deflection behaviors of restrained CWSBs with NUTD and UTD. Through including the catenary action of a restrained CWSB in a fire, the critical temperature was increased from the catenary temperature to the failure temperature.
And the increase of critical temperature was at least 200 °C, which could greatly reduce the fire protection cost a CWSB.

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ABSTRACT: This paper presents the design and experimental investigation of a miniature buckling-restrained brace (MBRB) which can act as a hysteretic damper to dissipate energy when subjected to inelastic axial deformations. The MBRB is similar to a buckling restrained brace (BRB) with a yielding steel core plate restrained from buckling by a grouted restraining tube. The MBRBs, however, are designed to have shorter lengths, smaller steel core dimensions, and smaller yield capacity as compared to a typical BRB. As a result, careful consideration is required for the detailing at the ends and the stability of the MBRB. Small capacity BRBs can be useful in a range of applications as a primary energy dissipating structural fuse or supplementary axial hysteretic damper in seismic force resisting systems. The design, construction, and testing of six MBRB specimens with nominal axial yield forces between 30 kN and 95 kN are reported. Issues related to global stability of the MBRBs are discussed and a stability criterion to prevent global buckling was adopted to design the MBRB end connection pieces. The MBRBs exhibited cumulative plastic deformations between 181 and 400 times the yield deformation and cumulative plastic strain between 46% and 106%. Conclusions about the behavior and recommendations for the design of the MBRB are presented.


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ABSTRACT: This study develops two (2) simple but effective techniques for enhancing buckling resistance of welded steel moment connections (WSMCs). The ANSI/AISC 358-10 prequalified connections satisfy the 4% interstory drift requirement, however experimental studies have shown that their strength degradation may initiate as early as 3% drift. This strength degradation has been observed to be initiated by buckling of the beam web which is followed by buckling of the beam flange and twisting of the beam. Consequently, buildings with the prequalified connections may sustain significant buckling damages under severe earthquakes and it is questionable as to whether these connections are capable of resisting gravity loads or lateral loads from strong aftershocks following a severe earthquake. To improve upon these shortcomings, two (2) performance enhancing techniques are proposed and investigated through finite element analysis (FEA). The more promising of the two involves reinforcing the beam web in the expected plastic hinge with a web reinforcement plate. Finite element analysis demonstrated that this reinforcement enhances the beam buckling resistance of WSMCs and thereby significantly reduces the beam buckling damages even at 5% interstory drift. The potential of this technique is analytically and experimentally demonstrated for the recently developed heat-treated beam section (HBS) WSMC. Test results confirm that the web reinforcement plate was effective in reducing local buckling damage and associated strength degradation, thereby improving the performance of HBS WSMCs. Areas for application and future development of the proposed techniques are identified.

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ABSTRACT: Buckling capacity of axially loaded steel columns with hot-rolled I-sections, circular and rectangular hollow sections in fire is studied. The current Eurocode method for checking the stability at elevated temperatures has been derived on the same basis as in ambient conditions. Due to significant nonlinearities in the behaviour in fire the standard method appears to be not fully appropriate in certain ranges of parameters. In the present work the behaviour of columns is studied by comprehensive numerical simulation at a wide range of temperatures and slenderness values. Based on the results two alternative analytical procedures have been proposed and validated for evaluation of buckling strength. One of them needs numerical determination of a number of parameters beforehand. The other is based on the modification of the nonlinear material model and despite some limitations, it is convenient to use with common design procedures and applicable for an appreciable range of typical sections.

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ABSTRACT: This paper reports development of a new type of buckling-restrained brace (BRB) named the welded overlap core steel encased BRB. A two phase experimental research program was undertaken where BRBs were investigated under subassemblage testing. The first phase of the program aimed at studying the performance of steel encased BRBs which utilize constant width core plates. Test results indicated that these braces develop unacceptably high compression and tension resistances and the behaviors of these BRBs under uniaxial testing and subassemblage testing are markedly different. In the second phase of the research program a new type of BRB which utilizes a welded overlap core was developed to improve the cyclic performance observed in the first phase. Experimental results showed that the braces sustain axial strains that vary between 2.0 and 2.5% and resistances in tension and compression were found to improve significantly when compared with the findings of the first phase. Welded overlap core steel encased BRBs were found to sustain cumulative axial strains that are 419 times the yield strain when properly detailed.

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ABSTRACT: This paper presents an analytical study on the elastic critical behaviour of cylindrically curved panels under pure compressive stresses, for which an energy formulation is developed. Firstly, this energy formulation is described, the general assumptions are stated, the degrees-of-freedom and the displacement functions are defined and, using strain-displacement relations, the strain energy and the potential energy are derived. Secondly, the resulting general energy formulation is used to obtain, whenever feasible, simple expressions or, otherwise, values of the elastic critical stress of simply supported cylindrically curved panels
under pure compression. A discussion on the number of degrees-of-freedom necessary to obtain accurate results is also presented. The analytical results are compared to numerical (finite element) results obtained by the authors. Finally, a parametric study is made regarding the influence of constraining (or not) the panel longitudinal edges on the elastic critical stress.

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ABSTRACT: This paper presents the results of an experimental investigation of L-shaped columns composed of concrete-filled steel tubes (LCFST) columns connected by steel linking plates. As a new kind of composite column, the fundamental structural behavior of LCFST columns connected by steel linking plates is discussed in this paper. Eight large-scale LCFST columns were constructed and loaded under either concentric axial compression or biaxial eccentric compression up to failure. Slenderness ratio, thickness of the steel linking plates and load eccentricities were all studied within the experimental program. The relationships of load versus longitudinal displacement, lateral deflection at mid-height, longitudinal strain at mid-height etc. are presented. It is demonstrated that specimens with larger slenderness ratios or eccentricities have lower ultimate load capacities, as expected. It is also demonstrated that the steel connection plates, also as expected, have a considerable influence on confining lateral deflections of the mono CFST columns and that they significantly contribute to the columns' ultimate carrying capacity. Predictive formulas for calculating the ultimate loads of LCFST columns connected by steel linking plates are proposed based on modifications of the ANSI/AISC 360-05 guidelines.


Many papers published in the journal, Computers & Structures (2012-2016):
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ABSTRACT: In this paper, we propose to use the Murakami’s Zig-Zag theory for the static, vibration and buckling analysis of laminated plates, by a local radial basis function-based differential quadrature (LRBFDQ) method. The equations of motion and the boundary conditions are obtained by the Carrera’s unified formulation, and further interpolated by the LRBFDQ method. The LRBFDQ method combines the excellent approximation of derivatives by differential quadrature (DQ) in a local mesh-free framework by radial basis functions (RBFs). The present mesh-free, local approximation method shows excellent accuracy in the static, free vibration, and buckling analysis of thick isotropic and laminated plates.

See also the analogous paper:

ABSTRACT: In this paper, we propose to use the Murakami's zig-zag theory for the static and vibration analysis of laminated plates, by local collocation with radial basis functions in a finite differences framework. The equations of motion and the boundary conditions are obtained by the Carrera's Unified Formulation, and further interpolated by a local collocation with radial basis functions and finite differences. This paper considers the analysis of static deformations, free vibrations and buckling loads on laminated composite plates.

References listed at the end of the analogous 2011 Composite Structures paper:
[18] Carrera E, Demasi L. Multilayered finite plate element based on Reissner mixed variational theorem, part I: theory and part II:
https://doi.org/10.1016/j.compstruct.2011.10.013
ABSTRACT: Since the geometry plays a key role in the structural behavior of shell structures, finding the optimal shell geometry is of crucial importance. In this paper, a methodology for structural optimization is proposed and applied for the preliminary design of a barrel vault. Initially, a size optimization is performed for the proposed shape. Adding a quadratic variation of the shell thickness or allowing a curvature change results in a significant volume reduction. The information provided by the optimization about both evaluated design options can be used for a trade-off between aesthetical and economical arguments in order to select a final design.

Alphose Zingoni (Department of Civil Engineering, University of Cape Town, Rondebosch 7701, Cape Town, South Africa), “Symmetry recognition in group-theoretic computational schemes for complex structural systems”, Computers & Structures, Vols. 94-95, pp 34-44, March 2012
https://doi.org/10.1016/j.compstruc.2011.12.004

ABSTRACT: Group theory provides a formal means for exploiting symmetry in the analysis of physical systems. In current group-theoretic formulations, it is assumed that the symmetry properties of the system are self-evident, and the symmetry group of the problem is deduced by the analyst and assigned as an input parameter. However, for complex systems with a large number of nodes or elements, the symmetry properties may not be obvious. The present paper proposes a procedure for the systematic search and identification of the symmetries of 2D and 3D structural configurations, and hence for the automatic recognition of the symmetry group to be used in a group-theoretic analysis of the system.

https://doi.org/10.1016/j.compstruc.2011.12.003

ABSTRACT: A layerwise finite element formulation of a newly developed higher-order shear deformation theory for the flexure of thick multilayered plates is presented. The proposed trigonometric layerwise shear deformation theory accounts for: (a) non-linear and constant variation of in-plane and transverse displacement respectively through the panel thickness; (b) adequate transverse shear deformation and satisfy transverse shear traction free conditions on the top and the bottom surfaces of the plate. The accuracy of the present code is ascertained by comparing it with the exact solution and various available results in the literature.

Antonio Tomás and Juan Pedro Tovar (Department of Civil Engineering, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 50, 30203 Cartagena (Murcia), Spain), “The influence of initial geometric imperfections on the buckling load of single and double curvature concrete shells”, Computers and Structures, Vol. 96-97, pp. 34-45, April 2012, DOI: 10.1016/j.compstruc.2012.01.007

ABSTRACT: Several traditional methods are available to address the problem of instability in concrete shells, usually by means of curves representing the influence of the initial geometric imperfections in the buckling load for simple geometries (spheres and cylinders). Although some revisions of these methods have been made, new curves for other geometries have not been stated. In this study, the imperfection sensitivity factor in shell structures with different geometries (spherical dome, barrel vault, and double-curvature ruled surface) is determined graphically. This graphical method is useful to the designer in the early stages of the design of shell structures when dimensioning.

ABSTRACT: The dynamic stiffness formulation for both inplane and bending free vibration based on the first order shear deformation theory for composite plates is presented. The explicit terms of the dynamic stiffness matrices are also given. Plates with different boundary conditions are considered. Rotation and offset matrices for the element are developed and an assembly technique given. The Wittrick and Williams algorithm is modified to avoid the troublesome computation of the clamped–clamped natural frequencies when solving the free vibration problem. The validation of the theory and its application to real structures are illustrated in the second part of this paper.


ABSTRACT: The dynamic stiffness method for composite plate elements based on the first order shear deformation theory is implemented in a program called DySAP to compute exact natural frequencies and mode shapes of composite structures. After extensive validation of results using published literature, DySAP is subsequently used to carry out exact free vibration analysis of composite stringer panels. For each example, a finite element solution using NASTRAN is provided and commented on. It is concluded that the dynamic stiffness method is more accurate and computational efficient in free vibration analysis than the traditionally used finite element method.


ABSTRACT: In Refs. [1,2], an effective implicit time integration scheme was proposed for the finite element solution of nonlinear problems in structural dynamics. Various important attributes were demonstrated. In particular, it was shown that the scheme remains stable, without the use of adjustable parameters, when the commonly used trapezoidal rule results in unstable solutions. In this paper we focus on additional important attributes of the scheme, and specifically on showing that the procedure can also be effective in linear analyses. We give, in comparison to other methods, the spectral radius, period elongation, and amplitude decay of the scheme and study the solution of a simple ‘model problem’ with a very flexible and stiff response.

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ABSTRACT: This paper presents an object-oriented architecture for structural design software. The architecture’s novel features are the representation of an artifact with distinct levels of idealization, a hierarchy of classification within each of these levels, and the appropriate separation of software components. These enable seamless integration of geometric modeling and structural analysis in an interactive environment, extensibility of modeling and analysis capabilities, and integration of interactive multi-objective optimization. The paper presents a design environment implemented on the basis of the architecture, and demonstrates the benefits of refocusing engineering software from analysis to design.

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ABSTRACT: We introduce and study a BDDC (Balancing Domain Decomposition by Constraints) method for the Naghdi shell problem discretized with MITC (Mixed Interpolation of Tensorial Components) elements. Compared with the Kirchhoff model, the Naghdi model uses both displacement and rotation as variables, and therefore is more accurate but also more complicated at the numerical level. The severe difficulties of finite element shell analysis are also reflected in the condition number of the problem, which quickly diverges as the thickness of the shell and/or the finite element mesh size tend to zero. The proposed BDDC preconditioner is based on a proper selection of primal continuity constraints, the implicit elimination of the interior degrees of freedom in each subdomain, and the iterative solution of the resulting shell Schur complement by a preconditioned conjugate gradient method. The preconditioner is built from the solutions of local shell problems on each subdomain with clamping conditions at the primal degrees of freedom and on the solution of a coarse shell problem for the primal degrees of freedom. Three choices of primal constraints, hence coarse spaces, are considered, yielding three BDDC preconditioner of increasing strength and cost. Several numerical tests are performed for cylindrical, hyperbolic and elliptic shells. The results show that the proposed BDDC preconditioners are scalable in the number of subdomains, quasi-optimal in the ratio subdomain/element sizes, robust with respect to discontinuities of the shell material properties, and almost robust with respect to the shell thickness.


ABSTRACT: Dynamic stiffness equations are formulated for variable thickness cylindrical shells, under the assumptions of Donnell, Timoshenko and Flügge theories. Transcendental dynamic stiffness matrices are formed by solving numerically the governing eighth order differential equations using the boundary-value solver COLSYS. Undamped natural frequencies are found using the Wittrick–Williams algorithm. The shell is divided into smaller elements whose clamped end natural frequencies exceed the highest frequency of interest. A parametric study examines the effects of varying the geometry, degree of thickness taper and end conditions on the natural frequencies and mode shapes, providing benchmark results for designers and future researchers.
L.E. Monterrubio (Department of Structural Engineering, University of California, San Diego, 9500 Gilman Drive, Mail Code 0085, La Jolla, CA 92093-0085, USA), “Frequency and buckling parameters of box-type structures using the Rayleigh-Ritz method and penalty parameters”, Computers & Structures, Vols. 104-105, pp 44-49, August 2012, https://doi.org/10.1016/j.compstruc.2012.03.010

ABSTRACT: The Rayleigh–Ritz method (RRM) is often used to solve eigen-problems of simple continuous systems, usually defined by a single element, but it is not easily applied to complex systems. This disadvantage is addressed in this work using the penalty function method (PFM) to define all constraints of the system and to join elements to build box-type structures. Frequency parameters of non-symmetrical structures and buckling parameters of symmetric box-type structures are presented in this work. The use of positive and negative penalty parameters added to either the elastic stiffness matrix or to the mass matrix (matrices associated with the eigenvalue) is also investigated.

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https://doi.org/10.1016/j.compstruc.2012.02.019

ABSTRACT: The effect of different in-plane boundary conditions on the critical load and post-buckling behaviour of a uniaxially compressed, simply supported corrugated paperboard panel is examined, with the aim of reducing the discrepancy between model and published experimental results. In-plane boundary conditions with uniform load distribution or uniform compression on the loaded edges, free or constant normal in-plane edge movement and shear free edges, are modelled. Analytical single-term Galerkin and finite element approaches are used. The critical loads obtained analytically and numerically, for different boundary conditions agree well with an analytical reference result.


ABSTRACT: In this paper, a new geometrically exact beam formulation is presented, aiming at calculating buckling (bifurcation) loads of Euler–Bernoulli/Vlasov thin-walled beams with deformable cross-section. The resulting finite element is particularly efficient for problems involving coupling between lateral-torsional buckling and cross-section distortion/local-plate buckling. The kinematic description of the beam is geometrically exact and employs rotation tensors associated with both cross-section rotation and the relative rotations of the cross-section walls in the cross-section plane. Moreover, arbitrary deformation modes, complying with Kirchhoff’s assumption, are also included, which makes it possible to capture local/distortional/global buckling phenomena. Load height effects associated with cross-section rotation/deformation are also included. The examples presented throughout the paper show that the proposed beam finite element leads to accurate solutions with a relatively small number of degrees-of-freedom (deformation modes and finite elements).
ABSTRACT: Based on the Von Karman theory, the equations of motion for a rectangular isotropic plate, considering the effect of shear deformation and rotary inertia, have been derived. For the nonlinear vibration of the plate, a nonlinear coupled equation is obtained with an Airy stress function. Using the Galerkin method, this equation is separated into position and time functions. The Homotopy Perturbation Method (HPM) is employed to solve the nonlinear time function. It is shown that the obtained results demonstrate excellent agreement with numerical solutions obtained using the fourth-order Runge–Kutta method.

ABSTRACT: When preparing a design model for engineering analysis, model idealization is often used, where defeatureing, and/or local dimension reduction of thin regions, are carried out. This simplifies the analysis, but quantitative estimates of the idealization error, the analysis error caused by this idealization, are necessary if the results are to be of practical use. The paper focuses on a posteriori estimation of such idealization error, via both a theoretical analysis and practical algorithms. Our approach can compute bounds for the errors induced by dimension reduction, defeatureting or both in combination. Performance of our error estimate is demonstrated using examples.

ABSTRACT: Stability analysis is a crucial aspect of structural design, particularly for beam type structures. This paper addresses the development of a complementary-energy based (dual) stability criterion for the quasi-static analysis of three-dimensional framed structures modeled using the so-called geometrically exact (Reissner–Simo) beam theory. The criterion is derived from the well known primal stability criterion based on the condition of minimum total potential energy. This is accomplished by resorting to the Lagrangian multiplier method together with the Legendre transformation. Several numerical benchmark problems are analyzed. The analyses are carried out using two dual finite element models and their corresponding stability criteria, namely, the traditional two-node displacement/rotation-based model with the primal stability criterion, and a recently introduced equilibrium-based model with the proposed dual stability criterion.
ABSTRACT: A layerwise mixed finite element model is developed based on the least-squares formulation for the coupled electromechanical static analysis of multilayered plates with piezoelectric and composite layers. The model assumes a layerwise variable description for displacements, transverse stresses and in-plane strains, along with the electrostatic potential, transverse electric displacement and in-plane electric field components, taken as independent variables. This original choice for the layerwise mixed formulation is intended to ensure the a priori and complete fulfilment of the interlaminar $C^0$ continuity of both mechanical and electrical variables, which is due to compatibility and equilibrium conditions. Numerical applications are shown for assessment of the model predictive capabilities by comparison with available exact three-dimensional solutions, considering multilayered piezoelectric composite plates of various side-to-thickness ratios, under an applied load or surface potential.

ABSTRACT: In this work a new three-node finite element with piezoelectric coupling is presented. It can be used for the static and dynamic analysis of light-weight smart structures, i.e. laminated composite structures with piezoelectric patches attached to its surface or embedded within the laminated layers. The element is a continuum-based degenerate plate element based on the Reissner–Mindlin theory. It uses the Allman formulation for the in-plane strains together with the generalization of the discrete Kirchhoff technique to include the transverse shear strains. It has six mechanical degrees of freedom per node with no difficulties in the drilling rotations and one electrical degree of freedom per finite element. The electric field is assumed constant across the thickness of each piezoelectric layer. The bending and membrane consistent mass matrices are derived for applications on structural dynamics. Since this finite element was firstly developed to allow the active vibration control of the flexible multibody components, which formulation may be based on the diagonalization of the mass matrix, a comparison of a set of numerical results is obtained using a mass matrix diagonalization. The numerical results obtained by this finite element correlated well with other published results.

ABSTRACT: In this work a new three-node finite element with piezoelectric coupling is presented. It can be used for the static and dynamic analysis of light-weight smart structures, i.e. laminated composite structures with piezoelectric patches attached to its surface or embedded within the laminated layers. The element is a continuum-based degenerate plate element based on the Reissner–Mindlin theory. It uses the Allman formulation for the in-plane strains together with the generalization of the discrete Kirchhoff technique to include the transverse shear strains. It has six mechanical degrees of freedom per node with no difficulties in the drilling rotations and one electrical degree of freedom per finite element. The electric field is assumed constant across the thickness of each piezoelectric layer. The bending and membrane consistent mass matrices are derived for applications on structural dynamics. Since this finite element was firstly developed to allow the active vibration control of the flexible multibody components, which formulation may be based on the diagonalization of the mass matrix, a comparison of a set of numerical results is obtained using a mass matrix diagonalization. The numerical results obtained by this finite element correlated well with other published results.
“Buckling analysis of functionally graded plates under thermal loadings using the finite strip method”, Computers & Structures, Vols. 108-109, pp 93-99, October 2012,
https://doi.org/10.1016/j.compstruc.2012.02.011

ABSTRACT: In the present article, a finite strip method is applied for analyzing the buckling behavior of rectangular functionally graded plates (FGPs) under thermal loadings. The material properties of FGPs are assumed to vary continuously through the thickness of the plate, according to the simple power law distribution. Derivations of equations are based on the classical plate theory (CPT). The fundamental equations for rectangular plates of functionally graded material (FGM) are obtained by discretizing the plate into some finite strips. The solution is obtained by the minimization of the total potential energy and solving the corresponding eigenvalue problem. In addition, numerical results for a variety of functionally graded plates with different boundary conditions are presented and compared with those available in the literature. Moreover, the effects of geometrical parameters and material properties on the FGPs’ buckling temperature difference are determined and discussed.

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ABSTRACT: In the current paper, it is the first time that a dynamic stability analysis of moderately thick cylindrical panels made from FG materials is conducted by employing finite strip formulations based on a Reddy-type third order shear deformation theory (HSDT). Two versions of finite strip methods (FSM), namely semi-analytical and B-spline methods are developed. The mechanical properties of FGM are assumed to change in thickness direction according to a power-law function. The temperature effects are ignored. The strain terms are expressed in terms of the Koiter–Sanders theory of shallow shells. In order to demonstrate the capabilities of the developed methods in predicting parametric behavior of the subject structures, some representative results are obtained and compared with those in the literature whenever available.

Henrik Hesse and Rafael Palacios (Department of Aeronautics, Imperial College, London SW7 2AZ, United Kingdom), “Consistent structural linearization in flexible-body dynamics with large rigid-body motion”, Computers & Structures, Vols. 110-111, pp 1-14, November 2012, https://doi.org/10.1016/j.compstruc.2012.05.011

ABSTRACT: A consistent linearisation, using perturbation methods, is obtained for the structural degrees of freedom of flexible slender bodies with large rigid-body motions. The resulting system preserves all couplings between rigid and elastic motions and can be projected onto a few vibration modes of a reference configuration. This gives equations of motion with cubic terms in the rigid-body degrees of freedom and constant coefficients which can be pre-computed prior to the time-marching simulation. Numerical results are presented to illustrate the approach and to show its advantages with respect to mean-axes approximations.

ABSTRACT: The objective of this study is to improve the performance of the MITC3 shell finite element. The Hellinger–Reissner (HR) variational principle is modified in the framework of the MITC method, and a special approximated transverse shear strain field is proposed. The MITC3-HR shell finite element improved by using the Hellinger–Reissner functional passes all the basic tests (zero energy mode test, patch test, and isotropic element test). Convergence studies considering a fully clamped plate problem, a sixty-degree skew plate problem, cylindrical shell problems, and hyperboloid shell problems demonstrate the improved predictive capability of the new 3-node shell finite element.


ABSTRACT: A generalized approach for adaptive finite element analysis of laminated composite structures is presented in this study. The approach quantifies and controls discretization and modeling error. The goal of this paper is to present an economical, easily computable and relatively robust error estimator. A patch recovery based discretization error estimator is used and a goal based one shot adaptive procedure is implemented to control the discretization error. An explicit indicator, for estimation of modeling error, has been proposed for the laminated composites. The quality of the discretization and modeling error estimators is studied through numerical examples. The effectiveness of the proposed approach is also demonstrated through the analysis of damaged laminates. The key advantage of the proposed approach is that the desired mesh and models in the laminate are adapted automatically to achieve the user specified error tolerances in discretization and modeling errors.


ABSTRACT: We consider the problem of the free vibration of plates, and develop an efficient group-theoretic formulation for the solution of the problem by the method of finite differences. The procedure requires the writing down of the finite-difference equations for a relatively small number of nodes. These equations are then transformed into uncoupled sets of symmetry-adapted equations for the various subspaces, which are solved independently to generate the eigenvalues in the original space of the problem. Not only does the procedure reduce computational effort, but it also allows valuable insights to be gained on the vibration properties of the system.


ABSTRACT: In this paper, we present a novel procedure to improve the stress predictions in static, dynamic and nonlinear analyses of solids. We focus on the use of low-order displacement-based finite elements – 3-node
and 4-node elements in two-dimensional (2D) solutions, and 4-node and 8-node elements in 3D solutions – because these elements are computationally efficient provided good stress convergence is obtained. We give a variational basis of the new procedure and compare the scheme, and its performance, with other effective previously proposed stress improvement techniques. We observe that the stresses of the new procedure converge quadratically in 1D and 2D solutions, i.e. with the same order as the displacements, and conclude that the new procedure shows much promise for the analysis of solids, structures and multiphysics problems, to calculate improved stress predictions and to establish error measures.

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ABSTRACT: The effect of preloading on thin composite plates subjected to underwater explosive loading has been studied through computational simulations. In this study the effects of three types of in plane preloading are considered: (1) directly applied compression, (2) indirectly applied compression, and (3) directly applied tension. The effects of the preloading conditions are assessed using the plate center point deflection, material damage, and delamination evolution. The results show that for thin composite plates subjected to underwater shock loading conditions there is a minimal effect of preload on the response of the plates or the amount of damage and delamination sustained.


ABSTRACT: The Immersed Finite Element Method (IFEM) is a mathematical formulation for fluid–structure interaction problem like the Immersed Boundary Method; in IFEM the immersed structure has the same space dimension of the fluid domain. We present a stability of IFEM for a scheme where the Dirac delta distribution is treated variationally, as in [1]; moreover the finite element space related to the structure displacement consists of piecewise continuous Lagrangian elements, at least quadratic. The analysis is performed on two different time-stepping scheme. We demonstrate also that when the structure density is smaller than the fluid one, the stability is assured only if the time step size is bounded from below.


ABSTRACT: We have proposed the governing equations of a composite planar beam which fully take into account the exact geometrical and material non-linearities as well as finite slip between the layers. The present equations also exactly account for the equilibrium between the contact surfaces of the layers in the deformed state as well as for the tangential separation of layers at the edges. The equations of the model are then cast into the discretized weak form by the modified principle of virtual work using the unconventional finite element technique, where strains and the interlayer normal contact traction represent the interpolated quantities. The computational efficiency and accuracy of the formulation has been validated by comparing the results with the
experimental ones on the steel–concrete beam using the results of an experiment of Chapman and Balakrishnan [Chapman JC, Balakrishnan S. Experiments on composite beams, Struct Eng 1964; 42(11):369–383]. Of a particular importance in assessing the present formulation are also the results for the buckling load of a composite timber column. The results, incorporating the non-linear stress–strain law of timber and a large range of slendernesses of the column, clearly show a substantial effect of slip modulus on the buckling load. Thus the present formulation is also well suited for the buckling investigations of composite beams.

ABSTRACT: This paper prepares new features for applying the Dynamic Relaxation (DR) method in buckling and post-buckling structural analyses. Here, controlling the displacement’s increment is the main concept so that the minimum residual displacement and the minimum kinetic energy criteria are designed for updating the load factor in DR iterations. These new formulations do not affect the DR’s stability and they are successfully applied to both viscous and kinetic DR algorithms. Numerical analyses of structures with snap-through and snap-back behaviors show that the accuracy and the convergence rate of the suggested methods are higher than the well-known existing approaches such as the arc-length technique, especially, if they are combined with the kinetic DR algorithm. Calculating the buckling load is another interesting application of the proposed methods, performed here. In this manner, the suggested DR algorithms could numerically present the accurate buckling load of structures.

ABSTRACT: This work investigates the performance of various remeshing and remapping algorithms for the finite element simulation of plane-strain large deformation elastoplastic problems using a decoupled arbitrary Lagrangian–Eulerian approach. The remeshing algorithms, which are herein adjusted to the needs of elastoplastic deformation analyses, are the Elastic Rebound approach, the Spring Analogy Method and the Radial Basis Functions. The remapping algorithms are the Inverse Distance Algorithm and two data interpolation schemes, namely the Radial Basis Point Interpolation Functions and the Radial Basis Functions. The efficiency and robustness of the algorithms are assessed by simulating the penetration of a rigid flat punch.

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ABSTRACT: The simplified calculation methods proposed in EN1993-1-2 for fire design of steel columns do not take into account the restraining to its thermal elongation. In order to provide data for developing a new simplified calculation method for fire design of HEA, HEB and HEM steel columns with restrained thermal
elongation a parametric study using the advanced calculation model ABAQUS, was carried out. This method was established taking into account the axial and rotational restraint to the column in case of fire, the column slenderness and the load level. The critical times and temperatures can be obtained directly from formulae.

ABSTRACT: In this paper, we focus on an enriched finite element solution procedure for low-order elements based on the use of interpolation cover functions. We consider the 3-node triangular and 4-node tetrahedral displacement-based elements for two- and three-dimensional analyses, respectively. The standard finite element shape functions are used with interpolation cover functions over patches of elements to increase the convergence of the finite element scheme. The cover functions not only capture higher gradients of a field variable but also smooth out inter-element stress jumps. Since the order of the interpolations in the covers can vary, the method provides flexibility to use different covers for different patches and increases the solution accuracy without any local mesh refinement. As pointed out, the procedure can be derived from various general theoretical approaches and the basic theory has been presented earlier. We evaluate the effectiveness of the method, and illustrate the power of the scheme through the solution of various problems. The method also has potential for the development of error measures.

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ABSTRACT: At critical points along the equilibrium path, sudden and sometimes catastrophic changes in the structural behaviour are observed. The equilibrium path, load-bearing capacity and locations of critical points can be sensitive to variations in parameters, such as geometrical imperfections, multi-parameter loadings, temperature and material properties. This paper introduces an incremental-iterative procedure to directly calculate the critical load for parameterized elastic structures. A modified Newton’s method is proposed to simultaneously set the residual force and the minimum eigenvalue of the tangent stiffness matrix to zero by using an iterative algorithm. To demonstrate the performance of this method, numerical examples are presented.


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ABSTRACT: The concept of isogeometric analysis, whereby the parametric functions that are used to describe CAD geometry are also used to approximate the unknown fields in a numerical discretisation, has progressed rapidly in recent years. This paper advances the field further by outlining an isogeometric boundary element Method (IGABEM) that only requires a representation of the geometry of the domain for analysis, fitting neatly with the boundary representation provided completely by CAD. The method circumvents the requirement to generate a boundary mesh representing a significant step in reducing the gap between engineering design and analysis. The current paper focuses on implementation details of 2D IGABEM for elastostatic analysis with particular attention paid towards the differences over conventional boundary element implementations. Examples of Matlab code are given whenever possible to aid understanding of the techniques used.

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ABSTRACT: This paper aims at finite element modeling of nonlinear vibration behavior of piezo-integrated structures subjected to weak electric field. This nonlinear vibration behavior was observed in the form of dependence of resonance frequency on the vibration amplitude and nonlinear relationship between excitation voltage and vibration amplitude. The equations of motion for the finite element model is derived by introducing nonlinear constitutive relations of piezoceramics in Hamilton’s principle. Modal reduction is used to reduce the equations of motion. Thus obtained reduced equation of motion is solved by numerical integration. Experimental validation of the finite element model is also carried out.


ABSTRACT: The shape of tensioned fabric structures is realised via a process of patterning, which involves ‘flattening’ of sections, or panels, of a 3D membrane, onto a plane. The patterning method proposed here uses bicubic spline descriptions of surfaces undergoing flattening, followed by elastic analysis of strains arising from this process and from membrane pre-stress. The results, which ensure stress compatibility along panel edges, produce a cutting pattern and stress variation within it when the panel is assembled into the 3D form. They confirm a general relationship between panel width and stress deviation from the intended pre-stress reported in [1].

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ABSTRACT:
We present a polygonal finite element method based on constrained adaptive Delaunay tessellation and conformal interpolants on arbitrary polygons. For mesh generation we use the adaptive Delaunay tessellation, an unstructured hybrid tessellation of a scattered point set that minimally covers the proximal space around each point, which is here extended to non-convex domains. Various types of polygonal interpolants are implemented. For the numerical integration of the Galerkin weak form we resort to classical Gaussian quadrature applied on triangular subdomains. The performance and efficiency of the interpolation and implementation are investigated for two dimensional elasticity in a stochastical analysis on random and regular meshes.

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ABSTRACT: In the present study the problem of axial impact of a clamped beam with initial imperfections is treated using two uncertainty descriptions. For the deterministic solution, the exact mode and an approximative approach using so called “cosinusoidal polynomials” by Filonenko-Borodich are used. Next, the uncertainty is represented by a convex set and subsequently by random variables. The comparison between both uncertainty descriptions is carried out numerically on the level of the design time of the considered beam.

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ABSTRACT: This paper uses a multilayered shell element to compute the dynamic response of multilayered poroelastic structures such as car instrument panels, car floors, or car roofs. It is based on the P-order Shear deformation Theory with an added Zigzag function (ZPST). Biot’s theory is used to describe the poroelastic layer and standard couplings are realized between elastic and poroelastic layers. A method based on Padé approximants is also used in order to reduce the computation time. This acceleration technique enables to achieve fast frequency sweep computations compared to a standard direct method. Finally, numerical validations on plates and curved geometries are presented.

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ABSTRACT: We present in this paper MITC shell elements for large strain solutions of shell structures. While we focus on the 4-node element, the same formulation is also applicable to the 3-node element. Since the
elements are formulated using three-dimensional continuum theory with the full three-dimensional constitutive behavior, they are referred to as 3D-shell elements. Specific contributions in this paper are that the elements are formulated using two control vectors at each node to describe the large deformations, MITC tying and volume preserving conditions acting directly on the material fiber vectors to avoid shear locking, and a pressure interpolation to circumvent volumetric locking. Also, we present solutions to some large strain shell problems that represent valuable benchmark tests for any large strain shell analysis capability.

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ABSTRACT: A stochastic model of an experimentally measured unit cell structure is computed using the multi-scale textile software WiseTex. The statistical characteristics of a sample, derived in prior work, are used to calibrate the recently proposed Markov Chain algorithm for textile fabrics. The generated variable tow reinforcements are transformed in the WiseTex format that is compatible with tools for micromechanical analysis and permeability simulation. The application is a seven ply polymer textile composite, with each ply consisting of a twill 2/2 woven carbon fabric in an epoxy matrix. The developed model possesses random tow centroid paths with nominal cross-sectional properties.

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ABSTRACT: Copeland and Moon’s experimental results for a long pipe conveying fluid in the presence of a relatively large end-mass have displayed some truly fascinating dynamical behavior. Numerical studies, on the other hand, have all dealt with shorter pipes and smaller end-masses, mainly because the numerical convergence of the theoretical results for long pipes with large end-masses is problematic. In this paper, numerical results are presented for Copeland and Moon’s system parameters, reproducing some of the rich dynamics they obtained, including coupled planar and pendular oscillations, planar oscillations rotating through a finite angle, and planar motions rotating clockwise or counter-clockwise.

ABSTRACT: It is the purpose of the study to investigate the nonlinear dynamics of catenary shaped pipelines using a frequency domain technique. The study emphasizes on marine applications modeling the structure as a top tensioned riser with constant physical and mechanical properties. The original nonlinear system is treated
using expansions of the dynamic components in perturbation series. The employed method results in discrete systems which can be treated separately and successively. It is shown that the mechanism that excites second-order effects relies on the quadratic nonlinearities due to the first-order components. The study is extended to capture the effects due to the interaction with the seafloor. To this end the boundary conditions which originally correspond to a pinned bottom-end point are expanded using a Taylor series around an average location. Following this approach it is shown that the associated phenomenon is itself nonlinear regardless the behavior of the soil. The proposed frequency domain approach was inspired by the solution methods employed in hydrodynamic boundary value problems which assume a perturbation series expansion for the velocity potential. The equivalent of the Taylor series approximation of the lower end boundary condition in the present structural model is the Taylor expansion of the free surface boundary conditions around an average, namely the undisturbed free surface.

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ABSTRACT: The paper presents the static, free vibration and buckling analyses of eccentrically stiffened plates by the cell-based smoothed discrete shear gap method (CS-FEM-DSG3) using triangular elements. In this method, the original plate element CS-DSG3 is combined with a membrane element and stiffened by a thick beam element. The eccentricity between the plate and the beam is included in the formulation of the beam. The compatibility of deflection and rotations of stiffeners and plate is assumed at the contact positions. The accuracy and reliability of the proposed method is verified by comparing its numerical solutions with those of analytical solutions, experimental results and others available numerical results.


ABSTRACT: The objective in this paper is to present some recent developments regarding the subspace iteration method for the solution of frequencies and mode shapes. The developments pertain to speeding up the basic subspace iteration method by choosing an effective number of iteration vectors and by the use of parallel processing. The subspace iteration method lends itself particularly well to shared and distributed memory processing. We present the algorithms used and illustrative sample solutions. The present paper may be regarded as an addendum to the publications presented in the early 1970s, see Refs. [1,2], taking into account the changes in computers that have taken place.

ABSTRACT: Explicit integration is often used in highly nonlinear finite element structural dynamics simulations. However, explicit time integration is stable only if the used time-step is smaller than a critical threshold, which can be shown to depend on the smallest geometrical dimension of the finite elements in the mesh. This aspect is particularly critical when solid-shell elements are used for the analysis of thin walled structures, since the small thickness can lead to unacceptably small time-steps. A selective mass scaling technique, based on a linear transformation of the element degrees of freedom, is proposed in this paper to increase the size of the critical time-step without affecting the dynamic response. An analytical procedure is also developed for the computation of the element highest eigenfrequency and estimate of the critical time-step size. The computational effectiveness and accuracy of the proposed methodology is tested on the basis of numerical examples.

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ABSTRACT: A new general formulation for the mechanical behavior of Single-Walled Carbon Nanotubes is presented. Carbon atoms are located at the nodes of an hexagonal honeycomb lattice wrapped into a cylinder. They are linked by covalent C–C bonds represented by a truss or spring element, and the three-body interaction among two neighboring covalent bonds is reproduced by a rotational spring. The main advantage of our approach is to allow general load conditions (and any chirality) with no need of specific formulation for each load case, in contrast with previous works [26,27,31]. Four load configurations are adopted: tension, compression, bending and torsion of cantilevered SWCNTs. Calculations with our own codes for both AMBER and Morse potential functions have been carried out, aimed to compare their final results. Initial positions of the atoms (nodes) into nanotube cylindrical geometry has been reproduced in great detail by means of a conformal mapping from the planar graphene sheet. Therefore, the effect of initial SWCNTs curvature has been introduced explicitly through a system of initial stresses (prestressed state) which contribute to maintain their circular cross-section. Numerical results and deformed shapes for nanotubes with several diameters and chiralities under each load case are used to obtain their mechanical parameters with the only objective of checking the present formulation with previous works [28,30,20,24]. Also, the significance of the atomistic discrete simulations at the nano-scale size against other continuum models is underlined.

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ABSTRACT: The paper presents an analytical formulation for the post-buckling analysis of composite aeronautical panels with omega stiffeners loaded in compression and shear. The formulation relies on an energy principle and the method of Ritz. In the first step, the panel is an assembly of plate elements, and the buckling analysis is performed. In the second step, the panel is an elastically restrained skin, and the post-buckling
behaviour is studied. The comparisons with finite element analyses and experimental results from the literature reveal the ability of the formulation to assess the post-buckling response.

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ABSTRACT: Sandwich panel with corrugated cores is considered. The spectral equations of plate elements containing in-plane and out-of-plane components are established using spectral element method (SEM). The spectral stiffness matrix of whole structure is assembled. Frequency responses are obtained by calculating the spectral equations. Numerical results show that SEM can be effectively applied to study vibration band gap properties of sandwich panels with corrugated cores. Comparing with the results by finite element method (FEM) indicates that more accurate results can be achieved by SEM. The unit cell number, structural damping, material property, plate thickness and core form have obvious influences on structural dynamic characteristics.

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ABSTRACT: An isoparametric four-node finite element for multilayered magneto-electro-elastic plates analysis is presented. It is based on an equivalent single-layer model, which assumes the first order shear deformation theory and quasi-static behavior for the electric and magnetic fields. First, the electro-magnetic state of the plate is determined in terms of the mechanical primary variables, namely the generalized displacements, by solving the strong form of the magneto-electric governing equations coupled with the electromagnetic interface continuity conditions and the external boundary conditions. In turn, this result is used into the layers constitutive law to infer the equivalent single-layer laminate constitutive relationships that express the plate mechanical stress resultants in terms of the generalized displacements taking the magneto-electro-elastic couplings into account. The weak form of the mechanical equilibrium equations is then written and used to determine the mechanical primary variables. Once these are determined the magneto-electric state can be recovered by simple post-processing. The finite element is formulated by using the mixed interpolation of tensorial components approach where the kinematical variables are usually written in terms of nodal values through shape functions, whereas the transverse shear strains are differently interpolated. These approximations are used in the weak form of the equilibrium equations to obtain the discrete stiffness and mass matrices together with the expression of the equivalent forces. The finite element is validated for static and free vibrations problems by comparison with available 3-D solutions. Its characteristics are ascertained in terms of convergence, accuracy and sensitivity with respect to plate thickness and element distortion. Performances of the method for the computation of through-the-thickness variables distributions are also investigated.

ABSTRACT: This paper presents a formulation of Generalised Beam Theory (GBT) intended to perform first-order elastic–plastic analyses of thin-walled members experiencing arbitrary deformations and made of non-linear materials exhibiting isotropic hardening. After presenting the GBT fundamental assumptions and kinematic relationships, the member non-linear equilibrium equations are derived and a non-linear one-dimensional (beam) finite element is formulated. The arc-length control technique is adopted in the numerical solution of the non-linear equations and J2-flow theory is used to model plasticity in conjunction with the Backward Euler return-mapping algorithm. In order to show the capabilities and potential of the implemented formulation, a set of numerical illustrative examples are presented and discussed. For validation purposes, most of the GBT results obtained (equilibrium paths, modal participation diagrams, displacement profiles, stress distributions and deformed configurations) are compared with values yielded by Abaqus shell finite element analyses.

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ABSTRACT: A new sliding mesh technique for finite element simulation of fluid–solid interaction problems with large structural motions is presented in this paper. Fluid meshes surrounding a solid can slide each other to accommodate a rotational motion of the solid, and a fluid mesh outside the sliding interface can translate through a background fluid mesh. Because of relative motions of sliding fluid meshes and independently designed fluid and solid meshes, non-matching meshes occur at their common interfaces. The non-matching meshes are connected by using variable-node elements which guarantee the continuity, the compatibility and the force equilibrium across the interfaces.


ABSTRACT: In a previous paper (Kim and Bathe, 2013) [1], we introduced a scheme to improve finite element displacement and stress solutions by the use of interpolation covers. In the present paper we show how the scheme can be used to automatically improve finite element solutions. As in Ref. (Kim and Bathe, 2013) [1], we focus on the use of the low-order finite elements for the analysis of solids, namely, the 3-node triangular and
4-node tetrahedral elements with the use of interpolation covers. An error indicator is employed to automatically establish which order cover to apply at the finite element mesh nodes to best improve the accuracy of the solution. Some two- and three-dimensional problems are solved to illustrate the procedure.


ABSTRACT: The introduction of the Proper Generalized Decomposition (PGD) is presented for the layer-wise modeling of heterogeneous cylindrical shells. The displacement field is approximated as a sum of separated functions of the in-plane coordinates and the transverse coordinate. This choice yields to an iterative process that consists of solving a 2D and 1D problem successively at each iteration. In the thickness direction, a fourth-order expansion in each layer is considered. For the in-plane description, classical Finite Element method is used. The approach is assessed through mechanical tests for thin/thick and deep/shallow laminated cylindrical shells. Both convergence rate and accuracy are discussed.

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ABSTRACT: Corrosion defects which occur in oil and gas pipelines may compromise the safety of such structures. This paper makes an assessment of the accuracy of some of the analytical procedures commonly employed by industry to calculate the failure pressure of corroded pipelines via finite element analyses (FEA). Second, this paper studies the stress distribution on isolated pit corrosion defects also via FEA. Analytical procedures to calculate the failure pressure associated to isolated pits are not available yet. Thus, based on the stress analysis results, such a procedure is devised and proposed here.

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ABSTRACT: This work presents a dynamic analysis of a stiffened cylindrical shell using the Dynamic Stiffness Method, also known as the Continuous Element Method. This approach is based on the determination of the dynamic stiffness matrix of an unmeshed structure. A method for calculating the dynamic stiffness matrix of an axisymmetric shell stiffened with multiple stiffeners at arbitrary locations is given. Thus a stiffened cylindrical shell is subjected to free-free boundary conditions and three types of loads. A finite element model is used in order to validate the numerical results obtained from the method.
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ABSTRACT: An efficient and accurate method for solving large-scale problems in non-linear structural dynamics is presented. The method uses dual-Schur domain decomposition to divide a large finite element mesh into a number of smaller subdomains, which are solved independently using a suitable mesh-size and time-step to capture the local spatial and temporal scales of the problem. Continuity of the solution between subdomains is enforced by Lagrange multipliers. It is shown that the proposed method is stable, accurate and computationally more efficient than using a uniform time-step for the entire mesh. Numerical examples are presented to illustrate and corroborate these properties.

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ABSTRACT: Spiral welding or bonding is a particularly efficient and cost-effective method of constructing continuous tubes. However the understanding of the mechanics of such structures is not yet well developed. This is in no small part due to the difficulties involved in their computational analysis. Cylindrical shells are traditionally modelled using rectangular finite elements oriented parallel to the meridional and circumferential axes. However, spiral features are particularly challenging to model because such features are not orthogonal to the axes of the cylinder. Commercial finite element pre-processors often struggle to mesh these with anything other than a free triangulation. A superior mesh would consist of well-conditioned rectangular elements oriented orthogonally with respect to the axes of the helix, termed a ‘helical mesh’, but this requires significant programming effort. A helical mesh is particularly important if features of the shell such as geometric imperfections, residual stresses, weld material and heat affected zones, and bonding in systems using adhesives are required to follow the helical form. Helically wound structural forms are widely used in different applications that demand continuous cylindrical forms. The most common uses in structural engineering are in spiral wound tubes, piles, chimneys and pipelines.

References listed at the end of the paper:


ABSTRACT: Materials with patterned microstructures can be represented by a unit cell within which micromechanical stresses can be analysed. This approach, with accurate boundary conditions, allows huge savings to be made in computation time without affecting the accuracy of the results. In this paper, sets of boundary conditions for unit cells with periodicity in axial and circumferential directions are derived. These are verified by analysis of circular and hexagonal rods subjected to thermal loading, uniform tension or uniform torsion. The analysis of a thermal barrier coating system with a periodic oxide interface is presented as an application of the boundary conditions.

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ABSTRACT: This paper presents a novel multidisciplinary framework for performing shape and topology optimization of a flexible wing structure. The topology optimization is integrated into a multidisciplinary algorithm in which both the aerodynamic shape and the structural topology are optimized concurrently using gradient-based optimization. The optimization results were compared with the results of a sequential procedure in which the aerodynamic shape was optimized separately and then used as a fixed design feature in a subsequent structural optimization. The results show that the concurrent approach offers a significant advantage, as this design achieved 42% less drag than the sequentially optimized wing.

ABSTRACT: The global buckling of a composite plate with a single rectangular delamination is studied using a smearing method and employing exact stiffness analysis and the Wittrick–Williams algorithm. Computational efficiency is achieved by avoiding discretisation into elements and non-linear analyses, making the method suitable for parametric studies in preliminary aircraft design. Numerical results for longitudinal compressive loading show the level of reduction in buckling load with increasing length and width of delamination. Global buckling strength is increased as the delamination is moved towards the plate surface, but is relatively insensitive to its widthwise and lengthwise location. The results are validated by finite element analysis.

ABSTRACT: In technical beam theory the six equilibrium states associated with homogeneous tension, bending, shear and torsion are treated as individual load cases. This enables the formulation of weak form equations governing the warping from shear and torsion. These weak form equations are solved numerically by introducing a cubic-linear two-dimensional isoparametric element. The cubic interpolation of this element
accurately represents quadratic shear stress variations along cross-section walls, and thus moderately thin-walled cross-sections are effectively discretized by these elements. The ability of this element to represent curved geometries, and to accurately determine cross-section parameters and shear stress distributions is demonstrated.

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ABSTRACT: A new consistent corotational formulation for nonlinear dynamics of beams with arbitrary thin-walled cross-section is presented. The novelty is that the warping deformations and the eccentricity of the shear center are fully taken into account. Therefore, additional terms are introduced in the expressions of the inertia force vector and the tangent dynamic matrix. Their contribution is then investigated considering several numerical examples. Besides, the element has seven degrees of freedom at each node and cubic shape functions are used to interpolate local transverse displacements and axial rotations. The formulation’s accuracy is assessed considering five examples with comparisons against 3D-solid solutions.

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ABSTRACT: In this paper, we develop a scheme to enrich the 3-node triangular MITC shell finite element by interpolation cover functions. The MITC method is used for the standard and enriched displacement interpolations. The enriched 3-node shell finite element not only captures higher gradients but also decreases inter-elemental stress jumps. In particular, the enrichment scheme increases the solution accuracy without any traditional local mesh refinement. Convergence studies considering a fully clamped square plate problem, cylindrical shell problems, and hyperboloid shell problems demonstrate the good predictive capability of the enriched MITC3 shell finite element, even when distorted meshes are used. We evaluate the effectiveness of the method, and also illustrate the use of the enrichment scheme applied only locally through the solution of two additional shell problems: a shaft–shaft interaction problem and a monster shell problem.

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ABSTRACT: The static bending and the free vibration analysis of composite plates are performed with Carrera’s Unified Formulation (CUF). We combine the cell-based smoothed finite element method (CSFEM) and the 4-noded mixed interpolation of tensorial components approach (MITC4). The smoothing method is used for the approximation of the bending strains, whilst the mixed interpolation allows the calculation of the shear transverse stress in a different manner. With a few numerical examples, the accuracy and the efficiency of the approach is demonstrated. The insensitiveness to shear locking is also demonstrated.

ABSTRACT: Bionic growth method, which is based on the growth mechanism of branch systems in nature, has been used as a new approach for structural topology design optimization. Currently, its application is limited because the iterative scheme in the optimization process is heuristic. This paper suggests a new approach combined with the bionic branch model and optimality criteria. Based on the Kuhn–Tucker optimality condition, an analytical iterative formula is derived. The minimum compliance problem with multi-loading condition, the maximum fundamental frequency problem and the multi-objective optimization problem are studied. Typical design examples are demonstrated to validate the effectiveness of the suggested approach. Compared with the current growth technique, the suggested approach is more effective, practicable and applicable. The results show that the new bionic growth method can effectively and flexibly deal with optimum stiffener layout design of plate/shell structures to achieve various design objectives, thus it provides a new solution approach for structural topology design optimization.

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ABSTRACT: Structural systems made of high-strength and/or high-ductility metals are usually also rather slender, which means that their structural behaviour and ultimate strength are often governed by a combination of plasticity and instability effects. Currently, the rigorous numerical analysis of such systems can only be achieved by resorting to complex and computationally costly shell finite element simulations. This work aims at supplying to designers/researchers with an efficient and structurally clarifying alternative to assess the geometrically and/or materially non-linear behaviour (up to and beyond the ultimate load) of prismatic thin-walled members, such as those built from cold-formed steel. The proposed approach is based on Generalised
Beam Theory (GBT) and is suitable for members exhibiting arbitrary deformation patterns (e.g., global, local, distortional, shear) and made of non-linear isotropic materials (e.g., carbon/stainless steel grades or aluminum alloys). The paper begins by providing an overview of the physically and geometrically non-linear GBT formulation recently developed and validated by the authors, which is followed by the presentation and thorough discussion of several illustrative numerical results concerning the structural responses of 5 members (beams and columns) made of distinct (linear, bi-linear or highly non-linear) materials. The GBT results consist of equilibrium paths, modal participation diagrams and amplitude functions, stress contours, displacement profiles and collapse mechanisms – some of which are compared with Abaqus shell finite element analysis (SFEA) values. An excellent correlation is found in all cases and, moreover, it is shown that GBT analyses including judiciously selected deformation mode sets involve only 25% (on average) of the number of d.o.f. required by similarly accurate SFEA. Moreover, it is clearly evidenced that the GBT modal nature makes it possible to acquire in-depth knowledge on the member behavioural mechanics in the elastic and elastic–plastic regimes.


ABSTRACT: This article presents a direct boundary element formulation for static torsional analysis of open section thin-walled members. All mathematical representations of the problem such as integral equations, fundamental solutions and algebraic systems are established in terms of typical quantities (twisting moment, bimoment, angle of twist and its rate) of Vlasov’s nonuniform torsion theory. Numerical results are presented for different cases of torque loadings and boundary conditions.


ABSTRACT: This paper presents an accurate semi-analytical technique to analyse piezoelectric plates. The proposed technique is built upon the scaled boundary finite-element method. No kinematic and electrostatic assumptions are introduced in the derivation process. The in-plane dimensions are divided into 2D elements and the 3D geometry is obtained by translating the mesh in thickness direction. The through-thickness solutions are expressed analytically with a matrix exponential function. The 3D-consistent nature allows the proposed technique to describe the through-thickness behaviour of piezoelectric plates accurately. Numerical shear locking does not arise. Four numerical examples are presented to highlight the performance of the proposed technique.


ABSTRACT: Elements in a conforming mesh are often distorted to fit the geometry which can cause numerical errors. If a background mesh is used for analysis, the elements can be regular shaped. The geometry must be
represented independently using equations and implicit boundary method can be used to enforce essential boundary conditions. In this paper, this approach is extended to traditional Reissner–Mindlin plate elements that use mixed interpolation to avoid shear locking. The convergence of plate elements that use implicit boundary approach and a background mesh is studied in this paper using several benchmark problems to test their validity and robustness.

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ABSTRACT: In this paper, we present an effective new 3-node triangular shell finite element, called the MITC3+ element. The new shell element is based on the concepts earlier published for the MITC3 shell element (Lee and Bathe, 2004) [1] but is enriched by a cubic bubble function for the rotations. A new assumed transverse shear strain field is developed for the element. The shell element passes the three basic tests (the isotropy, patch and zero energy mode tests) and shows excellent convergence behavior in basic and encompassing convergence tests.

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ABSTRACT: This paper addresses the behavior of three-dimensional multilayered pipe beams with interlayer slip condition, under general 3-D large displacements, in global riser and pipeline analysis applications. A new finite element model, considering the Timoshenko beam for each element layer, has been formulated and implemented. It comprises axial, bending and torsional degrees-of-freedom, all varying along the length of the element according to discretization using Hermitian functions: constant axial and torsional loadings, and linear bending moments. Transverse shear strains due to bending are included in the formulation by including two generalized constant degrees-of-freedom. Nonlinear contact conditions, together with various friction conditions between the element layers, are also considered. These are accounted in the model through a proper representation of the constitutive relation for the shear stress behavior in the binding material. The element formulation and its numerical capabilities are evaluated by some numerical testing results, which are compared to other numerical or analytical solutions available in the literature. The tests results show that the new element provides a simple yet robust and reliable tool for general multilayered piping analyses.

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ABSTRACT: The objective in this paper is to present an approach to improve component mode synthesis solutions using subspace iterations to obtain frequency and mode shape predictions of controlled accuracy. In traditional component mode synthesis analyses, the calculated frequencies and mode shapes are approximations of the exact frequencies and mode shapes of the finite element model, the error is unknown, may be large, and is usually not assessed. In the approach given here, the error is assessed and can be reduced to the desired level. The Craig–Bampton component mode synthesis is used, but the solution approach is also directly applicable to any other component mode synthesis scheme. Some example solutions are given to illustrate the use and the effectiveness of the solution approach.

ABSTRACT: In this study, we propose an accurate error estimator for the Craig-Bampton (CB) method, which is a widely used component mode synthesis (CMS) method. The proposed error estimator can precisely predict relative eigenvalue errors in finite element models reduced by the CB method. To develop the error estimator, we propose an enhanced transformation matrix for the CB method and, using the transformation matrix, the error estimator is derived from the global (original) eigenvalue problem. In this paper, we demonstrate the robustness of the proposed error estimator through various numerical examples.

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ABSTRACT: We demonstrate the existence of spurious modes in finite elements with incompatible modes when a geometrically nonlinear displacement analysis with small displacements and strains is performed. The spurious modes are a direct consequence of the incompatibility of the elements with displacement boundary conditions. We derive a critical compressive strain condition analytically, and show that the critical strain can be quite small, with small displacements, if the geometric aspect ratio of the elements is large but still practical. In numerical examples we give further insight and results in correspondence with the analytical theory, and demonstrate that spurious modes can be triggered in practical small strain analyses when using elements with incompatible modes.

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ABSTRACT: A simple mathematical approach is developed to model the nonlinear behaviour of thin isotropic rectangular plates in response to large thermoelastic deformations. A set of nonlinear equations are solved simultaneously to determine the plate responses to a thickness-dependent temperature field and/or a transverse mechanical loading. The plate is assumed to be unrestrained or restrained against lateral translation (in the plane of the plate) at all boundaries and free to rotate about the axes coincident with each boundary. It is shown that even without involving complex terms in the governing equations, the performance of the proposed method is very good.

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ABSTRACT: A generalized shear deformation theory for static, dynamic and buckling analysis of functionally graded material (FGM) made of isotropic and sandwich plates is presented in this paper. Two new distribution functions are proposed in the present formulation. These functions determine the distribution of the transverse shear strains and stresses across the thickness of the plates. The present theory is derived from the classical plate theory (CPT), and hence the shear locking phenomenon can be ignored. It has same number of degrees of freedom as the first order shear deformation theory (FSDT), but it does not require shear correction factors because the shear stress free surface conditions are naturally satisfied. As demonstrated in the following sections, the proposed theory yields very accurate prediction for displacement, stresses, natural frequencies and critical buckling load compared to three-dimensional (3D) elasticity solution. Galerkin weak form of static, free vibration and buckling models for FGM isotropic and sandwich plates are used to create the discrete system of equations. This weak form requires $C^1$-continuity for generalized displacements. It can be solved by a number of methods such as analytical methods, finite element methods based on the Hermite interpolation functions, meshfree method and recently developed NURBS based isogeometric analysis (IGA). The NURBS basis functions used in IGA are $C^{n-1}$ continuous and therefore can easily satisfy the $C^1$-continuity condition. Numerical examples are presented to illustrate the effectiveness of the proposed method compared to other methods reported in the literature.

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ABSTRACT: The Variational Theory of Complex Rays (VTCR) was developed in order to calculate the vibrational response of structures in the medium-frequency range. It leads to a numerical approximation of this response through the resolution of a small system of equations which, contrary to element-based methods, does
not result from a refined spatial discretization. This strategy has already been validated for assemblies of isotropic plates. In this paper, we extend it to the case of orthotropic planar structure. The method is illustrated through various orthotropic plate vibration problems under several types of harmonic loading in the medium-frequency range.

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ABSTRACT: A shape identification method of free-form shells is presented for controlling the static deformation mode to the desired one. This problem is formulated as a parameter-free shape optimization problem, in which a squared displacements error norm on the prescribed region is employed as an objective functional. The shape sensitivity, called shape gradient function, is theoretically derived using the adjoint variable method and the formula of the material derivative, and then applied to a gradient method with Laplacian smoother for shells to determine the smooth optimal shape. Several calculated examples are presented to verify the validity and practical utility of the proposed method.

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“Large deformation dynamic finite element analysis of delaminated composite plates using contact-impact conditions”, Computers & Structures, Vol. 144, pp 92-102, November 2014,
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ABSTRACT: A new $C^0$ composite plate finite element based on Reddy’s third order theory is used for large deformation dynamic analysis of delaminated composite plates. The inter-laminar contact is modeled with an augmented Lagrangian approach. Numerical results show that the widely used “unconditionally stable” $\beta$-Newmark method presents instability problems in the transient simulation of delaminated composite plate structures with large deformation. To overcome this instability issue, an energy and momentum conserving composite implicit time integration scheme presented by Bathe and Baig is used. It is found that a proper selection of the penalty parameter is very crucial in the contact simulation.

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ABSTRACT: In this paper, we newly present an effective shape optimization method for natural vibration design of stiffened thin-walled or shell structures. Both the stiffeners and their basic structures are optimized by solving two kinds of optimization problems. The first is a specified eigenvalue maximization problem subject to a volume constraint, and the second is its reciprocal volume minimization problem subject to a specified
eigenvalue constraint. The boundary shapes of a thin-walled structure are determined under the condition where the stiffeners and the basic structure are movable in the in-plane direction to their surface. Both problems are formulated as distributed-parameter shape optimization problems, and the shape gradient functions are derived using the material derivative method and the adjoint variable method. The optimal free-boundary shapes are determined by applying the derived shape gradient function to the H1 gradient method for shells, which is a parameter-free shape optimization method proposed by one of the authors. Several design examples are presented to validate the proposed method and demonstrate its practical usages.

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ABSTRACT: In this paper, we present the MITC3+ shell finite element for geometric nonlinear analysis and demonstrate its performance. The MITC3+ shell element, recently proposed for linear analysis [1], represents a further development of the MITC3 shell element. The total Lagrangian formulation is employed allowing for large displacements and large rotations. Considering several analysis problems, the nonlinear solutions using the MITC3+ shell element are compared with those obtained using the MITC3 and MITC4 shell elements. We conclude that the MITC3+ shell element shows, in the problems considered, the same excellent performance in geometric nonlinear analysis as already observed in linear analysis.

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ABSTRACT: This work presents a semi-analytical sensitivity analysis approach for geometric nonlinear shape optimization. A secant stiffness matrix is used in the nonlinear solution procedure. Conditions that an accurate derivative of the matrix should satisfy are determined. Following these conditions, a correction term for the finite differencing approximation is constructed. Due to the asymmetry of the secant stiffness matrix, the correction term is expressed in the product spaces of two sets of zero eigenvectors. The analytical formulas of these vectors are also presented, which increases the computational efficiency. Numerical examples highlight the ability of the technique to effectively eliminate sensitivity analysis errors.

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ABSTRACT: A belt-conveyor bridge is built inside a ring-stiffened cylindrical shell, the belt-conveyor supports being independent of the stiffeners. Reliability-based and deterministic optimization results are compared. The design variables are the shell thickness as well as the thickness and the number of flat rings. Optimum solutions are evaluated for different bridge lengths in view of finding the most effective cost/span ratios. The design constraints relate to the local shell buckling strength, to the panel ring buckling and to the deflection of the bridge. The cost function includes the material and fabrication costs. A level II reliability method (FORM) is used to find the probability of failure. The overall structural reliability is obtained by using Ditlevsen method of conditional bounding. The costs of the plate designed to ensure a stipulated probability of failure will be compared with the solutions obtained for a code based method, which employs partial safety factors. A branch and bound strategy coupled with an entropy-based algorithm is used to provide discrete solutions.

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ABSTRACT: An exact finite strip for the buckling and post-buckling analysis of moderately thick plates is presented in this paper by using First order Shear Deformation Theory (FSDT). In the buckling phase the Von-Karman’s equilibrium equation is solved exactly to obtain out-of-plane mode shapes and critical loads. The Von-Karman’s compatibility equation is solved exactly in the post-buckling phase with the assumption that the deflected form after buckling is a combination of obtained buckling modes (single or multiple mode shapes). The principle of minimum potential energy is invoked to solve for the unknown coefficients in the assumed out-of-plane deflections and rotation functions.

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ABSTRACT: Description is given of a semi-analytical finite strip method for analysing the post-buckling behaviour of functionally graded rectangular plates in thermal environments where plates are under uniform, tent-like or nonlinear temperature change across the thickness. The material properties are assumed to vary through the thickness according to the power law. The formulations are based on the classical plate theory and the concept of the principle of the minimum potential energy. The Newton–Raphson method is used to solve the equilibrium equations. A range of applications are described and the numerical results are compared to the available results, wherever possible.

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ABSTRACT: This work presents a discussion on the characteristics of sets of admissible functions to be used in the Rayleigh–Ritz method (RRM). Of particular interest are sets that can lead to converged results when penalty terms are added to model constraints and interconnection of elements in vibration and buckling problems of beams, as well as plates and shells of rectangular planform. The discussion includes the use of polynomials, trigonometric functions and a combination of both. In the past, several sets of admissible functions that have a limit on the number of terms that can be included in the solution without producing ill-conditioning were used. On the other hand, a combination of trigonometric and low order polynomials have been found to produce accurate results without ill-conditioning for any number of terms and any number of penalty parameters that can be accommodated by the computer memory.


ABSTRACT: This paper presents a unified Ritz-based method for the computation of modal properties of both thick and thin, circular and annular isotropic plates with different boundary conditions. The solution is based on an appropriate and simple formulation capable of handling in an unified way a large variety of two-dimensional higher-order plate theories. The formulation is also invariant with respect to the set of Ritz admissible functions. In this work, accurate upper-bound vibration solutions are presented by using kinematic models up to sixth order and products of Chebyshev polynomials and boundary-compliant functions. Considering the circumferential symmetry of annular plates and the 2-D nature of underlying theories, the present method is also computationally efficient since only single series of trial functions in the radial direction are required.

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ABSTRACT: A novel method to deal with structures with uncertain-but-bounded parameters is presented. In order to reduce or eliminate the overestimations due to the so-called dependency phenomenon arising in the classical interval analysis, the authors have recently introduced the parameterized interval analysis and the improved interval analysis via Extra Unitary Interval. The key idea is to develop a new method which, combining the previously two proposed procedures, overcomes their limits and by optimization and anti-optimization problem solutions allows to efficiently solve the set of governing algebraic interval equations in statics.

ABSTRACT: Continuation methods have proved to be very powerful tools when solving large finite element problems. However, implementation of these methods often require modifications to the standard finite element method. As a finite element code is already very complex, we would like to implement the continuation method as efficiently as possible. In this paper, we present a new implementation technique based on a Schur complement approach for the Moore–Penrose continuation method. This method facilitates the detection of bifurcation points and also enables branch following. Numerical examples will be presented and analyzed using the proposed approach.


ABSTRACT: One-step multiple-value methods are developed which involve an accurate predictor method with higher derivatives, followed by a corrector method cast in form of an enhanced Newton–Raphson scheme. The generalized Newmark (GNpj) method may be recovered as a special case. The algorithms serve to match the accuracy of the fourth-order Runge–Kutta–Fehlberg method. Challenges to solve more reliably, accurately and efficiently non-linear differential equations are highlighted as stemming from amplitude and phase shift errors introduced by discretization in space and time – a continuous-discrete transformation. The classical stability tool of spectral radius is performed on linear systems whereas Liapunov method on nonlinear systems.

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ABSTRACT: In this paper, we investigate the static and dynamic modal behavior of the MITC3+ triangular shell element (Lee and Bathe, 2004; Lee et al., 2014). We focus on bending-dominated situations because such shell problems are particularly difficult to solve when using low-order elements. For comparison, the pure displacement-based (DISP3), MITC3 and MITC4 shell elements are also studied. First, static mode solutions are performed for a single right-angled shell element and an assemblage of two right-angled shell elements. The detailed strain fields are established in the bending modes. This study provides insight into how shear locking occurs on the mode level. We then analytically show how the MITC3+ shell element properly represents the pure bending conditions in a two-sided clamped plate problem. Considering free plate and free hyperboloid shell problems, we finally present the excellent performance of the MITC3+ shell element in dynamic mode solutions.
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https://doi.org/10.1016/j.compstruc.2015.03.005
ABSTRACT: With the availability of user oriented software tools, dedicated architectures, such as the parallel computing platform and programming model CUDA (Compute Unified Device Architecture) released by NVIDIA, one of the main producers of graphics cards, and of improved, highly performing GPU (Graphics Processing Unit) boards, GPGPU (General Purpose programming on GPU) is attracting increasing interest in the engineering community, for the development of analysis tools suitable to be used in validation/verification and virtual reality applications. For their inherent explicit and decoupled structure, explicit dynamics finite element formulations appear to be particularly attractive for implementations on hybrid CPU/GPU or pure GPU architectures. The issue of an optimized, double-precision finite element GPU implementation of an explicit dynamics finite element solver for elastic shell problems in small strains and large displacements and rotations, using unstructured meshes, is here addressed. The conceptual difference between a GPU implementation directly adapted from a standard CPU approach and a new optimized formulation, specifically conceived for GPUs, is discussed and comparatively assessed. It is shown that a speedup factor of about 5 can be achieved by an optimized algorithm reformulation and careful memory management. A speedup of more than 40 is achieved with respect of state-of-the art commercial codes running on CPU, obtaining real-time simulations in some cases, on commodity hardware. When a last generation GPU board is used, it is shown that a problem with more than 16 millions degrees of freedom can be solved in just few hours of computing time, opening the way to virtualization approaches for real large scale engineering problems.

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ABSTRACT: This work presents a hybrid mixed stress finite element model for the linear stability analysis of frame structures and Reissner–Mindlin plate bending problems. This model approximates the stress and displacement fields in the domain and the displacement field on the static boundary. Legendre polynomials are used to define all approximation bases, in order to compute analytical solutions for all structural operators. It enables also the implementation of highly efficient $p$-refinement procedures. A material linear behaviour is assumed and to validate the model and to illustrate its potential, numerical tests are presented and compared with analytical and numerical solutions.

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The use of bending as self forming process allows the realization of shape-resistant systems, such as grid shell structures. Here, a numerical method for optimization of the cross-section of actively bent structures is introduced. For a given load distribution, the optimization objective consists of normalizing the bending stresses to a given value on the entire structure. In addition, strength and geometric compatibility constraints are taken into account. The method is demonstrated by numerical examples. Further, in order to handle the large displacements involved, a co-rotational Finite Element formulation is adopted and modified to take into account the changes in stiffness that occur in the forming process of active bending systems. The modified co-rotational formulation is solved for static equilibrium using a Dynamic Relaxation scheme, and is tested against the analytical solutions of some preliminary test cases, as well as experimental results, and shown to be ‘accurate’.

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The method of incompatible modes is applied to volumetric elements and so-called solid-shell elements with linear interpolation as an alternative to the well known method of enhanced assumed strains in order to reduce artificial stiffness effects. The incompatible modes are directly adjoint to known EAS elements. In the context of explicit time integration, the incompatible degrees of freedom are treated as regular unknowns with associated modal masses and incorporated into the global equations instead of being condensed-out locally decreasing the computational effort. The issue of artificial kinetic energy is briefly discussed. Further the implementation concept applying symbolic programming is described.


Easily deformable tall structures exposed to a strong vertical component of an excitation are endangered by auto-parametric resonance effect. This non-linear dynamic process in a post-critical regime might contribute to various damages caused by a kinematic excitation. Vertical and horizontal response components are independent on the linear level. However their interaction takes place due to non-linear terms in post-critical regime. Two generally different types of the post-critical regimes are presented: (i) post-critical state with possible recovery and (ii) exponentially rising horizontal response leading to a collapse. A special attention is paid to processes of transition from semi-trivial to post-critical state in case of time limited excitation period as it concerns the seismic processes. Solution method combining analytical and numerical approaches is developed and used. Its applicability and shortcomings are commented. A few hints for engineering applications are given.

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ABSTRACT: The Inverse Finite Element Method (IFEM) for degenerate solid shells is introduced. IFEM allows determining the undeformed shape of a body (in this case, a shell-like body) such that it attains a desired shape after large elastic deformations. The model is based on the degenerate solid approach, which enables the use of the standard constitutive laws of Solid Mechanics. First, IFEM is applied to three popular benchmarks for validation purposes. Then, the capabilities of IFEM for inverse design are demonstrated by means of its application to the design of a microvalve.

Xingjun Gao and Haitao Ma (State Key Laboratory of Subtropical Building Science, Department of Civil Engineering, South China University of Technology, Guangzhou 510640, China), “Topology optimization of continuum structures under buckling constraints”, Computers & Structures, Vol. 157, pp 142-152, September 2015, https://doi.org/10.1016/j.compstruc.2015.05.020
ABSTRACT: This paper presents a study on topology optimization of continuum structures under buckling constraints. New algorithms are developed for minimization of structural compliance considering constraints on volume and buckling load factors. The SIMP (Solid Isotropic Material with Penalization) material model is employed and nodal relative densities are used as topology design variables. A new approach based on the eigenvalue shift and pseudo mode identification is proposed for eliminating the effect of pseudo buckling modes. Two-phase optimization algorithms are also proposed for achieving better optimized designs. Numerical examples are presented to illustrate the effectiveness of the new methods.

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ABSTRACT: In the last few decades the interest of aerospace and automotive industries towards the study of the medium-frequency response of complex shell structure frames has grown. Recently some dedicated “wave” computational approaches have been developed. Among them, a Trefftz technique called Variational Theory of Complex Rays (VTCR) is catching on as an ad hoc method to deal with such vibration problems. This work presents the development of the VTCR in the shallow shell theory to increase its effectiveness and flexibility. First, general theory is given and two key properties of the solution demonstrated. After that, two numerical examples are deeply analyzed

ABSTRACT: A mathematical model able to describe the buckling behaviour of moderately thick, elastic/plastic plates rigidly connected along their longitudinal edges is presented. The governing equations are derived on the basis of incremental and deformation theories of plasticity. The Ramberg–Osgood model is used to describe the elastic/plastic behaviour, whereas a Green–Lagrange strain model is adopted to measure the geometrical nonlinearities. The plate is analyzed within the framework of the Mindlin theory. Comparison with results available in literature, as well as the effects of geometry, boundary conditions, loading conditions and nonlinearities on the buckling response of different stiffened plates are presented.


ABSTRACT: In the present paper, a special methodology for the fast generation and parameterization of ribbed thin-walled structures with a free topology is presented. The procedure employs the entire potential field irradiated by special-purpose skeleton-based integral soft objects to re-arrange the finite element surface of arbitrary shaped structural domains producing auto-blending ribs and protrusions with no topology constraints. The method has been structured to operate in parallel with a vectorial architecture or a Graphics Processing Unit. A rich library of soft object primitives with structural shapes have been developed. Demonstrative examples of self-stiffened panels, either regular or arbitrarily shaped, are illustrated.

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ABSTRACT: A new 2-node finite element for the Generalized Beam Theory is developed based on the hybrid complementary energy functional, involving nodal displacements and equilibrating stresses within the element as independent variables. Assumed stresses are rationally derived basing on the stresses associated to analytical solutions of some particular cases. Displacements within the element are a posteriori recovered by shape functions based on the same solutions. Numerical results show the high performance of the proposed element: generalized displacements and stresses are accurately predicted with very rough meshes, often using only one or two finite elements.


ABSTRACT: This paper introduces a nonlinear reduced-order modelling methodology for finite-element models of structures with slender subcomponents and inertia represented by lumped masses along main load paths. The constructed models have dynamics described by 1-D intrinsic equations of motion, which are further written in modal co-ordinates. This yields finite-dimensional approximations of the system dynamics with only quadratic nonlinearities. Evaluation of the problem coefficients is performed from static condensation of the original model on the lumped masses. The method exploits the multi-point constraints typically used to obtain
sectional loads in aircraft aeroelastic analysis. The technique is illustrated on simple 3D structural models built using solid elements.


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ABSTRACT: The paper reports the results of a numerical investigation on the relevance of web-triggered local–distortional interaction on the ultimate strength of a large number of cold-formed steel fixed-ended (plain) lipped channel, zed, hat and rack-section columns. These results concern columns with various geometries (cross-section dimensions and unrestrained length) and yield stresses, ensuring a wide variety of combined ratios between the (i) distortional and local critical buckling stresses ($R_{DL}$) and (ii) yield and non-critical buckling stresses ($R_y$). To avoid interaction with global buckling, all columns have global critical buckling stresses much higher than their local, distortional and yield counterparts. The aim of this study is to identify combinations of these ratios for which L–D interaction is relevant, in the sense that it affects visibly the column elastic and elastic–plastic post-buckling behaviours, ultimate strength and failure mechanism – special attention is devoted to the ultimate strength erosion. The numerical ultimate strength data obtained are then compared with the predictions of (i) the currently codified DSM (Direct Strength Method) strength curves for the design of columns failing in local and distortional modes and (ii) available DSM-based design approaches specifically developed to handle local–distortional interactive failures. Then, experimental results available in the literature concerning lipped channel and rack-section columns failing in local–distortional interactive modes are used to assess the quality of the estimates provided by the DSM-based design approaches. Finally, the paper closes with some considerations on the design of cold-formed steel columns undergoing L–D interaction.

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ABSTRACT: For their lightweight, versatile forms and architectural impact, cable-strut structural systems have been widely used as large span roofs of arenas, stadiums and open squares. In this paper, the matrix theory for pin-jointed trusses is firstly recalled. Then, through an elementary cable dome, the role of prestress is outlined and commented. Finally, a special optimization procedure, based on genetic algorithms, allows a thorough
comparison between classical structural schemes, whose bearing capacity is due to the mechanical stiffness, and prestressed structures, whose bearing capacity is also due to the geometrical stiffness provided by the prestress.

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ABSTRACT: In this paper, we simplify the error estimation technique developed for the Craig–Bampton (CB) method (Kim et al., 2014). The original formulation is simplified by neglecting insignificant terms, a new error estimator is obtained, and thus computational cost is significantly reduced with negligible accuracy loss. In addition, the contribution of a specific substructure to a relative eigenvalue error can be estimated using the new formulation, in which the estimated relative eigenvalue error is represented by a simple summation of the substructural errors estimated. Therefore, the new formulation can be employed for error control by using the detailed errors estimated for a certain substructure. Through various numerical examples, we verify the accuracy and computational efficiency of the new formulation, and demonstrate an error control strategy.

ABSTRACT: An exact method for free vibration analysis of plates with arbitrary boundary conditions is presented. This is achieved by integrating the spectral method into the classical dynamic stiffness method. The formulation satisfies the governing differential equation exactly and any arbitrary boundary conditions are satisfied in a series sense. The Wittrick–Williams algorithm is enhanced with several elegant techniques to obtain solutions. The exactness and computational efficiency of the method are demonstrated by comparing results obtained from other methods. Finally, mathematical and physical insights are gained and significant conclusions are drawn for various analytical methods for free vibration analysis of plates.

ABSTRACT: The complexity of state-of-the-art tools for shell optimization may limit their applicability in common practice. We propose two shape parametrizations, inserted into a robust and simple procedure, based on linear finite elements and gradient-based optimization. We represent the mid-surface by triangular Bézier surface and ad-hoc heuristic functions. The first method allows searching for a general shape, while in the second one the functions are chosen according to structural and aesthetical criteria. Small number of design variables ensures efficiency. The procedure is applied to Kresge auditorium at MIT. Both parametrizations provide satisfactory results, with slightly better performances of Bézier surface representation.
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“Formulation of the dynamic stiffness of a cross-ply laminated circular cylindrical shell subjected to distributed loads”, Computers & Structures, Vol. 166, pp 42-50, April 2016,
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ABSTRACT: This paper describes a procedure for taking into account distributed loads in the calculation of the harmonic response of a cross-ply laminated circular cylindrical shell using the dynamic stiffness method. This work is a direct continuation of a previous work concerning isotropic materials. Equivalent loads are established on element boundaries to determine the response of the system. Therefore, the vibration analysis is solved with numerical examples in order to determine the performances of this approach. The method allows reducing both the size of the model and computing time, and ensures higher precision compared to the finite element method.


ABSTRACT: The accuracy and reliability of structural analyses are significantly compromised owing to the utilization of simple beam elements to model the global mechanical behaviour of ship hulls. These 1D models entail various assumptions and do not provide accurate and reliable results for hulls with complex structural details, such as cut-outs or reinforcements. The 3D FEM solutions, on the other hand, are computationally expensive. In the present study, refined 1D FE models for the analysis of simplified naval engineering structures have been developed by using the well-known Carrera Unified Formulation (CUF). According to CUF, refined kinematics beam models that go beyond classical theories (Euler, Timoshenko) can be easily developed by expressing the displacement field as an expansion in terms of generic functions, whose form and order are arbitrary. Hence, the stiffness and mass matrices are written in terms of fundamental nuclei, which are independent of the adopted class of beam theory and the FE approximation along the beam axis. As a particular class of CUF models, Lagrange polynomials have been used to formulate beam models at the component scale. According to this approach, each structural component (e.g. hull, longerons, bulkheads, and floors) can be modelled by means of the same 1D formulation. The results clearly demonstrate the enhanced capabilities of the proposed formulation, which is able to replicate solid/shell ANSYS solutions with very low computational efforts.

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ABSTRACT: The objective in this paper is to improve the performance of the 4-node MITC quadrilateral shell finite element, referred to as the MITC4 element (Dvorkin and Bathe, 1984). We propose a new MITC4 shell element, the MITC4+ element, in which the mid-surface membrane strain components are assumed using the concept of the MITC method. The tying membrane strains are obtained from four triangular domains which subdivide the mid-surface of the 4-node quadrilateral shell element. This approach alleviates locking that can happen when the MITC4 shell elements are geometrically distorted in curved geometries. Several basic tests including the isotropy, zero energy mode, and patch tests are performed. Through the solution of various shell problems, the convergence behavior of the MITC4+ shell element is studied to show the improvements reached.

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ABSTRACT: A three-node triangular element with continuous nodal stress (Trig3-CNS) was recently proposed for static analysis. The Trig3-CNS element, which is the development of the partition-of-unity based “FE-Meshfree” quadrilateral element with continuous nodal stress (Quad4-CNS), uses hybrid shape functions that combine the meshfree and finite element shape functions so as to synergize the individual strengths of meshfree and finite element methods. As a result, high order global approximations in Trig3-CNS element could be easily constructed without adding extra nodes and DOFs, thereby achieving high accuracy and convergence rate. In this paper, the element is further applied to conduct free vibration analysis of two-dimensional solids. The numerical tests in the present work demonstrate that Trig3-CNS has higher tolerance to mesh distortion and gives more accurate solution as compared to the three-node triangular element (Trig3) and four-node quadrilateral element (Quad4).


ABSTRACT: Carbon nanotubes (CNTs) have distinct features in their remarkable mechanical, electrical, thermal, and chemical properties. However, material properties of CNTs can often not be validated due to experimental limitations. In this study, we developed finite element models of single-walled carbon nanotubes (SWCNTs) and double-walled carbon nanotubes (DWCNTs) based on molecular mechanics theory to evaluate mechanical properties such as Young’s modulus, ultimate strength, and strain in accordance with chirality. We performed tensile analyses with armchair/zigzag SWCNTs and armchair–zigzag/zigzag–armchair DWCNTs composed of nonlinear beam elements. We validated the proposed FE model of SWCNTs by comparing ultimate stress and strain with conventional approaches.

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ABSTRACT: In this paper, the Hamiltonian approach developed for beam with solid cross-section is generalized to deal with beams consisting of thin-walled panels. The governing equations of plates and cylindrical shells for the panels are cast into Hamiltonian canonical equations and closed-form central and extremity solutions are found. Typically, the end-effect zones for thin-walled beams are much larger than those for beams with solid cross-sections. Consequently, extremity solutions affect the solution significantly. Correct boundary conditions based on the weak form formulation are derived. Numerical examples are presented to demonstrate the capabilities of the analysis. Predictions are found to be in good agreement with those of plate and shell FEM analysis.


ABSTRACT: The paper presents an algorithm for buckling analysis of thin-walled laminated composite beam-type structures. One-dimensional finite element is employed under the assumptions of large displacements, large rotation effects but small strains. The equilibrium equations of a prismatic and straight spatial beam element are formulated using the virtual work principle. Stability analysis is performed in load deflection manner using corotational formulation. The cross-section mid-line contour is assumed to remain not deformed in its own plane, whereas the shear strains of middle surface are neglected. Laminates are modelled on the basis of classical lamination theory. Results have been validated on test examples.

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ABSTRACT: This work presents dynamic analyses of one-dimensional bar and Euler–Bernoulli beam problems with Generalized Finite Element Method (GFEM). Enrichment monomials are trigonometric and exponential functions. A beam free vibration problem is analyzed to assess the element’s robustness and efficiency. Next, an elastodynamic analysis of a bar is performed using several enrichment levels. Finally, a dynamic elastoplastic analysis of a beam problem is carried out. Error measures and nonlinear strains are estimated. Results from GFEM are compared to results from a conventional FE formulation to show GFEM’s level of efficiency in solving Euler–Bernoulli beam elastic as well as elastoplastic dynamic problems.
ABSTRACT: In this paper, we present the formulations of two four-node quadrilateral membrane finite elements with rotational degrees of freedom to analyze geometric linear and nonlinear plane problems. They are based on a plane adaptation of the space fiber rotation concept that considers virtual rotations of a nodal fiber within the element enhancing the displacement vector approximation of low-order elements. An updated Lagrangian approach is chosen to describe large displacement with small strain kinematics. Several geometric linear and nonlinear benchmarks are presented to assess the performance of the proposed membrane elements and the obtained results demonstrate their efficiency.


ABSTRACT: The paper describes various approaches for the mathematical modelling of Adaptive Inflatable Structures (AIS) along with the corresponding numerical methods. The introductory part presents a general idea of adaptive impact absorption (AIA) and the concept of inflatable structures equipped with controllable valves serving for internal pressure control. Application of AIS for adaptive absorption of the impact loading is briefly explained. The paper focuses on diverse methods of modelling of inflatable structures, which are based on interaction between solid walls and fluid enclosed inside. Modelling of the solid walls is based on rigid body dynamics or initial-boundary value problem of solid mechanics. In turn, modelling of the fluid utilizes either classical equilibrium thermodynamics or Navier–Stokes equations. Consequently, four possible combinations of the above approaches are distinguished, precisely analyzed and applied for the modelling of different types of inflatable structures. Each model takes into account controllable valves, which requires introducing additional coupling between parameters defining the valves and selected results of the analysis. Corresponding numerical methods include classical methods of solving ordinary differential equations, finite volume method (FVM) applied for problems with mobile boundaries, finite element method (FEM) applied for problems involving additional ODEs and, finally, FEM coupled with FVM. Proposed numerical methods and software tools are utilized for the simulation of adaptive pneumatic cylinders, adaptive pneumatic fenders and membrane valves.


ABSTRACT: This paper discusses instabilities occurring in thin pressurized membranes, important in biological as well as in engineering contexts. The membranes are represented by only their in-plane stress
components, for which an incompressible isotropic hyper-elastic behavior can be assumed. A hydro-static pressurization can give instabilities in the form of limit points with respect to a loading parameter, but also bifurcations and wrinkling. The hyper-elastic material model itself can also, under some circumstances, lead to a bifurcation situation. The instability situations can be included as constraints in a structural optimization. The paper discusses the formulation, the solution methods and some relevant instability situations. Numerical examples considering the pressurization of a flat and a cylindrical pre-stressed membrane illustrate some aspects of instability.


ABSTRACT: In this work, an original finite element modeling to investigate the effects of a viscoelastic layer on the sound transmission through double-wall sandwich panels is presented. This formulation is obtained from a coupled fluid–structure variational principle taking into account the frequency dependence of the viscoelastic material. The resolution approach is based on a reduced order model generated by a modal projection technique. The sound insulation of the panels is evaluated by computing its sound transmission factor using Rayleigh integral method. An efficient and inexpensive finite element for a sandwich plate with viscoelastic core is developed. Various results are presented in order to validate and illustrate the efficiency of the proposed finite element formulations.

References listed at the end of the paper:
The deflected form after buckling is a combination of obtained buckling modes (single or multiple mode shapes). In the post-buckling stage, the Von-Karman’s compatibility equation is solved exactly with the assumption that the deflected form after buckling is a combination of obtained buckling modes (single or multiple mode shapes).
The principle of minimum potential energy is invoked to solve for the unknown coefficients in the assumed out-of-plane deflection and rotations functions.


ABSTRACT: Functionally graded plates whose material properties vary continuously through the thickness are modelled as exactly equivalent plates composed of up to four isotropic layers. Separate models are derived for analysis using classical plate theory, first-order and higher-order shear deformation theory. For cases where Poisson’s ratio varies through the thickness, the integrations required to obtain the membrane, coupling and out-of-plane stiffness matrices are performed accurately using a series solution. The model is verified by comparison with well converged solutions from approximate models in which the plate is divided into many isotropic layers. Critical buckling loads and undamped natural frequencies are found for a range of illustrative examples.

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ABSTRACT: The medium frequency vibration of a built-up plate structure is studied by an energy flow analysis which extends the concept of statistical energy analysis. The propagative waves of the plates are considered as subsystems that carry and spread energy. Symplectic analytical solutions for mode count, modal density and group velocity of each wave subsystem are obtained based on accurate consideration of the plate geometry and boundary conditions, while the joint vibrational behavior is described by a finite element model. The input mobility and coupling factor associated with each wave subsystem are accurately obtained using a hybrid analytical wave and finite element formulation. Based on the power balance relation of each wave subsystem, the system energy equations are established. Numerical examples for built-up structures comprising rectangular plates demonstrate high accuracy and efficiency. In contrast with statistical energy analysis, the energy of each wave subsystem can be obtained, facilitating the understanding and control of structural vibration and local response. The computational time of the hybrid formulation decreases significantly with increasing length/width ratio of the plates. The wave scattering property of the joint can also be obtained and used to replace the finite element model in repetitive analysis.

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ABSTRACT: The present paper approaches fluid-structure interaction by means of a 4-equation model. Experimental data collected from a straight copper pipe rig lying directly on the lab floor is used for the model validation in terms of wave shape, timing and damping. The main focus lies on the friction coupling modelling considering skin and dry friction. For skin friction three approaches are analysed: quasi-steady, Brunone’s and Trikha’s unsteady friction. For dry friction Coulomb’s model is added in the beam momentum conservation equation. Results present a good fitting between experimental and numerical data, showing the dissipative effect of dry friction phenomenon which complement that of skin friction, specially in the short term simulation.


ABSTRACT: This paper presents a class of arc-length methods for the quasi-static analysis of problems involving material and geometric nonlinearities. A constraint equation accounting for geometric and dissipative requirements is adopted: the geometric part refers to the Riks and Crisfield equations, while the dissipative one refers to the dissipated energy. The approach allows for a continuous variation of the nature of the constraint, and a switch criterion is not needed to trace the elastic and the dissipative parts of the equilibrium paths. To illustrate the robustness and the efficiency of the methods, three examples involving geometric and material nonlinearities are discussed.

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ABSTRACT: A method is presented to study the free vibrations of rectangular laminated composite plates with general layups and arbitrary boundary conditions. Based on the first-order shear deformation theory, the governing differential equations and boundary conditions are deduced via Hamilton’s principle. Generalised displacements are expanded as series with Legendre polynomials as the base functions. A generalised eigenvalue problem is obtained by following a variational approach, where energy functional is extremised and boundary conditions are introduced by means of Lagrange multipliers. In order to overcome some difficulties in obtaining the natural frequencies and corresponding mode shapes, a new numerical strategy is proposed.

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ABSTRACT: This paper proposes a simple and efficient approach based on a moving Kriging interpolation-based (MKI) meshfree method and a two-variable refined plate theory for static, free vibration and buckling analyses of isotropic plates. A generalized formulation through various higher-order distributed functions is presented. Shear correction factors are not required due to zero-shear stresses satisfied at the top and bottom surfaces of plates. The governing partial differential equations are discretized by a weak Galerkin form and numerically solved by using MKI basis functions. The present theory considers the transverse, shear deflections and their derivations while only the deflections are included in approximate solutions. A new correlation function is proposed to construct MKI shape functions so that the underlying solution becomes stable. In addition, a rotation-free technique based on isogeometric analysis is presented to enforce boundary conditions of normal slopes for clamped plate cases, which is simpler and more efficient than several existing approaches. Numerical results show excellent performance of the present method.

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ABSTRACT: The critical buckling parameters and natural frequencies of defective functionally graded material (FGM) plates with internal cracks or voids are extracted by using an effective numerical approach, combining the extended isogeometric analysis based on non-uniform rational B-spline (NURBS) and Reissner-Mindlin plate theory. The defects are captured by enrichment while the discontinuities are represented by level sets. The shear locking is treated by multiplying a factor into the shear terms. Numerical examples of imperfect FGM plates demonstrate the accuracy of the present method. Effects of gradient index, discontinuity location, crack-length, width-to-thickness, boundary conditions, etc. on frequencies and buckling coefficients are investigated.

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ABSTRACT: We have previously proposed a numerical node-based parameter-free shape optimization method for designing the optimal free-form surface of shell structures. In this paper, this method is extended to deal with two vibration problems including a vibration eigenvalue maximization problem and a frequency response.
minimization problem. To avoid the repeated eigenvalue problem when a specified vibration eigenvalue is maximized, we provide two optional approaches, i.e., tracking the specified natural mode or increasing all the repeated eigenvalues. Each vibration problem is formulated as a distributed-parameter shape optimization problem, and the derived shape gradient function is applied to the gradient method for the shells proposed by the authors, where the shape gradient function is used as a distributed force function to vary the surface. With this method, the optimal and smooth free-form shape including a natural bead pattern can be obtained. Several calculated examples are presented to demonstrate the effectiveness of the proposed method for the free-form design of shell structures involving vibration problems.


ABSTRACT: This paper presents an efficient computational method for predicting the onset of buckling of axially loaded, corrugated or stiffened cylindrical shells. This method is a modification of the Bloch wave method which builds on the stiffness matrix method. A numerical method and an efficient algorithm have been developed to implement the proposed method in the commercial finite element package Abaqus. Numerical examples have shown that, compared to the nonlinear buckling analyses based on detailed full finite element models, the proposed method can obtain highly accurate buckling loads and buckling modes and can achieve very significant reductions in computational time.


http://www.sciencedirect.com/science/journal/00207683


ABSTRACT: A new trigonometric shear deformation theory for isotropic and composite laminated and sandwich plates, is developed. The new displacement field depends on a parameter “m”, whose value is determined so as to give results closest to the 3D elasticity bending solutions. The theory accounts for adequate distribution of the transverse shear strains through the plate thickness and tangential stress-free boundary conditions on the plate boundary surface, thus a shear correction factor is not required. Plate governing equations and boundary conditions are derived by employing the principle of virtual work. The Navier-type exact solutions for static bending analysis are presented for sinusoidally and uniformly distributed loads. The accuracy of the present theory is ascertained by comparing it with various available results in the literature. The
results show that the present model performs as good as the Reddy’s and Touratier’s shear deformation theories for analyzing the static behavior of isotropic and composite laminated and sandwich plates.

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“A planar rod model with flexible thin-walled cross-sections. Application to the folding of tape springs”, International Journal of Solids and Structures, Vol. 49, pp 73-86, January 2012,

ABSTRACT: This paper is focused on the modeling of rod-like elastic bodies that have an initially curved and thin-walled cross-section and that undergo important localized changes of the cross-section shape. The typical example is the folding of a carpenter’s tape measure for which the folds are caused by the flattening of the cross-section in some localized areas. In this context, we propose a planar rod model that accounts for large displacements and large rotations in dynamics. Starting from a classical shell model, the main additional assumption consists in introducing an elastica kinematics to describe the large changes of the cross-section shape with very few parameters. The expressions of the strain and kinetic energies are derived by performing an analytical integration over the section. The Hamilton principle is directly introduced in a suitable finite element software to solve the problem. The folding, coiling and deployment of a tape spring is studied to demonstrate the ability of the model to account for several phenomena: creation of a single fold and associated snap-through behavior, splitting of a fold into two, motion of a fold along the tape during a dynamic deployment, scenarios of coiling and uncoiling of a bistable tape spring. This 1D model may also be relevant for future applications in biomechanics, biophysics and nanomechanics.

References listed at the end of the paper:
ABSTRACT: This paper is an attempt to extend the approach of the second-order work criterion to the analysis of structural system instability. Elastic structural systems with a finite number of freedoms and subjected to a given loading are considered. It is shown that a general equation, relating the second-order time derivative of the kinetic energy to the second-order work, can be derived for kinetic perturbations. The case of constant, nonconservative loadings are then investigated, putting forward the role of the spectral properties of the symmetric part of the tangent stiffness matrix in the occurrence of instability. As an illustration, the case of the nonconservative loadings are then investigated, putting forward the role of the spectral properties of the kinetic energy to the second-order work criterion.

References listed at the end of the paper:

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“Nonlinear vibrations and instabilities of a stretched hyperelastic annular membrane”, International Journal of Solids and Structures, Vol. 49, Nos.3-4, pp 514-526, February 2012,
https://doi.org/10.1016/j.ijsolstr.2011.10.019

ABSTRACT: The mathematical modeling for the nonlinear vibration analysis of a pre-stretched hyperelastic annular membrane under finite deformations is presented. The membrane is initially fixed along the inner boundary and then subjected to a uniform radial traction along its outer circumference and fixed along the outer boundary. The pre-stretched membrane in then subjected to a transversal harmonic pressure. The membrane material is assumed to be homogeneous, isotropic, and neo-Hookean. First, the solution of the radially stretched membrane is obtained analytically and numerically by the shooting method. The equations of motion of the stretched membrane are then obtained. By analytically and numerically solving the linearized equations of motion, the vibration modes and frequencies of the hyperelastic membrane are obtained, and these normal
modes are used, together with the Galerkin method, to obtain reduced order models for the nonlinear dynamic analysis. A parametric analysis of the nonlinear frequency-amplitude relations, resonance curves, bifurcation diagrams and basins of attraction show the influence of the initial stretching ratio and membrane geometry on the type and degree of nonlinearity of the hyperelastic membrane under large amplitude vibrations. To check the accuracy of the reduced order models and the influence of the simplifying hypotheses on the results, the same problem is also analyzed using the finite element method. Excellent agreement is observed.


ABSTRACT: The effect of initial imperfections on the parametric vibrations of cylindrical shells is analyzed. The shell has moderate amplitudes of vibrations; therefore, geometrically nonlinear theory is used. The shell vibrations are described by the Donnell equations. The interaction of three pairs of conjugate modes is considered in the analysis. Therefore, the shell vibrations are described by six-degrees-of-freedoms nonlinear dynamical system. The multiple scales method and the continuation technique are used to analyze the system dynamics. The role of initial imperfections in nonlinear dynamics of shell is discussed using frequency responses.

References listed at the end of the paper:
ABSTRACT: The multistability of composite thin structures has shown potential for morphing applications. The present work combines a Ritz model with path-following algorithms to study bistable cylindrical panels. Polynomial discretisations of the displacements field are used to predict stable shapes’ geometry and other aspects of the nonlinear structural behaviour. In order to improve the inherently poor conditioning properties of Ritz approximations of slender structures, a non-dimensional Shell Lamination Theory with Sanders nonlinear strains is developed and presented. An investigation on the relative importance of different nonlinear strain terms is shown to provide useful insight into the applicability of common assumptions about shell kinematics.
In the current approach, we continue numerical solutions in parameter space, that is, we path-follow equilibrium configurations as the control parameter varies, find stable and unstable configurations and identify bifurcations. The numerics is carried out using a set of in-house Matlab® routines for numerical continuation. Results are compared with detailed finite elements analysis throughout the course of the paper.

References listed at the end of the paper:
ABSTRACT: A thin sheet clamped at opposite ends and stretched develops wrinkles parallel to the direction of the applied tensile strain due to the hindered Poisson lateral contraction at the clamps. To study this phenomenon, a variational model recently proposed by Puntel, Deseri and Fried is adopted. The relevant energy functional includes bending and membranal contributions and is minimized subject to a constraint on the area of the mid-surface of the sheet. A fourth order partial-differential equation is henceforth obtained and numerically implemented using B-splines. Predictions are obtained concerning the number of wrinkles, critical applied stretches, and scaling relationships for wrinkle amplitude and wavelength. Both a linearized version of the boundary-value problem based on the small-slope approximation and a fully nonlinear one are considered: their results are found to be in good agreement for the whole range of applied stretches taken into account. Comparisons with previous analytical results by Puntel, Deseri and Fried, who used different boundary conditions and an Ansatz on the deflection function are also provided. The numerical results substantially confirm the validity of the analytical predictions. The present work provides then an alternative numerical method for the study of wrinkling in thin sheets and supports the use of analytical and semi-analytical solutions
as viable options for specific geometries. Though further investigation, particularly experimental, is still needed, extensive comparisons of the results with other studies available in the literature provide confirmation for the scaling laws and signal that predicted values of the critical stretches may only be accurate for higher length-to-width aspect ratios.

References listed at the end of the paper:

Y. Xia (1), M.I. Friswell (1) and E.I. Saavedra Flores (1,2)
ABSTRACT: The design of corrugated panels has wide application in engineering. For example corrugated panels are often used in roof structures in civil engineering. More recently corrugated laminates have been suggested as a good solution for morphing aircraft skins due to their extremely anisotropic behaviour. The optimal design of these structures requires simple models of the panels or skins that may be incorporated into multi-disciplinary system models. Thus equivalent material models are required that retain the dependence on the geometric parameters of the corrugated skins or panels. An homogenisation-based analytical model, which could be used for any corrugation shape, is suggested in this paper. This method is based on a simplified geometry for a unit-cell and the stiffness properties of original sheet. This paper outlines such a modelling strategy, gives explicit expressions to calculate the equivalent material properties, and demonstrates the performance of the approach using two popular corrugation shapes.

References listed at the end of the paper:
ABSTRACT: This study examines the effect of randomness of the cellular microstructure on the calculated compressive response of a class of open-cell aluminum alloy foams. The foams are modeled using realistic random soap froth with $N^3$ cells generated using the Surface Evolver software. The ligaments are made straight but with non-uniform cross sectional area distributions that mimic those of the physical foams. The models are also assigned the density and anisotropy measured. The ligaments are modeled as shear deformable beams with the elasto-plastic material behavior of the Al-alloy. The microstructure is discretized with finite elements using LS-DYNA, which allows for beam-to-beam contact on the outer surface of the ligaments. $10^3$ cell domains compressed between rigid planes are shown to reproduce the measured compressive responses in both the rise and transverse directions. This includes the complete response from the initial elastic regime, through “yielding,” the extended stress plateau, to densification. More importantly, localized bands of crushed cells that develop and gradually spread throughout the domain resemble closely experimental observations made using X-ray tomography. This is a major improvement over previous models that idealized monodispersed foams as periodic Kelvin cells, and should allow modeling of polydisperse foams. The contact algorithm, friction between ligaments, and generally the discretization play crucial roles in the accuracy of the calculation as well as their numerical stability.

References listed at the end of the paper:

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ABSTRACT: This paper presents the test results under quasi-static and impact loadings for a series of aluminium honeycombs (3003 and 5052 alloys) of different cell sizes, showing significantly different enhancements of the crushing pressure between 3003 honeycombs and the 5052 ones. A comprehensive numerical investigation with rate insensitive constitutive laws is also performed to model the experimental results for different cell size/wall thickness/base material, which suggests that honeycomb crushing pressure enhancement under impact loading is mostly due to a structural effect. Such simulated tests provide detailed local information such as stress and strain fields (in the cell wall) during the whole crushing process of honeycombs. A larger strain (in the cell wall) under impact loading than for the quasi-static case before each successive folding of honeycombs is observed, because of the lateral inertia effect. Thus, differences of the ratios of the stress increase due to strain hardening over the yield stress between 3003 and 5052 alloys lead to the different enhancements of crushing pressure. This result illustrates that the lateral inertia effect in the successive folding of honeycombs is the main factor responsible for the enhancement of the crushing pressure under impact loading.

References listed at the end of the paper:

https://doi.org/10.1016/j.ijsolstr.2012.03.045

ABSTRACT: The dynamic compressive response of a sandwich plate with a metallic corrugated core is predicted. The back face of the sandwich plate is held fixed whereas the front face is subjected to a uniform velocity, thereby compressing the core. Finite element analysis is performed to investigate the role of material inertia, strain hardening and strain rate hardening upon the dynamic collapse of the corrugated core. Three classes of collapse mode are identified as a function of impact velocity: (i) a three-hinge plastic buckling mode of wavelength equal to the strut length, similar to the quasi-static mode, (ii) a ‘buckle-wave’ regime involving inertia-mediated plastic buckling of wavelength less than that of the strut length, and (iii) a ‘stubbing’ regime, with shortening of the struts by local fattening at the front face. The presence of strain hardening reduces the regime of dominance of the stubbing mode. The influence of material strain rate sensitivity is evaluated by introducing strain rate dependent material properties representative of type 304 stainless steel. For this choice of material, strain rate sensitivity has a more minor influence than strain hardening, and consequently the dynamic collapse strength of a corrugated core is almost independent of structural dimension.

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ABSTRACT: In this paper, we present a new Fourier-related double scale analysis to study instability phenomena of sandwich structures. By using the technique of slowly variable Fourier coefficients, a zig–zag theory based microscopical sandwich model is transformed into a macroscopical one that offers three numerical advantages. Firstly, only the envelopes of instability patterns are evaluated and this leads to a significant improvement on computational efficiency, especially when dealing with high wavenumber wrinkling phenomena. Secondly, the proposed macroscopical model allows one to select modal wavelength, which makes easy to control non-linear calculations. Thirdly, in contrast to Landau–Ginzburg envelope equations, it may also remain valid away from the bifurcation point and the coupling between global and local instabilities can be accounted for. The established non-linear system is solved by asymptotic numerical method (ANM), which is more reliable and less time consuming than other iterative classical methods. The proposed double scale analysis yields accurate results with a significant reduced computational cost.

References listed at the end of the paper:
REFERENCES LISTED AT THE END OF THE PAPER:


ABSTRACT: Dehydrated core/shell fruits, such as jujubes, raisins and plums, show very complex buckles and wrinkles on their exocarp. It is a challenging task to model such complicated patterns and their evolution in a virtual environment even for professional animators. This paper presents a unified physically-based approach to simulate the morphological transformation for the core/shell fruits in the dehydration process. A finite element method (FEM), which is based on the multiplicative decomposition of the deformation gradient into an elastic part and a dehydrated part, is adopted to model the morphological evolution. In the method, the dehydration pattern can be conveniently controlled through physically prescribed parameters according to the geometry and material of the real fruits. The effects of the parameters on the final dehydrated surface patterns are investigated and summarized in detail. Experiments on jujubes, wolfberries, raisins and plums are given, which demonstrate the efficacy of the method.

References listed at the end of the paper:


ABSTRACT: The paper focuses on wrinkling of lined pipes (sometimes referred to as clad pipes) under bending loading, where a corrosion-resistant thin-walled liner is fitted inside a carbon–steel outer pipe. The problem is solved numerically, using nonlinear finite elements to simulate liner pipe deformation and its interaction with the outer pipe. Stresses and strains are monitored throughout the deformation stage, detecting possible detachment of the liner from the outer pipe and the formation of wrinkles. The wrinkling behavior of elastic and elastic–plastic (steel) lined pipes under bending is examined. The results indicate that the lateral confinement of the liner pipe due to the deformable outer pipe and its interaction with the outer pipe has a decisive influence on the wrinkling behavior of the lined pipe. It is also shown that the behavior is characterized by a first bifurcation in a uniform wrinkling pattern, followed by a secondary bifurcation. The values of corresponding buckling curvature are determined and comparison with available experimental results is conducted in terms of wrinkle height development and the corresponding buckling wavelength. The results of the present research can be used for safer design of lined pipes in pipeline applications.

References listed at the end of the paper:

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ABSTRACT: We study a variation on the classical problem of the buckling of an elastica. The elastica models a nanoscale sheet that interacts with a rigid substrate by intermolecular forces. We formulate a buckling problem in which the sheet is perpendicular to the substrate and a load is applied to the edge of the sheet further from the substrate. Our study is motivated by problems in nanomechanics such as the bending of a graphene sheet interacting with a rigid substrate by van der Waals forces. After identifying a trivial branch, we combine computation and analysis to determine the stability and bifurcations of solutions along this branch. We also study the boundary-layer problem that arises if the length of the sheet is large compared to the characteristic length over which the van der Waals interaction is significant.

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ABSTRACT: The effect of additional kinematic constraints on eigenfrequencies of non conservative systems presenting a non symmetric stiffness matrix is investigated with the use of the second order work criterion. It is shown that there are always additional constraints that may soften structural systems, from both buckling and vibration points of view. The steps for building such constraints are given, consequences on stability are discussed and several illustrating examples are presented.

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ABSTRACT: Incremental equilibrium equations and corresponding boundary conditions for an isotropic, hyperelastic and incompressible material are summarized and then specialized to a form suitable for the analysis of a spherical shell subject to an internal or an external pressure. A thick-walled spherical shell during inflation is analyzed using four different material models. Specifically, one and two terms in the Ogden energy formulation, the Gent model and an formulation recently proposed by Lopez-Pamies. We investigate the existence of local pressure maxima and minima and the dependence of the corresponding stretches on the material model and on shell thickness. These results are then used to investigate axisymmetric bifurcations of the inflated shell. The analysis is extended to determine the behavior of a thick-walled spherical shell subject to an external pressure. We find that the results of the two terms Ogden formulation, the Gent and the Lopez-Pamies models are very similar, for the one term Ogden material we identify additional critical stretches, which have not been reported in the literature before.

References listed at the end of the paper:
ABSTRACT: Hollow-sphere structures could represent an alternative to classical cellular materials, such as metal foams or honeycombs, for various structural applications; such stainless steel random structures are already on the market. One advantage of hollow-sphere structures unlike metal foams ensues from the possibility to stack the spheres regularly, even if in the literature there are only examples of limited size regular stackings for the moment. Higher mechanical properties than those of random cellular structures are expected for such regular structures according to modelling studies. Nevertheless, because of the difficulty in processing perfect regular stackings, it seems to be critical to study the influence of architectural defects on the overall mechanical behaviour of these cellular structures. Emphasis is on geometrical defects by introducing some dispersions on the sphere thickness and the meniscus size. Influences of both the magnitude of dispersion and the distribution of the defects on the mechanical behaviour of hollow-sphere structure are investigated. Especially, collapse mechanisms resulting from plasticity and their inhomogeneous localisation in the structure are studied in details. The case of periodic defects is addressed too in order to compare the mechanical response of infinite stackings to that of finite ones. This work highlights the significant influence of the defects on the effective mechanical behaviour of hollow-sphere structures. Most of the time, geometrical dispersion and defects are detrimental for the stacking behaviour, especially when understructures made of the defective hollow spheres or menisci are observed.

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ABSTRACT: This work deals with the development, finite element implementation and application of a generalised beam theory (GBT) formulation intended to analyse the localised, local, distortional and global buckling behaviour of thin-walled steel beams and frames subjected to transverse loads applied at various member cross-section points (away from its shear centre). In order to take into account the effects stemming from the transverse load position, the GBT buckling formulation must incorporate geometrical stiffness terms stemming from either (i) the internal work of the pre-buckling transversal normal stresses (“exact” formulation) or (ii) the external work of the applied transverse loads (approximate/simplified formulation). After presenting the main concepts and procedures involved in the development of the above “exact” and simplified formulations, the paper addresses the corresponding numerical implementations. Then, in order to illustrate their application and capabilities, as well as the limitations of the simplified formulation, various numerical result sets are presented and discussed. The accuracy of the GBT-based results is assessed through the comparison with “exact” values, yielded by rigorous shell finite element analyses carried out in the code Ansys. References listed at the end of the paper:


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ABSTRACT: The problem is concerned with the parametric oscillations of a beam subjected to a longitudinal deterministic or stochastic force. The equation, describing the motion of the Euler–Bernoulli beam, is based on the nonlocal elasticity theory and nonlocal damping. The dynamic stability problem is solved for the beam, made from micro- and nano-materials. Asymptotic stability and almost sure asymptotic stability criteria involving a damping coefficient, structure and loading parameters are derived using the method of the maximal Liapunov exponent.

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ABSTRACT: The paper deals with geometrically nonlinear finite element analysis of folded-plate and shell structures. A Koiter asymptotic approach is proposed, based on the reuse of a linear element in the nonlinear context through a corotational formulation. The corotational approach represents a simple and effective way to satisfy the basic requirement of Koiter analysis, i.e. full objectivity in the finite element modeling. In fact, starting simply from a suitable linear finite element and implementing the corotational algebra proposed in Garcea et al. (2009), Zagari (2009) lead to objective explicit expressions for the first four variations of the strain energy which are needed by asymptotic analysis. The shell element used here is the flat shell quadrangular element with 4 nodes and 6 dofs per node proposed in Madeo et al. (2012) and called MISS-4: a mixed element, based on the Reissner–Mindlin plate theory, with an Allman-like quadratic interpolation for displacements and an equilibrated isostatic interpolation for the stress resultants. The element is free from locking and spurious zero-energy modes, so it appears a suitable candidate for nonlinear corotational analysis. The results of the numerical validation show the effectiveness and accuracy of the proposed approach, and its excellent overall robustness for both mono- and multi-modal buckling problems, also in the presence of strong nonlinear pre-critical behavior.

References listed at the end of the paper:

ABSTRACT: The unsymmetrical discharge of a granular solid from a thin-walled cylindrical metal silo is well known to be a potential prelude to catastrophic buckling failure. The mechanics of this structure have only been very slowly unraveled in recent years with the help of powerful nonlinear finite element analyses. The associated buckling collapse is now known to be caused by localized axial membrane compression and occurs under predominantly elastic conditions. However, such high compressive stress concentrations are also known to produce significantly less imperfection sensitivity than uniform compression. For this reason, the search for an appropriately detrimental imperfection form under eccentric discharge has been quite a long one. This study presents and explores a novel form of long-wave imperfection using a superellipse to parametrise the entire shell geometry. This imperfection, termed ‘superelliptical flattening’, is judged to be potentially present in practical silo construction, and is shown to cause significant decreases in the nonlinear buckling strength of an imperfect slender silo under eccentric discharge.

References listed at the end of the paper:

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ABSTRACT: The pseudo-bistable phenomenon already shown to exist in the case of spherical domes is demonstrated in pre-stressed composite panels. This new concept for morphing structures uses intrinsic material viscoelasticity to actuate the structure passively between its different states. A pseudo-bistable structure is first snapped into a buckled state and allowed to relax under a constant strain. Once the actuation is removed, the structure remains in its buckled configuration for a period of time, before quickly returning to its initial state. In this paper, the principles of the pseudo-bistable behaviour are first outlined using a discrete truss model. An equivalent numerical model is then used to show how the time-dependent behaviour imparted to the structure can be controlled by the choice of the pre-straining boundary conditions. Next, the effect of a composite layup on the pseudo-bistable behaviour is shown, and a volume fraction limit is given. Finally, preliminary experimental results confirm the numerical simulations.

References listed at the end of the paper:

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ABSTRACT: An analytical bifurcation solution is presented for axisymmetric wrinkling on a lined pipe under axial compression without internal pressure. The internal liner consists of corrosion-resistant alloy (CRA), it is not metallurgically bonded to the carbon steel backing pipe, and it is assumed to be in a snug fit condition: i.e. there is no gap between the liner and the backing pipe, but also no prestress that would lead to a positive contact or gripping pressure between the liner and the backing. The backing is assumed to be much thicker than the
liner, so that wrinkling-related deformations of the backing pipe can be neglected. The solution indicates that the incipient wrinkling strain for the snug-fit pipe without any imperfections is the same as the incipient wrinkling strain for a single pipe with (5/3) times the wall thickness of the liner, and the same midsurface diameter, as determined by the solution of Batterman (1965) for the case of small strains, or Peek (2000a) for the case of finite strains. For the case when the liner-pipe friction is included the factor (5/3) increases slightly. A positive contact pressure due to prestress or internal pressure raises the wrinkling strain, whereas imperfections (e.g. at seam or girth welds) reduces it. The snug-fit solution accounts for neither, but nevertheless provides a useful reference wrinkling strain, and can be used to validate numerical solutions, and it gives a bifurcation modeshape and wrinkle length that can be used in numerical models to investigate post-bifurcation behaviour.

References listed at the end of the paper:
12. E.S. Focke, E. Karjadi, A.M. Gresnigt, J. MeekReeling of tight fit pipe (TFP)

ABSTRACT: The mechanical response and fracture of metal sandwich panels subjected to multiple impulsive pressure loads (shocks) were investigated for panels with honeycomb and folded plate core constructions. The structural performance of panels with specific core configurations under multiple impulsive pressure loads is quantified by the maximum transverse deflection of the face sheets and the core crushing strain at mid-span of the panels. A limited set of simulations was carried out to find the optimum core density of a square honeycomb core sandwich panels under two shocks. The panels with a relative core density of 4%–5% are shown to have minimum face sheet deflection for the loading conditions considered here. This was consistent with the findings related to the sandwich panel response subjected to a single intense shock. Comparison of these results showed that optimized sandwich panels outperform solid plates under shock loading. An empirical method for prediction of the deflection and fracture of sandwich panels under two consecutive shocks – based on finding an effective peak over-pressure – was provided. Moreover, a limited number of simulations related to response and fracture of sandwich panels under multiple shocks with different material properties were performed to highlight the role of metal strength and ductility. In this set of simulations, square honeycomb sandwich panels made of four steels representing a relatively wide range of strength, strain hardening and ductility values were studied. For panels clamped at their edge, the observed failure mechanisms are core failure, top face failure and tearing at or close to the clamped edge. Failure diagrams for sandwich panels were constructed which reveal the fracture and failure mechanisms under various shock intensities for panels subjected to up to three consecutive shocks. The results complement previous studies on the behavior and fracture of these panels under high...
intensity dynamic loading and further highlights the potential of these panels for development of threat-resistant structural systems.

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ABSTRACT: The problem of deducing, from the Föppl–Von Kármán energy functional, a sequence of reduced discrete models having few degrees of freedom is analyzed. Similar discrete models have been recently intensively studied to analyze the multistable behavior of shallow shells, the bifurcations of composite laminates under temperature loads or the wrinkling in soft tissues. In particular three relevant examples are discussed and compared among them, where the curvature is assumed uniform, linearly and quadratically varying through the shell. While the uniform-curvature assumption dates back to Mansfield (1962), linear variations of the shell curvatures can describe smooth transitions between everted configurations, while quadratic variations can account for the, usually disregarded, bending boundary conditions. For their deduction we revisit the Maxwell–Mohr method: accordingly, a sequence of auxiliary elliptic problems of plane elasticity is solved to determine the statically unknown membranal stresses. This is a key ingredient for the presented models to compare extremely well with Finite Element approximations or with literature models with far more degrees of freedom.

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ABSTRACT: This work presents several higher-order atomistic-refined models for the static, free vibration and stability analysis of three-dimensional nano-beams. Stemming from a one-dimensional approach and thanks to a compact notation for the a priori kinematic field approximation over the beam cross-section, the model derivation is made general regardless the approximation order. This latter is a free parameter of the formulation. Several higher-order beam theories can be obtained straightforwardly. Classical beam models, such as Euler–Bernoulli’s and Timoshenko’s, are obtained as particular cases. The assumed constitutive equations for orthotropic materials account for the surface free energy effect as well as the third-order elastic constants. The
resulting stiffness coefficients depend upon the cross-section side length. The governing equations and boundary conditions are variationally obtained through the Principle of Virtual Displacements. A Navier-type, strong form solution is adopted. Simply supported beams are, therefore, investigated. Static, free vibration and buckling analyses are carried out in order to investigate the effect of the cross-section side as well as the crystallographic plane orientation on the mechanical response. Beams with different values of the length-to-thickness ratio are considered. Results are validated in terms of accuracy and computational costs towards three-dimensional FEM solutions. Numerical investigations show the advantages of refined beam models over the classical ones demonstrating that accurate results can be obtained with reduced computational costs.

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ABSTRACT: Variable angle tow (VAT) placement techniques provide the designer with the ability to tailor the point-wise stiffness properties of composite laminates according to structural design requirements. Whilst VAT laminates exhibiting substantial gains in buckling performance have been shown previously, beneficial ways of using VAT techniques to improve structural performance of composite laminates in the postbuckling regime remain unclear. In the present study, a semi-analytical formulation based on a variational approach is developed and the Rayleigh–Ritz method is subsequently applied to solve the postbuckling problem of VAT plates. The generality of the proposed formulation allows effective modelling of the pure or mixed stress boundary conditions and also provides a computationally efficient means to determine the postbuckling strength of VAT plates. The proposed methodology is applied to the postbuckling problem of simply supported VAT plates under uniform edge displacement compression. To show the accuracy and robustness of the proposed approach, results are validated using finite element analysis. The postbuckling characteristics of VAT plates subject to different in-plane boundary conditions are analysed by studying their nonlinear load-end shortening and transverse deflection responses. Furthermore, a parametric study on the postbuckling response of VAT plates with linear variation of fibre angle is performed and the stiffness values of VAT plates in both pre- and postbuckling ranges are compared with the results of straight-fibre laminates.
ABSTRACT: A pseudo beam model with 3-node beam element is proposed to simulate the modal behavior of the wrinkled single-layered graphene sheets (SLGS) based on molecular structural mechanics (MSM) method. The wrinkling characteristics are simulated using a direct perturbed-force technique originated from the continuum theory. The primary bifurcation and the secondary wrinkling behaviors are investigated so as to obtain the characteristics of the formation and the evolution of the wrinkles. The wrinkled shape, stress and effective mass are introduced into the modal model using the updated geometry technique. The effects of the wrinkles on the vibration characteristics of the SLGS are then interpreted by comparing with the unwrinkled case. The effects of the aspect ratio on the modal behavior of wrinkled SLGS are further studied. Based on the MSM simulation results and the continuum thin plate model, a prediction model is proposed to obtain the natural frequency of wrinkled SLGS. The predictions agree well with the MSM simulations. The results and observations are good references to design a wrinkled highly frequency nano-devices.

ABSTRACT: A nonlinear model of visco-elastic balloon, interposed between a couple of moving rigid bodies, is formulated. The pneumatic structure is modeled as a thin, infinitely long cylindrical membrane, pre-stressed by an internal pressure. External pressure is assumed to be zero. The pushing bodies are modeled as a couple of frictionless rigid parallel plates, approaching each other normally, and causing squeezing of the pneumatic body. Motion is assumed to be slow, in such a way that any inertial effects are negligible. Both cases of long and short plates are considered, the latter entailing the possibility of puncture of the deformable body. A thermoplastic polyurethane material behavior is considered, and proper constitutive relationships adopted. Several models are formulated, which differ for constitutive laws (inextensible, elastic, linearly or non linearly visco-elastic) and/or for kinematic description (small strains and displacements or finite kinematics). The governing mixed differential–algebraic equations are analytically or numerically integrated for several impressed motion time-histories and the main features of the phenomenon are investigated.

ABSTRACT: This works follows a generalised continuum framework developed by Sansour (1998) to derive a strain gradient formulation suitable to address scale effects of structures where one dimension is very small (e.g.
thin films, nano tubes etc.). Whereas a previous strain gradient approach by Sansour et al. (2009) considered the fully three-dimensional setting, the approach here proposes a shell theory which aims to run computations of thin structures more efficiently and to include scale effects. The theory features a generalised deformation description, new strain and stress measures. As consequence of these new quantities a corresponding generalised variational principle is formulated. The approach is completed by Dirichlet boundary conditions for the displacement field and its derivatives. A numerical example is presented based on a meshfree formulation which provides the necessary continuity.

References listed at the end of the paper:
ABSTRACT: This work analyzes nonlinear buckling of a spherical shell imperfectly bonded to an elastic medium with imperfect interface. The analysis is carried out using a shell theory that accounts for geometric and material nonlinearities. The interface conditions are modeled using a modified variational principle. The results are compared with available data in the literature, demonstrating the accuracy and applicability of the proposed approach. The study highlights the importance of considering interface effects in the design of spherical shells.
infinite elastic matrix under a compressive remote load. The inclusion is modeled using a nonlinear shell formulation and the matrix is treated as a linear elastic body. Imperfect bonding conditions are realized through a linear spring interface model. A variational method is used to derive the governing differential equations, which are cast into a tractable set of nonlinear algebraic equations using the Galerkin method. An incremental iterative technique based on the modified Newton–Raphson method is employed to find the critical load of the system. The accuracy and convergence properties of the proposed method are validated through finite element analysis. The study is relevant to the analysis of compressive failure of syntactic foams used in marine and aerospace applications. Results are specialized to glass particle-vinyl ester matrix syntactic foams to test the hypothesis as to whether microballoons’ buckling is a dominant failure mechanism in such composites under compression. Parametric studies are conducted to understand the effect of interfacial properties and inclusion wall thickness on the overall mechanical behavior of the composite. Comparisons between analytical findings and experimental results on compressive response of syntactic foams and isolated microballoons indicate that inclusion buckling is unlikely a determinant of compressive failure in vinyl ester-glass systems. In particular, the matrix is found to exert a beneficial stabilizing effect on the inclusions, which fail under brittle fracture before the onset of buckling.

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Waals forces also cause a decrease in the values of the critical compressing strain and the magnitude of this conditions occur between the tubes. Moreover, it is established that an increase in the deformation to decrease significantly with respect to those obtained in the case where complete contact results. In particular, it is established that $f$ is ignored and where full contact between the tubes is assumed are presented and compared with the mentioned deformation and on the outer surface of the inner tube (cylinder) of the DWCNT full slipping conditions occur. At the same cylinders between which there is free space. It is assumed that on the inner surface of the outer tube (cylinder) and on the outer surface of the inner tube (cylinder) of the DWCNT full slipping conditions occur. At the same time, it is assumed that the difference between the radial displacements of the adjacent surfaces of the tubes resists with the van der Waals forces. On the interface between the matrix and DWCNT complete contact conditions are satisfied. Numerical results on the influence of the problem parameters on the critical deformation are presented and discussed. Also, numerical results related to the cases where the interlayer space is ignored and where full contact between the tubes is assumed are presented and compared with the mentioned results. In particular, it is established that full slipping between the tubes causes the values of the critical deformation to decrease significantly with respect to those obtained in the case where complete contact conditions occur between the tubes. Moreover, it is established that an increase in the values of the van der Waals forces also causes a decrease in the values of the critical compressing strain and the magnitude of this.
decrease depends on the thicknesses of the tubes of the DWCNT.

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ABSTRACT: Sandwich structures are widely used in many industrial applications, due to the attractive combination of a lightweight and strong mechanical properties. This compromise is realized thanks to the presence of different parts in the composite material, namely the skins and possibly core reinforcements or thin-walled core structure which are both thin/slim and stiff relative to the other parts, namely the homogeneous core material, if any. The buckling phenomenon thus becomes mainly responsible for the final collapse of such sandwiches. In this paper, classical sandwich beam-columns (with homogeneous core materials) are considered and elastic buckling analyses are performed in order to derive the critical values and the associated bifurcation modes under various loadings (compression and pure bending). The two faces are represented by Euler–Bernoulli beams, whereas the core material is considered as a 2D continuous solid. A set of partial differential equations is first obtained from a general bifurcation analysis, using the above assumptions. Original closed-form analytical solutions of the critical loading and mode of a sandwich beam-column are then derived for various loading conditions. Finally, the proposed analytical formulae are validated using 2D linearized buckling finite element computations, and parametric analyses are performed.

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ABSTRACT: We study inextensional vibrations of zig-zag single-walled carbon nanotubes using nonlocal elasticity theories. We find that the frequency expressions for the Rayleigh and Love modes of inextensional vibrations, predicted by the stress and strain gradient theories, differ from the classical continuum theory expressions by a multiplicative factor only. The factor is different for stress and strain gradient theories. We also observe that the strain gradient theory with positive sign exhibits a saturation-like behavior of the inextensional mode frequency with the circumferential wave number. Using this fact and molecular mechanics simulation data we derive an expression for the nonlocal parameter.

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C. Farhat (1,2,3), K. Wang (3), A. Main, S. Kyriakides (4), L.-H. Lee (4), K. Ravi-Chandar (4) and T. Belytschko (5)

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ABSTRACT: The implosion of an underwater structure is a dynamic event caused by the ambient constant pressure environment. It produces a short duration pressure pulse that radiates outwards and can damage adjacent structures. This paper presents results from a combined experimental/numerical study that aims to understand the underlying physics and establish the parameters that govern the nature of such pressure pulses. Collapse experiments on small-scale metal shells were conducted in a custom testing facility under constant pressure conditions representative of those in deep waters. The dynamic collapse of the shells was monitored using high-speed photography and the pressure around the structure with dynamic pressure transducers.

Synchronization of the high-speed images with the data acquisition allowed temporal and spatial resolution of the events and the pressure pulses. Results from two experiments on shells that buckled and collapsed in modes 4 and 2 are reported. A computational framework developed for the solution of highly nonlinear fluid-structure interaction problems characterized by shocks, large deformations, and self-contact is outlined. It features an Eulerian embedded boundary method for Computational Fluid Dynamics capable of achieving second-order spatial accuracy including at the fluid-structure interface; an explicit structural analyzer with nonlinear geometric, material, and contact capabilities; and a loosely-coupled implicit-explicit fluid-structure time-integrator with a second-order time-accuracy and excellent numerical stability properties. The numerical tool is used to simulate the two experiments and shown to reproduce with good accuracy both the large deformations of the structure as well as the compression waves that emanate from it. The results demonstrate that the pressure pulse generated is influenced by the mode of buckling as well as the associated localization of collapse.

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ABSTRACT: The large bending behavior of a creased paperboard is studied in the range of rotation $\theta \in [0^\circ, 180^\circ]$ – new results, apparently not reported previously in literature – with the aim to point out some crucial aspect involved in an adaptive robotic manipulation of the industrial cartons. The loading tests show a great variability of the mechanical behavior, depending dramatically on the crease indentation depth (also for the specimens obtained from the same carton): (a) when the damage induced during the crease formation is relatively small, the bending response is unusually complex: the moment constitutive function, $m_L(\theta)$, presents (up to) two peaks followed by unstable branches; (b) for greater indentation, the $m_L(\theta)$ is monotone. In the unloading case the response $m_U(\theta)$ is always monotone and is practically independent of the formation conditions of the crease. These behaviors can be easily described analytically using (piecewise) third degree splines. In a companion paper, the erection of a typical carton corner with unstable constitutive behavior is fully analyzed to detect the possible criticalities.

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ABSTRACT: The mechanics of a paradigmatic typical carton corner with five creases is analyzed theoretically, in closed form. A general kinematical analysis of the mechanism (in finite rotation) is presented, assuming the versor of the intermediate crease, $s$, as a 2-degree-of-freedom Lagrangian parameter. The rotation $\theta_c$ of the $c$th crease is derived, together with the existence domain and a discussion of the singular configurations. The actions, driving the carton during a prescribed quasi-static erection program, are derived in a very efficient manner using the Virtual Works Equation, taking into account a non-linear anholonomic bending constitutive law of the creased paperboard. In particular, the active and reactive components of the moment $\varphi$, driving $s$ along its path, are identified. No resort to the tangent stiffness computation is required. Some numerical examples illustrate the rotation and the driving forces obtained for both monotone-loading and complex loading-unloading erection paths. The presented results, “exact” within the scope of the restrictive hypotheses assumed, may be used in a preliminary design approach as well as a benchmark for more realistic FEM or CAE simulators.


ABSTRACT: Atomistic simulations of the evolution of a strained thin film on a substrate has been reported and the formation of dislocations has been observed in the film/substrate interface after the film has buckled. In the framework of the linear elasticity theory, an analytical model has been developed to explain the buckle effect on the formation of the dislocations. A stability diagram with respect to the buckling and dislocation emission phenomena is finally presented for the film as a function of the uniaxial strain and the Burgers vector.

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ABSTRACT: The local-buckling-induced elastic interaction between two circular inclusions in a free-standing film is reported using numerical simulation. The simulation relies on a continuum model based on the modified Föppl-von Kármán plate theory for a film with arbitrarily distributed eigenstrain and eigencurvature. It is shown that due to the overlapping of the nonlinear local buckling the elastic interaction between the two inclusions with the same eigencurvature is repulsive, while the interaction between them with the opposite eigencurvature is attractive. The interaction strength in both cases decays with their mutual distance. In addition, the inclusion with positive/negative eigenstrain above critical values can trigger an axisymmetric/non-axisymmetric buckling, respectively, and the buckling induced elastic interaction between the two inclusions with eigenstrain shows a nonmonotonic behavior.

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ABSTRACT: One of the many uses of honeycomb is as core in sandwich plates, producing very high stiffness-to-weight ratio structures. The macroscopically observed crushing mechanism of these structures has its origin in instabilities at the local scale. Of particular interest here are the critical (i.e., onset of a buckling-type instability) loads and corresponding eigenmodes of honeycomb under general 3D loading involving simultaneous axial compression and transverse shear. Since the critical eigenmodes in honeycomb often involve more than one unit cell, numerical studies are limited by the size of the domain considered for their analyses. We propose a new theoretical approach to determine the critical loads and eigenmodes of perfect honeycomb of infinite extent under general loading conditions based entirely on unit-cell calculations. It combines Bloch wave representation theorem for the eigenmode with the analytical solution of the linearized von Kármán plate equations for the walls. The proposed approach uses the fact that the honeycomb walls remain flat in the principal solution prior to the onset of the first instability and solves analytically the corresponding eigenvalue problem. Three different geometries are considered: rectangular honeycomb with varying in-plane aspect ratios, an isotropic-section hexagonal honeycomb, and an anisotropic-section hexagonal honeycomb (resulting from its manufacturing process). Several different loading cases are investigated: axial compression under free or fully constrained lateral expansion, transverse shear and combined axial compression and transverse shear. The results show that the buckling mode is highly dependent on the type of loading: e.g., laterally unconstrained axial compression results in local critical eigenmodes, while constraining the lateral expansion leads to global ones. The addition of transverse shear not only reduces the critical axial strain, but also affects the wavelengths of the critical eigenmode.

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ABSTRACT: Developing benchmark analytic solutions for problems in solid and fluid mechanics is very important for the purpose of testing and verifying computational physics codes. In order to test the numerical results of physics codes, we consider the geometrically linear dynamic sphere problem. We present an exact solution for the dynamic response of a spherical shell composed of a linearly elastic material exhibiting transverse isotropic symmetry. The solution takes the form of an infinite series of eigenfunctions. We demonstrate, both qualitatively and quantitatively, the convergence of the computed benchmark solution under spatial, temporal, and eigenmode refinement.
References listed at the end of the paper:

L. St-Pierre, N.A. Fleck and V.S. Deshpande (Department of Engineering, University of Cambridge,
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ABSTRACT: In this study, we investigate the effect of geometrical imperfections on swelling-induced buckling patterns in gel films with a square lattice of holes. Finite element analysis is performed using the inhomogeneous field theory of polymeric gels in equilibrium proposed by Hong et al. (2009). Periodic units consisting of $2 \times 2$ and $10 \times 10$ unit cells are analyzed under a generalized plane strain assumption. Geometrical imperfections are introduced using randomly oriented elliptical holes. The $2 \times 2$ unit cells show that the resulting buckling patterns are sensitive to imperfections; three different buckling patterns are obtained, and the most dominant one is the diamond plate pattern observed in experiments, which cannot be described using the model without imperfections. The $10 \times 10$ unit cells reveal that random imperfections are responsible for inducing homogeneous transformation into the diamond plate pattern. Furthermore, domain wall formation is simulated using a $10 \times 10$ unit cell model containing two elliptic holes.


ABSTRACT: A higher order model for the analysis of linear, prismatic thin-walled structures that considers the cross-section warping together with the cross-section in-plane flexural deformation is presented in this paper. The use of a one-dimensional model for the analysis of thin-walled structures, which have an inherent complex three-dimensional (3D) behaviour, can only be successful and competitive when compared with shell finite element models if it fulfills a twofold objective: (i) an enrichment of the model in order to as accurately as possible reproduce its 3D elasticity equations and (ii) the definition of a consistent criterion for uncoupling the beam equations, allowing to identify structural deformation modes. The displacement field is approximated through a linear combination of products between a set of linear independent functions defined over the cross-section and the associated weights only dependent on the beam axis; this approximation is not constrained by any ab initio kinematic assumptions. Towards an efficient application of the approximation procedure, the cross-section is discretized into thin-walled elements, being the displacement field approximated for each element independently of the displacement direction. The approximation is thus $hp$ refined enhancing the “capture” of the 3D structural mechanics of thin-walled structures. The beam model governing equations are obtained through the integration over the cross-section of the corresponding elasticity equations weighted by the cross-section global approximation functions. A criterion for uncoupling the beam governing equations is established, allowing to (i) retrieve the classic equations of the thin-walled beam theory both for open and closed sections and (ii) derive a set of uncoupled deformation modes representing higher order effects. The criterion is based on the solution of the polynomial eigenvalue problem associated with the beam differential equations, allowing to quantify the Saint-Venant principle for thin-walled structures. In fact, the solution of the non linear eigenvalue problem yields a twelve fold null eigenvalue (representing polynomial solutions) that are verified to represent beam classic solutions and sets of pairs and quadruplets of non-null eigenvalues corresponding to higher order modes of deformation.
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ABSTRACT: Lining internally a carbon steel pipe with a thin layer of corrosion resistant material is an economical method for protecting offshore tubulars from the corrosive ingredients of hydrocarbons. In applications involving severe plastic bending, such as in the reeling installation process, the liner can detach from the outer pipe and develop large amplitude buckles that compromise the flow. This paper outlines a numerical framework for establishing the extent to which lined pipe can be bent before liner collapse. The modeling starts with the simulation of the inflation process through which the two tubes develop interference contact pressure. Bending the composite structure leads to differential ovalization and eventually separation of part of the liner from the outer pipe. The unsupported strip of the liner on the compressed side first wrinkles and at higher curvature buckles and collapses in a diamond shaped mode. The sensitivity of the collapse curvature to the various parameters of the problem is studied, and amongst other findings the onset of collapse is shown to be very sensitive to small geometric imperfections in the liner. It is also demonstrated that bending the pipe under modest amounts of internal pressure can delay liner collapse to curvatures that make it reliable.

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ABSTRACT: The growth of carbon onions is simulated using continuum mechanical shell models. With this models it is shown that, if a carbon onion has grown to a critical size, the formation of an additional layer leads to the occurrence of a structural instability. This instability inhibits further growth of carbon onions and, thus, can be a reason for the limited size of such particles. The loss of stability is mainly evoked by van der Waals interactions between misfitting neighboring layers leading to self-equilibrating stress states in the layers due to mutual accommodation. The influence of the curvature induced surface energy and its consequential stress state is investigated and found to be rather negligible. Furthermore, it is shown that the nonlinear character of the van der Waals interactions has to be considered to obtain maximum layer numbers comparable to experimental observations. The proposed model gives insight into mechanisms which are assumed to limit the size of carbon onions and can serve as basis for further investigations, e.g., of the formation of nanodiamonds in the center of carbon onions.

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ABSTRACT: In this paper, an analytical method is presented to investigate the nonlinear buckling and expansion behaviors of local delaminations near the surface of functionally graded laminated piezoelectric composite shells subjected to the thermal, electrical and mechanical loads, where the mid-plane nonlinear geometrical relation of delaminations is considered. In examples, the effects of thermal loading, electric field strength, the stacking patterns of functionally graded laminated piezoelectric composite shells and the patterns of delaminations on the critical axial loading of locally delaminated buckling are described and discussed. Finally, the possible growth directions of local buckling for delaminated sub-shells are described by calculating the expanding forces along the length and short axis of the delaminated sub-shells.

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ABSTRACT: This work examines the effects of manufacturing induced voids on the postbuckling behavior of delaminated unidirectional composites. In the finite element model developed, a through-width delamination is
introduced close to one surface of a flat panel, and a void is placed in the delamination plane ahead of each delamination front. The panel is subjected to compression in the fiber direction. The postbuckling delamination growth is studied by calculating the strain energy release rate (SERR) using the virtual crack closure technique. Local stress analyses of the region near the delamination front are also performed to further investigate the void effects. It is found that although the presence of void does not significantly alter the postbuckling transverse displacement of the delaminated panel, the induced stress perturbation by the void affects the SERR. The Mode II SERR as well as the total SERR increase depending on the size of the void and its distance from the delamination front. Since the Mode I SERR shows non-monotonic behavior with the applied load, the effects of voids are studied on its maximum value.

References listed at the end of the paper:

ABSTRACT: The two-part series of papers presents the results of a study of the crushing behavior of open-cell Al foams under impact. In Part I, direct and stationary impact tests are performed on cylindrical foam specimens at impacts speeds in the range of 20–160 m/s using a gas gun. The stress at one end is recorded using a pressure bar, while the deformation of the entire foam specimen is monitored with high-speed photography. Specimens impacted at velocities of 60 m/s and above developed nearly planar shocks that propagated at well-defined velocities crushing the specimen. The shock speed vs. impact speed, and the strain behind the shock vs. impact speed representations of the Hugoniot were both extracted directly from the high-speed images. The former follows a linear relationship and the latter asymptotically approaches a strain of about 90% at higher velocities. The Hugoniot enables calculation of all problem variables without resorting to an assumed constitutive model. The compaction energy dissipation across the shock is shown to increase with impact velocity and to be significantly greater than the corresponding quasi-static value. Specimens impacted at velocities lower than 40 m/s exhibited response and deformation patterns that are very similar to those observed under quasi-static crushing. Apparently, in this impact speed regime inertia increases the energy absorption capacity very modestly.


ABSTRACT: Part II of this study uses micromechanically accurate foam models to simulate and study the dynamic crushing of open-cell foams. The model starts as random soap froth generated using the Surface Evolver software to mimic the microstructure of the foams tested. The linear edges of the cellular microstructure are “dressed” with appropriate distributions of solid to match those of ligaments in the actual foams and their relative density. The ligaments are modeled as shear-deformable beams with variable cross sections discretized with beam elements in LS-DYNA, while the Al-alloy is modeled as a finitely deforming elastic–plastic material. The numerical contact algorithm of the code is used to model ligament contact and limit localized cell crushing. The quasi-static and all dynamic crushing experiments in Part I are simulated numerically. The models are shown to reproduce all aspects of the crushing behavior including the formation and evolution of nearly planar shocks, the force acting at the two ends, the shock front velocity, the strain in the crushed material behind the shock, and the energy absorbed. The transition to shock behavior is rather gradual. At speeds 20 m/s and lower all aspects of the crushing replicate the quasi-static behavior. Between 20 and 40 m/s inertial effects start to become apparent with a gradual increase in the stress and strain at the proximal end. Shocks were found to occur above impact speeds of 40–50 m/s. Models were also crushed at constant velocities up to 200 m/s. Different representations of the Hugoniot were calculated and are shown to reinforce the experimentally generated ones in Part I. This includes the linearity of the shock-impact velocities Hugoniot, the asymptotic increase with impact velocity of the strain in the crushed region, and the quadratic increase of the proximal stress with velocity. The results also confirmed that the stress ahead of the shocks is at the level of the limit stress of the quasi-static crushing response.

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ABSTRACT: This paper presents a study on stretch-induced wrinkling of thin polyethylene sheets when subjected to uniaxial stretch with two clamped ends. Three-dimensional digital image correlation was used to measure the wrinkling deformation. It was observed that the wrinkle amplitude increased as the nominal strain increased up to around 10%, but then decreased at larger strain levels. This behavior is consistent with results of finite element simulations for a hyperelastic thin sheet reported previously (Nayyar et al., 2011). However, wrinkles in the polyethylene sheet were not fully flattened out at large strains (>30%) as predicted for the hyperelastic sheet, but exhibited a residual wrinkle whose amplitude depended on the loading rate. This is attributed to the viscoelastic response of the material. Two different viscoelastic models were adopted in finite element simulations to study the effects of viscoelasticity on wrinkling and to improve the agreement with the experiments, including residual wrinkles and rate dependence. It is found that a parallel network model of nonlinear viscoelasticity is suitable for simulating the constitutive behavior and stretch-induced wrinkling of the polyethylene sheets.

References listed at the end of the paper:

ABSTRACT: The partially embedded submarine pipelines might buckle laterally at some segments under high pressure and high temperature (HP/HT) conditions. The buckling pattern localization introduces an extra level of analytical complexity when compared with the periodic buckling pattern. In the presented paper the lateral buckling pipeline is modeled by an axial compressive beam supported by lateral distributing nonlinear springs taking the soil berm effects in the horizontal plane. It is found that the model is governed by a time-independent Swift–Hohenberg equation. Based on John Burke and Edgar Knobloch’s work we conclude preliminarily that the equation will have localized solutions. Besides the qualitative conclusion, by AUTO 07P the localized solutions of the equation are studied in detail. The snakes-and-ladders structure of localized solutions explains the transition of buckling modes in theory. The range of the possible critical axial forces is found out. Meanwhile two critical axial force formulas corresponding to the range ends are presented. Finally a typical submarine pipeline is analyzed as an illustration.

References listed at the end of the paper:

Nonlinear elastic tubes

3. K. Balakhovsky, K. Volokh
1. J.E. Adkins, R.S. Rivlin

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ABSTRACT: The inflated elastomeric balloon structures are widely used in engineering fields such as elastomeric actuators and artificial muscles. This study, involving both experiment and modeling, is focused on the prestretch effect on non-linear behavior of inflated short-length tubular elastomeric balloons. In the experiment, the prestretched tubular elastomeric balloon is subjected to air pressure while the two ends are fixed with rigid tubes. The shape evolutions of the tubular elastomeric balloons are illustrated. The non-axisymmetric bulging is observed in the inflated tubular balloon with small prestretch. An analytical model based on continuum mechanics is developed to investigate the inflation behavior of the tubular balloons, and the analytical results agree well with the experimental observation. Analysis shows that snap-through instabilities may happen during the inflation of the tubular balloon. Prestretch along the axis of the tubular balloon can suppress instability during inflation and regulate the reaction force along the axial direction. This work can guide the future application of tubular balloons in elastomeric actuators and artificial muscles.

References listed at the end of the paper:

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ABSTRACT: It is well known that distribution of displacements through the shell thickness is non-linear, in general. We introduce a modified polar decomposition of shell deformation gradient and a vector of deviation from the linear displacement distribution. When strains are assumed to be small, this allows one to propose an explicit definition of the drilling couples which is proportional to tangential components of the deviation vector. The consistent second approximation to the complementary energy density of the geometrically non-linear theory of isotropic elastic shells is constructed. From differentiation of the density we obtain the consistently refined constitutive equations for 2D surface stretch and bending measures. These equations are then inverted for 2D stress resultants and stress couples. The second-order terms in these constitutive equations take consistent account of influence of undeformed midsurface curvatures. The drilling couples are explicitly expressed by the stress couples, undeformed midsurface curvatures, and amplitudes of quadratic part of displacement distribution through the thickness. The drilling couples are shown to be much smaller than the
stress couples, and their influence on the stress and strain state of the shell is negligible. However, such very small drilling couples have to be admitted in non-linear analyses of irregular multi-shell structures, e.g. shells with branches, intersections, or technological junctions. In such shell problems six 2D couple resultants are required to preserve the structure of the resultant shell theory at the junctions during entire deformation process.

References listed at the end of the paper:
ABSTRACT: The paper presents experimental and analytical studies on axial compression of aluminium spherical shells having Radius/wall thickness (R/t) ratios between 23 and 135. Quasi-static compressive load was applied centrally and with offset through a indenter having diameter of 22 mm. Testing was carried out on an INSTRON machine having 250 T capacity. Shells having different radius and wall thickness were tested, to classify their modes of collapse and their corresponding energy absorption mechanism. In experiments shells of lower R/t values were found to collapse due to formation of an inward dimple associated with a rolling plastic hinge in central as well as in offset loading. On the other hand, shells of higher R/t values were collapsed initially with formation of an axisymmetric inward dimple, but in later stage of compression showed buckling of non-symmetric shape consisting of integral number of lobes and stationary plastic hinges. The stationary hinges were formed between consecutive lobes. Experimental observations are used to propose an analytical model for prediction of load–compression and energy–compression curves. The results obtained from analytical model compared with the experimental results and found match fairly well.

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18. N.A. Shahin, A.R. Hayder, “Plastic buckling of thin hemispherical shell subjected to concentrated load at the apex”, Thin Walled
ABSTRACT: We apply a finite element analysis to examine the stability of spherical, thick-walled domes undergoing large deformation. We identify three energetic states, mono-stable, bi-stable, and pseudo-bi-stable that uniquely characterize the behavior of the dome during deformation. An empirical relation is developed using finite element simulations relating the stability of the dome to pertinent geometric parameters like height, length and thickness, which is verified experimentally. Using this relation, similar domes can be designed to have desired stability characteristics.

References listed at the end of the paper:

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ABSTRACT: Many thin-walled cylindrical shells are used in structural applications in which the dominant loading condition is global bending. Key examples include chimneys, wind turbine support towers, pipelines, horizontal tanks, tubular piles and silos. The buckling behaviour of these structures in bending is complex due to the coupling between cross-section ovalisation and local bifurcation buckling. Analytical treatments of this problem have a history going back almost a century and still constitute an active and challenging research area. This paper investigates in detail the effect of cylinder length on the nonlinear elastic buckling behaviour of clamped cylindrical tubes under global bending, covering a very wide range of lengths. It is found that the behaviour may be classified into four distinct length-dependent domains with clearly-defined boundaries which have here been assigned the names 'short', 'medium', 'transitional' and 'long'. Algebraic characterisations of the computed nonlinear moment-length relationships are proposed for design purposes.

References listed at the end of the paper:


Akselrad E.L. (1965). "Refinement of the upper critical loading of pipe bending taking account of the geometrical nonlinearity." Izvestia, AN, USSR, OTN, Mekhanika i Mashinostroenie, 4, 123-139.


ABSTRACT: Corrugated panels have gained considerable popularity in a range of engineering applications, particularly in morphing skin applications. The optimum design of these structures needs simple models of the corrugated panels that may be incorporated into multi-disciplinary system models. Considering the geometric and mechanical properties of the corrugated panel, a generic super element of a corrugated core unit cell with elastomeric coating for morphing structures is investigated in this paper. The super element captures the small deformation of a 2D thin curved beam with variable curvature and is based on an exact analytical equivalent model which avoids any homogenization assumption. The stiffness matrix of a general curved beam element for
a corrugated unit cell with elastomeric coating is derived. Different geometries are investigated to verify the accuracy and efficiency of the presented super element. The super element uses the geometric and mechanical properties of the panel as variables that may be applied for further topology optimization studies. The parametric studies of different corrugation shapes demonstrate the suitability of the proposed super element for application in further detailed design investigations.

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ABSTRACT: The present paper addresses the problem of establishing the boundary conditions of a geometrically nonlinear thin shell model, especially the kinematic ones. Our model is consistently derived from general 3D continuum mechanics statements. Generalized cross-sectional strains and stresses are based on the deformation gradient and the first Piola-Kirchhoff stress tensor. Since only the bending deformation is included in this model, no special technique needs to be adopted in order to avoid shear-locking. The theory is derived in such a way that any material model can be considered as a constitutive relation, once the zero transverse normal stress assumption is properly taken into account. Special attention is given to the question of devising the appropriate shell boundary conditions. Several parameters are proposed to characterize the boundary rotation for an arbitrary spatial shell configuration. The appearance of corner concentrated forces, related to jumps of torsion moments, is captured and justified. A weak form of the equilibrium is presented, which is suitable for implementation by means of any numerical technique that provides C1 continuity approximation. It is prone to be used with both interpolative, like the Finite Element Method, and non-interpolative methods, like the Element-Free Galerkin Method. The latter is used to exemplify the proposed approach.

References listed at the end of the paper:
ABSTRACT: Controlled buckling can impart stretchable mechanics to brittle materials when integrated as thin films on soft, elastomeric substrates. Typical elastomers are permeable to fluids, however, and therefore unable to provide robust barriers to entry of water, for instance, into devices built with the supported thin films. In addition, the mechanical strength of a system dominated by a soft substrate is often unsatisfactory for realistic applications. We show that introduction of a bi-layer substrate yields a robust, high strength system that maintains stretchable characteristics, with a soft layer on top of a relatively stiff layer in the substrate. As a mechanical protection, a soft encapsulation layer can be used on top of the device and the stretchability of the encapsulated system is smaller than that of the system without encapsulation. A simple, analytic model, validated by numerical analysis and FEA, is established for stiff thin films on a bi-layer substrate, and is useful to the design of stretchable systems.

References listed at the end of the paper:
ABSTRACT: A planar rod model with flexible cross-section has been recently proposed in literature (Guinot et al., 2012). This model is especially suitable for the modeling of tape springs, which develop localized folds due to the flattening of the cross-section. Starting from a complete non-linear elastic shell model, original kinematics assumptions (inspired from the *elastica* model) have been made to describe the important in-plane changes of the cross-section shape. In the present work, the choice of the position of the rod reference line is discussed. This choice plays an important role in the overall behavior because of the large changes of the cross-section shape. We show that the model published in Guinot et al. (2012) can be improved by considering the centerline as the rod reference line. This enhanced model is then validated through quantitative comparisons with experimental results of dynamic deployments taken from literature.

ABSTRACT: Thin membranes are used in the spacecraft industry as extremely lightweight structural components. They need to be stiffened, usually by applying discrete forces, and this increases their susceptibility to wrinkling in regions where high tensile stresses develop. We consider a regular polygonal membrane uniformly loaded at its corners by equal forces and we prevent wrinkle formation by trimming the edges of the polygon into very gentle curves. We confirm this performance through simple physical experiments using Kapton, a typical membrane material and, using computational analysis, we show how the distribution of compressive stresses, responsible for causing wrinkles, dissipates following trimming. Finally, we accurately predict the required level of trimming for any number of sides of polygon using a simple, linear model, which invokes a plate-bending analogy.

References listed at the end of the paper:


ABSTRACT: Thin, initially-flat plates can deform inextensionally and elastically during large out-of-plane deformations. This paper revisits an analytical method for describing the developable shapes of displaced plate, in order to quantify and validate its effectiveness. Results from practical experiments and finite element analysis are compared to theoretical predictions from well-known examples, and excellent correlations are obtained.

References listed at the end of the paper:
ABSTRACT: For a membrane structure, wrinkles have an important effect on its mechanical behaviors. Wrinkling level characterizes the development of wrinkles and reflects the performance of a membrane in its service, and it plays a very significant role in the wrinkling analysis. The shell elements combined with the stability theory would be an ideal solution to the wrinkling problem. However, this approach requires a dense mesh and the computation is very time consuming. Also the wrinkling parameters are very sensitive to the size of shell elements. Existing wrinkling models based on membrane elements are derived from the Tension Field Theory which are incapable of describing fully the wrinkling behaviors. A new wrinkling model adopting the wrinkling strain as a measure of the wrinkling level is proposed in this paper to address these issues. According to the analogy between the wrinkling strain and the elasto-plastic strain, a wrinkling potential surface is assumed to exist and its normal direction defines the direction of the wrinkling strain tensor by virtue of the flow rule. Based on the consistent condition of the wrinkling potential surface, a modified constitutive tensor is obtained. To avoid the switching of the wrinkling state in the numerical solution, a new wrinkling criterion is proposed, in which the predominant influence of the previous state is included. Besides, a new approach to determine the wrinkling orientation is given to improve the efficiency of convergence in the slack region. The objectivity of the wrinkling coordinate frame is also demonstrated as an accompanying set of results. Finally, two benchmark problems are analyzed with the proposed wrinkling model, and their results are compared with those in the literatures. Results indicate that the proposed wrinkling model is valid and accurate to characterize the wrinkling level of a membrane and it exhibits efficient convergence even in the slack region.

References listed at the end of the paper:

Sanjay Govindjee (1), Trevor Potter (2) and Jon Wilkening (2)
ABSTRACT: The study of spinning axisymmetric cylinders undergoing finite deformation is a classic problem in several industrial settings – the tire industry in particular. We present a stability analysis of spinning elastic and viscoelastic cylinders using ARPACK to compute eigenvalues and eigenfunctions of finite element discretizations of the linearized evolution operator. We show that the eigenmodes correspond to $N$-peak standing or traveling waves for the linearized problem with an additional index describing the number of oscillations in the radial direction. We find a second hierarchy of bifurcations to standing waves where these eigenvalues cross zero, and confirm numerically the existence of finite-amplitude standing waves for the nonlinear problem on one of the new branches. In the viscoelastic case, this analysis permits us to study the validity of two popular models of finite viscoelasticity. We show that a commonly used finite deformation linear convolution model results in non-physical energy growth and finite-time blow-up when the system is perturbed in a linearly unstable direction and followed nonlinearly in time. On the other hand, Sidoroff-style viscoelastic models are seen to be linearly and nonlinearly stable, as is physically required.

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ABSTRACT: Nonlinear buckling of elastic thin films on compliant substrates is studied by modeling and simulations to reveal the roles of pre-strain, elastic modulus ratio, and interfacial properties in morphological transition from wrinkles to buckle-delamination blisters. The model integrates an interfacial cohesive zone model with the Föppl–von Kármán plate theory and Green function method within the general framework of energy minimization. A kinetics approach is developed for numerical simulations. Subject to a uniaxial pre-strain, the numerical simulations confirm the analytically predicted critical conditions for onset of wrinkling and wrinkle-induced delamination, with which a phase diagram is constructed. It is found that, with increasing pre-strain, the equilibrium configuration evolves from flat to wrinkles, to concomitant wrinkles and buckle-delamination, and to an array of parallel straight blisters. The height and width of the buckle-delamination blisters can be approximately described by a set of scaling laws with respect to the pre-strain and interfacial toughness. Subject to an equi-biaxial pre-strain, the critical conditions are determined numerically to construct a similar phase diagram for the buckling modes. Moreover, by varying the pre-strain, modulus ratio, and interfacial toughness, a rich variety of equilibrium configurations are simulated, including straight blisters, and network blisters with or without wrinkles. These results provide considerable insight into diverse surface patterns in layered material systems as a result of the mechanical interactions between the film and the substrate through their interface, which suggests potential control parameters for designing specific surface patterns. References listed at the end of the paper:

ABSTRACT: Recently, a nanoscale lattice material, based upon the gyroid topology has been self-assembled by anisotropic buckling phase separation techniques (Scherer et al., 2012) and prototyped in thin film applications. The mechanical properties of the gyroid are reported here. It is a cubic lattice, with a connectivity of three struts per joint, and is bending-dominated in its elasto-plastic response to all loading states except for hydrostatic: under a hydrostatic stress it exhibits stretching-dominated behaviour. The three independent elastic constants of the lattice are determined through a unit cell analysis using the finite element method; it is found that the elastic and shear modulus scale quadratically with the relative density of the lattice, whereas the bulk modulus scales linearly. The plastic collapse response of a rigid, ideally plastic gyroid lattice is explored using the upper bound method, and is validated by finite element calculations for an elastic-plastic gyroid lattice. The effect of geometrical imperfections, in the form of random perturbations to the joint positions, is investigated for both stiffness and strength. It is demonstrated that the hydrostatic modulus and strength are imperfection sensitive, in contrast to the deviatoric response. The macroscopic yield surface of the imperfect lattice is adequately described by a modified version of Hill’s anisotropic yield criterion. The article ends with a case study on the stress induced within a gyroid thin film, when the film and its substrate are subjected to a thermal expansion mismatch.


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ABSTRACT: A fundamental experimental investigation, with corresponding computational simulations, was conducted to understand the physical mechanisms of implosions of cylindrical shells occurring within a tubular confining space which has a limited potential energy reservoir. In particular, attention was focused on studying the generation of pressure waves from the implosion, the interaction of the pressure waves with the confining tube walls and end caps, and the collapse mechanisms of the implodable volume. Experiments were conducted with three implodable volume geometries which had similar critical collapse pressures. The implodable volumes were aluminum 6061-T6 cylindrical tubing and were placed concentrically within the confining tube. Pressure histories recorded along the length of the confining tube during the experiments were utilized to analytically evaluate the deformation of the implodable volume using fluid–structure coupled deformation models. Computational simulations were conducted using a coupled Eulerian–Lagrangian scheme to explicitly model the implosion process of the tubes along with the resulting compressible fluid flow. The numerical model developed in this study is shown to have high correlation with the experimental results and will serve as a predictive tool for the simulation of the implosion of different cylindrical geometries as well as various tube-in-tube implosion configurations. The experimental results show that the limited hydrostatic potential energy available in a confined environment, as compared to a free field, significantly influences the implosion process. The wall velocities of the implodable volume during the collapse, as well as the extent of the collapse progression, are largely affected by the sudden decrease in the available hydrostatic potential energy. This energy is shown to be partially transformed into elasto-plastic strain energy absorbed in the deformation of the implodable volume, as well as the kinetic energy of the water during the implosion process. Experiments also show that the extent of the collapse progression of an implodable volume can potentially be inhibited within a closed environment, which can lead to the arresting of an implosion event prior to completion for larger implodable volumes. The pressure waves generated during collapse comprise of waves emitted due to the impact of the implodable volume walls, the arrest of rushing water and contact propagation along the walls. These processes later evolve into water hammer type axial wave behavior.

References listed at the end of the paper:


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ABSTRACT: Based on a microstructured beam-grid model, closed form solutions for Eringen’s length scale coefficient are derived for the buckling of nonlocal rectangular plates under compressive uniaxial load. The microstructured beam-grid model comprises rigid beam elements connected by rotational springs and torsional springs. Stiffness of the rotational springs and torsional springs are expressed in terms of the plate flexural and torsional rigidities, respectively. Exact buckling solutions are obtained for the microstructured beam-grid model. By interpreting the rigid element length as the internal characteristic length, the Eringen’s length scale coefficient may be determined by comparing the buckling load from the microstructured beam-grid model and the nonlocal rectangular plate model. The small length scale coefficient is shown to be dependent on the buckling mode, the aspect ratio of plate and boundary conditions.

References listed at the end of the paper:

ABSTRACT: A compressed stiff film/compliant substrate system undergoes a morphology transition from wrinkling to period-doubling. The perturbation method is used to obtain the approximate analytical solution incorporating both the quadratic and cubic nonlinearities of the substrate, which have a significant effect on the post-buckling behavior of the system. Based on the perturbation method, the post-buckling equilibrium path of the system is presented with the multi-modal analysis, and two bifurcation points appear on the stable equilibrium path. The wrinkling instability occurs at the first bifurcation point, where the uncoupled path bifurcates from the fundamental unbuckled state. Under further compression, the period-doubling instability occurs at the second bifurcation point due to the coupling of different modes, which is referred to as the mode coupling. The two-mode analysis shows that the coupled equilibrium path is hyperbola-like and there exists a stable branch which bifurcates from the primary uncoupled path. When more modes are included, the model is more accurate to predict the critical strain of the period-doubling bifurcation and the evolution of the amplitudes.

References listed at the end of the paper:
References listed at the end of the paper:

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ABSTRACT: Cellular solids are remarkably strong structures built from seemingly fragile materials. In order to gain new insight into the mechanical behaviour of these omnipresent materials, we analyse the deformation of seamless cellular bodies within the framework of finite strain elasticity and identify behaviours which are not captured under the small strain regime. Assuming that the cell walls are hyperelastic, we devise a mathematical mechanical strategy based on a successive deformation decomposition by which we approximate the large deformation of periodic cellular structures, as follows: (i) firstly, a uniformly deformed state is assumed, as in a compact solid made from the same elastic material; (ii) then the empty spaces of the individual cells are taken into account by setting the cell walls free. For the elastic structures considered here, an isochoric deformation that can be maintained in both compressible and incompressible materials is considered at the first step, then the stresses in this known configuration are used to analyse the free shape problem at the second step where the cell geometry also plays a role. We find that, when these structures are submitted to uniform external conditions such as stretch, shear, or torsion, internal non-uniform local deformations occur on the scale of the cell dimension. For numerical illustration, we simulate computationally the finite elastic deformation of representative model structures with a small number of cells, which convey the complexity of the geometrical and material assumptions required here. Then the theoretical mechanical analysis, which is not restricted by the cell wall material or number of cells, indicates that analogous finite deformation effects are expected also in other physical or computer models.

References listed at the end of the paper:
ABSTRACT: This paper examines the compressive failure mechanism in edge-to-edge loaded corrugated sandwich panels. The formation of face wrinkles is specifically considered. A detailed finite element model of face sheets and web core of a sandwich panel was developed to provide insight on the failure mechanism. A
gradient enhanced continuum damage theory was implemented to capture length effects caused by the material microstructure including formation of damage in the face sheets and core. Distributions of strains in the face sheets determined from finite element analysis (FEA) are compared to experimentally measured strains. The predicted location and orientation of the face wrinkle, as indicated by high values of the second principal strain, agrees well with experimental observations. Load vs. out-of-plane deflection curves obtained from FEA with the gradient enhanced damage material model are compared to those obtained from a linear-elastic material model and experimentally determined curves. The gradient enhanced solution gives qualitatively better agreement with experimental results, although the magnitudes of strains are less than those determined experimentally.

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ABSTRACT: Local wrinkles are widely observed in film–substrate systems both in nature and in engineering. In this paper, we investigate the surface wrinkling of a film–substrate structure subjected to local prestretch in a circular region. Hankel transform is used to unravel the interface condition between the stiff film and the compliant substrate. The critical prestrain and the corresponding wrinkling number are solved as functions of the radius of the prestretched region and the Young’s modulus ratio between the film and substrate. The theoretical analysis is validated by a semi-implicit numerical method based on the Fourier spectral technique. The postbuckling behavior is also simulated via the numerical method. It is found that during postbuckling, the surface wrinkles may experience a secondary bifurcation and evolve into branching patterns.

References listed at the end of the paper:
ABSTRACT: In this paper, the post-critical behavior and buckling modes of single-walled carbon nanotubes are analyzed via a Molecular Mechanics model. The main target is to develop a general formulation for the model, which has been simplified under small strains assumption, and to implement a versatile tool for the structural analysis of carbon nanotubes in the framework of geometrical nonlinearity. For this purpose, a
mechanical formulation able to reproduce any load configuration and supporting conditions has been derived by using an energy approach. Then, an incremental-iterative solution procedure has been implemented in order to trace several nonlinear equilibrium paths and to obtain the corresponding critical strains of clamped-clamped nanotubes under compressive, flexural and torsional loading distributions. The model shows a good numerical performance and results in agreement with previous atomistic works. Two interatomic potentials have been adopted in order to find out the influence of different constitutive relationships on the final nonlinear response. We have concluded that the choice of the potential function has no significant effect on the final buckling strains. Our results confirm that the final buckling response is strongly determined by geometrical imperfections in the nanotube, which can be well reproduced in the proposed model, but are much more difficult to handle in continuum models.

References listed at the end of the paper:

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ABSTRACT: A geometrically nonlinear analysis of symmetric variable angle tow (VAT) composite plates under in-plane shear is investigated. The nonlinear von Karman governing differential equations are derived for postbuckling analysis of symmetric VAT plate structures which are subsequently solved using the differential quadrature method. The effect of in-plane extension-shear coupling on the buckling and postbuckling performance of VAT composite plates is investigated. The buckling and postbuckling behaviour of VAT plates under positive and negative shear is studied for different VAT fibre orientations, aspect ratios, combined axial compression and their performance is compared with that of straight fibre composites. It is shown that there can be enhanced shear buckling and postbuckling performance for both displacement-control and load-control and that the underpinning driving mechanics are different for each.

References listed at the end of the paper:
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ABSTRACT: We investigate the effect of prestrains on swelling-induced buckling patterns in polymeric films with a square lattice of holes. To reproduce experiments conducted by Zhang et al. (2008), poly(dimethylsiloxane) (PDMS) films are pre-strained in in-plane uniaxial tension in a lattice direction, and subsequently swelled by toluene. Finite element analysis is performed using an inhomogeneous field theory of polymeric gels in equilibrium, and with the aid of artificial damping. Periodic units consisting of 2x2 and 10x10 unit cells are analyzed under a generalized plane strain assumption. Analysis of the 10x10 unit cell shows that the resulting buckling pattern depends on the increase in prestrain of $\varepsilon = 0, 0.2, 0.4$ and $0.6$, evolving as a diamond plate pattern ($\varepsilon = 0$), a slightly distorted diamond plate pattern ($\varepsilon = 0.2$), a binary pattern of circles and lines ($\varepsilon = 0.4$), and a monotonous pattern of ellipses ($\varepsilon = 0.6$). These predictions are in very good agreement with experiments. The 2x2 unit cell reveals that these different patterns appear continuously as transitional states during transformation into diamond plate patterns; prestrains in uniaxial tension delay the onset of the pattern transformation and equilibrium swelling interrupts the progress of the transformation. Parametric studies demonstrate that the pattern dependence on prestrains originates from intrinsic swelling features, and is a consequence of a particular combination of the selected polymer and solvent.

References listed at the end of the paper:


References listed at the end of the paper:


ABSTRACT: The manufacturing of multistable shells has been dominated by the use of pre-stressed and composite materials. Here we advocate the use of common materials through a simple design that requires no pre-stressing and has an initially developable geometry. A rudimentary demonstrator is constructed and serves as the starting point for further study. An existing homogenisation model for a lattice structure is combined with an analytical strain energy model from the literature to show the mechanical properties needed to construct an initially developable, bistable grid shell. The concept is also tested in a commercial finite element package, where a number of parametric studies are performed. Both the demonstrator and the FE model confirm the validity of the design while a series of parametric studies helps establish the limits of this behaviour with respect to local and global geometry of grid shell and honeycomb structures.
References list


ABSTRACT: Lined pipe describes a product where a carbon steel pipe is lined internally with a thin layer of a corrosion resistant material in order to protect it from corrosive constituents in the hydrocarbons it carries. Most commonly the liner is brought into contact with the carrier pipe by mechanical expansion. Full-scale tests on this product have demonstrated that, under mechanical loads that plastically deform the composite structure, the thin liner can buckle and collapse inside an intact outer pipe making the structure unserviceable. This paper investigates the extent to which typical lined pipes can be axially compressed before liner collapse. Demonstration experiments on model lined systems illustrate that the liner, although supported by contact with the outer pipe, first buckles unilaterally into an axisymmetric wrinkling mode at a relatively low strain. The wrinkles grow stably with compression but yield to a non-axisymmetric diamond-type mode that results in the collapse of the liner at a higher strain. This process has been modeled numerically starting with simulation of the mechanical expansion through which the composite structure is manufactured. The sensitivity of the collapse strain to the various parameters of the problem is studied and amongst other findings it is shown to be very sensitive to small geometric imperfections in the liner. It is also demonstrated that even modest amounts of internal pressure can delay liner collapse up to strains at which the outer pipe collapses.

References listed at the end of the paper:
5. H. Chai, “Lateral confinement as a means of enhancing load bearing and energy absorption in axially compressed tubes”, Thin-Walled Struct., 46 (2008), pp. 54-64
References listed at the end of the paper:


ABSTRACT: The high efficiency of monocoque cylindrical shells in carrying axial loads is curtailed by their extreme sensitivity to imperfections. For practical applications, this issue has been alleviated by introducing closely stiffened shells which, however, require expensive manufacturing. Here we present an alternative approach that provides a fundamentally different solution. We design symmetry-breaking wavy cylindrical shells that avoid imperfection sensitivity. Their cross-section is formulated by NURBS interpolation on control points whose positions are optimized by evolutionary algorithms. We have applied our approach to both isotropic and orthotropic shells and have also constructed optimized composite wavy shells and measured their imperfections and experimental buckling loads. Through these experiments we have confirmed that optimally designed wavy shells are imperfection-insensitive. We have studied the mass efficiency of these new shells and found them to be more efficient than even a perfect circular cylindrical shell and most stiffened cylindrical shells.

ABSTRACT: A thin film bonded to an elastic substrate and subjected to compressive in-plane stresses may
develop wrinkles. In this paper a theoretical model of formation of one-dimensional sinusoidal wrinkles in such a film/substrate system subjected to a commensurate spatially varying temperature field is first presented and then analyzed. It is shown that an initially flat thin film on an elastic substrate can develop controlled wrinkles when subjected to a carefully chosen spatial thermal modulation.

References listed at the end of the paper:

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ABSTRACT: In this paper we consider theoretically the finite deformation of a circular cylindrical tube of a transversely isotropic elastic material, specifically the combined axial stretch, inflation and helical shear deformation, with particular reference to the failure of ellipticity. For a simple form of strain-energy function
specific examples involving axial and radial directions of transverse isotropy are then considered, leading to different predictions of the onset of ellipticity failure.


ABSTRACT: Arches and beams buckled upward are analyzed. The structure is pushed downward from above at a specific location along the span until snap-through occurs and the structure jumps to an inverted equilibrium shape. Each beam or arch is modeled as an inextensible elastica. Critical displacements are computed for buckled beams with both ends pinned, both ends clamped, or one end clamped and the other end pinned. Circular arches with pinned ends are also investigated. The ends are immovable. The critical displacement is obtained directly from a theoretical equilibrium shape of the initial unloaded structure. Numerical results are presented for four height-to-span ratios of the initial structure, showing the critical displacement for any application point along the span. At the onset of snap-through, the imposed displacement is at or below the horizontal chord connecting the ends.

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ABSTRACT: The paper discusses membrane instability phenomena by a Fourier-related double scale approach that was introduced recently. This leads to a reduced-order model that is able to capture the main features of the wrinkles with few degrees of freedom. The paper focuses on the corresponding finite element procedure, its implementation and evaluation and applications to various cases of loading and boundary condition. The finite element model has first been implemented in a home-made code, the nonlinear system being solved by the Asymptotic Numerical Method (ANM), which has advantages of efficiency and reliability for stability analyses. It has also been implemented as a user element in a commercial software to evaluate the effectiveness of the reduction technique. Various loading cases were considered and the numerical tests establish that the reduced model can predict the wrinkling patterns, even when there are few wrinkles. The numerical results highlight the strong influence of a dimensionless parameter for wrinkling initiation.

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ABSTRACT: With the cross-sectional area function as the design variable, we seek the optimum design of clamped–clamped, thin, linearly elastic beam-columns under thermal load that maximizes the buckling temperature or the fundamental natural frequency of transverse vibrations. The beam-columns have given length, geometrically similar cross-sections of variable size and a given volume of material. A lower and/or upper bound constraint may be prescribed for the cross-sectional area of the beam-columns. To account for possible bimodality of the optimum designs, both the unimodal and bimodal optimality criterion approaches are applied. For a lower bound smaller than a specific value, bimodal optimum designs are obtained for problems of maximum buckling temperature. When maximizing the thermal fundamental natural frequency, optimum designs may be unimodal or bimodal depending on the values of the given thermal load and the lower bound on the cross-sectional area. The geometrically unconstrained optimum design for maximum fundamental natural frequency obtained by Olhoff (1976) without consideration of thermal load, is shown to be at the same time an optimum design that maximizes the fundamental natural frequency at any temperature rise, but it is found to be associated with zero buckling load. Moreover, the optimum design maximizing the critical buckling temperature is very similar to that maximizing the mechanical buckling load obtained by Olhoff and Rasmussen (1977). This interesting analogy is explained by studying optimum design for minimum axial compressive force.

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“Multi-scale method for modeling thin sheet buckling under residual stresses in the context of strip rolling”, International Journal of Solids and Structures, Vol. 66, pp 62-76, August 2015,
https://doi.org/10.1016/j.ijsolstr.2015.03.028

ABSTRACT: In cold strip rolling, the transverse gradient of thickness strain results in heterogeneous longitudinal stress. Whenever the latter is compressive in spite of strip tensions, an on-line manifested flatness defect may occur. It is of interest to determine the occurrence and geometric characteristics of such defects. To do this, a two-scale model based on the generalized continuum approach of Damil and Potier-Ferry (2006, 2008) is applied to this problem. It consists in developing the unknowns (in plane stress components and out-of-plane displacement) in Fourier series and solving von Karman equations of thin strip buckling, in an energetic formulation. For application to cold rolling, certain simplifications are made and commented. The potential of this method is analyzed using simple assumed stress fields via (i) parametric studies and (ii) comparison with other available studies: a semi-analytical solution and a more general FEM solution of sheet buckling by the Asymptotic-Numerical Method (ANM).

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“On the parameters which govern the symmetric snap-through buckling behavior of an initially curved microbeam”, International Journal of Solids and Structures, Vol. 66, pp 77-87, August 2015,
https://doi.org/10.1016/j.ijsolstr.2015.04.011
ABSTRACT: In this paper, we extend the earlier studies to investigate the effects of various parameters which govern the symmetric snap-through buckling of an initially curved microbeam subject to an electrostatic force. The governing formulations are developed using Euler–Bernoulli beam theory. The mid-plane stretching experienced during the snap-through buckling is considered using von Karman nonlinear strain, and the nonzero strain component is determined and solved using Galerkin decomposition approach. The studied parameters include: beam fixation type (double-clamped and simply-supported), arch shape, residual axial force, and uniform temperature variation. The results of our work reveal the significant effects of the type of the beam fixation, the residual force, and the temperature variation on the criterion for the symmetric snap-through buckling of microbeams, while the effect of the arch shape is somewhat insignificant.

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ABSTRACT: The mechanical and structural responses of high-density TRIP steel and TRIP-steel/zirconia composite honeycomb structures were studied under uniaxial compression in the out-of-plane loading direction over a wide range of strain rates. Their mechanical response, buckling, and failure mechanisms differ considerably from those of conventional thin-walled, low-density cellular structures. Following the linear-elastic regime and the yield limit of the bulk material, the high-density square honeycombs exhibited a uniform increase in compression stress over an extended range of (stable) plastic deformation. This plastic pre-buckling stage with axial crushing of cell walls correlates with the uniaxial compressive response of the bulk specimens tested. The dominating material effects were the pronounced strain hardening of the austenitic steel matrix accompanied by a strain-induced α’-martensite nucleation (TRIP effect) and the strengthening effect due to the zirconia particle reinforcement. The onset of critical plastic bifurcation was initiated at high compressive loads governed by local or global cell wall deflections. After exceeding the compressive peak stress (maximum loading limit), the honeycombs underwent either a continuous post-buckling mode with a folding collapse (lower relative density) or a symmetric extensional collapse mode of the entire frame (high relative density). The densification strain and the post-buckling or plateau stress were determined by the energy efficiency method. Apart from relative density, the crush resistance and deformability of the honeycombs were highly influenced by the microstructure and damage evolution in the cell walls as well as the bulk material’s strain-rate sensitivity. A significant increase in strain rate against quasi-static loading resulted in a measured enhancement of deformation temperature associated with material softening. As a consequence, the compressive peak stress and the plastic failure strain at the beginning of post-buckling showed an anomaly with respect to strain rate indicated by minimum values under medium loading-rate conditions. The development of the temperature gradient in the stable pre-buckling stage could be predicted well by a known constitutive model for quasi-adiabatic heating.

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ABSTRACT: Small and large deformation in-plane elastic response of a new class of hierarchical fractal-like honeycombs inspired by the topology of the “spiderweb” were investigated through analytical modeling, detailed numerical simulations, and mechanical testing. Small deformation elasticity results show that the isotropic in-plane elastic moduli (Young’s modulus and Poisson’s ratio) of the structures are controlled by dimension ratios in the hierarchical pattern of spiderweb, and the response can vary from bending to stretching dominated. In large deformations, spiderweb hierarchy postpones the onset of instability compared to stretching dominated triangular honeycomb (which is indeed a special case of the proposed spiderweb honeycomb), and exhibits hardening behavior due to geometrical nonlinearity. Furthermore, simple geometrical arguments were obtained for large deformation Poisson’s ratio of first order spiderweb honeycombs, which show good agreement with numerical and experimental results. Spiderweb honeycombs exhibit auxetic behavior depending on the non-dimensional geometrical ratio of spiderweb.

Xu, F., Koutsawa, Y., Potier-Ferry, M., Belouettar, S., “Instabilities in thin films on hyperelastic substrates by 3D finite elements”, Int. J. Solids Struct. 69–70, 71–85., September 2015, DOI: 10.1016/j.ijsolstr.2015.06.007
ABSTRACT: Spatial pattern formation in thin films on rubberlike compliant substrates is investigated based on a fully nonlinear 3D finite element model, associating nonlinear shell formulation for the film and finite strain hyperelasticity for the substrate. The model incorporates Asymptotic Numerical Method (ANM) as a robust path-following technique to predict a sequence of secondary bifurcations on their post-buckling evolution path. Automatic Differentiation (AD) is employed to improve the ease of the ANM implementation through an operator overloading, which allows one to introduce various potential energy functions of hyperelasticity in quite a simple way. Typical post-buckling patterns include sinusoidal and checkerboard, with possible spatial modulations, localizations and boundary effects. The proposed finite element procedure allows accurately describing these bifurcation portraits by taking into account various finite strain hyperelastic laws from the quantitative standpoint. The occurrence and evolution of 3D instability modes including fold-like patterns will be highlighted. The need of finite strain modeling is also discussed according to the stiffness ratio of Young’s modulus.

ABSTRACT: The manufacturing of sheets with high mechanical yield stress, low thickness and minimal flatness defects is a major challenge in the cold rolling of aluminum alloys or steels. Compressive residual stress may appear due to the manufacturing process and induce elastic wave buckling, leading to flatness defects. This study proposes an experimental setup to analyze the interaction between residual stress and buckling for wavy edge flatness defects. The residual stress is simulated by thermal stress. High-resolution full-field measurements are used to measure the wrinkling shape and thermal field. The influence of surface imperfections and global tension on the wrinkling characteristics is highlighted. Finite element tests are used for test validation.

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ABSTRACT: It is previously known that under inflation alone a spherical rubber membrane balloon may bifurcate into a pear shape when the tension in the membrane reaches a maximum, but the existence of such a maximum depends on the material model used: the maximum exists for the Ogden model, but does not exist for the neo-Hookean, Mooney–Rivlin or Gent model. This paper discusses how such a situation is changed when a pressurized dielectric elastomer balloon is subjected to additional electric actuation. A similar bifurcation condition is first deduced and then verified numerically by computing the bifurcated solutions explicitly. It is shown that when the material is an ideal dielectric elastomer, bifurcation into a pear shape is possible for all material models, and similar results are obtained when a typical non-ideal dielectric elastomer is considered. It is further shown that whenever a pear-shaped configuration is possible it has lower total energy than the co-existing spherical configuration.


ABSTRACT: Experiment and analysis are used to investigate the buckling and recovery of pseudoelastic NiTi tubes with a diameter-to-thickness ratio of 23.6 under compression and the associated energy absorption. At a stress level corresponding to the onset of transformation to martensite, the tube initially buckles into a periodic axisymmetric wrinkling mode. The wrinkled structure remains stable despite the loss in stiffness, but at larger strain levels wrinkling gives way to an unstable non-axisymmetric buckling mode, characterized by three circumferential waves. With the load decreasing, this mode localizes first into a single lobe followed progressively by others. Unlike elastoplastic material behavior, transformation terminates into a stiff, saturation-type response with the linear elastic modulus of the M-phase. This stiffening of the material limits the growth of deformation in the mode-3 lobes preventing them from folding up. As a consequence, this progressive collapse occurs at a much higher stress level relative to that at the onset of collapse, than in concertina folding observed in typical structural metal energy absorbers. Even more importantly, on unloading the material transforms back to the A-phase resulting in recovery of deformation, erasure of the buckles, and a nearly closed hysteresis. The buckling and recovery phenomena are simulated numerically using a finite element model coupled to a J2-type nonlinear kinematic hardening model. The model is customized to the primarily compressive stress state of the problem at hand and is calibrated to the compressive hysteresis of the material. The analysis captures the onset of wrinkling, the switch to mode-3, and its localization first into a single lobe followed by a second and subsequent ones. The recovery on unloading is also reproduced by the analysis resulting in a completely closed hysteresis. Idealizations made in the present version of the constitutive model resulted in an unloading stress that is at a higher level than that observed in the experiment. Despite this discrepancy, the results demonstrate the overall veracity of the constitutive model developed.

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ABSTRACT: Cellular materials such as aluminium honeycombs combine lightweight challenges with high mechanical performance for crash energy absorption regulations. This paper investigates experimentally the dynamic behaviour of an aluminium alloy honeycomb under mixed shear-compression loading with a special attention on the combined effects between the cells in-plane orientation and the loading angles. An improvement of an existing experimental SHPB set-up is proposed and an original measurement technique based on an electro optical extensometer is used to overcome a separation phenomenon observed during the test. A significant effect of the loading angle $\psi$ is reported in the crushing responses. The in-plane orientation angle $\beta$ effects become more significant when the loading angle increases. An investigation of collapse mechanisms is also presented. Three deforming pattern modes are identified and it is shown that their distribution is related to the combined effects of the in-plane orientation angle $\beta$ and the loading angle $\psi$.

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ABSTRACT: Based on Dorfmann and Ogden's nonlinear theory of electroelasticity and the associated linear incremental theory, the non-axisymmetric wave propagation in an infinite incompressible soft electroactive hollow cylinder under biasing fields is investigated. The biasing fields are uniform, including an axial pre-stretch and a radial stretch in the plane perpendicular to the axis of the cylinder as well as an axial electric displacement. Such biasing fields make the originally isotropic electroactive material behave during its incremental motion like a conventional transversely isotropic piezoelectric material, hence greatly facilitating the following analysis. The three-dimensional equations of wave motion in cylindrical coordinates are derived and exactly solved by introducing three displacement functions. The exact solution is expressed in terms of Bessel functions, and explicit frequency equations are presented in different cases. For a prototype nonlinear model of electroactive material, numerical results are given and discussed. It is found that the initial biasing fields as well as the geometrical parameters of the hollow cylinder have significant influences on the wave propagation characteristics.

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ABSTRACT: Many examples of multi-stable shell structures have been recently proposed with the underlying hypothesis of the shell being completely free on its boundary. We describe a class of shallow shells which are bistable after one of their sides is completely clamped. This result, which has relevant technological implications, is achieved by a suitable design of the initial, stress-free, shape.

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ABSTRACT: The wrinkling of a uniformly stretched thin elastic plate subjected to a pressure acting perpendicular to its surface is re-visited. The problem is tackled under the assumption that the basic state can be adequately described by an appropriate nonlinear membrane analysis. That this simplification might be reasonable was suggested by recent related work in which numerical simulations showed that bending effects tend to be negligible for typical load levels that cause the initial axisymmetric deformation of the plate to bifurcate into an asymmetric mode. The effect of this seemingly unimportant change on the asymptotic description of the wrinkling instability is fully investigated here, and a direct quantitative assessment is made with earlier results in which the bending resistance of the axisymmetric deformation mode was accounted for.

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ABSTRACT: Thick-walled steel pipes during their installation in deep-water are subjected to a combination of loading in terms of external pressure, bending and axial tension, which may trigger structural instability due to excessive pipe ovalization. The resistance of offshore pipes against this instability depends on imperfections and residual stresses due to the line pipe manufacturing process. The present study examines the effect of UOE line pipe manufacturing process on the structural response and resistance of offshore pipes during the installation process using advanced finite element simulation tools. The cold bending induced by the UOE process is simulated rigorously and, subsequently, the application of external pressure and structural loading (bending or axial force) is modeled, until structural instability is reached. A parametric analysis is conducted, focusing on the effects of line pipe expansion on the structural capacity of the pipe. The results show that there exists an optimum expansion at which the highest pressure capacity is achieved. The effect of the axial tension on the pressure capacity of the pipe is examined as well. The influence of the line pipe expansion on bending capacity in the presence of external pressure is also identified. Finally, a simplified methodology is employed, accounting for the material anisotropy induced by the manufacturing process, capable of determining the structural capacity of a UOE pipe in a simple and efficient manner with good accuracy, using more conventional modeling tools.
ABSTRACT: This paper presents an analytical method to investigate the nonlinear frequency shift of graphene–elastic–piezoelectric (GEP) laminated films as a resonant mass detector. Based on the nonlocal elastic theory and nonlinear geometrical relation, the nonlinear dynamic governing equations containing deflection function, stress function and electric potential function are constructed by Hamilton's principles, then are solved by Galerkin method and the iterative homotopy harmonic balance method. The effects of some key parameters on the nonlinear frequency shift are described. Results show that both nonlinearity and nonlocal parameter appear in significant influences on the frequency shift of GEP laminated nano-mass detector, and the frequency shift can be controlled by adjusting the external voltage acted on the piezoelectric layer when different mass particles attach to the detector surface. The present work can serve as a guideline for the design of a nanoscale resonant mass detector or other GEP-films based electromechanical resonator sensors.

ABSTRACT: A planar rod model with flexible cross-section has been proposed and discussed recently in literature (Guinot et al., 2012; Picault et al., 2014). This 1D model is especially suitable for the modeling of tape springs, which develop localized folds through the flattening of the cross-section, and represents a good alternative to 2D shell models which are numerically hard to perform. However, due to its planar nature, it does not account for the coupling between bending and twisting that is noticed experimentally. In this context, we propose an extension of this rod model to 3D motions that includes torsional warping of the cross-section, based on postulated assumptions that are approximations. Starting from a complete non-linear elastic shell model, we introduce an original kinematics inspired from the elastica model and from Vlassov’s theory (Vlassov, 1962) in order to describe in-plane and out-of-plane changes of the cross-section shape with few parameters. In the specific case of shallow tape springs, approximate expressions of the strain and kinetic energies are derived by performing an analytical integration over the cross-section. The 1D tape spring rod model eventually involves only eight kinematic variables: seven to describe the translation and the rotation of the cross-section (parameterized by a unit quaternion) and one for the shape of the cross-section which is assumed to remain circular. Expressions of the potential and kinetic energies are then introduced in a suitable finite element software that can perform an automatic differentiation to solve the problem. Two static cases are treated. The first one, a tape spring clamped at one end and submitted at the other end to a follower twisting moment, shows that the model account for the bending-twisting couplings in large displacements and large rotations. The second one, a novel test named the transverse bending test, illustrates the ability of the model to account for
complex scenarios of 3D foldings, involving bending and twisting as well as the creation of folds, their migration along the tape and their duplication. Quantitative comparisons to numerical results obtained with a shell finite element model are shown.

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ABSTRACT: A state-based peridynamic formulation for linear elastic shells is presented. The emphasis is on introducing, possibly for the first time, a general surface based peridynamic model to represent the deformation characteristics of structures that have one geometric dimension much smaller than the other two. A new notion of curved bonds is exploited to cater for force transfer between the peridynamic particles describing the shell. Starting with the three dimensional force and deformation states, appropriate surface based force, moment and several deformation states are arrived at. Upon application on the curved bonds, such states yield the necessary force and deformation vectors governing the motion of the shell. By incorporating a shear correction factor, the formulation also accommodates analysis of shells that have higher thickness. In order to attain this, a consistent second order approximation to the complementary energy density is considered and incorporated in peridynamics via constitutive correspondence. Unlike the uncoupled constitution for thin shells, a consequence of a first order approximation, constitutive relations for thick shells are fully coupled in that surface wryness influences the in-plane stress resultants and surface strain the moments. Our proposal on the peridynamic shell theory is numerically assessed against simulations on static deformation of spherical and cylindrical shells, that of flat plates and quasi-static fracture propagation in a cylindrical shell.

ABSTRACT: Properly introduced hierarchy in cellular materials has the potential to further improve their energy absorption capacity. The in-plane uniaxial collapse response of a second order hierarchical honeycomb (i.e., a regular hexagonal honeycomb with its cell walls consisting of an equilateral triangular honeycomb) is investigated. Its failure modes for quasi-static crushing and dynamic impact in two directions are systematically explored by finite element simulations. A two-scale method is proposed and analytical expressions for the quasi-static collapse stresses of the hierarchical honeycomb in the two directions are obtained. In conjunction with the conservation of momentum, the analytical quasi-static collapse stress models are extended to dynamic crushing. The obtained theoretical collapse stresses are validated by finite element simulations for a wide range of impact velocity and relative density. Both numerical and analytical results show that the hierarchical honeycomb has an improved collapse stress over traditional hexagonal and triangular honeycombs. The improvement is found to be more pronounced for low velocity impact than for high velocity impact.

T. Sigaeva and A. Czekanski (Lassonde School of Engineering, York University, Toronto, Canada), “Coupling of surface effect and hyperelasticity in combined tension and torsion deformations of a circular cylinder”,
ABSTRACT: During the past decade there has been increasing research into the role of surface mechanics which can be relevant for many of today’s elastomeric applications. This paper incorporates surface effects into large deformation elasticity for a well-known continuum model of a circular cylinder under combined torsion and tension loadings and thus, generalizes it for application at smaller scales, such as nano- and micro-scales. At these scales, the effect of the surface and residual surface stresses on the overall deformation of the bulk material is of critical importance. The proposed model employs the Gurtin–Murdoch theory to represent the surface effect as a residually prestressed thin hyperelastic film of separate elasticity, perfectly bonded to the bulk. Using a constitutive model for which analytical solution can be derived, we demonstrate the pronounced effect of the surface and residual surface stresses not only on the values of resultant axial force and twisting moment, but also on the axial stiffness, the torsional rigidity and the Poynting effect.

Olivier Perret, Arthur Lebee, Cyril Douthe and Karam Sab (Université Paris-Est, Laboratoire Navier UMR 8205 CNRS, ENPC, IFSTTAR, 6–8 Avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne F-77455 Marne-la-Vallée, France), “The Bending-Gradient theory for the linear buckling of thick plates: Application to cross laminated timber panels”, International Journal of Solids and Structures, Vol. 87, pp 139-152, June 2016, 
https://doi.org/10.1016/j.ijsolstr.2016.02.021
ABSTRACT: In this paper, the linear buckling of a heterogeneous thick plate is studied using the Bending–Gradient theory which is an extension of the Reissner–Mindlin plate theory to the case of heterogeneous plates. Reference results are taken from a 3D numerical analysis using finite-elements and applied to Cross Laminated Timber panels which are thick and highly anisotropic laminates. First, it is shown that critical buckling loads are close to the material failure load which proves the necessity of a design model for the buckling of Cross Laminated Timber panels. Second, the soft simple support boundary condition is introduced as an opposition to the conventional hard simple support condition. It is shown that this distinction could be taken into account for designing timber structures depending on the accuracy needed. Third, it is observed that for varying plate geometries and arrangements, the Bending–Gradient theory predicts more precisely the critical load of CLT panels than classical lamination and first-order shear deformation theories. Finally, it is demonstrated that one of the suggested projections of the Bending–Gradient on a Reissner–Mindlin model gives very accurate results and could favorably allow the development of engineering recommendations for estimating properly transverse shear effects.

Bruno Reinaldo Goncalves, Jasmin Jelovica and Jani Romanoff (Department of Mechanical Engineering, Aalto University School of Engineering, P.O. Box 12200, FIN-00076 Aalto, Finland), “A homogenization method for geometric nonlinear analysis of sandwich structures with initial imperfections”, International Journal of Solids and Structures, Vol. 87, pp 194-205, June 2016, 
https://doi.org/10.1016/j.ijsolstr.2016.02.009
ABSTRACT: A homogenization method for geometric nonlinear analysis of structural core sandwich panels is proposed. The method provides high computational performance based on an efficient separation of scales. In the macroscale, the sandwich panel is discretized with an equivalent single layer of shell elements. The macroscale shell stiffness matrix is nonlinear, obtained from the analysis of a representative volume element. Prescribed displacement boundary conditions are applied to the representative unit based on the strain definitions of the first-order shear deformation theory. Changes in local wavelength in the post-buckling are considered in the analyses. Manufacturing-induced imperfections are introduced to local and global scales. The method allows for description of buckling in these two scales and is shown to hold good accuracy with respect
to equivalent 3D FEM models. Examples include web-core and corrugated-core sandwich panels. The method can be extended to any periodic structure of complex local topology. It can be easily implemented to commercial FE packages.

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“Post-bifurcation and stability of a finitely strained hexagonal honeycomb subjected to equi-biaxial in-plane loading”, International Journal of Solids and Structures, pp 296-318, June 2016,
https://doi.org/10.1016/j.ijsolstr.2016.02.016

ABSTRACT: The buckling and crushing mechanics of cellular honeycomb materials is an important engineering problem. Motivated by the pioneering experimental and numerical studies of Papka and Kyriakides (1994, 1999a,b), we review the literature on finitely strained honeycombs subjected to in-plane loading and identify two open questions: (i) How does the mechanical response of the honeycomb depend on the applied loading device? and (ii) What can the Bloch wave representation of all bounded perturbations contribute to our understanding of the stability of post-bifurcated equilibrium configurations? To address these issues we model the honeycomb as a two-dimensional infinite perfect periodic medium. We use analytical group theory methods (as opposed to the more common, but less robust, imperfection method) to study the honeycomb’s bifurcation behavior under three different far-field loadings that produce (initially) the same equi-biaxial contractive dilatation. Using an FEM discretization of the honeycomb walls (struts), we solve the equilibrium equations to find the principal and bifurcated equilibrium paths for each of the three loading cases. We evaluate the structure’s stability using two criteria: rank-one convexity of the homogenized continuum (long wavelength perturbations) and Bloch wave stability (bounded perturbations of arbitrary wavelength). We find that the post-bifurcation behavior is extremely sensitive to the applied loading device, in spite of a common principal solution. We confirm that the flower mode is always unstable, as previously reported. However, our (first ever) Bloch wave stability analysis of the post-bifurcated equilibrium paths shows that the flower mode is stable for all sufficiently short wavelength perturbations. This new result provides a realistic explanation for why this mode has been observed in the finite size specimen experiments of Papka and Kyriakides (1999a).

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https://doi.org/10.1016/j.ijsolstr.2016.04.006

ABSTRACT: Hollow tetrahedral truss cores composed of nanocrystalline nickel are fabricated and tested, and the resulting strengths compared to Nomex honeycomb, a sandwich core commonly in use in aerospace applications. We conduct a systematic finite element study to determine optimal geometric parameters of hollow tetrahedral truss cores given height and density constraints. We introduce nodal height truncation as an additional parameter for this architecture, and demonstrate that nodal truncation can yield further improvements in the shear and compression strength of truss cores. Informed by the finite element results, we proceed to fabricate specimens by additively manufacturing polymer templates, coating the templates with nanocrystalline nickel, and subsequently removing the templates resulting in free-standing, hollow truss cores. Mechanical testing demonstrates that judicious selection of the architecture of hollow truss cores results in structures with shear and compression strengths exceeding those of Nomex honeycombs at comparable densities.
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“A hybrid elastomeric foam-core/solid-shell spherical structure for enhanced energy absorption performance”,
International Journal of Solids and Structures, Vols. 92-93, pp 17-28, August 2016,
https://doi.org/10.1016/j.ijsolstr.2016.05.001
ABSTRACT: Energy absorption structures have been pursued to protect personnel and infrastructures over the last few decades. In this study, a novel hybrid foam-core/solid-shell spherical (FSS) structure is presented and investigated. The internal foam core inherits merits of large deformation from conventional foam structures and the introduction of the external thin solid shell is to reach high strength and delay deformation further, thereby achieving high energy absorption efficiency in FSS structures. Theoretical models are developed to characterize elastic modulus and buckling behavior of FSS structures under a compressive loading, and are verified through extensive finite element analysis (FEA). Typical deformation mechanisms are revealed by addressing competition of buckling deformation of the foam core and solid shell, and are identified through the proposed theoretical models. Further, the energy absorption efficiency is proposed to optimize the specific energy absorption density and critical triggering force of activating energy absorption, and is correlated with deformation mechanism and geometric parameters of FSS structures. Both numerical and theoretical analyses show that the employment of a thin solid shell surrounding the foam structures will enhance the energy absorption efficiency with high capability and safe comfort. The present study is expected to provide a useful guideline for a hybrid design of future energy absorption structures with unprecedented performance.

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“Imperfection sensitivity of locally supported cylindrical silos subjected to uniform axial compression”,
International Journal of Solids and Structures, Vol. 96, pp 92-109, October 2016,
https://doi.org/10.1016/j.ijsolstr.2016.06.019
ABSTRACT: For the prediction of the real failure load of shell structures, such as locally supported cylindrical steel silos under axial compression, it is convenient to take into account imperfections. It is assumed that such silos are very sensitive to a wide range of (even small) geometric imperfections, and that they lower the failure load significantly. Furthermore, these imperfections caused by the fabrication or the manufacturing process, are the dominant factor in the discrepancy between the theoretical/numerical predictions based on a perfect geometry and the experimental results of an imperfect geometry. In other words, it is important to make a well-considered choice for an imperfection when predicting the real failure load. However, the imperfection sensitivity depends, among other things, on the shape of the shell, the stiffening configuration, the boundary and loading conditions, etc. Before proceeding to the calculation of interaction curves and the development of new design rules for imperfect barrels, it is essential to perform an extensive study to examine the influence of imperfections to the failure behaviour and to choose a sufficiently detrimental imperfection shape. In this study, different imperfection forms are numerically investigated: the linear bifurcation mode, the non-linear buckling mode, several post-buckling deformed shapes of the perfect shell, and a weld depression type A and B.
Additional aspects, such as the orientation, the amplitude of the equivalent imperfection, and the position of the influence of the weld depression are also investigated. The present study takes into account the European normative documents and the guidelines of the recommendations of the ECCS.

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ABSTRACT: In computational solid mechanics path-following methods have been proven useful when dealing with non-monotonously evolving loading magnitudes as encountered e.g. in instability or softening behaviour. The present work derives from a displacement-based method a cavity-volume-based path-following method and considers its application specifically to cardiac mechanics problems. Both methods are able to account for an arbitrary number of simultaneously acting loading conditions. When applied to the Newton-Raphson method, the corresponding loading increments are computed by means of volume increments or point-wise prescribed displacement increments, respectively. No additional variables are required and the physics of the problem at hands is not altered. Both methods are implemented in an in-house meshfree modelling software and successfully applied to non-linear elastic and inelastic problems in structural mechanics. The cavity-volume control method, in particular, is demonstrated to accurately predict the highly non-linear elastic and anisotropic material behaviour encountered when modelling the heart. Albeit, the proposed methods can be equally used e.g. in finite element methods, they are very well suited for meshfree methods where the Kronecker delta property does not apply.

Broderick H. Coburn and Paul M. Weaver (Advanced Composites Centre for Innovation and Science, University of Bristol, Queen’s Building, Bristol BS8 1TR, United Kingdom), “Buckling analysis, design and optimization of variable-stiffness sandwich panels”, International Journal of Solids and Structures, Vol. 96, pp 217-228, October 2016, https://doi.org/10.1016/j.ijsolstr.2016.06.007

ABSTRACT: In recent years variable-stiffness (VS) technology has been shown to offer significant potential weight savings and/or performance gains for both monolithic and stiffened plate structures when buckling is a driving consideration. As yet, little work has been reported on VS sandwich structures. As such, a semi-analytical model is developed based on the Ritz energy method for the buckling of sandwich panels with fibre-steered VS face-sheets. The model captures both global and shear crimping instabilities and is shown to explain both types of buckling responses observed and the mode switching between them. Quantitative agreement with detailed three-dimensional finite element analysis was found to be within 13%. Subsequent parametric and optimisation studies, which were performed for many practical geometries using the developed model, reveal that, whilst VS sandwich panels show a significant improvement in global buckling performance, they suffer a reduction in shear crimping performance when compared to their straight-fibre counterparts. This behaviour is found to be due to the VS face-sheets creating a pre-buckling load redistribution where regions locally exceed the critical shear crimping load and induce the short wavelength instability at a reduced panel level load. For VS
sandwich panels with modest to low transverse shear moduli of the core, shear crimping can become the critical mode diminishing performance benefits relative to straight-fibre configurations. Cores with sufficient rigidity, thus preventing shear crimping, showed improvements in critical buckling load in the order of 80% when using VS, however this improvement reduces to a negligible amount with decreasing core transverse shear moduli. The transverse shear flexibility and load redistribution are thus two key parameters that must be considered carefully in the design of sandwich panels, in order to exploit the benefits of VS fully in this novel structural configuration.

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ABSTRACT: A continuum model is developed for hexagonal lattices, composed of a set of masses connected by linear axial and angular springs, with nonlinearity arising solely from geometric effects. For a set of lattice parameters, these lattices exhibit complex deformation patterns under uniform loading conditions due to instabilities. A continuum model accounting for these instabilities is developed from explicit expressions of the potential energy functional of a unit cell. This functional is non-convex, it captures the bistable nature of the lattice, and is used to derive its effective constitutive behavior. Finite element simulations of continuum medium illustrate the formation of microstructural patterns with discontinuous displacement gradients, similar to the features observed in nonlinear elasticity and finite deformation plasticity. A comparison of discrete lattice simulations and finite element analysis under general loading conditions illustrates that the continuum model captures the effective behavior due to instabilities within the lattice.

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ABSTRACT: Recent work on ductile failure under shear-dominant stress states has challenged the long-accepted premise that the strain at failure monotonically decreases with increasing triaxiality. This paper presents results from experiments in which custom Al-6061-T6 tubular specimens are loaded to failure under radial paths of shear and tension, spanning a range of triaxiality from 0.07 to 0.58. A long, thin-walled test section machined into the specimens has nearly uniform stress and deformation until a load maximum is reached and provides minimum constraint to the localized deformation that follows. Localization takes the form of a circumferential band with width the order of the wall thickness. Stereo digital image correlation (DIC) is used to monitor the deformation inside these localization zones up to failure. The specimen geometry, experimental setup, and use of DIC allow the true stresses and strains to be established directly from experimental measurements. The measured strains at failure are found to monotonically decrease as the triaxiality increases, a trend that is in concert with long accepted theory. However, the failure strains are significantly larger than previously reported values, approaching measurements based on statistical grain-level measurements. The results highlight the important role of localization in ductile failure, and the need for a
diagnostic technique with sufficient resolution to accurately establish the strain at failure. In incorporating the reported failure strains in the modeling of ductile failure, the observation that this alloy deforms to rather large strains free of damage must be taken into account. In other words, plasticity governs this behavior until very close to the end of life of the material.

ABSTRACT: This paper presents a general finite-strain shell theory, which is consistent with the principle of stationary three-dimensional (3-D) potential energy. Based on 3-D nonlinear elasticity and by a series expansion about the bottom surface, we deduce a vector shell equation with three unknowns, which preserves the local force-balance structure. The key in developing this consistent theory lies in deriving exact recursion relations for the high-order expansion coefficients from the 3-D system. Appropriate 2-D boundary conditions and associated 2-D weak formulations are also proposed, including various practical cases on the edge. Then, to demonstrate its validity, axisymmetric deformations of spherical and circular cylindrical shells are investigated, and comparisons with the exact solutions are made. It is found that the present shell theory produces second-order correct results for the general dead-load case and internally pressurized case. The advantages of the present shell theory include consistency, high accuracy, incorporating both stretching and bending effects, no involvement of higher-order stress resultants and its applicability to general loadings.

ABSTRACT: In a recent work (Healey et al., 2013. J. Nonlin. Sci. 23, 777–805.) it is predicted that stretch-induced wrinkled pattern in thin, clamped, elastic sheets eventually disappear as the imposed stretch is increased. The prediction stems from a precise bifurcation analysis of the Föppl–von Kármán equations generalized for finite mid-plane strains. There it is also revealed that for some aspect ratios of the rectangular domain, wrinkles do not occur at all regardless of the applied extension. To verify these predictions we carried out experiments on thin (20 µm thick adhesive covered), previously prestressed elastomer sheets with different aspect ratios under displacement controlled pull tests. On the one hand the adjustment of the material properties during prestressing is advantageous since in the targeted strain regime the film becomes substantially linearly elastic (which is not the case without prestress). On the other hand, a significant, non-negligible orthotropy develops during this first extension. To enable quantitative comparisons we abandon the assumption about material isotropy inherent in the original model and derive the governing equations for an orthotropic medium. We find good agreement between numerical simulations and experimental data by comparing measurements on prestressed specimen with predictions of the orthotropic model. Analysis of the negativity of the second Piola-Kirchhoff stress tensor reveals that the critical stretch for the bifurcation point at which the wrinkles disappear must be finite for any aspect ratio of the domain. On the contrary, there is no such bound if the continuation parameter is the aspect ratio, which manifests as complicated wrinkled patterns with more than one highly wrinkled zone for elongated rectangles. These arrangements have been found both numerically and experimentally. These findings also support the new finite strain model, since the Föppl–von Kármán equations based on infinitesimal strains do not exhibit such a behavior.
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ABSTRACT: Soft electroactive materials show great potential for device and robot applications. However, these materials are apt to experience buckling and pull-in instability under critical pressure or voltage, and, therefore, their practical applications are more or less prevented. In this paper, buckling behavior of incompressible soft electroactive hollow cylinders is investigated based on the nonlinear theory of electroelasticity and the associated linear incremental field theory. Hollow cylinders including or excluding the effects of exterior electric field are studied in a comparison manner. The equations governing the linearized incremental motion upon a finitely deformed configuration in the presence of an electric field are derived and exactly solved by introducing three displacement functions. As an illustrative example, the generic isotropic electroactive materials are considered and results are presented for a simple model of ideal electroelastic material. Numerical calculations show that the buckling of electroactive hollow cylinders is significantly influenced by the biasing fields, the electromechanical coupling parameters, the geometrical parameters of the cylinder, and the electric field outside the cylinder. In particular, a phase diagram is constructed based on the numerical results to clearly identify the dominant buckling modes and the transition between them in the axial wave number versus radius ratio plane.

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ABSTRACT: A membrane is prone to wrinkle under a very small amount of compression when the stiffness in the direction perpendicular to wrinkles vanishes. This kind of abrupt change in the mechanical properties may make the membrane vulnerable to deformation with poor definition on the profile of the surface and other adverse influences on its performances. It is important to find the factors influencing the wrinkles and take measures to prevent the wrinkling from happening. In this paper, the wrinkle-influencing factors such as prestress and thickness of membrane, Poisson's ratio and Young's modulus of material are studied and two benchmark examples, i.e. a rectangular membrane under bending and an annular membrane under torsion are analyzed with the wrinkling model proposed by the authors previously. In addition, the similarity between the wrinkling and perfectly plastic deformations, the physical meaning of wrinkling strain and the finite element implementation of the proposed wrinkling model are also presented.
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ABSTRACT: The wrinkling morphology resulted from the multi-buckling process of graphene sheet supported on a PDMS substrate is modeled by a continuum mechanics approach. The effects of randomly distributed interfacial debonded regions as well as adhesive and shear stresses between graphene sheet and substrate are considered. The buckling process has be examined. The present approach reveals the mechanism of multi-buckling in graphene sheet supported by an elastic substrate and can simulate the initiation, growth and saturation of the buckles. The value of adhesive stress controls the morphology of buckling in graphene. Higher values of adhesive stress lead to more uniformly distributed buckles with tiny sizes while lower values lead to large buckle sizes. This study also has demonstrated the capability in estimating the interfacial shear strength and adhesive stress.


ABSTRACT: Railway tracks are vulnerable to buckling when subjected to temperature increases, as occurs frequently during heatwaves. This paper presents an investigation of the lateral buckling and postbuckling response of railway tracks under thermal loading that includes the restraining effect of the ballast in the longitudinal and lateral directions. The principle of stationary total potential is used to develop the differential equations of equilibrium, as well as the bifurcation buckling from this equilibrium, and these equations are shown to be highly non-linear. The buckling analysis shows that first-order symmetric and antisymmetric modes may govern the buckling, and that for very long members the two buckling loads are the same. The highly non-linear equations for the postbuckling response are solved by making recourse to a shooting technique, and it is shown that following the bifurcation buckling under displacement control the response is initially unstable, followed by a stable branch of the postbuckling equilibrium response. Under thermal loading, which occurs in practice, the response is one of snap-through buckling to the remote stable path, and the solution is shown to capture the localisation of the buckling modes that is observed in practice. The effects of the lateral and longitudinal ballast resistance are quantified, and it is shown that the lateral resistance is predominant when compared with the longitudinal resistance. The influence of lateral track imperfections is also studied, which is shown to have considerable effect on the critical temperature.

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“Analytical and numerical analysis of swelling-induced large bending of thermally-activated hydrogel bilayers”,
https://doi.org/10.1016/j.ijsolstr.2016.08.017
ABSTRACT: Temperature-sensitive hydrogels have recently been implemented vastly for biomedical and microfluidic sensors and actuators. The accurate and efficient design of the bilayer sensors and actuators made of temperature sensitive hydrogels are of crucial importance. In this work, we develop an analytical method to solve the swelling induced bending of temperature responsive hydrogel bilayer under plane strain condition. The bilayer consists of a neutral incompressible elastomer layer attached to a temperature sensitive hydrogel layer. An analytical approach is developed to predict the thermomechanical response of these bilayers. At the other hand, the finite bending of the bilayer is simulated applying the finite element method. Several cases are solved to demonstrate the validity and performance of the proposed analytical method. The deformation and the stresses inside the layers are presented for various material parameters employing both the developed analytical formulation as well as the finite element method. A good correspondence between the presented method and the finite element method is observed. Finally, the effect of material and geometrical parameters on curvature are also investigated.

Dongjie Jiang, Chad M. Landis and Stelios Kyriakides (Research Center for Mechanics of Solids, Structures & Materials, WRW 110, The University of Texas at Austin, Austin, Texas 78712), “Effects of tension/compression asymmetry on the buckling and recovery of NiTi tubes under axial compression”,
https://doi.org/10.1016/j.ijsolstr.2016.07.003
ABSTRACT: We recently demonstrated that pseudoelastic NiTi tubes compressed axially buckle first into an axisymmetric wrinkling mode but subsequently collapse by progressive development of buckle lobes with three circumferential waves. This behavior is governed by the material nonlinearity associated with the austenite to martensite solid-state transformation. On unloading, the material transforms back to austenite, deformation is recovered, and the buckling lobes are erased (Jiang et al., 2016). The problem was simulated numerically using a constitutive model framework for the pseudoelastic behavior of NiTi based on a $J_2$-type nonlinear kinematic hardening model with the back stress represented through a potential. The first generation of the model did not account for the significant tension/compression asymmetry exhibited by the material so the buckling response did not reproduce well the experiments underestimating the dissipated energy. In the present work the constitutive model is extended to include the tension/compression asymmetry. It is introduced through a weighted mix of two potentials that are calibrated to the tensile and compressive stress-strain responses of the material. In addition, the present model allows for plastic deformations at the completion of martensite transformation. Incorporation of the tension/compression asymmetry significantly improves the calculated response of the buckling and recovery of NiTi tubes both qualitatively and quantitatively. The addition of plastic deformations to the model further improves the predictions. The initial axisymmetric wrinkling and the switch to the buckling mode with three circumferential waves are now reproduced correctly, and so are the evolution of localized collapse and the recovery of deformation on unloading. Furthermore, the stress levels during collapse and recovery follow the experimental levels quite closely thus reproducing the energy dissipated.

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ABSTRACT: Edge effects play an important role for many properties of graphene. While most works have focused on the effects from isolated free edges, we present a novel knotting phenomenon induced by the interactions between a pair of free edges in graphene, and investigate its effect on the buckling of monolayer graphene. Upon compression, the buckling of graphene starts gradually in the form of two buckling waves from the warped edges. The collision of these two buckling waves results in the creation of a knot structure in graphene. The knot structure enables the buckled graphene to exhibit two unique post-buckling characteristics. First, it induces a five-fold increase in graphene’s mechanical stiffness during the buckling process. Second, the knotted structure enables graphene to exhibit a mechanically stable post-buckling regime over a large (3%) compressive strain regime, which is significantly larger than the critical buckling strain of about 0.5%. The combination of these two effects enables graphene to exhibit an unexpected post-buckling stability that has previously not been reported. We predict that numerical simulations or experiments should observe two distinct stress-strain relations for the buckling of identical graphene samples, due to the characteristic randomness in the formation process of the knot structure.

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“Global and local interactive buckling behavior of a stiff film/compliant substrate system”, International Journal of Solids and Structures, Vols. 102-103, pp 176-185, December 2016,
https://doi.org/10.1016/j.ijsolstr.2016.10.006
ABSTRACT: This paper elucidates the global and local interactive buckling behavior of a stiff film resting on a compliant substrate under uniaxial compression. The resulting governing non-linear equations (non-autonomous fourth-order ordinary differential nonlinear equations with integral conditions) are then solved by introducing a continuation algorithm, which offers considerable advantages to detect multiple bifurcations and trace a complex post-buckling path. The critical conditions for local and global buckling and respective post-buckling equilibrium paths are carefully studied. Two different evolution mechanisms of buckling modes and processes from destabilization to restabilization (snap-back) are observed beyond the onset of the primary sinusoidal wrinkling mode in the post-buckling range. In addition, the shear modulus of an orthotropic substrate acts as a dominant role in the bifurcation portrait. Our results offer better understanding of the global and local buckling behaviors of such a bilayer system, and can open up new opportunities for the design and applications of novel nanoelectronics.

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“Deformation and energy absorption of aluminum foam-filled tubes subjected to oblique loading”, International Journal of Mechanical Sciences”, Vol. 54, No. 1, pp 48-56, January 2012,
https://doi.org/10.1016/j.ijmecsci.2011.09.006

ABSTRACT: Research to quantify the energy absorption of empty and foam-filled tubes under oblique loading with different loading angles and geometry parameters was carried out. Tests on circular tubes made of aluminum alloy AA6063 under quasi-static axial or oblique loading were performed. The collapse behavior of empty, foam-filled single and double tubes was investigated at loading angles of 0°, 5°, 10° and 15° with respect to the longitudinal direction of the tube. The tubes were fixed at both ends and oblique load was realized by applying a load at the upper end of a pair of specimens. When the foam-filled tubular structures subjected to oblique quasi-static loading, some new deformation modes, such as spiral folding mode, irregular extensional folding mode and irregular axi-symmetric or diamond deformation mode, were identified and ascribed to the bending of tubes and shearing of foam filler, as well as the interaction between the tubes and the foam. The energy absorption characteristics of empty and foam-filled single and double tube structures with respect to the load angle and wall thickness are determined. It is found that the energy-absorbing effectiveness factors of the circular tube structures with aluminum foam core are significant higher than those of the empty tubes and the energy absorption capacity of the foam-filled double tubes is better than that of the empty and foam-filled single tubes.

Farough Mohammadi and Ramin Sedaghati (Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Blvd. West, Montreal, Que., Canada H3G 1M8), “Linear and nonlinear vibration analysis of sandwich cylindrical shell with constrained viscoelastic core layer”, International Journal of Mechanical Sciences, Vol. 54, No. 1, pp 156-171, January 2012,
https://doi.org/10.1016/j.ijmecsci.2011.10.006

ABSTRACT: Damping characteristics of three-layered sandwich cylindrical shell for thin and thick core viscoelastic layers are studied using semi-analytical finite element method. The finite element method is developed based on the linear and nonlinear variations of the displacement distribution through the thickness of the core layer. Transient vibration has been conducted using the developed linear and nonlinear models and shown that the nonlinear formulation exhibits more damping property than the linear model. The effect of geometric nonlinearity due to the large deformation of the shell has also been considered assuming small strain and moderate rotation. Different assumptions based on the continuity and discontinuity in transverse shear stresses and slope of in-plane displacements are considered in the finite element formulation and their effects have been investigated. Considering nonlinearity of eigenvalue problem due to the frequency dependent property of viscoelastic material, an efficient algorithm has been developed to find the natural frequencies and loss factors of the viscoelastic cylindrical shell considering large deformation. The effect of imperfect bonding
between the layers has also been investigated in the modeling and it is shown that slippage between layers at the interfaces leads to reduction in loss factor at the majority of modes.

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ABSTRACT: The paper uses experiment and analysis to investigate the effect of local dents on the collapse curvature of pressurized pipes under pure bending. A series of experiments is conducted on stainless steel 321 seamless tubes with diameters of 1.5 in. and $D/t$ of 52. Small transverse dents are introduced to the specimens using a custom technique that limits their axial and circumferential spans. The dented tubes are internally pressurized to approximately one half the yield pressure and then bent to collapse in a pure bending testing machine. Tubes with dent depths ranging from very small to about 1.7 times the tube wall thickness were tested. It was found that such local imperfections tend to reduce the bending strain capacity of the pipe quite significantly. Smaller depth dents tend to cause relatively larger reduction to the collapse curvature, or bending strain, whereas for deeper ones the collapse curvature tends to level off at about 50% of the value of the intact case. The tube denting, pressurization, and bending to collapse have been simulated using solid finite element models. In addition to proper modeling the elastic–plastic behavior of the material, the model includes measured yield anisotropies, residual stresses, and wall eccentricity. The model reproduced quite well all aspects of the observed behavior including denting, bending and the ensuing collapse of the dented section, resulting in an inward kink with outward protrusions on either side. All predicted collapse curvatures were slightly lower than measured values. The cause of this discrepancy was traced to several small misalignments of the experimental dents, each of which tends to delay collapse somewhat.

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“Numerical and analytical approximations to large post-buckling deformation of MEMS”, International Journal of Mechanical Sciences, Vol. 55, No. 1, pp 95-103, February 2012,
https://doi.org/10.1016/j.ijmecsci.2011.12.010
ABSTRACT: This paper analyzes the electromechanical post-buckling response of an axially stressed clamped–clamped beam actuator subjected to a symmetric electrostatic field. Numerical solutions of the nonlinear integral–differential governing equation are first obtained by constructing the extended systems and applying the shooting method. The corresponding analytical approximate solutions are then established by combining Newton's linearization with Galerkin's method. In contrast to the classical Galerkin's method, the linearization is performed prior to its application. This yields a set of linear algebraic equations instead of nonlinear algebraic equations, and hence analytical approximate solutions are established. These analytical approximate solutions show excellent agreement with numerical solutions from the shooting method, and they are valid for a wide...
range of beam-center deflection. The analytical approximate method presented here is simple in principle and it is easy to be implemented with the help of any symbolic computational software.


ABSTRACT: The use of nanocomposites could be an interesting innovation in aeronautics and space structures such as multilayered plates and shells. The static analysis of layered shells embedding nanocomposites is here accomplished by means of classical and refined two-dimensional models. The shells analyzed are simply supported with a sinusoidal pressure applied at the top. These boundary and loading conditions allow the governing equations to be solved in a closed form. In nanocomposites a small amount of nanoscale reinforcements is embedded which have effects on the macroscale properties. The reinforcements considered are carbon nanotubes (CNTs) and clays, the former ones are nanometer-diameter cylinders, the second fillers are nanometer-thin platelets. Several types of nanocomposites are used in the static analysis of the shells proposed, their elastic properties have been obtained from a critical literature review. Classical two-dimensional models such as Classical Lamination Theory (CLT) and First order Shear Deformation Theory (FSDT), and a refined mixed model based on Carrera Unified Formulation (CUF) are used to investigate four shell configurations: a single layered cylindrical shell panel with CNT reinforcements in elastomeric or thermoplastic polymers, a single layered shell with CNT reinforcements in a polymeric matrix embedding carbon fibers, a sandwich shell with external skins in aluminium alloy and an internal core in silicon foam filled with CNTs and a single layered shell with clay reinforcements in a polymeric matrix. The aims of the paper are to demonstrate that the use of classical shell theories is inadequate to investigate the static response of nanocomposite shells, to quantify the beneficial effect of the nanoreinforcements in terms of displacements and stresses, to show that the curvature of shells does not give further effects with respect to the plate case.

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ABSTRACT: Closed-form formulation of three-dimensional (3-D) refined higher-order shear deformation theory (RHOST) for the free vibration analysis of simply supported–simply supported and clamped–clamped homogenous isotropic circular cylindrical shells is presented. The proposed RHOST accounts for the effects of in-plane and rotary inertias as well as the effects of transverse normal and shear strains on the dynamic response of cylindrical shells. Also, the present analysis incorporates trapezoidal shape factor of a shell element that arise due to the fact that the stresses over the thickness of the shell are to be integrated on a trapezoidal-like cross-section of a shell element to obtain the accurate stress-resultants. Therefore, the present theory refines other HOSTs established hitherto for free vibration analysis of thick circular cylindrical shells. The equations of motion are obtained using Hamilton’s principle. Solutions are obtained using the Galerkin method. Numerical results, not hitherto reported in the literature, are presented for the natural frequencies of isotropic long/short
and hollow/solid cylinders. Numerical results indicate that for thick cylinders with large length-to-radius ratios, approximate series truncation methods are inadequate for calculating the stress-resultants and just exact integration yields accurate stress-resultants leading to a reliable prediction of natural frequencies. Natural frequencies associated to higher-mode numbers of thick isotropic cylinders, never published in the literature before, are also considered in this paper. It is shown that stress-resultants calculated using exact integration over the cylinder cross-section are necessary to obtain accurate results of the free vibration analysis, especially for higher-mode numbers of thick isotropic cylinders. The closed-form solutions presented herein are compared with the available exact 3-D elasticity and analytical solutions in the available literature and excellent agreement is obtained. Also, the validity of the results is established with the aid of commercial finite element software.


ABSTRACT: This paper investigates the vibroacoustic behavior of stiffened composite panels. Airborne and structure borne excitations are considered. Two models are presented. The first is based on the modal expansion technique and handles both symmetric and asymmetric laminate composite panels and stiffening beams. It uses the first order shear deformation theory for the skin and accounts for the in-plane/bending effects, cross modal coupling and eccentricity of the stiffening beams. The latter are accounted for using equivalent forces and moments and integrated in the skin model using the continuity relations. The second model uses the equivalent properties of the composite panel and beams to extend an existing model, widely used in statistical energy analysis (SEA) of stiffened metallic structures, to composite stiffened structures. Composite panels reinforced by composite stiffeners with three types of cross-sections (I, C and omega) are analyzed. Both irregularly and periodically stiffened panels are studied and compared to the finite element (FEM) for the vibration response and boundary element methods (BEM) for the acoustic response. In FEM simulations, the stiffeners are modeled as surfaces assembly in order to highlight their in-plane displacements and their deformations effects. Excellent agreement with the FEM/BEN analysis is observed in all investigated configurations.

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ABSTRACT: In this paper the nonlocal shell and beam theories are used to study the transverse vibration of slender NTs. The agreement between the shell model and molecular dynamics simulations shows that the nonlocal effect originates predominantly from the atom-atom interaction in circumferential direction. It thus does not decrease with rising axial wavelength. In this case, a nearly constant nonlocal coefficient $e_0$ can be achieved for vibrating NTs. These behaviors however cannot be captured by the widely used nonlocal beam theory where only the axial nonlocal effect is included. Thus, caution must be taken when the one-dimensional nonlocal model is applied to slender NTs.

ABSTRACT: The critical buckling characteristics of hydrostatically pressurized complete spherical shells filled with an elastic medium are demonstrated. A model based on small deflection thin shell theory, the equations of which are solved in conjunction with variational principles, is presented. In the exact formulation, axisymmetric and inextensional assumptions are not used initially and the elastic medium is modelled as a Winkler foundation, i.e., using uncoupled radial springs with a constant foundation modulus that is independent of wave numbers of shell buckling modes. Simplified approximations based on a Rayleigh-Ritz approach are also introduced for critical buckling pressure and mode number with a considerable degree of accuracy. Characteristic modal shapes are demonstrated for a wide range of material and geometric parameters. A phase diagram is established to obtain the requisite thickness to radius, and stiffness ratios for a desired mode profile. The present exact formulation can be readily extended to apply to more general cases of non-axisymmetric buckling problems.

References at the end of the paper:

ABSTRACT: This paper presents a set of analytical solutions for the vibrational behavior of thin tubes under sequences of internal moving pressures. Such analyses are applicable to a number of theoretical and practical problems, like transient dynamic response of arteries due to pulsatory blood flow, transient deformations of gas pipelines due to pressure fluctuations, or the vibrational response of pulse detonation engines (PDE). However, the presented solutions are tailored for successive applications of specific loading profiles that represent gaseous detonations. The solutions are compared with the available experimental data and complementary finite element simulations. Representative analyses are carried out for an experimental detonation tube under loading spectra traveling with different time delays. It is shown that the resulting vibrational spectra can be highly affected by the frequency of the sequential loadings and high dynamic amplification factors can exist even at non-critical speeds. It is also shown that application of sequential moving pressures with proper loading frequencies can substantially reduce the structural vibration.

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ABSTRACT: In this paper a high order theory for functionally graded (FG) axisymmetric cylindrical shells based on the expansion of the axisymmetric equations of elasticity for functionally graded materials (FGMs) into Fourier series in terms of Legendre's polynomials is presented. Starting from the axisymmetric equations of elasticity, the stress and strain tensors, the displacement, traction and body force vectors are expanded into Fourier series in terms of Legendre's polynomials in the thickness coordinate. The obtained boundary-value problems are solved by the finite element method (FEM) with COMSOL Multiphysics and MATLAB software. Numerical results are presented and discussed.
ABSTRACT: This paper presents an analytical study on the influence of in-plane forces on the dynamic characteristics of a plate with grooves in different sizes. A sub-structuring approach, the reverse receptance method, is applied to solve the eigenvalues of an in-plane forces loaded plate with two parallel grooves and two orthogonal grooves, respectively. On considering coupling and interaction between two orthogonally connected grooves, the point receptance arrays are employed. Accuracy is evaluated by comparing the analytical solutions with numerical results obtained from the finite element model. Parametric study reveals, the deeper the groove, the lower the natural frequencies and buckling loads of the grooved plate will be. With in-plane tensions applied and increased linearly, the grooved plate is stiffened gradually and its natural frequencies increase accordingly. With equal bi-axial tensions, the natural frequencies of the grooved plates increase twice as much as those with uni-axial tension do. With in-plane compressive forces on the plate, the situations are reversed. The lowest natural frequency of a grooved plate with sufficient tensions can be higher than that of a non-grooved unloaded plate. When the groove size and the loading condition are the same, the orthogonal grooves decrease the natural frequencies and the buckling loads of a plate more than the parallel grooves do. The in-plane forces do not affect the mode shapes of the grooved plate; but the grooves do. The analytical evaluation demonstrates the accuracy and applicability of the proposed approach.

Francesco Tornabene, Alfredo Liverani and Gianni Caligiana (DIEM—Department, Faculty of Engineering, University of Bologna, Italy), “Static analysis of laminated composite curved shells and panels of revolution with a posteriori shear and normal stress recovery using generalized differential quadrature method”, International Journal of Mechanical Sciences, Vol. 61, pp 71-87, August 2012, https://doi.org/10.1016/j.ijmecsci.2012.05.007
ABSTRACT: The Generalized Differential Quadrature (GDQ) Method is applied to study laminated composite shells and panels of revolution. The mechanical model is based on the so called First-order Shear Deformation Theory (FSDT) deduced from the three-dimensional theory, in order to analyze the above moderately thick structural elements. In order to include the effect of the initial curvature from the beginning of the theory formulation a generalization of the kinematical model is adopted for the Reissner–Mindlin theory. The solution is given in terms of generalized displacement components of points lying on the middle surface of the shell. The results are obtained taking the two co-ordinates into account, without using the Fourier expansion methodology, as done in semi-analytical methods. After the solution of the fundamental system of equations in terms of displacements and rotations, the generalized strains and stress resultants can be evaluated by applying the Differential Quadrature rule to the generalized displacements themselves. The transverse shear and normal stress profiles through the laminate thickness are reconstructed a posteriori by simply using local three-dimensional equilibrium equations. No preliminary recovery or regularization procedure on the extensional and flexural strain fields is needed when the Differential Quadrature technique is used. By using GDQ procedure through the thickness, the reconstruction procedure needs only to be corrected to properly account for the boundary equilibrium conditions. In order to verify the accuracy of the present method, GDQ results are compared with the ones obtained with 3D finite element methods. Stresses of several composite shell panels are evaluated. Very good agreement is observed without using mixed formulations and higher order kinematical models. Various examples of stress profiles for different shell elements are presented to illustrate the validity and the accuracy of GDQ method.
ABSTRACT: In this study, the second order statistics of postbuckling analysis of functionally graded materials (FGMs) plates subjected to mechanical and thermal loadings without and with square and circular holes at center having random material properties is presented. Material properties of each constituent's materials, volume fraction index, thermal expansion coefficients and thermal conductivities are modeled as independent random input variables. The basic formulation is based on higher order shear deformation theory (HSDT) using modified $C^0$ continuity. A nonlinear finite element method (FEM) based on direct iterative technique combined with mean centered first order perturbation technique (FOPT) developed by the author for composite plate is extended for FGM plates to solve the random nonlinear eigenvalue problem. Typical numerical results are presented to examine the effect of volume fractions index, plate length to thickness ratios, plate aspect ratios, types of loadings, amplitude ratios, support conditions and various shaped and sized holes with random thermomechanical properties. The results obtained by the present solution approach are validated with those available in the literatures and independent Monte Carlo Simulation (MCS). It is observed that the plates with circular and square hole have a significant influence on the postbuckling response under mechanical and thermal loading conditions and some new results are presented to demonstrate the applications of present work.

ABSTRACT: In the present paper, nonlinear generalized (with second sound effects) and classical thermoelasticity analyses are performed for functionally graded thick cylinders with temperature-dependent material properties subjected to various thermomechanical shocks at their inner and outer surfaces, employing Hermitian elements. The unified generalized thermoelasticity approach is composed of three distinct theories and employed to study the thermoelastic wave propagation and reflection phenomena. In contrast to the available rare researches proposed so far based on the generalized theories, the continuity condition of the stress components at the mutual boundaries of the elements and the temperature-dependency of the material properties are taken into account. Furthermore, Mori–Tanaka homogenization model of variations of the material properties is employed instead of the simple rule of mixture. Transfinite element approach is employed to determine the transient responses. Besides, the formulation considers effects of both mechanical and thermal shocks. Influences of the lags between the thermal and elastic waves are among the interesting observations of the present paper.

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ABSTRACT: This article derives some theoretical relations to predict diagrams of absorbed energy and axial force versus axial displacement during the folding process in square and rectangular columns. By considering the folding wavelength as a constant parameter during the folds creation and using balance of internal and external energy and minimum principle in plasticity, final relations are calculated. Also, two different relations are introduced to predict the maximum folding force of the empty and polyurethane foam-filled columns with square and rectangular cross sections, by considering the interaction effects between column wall and foam-filler. Furthermore, some experiments were carried out on the empty and foam-filled metal columns and the experimental measurements were compared with predictions of the theoretical formulas that showed good correlation.

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ABSTRACT: In this study, the non-linear dynamic analysis of functionally graded (FG) truncated conical shells surrounded by an elastic medium has been investigated using the large deformation theory with von Karman–Donnell-type of kinematic non-linearity. The material properties of FG truncated conical shell are assumed to vary continuously through the thickness direction. The Pasternak model is used to describe the reaction of the elastic foundation on the FG conical shell. The fundamental relations, the non-linear motion and compatibility equations of FG truncated conical shells surrounded by an elastic medium are derived. By using the Superposition method, Galerkin method and Harmonic balance method, the problem of non-linear vibration of the FG truncated conical shell surrounded by an elastic medium is solved. Finally, the influences of variations of the elastic medium, compositional profiles and conical shell characteristics on the frequency–amplitude relations are investigated. The present results are compared with the available data for a special case.


ABSTRACT: This paper investigates computationally the buckling of simply supported sandwich columns constructed using elastic cores reinforced by skin-sheets of triaxial weave fabric (TWF) composites. A novel computationally cheap volume segmentation based thin plate model for the elastic properties of TWF is first developed. The predicted elastic properties of TWF exhibit quasi-isotropic behavior and correlate well with published numerical and measured results. Having demonstrated strong agreement with established results, these properties are then employed in the use of a plate on elastic foundation concept to study the stability of sandwich columns under a uniaxially compressed load environment. The parametric study comprises the effects of thickness, aspect ratio, and modulus of the sandwich core (treated as an elastic foundation), as well as the inclusion of the effects of the initial in-plane and out-of-plane imperfections of the skin-sheets on the critical
buckling load. Remarkable dependencies of the critical buckling load on these parameters are demonstrated, due to both independent and wedding actions, noting that a perturbation due to out-of-plane imperfections has been observed to be the most significant contributor to reduction in compressive resistance.

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ABSTRACT: A symplectic approach is developed within the perspective of stress wave propagation to study theoretically the localization of dynamic buckling of a cylindrical shell subjected to an axial impact. In this analysis, a set of lower-order fundamental equations, the Hamiltonian canonical equations, is presented in dual variables. Subsequently, the critical load and buckling mode are reduced to solving the symplectic eigenvalue and eigensolution, respectively. The result shows that the localization of dynamic buckling patterns in the elastic shell is mainly caused by the relaxation of boundary conditions. With stress wave propagation and no reflection, the corresponding buckling mode deformation should exist near the impact end. This behavior has significant influence on the reduction of dynamic buckling loads. In conclusion, this paper provides some new analytical and numerical rules for dynamic buckling and the new results are useful in the critical design of shell structures against buckling.

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ABSTRACT: Patterned windows are introduced to the thin-walled square tubes to reduce the weight while maintaining the mechanical property of the original tube. The topologic pattern design is studied under axial compressing condition. Experimental results show that these windowed tubes have enhanced crushing performance over the conventional tube, with 63% as the maximum reduction in the initial peak load and 54% as the maximum increase in the specific energy absorption. Parametric study is conducted by using a finite element analysis to investigate the effect of the size of windows on tubes' collapse characteristics. Three collapse modes, the symmetric, extensional and diamon modes, are distinguished. Tubes collapsing in the diamond mode perform less well in terms of both the energy absorption and SEA, while those with the symmetric or extensional mode generally show an increase in SEA.

ABSTRACT: Free vibration of FGM box beam is investigated by the formulation of an exact dynamic stiffness
matrix on the basis of first-order shear deformation theory (FSDT). Primary and secondary torsional warping, shear and bending deformations are incorporated in the one-dimensional beam model. Material properties of the beam are assumed to be graded across the wall-thickness. A recent function characterising the distribution of shear stresses is introduced. The present model is validated by comparison with finite element analysis for various boundary conditions. Good correlation exists between the values of Abaqus analysis and those calculated with the present method.

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ABSTRACT: Three-dimensional reinforced sandwich structures are generally designed in order to provide optimal out-of-plane mechanical properties, beside traditional sandwiches which generally display satisfactory specific flexural properties but fatally insubstantial stiffnesses in the through-thickness direction. This paper deals with sandwich structures manufactured with polymeric foam core reinforced thanks to the technology (which is based on transverse needling) and specially investigates the compression behavior through the thickness direction. The compressive longitudinal moduli of such sandwiches are shown to be significantly improved in the presence of fibrous orthogonal reinforcements but the experimental estimations rather differ from analytical predictions that can be easily obtained using classical mixture laws. These discrepancies are mainly due to the buckling phenomenon, inherent in the geometry of the reinforcements, and the associated imperfection sensitivity. This work is thus devoted to the prediction of the critical loading of such a sandwich structure under through-thickness compression. A closed-form analytical expression is first derived from a general 3D elastic bifurcation analysis, then compared to finite element numerical solutions (obtained by both linearized buckling and incremental post-buckling analyses) for validation purposes, and finally confronted to experimental results. The buckling phenomenon is actually proved to be mainly responsible for the final collapse of the through-thickness reinforced sandwich.

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ABSTRACT: Recently developed inverse hyperbolic shear deformation theory by the authors is extended to analyze the free vibration response of laminated composite and sandwich plates. Euler–Lagrange equations are derived employing the principle of virtual work for the dynamic problem. A Navier type and finite element solutions are proposed to obtain the free vibration response of laminated composite and sandwich plates. A C⁰-continuous isoparametric biquadratic-quadrilateral serendipity element is used for the finite element solution of generalized higher order shear deformation theory so as to ensure its applicability to general laminates subjected to different combinations of boundary conditions. Higher modes of vibration are obtained for laminated cross-ply and angle-ply plates and efficiency of the theory is ensured by comparing the results with the existing
results. It is observed that both analytical and finite element solutions with the present theory are capable for accurate prediction of the free vibration response.


ABSTRACT: In the context of nonlocal continuum theory, seeking an analytical solution to the equations of motion of stocky double-walled carbon nanotubes (DWCNTs) with arbitrary boundary conditions is a very problematic task. Thereby, proposing efficient numerical techniques for frequency analysis and optimal design of such nanostructures is of great advantageous. Herein, free transverse vibration of an elastically supported stocky DWCNT embedded in an elastic matrix under initial axial force is of interest. To this end, the equivalent continuum structures (ECSs) associated with the innermost and outermost tubes are taken into account. The interaction of the DWCNT with its surrounding matrix is modeled using lateral and rotary continuous springs. Through consideration of interlayer van der Waals forces via an equivalent spring system, the two tubes are appropriately interacted. Using Hamilton's principle, the dimensionless equations of motion of elastically supported DWCNTs are established using nonlocal Rayleigh, Timoshenko, and higher-order beam theories. The unknown fields of the equations of motion for each model are discretized in the spatial domain using reproducing kernel particle method. After tedious calculations, the set of eigenvalue equations pertinent to each model is extracted and numerically solved. The convergence checks of the proposed numerical models in predicting flexural frequencies of DWCNTs are carried out. The obtained results are also compared with those of other works and a reasonably good agreement is achieved. Through various numerical studies, the influences of slenderness ratio, ratio of the mean radius to the thickness of the ECSs, small-scale parameter, initial axial force, lateral and rotational stiffness of the surrounding matrix on the flexural frequencies of stocky DWCNTs are carefully examined for different boundary conditions. The capabilities of the proposed nonlocal models in capturing the flexural frequencies of stocky DWCNTs are discussed as well.

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ABSTRACT: A general approach is presented for the vibration studies of rotating cylindrical shells having arbitrary edges. The present analysis is based on the Sanders' shell theory and the effects of centrifugal and Coriolis forces as well as initial hoop tension due to rotating are all taken into account. By taking the characteristic orthogonal polynomial series as the admissible functions, the Rayleigh–Ritz method is employed to derive the frequency equations of rotating cylinders with classical homogeneous boundary conditions. Further, utilizing artificial springs to simulate the elastic constraints imposed on the cylinders’ edges, one can derive the frequency equations of rotating cylindrical shells with more general boundary conditions by considering the strain energy of artificial springs during the Rayleigh–Ritz procedure. To validate the approach proposed in this paper, a series of comparison and convergence studies are performed and the investigations
demonstrate high accuracy and low computational cost of the present approach. Finally, some further numerical results are given to illustrate the influence of the variations of spring stiffness on the frequencies of rotating cylinders.

ABSTRACT: In contrast to a conventional cylindrical pipe, a textured pipe is proposed for deep subsea operations. The basic geometric parameters, the stiffness properties and the stress distribution in the textured pipe are presented. The propagation buckling response of the textured pipe is analysed and compared to equivalent cylindrical pipe. The effects of geometric imperfection and the basic geometric parameters defining the textured pipe on the propagation response are evaluated. The textured pipe offers a substantial increase in propagation buckling capacity when compared to equivalent cylindrical pipe.

ABSTRACT: The lateral buckling analysis of the shear deformable laminated composite I-beams with symmetric and non-symmetric lay-ups is performed. The general linear theory of the laminated composite beams is presented for all structural couplings coming from the material anisotropy and the shear deformation effects. The current composite beam includes the transverse shear and the restrained warping induced shear deformation. Especially the geometrically non-linear theory for the lateral stability analysis of the composite beams is derived. Based on the present analytical model, three different types of finite beam elements, namely, 2-, 3-, and 4-noded isoparametric beam elements are developed to analyze the lateral stability problems. In order to demonstrate the validity of this study, the numerical solutions for the lateral stability of the bisymmetric and mono-symmetric I-beams under the pure bending are presented and compared with the results obtained from other researchers and the detailed three-dimensional analysis results using the shell elements of ABAQUS. The effects of shear deformation, fiber angle change, modulus ratios, boundary condition, and span-to-height ratio on the critical buckling moments are parametrically investigated.

ABSTRACT: The stability of stationary or rotating cylindrical shells interacting with a rotating internal fluid flow is studied. The paper presents the results of the finite element solutions for shells having different linear dimensions and subjected to various boundary conditions. It has been found that the form of stability loss in the stationary and rotating shells under the action of the fluid flow, having both the axial and circumferential components, depends on the type of the boundary conditions specified at their ends. It has been shown that for different variants of boundary conditions and different geometrical dimensions rotation of the fluid in a stationary shell or co-rotation of the shell and the fluid may increase or decrease the critical velocity of the axial fluid flow.
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ABSTRACT: A general variational formulation for the determination of natural frequencies and mode shapes of free vibration of symmetric laminated plates of trapezoidal and triangular shapes is presented in this work. The kinematics corresponding to the first-order shear deformation plate theory (FSDT) is used to take into account the effects of shear deformation and rotational inertia in the analysis. The developed approach is based on the Ritz method and the plate geometry is approximated by non-orthogonal right triangular co-ordinates. The transverse deflection and two rotations of the laminate are independently approximated by sets of simple polynomials. The algorithm allows obtaining approximate analytical solutions for laminated plates with different shapes, aspect ratio, number of layers, stacking sequence, angle of fiber orientation and boundary conditions including translational and rotational elastically restrained edges. The algorithm is simple to program and numerically stable.

Yegao Qu, Shihao Wu, Yong Chen and Hongxing Hua (State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “Vibration analysis of ring-stiffened conical-cylindrical-spherical shells based on a modified variational approach”, International Journal of Mechanical Sciences, Vol. 69, pp 72-84, April 2013, https://doi.org/10.1016/j.ijmecsci.2013.01.026

ABSTRACT: In this paper, free vibration characteristics of conical–cylindrical–spherical shell combinations with ring stiffeners are investigated by using a modified variational method. Reissner–Naghdi’s thin shell theory in conjunction with a multilevel partition technique, viz., stiffened shell combination, shell component and shell segment, is employed to formulate the theoretical model. The displacement fields of each shell segment are expressed as a product of orthogonal polynomials along the meridional direction and Fourier series along the circumferential direction. The ring stiffeners in shell combinations are treated as discrete elements. Convergence and comparison studies for both non-stiffened and stiffened conical–cylindrical–spherical shells with different boundary conditions (e.g., free, clamped and elastic supported boundary conditions) are carried out to verify the reliability and accuracy of the present solutions. Some selected mode shapes are illustrated to
enhance the understanding of the research topic. It is found the present method exhibits stable and rapid convergence characteristics, and the present results, including the natural frequencies and the mode shapes, agree closely with those solutions obtained from the finite element analyses. The effects of the number and geometric dimensions of ring stiffeners on the natural frequencies of a submarine pressure hull are also investigated.

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ABSTRACT: In this study the large deflection behaviors of stiffened annular functionally graded (FG) sector plates under mechanical and thermo-mechanical loadings with various boundary conditions are investigated. Material properties are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. Based on first-order shear deformation plate theory (FSDT) and von Karman relations for large deflection, nonlinear equilibrium equations are developed. Dynamic relaxation (DR) numerical method combined with the finite difference discretization technique is used to solve the plate nonlinear equations. Effects of material grading index, boundary condition, stiffener depth to the plate thickness ratio and thermal gradient are discussed.

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ABSTRACT: This study presents the buckling analysis of radially solid circular plate made of porous material bounded with the layers of piezoelectric actuators. Porous material properties vary through the thickness of plate with a specific function. The general mechanical non-linear equilibrium and linear stability equations are derived using the variational formulations to obtain the governing equations of piezoelectric porous plate. Buckling load is derived for solid circular plates under uniform radial compressive loading, for the clamped edge condition. The effects of piezoelectric layers on the buckling load of plate, piezoelectric layer-to- porous plate thickness ratio, and variation of porosity are investigated. The results are verified with the known results in the literature.

ABSTRACT: The present investigation proposes a nonclassical mathematical model and an algorithm for the axisymmetrically nonlinear free vibration analysis of a circular microplate. Based on the modified couple stress theory and von Kármán geometrically nonlinear theory, the governing equations for microplates are established in variational form from Hamilton principle containing only one material length scale parameter which can
capture the size-dependent behavior. These partial differential equations are reduced to corresponding ordinary ones by elimination of the time variable with Kantorovich method following an assumed simple harmonic function in time. The resulting nonlinear spatial boundary value problem is then solved numerically by shooting method, and the size-dependent characteristic relationships of nonlinear vibration frequency versus central amplitude of the microplates are obtained. The parametric studies are conducted for immovable clamped and simply supported edge conditions, some of the results in special cases are verified by comparing with those in the literature. The numerical results indicate that the microplates modeled by the modified couple stress theory cause more stiffness than modeled by the classical continuum plate theory, such that the differences between the results of these two theories are large when the thickness to material length scale ratio is small, whereas they are decreasing with the increase of the ratio.


ABSTRACT: A simple refined shear deformation theory is proposed for bending, buckling, and vibration of thick plates resting on elastic foundation. The theory accounts for parabolic distribution of transverse shear stress, and satisfies the free transverse shear stress conditions on the top and bottom surfaces of the plate without using shear correction factor. The number of unknowns of present theory is two as against three in the case of other shear deformation theories. The elastic foundation is modeled as two-parameter Pasternak foundation. Equations of motion are derived from Hamilton's principle. Analytical solutions are obtained for rectangular plates with two opposite edges simply supported and the other two edges having arbitrary boundary conditions. Comparison studies are presented to verify the validity of present solutions. It can be concluded that the proposed theory is accurate and efficient in predicting the bending, buckling, and vibration responses of thick plates resting on elastic foundation.


ABSTRACT: This paper presents the analytical solutions of nonlinear instability of channel-section beams subjected to pure bending about its minor axis. The solutions are derived using energy methods by taking into account the cross-section flattening. The present results show that, the section flattening is very important during the bending, which can induce the nonlinear snap-through instability of the beam. It is also shown that the dynamic instability of channel-section beams under the action of a sudden step moment occurs at a moment about 71% of the corresponding critical static moment, but the deformations of the longitudinal curvature and flattening at the critical dynamic state are almost twice of those corresponding to the static instability case. To validate the analytical solutions, nonlinear finite element analyses using ANSYS are also conducted. Good agreement between the analytical solutions and FEA results is found.

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ABSTRACT: A cell-based smoothed discrete shear gap method (CS-DSG3) for static and free vibration analyses of Reissner–Mindlin shells is formulated by combining the cell-based strain smoothing technique with the discrete shear gap method (DSG3) using three-node triangular elements. In the CS-DSG3, each triangular element will be divided into three sub-triangles, and in each sub-triangle, the stabilized DSG3 is used to compute the strains and to avoid the transverse shear locking. Then the strain smoothing technique on whole of the triangular element is used to smooth the strains on these three sub-triangles. The CS-DSG3 hence not only overcomes the drawback of the DSG3 but also improves the accuracy as well as the stability of the DSG3. The numerical examples demonstrated that the CS-DSG3 is free of shear locking and achieves the high accuracy compared to other existing shell elements.

ABSTRACT: As far as the study of circular cylindrical shell is concerned, most of the existing works are limited to classical homogeneous boundary conditions. However, complicated boundary conditions, such as elastic and non-uniform boundary conditions are encountered in many engineering applications. Thus, it is of important practical significance to investigate the vibrations of cylindrical shell with this kind of boundary conditions. This paper is mainly concerned with the free vibrations of cylindrical shell with non-uniform elastic boundary constraints. The exact solution for the problem is obtained using improved Fourier series method, in which each of three displacements of the shell is represented by a Fourier series supplemented by several terms introduced to ensure and accelerate the convergence of the series expansions. The unknown expansions coefficients are treated as the generalized coordinates and determined using the Rayleigh–Ritz procedure. The change of the boundary conditions can be easily achieved by only varying the stiffness of the four sets of boundary springs at each end of the shell without the need of making any change to the solution procedure. The excellent accuracy of the current results is validated by comparison with the finite element method (FEM) results. Numerical results are presented to illustrate the effects of some interesting and practically important boundary restraints on free vibrations of circular cylindrical shell, including varying stiffness of boundary springs, point supported and partially supported boundary conditions.

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“Solid or shell finite elements to model thick cylindrical tubes and shells under global bending”, International Journal of Mechanical Sciences, 74, 143-153, 2013,
DOI: http://dx.doi.org/10.1016/j.ijmecsci.2013.05.008
ABSTRACT: This paper explores the use of solid continuum finite elements and shell finite elements in the modelling of the nonlinear plastic buckling behaviour of cylindrical metal tubes and shells under global bending. The assumptions of shell analysis become increasingly uncertain as the ratio of the radius of curvature to the thickness becomes smaller, but the classical literature does not draw a clear line to define when a shell
treatment is inappropriate and a continuum model becomes essential. This is a particularly important question for the bending of tubular members, pipelines, chimneys, piles, towers and similar structures. This study is therefore concerned solely with the uniform bending of thin tubes or thick shells which fail by plastic buckling well into the strain-hardening range. The analyses employ finite element formulations available in the commercial software ABAQUS because this is the most widely used tool for parametric research studies in this domain with an extensive and diverse element library. The results are of general validity and are applicable to other finite element implementations. This paper thus seeks to determine the adequacy of a thin or thick shell approximation, taking into account geometric nonlinearity, complex equilibrium paths, limit points and bifurcation buckling, extensive material ductility and linear strain hardening. It aims to establish when it is viable to employ shell elements and when this decision will lead to outcomes that lack sufficient precision for engineering design purposes. The results show that both thin and thick (shear-flexible) shell elements may give a reasonably accurate prediction of the buckling moment under global uniform bending for cylindrical tubes as thick as R/t = 10. A finite strain and thick shell formulation are additionally shown to model the ductility of such thick tubes well, even when ovalisation of the cross-section and strain hardening are included. The use of solid continuum elements to model tubes in bending is found to be increasingly uneconomical as the R/t ratio rises above 25 with reduced advantages over shell elements, both in terms of the accuracy of the solution and the computation time.

References listed at the end of the paper:


ABSTRACT: Fuel assemblies of a research reactor consist of a number of rectangular fuel plates with an equal gap and the coolant flows between the fuel plates for heat exchange. The paper deals with a theoretical dynamic model of the fuel assembly submerged in the coolant, and presents a free vibration analysis of a bundle of identical rectangular plates fully in contact with an ideal liquid. The orthogonal polynomial functions, as
admissible functions, were generated using the Gram–Schmidt process to approximate the wet dynamic
displacements of the plates with a clamped-clamped-free-free boundary condition. The liquid displacement
potential satisfying the boundary conditions was derived, and the wet dynamic modal functions of the plates
were expanded by the finite Fourier transform for a compatibility requirement along the contacting surface
between the plates and the liquid. The natural frequencies under the wet condition were calculated using the
Rayleigh–Ritz method based on minimizing the Rayleigh quotient of the ratio between the maximum potential
energy and total kinetic energy. The comparison showed excellent agreement between the results from the
proposed theoretical method with the finite element analysis results. The effect of the liquid gap between the
plates on the normalized natural frequencies was discussed.

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“Nonlinear static and dynamic buckling analysis of imperfect eccentrically stiffened functionally graded
circular cylindrical thin shells under axial compression”, International Journal of Mechanical Sciences, Vol. 74,
pp 190-200, September 2013, DOI: 10.1016/j.ijmecsci.2013.06.002
ABSTRACT: An analytical approach is presented to investigate the nonlinear static and dynamic buckling of
imperfect eccentrically stiffened functionally graded thin circular cylindrical shells subjected to axial
compression. Based on the classical thin shell theory with the geometrical nonlinearity in von Karman–Donnell
sense, initial geometrical imperfection and the smeared stiffeners technique, the governing equations of motion
of eccentrically stiffened functionally graded circular cylindrical shells are derived. The functionally graded
cylindrical shells with simply supported edges are reinforced by ring and stringer stiffeners system on internal
and (or) external surface. The resulting equations are solved by the Galerkin procedure to obtain the explicit
expression of static critical buckling load, post-buckling load–deflection curve and nonlinear dynamic motion
equation. The nonlinear dynamic responses are found by using fourth-order Runge–Kutta method. The dynamic
critical buckling loads of shells under step loading of infinite duration are found corresponding to the load value
of sudden jump in the average deflection and those of shells under linear-time compression are investigated
according to Budiansky–Roth criterion. The obtained results show the effects of stiffeners and input factors on
the static and dynamic buckling behavior of these structures.

H.N. Jaromi, M.M. Aghdam and A. Fallah (Department of Mechanical Engineering, Amirkabir University of
Technology, Hafez Ave, Tehran, Iran), “Free vibration analysis of Mindlin plates partially resting on Pasternak
foundation”, International Journal of Mechanical Sciences, Vol. 75, pp 1-7, October 2013,
https://doi.org/10.1016/j.ijmecsci.2013.06.001
ABSTRACT: In this paper, the generalized differential quadrature (GDQ) method is used to study free vibration
of moderately thick rectangular plate partially resting on Pasternak foundation. The foundation is considered to
support the plate either completely or partially. The governing equations which consist of a system of partial
differential equations (PDEs) are obtained based on the first-order shear deformation theory. Various
combinations of simply supported, clamped and free boundary conditions are considered. Application of the
GDQ method to the governing PDEs resulted in a system of algebraic equations. Solution of this system with
accordance to the considered boundary conditions leads to an eigenvalue problem to obtain natural frequencies
of the plate. Results of this study are validated with available results in the literature which reveal accuracy and
fast convergence rate of the method. Effects of different parameters such as foundation stiffness, foundation
geometry, boundary conditions and geometrical parameters on the natural frequencies of the plate are presented.

ABSTRACT: Closed-form solution for buckling analysis of thick functionally graded plate resting on elastic foundation is presented using the third-order shear deformation theory. It is assumed that the plate rests on Pasternak foundation and its material properties vary through the plate thickness as a power function. By decoupling the governing equations, the neutral surface position for such plate is determined, and the third-order shear deformation theory based on exact neutral surface position is employed to derive the governing equations. Comparing with the middle surface based formulations, the neutral surface based formulations do not exhibit the stretching–bending coupling; hence, the values of buckling load can be obtained by eigenvalue analysis. Closed-form solutions are obtained for rectangular with different boundary conditions. Numerical results are presented and discussed for a wide range of plate and foundation parameters.


ABSTRACT: A three-dimensional analytic model involving products of angular and radial Mathieu functions is developed for the exact free vibration analysis and transient acousto-structural response of two parallel elliptical plates, coupled with an internal bounded inviscid and compressible fluid medium, and under general external transverse loads of arbitrary temporal and spatial variations. Extensive numerical data are presented in an orderly fashion for the first ten symmetric/anti-symmetric system natural frequencies as a function of fluid layer thickness parameter for selected plate aspect ratios. Also, the occurrences of frequency veering phenomena between various modes of the same symmetry group and the interchange of associated mode shapes in the veering region are noted and discussed. Moreover, selected fluid-coupled structural deformation mode shapes are presented in vivid graphical form and the issue of mode localization is examined. The Laplace transform with respect to the time variable is subsequently invoked and a linear system of coupled algebraic equations is ultimately obtained, which is truncated and then solved by implementing Durbin's Laplace inversion algorithm accompanied with special solution convergence enhancement techniques for eradication of spurious oscillations (Gibbs' phenomenon). Numerical simulations are conducted for the displacement time histories of water-coupled double aluminum plates of selected aspect ratios and fluid depths, subjected to external loads of practical interest (i.e., an impulsive point load, a concentrated pulse load, and a uniformly distributed blast load). Validity of the results is established through computations made by using a commercial finite element package as well as by comparison with the data available in literature.


ABSTRACT: In this paper, instability of a thick through-the-thickness functionally graded material (FGM) rectangular plates under the practical cases of thermal and mechanical loading conditions is analyzed. Uniform
shear, uniform uni-axial or biaxial compression/tension, uniform temperature rise, heat conduction across the thickness, and combined cases are considered. For thermal buckling and combined cases in thermal field, temperature dependency of the properties is also taken into account. The four-variable refined plate theory with parabolic distribution of shear strains through-the-thickness is implemented to establish the governing equilibrium and stability equations. Only the clamped type of boundary conditions is considered after the proof of bifurcation type buckling existence. The resulted equations are uncoupled in a reasonable manner. The multi-term Galerkin method is used to derive the critical buckling loads/temperatures and buckled shapes of the plate under various loading conditions.

ABSTRACT: Two dimensional laminate theories in which the number of primary displacement variables is independent of the number of layers are generally not capable of accurately predicting the transverse stresses in hybrid piezolaminated plates, directly from the constitutive equations. The prediction is particularly poor for the electric potential and thermal loadings. In a recent publication, the authors presented a coupled global–local theory (GLT) with 11 displacement unknowns and a zigzag-local theory (ZLT) with nine unknowns for hybrid plates, with a view to predict the transverse shear stresses accurately under electromechanical loading. It was found that the ZLT yields accurate and superior prediction compared to the GLT. In this study, we extend the two theories for thermal loading and assess their performance in comparison with the three dimensional piezothermoelasticity solution. It is found that, contrary to the electromechanical loading, the GLT performs better than the ZLT for thermal loading, in predicting transverse shear stresses, besides predicting displacements and inplane stresses accurately. The thermoelectric transverse normal strain is accounted for without introducing additional variables. Without this term, the GLT yields much worse results not only for deflection, but also for inplane displacements and stresses.

ABSTRACT: The obtaining of exact solutions for free vibration of circular cylindrical shells with classical boundary conditions, except for all edges being shear diaphragm, was known to be difficult or impossible. This work presents those exact solutions based on the Donnell–Mushtari shell theory . They are shown to be in simple and compact form, and not as complex as they have generally been regarded. The computed natural frequencies are in excellent agreement with those in literature and those of the highly accurate semi-analytical differential quadrature finite element method developed in this study. The exact solutions can be used as benchmarks for researchers to check their numerical methods and for engineers to design such shell structures. Two of the four eigenvalues are found to be much larger than the other two for some boundary conditions. High accurate membrane approximate solutions are also presented for the circular cylindrical shells.

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ABSTRACT: The progressive collapse of tubular structures under axial loading is a challenging problem in mechanics. Due to the nonlinearities in large plastic deformation, such a problem can only be solved case by case under the assumption of an appropriate collapse mechanism. In this paper, a relationship between the progressive collapse of an axially loaded tube and the initial buckling of its windowed counterpart is presented. Numerical investigation was performed on the axial crushing of triangular, square and pentagonal tubes and the initial buckling modes of the corresponding windowed tubes. Results show that at the critical symmetric buckling mode, the theoretical mean crushing force of the angle-shaped column in the windowed tube matches very well with the actual mean crushing force of the conventional one. This relationship is crucial to the development of a generalized method for progressive collapse without assuming collapse mechanism. Based on it, an empirical equation on the mean crushing force of axially loaded square tubes is presented. The mean crushing forces predicted by this equation are in good agreement with the experimental results and theoretical values.


ABSTRACT: In this study, we first propose the determination conditions of secondary wrinkling based on which we may obtain the secondary wrinkling region and critical load for membrane structures. The nonlinear post-wrinkling simulation is then performed to evaluate the determination conditions, as well as elucidate the wrinkling nature based on secondary wrinkling behavior analysis. In the end, the secondary wrinkling characteristics are experimentally tested using the non-contact digital image correlation technology. The results reveal that the proposed determination conditions are validated by the simulation and experiments. The secondary wrinkling is a split of old wrinkle which drives the wrinkling evolution in post-wrinkling progress. Our results will be of great benefit to the analysis and the control of the wrinkles in the membrane structures.


ABSTRACT: In the present work, a new Inverse Trigonometric Zigzag Theory is proposed and implemented for the static analysis of laminated composite and sandwich plates. The theory assumes the higher order displacement field across the plate thickness satisfying the continuity conditions at the layer interfaces. Zero transverse shear stress boundary conditions at the top and bottom surfaces of the plate are also satisfied. An efficient C0 finite element model is developed and employed to investigate the static response of laminated and sandwich plates. Numerical examples covering different features of laminated composite and sandwich plates are pronounced in the present study. The performance of the model is observed by comparing the evaluated
results with different published results available in literature which ascertain its precision and range of applicability.


ABSTRACT: A unified analytical method based on the first-order shear deformation theory is developed for the vibration analysis of moderately thick composite laminated cylindrical shells subjected to general boundary conditions and arbitrary intermediate ring supports, and various lamination schemes. Each of the displacements and rotation components of the shell, regardless of boundary conditions, is expanded as the linear combination of a standard Fourier series and several supplementary terms are introduced to ensure and accelerate the convergence of the series expansions. Since the displacement field is constructed adequately smooth throughout the entire solution domain, an exact solution can be obtained by using Rayleigh–Ritz procedure based on the energy functions of the shell. Furthermore, in contrast to most existing solution procedures, the current method offers a unified solution for laminated cylindrical shells with various boundary conditions, and arbitrary boundary conditions including all classical ones and elastic restraints can be easily achieved by simply setting the stiffnesses of restraining springs without requiring any special procedures or schemes. The excellent accuracy and reliability of current solutions are demonstrated by numerical examples and comparisons with the results available in the literature. The effects of restraining stiffnesses and lamination schemes on frequency parameters are illustrated. Numerous new results for cross-ply and angle-ply laminations with elastically restrained edges and intermediate ring supports are presented, which may serve as benchmark solutions for validating new computational techniques in future.


ABSTRACT: This paper presents an exact analytical solution for free vibration of a rotating functionally graded circular cylindrical shell based on Sanders shear deformation theory. The state space method is employed to solve the problem. The equations of motion are extracted by considering Coriolis, centrifugal and initial hoop tension effects. Several comparison studies with results reported in literature as well as a finite element model are carried out, to demonstrate accuracy of the present new exact results. Effects of various combinations of boundary conditions, rotational speed, geometrical and material properties of the shell on the forward and backward waves of the natural frequencies are investigated. Also, variations of the critical speed versus material properties are discussed. Due to the inherent features of the present exact solution, the present findings will be a useful benchmark for evaluating the accuracy of other analytical and numerical methods and can be utilized as a reliable reference by the other researchers.

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ABSTRACT: Integrally Stiffened Panels (ISP) structures are composed of a base plate and one (or several) longitudinal stiffness sections of simple or complex shape. When compared to conventional reinforced structures, they present an integral profile, as the stiffened panel is obtained as a whole by means of an extrusion process. The choice of an ISP profile can lead to a more robust and defects-free solution, simultaneously maintaining the possibility to adopt complex reinforcement shapes. In the present work, three algorithms are studied and compared in the cross-section optimization of Integrally Stiffened Panels for aeronautical applications: (i) the classical Levenberg–Marquardt, (ii) the Simulated Annealing methodology, and a recently proposed approach involving (iii) a differential/nature-based algorithm called Hybrid Differential Evolution Particle Swarm Optimization (HDEPSO). Numerical simulation models are introduced for several shapes of ISP. Additionally, the presence of a Friction Stir Weld (FSW) zone is also taken into account, from the joining between distinct ISP’s. This can allow us to infer about the influence of the heat affected zoned (HAZ) in the overall stability of the structure, under compressive buckling loads within the elasto-plastic regimen. Results show that the use of the proposed optimization algorithm represents a viable option, giving an added insight in terms of the buckling resistance and mechanical design in nonlinear material and geometric scenarios.


ABSTRACT: This paper presents a novel and efficient solution for free vibrations of thin cylindrical shells subjected to various boundary conditions by using the Haar wavelet discretization method. The Goldenveizer–Novozhilov shell theory is adopted to formulate the theoretical model. The displacements and their derivatives in the governing equations are represented by Haar wavelet series and their integrals in the axial direction and the Fourier series in the circumferential direction. The constants appearing from the integrating process are determined by boundary conditions and thus the partial differential equations are transformed into a set of algebraic equations. The frequency parameters of the cylindrical shells are obtained by solving the algebraic equations. The present solution is verified by comparing the numerical results with those previously published in literature. Very good agreement is observed. It is shown that accurate frequency parameters can be obtained by using a small number of collocation points and boundary conditions can be easily achieved. The advantages of this current solution method consist in its simplicity, fast convergence, low computational cost and high precision.

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ABSTRACT: An exact closed-form analysis for describing the natural vibrations of a FG moderately thick spherical shell panel is developed. The strain–displacement relations of Donnell and Sanders theories are used to obtain the exact solutions. The shell has two opposite edges simply supported (i.e., Lévy-type). The material properties change continuously through the thickness of the shell, which can vary according to a power-law distribution of the volume fraction of the constituents. The new auxiliary and potential functions are employed to exactly decouple the governing equations of the vibrated spherical shell panel, leading to the exact closed-form frequency equation in the form of determinant. The accuracy and validity of the solutions are established with the aid of a 3D finite element analysis as well as by comparing the results with the data reported in the literature. The effects of various stretching–bending couplings on the frequency parameters are discussed.

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ABSTRACT: This paper focuses on free vibration analysis of corrugated-core sandwich plates (CSP) via a meshfree Galerkin method based on a first-order shear deformation theory (FSDT). A CSP is considered as a composite structure of three members — two face sheets at the top and the bottom, and one corrugated sheet in the middle of the structure. The face sheets are taken as isotropic plates, and the corrugated sheet is approximated by an orthotropic plate that has different elastic properties along the two perpendicular directions. Dynamic equations of the members are given by the meshfree Galerkin method based on the FSDT. After overcoming the difficulty to implement the displacement compatibility conditions among the members, the governing equation for the entire CSP is obtained by superposing the dynamic equations of the members. The meshfree characteristic of the proposed method guarantee that no meshes are used in deriving the dynamic equations, therefore the proposed method is more flexible in studying problems for which remeshing is inevitable with the finite element methods. The approximation of the corrugated sheet with an orthotropic plate also simplifies the analysis without much loss of precision. A few selected examples are studied to demonstrate the accuracy and convergence of the proposed method. The results obtained for these examples are compared with the ANSYS solutions. Good agreement is evident for all cases.

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ABSTRACT: The present study deals with vibrational behavior of two joined cross-ply laminated conical shells. The natural frequencies and mode shapes are investigated. The joined conical shells can be considered as the general case for joined cylindrical–conical shells, joined cylinder-plates or cone-plates, cylindrical and conical shells with stepped thicknesses and also annular plates. Governing equations are obtained using thin-walled shallow shell theory of Donnell type and Hamilton's principle. The appropriate expressions among stress resultants and deformations are extracted as continuity conditions at the joining section of the cones. The equations are solved assuming trigonometric response in circumferential and series solution in meridional directions. All combinations of boundary conditions can be assumed in this method. The results are compared and validated with the available results in other investigations. The effects of semi-vertex angles, meridional lengths and shell thicknesses on the natural frequency and circumferential wave number of joined shells are investigated.


ABSTRACT: An analytical study of active structural acoustic control of an elastic cylindrical shell coupled to a two-stage vibration isolation system is presented. An analytical active–passive model is developed in order to attenuate sound radiating from the base shell structure, which consists of a rigid-body machine, an intermediate rigid mass, and a supporting cylindrical shell, all connected by a combination of passive and active isolators. Various active control strategies are considered and the corresponding optimal control forces are formulated, including (a) minimizing the vibratory power transmitted to the foundation, (b) minimizing the structural kinetic energy of the supporting shell, (c) minimizing the sum of the square accelerations at the isolator locations on the supporting shell, and (d) minimizing the acoustic power radiated from the supporting shell. Numerical results are presented and discussed in detail. The control performance of all control strategies and system configurations are evaluated and compared in terms of acoustic power radiating from the supporting shell. The effects of key system parameters, i.e., the number and location of the actuators, and the fact that the output forces from the actuators are limited in engineering applications, are also considered and discussed. Finally, some concluding remarks and general design principles for the active control system are also discussed.


ABSTRACT: This paper provides a new technique for solving free vibration problems of composite arbitrarily shaped membranes by using Generalized Differential Quadrature Finite Element Method (GDQFEM). The proposed technique, also known as Multi-Domain Differential Quadrature (MDQ), is an extension of the classic Generalized Differential Quadrature (GDQ) procedure. The multi-domain method can be directly applied to regular sub-domains of rectangular shape, as well as to elements of general shape when a coordinate
transformation is considered. The mapping technique is used to transform both the governing differential equations and the compatibility conditions between two adjacent sub-domains into the regular master element in the parent space, called computational space. The numerical implementation of the global algebraic system obtained by the technique at issue is simple and straightforward. Computer investigations concerning a large number of membrane geometries have been carried out. GDQFEM results are compared with those presented in the literature and a perfect agreement is observed. Membranes of complex geometry with a material inhomogeneity are also carefully examined. Numerical results referring to some new unpublished geometric shapes are reported to let comparisons with further research on this subject.


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear dynamic response and vibration of imperfect eccentrically stiffened FGM thick double curved shallow shells on elastic foundation using both the first order shear deformation theory and stress function with full motion equations (not using Volmir's assumptions). The FGM shells are assumed to rest on elastic foundation and subjected to mechanical and damping loads. Numerical results for dynamic response of the FGM shells are obtained by Runge–Kutta method. The results show the influences of geometrical parameters, the material properties, imperfections, the elastic foundations, eccentrically stiffeners and mechanical loads on the nonlinear dynamic response and nonlinear vibration of functionally graded double curved shallow shells. The numerical results in this paper are compared with results reported in other publications.


ABSTRACT: In this paper, a unified solution method for free vibration analysis of functionally graded cylindrical, conical shells and annular plates with general boundary conditions is presented by using the first-order shear deformation theory and Rayleigh–Ritz procedure. The material properties of the structures are assumed to change continuously in the thickness direction according to the general four-parameter power-law distributions in terms of volume fractions of constituents. Each of displacements and rotations of those structures, regardless of boundary conditions, is expressed as a modified Fourier series, which is constructed as the linear superposition of a standard Fourier cosine series supplemented with auxiliary polynomial functions introduced to eliminate all the relevant discontinuities with the displacement and its derivatives at the edges and accelerate the convergence of series representations. The excellent accuracy and reliability of the current solutions are confirmed by comparing the present results with those available in the literatures, and numerous new results for functionally graded cylindrical, conical shells and annular plates with elastic boundary conditions are presented. The effects of boundary conditions and the material power-law distribution are also illustrated.
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ABSTRACT: In this paper, the classical and nonlocal elasticity are applied to investigate the deflection and instability of electrostatically actuated carbon nanotubes. The results are presented for different geometries and boundary conditions. They reveal that increasing radius and gap and decreasing length confine to increasing pull-in voltages of the carbon nanotubes. The results prove that application of the nonlocal elasticity theorem leads to stiffer structures with higher pull-in voltages. Thus, in order to obtain more accurate results about the mechanical and electromechanical behaviors of the carbon nanotubes, one should apply the nonclassical elasticity theories such as that applied in this paper.

ABSTRACT: In this paper, an analytical approach is presented to investigate the nonlinear static buckling for imperfect eccentrically stiffened functionally graded thin circular cylindrical shells with temperature-dependent properties surrounded on elastic foundation in thermal environment. Both shells and stiffeners are deformed simultaneously due to temperature. Material properties are graded in the thickness direction according to a Sigmoid power law distribution in terms of the volume fractions of constituents (S-FGM) with metal–ceramic–metal layers. The Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation, stress function and the Bubnov–Galerkin method are applied. Numerical results are given for evaluating effects of temperature, material and geometrical properties, elastic foundations and eccentrically outside stiffeners on the buckling and post-buckling of the S-FGM shells. The obtained results are validated by comparing with those in the literature.

References listed at the end of the paper:
ABSTRACT: This paper presents a unified formulation for the free vibration analysis of open shells subjected to arbitrary boundary conditions and various geometric parameters such as subtended angle, conicity. Under the current framework, a general classical shell theory in conjunction with Chebyshev polynomials and Rayleigh–Ritz procedure is developed. Each displacement components of the open shell, regardless of shell types and boundary conditions, is expanded as Chebyshev polynomials of first kind in both directions. All the Chebyshev expanded coefficients are treated equally and independently as the generalized coordinates and solved directly by using the Rayleigh–Ritz procedure. The convergence, accuracy and reliability of the current formulation are validated by comparisons with existing experimental and numerical results published in the literature, with excellent agreements achieved. A considerable number of new vibration results for open cylindrical, conical and spherical shells with various geometric parameters and boundary conditions are presented, which may be used for benchmarking of researchers in the field. The effects of boundary stiffness, subtended angle and conicity on the frequency parameters of different open shells are also discussed in detail. The presented formulation is general compared to the existing literature. Different boundary conditions and geometric dimensions (shallow or deep), different types of shells (cylindrical, conical or spherical), can be easily accommodated in this formulation. It also offers a unified operation for the entire restraining conditions and the change of boundary conditions from one case to another is as easy as changing structural parameters without the need of making any change to the solution procedure. In addition, it can be readily applied to open shells with more complex boundaries such as point supports, non-uniform elastic restraints, partial supports and their combinations.

ABSTRACT: In this paper, a new microstructure-dependent sinusoidal beam model for buckling of microbeams is presented using modified strain gradient theory. This microbeam model can take into consideration microstructural and shear deformation effects. The equilibrium equations and corresponding boundary conditions in buckling are derived with the minimum total potential energy principle. Buckling problem of a simply supported microbeam subjected to an axial compressive force is analytically solved by Navier solution procedure. Influences of thickness-to-length scale parameter and slenderness ratios on buckling behavior are discussed in detail. It is observed that the size dependency becomes more important when the thickness of the microbeam is closer to material length scale parameter. Also, it can be said that the effects of shear deformation are more considerable for short and thick beams with lower slenderness ratios.

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ABSTRACT: The static response of beam structures to inertial loads is investigated in this work. Refined beam models are adopted for the analyses due to the ineffectiveness of classical theories in dealing with three-dimensional (3D) phenomena. The Carrera Unified Formulation (CUF) has therefore been used to develop higher-order beam theories without the need of any ad hoc assumptions on the kinematics of the model. According to CUF, the 3D displacement field is expressed as the expansion, above the beam cross-section, of the generalized displacements, which lie along the beam axis. Different classes of refined one-dimensional (1D) models can be formulated, depending on the cross-sectional functions used for the expansion of the generalized unknowns. The weak form of the principle of virtual displacements is used in this paper and 1D finite element (FE) arrays are written in the form of fundamental nuclei, which do not depend on the class of the beam theory. Both closed and open thin-walled beams are considered in the proposed analysis, and the effects of uniform as well as arbitrarily distributed load factors are investigated. Non-structural masses are also contemplated. The results are compared with those obtained using solid finite elements from a commercial FE code. Attention is focused on the need to adopt refined models because of the inability of classical beam theories to foresee cross-sectional deformations, shear effects, and bending-torsion couplings caused by non-symmetric inertial fields.

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ABSTRACT: Anisotropic hierarchical honeycombs of uniform wall-thickness are constructed by repeatedly replacing each three-edge vertex of a base hexagonal network with a similar but smaller hexagon of the same orientation, and stretching the resulting structure in horizontal or vertical directions to break the isotropy. The uniform overall thickness is then adjusted to maintain the constant average density. The resulting fractal-appearing hierarchical structure is defined by the ratios of replacement edge lengths to the underlying network edge length and also the cell wall angle. The effective elastic modulus, Poisson’s ratio and plastic collapse strength in the principal directions of hierarchical honeycombs were obtained analytically as well as by finite element analyses. The results show that anisotropic hierarchical honeycombs of first to fourth order can be 2.0–8.0 times stiffer and at the same time up to 2.0 times stronger than regular honeycomb at the same wall angle and the same overall average density. Plastic collapse analysis showed that anisotropic hierarchical honeycomb has the larger plastic collapse strength compared to regular hierarchical honeycomb of the same order at certain oblique wall angles. The current work provides insight into how incorporating anisotropy into the structural organization can play a significant role in improving the mechanics of the materials structure such as regular or hierarchical honeycombs, and introduces new opportunities for development of novel materials and structures with desirable and actively tailorable properties.

ABSTRACT: Bifurcation behaviour of moderately thick heated annular plates made of FGMs is discussed in this study. Properties of the graded plate are distributed across the thickness based on the simple power law form. Temperature-dependency of the material properties is also taken into account. Two types of frequently used thermal loading, i.e. uniform temperature rise and heat conduction across the thickness loadings are considered. General nonlinear equilibrium equations based on the first order shear deformation plate theory (FSDT) and the associated boundary conditions are obtained employing the static version of the virtual displacements method. The pre-buckling solution is accomplished and the proper boundary conditions are chosen to assure the occurrence of bifurcation phenomenon. Stability equations are obtained based on the adjacent equilibrium criterion. Five resulted stability equations are decoupled and reduced to new equations in terms of lateral deflection and the edge zone functions. An exact asymmetrical solution is developed to calculate the critical buckling temperature difference of the plate for the above-mentioned cases of thermal loading. It is shown that the fundamental buckled configuration of annular plates may be asymmetric as previously assumed.


ABSTRACT: In recent years, people were puzzled about two reverse nonlocal models in studying transverse bending of nanobeams. Following the ideologies of both nonlocal models, two kinds of torsional models were constructed to investigate the nonlocal torsional vibration of carbon nanotubes, respectively. Just like the transverse bending of nanobeams, it is strange to observe two opposite size-dependent performances. The first nonlocal continuum model (weakened model) was based on equilibrium equations and nonlocal torsional shear stress relation. Natural frequency decreases with an increase in nonlocal nanoscale parameter, or it increases with increasing length of the carbon nanotube. Thus the torsional stiffness of carbon nanotubes is weakened. On the other hand, the second nonlocal model (enhanced model) was developed from the strain energy variational principle. Natural frequency increases (or decreases) with increasing nonlocal nanoscale parameter (or length of the carbon nanotube), or the nanostructural stiffness is strengthened. For judgment, a torsional semi-continuum model with discrete atomic layers in the cross section of a carbon nanotube was proposed. The relaxation effects on surface atoms were considered in the torsional semi-continuum model. It is concluded that the relaxation type (attractive or repulsive) of surface atoms results in two different nonlocal results. Consequently, both the existing reverse models are proved to be valid.

A. Rajaneesh, I. Sridhar and S. Rajendran (School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore), International Journal of Mechanical Sciences, Vol. 83, pp 184-195, June 2014, https://doi.org/10.1016/j.ijmecsci.2014.03.029

ABSTRACT: Competing failure modes are investigated for circular sandwich plates comprising quasi-isotropic E-glass/epoxy composite faceplates (with \([-60/0/60]_m\) configuration) and polyvinyl chloride (PVC) foam core under bending. Clamped sandwich plates are loaded using flat-ended punch at the center of the plate. Three competing failure modes, viz., core indentation, core shear and face failure/microbuckling, are considered. Analytical estimates for elastic response (stiffness) and initial failure load are proposed, and these are verified by experimental measurements and finite element (FE) predictions. Good agreement (with in ±20%) is observed among analytical estimates, experimental measurements and FE predictions. Analytical estimates for the failure modes are used to plot the failure mode map in non-dimensional plate radius versus faceplate thickness plane.
for a given material system. The failure mode map thus constructed is assessed by considering a few sandwich plate geometries. Normalized sandwich mass and failure load contours are superimposed onto the failure mode map to identify the locus of minimum weight design by numerical search. Effect of geometrical parameters of the sandwich plate on failure load and mode is also investigated.


ABSTRACT: A unified method based on the three-dimensional theory of elasticity is developed for the free vibration analysis of thick cylindrical shells with general end conditions and resting on elastic foundations. Each shell displacements, regardless of boundary conditions, is expanded as a standard Fourier cosine series supplemented with four auxiliary functions introduced to eliminate any possible discontinuities of the original displacement and its derivatives throughout the entire shell space including the boundaries and then to effectively enhance the convergence of the results. Mathematically, such series expansions are capable of representing any functions (including the exact displacement solutions). Since the displacement field is constructed adequately smooth throughout the whole solution domain, an accurate solution can obtained by using Rayleigh–Ritz procedure based on the energy functions of the shell. The current method can be universally apply to a variety of end conditions including all the classical cases and their combinations and arbitrary elastic foundations. The excellent accuracy and reliability of current solutions are demonstrated by numerical examples and comparisons with the results available in the literature. Effects of the boundary restraining parameters and foundation coefficients on frequency parameters are investigated as well. New results for thick cylindrical shells with various end conditions and resting on elastic foundations are presented, which may serve as benchmark solutions for validating new computational techniques in future.


ABSTRACT: This paper investigates the thermal vibration of magnetostrictive functionally graded material (FGM) cylindrical shells by using the generalized differential quadrature (GDQ) method based on the first-order shear deformation theory (FSDT). The varied effects of shear correction coefficient are employed and obtained by using the total strain energy principle. The computed and varied values of shear correction coefficient are usually functions of magnetostrictive layer thickness, FGM power law index and environment temperature. In the thermo-elastic stress–strain relations, the simpler form stiffness of FGM shells and the effect of the magnetostrictive coupling terms with velocity feedback control under linear temperature rise are considered. The effects of magnetostrictive layer thickness, control gain values, environment temperature and FGM power law index on the thermal vibration of magnetostrictive FGM thick cylindrical shells are obtained and analyzed.

ABSTRACT: In the present work, the buckling and vibration of rectangular single-layered graphene sheets is analyzed based on the nonlocal theory of elasticity which takes the small scale effects into account. The graphene sheet is assumed as a thin plate, and the classical plate theory is applied to obtain the differential equation of the sheet. For the first time, the complex finite strip method is employed to study the vibration and buckling behavior of graphene sheets. The weighted residual method is employed to obtain the stiffness, stability and the mass matrices of the graphene sheet which is assumed to be an isotropic nanoplate. A sinusoidal displacement function is used for the longitudinal direction, which satisfies the simply supported boundary condition, while piecewise interpolation polynomials including the Hermitian and bubble functions are assumed for the other direction. A matrix eigenvalue problem is solved to find the vibration frequency and buckling load of graphene sheets subjected to different types of in-plane loadings including the uniform and non-uniform uniaxial and biaxial compressions as well as shear loading. The accuracy of the proposed model is validated by comparing the results with those reported by the available references. Furthermore, a number of examples are presented to investigate the effects of various parameters (e.g., boundary conditions, nonlocal parameter, aspect ratio, and type of loading) on the results.

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ABSTRACT: As an advanced lightweight porous medium, SKYDEX material has been applied as the energy absorbing structures for personnel protection. Its hourglass-like microstructures made of thermoplastic can dissipate kinetic energy and reduce pressure transfer during crushing. Based on the SKYDEX® cell, this paper develops a novel twin-spherical microstructure, where the shape and size were represented with two key geometric parameters. 3D finite element models were then constructed to demonstrate the cellular deformation modes with different configurations along with the quantitative responses in terms of the energy absorption and pressure transfer. An optimization was performed to find the best design. Using this optimal configuration thus obtained, models with multilayers were built, and each layer was either uniformed or graded in density. Their responses under low and high speed compressive loadings were compared, and the results showed that the direction and degree of the density gradient as well as impact velocity are important parameters affecting the energy absorbing capability.

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ABSTRACT: The design of magnetorheological materials with mechanical properties adjusted to the action of dynamic loads is a recent field of research. The few bibliographic literatures in this area concern the beams. This paper is devoted to a numerical and an experimental study of the dynamic behavior of sandwich plates consisting of two aluminum skins and a magnetorheological elastomer (MRE) core of different loads of micron-size ferromagnetic particles elaborated under the action of a magnetic field. Firstly, the rheological properties of the loaded elastomer with and without the impact of the magnetic field have been evaluated experimentally. Secondly, an experimental analysis of the impact of the loading rate of micron-size ferromagnetic particles of the elastomer as well as the magnetic field intensity on the vibration behavior of the elaborated plates is conducted. To evaluate the variation of the plate rigidity and damping factor, a confrontation of experimental values against numerical results, using the finite elements software Abaqus and the Ritz method of approximation for an appropriate model, was made for various dimensions and boundary conditions of the plate.


ABSTRACT: Using nonlocal Rayleigh, Timoshenko, and higher-order beam theories, the free dynamic deflection of elastically supported double-walled carbon nanotubes (DWCNTs) subjected to a longitudinally varying magnetic field (LVMF) is examined. By employing reproducing kernel particle method (RKPM), the equations of motion of the magnetically affected DWCNT (MADWCNT) for each model are reduced to a set of algebraic equations. For four common boundary conditions, namely fully simple, fully clamped, simple-clamped, cantilevered supports, the dominant frequencies of the nanostructure are calculated. In particular cases, the predicted results by the RKPM are compared with those of the exact solution. Additionally, the convergence checks of the proposed numerical models are performed. The effects of the innermost radius, slenderness ratio, small-scale parameter, maximum strength of the LVMF, transverse and rotational stiffness of the surrounding medium on the fundamental frequency of the MADWCNT are addressed. The capabilities of the proposed models in predicting the characteristics of free vibration are also discussed. Further, the limitations of the local analysis as well as the classical beam theory in capturing the lateral vibrations of the MADWCNTs are revealed.

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ABSTRACT: Foam-filled thin-walled structures have drawn considerable attention and been widely applied in automotive and aerospace industries for their significant advantages in high energy absorption and light weight. This paper aims to compare the energy absorption characteristics of foam-filled single and bitubal polygonal tubes with different cross-sectional configurations under different axial crushing load conditions. The coupled finite element method (FEM) and element free Galerkin method (EFGM) are applied in modeling the foam-filled tubes for their interaction associated with large deformation, failure and damage. By the complex
proportional assessment (COPRAS) technique – the multicriteria decision-making method, the comparisons of energy absorption characteristics of the considered single and bitubal polygonal tubes are conducted herein, respectively. The results show that the foam-filled circular bitubal column has outstanding energy absorption characteristics under all the conditions considered. It is found that the mean crushing force and energy absorbed generally increase with the increase in the edge number of foam-filled bitubal columns. The multiobjective optimization of foam-filled circular bitubal tube is finally conducted by using Non-dominated Sorting Genetic Algorithm (NSGA-II) for the maximization of specific energy absorption (SEA) and the minimization of peak crushing force (PCF).

ABSTRACT: In present work, limit loads for pipe bends under combined internal pressure and out-of-plane bending moment have been investigated systematically via finite element simulation based on both small displacement analysis and large displacement analysis. By normalized methods, a wide range of non-dimensional parameters were considered and limit bending moment expression has been suggested which shows that $r/l$ is the main factor affecting the limit bending moment. In addition, the effect of internal pressure on the limit loads was studied in detail which is significant for thin walled pipe bends. It is found that yield strain $\varepsilon_0$ has an obvious effect on limit load based on large displacement analysis. According to the finite element results, practicable engineering assessment equations of limit loads have been proposed for pipe bends under combined loads. These proposed equations are validated with experiment data and also justified to be a good choice for limit loads assessment.

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ABSTRACT: This paper presents a free and forced vibration analysis of coupled conical–cylindrical shells with arbitrary boundary conditions using a modified Fourier–Ritz method. Under the current framework, regardless of the boundary conditions, each of the displacement components of both the conical and cylindrical shells are expanded invariantly as a modified Fourier series, which is composed of a standard Fourier series and closed-form supplementary functions introduced to accelerate the convergence of the series expansion and remove all the relevant discontinuities at the boundaries and the junction between the two shell components. All the expansion coefficients are determined by using the Rayleigh–Ritz method as the generalized coordinates. By using the present method, a unified solution for the coupled conical–cylindrical shells with classical and non-classical boundary conditions can be directly derived without the need of changing either the equations of motion or the expressions of the displacements. The reliability and accuracy of the present method are validated by comparison with FEM results and those from the literature. Studies on the effects of dimensional and elastic restraint parameters on the free vibrations are also reported. Investigation on vibration of the conical–cylindrical–conical shell combination shows the extensive applicability of present method for more complex
shell combinations. New numerical examples are also conducted to illustrate the forced vibration behavior of
the coupled conical–cylindrical shell subjected to the excitation forces in different directions.

ABSTRACT: Buckling of cracked functionally graded plates resting on Pasternak foundation under tension has been studied. Classical plate theory in framework of the finite element method has been used. Shape functions for elements surrounding crack tips have been derived using previous solutions of displacement fields around crack tips. In-plane loads have been obtained by a pre-buckling solution using quarter-point elements around crack tips. Results show that an increase of foundation stiffness, leads to greater values of buckling loads. For longer cracks the effect of foundation stiffness on buckling load diminishes. For bi-axial loading such stiffness has less effect on buckling compared to uni-axial case.

ABSTRACT: This paper deals with the active vibration control of thin rotating laminated composite truncated conical shells using vertically and obliquely reinforced 1-3 piezoelectric composite (PZC) materials as the constraining layer of an active constrained layer damping (ACLD) treatment. A finite element model has been derived to formulate the dynamics of the rotating thin laminated truncated conical shells integrated with the patches of ACLD treatment. Hamilton’s principle has been used to derive the equations of motion of rotating shell integrated with patches. The finite element model includes the effects of the Coriolis, Centrifugal acceleration, and the initial hoop tension caused due to rotation. The effectiveness of these patches for the vibration attenuation of thin rotating symmetric/antisymmetric cross-ply and antisymmetric angle-ply laminated truncated conical shell has been examined. Both in-plane and out-of-plane actuations of the constraining layer of the ACLD treatment has been utilized. The effects of variation of the semi-cone angle and the rotational speed of the shell on the performance of these patches have been investigated. Particular emphasis has been placed on ascertaining the performance of patches when the orientation angle of the piezoelectric fibers in the constraining layer is varied in two mutually orthogonal vertical planes. It is found that the maximum performance of patches is obtained for the piezoelectric fiber orientation angle of 0° and the vertically and obliquely reinforced 1-3 PZCs have great potential for controlling the vibration of rotating shells.

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“Theoretical prediction and crashworthiness optimization of multi-cell square tubes under oblique impact
ABSTRACT: Multi-cell square tubes under dynamic oblique impact loading were studied in our work. The theoretical predictions of mean crushing force, mean horizontal force, and mean bending moment were proposed by dividing the profile into basic angle elements based on a Simplified Super Folding Element (SSFE) theory. The formulas of an oblique impacting coefficient ($\lambda$) with a load angle of 15° were proposed based on the geometric parameters, the inertia effect and the oblique loading angle by taking the effect of oblique loading and dynamic crushing into account for aluminum alloy tubes. A new method was proposed to find out a “knee point” from Pareto set with maximizing the reflex angle. The optimal configurations of multi-cell tubes were analyzed under axial and more than one oblique impact loadings. The results showed that the FE numerical results agreed well with the theoretical predictions.


ABSTRACT: In this paper, a three-dimensional (3-D) solution method is presented for the free vibration of isotropic and orthotropic conical shells with elastic boundary restraints. The formulation is derived by means of the Rayleigh–Ritz procedure based on the three-dimensional elasticity theory. Displacement components of the conical shells are represented by Fourier series in the circumferential direction and a double Fourier cosine series supplemented with several auxiliary functions in thickness and meridional directions. The supplementary functions in the form of the product of a polynomial function and a single cosine series are introduced to ensure and accelerate the convergence of the series representations. To validate the present method, the convergence behavior is demonstrated, and several comparisons of the numerical results with those published in the literature and obtained by ANSYS are performed. Numerous new results for the isotropic and orthotropic conical shells with elastic boundary conditions are presented. The effects of the geometrical parameters, orthotropic properties and boundary conditions on the natural frequencies of conical shells are illustrated.

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ABSTRACT: This paper highlights the effects of cell wall material strain hardening and density functional gradation (FG) on in-plane constant-velocity dynamic crushing response and impact behavior of hexagonal honeycombs. Results show that cell wall material strain hardening influences the distinct deformation modes induced by crushing velocity generally observed in regular hexagonal honeycombs. This is seen by a delay in the onset of localized deformation up until intermediate crushing velocities after which localization becomes dominant smearing out differences brought about by cell wall material strain hardening (plasticity convergence). In addition, during the impact loading on regular honeycombs, it was found that increasing the cell wall material strain hardening decreases the rate of gain of maximum crushing strain with increments in
initial kinetic energy of impact. On the other hand, introducing FG brings about new deformation patterns due to changes in material distribution and preferential cell wall collapse of the weaker members. Interestingly, although the dynamic localization effect at higher crushing velocities observed earlier was not found to be particularly affected by FG, gradient convergence (i.e. smearing out the effects of FG due to higher velocities analogous to plasticity convergence) was not observed. On the contrary, gradient convergence emerged at higher impacting velocities primarily brought about by a combination of initial deformation localization and its subsequent advancement into FG region ahead. The kinetic energy threshold for the emergence of this gradient convergence effect was found to be considerably delayed by cell wall material hardening.

References listed at the end of the paper:
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“Crushing analysis and multiobjective optimization for functionally graded foam-filled tubes under multiple load cases”, International Journal of Mechanical Sciences, Vol. 89, pp 439-452, December 2014, 
https://doi.org/10.1016/j.ijmecsci.2014.10.001

ABSTRACT: Functionally graded foam (FGF)-filled tubes have been recently gaining comprehensive attention due to its excellent energy absorption capacity under axial impact. However, energy absorption devices generally rarely experience pure axial loading in real working condition, but rather oblique loads, especially during a vehicle crash event. This paper aims at investigating the crashworthiness of the FGF-filled square tubes under multiple load cases. The foam density of the FGF-filled tubes varies along the axial direction and is controlled by the gradient exponent. Numerical comparative analysis results reveal that impact angle and the gradient exponent have a significant effect on crashworthiness of the FGF-filled tubes, and the FGF-filled tubes surpass the uniform foam (UF)-filled tubes in crashworthiness for various impact angles. To optimize the crashworthiness of FGF-filled tubes, the non-dominated sorting genetic algorithm (NSGA-II) is used to seek for an optimal gradient exponent, where the specific energy absorption is maximized and peak crashing force is minimized simultaneously. The multiple impact angles are considered to improve the robustness of the optimal results. The optimal designs of the FGF-filled tube demonstrate better crashworthiness characteristics than the UF-filled tubes.

Hui-Shen Shen (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China), “Postbuckling of FGM cylindrical panels resting on elastic foundations subjected to lateral pressure under heat conduction”, International Journal of Mechanical Sciences, Vol. 89, pp 453-461, December 2014, 
https://doi.org/10.1016/j.ijmecsci.2014.10.010

ABSTRACT: A postbuckling analysis is presented for FGM cylindrical panels resting on elastic foundations subjected to lateral pressure under heat conduction. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. Material properties of functionally graded materials (FGMs) are assumed to be temperature-dependent, and graded in the thickness direction based on Mori–Tanaka micromechanics model. The formulations are based on a higher order shear deformation theory and von Kármán strain–displacement relationships. The panel–foundation interaction and thermal effects are also included. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach. The effects of volume
fraction index, temperature variation, foundation stiffness, as well as panel curvature ratio on the postbuckling behavior of FGM cylindrical panels are discussed in detail.

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“Web-flange distortional buckling of partially restrained cold-formed steel purlins under uplift loading”,
International Journal of Mechanical Sciences, Vol. 89, pp 476-481, December 2014,
https://doi.org/10.1016/j.ijmecsci.2014.10.011
ABSTRACT: It is well-known that cold-formed steel (CFS) members of open section can buckle locally, distortionally and/or lateral-torsionally. Since they are usually used as the secondary structural members in buildings to support roof and side cladding or sheeting, CFS beams are mostly treated as the restrained beams either fully or partially in its lateral and/or rotational directions. For a thin-walled channel- or zed-section beam subjected to uplift loading, if its upper flange is fully restrained in its lateral and rotational directions, the beam will not buckle lateral-torsionally, but may have a web-flange distortional buckling. In the literature there is limited information on the web-flange distortional buckling and currently the critical stress for the web-flange distortional buckling is calculated mainly by using numerical methods. In this paper an analytical model is presented to describe the web-flange distortional buckling behavior of the partially restrained CFS beams when subjected to uplift loading. Formula used to calculate the critical stress of web-flange distortional buckling is derived. Comparisons of the predicted critical stresses with those obtained using finite strip and finite element methods are provided to demonstrate the appropriateness of the model proposed.

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“Comparative studies on buckling behaviors of T joint and pipe by varying geometric parameters and analysis methods”, International Journal of Mechanical Sciences, Vol. 90, pp 113-121, January 2015,
https://doi.org/10.1016/j.ijmecsci.2014.11.001
ABSTRACT: In this study, buckling behaviors of T joint and pipe are comparatively investigated by varying geometric parameters and analysis methods. The effects of the wall thickness and ellipticity on buckling behavior are taken into account. According to the lowest potential energy principle, the equations of critical pressure and buckling wave number are established on the assumption of elastic buckling in the paper. However, in practice, if the structures deform largely, the T joint and pipe always experience elastic–plastic buckling, so the geometric and material nonlinearities are considered in buckling calculation. In achieving it, the finite element method (FEM) is adopted to explore the effects of those nonlinearities on buckling. Moreover, the effects of initial defect on the critical pressure are elucidated on the object of the T joint and pipe. Through rigorous FE numerical analysis, the buckling behaviors of the T joint and pipe are discussed in terms of deformation pattern, stress distribution, and critical pressure. Some interesting and useful conclusions are summarized in the paper.

**ABSTRACT:** Quasi-static punching tests and dynamic drop weight impact tests have been performed to examine the plastic response and failure of clamped rectangular cross-section tubes struck transversely by a hemispherical indenter. The laboratory results are compared with numerical simulations. The span lengths of the tube specimens are 125 and 250 mm, and they are impacted at different locations along the span. The results show that the impact location strongly influences the impact response of the tubes. Since the tubes are fabricated with strain-rate-insensitive high strength steel, the experimental plastic response and failure are similar when the tubes are loaded statically or under low impact velocity. The experimental results are presented in terms of the force–displacement responses and the failure modes, showing a good agreement with the simulations performed by the LS-DYNA finite element solver. The numerical results manage to describe the process of initiation and propagation of the material fracture and provide detailed information to analyze the large inelastic deformation and failure of ship structural components subjected to impact loading. The deformation and failure characteristics of the tube specimens are well described on the basis of the failure modes of the beam and plate models. Moreover, the crack initiation in both upper and lower walls is well described by the matrix of the infinitesimal strain tensors and the deformed shape of the first failing element.


**ABSTRACT:** This paper describes an analytical method to calculate the sensitivity of the frequencies and modes with respect to fibre volume fractions and orientations, for the large-scale composite laminated structures with complex boundaries. Structural stiffness, mass matrices and their first derivatives with respect to fibre volume fractions and orientations are derived based on classical laminated plate theory and nonconforming rectangular element theory. The analytical sensitivity of the frequencies and modes with respect to fibre volume fractions and orientations is formulated based on vibration theory. Finally, the sensitivity analysis of the dynamic characteristics of T-shape and square composite laminated plates is demonstrated using the proposed analytical method. The accuracy and efficiency of the proposed method are also discussed. The proposed method can be employed to analyze the sensitivity of the frequencies and modes for the composite laminated structures.

Shuguang Li (Institute for Aerospace Technology, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, UK), “Reflection on ‘finite rotation problem’ in plate and shell theories and in finite element formulation – back to basics”, International Journal of Mechanical Sciences, Vol. 91, pp 12-17, February 2015, https://doi.org/10.1016/j.ijmecsci.2014.07.004

**ABSTRACT:** This paper results from a reflection on the problem of finite rotations in plates and shells and its presentation in finite element formulation, a well-attended subject with a wide diversity of treatments, often extremely complicated. For instance, the very topic attracted 3 out of total 15 chapters over 120 out of total 494 pages in a monograph on nonlinear FEA [5]. In another instance, a 71 page journal paper was published [2] specifically on this topic alone. Review papers on this matter can be found in various sources including Appl Mech Rev, (e.g. Ibrahimbegovic, 1997 [8]). No attempt is to be made on reviewing these sophisticated approaches but the present paper will bring answers to questions, if they have ever been asked, such as whether the sophistication in existing approaches is really necessary and whether there is a much simpler and conceptually more direct and accurate approach. A proper re-examination of the existing approaches would
reveal a fundamental inconsistency: rigid body rotations have been assumed without reservation to describe the deformations of deformable plates and shells. After re-establishing the consistency based on the very basics of conventional plate and shell theories as a simple reflection, one can conclude surprisingly that the whole issue on ‘finite rotations’ results from a logic fallacy of faulty generalisation. The so-called ‘rotations’ should be displacement gradients instead. They can be considered as ‘rotations’ as conventionally perceived hitherto under the condition of small deformation. Somewhere, the concept of ‘rotations’ got generalised regardless the magnitude of the deformation. Instead of calling the problem as ‘finite displacement gradients’ as it should be called, a falsely generalised term of ‘finite rotations’ have been used. Since they were called ‘rotations’, the definition of those of rigid body kinematics has been taken for granted. Finite displacement gradients should not present any additional problem apart from introducing nonlinear nature into the problem, which can be addressed as a geometrically nonlinear problem in a conventional manner. However, along the line of a falsely generalised concept of finite rigid body rotations, complications have been the norm. The complicated accounts on the ‘finite rotation’ problem in the literature, which might have enhanced the understanding of rigid body kinematics, are entirely unnecessary as far as the deformable plates and shells are concerned, involving infinitesimal or finite deformations.


ABSTRACT: The low speed impact responses of simply-supported and clamped sandwich beams with corrugated and Y-frame cores have been measured in a drop-weight apparatus at 5 m s\(^{-1}\). The AISI 304 stainless steel sandwich beams comprised two identical face sheets and represented 1:20 scale versions of ship hull designs. No significant rate effects were observed at impact speeds representative of ship collisions: the drop-weight responses were comparable to the ones measured quasi-statically. Moreover, the corrugated and Y-frame core beams had similar performances. Three-dimensional finite element (FE) models simulated the experiments and were in good agreement with the measurements. The simulations demonstrated correctly that the sandwich beams collapsed by core indentation under both quasi-static loading and in the drop-weight experiments. These FE models were then used to investigate the sensitivity of impact response to (i) velocity, over a wider range of velocities than achievable with the drop-weight apparatus, and (ii) the presence of the back face sheet. The dynamic responses of sandwich beams with both front and back face sheets were found to be within 20\% of the quasi-static responses for speeds less than approximately 5 m s\(^{-1}\). This suggests that quasi-static considerations are adequate to model the collision of a sandwich ship hull. By contrast, beams without a back face collapsed by Brazier buckling under quasi-static loading conditions, and by core indentation at a loading velocity of 5 m s\(^{-1}\). Thus, dynamic considerations are needed in ship hull designs that do not employ a back face.

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ABSTRACT: Commonly used hexagonal honeycomb is manufactured by cold expansion of a laminate of thin metal foils that are bonded along periodically placed strips. The process results in nearly hexagonal cells with
double walls in one direction, small rounding at the bent corners, and leaves behind residual stresses. This paper evaluates the effect of the expansion on the compressive response of the honeycomb. A finite element model of a characteristic cell is developed using shell elements and by applying to it the appropriate periodicity conditions. The model is first expanded mechanically producing the realistic geometry and changes to the mechanical properties of the material. The cell is subsequently compressed laterally leading first to buckling, followed by collapse by progressive folding, all similar to the behavior of ideal, stress free hexagonal honeycomb. The calculated buckling stress is about 10% higher than the ideal case, the collapse stress about 5% lower and the average crushing stress somewhat higher. In addition, the buckling and collapse stresses show some sensitivity to the size of periodic domain analyzed, as indeed was the case for the ideal case.

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ABSTRACT: For an elastic system that is non-conservative but autonomous, subjected for example to time-independent loading by a steadily flowing fluid (air or water), a dangerous bifurcation, such as a sub-critical bifurcation, or a cyclic fold, will trigger a dynamic jump to one or more remote stable attractors. When there is more than one candidate attractor, the one onto which the structure settles can then be indeterminate, being sensitive to infinitesimally small variations in starting conditions or parameters. In this paper we develop and study an archetypal model to explore the nonlinear dynamic interactions between galloping at an incipient sub-critical Hopf bifurcation of a structure with shell-like buckling behaviour that is gravity-loaded to approach a sub-critical pitchfork bifurcation. For the fluid forces, we draw on the aerodynamic coefficients determined experimentally by Novak for the flow around a bluff body of rectangular cross-section. Meanwhile, for the structural component, we consider a variant of the propped-cantilever model that is widely used to illustrate the sub-critical pitchfork: within this model a symmetry-breaking imperfection makes the behaviour generic. The compound bifurcation corresponding to simultaneous galloping and buckling is the so-called Takens-Bodganov Cusp. We make a full unfolding of this codimension-3 bifurcation for our archetypal model to explore the adjacent phase-space topologies and their indeterminacies.

References listed at the end of the paper:
ABSTRACT: This paper is concerned with the lateral crushing behaviour of short sandwich tubes, which consist of two concentric aluminium tubes of different diameters filled with aluminium foam. Experimental results and corresponding analytical models are presented. Aluminium sandwich tubes 50 mm long and of different values of diameter to thickness ratios were laterally crushed using an MTS machine at a displacement rate of 2 mm/min. Two bonding cases between the foam and monolithic component tubes, i.e. fully bonded and bonding free, were employed for all the configurations. Load–displacement curves were obtained. Deformation mechanisms were observed and three different crushing patterns have been identified. The experiments reveal that the bonding between the tubes and core for sandwich tubes played a different role in the three crushing patterns. Analytical models using rigid, perfectly plastic theory have been developed, which agree well with the corresponding experimental results.

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ABSTRACT: This paper aims to investigate the energy absorption characteristics of tapered circular tubes with graded thickness (TCTGT) under axial loading. TCTGT specimens were fabricated by a tube tapering machine and the forming effects on crush response were investigated. Both the original straight circular tube and the fabricated TCTGT were tested and compared to analyze the relative merits of TCTGT. Numerical simulations of the tests were conducted by using nonlinear finite element code LS-DYNA and a simplified fabrication process was also simulated. The energy absorption efficiency of the fabricated TCTGTs was found to be considerably higher than that of straight tubes and the forming effects showed important influence on the increase of efficiency. In addition, a novel approach was proposed to predict the mean crushing force of circular and tapered tubes with and without forming effects. The outcomes of the present study will facilitate the design of TCTGT structures with better crashworthiness performance.

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ABSTRACT: Free vibrations of the laminated composite cylindrical shell with clamped edges are considered in this paper. Equations of the theory of laminated shells taking into account the average transverse shear strains are employed for the vibration analysis. A solution of the equations of motion of the shell is based on the Fourier decomposition and the Galerkin method and yields an analytical formula for the calculation of a fundamental frequency. Applications of this formula to the determination of the fundamental frequencies for the filament-wound composite cylindrical shells are demonstrated using numerical examples. The calculations have been verified by comparison with a finite-element solution. It has been shown that the analytical formula presented in this paper provides an efficient means for rapid and reliable calculation of the fundamental frequency which can be used for the assessment of the structural stiffness of the shells in the design analysis.


ABSTRACT: In present paper, 3D finite element (FE) method is used to determine plastic limit load solutions for pipe bends under combined bending and torsion moment. With a detailed analysis and comparison, a common awareness for loading effect is showing which will raise researchers concern. By the way, past solutions are not appropriate to estimate FE results. In this respect of finite element analysis, overall yielding considering the spread process of yield region from crown to the straight pipe shows these promising finite element results. A wide range of non-dimensional parameters for pipe bends are considered and plastic limit load solutions are suggested. The results show that $r/t$ is the main factor affecting the limit loads. Plastic limit load is independent on the loading path and material constants by normalizing. Results show that the circular interaction rule is a great approximation for pipe bends under combined bending and torsion moment. A series of approaches are confirmed in order to validate our finite element method on plastic limit analysis. Based on the finite element results, approximate plastic limit load solutions are proposed. Present work will further improve the limit load solution for pipe bends under complex loading conditions.

ABSTRACT: In this work a finite element model is presented for buckling and nonlinear analysis of multilayer sandwich plates and shells, with a soft core sandwiched between stiff elastic layers. The finite element is obtained by assembling all element-layers through the thickness using specific assumptions on the displacement continuity at the interfaces between layers, but allowing for different behaviors of the layers. The stiff elastic layers are modeled using the classic plate theory and the core is modelled using Reddy's third order shear deformation theory. The present finite element model is a non-conforming triangular plate/shell element with 24 degrees of freedom for the generalized displacements. This model is applied in the solution of illustrative examples and the results are presented and discussed.

References listed at the end of the paper:

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ABSTRACT: An accurate solution approach based on the first-order shear deformation theory (FSDT) is developed for the free vibration and damping analysis of thick sandwich cylindrical shells with a viscoelastic core under arbitrary boundary conditions. Laminated and sandwich theories are employed to describe the laminated composite layers and viscoelastic material layer, respectively. The present solution is based on a set of new displacement field expression in which the displacements of the middle surface are expanded as a combination of a standard Fourier series and auxiliary functions. Due to the improved displacement expansions, rapid convergence and high accuracy can be easily obtained. The current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations. Natural frequencies and loss factors under various boundary conditions and lamination schemes are calculated, which may serve as benchmark solutions in the future. The effects of some key parameters including the boundary conditions, fiber orientation angle, and number and thickness of the layers on free vibration and damping characteristics of the shells are illustrated and analyzed.

ABSTRACT: Analytical solutions of natural frequencies and critical buckling loads for a set of homogenous plates in the complex plate system are determined in this paper. A different layerwise approach is found via interconnecting several plates into one kind of layered block. For this determination, the classical, first order and high order shear deformation theories are used to present rotary inertia and shear effects on systems with different numbers of elastically connected plates. Closed form solutions are determined in the form of explicit
expressions of natural frequencies and critical buckling loads. General mode shapes are presented for systems of elastically connected plates. The stability of the complex system is determined and discussed for different stiffnesses of the support, layers and various geometric dimensions. These results are of considerable practical interest and have a wide application in the engineering practice of frameworks. The range of frequencies depending on number of elastically connected plates in the block is discovered.


ABSTRACT: In order to investigate the wrinkling behavior of thin-walled tubes under complex stress states, a dedicated experimental setup was designed and manufactured. In this experimental setup, the internal pressure, the external pressure and the axial feeding of left and right punches were coupled together through accurate closed-loop servo control. Thin-walled 5A02 aluminum alloy tubes were pushed into the die cavity under different internal pressures or under the combined actions of internal and external pressures with the same amount of axial feeding. Meanwhile, the wrinkle formation, as well as the stress state, was predicted numerically using the FEA Abaqus/Explicit solver. It has been found that the number and shape of wrinkles are strongly dependent on the internal pressure when only internal pressure is applied to the inner surface of the tube. Furthermore, the wrinkle formation is closely related to the inhomogeneous stress distribution induced by local bending and axial displacement. Moreover, the shape of wrinkles can be fitted effectively using the GaussAmp function when the internal pressures of 1.2p, 1.6p and 1.8p (“p” represents the initial yield pressure for the tube) are applied. In addition, the effect of external pressure has been discussed under three cases and it is shown that the wrinkling behavior exhibits hardly any dependence on the external pressure for the constant pressure difference. Finally, the formation of middle wrinkle can be prevented by higher external pressure both for the constant internal pressure and the variable internal pressure.


ABSTRACT: The dynamic indentation response of stainless steel sandwich panels with a corrugated core or a Y-frame core has been explored using the finite element method to gain insight into the potential of the cores to mitigate against collisions over a wide range of impact velocities pertinent to land and sea-borne vehicles. Back-supported sandwich panels were impacted on the front face by a flat-bottomed or a circular punch at constant velocity ranging from quasi-static loading to 100 m/s. At velocities below 10 m/s the forces on the front and back faces are equal but inertia stabilisation raises the peak load above its quasi-static value. This strength elevation is greater for the corrugated core than for the Y-frame core, and more pronounced for the flat-bottomed punch than for the circular punch. For velocities greater than 10 m/s, the indentation force applied to the front face exceeds the force transmitted to the back face due to plastic-shock effects. In this regime, the force transmitted to the back face by the Y-frame core is markedly less than for the corrugated core, and this brings a performance benefit to the Y-frame, i.e. it protects the underlying structure in the event of a collision.

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ABSTRACT: This work was motivated by a necessity of simple and efficient models approximating the responses associated with all the possible failure modes of corrugated core sandwich columns in dynamic compression. In this study, an analytical model was proposed for the prediction of face wrinkling behavior of corrugated core sandwich columns under dynamic compressive loading perpendicular to corrugations. The proposed analytical model has been based on the calculation of transverse motion of face ligaments near the front and back ends of a sandwich column. The governing equation for the face ligaments has been a dynamic version of Euler–Bernoulli beam–column equation, and the motions were obtained by employing the Galerkin method to solve the equation. For validation of the proposed model, FE simulations were performed to compare several metrics such as reaction force and the transverse deflection of face ligaments. It was revealed that the dynamic face wrinkling response was also affected by overall column length and the rate of loading unlike the face wrinkling strength of corrugated core sandwich columns in quasi-static compression. Finally, the model’s limitation and efficiency were discussed.


ABSTRACT: This paper presents a modified Fourier–Ritz approach for free vibration analysis of laminated functionally graded shallow shells with general boundary conditions in the framework of first-order shear deformation shallow shell theory. The displacement and rotation components of the shells are represented by the modified Fourier series consisted of standard Fourier cosine series and several closed-form auxiliary functions introduced to ensure and accelerate the convergence of the series representation. The material properties are assumed to vary continuously through the thickness according to power-law distribution. Four common types of sandwich functionally graded shallow shells are studied. The bi-layered and single-layered functionally graded shallow shells are obtained as special cases of sandwich shells. By setting groups of boundary springs and assigning corresponding stiffness constants to the springs, different boundary conditions including free, clamped, simply supported, elastic boundaries and their combinations are considered. A comprehensive investigation concerning the free vibration of the laminated functionally graded shallow shells with completely free and simply-supported edges is given. The results show that the present method enables rapid convergence, high reliability and accuracy. Numerous new vibration results for shallow shells with different material distributions, lamination schemes and elastic restraints are provided. Some mode shapes of the shallow shells are depicted. Parameter studies illustrate that changes of boundary conditions, material types, thickness schemes and power-law exponents will affect obviously the free vibration characteristic of the shallow shells. In contrast to most existing techniques, the current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations without the need of making any change to the solution procedure.
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ABSTRACT: The LS-DYNA software was employed to analyze the dynamic responses of a sandwich cylindrical shell system under internal blast loading. The system consisted of metallic face sheets and graded aluminum tubular cores with different wall thicknesses. The response of this system was also compared with that of conventional ungraded ones. The dynamic response of graded cylindrical shells with a series of different core arrangements is reported in this paper. The deformation and blast resistance of the structures were discussed in detail, and the optimum sandwich configuration was obtained. The core layers, which had thickness-tapered arrangement from the inner to the outer layer, were favorable for the energy dissipation and the out face-sheet deflection. Finally, two new response types were defined based on the core compression consequence, which is unique to sandwich structures with graded cores.  
References listed at the end of the paper: (See Part 2)  
ABSTRACT: This paper studies the thermal buckling and postbuckling of functionally graded tubes whose material properties are temperature-dependent based on a refined beam model. Firstly, the displacement field of the tubes is expanded in a Laurent series expansion form so that the shear stress on the inner and outer surfaces is vanished. Then, the nonlinear governing equations of the tubes are obtained by the generalized variational principle. Finally, the problem is solved by adopting a two-step perturbation technique. In order to valid the correctness of a present high-order beam model and calculation method, the analytical solution of Timoshenko beam model and Euler beam model for thermal postbuckling are presented. In numerical results, effects of transverse shear deformation, the volume fraction and inner radius on critical thermal buckling and postbukling are investigated.  
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ABSTRACT: The energy absorption characteristics of a type of conical tubes with graded thickness (CTGT) under oblique impact loads were investigated in this paper. The influences of load angle, structure layout, strain
rate effect, inertia effect and forming effects on the responses of CTGT were analyzed numerically by using finite element model validated by experiments. The reverse layout of CTGTs showed very much better performance against oblique loads than the original straight circular tubes employed to fabricate it. The thickness variation and material hardening during fabrication delayed the switch from progressive to global buckling for reverse layout of CTGT and enabled it to preserve most of the axial crush resistance when subjected to oblique loads with load angle up to 20°. The increase in the extent of forming effects was not always found to be beneficial and moderate extent of forming was suggested in applications against oblique loads. The outcomes of this study will facilitate the crashworthiness design of CTGT structures with better performance when subjected to oblique loads.

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ABSTRACT: In this paper, the spectral collocation method based on integrated orthogonal polynomials is applied to the free vibration analysis of coupled axisymmetric laminated shell structures with arbitrary elastic-support boundary conditions (BCs). The coupled shell structure is firstly divided into its multiple components (i.e. the cone, cylinder, sphere and annular plate) at the location of junction in the meridional direction. Then by applying Hamilton's principle, the equations of motion for all the individual shell segments are derived on the basis of the first-order shear deformation theory. Instead of adopting conventional differentiation scheme, an integration technique is used to each individual segment which leads to a set of algebraic equations. These shell segments are further coupled together by matching all of the required displacement and force continuous conditions at the interface. The remaining elastic-support boundary conditions are employed at the ends of the coupled shells. Accuracy and efficiency of the proposed numerical method are explored through a series of free vibration analysis of joined and stepped shell structures, and the results are compared with those available solutions in open literature. Furthermore, the frequency parameters and mode shapes of selected coupled shell structures including cylindrical–spherical, coupled conical and stepped shells are presented to reveal their geometry- and BC-dependent free vibration characteristics.

Nan Liu, He Yang, Heng Li, Zhijun Tao and Xiao Hu (State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi’an 710072, China), “An imperfection-based perturbation method for plastic wrinkling prediction in tube bending under multi-die constraints”, International Journal of Mechanical Sciences, Vol. 98, pp 178-194, July 2015, https://doi.org/10.1016/j.ijmecsci.2015.03.023

ABSTRACT: The prediction of plastic wrinkling in sheet metal forming process with multi-die constraints is difficult. In this paper, taking rotary draw bending of large diameter thin-walled Al-alloy tube bending as research objective, combined with initial imperfection and finite element (FE) method, an imperfection-based perturbation method is proposed to accurately predict wrinkling in tube bending process under multi-die constraints. Considering the distribution of compressive stress in the tube bending process, two simplified models, i.e., tube under pure bending and tube under axial compression, are employed to obtain the buckling modes of a tube in rotary draw bending. By using the eigenvalue buckling analysis and Timoshenko’s energy
method, two kinds of geometrical imperfection are generated based on the above simplified models, respectively; These geometrical imperfections are embedded into a series of explicit FE models to induce wrinkling in tube bending under multi-die constraints; By updating the wavelength and the magnitude of the imperfection, the imperfection leading to the lowest deformation energy is chosen as the appropriate imperfection; The predictive capability of the imperfection-based perturbation method is validated by using two types of bending experiments, viz., bending with wrinkling and wrinkling-free bending. It is shown that the proposed predictor is more sensitive to the wrinkling compared with the pure explicit FE results with perfect geometry. By providing an over prediction of wrinkling, a “lower bound” forming conditions are obtained, which ensures a reliable wrinkling-based process design for complicated forming process under multi-die constraints.

ABSTRACT: The interaction between the thermoelastic distortion and pressure-dependent thermal contact resistance can cause the thermoelastic instability when the conductive heat transfers between two elastic bodies in the static frictionless contact. Using the perturbation method, this paper investigates the thermoelastic instability of a system consisting of a functionally graded material (FGM) layer and a homogeneous layer under the plane strain state. The two layers are pressed together by a uniform pressure, and transmit a uniform heat flux at their interface. The material properties of the FGM layer are assumed to be of exponential variation along the thickness direction. The thermoelastic stability behavior of five types of material combinations depending on the ratio of their material properties are discussed in details. The results imply that the FGMs can be used to improve the thermoelastic contact stability of the systems.

ABSTRACT: This paper presents non-linear finite element analysis to carry out the dynamic response of foam-filled double circular tubes for axial progressive and global bending collapse modes. Some aspects were considered to investigate the crashworthiness capability of cylindrical tube for instance geometry, material and loading parameters. In addition, three types of structures namely empty double tubes (ED), foam-filled double tubes (FD), and foam-filled single tubes (FS) were observed under oblique impact. Crashworthiness parameters were determined in the numerical solution after validated with experiment and theoretical results in relevant references. Moreover, it is evident that the crash ability of the foam-filled double tube is better than the other structures. Finally, the main outcome of this study is the new design information of different tube configurations as energy absorber where two collapse modes are expected.

Qiang He, Dawei Ma, Zhendong Zhang and Lin Yao (Department of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210014, China), “Mean compressive stress constitutive equation and crashworthiness optimization design of three novel honeycombs under axial compression”,

ABSTRACT: Taking typical type of honeycomb as research object, three types of novel honeycombs are studied on the aspects of theoretical prediction under axial crushing. The simplified super folding element (SSFE) theory is applied to estimate the energy dissipation of the typical elements. Taking the inertia effects into account, dynamic mean compressive stress calculating equation is further deduced by utilizing the dynamic enhancement coefficient. In order to validate these theoretical solutions, LS-DYNA is used to simulate the axial loading of three novel honeycombs. The analytical results correlate with these simulation results in an ideal manner. During the multi-objective optimization design, optimal Latin hypercube design (OLHD) method is used to select sampling points in the design space. Meanwhile, the response surface method (RSM), as an accurate surrogate modeling method, is adopted to obtain a maximum specific energy absorption per mass ($SEA_m$) capacity and minimum peak crushing stress ($\sigma_{peak}$). These results yielded from the optimization indicate that the bending cellular honeycomb (BC-H) has the best energy absorption performance under the same limitation of $\sigma_{peak}$. Furthermore, the theoretical equations proposed are utilized to validate the simulation results of three optimal structures. The theoretical predictions show excellent agreement with these simulation values, which hence illustrate the feasibility and efficiency of the crashworthiness optimization method based on surrogate models and finite element analysis techniques.

S. Sahmani, M. Bahrami and M.M. Aghdam (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “Surface stress effects on the postbuckling behavior of geometrically imperfect cylindrical nanoshells subjected to combined axial and radial compressions”, International Journal of Mechanical Sciences, Vol. 100, pp 1-22, September 2015, https://doi.org/10.1016/j.ijmecsci.2015.06.004

ABSTRACT: Because of surface free energy effects at nanoscale, study of the mechanical behavior of nanostructures including surface stress effects is a topic of substantial interest. Herein, the nonlinear buckling and postbuckling characteristics of geometrically imperfect cylindrical nanoshells under combined axial and radial compressive loads are investigated in the presence of surface stress effects. An efficient size-dependent shell model is proposed based on Gurtin–Murdoch elasticity theory and von Karman–Donnell-type of kinematic nonlinearity. On the basis of variational approach using the principle of virtual work, the non-classical governing differential equations are derived. Afterwards, a boundary layer theory is employed incorporating surface stress effects in conjunction with nonlinear prebuckling deformations, initial geometric imperfections and large postbuckling deflections. Then a two-stepped singular perturbation methodology is put to use in order to solve the size-dependent nonlinear problem corresponding to axial dominated and radial dominated loading cases. It is shown that in the case of radial dominated loading, the combination of hydrostatic pressure with axial compression causes to decrease approximately the effect of surface stress compared to the absence of axial load. However, for the axial dominated loading case, in comparison with no applied radial load, the surface stress effects is more significant in the presence of hydrostatic pressure.


ABSTRACT: This paper studies the effect of a central dented imperfection on the load carrying capacity of stiffened panels considering the residual stress caused by the indentation, and identifying the type of boundary
conditions to adopt for a model to be used in an experimental programme for damaged panels. A quasi-static nonlinear finite element analysis is used to simulate the production of the local dent, followed by an ultimate strength analysis of the stiffened panels under uniaxial compressive load. The structural plastic strain causes the residual stress and the dent, which are included in the ultimate strength analysis of the stiffened panels under compressive load. To prescribe appropriately the boundary conditions for the central span of stiffened panels, two and three spans models are adopted in the FE analyses. The effects of residual stress, geometric range and dent depth on the ultimate strength of the stiffened panels with a central dented imperfection are investigated using nonlinear quasi-static finite-element analysis.

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“Buckling behaviour of laminated composite skew plates with various boundary conditions subjected to linearly varying in-plane edge loading”, International Journal of Mechanical Sciences, Vol. 100, pp 136-144, September 2015, https://doi.org/10.1016/j.ijmecsci.2015.06.018

ABSTRACT: In the present study, the buckling behaviour of laminated composite skew plates with different boundary conditions subjected to linearly varying in-plane loads are presented. The skew plate is modelled based on higher order shear deformation theory, which accurately predicts the buckling behaviour for the thick plate. The in-plane stress distribution within the skew plate due to linearly varying in-plane load is equal to the applied in-plane edge load in the pre-buckling range. Using these in-plane stress distributions, the total potential energy functional is formulated. Total potential energy is a function of the total strain energy of skew plate and potential energy due to in-plane stress distributions. The total strain energy of skew plate contains membrane energy, bending energy, additional bending energy due to additional change in curvature and shear energy due to shear deformation, respectively. The total potential energy functionals mapped from physical domain to computational domain over which a set of orthonormal polynomials satisfying the essential boundary conditions is generated by Gram–Schmidt orthogonalization process. Using a Rayleigh-Ritz method in conjunction with Boundary Characteristics Orthonormal Polynomials, the total potential energy functional is converted into sets of algebraic equations. Finally, these algebraic equations are rearranged as a linear eigenvalue problem, which is solved to obtain the critical buckling loads. The numerical results are presented for different skew angles, boundary conditions, length to thickness ratios, aspect ratios and in-plane loadings. It is observed that the critical buckling load increase with the increase of skew angle as well as change in the mode shape at a lower aspect ratio with the increase of skew angle.

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ABSTRACT: The parametric instability of simply-supported sandwich cylindrical shell with a functionally graded (FG) core under static and time dependent periodic axial compressive loads is investigated in this study. The governing equations of sandwich cylindrical shell with an FG core are derived based on Donnell’s shell
theory using first order shear deformation theory (FSDT). Considering the time-dependent periodic axial compressive load, the governing equations are reduced the second order differential equation with the time-dependent periodic coefficient or Mathieu-type equation by using the Galerkin’s method. This equation is solved by Bolotin’s method and the closed form solutions for dimensionless excitation frequencies of parametric vibration of sandwich cylindrical shells with an FG core based on the FSDT are obtained. Numerical simulations are conducted to verify the analytical results. Finally, the effects of variations of volume fraction index of the FG core, static and dynamic load factors and shell characteristics on the dimensionless excitation frequencies of parametric vibration are studied numerically.


ABSTRACT: In this paper, recently developed inverse trigonometric zigzag theory by the authors is extended for the stability analysis of laminated composite and sandwich plates. The model satisfies the inter-laminar continuity at layer interfaces as well as the traction free boundary conditions at top and bottom surfaces of the plate. This theory assumes the non-linear distribution of transverse shear stresses. Green–Lagrange non-linear strain–displacement relations are used to represent geometric nonlinearity in buckling analysis. An efficient C₀ finite element is employed for discretization of the laminate. Numerical results on buckling load parameters are evaluated for laminated composite and sandwich plates covering with different features such as aspect ratios, span thickness ratios, modular ratios, loading and boundary conditions. To ensure the potentiality of the present theory, the evaluated results are validated with the three dimensional elasticity results and the existing results based on different deformation theories as well. Higher modes with corresponding mode shapes are also presented for laminated composite plates. The exemplary results with minimum percentage error with respect to exact results ascertain the accuracy and efficiency of the present theory.

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ABSTRACT: This paper presents an analytical approach to investigate the nonlinear dynamic response and vibration of imperfect functionally graded materials (S-FGM) thick circular cylindrical shells surrounded on elastic foundation using the third order shear deformation shell theory. Material properties are assumed to be temperature dependent and graded in the thickness direction according to a Sigmoid power law distribution (S-FGM) in terms of the volume fractions of constituents with metal–ceramic–metal layers. The S-FGM shells are subjected to mechanical, damping and thermal loads. The Galerkin method and fourth-order Runge–Kutta method are used to calculate natural frequencies, nonlinear frequency–amplitude relation and dynamic response of the shells. In numerical results, the effects of geometrical parameters, the material properties, imperfections, the elastic foundations and mechanical loads on the nonlinear dynamic response and nonlinear vibration of the shells are investigated. Accuracy of the present formulation is shown by comparing the results of numerical examples with the ones available in literature.
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https://doi.org/10.1016/j.ijmecsci.2015.08.013  
ABSTRACT: This paper explores a range of kirigami-inspired folded core structures for use in sandwich panels. Focus has been on assessing the energy-absorption capabilities of the cores, specifically on benchmarking core performance against the widely studied Miura-ori folded core. Four core architectures were investigated. Two cores are based on cube and eggbox known tessellated kirigami patterns. Two cores, the cube strip and the diamond strip, are developed from geometric modifications of the cube tessellation. The cube strip is generated by removing face portions of the cube pattern that contribute little to energy absorption, effectively making a cellular square tube configuration. The diamond strip introduced a pre-folded origami pattern into the core which has been shown in previous research to substantially increase square tube energy absorption. The performance of each core is assessed under quasi-static loading with experimental and numerical analyses. The non-optimised diamond strip cube strip core offered a 41% increase in average force compared to the best-performing curved-crease Miura-type foldcore previously reported and a 92% improvement over the standard Miura-type foldcore.

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ABSTRACT: Multi-cell structures are highly efficient energy absorber under axial crushing. The present work aimed to resolve some problems concerned with energy absorption of a type of quadruple cells. These problems include influence of geometric compatibility among elements, type of trigger, structural parameter or topology change on crush resistance of the structure. Experimental study was conducted first and numerical simulation was then carried out by using commercial explicit finite element code. Theoretical prediction for the mean crushing force of the quadruple cells was also performed by the existing theoretical models. The results showed that when the structural parameter in the section was varied, the geometric compatibility problem became severe if the discrepancy of folding wavelength among constituent elements was large. However, it generally had limited influence on crush resistance of the multi-cell structure and the existing theoretical models can still predict the crush resistance of the section with good accuracy.

V.V. Zozulya (Centro de Investigacion Cientifica de Yucatan, A.C., Calle 43, No 130, Colonia: Chuburna de Hidalgo, C.P. 97200 Merida, Yucatan, Mexico), “A higher order theory for shells, plates and rods”,  
International Journal of Mechanical Sciences, Vol. 103, pp 40-54, November 2015,  
https://doi.org/10.1016/j.ijmecsci.2015.08.025
ABSTRACT: In this paper a new theory for shells, plates and rods has been developed. The proposed theory is based on the expansion of the equations of the theory of elasticity into Fourier series in terms of Legendre polynomials. First, stress and strain tensors, vectors of displacements, traction and body forces have been expanded into Fourier series in terms of Legendre polynomials with respect to a thickness coordinate. Thereby, all equations of elasticity including Hooke’s law have been transformed to the corresponding equations for Fourier coefficients. Then, in the same way as in the theory of elasticity, a system of differential equations in terms of displacements and boundary conditions for Fourier coefficients has been obtained. The case of axially symmetric shell has been considered in more details. As a special case of the general approach the equations of the first and second approximations have been developed for circular plates, curvilinear rods and cylindrical shells. Numerical calculations have been done numerically using the finite element method (FEM) along with the Comsol Multiphysics, Matlab and Mathematica software.

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ABSTRACT: Multi-cell structures have been extensively studied for their outstanding performance as potential energy absorbers. Unlike existing multi-cell tubes with a uniform thickness (UT), this paper introduces a functionally graded thickness (FGT) to multi-cell tubes under dynamic impact, which can be fabricated by an extrusion process. A numerical model is first established using the nonlinear finite element analysis code LS-DYNA and validated with experimental data. Based on a numerical study, the thickness gradient parameters in different regions have considerable effects on the crashworthiness of the FGT multi-cell tubes. Moreover, the FGT multi-cell tubes are able to absorb more energy while yielding a similar level of peak impact force to the UT multi-cell tubes. Finally, multiobjective optimizations of the UT and FGT multi-cell tubes are then performed to determine the optimal gradient parameters that simultaneously improve the specific energy absorption (SEA) and reduce the maximum impact force. In these optimizations, the multiobjective particle optimization (MOPSO) algorithm and response surface (RS) surrogate modeling technique are adopted. The optimization results demonstrate that the FGT multi-cell tubes produce more competent Pareto solutions than the conventional UT counterparts; similar gradients in the outer walls and stronger internal ribs are recommended for the FGT multi-cell tubes because of their improved interactions.

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ABSTRACT: Wrinkling on the unsupported area of some deep drawn shells with curved surface and thin
thickness is extremely hard to control. Sheet hydroforming process is of concern to eliminate this defect, but the analytical prediction of a proper liquid pressure path is far from perfection. In this article, an analytical model on the wrinkling suppression for the hydroforming of curved surface shell was proposed and achieved by the combination of stress model and geometrical model. An experimental setup and simulation model were designed to verify the accuracy of analytical model. The mechanisms for the wrinkling-suppression effect of the liquid pressure were analyzed by stress analysis. What's more, the effects of different parameters for the required liquid pressure were discussed using multiple linear regression analysis. Results show the proper liquid pressure can be used to form wrinkling-free shell. Both the experimental results and the stress distribution agree well with the analytical prediction. The most influential parameters for the liquid pressure are the axis length ratio and the surface quality of the punch. It can be seen that the sheet hydroforming process is very effective for the wrinkling suppression of deep drawn shells with large area of unsupported area, meantime the analytical model can be used in engineering applications and reducing simulation time.

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ABSTRACT: In many industrial processes, geometric strip defects may be generated by buckling due to excessive residual stresses and these defects are difficult to control. Usually residual stresses have complex distributions so that defects with complex shapes appear. In strip rolling, strips are fabricated under tension, which has an impact on the shape and the amplitude of the defects. This tension can hide completely or partially the defects that increase and evolve during tension release. In this work we calculate flatness defects of strips generated by residual stresses, with and without tension, by using a shell finite element model based on the asymptotic numerical method (ANM).

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ABSTRACT: In this paper, a mathematic expression is presented to describe the mode jumping and the equilibrium path reversal characteristics of thin film secondary wrinkling based on the non-linear bifurcation buckling theory. With the usage of variable transformation and the introduction of dimensionless parameters, the non-linear Von-Karman equilibrium equation considering the two-direction loading characteristics, is transformed into a non-linear boundary value problem with zero trivial solution. Based on the bifurcation theory, the eigenvalue problem is addressed through the linearization of non-linear boundary value problem. An approach to critical load prediction of thin film secondary wrinkling is proposed by introducing a critical aspect
ratio parameter, since the mechanism of thin film secondary wrinkling is double eigenvalues splitting. Furthermore, this paper presents an analysis in detail on the critical load of the rectangular thin film secondary wrinkling under shear, indicating that the critical load is linearly proportional to the initial stretching displacement, while its relationship with the size of the free edge is nonlinear. The validity of this critical load prediction approach is verified via the digital image correlation experiment. The results provide strong supports for the controlling and tuning of the wrinkles for high precision pre-tensioned thin film structures.


ABSTRACT: A variational model that describes the nonlinear interaction between global and local buckling of an imperfect thin-walled I-section strut under pure compression is developed. An initial out-of-straightness of the entire strut and an initial local out-of-plane displacement in the flanges are introduced as a global and a local type of imperfection respectively. A system of differential and integral equilibrium equations is derived for the structural component from variational principles, an approach that was previously validated. Imperfection sensitivity studies focus on cases where the global and local critical loads are similar. Numerical results reveal that the strut exhibiting cellular buckling (or ‘snaking’) is highly sensitive to both types of imperfections. The worst forms of local imperfection are identified in terms of the initial wavelength, amplitude and degree of localization and these change with the generic imperfection size and highlight the potential dangers of unsafe predictions of actual load-carrying capacity.


ABSTRACT: We study the stability of thin walled circular cylindrical shells subject to radial pressure loading. Towards this end, we first develop the equations of motion of these shells with predominant radial deflections. We identify additional terms in the shell equations of motion which have mostly been neglected in existing studies and ascertain their importance in predicting the correct static buckling pressure. For finite cylinders, incorporation of these terms results in the best prediction of the static buckling pressure. Furthermore, we also find that the assumed relationships between the in-plane displacements of a generic point and the in-plane displacements of the mid-surface, which change from one shell theory to the other, play a critical role in determining the correct onset of the buckling instability under radial loading. In particular, the Donnell shell theory which is very popular for the study of dynamic problems related to cylindrical shells does not predict the correct buckling pressure. We find that the Flügge–Luré–Byrne theory is best suited for this purpose. Accordingly, the shell equations with the additional terms and the in-plane displacements related as per the Flügge–Luré–Byrne shell theory have been used for the study of parametric instability of a cylinder subject to a uniform radially fluctuating pressure. Stability charts with respect to different combinations of the forcing parameters viz. the static component of the pressure, the amplitude and frequency of the fluctuating component of the pressure have been presented which can serve as design guideline for shells subject to fluctuating radial loads.
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“On the energy absorption of tube reinforced foam materials under quasi-static and dynamic compression”,
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ABSTRACT: Theoretical and numerical analyses are carried out to reveal the role of metal tube reinforcement in the enhancement of the energy absorption capacity of foam materials with different densities and strength. A theoretical model is proposed to estimate the strength increase of the reinforcement due to the confined tube, which buckles. Using this model, the contribution of the reinforcement is obtained to the mean quasi-static tube force and also to the total quasi-static average force of reinforced materials comprising different foam and reinforcing components. The proposed model is also used to estimate the efficiency of the reinforced foam materials in the quasi-static loading regime. FE simulations are carried out to verify the theoretical quasi-static model and to examine some essential dynamic effects due to the inertia of the foam and reinforcing tubes on the energy absorption of the material when subjected to impact loading. Attention is paid to the force enhancement at the impacted end and to the dynamic load transfer to the distal end of blocks of reinforced materials.


ABSTRACT: In this study single and double wall structures for crashworthiness are investigated to introduce a novel system with better energy absorption and crushing characteristics under both axial and oblique loading. The new developed double wall structure is constructed from inner conical and outer circular tubes, incorporated with and without foam filler. Foam filled bi-tubular structure subject to direct axial and oblique impact loadings are simulated using nonlinear finite element analysis software package LS-DYNA. Numerical simulations obtained via non-linear explicit dynamic FEM are firstly validated using theoretical and experimental solutions. Next, effectiveness of the new developed bi-tubular structure has been shown by comparing with similar common thin-walled structures. Different types of structures namely bi-tubular empty and foam filled new design, empty and filled frusta as well as empty and foam filled circular tubes were considered in order to make a more insightful of capabilities of the proposed structure. A parametric study including the effect of geometrical and material properties of the structure on the crashworthiness has been carried out. Results show the possibility of amending the peak crushing load along with keeping other energy absorption characteristics unchanged or even improved. Also an improvement in absorbed energy under oblique loading by using the new developed structure is observed.

ABSTRACT: Most of the existing methods for sandwich plates are only suitable for a particular type of boundaries which typically require modifications in solution procedures to adapt different boundary cases. The main aim of this paper is to provide a unified yet accurate solution for vibration and damping analysis of viscoelastic and functionally graded (FG) sandwich plates with arbitrary boundary conditions. The two-parameter power-law distributions in terms of volume fractions are used for FG layer and a lamination theory is applied in composite laminated layers. The formulation is derived by the modified Fourier series in conjunction with Rayleigh–Ritz method according to the first-order shear deformation theory. The modified Fourier series is expressed in the form of the linear superposition of a double Fourier series and auxiliary functions which are introduced to ensure and accelerate the convergence of the series representations. The current method can be universally applicable to all classical boundaries, elastic boundaries and their combinations. New results about natural frequencies and loss factors of common and new types of sandwich plates are calculated, which may serve as benchmark solutions in future. The effects of some key parameters such as the boundary conditions, geometric properties and power-law indices on free vibration and damping characteristics of the plates are illustrated and analyzed. The effect of fiber orientation angle of composite facings on modal shapes is also investigated.

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ABSTRACT: The high velocity compressive response of metallic corrugated core sandwich columns was characterized. One end of a column was compressed, either perpendicular-to-corrugations or parallel-to-corrugations, at a uniform velocity up to 100 m/s whereas the other end was held fixed. Numerical simulations revealed that the response differs from the low velocity response dominated by inertial stabilization; the perpendicular-to-corrugations compressive response was characterized by repetitive densification in a unit cell while the parallel-to-corrugations one occurred during one-way trip of stress wave. The effects of geometric imperfections, column length, compression velocity were investigated through the analysis on rate independent Al6061-T6 corrugated core sandwich columns. On the other hand, the influence of material strain-rate sensitivity was numerically assessed for SS304 corrugated core sandwich columns. As a result, the front end reaction forces increased with imposed velocity while the peak reaction forces on the back end remained invariant. No significant effect of geometric imperfections was observed, and the column length effect was associated with the time scale: the arrival time of stress wave and reaction force variation. Consequently, the analytical expressions for the response were given in terms of sandwich geometric dimensions and loading intensity.

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“How does axial prestretching change the mechanical response of nonlinearly elastic incompressible thin-

ABSTRACT: Human arteries provide an example of anisotropic, nonlinearly elastic, incompressible tubes. It is known that they operate in situ with significant axial prestretching. In ageing, this prestretching is successively relaxed due to arteriosclerosis. Ex vivo inflation-extension experiments have shown that axial prestretching is advantageous from the mechanical point of view, because it reduces the extent of the axial stress and strain that is experienced by arteries during the heart cycle. It has also recently been found that axial prestretch enhances circumferential deformations. Highly prestretched arteries exhibit higher circumferential stretches than their weakly prestretched counterparts, and this is advantageous when blood is transported to the periphery. However, this effect of axial prestretch on the mechanical response of a tube has until now been overlooked in the scientific literature. The objective of our study is to elucidate the physical cause of this phenomenon. An analytical model of an incompressible thin-walled closed tube was used to simulate the mechanical response of an initially prestretched tube to internal pressure. Four different situations were considered: (I) a hyperelastic material with a large strain stiffening property, (II) a neo-Hookean material, (III) a neo-Hookean material with small strains but large displacements (second order linear elasticity), and (IV) a neo-Hookean material with small strains and small displacements (first order linear elasticity). The results have shown that the positive effect of axial prestretch is not a property exclusively related to anisotropy. It has been proved that nonlinear effects are crucial. Nonlinear constitutive models depending on more than one parameter can both enhance and suppress the circumferential distensibility of the tube due to prestretching. However, a one-parameter neo-Hookean model showed only increased circumferential distensibility. A reduction in second order linear elasticity led to mechanical responses that exhibited only a slight effect of being prestretched. Total linearization proved that axial prestretch has a positive effect only to the point where deformed configuration and reference configuration are distinguished.

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ABSTRACT: This paper aims to study the bending collapse behavior of thin-walled square tubes with variable thickness in the cross-section. Three-point bending test is carried out for thin-walled square beams with different thickness for flanges and webs. The relative strength of the flanges versus the web plates is found to have significant influence on the force response and deformation pattern. Numerical simulation of the experimental test is also performed and the numerical results compared very well with the experimental results. Moreover, the difference between the quasi-static and dynamic responses of the square tubes under transverse loading is analyzed. A response surface method is finally employed to optimize two thin-walled beams under impact loading. The optimization results show that putting less material in flanges and more in the web plates is an efficient way to improve the bending resistance of the beams under transverse loading. Adopting graded thickness in the web plates is an effective and promising approach to further increase the energy absorption efficiency of the beams.
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ABSTRACT: By assuming the neutral axis is perpendicular to the bending plane, this paper presents a general analytical solution to predict the limit bending moment for pipes with two inner surface circumferential flaws under combined internal pressure and bending moment. The circumferential stress caused by internal pressure is taken into account through Mises yield criterion. Based on the general solution, expressions for symmetrical and unsymmetrical bending with two flaws of the same size are proposed. Then the influence of perpendicularity assumption is discussed and it demonstrates that the deviation caused by perpendicularity assumption is negligible. Finite element analyses and experiments are both carried out. The results calculated by proposed expressions are found to be in good agreement with both numerical results and experimental ones. The effect of several parameters on the limit bending moment is also studied. Results reveal that circumferential stress caused by internal pressure has important influence on bending moment, and should be taken into account.

ABSTRACT: The paper deals with modelling and testing of a logistic trucks supporting military operations tyre under strongly dynamic loading conditions. A detailed discrete model of a tyre was developed and validated with the actual one. As a consequence, the blast loading tests were carried out taking into consideration two different explosive distance of the tyre tread. The tests were repeated using numerical methods. During the investigations, a characteristic of tyre structure destruction was compared and the pressure distribution in numerical simulations was analysed. In the finite element modelling, the Simplified Rubber constitutive model, available in commercial LS-Dyna code, was implemented with material characteristics obtained experimentally. The mechanical properties of rubber were assessed within various strain rates: from quasi-static conditions to strongly dynamic ones. Considering erosion in an FE model, the results obtained from comparison with the actual wheel (tyre) showed good accuracy.

ABSTRACT: An analytical model of investigating the pull-in characteristics of CNTs reinforced nano-actuator with temperature-dependency subjected to coupled electrostatic loading, dispersion forces as van der Waals and thermally corrected Casimir force, and surface stress are derived based on von Karman’s geometric nonlinearity and surface elasticity. The results illustrate that increment of volume fraction of CNTs enhances the structural stiffness and leads to the increases of pull-in voltage of CNTs reinforced nano-actuator; the growth of
temperature increases the axial compression stress and thus decreases the pull-in voltage; and free-standing behavior depends on the characteristic scale of the CNTs reinforced nano-actuator. The doubly-clamped and doubly-supported configuration of nano-actuator are considered and the pull-in voltage of doubly-clamped nano-actuator is larger than that of doubly-supported type. Casimir force with thermal correction significantly depends on the temperature and initial gap between electrodes. The results show the difference between Casimir force with and without thermal correction is small within couples of nanometers gap but the effect of Casimir force on pull-in instability of CNTs reinforced nano-actuator cannot be neglected.

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ABSTRACT: The crush resistance of corner elements with various thickness configurations is investigated in this paper. Experimental study and numerical analyses are performed for square tubes with uniform and nonuniform wall thickness. The variation of wall thickness is found to have great influence on both deformation mode and force responses of the tubes. Two theoretical methods are proposed to predict the mean crushing force of the corner elements with nonuniform wall thickness. One is based on data fitting with average wall thickness and another is a newly proposed analytical model. Both methods can give satisfactory predictions for crush resistance of corner elements developing inextensional mode.

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ABSTRACT: The current article analyses the buckling response of piezoelectric cylindrical composite panels reinforced with carbon nano-tubes subjected to axial load. Classical laminated plate theory (CLPT) is employed to reach stress and displacement correlations embracing mechanical and magnetic terms. Stress–strain equations for piezoelectric cylindrical panels reinforced with carbon nanotubes are then written by using Mori–Tanaka method. The coupled electro-mechanical governing equations, Donnell theory as well as minimum potential energy method are thereafter utilized to calculate buckling loads and modes. The effects of such parameters as volume fraction of nano-tube, geometrical characteristics as well as two loading types of axial and biaxial on buckling load of the composite panel are investigated. The results show that increasing the volume fraction of nano-tube eventuates in increasing the buckling load. The results were compared with those already available in the existed literature using different shell theories for isotropic and composite cylindrical panels and a very good agreement was observed.
ABSTRACT: The crushing response of the pressurized cylindrical tubes under low-speed axial crushing is investigated by both numerical simulations and theoretical analysis. The internal pressure inside the tubes varies in a wide range from 0% to 80% of the tube's yield pressure. Numerical simulations with lower internal pressure are verified by the experiments reported in literatures. It is shown that under axial crushing the tubes with lower internal pressure deform into the mixture of symmetric mode and unsymmetrical mode. With the increase of internal pressure, the tube's deformation under axial crushing is dominated by the symmetric mode. The total load-carrying capacity of the pressurized structure increases with the internal pressure. However, the load-carrying capacity of the tube wall itself decreases with the increase of internal pressure once the pressure is greater than 13% of the yield pressure. This behavior is very different from the foam-filled tubes, for which the load-carrying capacity of the tube wall is enhanced by the filler inside. Based on the symmetric fold's evolution process observed from numerical simulations, an analytical model is proposed to establish the expression of the tube wall's load-carrying capacity in relation to the internal pressure and the tube's size. It is shown that the tube wall's load-carrying capacity under higher internal pressure decreases with the internal pressure, while it increases with the cross-sectional area of the tube. By combining the analytical predictions obtained in the present paper under symmetric mode and that under non-symmetric mode reported in literature, the critical internal pressure for the transformation between the two deformation modes is estimated. All the analytical predictions are found to be in good agreements with the numerical simulation results.

S. Sahmani, M.M. Aghdam and M. Bahrami (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “Size-dependent axial buckling and postbuckling characteristics of cylindrical nanoshells in different temperatures”, International Journal of Mechanical Sciences, Vol. 107, pp 170-179, March 2016, https://doi.org/10.1016/j.ijmecsci.2016.01.014

ABSTRACT: One of the most important reasons that give rise to the extraordinary behaviors of nanostructures is the free surface energy. In the current investigation, a size-dependent shell model is introduced which has an excellent capability to take surface energy effects into account. To this end, Gurtin–Murdoch elasticity theory is implemented into the classical shell theory. Using virtual work's principle, the non-classical governing differential equations related to the cylindrical nanoshell subjected to axial compressive load are derived. Subsequently, a boundary layer theory is extended to solve the problem with considering the effects of surface free energy in addition to the nonlinear prebuckling deformations and the large postbuckling deflections. Finally, a solution methodology based on a two-stepped perturbation technique is put to use in order to obtain the size-dependent critical buckling loads and related postbuckling equilibrium paths corresponding to different surface properties and various sets of thermal environments. It is found that for all sets of thermal environment, the surface free energy has significant influence on the postbuckling strength of nanoshell. Also, it is seen that thermal environment causes to decrease the both critical buckling load and critical end-shortening, but it has a negligible influence on the value of minimum postbuckling load.
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ABSTRACT: This paper presents an investigation on the postbuckling behavior of doubly curved nanocomposite panels reinforced by carbon nanotubes (CNTs) subjected to lateral pressure. The functionally graded carbon nanotube-reinforced composites (FG-CNTRCs) are assumed to have CNTs linearly graded in the thickness direction. The overall mechanical properties of the FG-CNTRCs, which include the thermal effect of CNTs and the matrix, are estimated through a micromechanical model. The panels may rest on elastic foundations. The governing differential equations for the doubly curved panels are based on a higher order shear deformation shell theory with von Kármán strain–displacement relationships and the panel–foundation interaction. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. The governing equations are further deduced to a boundary layer type problem that includes nonlinear prebuckling deformations and initial geometric imperfections of the panels which are subsequently solved using a two-step perturbation approach. The influences of CNT volume fraction, temperature variation, panel geometric parameters, as well as foundation stiffness on the postbuckling behavior of FG-CNTRC doubly curved panels are investigated.

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ABSTRACT: The progressive buckling behavior of a gradient grooved tube (GGT) designed for high temperature gas cooled reactor (HTR) is systematically studied in this paper. Based on the plastic hinge formation process, a sectionalized theoretical model is established to predict the quadratic upward trend of crushing force of GGT. The ordered and stable energy absorbing process of GGT is examined by low-speed axial impact using drop hammer test machine. The effect of proactive regulation parameters, including non-dimensional groove width $W/(h+h_0)$, groove depth $h_0/h$ and half wavelength (math) on buckling modes and force–displacement curve is determined by experiments and FE simulation. The non-dimensional groove width $W/(h+h_0)$ is determined as pi/2 according to the geometry coordination of bending grooves. The non-dimensional groove depth $h_0/h$ influences local buckling behavior and the critical value 0.6 for regular bending has been determined by numerical simulation. The quadratic trend force–displacement curves of GGT can be actively controlled by (math) within a certain range less than 1.2. Free-fall impact experiments show that GGT
has a better stability than perfect tube when used as an energy absorber to protect the graphite in HTR from slender control rod impact.


ABSTRACT: An exact elastodynamic model based on Navier equations of linear elasticity is formulated to describe the three-dimensional natural oscillations of an elliptic cylinder of finite length with shear diaphragm end conditions, and containing an inner ( coaxial) elliptical cavity of arbitrary size, location, and orientation. The formulation is based on Helmholtz decomposition theorem, the method of separation of variables in elliptical coordinates, and the translational addition theorems for Mathieu functions. The first three natural frequencies are calculated for selected cylinder lengths, cross-sectional aspect ratios, and cavity location/orientation parameters. Also, some representative 3D deformation mode shapes are depicted in vivid graphical form. The precision of solutions is checked through proper convergence studies, and the validity of results is verified with the aid of a commercial finite element package as well as by comparison with the available literature data. The presented exact Mathieu series solution is believed to be the first attempt on the vibrational characteristics of finite-length eccentric elliptical cylinders.

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ABSTRACT: In the present work, a free vibration analysis of Carbon Nanotube-Reinforced Composite (CNTRC) conical shells is performed considering the agglomeration effect of Carbon Nanotubes (CNTs). The material properties of the nanocomposite conical shell are estimated employing the Eshelby-Mori-Tanaka approach based on an equivalent fiber assumption. The numerical results are compared with the experimental data available from the literature. The equations of motion are derived based on the First-order Shear Deformation Theory (FSDT). The Generalized Differential Quadrature (GDQ) technique is originally implemented to solve the governing equations of the problem and to obtain the natural frequencies of the structures, since it has proven to be an efficient and accurate numerical tool. A parametric study is herein developed to investigate the influence of some characteristic parameters on the vibrational behavior of the CNTRC conical shell, e.g. the CNTs volume fraction and agglomeration, or the boundary conditions and geometrical parameters like the thickness to radius ratio. Based on results, it is found that agglomeration of CNTs plays a significant role on the natural frequency of the structure.

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ABSTRACT: This paper investigates the torsional wrinkling behavior of an annular thin film. Non-dimensional nonlinear von Karman buckling equations are established, which are solved by introducing a compound series method to acquire the post-wrinkling characteristics. The proposed theoretical model can accurately predict the critical wrinkling behavior and post-wrinkling characteristics of the annular thin film, which are verified by the experimental measurement based on the digital image correlation (DIC) technique. The theoretical results show that the post-wrinkling stress is intimately associated with the wrinkle configuration in the post-wrinkling stage. The hoop post-wrinkling stress along the wrinkle texture direction of the annular thin film dictates the wrinkle evolution. The wrinkle number remains constant in the elastic regime, which is determined by the critical buckling load factor. The results provide good guides to tune or control the wrinkles in the thin film.

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ABSTRACT: A new accurate four-variable shear deformation plate theory is introduced in this paper to illustrate the hygrothermal vibration and buckling of FGM sandwich plates resting on Winkler–Pasternak elastic foundations. Based on the suggested theory, the equations of motion are derived from Hamilton's principle containing the hygrothermal effects. This theory involves only four unknown functions and accounts for quasi-parabolic distribution of transverse shear stress. In addition, the transverse shear stresses are vanished at the top and bottom surfaces of the sandwich plate. A power law distribution is used to govern the gradation of material properties through the plate thickness. Various types of FGM sandwich plates are considered. To check the validity of the theory and formulations, the obtained results are compared with the previous results. Comparison studies reveal that the results of the proposed theory are more accurate than those of other shear deformation plate theories. Parametric study is performed to show the influences of moisture condition, temperature rise, elastic foundation coefficients and power law index on the buckling and natural frequency of FGM sandwich plates.


ABSTRACT: This paper presents an approximate closed-form solution for the free-vibration problem of thin-walled clamped–clamped cylinders. The used indefinite equations of motion are classic. They derive from Reissner's version of Love's theory, properly modified with Donnell's assumptions, but an innovative approach has been used to find the equations of natural frequencies, based on a solving technique similar to Rayleigh's method, on the Hamilton's principle and on a proper constructions of the eigenfunctions. Thanks to the used
approach, given the geometric and mechanical characteristics of the cylinder, the model provides the natural frequencies via a sequence of explicit algebraic equations; no complex numerical resolution, no iterative computation, no convergence analysis is needed. The predictability of the model was checked both against FEM analysis results and versus experimental and numerical data of literature. These comparisons showed that the maximum error respect to the exact solutions is less than 10% for all the comparable mode shapes and less than 5%, on the safe side, respect to the experimental data for the lowest natural frequency. There are no other models in the literature which are both accurate and easy to use. The accurate models require complex numerical techniques while the analytical models are not accurate enough. Therefore the advantage of this novel model respect to the others consists in a best balance between simplicity and accuracy; it is an ideal tool for engineers who design such shells structures.

ABSTRACT: The splitting and bending behaviour of steel plates was used as energy absorber in our previous work. Two experiments with 9 mm steel plates were carried out. The finite element models presented in this study are based on experimental tests and good agreement is achieved between the experimental and finite element results. Through the observation of the results of numerical simulation, the typical deformation process and variations of the stress triaxiality of the elements are presented. The parametric study was performed using finite element models under quasi-static loading conditions. It was found that the plate thickness, die angle, width of the die and the distance between the steel plate and the baffle have a distinct effect on the energy absorption. The outcome of this parametric study was full and detailed design guidelines for such energy-absorbing structures. The effect of the velocity was investigated and the result shows that under dynamic loading the deformation of the steel plates is similar to the quasi-static loading, and the steady state force increased as the impact velocity increased. With a bigger angle, the increase of the steady state force is larger.

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ABSTRACT: The Layerwise/Solid-Element (LW/SE) method, which was developed based on the layerwise theory and the eight-noded solid element for the laminated composite stiffened plates and sandwich plates in the previous works [1–3], is extended to the static response and free vibration analysis of the composite sandwich structures with multi-layer cores. In the LW/SE method, the layerwise theory is used to model the behavior of the laminated composite facesheets while the eight-noded solid element is employed to discretize the cores. The total governing equations of the composite sandwich plates are assembled by using the compatibility conditions to ensure the compatibility of displacements and the equilibrium conditions to ensure the equilibrium of internal force at the interface between facesheets and cores. In the numerical examples, the static analysis and free vibration analysis of the composite sandwich plates are investigated for the sandwich plates with double-layer honeycombs and pyramidal lattice cores. The proposed method is validated by using the 3D elastic models developed in MSC.Patran/Nastran code. Two kinds of local models of the sandwich plates with double-layer
honeycombs are presented for the local response problems to reduce the computational cost in the case of guarantee analysis accuracy of the local response.

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ABSTRACT: This paper studies the plastic collapse mechanisms of uniaxially-loaded cylindrical shell-plate periodic honeycombs with identical mass (or relative density) but varying geometric parameters, by series of in-plane and out-of-plane experiments and finite element numerical simulations. The coupled experimental-numerical results show that mechanical properties of the honeycomb can be optimized in all three loading cases, thanks to the complementary changes of the mechanical properties of cylindrical shell and plate as the geometric parameters vary. The work presents a concept to optimize lattice structures by combining different substructures, and can be used in designing new low-density honeycomb structures with desired mechanical requirements but less base materials and weight.

References listed at the end of the paper:


ABSTRACT: In this article, the nonlinear free vibration behavior of circular cylindrical nanoshells is investigated within the framework of surface stress elasticity theory. To accomplish this goal, a nonlinear shell model is developed based upon the model proposed by Ru [Continuum Mech. Thermodyn., 2016, vol. 28, pp. 263–273] and the classical shell theory. The geometric nonlinearity is taken into account using von Kármán's hypothesis. Hamilton's principle is also utilized to derive the governing equations including surface effects. Thereafter, using the multiple scales method, an analytical solution is obtained for the nonlinear free vibrations of simply-supported nanoshells. In the numerical results, the influences of surface stress, initial surface tension, length-to-radius and radius-to-thickness ratios on the vibration characteristics of nanoshells are studied.


ABSTRACT: The present paper proposes the study of the approximation of the curvature terms in the three-dimensional (3D) equilibrium shell equations used for the free vibration analysis of one-layered and multilayered composite and sandwich structures. 3D equilibrium equations written for spherical shells
degenerate into 3D equilibrium equations for cylindrical shells and plates considering one of the two radii of curvature or both as infinite, respectively. The approximation of curvature terms has been introduced in 3D equilibrium equations in order to study its effects in terms of frequency values. This study has been conducted by means of a comparison between 3D equilibrium equation results and 3D approximate curvature equilibrium equation results. These effects depend on the thickness and curvature of the considered structure, on the embedded material and lamination sequence, on the frequency order and vibration mode. The 3D equations have been considered in exact form for simply supported structures. The system of partial differential equations has been solved by means of the exponential matrix method. A layer-wise approach is considered for multilayered structures. The approximation of the curvature has been introduced in the 3D equilibrium shell equations and not in the interlaminar continuity conditions and in the top and bottom boundary and loading conditions. This choice has been made for numerical reasons. The investigation of curvature approximation effects in the equilibrium equations allows an exhaustive analysis to understand the importance of curvature terms in the free vibration problems.

Wu Yuan, Hongwei Song and Chenguang Huang (Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, No. 15 Beisihuaxi Road, Beijing 100190, China), “Failure maps and optimal design of metallic sandwich panels with truss cores subjected to thermal loading”, International Journal of Mechanical Sciences”, Vols. 115-116, September 2016, https://doi.org/10.1016/j.ijmecsci.2016.06.006

ABSTRACT: Sandwich panels with truss cores have been widely investigated due to their superior mechanical performances. When being used in the thermal protection system of a high-speed aircraft, sandwich panels are usually subjected to intense thermal loading and may fail due to various mechanisms. This paper presents a theoretical and numerical analysis on the failure mechanisms and optimal design of metallic sandwich panels with truss cores subjected to uniform thermal loading. Five failure modes are considered: global buckling, face sheet buckling, face sheet yielding, core member buckling and core member yielding. Failure maps of sandwich panels with several truss core topologies are developed based on these failure modes. Taking the five failure modes as constraint conditions, sandwich panels with truss cores are optimally designed for the minimum weight at given thermal loadings. It is found from the optimal analysis that sandwich panels with Kagome and X-type truss cores are more efficient than those with tetrahedral and pyramidal truss cores. Sandwich panels with fully-clamped boundary conditions have superior thermal loading resistance than those with simply-supported boundary conditions.

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ABSTRACT: Postbuckling and postbuckled vibration characteristics of sandwich plate subjected to non-uniform in-plane loadings is investigated in this article. The core compressibility effects are considered in the model by assuming fourth and fifth order expansions for the transverse and tangential displacement of the core. The exact stress distributions within the panel are determined by panel prebuckling analysis for the applied parabolic and partial edge loadings. Multi-term Galerkin's method is employed to reduce the governing partial differential equation to a set of non-linear ordinary differential equations in the case of dynamic analysis and to
a set of non-linear algebraic equations in the case of static stability analysis. Newton-Raphson method in conjunction with Riks approach is used to trace the postbuckling path. Free vibration frequencies of the sandwich plate about a static equilibrium state are obtained by solving the associated linear eigenvalue problem. From numerical study it is observed that the postbuckling path becomes more softening type with increase of aspect ratio. Moreover, unloaded fixed edge of SCSC sandwich plate gives more rigidity than unloaded simply supported edge of CSCS. The prebuckling and postbuckling frequency increases with increase in edge restraint, and in postbuckling range, frequency increases with increase of in-plane load.

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“Post-buckling behaviour of shear deformable functionally graded curved shell panel under edge compression”, International Journal of Mechanical Sciences, Vols. 115-116, pp 318-324, September 2016,
https://doi.org/10.1016/j.ijmecsci.2016.07.014
ABSTRACT: In this article, the post-buckling behaviour of functionally graded curved shell panels of different shell geometries (spherical, elliptical, cylindrical and hyperbolic) are investigated under the uniaxial and the biaxial edge compression. The inhomogeneity of the functionally graded material along the thickness direction is achieved using power-law distribution through Voigt's micromechanical model to obtain the effective material properties. The kinematic model is developed with the help of higher-order shear deformation theory in conjunction with Green-Lagrange geometrical nonlinear strains. The governing equation of the axially loaded functionally graded curved panel is derived using the minimum total potential energy principle. The nonlinear finite element steps have been employed to discretise the shell panel domain and solved with the help of Picard's iterative method to obtain the desired load parameter. Further, the effects of different parameters such as the amplitude ratios, the power-law indices, the curvature ratios, the thickness ratios, and the support conditions on the buckling and post-buckling responses of the functionally graded curved panels are demonstrated through suitable numerical illustrations.

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ABSTRACT: Vibration characteristics of CNT-reinforced functionally graded composite closed cylindrical shells are studied. Thermal effect is taken into account. In the structural modeling, Reddy's high-order shear deformation theory is applied. Hamilton's principle and the assumed mode method are used to formulate the equation of motion of the CNT-reinforced functionally graded cylindrical shell. Vibration properties of the cylindrical shell are analyzed through the time- and frequency-domain methods. Influences of temperature change, CNTs distribution as well as CNTs volume fractions on the natural frequency of the CNT-reinforced cylindrical shell are investigated. Vibration responses of the cylindrical shell computed by the FSDT and TSDT are compared to verify the necessity of the high-order shear deformation theory in the vibration analysis for thick CNT-reinforced structures. The effects of CNTs volume and distribution on the free and forced vibration
of the cylindrical shell are studied. The influences of thermal effect on the vibration responses of the CNT-reinforced cylindrical shell are also investigated.

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ABSTRACT: This paper presents a novel stiffened plate buckling model for describing the distortional buckling of cold-formed steel zed- and channel-section beams when they are bent about their major axis. In the model the compression flange and lip together with the web are treated as a plate with an angle stiffener. By using the classical principle of total potential energy, an analytical expression for the critical buckling stress of the stiffened plate is obtained. In order to validate the present model, finite strip analysis is also carried out for 59 CFS channel-section beams used in the UK market. The comparison of the critical stresses calculated from the present stiffened plate buckling model and those obtained from the finite strip analysis demonstrates that the present model provides an excellent prediction for the critical stress of distortional buckling of CFS section beams.

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ABSTRACT: As a relatively new configuration with higher efficiency of material utilization, functionally graded thickness (FGT) structure has become more and more attractive. In order to understand transverse load bearing behaviors, three circular FGT tubes with different linear thickness gradients from one end to its nearest indenter are investigated through three-point and four-point bending tests in this study. A series of loading conditions, namely different loading offset for three-point bending and different loading span for four-point bending tests, are considered to explore the energy absorption characteristics of the FGT tubes. The experimental deformation modes and force-displacement curves of FGT tubes are first compared with corresponding uniform thickness (UT) tubes. Second, the finite element (FE) models of circular FGT tubes are established for comparisons with the experimental tests. Third, a dimensionless analysis is conducted to compare the deflections in the three-point and four-point bending tests of the circular FGT tubes with different thickness gradient. It is shown that the FGT tubes have more regions to participate in deformation than the UT counterparts to bear the transverse loads. Based on the validated FE models, a parametric study is finally carried out to explore the influence of thickness gradient or thickness difference on the three-point and four-point bending behaviors of the FGT tubes in comparison with the same mass UT counterparts. The results show that a
proper selection of thickness gradient can effectively enhance the energy absorption of tubal structures under transverse loading, exhibiting that the FGT tubes are considerably more advantageous over the uniform tubes.

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ABSTRACT: Since classical theory is incapable to justify size-dependency of small scale systems such as micro-electro-mechanics (MEMs) or nano-electro-mechanics (NEMs) systems, modified couple stress theory (MCST) has been developed in order to capture the size effect in the small size investigation. A novel study on the free vibrations of the micro/nano-scale spherical shell based on First-order Shear Deformation Theory (FSDT) and MCST is done. Fullerene (C60) is an appropriate example of spherical micro-scale structures. The governing equations of the modified couple stress spherical shell are derived by using Hamilton's principle. Obtained equations are solved using Generalized Differential Quadrature (GDQ) method. The influences of changing geometrical parameter and scale parameter on the natural frequency are investigated. It is shown that the scale parameter is extremely effective on the natural frequency of the micro/nano-sphere. This issue is bolder in the thick spherical shell. Finally, proper scale parameters are proposed for different nano-scale spheres by comparing numerical results with experimental results.

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ABSTRACT: Considering thermal loads, a dynamic stability analysis is presented for a flexible cylindrical shell conveying a viscous, incompressible, swirling fluid in the annulus between the inner shell and the outer shell in this paper. The inviscid fluid-dynamic forces associated with shell motions are treated in the frame of the potential flow theory. And the steady viscous forces are derived by using fully developed turbulent theory. The thermal loads are determined by the thermo-elastic theory. Shell motions are described by Flügge's thin shell equations, which are modified to incorporate the prestresses relating to the steady viscous forces. The theoretical analysis is conducted by the zero-level contour method and the Galerkin's method. This study shows that, for annular flow, the effect of viscosity renders the system more unstable. Fluid rotation strongly degrades the stability of the shell. The influences of a combined action of the viscous annular flow having two velocity components and the thermal loads on the stability of shells are discussed in detail. Also, the critical temperature rise is found.
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ABSTRACT: An understanding of the dynamic behavior of the carbon nanotubes (CNTs) conveying fluid is very important for exploring the applications in nanoscale systems. Due to the molecular network disruption, the passing flow has multiphase nature. In this regard, the nonlinear vibration behavior of the CNT conveying multiphase flow is investigated by considering the small scale effects based on the nonlocal theory. The effect of the multiphase flow on the CNT’s vibration behavior is modeled by the resultant random uncertainty in the external excitation along with considering the slip flow velocity profile. After extraction of the governing equation by implementing Hamilton's principle and discretizing it by the Galerkin method, the resulting equations are solved numerically. Due to the stochastic nature of the differential equations, the statistical parameters of the response have been obtained by Monte–Carlo simulation. By studying the deflection of the midpoint of the CNT and also considering corresponding upper and lower limit band (confidence interval), extended results of uncertainty effects have been obtained. Moreover the effect of nonlocal parameter, flow velocity and Knudsen number on the statistical dynamic behavior of the system have been investigated. The results show that as the molecular behavior of the flow increases the uncertainty in the system and the confidence interval increase.

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ABSTRACT: Static and dynamic loading of a type of folded tubes under three-point bending are investigated in this work. The folded tubes are easily prepared, cost-effective and flexible in sectional shape, and hence quite promising to be applied widely in various engineering fields. Experimental investigations are firstly performed for folded square tubes and numerical analyses by nonlinear finite element methods are then carried out. The influences of various factors, including the load direction, velocity, fillet radius and sectional shape, on the force and deformation responses of the folded tubes are investigated. The comparison between traditional tubes and folded tubes is performed and shows that the folded tubes outperform the traditional tubes in some aspects. In addition, some suggestions for the design of folded tubes are presented.

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ABSTRACT: Thirty-three dynamic tests on thin-walled tubes including conventional square tubes and two types of origami crash boxes were conducted on a drop hammer rig. All of the origami crash boxes have identical thickness $t$ and surface area $A$ to those of conventional square tubes. Experimental results validate that origami crash boxes perform better than the conventional square tubes. And the mean crushing force of origami crash boxes with longer modules ($l/t=60$) is larger than that with shorter ones ($l/t=40$). Complete diamond mode as well as two new collapse modes, which are local buckling mode and symmetric mode, were observed in tests. The comparison among those three collapse modes suggests that the complete diamond mode is the most efficient one and the symmetric mode is the most inefficient one in terms of energy absorption. The effect of local buckling on the mean crushing force is presented to analyze the characteristics of those three collapse modes. It is found that the mean crushing force decreases with the increase of the number of buckling points.

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ABSTRACT: An innovative double-hat thin-walled beam comprised of aluminum-steel hybrid materials is proposed for potential application in passenger vehicle bumper systems to reduce pedestrian injury. The beams are featuring an aluminum alloy upper hat and a high strength steel lower hat riveted together to increase the specific energy absorption (SEA) and to reduce the initial peak force ($F_{ip}$) simultaneously under lateral impacts. Quasi-static three-point bending test was performed to explore the bending resistant characteristics of such a double-hat beam. Furthermore, bending behavior of the hybrid beam under lateral impact was numerically investigated using LS-DYNA and compared with that of its counterparts with homogeneous materials and identical geometrical dimensions. It was found that the aluminum-steel hybrid beam shows a well-balanced and better bending performance under lateral impact compared to beams made of a single material. Parametric studies were further conducted to investigate the influences of critical geometric parameters on the crashworthiness performances of such double-hat beams under lateral impacts. Based on radial basis function (RBF) metamodels and using non-dominated sorting genetic algorithm (NSGA-II), bi-objective optimizations to maximize $SEA$ and minimize $F_{ip}$ were carried out for both the hybrid and the two homogeneous beams. The optimization results show that the hybrid beam possesses better Pareto solutions than the homogeneous beams, and is more preferable for use in vehicle bumpers. Finally, a tri-objective optimization problem is solved for the hybrid beam to further maximize its bending moment ($Mb$). It was found that $SEA$ and $Mb$ of the hybrid beam are cooperating with each other and emphasize on different objectives will result in optimal configurations with slight differences.

X. Chen, C. Li and X.X. Wei (State Key Laboratory of Mechatronics and Control, School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China), “Stress analysis of a hollow sphere
ABSTRACT: The theoretical basis for determination of tensile strength and elastic constants by compression of hollow spheres between two flat platens is provided in this paper. The method of solution follows the displacement function approach, and three displacement functions are introduced so that the fifteen governing equations can be uncoupled analytically. The Hertz contact between the out surface of the hollow sphere and the flat loading platens is considered, and Fourier-Legendre expansion technique is applied on the Hertz contact stress in order to determine the unknown constants in the general analytical expression for stress components. An analytical solution for the stress and displacement components within a hollow sphere compressed between two flat platens is obtained. Numerical results of the analytical solution show that the stress distributions within hollow spheres are not uniform, two tensile stress concentration zones are usually developed at the inner surface and near the loading area along the loading axis of the hollow spheres within both thick and thin hollow spheres, but the maximum tensile stress is usually developed at the inner surface, except few cases for relatively thick hollow sphere with a very small Poisson ratio. The maximum tensile stress developed along the axis of loading can be used to estimate the tensile strength of hollow spheres. The curves obtained by the analytical solution for the ratio between the vertical and horizontal strains at the equator of the out surface of the hollow sphere, together with those for nominal stress versus the normalized displacement between the two flat loading platens, may provide optional way to determine Poisson's ratio and Young's modulus of the hollow sphere, respectively.

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ABSTRACT: The present research deals with the thermoelastic response of a thick sphere based on the Lord–Shulman theory of generalized thermoelasticity. Unlike the other available works in which energy equation is linearized, the assumption of ignorance of temperature change in comparison to the reference temperature is not established in this research resulting in a nonlinear energy equation. Such nonlinearity is called thermally nonlinear. The one-dimensional radial equation of motion and energy equation are established for an isotropic homogeneous sphere. The resulting equations are discreted by means of the generalized differential quadrature in radial direction and traced in time by means of the Newmark time marching scheme. Numerical results are provided to demonstrate the discrepancies between the thermally linear and nonlinear results. As the numerical results reveal, thermally linear theory fails for precise analysis of structures under thermal loads especially at high temperature shocks, large coupling coefficient, and large relaxation time.


ABSTRACT: Based on nonlocal Euler-Bernoulli beam theory, vibration characteristics are investigated for a horn-shaped single-walled carbon nanotube (SWCNT) which is embedded in a viscoelastic medium and
subjected to a longitudinal magnetic field. Governing equations of motion are derived for vibration analysis of horn-shaped SWCNTs, where the Lorentz magnetic force, the surrounding viscoelastic medium and variable cross-section have been taken into consideration. Subsequently, perturbation method (PM) and transfer function method (TFM) are employed to compute the natural frequencies and the corresponding mode shapes for horn-shaped SWCNTs with arbitrary boundary conditions. The obtained results are first compared with the results available in the literature, where good agreement is achieved. The validation of the model is followed by a detailed parametric study of the effects of nonlocal parameter, taper parameter and longitudinal magnetic field on the vibration of horn-shaped SWCNTs. The results demonstrate the efficiency of the developed model for vibration analysis of a complicated multi-physics system comprising horn-shaped SWCNTs, viscoelastic medium and a magnetic field in longitudinal direction.

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ABSTRACT: A new model depicting the full phase of tubular string buckling in vertical wellbores is proposed. The buckling modes of the tubular string are divided into: no buckling, 2D lateral buckling, 3D lateral buckling, continuous contact buckling and helical buckling. For the 2D lateral and 3D lateral buckling, the tubular string is respectively depicted by two and four suspended sections; for the continuous contact and helical buckling, the tubular string includes four suspended sections and one continuous contact section. With the suspended and continuous contact sections respectively depicted by beam-column model and buckling differential equation, the general buckling configurations of the entire tubular string are deduced. Substituting relevant continuity, boundary and stability conditions, the tubular string buckling problem is converted into a system of nonlinear equations. Solving these equations with iteration method, the critical buckling loads and the buckling configurations under different buckling modes for a weightless tubular string are obtained. Later, the weightless model is extended to the case for a tubular string with weight. On the basis of the new buckling model, the axial force and torque transfer along the tubular string under the coupling effect of friction force and buckling is discussed. The results show that the existence of tubular string weight increases the complexity of buckling mechanism and calculation. The continuous contact between the tubular string and wellbore reduces the axial force and torque transfer along the tubular string. To increase the axial force and torque transfer and inhibit buckling, the installation of stabilizers of low friction and buckling inhibition on the buckling-prone sections is wiser than unilaterally increasing the diameter and thickness of the tubular string. Compared with the previous results, the new model provides a more sophisticated description of tubular string buckling in vertical wellbores.

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ABSTRACT: As a relatively new sectional configuration with a higher efficiency of material utilization, laterally variable thickness (LVT) structure has demonstrated its compelling features in energy absorption. To explore the crushing behavior of LVT multi-cell tubes as well as validate the corresponding finite element (FE) models and analytical solution for the mean crushing force, the quasi-static axial crushing experiments are first performed for the five-cell and nine-cell LVT tubes in this study. The FE models of LVT tubes are then created for investigating the crushworthiness of these structures; and the simulation results are found to agree well with the experimental data. Following the validated FE models, a parametric study is carried out to quantify the influence of the thickness gradient on the crushworthiness of the LVT tubes with the same mass as the uniform thickness (UT) counterparts. The results show that the LVT multi-cell tubes are of certain advantages over the uniform counterparts to be an energy absorber. Based on Super Folding Element (SFE) theory, the analytical models for the mean crushing force (MCF) and energy dissipation of the LVT multi-cell square tubes have been established with regard to the thickness gradient. The analysis is also performed to explore the mechanism of energy absorption enhancement by the evolution of theoretical models. It is confirmed that the derived analytical solutions provide fairly good prediction of the mean crushing force and energy absorption of LVT multi-cell tubes.


ABSTRACT: New torsional models of carbon nanotube in which axial velocity and the velocity gradient effect are separately considered on the basis of newly proposed nonlocal strain gradient theory are presented in this study. The nonlocal strain gradient theory developed from nonlocal theory contains additional strain gradient scale parameter representing the effect of high-order strain gradient besides the nonlocal scale parameter depicting interactions of neighboring particles. For torsional vibration of carbon nanotube considering axial velocity, the influence of axial velocity is included in kinetic energy. For that in view of velocity gradient effect, additional kinematic component which represents material particles in micro/nano-scale distinguishing those in macro-scale is involved in the kinetic energy. The governing equations are derived by Hamilton's principle and the high-order boundary conditions are also deduced simultaneously. As study case, fixed-fixed boundary condition is considered. The two scale parameters impacting on torsional frequencies are discussed in detail, meanwhile, comparisons of current model with other high-order non-classical and classical models, and the relations between axial velocity and torsional frequencies are shown in this paper. The relations between critical velocity and two scale parameters are also illustrated. Ultimately, the influences of velocity gradient effect on torsional frequencies are presented.


ABSTRACT: The general equations of motion of a flexible spinning missile under thrust in the powered flight phase are established and the stability of the motion of the missile is analyzed. The spinning missile is approximated to the unconstrained flexible rotor. Moreover, the thrust in the powered flight phase is deemed as a follower load when the factors of gyroscopic effect, aeroelastic effect, and axial force are considered under the mean axis condition. The equations of motion and stability of the flexible spinning missile in the powered flight
phase are then deduced. The stability and dynamic response of the flexible spinning missile under thrust is analyzed through numerical calculation. Calculation results show that thrust, spinning speed, and dynamic pressure exert different influences on the stability of the spinning missile. These factors should be considered and analyzed comprehensively.

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ABSTRACT: Buckling of anisotropic piezoelectric cylindrical shells subjected to axial compression and lateral pressure is investigated based on the new modified couple stress theory and using the shear deformation theory with the von Kármán geometrical nonlinearity. By applying the principle of minimum potential energy, the governing equations and boundary conditions are derived. Unlike the classical continuum model, the present model is size-dependent, and the size effects are captured using the new modified couple stress theory. The critical buckling load is obtained for simply supported, clamped-simply supported and clamped piezoelectric cylindrical shells. A detailed numerical study is carried out to discuss the effects of different parameters, such as material length scale parameter, thickness ratio, length ratio, load interaction parameter and the external electric voltage on the critical buckling load. The critical buckling load is found to be significantly size-dependent, especially for large values of thickness and small values of length ratio. Besides, the influence of load interaction parameter is found to be negligible for large values of length and small values of thickness ratio.


ABSTRACT: This paper presents an analytical solution of the linear buckling, free vibration and bending behavior of simply supported functionally graded sandwich plates subjected to transverse and axial mechanical loads. The used optimization strategy allows to express the transverse and in-plane displacement fields as a function of the $n$ and $m$ parameter, respectively, so the used Carrera's unified formulation (CUF) is also $n$ and $m$ parameters dependent. Principle of virtual displacement (PVD) is utilized to obtain the highly coupled differential equations. The solution is obtained via Navier-Type solution. Good agreements with quasi-3D solutions are found. The optimized parameters are used for solving the buckling problem of functionally graded sandwich plates with different side-to-thickness ratios. Numerical results for buckling are compared to different advanced theories since there isn’t 3D solution available in the literature. Overall, the presented results have a high accuracy to estimate the critical loads, modes and natural frequencies.

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“A stiffened-plate buckling model for calculating critical stress of distortional buckling of CFS columns”,
https://doi.org/10.1016/j.ijmecsci.2016.10.025
ABSTRACT: This paper presents a stiffened-plate buckling model for calculating the critical stress of distortional buckling of cold-form steel (CFS) channel-section columns. The model is the further extending of the buckling model we developed recently for beams (International Journal of Mechanical Sciences 2016, 115/116: 457–464) to columns. In the present buckling model, the web is treated as a plate which has both in-plane and out of plane bending deformations, whereas the flange and lip are modelled as the angle stiffener applied at the two ends of the web, which is subjected to asymmetric bending and torsion. The critical buckling stress of the stiffened plate is calculated using the classical principle of minimum potential energy. To validate the present stiffened plate buckling model, finite strip analysis is also carried out to the CFS channel-section columns. Good agreement is demonstrated between the critical stress calculated from the present stiffened plate buckling model and that obtained from the finite strip analysis.

D.H. Li, F. Zhang, and J.X. Xu (College of Aeronautical Engineering, Civil Aviation University of China, Tianjin 300300, China), “Incompatible extended layerwise method for laminated composite shells”,
International Journal of Mechanical Sciences, Vol. 119, pp 243-252, December 2016,
https://doi.org/10.1016/j.ijmecsci.2016.10.022
ABSTRACT: The extended layerwise method (XLWM) was established in the previous studies [1,2] for the laminated composites with multiple delaminations and transverse crack based on the layerwise theory and extended finite element method (XFEM). In order to improve convergence rate, Wilson's incompatible freedom is introduced into the in-plane displacement discretization of the XLWM, and an incompatible extended layerwise method (IXLWM) is established for the laminated composite shells in this paper. The finite formulation of IXLWM is deduced from Hamilton's principle for composite shells with delamination and/or transverse crack. In the numerical examples, the composite beams, plates and spherical shells are used to validate the proposed IXLWM and investigate its convergence rate for the static responses and stress intensive factor (SIF). In addition, the influence of incompatible freedom in different directions on the convergence rate is studied.

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ABSTRACT: Analysis of the deformation of cylindrical membranes is important for understanding various mechanical systems, including biological structures such as the incudostapedial joint in the middle ear. Although the deformations of long cylindrical membranes have been extensively investigated, studies of short cylindrical membranes have not been published. Here we present an analytical solution for the deformation of moderate-length and short cylindrical membranes using the Mooney-Rivlin form for the strain-energy function. The membrane profiles and the internal pressures fit well with a finite-element model. We show that both moderate-length and short membranes become unstable when passing a certain limit pressure, and this instability persists even for very short membranes. Furthermore, we show that increasing the initial length, the pre-stretch and the stiffness all tend to stabilize a short membrane. The results may furnish insight into the mechanical behaviour of the incudostapedial joint.

ABSTRACT: The paper deals with the predicting critical flow velocity of a fluid-conveying magneto-electro-elastic pipe resting on a Winkler-like elastic foundation. Taking into account the Timoshenko beam theory, the constitutive law of magneto-electro-elastic materials and Maxwell's theory, the Hamilton's principle is applied for deducing the governing equations and corresponding boundary conditions of fluid-conveying magneto-electro-elastic pipes resting on the Winkler-like elastic foundation. The closed-form solutions of the critical flow velocity are obtained for fluid-conveying magneto-electro-elastic pipes with clamped-clamped and pinned-pinned ends, and can serve as benchmarks for any future numerical results. The effects of shear deformation, Winkler-like foundation and the magnetic and voltage potentials applied in magneto-electro-elastic pipes on the critical flow velocity are discussed in detail. Results show that the magnetic and voltage potentials have a significant effect on the critical flow velocities and therefore can be used to control the critical flow velocity by choosing some appropriate values of magnetic and electric potentials.


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ABSTRACT: A version of the imperfection method is used to investigate the wrinkling (tension buckling) of thin, elastic, homogeneous, isotropic circular plates of uniform thickness undergoing small deflections without inplane twisting. A numerical procedure based on the finite difference approach is employed to quantitatively predict wrinkling loads and wrinkling patterns for three sets of support conditions. Representative numerical results are presented in tabular and graphical formats and used to illustrate interesting aspects of the predictions.

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ABSTRACT: Recent studies on localized bulging in inflated membrane tubes have shown that the initiation pressure for the onset of localization is determined through a bifurcation condition. This kind of localization has also been shown to be much more sensitive to geometrical and material imperfections than classical sub-critical bifurcation into periodic patterns. We use these results to show that the initial formation of aneurysms in human arteries may also be modeled as a bifurcation phenomenon. This bifurcation interpretation could provide a theoretical framework under which different mechanisms leading to, or reducing the risk of, aneurysm formation can be assessed in a systematic manner. In particular, this could potentially help in assessing the integrity of aneurysm repairs.

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ABSTRACT: Solution to the problem of a spherical balloon made out of an electroactive polymer which is subjected to coupled mechanical and electrical excitations is determined. It is found that for certain material behaviors instabilities that correspond to abrupt changes in the balloon size can be triggered. This can be exploited to electrically control different actuation cycles as well as to use the balloon as a micro-pump.

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ABSTRACT: Morphoelastic theories have demonstrated that elastic instabilities can occur during the growth of soft materials, initiating the transition toward complex patterns. Within the framework of non-linear elasticity, the theory of incremental elastic deformations is classically employed for solving stability problems with finite strains. In this work, we define a variational method to study the bifurcation of growing cylinders with circular section. Accounting for a constant axial pre-stretch, we define a set of canonical transformations in mixed polar coordinates, providing a locally isochoric mapping. Introducing a generating function to derive an implicit gradient form of the mixed variables, the incompressibility constraint for the elastic deformation is solved exactly. The canonical representation allows to transform a generic boundary value problem, characterized by conservative body forces and surface traction loads, into a completely variational formulation. The proposed variational method gives a straightforward derivation of the linear stability analysis, which would otherwise require lengthy manipulations on the governing incremental equations. The definition of a generating function can also account for the presence of local singularities in the elastic solution. Bifurcation analysis is performed for few constrained growth problems of biomechanical interests, such as the mucosal folding of tubular tissues and surface instabilities in tumor growth. In a concluding section, the theoretical results are discussed for
clarifying how anisotropy, residual strains and external constraints can affect the stability properties of soft tissues in growth and remodeling processes.


ABSTRACT: Geometrically non-linear forced vibrations of a shallow circular cylindrical panel with a complex shape, clamped at the edges and subjected to a radial harmonic excitation in the spectral neighborhood of the fundamental mode, are investigated. Both Donnell and the Sanders–Koiter non-linear shell theories retaining in-plane inertia are used to calculate the elastic strain energy. The discrete model of the non-linear vibrations is built using the meshfree technique based on classic approximate functions and the R-function theory, which allows for constructing the sequences of admissible functions that satisfy given boundary conditions in domains with complex geometries; Chebyshev orthogonal polynomials are used to expand shell displacements. A two-step approach is implemented in order to solve the problem: first a linear analysis is conducted to identify natural frequencies and corresponding natural modes to be used in the second step as a basis for expanding the non-linear displacements. Lagrange approach is applied to obtain a system of ordinary differential equations on both steps. Different multimodal expansions, having from 15 up to 35 generalized coordinates associated with natural modes, are used to study the convergence of the solution. The pseudo-arclength continuation method and bifurcation analysis are applied to study non-linear equations of motion. Numerical responses are obtained in the spectral neighborhood of the lowest natural frequency; results are compared to those available in the literature. Internal resonances are also detected and discussed.

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ABSTRACT: This paper treats the classical problem of radial motions of cylindrical and spherical shells under pulsating pressures. The novelty in this work is that the shells are taken to be non-linearly viscoelastic (of strain-rate type). It is remarkable that this classical problem, which does not treat the loss of stability to non-radial motions (but which is essential for such treatments), has such a rich dynamics due to the often neglected effects of non-linear material response, to the role of prestress under the action of the mean pressure, and to the different effects of pressure on cylindrical and spherical shells. The study of radial motions near primary resonance (when the frequency of the pulsating pressure is near the natural frequency about an equilibrium state under a constant pressure) gives formulas ensuring that the motions are of hardening or softening type depending on the constitutive functions and whether the constant mean pressure is compressive or inflational. The method of multiple scales gives asymptotic formulas for the principal parametric instability regions (Mathieu tongues) and for the stable and unstable motions at twice the forcing frequency, which closely agree with those obtained by numerical continuation methods. The dependence of frequency on amplitude and the form of instability regions are critically influenced by deviations (even very slight deviations) of material
response from that of linearly viscoelastic shells, by the constant mean pressure, and by the type of shell. This paper exhibits the rich diversity of postcritical periodic motions.

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ABSTRACT: This study introduces a non-linear finite element analysis approach to the procedure of modeling hybrid laminate composite shells with embedded shape memory alloy (SMA) wire subjected to coupled structural and thermal loading. Numerical analyses of SMA wire reinforced composite laminates were carried out by synergizing the non-linear laminate shell element with Brison's model of the SMA constitutive law. To verify the proposed procedure, the present illustrative applications involve rectangular laminated panels clamped along one side. Analysis results were compared with corresponding experimental results from a prior study. Several test cases that depend on the volume fraction of SMA, temperature, and ply angles are presented to illustrate the highly entangled thermo-mechanical behavior of shape memory alloy hybrid composites (SMAHCs). The results of the numerical analysis show the ability of the suggested procedure to compute the thermo-mechanical behavior of a SMAHC in accordance with the SMA's internal phase transformations induced by stress and temperature variation and demonstrate very good agreement with experimental results.


ABSTRACT: The lateral buckling and helical buckling problem of a circular cylinder constrained by an inclined circular cylinder under a compressive force, torsion, and its own weight is complicated and difficult to obtain an exact analytical solution. Thus, the non-linear differential equation is solved incrementally using the discrete singular convolution (DSC) algorithm together with the Newton–Raphson method. Detailed formulations are worked out. A simple way to numerically simulate the helical buckling is proposed and solution procedures are given. Four examples with various inclined angles, weights per unit length of the inner cylinder, axial applied loads, and boundary conditions are investigated. To verify the formulations and solution procedures, comparisons are firstly made with data obtained using the finite element method. It is verified that under certain circumstance, only lateral or helical buckling alone will occur. On some other circumstance, both lateral buckling and helical buckling may occur and the critical helical buckling loads are higher than the critical lateral buckling loads if friction is not considered. Some conclusions are made based on the results presented herein.

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ABSTRACT: This paper presents the theoretical developments of a high accuracy method for the post-buckling analysis of some channel section struts. In this method, the Von-Karman's equilibrium equation is solved exactly to obtain the buckling loads and the corresponding form of out-of-plane buckling deflection modes. The investigation of channel section buckling behaviour is then extended to the post-buckling study with the assumption that the deflected form after the buckling is the combination of first, second and higher (if required) modes of buckling. Thus, the full-analytical post-buckling study is effectively a multi term analysis, which is attempted by utilizing the so-called semi-energy method. In this method the Von-Karman compatibility equation is used together with a consideration of the total strain energy of the strut. Through the solution of the compatibility equation, the in-plane displacement functions which are themselves related to the Airy stress function are developed in terms of the unknown coefficients in the assumed out-of-plane deflection function. The in-plane and out-of-plane deflection functions are substituted in the total strain energy expressions and the theorem of minimum total potential energy is applied to solve for the unknown coefficients. It is noted that the Classical Plate Theory (CPT) is applied throughout the theoretical developments. Through the comparison of the results and the appropriate discussion, the knowledge of the level of capability of the method is significantly promoted.

Zhi-Min Li and Zhong-Qin Lin (School of Mechanical Engineering, Shanghai Key Lab of Digital Autobody Engineering, State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, PR China), “Thermal postbuckling of shear-deformable anisotropic laminated cylindrical shells with temperature-dependent properties”, International Journal of Non-Linear Mechanics, Vol. 47, No. 9, November 2012, https://doi.org/10.1016/j.ijnonlinmec.2012.06.006

ABSTRACT: Thermal postbuckling analysis is presented for shear-deformable anisotropic laminated cylindrical shell of finite length. The temperature field considered is assumed to be a uniform or non-uniform parabolic temperature distribution varying in the circumferential or axial direction. Temperature-dependent material properties are taken into account. The governing equations are based on Reddy's higher order shear deformation shell theory with von Kármán–Donnell-type of kinematic non-linearity and including the extension/torsion, extension/flexure, flexure/torsion couplings and thermal effects. The non-linear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to determine the buckling temperature and postbuckling load–deflection curves. The numerical illustrations concern the postbuckling response of perfect and imperfect, anisotropic laminated cylindrical shells with different values of shell parameters and stacking sequence. The results confirm that there exists a compressive stress along with an associated shear stress and torsional effect when the anisotropic shell is subjected to thermal loads. They also confirm that the thermal postbuckling equilibrium path is stable or weakly unstable for the moderately long cylindrical shell and the shell structure is virtually imperfection-insensitive.

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ABSTRACT: This paper is concerned with numerical simulations of three-dimensional finite deformation of a thick-walled circular elastic tube subject to internal or external pressure and zero displacement on its ends. We formulate the system of equations that can accommodate large strain and displacement for the incompressible isotropic neo-Hookean material. The fully non-linear governing equations are solved using the C++ based object-oriented finite element library libMesh. A Lagrangian mesh is used to discretize the governing equations, and a weighted residual Galerkin method and Newton iteration solver are used in the numerical scheme. To overcome the sensitivity of the fully non-linear system to small changes in the iterations, the analytical form of the Jacobian matrix is derived, which ensures a fast and better numerical convergence than using a numerically approximated Jacobian matrix. Results are presented for different parameters in terms of wall thickness/radius ratio, and length/radius ratio, as well as internal/external pressure. Validation of the model is achieved by the excellent agreement with the results obtained using the commercial package Abaqus. Comparison is also made with the previous work on axisymmetric version of the same system (Zhu et al., 2008 [34]; Zhu et al. 2010 [43]), and interesting fully three-dimensional post-buckling deformations are highlighted. The success of the current approach paves the way for fluid–structure interaction studies with potential application to collapsible tube flows and modeling of complex physiological systems.


ABSTRACT: In this work, we have studied the finite inflation of a hyperelastic toroidal membrane with an initially circular cross-section under internal pressure. The membrane material is assumed to be a Mooney–Rivlin solid. The inflation problem is formulated as a variational problem for the total potential energy comprising the membrane strain energy and internal energy of the gas. The problem is then discretized and solved up to a high degree of accuracy through a sequence of approximations based on the Ritz expansion of the field variables combined with a potential energy density perturbation and Newton–Raphson method. The effects of the inflation pressure and material properties on the state of stretch and geometry of the inflated torus have been studied, and some interesting results have been obtained. The stability of the inflated configurations in terms of impending wrinkling of the membrane has been investigated on the principal stretch parameter plane for both isotropic and anisotropic (transversely isotropic) material cases. Certain shape factors quantifying the geometry of the membrane have been defined and calculated which characterize the cross-sectional shape and size of the torus during inflation.


ABSTRACT: Present analysis deals with the buckling and Post-buckling behavior of laminated composite and sandwich skew plates. Higher order shear deformation theory and von-Karman's nonlinearity is considered in the problem formulation. The physical domain is mapped into computational domain using linear mapping. Finite degree double Chebyshev series method is employed for spatial discretizations of governing differential
equations and boundary conditions. The nonlinear terms are linearized using quadratic extrapolation technique. Post-buckling response of the skew plates is investigated for different types of in-plane compressive loadings. Effects of skew angle, lamination scheme, core thickness and face to core material property ratio of the sandwich plate on the buckling and Post-buckling response are studied in detail.

Qinkai Han, Zhaoye Qin, Jingshan Zhao and Fulei Chu (Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China), “Parametric instability of cylindrical thin shell with periodic rotating speeds”, International Journal of Non-Linear Mechanics, Vol. 57, pp 201-207, December 2013
DOI: 10.1016/j.ijnonlinmec.2013.08.002
ABSTRACT: Parametric instability of a cylindrical thin shell with periodically time-varying rotating speeds is studied in the paper. Energy formulation based upon Love's thin shell theory and the assumed mode method is utilized to obtain the governing equations of a rotating cylindrical shell under simply supported condition. Considering the time-varying rotating speeds, the second order differential equations of the system have time-periodic gyroscopic and stiffness coefficients. The multiple scales method is utilized to obtain the boundaries of both primary and combination instabilities analytically. The primary instability occurs when the excitation frequency is near twice of the natural frequency. The excitation frequency close to the sum of two natural frequencies might lead to the occurrence of combination instability. Numerical simulations are conducted to verify the analytical results. It is shown that the primary instability regions for each mode always appear in the periodically rotating cylindrical shell. Their widths increase continually with excitation amplitude of the time-periodic rotating speed. For certain modes, the combination instability region might not exist. The conditions for its existence are obtained analytically and verified by numerical simulations. Increasing the constant rotating speed would greatly enhance the instability regions. Moreover, it might also cause the appearance of combination instability region.

M. Amabili (Department of Mechanical Engineering, McGill University, Macdonald Engineering Building, 817 Sherbrooke Street West, Montreal, PQ, Canada H3A 0C3), “A non-linear higher-order thickness stretching and shear deformation theory for large-amplitude vibrations of laminated doubly curved shells”, International Journal of Non-Linear Mechanics, Vol. 58, pp 57-75, January 2014,
https://doi.org/10.1016/j.ijnonlinmec.2013.08.006
ABSTRACT: A geometrically non-linear theory is developed for shells of generic shape allowing for third-order thickness stretching, higher-order shear deformation and rotary inertia by using eight parameters; geometric imperfections are also taken into account. The geometrically non-linear strain–displacement relationships are derived retaining full non-linear terms in the in-plane and transverse displacements and are presented in curvilinear coordinates, ready to be implemented in computer codes. Higher order terms in the transverse coordinate are retained in the derivation so that the theory is suitable also for thick laminated shells. The theory uses the three-dimensional constitutive equations and does not need the introduction of traction/compression free hypothesis at the shell inner and outer surfaces. The traction/compression free condition is introduced only to obtain a simplified model with six parameters instead of eight. The third-order thickness stretching theory is applied to cross-ply symmetrically laminated circular cylindrical shells complete around the circumference and simply supported at both ends. Geometrically non-linear forced vibrations are studied by using the present theory and results are compared to those obtained by using a refined higher-order shear deformation non-linear shell theory, which neglects thickness stretching, and to results obtained by using first-order and second-order thickness stretching theories. Results obtained by using the reduced third-order thickness stretching model with six parameters are also presented and compared.
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ABSTRACT: Most of real systems are non-linear and they require damage detection. For such non-linear systems, non-linear damage detection methods are necessary for more accurate results. In this paper, a novel non-linear method is introduced using limit cycle oscillations that arise once the bifurcation (flutter) boundary is exceeded and shows greater sensitivity for damage detection versus linear damage detection techniques. Another advantage of this method is that it can be used for health monitoring of linear or non-linear systems. Here a non-linear aeroelastic panel is considered as a model to show the capabilities of the proposed damage detection technique. Also Proper Orthogonal Decomposition (POD) is used to find the number of independent damage locations in the panel. Rayleigh–Ritz method is used to discretizing spatial domain of the system. Damage is modeled as stiffness reduction in the certain region. By comparing Limit Cycle Oscillation of healthy and damaged panel damage level and its location could be obtained with good sensitivity.

ABSTRACT: In this study, the effect of steady viscous forces (skin friction and pressurization) on the non-linear behaviour and stability of cantilevered shells conveying fluid is investigated for the first time. These forces are obtained by using the time-mean Navier–Stokes equations and are modelled as initial loadings on the shell, which are in a membrane-state of equilibrium with in-plane stresses. The unsteady fluid-dynamic forces, associated to shell motions, act as additional loadings on this pre-stressed configuration; they are modelled by means of potential flow theory and obtained by employing the Fourier transform technique. The problem is formulated using the extended Hamilton's principle in which the shell model is geometrically non-linear and based on Flügge's thin shell assumptions. This model includes non-linear terms of mid-surface stretching and the non-linear terms of curvature changes and twist, as well. The displacement components of the shell are expanded by using trigonometric functions for the circumferential direction and the cantilevered beam eigenfunctions for the longitudinal direction. Axisymmetric modes are successfully incorporated into the solution expansion based on a physical approximation. The system is discretized and the resulting coupled non-linear ODEs are integrated numerically, and bifurcation analyses are performed using the AUTO program. Results show that the steady viscous effects diminish the critical flow velocity of flutter and extend the range of flow velocity over which limit cycle responses are stable. On the other hand, the non-linear terms of curvature changes and twist have very little effect on the dynamics. The system exhibits rich post-critical dynamical behaviour and follows a quasiperiodic route to chaos.

ABSTRACT: This paper presents a weak form quadrature element formulation of the stress resultant geometrically exact shell model proposed by Simo. A total Lagrangian updating scheme of rotation is adopted by the use of rotational quaternion. In addition to its conciseness for the coincidence of discrete nodes and integration points, the weak form quadrature element formulation exhibits computational feasibility as well as avoidance of shear and membrane locking problems for its high-order approximation property in nonlinear shell analysis. Several numerical examples are presented to illustrate the effectiveness of the proposed formulation.


ABSTRACT: Sandwich structures are widely used in many industrial applications thanks to their interesting compromise between lightweight and high mechanical properties. This compromise is realized thanks to the presence of different parts in the composite material, namely the skins which are particularly thin and stiff relative to the homogeneous core material and possibly core reinforcements. Owing to these geometric and material features, sandwich structures are subject to global but also local buckling phenomena which are mainly responsible for their collapse. The buckling analysis of sandwich materials is therefore an important issue for their mechanical design. In this respect, this paper is devoted to the theoretical study of the local/global buckling and post-buckling behavior of sandwich columns under axial compression. Only symmetric sandwich materials are considered with homogeneous and isotropic core/skin layers. First, the buckling problem is analytically addressed, by solving the so-called bifurcation equation in a 3D framework. The bifurcation analysis is performed using an hybrid model (the two faces are represented by Euler–Bernoulli beams, whereas the core material is considered as a 2D continuous solid), considering both an elastic and elastoplastic core material. Closed-form expressions are derived for the critical loadings and the associated bifurcation modes. Then, the post-buckling response is numerically investigated using a 2D finite element bespoke program, including finite plasticity, arc-length methods and branch-switching procedures. The numerical computations enable us to validate the previous analytical solutions and describe several kinds of post-critical responses up to advanced states, depending on geometric and material parameters. In most cases, secondary bifurcations occur during the post-critical stage. These secondary modes are mainly due to the modal interaction phenomenon and give rise to unstable post-buckled solutions which lead to final collapse.

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ABSTRACT: We consider the axial compression of a thin sheet wrapped around a rigid cylindrical substrate. In contrast to the wrinkling-to-fold transitions exhibited in similar systems, we find that the sheet always buckles into a single symmetric fold, while periodic solutions are unstable. Upon further compression, the solution breaks symmetry and stabilizes into a recumbent fold. Using linear analysis and numerics, we theoretically
predict the buckling force and energy as a function of the compressive displacement. We compare our theory to experiments employing cylindrical neoprene sheets and find remarkably good agreement.

References listed at the end of the paper:

ABSTRACT: Uniaxial compressed stiff films on soft substrates can evolve into the period-doubling and folding instabilities, beyond the onset of sinusoidal wrinkling. The substrate is modeled as a neo-Hookean solid with a pre-stretch prior to film attachment, and its nonlinearity is obtained. Both the pre-stretch and the external nominal strain imposed on the film/substrate system can induce different substrate nonlinearity, and thus have different effects on the post-buckling mode evolution of the system. This study shows that the critical strain of period-doubling instability is linear to the pre-stretch. As the compressive nominal strain increases, the folding mode occurs beyond the onset of period-doubling in both the pre-tension and the pre-compression case, due to the softening/hardening effects for the inward/outward displacements generated by the positive substrate nonlinearity.

References listed at the end of the paper:
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“Nonlinear vibration of fluid-conveying single-walled carbon nanotubes under harmonic excitation”,
International Journal of Non-Linear Mechanics, Vol. 76, pp 48-55, November 2015,
https://doi.org/10.1016/j.ijnonlinmec.2015.05.005

ABSTRACT: In this paper, the nonlinear vibration of a single-walled carbon nanotube conveying fluid is investigated utilizing a multidimensional Lindstedt–Poincaré method. Considering the geometric large deformation of the single-walled carbon nanotube and external harmonic excitation force, based on nonlocal elastic theory and Euler–Bernoulli beam theory, the nonlinear vibration equation of a fluid-conveying single-walled carbon nanotube is established. Analyzing the equation through the multidimensional Lindstedt–
Poincaré method, and from the solvability condition of the nonlinear vibration equation, the cubic algebraic equation which indicates the amplitude–frequency relation is obtained. Based on the root discriminant of the cubic equation, the first order primary response of the pinned–pinned carbon nanotube is discussed. The relations among internal resonance, the amplitude and frequency of the external excitation force are analyzed in detail. When the external excite force frequency is around the first mode natural frequency, the first mode primary resonance occurs. If simultaneously the first two modes natural frequency ratio is around 3, internal resonance occurs and the internal resonance region depends on the amplitude of external excitation force.

ABSTRACT: Membrane structures subjected to hydrostatic load are prone to undergo large deformations and lose stability. This paper investigates different instability phenomena for a thin, circular and initially flat and horizontal membrane. The Mooney–Rivlin hyper-elastic model is used to provide the material description. An axisymmetric and a 3D model have been set up to show the large deformations and stability behavior with different parameter settings. Numerical examples show that the methods developed are capable to describe the deformation dependent loading conditions and the instability phenomena. The numerical simulations show fundamental differences in the response and instability behavior when the horizontal membrane is loaded from above or below. The parameters of fluids and membranes and the means for introducing the pressure are of essence for interpreting the instability behavior.

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ABSTRACT: Wrinkling phenomena of stiff thin films on compliant substrates are investigated based on a non-linear finite element model. The resulting non-linear equations are then solved by the Asymptotic Numerical Method (ANM) that gives interactive access to semi-analytical equilibrium branches, which offers considerable advantage of reliability compared with classical iterative algorithms. Bifurcation points are detected through computing bifurcation indicators well adapted to the ANM. The effect of boundary conditions and material properties of the substrate on the bifurcation portrait is carefully studied. The evolution of wrinkling patterns and post-bifurcation modes including period-doubling has been observed beyond the onset of the primary sinusoidal wrinkling mode in the post-buckling range.

References listed at the end of the paper:


[34] Y. Guevel, E.H. Boutyour, J.M. Cadou, Automatic detection and branch switching methods for steady bifurcation in fluid
ABSTRACT: Mechanical responses of materials undergoing large elastic deformations can exhibit a loss of stability in several ways. Such a situation can occur when a thin-walled cylinder is inflated by an internal pressure. The loss of stability is manifested by a non-monotonic relationship between the inflating pressure and internal volume of the tube. This is often called limit point instability. The results, known from the literature, show that isotropic hyperelastic materials with limiting chain extensibility property always exhibit a stable response if the extensibility parameter of the Gent model satisfies $J_m < 18.2$. Our study investigates the same phenomenon but for tubes with anisotropic form of the Gent model (finite extensibility of fibers). Anisotropy, used in our study, increases the number of material parameters the consequence of which is to increase degree of freedom of the problem. It will be shown that, in stark contrast to isotropic material, the unstable response is predicted not only for large values of $J_m$ but also for $J_m \approx 1$ and smaller, and that the existence of limit point instability significantly depends on the orientation of preferred directions and on the ratio of linear parameters in the strain energy density function (this ratio can be interpreted as the ratio of weights by which fibers and matrix contribute to the strain energy density). Especially tubes reinforced with fibers oriented closely to the longitudinal direction are susceptible to a loss of monotony during pressurization.
ABSTRACT: Two flat annular hyperelastic membranes, stacked and bonded together at both the boundaries (equators), form a closed inflatable structure of toroidal topology. The response and stability of the inflated toroidal structure subjected to a radial line force distribution at the inner boundary are studied. The forcing is considered under constant pressure and constant amount of gas inflation conditions. Two hyperelastic models described by the corresponding relaxed strain energy density functions are considered for the membrane material. The influence of geometry, material and level of inflation on the response and stability of the structure under load has been brought out. The structure exhibits pressure limit points with increasing levels of inflation. The force–deflection (stiffness) behaviour is found to be qualitatively different below and above the pressure limit points. Below the pressure limit point, wrinkling and pull-in under loading are revealed for different inflation conditions, and the stability boundaries are determined. Under certain conditions, a counter-intuitive stretch-softening behaviour is also observed.

ABSTRACT: The formulation of the displacement dependent pressure load for shells of generic shape and plates is derived in the present study in curvilinear coordinates without any approximation and any hypothesis on material properties. Derivation is initially carried out for pressure load on the middle shell surface, and then for load on the external and internal surfaces by making use of a third-order shear and thickness deformation shell theory, which is a significant improvement for thick shells. The explicit formulation in curvilinear coordinates allows immediate implementation in numerical codes. An approximate formulation is also derived and compared to (i) the exact formulation and to (ii) the displacement independent pressure load which is still widely used in the literature. Applications to circular cylindrical shells and rectangular plates are presented. Comparison of results show that only the exact formulation for displacement dependent pressure load can be used for large deformations of shells and plates, while the displacement independent pressure load can be used only in case of small displacements of the middle surface (or middle plane).

ABSTRACT: Dynamic pulse buckling of a fully clamped, double-curvature composite shell was examined using Novozhilov non-linear shell theory and Lagrange’s equations of motion. Predictions of the shell’s stable transient response were shown to compare well with finite element analysis using ABAQUS Explicit. Critical buckling curves were then computed for a given shell geometry using the Budiansky–Roth criterion. It was shown that the dynamic pulse buckling strength of a shell may be increased by decreasing the radius of curvature of the shell, thereby increasing its angular extent or making it deeper. Higher buckling modes are induced by making the shell deeper, and these are responsible for the increased buckling strength.

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ABSTRACT: The asymmetric bifurcation problem for a shallow spherical cap is examined. The applied pressure can act either external or internal to the cap and both cases are treated here. Assuming a non-linear axisymmetric basic state, the linearised bifurcation equations for the pressurised shell are investigated in the limit when the thickness of the cap is much less than the maximum rise of the shell mid-surface. Within this regime the wrinkling patterns in both cases are confined to a narrow zone near the edge of the shell, making it possible to solve asymptotically the corresponding equations and derive analytical predictions for both the critical pressure and the corresponding number of wrinkles. Some comparisons with direct numerical simulations are included as well.

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ABSTRACT: The numerical structural analysis schemes are extensively developed by progress of modern computer processing power. One of these approximate approaches is called "dynamic relaxation (DR) method." This technique explicitly solves the simultaneous system of equations. For analyzing the static structures, the DR strategy transfers the governing equations to the dynamic space. By adding the fictitious damping and mass
to the static equilibrium equations, the corresponding artificial dynamic system is achieved. The static equilibrium path is required in order to investigate the structural stability behavior. This path shows the relationship between the loads and the displacements. In this way, the critical points and buckling loads of the non-linear structures can be obtained. The corresponding load to the first limit point is known as buckling limit load. For estimating the buckling load, the variable load factor is used in the DR process. A new procedure for finding the load factor is presented by imposing the work increment of the external forces to zero. The proposed formula only requires the fictitious parameters of the DR scheme. To prove the efficiency and robustness of the suggested algorithm, various geometric non-linear analyses are performed. The obtained results demonstrate that the new method can successfully estimate the buckling limit load of structures.


ABSTRACT: The instability behavior of spherical membranes completely or partially filled with fluid, also with internal gas over-pressure, placed on a friction-less rigid plane was investigated. The two-parameter Mooney–Rivlin model was used for material description. A third order penalty function was used to describe the rigid support. Different problem settings were considered, and different instability responses were observed. For the partially fluid-filled membrane, a multi-parametric problem was defined and analyzed. Augmenting equations were introduced to impose control constraints on variables chosen. These equations also affect the instability analysis. A generalized eigenvalue analysis was used for the stability conclusions. Numerical simulations showed that appropriate control constraints are of essence to interpret the instability conclusions. Fold line evaluations were performed to analyze the dependence of the instability behavior on the parameters. A solution surface algorithm was utilized to analyze and visualize the mechanical responses to multi-variable loading.


ABSTRACT: The structural performance of thin shells is largely dictated by their curvature and the degree of lateral restraint at the shell edges. The present study is an attempt to theoretically investigate the influence of such factors on nonlinear thermo-mechanical response of shallow shells with single and double curvatures. For the mechanical loading, a transverse load is assumed and for the thermal loading, a through-depth thermal gradient is applied on the shallow shell. Two types of boundary conditions are considered for the shallow shell, both of which constrain transverse deflections of the shell but allow rotations parallel to the shell boundaries to be free. One of the boundary conditions permits lateral translation (laterally unrestrained) and the other one does not (laterally restrained). The fundamental nonlinear equations of shallow shells are derived based on the quasi-static conditions. The validity and reliability of the proposed approach is assessed by calculating several numerical examples for shallow shells under various mechanical and thermal loads. It is found that the proposed formulation, in particular, can adequately capture the nonlinear behaviour of laterally restrained shallow shells.

ABSTRACT: Compression fracture in carbon fiber reinforced plastics (CFRP) involves multiple physical mechanisms operating at multiple scales ranging from angstroms to cms and beyond. First, at the macro/meso-scale, combined effects of modal imperfections, transverse shear/normal deformation along with the non-linear hypo-elastic transverse shear ($G_{TT}$) material property on the emergence of interlaminar shear crippling type instability modes, related to the localization (onset of deformation softening), delocalization (onset of deformation hardening) and propagation of mode II compression fracture/damage, in thick imperfect cross-ply very long cylindrical shells under applied hydrostatic pressure, are investigated. The primary accomplishment is the (hitherto unavailable) computation of the layer-wise mode II stress intensity factor, energy release rate and kink crack band-width, under hydrostatic compression, from a non-linear finite element analysis (FEA), using Maxwell’s construction and Griffith’s energy balance approach. Numerical results include the effects of hypoelastic ($G_{TT}$ only) material property, on localization and delocalization leading to compression fracture.

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ABSTRACT: Theoretical and experimental non-linear vibrations of thin rectangular plates and curved panels subjected to out-of-plane harmonic excitation are investigated. Experiments have been performed on isotropic and laminated sandwich plates and panels with supported and free boundary conditions. A sophisticated measuring technique has been developed to characterize the non-linear behavior experimentally by using a Laser Doppler Vibrometer and a stepped-sine testing procedure. The theoretical approach is based on Donnell's non-linear shell theory (since the tested plates are very thin) but retaining in-plane inertia, taking into account the effect of geometric imperfections. A unified energy approach has been utilized to obtain the discretized non-linear equations of motion by using the linear natural modes of vibration. Moreover, a pseudo arc-length continuation and collocation scheme has been used to obtain the periodic solutions and perform bifurcation analysis. Comparisons between numerical simulations and the experiments show good qualitative and quantitative agreement. It is found that, in order to simulate large-amplitude vibrations, a damping value much larger than the linear modal damping should be considered. This indicates a very large and non-linear increase of damping with the increase of the excitation and vibration amplitude for plates and curved panels with different shape, boundary conditions and materials.
ABSTRACT: A non-linear identification technique based on the harmonic balance method is presented to obtain the damping ratio and non-linear parameters of isotropic and laminated sandwich rectangular plates and curved panels, subjected to harmonic excitation orthogonal to the surface. The response of structures under consideration is approximated by a single-degree of freedom Duffing oscillator accounting for viscous damping, quadratic and cubic non-linear stiffness. The method uses experimental frequency-amplitude data and a least-squares technique to identify parameters and reconstruct frequency-response curves by spanning the excitation frequency in the neighborhood of the lowest natural frequencies. In particular, an iterative procedure is implemented to construct the mean displacement and identify the damping ratio. Close agreement is seen between the reconstructed non-linear frequency-amplitude curves, the experimental data and the results of the reduced-order model obtained in part 1 of the present study (Alijani et al., 2015 [1]). The proposed identification technique confirms the very large increase of damping during large-amplitude vibrations, as observed in part 1 of the present study, and demonstrates a non-linear correlation between damping, vibration amplitude and excitation level.

ABSTRACT: In reality, nanotubes may not be straight structures. In this work, we study free vibration analysis of curved nanotube structures, based on a proposed nonlocal shell model. The free vibration of curved single-walled nanotubes (SWNTs), double-walled nanotubes (DWNTs) and multi-walled nanotubes (MWNTs) is analyzed. The governing equations of a curved nanotube are developed using the proposed nonlocal shell model based on elasticity theory of Eringen. Governing differential equations of motion are simplified to the ordinary differential equations using Fourier series expansion. And solutions are obtained by applying Galerkin method. Results obtained by the present model are verified by those presented in the literature. The numerical results demonstrate the effects of the curved nanotube length, thickness, bend angle and nonlocal parameter on the natural fundamental frequency.

ABSTRACT: Carbon nanotubes (CNTs) based NEMS with electrostatic sensing/actuation may be employed as sensors, in situations where it is fundamental to understand their dynamic behaviour. Due to displacements that are large in comparison with the thickness and to the non-linearity of the electrostatic force, these CNT based NEMS operate in the non-linear regime. The knowledge of the modes of vibration of a CNT provides a picture of what one may expect from its dynamic behaviour not only in free, but also in forced vibrations. In this paper, the non-linear modes of vibration of CNTs actuated by electrostatic forces are investigated. For that purpose, a $p$-version finite element type formulation is implemented, leading to ordinary differential equations of motion in the time domain. The formulation takes into account non-local effects, which influence the inertia and the stiffness of CNTs, as well as the electrostatic actuation. The ordinary differential equations of motion are transformed into algebraic equations of motion via the harmonic balance method (HBM) and then solved by an arc-length continuation method. Several harmonics are considered in the HBM. The importance of non-local effects, combined with the geometrical non-linearity and with the action of the electrostatic force, is analysed. It is found that different combinations of these effects can result in alterations of the natural frequencies, variations in the degrees of softening or hardening, changes in the frequency content of the free vibrations, and alterations in the mode shapes of vibration. It is furthermore found that the small scale, here represented by the non-local theory, has an effect on interactions between the first and higher order modes which are induced by the geometrical and material non-linearities of the system.

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ABSTRACT: Several nonlinear phenomena have shown to have significant effect on the electromechanical performance of single-walled carbon nanotube (SWCNT) based nanoelectromechanical (NEMS) devices. To name few: the van der Waals forces, the Casimir forces, the tip charge concentration and the rippling phenomenon. Some of these effects have been take care of in previous investigation; however, some have been disregarded in the mechanical models suggested for simulation of the SWCNT based structures. In this paper, the influence of rippling deformation on the vibration characteristics of SWCNT based actuators is investigated using a nonlinear Euler-Bernoulli beam theory that incorporates the effect of rippling deformation using an improved function including some correcting terms for the SWCNT curvature (rippling deformation). The influence of the Casimir and the van der Waals attraction forces are considered in the proposed model as well as the size-dependent behavior assuming the so-called Eringen nonlocal elasticity theory. The dynamic response of CNT is investigated based on time history and phase portrait plots of the CNT based nano-actuator. It is shown that the rippling deformation can significantly decrease the static as well as the dynamic pull-in voltage of the SWCNT based actuator. The rippling deformation of SWCNT decreases the dynamic pull-in time as well. Effect of various factors such as the DC actuation load and the Casimir attractive forces on the dynamic stability and the pull-in characteristics of the nano-actuator are examined. Results of the present study are beneficial to accurate design and fabrication of electromechanical CNT based actuators. Comparison between the obtained results and those reported in the literature by experiments and molecular dynamics, verifies the integrity of the present numerical analysis.

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“Comparison of existing plastic collapse load solutions with experimental data for 90-degree elbows”,
https://doi.org/10.1016/j.ijpvp.2011.09.001

ABSTRACT: This paper compares published experimental plastic collapse loads for 90° elbows with existing closed-form solutions. A total of 46 experimental data are considered, covering pure bending (in-plane closing, in-plane opening and out-of-plane bending) and combined pressure and bending loads. The plastic collapse load solutions considered are from the ASME code, the Ductile Fracture handbook of Zahoor, by Chattopadhyay and co-workers, and by Y.-J. Kim and co-workers. Comparisons with the experimental data shows that the ASME code solution is conservative by a factor of 2 on collapse load for in-plane closing bending, 2.3 for out-of-plane bending, and 3 for in-plane opening bending. The solutions given by Kim and co-workers give the least conservative estimates of plastic collapse loads, although they provide slightly non-conservative estimates for some data.

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ABSTRACT: Based on the three-dimensional theory of elasticity, free vibration analysis of a functionally graded cylindrical shell embedded in piezoelectric layers is performed by using an analytical method for simply supported boundary conditions and a semi-analytical method for non-simply supported conditions. Material properties are assumed to vary along the thickness according to an exponential law with Poisson’s ratio held constant. For non-simply supported conditions, this method can give an analytical solution along the graded direction using the state space method (SSM) and an effective approximate solution along the axial direction using the one dimensional differential quadrature method (DQM). Numerical results are compared to those available in the literature to validate the convergence and accuracy of the present approach. The effects of material property gradient index, edge conditions, mid-radius to thickness ratio, length to mid-radius ratio and the piezoelectric thickness on vibration behavior of shell are investigated.
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“Analytical solution for stress, strain and plastic instability of pressurized pipes with volumetric flaws”,
https://doi.org/10.1016/j.ijpvp.2011.11.002
ABSTRACT: The mechanical behavior of internally pressurized pipes with volumetric flaws is analyzed. The
two possible modes of circumferentially straining the pipe wall are identified and associated to hypothesized
geometries. The radial deformation that takes place by bending the pipe wall is studied by means of
axisymmetric flaws and the membrane strain developed by unequal hoop deformation is analyzed with the help
of narrow axial flaws. Linear elastic shell solutions for stress and strain are developed, the plastic behavior is
studied and the maximum hoop stress at the flaw is related to the undamaged pipe hoop stress by means of
stress concentration factors. The stress concentration factors are employed to obtain equations predicting the
pressure at which the pipe fails by plastic instability for both types of flaw. These analytical solutions are
validated by comparison with burst tests on 3” diameter pipes and finite element simulations. Forty-one burst
tests were carried out and two materials with very dissimilar plastic behavior, carbon steel and austenitic
stainless steel, were used in the experiments. Both the analytical and the numerical predictions showed good
correlation with the experimentally observed burst pressures.

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“Three-dimensional free vibration of functionally graded truncated conical shells subjected to thermal
environment”, International Journal of Pressure Vessels and Piping, Vol. 89, pp 210-221, January 2012,
https://doi.org/10.1016/j.ijpvp.2011.11.005
ABSTRACT: A three-dimensional (3D) free vibration analysis of the functionally graded (FG) truncated
conical shells subjected to thermal environment is presented. The material properties are assumed to be
temperature-dependent and graded in the radius direction, which can vary according to a simple power law
distribution. The initial thermal stresses are obtained accurately by solving the thermoelastic equilibrium
equations and by considering the two-dimensional axisymmetric temperature distribution in the shell. The
differential quadrature method (DQM) as an efficient and accurate numerical tool is adopted to solve the
thermal and thermo-mechanical governing equations. For this purpose, a mapping technique is employed to
transform the cross section of the shell into the computational domain of DQM. The convergence behavior of
the method is numerically demonstrated and comparison studies with the available solutions in the literature are
performed. The effects of temperature dependence of material properties, geometrical parameters, material
graded index, thermal and mechanical boundary conditions on the frequency parameters of the FG truncated
conical shells are carried out.

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L69 3GH, United Kingdom), “Combined stability of unstiffened cones – Theory, experiments and design
ABSTRACT: The elastic-plastic buckling of short and relatively thick unstiffened truncated conical shells subjected to axial compression and external pressure is investigated. This is done using numerical and experimental approach. For the numerical analysis, the finite element code is employed to obtain the domain of combined stability. To validate numerical predictions, thirteen nominally identical laboratory scale cones with 26.56° semi-vertex angle and 3 mm nominal wall thickness with integral top and bottom flanges were CNC machined from 252 mm diameter mild steel billet. Two of the models were subjected to axial compression, with further two subjected to pure lateral external pressure, while the remaining nine cones were subjected to combined action of axial compression and external pressure of different ratio. Experimental results compare well with numerical predictions except for pure axial compression. However, the accuracy of these results is strongly dependent on the approach to modeling of material. Experimental results were compared with predictions of failure loads obtained from ASME code case 2286–2, and with the ECCS design rules for the case of axial compression and lateral pressure.


ABSTRACT: Three-dimensional elastic analysis is carried out for functionally graded cylindrical shells bonded with piezoelectric layers subjected to dynamic and thermal loads. Material properties are assumed to be graded in the radial direction obeying a simple power law with constant Poisson's ratio. Two versions of differential quadrature (DQ) method coupled with the finite difference (FD) method are employed to discretize the governing differential equations in space and time domains. The convergence is studied and results of the axisymmetric loadings are verified with reported results. Effects of the grading index of material properties, thermal gradient, boundary conditions, thickness of piezoelectric layers and electric excitation on stress, displacement, electric and temperature fields are presented.

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ABSTRACT: Based on the elasticity theory, the transient analysis of dynamically pressurized rotating multi-layered functionally graded (FG) cylindrical shells in thermal environment is presented. The variations of the field variables across the shell thickness are accurately modeled by dividing the shell into a set of co-axial mathematical layers in the radial direction. The initial thermo-mechanical stresses are obtained by solving the thermoelastic equilibrium equations. The differential quadrature method and Newmark's time integration scheme are employed to discretize the obtained governing equations of each mathematical layer. After performing the convergence and comparison studies, parametric studies for two common types of FG sandwich shells, namely, the shell with homogeneous inner/outer layers and FG core and the shell with FG inner/outer
layers and homogeneous core are carried out. The influences of the temperature dependence of material properties, material graded index, the convective heat transfer coefficient, the angular velocity, the boundary condition and the geometrical parameters (length and thickness to outer radius ratios) on the dynamic response of the FG shells are investigated.

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ABSTRACT: Free vibration response of laminated composite shells with delamination is presented using the finite element method based on first order shear deformation theory. The shell theory used is the extension of dynamic, shear deformable theory according to the Sanders' first approximation for doubly curved shells, which can be reduced to Love's and Donnell's theories by means of tracers. An eight-noded $C^0$ continuity, isoparametric quadrilateral element with five degrees of freedom per node is used in the formulation. For modeling the delamination, multipoint constraint algorithm is incorporated in the finite element code. The natural frequencies of the delaminated cylindrical (CYL), spherical (SPH) and hyperbolic paraboloid (HYP) shells are determined by using the above mentioned shell theories, namely Sanders', Love's, and Donnell's. The validity of the present approach is established by comparing the authors' results with those available in the literature. Additional studies on free vibration response of CYL, SPH and HYP shells are conducted to assess the effects of delamination size and number of layers considering all three shell theories. It is shown that shell theories according to Sanders and Love always predict practically identical frequencies. Donnell's theory gives reliable results only for shallow shells. Moreover, the natural frequency is found to be very sensitive to delamination size and number of layers in the shell.

ABSTRACT: The comparison of limit load based on small displacement limit analysis and collapse load based on large displacement analysis for shape-imperfect pipe bends, under combined in-plane closing bending and an internal pressure, were carried out using finite element method. The limit and collapse moments were obtained from moment–rotation curves drawn for each model. Twice-elastic-slope method was used to obtain collapse load. The effect of thinning on limit and collapse moments are minimal and hence thinning need not be considered for the analysis of pipe bends. The influence of ovality on both limit and collapse loads for most of the cases considered are significant. Comparison of effect of ovality on limit and collapse loads reveals that the determination of collapse load is preferable when ovality is included in the analysis of pipe bend. A closed-form solution is presented to include ovality in the determination of the collapse load of pipe bends.

Licai Yang, Zhiping Chen, Guowei Cao, Chulin Yu, Wenjing Guo (Institute of Process Equipment, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang 310027, People’s Republic of China), “An analytical formula for elastic-plastic instability of large oil storage tanks”, International Journal of Pressure Vessels and Piping,
ABSTRACT: Assuming axisymmetric buckling and according to the adjacent equilibrium criterion, a buckling critical stress formula of a perfect tank wall is first obtained through analysis of elastoplastic buckling carried out by J2 plastic flow theory. Furthermore, combining the current tank seismic design standards and the results obtained in this paper, a new critical buckling stress formula of the tank wall is derived after correction for material plasticity by introducing a plasticity influence coefficient. Comparisons between the results obtained and those from the relevant formulas in the design standards of America, Japan, China and Europe are also performed. Our research shows that under interaction of high hydraulic and axial compression, the material properties of the tank wall change rapidly, and the buckling strength of the tank wall also decreases rapidly. The relation between the tank wall buckling critical stress and the hydraulic pressure is similar to Rotter’s semi-empirical formula. The results presented in this paper can provide technical support in further protection of large oil storage tanks.

References listed at the end of the paper:
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ABSTRACT: A huge body of literature in the field of lateral indenter loading of tubular members has focused on denting of spanned structural members with two distinct supports. However, the behavior of continuously base supported tubular members has not been studied, sufficiently. This investigation presents some experimental data recorded from six lateral indentation tests on axially pre-compressed steel pipes supported continuously along their bases. Furthermore, modes of deformation, as well as strain behavior in different positions, have been investigated. Consequently, comparisons are made between relevant Finite Element (FE) simulations and some previously published results of denting load-displacement. Results of the investigation...
showed that fairly low magnitudes of pre-compression, does not have a significant effect on denting behavior of continuously supported pipelines. Also the strain study showed that, in dented area, different behaviors of compression and tensile (or a combination of both) and even reverse growth of strain can be observed.

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“Fourier series analysis of a cylindrical pressure vessel subjected to axial end load and external pressure”,
International Journal of Pressure Vessels and Piping, Vol. 107, pp 27-37, July 2013,
https://doi.org/10.1016/j.ijpvp.2013.03.008

ABSTRACT: This paper presents the comparison of a reliability technique that employs a Fourier series representation of random axisymmetric and asymmetric imperfections in a cylindrical pressure vessel subjected to an axial end load and external pressure, with evaluations prescribed by the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 Rules. The ultimate goal of the reliability technique described herein is to predict the critical buckling load associated with the subject cylindrical pressure vessel. Initial geometric imperfections are shown to have a significant effect on the calculated load carrying capacity of the vessel. Fourier decomposition was employed to interpret imperfections as structural features that can be easily related to various other types of defined imperfections. The initial functional description of the imperfections consists of an axisymmetric portion and a deviant portion, which are availed in the form of a double Fourier series. Fifty simulated shells generated by the Monte Carlo technique are employed in the final prediction of the critical buckling load. The representation of initial geometrical imperfections in the cylindrical pressure vessel requires the determination of respective Fourier coefficients. Multi-mode analyses are expanded to evaluate a large number of potential buckling modes for both predefined geometries in combination with asymmetric imperfections as a function of position within the given cylindrical shell. The probability of the ultimate buckling stress exceeding a predefined threshold stress is also calculated. The method and results described herein are in stark contrast to the “knockdown factor” approach as applied to compressive stress evaluations currently utilized in industry. Further effort is needed to improve on the current design rules regarding column buckling of large diameter pressure vessels subjected to an axial end load and external pressure designed in accordance with ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 and ASME STS-1.

Sofiyev, A.H. and Kuruoglu, N. (Department of Civil Engineering of Suleyman Demirel University, Isparta Turkey and Department of Mathematics and Computer Science, Faculty of Arts and Sciences, Bahcesehir University, Istanbul, Turkey), “Non-linear buckling of an FGM truncated conical shell surrounded by an elastic medium”, International Journal of Pressure Vessels and Piping, Vol. 107, pp 38-49, July 2013

ABSTRACT: In this paper, the non-linear buckling of the truncated conical shell made of functionally graded materials (FGMs) surrounded by an elastic medium has been studied using the large deformation theory with von Karman–Donnell-type of kinematic non-linearity. A two-parameter foundation model (Pasternak-type) is used to describe the shell–foundation interaction. The FGM properties are assumed to vary continuously through the thickness direction. The fundamental relations, the modified Donnell type non-linear stability and compatibility equations of the FGM truncated conical shell resting on the Pasternak-type elastic foundation are derived. By using the Superposition and Galerkin methods, the non-linear stability equations for the FGM truncated conical shell is solved. Finally, influences of variations of Winkler foundation stiffness and shear
subgrade modulus of the foundation, compositional profiles and shell characteristics on the dimensionless critical non-linear axial load are investigated. The present results are compared with the available data for a special case.

M. Muscat and D. Camilleri (Department of Mechanical Engineering, University of Malta, Msida MSD2080, Malta), “Comparison between different design approaches to prevent buckling of torispherical heads under internal pressure”, International Journal of Pressure Vessels and Piping, Vols. 108-109, pp 61-66, August-September 2013, [https://doi.org/10.1016/j.ijpvp.2013.04.008](https://doi.org/10.1016/j.ijpvp.2013.04.008)

**ABSTRACT:** Under the action of internal pressure compressive circumferential stresses develop in the knuckle region of torispherical heads making them susceptible to buckling. Current pressure vessel design codes such as the European Unfired pressure vessel code MSA EN13445 Part 3 present buckling as a failure mode that needs to be prevented. The latest version of the code has a Design by Analysis route that requires the designer to perform a buckling check on the design model. This study considers the different design approaches (Design by Analysis and Design by Rule) presented in MSA EN13445 Part 3 and compares computational results with experimental data available from literature. The study shows that the pressure vessel design code MSA EN13445 Part 3 guarantees that the calculated design load will not subject torispherical heads to buckling in the knuckle region, under the action of internal pressure.


**ABSTRACT:** The combined effect of ovality and thinning/thickening on collapse load of pipe bends under in-plane opening bending moment was investigated using finite element limit analysis considering large geometric change effect. The material is assumed to be elastic-perfectly plastic. Twice-elastic-slope method is used to obtain collapse moment from moment–rotation curves drawn for each bend. Variation of thickness due to thinning in the cross section of pipe bend produces negligible effect on collapse load. The effect of ovality is significant except for pipe ratio 20 with $\lambda = 0.5$. A new closed-form solution is proposed to determine collapse moment of pipe bends with ovality and it is validated with existing experimental data.


**ABSTRACT:** Influences of the thickness variability and bidirectional material heterogeneity on the thermal buckling of the cylindrical shells have not been investigated so far. In the present paper, nonlinear thermal buckling and postbuckling analyses of imperfect, variable thickness cylindrical shells made of bidirectional functionally graded materials undergoing uniform temperature rises are accomplished for the first time, employing a third-order shear-deformation theory, von Karman-type kinematic nonlinearity, and a nonlinear finite element method. Material properties may vary in both radial and axial directions and can be temperature-dependent. Buckling temperature is detected by a modified Budiansky's criterion. The results reveal that temperature-dependency of the material properties reduces the buckling temperature. Moreover, effects of the
volume fraction index on decreasing the buckling temperature are more remarkable for higher radius to thickness ratios. Furthermore, effects of reduction of the thickness in the axial direction may be compensated by an appropriate distribution of the material properties.


ABSTRACT: In the present study nonlinear static and dynamic responses of shallow spherical shells resting on Winkler–Pasternak elastic foundations are carried out. The formulation of the shells is based on the Donnell theory. The nonlinear governing equations of motion of shallow shells are discretized in space and time domains using the discrete singular convolution and the differential quadrature methods, respectively. The validity of the present method is demonstrated by comparing the present results with those available in the open literature. The effects of the Winkler and Pasternak foundation parameters on nonlinear static and dynamic response of shells are investigated. Some results are also presented for circular plate as special case. Damping effect on nonlinear dynamic response of shells is studied. It is important to state that the increase in damping parameter causes decrease in the dynamic response of the shells. It is shown that the shear parameter of the foundation has a significant influence on the dynamic and static response of the shells. Also, the response of the shell is decreased with the increasing value of the shear parameter of the foundation. Parametric studies considering different geometric variables have also been investigated.

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ABSTRACT: The paper aims to investigate plastic limit pressure of spherical vessels of nonlinear combined isotropic/kinematic hardening materials. The Armstrong-Frederick kinematic hardening model is adopted and the Voce hardening law is incorporated for isotropic hardening behavior. Analytically, we extend sequential limit analysis to deal with combined isotropic/kinematic hardening materials. Further, exact solutions of plastic limit pressure were developed analytically by conducting both static and kinematic limit analysis. The onset of instability was also derived and solved iteratively by Newton's method. Numerically, elastic–plastic analysis is also performed by the commercial finite-element code ABAQUS incorporated with the user subroutine UMAT implemented with user materials of combined hardening. Finally, the problem formulation and the solution derivations presented here are validated by a very good agreement between the numerical results of exact solutions and the results of elastic–plastic finite-element analysis by ABAQUS.

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ABSTRACT: Global limit load solutions for thick-walled cylinders with circumferential internal/external surface and through-wall defects under combined positive/negative axial force, positive/negative global bending moment and internal pressure are derived based on the von Mises yield criterion and the net-section collapse principle. Solutions for cases both with/without considering crack face contact when all or part of the crack is located inside the compressive stress zone are obtained. For some limiting cases, the solutions are compared with available solutions and with some published finite element (FE) data, showing good agreement. Systematic validation of the solutions using a wide range of elastic–perfectly plastic 3-D FE data is described in part II.

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ABSTRACT: Global limit load solutions for thick-walled cylinders with circumferential internal/external surface and through-wall defects under combined positive/negative axial force, positive/negative global bending moment and internal pressure have been developed in Part I of this paper. In this Part II, elastic-perfectly plastic 3-D finite element (FE) analyses are performed for selected cases, covering a wide range of geometries and load combinations, to validate the developed limit load solutions. The results show that these limit load solutions can predict the FE data very well for the cases with shallow or deep and short cracks and are conservative. For the cases with very long and deep cracks, the predictions are reasonably accurate and more conservative.

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ABSTRACT: The load-bearing capacity of cylindrical pressure vessels closed by Klöpperböden torispherical drumheads with piping nozzle connections placed in the head's knuckle region is determined by using shakedown analysis. The pressure vessels under consideration are subjected to internal pressure, an axial force in the direction of the nozzle, in-plane bending moment at the nozzle, and temperature loading, all of which may vary independently. In particular, the interactions are investigated in several combinations of two and three of these loads, leading to two- and three-dimensional loading domains. The corresponding elastic and shakedown limits are computed based on Melan's statical shakedown theorem. The obtained results are compared to those taken from literature where available.
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ABSTRACT: A hybrid method based on the three-dimensional (3-D) elasticity theory is developed for transient analysis of functionally graded (FG) truncated conical shell with variable thickness, subjected to asymmetric dynamic pressure. The FG shell is functionally graded in the radial direction. A hybrid method composed of the layerwise theory, differential quadrature method (DQM), and Fourier series expansion is employed. A Fourier series expansion is used for the displacement components and dynamic pressure in the circumferential direction. Then the layerwise theory across the thickness direction in conjunction with Hamilton's principle is employed to obtain equations of motion and boundary conditions. Eventually, the DQM is implemented to discretize the governing equations in both spatial and time domains. This research shows some interesting results that can be helpful for design of FG conical shells.


ABSTRACT: Snap-through buckling of shallow clamped spherical shells made of functionally graded material (FGM) and surface-bonded piezoelectric actuators under the thermo-electro-mechanical loading is studied in this paper. The governing equations are based on the classical shell theory and the Sanders nonlinear kinematics equations. It is assumed that the property of the functionally graded materials vary continuously through the thickness of the shell according to a power law distribution of the volume fraction of the constituent materials. The constituent materials of the functionally graded shell are assumed to be mixture of ceramic and metal. The results show that the axisymmetric buckling of Piezo-FGM shallow clamped spherical shells under thermo-electro-mechanical loading is of snap-through type. The intensity of buckling is dependent on the geometry of the shell, value of thermo-electro-mechanical loading and type of thermal loading.


ABSTRACT: The combined effect of ovality and variable wall thickness on collapse load of pipe bends under in-plane opening bending moment with internal pressure was investigated using finite element limit analysis considering large geometric change effect. The material was assumed to be elastic–perfectly plastic. The collapse moments were obtained from moment-rotation curves drawn for each bend using twice-elastic-slope method. Thickening/thinning effect on collapse load is very minimal and can be neglected. The effect of ovality is significant with the reduction of collapse load by a maximum of 39.1% for the maximum internal pressure and ovality considered. Based on the finite element results, a mathematical expression is proposed to determine collapse load of the pipe bends with ovality and this equation has been verified with experimental collapse

ABSTRACT: In this research, applied methods of nonlinear analysis and results of determining the plastic limit loads for shell intersection configurations under combined internal pressure, in-plane moment and out-plane moment loadings are presented. The numerical analysis of shell intersections is performed using the finite element method, geometrically nonlinear shell theory in quadratic approximation and plasticity theory. For determining the load parameter of proportional combined loading, the developed maximum criterion of rate of change of relative plastic work is employed. The graphical results for model of cylindrical shell intersection under different two-parameter combined loadings (as generalized plastic limit load curves) and three-parameter combined loading (as generalized plastic limit load surface) are presented on the assumption that the internal pressure, in-plane moment and out-plane moment loads were applied in a proportional manner.

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“Effect of local wall thinning on shakedown regimes of pressurized elbows subjected to cyclic in-plane and out-of-plane bending”, International Journal of Pressure Vessels and Piping, Vol. 134, pp 11-24, October 2015, [https://doi.org/10.1016/j.ijpvp.2015.08.003](https://doi.org/10.1016/j.ijpvp.2015.08.003)

ABSTRACT: The current research utilizes a direct non-cyclic technique to generate elastic shakedown domains for thinned-wall 90° elbows. The elbows are subjected to simultaneous steady internal pressures and cyclic in-plane and out-of-plane bending moments. Wall thinning is located at the intrados, extrados, and crown once at a time. Effects of thinning depth and thinning location under both cyclic in-plane and out-of-plane bending modes are investigated. Generated shakedown boundaries are compared to those corresponding to sound elbows. Elbows subjected to out-of-plane bending moments revealed relatively higher shakedown domains compared to corresponding elbows subjected to in-plane bending. It is generally noticed that thinning at the intrados or crown has more severe effect on reducing elbows shakedown domains as compared to thinning at the extrados for both in-plane and out-of-plane bending modes.

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ABSTRACT: Ratcheting behavior of 90°-elbow pipe is experimentally investigated under constant inner pressure and force-controlled cyclic loading (abbr. cyclic reversed bending). The results indicate that the ratcheting strain occurs mainly in the circumferential direction. It is shown that the ratcheting strain per cycle...
increases with a reversed bending loading under the same inner pressure or inner pressure under the same reversed bending loading. In addition, the ratcheting behaviors of pressurized elbow pipe characterized by the Ohno-Wang (OW) II model with and without isotropic hardening rule are compared with experiments data. The predicted results show that the OW II model with isotropic hardening rule is slightly better than those without isotropic hardening rule. The ratcheting boundary of elbow pipe is determined by the Elasto-Plastic Finite Element Analysis and OW II model with and without isotropic hardening rule. It is observed that the determined ratcheting boundary of elbow pipe by OW II model with isotropic hardening rule is larger than that without isotropic hardening rule.

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ABSTRACT: Ratcheting deformation is studied on straight pipe made of Z2CND18.12 N stainless steel with local wall thinning subjected to constant internal pressure and reversed bending using finite element analysis. The local wall thinning is located at the center of straight pipe, whose geometry is rectangular cross-section. The effect of depth, axial length and circumferential length on the ratcheting behavior of straight pipe is studied in this paper. Three-dimensional elastic-plastic analyses with ANSYS employed Chen–Jiao–Kim (CJK) kinematic hardening model is carried out to evaluate structural ratcheting behaviors. Results indicate that ratcheting strain is along the center of straight pipe extending to the two ends. The ratcheting strain occurs mainly at hoop direction. Axial ratcheting strain is relatively small. The effects of the depth, axial length and circumferential length of local wall thinning on the ratcheting response are discussed by CJK model.

ABSTRACT: The inclusion of toroidal (knuckle) segment between cylinder and conical vessel end closure is a natural way for diffusing the stress jump at the junction. But there is very little experimental data in support of the knuckle’s role and its influence. Hence eight steel toriconical shells have been buckled by quasi-static external pressure in order to measure this problem. Diameter of all models was 200 mm at the base and their wall thickness was 2 mm. The apex semi-angle was 45 deg for all shells. Experimental buckling pressures varied from 3.9 MPa to 4.4 MPa despite large variations in shape. Comparisons of experimental failure pressures with numerical predictions based on several approaches to modelisation are given. The latter are based on axisymmetric modelling as well as on measured geometry and wall thickness. The ratio of experimental to numerical failure loads varies from 1.05 to 1.16.

ABSTRACT: The analytical study for plastic deformation of clamped–clamped conical reducer pipe under
internal pressure does not deduce a closed form expression for the pressure at plastic instability. The presented study employs finite element analysis (FEA) to estimate the internal pressure at instability for conical reducers made of different materials and having different dimensional configurations. Forty dimensional configurations, classified as medium type, and five types of materials have been included in the analysis using ABAQUS package. A correlation expression is derived by nonlinear regression to predict the instability pressure. The proposed expression is verified for other dimensional configurations out of the above used forty models and for other materials. Experiments have been conducted by pressurizing conical clamped-clamped reducers until bursting in order to verify the finite element models. Comparison of instability pressures, strains and deflections at specific points along the conical surface shows satisfactory agreement between analysis and experiments.

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ABSTRACT: In this paper, a mathematical modeling of flutter and divergence analyses of fluid conveying pipes based on integral equation formulations is presented. Dynamic stability problems related to fluid pressure, velocity, tension, topography slope and viscoelastic supports and foundations are formulated. A methodological approach is presented and the required matrices, associated to the influencing fluid and pipe parameters, are explicitly given. Internal discretizations are used allowing to investigate the deformation, the bending moment, slope and shear force at internal points. Velocity–frequency, pressure–frequency and tension–frequency curves are analyzed for various fluid parameters and internal elastic supports. Critical values of divergence and flutter behaviors with respect to various fluid parameters are investigated. This model is general and allows the study of dynamic stability of tubes crossed by stationary and instationary fluid on various types of supports. Accurate predictions can be obtained and are of particular interest for a better performance and for an optimal safety of piping system installations.

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ABSTRACT: In this paper, the general theoretical analysis of a thick-walled cylinder made of functionally graded piezoelectric materials subjected to a non-axisymmetric hygro-thermo-electro-mechanical loading is presented. The transversely isotropic and non-homogeneous cylinder is rested on a Winkler-type elastic foundation on the outer surface. All mechanical, hygrothermal and electrical properties are assumed to obey a
power-law function in the radial direction with different non-homogeneity constants. Non-axisymmetric moisture concentration and temperature distributions are assumed to be a function of radial and circumferential directions and are obtained by solving two-dimensional and steady-state Fourier heat conduction and Fickian moisture diffusion equations. By substituting constitutive equations into electrical and mechanical equilibrium equations, three second-order non-homogeneous partial differential equations in terms of electric potential and mechanical displacements are derived. The separation of variables and complex Fourier series method are employed to solve heat conduction, moisture diffusion and Navier equations. Numerical results clearly illustrate the effects of hygrothermal loading, elastic foundation and non-homogeneity constants on hygro-thermo-electro-elastic behavior of the functionally graded piezoelectric cylinder. It is observed that non-homogeneity constant, hygrothermal loading and elastic foundation have considerable effects on displacements, stresses and electric potential distributions.


ABSTRACT: A finite element buckling eigenvalue solution is developed for the analysis of sandwich pipes subjected to internal and external hydrostatic pressure. The principle of stationary potential energy is used to formulate the conditions of equilibrium and neutral stability using polar coordinates. The formulation accounts for shear deformation effects and is suited for sandwich pipe systems with thick cores. It involves two destabilizing terms: one is due to the external hydrostatic pressure and incorporates the follower effects, and the other, is due to the pre-buckling stresses undergoing nonlinear components of strains. The formulation adopts a work conjugate triplet consisting the Cauchy stress tensor, the Green Lagrange strain tensor, and constant constitutive relations. A finite element solution is developed and implemented under MATLAB and is then applied to predict the buckling capacity of sandwich pipes consisting of two steel pipes with a soft core. A verification study is conducted, and the validity of the formulation is established through comparison with other solutions. A parametric study is then conducted to investigate the effect of hydrostatic internal pressure, core material, core thickness, internal and external pipe thicknesses, on the buckling capacity of sandwich pipes.


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ABSTRACT: The axial dynamic buckling responses of pseudo-elastic NiTi alloy cylindrical shells were investigated experimentally for various length/diameter ratios and end constraint conditions by using a modified single pulse SHPB apparatus. The results show that under single pulse axial loading it will first appear the axisymmetrical buckling waviness and then transit into non-axisymmetric buckling mode. This multiple buckling mode and mode transition behavior is possibly due to the wave effect under dynamic loading. The non-axisymmetric buckling patterns are significantly related to the length/diameter ratio and end constraint condition. The initial defect distribution will affect even dominate the non-axisymmetric buckling pattern. It was observed that multiple phase transition hinges (THs) formed in the specimen, which can increase the energy absorption efficiency. The critical buckling threshold and the energy absorption efficiency under impact loading are much greater than that under quasi-static loading. The THs and the dynamic buckling folds are recoverable for NiTi specimens due to the thermo-elastic austenite–martensite phase transition, which differs substantially from the behavior of the conventional elastic–plastic shells.

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ABSTRACT: As shown in the extensive studies of the dynamic responses of cellular materials, when the impact velocity is high, ‘shock’ waves can be generated. Because of the nature of the cellular structure, behind the ‘shock (or compaction) front’, there is a region of thickness approximately one single-cell-layer, across which the deformation can vary enormously, with strains of the order of ~0.8, say. This is due to the extensive and progressive crushing of the cells. The compressed part of the cellular material is crushed and densified as the material crosses the front. Depending on the details of the cellular geometry, this locally large deformation can be very intricate to model, however, a first order ‘shock’ model can be defined, which permits a useful understanding of the phenomenology of the dynamic deformation of cellular materials, particularly metal foams. However, when the impact velocity is not very high, there exists a different type of front behind which the strain, though plastic, does not reach the densification strain. Based on one-dimensional continuum-based stress wave theory with a ‘rigid unloading’ assumption, in this paper a theoretical framework is established to explore the corresponding inherent mechanisms as a simple extension of the original ‘shock’ theory. Two models, namely the Shock-Mode model and the Transitional-Mode model, are introduced. The distributions of stress, strain and velocity in the foam rod are derived. The theoretical results show that for a Shock Mode, behind the front the initial strain remains constant and the initial stress varies proportionally with the square of the impact velocity, but for a Transition Mode, the initial strain and stress behind the front reduce linearly with reducing impact velocity. The critical impact velocities for modes transition are predicted. Two dimensionless parameters, namely the shock-enhancement parameter and the stress-hardening parameter, are defined and the features of the theoretical predictions are presented. Compared to the experimental results, the responses at the ends of foam rod are well predicted by the present models and also by the R-P-P-L model. However, deformation mechanisms uncovered by the present models and the R-P-P-L model are very different when the
impact velocity is not very high. The present simple, wave-based models extend the understanding of metallic foams to loading over a wider range of impact velocities than the previous models. In particular, the sub-shock-like behaviour, which has not yet been dealt within the literature, can be better understood through the new Transitional-Mode model.

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ABSTRACT: The axial crushing and crashing of thin-walled high-strength steel tubes is performed using 3D-shell finite elements and an implicit time integration scheme. The calculated results are compared with published experimental data and results obtained using explicit time integration. The objective is to show that, while for such analyses generally explicit time integration is used, with the current state of the art also an implicit time integration solution should be considered, and such solution approach can provide an effective alternative for a simulation.

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ABSTRACT: The dynamic response of metallic lattice sandwich plates under impulsive loading is studied by experimental investigation. The sandwich structures composed of two identical face sheets and tetrahedral lattice cores, were designed and fabricated through perforated metal sheet forming and welding technology. The air blast experiment of lattice sandwich structures was performed by use of a four-cable ballistic pendulum system. The deformation/failure mechanisms were investigated through experimental observation and analysis. The impulsive resistance of the tetrahedral lattice sandwich structures is quantified by the maximum permanent transverse deflection of the back face sheet as a function of transmitted impulse. The maximum transverse deflections of tetrahedral lattice sandwich plates are compared with that of hexagonal honeycomb ones with identical parent materials and core relative density. The comparison implies that the tetrahedral lattice sandwich structures possess a better impulsive resistance.

V. Crupi, G. Epasto and E. Guglielmino (DCIIM, University of Messina, Contrada Di Dio, Sant'Agata (ME), 98166 Messina, Italy), “Collapse modes in aluminium honeycomb sandwich panels under bending and impact
ABSTRACT: Sandwich structures have been widely employed to build lightweight components having good mechanical properties and energy absorbing capacity, especially in the transport industry. The aim of this paper was the analysis of static and low-velocity impact response of two typologies of aluminium honeycomb sandwich structures with different cell size. The static bending tests produced various collapse modes for panels with the same nominal size, depending on the support span distance and on the honeycomb cell size. Simplified collapse models were applied to explain the experimental observations and a good agreement between predicted and experimental limit loads was achieved. Low-velocity impact tests were, also, performed on the two typologies of aluminium honeycomb sandwiches and a theoretical approach, based on the energy balance model, has been applied to investigate their impact behaviour. The failure mode and damage of the honeycomb panels have been investigated using the 3D Computed Tomography.


ABSTRACT: Sandwich panels with a foldcore are of interest to the aerospace industry due to their promising properties. There is an increasing interest in the basic properties of such a core and response of these panels to low energy impact loading. In this paper experiments to determine quasi-static properties of such a core and a sequence of impact experiments using a drop tower and 4-point bending tests are presented. The aim of the latter is to assess the damage tolerance of sandwich panels with aramid paper foldcores and carbon fibre reinforced plastic (CFRP) skins under impact loading. The impact energy range in these experiments was chosen to investigate a variety of damage scenarios from barely visible damages (BVID) to fibre fractures in all plies of the impacted face sheet. 4-point bending tests were performed with the panels previously damaged by impact loadings to assess the residual bending strength of these samples. A numerical procedure has also been developed to reproduce these experiments (the impact as well as the 4-point bending tests). The method can also be employed to predict the results of the residual strength in other experiments like compression (CAI) or edgewise compression after the impact.

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ABSTRACT: Honeycomb cellular structures and multi-cell prismatic columns are highly efficient and effective energy dissipating components and are widely used in the crashworthiness design of vehicles. Due to the complex features during large plastic deformation, only few special sections have been theoretical modeled for their energy absorption capacity under axial compression. In this paper, based on a simplified FE model, the energy absorption characteristics of angle elements with three panels are investigated by using the non-linear
finite element code LS-DYNA. Theoretical models are proposed to predict the crush resistance of three-panel angle elements with different angles. Numerical results show that the proposed theoretical model can predict the energy absorption of these angle elements with good accuracy.

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ABSTRACT: Experimental and numerical studies were conducted to understand the effect of plate curvature on blast response of aluminum panels. A shock tube apparatus was utilized to impart controlled shock loading to aluminum 2024-T3 panels having three different radii of curvatures: infinity (panel A), 304.8 mm (panel B), and 111.8 mm (panel C). Panels with dimensions of 203.2 mm × 203.2 mm × 2 mm were held with mixed boundary conditions before applying the shock loading. A 3D Digital Image Correlation (DIC) technique coupled with high speed photography was used to obtain out-of-plane deflection and velocity, as well as in-plane strain on the back face of the panels. Macroscopic postmortem analysis was performed to compare the yielding and plastic deformation in the three panels. The results showed that panel C had the least plastic deformation and yielding as compared to the other panels. A dynamic computational simulation that incorporates the fluid-structure interaction was also conducted to evaluate the panel response. The computational study utilized the Dynamic System Mechanics Analysis Simulation (DYSMAS) software. The model consisted of the shock tube wall, the aluminum plate, and the air (both internal and external) to the tube walls. The numerical results were compared to the experimental data. The comparison between the experimental results and the numerical simulation showed a high level of correlation using the Russell error measure.

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ABSTRACT: The out-of-plane crushing behaviour of aluminium hexagonal honeycombs containing different percentages of holes (i.e., the fraction of penetrated cells to the total) was extensively investigated over a wide range of strain rates where each test was conducted at constant compression velocity. Strength enhancement due to the increase of the strain rate and the entrapped air was studied. It is found that the strain hardening of honeycomb structures during the dynamic crush is mostly attributed to the pressure change caused by the entrapped air. The leaking rate, delta, was then studied and found to be dependent on the strain and strain rate,
and independent of the wall thickness to edge length ratio, $t/l$. An empirical constitutive relation describing the plastic collapse stress in relation to the $t/l$ ratio, the strain and strain rate is proposed, which agrees well with the experimental results.


ABSTRACT: The response of clamped sandwich beams subjected to impact loading is analyzed based on the works of Fleck & Deshpande (2004) [9] and Reid et al. (2010) [14]. This study differentiates itself from that of Fleck & Deshpande in that the “conservation of momentum” method instead of the “energy balance” method is adopted to model the “compaction stage” of the core upon impact loading. Finite element method (FEM) is used to validate the developed analytical model and good agreement between the analytical method and FEM results is observed. Obtained results also show that, compared to the Fleck & Deshpande model, the present model gives improved predictions of the maximum lateral deflection of the front face and the boundary of the two regions where the cellular core is totally compacted and partly compacted. The developed model is then applied to study the effects of core relative density and core thickness on the maximum impulsive momentum that the sandwich beam can sustain (impact resistance), and near-optimum design is identified for a regular hexagonal core sandwich beam with given mass. In addition, based on the present model, the performance of sandwich beams with self-similar hierarchical hexagonal honeycomb cores under impact loading is studied. It is shown that, for given relative density, the strength of the self-similar hierarchical hexagonal honeycomb decreases with the hierarchical order increasing. Therefore, both the energy absorbed per unit mass of the core during the compaction stage and the impact resistance of the sandwich beam decrease as the hierarchical order increases.

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ABSTRACT: The dramatic increase of Improvised Explosive Device (IED) related injuries has stimulated many studies to reconsider the design of the current state-of-the-art vehicle and body protective equipment. Materials now need to be chosen not only to stop solid projectiles such as shrapnel or bullets but also to attenuate the injurious effects of incoming blast waves. New advanced computational models of such events have been proved to facilitate the access to information currently inaccessible to experiments. To this end, we developed a fluid–structure interaction computational continuum model to investigate the attenuation properties of foam specimens containing filler materials under shock loading. Three test specimens were examined: a solid foam sample, and two other foam samples incorporating an intermediate layer of filler material: $\text{SiO}_2$ aerogel and soda-lime glass beads. The model was then calibrated and the results compared to the corresponding shock tube experimental results [M.D. Alley, S.F. Son, G. Christou, R. Goel, L. Young, 2009]. In conclusion, the model shows good agreement with experiment values for the peak pressure of the transmitted wave as well as its propagation time. Complementing the existing experimental results, high density soda-lime glass beads filler material is shown to substantially decrease the peak magnitude of the transmitted wave and to decrease the
spatial gradient of the pressure compared to the other lower density filler samples. However, the history of the sample reaction force suggests that the frame constraining the test specimen is being subjected to a higher impulse using the high density filler. Such a model paves the road to a new series of complex numerical models designed to accompany experimental testing by providing new insights on the mechanisms of fluid–structure interaction.

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ABSTRACT: A generic experimental study on the transition from progressive buckling to global bending during axial crushing of long square tubes was carried out. The tubes were made of the aluminium alloy 6060 T6 with 2.5 mm thickness and 80 mm outer width. Impact tests on tubes having free lengths of 1300, 1600 and 1900 mm were carried out in a pendulum accelerator. The tubes were fixed at the distal end to a rigid wall and impacted at the free end by a trolley with a mass of 1400 kg at an initial velocity of 13 m/s. For each length 15 samples were tested. Buckling initiated at the clamped end and progressed towards the impacted end for all the tubes. Two deformation modes were observed: progressive buckling and transition from progressive buckling to global bending. The number of tubes experiencing the latter mode increased with the free length of the tube. The transition to global bending was due to a developing eccentricity, which seems highly related to the deformation behaviour at the fixed end. The study clearly shows that there is a gradual change in crushing behaviour from the progressive mode to the mixed mode, appearing over a rather large range of tube lengths.

ABSTRACT: The dynamic response of end-clamped monolithic beams and sandwich beams of equal areal mass have been measured by loading the beams at mid-span with metal foam projectiles to simulate localised blast loading. The sandwich beams were made from carbon fibre laminate and comprised identical face sheets and a square-honeycomb core. The transient deflection of the beams was determined as a function of projectile momentum, and the measured response was compared with finite element simulations based upon a damage mechanics approach. A range of failure modes were observed in the sandwich beams including core fracture, plug-type shear failure of the core, debonding of the face sheets from the core and tensile tearing of the face sheets at the supports. In contrast, the monolithic beams failed by a combination of delamination of the plies and tensile failure at the supports. The finite element simulations of the beam response were compared with finite element simulations based upon a damage mechanics approach. A range of failure modes were observed in the sandwich beams including core fracture, plug-type shear failure of the core, debonding of the face sheets from the core and tensile tearing of the face sheets at the supports. In contrast, the monolithic beams failed by a combination of delamination of the plies and tensile failure at the supports. The finite element simulations of the beam response were accurate provided the carbon fibre properties were endowed with rate sensitivity of damage growth. The relative performance of monolithic and sandwich beams were quantified by the maximum transverse deflection at mid-span for a given projectile momentum. It was found that the sandwich beams outperformed both monolithic composite beams and steel sandwich beams with a square-honeycomb core. However, the composite beams failed catastrophically at a lower projectile impulse than the steel beams due to the lower ductility of the composite material.
ABSTRACT: The dynamic lateral crushing behaviour of short empty and sandwich circular tubes is examined in this paper. Unlike the conventional impact method, the specimens were placed on the bottom platen of an Instron machine with a constant upwards velocity and then the tube collided with the fixed upper rigid platen. Load-deflection curves of empty tubes were first obtained and analysed. From the viewpoint of deformation modes and plastic strain energy absorbed by the tube quadrants around the proximal surface and distal surface, a critical velocity of impact is determined which corresponds to a mode change. A relationship is found to exist between the critical velocity and thickness-to-diameter ratio as well as the yield stress and density of the material. To understand the dynamic crushing behaviour of short aluminium foam-filled sandwich tubes by two rigid platens, further tests and corresponding finite element analysis were performed, respectively. Similar to the observations in the quasi-static tests, the mode of dynamic collapse is bending, with the formation of plastic bending zones accompanied with core crushing. Corresponding FE models for ABAQUS/Explicit were developed and validated against the experimental observations. Detailed deformation features and energy absorption characteristics during the crushing process were identified. It was found that increasing the compression velocity leads to an increase in the total internal plastic energy dissipation for both empty and sandwich tube. The propagation of plastic bending in the form of double-moving-hinges is the main mechanism of energy dissipation, as opposed to the low velocity impact which involves stationary plastic deformation zones.

ABSTRACT: Strength enhancement and deformation localisation are typical features of the dynamic response of cellular materials. Several one-dimensional shock models have been developed to explain these features. A unified framework of one-dimensional plastic shock wave models was established in this paper. Based on an arbitrary plastic hardening constitutive model for cellular materials, general solutions, although implicit, have been derived for two impact scenarios. For a rigid–power-law hardening (R-PLH) idealisation involved in three material parameters, namely the yield stress, the strength index and the strain-hardening index, closed-form/semi-closed-form solutions of the physical quantities across the shock front have been derived. The linearly hardening and locking idealisations are found to correspond to the two opposite limit cases with the strain-hardening index of one and infinity, respectively. The shock models based on three different idealisations are verified with cell-based finite element models including an irregular honeycomb and a closed-cell foam. It is found that the force responses predicted by the shock models are not very sensitive to the choice of the idealisations and they are in good agreement with the cell-based finite element results. Deformation features predicted by the shock models are compared well with the cell-based results when the impact velocity is not
The comparisons show that using more realistic constitutive models such as the R-PLH idealisation may present more accurate predictions.

ABSTRACT: A study was published recently by ASME which contain the views of experienced numerical analysts on the credibility of numerical calculations in engineering design. Various important issues were raised so this paper is an attempt to examine some of these concerns from the narrower perspective of the response of structures subjected to large dynamic, impact and blast loadings producing inelastic deformations and failure. This area is relevant for hazard assessment and security studies, safety calculations, structural crashworthiness and energy-absorbing systems, structural protection and related topics. Some observations are offered on the paucity of information for the dynamic properties of materials, approximations of external dynamic loadings, modelling of structural details, accuracy of experimental test programmes and the influence of several other topics, including similitude. These factors can influence the potential accuracy and credibility of validation exercises and design studies for Finite-Element Analyses.

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ABSTRACT: The paper reports on an experimental and numerical investigation into the response of sandwich panels, with PVC foam cores and glass fibre reinforced vinyl ester face sheets, to localised blast loading. It also reports on the response of equivalent mass glass fibre reinforced vinyl ester panels. The loading was generated by detonating discs of plastic explosive at a small stand-off distance of 50 mm. Multiple failure modes were exhibited by the panels, including core compression, fragmentation and complete penetration, debonding between the face sheet and core, delamination between the fibre layers and rupture of the fibres. The sandwich panels exhibited complete penetration failure while no penetration occurred in the equivalent mass composite only panels. Reasonable agreement between the experimental results and numerical simulations is observed. The analysis reveals the reasons why the composite only panels perform better than the sandwich panels with PVC foam core. Due to the lower transverse stiffness of the individual components of the sandwich panel, considerably higher transverse velocity of the face sheet develops at the beginning of the process causing larger deflections and therefore larger in-plane stresses in the face sheet despite the high energy absorbing capacity of the foam core. The influence of the core density on the sandwich panel resistance to blast loading is also briefly discussed.
Shu Yang and Chang Qi (State Key Laboratory of Structural Analysis for Industrial Equipment, School of Automotive Engineering, Dalian University of Technology, B1211 Chuangxinyuan Building, No. 2 Linggong Road, Ganjingzi District, Dalian 116024, China), “Multiobjective optimization for empty and foam-filled square columns under oblique impact loading”, International Journal of Impact Engineering, Vol. 54, pp 177-191, April 2013, https://doi.org/10.1016/j.ijimpeng.2012.11.009
ABSTRACT: This paper aims at optimizing the crashworthiness of empty and foam-filled thin-walled square columns under oblique impact loading, for variations in the load angle, geometry and material parameters of the column. Another focus is to reveal the relative merits of the optimized configurations for both types of columns under such loads. Dynamic finite element analysis (FEA) techniques validated by theoretical solutions and experimental data in the literature are used to simulate the crash responses of such devices subjected to different impact angles. Based on the FEA results, the Kriging metamodels are constructed for the two columns to predict the crashworthiness criteria of specific energy absorption (SEA) and peak crushing force (PCF) under oblique impact loading, which are set as design objectives in the following multiobjective optimization design (MOD) process. The Pareto fronts are identified for the MOD problems of the two types of columns under both single angle impact and the cases involving multiple impact angles, using the multiobjective particle swarm optimization (MOPSO) algorithm. It is found that the optimal designs are generally different under different load angles for either empty or foam-filled column. Results also indicate that more robust designs against oblique impact could be achieved by including multiple load angles in the MOD process. Compared to the empty column, the optimal foam-filled column may have better crashworthiness under pure axial loading, but the optimal empty column has more room to enhance the crashworthiness under oblique impact.

Jie Song (School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore), “Numerical simulation on windowed tubes subjected to oblique impact loading and a new method for the design of obliquely loaded tubes”, International Journal of Impact Engineering, Vol. 54, pp 182-205, April 2013, https://doi.org/10.1016/j.ijimpeng.2012.11.005
ABSTRACT: Tubular structures under oblique loading may collapse in axial or bending mode when the load angle is smaller or larger than certain critical value, and the bending mode has much lower energy absorption. In the present study, windowed square tubes subject to oblique impact were numerically studied, with variables being load angle, width and height of window and impact velocity. Next, a new design method was proposed which can effectively increase the tube’s critical load angle without compromising its energy absorbing capacity. The method therefore has great potential in industrial applications where large load angles are expected.

ABSTRACT: Continuum-based shock models have been proposed by different authors to understand the strength enhancement and deformation localization phenomena observed in the dynamic response of cellular materials, but their applicability is still debatable due to continuum-based stress wave theory being used to cellular materials with finite cell sizes. A method based on the optimal local deformation gradient is developed to calculate the local strain field of a deformed cellular structure using a cell-based finite element model. The strain field provides evidences of the existence of a plastic shock front in cellular materials under a high or
moderate velocity impact. Due to the feature of shock front propagation, the 2D strain fields are simplified to one-dimensional distributions of strain in the loading direction. Shock wave velocity is measured by an approach that gives the location of the shock front varying with the impact time. A comparison of the cell-based finite element model with continuum-based shock models indicates that the shock model based on a material accounting for the post-locking behaviour is more accurate in predicting the shock wave velocity. Finally, stress–strain states ahead of and behind the shock front are obtained. These results provide an explanation in terms of deformation mechanism for the stress reduction at the support end with increasing impact velocity, which was previously observed in experimental and numerical studies.

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ABSTRACT: The present work is aimed at finding the maximum energy absorption efficiency of plates in thin-walled structures under compression. In thin-walled structures, the plates are connected with different angles and by different edge connectivity. The influences of these two major factors on the crush resistance of structures are investigated numerically by nonlinear finite element code. Two extreme modes: uniform mode and opposite mode are defined for the angle elements with different edge connectivity. The energy absorption characteristics of these two modes are investigated and a theoretical model is established to predict the energy absorption capacity of elements deforming in uniform mode. Experimental tests of multi-cell columns are conducted to validate the numerical analyses and theoretical models for angle elements. The numerical simulations and theoretical predictions of the crush resistance of multi-cell columns show a very good agreement with the experimental results.

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ABSTRACT: This paper details a numerical modeling and experimental test program focused on high energy ballistic impacts on composite rib-stiffened structures. The numerical model used in this paper is designated as the Multiconstituent Composite Model (MCM), which is implemented within the CTH shock physics code for simulation of ballistic impact damage on composite structures. The presented work utilized a building block approach, where component level flat panels were studied first, followed by sub-structure level T-joint specimens, both fabricated from a carbon/epoxy composite material. All numerical studies and experimental tests utilized the military grade 0.50 caliber M2 Ball round as a projectile. Following testing, each panel was inspected both visually and using Ultrasonic C-Scan techniques to determine the extent of damage sustained upon impact. Finally, comparisons of the experimental data with the numerical predictions are presented and
discussed. Both the flat panel and T-joint damage predictions were in good agreement with the experimental data.


ABSTRACT: This research is interested in the impact toughness of a reinforced composite face-sheet and cores materials used in lightweight sandwich panels. It investigated the degrees of damage inflicted on the contact surface, through thickness and rear surface of the sandwich panels. The sandwich specimens were prepared in configurations of natural silk (NS)/Epoxy/Foam, NS/Epoxy/Coremat, NS/Epoxy/Honeycomb and reinforced NS/Epoxy serving as referral. For all experiments, drop weight impact test was carried out under low velocity impact energies of 32 J, 48 J and 64 J. Parameters measured were load bearing capability, energy absorption capability and damage fragmentation of the specimen with regards to increasing impact loads. Dominant deformation modes were seen as upper face-sheet compression failure, lower face-sheet delamination and lower face-sheet tensile failure.


ABSTRACT: The paper addresses the low velocity, drop weight behaviour of small (100 mm by 100 mm) sandwich panels with CFRP skins. The main point of interest is the core material, and the focus of the paper is in the use of body centred cubic (BCC) micro lattice cores made from Ti 6Al 4V titanium alloy and 316L stainless steel manufactured using selective laser melting. The mechanical behaviour of the micro lattice core is compared to that of conventional aluminium honeycomb. The paper discusses the manufacture and characterisation of the core materials, the measurement of core properties from strut tensile tests, block compression tests and the drop weight impact performance of the panels. Impact performance is expressed in terms of panel penetration. It is shown that the current Ti 6Al 4V BCC micro lattice cores are competitive with aluminium honeycomb, but that there is scope for improvement in Ti 6Al 4V micro strut mechanical properties. The SLM manufacturing process gives lattice structures with open cell architecture, which is an advantage for aerospace applications, and the SLM process can be used to realise a variety of cell lattice geometries.


ABSTRACT: An experimental impact study has been conducted on sandwich structures to identify and improve armour solutions for aeronautical applications. The objectives are to find the best configurations, i.e. the non-perforated targets with the minimal weight and back deformations. Medium-velocity impacts (120 m/s) have been conducted using a 127 g spherical projectile. The targets are simply supported at the rear of the structure.
Two potential choices of front skin have been identified for the sandwich structure: 3 mm thick AA5086-H111 aluminium plates and dry aramid stitched fabrics (between 8 and 18 plies). The dry stitched fabrics appear to be an original solution, which associates a lightweight structure and a good perforation resistance. Moreover, a strong coupling has been found between the front skin and the core. The impact tests indicate that aluminium honeycomb core associated with aluminium skins show mitigated results. However, the combination of dry fabric front skin and aluminium honeycomb show better performances than aluminium sandwiches, with a global weight decrease.


ABSTRACT: The mechanisms of projectile penetration of extruded 6061T6 aluminum alloy sandwich panels with empty and alumina filled, triangular corrugated cores have been experimentally investigated using zero obliquity, 12.7 mm diameter hard steel projectiles whose diameter was about a half that of the core's unit cell width. We find that low momentum impacts are laterally deflected by interactions with the inclined webs of the empty core. Complete penetration occurred by shear-off within the impacted front face sheet, followed by stretching, bending and tensile fracture of the core webs and finally shear-off within the back face sheet. This combination of mechanisms was less effective at dissipating the projectiles kinetic energy than the shear-off (plugging) mechanism of penetration of the equivalent solid aluminum panel. Inserting ballistic grade alumina prisms in the triangular cross section spaces of the corrugated core significantly increased the panel's ballistic resistance compared to the empty panel. The presence of the hard ceramic led to severe plastic deformation and fragmentation of the projectile and comminution and macroscopic fracture of the ceramic. The Al/Al₂O₃ hybrid panel ballistic limit was reached when pairs of parallel cracks formed in the rear face sheet at core web-face sheet nodes. The separation distance between these cracks was dependent upon the location of the impact with respect to that of the web-face sheet nodes. Nodal impacts resulted in pairs of fractures that were separated by one cell width and a critical velocity below that of the equivalent solid plate. Impacts mid-way between pairs of nodes resulted in back face sheet crack pairs separated by twice the cell width, and a critical velocity higher than the equivalent solid plate. Using X-ray tomography we show this resulted from the formation of oval (not circular) cross section fracture conoids in the ceramics. The conoid angle was about 60° in the extrusion direction but only 30° in the transverse direction. This observation may have interesting consequences for a panel's resistance to a second, close proximity impact.

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ABSTRACT: Effects of soil–pipe interaction on the response of continuously supported offshore pipelines subjected to transverse impacts caused by dropped objects are studied. For this, the impact on an internally pressurized pipeline resting on a flexible bed has been numerically simulated. The numerical model has first been validated against different sets of experimental data from the authors and a number of researches. A relatively extensive parametric study has then been carried out to examine effects from variations in the pipe
geometry, internal pressure, boundary conditions, indentor shape and orientation, embedment depth of the pipe into the soil bed and subsoil mechanical properties on the pipeline response. It has been noticed that the presence of internal pressure results in substantial increase in the impact force. It, however, reduces the denting length, causing the deformation to become spatially more localized. It has also been shown that the flexibility of pipe bed plays an important role in the impact energy dissipation. This effect becomes more pronounced when the internal pressure is relatively low.

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ABSTRACT: To enhance the energy absorbing ability of thin-walled structures, multi-cell tubes with triangular and Kagome lattices were designed and manufactured. Quasi-static axial compression experiments were carried out to reveal the progressive collapse mode and folding mechanism of thin-walled multi-cell tubes. Combining with the experiments, deformation styles were revealed and classical plastic models were suggested to predict the mean crushing forces of multi-cell tubes. Compared with anti-crushing behaviors of single-cell tubes, multi-cell lattice tubes have comparable peak loads while much greater mean crushing forces, which indicates that multi-cell lattice tubes are more weight efficient in energy absorption.

Wensu Chen and Hong Hao (Tianjin University and the University of Western Australia Joint Research Center of Protective Structures, School of Civil and Resource Engineering, the University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia), “Experimental investigations and numerical simulations of multi-arch double-layered panels under uniform impulsive loadings”, International Journal of Impact Engineering, Vol. 63, pp 140-157, January 2014, https://doi.org/10.1016/j.ijimpeng.2013.08.012
ABSTRACT: A double-layered panel with a structural form of multi-arch-surface has recently been numerically demonstrated capable of absorbing considerable energy and mitigating the blast loading effects on structures. In this study, experimental tests were conducted to further verify the performance of multi-arch double-layered panels subjected to uniform impulsive loadings by using a pendulum impact test system at the University of Western Australia (UWA) Structural Lab. The uniform impulsive loadings were generated by pendulum striking on the surface of a fully confined airbag placed in front of the specimen. Specimens with various configurations were designed and tested to investigate the effects of different configurations, i.e. arch height, arch number, thickness and different loadings on the structural response to the uniform impulsive loads. Single-layered flat steel panels were also tested as control panel for comparison to study the efficiency of double-layered multi-arch panel in resisting impulsive loads. The experimental data including air pressure time history acting on the front arched layer, displacement time history at the center point on the back flat layer and strain history at some representative points on the back flat layer were recorded. The deformation modes of specimens are also identified and discussed. The experimental data show that the multi-arch panel with specific
configuration performs better than the flat monolithic panel in resisting uniform impulsive loadings. Numerical models were also developed to simulate the experimental tests by using finite element codes Ls-Dyna. The predicted data from the numerical simulations were compared with the experimental results. A good agreement between the experimental and numerical results was achieved. The responses of peak boundary reaction forces were extracted from numerical results to further examine the effectiveness of multi-arch panels against uniform impulsive loadings. The validated numerical model can be used to conduct intensively numerical simulations to define the best performing multi-arch panel configurations for blast loading resistance.


ABSTRACT: The use of lightweight materials in vehicle structures requires appropriate joining techniques, among them adhesive bonding. Testing full-size structures such as vehicle crush tubes can be prohibitive in terms of cost and appropriate facilities may not be available, so it is often desirable to test sub-size structures. To address this need, the suitability of scaling to accurately describe the behavior of bonded crush tube structures during axial impact scenarios was investigated. A numerical simulation was validated using literature sources and experimental testing, and then used to investigate scaling. The predictions for structures constructed out of a single material, in terms of stress distributions and deformations were in good agreement between the numerical simulations of the model (experiment modified in size by a scale factor) and the prototype tubes (actual size experiment). When considering bonded structures with the possibility for joint separation, the Non-Direct Similitude technique was applied to scale the structure and the results showed a small departure between the predictions of the model and the prototype. For bonded crush tubes, where the presence of a second material in the form of an adhesive layer was small, the scaling method provides acceptable results. The limitations of the scaling technique were discussed.

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ABSTRACT: This study investigates the energy absorption response of rectangular woven natural silk/epoxy composite tubes when subjected to an axial quasi-static crushing test using a trigger mechanism. The resulting deformation morphology of each failure region was captured using high resolution photography. The rectangular composite tubes were prepared through the hand lay-up technique, in which 24 layers of silk fabric were used, each with a thickness of 3.4 mm and tube lengths of 50, 80, and 120 mm. The parameters measured were peak load, energy absorption, and specific energy absorption as functions of the tube lengths. Specific energy absorption values decreased with increased length of the composite specimen, whereas total energy absorption increased with the increased length of the composite specimen. The deformation morphology showed that the failure mechanism proceeded in two stages, namely, (i) onset of tear and (ii) propagation of
tear, which included progressive buckling and delamination. The composite tubes only exhibited progressive but not catastrophic failure.

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“Crashing analysis and multiobjective optimization for thin-walled structures with functionally graded thickness”, International Journal of Impact Engineering, Vol. 64, pp 62-74, February 2014,
https://doi.org/10.1016/j.ijimpeng.2013.10.004

ABSTRACT: Thin-walled structures have exhibited significant advantages in light weight and energy absorption and been widely applied in automotive, aerospace, transportation and defense industries. Unlike existing thin-walled structures with uniform thickness, this paper introduces functionally graded structures with changing wall thickness along the longitudinal direction in a certain gradient (namely, functionally graded thickness – FGT). Its crashing behaviors are the key topics of the present study. We examine the crashing characteristics of functionally graded thin-walled structures and evaluate the effect of different thickness gradient patterns on crashing behaviors. It is shown that the gradient exponent parameter $n$ that controls the variation of thickness has significant effect on crashworthiness. To optimize crashworthiness of the FGT tubes, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to seek for an optimal gradient, where a surrogate modeling method, specifically response surface method (RSM), is adopted to formulate the specific energy absorption (SEA) and peak crashing force functions. The results yielded from the optimization indicate that the FGT tube is superior to its uniform thickness counterparts in overall crashing behaviors. Therefore, FGT thin-walled structures are recommended as a potential absorber of crashing energy.

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ABSTRACT: Corrugated sandwich panels are widely used in various fields because such panels have lower density, easier fabrication methods and higher strength compared with monolithic plates. In this study, the dynamic response of corrugated sandwich panels under air blast loading was investigated using a ballistic pendulum system. Two configurations of the specimen were considered. The residual deflection of the back face sheet and the deformation/failure modes of the sandwich panel under different impulse levels were analysed. Finite element simulations were performed by using AUTODYN. The deformation process and energy absorption of the face sheets and the core were investigated in the numerical simulation.

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ABSTRACT: Multi-cell columns are highly efficient energy absorbing components under axial compression. However, the experimental investigations and theoretical analyses for the deformation modes and mechanisms of them are quite few. In this paper, the axial crushing of circular multi-cell columns are studied experimentally, numerically and theoretically. Circular multi-cell columns with different sections are axially compressed quasi-statically and numerical analyses are carried out by nonlinear finite element code LS-DYNA to simulate the experiments. The deformation modes of the multi-cell columns are described and the energy absorption properties of them are compared with those of simple circular tube. Theoretical models based on the constituent element method are then proposed to predict the crush resistance of circular multi-cell specimens. The theoretical predictions are found to be in a good agreement with the experimental and numerical results.

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ABSTRACT: The effect of through-the-thickness stitching on the blast resistance of sandwich panels is investigated both experimentally and numerically. Panels based on three-dimensional woven S-glass/epoxy skins and a crosslinked PVC core were manufactured using a vacuum assisted resin infusion process. The panels were stitch-bonded using Kevlar 129 yarn, by means of a multi-needle stitch-bonding machine developed in a previous investigation. The performance of both orthogonal (0°) and biased (45°) stitching procedures were considered and their respective responses were compared to that of a similar unstitched panel. The blast resistance of the sandwich panels was modelled using finite element techniques. An examination of the blast-loaded samples highlighted a number of failure mechanisms, including crushing of the foam core, skin-core debonding, fracture of the glass fibre/epoxy skins, fibre-matrix debonding with fibre pull-out and delamination. If evaluated on the basis of specific impulse (applied impulse normalized by plate mass), the results indicate that stitching has no obvious effect on the blast resistance of the sandwich structures. Agreement between the finite element models and the experimental data was good over the range of loading conditions considered. Here, the FE models accurately predicted the overall deformation responses of the panels and also captured the primary failure modes.

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ABSTRACT: Commercial aluminum honeycombs with various cell configurations are experimentally tested to study the influence of cell number and central angle on the out-of-plane crush resistance of the structures. The boundary effect is found to have significant impact on the crush strength of the structure when the number of cells is small and the central angle is observed to get a difference less than 10% in the strength of the honeycombs. Numerical analyses based on whole honeycomb model and Y-shaped element model are carried out to simulate the crush and deformation process of the specimens. The adhesive bonding of the double thickness foil is considered in the simulation and the numerical results show good agreement with the experimental data and theoretical predictions. Finally, the reason for the small influence of central angle on the out-of-plane strength of honeycombs is investigated and the interaction effect between wall thickness and central angle is believed to account for it.

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ABSTRACT: Joints play an important role in resisting impact loading in Tubular structures. In this paper, a finite element model validated by experimental results is developed to numerically study the failure modes and energy dissipation mechanism of tubular T-joint impacted by a drop hammer with the initial velocity of 7–10 m/s. The resistant mechanism is investigated based on the dynamic responses of the joints under impact loading. Strain, displacement and the failure modes of the T-joints are also predicted. Global and local deformations of the tubular joints are distinguished using an equal area axis method, which helps to discover the failure mechanism of the joints. Using the yield line theory, an equivalent impact force estimation method is also proposed based on the impact load versus displacement relationship. The numerical analysis and the simplified method provide a basis for impact resistance evaluation and progressive collapse mitigation of steel tubular structures in design practice in the future.

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ABSTRACT: Fluid-structure interaction (FSI) experiments and finite element (FE) calculations are performed in order to examine the one-dimensional response of water-backed and air-backed sandwich plates subject to blast loading in either deep or shallow water. The sandwich plates comprise rigid face sheets and low-density foam cores. Experiments are conducted in a transparent shock tube, allowing measurements of both structural responses and cavitation processes in the fluid. Measurements are found in good agreement with predictions and allow concluding that the advantages of using the sandwich construction over the monolithic one are maximised for the case of water-backed sandwich plates in deep water.

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ABSTRACT: The deformation/failure modes and blast resistance of cylindrical sandwich shells comprising two aluminum face-sheets and an aluminum foam core, subjected to air blast loading, were investigated experimentally. Specimens of two different radii of curvature and geometrical configurations, clamped along their peripheries, were studied. A four-cable ballistic pendulum system was employed to measure the impulse imparted to the specimens. Typical deformation/failure modes were classified and analyzed; the effects of face-sheet thickness, core relative density, arrangement of foam core layers of different densities, specimen curvature and mass of charge on the structural response were also examined. The results indicate that both the deformation/failure modes and the structural response of the shells are sensitive to the geometrical
configurations and blast impulse. Various failure modes – indentation or tearing of the front face-sheet, collapse of the core, severe inelastic deformation or tearing of the rear face-sheet, and failure between the face-sheets and foam core, were observed. The findings are useful for validating theoretical predictions, as well as to guide application of cellular metal sandwich structures for blast protection purposes.


ABSTRACT: In this paper, the dynamic behavior of a viscoelastic sandwich composite plate subjected to the non-uniform blast load is investigated. The theoretical and experimental study is carried out. The plate examined has carbon/epoxy face sheets and an aramid honeycomb core. In the theoretical study, the sandwich plate is modeled using first order shear deformation theory. Because of the large deformations which occurred after the blast load in some tests, geometrical nonlinearities are considered in the derivations. The shear and large deflection effects are considered. The equations of motion are derived by the use of virtual work principle for the sandwich plate. The clamped boundary conditions are considered for all edges of the plate. The viscoelastic properties of carbon/epoxy coupons and sandwich coupons are determined using Dynamic Mechanical Analyzer. The viscoelastic behavior is modeled by using the Kelvin-Voigt linear viscoelastic theory. The equations of motion are obtained in the time domain using Galerkin's method. The nonlinear coupled equation system is solved by Mathematica Software. A special experimental setup is used to obtain the blast pressure for the blast test. The experimental, theoretical and finite element analysis results are compared and the vibration characteristics, peak points, vibration frequencies are found to be in an agreement.

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ABSTRACT: The dynamic crushing of circular-celled honeycombs under out-of-plane impact is studied within a wide range of impact velocity by using both theoretical and numerical methods, and verified by the experiments. Two kinds of honeycombs with different cell package, i.e., the SP and HP honeycombs, are considered. The results of the honeycombs are discussed and compared with those of the cylindrical tubes under axial compression. An analytical expression is deduced to predict the honeycombs' crushing stress, showing good agreements with the numerical results. It is shown that the energy absorption per unit mass of the HP honeycomb and the SP honeycomb is at least 13.3% and 6.4%, respectively, greater than that of the cylindrical tubes. And the HP honeycomb can absorb at least more 23% energy per unit volume than the SP ones mainly due to the denser package mode of the cells. The different energy absorption ability among the two kinds of honeycombs and the cylindrical tubes can be attributed to the different constraints around the cylindrical cells and tubes, which is verified by the experiments. A non-dimensional “dynamic sensitivity index” is used to quantitatively evaluate the sensitivity of the structure's load capacity to the impact velocity, showing the most
sensitivity of the tube and the least sensitivity of the HP honeycomb, which are confirmed by the numerical results.

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ABSTRACT: As a relatively new component with a higher efficiency of material utilization, functionally graded thickness (FGT) structure with probably varying wall thickness becomes fairly promising. This paper compares the energy absorption capabilities of FGT, tapered uniform thickness (TUT) and widely-utilized straight uniform thickness (SUT) tubes subjected to oblique impact loading. The analytical formula is derived for the geometric relationships of these three different configurations (FGT, SUT and TUT) with the same weight. Based on the validated finite element (FE) models, a series of crushing analyses are performed to quantify the specific energy absorption (SEA) of different tubes under axial (0°) and oblique impact loading by varying the loading angles (10°, 20°, 30°). The FGT tubes demonstrate to be more preferable to the others as an energy absorber attributable to their higher capacity of withstanding the oblique loads. Then, crushing analyses of FGT tubes with different gradient exponents are performed to quantify specific energy absorption (SEA) and maximum crashing force. The critical loading angle at which the global buckling occurs is identified for the FGT tubes, and it is found that the energy absorption capacity of FGT tubes, especially with gradient exponent 2.0, was well maintained as the impacting angle increases. The results obtained from this study provide some insights into the design of FGT tube as a potential energy absorber where oblique impact loading is inevitable.

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ABSTRACT: The present investigation examines the response of the aluminum cenosphere syntactic foam core stiffened and unstiffened structures subjected to blast load. The blast is applied using blast load equations available in LS-DYNA by defining the charge and standoff distance to analyze the structures under a particular blast load. The dynamic response of the sandwich structures is studied in terms of quantitative assessment, which mainly focuses on the peak central point displacement of the back-sheet (opposite to the explosion) of the sandwich structures. The analysis is carried out with an objective of understanding the effects of the foam thickness, strain rate, and the stiffener configurations on the response of sandwich structure to the blast load. The results obtained indicate that the provision of the stiffeners and foam core considerably improves the blast resistance as compared to both, the unstiffened panels with foam core and without using syntactic foam core.

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ABSTRACT: Underwater implosion, the rapid and catastrophic collapse of a structure caused by hydrostatic pressure, generates a short-duration, high-pressure pulse in the surrounding water that is potentially damaging to adjacent structures or personnel. This paper presents a method to estimate the energy in the pressure pulse as the difference between the known total potential energy and energy lost by plastic deformation. The implosion pulse energy is proportional to the maximum system kinetic energy developed during collapse. The pulse was approximated by considering only the first phase of collapse (up to the instant of first contact), because the maximum kinetic energy occurs very near that instant. The plastic energy dissipated by the structure during the initial phase of implosion was evaluated analytically, using the principle of virtual velocities. The solution for energy dissipation agreed with numerical simulation within 1% at the end of the initial collapse phase. It was found that for a representative aluminum cylinder, the implosion pulse represents only 15% of the total available energy.

ABSTRACT: The paper presents a simplified analytical method to examine the energy absorbing mechanisms of small-scale stiffened plate specimens, quasi-statically punched at the mid-span by a rigid indenter with a knife or a flat edge shape. To validate this method, experiments and numerical simulations are conducted on specimens scaled from a tanker side panel limited by one span between the web frames and the stringers. Therefore, the paper provides practical information to estimate the extent of structural damage within ship side panels during collision accidents. The experimentally obtained force–displacement responses and shapes of the deformation show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The numerical results manage to describe the process of initiation and propagation of the material fracture in the side panel specimens and provide detailed information of the energy dissipated by each structural component and its contribution to total energy during the entire deformation process. The analytical method derives expressions to estimate the relation between the plastic deformation and the energy dissipation of the stiffened plates. Both the plate and the stiffener elements dissipate the energy through rotation of the plastic hinges at the applied load and the support and the membrane tension over the plastically deformed region between the loading and the supports. The proposed simplified expressions give a good agreement with the experimental and numerical results.

ABSTRACT: This paper presents a numerical and experimental study of several configurations of multi-cell columns compared to single-walled and double-walled columns subjected to dynamic axial impact forces. The
impact of the columns was numerically analysed using FEM and also verified by experimental testing. The effect of the column mass and thickness of the multi-cell columns compared to single- and double-walled columns was also studied. The results showed that, by analysing a group of columns with the same thickness and weight, the energy absorption efficiency can be significantly improved by introducing internal ribs to the double-walled columns. The results showed that the crushing force of the middle ribs (MR) multi-cell columns was the highest, followed by the corner ribs (CR) multi-cell columns, the double-walled (DW) columns and the single-walled (SW) columns, respectively.

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ABSTRACT: As a relatively new component with a higher efficiency of material utilization, functionally graded thickness (FGT) structure with desired varying wall thickness has been becoming more and more attractive. In order to sufficiently understand the crashworthiness of FGT under lateral impact, firstly, the finite element (FE) models of thin-walled columns with uniform thickness (UT) and FGT under lateral loading are established and validated by experimental results. It is exhibited that the FE simulations are in good agreement with experimental tests. Then, the crashworthiness of UT tube and the corresponding FGT tube is compared, and the results reveal that the FGT tube can absorb more energy but generate larger force than UT tube under the same weight. Further, parametric analyses show the gradient exponent, wall thickness range, the tube diameter and yielding stress have significant effects on the crashworthiness of FGT tubes. Finally, a multiobjective particle swarm optimization (MOPSO) method is used to optimally seek for those design parameters, where surrogate modeling methods are adopted to formulate the specific energy absorption (SEA) and peak crushing force functions. The results yielded from the optimization demonstrate that the FGT tube is superior to its uniform thickness counterpart in overall crashing behavior under lateral impact. Therefore, FGT tubes are recommended as potential absorbers of crushing energy under lateral loading.

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ABSTRACT: In this paper we present a hybrid model of church bell. The dynamical system of yoke-bell-clapper is nonlinear and discontinuous. We use the Lagrange equations of the second type to derive formulas that describe the system's motion. The energy between the bell and the clapper is transmitted via impacts, here modeled using a coefficient of energy restitution. The values of the system's parameters have been determined basing on the measurements of the biggest bell “The Heart of Lodz” in the Cathedral Basilica of St Stanislaus
Kostka, Lodz, Poland. Using the same bell we also validate the model by comparing the results of numerical simulations with experimental data. The presented results show that the described model is a reliable predictive tool which can be used both to simulate the behavior of the existing yoke-bell-clapper systems as well as to design the yokes and predict the motion of new bells.


ABSTRACT: A kinematically admissible mechanism is presented for the progressive collapse of a foam-filled and unfilled circular frustum. The mechanism uses a three-limb model of collapse for the frustum shell, taking into account the plastic strain and circumferential strain energy dissipation during collapse. For the foam-filled case, the energy dissipation due to the plastic collapse of the foam and the interaction effects between it and outer frustum shell were considered. To account for the interaction effects, a pressure equivalent to the stress plateau of the foam was applied only to the inward bending proportion of the frustum. This is the result of our extensive experimental studies, which shows that Poisson's effects are negligible and that there will be no transverse strains resulting from the axial collapse of the frustum. We have further conducted analysis of empty frustum. A comparative analysis for the developed mechanism and previously conducted experimental studies showed good agreement between the two. Lastly, a parametric study of the mechanism correctly predicts that the magnitude of the crushing load depends on the length and proportion of the inward folds. Our upper-bound model gives a closed form solution for the collapse of foam-filled and unfilled frustums that can be used for crash energy management in automobiles.

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ABSTRACT: In this paper, the sandwich tubes, which consist of thin-walled circular tubes with aluminium foam core, were proposed as energy absorption devices. The sandwich tubes were laterally crushed under quasi-static loading conditions. Detailed finite element model, validated against existing experimental results, was developed using the explicit code (ANSYS-LSDYNA) to assess the energy absorption responses and deformation modes. Response surface methodology (RSM) was employed in parallel with the finite element models to perform both parametric studies and multi-objective optimization in order to establish the optimal configuration of the sandwich tube. Sampling designs of the sandwich tubes were constructed based on a D – optimal design of experiment (DOE) method. Factorial analysis was performed using the DOE results to investigate the influences of the geometric parameters on the responses of sandwich tubes. In addition, multi-objective optimization design (MOD) of the sandwich tubes is carried out by adopting a desirability approach. It was found that the tube with a minimum diameter of the inner layer and a maximum foam thickness are more suitable for use as energy absorbing components.
ABSTRACT: This paper presents a fast and reliable method for failure prediction of coarsely meshed shell structures. The method is especially relevant when investigating the impact performance of offshore structures, typically stiffened panel structures where the size of the structure limits the possible detailing level during analysis. The method combines a local instability criterion with post-necking damage in order to numerically model the failure process in large shell elements. The failure model is based on power law plasticity with the stress-based Bressan–Williams–Hill (BWH) local instability criterion and a coupled damage model after incipient necking. The BWH criterion gives a robust estimation of incipient necking for coarsely meshed shell structures. After necking starts, a mesh-size dependent damage model is coupled to the element strength for material softening until failure, assuming that the strain localization occurs locally inside the element within a virtual neck. The model is incorporated in the explicit FE code LS-DYNA. The material model formulation is validated against experiments at several levels; from formability tests with varying strain states to medium and large scale impact experiments, giving a robust prediction of energy dissipation and material failure in the structure with low mesh dependency. The material model is calibrated from a single uniaxial test, and gives robust and consistent simulation results in which details of the localized necking phenomenon is included in the behavior of large shell elements. Thus, it is readily used for structural design of offshore structures in order to assess the technical safety level of the structure against collisions in all phases of the design process.

ABSTRACT: This study presents the experimental and simulation results for the low velocity impact response of sandwich panels reinforced with lattice core reinforcement. Two different core material and architecture combinations are investigated; a UV-cured photopolymer lattice, produced from a network of self-propagating waveguides, and an aluminum alloy lattice cast from an initial polymer template. For each of these sandwich panel configurations, impact tests were performed with a drop-weight hemispherical impactor under four different energy levels. The applied impact force, impactor velocity and residual damage in the sandwich panel were all measured and used for comparison against finite element simulations of the impact tests. These simulations employed a homogenized continuum constitutive model, designed to replicate the deformation response of the lattice core without requiring explicit representation of the geometric features of the lattice. For both sandwich panel designs at all impact energy levels, excellent correlation was observed between the experimental measurements and impact simulations. Additionally, each sandwich design was shown to be effective at absorbing the kinetic energy of the impactor with minimal damage to the back (non-impacted) face.
of the panel. Implementation of these lattice core sandwich panels and extension of the homogenized constitutive model to other sandwich applications are also discussed.


ABSTRACT: This paper addresses the impact response of large-diameter thin-walled steel ring-stiffened cylinders subjected to low velocity mass impact and resulting local damage. Drop-weight impact tests with a striking mass, which had a knife-edge indenter, were conducted on two fabricated steel small-scale models. Details of the experiment setup, the procedure and the tests to obtain both quasi-static and dynamic material properties are described. With these observations, the experimental data, which include the final deformed shape, dynamic force-displacement curves and strain gauge measurements, are reported to be useful for future benchmark studies. The numerical prediction accuracy of the impact response of the test models were evaluated using the explicit solver of the finite element software package ABAQUS. The effect of the strain-rate hardening definition on the results is highlighted. Finally, the results that were obtained using a simplified analysis method based on smearing ring-stiffeners to obtain an equivalent circumferential bending strength were evaluated. The limitations of this simplified method were also discussed.

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ABSTRACT: The structural performance of water tank under static and dynamic pressure loading was experimentally investigated in this paper. The loading was applied using hydraulic actuator/dropped projectile on an inflated high pressure airbag to assert static/dynamic pressure on the specimens. The failure modes and maximum resistance of the specimens were obtained from the test and compared to the numerical results. It was found from the static pressure test that the water tank filled with water exhibited up to 31% increase in flexural resistance under static loading as compared to the empty water tank with the same material and geometry. The improvement was attributed to the effects of water in maintaining the section modulus and delaying the local buckling of the tank. Water was also found to be useful in reducing the deformation of the tank under dynamic pressure loading. Nonlinear finite element analysis was conducted to investigate the behavior of water tank subject to static and dynamic pressure loading and the accuracy of the numerical models was verified by comparing the predicted displacement responses with those observed from the tests.


ABSTRACT: The water storage tank was proposed as a multi-functional facade system characterizing energy saving and blast resisting. The energy saving performance, not presented in this paper, has been evaluated by experimental and numerical methods. The aim of this study is to propose simplified methods to reasonably
predict the response of water storage tank under blast loading. Based on the equivalent single-degree-of-freedom (SDOF) method, the shock spectrum and dimensionless pressure–impulse (P–I) diagram were established, which can be used to evaluate the damage levels of water storage tanks subject to blast loading. The equivalent SDOF method cannot capture the varying deflection shape of structure during motion, herein the Lagrange equation method that allows for multiple deflection shape functions was proposed to predict the structural response. It was shown that the Lagrange equation method was better than the SDOF method since it could provide conservative predictions in all response regimes. Furthermore, the varying dynamic increase factor (DIF) with strain rate was incorporated into the Lagrange equation method to capture the strain rate effects.

ABSTRACT: The paper presents experiments and finite element simulations of small-scale stiffened web girders subjected to local in-plane loads, in order to examine their crushing deformations and energy absorbing mechanisms. The specimens, scaled from a tanker bottom floor, are limited by one span between the longitudinal girders and the inner and outer bottom plates. Three small-scale specimens are designed, one unstiffened web girder and two vertically stiffened web girders, in order to compare the influence of the vertical stiffeners on the structural deformation and response of stiffened web girders. This investigation provides practical information to evaluate grounding scenarios where ship bottom floor sustains local penetration. Moreover, it should have relevance to evaluate the extent of structural damage within stiffened decks during side or bow collision accidents. The experimentally recorded force–displacement responses, deformation processes and permanent deformations show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The numerical analysis discusses some aspects of particular relevance to the behaviour of ship structures subjected to accidental loads. In particular, some comments are offered on the material plasticity and fracture, the importance of specifying the precise boundary conditions and the joining details of the structure.

ABSTRACT: The Buncefield incident in the UK in 2005 involved an explosion of 240,000 m³ of vapour cloud which resulted in considerable damage to properties in the surrounding area. A number of objects that can be used as overpressure indicators such as standard steel drums were located at various points around the site. These were found deformed to different levels after the explosion. These overpressure sensitive objects were used to assess the overpressure level at the locations of the objects during the incident. This study describes full scale validation tests and numerical simulations of far-field air blast loading acting on deformable steel drums in order to investigate possible forensic methods to aid the incident investigation. Subsequently, a number of numerical models are developed in order to simulate the tests. Two models with varying complexity are used in the simulations: uncoupled Eulerian–Lagrangian model and coupled Eulerian–Lagrangian approaches. These models are validated against the test data from gas detonation explosion. Comparison between the numerical and experimental results suggests that both approaches tend to over-predict the deformation of drums due to
identified inaccuracies from test measurements and numerical methods. However, both methods can comparatively capture the different levels of damage arising from blast loads with various intensities. These comparative levels are in general agreement with observations from test data. Parametric studies using the validated techniques are also carried out to further examine the response of steel drums. The results are summarised in the form of pressure–impulse diagrams, and typical residual shapes of drum models are selected to complement the pressure–impulse diagrams. The methods and results presented in this paper offer a very useful tool which could be employed to aid forensic investigations of future explosion incidents involving steel drums or similar field objects.

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ABSTRACT: Multi-cell thin-wall structures have drawn increasing attention and been widely applied in automotive and aerospace industries for their significant advantages in high energy absorption and lightweight. The number of cells and the topological configurations of the multi-cell thin-wall structures have a significant effect on the crashworthiness. In order to investigate the effect of the number of cells and the topological configurations of multi-cell structures on their crashworthiness characteristics, this paper first sets up the simulation models of multi-cell tubes and verifies their accuracy with the quasi-static and dynamic impact experiments. Second, it compares the energy absorption characteristics of the multi-cell structures with different numbers of cells and topological configurations under dynamic impact condition using finite element analysis (FEA). The results show that the mean crushing force (MFC) and specific energy absorption (SEA) increase with the increase in the number of cells of the multi-cell tubes, among which the five-cell tube has the best energy absorption characteristics. Third, a parametric study is carried out to investigate the effects of wall thickness and topology configurations on the crashworthiness of five-cell tubes. Finally, the multiobjective Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to further optimize the five-cell tube for maximizing specific energy absorption and minimizing peak crushing force (PCF). The optimal five-cell tube has excellent crashworthiness and is a potential energy absorber.

ABSTRACT: The findings from an experimental study investigating the mechanical response and deformation mechanisms of empty and aluminum foam filled braided stainless steel tubes are presented within this manuscript. Tube specimens were impacted using a custom built pneumatic gun and projectile at incident velocities ranging from roughly 21 m/s to 27 m/s. Deformation and failure mechanisms resulting from the impact process were identified through the use of a high speed, high-resolution camera. Forces arising during the impact event were measured using ICP load cells and a modular DAQ system mounted within the projectile. The braided tubing utilized within this study was woven from AISI 304 stainless steel possessing a nominal
wire diameter of 0.51 mm, nominal external diameter of 64.5 mm, and a length of 330 mm. Aluminum foam cores of density levels ranging from 179.22 kg/m$^3$ to 520.47 kg/m$^3$ were incorporated within the braided tubes having rectangular foam core geometry. Failure of tube specimens, for foam core densities typically less than 400 kg/m$^3$, was observed to initiate within the vicinity of the annular clamps as a result of the elevated tensile forces and localized bending present within the clamped regions. For foam core densities greater than approximately 400 kg/m$^3$, failure was noted to shift the initiation of failure to the tube mid-span as a result of localized wire failure. Levels of absorbed energy were noted to range from 1.78 kJ to 2.95 kJ for the tube specimens examined within this study.


ABSTRACT: This paper presents a computational framework that analyzes the effect of fluid–structure interaction (FSI) on the impact dynamics and puncture failure of pressurized commodity tank cars carrying hazardous materials. Shell (side) impact tests have been conducted on full scale tank cars resulting in deformed or punctured tank cars. A finite element (FE) modeling method is applied that explicitly simulates the three distinct phases in a tank car loaded with a liquefied substance: pressurized gas, pressurized liquid and solid structure. Furthermore, an equivalent plastic strain based fracture initiation criterion expressed as a function of stress triaxiality is adopted to depict the fracture behavior of the tank car steel material. The fracture initiation is implemented for ductile, shear and mixed fracture modes and followed by further material deterioration governed by a strain softening law. The force, displacement and impact energy results obtained from the FE analysis show good agreement with the corresponding shell impact test data. The simulations demonstrate that FSI plays a critical role in predicting the correct dynamics of tank car impact. The puncture resistance of a tank car, characterized as limit impact conditions in terms of puncture energy or puncture velocity, is further analyzed in shell impact scenarios. The puncture energy is shown to increase as the initial fluid pressure decreases, the tank car thickness increases or the effective impactor size increases. Quantitative correlations between puncture energy/velocity and each of these factors are obtained using the FE analysis method developed in this paper.


ABSTRACT: Composite materials currently have several uses, including aeronautical, marine, and piping applications. Composites are well-known for their specific strength and stiffness; however, the tolerance of composites to out-of-plane loading is a disadvantage. Impact can dramatically reduce the load carrying capacity to 30%. On the other hand, crashworthiness should be considered when characterizing the materials for transportation applications. In the current paper, glass/epoxy pipes were laterally compressed after being impacted by a Charpy impact tester. The objective was to characterize the residual crashworthiness assessment parameters and attempt to correlate them with the applied impact energy levels. The value of the impact energy ranged from 41 J to 171 J. The effects of the number/position of impacts and the impact energy values on the crashworthiness of the tube were investigated. The results showed that the peak load, crush force efficiency, and
crush load stability were highly affected by the existence of the impact damage. The peak load was reduced by 44% of its original value, whereas the crush force efficiency and crush load stability were increased by 61% and 53%, respectively, when subjected to four 114.3 J impacts. The other test parameters did not show a significant dependency on the impacts. In general, the impacts before compression act as damage initiators (i.e., triggering of composite tubes).

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ABSTRACT: The low velocity impact response of lightweight aluminium sandwich panels, based on a curvilinear aluminium alloy core, has been investigated to evaluate their energy-absorbing characteristics and to identify the associated failure mechanisms. Finite element models are then developed to predict the dynamic response of these lightweight structures. Here, an elasto-plastic model, capable of accounting for strain-hardening effects, material rate-dependence, as well as the relevant damage criteria, was employed to predict the dynamic response of the targets. The finite element models were then validated by comparing their predictions against the corresponding experimental results. Good agreement was obtained, indicating that the models are capable of predicting the dynamic behaviour of these all-metal sandwich structures under low velocity impact conditions. Once the finite element model had been validated, it was used to assess the effect of varying key test parameters, such as the projectile diameter, the material properties of the metal substrate as well as the angle of obliquity on the impact response. Here, it has been shown that the perforation energy increases as the impact angle is increased and also as the projectile diameter increases. An investigation of seven different all-metal sandwich structures has shown that an aluminium alloy offers the highest specific perforation resistance under conditions of low velocity impact loading.


ABSTRACT: This paper presents an analytical method to evaluate the crushing force of girders with stiffened web subjected to local in-plane loads. A new theoretical model, inspired by existing simplified approaches, is developed to describe the progressive plastic deformation behaviour of girders with stiffened web, which is of considerable practical importance to estimate the extent of structural deformation within ship web girders during collision and grounding accidents. In the last two decades, various simplified methods have been proposed to describe the crushing characteristics of girders with unstiffened web, but the existing theories cannot capture well the crushing behaviour of girders with stiffened web. Therefore, a new simplified deformation model of girder with stiffened web is proposed comprising two equal folding elements and new formulae for evaluating the crushing force are proposed on the basis of this new folding deformation model. The predictions are compared with experimental force–displacement responses.
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ABSTRACT: Ships and offshore platforms that operate in Arctic regions at low temperatures are likely subjected to impact loads that arise from collisions with icebergs. The aim of this paper was to examine the nonlinear impact response of steel-plated structures in an Arctic environment. In addition to material tensile tests for characterisation of the mechanical properties of polar-class high-tensile steel of grade DH36, an experimental study was undertaken in a dropped-object test facility on steel-plated structure models under impact loads and at low temperatures equivalent to those in Arctic regions. LS-DYNA nonlinear finite element computations were also performed for the corresponding test models. We conclude that nonlinear finite element analyses are useful in the analysis of the nonlinear impact structural responses involving yielding, crushing and brittle fracture at low temperatures as long as the modelling techniques are adequate. The conclusions and insights developed in this paper should be useful in the safety design of ships and offshore platforms intended for operation in Arctic regions.

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ABSTRACT: A series of close-in underwater blast tests were performed on sandwich panels consisting of two aluminum alloy face-sheets and a honeycomb core to investigate blast resistance of metallic sandwich panels. The blast resistance of sandwich panels was assessed in terms of structural deformation resistance represented by back face-sheet deflection and intensity of the secondary pressure wave, which is determined by the maximum velocity of the back face-sheet. It was found that the secondary pressure wave shows an inverse trend with face-sheet thickness while a positive relationship with core density, which is determined by foil thickness in this study. A failure mode map was adopted to identify the effect of design parameters on the structural failure mechanism at this blast magnitude. Finally, a comparison of underwater blast resistance between sandwich panels and monolithic plates of equivalent mass was performed. The comparative study provided further experimental evidence for the benefit of sandwich construction in terms of deformation resistance and secondary pressure wave intensity even at high blast magnitude. It was also suggested that the benefit of deformation resistance was amplified with increase in equivalent thickness.

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ABSTRACT: The compressive response of sandwich plates with polyvinyl chloride (PVC) foam cores and aluminum facesheets to water-based impulsive loading is analyzed using an instrumented impulsive loading apparatus called the underwater shock loading simulator (USLS) and a fully-dynamic 3-D computational framework. The loading conditions analyzed are similar to those in underwater blasts. The study focuses on the overall deformation, strain recovery and impulse transmission which are quantified as functions of structural attributes such as core density, front and backface masses, and incident impulsive load intensity. Measurements obtained using high-speed digital imaging and pressure and force sensors allow the computational models to be calibrated and verified. Quantitative loading–structure–performance maps are developed between the response variables and structural and load attributes. The results reveal that core density has the most pronounced influence on core compressive strain and impulse transmission. Specifically, for severe impulse intensities, a 100% increase in core density leads to a 200% decrease in compressive strain and a 500% increase in normalized transmitted impulse. On the other hand, structures with low density cores are susceptible to collapse at high impulse intensities. Additionally, the compressive strains and transmitted impulses increase monotonically as the mass of the frontface increases, but are unaffected by backface mass. For the same core density, a 100% increase in facesheet thickness leads to a 25% and 50% increase in the core strain and normalized transmitted impulse, respectively. The results and performance maps are useful for designing marine structures with restricts, such as hull sections and pipelines backed by water or machinery.

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ABSTRACT: A fluid model is developed and used in combination with Abaqus/Explicit to investigate the effects of graded foam cores on the loading of a sandwich spherical shell subject to underwater explosion from the inner side, after having validated the modeling technique by reproducing results by other authors. Based on the relation between the core strength and the stiffness of the outer face sheet (OFS), four different situations are considered to discuss the graded effects. It is demonstrated that for the case of relatively strong cores and the OFS with low stiffness or soft cores and the OFS with high stiffness, the core arrangement of low/medium/high (relative density from the inside to the outside) has the best performance to shock loadings which is a consequence of the effects of the fluid–structure interaction and the energy absorption capability; on the other hand, for the case of intermediate core strengths and stiffness of the OFS where the pulling-back force due to the stretching of the OFS is close to the core strength, the configuration of high/medium/low has the best performance due to its higher energy absorption efficiency of the foam and lower transmitted stress.

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ABSTRACT: Structural response and failure modes of honeycomb sandwich panels subjected to a shock (impulsive pressure) followed by a high velocity projectile impact were investigated using detailed finite element simulations. Performance of sandwich panels was quantified by maximum transverse deflection of the bottom face sheet and core crushing strain along with an investigation of their optimal behavior. Three failure modes were observed in panels – core failure, top face failure, and tearing and detachment from support. Failure maps of honeycomb sandwich panels were constructed to show the failure mode of panels as a function of shock intensity, projectile velocity and panel core relative density. In addition, a limited set of simulations were carried out to study the role of incident angle of projectile on the overall performance of a panel. These simulations showed that maximum deflection occurred for vertically impacting projectiles. However, we found that this did not directly translate to maximum core crushing strain in sandwich panels. The results provide new insight into the performance and failure of sandwich panels under complex dynamic loading conditions, and further highlight the potential of these panels for development of threat-resistant structural systems.

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“Crashworthiness design of quenched boron steel thin-walled structures with functionally graded strength”,
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ABSTRACT: Thin-walled structures have been widely used as energy absorbers in industries such as automobile, shipping and aerospace. Different from recent well-studied columns consisting of aluminum, this paper introduced a kind of quenched boron steel column formed by hot stamping technology, with wall strength varying along the axial direction with a specific gradient, i.e. functionally graded strength (FGS). These FGS structures are found to have higher crashworthiness in terms of peak crash force (PCF) and specific energy absorption (SEA) compared with the counterpart structures with uniform strength (US). Based on a series of numerical simulation results, it revealed that the crashing behavior of FGS columns is significantly affected by both the strength gradient and the strength in the impact end. To optimize the crashworthiness (PCF and SEA) of the FGS structures, multi-optimization based on different metamodeling techniques such as response surface method (RSM), radial basis function (RBF) neural network model, kriging (KRG) model and optimization algorithm of non-dominated sorting genetic algorithm (NSGA-II) are performed. Pareto fronts of several alternative thicknesses were obtained to provide guidance for the FGS column design and give a good insight into actual crashing engineering. It is interesting to find that the gradient exponent is taken as the main design variable when the PCF is restricted below a certain value while the parameter of steel strength in impact end will be taken as the main design variable on the contrary. The comparison of Pareto fronts between the FGS and US columns showed that the FGS columns enhance the SEA and lower the PCF concurrently. Furthermore, among the three metamodeling techniques, the RSM models are proven to be the most suitable approach for the crashworthiness optimization of FGS structure.

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ABSTRACT: The large-deflection behavior of the clamped stiffened plates subjected to confined blast load is investigated through experimental tests, theoretical calculation and numerical simulation in this paper. The blast load in confined space lasts longer and has more complex form compared to the shock waves from an open space explosion. The influence of elastic-plastic effect on the dynamic response of blast loaded plate should be taken into account in theoretical prediction of permanent displacement. Besides, evident yield lines, which could change the deformed shape of the plates, can be always found around the clamped edges and the diagonals of plates. The global deformation of a plate cannot be represented by a simple shape function of a smooth surface. In this paper, a series of experimental tests of square stiffened plates under confined blast load was conducted. Based on experimental observation and assumed-modes, an elastic-plastic analytical model for blast loaded stiffened plates is presented, in which the effects of yield line pattern and elastic-plastic deformation are considered. The Lagrange motion equation that contains the total strain energy, potential energy and kinetic energy of stiffened plates and blast load system is established and solved. Numerical simulations are performed to investigate the influence of strain rate effect of material and boundary conditions on the dynamic responses of stiffened plates. By comparing the numerical results, the rationality of hypothetic conditions employed in analytical model is verified. The classical rigid-plastic and elastic-plastic methods were also used to calculate the dynamic response and permanent displacements of test specimens. The comparison results showed that the theoretical calculation model presented in this paper is feasible and of high precision and practicability.


ABSTRACT: Current study investigates the deformation behavior and energy absorption of thin walled cylinders having multiple holes when subjected to dynamic compressive loading. A split-Hopkinson pressure bar (SHPB) was utilized for obtaining short duration dynamic loading. A SIM02-16 high speed camera was employed to capture the real time images of the deformation process. Holes of different diameters were arranged in different geometric configurations along the length of the cylinders. The effect of holes and their arrangement on peak load reduction and energy absorption characteristics of the cylinders was investigated. From the experimental study, it was observed that the diameter of the holes, their spacing, and pattern of arrangement, all have a strong influence on the peak load transmitted by the cylinders and also on the deformation pattern. Larger number of smaller diameter holes resulted in higher peak load reduction. Subsequently a numerical analysis was carried out using the commercially available finite element package Abaqus Explicit 6.11. The results of the analysis revealed that both the level of stress concentration induced by the holes and the interaction of stresses between adjacent holes have a role to play in reducing the peak load through controlling the deformation.

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ABSTRACT: A tube-core sandwich panel was designed to serve as anti-blast panel of blast resistant walls. Steel tubes are non-expensive and strong for anti-blast walls, and can be easily connected with face sheets through welding. Static three-point bending experiments, close-in explosion experiments and contact explosion experiments were performed to explore its anti-blast ability. The tough interface and shear-resistant tube-core endow the panel with high bending rigidity. In close-in explosion, the front face mitigates the shock wave corrugations through corrugated plastic deformation and the panel is rigid enough to resist the shock wave. In contact explosion, the panel attenuates the shock wave through tube-crushing and skin-tearing. Appropriate thicknesses of the front face and the tube wall promote energy absorption. The experiments indicate that spaced tube-core panel is the better choice for close-in explosions while connected tube-core panel has advantages under contact explosions.


ABSTRACT: This study presents the analytical, numerical, and experimental results of moderately thick hemispherical metal shells into the plastic buckling range illustrating the importance of geometry changes on the buckling load. The hemispherical shell is rigidly supported around the base circumference against horizontal translation and the load is vertically applied by a rigid cylindrical boss at the apex. Kinematics stages of initial buckling and subsequent propagation of plastic deformation for rigid-perfectly plastic shells are formulated on the basis of Drucker–Shield’s limited interaction yield condition. The effect of the radius of the boss, used to apply the loading, on the initial and subsequent collapse load is studied. In the numerical model, the material is assumed to be isotropic and linear elastic perfectly plastic without strain hardening obeying the Tresca or Von Mises yield criterion. Both axisymmetric and 3D models are implemented in the numerical work to verify the absence of non-symmetric deformation modes in the case of moderately thick shells. In the end, the results of the analytical solution are compared and verified with the numerical results using ABAQUS software and experimental findings. Good agreement is observed between the load–deflection curves obtained using three different approaches.

ABSTRACT: Poorly designed structures buckle under the action of an unbearable axial force, self-weight or a combination of different axial forces. The increasing exploration of nanostructures for future devices dictates that the buckling of uniform single-walled carbon nanotubes (SWCNTs) and single-walled carbon nanocones (SWCNCs) should be well studied. Therefore in this paper, the investigation of the boundary value problems associated with the buckling of the SWCNTs and SWCNCs is carried out. The theoretical formulation of the mathematical model for these nanostructures is premised on the newly advanced nonlocal continuum theory. Predictions of the \( nN \) range critical loads of SWCNT and SWCNT under self-weight and an axial tip force are carried out with an optimized variant of the Galerkin method. The analysis reveals the degree of influence of the nonlocal parameter on the critical loads of the SWCNTs and the SWCNCs under different boundary conditions. A non-monotonically increasing trend is observed between the critical load values and increasing aspect ratio of the SWCNT. In the case of the SWCNC, the analysis reveals a positive linear relationship between the critical loads and the apex angles of the SWCNC. The apex angle also acts as a counterbalance to the small-scale coefficient.


ABSTRACT: Koiter’s linear shell theory applies to isotropic elastic materials and to anisotropic materials that exhibit reflection symmetry of the elastic properties with respect to the shell mid-surface. To the extent that such shells are exceptional, classical linear shell theory is incomplete. This lacuna is addressed here through a systematic procedure, applicable equally to all kinds of material symmetry, which entails an expansion of the potential energy of the shell in powers of its thickness in a manner reminiscent of Koiter’s work. The variables are the displacement field of the shell mid-surface and certain director fields that arise in the course of the expansion procedure. The directors are constrained in accordance with necessary conditions arising in the exact three-dimensional theory, yielding the optimal expression for the potential energy among those of third order in the small thickness. For materials lacking reflection symmetry, it is found that the strain energy of the shell is sensitive to tangential gradients of strain in addition to the usual strain and bending strain of the conventional theory.


ABSTRACT: In this paper, a concept of “stability of quasi-static paths” that takes into account the existence of fast (dynamic) and slow (quasi-static) time scales is discussed. It is essentially a continuity property with respect to the smallness of the initial perturbations (as in Liapunov stability) and to the smallness of the quasi-static loading rate (that plays the role of the small parameter in singular perturbation problems). Three mechanical examples are presented that illustrate the similarities, the differences and the relations between this concept of “stability of quasi-static paths” and the one of Liapunov stability of some related equilibrium configurations or dynamic trajectories.
Chih-Ping Wu, Kuan-Hao Chiu and Ruei-Yong Jiang (Department of Civil Engineering, National Cheng Kung University, 1 University Road, Tainan 70101, Taiwan, ROC), “A meshless collocation method for the coupled analysis of functionally graded piezo-thermo-elastic shells and plates under thermal loads”, International Journal of Engineering Science, Vol. 56, pp 29-48, July 2012, https://doi.org/10.1016/j.ijengsci.2012.03.001

ABSTRACT: A meshless collocation method, based on the differential reproducing kernel (DRK) interpolation, is developed for the three-dimensional (3D) coupled analysis of simply-supported, doubly curved functionally graded (FG) piezo-thermo-elastic shells. The material properties of FG shells are regarded as heterogeneous through the thickness coordinate, and then specified to obey an exponent-law dependence on this. In the present formulation, the shape function at each referred node is separated into a primitive function possessing Kronecker delta properties and an enrichment function constituting reproducing conditions. By means of the present DRK interpolation, the essential boundary conditions can be readily applied, exactly like the implementation in the finite element method (FEM). An additional innovation of the present meshless method is that the shape functions for derivatives of the reproducing kernel (RK) functions are determined using a set of differential reproducing conditions, rather than differentiating these RK functions. In the implementation of the DRK interpolation-based collocation method presented in this work, several crucial parameters are discussed, such as the optimal support size and highest-order of the basis functions. The influence of the material-property gradient index on the field variables induced in the FG shells and plates under thermal loads is also studied.


ABSTRACT: In this work, the dynamics of in-plane surface deformation modes of an inflated toroidal membrane has been studied. We have considered both isotropic and anisotropic but homogeneous material properties. The covariant form of the equation of motion assuming a general in-plane small amplitude displacement field has been derived from the variational formulation which clearly shows the effect of curvature on the dynamics. The curvature term in the equation of motion may be interpreted as an effective quadratic potential in the Lagrangian with a coupling proportional to the Ricci curvature scalar of the membrane. The variational problem is discretized, and is subsequently analyzed to obtain the eigenfrequencies and modes of vibration. The effect of geometric and material properties on the modal dynamics has been studied. The effect of anisotropy on the modal dynamics of the torus has also been studied. Certain invariant deformation measures have been defined which are found to characterize the modes in terms of presence or absence of nodal curves/points.


ABSTRACT: In this paper, the in-plane and out-of-plane flexural vibrations of microscale pipes conveying fluid with clamped–clamped ends are examined theoretically, by modifying the classical equations of motion with consideration of the size effects of micro-flow and micro-structure. The theoretical model including an additional parameter associated with the flow velocity profile and another material length scale parameter representing the size effect of micro-structure is valid for both straight and curved pipe systems. The results of
calculating the evolution of natural frequencies for straight pipes with increasing mean flow velocity show that the material length scale parameter tends to stiffen the microscale pipe and hence increases the critical flow velocity while the parameter describing the effect of flow velocity profile would decrease the critical flow velocity. For curved pipes, however, the modified inextensible theory predicts that the effect of micro-flow on the in-plane and out-of-plane natural frequencies may be not visible.


ABSTRACT: The dynamics of fluid-conveying cantilevered pipe consisting of two segments made of different materials is studied, focusing on the effects induced by different length ratios between the two segments. Two kinds of hybrid pipes are considered: one is made of steel and aluminum and the other is made of aluminum and epoxy. The complex frequency of the four lowest modes of the hybrid system is calculated in two representative cases for successively increasing values of the flow velocity to demonstrate how transition from stability to instability takes place. Compared with a uniform pipe conveying fluid, it is found that the hybrid pipe is capable of displaying more complex and sometimes unexpected dynamical behaviors. The numerical results show that in such a hybrid pipe system, an instability–restabilization–instability sequence would occur as the flow velocity is successively increasing. When the length ratio between the two segments is successively increased, the lowest order of unstable modes may frequently shift from one to another. It is also demonstrated that with increasing flow velocity, the flutter instability first occurring in the fourth mode is possible and a certain unstable mode may suddenly regain stability, which has not been reported before. Furthermore, when the segment made of softer material is placed at the clamped end, the system is much easier to lose stability. Some of these new results observed in the hybrid pipe system are also expected to be helpful in controlling the dynamical behaviors of fluid-conveying pipes.

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ABSTRACT: The microfluid-induced nonlinear free vibration of microtubes is studied in this paper. A derivation of the nonlinear equation of motion is presented based on Hamilton’s principle and a modified couple stress theory. The geometric nonlinearity, arising from the mid-plane stretching, is taken into account. The modified couple stress theory is used to capture the micro-structure dependent size effects when the microtubes are at micron- and submicron scales. The static postbuckling problem is then studied and the size-dependent postbuckling configurations are analyzed. The approximate solution to the nonlinear free vibration is obtained using the homotopy analysis method. The influences of internal material length scale parameter, outer diameter, flow velocity, and Poisson’s ratio on the dynamic behavior are discussed in detail.

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ABSTRACT: When simulating the propagation of a pressure pulse in arteries, the discretization parameters (i.e. the time step size \( \Delta(t) \) and the grid size \( \Delta(x) \)) need to be chosen carefully in order to avoid a decrease in amplitude of the traveling wave due to numerical dissipation. In this paper the effect of numerical dissipation is examined using a numerical fluid–structure interaction (FSI) model of the pulse propagation in an artery. More insight in the influence of the temporal and spatial resolution of the wave on the results of these simulations is gained using an analytical study in which the scalar linear one-dimensional transport equation is considered. Although this model does not take into account the full complexity of the problem under consideration, the results can be used as a guidance for the selection of the numerical parameters. Furthermore, this analysis illustrates the difference in accuracy that can be obtained using a second-order implicit time integration scheme instead of a first-order scheme. The results from the analytical and numerical studies are subsequently used to determine the settings necessary to obtain a grid and time step converged simulation of the wave propagation and reflection in a simplified model of an aorta with repaired aortic coarctation. This FSI model allows to study the hemodynamic impact of a stiff segment and demonstrates that the presence of a stiff segment has an important impact on a short pressure pulse, but has almost no influence on a physiological pressure pulse. This phenomenon is explained by analyzing the reflections induced by the stiff segment.


ABSTRACT: Mechanics of a functionally graded cylinder subject to static or dynamic axial loading is considered including a potential application as energy absorber. The grading in the radial direction is such that the mass density and stiffness are power functions of the radial coordinate as may be the case with variable-density open-cell or closed-cell foams. Exact solutions are obtained in the static problem and in the case where the applied load is a periodic function of time. The absorption of energy is analyzed in the static problem that is reduced to an easily implementable nondimensional formulation. It is demonstrated that by grading the material in the radial direction it is possible to achieve higher energy absorption while at the same time saving weight.


ABSTRACT: In this paper, the cylindrical thin-shell model is developed based on modified strain gradient theory. For this purpose, the study develops the thin shell theory, having considered size effects through modified strain gradient theory. Besides, partial equations of shell motion with classical and non-classical corresponding boundary conditions are derived from Hamilton principle. Finally, by way of example, the free vibration of the single-walled carbon nanotube (SWCNT) is investigated. The study models the SWCNT as a simply-supported shell. Besides, the Navier procedure is used to solve the vibration problem. The results of the new model are compared with those of the couple stress model and the classical theory, leading to the conclusion that the mentioned models are special cases of the modified strain gradient theory. The findings also
indicate that the rigidity of the nanoshell in the modified strain gradient theory is greater than that in couple stress model and the classical theory, which leads to the increase in natural frequencies. Furthermore, the effect of the material length scale parameter on the vibration of the nanoshell for different lengths is taken into account.

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ABSTRACT: Some geometric and kinematic relations associated with the curve moving on the shell base surface are discussed. The extended surface transport relation and the extended surface divergence theorems are proposed for the piecewise smooth tensor fields acting on the regular and piecewise regular surfaces. The recently formulated resultant, two-dimensionally exact, thermodynamic shell relations – the balances of mass, linear and angular momenta, and energy as well as the entropy inequality – are completed by the corresponding jump conditions at the moving (non-material) and stationary (material) singular surface curve.

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ABSTRACT: In the framework of the geometrically nonlinear 6–parameter resultant shell theory we give a characterization of the shells without drilling rotations. These are shells for which the strain energy function \( W \) is invariant under the superposition of drilling rotations, i.e. \( W \) is insensible to the arbitrary local rotations about the third director \( d_3 \). For this type of shells we show that the strain energy density \( W \) can be represented as a function of certain combinations of the shell deformation gradient \( F \) and the surface gradient of \( d_3 \), namely (math). For the case of isotropic shells we present explicit forms of the strain energy function \( W \) having this property.

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ABSTRACT: The purpose of this paper is to use a weak setup to justify application of the finite element method (FEM) to the equilibrium problem for a nonlinear model of a shallow shell clamped along part of an edge constrained by a frictionless obstacle. A suitable energy space is constructed and the generalized (weak) solutions are introduced. The obstacle condition is represented by a linearized model, and convergence of approximate FEM solutions to a weak solution is established. In particular, existence of a weak solution to the problem is proved. The result essentially extends that obtained in the paper Lebedev and Neymark (2006).

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ABSTRACT: It is now well-known that when an infinitely long hyperelastic membrane tube free from any imperfections is inflated, a transcritical-type bifurcation may take place that corresponds to the sudden formation of a localized bulge. When the membrane tube is subjected to localized wall-thinning, the bifurcation curve would “unfold” into the turning-point type with the lower branch corresponding to uniform inflation in the absence of imperfections, and the upper branch to bifurcated states with larger amplitude. In this paper stability of bulged configurations corresponding to both branches is investigated with the use of the spectral method. It is shown that under pressure control and with respect to axi-symmetric perturbations, configurations corresponding to the lower branch are stable but those corresponding to the upper branch are unstable. Stability or instability is established by demonstrating the non-existence or existence of an unstable eigenvalue (an eigenvalue with a positive real part). This is achieved by constructing the Evans function that depends only on the spectral parameter. This function is analytic in the right half of the complex plane where its zeroes correspond to the unstable eigenvalues of the generalized spectral problem governing spectral instability. We show that due to the fact that the skew-symmetric operator involved in the Hamiltonian formulation of the basic equations is onto, the zeroes of the Evans function can only be located on the real axis of the complex plane. We also comment on the connection between spectral (linear) stability and nonlinear (Lyapunov) stability.


ABSTRACT: The goal of this research is to construct a mathematical model of the micromechanical experiment: an aspiration of spherical cells. Such experiment is often used to study properties of cells and their membranes. In our model the cell is considered as a fluid-filled membrane with solid-like behavior. The membrane is modeled by a hyperelastic isotropic momentless shell. The action of the internal environment is considered in two ways: a constant internal pressure and a constant internal volume. Usually the aspiration process is controlled directly by a suction pressure in a micropipette. In this paper it is also considered a model of aspiration with control by motion of a syringe piston.

Yang Liu and Hui-Hui Dai (Department of Mathematics, City University of Hong Kong, 83 Tat Chee Avenue, Hong Kong, China), “Compression of a hyperelastic layer-substrate structure: Transitions between buckling and
ABSTRACT: This paper studies the bifurcation behaviors of a hyperelastic layer bonded to another hyperelastic substrate of finite thickness subjected to compression. We aim at revealing some interesting transitions between different bifurcation modes as the geometrical parameters vary. A linear bifurcation analysis is carried out for obtaining the bifurcation condition in the framework of exact theory of nonlinear elasticity. This condition, in the form of a determinant with complicated elements, contains a few parameters, and here the task is to analyze it to determine different behaviors. From the critical stretch curves, it is found that there are two mode types for the layer: buckling mode and wrinkling mode. By further considering the eigenfunction, three types of modes for the substrate are identified, including buckling mode, buckling-surface mode and wrinkling-surface mode. A careful analysis is carried out to determine the parameter constraints for each type of modes. In particular, three critical thickness ratios and two critical aspect ratios of the layer are found. As a result, we manage to classify the plane of the aspect ratio of the layer and the thickness ratio into six domains for different mode types and whose boundaries determine where the transitions of mode types take place. Finally, an asymptotic analysis with double expansions for each unknown is carried out to give the explicit formulas for the critical mode number and the critical stretch (which also give an improvement on the existing results for a layer coated to a half-space). Also, simplified relations for those critical thickness ratios and aspect ratios are derived. The asymptotic results also reveal some interesting insights, e.g., why the Poisson’s ratio has little effect and in a wrinkling mode the critical stretch is almost independent of the layer thickness.


ABSTRACT: This article studies nonlocal postbuckling behavior of both uniaxially and biaxially loaded graphene sheets (GSs) in a polymer environment based on an orthotropic nano-plate model. The van der Waals interaction force between the graphene sheets and the polymer medium is considered as a nonlinear function of the graphene’s deflection. Considering the small scale effect and using the thin plate theory, postbuckling equilibrium equations are derived with the von Karman-type geometrical nonlinearity. These equations are solved using the Galerkin method for GSs with different boundary conditions. Finally, postbuckling equilibrium path is plotted and the effects of nonlocal parameter, polymer medium, linear and nonlinear coefficients of the vdW interaction, boundary and loading conditions and geometric properties are studied in detail.

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ABSTRACT: In this paper, the thin conical shell model is developed by using the modified couple stress theory. This non-classical formulation can incorporate size effects in nano/micro scales. For this purpose, the thin shell model is used along with the modified couple stress theory, and the equations of motion with partial differentials and classical and non-classical boundary conditions are derived by using Hamilton’s principle. Finally, the free vibrations of the single-walled carbon nanocone (SWCNC) are examined as a special case. The SWCNC is modeled as simply supported, and the Galerkin method is used to solve the vibrational problem.
Results of the new formulation are compared to the classical theory. The results show that nanoshell rigidity is greater in the modified couple stress theory than in the classical theory, which leads to an increase in the natural frequencies. Also, the effect of size parameter on the vibration frequency of SWCNC in different lengths and apex angles is examined.


ABSTRACT: In this paper, a nonlinear theoretical model for three-dimensional vibration analysis of curved microtubes conveying fluid with clamped–clamped ends is developed and analyzed based on a modified couple stress theory and the Hamilton’s principle. This new theoretical model contains a material length scale parameter that can capture the size effect. In-plane and out-of-plane bending motions, axial motion and twist angle of the microtube are considered in the proposed model. The Lagrange nonlinear axial strain is adopted to obtain the static deformation induced by internal fluid flow. The derived equations of motion are discretized through the Galerkin method. Linearized equations around the static deformation are obtained from the discretized equations, and then the evolution of in-plane and out-of-plane natural frequencies for the curved microtube with various values of flow velocity and material length scale parameter is investigated. The results show that size effect on the vibration properties is significant when the characteristic size of the microtube is comparable to the internal material length scale parameter, and no instabilities are possible for curved microtubes if the nonlinear axial deformation is considered. Therefore, both the size effect and the axial nonlinearity have to be incorporated in the design of curved microscale beam/tube devices and systems.

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ABSTRACT: The ascending branch of the aorta is one of the most stressed organ of the arterial system. We aim to design a biomechanical model for analysing the aorta dynamics under a shock. The model includes the aorta layers and the influence of the blood pressure. We undertake a three-dimensional modal analysis of the coupled aorta–blood system. We determine in the present work the coupled natural frequencies and the modes shapes of the system of the aorta and blood. Three models are presented in this study: three-layers model, two-layers model and one layer model. For the analytical solving a potential technique is used to obtain a general solution for an aorta domain. The finite element model is then validated by these original analytical solutions. The results from the proposed method are in good agreement with numerical solutions.

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ABSTRACT: In this paper the theory of nonlinear electroelasticity is used to examine radial deformations of a thick-walled spherical shell of soft dielectric material with compliant electrodes on its inner and outer surfaces combined with an internal pressure. A general expression for the dependence of the pressure on the deformation and a potential difference between the electrodes, or uniform surface charge distributions on the electrodes, is obtained in respect of a general incompressible isotropic electroelastic energy function. To illustrate the behavior of the shell specific forms of energy functions are used for numerical purposes, for either fixed potential difference or fixed charge distribution. Explicit general results are given for the limiting case of a thin-walled (or membrane) shell. Depending on the elastic part of the energy function (as distinct from that part which involves the electric field) different behaviors are obtained, including non-monotonicity of the pressure–radius relationship reminiscent of that known in the purely elastic situation, but moderated by the presence of an electric field.

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ABSTRACT: The extension of a cylinder subjected to torsion was investigated by Poynting (1909) and the nonlinear phenomenon has since been called the Poynting effect. Under combined axial and torsional loading, the twist is also dependent on the axial loading as shown by Wang and Wu (2014a), who named this the axial force–twist effect. This paper investigates the relations between these effects in a bilayered cylindrical composite within the framework of second-order elasticity. The results show that: (1) either effect can be positive or negative, (2) there can only be three states, e.g., under tension–torsion either both effects are negative, or both positive, or if they differ in sign the Poynting effect must be positive and the axial force–twist...
effect must be negative, (3) certain logical relations between the effects exist, e.g., if under tension–torsion loading the Poynting effect is negative, the axial force–twist effect must be negative, (4) there exists a reduced elastic-geometric parameter between each effect and the associated applied loading, and (5) both effects are strong functions of the elastic and geometric inhomogeneities. These findings are significant for applications in regenerative medicine such as the design of replacement tissues.


ABSTRACT: In this work the mechanical response of hyper-elastic spherical membranes subjected to dynamic inflation is revisited. Specifically, a comprehensive analysis on the role that the constitutive behaviour of the material has on the mechanical stability of the membrane has been developed. Six different strain-energy functions, frequently used to approximate the constitutive behaviour of elastomeric solids, have been considered: three of the Mooney–Rivlin class and three of the Ogden class. For all the constitutive models used, the material parameters have been obtained from Bucchi and Hearn (2013a, 2013b), where the same set of experimental results was used to calibrate the models. We show that essential features of the dynamic response of the spherical shell are closely related to the strain-energy function selected to describe the constitutive behaviour of the membrane. As reported by Bucchi and Hearn (2013a, 2013b), this issue is frequently overlooked within the literature since too often only one strain-energy function is used to address this type of dynamic problems.


ABSTRACT: For structures at nanoscale, the surface effects can be important due to the high ratio of surface area to volume. In the current investigation, the nonlinear axial postbuckling behavior of geometrically imperfect cylindrical nanoshells is studied including surface stress effects. For this purpose, Gurtin–Murdoch continuum elasticity theory in conjunction with von Karman–Donnell-type geometric nonlinearity is implemented into the classical shell theory. By the developed size-dependent shell model, the surface effects which include surface elasticity and residual surface stress are taken into account. In order to satisfy balance conditions on the surfaces of nanoshell, a linear variation through the thickness is considered for the normal stress component of the bulk. Based on the variational approach using virtual work's principle, the non-classical governing differential equations are derived. In order to solve the nonlinear problem, a boundary layer theory is employed which contains simultaneously the nonlinear prebuckling deformations, initial geometric imperfections and large deflections corresponding to the postbuckling domain. Subsequently, a two-stepped singular perturbation methodology is utilized to predict the nonlinear critical buckling loads as well as the postbuckling equilibrium paths. It is observed that by taking surface stress effects into account, the both critical buckling load and critical end-shortening of a cylindrical nanoshell made of Silicon increase.

ABSTRACT: In this study, the buckling and postbuckling analysis of FG micro-plates under different kinds of traction on the edges is investigated based on the modified couple stress theory. The static equilibrium equations of an FG rectangular micro-plate as well as the boundary conditions are derived using the principle of minimum total potential energy. The analytical solutions are developed for three case studies including: simply supported micro-plates subjected to uniform transverse load and biaxial tractions, clamped-simply supported micro-plates under uniform transverse load and axial traction, and simply supported micro-plates subjected to shear traction. All plate properties except the length scale parameter are assumed to vary through the thickness according to the simple power law. The numerical results present the effects of the aspect ratio, material length scale parameter and power index on the critical values of traction and the curves of static equilibrium paths. Findings indicate that the length scale parameter is the most effective factor on the critical buckling values. Meanwhile, the aspect ratio has the most influence on the forms of the static equilibrium paths.

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ABSTRACT: It is well-known that for most spherical and cylindrical rubber balloons the pressure versus volume curve associated with uniform inflation both has an N-shape, but their shape bifurcation has different characters: whereas a spherical balloon tends to bifurcate into a pear shape through localized thinning near one of the poles, a cylindrical balloon would always bulge out locally in a symmetric manner. To understand the connection between these two different bifurcation behaviors, we study in this paper the shape bifurcation of an ellipsoidal balloon which becomes a spherical balloon when the three axes are identical, and approximates a cylindrical balloon when one axis is much larger than the other two axes. The ellipsoidal shape is obtained by rotating an ellipse about one of its axes, that gives rise to two possibilities: a rugby shape or a pumpkin shape. It is shown that for a rugby-shaped balloon, there exists a threshold axes ratio below which the slender ellipsoidal balloon behaves more like a tube and bifurcation into a pear shape becomes impossible, whereas for a pumpkin-shaped balloon bifurcation into a pear shape is always possible.

Mehdi Dehghan, Mohammad Zamani Nejad and Amin Moosaie (Mechanical Engineering Department, Yasouj University, P. O. Box 75914-353, Yasouj, Iran), “Thermo-electro-elastic analysis of functionally graded piezoelectric shells of revolution: Governing equations and solutions for some simple cases”, International Journal of Engineering Science, Vol. 104, pp 34-61, July 2016. In this article, the three-dimensional multi-field equations of functionally graded piezoelectric (FGP) shells of revolution under thermo-mechanical loading are derived. First, the heat conduction equation for an FGP is derived and then, the displacement equations are developed considering thermal effects. The coupling is one-way, i.e. the temperature field affects the displacements and stresses while the back influence of the displacement on the temperature is disregarded. The Hamilton's principle is used to derive the governing equations of motion, in presence of system rotation effects,
for thick shells of revolution with variable thickness and arbitrary curvature. Material properties are assumed to vary in various directions according to an arbitrary function. For the sake of simplicity and verification of derivation, the heat conduction and governing equations of motion have been reduced for a functionally graded piezoelectric cylindrical shell under thermal loading. In order for the general equations to be verified, two simple examples are investigated, i.e. thermal stresses in hollow cylinder and sphere. Correctness and generality of the present results can be justified given the capability of these equations for different geometries and material properties.


ABSTRACT: The aim of this paper is to develop a nonlinear theoretical model for cantilevered micropipes/microbeams conveying fluid and to explore the possible size-dependent nonlinear responses based on the modified couple stress theory. Compared to previous work, this newly developed nonlinear model can be utilized for predicting the post-instability nonlinear dynamics of fluid-conveying micro-cantilever more than its linear dynamics. By considering the geometric nonlinearities, the gravity, and the effect of loose supports at the downstream end, the nonlinear equation of motion is derived using the Hamilton's principle. The governing partial differential equation is further discretized with the aid of Galerkin's approach. Numerical results show that the fluid-conveying micro-cantilever is capable of displaying rich dynamical behaviors. For a ‘horizontal’ or ‘hanging’ micropipe conveying fluid, it is found that flutter instability occurs at a critical flow velocity, beyond which the micropipe would undergo a limit cycle motion; for a ‘standing’ micropipe with relatively long length, however, both buckling and flutter instabilities could occur. More interesting dynamical behavior has been obtained for a modified micropipe system with loose supports at its tip end. In the presence of nonlinear constraining force resulted from loose supports, construction of bifurcation diagrams with the flow velocity as variable parameter and some corresponding phase-plane portraits have shown that chaotic vibrations do indeed arise, following a sequence of period-doubling bifurcations. It is also demonstrated that the presence of small length scale can enhance the stability of the micropipe. However, size dependence of the post-flutter responses for the system is not pronounced.

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ABSTRACT: This paper proposes an improved molecular structure mechanics (iMSM) method to study the wrinkling characteristics of annular graphene sheet (AGS). An idea of variable cross-section beam, combined with 3-node Timoshenko beam, is introduced in the iMSM model for considering the flexibility of C-C bond and C-C joint simultaneously, and the stiffness matrix of beam element is deduced for later calculation. The parameters of equivalent beam are obtained by using an interior point optimization approach. Based on the proposed iMSM model, the wrinkling characteristics of AGS are simulated, which are verified by molecular
dynamic (MD) simulation. A predicted model is used to evaluate the wrinkling level of AGS, which agrees well with the iMSM simulation, and then the effects of beam parameters on graphene wrinkling are also analyzed. The results indicate that our proposed model is reliable to the wrinkling analysis of AGS and may be further used for other researches on graphene.

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ABSTRACT: An asymptotically exact two-dimensional theory of elastic-piezoceramic sandwich shells is derived by the variational-asymptotic method. The error estimation of the constructed theory is given in the energetic norm. As an application, analytical solution to the problem of forced vibration of a circular elastic plate partially covered by two piezoceramic patches with thickness polarization excited by a harmonic voltage is found.

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ABSTRACT: The edge wrinkling of a uniformly stretched circular elastic plate subjected to a central concentrated load is considered within the framework of the Föppl–von Kármán nonlinear plate theory. Singular perturbation methods are employed to obtain a three-term asymptotic formula for the critical load in terms of a non-dimensional quantity that depends on the initial pre-stress. Comparisons between the analytical predictions and direct numerical simulations of the full bifurcation eigenproblem provide further insight into the accuracy and limitations of the derived results.

ABSTRACT: It is well-known that the implementation of concentrated forces, such as point and line loads, represents a challenging task, especially from the computational point of view, since a strong discontinuity has to be inserted in the structural model. The present paper aims to solve the static problem of laminated composite doubly-curved shell structures subjected to concentrated loads employing the Generalized Differential Quadrature (GDQ) as numerical tool, according to what has been shown by the authors in their previous works. Its accuracy and reliability features are proven for several grid distributions when the concentrated loads are modeled through the Dirac-delta function. The theoretical framework on which this approach is based is a Unified Formulation, which allows to investigate several Higher-order Shear Deformation Theories (HSDTs). The differential geometry is used to describe accurately the reference surface of various doubly-curved shell structures. The validity of the current approach is shown comparing the GDQ results with the exact and semi-
analytical ones available in the literature. A posteriori recovery procedure based on the three-dimensional equilibrium equations for a shell structure is introduced to compute the through-the-thickness variation of strain, stress and displacement components by means of the GDQ method.


**Many papers published in the journal, Engineering Structures (2012-2016):**
http://www.sciencedirect.com/science/journal/01410296

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ABSTRACT: Aircraft structures operating in severe environments may experience snap-through, causing the curvature on part or all of the structure to invert inducing fatigue damage. This paper examines the performance of beam and continuum nonlinear finite element formulations in conjunction with several popular implicit time stepping algorithms to assess the accuracy and stability of numerical simulations of snap-through events. Limitations of the structural elements are identified and we provide examples of interaction between spatial and temporal discretizations that affect the robustness of the overall scheme and impose strict limits on the size of the time step. These limitations need to be addressed in future works in order to develop accurate, robust and efficient simulation methods for response prediction of structures encountering extreme environments.

ABSTRACT: Methods of designing steel monosymmetric I-beams against lateral buckling are not well supported by research. For this paper, the inelastic buckling of monosymmetric steel I-beams under moment gradient is studied and compared with design recommendations. For welded beams in uniform bending, inelastic buckling is initiated at moments which are often close to those which cause first yield in the compression flange. Once initiated, the inelastic buckling resistance remains constant as the slenderness decreases until strain-hardening occurs. For hot-rolled beams in uniform bending, the inelastic buckling resistance increases almost linearly as the slenderness decreases. Three regimes are significant in the inelastic buckling resistances of hot-rolled monosymmetric beams under moment gradient, depending on which flange yields first and the end moment ratio. Simple linear approximations of good accuracy are developed for designing hot-rolled monosymmetric beams in uniform bending, while less accurate but conservative approximations are developed for moment gradient. The use of these approximations is illustrated by a worked example.

ABSTRACT: A model and experimental validation of shear buckling and local bearing failure of web core sandwich panels are presented. Of particular interest are steel-faced panels with stiffening metal webs and a polymer core. The metal webs provide the required panel stiffness and the foam core serves the dual purposes of preventing local buckling and providing thermal insulation. In applications, such as the building sector, in which thermal performance is crucial, the webs are thin and widely spaced to reduce conduction between the face sheets. The models of shear buckling and bearing failure account for the influence of the core material on web strength and provide closed-form solutions. The models are validated by symmetric four-point bending tests to evaluate shear buckling and asymmetric three-point bending for bearing failure. The shear buckling model predicted buckling strength to within 4% of the test results. The bearing failure model overpredicted the observed strength by 11% on average, similar to test results reported in the literature for the bearing strength of webs with no foam support.


ABSTRACT: In this paper a general solution to the geometrically nonlinear analysis of plates stiffened by arbitrarily placed parallel beams of arbitrary doubly symmetric cross section, subjected to arbitrary loading is presented. The plate–beam structure is assumed to undergo moderate large deflections and the nonlinear analysis is carried out by retaining nonlinear terms in the kinematical relations. According to the proposed model, the stiffening beams are isolated from the plate by sections in the lower outer surface of the plate, while the arising tractions in all directions at the fictitious interfaces are taken into account. These tractions are integrated with respect to each half of the interface width, yielding two interface lines along which the loading of the beams as well as the additional loading of the plate is defined. Their unknown distribution is established by applying continuity conditions at the interfaces, in all directions. The utilization of two interface lines for each beam enables the nonuniform distribution of the interface transverse shear forces and the nonuniform torsional response of the beams to be taken into account. Six boundary value problems are formulated and solved using the Analog Equation Method (AEM), a BEM based method. Application of the boundary element technique leads to a system of nonlinear and coupled algebraic equations which is solved using iterative numerical methods. The adopted model permits the evaluation of the shear forces at the interfaces in both directions, the knowledge of which is very important in the design of prefabricated ribbed plates.


ABSTRACT: Very different strengths are predicted by two different methods of designing steel cruciform columns. Both methods require design against local and flexural buckling, and while one method also requires design against torsional buckling, the other does not. Investigations of the elastic local and torsional buckling
and post-buckling of cruciforms columns show that these two modes are virtually identical. The first yield and inelastic buckling approaches often used to formulate methods of designing columns against flexural buckling are extended to the torsional buckling design of cruciforms. These extensions show that it is sufficient to use local buckling design to guard against torsional buckling. It is found that design methods which make separate checks against local and torsional buckling are unnecessarily severe, and are equivalent to making the same strength reduction twice. Instead, it is sufficient to ignore the torsional buckling of cruciforms provided design checks are made against local buckling as well as flexural buckling.

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ABSTRACT: The response of composite sandwich structures to blast loading has received little attention from researchers when compared to the research performed on their metallic counterparts, despite the fact that composite sandwich panels are becoming more generally used in practice. This paper reports on a preliminary experimental investigation into the response of sandwich panels comprising E-glass fibre reinforced vinyl ester facesheets and closed cell PVC foam cores to localised blast loading. The loading is generated by detonating discs of plastic explosive in close proximity to the panel. Multiple failure modes were exhibited by the panels. A failure progression pattern was identified, with increasing impulse: front facesheet delamination, core compression, back facesheet delamination, fibre fracture, core fragmentation, plastic deformation and debonding of the back facesheet following by complete core penetration. No back facesheet rupture was observed, but this was anticipated as the next failure mode to occur at higher impulse levels. The panels with denser cores exhibited lower levels of damage. Theoretical estimates of midpoint displacement were calculated using an analytical beam model. Simple estimates of the delamination, core compression and fibre fracture energies were also made. The energy partition showed that delamination, core compression and fibre fracture were significant energy absorption modes, and that fibre fracture energies exceeded the core compression and delamination energies at higher impulses. This was particularly evident for the lower density core which provided lower resistance to front facesheet deflection.

Chiara Bedon and Claudio Amadio (Dept. of Civil Engineering and Architecture, Univ. of Trieste, Piazzale Europa 1, Trieste 34127, Italy), “Buckling of flat laminated glass panels under in-plane compression or shear”, Engineering Structures, Vol. 36, pp 185-197, March 2012, https://doi.org/10.1016/j.engstruct.2011.12.010

ABSTRACT: Because of evident aesthetic, lighting and architectural advantages, glass curtain walls are largely used to clad modern buildings. Since these elements are considered to constitute purely architectural systems, they are essentially designed to resist loads acting orthogonally to the plane of the façade (e.g. wind loads). Contrarily, glass elements are frequently used as structural components able to sustain in-plane loads (e.g. columns, stiffening fins, beam elements, stairs, etc.), thus to preserve their integrity a buckling verification could assume great importance. In order to overcome these problems, an analytical formulation is proposed for the estimation of the buckling resistance of flat laminated glass panels under in-plane compression or shear. Two different design approaches are taken into account and compared: the first one directly derives from the
theory of sandwich panels, whereas the second one is based on the approximate concept of equivalent thickness. As discussed in the paper, this last approach constitutes a useful design expedient for the deformability and resistance check of buckled laminated panels under in-plane compression or shear, in presence of different boundary conditions. Since the resistance of such brittle elements directly depends on the level of connection between the glass panes offered by the interlayer, the effects of possible temperature and time-loading variations are highlighted. The obtained analytical results are in agreement with sophisticated numerical simulations.

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ABSTRACT: Torsional bracing systems have been used widely in I-girder bridges to increase the flexural-torsional buckling strength and distribute the load to the adjacent girders. To evaluate the required stiffness of the bracing and the flexural-torsional buckling strength of the I-girder with a multiple torsional bracing system, the equivalent continuous torsional bracing concept is often adopted regardless of the type of torsional bracing system. However, a previous study on the I-girder with discrete torsional bracings under uniform bending reported that the equivalent continuous torsional bracing concept has certain limitations on discrete torsional bracing problems and it needs to be investigated for general loading cases. This article presents an analytical solution for the elastic flexural-torsional buckling strength and stiffness requirements of I-girders with discrete torsional bracings under various loading conditions. First, a review was performed of the previous study on the elastic critical buckling moment and torsional stiffness requirement of the I-girder with discrete torsional bracings under uniform bending. This solution was then extended for various loading conditions. From the derived analytical solutions, the equivalent moment factor was proposed for practical engineering purposes and the proposed solutions were verified by comparing them with the results of finite element analysis and those of other previous studies. Finally, non-linear finite element analyses including the effects of the initial imperfection and residual stresses were conducted to examine the inelastic buckling strengths of I-girders with discrete torsional bracings under various loading conditions. The results showed that the buckling curves from the current design specification provide reasonably conservative flexural-torsional buckling strengths of the I-girder with discrete torsional bracings when the proposed elastic solutions are applied to obtain the buckling parameters.

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ABSTRACT: This paper is concerned with the axial load behavior of L-shaped concrete-filled steel tubular (CFT) stub columns with binding bars provided to improve the mechanical behavior of these elements. Six specimens with binding bars and one specimen without binding bars were tested to examine the effects of

ABSTRACT: Lateral instability of elliptical hollow section (EHS) members in bending is studied in this paper. Eight laterally unrestrained EHS beams, with a constant cross-sectional aspect ratio of two, were tested in three-point bending. The test set-up, material properties, section geometry, residual stress measurements and full load-deformation responses of the test specimens are reported herein. To supplement the experimental data, numerical models were also developed and validated against the test results. Parametric studies were then performed, to assess the influence of cross-sectional aspect ratio and member slenderness on lateral stability. Based on the assembled structural performance data, lateral torsional buckling curves for elliptical hollow section beams have been developed and statistically verified. Limiting lengths below which lateral torsional buckling (LTB) need not be considered have also been proposed.


ABSTRACT: This paper presents the first part of an experimental investigation carried out on a construction system based on completed in situ sandwich panels with non-shear connectors, concerning the study of vertical panels used as structural walls. Compression tests with axial and eccentric loads were carried out on several full scale panel specimens with different slenderness ratios in order to study the behaviour of panels under vertical in-plane forces. Additionally, diagonal compression tests were performed on square specimens in different configurations in order to study the behaviour of panels under horizontal in-plane forces. The most significant load–displacement diagrams for increasing load are illustrated and the failure modalities are discussed. The semi-composite behaviour of the panels, guaranteed by the internal layer of polystyrene and the reinforced concrete beams at the panel ends, is highlighted. Finally, some numerical simulations are performed with non-linear finite element models and some useful design indications are given.

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ABSTRACT: Cylindrical shells subjected to non-uniform wind pressure display different buckling behaviours from those of cylinders under uniform external pressure. At different aspect ratios, quite varied and complex buckling patterns occur: the results of linear and nonlinear buckling analysis can also be quite different. By contrast, cylinders under uniform external pressure always experience circumferential buckling and are little affected by changes in geometry, except in very short cylinders or changed boundary conditions. This paper presents a wide-ranging study of anchored stocky and intermediate length cylindrical shells of uniform thickness under wind pressure. Its aim is to produce useful information for the design of silos and anchored tanks against buckling under wind. The finite element analyses indicate that both linear and nonlinear analyses predict the circumferential compression buckling mode in stocky cylinders. For intermediate cylinders, pre-buckling ovalization of the cross-section has an important influence on the buckling strength. Empirical expressions are developed to relate the linear and nonlinear critical stagnation pressures under wind to the classical critical value for uniform external pressure. The effects of yielding and imperfection sensitivity are also briefly explored.


ABSTRACT: The goal of this study is to experimentally and analytically evaluate the influence of circular openings in reinforced concrete deep beams with low shear span-to-depth ratio. Twenty reinforced concrete small-scale deep beams with or without openings were tested in flexure under four-point loading. The beams had a small shear span-to-depth ratio in order to stress the shear behavior. The specimens had different reinforcement arrangements and opening positions. The load was transmitted to the specimen with bearing plates having the same side length as the beam. Two LVDT’s were arranged to record the transverse and axial strain of the theoretical struts forming in the beam. Additionally another device was mounted to measure the middle deflection of the beam. Comparative analysis of the experimental results shows that: the effect of the hole depends on its position in the beam; the benefit of the presence of reinforcement depends on its arrangement. An analytical model is proposed to predict the shear strength and corresponding deflection of deep beams with openings and the results are also compared with a non-linear finite element analysis showing good agreement.

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ABSTRACT: An approach based on the transverse or out-of-plane nonlinear dynamic responses at the centers of edges of cracks is being proposed as a viable alternative to bulging factors for damage tolerance design and characterization of cracked cylindrical shell structures under applied internal pressure. This approach circumvents the problems of mesh selection at the crack tip in the finite element analysis for bulging factors and provides information about the influence of crack lengths as well as crack widths on responses. The influence of crack widths on responses has been found to be significant but it is not available in bulging factors. Furthermore, existing individual bulging factor only applies to a different range of ratios of crack length to radius of shell. It is concluded that (i) the proposed approach has no limit on the range of ratios of crack length...
to radius of shell; (ii) conceptually, the proposed approach is simple, and (iii) computationally, the nonlinear responses at the centers of edges of cracks are relatively easy to obtain accurately and efficiently by using the mixed formulation-based shell finite elements since the present dynamic approach converges quickly at very coarse meshes.


ABSTRACT: In this paper, the dynamic behavior of cylindrical open top ground-supported water tanks is investigated. The main focus of this study is to identify the major parameters affecting the dynamic response of such structures and to address the interaction between these parameters. Examined parameters include sloshing of liquid free surface, tank wall flexibility, vertical ground acceleration, tank aspect ratio, and base fixity. In addition, the dynamic results obtained from the rigorous finite element (FE) method are compared with those recommended by current practice and thereby the adequacy of current code provisions in estimating the dynamic response of liquid-filled cylindrical containers is investigated. The validity of the proposed FE method is verified by comparing the results with those calculated from well-proved analytical methods available in the literature. Both time history and free vibration analyses are carried out on concrete tank models with different aspect ratios. Time history response of both rigid and flexible tanks having different conditions at the base; fixed and hinged under both horizontal and vertical components of earthquake is obtained using the direct integration method. Based on the computed results, recommendations on seismic design of cylindrical liquid containers are made. It is concluded that the current design procedure in estimating the hydrodynamic pressure is too conservative.


ABSTRACT: The axisymmetric linear bending theory of shells is treated for thin-walled orthotropic cylindrical shells under any smooth axial distribution of normal and shear pressures. The equations are developed, solved and explored in this paper. The derivation is presented in terms of a generalised Hooke’s Law with coupling between the axial membrane stress resultant and axial bending moment. This formulation permits the shell to be alternatively treated as a composite isotropic cylinder with axial stiffeners, rendering it useful for many practical problems. A linear kinematic relationship is assumed between the generalised strains and displacements. Expressions for the linear axial bending half-wavelength are presented for special cases of the stiffness matrix. The equations developed here are simple enough to be applied to the analysis of anisotropic thin-walled cylindrical shells using basic spreadsheet tools, removing the need to perform an onerous finite element analysis. Engineering applications potentially include corrugated metal, axially-stiffened or reinforced concrete silos under granular solid pressures, tanks under hydrostatic pressures, tubular piles under earth pressures, gas-filled cisterns and chimneys.

References listed at the end of the paper:


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ABSTRACT: Buckling-Restrained Braces (BRBs) are commonly used as ductile bracing elements in seismic zones. Key limit states governing BRB design include preventing both flexural buckling and local buckling failures. In this study, the authors propose a strategy for the prevention of in-plane local buckling failure of a BRB whose restrainer is composed of a mortar in-filled circular or rectangular steel tube with various mortar thicknesses. Cyclic loading tests on BRBs possessing various mortar restrainers and circular tube thicknesses were carried out to investigate the effect of the mortar and the sectional shape of the restraint tube on the local buckling failure of buckling-restrained braces.

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ABSTRACT: The behaviour of stiffened panels are simulated numerically under uniaxial compression until collapse and beyond, and then compared with tests made to investigate the influence of the stiffener’s geometry and the boundary conditions. The stiffened panel models have three longitudinal bays to produce reasonable boundary conditions in the longitudinal direction. The material and geometric nonlinearities are accounted for in the FE analyses. The initial geometric imperfections, which affect significantly the collapse behaviour of stiffened panels, are assumed to have the shape of the linear buckling mode. Four types of stiffeners were made of mild or high tensile steel for bar stiffeners and mild steel for ‘L’ and ‘U’ stiffeners to investigate different material and geometry configurations, and four boundary conditions are analysed.

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ABSTRACT: Sandwich structures can often sustain large deformations under constant load enabling them to absorb significant amounts of energy. The mechanical properties of cork (e.g. low density and high specific stiffness and strength) suggest that this material—and its compounds—may have excellent properties when acting as core in energy absorbing sandwich systems and structures. Cork is a natural material with a cellular structure (closed cell). After reaching yield stress, cork exhibits a region of almost constant stress for increasing strains until densification is reached, allowing it to absorb considerable amounts of energy. Within the scope of the present work, two micro-agglomerated cork (MAC) compounds are incorporated as cores in sandwich structures with 5754-H22 aluminium alloy face sheets. Samples with constant thickness of the face sheets and different core thicknesses are tested. These structures are fixed on a 4-cable ballistic pendulum and subjected to blast waves originated from the detonation of 30 g of high explosive (C4) at a fixed stand-off distance (300 mm). The deflection of the front and back face sheets is measured as well as the transmitted impulse and movement of the pendulum. The effects on the structural response of the core thicknesses and core densities are determined. A linear dependence between the relative core thickness reduction and the initial core thickness is
determined for both MAC compounds. A value of ≈11% was obtained for the relative thickness reduction, strongly indicating the possibility of energy dissipation by the core, most probably due to crushing of the cellular structure of cork.

ABSTRACT: The progressive collapse of a box beam under longitudinal bending can be predicted using various computational approaches, including finite element methodologies and the simplified progressive collapse method. These methodologies are employed to complete a series of analyses on three small box girders. The models are first analysed in the intact condition and then several damage scenarios are investigated. The results from the different computational approaches are compared to determine their relative performance. The study demonstrates the significance of residual stresses that are created during the damage simulation and are represented using differing assumptions in each of the compared methodologies.

ABSTRACT: This paper presents the research works on the cyclic behavior of trapezoidally corrugated as well as unstiffened steel shear walls. A series of experimental studies were carried out on the half-scale, one-story, single-bay steel shear walls with unstiffened and trapezoidally corrugated panels. This experimental study was conducted to compare the stiffness, strength, ductility ratio and energy dissipation capacity of three different steel shear walls: unstiffened, trapezoidally vertical corrugated and trapezoidally horizontal corrugated. Gravity loads were not applied at the top of the walls and horizontal load was applied at the top of each specimen. Loading sequence was applied as displacement-control with increasing and decreasing amplitudes. The results reveal that although the ultimate strength of the unstiffened specimen is nearly 17% larger compared to that of the corrugated specimens, energy dissipation capacity, ductility ratio and the initial stiffness of the corrugated specimens are approximately 52%, 40% and 20% larger compared to the unstiffened specimen, respectively. The existing methods of analyzing unstiffened steel shear walls were also employed to evaluate the corrugated specimens. Although fairly good correlations were found between experimental and analytical studies in the initial stiffness and ultimate strength, more studies need to be implemented.

Niloufar Emami (University of Michigan, Ann Arbor, Michigan, USA), “Structure and daylighting performance comparisons of Heinz Isler’s roof shell based on variations in parametrically derived multi opening topologies”, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium Future Visions, Amsterdam, 17-20, August 2015
ABSTRACT: The design of building envelopes consists of two major phases in two different disciplines: structural design, and climatic design. Additional performance criteria such as acoustics may also be considered based on the program of the space. In general, a mono-disciplinary approach to design evaluates performance in each discipline detached from other disciplines and sometimes in a hierarchical order. This may be due to disjointed parameters that affect the design and optimization process, as well as different expertise of the
designers and engineers in each field. Considering some structures such as post and beam systems, this method seems appropriate since each discipline has little influence on other fields. This provides relatively adequate freedom for the designers to decide about different design variables, such as size and orientation of the apertures, material of the cladding and the structure. However, there are some other building envelopes in which making a design decision in one field largely affects the performance in other fields. These building envelopes which cover the architectural space have a high potential for an interdisciplinary design approach. Heinz Isler is an engineer who has designed extremely efficient shells with excellent performance over time. Considering his works, there are a few shell structures which have one or multiple apertures, mainly designed to introduce daylighting into the space. But how have these apertures influenced the force flow and structural performance of the shell? What daylighting levels have they provided for the space? And by manipulating the size and number of these apertures, how may the structural and daylighting performance of a shell vary? This paper intends to look at a perforated concrete shell designed by Heinz Isler and assess its structural and daylighting performance. Then, the size, number and location of the openings is altered in order to observe the effect on the structural and daylighting performance of the shell. Rhino and Grasshopper are used as the modelling platform, while Karamba, which is a plugin for Rhino, is employed for assessing the structural performance, and the DIVA plugin for Rhino is employed to assess the daylighting performance. Finally, a comparison between different topologies is made using different numeric indicators. For structural performance, deflection, weight and maximum von Mises stress levels are considered, along with Daylight Autonomy on horizontal and vertical planes as the daylighting numeric indicator. The goal of this comparative study is to demonstrate tradeoffs among various performance criteria, regarding the relation between topology, structural performance and daylighting performance, and may be used by designers who consider multiple performance criteria in early design phases.

References listed at the end of the paper:


ABSTRACT: The elastic post-torsional-buckling behaviour of a simply supported cruciform column has been analysed, and its strength has been approximated by assuming that it fails when it first yields due to the
maximum normal stress induced by the axial compression. However, torsional shear stresses are induced in the post-buckling regime. The purpose of this note is to investigate the effects of these shear stresses on the first yield strength.

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ABSTRACT: This paper presents the findings from an experimental study of nine H-shaped steel beam-columns with large width-thickness ratios subjected to combined constant axial force and cyclic bending about the weak-axis. Considering different categories of cross-sections, various width-thickness ratios for the flange and web of the specimens are selected, and a reliable structural testing system is developed. The test results show that local buckling dominates the failure mechanism of all the specimens without overall buckling being observed. For bending about the weak-axis, the H-shaped steel members exhibit favorable plastic deformability, and it is concluded that the classification rules in the current design specifications for H-sections are unsuitable for weak-axis bending scenarios. In addition, it is found that the effects of the flange/web width-thickness ratios as well as the axial force ratios on the hysteretic behavior are strongly dependent on each other, and thus should be considered in an interactive way.

ABSTRACT: The aim of the present paper is to study the influence of a local dent on the collapse behaviour of stiffened panels. A quasi-static nonlinear finite element analysis is used to simulate the production of the local dent which will model the residual stress and the springback effect of the stiffened panels. The effect of residual stress caused by the local dent on the collapse behaviour of stiffened panels is investigated. The material properties used in the finite element analysis have been evaluated by tensile tests. Stiffened panel models with three and two bays in the longitudinal direction are used to prescribe appropriately boundary conditions for the middle bay. The relationship of the maximum indentation load and length of plate are almost linear and the springback displacements converge to a constant with increasing final depth of the dent. The residual stress caused by the indentation affects slightly the ultimate strength of the dented stiffened panels under consideration.

ABSTRACT: The objective of this paper is to analyse the ultimate strength of ageing ship structures based on experimental and numerical assessments. Three experimental ultimate strength tests have been carried out on box girders under vertical bending moment and several effects have been detected due to corrosion. Extensive nonlinear finite element analyses have been performed to compare the numerical and experimental results. The ultimate bending moment of corroded box girders has been compared with existing formulas. A relationship to calculate the equivalent tangent modulus as a function of the total reduction of the cross-sectional area due to corrosion degradation has been proposed. A new stress–strain relationship has been developed, taking into account the residual stresses and the corrosion effect, which may be directly used as a master stress–strain curve for a non-linear finite element analysis.

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ABSTRACT: In conventional steel–concrete–steel (SCS) construction, the external steel plates are connected to the concrete infill by welded shear stud connectors. This paper describes a programme of experimental and numerical investigations on reduced-scale non-composite SCS panels with axially restrained connections. The experimental results have demonstrated that the non-composite SCS panels are capable of developing enhanced load-carrying capacity through the tensile membrane resistance of the steel faceplates. This type of construction was found to exhibit highly ductile response and be able to sustain large end rotations of up to 18° without collapse. High fidelity finite element models for SCS panels under impact loading conditions were developed and the simulation results were validated against the experimental data. With the validated FE models, a full-scale barrier structure composed of the non-composite SCS panels and steel posts was subjected to a head-on collision by the Ford F800 single unit truck. The simulation results showed that the non-composite SCS barrier construction is able to resist very large impact energy and effectively terminate the fast moving vehicle. The axially restrained non-composite SCS panels were found to provide an effective means for protecting assets against severe impact attacks.

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ABSTRACT: LiteSteel beam (LSB) is a new cold-formed steel hollow flange channel section produced using a patented manufacturing process. It is commonly used as flexural members in residential, industrial and commercial buildings. Current practice in flooring systems is to include openings in the web element of floor joists or bearers so that building services can be located within them. Test results have shown that the shear capacity of LSBS can be reduced considerably by the inclusion of web openings. A cost effective method of eliminating the detrimental effects of a large web opening is to attach suitable stiffeners around the web openings of LSBS. A detailed experimental study consisting of 17 shear tests was therefore undertaken to investigate the shear behavior and strength of LSBS with stiffened circular web openings. Both plate and stud
stiffeners with varying sizes and thicknesses were attached to the web elements of LSBs using a number of screw-fastening arrangements in order to develop a suitable stiffening arrangement for LSBs. Simply supported test specimens of LSBs with an aspect ratio of 1.5 were loaded at mid-span until failure. This paper presents the details of this experimental study of LSBs with stiffened web openings, and the results of their shear capacities and associated behavioral characteristics. Suitable screw-fastened plate stiffener arrangements have been recommended in order to restore the original shear capacity of LSBs.

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ABSTRACT: Shell-like and beam structures made of Functionally Graded Materials (FGMs) show a gradual variation of material properties in one, two or three directions. In this paper an efficient low-order shell element with six nodal degrees of freedom (including the drill rotation) is presented, supplemented with a proper method for calculating effective elastic properties. This new FGM shell element is coupled with 3D FGM beam elements and combined elastostatic beam-shell structures are analyzed. The results indicate high a effectiveness and accuracy of the proposed approach.

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ABSTRACT: The paper presents the experimental tests carried out on two prestressed thin walled V-shaped elements, used over a period of 18 years as the roof of an industrial building and removed after having exhibited marked deflections and crack patterns. The experimental program, including material characterization, impact load and ultimate static load tests, is aimed at evaluating the actual load carrying capacity of the elements. The survey of the elements geometry, with special attention to imperfections, is presented; then results of the impact load test, namely the fundamental frequencies and modal shapes of free vibration, are reported. Successively, the results of static load tests up to failure are discussed. Due to the small thickness of the cross section walls, second order effects strongly interact with the global failure mechanism. The combination of dynamic impact and ultimate static load tests allowed the calibration of an accurate finite element model, accounting for both mechanical and geometrical nonlinearities, capable to predict the behaviour of the elements up to collapse and useful to design repairing and strengthening works.

ABSTRACT: The harmonic compound finite strip method has been applied to linear transient vibration analysis of stiffened plates. In this method, eigenfunctions of Bernoulli-Euler beam have been used as the displacement interpolation functions in longitudinal direction, while finite element shape functions have been used for it in transverse direction. The Kirchhoff–Love thin plate theory has been used and the equation of motion of structure is derived from Lagrange’s equation of motion. The governing equations have been solved by the mode superposition where step-by-step procedure has been used for the solution of modal equation. The stiffener has been modeled so that it may lie anywhere within the plate strip which helps to increase the flexibility in mesh generation. The formulation is applicable for rectangular plates stiffened with longitudinal and transverse beams and supported on columns. The proposed method is validated through several examples. The strips with free end give erroneous results for non-zero Poisson’s ratio.

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ABSTRACT: In addition to typical perforated beams with regular openings of circular or hexagonal holes, the use of beams with irregular web holes of different shapes and arrangement is also widespread in steel construction. Despite some advantages over typical perforated beams, the behaviour of such beams is complicated by the irregularity of openings, which demands more reliable tools for assessing their local buckling response. This paper considers the efficient local buckling analysis of beams with regular and irregular web openings, employing the Element Free Galerkin (EFG) method for the numerical discretisation together with a simplified buckling assessment approach from the Rotational Spring Analogy (RSA). This combination offers a more effective means of buckling assessment utilising an iterative procedure of a rank 2 reduced eigenvalue problem along with a shifting local region. Several illustrative examples are provided to demonstrate the effectiveness of the proposed EFG/RSA approach for local buckling analysis of steel beams with irregular openings.

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ABSTRACT: This paper demonstrates a novel two-phase approach to the preliminary structural design of grid shell structures, with the objective of material minimization and improved structural performance. The two-phase approach consists of: (i) a form-finding technique that uses dynamic relaxation with kinetic damping to determine the global grid shell form, (ii) a genetic algorithm optimization procedure acting on the grid topology and nodal positions (together called the ‘grid configuration’ in this paper). The methodology is demonstrated on a case study minimizing the mass of three 24 x 24 m grid shells with different boundary conditions. Analysis of
the three case studies clearly indicates the benefits of the coupled form-finding and grid configuration optimization approach: material mass reduction of up to 50% is achieved.

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ABSTRACT: The lateral and upheaval buckling of subsea pipelines is investigated in this paper. For lateral buckling, analytical and numerical studies are conducted and compared and a new interpretation of localisation is given based on an isolated half-wavelength model. For upheaval buckling, a tabulated analytical solution based on a long heavy elastic beam resting on a rigid frictional foundation is given and the response under three types of localised initial imperfection is compared. A comparison of the lateral and upheaval responses of a subsea pipeline is made and indicates that excessive bending stress can be induced, particularly under upheaval buckling. The paper also highlights some differences between the current and previously published results.

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ABSTRACT: For steel tubular truss arches, calculations of sectional rigidity especially the torsional rigidity, as well as the effect of shear deformation on out-of-plane buckling are not available yet. This paper investigates the sectional rigidities of trusses and the out-of-plane buckling loads of pin-ended circular steel tubular truss arches in uniform axial compression and in uniform bending. Firstly the compression rigidity, flexural rigidity, shear rigidity and torsional rigidity of latticed configuration for trusses are deduced. Then the out-of-plane buckling equations for circular monosymmetric arches incorporating the effect of shear deformation are established using a static equilibrium approach. Lastly the closed form solutions for out-of-plane buckling loads of pin-ended circular truss arches in uniform compression and in uniform bending are obtained. It is found that the axial deformation of chord tubes need be taken into account in the derivation of shear rigidity and torsional rigidity of latticed configuration. Due to the curved arch profile, the effect of shear deformation on out-of-plane buckling loads of truss arches is much smaller than that on straight truss columns.

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ABSTRACT: The response of sandwich tubes under internal explosive loading was investigated experimentally, numerically and analytically in this paper. Experiments were conducted first to capture the fundamental deformation and failure patterns and they served as a basis of validation for both the FE and analytical models. Further detailed deformation and blast loading history were revealed by the FE model. An explicit analytical solution for the deformation of sandwich tubes under blast loading has been worked out and used to obtain the optimum sandwich configurations, which would outperform their corresponding monolithic tubes.

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ABSTRACT: Recently more attention has been paid to the energy absorption capability of novel structures in the retrofit of impact or blast protection structure. As the most versatile components, thin-walled metal tubes with different cross-sections are used and specifically explored by many researchers. One method for improving crashworthiness performance under quasi-static axial crushing is to vary the cross-sectional shape with only convex polygons. As an alternative, it is also necessary to develop tubes with concave polygon sections. In this paper, four types of geometries are studied experimentally. They are hexagon, octagon, 12-sided and 16-sided star, respectively. Experimental data are then compared with those predicted from FE simulations using ABAQUS. It is shown that the experimental and the corresponding numerical results are in agreement with each other. The increase in the number of inward corners demonstrates a promising improvement in energy absorption, but to a certain extent. It is found that the 12-sided star shape has the best energy absorption capability when $D/t$ ratio is less than 50, where $D$ is notional diameter and $t$ is the thickness. The 16-sided star shape performed poorly compared to the others studied.

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ABSTRACT: Lean duplex stainless steel material (EN 1.4162) has recently gained significant attention for its higher structural performance and corrosion resistance compared to the austenitic type. Circular lean duplex stainless steel tubes filled with concrete are innovative composite columns which have not been studied experimentally or numerically. This paper presents the fundamental behaviour of circular concrete-filled lean duplex stainless steel tubular (CFSST) short columns under axial compression. Three dimensional finite element (FE) models for CFSST columns subjected to axial compression are developed using the FE package ABAQUS. The lean duplex stainless steel material is modelled using the two-stage constitutive laws while the concrete is simulated using accurate concrete confinement models. The FE models are verified by comparisons with existing experimental results on hollow stainless steel columns, concrete-filled steel tubular columns and
CFSST columns. Parametric studies are undertaken to investigate the effects of concrete compressive strength and diameter-to-thickness ($D/t$) ratio on the behaviour of CFSST columns. The results show that the ultimate axial strength of circular CFSST columns increases with increasing the concrete compressive strength but decreases with an increase in the $D/t$ ratio. Circular CFSST columns with different $D/t$ ratios exhibit the same initial stiffness. The lean duplex stainless steel tubes cannot provide good confinement on the concrete when $D/t$ ratio is large. The ultimate axial strengths of CFSST columns predicted by the FE models are also compared with those calculated by the Eurocode 4, ACI code, the continuous strength method (CSM) by Lam and Gardner and Liang and Fragomeni’s design formulas. The comparative study shows that Eurocode 4 and the CSM give good estimates of the ultimate axial strengths of CFSST columns with $D/t<40$ but overestimates the strengths of columns with $D/t\geq40$. The ACI code gives too conservative estimates of the ultimate loads of CFSST columns as it does not consider the concrete confinement effects. Finally, it was found that the modified Liang and Fragomeni’s design formulas yield the best predictions of the ultimate axial strengths of CFSST columns over the entire range of $D/t$ ratios.

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ABSTRACT: In this paper, the lateral–distortional buckling (LDB) of hollow tubular flange plate girders (HTFPGs) with slender unstiffened webs is investigated. Firstly, shell finite element analyses are performed in order (i) to study the elastic buckling behaviour of simply supported HTFPGs under uniform bending and (ii) to compare it with the behaviour of I-section plate girders (IPGs) with unstiffened and stiffened webs. The results show that HTFPGs (without stiffeners) have much higher critical moments than IPGs (with stiffeners). Secondly, the LDB behaviour of HTFPGs is investigated using finite strip analyses and the results show the girder length range in which LDB is relevant. After that, an analytical model to estimate the critical LDB moment is proposed and validated by comparison between analytical and numerical values. Thirdly, the investigation is extended to the inelastic domain and non linear shell finite element analyses are performed to evaluate the ultimate strengths of the HTFPGs. Several remarks regarding the flexural strength of HTFPGs are presented. Finally, the predictions given by Eurocode 3 are compared with the numerical results and it is found that the predictions given by the design equations are unconservative. Therefore, it is recommended to use the European specifications by adopting the proposed expression to estimate the critical LDB moment.


ABSTRACT: The paper presents an analytical method to determine the ultimate shear capacity of composite plate girders containing web openings. Since one of the flanges of the steel girder is connected to reinforced concrete slab through shear connectors the behavior differs from that of a bare steel plate girder. The analysis of such behavior is complex and hence it is necessary to have a simple method for design office use. A simple analytical method to determine the shear strength of the girder is presented herein. The method considers the effects of composite action between the concrete deck and steel part of the girder and the presence of openings in the webs. Contributions to the shear strength of the girder by tension field action in the plate girder web panel
and shear failure of concrete slab are accounted for in the proposed method. The accuracy of the method is assessed by comparing the predicted values with the corresponding experimental results. Effects of web openings on ultimate shear capacity of composite girders are investigated.

ABSTRACT: Free vibration response of laminated composite and sandwich shell is studied by using an efficient 2D FE (finite element) model based on higher order zigzag theory (HOZT). This is the first finite element implementation of the HOZT to solve the vibration problem of shells incorporating all three radii of curvatures including the effect of cross curvature in the formulation using Sanders’ approximations. The proposed finite element model satisfies the inter-laminar shear stress continuity at the interfaces in addition to higher order theory features, hence most suitable to model sandwich shells along with composite shells. The $C_0$ finite element formulation has been done efficiently to overcome the problem of $C_1$ continuity associated with the HOZT. The present model can also analyze shells with cross curvature like hypar shells, etc., besides normal curvature shells like cylindrical, and spherical shells. The numerical studies show that the present 2D FE model is more accurate than existing FE models based on first and higher order theories for predicting results close to those obtained by 3D elasticity solutions for laminated composite and sandwich shallow shells. Many new results are presented by varying different parameters which should be useful for future research.

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ABSTRACT: This paper reports a numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. Finite element analysis was conducted on cold-formed high strength austenitic and duplex stainless steel material. Four loading conditions specified in the American Specification and Australian/New Zealand Standard for cold-formed stainless steel structures were investigated in the numerical study. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. It was shown that the finite element model closely predicted the web crippling strengths and failure modes of the tested specimens under the four loading conditions. Hence, parametric study was carried out to investigate the web crippling behaviour of cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures. The web crippling strengths predicted from the finite element analysis were compared with the design strengths obtained using the American, Australian/New Zealand and European specifications for stainless steel structures by substituting the reduced material properties in the current web crippling design equations. A unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures is proposed. It is demonstrated that the web crippling strength obtained using the proposed equation is safe and reliable using reliability analysis.

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ABSTRACT: The cross-section distortion of thin-walled beams of open section assembled of three plates with two axis of symmetry is considered analytically. The consideration is based on the assumption that stresses and displacements due to the cross-section distortion have small influence on stresses and displacements according to the classical theories of thin-walled beams of open sections, where the cross-section contour maintains its shape, and may be ignored. It is assumed that stresses and displacements due to the cross-section distortion are proportional to the angle of torsion due to shear, according to the theory of torsion of thin-walled beams of open cross-sections with influence of shear. The results are compared with the finite element method, by using shell elements. Several examples are examined by both methods.

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ABSTRACT: The influence of viscoelastic and auxetic (Negative Poisson’s Ratio NPR) layers on the free vibration modeling of a composite sandwich structure is analyzed in this work. For such purpose, an analytical formulation is performed based on the specification of kinematic theories in terms of displacement fields within each layer of the structure. For instance, simple theories like classical laminate theory (CLT) and high order shear deformation theory (HSDT) are considered. This enables the definition of a dynamic problem for 5-layered sandwich composite using the principle of virtual displacement. Moreover, modal parameters in terms of natural frequencies and associate loss factors are given through the transversal displacement. For linear and isotropic layers, numerical applications highlight the result of the Poisson’s ratio on the modal responses. It is particular observed that the natural frequency and loss factor show an increase with respect to the auxeticity of the viscoelastic layers while no significant variations related to the shear function are noticed from one theory to another.

ABSTRACT: This paper explores the behaviour of square and triangular fabricated stub columns consisting of Grade 316L stainless steel tubes and Grade 350 mild steel plates at ambient and elevated temperatures. The nominal dimensions of the stainless steel tubes were 31.8 and 38.1 mm diameters with 2 and 1.6 mm thicknesses, respectively. The plates had widths of 120 and 400 mm and a 3 mm thickness. Utilising all combinations of geometries, a variety of the fabricated stub columns were experimentally tested and their behaviour were compared with conventional square or triangular welded hollow sections utilising mild steel plates as well as single tubes. The experimental tests at elevated temperatures followed ISO834 curve and were performed under 70% of the column capacity given by the experimental tests performed at ambient state. The
proposed fabricated sections defined above outperformed the conventional welded hollow columns under both room temperature and elevated temperature circumstances. The ductility of the sections was also increased by utilising stainless steel tubes. Furthermore, the results obtained from the experimental tests were compared with those given by finite element modelling whereas the accurate prediction of the failure modes was demonstrated.


ABSTRACT: Using large suction caissons for offshore wind turbines is an upcoming cost-effective technology also referred to as bucket foundations. During operation, the monopod bucket foundation is loaded by a large overturning moment from the wind turbine and the wave loads. However, during installation the suction caisson is loaded by external pressure (internal suction) due to evacuation of water inside the bucket and vertical forces due to gravity. The risk of structural buckling during installation of large-diameter suction caissons is addressed using numerical methods. Initial imperfect geometries are introduced, based on the buckling mode shapes from a linear eigenvalue buckling analysis. Different imperfect geometries are introduced to reveal how sensitive the buckling load is to these imperfections. Including the first 21 mode shapes as imperfect geometries will reduce the buckling pressure compared to only considering mode 1. The results of the finite element analysis are compared with current standards for evaluating buckling loads.


ABSTRACT: The current paper focuses on the shear strength of bridge girders with corrugated webs (BGCWs) using the realistic initial imperfection amplitudes. Firstly, the results of full-scale experimentally tested BGCWs, available in literature, are used to check the validity of the available design shear strengths. Secondly, they are checked using the same equations utilizing the interactive shear buckling strength formula, recently, proposed by the current authors to account for the realistic support condition at the juncture between the web and flanges which was found to be nearly fixed. However, the comparison indicated that the available design shear strengths in the literature are conservative and need to be improved. Hence, the ABAQUS software is used to construct a nonlinear finite element (FE) analysis, including geometric and material nonlinearities, on full-scale BGCWs failing by shear. To ensure the accuracy of the FE models, the models are verified using the available experimental results provided by other researchers. The available design shear strength formulae were in addition compared with the FE shear strengths of the corrugated webs. However, among the strengths using the proposed interactive shear buckling strength formula, the one adopting Sause and Braxtan (2011) [7] equation was found to be the most suitable. It was as well found that stocky corrugated webs cannot practically reach the yield shear strength. At the end, an illustrative example for the calculation of the shear strength of BGCWs using the currently proposed formula is provided.

M.F. Hassanein and O.F. Kharoob (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Behavior of bridge girders with corrugated webs: (I) Real boundary condition at the juncture of the web and flanges”, Engineering Structures, Vol. 57, pp 554-564, December 2013, https://doi.org/10.1016/j.engstruct.2013.03.004
ABSTRACT: In this paper, the real behavior at the juncture between the corrugated web and flanges of bridge girders is studied. An elastic bifurcation buckling analysis is carried out using ABAQUS computer package for corrugated webs with simple (S) and fixed (F) boundary conditions at their juncture with the flanges. The dimensions of the generated corrugated webs are assumed based on the average dimensions of the available bridges with corrugation webs. The principle aim is to firstly compare them with each other. Secondly, the critical shear buckling strengths of the corrugated webs with both boundary conditions are compared with the interactive shear buckling strength formulae available in the literature. The paper is then extended to compare girder segments composed from corrugated webs and flanges with corrugated webs with well-defined boundary conditions; simple (S) and fixed (F). Based on the numerical results, the relative critical shear stress of the corrugated webs of simple juncture to that of the corresponding fixed boundary condition has an average value of 0.96. The comparison with the available interactive shear buckling strength formulae shows that the 1st-order interactive buckling strength is suitable for the case of corrugated webs with simple-juncture, while it is unconservative for the case of fixed-juncture corrugated webs. Hence, a new interactive shear buckling strength formula is proposed for the case of fixed (F) juncture in the current paper. The results as well obviously indicated that when the flanges are rigid enough \( t_f/t_w \geq 3.0 \), the girder segments exhibit shear failure mechanisms. Whereas, if the corrugated web plates are relatively rigid \( t_f/t_w < 3.0 \), the strengths of the girders become controlled by the deformation of flanges. Finally, it is found that the realistic support condition at the juncture is nearly fixed.

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ABSTRACT: The establishment of current design curves for predicting the maximum strengths of centrally loaded columns was mostly based on the experimental and analytical studies of mild carbon steels. In order to study the overall buckling behavior of welded high strength steel (HSS) box-columns, an experimental study on the ultimate strength of welded box-columns with a nominal yield strength of 460 MPa under axial compression was conducted. This experiment program includes six welded box-columns with slenderness varying from 38 to 80. A nonlinear finite element model considering the actually measured geometric imperfections and residual stresses was developed and verified in order to perform an extensively parametric study. The effect of residual stresses on the ultimate bearing capacity and the sensitivity of yield strength to initial geometric imperfections were investigated and discussed. The purpose of the parametric study is to select an appropriate design curve for welded 460 MPa HSS box-columns. By comparing the theoretical curves with the design curves specified in Eurocode3 and GB 50017-2003, it is found that the currently adopted design curves underestimate the ultimate bearing capacity of the welded box-columns fabricated from 460 MPa HSS plates by 18.7% and 23.2% in average, respectively. The curves b in both Eurocode3 and GB 50017-2003 show a good agreement with the generated theoretic curve for the welded box-columns with the nominal yield strength of 460 MPa buckling about both principle axes.

ABSTRACT: In this paper, the influence of square opening sizes on the shear behavior of hollow tubular flange plate girders (HTFPGs) is investigated. A three-dimensional finite element (FE) modelling using the ABAQUS computer package has been employed to analyze HTFPGs containing central web openings at end panels. The results of the HTFPGs with web openings are analyzed and then compared with equivalent plate girders (IPGs) with such openings. The collapse behavior of such girders is examined considering the following parameters: the flange type; the flange size; the type of the web (solid web or web with opening); the web plate slenderness \((h_{w}/t_{w})\) and the relative opening depth to the web depth \((d_{o}/h_{w})\). The results indicate that employing the HTFPGs with unreinforced central web opening without curved corners instead of the corresponding IPGs with the similar weight and the web opening size is a high performance solution to avoid the reduction in shear resistance due to the presence of web openings. An optimum web opening depth \((d_{o,op})\) for a HTFPG with a slender web is additionally recommended at which its shear strength becomes higher than the corresponding value of the similar weight IPG with solid web. It is furthermore found that the design strength of such girders should consider the sum of the contributions of both the web and the tubular flanges. However, new conclusions on the shear strength and behaviour of HTFPGs with web openings are presented.


ABSTRACT: The objective of this work is to evaluate the reliability of a rectangular steel plate subjected to compressive load and nonlinear time variant non-uniform corrosion wastage. Based on the analysis of the ultimate strength of a rectangular plate with surfaces locally nonuniformly deteriorated by different degrees of random corrosion as a function of time, FORM techniques are applied to assess the structural reliability accounting for the global ship hull structural deterioration. The strength failure events, due to corrosion degradation, are defined by two possible formulations. Either the plate is subjected to random non-uniform distributed type of corrosion wastage that is formed by non-uniform prismatic pits or the plate is subjected to a more severe type of degradation that is developed as random non-uniform localized corrosion wastage, which forms peats like a hemisphere. Two different correlated failure events are evaluated as a series system defined based on the Classification Society Rules wastage allowance and ultimate strength estimated for the two corrosion wastage models.


ABSTRACT: This paper investigates the influence of long-duration blast loads on the structural response of aluminium cylindrical shell structures. Full scale coupled non-linear dynamics are examined experimentally at one of the worlds’ most powerful air blast testing facilities. Evaluating structural response to blast loads of this magnitude is exceptionally difficult using only computational fluid dynamics; typically not achievable without incurring unmanageable solution domains. Clearing, diffraction and exhaust of a long-duration blast wave across any comparatively small structure imposes constraints leading to the use of approximated drag coefficients, designed primarily to expedite the calculation of net translational forces. In this research, detailed pressure histories measured experimentally on the surface of the cylindrical shell are used to accurately configure a computational analysis dispensing with the requirement to utilise approximated drag forces. When
References listed at the end of the paper:


**ABSTRACT:** Glass panels are widely used in modern architectures in the form of stiffeners and load-carrying elements. The frequent use of structural glass and the lack of standardized rules for designers gradually increased the interest of scientists and researchers in the analysis of structural behaviors associated to various combinations of boundary and loading conditions. Buckling failure certainly represents one of the most crucial condition of collapse. In the paper, particular attention is dedicated to the buckling response of simply supported glass panels subjected to combined in-plane compressive and shearing forces. Based on large series of numerical incremental simulations, the effects of loading ratios, imperfection shapes, slenderness ratios and glass types on their buckling response are investigated. At last, based on analytical interaction formulations of literature, a normalized domain is proposed for their stability check.

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**ABSTRACT:** The behaviour and design of stainless steel plate girders loaded in shear is investigated in this paper. A review of existing methods for the design of stainless steel plate girders, including codified provisions, is first presented. A database of thirty-four experiments carried out on austenitic, duplex and lean duplex stainless steel plate girders is then reported, and used to assess the current shear resistance design equations from Eurocode 3: Part 1.4 and Eurocode 3: Part 1.5 and the recent proposals from the literature. The comparisons clearly indicate that the design provisions of Eurocode 3: Part 1.4 are conservative and that improved results can be achieved by applying Eurocode 3: Part 1.5 and the proposed expressions of Estrada et al. However, yet further improvements are possible and, based on the available structural performance data, revised design expressions for the calculation of the ultimate shear capacity of stainless steel plate girders suitable for incorporation into future revisions of Eurocode 3: Part 1.4 have been proposed and statistically verified. Unlike the current provisions of Eurocode 3: Part 1.4, the design rules proposed herein differentiate between rigid and non-rigid end posts, and, offer enhancements in shear buckling capacity of around 10%.


**ABSTRACT:** This paper describes an efficient finite element method of analysing the elastic in-plane bending and out-of-plane buckling of indeterminate beam structures whose members may be tapered and of monosymmetric I cross-section. The structure’s loading includes concentrated moments and concentrated or uniformly distributed off-axis transverse and longitudinal forces, and its deformations may be prevented or
resisted by concentrated or continuous rigid or elastic off-axis restraints. Tapered finite element formulations are developed by numerical integration instead of the closed forms often used for uniform elements. Difficulties in specifying the load positions for tapered mono-symmetric members caused by the variations of the centroidal and shear centre axes are avoided by using an arbitrary axis system based on the web mid-line. Account is taken of additional Wagner torque terms arising from the inclination of the shear centre axis. A computer program based on this method is used to analyse a number of examples of the elastic in-plane bending of tapered cantilevers and built-in beams, and very close agreement is found between its predictions and closed form solutions. The program’s predictions of the elastic out-of-plane flexural–torsional buckling of a large number of uniform and tapered doubly and mono-symmetric beams and cantilevers under various loading and restraint conditions are generally in close agreement with existing predictions and test results. The common approximation in which tapered elements are replaced by uniform elements is shown to converge slowly, and to lead to incorrect predictions for tapered mono-symmetric beams.

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ABSTRACT: Because fixed arches have much higher flexural–torsional buckling resistance than pin-ended arches, they are used for engineering structures in many cases. However, studies on their flexural–torsional buckling behaviour have rarely been reported in the open literature hitherto. This paper investigates the elastic flexural–torsional buckling of fixed circular arches subjected to uniform compression and uniform bending because they play important roles in the design of steel arches against their flexural–torsional failure. One of the major difficulties in solving the flexural–torsional buckling problem of a fixed arch is to determine its accurate buckling shapes. The flexural–torsional buckling shapes are studied using a finite element (FE) method in association with eigenvalue analyses. It is found that the flexural–torsional buckling shape of a fixed arch becomes more complicated than the case of a straight beam-column or a shallow arch when the rise-to-span ratio increases, and so the theoretical analysis requires more terms of Fourier trigonometric series to describe the buckling shapes. Based on this, analytical solutions for flexural–torsional buckling loads of fixed arches are derived both by the Rayleigh–Ritz method and by solving differential equations for buckling deformations. Comparisons with the FE results show that the analytical solutions by the Rayleigh–Ritz method are reasonably accurate and that the analytical solutions by solving the equations for buckling deformations are exactly the same as the FE results. Simple approximate formulas for buckling loads of fixed arches with box-sections are proposed based on the extensive FE results for structural designers to use. The validity of the effective length method for the fixed arches is also discussed. It is found that in the case of circular arches the effective length method should not be used because the rise-to-span ratios and boundary conditions have complicated and significant influence on the buckling load.

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ABSTRACT: Due to the large increase of structural glass applications, the lateral torsional buckling behavior of glass beams actually represents a topic of great interest for researchers. Although several analytical models and design approaches exist in literature, various aspects complicate the realistic prediction of their typical out-of-plane response, especially if composed of two (or more) laminated glass sheets. Based on viscoelastic numerical results and predictions of a large experimental campaign of lateral torsional buckling tests performed on PVB and SG beams, the paper investigates the accuracy of existing analytical models in the prediction of the elastic critical load and load-lateral displacement path of these elements.


ABSTRACT: Modern architectural applications are frequently developed on the esthetic requirements of transparency and light that find good correspondence in the use of structural glass elements. Glass panels, for example, are widely used in the construction of domes, roofs, façades or frameworks in which, in conjunction with metallic bearing structures, they allow the realization of fascinating buildings. At the same time, they could be subjected to in-plane loads or multiple interacting actions that, in combination with high slenderness ratios, possible imperfections, limited tensile strengths and brittle behavior could put forward their collapse. Because of these reasons, numerous authors recently focused on the experimental, analytical, numerical analysis of the load-carrying behavior of glass panels under various loading conditions. In this paper, the buckling response of simply supported glass panels, affected by initial sine-shaped geometrical imperfections and subjected to various combinations of in-plane biaxial compressive/tensile loads, is investigated by means of large series of numerical simulations. The effects of various aspects (geometrical imperfections, slenderness ratio, boundary conditions, aspect ratio, and biaxial loading ratio) are highlighted. Finally, a normalized interaction resistant domain is proposed for a possible verification approach.


ABSTRACT: A cantilever column is loaded by a compression force and a bending moment caused by a horizontal force. It can be derived that, in the case of uniaxial bending, the rectangular cross section is more economic than the square one. In the given numerical case, the plate thicknesses are too large for enabling fabrication. Therefore stiffened plates should be used. Thus, the aim of the present study is to elaborate the minimum cost design of a column with rectangular cross-section and cellular plate walls. Cellular plates are constructed from two plates and longitudinal stiffeners welded between them. Previous studies have shown that welded T-stiffeners are more economic than the halved rolled I-section stiffeners, thus, welded T-stiffeners are used. Stress and horizontal deformation constraints are formulated. In the stress constraint, face plate buckling is taken into account by using effective widths. Local buckling constraint is used for the web of T-stiffeners.
Variables are as follows: heights of welded T-sections, thicknesses of stiffener webs and flanges, number of stiffeners in both directions, main dimensions of the rectangular box section, thicknesses of outer and inner face plates in smaller and larger walls. The cost function is formulated according to the fabrication sequence and consists of cost of material, welding and painting. The constrained function minimization is performed by using an effective mathematical optimization method.


ABSTRACT: In many papers about the shear lag analysis of thin-walled box girders, the maximum angular rotation attributable to the in-plane shear deformation of flanges is adopted as generalized displacement. However, the generalized displacement is not very simple and clear and the analytical procedure is relatively complicated. Moreover, various types of warping displacement function for shear lag were assumed which may cause some confusion. In this paper, a new method for analyzing shear lag effect in thin-walled box girders is proposed in which the additional deflection induced by shear lag effect is adopted as the generalized displacement. Based on the generalized moment defined in this paper, the shear lag deformation state is separated from the flexural deformation state of the corresponding elementary beam and analyzed as a fundamental deformation state. The quadratic parabola is demonstrated to be the reasonable curve of the warping displacement function in the shear lag effect analysis of a box girder and the accuracy of the degrees of the warping functions is evaluated. The so-called negative shear lag is illustrated through the generalized moment. The governing differential equation and the boundary condition for the additional deflection are established by applying the principle of minimum potential energy, and the initial parameter solution to the differential equation is provided. A very simple and convenient formula of the shear lag warping stress is proposed which has the same form as that of the bending stress of elementary beam. A finite beam segment element with 8 degrees of freedom is developed to analyze the shear lag effect in complex continuous box girders with varying depth. Two plexiglass models of continuous box girders are analyzed and the calculated results are in agreement with the test results, which validates the analytical method and the element presented.


ABSTRACT: In this work, the modal and harmonic analysis of elastic shallow shells, using a Dual Reciprocity Boundary Element formulation, is presented. A boundary element formulation based on a direct time-domain formulation using the elastostatic fundamental solutions was used. Effects of shear deformation and rotatory inertia were included in the formulation. Shallow shell was modeled coupling boundary element formulation of shear deformable plate and two-dimensional plane stress elasticity. Domain integrals related to inertial terms were treated using the Dual Reciprocity Boundary Element Method. Several examples are presented to demonstrate the efficiency and accuracy of the proposed formulation.

ABSTRACT: There have been comparatively few studies of the elastic lateral buckling of braced or continuous tapered beams, and these are limited in their application. Lateral buckling is affected by the separate effects of moment distribution, taper, and restraints between adjacent segments. Moment distribution effects are commonly allowed for in design codes by using $C_{bm}$ factors to multiply the classic lateral buckling moments $M_u$ of simply supported uniform beam segments in uniform bending. Taper effects for linearly web tapered beam segments may conveniently be allowed for by multiplying the segment lateral buckling moments $C_{bt} M_u$ computed using the mid-segment section properties by taper factors $C_{bt}$. Values of $C_{bt}$ for a number of different segment moment distributions have been determined using a finite element computer program for the buckling of tapered beam structures. Lateral buckling of a braced or continuous beam is also affected the interaction between the segments into which it is divided by its braces and supports. One segment will be more critical than its neighbours, which will restrain the critical segment and increase its buckling resistance. The effects of restraints on buckling are commonly allowed for by using effective length factors to multiply the segment length used in the formulation of the elastic lateral buckling moment $M_u$ of a uniform segment in uniform bending. Methods of determining the critical segment and of approximating its increased resistance developed for uniform beams have been adapted for web-tapered braced and continuous beams. This paper shows how these effects can be allowed for separately to develop good approximations for the elastic lateral buckling resistances of tapered braced and continuous beams. The accuracy of the approximations is demonstrated by comparisons with the predictions of the finite element computer program for the buckling of tapered beam structures.

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ABSTRACT: Finite element model for vibration and buckling of functionally graded sandwich beams based on a refined shear deformation theory is presented. The core of sandwich beam is fully metal or ceramic and skins are composed of a functionally graded material across the depth. Governing equations of motion and boundary conditions are derived from the Hamilton’s principle. Effects of power-law index, span-to-height ratio, core thickness and boundary conditions on the natural frequencies, critical buckling loads and load–frequency curves of sandwich beams are discussed. Numerical results show that the above-mentioned effects play very important role on the vibration and buckling analysis of functionally graded sandwich beams.


ABSTRACT: Experimental and finite element results for buckle interaction in subsea pipelines are presented in this paper. Experimental results for buckle propagation and pure bending of pipes are presented first followed
by buckle interaction results. A finite element model, verified against the experimental results, is used to develop buckle interaction envelopes. The analysis is conducted using both transient and steady state conditions. The results highlight the vulnerability of subsea pipelines to buckle interaction particularly in deep waters.

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ABSTRACT: The local stability of buckling-restrained braces (BRBs) is one of the most concerned issues. However, few discussions were conducted on the BRBs using section steel or welded cruciform core members, and the currently proposed methods concentrated on the design of casing only. In this study, incremental cyclic tests were conducted on eight BRB specimens using steel angle core members. Key parameters included the core width-to-thickness (b/t) ratio and the gap between the core and the casing. The test results show that two types of local buckling modes of the core were observed, while no local failure of the casing induced by local buckling was found. Significant local buckling and cyclic deterioration behavior were observed for the specimens with the b/t ratio of around 8.5 when the axial core strain reached 1.4%, causing 13% reduction in energy dissipation. Local buckling waves tended to concentrate near the core ends with enlarged buckling amplitudes due to the friction and uneven gap. The ratio between buckling amplitude and buckling half-wave length is found to be a governing parameter for BRB seismic performance. This ratio is recommended to be smaller than 0.04 to ensure stable cyclic behavior. The analytical model for the local stability of steel angle core members is proposed and the inelastic local buckling critical load is obtained. The analytical results show good agreement with experiment. Three re-defined general requirements for BRB local stability design are proposed, and the design recommendations for the steel angle core members are provided. Several implications of this study to other BRB configurations are presented finally.

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ABSTRACT: The interaction between local and overall buckling of welded stainless steel columns has been investigated experimentally and numerically in this study. Eight stainless steel box section compression members were fabricated from slender hot-rolled plates. The material properties and welding residual stress patterns in the test specimens had been obtained previously. Initial geometric imperfections, both local and global, were accurately measured prior to the tests. The test specimens were axially loaded between two pin-
ended supports, and both local plate buckling and overall flexural buckling featured visibly in the observed failure modes. Finite element (FE) models were also set up using the ABAQUS software package to conduct numerical simulations, which were initially validated by means of comparison with the experimental data. Using the validated FE models, parametric studies were carried out to assess the influence of the key input parameters, such as the residual stresses, the material strain hardening exponent and non-dimensional proof stress, geometric imperfections and slenderness ratios. Existing design methods, including the design provisions of Eurocode 3 Part 1.4, the design proposal of Rasmussen and Rondal, the direct strength method (DSM) for cold-formed carbon steel and two revisions thereof, were all evaluated against the obtained test and numerical results. It was revealed that the EN 1993-1-4 buckling curves, which do not differ with grade, provide reasonable average strength predictions, but tend to slightly overpredict the local–overall buckling resistances of welded austenitic stainless steel members and slightly underestimate those of duplex stainless steel members. Furthermore, the three considered DSM design curves, all of which were developed on the basis of structural performance data from cold-formed sections, provide generally unconservative strength predictions for welded stainless steel sections. Based on the generated data points, modifications to the current EN 1993-1-4 provisions and the DSM have been proposed, which offer more accurate strength predictions for local–overall interactive buckling resistances of welded stainless steel box section columns.


ABSTRACT: Rapidly deployable shelters, which can be packaged small but offer a high volume expansion ratio, are a critical asset for forward operating bases and can also be effective for disaster relief. Origami-inspired deployable shelters provide significant design advantages, including that (1) the rigid folded plates of these structures provide enhanced structural performance in the deployed form and (2) origami folds permit easy packaging in a small volume. Key design priorities include that the structure be lightweight and that it have thermal insulation for energy efficiency in heating and cooling. Energy efficiency is particularly critical for forward operating bases where fuel is at a premium. Honeycomb core sandwich panels, which provide a high stiffness to mass ratio, offer a lightweight option for rigid-wall origami-inspired shelters and can provide thermal insulation. A challenge in using this material, however, is the wide variety of options for material selection (for the face and core) and the thickness of each component. To achieve weight and energy efficiency priorities, this paper presents a multi-objective optimization procedure to design material properties of honeycomb core sandwich panels for minimum weight and maximum thermal resistance within the context of origami-inspired shelters. The novelty of this work includes the specific application to origami shelters, the simplified approach employed which approximates the structural behavior of the panels to avoid time-intensive finite element analyses, and a focus on selecting commercially available materials. While final design would require a three-dimensional finite element analysis, this procedure offers designers a valuable, simplified tool to rapidly narrow-in on sandwich panel configurations which are lightweight while offering thermal insulation. This approach is demonstrated for one origami-inspired topology which carries loads prescribed by the US Army Natick Soldier Research, Development & Engineering Center.

ABSTRACT: Many above-ground steel liquid storage tanks have suffered significant damages during past earthquakes. Such failures are due to several causes. The most common one is dynamic buckling. Several theoretical and experimental research studies were performed without solving this complex problem completely. Design codes such as AWWA-D100 and EC8 based their seismic standards on the recommendations given by some of these research results. The present contribution tries to evaluate these recommendations by using a numerical model with a robust and stable shell finite element. By using several seismic excitations and tanks with different geometrical parameter, this contribution tries to evaluate the PGA values that cause the tank instability. These numerical values are compared with standard code previsions. The obtained results confirm some code guidelines in the case of broad tanks, and show the need for improving them in the case of tall ones.

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ABSTRACT: Sandwich construction has been extensively used in various fields. However, sandwich panels have not been fully exploited in critical structural applications due to damage tolerance and safety concern. A major problem of sandwich panels is the vulnerability to impact loading, which can lead to a sudden loss of structural integrity and cause catastrophic consequences. In order to improve the energy absorption of sandwich panel under impact loading, a new sandwich core is proposed which is a hybrid core consisting of hollow metallic millitube grid stiffened polymer matrix. The objective of this study is to characterize its impact performances. Quasi-static low velocity impact test and ballistic impact test demonstrate that the new sandwich panel may be considered as a promising option for critical structural applications featured by multiple impact tolerance.


ABSTRACT: This paper presents the behaviour of circular concrete-filled double-skin steel tubular (CFDST) stub columns compressed under concentric axial loads. To predict the performance of such columns, a finite element analysis is conducted. Herein, for the accurate modelling of the double-skin specimens, the identification of suitable material properties for both the concrete infill and steel tubes is crucial. The applied methodology is validated through comparisons of the results obtained from the finite element analysis with those from past experiments. Aiming to examine the effect of various diameter-to-thickness (D/t) ratios, concrete cube strengths and steel yield strengths on the overall behaviour and ultimate resistance of the double-skin columns, a total of twenty-five models are created to conduct the parametric study. In addition, four circular concrete-filled steel tubes (CFST) are included to check the dissimilarities, in terms of their behaviour
and weight, when compared with identical double-skin tubes. A new formula based on Eurocode 4 is proposed to evaluate the strength of the double-skin specimens. Based on the comparison between the results derived from the analysis, the proposed formulae for the concrete filled double-skin would appear to be satisfactory.

Chiara Bedon and Claudio Amadio (University of Trieste, Department of Engineering and Architecture, Piazzale Europa 1, 34127 Trieste, Italy), “Flexural-torsional buckling: Experimental analysis of laminated glass elements”, Engineering Structures, Vol. 73, pp 85-99, August 2014, https://doi.org/10.1016/j.engstruct.2014.05.003
ABSTRACT: Buckling failure is a common condition of collapse for structural glass elements typically characterized by high slenderness ratios. Due to a combination of multiple mechanical and geometrical aspects, the effective buckling resistance of glass load-carrying elements is complex to predict, especially in presence of laminated cross sections or interacting applied loads. In this work, buckling experiments are performed on laminated glass beam-columns having rectangular cross section and subjected to combined uniaxial compression and bending. Extended numerical and analytical comparisons with test results are performed. As shown, a general good agreement is found between experimental results and existing prediction models.

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ABSTRACT: Evaluation of the capacity of steel bridge piles with localized severe corrosion is an important task for maintenance and retrofit activities. To facilitate maintenance and rehabilitation activities for deteriorated H-piles, numerical simulation for inelastic buckling of small-scale piles was conducted. The non-linear finite element model included the effect of initial geometric imperfection, residual stresses, material non-linearity, and geometric non-linearity at various levels of deterioration. The model was validated using experimental results of small-scale piles. A parametric study was conducted to analyze different factors that affect the axial capacity and failure mode of these piles. The parameters that were considered include the magnitude of initial imperfections, residual stresses, slenderness of the pile, location and extent of the corroded region, and severity of corrosion. Different pile slendernesses were considered ranging from 32 to 64. Different levels of corrosion were simulated by reducing the thickness of the flanges and web by 20–100%. The corroded length was varied from 15.2 cm, 30.5 cm and 61.0 cm. Different deterioration locations, namely mid-height and third-height of the pile, were considered. Numerical analysis results were compared to three design methods from current AASHTO (2012) [1], AISC (2011) [2], and AISI (2007) [3] specifications. A damage classification system is proposed based on the remaining capacity of the corroded pile and rehabilitation guidelines are suggested.

ABSTRACT: Vierendeel failure of castellated steel beams (CSBs) with fillet corner web openings is investigated by the Finite Element Method. Compared to beams with circular openings, CSBs with the proposed fillet corner web openings need only one cut along the web centerline. Therefore the fabrication cost can be reduced. Effects of opening dimensions and opening shapes on the Vierendeel failure of web-perforated members are investigated in this paper. Numerical results indicate that CSBs with the proposed fillet corner web openings enjoy a higher load bearing capacity than those with traditional rectangular or hexagonal openings on condition that they have the same opening height. The $M-V$ interaction method for predicting the load bearing capacity of CSBs with fillet corner web openings is proposed. Predictions obtained from the proposed $M-V$ interaction equation agree well with numerical results.

M.F. Hassanein and O.F. Kharoob (Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt), “Shear buckling behavior of tapered bridge girders with steel corrugated webs”, Engineering Structures, Vol. 74, pp 157-169, September 2014, https://doi.org/10.1016/j.engstruct.2014.05.021

ABSTRACT: The existing literature on bridge girders with steel corrugated webs (BGCWs) is focused on prismatic girders; i.e. with constant depth. To the authors’ best knowledge, no work has been done on the shear stability of tapered BGCWs although they have been increasingly used in bridges in recent years. Research presented in this paper focuses, first, on the critical shear buckling stress ($\tau_{cr}$) of the corrugated webs of tapered BGCWs. This is made by carrying out elastic bifurcation buckling analyses using ABAQUS software on isolated corrugated webs with simple and fixed boundary conditions. Webs in different typologies of tapered girders with steel corrugated webs are considered. The corrugation dimensions of the considered corrugated webs are taken typical of those used in Shinkai and Matsnoki bridges. Opposite to prismatic corrugated webs which may buckle globally, it is found that the tapered corrugated webs buckle interactively without nothing buckling globally. It is additionally found that predicting $\tau_{cr}$ values for tapered webs based on prismatic web calculations are not accurate. Therefore, critical buckling stresses of the tapered webs based on the prismatic ones with different equation for each typology are proposed. The paper is, then, extended to investigate the nonlinear shear strengths of the BGCWs. The available design shear strength formulas for prismatic girders are compared with the FE shear strengths of the tapered BGCWs. Based on these comparisons, design strengths for the different cases of the tapered BGCWs are suggested. An illustrative example is given at the end to explain the application of the proposed predictions.


ABSTRACT: A distortional theory is developed for the analysis of doubly symmetric and mono-symmetric wide flange beams under general loading. The governing differential equations of equilibrium and associated boundary conditions are derived based on the principle of potential energy. The theory captures shear deformation effects in the web and local and global warping effects. In contrast to classical beam theories, the present study captures web distortion by accounting for its flexibility within the plane of the cross-section while considering the flanges as Euler–Bernoulli beams. The formulation yields two systems of coupled differential equations of equilibrium in seven displacements fields. The first system governs the longitudinal transverse response and involves three displacement fields, and the second system governs the lateral torsional response and involves four displacement fields. Closed form solutions are then developed for both coupled systems under general loading. Numerical solutions for practical problems are then provided to illustrate the applicability of the formulation. Comparisons to results based on 3D shell finite element solutions show the validity of the
results. The theory preserves the relative simplicity of one-dimensional beam theories while effectively capturing the three-dimensional distortional phenomena normally captured within computationally expensive 3D FEA.

Poologanathan Keerthan, Mahen Mahendran and David Hughes (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Numerical studies and design of hollow flange channel beams subject to combined bending and shear actions”, Engineering Structures, Vol. 75, pp 197-212, September 2014, [https://doi.org/10.1016/j.engstruct.2014.05.022](https://doi.org/10.1016/j.engstruct.2014.05.022)
ABSTRACT: LiteSteel beam (LSB) is a cold-formed steel hollow flange channel section produced using a patented manufacturing process involving simultaneous cold-forming and dual electric resistance welding. It is commonly used as floor joists and bearers in residential, industrial and commercial buildings. Design of the LSB is governed by the Australian cold-formed steel structures code, AS/NZS 4600. Due to the geometry of the LSB, as well as its unique residual stress characteristics and initial geometric imperfections resultant of manufacturing processes, currently available design equations for common cold-formed sections are not directly applicable to the LSB. Many research studies have been carried out to evaluate the behaviour and design of LSBs subject to pure bending actions and predominant shear actions. To date, however, no investigation has been conducted into the strength of LSB sections under combined bending and shear actions. Hence experimental and numerical studies were conducted to assess the combined bending and shear behaviour of LSBs. Finite element models of LSBs were developed to simulate their combined bending and shear behaviour and strength of LSBs. They were then validated by comparing the results with available experimental test results and used in a detailed parametric study. The results from experimental and finite element analyses were compared with current AS/NZS 4600 and AS 4100 design rules. Both experimental and numerical studies show that the AS/NZS 4600 design rule based on circular interaction equation is conservative in predicting the combined bending and shear capacities of LSBs. This paper presents the details of the numerical studies of LSBs and the results. In response to the inadequacies of current approaches to designing LSBs for combined bending and shear, two lower bound design equations are proposed in this paper.

ABSTRACT: The use of grid shell structures in architecture and structural engineering has risen in the past decade, yet fundamental research on the mechanics of such structures is lacking. Grid shells are long span structures comprised of a lattice of single layer members forming a curved surface. Grid shells can be made of a wide range of materials from steel to wood. They have potential to be used in readapting existing spaces or in new aesthetically pleasing structures. By studying their mechanics, engineers can be more effective at the schematic phase of design so that the potential of grid shells can be maximized. This research conducts a parametric study that varies the topology and topography of grid shells. The parametric space is framed around real-world design constraints including the grid spacing, panel shape, span-to-height ratio and the use of double curvature. In this thesis, the buckling capacity is evaluated using finite element analysis for two typical grid shell geometries: the spherical cap and the corrugated vault. First, a spherical cap is considered for which an analytical solution exists and therefore the accuracy of the numerical procedure is validated. Simple closed-form solutions are derived using the concept of the equivalent continuum and compared to the numerical
models. Then, the parametric study of the spherical cap is performed including variations of the grid spacing, the span to height ratio and the panel shape (triangles and quadrilaterals). Having determined the efficiency of the computational tool the study is extended to the barrel vault. Here the new features of the analysis are the use of double curvature by introducing corrugation along the edge and the crown. By understanding the fundamental mechanical behavior of grid shells, design guidelines aimed to maximize their capacity and efficiency and intended to facilitate the discussion between architect and engineer are proposed.


ABSTRACT: The shear buckling behavior of the web-post in a castellated steel beam with fillet corner hexagonal web openings is studied using the finite element method. The buckling modes and buckling capacity of the web-post in the castellated beam with fillet corner hexagonal web openings are compared with those having circular and elongated circular openings. The web-post in a castellated steel beam with the proposed opening shape can achieve as good structural performance as that with circular openings. The effects of the opening distance, the opening height, and the web thickness on the buckling behavior of the web-post are investigated. The Strut Model is modified for predicating the shear buckling capacity of the web-post in the castellated steel beam with fillet corner openings. The equivalent rectangular opening is also modified to calculate the Vierendeel failure capacity of the castellated steel beam with the fillet corner hexagonal openings at the perforated sections. The load bearing capacity of the castellated steel beam with the proposed opening shape is the minimum value among the web-post buckling capacity, the Vierendeel failure capacity at the perforated section, and the shear rupture capacity of the horizontal weld.

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ABSTRACT: It is widely accepted that for many buckling problems of plates and shells in the plastic range the flow theory of plasticity leads to a significant overestimation of the buckling stress while the deformation theory provides much more accurate predictions and is therefore generally recommended for use in practical applications. The present work aims to contribute to further understanding of the seeming differences between these two theories with particular regards to circular cylindrical shells subjected to axial compression. A clearer understanding of the two theories is established using accurate numerical examples and comparisons with some widely cited accurate physical test results. It is found that, contrary to common perception, by using a geometrically nonlinear finite element formulation with carefully determined and validated constitutive laws very good agreement between numerical and test results can be obtained in the case of the physically more sound flow theory of plasticity. The reasons underlying the apparent buckling paradox found in the literature regarding the application of deformation and flow theories and the different conclusions reached in this work are investigated and discussed in detail.
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ABSTRACT: The function of intermediate transverse stiffeners attached on plate girder web panels is to provide simple supports so as to reduce the panel aspect ratio, thereby increasing the shear buckling strength. This study investigates the moments of inertia of the transverse stiffeners required to maintain the simple support condition not just for elastic buckling but also for postbuckling through linear buckling and nonlinear finite element analyses. From nonlinear regression analyses of the FEA results, a set of design equations are formulated and compared with the current provisions in AISC and AASHTO LRFD specifications. It is found that the design equation for elastic buckling in AISC and AASHTO LRFD specifications is too conservative especially when the aspect ratio is greater than 1.0. Also, the design equation for postbuckling in AISC and AASHTO specifications results in designs that are too conservative due to oversimplification.

ABSTRACT: This paper presents an efficient mathematical model for studying the slip-buckling behaviour of longitudinally delaminated elastic Reissner’s two-layer composite columns. The present mathematical model is used to evaluate exact critical buckling loads of these columns for the first time. The results prove that the presence of longitudinal delamination can significantly reduce the critical buckling load. The comparison of the results show that if sections outside of full delamination are undelaminated, the results are identical to the ones in the literature. On the other hand, the significant discrepancy may exist when those sections are partially longitudinally delaminated. Moreover, the critical buckling load for shear-stiff column with almost freely sliding longitudinal delamination along the whole column length can be up to approximately 4 times smaller compared to the buckling load of the same but undelaminated column.

Shanmuganathan Gunalan, Yasintha Bandula Heva and Mahen Mahendran (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Flexural-torsional buckling behaviour and design of cold-formed steel compression members at elevated temperatures”, Engineering Structures, Vol. 79, pp 149-168, November 2014, DOI: 10.1016/j.engstruct.2014.07.036
ABSTRACT: Current design rules for the member capacities of cold-formed steel columns are based on the same non-dimensional strength curve for both fixed and pinned-ended columns at ambient temperature. This research has investigated the accuracy of using current ambient temperature design rules in Australia/New Zealand (AS/NZS 4600), American (AISI S100) and European (Eurocode 3 Part 1.3) standards in determining the flexural–torsional buckling capacities of cold-formed steel columns at uniform elevated temperatures using appropriately reduced mechanical properties. It was found that these design rules accurately predicted the member capacities of pin ended lipped channel columns undergoing flexural torsional buckling at elevated temperatures. However, for fixed ended columns with warping fixity undergoing flexural– torsional buckling, the current design rules significantly underestimated the column capacities as they disregard the beneficial
effect of warping fixity. This paper has therefore recommended the use of improved design rules developed for ambient temperature conditions to predict the axial compression capacities of fixed ended columns subject to flexural–torsional buckling at elevated temperatures within AS/NZS 4600 and AISI S100 design provisions. The accuracy of the proposed fire design rules was verified using finite element analysis and test results of cold-formed lipped channel columns at elevated temperatures except for low strength steel columns with intermediate slenderness whose behaviour was influenced by the increased nonlinearity in the stress–strain curves at elevated temperatures. Further research is required to include these effects within AS/NZS 4600 and AISI S100 design rules. However, Eurocode 3 Part 1.3 design rules can be used for this purpose by using suitable buckling curves as recommended in this paper.

ABSTRACT: Current applications in buildings of structural glass elements often require design rules and formulations able to provide acceptable predictions for phenomena complex to describe, which generally depend on combination of several geometrical and mechanical aspects. The estimation of the buckling resistance of glass elements, for example, represents a topic of large interest for researchers, due to typical high slenderness ratios, limited tensile strength and brittle material behavior. In the paper, the buckling response of glass columns under impulsive orthogonal pressures (e.g. blast) and combined static compressive vertical loads (e.g. gravity loads or further service loads) is investigated. The dynamic buckling behavior of columns in out-of-plane bending is primarily analyzed. Advanced numerical nonlinear dynamic simulations are then performed on various laminated columns, by means of 3D numerical FE-models able to take into account the interaction of simultaneous loads and possible glass cracking. Analytical calculations are also carried-out by means of single-degree-of-freedom (SDOF) formulations derived from structural dynamics theories, in order to properly estimate blast and second-order effects on maximum deflections and corresponding tensile stresses. Finally, based on the rather good correlation generally found between numerical and analytical calculations, a design approach is proposed for practical estimation of buckling strength of glass elements in the analyzed loading and boundary conditions.

ABSTRACT: An analysis of cylindrical sandwich structures with weak orthotropic core subjected to patch loading is presented. A high order theory model combined with a novel formulation technique is used to predict the static response of the structure. The face-sheets are considered as thin shells that follow the first order shear deformation theory, whereas the core is considered as a linear elastic medium. The effects of core elastic and shear stiffness, curvature to length ratio, and stacking sequence and orientation on the core’s stresses and displacements are presented. The case of a moving load is explored and performance charts are generated to design and optimize the structure in response to the patch loads. In particular, considering an orthotropic core with quasi-isotropic lay-up in the face-sheets, limit the variation of the transverse core shear stress and provide an efficient structural design configuration.
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“Nonlinear bending of nanotube-reinforced composite cylindrical panels resting on elastic foundations in thermal environments”, Engineering Structures, Vol. 80, pp 163-172, December 2014,
https://doi.org/10.1016/j.engstruct.2014.08.038
ABSTRACT: Nonlinear bending analysis is presented for nanocomposite cylindrical panels subjected to a transverse uniform or sinusoidal load resting on elastic foundations in thermal environments. Carbon nanotubes are used to reinforce the cylindrical panels in two distinguished patterns, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements. The material properties of CNTRCs are assumed to be temperature-dependent and are estimated by a micromechanical model. The governing equations of the panel are derived based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity and are solved by a two-step perturbation technique. The nonlinear bending behaviors of the CNTRC panels with different CNT volume fraction distributions, foundation stiffnesses, temperature rise, and the character of in-plane boundary conditions are studied in details.

https://doi.org/10.1016/j.engstruct.2014.09.018
ABSTRACT: Stiffened plate buckles in different modes, including web/flange buckling, torsional buckling, plate buckling and interaction of these. Design codes ignore interaction of different buckling modes and each mode is treated separately. By introducing an effective breadth/web concept, coupled plate-torsional-web buckling in flat-bar stiffened plates is simply analyzed by torsional buckling analysis of equivalent cross section. The model provides a tool that is more accurate than existing design codes, and more efficient than finite element method. An expression for effective breadth/web of flat-bar stiffened plate has been derived and Euler stress for coupled buckling mode in flat-bar stiffened plate are calculated and compared with finite element method and rule-base equation. It is found that this method has better agreement irrespective of dominant mode of buckling.

Sherif A. Ibrahim (Structural Engineering Department, Ain Shams University, Abbassia, Cairo, Egypt), “Lateral torsional buckling strength of unsymmetrical plate girders with corrugated webs”, Engineering Structures, Vol. 81, pp 123-134, December 2014,
https://doi.org/10.1016/j.engstruct.2014.09.040
ABSTRACT: This paper deals with lateral torsional buckling of plate girders with corrugated webs (CWG). The research includes both theoretical and finite element analyses for un-symmetrical plate girders with corrugated webs subjected to uniform moment. A new warping constant for this un-symmetrical cross-section is derived taking into consideration the cross-sectional variation along the girder length. Trapezoidal corrugated web profile is taken into consideration in the derivation. The location of the shear center is determined and a closed form of the warping constant is derived. The un-symmetry of the web-less beam, which agrees with the case of CWG, is considered in the calculation of the lateral torsional buckling strength. The results are verified with those obtained using the finite element technique and gave good agreement. A comparison with different
specifications and codes is conducted to investigate the effect of un-symmetry on the plate girder strength. The effect of cross-section geometrical configurations on the lateral torsional buckling strength under uniform moment is investigated and discussed.

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ABSTRACT: In this paper, the structural response of steel tubular wind turbine towers with various design configurations is analysed using FEM modelling. Towers of various heights between 50 and 250 m are considered and investigated with three different design options as follows: (i) thick walled tower with internal horizontal stiffening rings, (ii) thick walled tower without stiffening rings and (iii) thin walled tower with stiffening rings. Based on this analysis, weight reduction ratios are examined in relation to the horizontal sway and von Mises stress increase ratios in order to identify a more efficient design approach between reducing the wall thickness and adopting internal stiffeners. All studied design solutions satisfy the strength and serviceability requirements as specified by the design codes of practice. In the final part of paper, the dynamic characteristics of these three types of towers have been examined to obtain the natural frequencies and mode shapes. The studied model ignored the mass of nacelle-rotor system and the wind turbines, namely, only the isolated tower was included. Furthermore, the recommendations to avoid resonance for each height case are proposed.

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ABSTRACT: This paper presents a continuation algorithm based on the Asymptotic Numerical Method (ANM) to study instability phenomena of large torsion of thin-walled open sections beams under various external loadings. The proposed algorithm connects perturbation techniques with a discretization principle and a continuation method without the use of a correction process. In the model, the equilibrium and material constitutive equations are established without any assumption on torsion angle amplitude. In presence of eccentric loads and large torsion context, the right hand side of the equilibrium equations is highly nonlinear and contributes to the tangent stiffness matrix. A 3D beam element having two nodes with seven degrees of freedom is considered in mesh process. Several numerical examples from buckling of thin-walled open sections beams are analyzed to assess the efficiency and the reliability of the method. Comparisons are made with known commercial software. The proposed ANM algorithm is more reliable and less time consuming than other iterative classical methods.
ABSTRACT: Developments and advances in fabrication technology have led to a new generation of structural shapes, among them, the sinusoidal-web girder. Due to easy execution and potential for structural efficiency, the use of sinusoidal-web girder has been increasing significantly in several segments of civil engineering construction such as bridges, pedestrian walkways, hangars and industrial buildings. In spite of the advantages this type of structural component may offer, there are no design standards or specifications dealing with all the phenomena involved in the behavior of such beams, such as the resistance against lateral-torsional buckling (LTB). As a result, there is a need to develop design recommendations that properly address the flexural capacity of these elements. Following the current trend of semi-probabilistic codes (e.g. load and resistance factor design format), these recommendations shall be developed within the concepts and methods of Structural Reliability. In this paper, reliability-based design recommendations for sinusoidal-web beams for the limit state of LTB are presented. To this end: (i) an experimental investigation on the resistance of sinusoidal-web beams has been performed, (ii) a finite-element model has been developed and validated by experimental results, (iii) a theoretical model for the sinusoidal-web beam resistance prediction is proposed, (iv) a comprehensive program was established toward the assessment of both physical and epistemic uncertainties related to the basic variables, (v) reliability analyses are performed using First Order Reliability Method (FORM), and (vi) resulting implicit reliability levels are checked against current practice. It is shown that the implicit safety levels in the proposed recommendations are in agreement with current trends in structural engineering practice.

ABSTRACT: Pipe-in-pipe systems are widely used in offshore pipeline applications due to favorable thermal insulation capacity. In deep waters, the outer pipe of pipe-in-pipe systems is prone to local collapse and consequent buckle propagation along the length under external hydrostatic pressure. This paper presents the experimental study and numerical simulation of the buckle propagation scenarios for pipe-in-pipe systems in the quasi-static steady-state conditions. The experiments of the buckle propagation for the pipe-in-pipe specimen using 316 grade stainless steel tubes are carried out in a sealed hyperbaric chamber. The comparison between experimental observations and numerical results is made to demonstrate the effectiveness and practicality of numerical simulation technique developed. Based upon the experimental observations and extensive numerical results, as well as the closed-form expressions for the propagation pressures from uniform ring collapse models, a more accurate empirical formula for the propagation pressure $P_{ps}$ of an outer pipe with a solid rod insert of the same diameter as the inner pipe, and a more reasonable empirical formula for the propagation pressure $P_{p2}$ of pipe-in-pipe systems are proposed, respectively. Furthermore, four collapse propagation modes are identified in the light of geometric characteristics of pipe-in-pipe systems.

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ABSTRACT: The LiteSteel beam (LSB) is a cold-formed high strength steel channel section made of two torsionally rigid closed flanges and a slender web. Due to its mono-symmetric characteristics, its centroid and shear centre do not coincide. The LSBs can be used in floor systems as joists or bearers and in these applications they are often subjected to transverse loads that are applied away from the shear centre. Hence they are often subjected to combined bending and torsion actions. Previous researches on LSBs have concentrated on their bending or shear behaviour and strengths, and only limited research has been undertaken on their combined bending and torsion behaviour. Therefore in this research a series of nine experiments was first conducted on LSBs subject to combined bending and torsion. Three LSB sections were tested to failure under eccentric loading at mid-span, and appropriate results were obtained from seven tests. A special test rig was used to simulate two different eccentricities and to provide accurate simple boundary conditions at the supports. Finite element models of tested LSBs were developed using ANSYS, and the ultimate strengths, failure modes, and load–displacement curves were obtained and compared with corresponding test results. Finite element analyses agreed well with test results and hence the developed models were used in a parametric study to investigate the effects of load locations, eccentricities, and spans on the combined bending and torsion behaviour of LSBs. The interaction between the ultimate bending and torsional moment capacities was studied and a simple design rule was proposed. This paper presents the details of the tests, finite element analyses, and parametric study of LSBs subject to combined bending and torsion, and the results.


ABSTRACT: This work analyses the effect of residual stress on the ultimate strength of a thin rectangular stiffened and single plate. The analysis is performed by the finite element method employing commercial software. The heat source is defined as a moving heat one in order to simulate welding processes and consequently the corresponding residual stresses. Three types of welding sequences have been conducted for the stiffened panel. A sensitivity analysis is performed accounting for the plate thickness, heat source, speed and level of residual stresses. Modified material stress strain curves have been developed accounting for the plate thickness that can be directly used in the non-linear finite element analyses of ultimate strength of thin plates.


ABSTRACT: The Perforated Core Buckling Restrained Brace (PCBRB) is a new energy dissipation device for the seismic design of buildings. Its core consists of a perforated steel yielding plate which is guided and partially stabilized by the restraining unit. The core is mechanized to obtain two yielding lateral bands which are connected by several equidistant stabilizing bridges. The lateral bands are designed to yield to axial forces, as conventional BRBs do, so the force and the displacement at the yielding point can be calculated by the usual expressions of conventional buckling restrained braces, based on uniform strain distribution. To distribute the stabilizing bridges along the core, an expression based on Euler’s formulation is proposed. Under this formulation two types of specimens have been designed and tested (Type I and Type II) using three different loading protocols. The Type I specimens exhibited a stable response, while the Type II specimens suffered a
progressive loss of compression capacity produced by the local buckling. Finally, the hysteretic behaviour of the tested braces and a large scale brace has been analysed with an FEM model which considers the interaction between the core and the encasing member. The model reproduces the hysteretic response during the first cycles and the influence of friction on the axial strain distribution along the yielding core.

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ABSTRACT: Geometric imperfections have long been known to play an important role in determining the buckling resistance of metal cylindrical shells and tubes. Though the effect is more important in thin shells rather than thicker tubular members, it may still have a significant impact on the strength of tubulars where buckling occurs in the plastic range. Spiral welded carbon steel tubes with $D/t$ ratios in the approximate range 50–150 are often used as primary load-bearing members together with sheet piling in deep retaining walls. A recent European study on such tubes aimed to devise improved and more economical design guidelines for their use. As a central part of this project, a representative selection of 18 tubes was subject to a laser survey to obtain detailed scans of the initial imperfections found on their outer surfaces, in addition to careful wall thickness measurements. The resulting high quality data set is considered to be the first of its kind. The surface imperfections of the full set of 18 tubes were collectively analysed using a combination of single and double Fourier series to assess the dominant imperfection modes and their amplitudes. It was found that the spiral welding process results in a very unique pattern of surface imperfections which is here characterised algebraically. The systematic peak geometric deviations of the tube surfaces were found to be modest and consistent with the imperfection amplitudes defined by EN 1993-1-6 for this $D/t$ range.

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ABSTRACT: Buckling and postbuckling behavior of shear deformable anisotropic laminated composite beams with initial imperfection subjected to axial compression is presented. The material in each layer of beams is assumed to be linearly elastic, anisotropic and fiber-reinforced. The governing equations are based on the higher order shear deformation beam theory with a von Kármán-type of kinematic nonlinearity. Composite beams with the fixed–fixed, fixed–hinged, and hinged–hinged boundary conditions are considered. A generic imperfection function for one-dimensional composite beams is adopted to model various possible initial geometric (e.g., sine, local, and global type) imperfections. The nonlinear prebuckling deformation and initial geometric imperfection of the beam are both taken into account. A numerical solution of nonlinear partial–integral differential form in terms of the transverse deflection is employed to determine the buckling load and postbuckling equilibrium path of composite beams. The results obtained by combining the Newton’s iterative method with the Galerkin’s method are theoretically exact from the transverse and longitudinal displacements for anisotropic laminated beams under the axial compressive loads using the secondary parameter conversion technique, and they are validated by comparing with those available in the literature. The numerical illustrations are presented for the postbuckling response of laminated beams with different types of boundary conditions, ply arrangements (layups), geometric and physical properties. The results reveal that the geometric and physical properties and boundary conditions have a significant effect on postbuckling behavior of anisotropic laminated composite beams.
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ABSTRACT: Thirty-nine stub columns were tested to failure to investigate the compressive behaviour of normal-strength recycled aggregate concrete filled steel tubular (RACFST) stub columns under axial loading. Study parameters included recycled coarse aggregate (RCA) substitution level, source of RCA, compressive strength of recycled aggregate concrete (RAC) core and ratio of steel area over concrete area. Experimental results showed that the scatter in the mechanical properties of RACFST stub columns is smaller than that in RACs due to the contribution of steel tubes. The source of RCA had little effect on the compressive behaviour of axially loaded RACFST stub columns within the parameter range adopted in the tested specimens. A reduction of less than 10% was measured in the compressive strength of RACFST due to the incorporation of RCA, which is smaller than that for RAC samples in material tests. As part of the work, confinement effects of the steel tubes to the RAC cores during the whole loading process were investigated based on the strain gauge measurements. Model equations were then proposed to predict the longitudinal stress–strain relationships for both steel tubes and RAC cores. Current CFST design provisions are compared with the RACFST stub columns test results, and the design recommendations are presented.

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ABSTRACT: In this paper attention is focused on the uprights, i.e. vertical elements of the skeleton frames of steel storage rack systems. Their response is quite difficult to predict because of the significant influence of the interaction between local, distortional and overall buckling phenomena, owing to the presence of open mono-symmetric thin-walled cold-formed cross-sections. As a consequence, very high engineering competences are necessarily required to guarantee relevant load carrying capacities with structural systems of extremely limited weight and of very modest costs. Design provisions admit few alternatives, leading to different sizes and weight of the racks and, as consequence, to different degrees of economic competitiveness on the market. In the framework of a more general research project on steel storage rack structures, three options of designing the uprights in Europe have been investigated in the present paper. Several cases from practice have been selected, which comprise of uprights differing for cross-section geometry, slenderness and load conditions. A suitable finite element program for academic use characterized by a refined beam formulation capable of capturing key features of uprights has been used to model the elastic buckling interaction between the axial load and the bending moment. Non-negligible differences have been detected for what concerns the admitted design approaches in terms of beam–column load carrying capacity; furthermore, the direct comparison of the research outcomes offers practical indications for an optimal use of the material in accordance with the required safety standards.
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“Transient dynamic analysis of shear deformable shallow shells using the boundary element method”,
ABSTRACT: Dynamic plate bending problems appear on civil, mechanical, aerospatial and naval applications.
The complexity involved in the dynamic response of plates brings many challenges from a mathematical standpoint.
In this work, the transient dynamic analysis of elastic shallow shells under uniformly distributed pressure loads, using a dual reciprocity boundary element formulation, is presented. A boundary element formulation based on a direct time-domain formulation using elastostatic fundamental solutions was used. Effects of shear deformation and rotatory inertia were included in the formulation. Shallow shells are modeled coupling boundary element formulation of shear deformable plate and two-dimensional plane stress elasticity. Domain integrals related to inertial terms were treated using the Dual Reciprocity Boundary Element Method. Numerical examples are presented to demonstrate the efficiency and accuracy of the proposed formulation.

ABSTRACT: A linear-elastic theoretical formulation is presented for the complete determination of the state of stress in large thin-walled liquid-filled vessels in the form of multi-segmented spherical shells. The transfer of membrane forces between adjacent shell segments is such that only vertical equilibrium of stress resultants needs to be preserved. The edge effect in the vicinity of the shell junctions is quantified on the basis of an approximate but accurate bending theory for spherical shells. The effectiveness of the developed formulation is demonstrated by consideration of a numerical example. Agreement with the results of finite-element modelling is excellent, showing that the presented theoretical formulation is a reliable, computationally efficient and accurate means of obtaining stresses in large multi-segmented spherical vessels.

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ABSTRACT: To improve crashing behavior of aluminum foam-filler columns design optimization has proven rather effective and been extensively used. Nevertheless, an optimal design could become less meaningful or even unacceptable when some uncertainties present. Parametric uncertainties are often treated as random variables in conventional robust optimization. Taking foam filled thin-walled structure as an example, which could also exhibit probabilistic and/or bounded nature of uncertainties, it may be more appropriate to describe
them with hybrid uncertainties by using random variables and interval variables. Furthermore, evaluation of product quality often involves a number of criteria which may conflict with each other. To address the issue, this paper presents a multiobjective robust optimization to explore the design problems of parametric uncertainties involving both random and interval variables in foam filled thin-walled tube, in which specific energy absorption (SEA) and peak crushing force are considered as the design objectives and the average crash force is considered as the design constraint. A nesting optimization procedure is proposed here to solve the multiobjective robust optimization problem. In the outer loop, the Non-dominated Sorting Genetic Algorithm II (NSGA-II), is implemented to generate robust Pareto solution. In the inner loop the Monte Carlo simulation is performed to evaluate the impact responses of the mixed uncertainties to the robustness of optimized design. The example demonstrates the effectiveness of the proposed robust crashworthiness optimization involving both random and interval variables.

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ABSTRACT: Stainless steel has been gaining increasing use in a variety of engineering applications due to its unique combination of mechanical properties, durability and aesthetics. Significant progress in the development of structural design guidance has been made in recent years, underpinned by sound research. However, an area that has remained relatively unexplored is that of combined loading. Testing and analysis of stainless steel cross-sections under combined axial load and bending is therefore the subject of the present paper and the companion paper (Zhao et al., submitted for publication). The experimental programme covers both austenitic and duplex stainless steels, and five cross-section sizes including three square hollow sections (SHS) and two rectangular hollow sections (RHS). In total, five stub column tests, five four-point bending tests, 20 uniaxial bending plus compression tests and four biaxial bending plus compression tests were carried out to investigate the cross-sectional behaviour of stainless steel tubular sections under combined loading. The initial loading eccentricities for the combined loading tests were varied to provide a wide range of bending moment-to-axial load ratios. For each type of test, the test setup, experimental procedures, full experimental load–deformation histories and key test results are reported in detail. All the experimental results are then employed in the companion paper (Zhao et al., submitted for publication) for the validation of finite element (FE) models, by means of which a series of parametric results is generated, and for the assessment of the design provisions given in EN 1993-1-4 (2006) and SEI/ASCE-8 (2002). Improved design rules for stainless steel cross-sections under combined loading are also sought through extension of the deformation-based Continuous Strength Method (CSM).

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ABSTRACT: In parallel with the experimental study described in the companion paper (Zhao et al., submitted for publication), a numerical modelling programme has been carried out to investigate further the structural behaviour of stainless steel cross-sections under combined loading. The numerical models, which were developed using the finite element (FE) package ABAQUS, were initially validated against the experiments, showing the capability of the FE models to replicate the key test results, the full experimental load–deformation histories and the observed local buckling failure modes. Upon validation of the FE models, parametric studies were conducted to generate additional structural performance data over a wide range of cross-section slenderness and combinations of loading. The experimental and numerical results were then compared with the design capacity predictions from the current European Standard EN 1993-1-4 (2006) and American Specification SEI/ASCE-8 (2002) for stainless steel structures. The comparisons revealed that the current design standards can significantly underestimate the resistance of stainless steel cross-sections subjected to combined loading; this under-prediction of capacity can be primarily attributed to the lack of consideration of strain hardening of the material under load. The Continuous Strength Method (CSM) is a deformation-based design approach that accounts for strain hardening and has been shown to provide accurate predictions of cross-sectional resistance under compression and bending, acting in isolation. In the present paper, proposals are made to extend the scope of the CSM to the case of combined loading. Comparisons between the CSM design proposals and the test and FE results indicated a high level of accuracy and consistency in the predictions. The reliability of the proposals was confirmed by means of statistical analyses according to EN 1990 (2002).


ABSTRACT: This paper presents the results of the first-ever experimental study on the axial compressive behavior of steel fiber reinforced high-strength concrete (SFRHSC)-filled FRP tubes. A total of 27 circular unreinforced and steel fiber reinforced high-strength concrete FRP tubes (SFRHSCFFT) were tested under axial compression. The effects of steel fiber parameters, including fiber shape, fiber aspect ratio and fiber volume fraction were examined. Concrete type was also investigated as a parameter, where two different types of concrete, including a conventional HSC and slurry infiltrated fiber concrete (SIFCON) were considered. The results indicate that both SFRHSCFFT and SIFCON-filled FRP tubes (SIFCONFFT) exhibit highly ductile compressive behavior. The results also indicate that the axial stress–strain behavior of CFFT is influenced by the presence and amount of internal steel fibers, with particularly significant influences noted on the FRP hoop rupture strains and post-peak strength losses. It is found that fiber volume fraction significantly affects the compressive behavior of CFFT. Concrete type, fiber shape and fiber aspect ratio also have some, but less significant, influence on the behavior of CFFT. It is observed that the compressive strength and ultimate strain of CFFT increases with an increase in fiber volume fraction or a decrease in fiber aspect ratio. It is also observed that CFFT reinforced with hooked end steel fibers exhibit improved compressive behavior compared to the companion CFFT reinforced with crimped fibers.

ABSTRACT: This study proposes a two-stage approach to predict the lateral load \( (P) \) versus the local indentation \( (\delta) \) relationship for cement composite filled pipe-in-pipe structures. The first stage extends a theoretical shell model used in predicting the \( P-\delta \) relationship for hollow steel pipes, to the sandwich composite pipes by introducing an equivalent thickness to describe the composite action. This composite action, however, deteriorates at large indentation levels. The indentation resistance in the second stage, therefore, combines the resistance of three individual layers of materials. This approach predicts closely the \( P-\delta \) relationship measured for the pipe-in-pipe composite specimens under lateral loads.


ABSTRACT: This paper presents an experimental study, which investigated the compressive behavior of square fiber reinforced polymer (FRP)–concrete composite columns through the tests of 40 column specimens. 24 FRP–concrete–steel double-skin tubular columns (DSTCs), four concrete-filled FRP tubes (CFFTs), and 12 CFFTs with inner voids (H-CFFTs) were tested under axial compression. The majority of the specimens were manufactured using high-strength concrete (HSC). The key parameters examined included the influence of the strength of the concrete, cross-sectional shape (i.e. circular and square) and dimension of the inner steel tube, and presence (or absence) of a concrete filling inside the steel tube. The results of the DSTCs with circular inner steel tubes indicate that concrete-filling inner tubes results in an increase in the ultimate axial stress but a decrease in the ultimate axial strain of concrete compared to those seen in DSTCs with hollow inner steel tubes. It is observed that concrete in hollow DSTCs manufactured with square inner steel tubes develop significantly lower ultimate axial stresses and strains than concrete in companion hollow DSTCs with circular inner steel tubes. It is found, however, that the performance of these specimens improves dramatically when the square inner steel tube is filled with concrete. Comparisons of the results indicate that concrete in filled DSTCs develops larger ultimate axial stresses and strains than concrete in companion CFFTs. Finally, the results demonstrate that H-CFFTs perform significantly worse than DSTCs and CFFTs, and their performance further degrade as the diameter of the inner void increases.

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ABSTRACT: An approach to simulate the behaviour of steel stiffened plates subjected to weld-induced grooving corrosion using nonlinear finite element modelling is proposed. The model includes the effects of different initial geometric imperfections and weld-induced residual stresses. The influence of corrosion damage on the load shortening curves and ultimate strength is investigated. It is shown that grooving corrosion depth has a greater influence on structural performance as compared with corrosion width for the same volume loss. Such corrosion damage could cause a significant reduction in the ultimate strength of a plate panel. Considerations of weld-induced deflection and residual stresses further enhance the corrosion influence on the strength capacity.
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ABSTRACT: This paper focuses on the development of much-needed numerical and experimental models for understanding the mechanical behaviour, section capacity and energy absorption of the innovative fabricated columns consisting of corrugated mild-steel plates. The corrugated square columns proposed in this paper are fabricated by welding four corrugated plates which are originally produced from 3 mm thick flat mild steel plates. The experiments consist of applying a compressive axial force to the columns to determine load–displacement curves of the fabricated sections. The effects of geometric parameters such as inclination angle and corrugation height are also investigated experimentally by considering three different types of corrugated columns. Moreover, a finite element model in which the effects of material and geometric nonlinearities as well as residual stresses are taken into account is developed using ABAQUS. The experimental results are also compared with those given by the finite element (FE) model whilst a good agreement is achieved. A cost analysis is also conducted in which the cost of the innovative columns proposed in this research is compared to those of conventional welded columns currently available in the civil engineering market.

Mei Liu, Lulu Zhang, Peijun Wang and Yicun Chang (School of Civil Engineering, Shandong University, Jinan, Shandong Province 250061, China), “Buckling behaviors of (?) section aluminum alloy columns under axial compression”, Engineering Structures, Vol. 95, pp 127-137, July 2015, https://doi.org/10.1016/j.engstruct.2015.03.064
ABSTRACT: Thin-walled columns with section are used widely as columns in aluminum alloy framed structures, offering high strength-to-weight ratios and convenience in connection with maintaining walls. In this paper, thin-walled aluminum alloy columns with section were studied experimentally and numerically to investigate the buckling behavior and to assess the accuracy of current design methods. A finite element model (FEM) was developed and used to perform parametric studies after being verified by tests. Effects of plate thickness on elastic buckling stress was studied using finite strip method (FSM) and to find the potential buckling failure mode at a given length. Tested ultimate strengths were compared with those predicted by the current American, European and Chinese specifications on aluminum alloy structures and the Direct Strength Method (DSM) on thin-walled structures. Following reliability analysis, the design strength predicted by current design specifications were found to be generally conservative, whereas DSM offered more accurate results.

ABSTRACT: The purpose of this paper is to present a proposal for the design of steel structures sensitive to lateral torsional buckling due to bending moment in order to fill the gaps in the current Standard EN 1993-1-1, guidelines for obtaining the magnitude of the imperfection. The proposal generalizes the approach provided in clause 5.3.2(11) of EN 1993-1-1 for steel structures sensitive to flexural buckling under compression.
ABSTRACT: Flanged cruciform sections (FCSs), as an appropriate alternative for column cross-section in orthogonal moment-resisting frames, need more cross-section specific code requirements in design specifications. To extend the specifications for FCSs, local buckling of webs, flexural ductility under axial compression and cyclic bending moments, and also $P-M_P$ interaction relationships have been studied. A validated material and geometric nonlinear finite element model in ABAQUS has been used to perform a comprehensive parametric study on FCSs. The modeling protocol includes a new residual stress distribution, as well as appropriate geometric imperfections. A wide range of web depth-to-thickness ratios is considered to evaluate the current AISC-341 seismically compact limit state. As the web slenderness and axial load have significant effects on the cyclic behavior and ductility of the FCS beam-columns, a new web seismically compact limiting ratio is proposed for FCSs as a function of the axial load to provide the desired ductility. It is shown that taking half of the depth in calculating web slenderness of FCSs and using the current I-section web compactness limitations for FCSs, can be non-conservative. The study shows that the AISC-341 and ASCE-41 $P-M_P$ interaction curves for beam columns made from wide flange sections are overly conservative when applied to FCSs. A modified interaction curve is proposed which more accurately represents beam column behavior of FCSs.

ABSTRACT: The purpose of this paper is to present a proposal for the design of steel structures sensitive to flexural and/or torsional buckling due to compression in order to fill in the gaps in the current Standard EN 1993-1-1 guidelines for obtaining the magnitude of the geometric equivalent imperfection. The proposal generalizes the approach provided in Clause 5.3.2(11) of EN 1993-1-1 (EC-3) for cases in which a torsional or flexural–torsional buckling mode may occur. The extension of the procedure also allows designers to obtain the magnitude and shape of the imperfection as well as the worst direction of the imperfection due to the external loads applied. It also identifies the cases in which it is necessary to consider the shape of the imperfection given by higher buckling modes.

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ABSTRACT: The response of sandwich steel beams with corrugated cores to quasi-static loading is investigated by employing experimental and computational approaches. The sandwich steel beam consists of top and bottom substrates made of AISI Steel 1018 and four corrugated core layers made of AISI Steel 1008. Various arrangements of the corrugated core layers with both uniform and graded layer thicknesses are considered. Three core arrangements with identical relative densities are used to study the effects of uniform versus graded core layer thicknesses onto the quasi-static behavior of corrugated steel beams. Finite element models are validated against quasi-static tests, and lend themselves suitable for a parametric study. A parametric study is also carried out on large-scale structural size beams of a few meters in length. The deformation modes observed in this study include core crushing, and plate bending and shear. It is found that core arrangement and beam span is key factors governing the quasi-static response of sandwich beams with corrugated cores.


ABSTRACT: Seismic protection of wine storage tanks has become a very important issue due to the booming of the wine industry in seismic countries such as the US, Italy, New Zealand, Chile and Argentina. In order to improve the seismic reliabilities of structures, external energy dissipation may be used beneficially. In this study, the reliabilities of two continuously supported cylindrical steel tanks (one slender and one broad), used for fermentation and wine storage, with and without an external energy dissipation system are calculated by using simulation. A group of non-linear time history analyses is established in order to assess the influence of the energy dissipation system. Each non-linear time history is obtained by means of a mathematical model that considers the fluid–structure–soil interaction. A set of different seismic ground motions is used for the purpose of obtaining robust results in the reliability analysis. Finally, the seismic reliability analysis shows that, for steel wine storage tanks, an external energy dissipation system would reduce the limit state probability in the order of 80%.


ABSTRACT: Beam to column connections subjected to loads in the beam minor axis direction are usually considered either as pinned or rigid for both resistance and stiffness checks. However, modern codes contemplate the possibility of semi-rigid and partial strength connections. The Eurocode 3 provides criteria, based on the component method, to characterise such connections. There are unresolved issues regarding three-dimensional connections and connections subjected to out-of-plane effects that need further research. Their behaviour relies mainly on the characterisation of the components acting on the T-stub under out-of-plane bending, and this characterisation is the aim of this paper. An experimental program consisting of five T-stub tests has been carried out and finite element models have been developed. The finite element models have been
validated with the experimental results and prove to be an accurate tool for the characterisation of 3D connections. The connection characteristics have been obtained by means of tests and finite element models, and after comparison with the limits provided by the Eurocode 3, it is concluded that all connections under study are indeed semi-rigid and partial strength.

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ABSTRACT: Beam to column connections subjected to loads in the beam minor axis direction are usually considered either as pinned or rigid for both resistance and stiffness checks. This simplification is also assumed at the time of considering the stability of the column and the lateral buckling of the beams. However, as proven in the companion paper by means of laboratory tests and numerical simulations, these types of connections are actually semi-rigid and partial strength. The consideration of their real semi-rigid behavior can lead to a more accurate global analysis and, consequently, more optimized structures. Their behavior relies mainly on the characterization of the components acting on the T-stub under out-of-plane bending. In this paper a parametric analysis is performed to define the components involved. Analytical expressions are specified to describe each one of the components and the assembly process following a proposed mechanical model. The stiffness and strength that are obtained compare very satisfactorily with the experimental results of the T-stubs described in the companion paper.

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ABSTRACT: A 3D finite element beam element model is investigated for the behavior, the buckling and the post-buckling analyses of thin-walled tapered beams with open cross sections. For the purpose, a non-linear model is performed in large torsion context according to a new kinematics that accounts for large torsion, flexural–torsional coupling and the presence of tapering terms in bending and torsion. The equilibrium equations are carried out and new tapering stress resultants are then present. This model is extended to finite element formulation in the same circumstances. 3D beams elements with two nodes and seven degrees of freedom per node are adopted. Due to large torsion assumption and flexural–torsional coupling, new matrices are established in both the geometric and the initial stress parts of the tangent stiffness matrix. The Arclength method is adopted as solution strategy of the non-linear equations. Many applications are presented that deal with the behavior, the buckling and the post-buckling equilibrium. Comparisons are made with some available solutions and with shell elements of a commercial code. The bifurcation points are in accordance with non-linear stability solutions. Moreover, the present element is also compared to similar tapered beam finite element
without the new tapering terms. The proposed beam element is efficient and accurate in both linear and non-linear behavior analyses. It follows a non negligible gain in computation time especially when the post-buckling behavior is performed.

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ABSTRACT: Hybrid FRP–concrete–steel double-skin tubular columns (DSTCs) are a new form of hybrid columns, consisting of an outer tube made of fiber reinforced polymer (FRP) and an inner tube made of steel, with the space between filled with concrete. In hybrid DSTCs, the three constituent materials are optimally combined to achieve several advantages not available with existing columns, including their excellent corrosion resistance and seismic performance. Although two existing studies have examined the seismic performance of circular hybrid DSTCs, they have been limited to normal strength concrete, small column dimensions, and small void ratios (ratios between the inner diameter and the outer diameter of the annular concrete section). Against this background, this paper presents the first experimental study on hybrid DSTCs filled with HSC subjected to axial compression in combination with cyclic lateral loading. A relatively large column section (with a diameter of 300 mm) was chosen to allow reliable experimental modeling of real columns. The test results indicate that hybrid DSTCs possess excellent ductility and seismic resistance even when high strength concrete with a cylinder compressive strength of around 120 MPa is used; column damage is concentrated in a small plastic hinge region near the column bottom end; and the performance of hybrid DSTCs can be enhanced by filling the inner void in the plastic hinge region. The test results provide valuable data needed for the formulation and verification of a theoretical model for the hysteretic behavior of hybrid DSTCs, particularly when they are filled with HSC.
ABSTRACT: Across many industries damage events leading to a breach in structural integrity continue to occur. An area where this can lead to particularly unsafe conditions is in the maritime environment, where it may be difficult to rescue crew and cargo. In order to improve structural safety through design for the survivability or to assess the residual strength of a damaged vessel in an emergency response or salvage scenario, it is critical to understand the influence of the damage. This paper, for the first time, investigates the use of FEA on ultimate collapse strength of damaged steel grillages and the influence of the damage aperture on the developing failure modes within the structure. The study finds that the presence of damage, in the form of a hole, can lead to the failure mode changing as damage aperture size is increased leading to significant changes to the ultimate collapse strength of the structure. It concludes that to assess the damaged strength of steel plated structures, it is critical that modelling methods are able to capture and account for such mode changes in order to accurately assess the true residual strength of the structure.


ABSTRACT: The present paper deals with the nonlinear finite element analysis of elastic water tanks. Both fluid and tank walls are discretized and modeled by two dimensional eight-node isoperimetric elements. In the governing equations, displacement for tank walls and pressure for the fluid domain are considered as independent nodal variables. The nonlinear term for the convective acceleration in Navier–Stokes equations is incorporated in the present analysis. The nonlinearity effects of the fluid are studied considering excitations both harmonic of various frequencies and random. The hydrodynamic pressure on tank wall is presented both from linear and nonlinear analysis for a comparison. The results show that the convective nonlinearity increases the magnitude of hydrodynamic pressure to a considerable amount when the excitation frequency approaches to the fundamental frequency of the water tank. The magnitude of hydrodynamic pressure in nonlinear analysis is quite large compare to that in linear analysis when the distance between the two vertical walls are relatively closer. However, the increase in pressure is insignificant when the tank is vibrated with a frequency higher than the frequency of the fluid domain. The seismic analysis results show that the distribution of nonlinear hydrodynamic pressure is almost similar to the linear pressure due to ground excitation.


ABSTRACT: We present a computational procedure for evaluating the collapse load and assessing the cross-section classification of thin-walled sections of arbitrary shape on the basis of Eurocode prescriptions. The procedure is based on two algorithms which address separately the rigid-plastic model adopted by the Eurocode for ordinary steel cross-sections and arbitrary uniaxial constitutive laws typically used for stainless steel and aluminum. Both algorithms are based on a polygonal description of the cross section boundary so that integrals extended to the section domain are conveniently expressed as algebraic sums depending upon the coordinates of
the section vertices. Accordingly, a further algorithm is illustrated in order to automatically convert the plate and node model adopted by Eurocode to a polygonal description of the section geometry. The numerical effectiveness of both algorithms is assessed with reference to an I-shaped, a Z-shaped and a RHS cross sections.

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“Topology optimization applied to 2D elasticity problems considering the geometrical nonlinearity”,  

ABSTRACT: Topological Optimization (TO) of structures in plane stress state with material elastic-linear behavior, but taking into consideration the geometrical nonlinearities, was performed and the results are presented herein. For this process, an evolutionary heuristic formulation denominated SESO (Smoothing Evolutionary Structural Optimization) associated with a finite element method was applied. SESO is a variant of the classic evolutionary structural optimization (ESO) method, where a smoothing process is applied in the “hard-kill” process of element removal – that is, their removal is done smoothly, reducing the values of the constitutive matrix of the element as if it were in the process of damage. It has been demonstrated that this non-linear geometric phenomenon clearly influences the final optimized topology when compared to an optimum configuration obtained with the equilibrium equations written at an undeformed position. Some numerical examples from literature are presented in order to show the differences in the final optimal topology when linear and non-linear analyses are used, allowing the verification of the importance of correctly analyzing the final optimum topology and as such, demonstrate the advantages of SESO as a structural optimization method.

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ABSTRACT: Numerous experimental investigations have demonstrated the advantages of Concrete Filled FRP Tubes (CFFT) over reinforced concrete members under various loading conditions. None of the studies, however, investigated whether these advantages of CFFT extended to resisting dynamic impact loads. This presented a fertile field for investigation as it was well known that the addition of the tube confined and protected the concrete core and increased its load carrying capacity, and by extension, its energy absorption. This investigation aimed at understanding the dynamic behaviour of CFFT under impact loading and to develop a procedure for their analysis and design. These aims were achieved by testing six specimens, three of which were CFFTs and three were reinforced concrete. The specimens were tested in pairs to facilitate comparisons. The first pair were tested monotonically to act as a benchmark and tie into previous research. The remaining two pairs were tested under impact loading. The parameters investigated were the presence of the GFRP tube, the internal steel reinforcement ratio, and the input kinetic energy. The monotonic tests showed that the addition of the tube increased the flexural capacity and maximum displacement by 112%, which translated into a 487.5% increase in energy absorption, when compared to the reinforced concrete counterpart. The
addition of the tube increased the impact specimens’ energy absorbing capacity by 467% when the steel reinforcement ratio was 1.2% and 1223% when the steel reinforcement ratio was 2.4%, compared to the reinforced concrete specimens. The GFRP tube also protected the concrete core and prevented its spalling and crushing during the impact tests. These encouraging experimental results led to the development of a nonlinear single degree of freedom (SDOF) model capable of capturing the behaviour of the system under multiple impacts to be used as a sophisticated analysis and design tool. Additionally, a simplified design method based on the conservation of energy was outlined.

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ABSTRACT: Imperfection sensitive CFRP cylindrical shells are used in a variety of civil and aerospace applications and feature a large scatter in buckling load levels induced from imperfections introduced from their manufacture. Currently, there are no complete methods that can realistically simulate cylinders with a full spectrum of imperfection types for a complete diagnosis of possible buckling loads. This forces shell designers to utilise an outdated, inefficient and conservative design philosophy that is unsuitable for modern manufacturing methods and materials. Stochastic analyses can optimise and improve the robust design and reliability of such cylinders through accurate prediction of the range of conceivable buckling loads by realistic simulation of structural imperfections. Such imperfections include initial shell-wall geometric, thickness and material imperfections and non-uniform applied end-loads. A procedure which aims to improve the stochastic modelling of thickness and material imperfections in imperfection sensitive composite cylindrical shells is proposed. Monte-Carlo simulations of axially compressed cylinders are performed to show that the stochastic methods described here are able to capture the scatter introduced from the imperfections. The results show that the axial buckling load of the specific cylinder analysed here can be reduced to 29.5 kN and increased to over 40 kN from a perfect load of 38.2 kN from material and thickness imperfections alone.

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ABSTRACT: Concrete-filled double skin tubular (CFDST) columns consist of two concentric steel tubes, the void between which is filled with concrete. For the current studied configuration, a square tube is used for the
outer columns, which enables more straightforward fabrication and installation of beam-to-column joints compared with the case of circular outer columns. To date there have been no significant applications of square CFDST columns with inner circular tubes worldwide, partly due to the lack of design provisions. This paper addresses the axial compressive performance of these columns. Nonlinear finite element (FE) analyses are employed to conduct parametric studies, having first validated the models against available experimental data. The depth-to-thickness (D/t) ratios of the outer tubes were varied such that all cross-section classes were considered. Based on the generated numerical results, a new design model is proposed to provide reliable predictions for the ultimate axial strength of short CFDST columns. The work is then extended to investigate the behaviour of slender CFDST columns. Comparisons of the generated FE ultimate loads for the slender columns are made with strength predictions according to the provisions of Eurocode 4 (EC4) and the AISC 360 Specification for CFST columns, but with allowance made for the inner tube. It is found that the AISC provisions generally give good predictions of the strengths of the CFDST columns, while EC4 gives rather conservative predictions for the columns with slender and very-slim cross-sections.

ABSTRACT: An analytical model was developed for predicting the blast response of a double-curvature, composite sandwich shallow shell with PVC foam core. Based on Donnell’s nonlinear shallow shell formulation, the PVC foam core was modeled with isotropic and transversely isotropic elastic–plastic properties. The predicted transient response was shown to be in good agreement with Finite Elements (ABAQUS Explicit) when assuming isotropic foam crushing. For sandwich shells with higher curvature and in-plane membrane resistance, lower blast resistance was found with transversely isotropic than isotropic core crushing. This indicated that modeling the core of the sandwich shell as isotropic instead of transversely isotropic would give non-conservative estimates of the structure’s ability to resist blast loading for some sandwich shell geometries.

ABSTRACT: The objective of this work is to perform a hull girder ultimate strength verification according to the Class Society rules based on experimental results and the dimensional theory. The results of the ultimate strength test of three box girders, that may represent the behaviour of a mid-ship section of a ship, deteriorated in a real corrosive seawater environment representing different levels of corrosion degradation of ageing ship structures, is used to evaluate the ultimate strength. The analysis is based on a structural model, used in the experimental test, which maintains the first-order similarity between the model and real structures. The present analysis may be used to validate the global ultimate strength of ship hull structures in the phase of the new structural design or during the service life and to calibrate the new developed codes.

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ABSTRACT: In the non-linear in-plane elastic buckling and postbuckling analyses of shallow parabolic arches, to overcome the difficulty in deriving an accurate expression for the non-linear normal strain, an approximation assumption that the derivative of the vertical coordinate with respect to the horizontal coordinate satisfies dy/dz much less than 1.0 has been adopted in many investigations. The merit of the assumption is that it leads to the same differential equations of equilibrium and the same solutions as those for shallow circular arches. However, the accuracy of the assumption and the limitation of the analytical solutions have not been examined and because of the approximation, the analytical solutions may lead to significant errors for the buckling loads of shallow parabolic arches in some cases. This paper investigates the effects of the approximation assumption on the accuracy of in-plane buckling and postbuckling analyses of pin-ended and fixed shallow parabolic arches by comparing the analytical solutions with their finite element counterparts. It is found that the analytical solutions based on the assumption have some limitations because the assumption holds approximately only for extremely shallow parabolic arches, but is not valid for most shallow parabolic arches. The analytical solutions for the buckling loads based on the assumption are larger than the corresponding finite element results for parabolic arches with a rise-to-span ratio greater than 0.08, the error of the analytical solution increases with an increase of the rise-to-span ratio of the arch, and the sources for the errors are identified and discussed. Hence, caution should be exercised when using the analytical solutions to predict the buckling load of shallow parabolic arches, particularly of those with a rise-to-span ratio greater than 0.08.


ABSTRACT: Offshore pipeline is generally recognised to be the safest and most economical way to transport oil and gas. These pipelines are operated in elevated temperatures and pressures those are much higher than the ambient conditions. That will causes axial expansion in the pipeline, if such expansion is restrained by soil friction, the compressive force will be built up in the pipe, finally, induces the buried pipeline to buckle in the vertical plane. This paper investigates the effect of uncertainty in soil, operating condition and pipe properties on upheaval buckling behaviour of offshore pipeline buried in clayey soil. To simulate the upheaval buckling, a 2-D finite element model of 500 m long pipeline-seabed soil system was developed in OpenSEES using the thermal element. Using the finite element model prediction of upheaval buckling height, a total number of 12 upheaval buckling height prediction models were proposed by using genetic programming with varying levels of complexity and accuracy. To achieve the best performance model, a scoring table was proposed considering several factors including coefficient of determination, sum of errors, difference between training and testing errors, sum of residuals, deviation of predicted results from experimental one and complexity and generality of the models. Finally, the effect of each parameter on upheaval buckling displacement was studied by parametric analysis and the results were compared by simulated ones. On the basis of the results, most of the models developed using genetic programming show very good prediction with the numerical results. The developed model can be used to improve the design and upheaval bucking risk assessment of buried pipeline.

ABSTRACT: The article analyses one of possible optimization methodologies for ideal elastic–plastic structures at shakedown and its application for shallow spherical shells having prescribed geometry and affected by a variable repeated load (VRL) – a system of external forces that may vary independently of each other. The paper accepts that only time-independent upper and lower bounds of variations in external forces are given. The pronounced effect of external forces, i.e. in this context, possible histories of variations in forces, is not examined (the unloading phenomenon of cross-sections is ignored in the course of plastic deformation). The discussed concept of the structure at shakedown refers to the Melan theorem related to statically allowable admissible internal forces. Thus, for the discretization of the spherical shell, with the help of an assumption about small displacements, the equilibrium finite element method based on internal force approximation is applied. The limit axial force of the cross-section is supposed to be constant within the bounds of the finite element, and only the optimal distribution of limit internal forces among elements, according to the selected criterion, is in need of search. The article presents a discrete mathematical model for determining the optimal allocation problem with strength and stiffness requirements. The model conforms to the limit axial force of the shallow spherical shell of the variable repeated load and takes into account ultimate and serviceability limit states of EC3 with corresponding reliability levels. Structural optimization methods refer to extreme energy principles of mechanics and are illustrated with the numerical examples of spherical shell optimization.

Eyas Azzuni and Sukru Guzey (Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA), “Comparison of the shell design methods for cylindrical liquid storage tanks”, Engineering Structures, Vol. 101, pp 621-630, October 2015, https://doi.org/10.1016/j.engstruct.2015.07.050

ABSTRACT: The three methods for determining the shell thickness of steel cylindrical liquid storage tanks designed in conformance with API Standard 650, Welded Tanks for Oil Storage (API 650) are: (1) one-foot method (1FM), (2) variable-design-point method (VDM) and (3) linear analysis. We compared the shell designs based on these three methods for different tank properties: diameter, height and allowable stress. For linear analysis, we developed a stiffness–flexibility matrix method based on thin shell theory that gives the theoretical displacements and stresses at each shell course without any approximation or simplification. Results show that shell designs using VDM may produce overstressed shell courses for some of the large steel liquid storage tanks when VDM is permissible to use. Linear analysis would give more accurate shell designs for those cases.


ABSTRACT: In this paper, a stiffness reduction method for the flexural–torsional buckling assessment of steel beam–columns subjected to major axis bending and axial compression is presented. The proposed method is applied by reducing the Young’s $E$ and shear $G$ moduli through the developed stiffness reduction functions and performing Linear Buckling Analysis. To account for second-order forces induced prior to buckling, the in-plane (in the plane of bending) and out-of-plane analyses of a member are separated and stiffness reduction for the out-of-plane instability assessment is applied on the basis of member forces determined from the in-plane
analysis. Since the developed stiffness reduction functions fully take into account the detrimental influence of
imperfections and spread of plasticity, the proposed method does not require the use of member design
equations, thus leading to practical design. For the purpose of verifying this approach, the strength predictions
determined through the proposed stiffness reduction method are compared against those obtained from
nonlinear finite element modelling for a large number of regular, irregular, single and multi-span beam–
columns.

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“Simplified analytical solution for axial load capacity of concrete-filled double-skin tube (CFDST) columns
subjected to fire”, Engineering Structures, Vol. 102, pp 156-175, November 2015,
https://doi.org/10.1016/j.engstruct.2015.08.007
ABSTRACT: Concrete-filled steel tube (CFST) columns and even more so concrete-filled double-skin tube
(CFDST) columns have demonstrated a desirable behavior when subjected to fire loading conditions. Current
methods to estimate the axial load capacity for these columns exposed to fire are either limited to simple cases
using tables or require complex finite element analysis. In an effort to develop a more general and practical
approach to this problem, a simplified step by step analytical procedure is proposed for the calculation of the
axial load capacity of CFDST columns subjected to any given time–temperature (fire) curve. The procedure was
defined by combining an analytical solution to the heat transfer problem with calculation of axial load capacity
using the fire-modified material properties adopted from the Eurocode 4 general rules for structural fire design.
The proposed method was verified with existing experimental and advanced finite element simulation results. A
number of design recommendations, based on the knowledge gained from using the procedure for different case
studies, are proposed for CFDST columns subjected to fire.

Jianbei Zhu, Mario M. Attard and David C. Kellermann (School of Civil and Environmental Engineering, The
University of New South Wales, Sydney 2052, Australia), “In-plane nonlinear localized lateral buckling of
straight pipelines”, Engineering Structures, Vol. 103, pp 37-52, November 2015,
https://doi.org/10.1016/j.engstruct.2015.08.036
ABSTRACT: The lateral buckling problem for thermally loaded pipelines is known to involve a localisation
phenomenon within a limited region of the pipeline rather than an extensive global mode shape. In this paper, a
strategy is presented to investigate the localised lateral buckling of pipelines under thermal loading and friction
whereupon the constitutive relations are derived for thermal stress and finite strain based on a hyperelastic
constitutive model. Using this hyperelastic formulation, we investigate the critical overall pipeline length above
which localised buckling remains unchanged. The results show that increasing the length of the pipeline or
changing the end boundary conditions when the pipeline length is greater than or equal to the critical overall
length does not influence the localised buckling behaviour. The solutions to several examples are compared
with the results in the literature and validated by use of the finite element package ANSYS. Parametric studies
on diameter, imperfection, friction and shear deformation effects are subsequently performed on examples that
identify which factors influence the localised buckling of thermal pipelines.

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ABSTRACT: The tubed-reinforced-concrete (TRC) column is a kind of confined reinforced-concrete (RC) columns using the outer encasing thin-walled steel tube which discontinues at the beam-column joints and thus does not carry any direct axial load. Although this composite column has been used in some practical applications in China, there is still a lack of sufficient experimental data and design methods for the TRC columns subjected to eccentric compression. In this paper, 18 short circular TRC columns are tested under axial and eccentric compression considering parameters of eccentricity and diameter-to-thickness ratio of the steel tube. Failure mode, axial load-carrying capacity, and stress in the steel tube of the specimens are discussed in detail. The test results indicate that the average confining stress in the columns with small eccentricity is close to that in the columns under axial load at the peak load. To validate the employed stress–strain relationship for the confined concrete, a fiber-based model is developed and the predicted results agree well with the test results. Based on the strain energy equivalence principle, a regression formula to estimate the ultimate compressive strain of concrete confined by the steel tube is proposed. The equivalent concrete stress block parameters of circular TRC members are theoretically studied and the modified values are purposely suggested for the calculation of capacity interaction diagram.

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ABSTRACT: The capacity of a truss model introduced in the past to represent steel and steel–concrete composite I-girders is examined to non-linear stability problems that include various stability modes. Linear buckling and geometrical and material non-linear analyses including equivalent geometrical imperfections are performed applying the truss model and a detailed shell finite element model. The results indicate that the truss model correctly determines the critical buckling modes and accurately describes the structural response up to and after the limit load. Its big advantage compared to a detailed shell element model is the easier implementation, the smaller computation time and the easier interpretation and exploitation of results. The truss model constitutes accordingly a viable alternative to Codes’ prescribed simplified methods for buckling design of specific topologies, like for plate girder bridges, both in the construction and the service phase.

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ABSTRACT: This article presents results from the experimental testing of two half-scale RC U-shaped walls under quasi-static cyclic bi-directional loading along the diagonal direction of the U-shaped section, which were recently completed at EPFL. The main objective of the article is to emphasise particularities in the behaviour of U-shaped walls under diagonal loading and to point out related design and analysis issues. Several phenomena specific to diagonal loading are discussed: (1) strain gradient across the wall width promotes out-of-plane buckling of the boundary elements in the flange ends; (2) plane section analysis does not yield reliable moment capacity estimates for the diagonal loading direction and (3) under diagonal loading the compression depth in the flange end boundary elements is larger than for the other loading directions, exposing unconfined concrete to large compressive strains. These phenomena lead to a reconsideration of the following design and analysis issues for U-shaped walls: (a) the distribution of the vertical reinforcement layout; (b) the use of plane section analysis for estimating the strength capacity of the wall; (c) the confinement length of the boundary elements of the flanges; and (d) the assessment of the out-of-plane stability of flange ends.


ABSTRACT: This paper presents a proposal for an overall imperfection method utilizing Linear Buckling Analysis (LBA) and developed equivalent initial imperfection for the assessment of the out-of-plane buckling resistance of steel members. The equivalent initial imperfection for the flexural buckling assessment of columns subjected to compressive force has been specified in the Eurocode 3. In this paper this formula is reorganized in order to establish a suitable computer-aided procedure, and then the equivalent initial imperfection for the fundamental cases of lateral torsional buckling and coupled buckling are defined. (Fundamental case: simply-supported member with uniform cross-section subjected to uniformly distributed forces; the buckling resistance of this reference member has been defined by a standardized design equation based on theoretical and empirical background). The amplitude for the equivalent initial imperfection in the shape of the buckling mode is expressed with second-order normal stresses, on one hand calculated with the equivalent amplitude specified in the relevant standard (e.g. Eurocode 3), and on the other hand calculated with the initial imperfection in the shape of the buckling mode with arbitrary amplitude. The design formula derived for the fundamental case is generalized by the equivalent member concept. The stability assessment is carried out verifying the cross-section resistance of the designed member using second-order elastic analysis with the derived equivalent initial imperfection. The proposed overall imperfection method is adequate for computer-aided design methodology which is based on advanced elastic beam–column finite element method. The accuracy and practicality of the proposed method are illustrated for regular, irregular, single and multi-span members.


ABSTRACT: It is widely accepted that wrinkling of thin sheets under tension is due to the compressive stresses that emerge in central zone, orthogonally to the direction of applied tension, being caused by the variation of Poisson’s effect from the fixed supports to central zone of the sheet. By means of an analytical approach consisting of displacement fields (designated as “modes”) that kinematically enrich the solution of pre-
wringling stress field, this paper shows that Poisson’s effect is not the sole cause of wrinkling. Starting from an
extensional mode, other modes with physical meaning (associated to Poisson’s effect and warping shear) are
consecutively added to the final displacement field. This modal approach unveils that transversal compressive
stresses, which trigger the sheet wrinkling, are due not only to restrained Poisson’s effect (known factor) but
also due to warping shear deformation. This identification is the main and original contribution of the present
work. The reduction of warping shear in stretched sheets (e.g., via the addition of transversal fibers) could
possibly avoid wrinkling phenomena of elastic thin sheets and membranes used in aerospace applications, such
as inflatable antennas and solar sails. Additionally, the paper presents approximate analytical solutions of pre-
wrinkling fields (displacements, strains, stresses) that are deemed useful to derive future fully analytical
formulae for the prediction of critical wrinkling loads.

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ABSTRACT: This paper aims at investigating the quasi-static shear response of expanded metal panels. A
nonlinear finite element analysis of standard and flattened expanded metal panels subjected to shear loads is
conducted. For both panel types, the influence of the cell orientation is also analyzed. Numerical models are
validated against experimental results available in the literature. Thereafter, the numerical models are used to
study the structural behavior of the expanded metal shear panels in depth. Furthermore, a parametric analysis is
conducted in order to investigate the influence of cell geometry parameters and panel size on the shear response
of the panels. The results show that shear response depends mainly of cell geometry and panel length, whereas
the effect of the panel height is almost negligible. Finally, the results are also used to examine the suitability of
expanded metal panels for steel plate shear walls.

Chiara Bedon and Claudio Amadio (University of Trieste, Department of Engineering and Architecture,
Piazzale Europa 1, 34127 Trieste, Italy), “Exploratory finite-element investigation and assessment of
standardized design buckling criteria for two-side linear adhesively supported glass panels under in-plane shear
loads”, Engineering Structures, Vol. 106, pp 273-287, January 2016,
https://doi.org/10.1016/j.engstruct.2015.10.033

ABSTRACT: In this paper, the buckling response of glass panels linearly supported along the top and bottom
edges, under the action of in-plane shear loads, is investigated by means of analytical and Finite-Element (FE)
methods. The typical buckling behaviour is first assessed in the hypothesis of fully neglecting the possible
deformability contribution of adhesive linear supports, while successively the effects of linear, flexible sealant
joints on the overall structural response of the same panels are also properly taken into account and highlighted.
Based on extended parametric FE linear buckling and nonlinear incremental simulations, the influence of initial
geometrical imperfections with various shapes and amplitudes, adhesive stiffnesses and glass types is
investigated, both for monolithic and laminated glass panels. In the latter case, the accuracy of an equivalent
thickness approach derived from early contributions is also demonstrated. Analytical approximating curves are
proposed for the fitting of numerically derived buckling coefficients, so that they could represent a practical tool
in the calculation of the expected Euler’s critical load. A normalized buckling curve for ideally simply
supported glass panels under in-plane shear loads is finally recalled from past research projects and proposed as a rational design method for the examined loading and boundary condition.

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ABSTRACT: In this paper the influence of torsional warping of cross-sections of twisted beams on their eigenvibrations is investigated, considering the secondary deformations due to the angle of twist. The investigation is based on the analogy of second-order bending beam theory, including the effect of the deformations due to the shear forces on the deformations, and the non-uniform torsion theory of thin-walled open and closed cross-sections, including the secondary torsion moment deformation effect. The solutions of the underlying differential equations are used for setting up the transfer matrix relations. The numerical investigation is focused on modal analysis of straight beams with and without consideration of warping of doubly symmetric open and closed cross-sections. The influence of the secondary torsion moment on the non-uniform torsional eigenfrequency is also studied and evaluated. The obtained results are compared with the ones calculated by standard solid and warping beam finite elements.

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ABSTRACT: An extensive numerical study is performed to investigate the lateral–torsional buckling of steel beams with slender cross sections for the case of fire. The influence of local buckling is analysed, and the numerical results are compared to the simplified design methods of Part 1-2 of Eurocode 3 for the case of beams with Class 1 and 2 cross sections. The actual provisions of Eurocode 3 Part 1-2 are demonstrated to be unreliable. A parametric study is carried out to investigate the influence of several parameters on the resistance of laterally unrestrained steel beams with slender cross sections for the case of fire: the effective section factor, temperature, steel grade, depth-to-width ratio \((h/b)\) and residual stresses. Based on the parametric study, a proposal for a new design curve is made for beams with slender cross sections for the case of fire, taking into account the influence of local buckling by grouping the response of beams into different ranges of effective section factors. The capacity predicted by the simplified methods using the proposed design curve leads to an improved yet safe design method compared to the results of the finite element analysis.
ABSTRACT: In site suitability assessment of wind turbines, it is often the case that one or several wind climate parameters exceed the reference values for the wind turbine design class. In such cases, the IEC 61400-1 requires a load calculation based on the site specific wind climate conditions in order to document the structural integrity. This load calculation demands a significant number of aero-elastic simulations which are time consuming to perform and require expert knowledge. In this paper it is investigated, to which extent the site specific loads can be determined based on a response surface methodology (RSM). Two response surfaces are presented, formulated based on Taylor approximation and Central Composite Design. For each RSM, the model uncertainty is estimated for different combinations of the wind climate parameters, along with the statistical uncertainty introduced by a limited number of random seeds. The results show that fatigue loads during power production, in general, can be assessed accurately using both RSMs. However, central composite design introduces the smallest model uncertainty. For ultimate loads resulting from extreme turbulent inflow, a larger model uncertainty is introduced. Central composite design leads, again, to the lowest model uncertainty. The statistical uncertainty related to the number of aero-elastic simulations is modelled for each RSM using bootstrapping. In general, the statistical uncertainty related to the number of random seeds is larger than the model uncertainty related to the RSMs.

ABSTRACT: This paper presents an experimental investigation on thin-walled prestressed concrete roof elements, characterized by different shapes, test arrangements and failure modes (e.g. longitudinal and transverse bending or shear). The aim of this experimental program is to investigate roof elements behavior up to their ultimate capacity under different loading conditions, as well as to study second order effects and the influence of transverse flexure in the optimization of wing reinforcement. The response of tested roof elements is subsequently numerically analyzed, by adopting PARC constitutive model to perform non-linear finite element analyses (NLFEA), able to take into account the interaction between transverse and longitudinal bending, as well as geometric non-linearity. Finally, an application of the proposed numerical procedure for design purposes is also discussed.

ABSTRACT: In this paper, a shaking table test was conducted on a 1/55 scaled reinforced concrete super-large cooling tower. Structural dynamic responses corresponding to different levels of seismic actions were measured and analysed. The structural weakness, collapse mode and failure mechanism were investigated. A numerical
model was also developed for elasto-plastic time history analysis of the prototype tower. It was found that the columns were the weakest part of the tower. The acceleration and displacement responses at the top of the columns increased most as the peak ground accelerations increased. Under strong-motion earthquake actions, the tower lost support after the columns failed and collapsed aslant overall. The research presented in this paper can contribute to the improved design of future cooling towers.

Kaiming Bi and Hong Hao (Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia), “Using pipe-in-pipe systems for subsea pipeline vibration control”, Engineering Structures, Vol. 109, pp 75-84, February 2016, https://doi.org/10.1016/j.engstruct.2015.11.018
ABSTRACT: Pipe-in-pipe (PIP) systems are increasingly used in subsea pipeline applications due to their favourable thermal insulation capacity. Pipe-in-pipe systems consist of concentric inner and outer pipes, the inner pipe carries hydrocarbons and the outer pipe provides mechanical protection to withstand the external hydrostatic pressure. The annulus between the inner and outer pipes is either empty or filled with non-structural insulation material. Due to the special structural layout, optimized springs and dashpots can be installed in the annulus and the system can be made as a structure-tuned mass damper (TMD) system, which therefore has the potential to mitigate the pipeline vibrations induced by various sources. This paper proposes using pipe-in-pipe systems for the subsea pipeline vibration control. The simplification of the pipe-in-pipe system as a non-conventional structure-TMD system is firstly presented. The effectiveness of using pipe-in-pipe system to mitigate seismic induced vibration of a subsea pipeline with a free span is investigated through numerical simulations by examining the seismic responses of both the traditional and proposed pipe-in-pipe systems based on the detailed three dimensional (3D) numerical analyses. Two possible design options and the robustness of the proposed system for the pipeline vibration control are discussed. Numerical results show that the proposed pipe-in-pipe system can effectively suppress seismic induced vibrations of subsea pipelines without changing too much of the traditional design. Therefore it could be a cost-effective solution to mitigate pipe vibrations subjected to external dynamic loadings.

ABSTRACT: Instability problems are going to be more and more important for long-span structures, especially for those where structural shape and loading capacity are strictly correlated. In view of this, a complete buckling analysis seems to be essential for the correct prediction of structural behaviour. At the same time, recent disasters, occurred in the last few years, such as the collapse of the new pavilion of Charles de Gaulle Airport in Paris (2006), have brought the instability of shallow long-span roofs at the cutting edge of structural engineering research. In this paper, different studies devoted to the stability of the large span roof of the new railway station of Porta Susa in Torino (Italy) are proposed. In particular, 2D models were realized in order to evaluate in-plane linear and nonlinear instabilities for different loading and restraining conditions of the steel arches constituting the bearing framework of the roof. These arches have been subdivided into different groups according to the geometric characteristics. It has been found that nonlinear analyses are able to give not only an interpretation of the post-buckling behaviour, but also a more correct evaluation of the safety factor for this kind of structures. Moreover, a parametric evaluation, taking into account different cross sections, is presented. The results reveal that much slender arches would offer the same safety factor as the existing ones due to the
activation of a different resisting mechanism, although with an evident reduction in the employed material. Finally, the outcomes of this case-study could be generalized in order to investigate the behaviour of other structural typologies and to suggest alternative design approaches.

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ABSTRACT: This paper reports experimental and numerical investigations used to develop a simple and accurate design method for the in-plane strength of circular steel I-section arches having a sinusoidal corrugated web under a uniform vertical load over the entire span. In deference to a flat web that can resist both shear and normal stresses, a sinusoidal corrugated web can resist only shear stresses, since its axial and bending stiffnesses are quite small. Tests are carried out to investigate the global in-plane elasto-plastic behaviour and strength of a circular steel I-section arch with a sinusoidal corrugated web under symmetric loading. A finite element model is also developed, validated by the test results, and then used to further investigate the global in-plane elasto-plastic behaviour and strength of the steel arches. Based on the test and finite element results, a design equation for predicting the global in-plane strength of circular steel I-section arches with a sinusoidal corrugated web subjected to a uniform vertical load over the entire span is proposed. It is found from the finite element results that in addition to an in-plane global failure mode, a circular steel I-section arch with a corrugated web may also fail in an elasto-plastic web shear buckling mode. Hence, elasto-plastic shear buckling of the sinusoidal corrugated web in arches must also be considered in their design.

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ABSTRACT: In order to eliminate buckling in thin-walled steel tube confined reinforced concrete (RC) columns, the external fiber-reinforced polymer (FRP) composite wraps may be applied. This paper reports the details and results of a series of seismic tests on FRP-wrapped thin-walled steel tube confined RC columns. A total of six full-scale circular cantilever columns were tested under combined constant axial load and lateral cyclic displacement excursions. The test specimens consisted of a control RC column, a carbon FRP (CFRP) confined RC column, a glass FRP (GFRP) confined RC column, a thin-walled steel tube confined RC column, and two GFRP-wrapped thin-walled steel tube (GST) confined RC columns of varying axial load levels. The diameter and height of the RC columns were 400 mm and 1600 mm, respectively, and the outer diameter to thickness ratio of the steel tubes was 135. The seismic responses of the test specimens were compared in terms of failure mode, hysteretic behavior, ductility, stiffness degradation, energy dissipation capacity and equivalent viscous damping ratio. The effects of the GFRP wraps and the steel tube on the behavior of the GST confined column were revealed respectively. Test results showed that the steel tube confined column experienced local buckling and abrupt welding seam splitting resulting from high biaxial stresses, whereas such premature failure
was prevented in the GST confined RC columns. For the specimens designed and tested in this study, both components in the GST contributed much to the seismic performance of the GST confined column, while the thin-walled steel tube was more effective than the GFRP wraps in improving the ultimate drift ratio. In addition, as the axial compression ratio was increased from 0.2 to 0.45, there was almost no decrease in displacement ductility for the GST confined columns.


ABSTRACT: A beam finite element method based on Generalized Beam Theory (GBT) is developed for the modeling of nonlinear elastoplastic behavior of prismatic thin-walled members. The kinematic relationships, strains and nonlinear equilibrium equations are derived, and the corresponding numerical discretization and implementation schemes are presented. The buckling, warping and transverse extensions of cross-sections are defined by the linear combination of GBT cross-section deformation modes, and the longitudinal variation of amplitude of each GBT mode is approximated by the cubic B-splines. The cross-section rigid-body motion concerning global longitudinal extension, major/minor-axis bending and torsion is described by three translational displacements and three consecutive Euler angles (only four of them are independent variables). The $J_2$-plasticity conjugated return mapping algorithm is introduced to integrate the rate equations of the constitutive model. In order to track the post-collapse equilibrium path, the arc-length control technique is utilized in solving the nonlinear equilibrium equations. Five illustrative examples are employed, and the validation of the proposed GBT formulation is verified by comparing GBT results with ANSYS FEM outputs. The modal decomposition analyses of five thin-wall members also provide a deep insight into their mechanical behavior, e.g., collapse mechanisms.

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ABSTRACT: The local buckling behaviour and ultimate cross-sectional strength of tubular elliptical profiles in compression is examined in this study through numerical modelling. The numerical models were first validated against previous experimental data with good agreement observed, enabling an extensive parametric study to be performed. A total of 270 elliptical sections were simulated in order to examine the influence of cross-section aspect ratio, geometric imperfections and local slendernesses. The obtained ultimate capacities, load–deformation responses and failure modes are discussed. It was found that for lower cross-section aspect ratios the behaviour of the elliptical hollow sections (EHS) was similar to that of cylindrical shells across a number of metrics; however, as the aspect ratio increased, more plate-like stable postbuckling behaviour was observed. Imperfection sensitivity was found to decrease with increasing slenderness and aspect ratio. The influence of the
shape of the initial imperfection on the strengths of the EHS columns was also assessed and was found to be generally limited. Finally, a design method has been proposed for Class 4 EHS members that reflects the reduction in capacity due to local buckling with increasing slenderness, but also recognises the improved postbuckling stability with increasing aspect ratio; the proposals were shown to provide safe and accurate predictions for the strengths of the EHS columns with nondimensional local slendernesses up to 2.5 and aspect ratios from 1.1 to 5.0.

References listed at the end of the paper:

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ABSTRACT: This paper deals with the static compression behaviour of concrete-filled double-skin tubular (CFDST) columns with corrugated plates. These sections take advantage of the high strength of their infill concrete as well as the ductility of their steel skins. Static compression tests were performed on CFDST column specimens with inner or outer skins built up from corrugated plates. The steel hollow sections fabricated from corrugated plates exhibited a more stable response under axial compression loading. Hence, implementing them in CFDST columns is expected to enhance the overall behaviour of these columns. These tests reveal how the overall behaviour of CFDST columns is affected by replacing their inner/outer skin with one fabricated from corrugated plates. The corrugated plates have an insignificant effect on the strength of column specimens. However, the ductility and energy absorption capacity of CFDST columns are improved dramatically. A finite element modelling framework was also developed to simulate the response of CFDST columns with corrugated plates and validated against the results of the experiments.

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ABSTRACT: Seven all-steel buckling-restrained braces (BRBs) were tested under cyclic loading to investigate the effect of the unbonding materials on the performance of BRBs, via the employment of a layer of 1-mm thick butyl rubber or pure air gap between the core plate and the restraining system. Test results indicate that all the BRBs exhibited rather well energy dissipation capacities and sustained cumulative plastic deformations over 1000 times the yield strain. However, significantly higher compression strength adjustment factor $\beta$ was developed for the specimens without the unbonding materials, due to the gradually increasing friction force and the jamming between the end of the core plate and the restraining members. Moreover, the gradually increasing friction force and the jamming also induced the considerably nonuniform residual deformation for the specimens without the unbonding materials both observed in the test and the finite element models. Especially, for high performance BRBs with relatively long yielding segment and thin core plate, the unbonding materials are recommended to apply.


ABSTRACT: Since the 1960s, researchers have proposed different empirical formulas and analytical models for the shear strength of deep reinforced concrete beams. Some of these approaches have shown adequate accuracy when applied to small sets of beam tests, while their ability to predict the effect of a large range of test variables remains unknown. This paper presents a summary of models for deep beams from 73 publications, and focuses on a detailed evaluation of ten more recent models by using a database of 574 deep beam tests. It is found that a semi-empirical strut-and-tie model (STM) and a two-parameter kinematic theory (2PKT) for deep beams produce the least scattered predictions. The former model produced an average shear strength experimental-to-predicted ratio $V_{exp}/V_{pred}$ of 1.00 with a coefficient of variation (COV) of 19.8%, while the latter
resulted in an average of 1.08 with a COV of 15.4%. The two models are also compared by plotting the \( \frac{V_{\text{exp}}}{V_{\text{pred}}} \) ratios against different tests variables, and by performing parametric studies with individual test series. It is shown that the semi-empirical STM exhibits certain bias with respect to the shear-span-to-depth ratio, while the 2PKT produces uniform results across the entire range of experimental data. It is also noted that the semi-empirical STM requires somewhat less computational effort than the 2PKT approach.

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ABSTRACT: The present paper discusses the sensitivity of the global and local stability of a hybrid single layer grid shell to a set of Equivalent Geometric Nodal Imperfections representative of the actual structural and construction imperfections. Since imperfections are hard to be measured and controlled in experimental facilities, the stability of the structure is extensively investigated in numerical experiments. The imperfections are set by means of the so-called Eigenmode Imperfection Method. The method parameter space is densely sampled, and different structural models are adopted. The results are given in terms of two bulk parameters: the well established Load Factor and the proposed Buckling Shape Length, the latter being introduced to provide a continuous measure of the degree of “globalness” of the instability. Significant and non monotonic changes in both the Load Factor and Buckling Shape Length are observed versus the growth of the imperfection amplitude. Further, a local metrics of the grid shell geometry, named nodal apex, is introduced for each structural node. Special emphasis is given to the analysis of the correlation between the apex of the initial imperfect geometry and the apex of the deformed shape at collapse. The observed high correlation suggests that the mechanical behavior of the imperfect grid shell is significantly influenced by this local geometrical feature.

Chiara Bedon and Claudio Amadio (University of Trieste, Department of Engineering and Architecture, Piazzale Europa 1, 34127 Trieste, Italy), “Shear glass panels with point-fixed mechanical connections: Finite-element numerical investigation and buckling design recommendations”, Engineering Structures, Vol. 112, pp 233-244, April 2016, https://doi.org/10.1016/j.engstruct.2016.01.024
ABSTRACT: In the paper, an extensive Finite-Element (FE) numerical study is carried out on glass shear walls with point mechanical connectors. Based on calibration of FE models to experimental and numerical data of literature, both linear bifurcation analyses (lba) and incremental nonlinear static simulations (inls) are performed, in order to assess the shear buckling response of the examined structural panels. Analytical fitting curves are proposed for the shear buckling reduction factor, so that the Euler’s critical load associated to a given number of point connectors could be correctly calculated. Based on extensive inls analyses, the buckling failure mechanism is emphasised for a wide set of geometrical configurations of practical interest. Finally, simple buckling design considerations derived from earlier research projects are extended to glass shear walls with point mechanical connectors.

D.G. Pavlou (Department of Mechanical & Structural Engineering and Materials Science, University of Stavanger, 4036 Stavanger, Norway), “Dynamic response of a multi-layered FRP cylindrical shell under

ABSTRACT: Taking into account the composite material damping and elastic behavior, the dynamic response of thin-walled FRP pipelines made of symmetric and balanced laminate, under moving singular pressure shock is derived. The methodology is based on double integral transforms and generalized functions’ properties. An analytical inversion of the derived Laplace transform is achieved and implementation of the solution on a long multi-layered E-Glass/Epoxy FRP pipeline under fluid-hammer conditions is discussed.

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ABSTRACT: An experimental investigation on the strength and ductility of short steel tubes filled with rubberised concrete (RuC), sourced from recycled scrap tyres, is presented in this paper. Firstly, a brief literature review on (i) concrete-filled steel tubes (CFST) and (ii) mechanical characterisation of rubberised concrete is presented. Then, the experimental investigation is described and test results are shown and discussed, namely, the assessment of (i) RuC and steel mechanical properties and (ii) RuCFST column structural properties. The influence of various parameters, such as the cross-section shape (square, rectangular, circular), steel grade, and concrete mix (standard concrete versus RuC), on the short column strength and ductility is analysed and discussed. Eurocode 4 is considered (i) to determine the strength of the tested columns and, in particular, (ii) to assess its applicability to RuCFST columns based on a comparison with the experimental results. The main conclusion of this research is that RuCFST short columns present higher ductility than those made of standard concrete, even though they also show lower strength. This improved ductility is noticeable in columns with circular sections, rather than in square and rectangular sections. From a practical viewpoint, this could be a major benefit for structures in seismic areas where energy dissipation is needed.

References listed at the end of the paper:
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ABSTRACT: In this paper, the results of pilot experiments carried out on glass columns are presented and critically discussed. The aim of this preliminary experimental study consists in the verification and assessment of the actual global behaviour of monolithic glass columns with square hollow cross-section under axial compression, as well as in the estimation of the compressive loading ratios leading to the opening of first cracks and collapse of the same specimens, respectively, together with the corresponding failure mechanisms. In order

to properly interpret the obtained test results, the experimental predictions are first compared and assessed towards analytical calculations (e.g. in terms of Euler’s buckling load) and Finite-Element (FE) models later (e.g. in the form of load–displacement response). In the first case, classical analytical formulations not able to take into account the effects deriving from a combination of several aspects (e.g. possible initial geometrical imperfections in each glass pane or in the assembled square hollow section, load or boundary eccentricities, as well as the actual bonding effect of the glued joints connecting the glass components) typically result in a marked overestimation of the actual load bearing capacity for the tested columns, hence suggesting more refined investigations. Rather close agreement is found in fact with properly assembled fully 3D solid FE models. In them, a key role is assigned to the geometrically refined description of each specimen component (including the glued joints and the end restraints), as well as to the accurate mechanical calibration of the materials, based also on further experimental tests carried out on small adhesive specimens. Finally, the feasibility and accuracy of simplified 2D FE-models – less time consuming than fully 3D assemblies – is also assessed, so that practical recommendations could be provided. In the latter case, as shown, higher sensitivity of FE results to the main input parameters is found, with consequent underestimation of the actual elastic resistance for the tested columns. Based on the current comparisons and findings, however, it is expected that the current research outcomes could be further extended to various glass columns typologies and configurations (e.g. including laminated glass specimens and several cross-sectional shapes, as well as full-scale experiments), in order to develop appropriate practical design rules.

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ABSTRACT: Lateral-torsional buckling (LTB) is an ultimate limit state that can occur in the hogging moment regions of continuous composite steel and concrete beams. This limit state is characterised by the buckling of the steel profile compressed flange (bottom flange) about the minor axis, together with a distortion of the steel profile web. The European Standard EN 1994-1-1:2004 provides an approximate procedure for LTB design that is applicable to continuous composite beams, but only those with a plane web steel profile. The most important step of this procedure is the determination of the elastic critical moment. In this paper, a finite element analysis (FEA) model was developed using the software ANSYS to determine the elastic critical moments of continuous composite steel and concrete beams with corrugated sinusoidal-web steel profiles, which were evaluated against numerical data from the literature. Ultimately, a study involving 45 models was conducted based on FEA modelling, and a procedure for predicting the elastic critical moment of composite beams with sinusoidal-web steel profiles was proposed.

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ABSTRACT: Because of public construction budgets were cut over the last few years, new bridge girders with corrugated webs to reduce the construction costs have become more widely studied and used. In spite that tapered bridge girders with corrugated webs (BGCWs) are used in modern bridges, their shear strength and behaviour rarely exists in literature. Based on available literature, the web of the linearly tapered BGCWs may be divided into three typologies with different structural response to shear force. This paper presents a study into the shear strength and behaviour of the different web panels of the tapered BGCWs near the end and intermediate supports of continuous bridges using the dimensions of constructed bridges. Accordingly, parametric studies are conducted with variations in the aspect ratio of the web panel, different inclination angles of the tapered web panel and the flange slenderness ratio. After that, the paper checks the available design model under these additional parametric study models. The paper is extended to check corrugation dimensions for the use in conventional structures. It is noticed that as the corrugation angle ($\alpha$) between longitudinal and inclined sub-panels decreases, the ultimate shear of the girders decreases because the rigidity of the web decreases. The available design model is compared to the FE results and it is found to yield suitable results for girders used in bridges as well as conventional structures. Overall, new conclusions on the shear strength and behaviour of tapered BGCWs are presented.

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ABSTRACT: TRC composite material, made from a combination of fine-grained cement matrix and textile reinforcement, possesses properties, particularly mechanical ones, which makes it a suitable candidate a priori for the manufacture of low-thickness facings in applications such as sandwich panels. The aim of this study is to supplement and enrich as far as possible the rare studies dedicated to the subject. The aim, more precisely, is to add to the experimental database but also to attempt to make a useful contribution regarding damage and failure mechanisms as observed in the interplay between local and global levels. In addition, the possible use of discrete connectors and stiffeners designed to improve the mechanical properties of the panels is envisaged from a technological viewpoint and the consequences of the technological processes involved are assessed. Finally, a simple calculation model designed to help engineers with pre-dimensioning will be proposed and validated and its limits will be determined on the basis of a comparative theoretical/experimental study.


ABSTRACT: The behaviour of thin-walled structures is deeply influenced by non-uniform torsion and cross section distortion. In this paper the extension of the Hamiltonian Structural Analysis (HSA) Method to thin-walled straight and curved beams is presented. The proposed method solves the structural elastic problem of
thin-walled beams through the definition of a Hamiltonian system composed of 1st order differential equations. The method allows engineers to solve the elastic problem by introducing the degrees of freedom and the corresponding compatibility equations, founding equilibrium equations in the variational form. The methodology is explained in the framework of the so-called Generalized Beam Theory, considering beams on elastic foundation and thin-walled structures with non-uniform torsion and distortion in a unified theory for open and closed cross section considering the shear deformability of the wall midline. The exact solution is found for straight and horizontally curved beams and distortion of box section is directly solved avoiding the analysis through the Beam on Elastic Foundation (BEF) analogy. Numerical applications are given in order to show the wide range of applicability of the proposed method and to validate it through comparisons with literature data.

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“Stability and free vibration analyses of orthotropic 3d beam-columns with singly symmetric section including shear effects”, Engineering Structures, Vol. 113, pp 315-327, April 2016,  
https://doi.org/10.1016/j.engstruct.2016.01.036  
ABSTRACT: A complete beam–column classification and the corresponding characteristic equations for the stability and undamped natural frequencies of 3D orthotropic Timoshenko beam–columns with singly symmetric closed section and with elastic end connections subjected to an eccentric end axial load are presented and derived using three different approaches. The first two approaches are those by Engesser and Haringx that include the shear component of the applied axial force proportional to the slope \( \frac{du}{dx} \) and \( \frac{dv}{dx} \) in planes \( xz \) and \( yz \), respectively) and to the angle of rotation of the cross-section ( and in planes \( yz \) and \( xz \), respectively) along the span of the member, respectively. The third approach is a simplified formulation based on the classical Euler theory that includes the effects of shear deformations but neglects the induced shear component of the applied axial force along the member. The proposed methods and characteristic equations are capable of determining the critical axial loads and undamped natural frequencies of beam–columns with elastic end connections. Four comprehensive examples are included that show the effectiveness and simplicity of the proposed method and the results obtained are compared with experimental results available in the technical literature. It is shown that: (1) the natural frequencies and critical axial loads of beam–columns increase as the shear stiffness , the degrees of fixity and lateral bracings at the ends of the member increase; (2) the natural frequencies calculated using the three approaches are identical to each other when the applied axial load is zero; (3) the critical axial load in compression using the Engesser approach is lower than the one obtained using the Haringx approach; (4) the critical axial loads in compression are highly affected by the degree of flexural fixity at the supports, but those in tension are not affected much; and (5) the Haringx approach is the only one among the three approaches capable of capturing the phenomena of tension buckling observed in seismic isolators.

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“Buckling behaviour of partially restrained cold-formed steel zed purlins subjected to transverse distributed uplift loading”, Engineering Structures, Vol. 114, pp 14-24, May 2016,  
https://doi.org/10.1016/j.engstruct.2016.01.048
ABSTRACT: This paper presents a numerical investigation into the buckling behaviour of cold-formed steel zed purlins when subjected to transverse distributed uplift loading. The study uses both linear and non-linear finite element methods (ABAQUS shell Finite Element analyses) to investigate the pre-buckling, buckling and post-buckling behaviour of zed-section purlins in purlin-sheeting systems. The numerical modelling strategy is carefully validated using the results of available experimental data. Influences of boundary conditions and restraints from sheeting on web shear buckling, local, distortional and lateral-torsional buckling behaviour, and the buckling interactions of the purlins are discussed. Furthermore, the strengths and failure modes of the purlins obtained from numerical results are compared with the design strengths predicted using the direct strength method (DSM) specified in the ‘North American Specification’ (AISI S100). The comparisons show that the ultimate strengths of buckling interactions are generally underestimated. Hence, the DSM is modified to cover the partially restrained zed-sections in purlin-sheeting systems.

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ABSTRACT: The mechanical behavior of a convex steel box section under axial compression is studied using loading test on reduced scale-model and nonlinear FE analysis, taking into consideration initial geometric deflection and residual stress. The actual bearing capacity of the convex steel section used for the arch ribs of the Yongjiang Bridge is obtained. The difference in critical stress among the stiffened plates is revealed. The influence of width ratio $\eta$ between upper and lower boxes, stiffened plate width–thickness ratio $R_R$ and ratio of stiffener’s relative flexural rigidity to its optimum value $\gamma/\gamma^*$ on the normalized stress–strain relation of the section are examined. It is found that the bottom plate has the lowest critical stress among all the stiffened plates in the convex section. A smaller width ratio increases the critical stress of the middle plate and hardens the post-buckling behavior. The effect of width ratio on the normalized stress–strain relation of convex section is so small as to be negligible. $R_R$ and $\gamma/\gamma^*$ values influence the critical stress of the convex section and significantly affect the post-buckling behavior. Larger $R_R$ and smaller $\gamma/\gamma^*$ values reduce the critical stress of the cross section. Equations representing the normalized stress–strain relation of the convex section under axial compressive loading are proposed as a function of these influential parameters and their validity is demonstrated through numerical analysis.

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ABSTRACT: I-shape steel columns in many old bridges can be rehabilitated by welding steel plates to the flanges of the existing columns. However, the effect of welding residual stresses, initial imperfections, and column load at the time the reinforcing plates are welded to the column can significantly affect the column strength. Currently there are no guidelines available for the design of columns reinforced under load with
welded cover plates. This paper presents a numerical study to determine the appropriate column curve, whether SSRC column curve 1 or 2, i.e. $n = 2.24$ or $1.34$ in the Canadian steel design standard, to use for design of columns reinforced with steel cover plates welded to the flange tips, either parallel to the web or parallel to the flanges. A validated finite element model is used to conduct a parametric study to investigate several parameters that affect the strength of the reinforced column. Considering the variation in the resistance, a detailed statistical analysis, which provides a uniform level of safety, is conducted based on the results obtained from the parametric study to determine appropriate resistance factor to use for limit state design of columns reinforced with welded steel plates. A reliability analysis indicated that steel columns reinforced with plates welded under load should be designed using SSRC column curve 2 ($n = 1.34$) with a resistance factor of 0.90.


ABSTRACT: A simplified procedure for assessing the overall elastic buckling stability of cable-stayed girder bridges at preliminary design stages is presented. The evaluation of the buckling modes and load factors is based on the analogy of taking a cable-stayed bridge deck as a beam–column on an elastic foundation. A new method of assessment of the model uniform continuous vertical stiffness, provided by the main span stays and reduced by the stays side span flexibility, is proposed. The results of this method are in good agreement with those of geometrical non-linear finite element analyses, typically performed at final design stages. The influence of the stay system, cable spacing, towers height, the live load pattern, and the number of the intermediate piers are finally analyzed.


ABSTRACT: A methodology for reliability assessment for hull girder ultimate strength of FPSOs is presented in the paper. The hull girder ultimate strength of a FPSO is calculated by a progressive collapse analysis using the Smith method. Uncertainty of still-water bending moment (SWBM) is evaluated based on the loading conditions from FPSO operational manuals. A stochastic model of the extreme value of vertical wave-induced bending moment (VWBM) is developed in accordance with the extreme value theories based on the long-term distribution of VWBM. A first-order reliability method coupled with finite difference methods is proposed for reliability estimate dealing with the complicated implicit limit state function for hull girder ultimate strength assessment. Reliability assessments for four FPSOs are performed to demonstrate the capability of the methodology developed. The effects of the return period of the extreme value of VWBM, environmental severity factor and corrosion effects on hull girder reliability are investigated. A sensitivity analysis for each random variable is also conducted.

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ABSTRACT: Single-layer reticulated domes are typical structures with high degree of static indeterminacy. The stability of the reticulated dome structures is complicated and closely related to both the member buckling and the overall buckling of the structure. However, little theoretical research work deals with this very complex phenomenon. Meanwhile, for the statically indeterminate structures, it is a common belief that the local failure would occur first and result in the change of internal force paths, while the structure could support load continually before the overall collapse of the structure. In this paper, the interaction between the member buckling and the overall buckling of the structure was investigated, and this common belief was explored. The geometrically and materially nonlinear analyses (GMNA) were carried out for the reticulated domes with eight types of different grid forms, and the examination of member buckling for each dome was conducted based on the examination method of the $P-\delta_{\text{end}}$ curve or the $P-\delta_{\text{mid}}$ curve of the member. The relationship between the member buckling and the global instability of the structure was obtained by evaluation results of member buckling. Consequently, for the common reticulated domes, two instability patterns were identified, i.e. progressive instability and synchronous instability. In the case of progressive instability, the member buckling occurs in advance of the overall buckling of the structure. Then the number of the instable member increases, and finally the overall buckling of the structure occurs. In the case of synchronous instability, the member buckling and the overall buckling of the structure happen simultaneously. The interaction mechanism between the member buckling and the global instability of the structure was analyzed for both instability patterns.


ABSTRACT: In this study, the hybrid probabilistic interval limit analysis is introduced to assess the safety of engineering structures against plastic collapse. The presented hybrid uncertainty analysis framework can flexibly model different types of uncertain variables basing on the primitive information of uncertain system parameters. A hybrid probabilistic and interval computational scheme, namely the unified interval stochastic sampling (UISS) approach, is proposed to determine the statistical characteristics (i.e., mean and standard deviation) of the lower and upper bounds of the collapse loads of engineering structures involving mixture of random and interval uncertain system parameters. Consequently, the bounds of structural reliability against collapse failure can be efficiently estimated. The applicability and accuracy of the proposed hybrid uncertain limit analysis are critically justified through the investigations on both academic and practically motivated engineering structures.

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ABSTRACT: The response behavior of steel–concrete–steel (SCS) sandwich panels without shear connectors was experimentally studied under lateral pressure loading in this paper. The loading was applied by a hydraulic actuator on an inflated airbag to assert lateral pressure on the SCS panels. The failure modes and maximum resistance of the SCS panels were obtained from the test and compared with the numerical analysis results. It was found from the experimental and numerical studies that the end plates could function as shear connectors to achieve the composite action between face plates and concrete core. Based on the experimental and numerical observations, the formulae to predict the bending resistance and transverse shear resistance of SCS panel without shear connectors were developed and the accuracy of the proposed formulae was verified by comparing with the experimental and numerical results.

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ABSTRACT: Grid-shells are lightweight structures used to cover long spans with few load-bearing material, as they excel for lightness, elegance and transparency. In this paper we analyze the stability of hex-dominant free-form grid-shells, generated with the Statics Aware Voronoi Remeshing scheme introduced in Pietroni et al. (2015). This is a novel hex-dominant, organic-like and non uniform remeshing pattern that manages to take into account the statics of the underlying surface. We show how this pattern is particularly suitable for free-form grid-shells, providing good performance in terms of both aesthetics and structural behavior. To reach this goal, we select a set of four contemporary architectural surfaces and we establish a systematic comparative analysis between Statics Aware Voronoi Grid-Shells and equivalent state of the art triangular and quadrilateral grid-shells. For each dataset and for each grid-shell topology, imperfection sensitivity analyses are carried out and the worst response diagrams compared. It turns out that, in spite of the intrinsic weakness of the hexagonal topology, free-form Statics Aware Voronoi Grid-Shells are much more effective than their state-of-the-art quadrilateral counterparts.


ABSTRACT: Methods for assessing structural robustness need to move away from the traditional norms of prescriptive rules and become more similar to those used in conventional structural design. They should therefore be based on a sound understanding of the mechanics of the problem and provide quantitative indication of its effects. Several Codes and Design Guides consider the sudden column removal approach as their principal method for progressive collapse assessment. The level of robustness is defined based on the capability of the remaining structure for sustaining the additional loading imposed by the column loss. Most likely, the beams adjacent to the lost column and their supporting connections form the principal load paths. The present paper presents a detailed study of the response of those components under the conditions experienced following column removal. Suitable analysis approaches that have been previously developed at Imperial College London are employed to investigate the basic features of the behaviour, while several
simplifications are applied for exploring particular effects. The study concludes with the development of a simplified method for simulating the nonlinear dynamic response of axially restrained and unrestrained beams following column removal. The capability of the new simplified method to accurately describe performance is demonstrated through a set of suitable applications presented in a separate publication.

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ABSTRACT: A novel concept of steel–concrete–steel (SCS) sandwich conical structure has been developed for the Arctic offshore platforms. In this structure, punching shear resistance to localized patch loading is the main concern that considers the high pressure zones due to nonuniform distribution of the ice contact pressure. In this paper, quasi-static tests on nine large scale SCS sandwich shell structure were firstly carried out to investigate the ultimate strength behavior of the SCS sandwich shell structure under patch loading. Based on these test results, the influences of different parameters on the ultimate resistance were discussed and analyzed. These studied parameters are composite action, steel shell thickness, spacing of connector, strength of concrete core, and curvature of the sandwich shell. Theoretical models were developed to predict the shear resistance of the SCS sandwich shell structure. The innovations of the developed models include developing formulae to predict the resistances of the connector used in the sandwich shell structure, redefining the critical perimeter to analyze the punching shear resistance of SCS sandwich shell, and modifying the formulae in Eurocode 2 to calculate the punching shear resistance. The accuracy of the developed prediction models were checked and confirmed by nine reported tests and 11 tests in the literature. Finally, design recommendations on the punching shear resistance of the SCS sandwich shell were offered based on the discussions and validations.

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ABSTRACT: This paper develops a three-dimensional damage plasticity based finite element model (FEM) to study the ultimate strength of the steel–concrete–steel (SCS) sandwich shell structure under patch loading. The FEM considers complex geometric nonlinearities of hundreds of stud connectors in the structure, complex interaction between the connectors and concrete, and material nonlinearities of steel and concrete used in the structure. In the developed FEM, the concrete core material adopts the concrete damage plasticity model to predict the post-peak softening and residual strength; the stud connectors and steel shells adopt a continuum damage model to phenomenologically describe the damage evolution in the steel material. The reasonable agreement between FE analysis and the quasi-static tests on the SCS sandwich shell structure confirms the accuracy of the FEM in predicting the ultimate shear resistance, load–deflection relationship, cracks in the
concrete core, and punching shear failure of the top steel shell. A subsequent parametric study based on the validated FEM investigates the influence of the curvature on the first peak resistance of the SCS sandwich structure. Finally, the paper validates accuracy of an analytical model on the punching shear resistance of the concrete core of the SCS sandwich shell.

Hale Mathieson and Amir Fam (Department of Civil Engineering, Queen’s University, Canada), “Numerical modeling and experimental validation of axially loaded slender sandwich panels with soft core and various rib configurations”, Engineering Structures, Vol. 118, pp 195-209, July 2016, https://doi.org/10.1016/j.engstruct.2016.03.044

ABSTRACT: In this paper experimental and analytical investigations of axially loaded sandwich panels are presented. Large scale slender panels with and without ribs were tested. A robust analytical model applicable to panels of various slenderness ratios was developed. It accounts for geometric non-linearity through a rigorous P-Delta analysis, including the initial out-of-straightness profile and end eccentricities. The excessive shear deformation of the soft core and its effect on the overall stiffness and global buckling is accounted for. Additionally, the model detects localized skin wrinkling or crushing. The model showed reasonable agreement, within ±20%, with test results for strength and stiffness and was used in a parametric study. It was shown that the addition of a longitudinal rib connecting the skins at mid-width resulted in 180% increase in axial strength, by changing failure mode from skin wrinkling to global buckling. Adding longitudinal external ribs to the internal one changed failure mode to skin crushing and increased stiffness by 40% but did not enhance strength. Axial stiffness and strength also increased as skins or ribs became thicker, or their Young’s modulus increased, or as core shear modulus increased, however, failure mode varied depending on length. As the amplitude of out-of-straightness increased, failure load always reduced, weather governed by global buckling or skin wrinkling.

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ABSTRACT: This paper presents an experimental study on seismic behavior of square fiber reinforced polymer (FRP)–concrete–steel columns. Six hybrid double-skin tubular columns (DSTCs) manufactured using high-strength concrete (HSC) were tested under combined axial compression and reversed-cyclic lateral loading. The main parameters under investigation were the axial load level, size of inner steel tube, provision (or absence) of a concrete-filling inside the steel tube, and the column aspect ratio. The results indicate that, in general, square DSTCs exhibit very ductile behavior under combined axial compression and reversed-cyclic lateral loading. However, the important influence of the axial load level on the column behavior is evident, with an increase in the load level leading to a significant decrease in the lateral deformation capacity of DSTCs. The results also indicate that a DSTC with a larger inner steel tube exhibits lower lateral displacement capacity than that of a companion DSTC with a smaller inner steel tube. It is shown, however, that provision of a concrete-filling inside the inner steel tube leads to a significant increase in the lateral deformation capacity of a DSTC with a larger inner steel tube to a level that is higher than that seen in a companion DSTC with a smaller hollow inner steel tube. Experimental results are presented together with accompanying discussions on the influence of the investigated parameters on the seismic behavior of square DSTCs.
ABSTRACT: The paper presents a simplified analytical method to examine the energy absorbing mechanisms of double-hull ship structures subjected to a flat edge indenter. To validate this method, a numerical simulation is conducted on a structural module derived from an experimentally scaled stiffened panel in previous work. The structural module represents one-fifth scaled double-hull tanker side structures, including three frame spacings along the longitudinal direction and two stringer spacings along the vertical direction. The paper provides practical information to estimate the extent of structural damage within double-hull tanker side structures during minor head-on collisions, where the inner hull does not participate in absorbing impact energy. The numerical definition of material nonlinearities for the selected mesh size is validated against previous experimental results. The numerical simulation describes the plastic deformation and material rupture in the double-hull structure and provides detailed information of the energy dissipated by each structural component. The simplified analytical method estimates the relation between the plastic deformation and the crushing force of the double-hull structure, giving a good agreement with the corresponding numerical force–displacement response. Moreover, the analytical method of internal mechanics is combined with a theoretical analysis of external dynamics to evaluate the energy absorption in a ship-to-ship collision. A procedure for assessing the strength of a collided ship is presented on the basis of the experiments of scaled structures.

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ABSTRACT: In this paper, the forced nonlinear dynamic behavior of thin-walled beams with open cross section under external dynamic loads is analyzed by means of a high order implicit algorithm. This algorithm is developed using a 3D nonlinear model that takes into account the large torsion without any assumption on the torsion angle amplitude neither in the constitutive law nor in the derivation for governing dynamic equations. This algorithm is built by employing the following four steps: 1 – the space and time discretization procedures, 2 – a change of variable, 3 – a homotopy transformation, 4 – techniques used in the Asymptotic Numerical Method (ANM) (Cochelin et al., 2007; Mottaqui et al., 2010) [1,2]. The originality of this work reside in the fact that we use, for the first time, this algorithm for nonlinear analysis of thin-walled beams with open cross section under an arbitrary load. The space and time discretizations are performed respectively by the finite elements method and by the classical implicit Newmark scheme. The performance of the high order implicit algorithm is tested on four examples of nonlinear dynamic: a mono-symmetrical beam with a T cross section under external dynamic load, a mono-symmetrical beam with U cross-section under external dynamic load, a bi-symmetrical clamped-free beam under harmonic loads and a bi-symmetrical simply supported beam with cruciform section under harmonic loads. A comparison of the obtained results with those computed by the Abaqus industrial code is given. This comparison confirms the robustness, accuracy and efficiency of this high order implicit algorithm.
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ABSTRACT: This paper deals with elastic shear buckling behavior of infill panels in sinusoidally corrugated steel plate shear walls, and fitting equations predicting the shear buckling loads are presented. Firstly by using finite element analyses (FEA), the previous formulae for bending rigidities of sinusoidally corrugated plates are revised, then pure shearing model are established to study the effects of key parameters on elastic shear buckling of sinusoidally corrugated infill panels, such as the aspect ratio, corrugation ratio, corrugation depth to plate thickness ratio and corrugation repeating number. Based on extensive FEA numerical results, fitting equations with good accuracy are proposed to estimate elastic shear buckling loads of sinusoidally corrugated panels, which are improved much compared with the solutions in previous studies. It is found that, the formulae for bending rigidities of corrugated plates revised in this paper are accurate compared with the previous ones. For sinusoidal corrugated infill panels, only global buckling and local buckling can be observed in the lowest buckling mode of eigenbuckling analysis, while interaction buckling is not obvious. The parameter of corrugation repeating number has a significant influence on elastic shear buckling loads, whereas it was neglected in previous studies.

Hui-Shen Shen (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China), “Postbuckling of nanotube-reinforced composite cylindrical panels resting on elastic foundations subjected to lateral pressure in thermal environments”, Engineering Structures, Vo. 122, pp 174-183, September 2016, https://doi.org/10.1016/j.engstruct.2016.05.004
ABSTRACT: Modeling and analysis for the postbuckling of carbon nanotube-reinforced composite cylindrical panels resting on elastic foundations subjected to lateral pressure in thermal environments are presented. Various profiles of single walled carbon nanotubes (SWCNTs) which are assumed to be uniformly distributed (UD) or functionally graded (FG) distribution along the thickness are taken into consideration. The temperature dependent material properties of FG-CNTRC panels are estimated through a micromechanical model. The formulations are developed based on a higher order shear deformation theory. To capture the large deflections, geometrical nonlinearity in von Kármán sense is taken into account. The panel-foundation interaction and thermal effects are also included. The initial deflections caused by lateral pressure and thermal bending stresses are both taken into account. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformations and initial geometric imperfections of the panel. These equations are then solved by means of a singular perturbation technique along with a two-step perturbation approach. The influences of CNT volume fraction, temperature variation, panel geometric parameters stiffness on the postbuckling behavior of FG-CNTRC cylindrical panels are investigated.
Kaiming Bi and Hong Hao (Centre for Infrastructure Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia), “Numerical simulation on the effectiveness of using viscoelastic materials to mitigate seismic induced vibrations of above-ground pipelines”, Engineering Structures, Vol. 123, pp 1-14, September 2016, https://doi.org/10.1016/j.engstruct.2016.05.022

ABSTRACT: Pipeline systems are commonly used to transport oil, natural gas, water, sewage and other materials. They are normally regarded as important lifeline structures. Ensuring the safety of these pipeline systems is crucial to the economy and environment. There are many reasons that may result in the damages to pipelines and these damages are often associated with pipeline vibrations. Therefore it is important to control pipeline vibrations to reduce the possibility of catastrophic damages. This paper carries out numerical investigations on the effectiveness of using viscoelastic materials to mitigate the seismic induced vibrations of above-ground pipelines. The numerical analyses are carried out by using the commercial software package ANSYS. The numerical model of the viscoelastic material is firstly calibrated based on the experimental data obtained from vibration tests of a 1.6 m long tubular sandwich structure. The calibrated material model is then applied to the above-ground pipeline system. The effectiveness of using viscoelastic materials as the seismic vibration control solution is investigated. The influences of various parameters, including the constraining arrangement scenarios, the constraining length and angle, the thicknesses of the viscoelastic material and constraining layer are discussed in detail. The influence of earthquake frequency content is discussed as well. Numerical results show that with properly selected viscoelastic materials and constraining layers, the proposed method can be used to effectively mitigate seismic induced vibrations of above-ground pipelines.

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ABSTRACT: A variational model that describes the nonlinear interaction between the global and local buckling of a thin-walled I-section strut under pure compression is presented and subsequently exploited. A parametric study is conducted for two limiting cases, where the flange–web joint is assumed to be pinned or rigid. For a chosen set of geometries, the most undesirable parametric spaces are identified for both global and local slendernesses, in terms of the strut length and the flange width respectively, where highly unstable behavior is observed in the post-buckling range. Practical implications are discussed in terms of the idealized design strength relationship.

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ABSTRACT: A new semi-implicit stress integration algorithm for finite strain plasticity (compatible with hyperelasticity) is introduced. Its most distinctive feature is the use of different parameterizations of equilibrium and reference configurations. Rotation terms (nonlinear trigonometric functions) are integrated explicitly and correspond to a change in the reference configuration. In contrast, relative Green–Lagrange strains (which are quadratic in terms of displacements) represent the equilibrium configuration implicitly. In addition, the adequacy of several objective stress rates in the semi-implicit context is studied. We parametrize both reference and equilibrium configurations, in contrast with the so-called objective stress integration algorithms which use coinciding configurations. A single constitutive framework provides quantities needed by common discretization schemes. This is computationally convenient and robust, as all elements only need to provide pre-established quantities irrespective of the constitutive model. In this work, mixed strain/stress control is used, as well as our smoothing algorithm for the complementarity condition. Exceptional time-step robustness is achieved in elasto-plastic problems: often fewer than one-tenth of the typical number of time increments can be used with a quantifiable effect in accuracy. The proposed algorithm is general: all hyperelastic models and all classical elasto-plastic models can be employed. Plane-stress, Shell and 3D examples are used to illustrate the new algorithm. Both isotropic and anisotropic behavior is presented in elasto-plastic and hyperelastic examples.

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ABSTRACT: Buckling is one of the typical failure modes for single-layer reticulated shells (SLRSs). To prevent buckling, it is necessary to predict the critical buckling load and post-buckling path of the structure, and hence, structural stability analysis should be carried out. Unlike ideal structures, SLRSs with stochastic imperfections could experience different failure modes with varied post buckling paths. In the present paper, a stochastic imperfection modal superposition method is proposed for SLRS with stochastic imperfections. The SLRS structure is modeled using Timoshenko beams. Considering several possible buckling modes and random variables, Monte Carlo simulations are performed to analyze the superposition of buckling modes of the structure with stochastic imperfections. The modal combination factor is treated as a random variable and different distributions types are used for comparisons, such as uniform distribution, Gaussian distribution, T-Gaussian distribution, and triangular distribution. Based on parametric study results and comparisons with other traditional stability analysis method, the proposed method is found to provide good accuracy at considerably less computation cost.

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ABSTRACT: This paper presents a comprehensive investigation on local web buckling mechanism and design of double-coped beam connections. Following a careful validation study, a series of finite element (FE) models are established, covering a spectrum of geometric and material variables including cope length, cope depth, web slenderness, and steel grade. The study reveals that the main failure mode of the models is either inelastic or elastic local web buckling, and the considered parameters can evidently influence the buckling capacity. The models with short copes tend to fail by inelastic buckling accompanied by excessive shear yielding. For the models with long copes, especially for those with thin webs and high steel grades, stable post-buckling equilibrium path could be sustained after the occurrence of initial buckling, and as a result the ultimate reaction can be evidently higher than that governed by elastic buckling. In addition, stress concentration is significant near the cope corners, and the peak elastic stress concentration factor (SCF) could achieve around 2.0. A further discussion is made on various support and boundary conditions, and these variables are also shown to have clear influences on the local web buckling capacity of double-coped beams. Based on the numerical results, and recognising the potential limitations of the existing design rule, a modified design method, taking account of all the various influential factors revealed in this study, is finally proposed. The available experimental and numerical results show that the modified method can effectively improve the accuracy of local web buckling design for double-coped beam connections.

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ABSTRACT: The flexural strength of steel I-beams is influenced by the local and lateral-torsional instabilities, where the presence of shear also reduces the moment carrying capacity. The objective of this research is to investigate the interactive buckling modes for hybrid steel I-shaped flexural members subjected to uniform moment loading. A three-dimensional finite element (FE) model subjected to monotonic loading is developed using nonlinear buckling analysis. The analytical model was experimentally verified based on the results of six full-scale 3 m beams that were tested previously. An extensive parametric study is conducted for 526 FE models and different instability modes including local buckling, lateral-torsional buckling, and shear buckling modes are identified. Subsequently a classification is proposed based on slenderness to predict buckling mode shapes of flexural member. Attention is given to the interaction between shear and flexural buckling modes, and their effect on inelastic flexural capacity. The flexural strength is evaluated based on local and overall slenderness and interactive buckling behavior. Based on the obtained buckling modes as well as local and overall slenderness ratios, some mathematical expressions are developed and presented to determine the ultimate shear-moment capacity when lateral torsional buckling is also associated with interactive buckling modes in hybrid and non-hybrid I-shaped flexural members.

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ABSTRACT: Elevated conical tanks are widely used as water reservoirs in various locations around the globe. The vessel of a conical tank can consist of a truncated cone solely or a truncated cone with a top cylindrical part. Current codes of practice do not provide any provisions or guidelines for designing reinforced concrete conical tanks under hydrostatic loading. Available provisions are limited only to cylindrical and rectangular tanks. In this paper, a nonlinear Finite Element Model (FEM), based on shell element discretization, is used to analyze hydrostatically loaded reinforced concrete conical tanks. A common simplified approach used in the design of conical tanks involves replacing the conical vessels with equivalent cylinders. The adequacy of this simplified method is assessed in this study through comparison with the detailed finite element results. The FEM is then used to develop a set of charts which can be used to determine the adequate thickness as well as straining actions that develop in a liquid filled reinforced concrete conical tank. The use of this set of charts in designing reinforced concrete conical tanks is illustrated through worked examples.

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ABSTRACT: This paper presents a test program on cold-formed high strength steel tubular beams. The nominal 0.2% proof stresses of the high strength steel were 700, 900 and 1100 MPa in this study. Twenty-five four-point bending tests on circular, rectangular and square hollow structural sections were conducted. Load-deformation histories and failure modes of the beams were reported. Experimental results were compared against design values calculated from European code, Australian standard and North American specification for hot-rolled and cold-formed steel structures. In addition, the test strengths were also compared with the Direct Strength Method predictions. The compactness criteria were assessed by comparing the section slenderness to the slenderness limits in codes.


ABSTRACT: The innovative, rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new type of cold-formed steel section, proposed as an extension to the widely researched hollow flange beams. The hollow flange beams have garnered much interest in the past due to the sections having capacities more typically associated with hot-rolled steel sections. This paper presents the details of finite element models developed to simulate fifteen back to back, four-point bending tests, previously carried out by the authors to investigate the section moment capacities of rivet fastened RHFCBs. The test specimens were laterally restrained to ensure predominant local buckling failures, commonly observed in short-span hollow flange beams. The developed finite element models were able to simulate the test results in terms of ultimate moment capacities, applied moment versus deflection graphs and deformation modes. In addition, elastic buckling analysis results based on the finite element models also agreed well with the results from Thin-Wall finite strip analyses. Upon validation, finite element modeling was extended to include a larger slenderness region in a
parametric study. The ultimate moment capacities from the tests and finite element analyses were compared with currently available design standards: AS/NZS 4600, AS 4100 and AISI S100. The suitability of the Direct Strength Method was also investigated for the rivet fastened RHFCBs and a suitable modification was proposed.

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ABSTRACT: The load-carrying capacity of shell structures and shell-like space frames can be sensitive to initial geometric imperfections. Conventional methods of modeling geometric imperfections have focused on estimating the lower bound of the load-carrying capacity of reticulated shells. This paper proposes a random field model for the initial geometric imperfection of reticulated shell structures. The model accounts for the spatial distribution of the initial geometric imperfections, in which the correlation between imperfections at two different nodes depends on the length and number of the connecting members between the two nodes. The paper also presents the findings of the measurements of the initial geometric imperfections of a real reticulated shell structure. Based on the measurement data, the statistical characteristics of the random field model are determined. The role of initial geometric imperfections on structural ultimate strength is examined using numerical examples.

ABSTRACT: This paper proposes a new type of buckling-restrained braces (BRB), namely a pre-tensioned cable stayed buckling-restrained brace (PCS-BRB) which is formed through introducing an additional structural system of pre-tensioned cables and a number of cross-arms to the outside of a common BRB. This new system significantly improves the BRB’s overall external restraining stiffness, hence increasing the load-carrying efficiency in its structural design. Due to its aesthetically appealing structure, it can be utilised in stadiums and so forth as a laterally resistant brace. Equilibrium method is utilised to deduce formulas of elastic buckling load of pin-ended PCS-BRB. The restraining ratio and the initial pre-tensioning force of cables are investigated to explore the effect on the axial compressive load-carrying capacity of the PCS-BRB through finite element analyses in elastic-plastic range. The findings indicate that two different types of buckling modes may occur in this PCS-BRB, namely single-wave symmetric and double-wave antisymmetric buckling modes. It was found from theoretical and numerical analyses that: a negative linear correlation exists between elastic buckling load and initial pre-tensioning force of the cables; the geometric parameters of the cable stayed system possessed remarkable effect on the elastic buckling load. In addition, the post-yield behaviour and ultimate compressive load-carrying capacity of the PCS-BRB is directly proportional to the restraining ratio, and there exists a lower limit of the restraining ratio which allows the inner core to reach full cross-sectional yielding without overall instability failure of the PCS-BRB. Furthermore, there exists an optimal initial pre-tensioning force of cables to make the load-carrying capacity of the PCS-BRB to reach a maximum value. The investigation of elastic buckling and load resistance of PCS-BRB provides fundamentals to further develop a complete design method of PCS-BRB.
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ABSTRACT: This paper presents experimental investigations and finite element (FE) analyses of sandwich beams with thin-walled tubes as core that were subjected to transverse blast loads. Three types of cores were studied, namely, closely arranged identical circular tubes, spaced circular tubes, and spaced square tubes. Different masses of TNT with various standoff distances were applied to the sandwich beams. The blast loads were large enough to cause permanent local deformation of the thin-walled tubes and significant global flexural deformation of the entire beams. The FE simulations using Ls-Dyna were compared to the experimental profiles, and an insight into the energy absorption of the local and global deformations as a result of impulsive loading was observed. From the FE analyses, influence of the diameter, the thickness and the number of the circular tubes on the final displacement was investigated.


ABSTRACT: This paper examines the behaviour of 29 square concrete-filled steel tubes (CFST) under concentric axial compression. The cross-section of the hot-rolled steel tubes ranges from 60 × 60 × 3.0 mm to 150 × 150 × 4.5 mm, and are grouped in three series (Series 1, 2 and 3). For the sections tested, the slenderness ratio (L/b) for Series 1, 2 and 3 ranges from 6.67 to 24.61, 27.00–45.00 and 18.00–27.0, respectively; and the depth-to-wall thickness (b/t) ranges from 33.87 to 42.86, 13.33–33.33 and 22.22–50.00, respectively. The slenderness ratio provides a range of columns, from relatively short to slender composite columns. Particular attention is paid to the existence of circumferential strain in the square composite columns. The compressive resistance of the composite columns are compared with the design strengths predicted by the South African standard (SANS 10162-1), as well as the European design standard (EN 1994-1-1). SANS10162-1 is based on the Canadian steel code (CAN/CSA-S160-01). A two-stage equation is proposed to model the results of short columns (Eq. (4)) and intermediate to slender columns (Eq. (5)).
ABSTRACT: In this work, the influence of initial geometric imperfection modes on the ultimate strength of a ship’s hull is studied, with a focus on the buckling behavior of stiffened panels that initiates the structural hull failure. A numerical model of a cargo compartment at the midship of a Suezmax tanker is developed by using the finite element method and by considering both geometric and material nonlinearities. Analyses are conducted under hogging conditions to evaluate the double bottom stiffened panels experiencing axial compression by hull girder bending. Different imperfection modes on the bottom and inner bottom plates are considered in the model. Two cases are studied. In the first one, a half-wave imperfection mode is employed in the longitudinal and transversal directions. In the second case, the imperfection mode coincides with the main natural buckling mode of the plate between the stiffeners. Experimental tests were performed using small-scale models that are representative of the bottom panels, and the results are correlated with those from numerical simulations to define a proper mesh refinement to reproduce the buckling phenomenon. The ultimate strength of the ship hull, in full-scale, employed the same mesh refinement for the bottom panels, assuming the two proposed initial imperfections. The results from the ultimate strength are compared with the reference values for the design bending moment recommended by a classification society.

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ABSTRACT: Laser-welding is a high precision fabrication process suitable for joining a wide range of steels and stainless steels. Laser-welded structural stainless steel members, for which there are currently little experimental data owing to their recent introduction to the construction industry, are the focus of the present study. To address the lack of test data and to investigate their structural response, a total of 9 stub column tests and 22 flexural buckling tests (14 buckling about the minor axis and 8 about the major axis) have been performed on laser-welded austenitic stainless steel I-section members. Complementary tensile coupon tests, initial geometric imperfection measurements, and residual stress measurements have also been carried out and are reported herein. Based on the results obtained, a representative residual stress pattern is proposed, the design provisions of Eurocode 3 Part 1.4 and the continuous strength method are assessed, and column buckling curves for laser-welded stainless steel I-section members are recommended.

ABSTRACT: A torsion differential equation previously used for analysing the elastic lateral buckling of simply supported doubly symmetric beams with distributed loads acting away from the centroidal axis omits an expected term and includes an unexpected term. A different equation is derived by two different methods, either by using the calculus of variations with the second variation of the total potential, or by considering the equilibrium of the deflected and twisted beam. Four different methods are used to find solutions for the elastic buckling of beams with uniformly distributed loads. Two of these solve the differential equations numerically, either by using a computer program based on the method of finite integrals, or by making hand calculations with a single term approximation of the buckled shape. These methods produce different solutions for the two torsion differential equations. The two other methods used are based on the energy equation for lateral buckling.
The first of these uses hand calculations and a limited series for the buckled shape, while the second uses a finite element computer program based on cubic deformation fields. Both of these produce solutions which agree closely with the finite integral and approximate solutions for the different differential equation derived in this paper, but are markedly different from the solutions for the previously used equation. It is concluded that the previously used torsion differential equation is in error.

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ABSTRACT: In recent years several investigations were performed about the behavior of laminated structural glass elements, namely in terms of their flexural and torsional stiffness, with the lateral-torsional buckling of beams being one of the most relevant and complex topics. Various analytical formulations were proposed to describe the equivalent stiffness of laminated elements; however, none covers more than three layers of glass in a comprehensive and unified manner, and those that exist are not consensus. This work proposes a new formulation, based on sandwich theory, which provides equivalent results to previous formulations in a limited set of conditions, but that is also able to characterize the behavior of simply supported laminated glass columns and beams up to five layers, subjected to compressive axial loads, mid-span loads, uniformly distributed loads, four-point bending, pure bending or torsion. The fundamentals of the formulation presented in this paper allow it to be extended to a larger number of layers and to different load and support conditions. The proposed formulation is assessed by means of a parametric study based on the comparison with numerical results retrieved from finite element simulations, in order to assess the range of validity of each expression. Two analytical approaches for the lateral-torsional buckling problem are studied in detail, with their fundamentals being explained. Another formulation, proposed in Australian Standard AS 1288, is also addressed. An experimental assessment of the work developed is achieved by comparing the results from flexural tests available in the literature with analytical and numerical predictions.

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ABSTRACT: The present study analyses an aircraft composite fuselage structure manufactured by the Liquid Resin Infusion (LRI) process and subjected to a compressive load. LRI is based on the moulding of high
performance composite parts by infusing liquid resin on dry fibres instead of prepreg fabrics or Resin Transfer Moulding (RTM). Actual industrial projects face composite integrated structure issues as a number of structures (stiffeners, ...) are more and more integrated onto the skins of aircraft fuselage. A representative panel of a composite fuselage to be tested in buckling is studied numerically. This paper studies which of the real behaviours of the integrated structures are to be observed during this test. Numerical models are studied at a global scale of the composite stiffened panel. Linear and non linear analyses are conducted. The Tsai–Wu criterion with a progressive failure analysis is implemented, to describe the global behaviour of the panel up to collapse. Also, three stiffener connection methods are compared at the intersection between two types of integrated structures. Load shortening curves permit to estimate the expected load and displacements.

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ABSTRACT: The present study analyses an aircraft composite fuselage structure manufactured by the Liquid Resin Infusion (LRI) process and subjected to a compressive load. LRI is based on the moulding of high performance composite parts by infusing liquid resin on dry fibres instead of prepreg fabrics or Resin Transfer Moulding (RTM). Actual industrial projects face composite integrated structure issues as a number of structures (stiffeners, ...) are more and more integrated onto the skins of aircraft fuselage. A post-buckling test of a composite fuselage representative panel is set up, from numerical results available in previous works. Two stereo Digital Image Correlation (DIC) systems are positioned on each side of the panel, that are aimed at correlating numerical and experimental out-of-plane displacements (corresponding to the skin local buckling displacements of the panel). First, the experimental approach and the test facility are presented. A post-mortem failure analysis is then performed with the help of Non-Destructive Techniques (NDT). X-ray Computed Tomography (CT) measurements and ultrasonic testing (US) techniques are able to explain the failure mechanisms that occured during this post-buckling test. Numerical results are validated by the experimental results.

References listed at the end of the paper:

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ABSTRACT: The present paper considers the static analysis of plates and shells made of Functionally Graded Material (FGM), subjected to mechanical loads. Refined models based on the Carrera’s Unified Formulation (CUF) are employed to account for grading material variation in the thickness direction. The governing equations are derived from the Principle of Virtual Displacement (PVD) in order to apply the Finite Element Method (FEM). A nine-nodes shell element with exact cylindrical geometry is considered. The shell can degenerate in the plate element by imposing an infinite radius of curvature. The Mixed Interpolation of Tensorial Components (MITC) technique is extended to the CUF in order to contrast the membrane and shear locking phenomenon. Different thickness ratios and orders of expansion for the displacement field are analyzed. The FEM results are compared with both benchmark solutions from literature and the results obtained using the Navier method that provides the analytical solution for simply-supported structures subjected to sinusoidal pressure loads. The shell element based on refined theories of the CUF turns out to be very efficient and its use is mandatory with respect to the classical models in the study of FGM structures.

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ABSTRACT: Carbon fibre composites have shown to be able to perform extremely well in the case of a crash and are being used to manufacture dedicated energy-absorbing components, both in the motor sport world and in constructions of aerospace engineering. While in metallic structures the energy absorption is achieved by plastic deformation, in composite ones it relies on the material diffuse fracture. The design of composite parts should provide stable, regular and controlled dissipation of kinetic energy in order to keep the deceleration level as least as possible. That is possible only after detailed analytical, experimental and numerical analysis of the structural crashworthiness. This paper is presenting the steps to follow in order to design specific lightweight impact attenuators. Only after having characterised the composite material to use, it is possible to model and realise simple CFRP tubular structures through mathematical formulation and explicit FE code LS-DYNA. Also, experimental dynamic tests are performed by use of a drop weight test machine. Achieving a good agreement of the results in previously mentioned analyses, follows to the design of impact attenuator with a more complex geometry, as a composite nose cone of the Formula SAE racing car. In particular, the quasi-static test is performed and reported together with numerical simulation of dynamic stroke. In order to initialize the collapse in a stable way, the design of the composite impact attenuator has been completed with a trigger which
is consisted of a very simple smoothing (progressive reduction) of the wall thickness. Initial requirements were set in accordance with the 2008 Formula SAE rules and they were satisfied with the final configuration both in experimental and numerical crash analysis.


ABSTRACT: The paper deals with a refined analytical model for the local buckling failure modes of composite anisogrid lattice cylindrical shells made of a regular system of triangular cells. Such structures are preliminarily designed with the aid of closed-form solutions specifying the minimum mass and the corresponding optimal design variables under a set of formulated constraint equations. These equations address the main failure mechanisms that can be typically experienced by the structure due to axial compressive loads, namely, the global buckling of the shell, the local buckling of helical ribs, and the material failure of helical ribs. However, the local buckling of helical ribs is normally based on a simplified and qualitative approach. Thus, the scope of the present work is to improve the prediction of this failure mode by means of a rather accurate modelling which accounts for the interaction of intersecting hoop and helical ribs, the influence of the number of hoop sections of the shell, and the effect of the prebuckling tensile force in hoop ribs. The proposed model – that has been verified with the aid of finite-element analysis – lastly suggests the possibility to improve the preliminary design solution with respect to the fully analytical approach.

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ABSTRACT: This paper presents an analytical procedure and closed-form vibration solutions with analytically determined coefficients for orthotropic circular cylindrical shells having classical boundary conditions. This analysis is based upon the Donnell–Mushtari shell theory. This is the simplest thin shell theory and its results for the lowest frequencies of a closed cylinder may not be as accurate. It is known that the exact procedure is complicated for orthotropic shells and this complexity has apparently prevented most researchers from getting results. Using the separation of variables method, the closed-form natural frequencies are successfully obtained in this work. They are found in a compact form. Moreover, the characteristics of the eigenvalues are examined. The exact solutions are validated through numerical comparisons with available solutions in literatures and the semi-analytical differential quadrature finite element method (S-DQFEM) solutions calculated by the authors.

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ABSTRACT: Equations of motion with required boundary conditions for doubly curved deep thick composite shells are shown using two formulations. The first is based upon the formulation that was presented initially by Rath and Das [1] and followed by Reddy [2]. In this formulation, plate stiffness parameters are used for thick shells, which reduced the equations to those applicable for shallow shells. The second formulation is based upon that of Qatu [3,4]. In this formulation, the stiffness parameters are calculated using exact integration (and/or terms truncated to a specific order) of stress resultant equations. In addition, Qatu considered the radius of twist in his formulation. In both formulations, first order polynomials for in-plane displacements in the z-direction are utilized allowing for the inclusion of shear deformation and rotary inertia effects (first order shear deformation theory or FSDT). Exact static and free vibration solutions for isotropic and symmetric and anti-symmetric cross-ply cylindrical shells for different length-to-thickness and length-to-radius ratios are obtained using the above theories. Results of both theories are compared with those obtained using a three-dimensional (3D) analysis to test the accuracy of the shell theories presented here.

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ABSTRACT: In this paper a solution is presented for a buckling problem formulated for the cantilever circular cylindrical composite shell subjected to uniform external lateral pressure. The edge of the shell is fully clamped at one end of the cylinder and is free at the open section of the other end. An analytical formula for critical pressure has been derived using the generalised Galerkin method. The approach is illustrated by the buckling analyses of composite, orthotropic and isotropic shells. The results are verified using the finite-element method. It has been shown that the analytical solution provides an accurate estimate of the critical load and does not involve any computationally expensive procedures. This is particularly useful in the design optimisation of composite structures.


ABSTRACT: Accurate analysis using the refined theories, incorporating the non-classical effects which can not be obtained with the Euler-Bernoulli and Timoshenko beam theories, is of paramount importance for thin walled composite structures frequently used in modern engineering applications like aerospace, marine and civil structural components. Literature on the buckling analysis of thin walled composite structures using refined beams theories is limited as compared to that on the static analysis [1-3]. Further, the literature on the buckling analyses highlights the fact that features like the torsional buckling modes are scarcely reported, in spite of their fundamental significance.
ABSTRACT2 (from the 2012 paper in Composite Structures): This work presents the buckling analysis of laminated composite thin walled structures by the 1D finite element based unified higher-order models obtained within the framework of the Carrera Unified Formulation (CUF). In the present study, the refined beam theories are obtained on the basis of Taylor-type expansions. The finite element analysis has been chosen to easily handle arbitrary geometries as well as boundary conditions. Buckling behavior of laminated composite beam and flat panels are analyzed to illustrate the efficacy of the present formulation and various types of buckling modes are observed depending on the geometrical and material parameters. It is observed that the lower order models are unable to deal with torsion.

References listed at the end of the paper (From ICCS 16):

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ABSTRACT: Wrinkle defects can be formed during the production of wind turbine blades consisting of composite monolithic and sandwich laminates. Earlier studies have shown that the in-plane compressive strength of a sandwich panel with wrinkle defects may decrease dramatically. This study focuses on the failure modes of sandwich specimens consisting of thick GFRP face sheets with a wrinkle defect and a balsa wood core subjected to in-plane compression loading. Three distinct modes of failure were found, and the strain distributions leading up to these failures were established by use of digital image correlation (DIC). Finite element analyses were subsequently conducted to model the response of the test specimens prior to failure, and
generally a very good agreement was found with the DIC measurements, although slight differences between
the predicted and measured strain fields were observed in the local strain values around the wrinkle defect. The
Northwestern University (NU) failure criterion was applied to predict failure initiation, and a good correlation
with the experimental observations was achieved.

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“Buckling of conical composite shells”, Composite Structures, Vol. 94, No. 2, pp 787-792, January 2012,
https://doi.org/10.1016/j.compstruct.2011.09.016
ABSTRACT: A semi-analytical approach is proposed to obtain the linear buckling response of conical
composite shells under axial compression load. A first order shear deformation shell theory along with linear
strain–displacement relations is assumed. Using the principle of minimum total potential energy, the governing
equilibrium equations are found and Ritz method is applied to solve them. Parametric study is performed by
finding the effect of cone angle and fiber orientation on the critical buckling load of the conical composite
shells.

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“Compression and impact testing of two-layer composite pyramidal-core sandwich panels”, Composite
ABSTRACT: Quasi-static uniform compression tests and low-velocity concentrated impact tests were
conducted to reveal the failure mechanisms and energy absorption capacity of two-layer carbon fiber composite
sandwich panels with pyramidal truss cores. Three different volume-fraction cores (i.e., with different relative
densities) were fabricated: 1.25%, 1.81%, and 2.27%. Two-layer sandwich panels with identical volume-
fraction cores (either 1.25% or 2.27%), and also stepwise graded panels consisting of one light and one heavy
core, were investigated under uniform quasi-static compression. Under quasi-static compression, load peaks
were identified with complete failure of individual truss layers due to strut buckling or strut crushing, and
specific energy absorption was estimated for different core configurations. In the impact test, the damage
resulting from low-velocity concentrated impact was investigated. Our results show that compared with glass
fiber woven textile truss cores, two-layer carbon fiber composite pyramidal truss cores have comparable
specific energy absorptions, and thus could be used in the development of novel light-weight multifunctional
structures.

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ABSTRACT: Composite materials have been known for its low density, ease in fabrication, high structural rigidity, and wide range applications, i.e. aeronautic applications and automotive industry. Due to this, extensive studies had been conducted to evaluate its axial crushing ability to replace metallic materials. In this paper, it reviewed the usage of fibre reinforced plastic composite (FRP) as an energy absorption application device. Failure modes and geometrical designs such as shapes, geometry and triggering effect have been studied where these factors affected on peak load and specific energy absorption significantly. Accordingly, numerical analysis for axial crushing of affected factors had been simulated to predict the failure mechanisms of FRP composites.

ABSTRACT: FBG sensors were embedded in each of two CFRP stiffened panels fabricated by VaRTM. Low-velocity impacts were applied to one of the panels in order to compare the methods of monitoring impact events using FBG sensors. The main impact damage was an interlaminar delamination inside the skin, which could be observed by an ultrasonic C-scan. A monitoring method using the full spectral signals was more effective in evaluating the impact damages in detail than that using the center wavelength. Following the impact tests, buckling behaviors were investigated under compressive loading using FBG sensors and surface-attached strain gauges. The FBG sensors could evaluate strain changes resulting from buckling behaviors under relatively low compressive loading. They could also evaluate damage growth until the final failure and difference of buckling behaviors between panels with and without impact damages.

ABSTRACT: The use of genetic algorithms (GAs) for structural optimisation is well established but little work has been reported on the inclusion of damage variables within an optimisation framework. This approach is particularly useful in the optimisation of composite structures which are prone to delamination damage. In this paper a challenging design problem is presented where the objective was to delay the catastrophic failure of a postbuckling secondary-bonded stiffened composite panel susceptible to secondary instabilities. It has been conjectured for some time that the sudden energy release associated with secondary instabilities may initiate structural failure, but this has proved difficult to observe experimentally. The optimisation methodology confirmed this indirectly by evolving a panel displaying a delayed secondary instability whilst meeting all other design requirements. This has important implication in the design of thin-skinned lightweight aerostructures which may exhibit this phenomenon.

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ABSTRACT: Polymer composite sandwich structures are promising candidate structures for reducing vehicle mass, thereby improving the fuel economics. Nonetheless, to fully explore this material as the primary structure and energy absorber in vehicles, it is important to understand the energy absorption capability of this material. Hence, in the present work, comprehensive experimental investigation on the response of composite sandwich structures to quasi-static compression has been carried out. The crashworthiness parameters, namely the peak force, absorbed crash energy, specific absorbed energy, average crushing force and crush force efficiency of various types of composite sandwich structures were investigated in a series of edgewise axial compression tests. The tested composite sandwich specimens were fabricated from glass and carbon fiber with epoxy resin. Four distinct modes of failure were observed and recorded. The primary mode of failure observed was progressive crushing with high energy absorption capability. The optimized design in this study had a specific energy absorption capability of 47.1 kJ/kg with a good crush force efficiency of 0.77, higher than conventional metals.


ABSTRACT: In this paper, free vibration of a fiber reinforced composite cylinder in which volume fraction of its fibers vary longitudinally, is studied using a semi-analytical method. The distribution of volume fraction of fiber in base matrix is based on power law model. A micromechanical model is employed to represent its mechanical properties including elastic and physical properties of this composite cylinder. In addition, kinematically the first order shear deformation shell theory is employed for strain field. Then, weak form formulation and spatial approximations of variables are utilized to discretize the equations of motion. Different problems are solved in which primarily the validity of the results obtained for natural frequencies are evaluated by those similar results reported in the literature and with other commercial F.E. code for different boundary conditions. Furthermore, for different values of volume fractions and under various boundary conditions, computed natural frequencies of this composite cylinder with variable volume fraction of fiber are compared with the traditional one in which the volume fraction of fiber is constant throughout the structure. In spite the fact that average volume fraction of fiber and the layer fiber orientation are the same in both configurations, numerical results show that using variable volume fraction of fiber affects the shell natural frequencies and its mode shapes.

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ABSTRACT: An efficient high-fidelity shell model is developed for heterogeneous multilayer cylindrical shells
made of functionally graded material by using the variational asymptotic method (VAM). Taking advantage of
the smallness parameters inherent in the shell structure, the VAM is applied to rigorously decouple the 3-D,
anisotropic elasticity problem into a 1-D through-the-thickness analysis and a 2-D shell analysis. The through-
the-thickness analysis servers as a link between the original 3-D analysis and the shell analysis by providing a
constitutive model for the shell analysis and recovering the 3-D field variables in terms of global responses
calculated by the shell analysis. The present model is valid for large displacements and global rotations and can
capture all the geometric nonlinearity of a shell when the strains are small. A cylindrical bending example of a
homogeneous substrate with a thin SiC–Al functionally graded coating under sinusoidal pressure on the top
surface is used to validate this model.

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51154, Islamic Republic of Iran), “Nonlocal anisotropic elastic shell model for vibrations of single-walled
carbon nanotubes with arbitrary chirality”, Composite Structures, Vol. 94, No. 3, pp 1016-1022, February 2012,
https://doi.org/10.1016/j.compstruct.2011.10.014
ABSTRACT: A nonlocal anisotropic elastic shell model is developed to study the effect of small scale on shell-
like vibration of single-walled carbon nanotubes (SWCNTs) with arbitrary chirality. Anisotropic elastic shell
model is reformulated using the nonlocal differential constitutive relations of Eringen. The equations of motion
are derived and analytical solution for the vibration of anisotropic SWCNTs is presented by using the Flügge
shell theory and complex method. The suggested model is justified by a good agreement between the results
given by the present model and available data in literature. Furthermore, the model is used to elucidate the
effect of small scale on the vibration of zigzag, armchair and chiral SWCNTs. Our results show that small
scale is essential for vibration of SWCNTs when the axial wave-length is not extremely long. Moreover, the results
show that local model substantially overestimates vibrational frequencies of almost all modes.

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“Variational asymptotic modeling of the thermomechanical behavior of composite cylindrical shells”,
Composite Structures, Vol. 94, No. 3, pp 1023-1031, February 2012,
ABSTRACT: An efficient shell model is developed for analyzing one-way coupled thermomechanical behavior
of composite cylindrical shells by using the variational asymptotic method (VAM). Taking advantage of the
smallness parameter inherent in the shell structure, the VAM is applied to rigorously decouple the 3-D,
thermoelasticity problem into a 1-D through-the-thickness analysis and a 2-D shell analysis. The through-the-
thickness analysis servers as a link between the original 3-D analysis and the shell analysis by providing a
constitutive model for the shell analysis and recovering the 3-D field variables in terms of global responses
calculated by the shell analysis. The present model is valid for large displacements and global rotations and can
capture all the geometric nonlinearity of a shell when the strains are small. A few examples are used to validate
this model.

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ABSTRACT: An analysis on the nonlinear dynamics of a clamped–clamped FGM circular cylindrical shell subjected to an external excitation and uniform temperature change is presented in this paper. Material properties of the constituents are assumed to be temperature-independent and the effective properties of FGM cylindrical shell are graded in thickness direction according to a simple power law function in terms of the volume fractions. Based on the first-order shear deformation shell theory and von Karman type nonlinear strain–displacement relationship, the nonlinear governing equations of motion are derived by using Hamilton’s principle. Galerkin’s method is then utilized to discretize the governing partial equations to a two-degree-of-freedom nonlinear system including the quadratic and cubic nonlinear terms under combined external excitations. Numerical results including the bifurcations, waveform, phase plots and Poincare maps are presented for clamped–clamped FGM cylindrical shells showing the influences of material gradient index, the thickness and the external loading on the nonlinear dynamics.


ABSTRACT: This paper investigates the large amplitude vibration behavior of a shear deformable FGM cylindrical shell of finite length embedded in a large outer elastic medium and in thermal environments. The surrounding elastic medium is modeled as a Pasternak foundation. Two kinds of micromechanics models, namely, Voigt model and Mori–Tanaka model, are considered. The motion equations are based on a higher order shear deformation shell theory that includes shell-foundation interaction. The thermal effects are also included and the material properties of FGMs are assumed to be temperature-dependent. The equations of motion are solved by a two step perturbation technique to determine the nonlinear frequencies of the FGM shells. Numerical results demonstrate that in most cases the natural frequencies of the FGM shells are increased but the nonlinear to linear frequency ratios of the FGM shells are decreased with increase in foundation stiffness. The results confirm that in most cases Voigt model and Mori–Tanaka model have the same accuracy for predicting the vibration characteristics of FGM shells.

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ABSTRACT: The compressive post-buckling behavior of composite laminates containing embedded...
delamination with arbitrary shape is investigated analytically. For modeling the embedded delamination, the laminate is divided into three smaller regions. The higher order shear deformation theory is implemented and the formulation is based on the Rayleigh–Ritz approximation technique by the application of the simple/complete polynomial series for each region. The nonlinear equilibrium equations, which are achieved through the application of the principle of Minimum Potential Energy, are solved by employing the Newton–Raphson iterative procedure. Some interesting results are obtained and compared with those achieved by the finite element method of analysis using ANSYS commercial software. A good agreement is seen to exist between the results. This is while for a given level of accuracy in the results, ANSYS requires a markedly larger number of degrees of freedom compared to that needed by the developed method. Moreover, a considerable reduction in the load carrying capacity of laminate is noticed due to the presence of delamination.


ABSTRACT: A Reddy type, third order shear deformation theory of plates is applied to the development of two versions of finite strip method (FSM), namely semi-analytical and spline methods, to predict the behavior of the moderately thick plates containing cutouts. The internal cutouts are modeled based on two different modeling approaches, and the effects of cutouts on the buckling critical stresses as well as natural frequencies are investigated.


ABSTRACT: The dynamic instability of moderately thick laminated cylindrical shell panels having internal cutouts is studied by using the developed finite strip methods (FSM). The effects of perforations are investigated using a negative stiffness modeling approach. Good accuracy in the results is achieved.


ABSTRACT: Buckling and postbuckling behavior are presented for fiber reinforced composite (FRC) laminated cylindrical shells subjected to axial compression or a uniform external pressure in thermal environments. Two kinds of fiber reinforced composite laminated shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The governing equations are based on a higher order shear deformation shell theory with von Kármán-type of kinematic non-linearity and including the extension-twist, extension-flexural and flexural-twist couplings. The thermal effects are also included, and the material properties of FRC laminated cylindrical shells are estimated through a micromechanical model and are assumed to be temperature dependent. The non-linear prebuckling deformations and the initial geometric imperfections of the shell are both taken into account. A singular perturbation technique is employed to
determine the buckling loads and postbuckling equilibrium paths of FRC laminated cylindrical shells.


ABSTRACT: In this Part, the extensive parametric studies performed are reported and numerical results are presented for the buckling and postbuckling of fiber reinforced polymer matrix and metal matrix composite laminated shells subjected to axial compression or external pressure under different sets of environmental conditions. Two kinds of fiber reinforced composite laminated shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The numerical results show that the buckling loads as well as postbuckling strength of the shell can be increased as a result of functionally graded fiber reinforcements. The results reveal that the effect of functionally graded fiber reinforcements on the buckling loads and postbuckling strength of shell with polymer matrix is more pronounced compared to the shell with metal matrix in the case of axial compression. In contrast, in the case of external pressure, the functionally graded fiber reinforcements may have a significant effect on the buckling pressure and postbuckling strength of the shell with metal matrix.

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ABSTRACT: This paper presents a molecular dynamics (MDs) study on the linear, buckling and post-buckling behaviour of carbon nanotubes (CNTs) under pure shortening and pure twisting. Its objectives are (i) to clarify the issue about the most correct thickness value to adopt in the simulation of CNTs using shell models and (ii) to evaluate their post-critical strength. Three CNTs with similar length-to-diameter ratio but different atomic structures (zig-zag, armchair and chiral) are selected for this study. Then, MD simulations are performed to investigate the pre-critical, critical buckling and post-critical behaviour of CNTs under pure shortening and pure twisting. Using available analytical formulae derived from shell models, the influence of CNT thickness on their critical strain and critical angle of twist is investigated. Some conclusions are drawn regarding (i) the most appropriate choice of the thickness value to use in shell models and (ii) the effectiveness of post-critical stiffness and strength of CNTs.

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ABSTRACT: This paper presents an analytical approach to investigate the linear buckling of truncated conical
panels made of functionally graded materials and subjected to axial compression, external pressure and the combination of these loads. Material properties are assumed to be temperature-independent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Equilibrium and linear stability equations in terms of displacement components for conical panels are derived by using the classical thin shell theory. Approximate analytical solutions are assumed to satisfy simply supported boundary conditions and Galerkin method is applied to obtain closed-form relations of bifurcation type buckling loads. An analysis is carried out to show the effects of material and geometrical properties and combination of loads on the linear stability of conical panels.

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ABSTRACT: This work presents a multi-scale model of viscoelastic constrained layer damping treatments for vibrating plates/beam. The approach integrates a finite element (FE) model of macro-scale vibrations and a statistical-continuum homogenization model to include effects of micro-scale structure and properties. The statistical-continuum homogenization model makes the micro-to macro-scale transition to approximate the effective behavior of the heterogeneous core by using n-point probability functions. A simple sound transmission model is used to show the effect of material microstructure on the sound transmission loss of the sandwich structure. The damping behavior resulting from the presence of voids and negative stiffness regions in the core material is modeled. This study clearly shows that, it is of high interest to research either material structures or processing techniques which lead to negative stiffness behavior. The results also poignantly show that the proposed multi-scale model yields insight on heterogeneous material behavior leading to increased damping properties and ultimately enhances the ability to design sandwich beam/plates.


ABSTRACT: The durability of structures made of composite materials is affected by diverse factors, among which creep deformation, ageing and damage. Ageing is related to elapsed time (with different effects in different environmental conditions); damage is related to microstructural modifications due stress and/or strain inputs. The formal definition of these effects and the corresponding constitutive formulations are presented. These formulations are used to obtain analytical solutions and also to implement a Finite Element programme for viscoelastic analysis of laminar structures in a large displacement with small strains context. Then, the effects of ageing and damage on both the short and the long term stability of beam columns are analyzed. Some examples for verification of the formulation and for the comparison of effect are presented.

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ABSTRACT: For multilayered plated and shell structures the formulation of the optimization problem is strongly dependant on the definition of the design variables. Therefore, the first part of the work is devoted to the definition of design variables and the forms of objective functions. Those design variables define stacking sequences of structures have discrete fiber orientations $0^\circ$, $\pm 45^\circ$, $90^\circ$ and a finite number of key points that are required in the evaluation of the curve $\Gamma$ characterizing an external boundary of the structure or a structural shape understood in the sense of a structural geometry representing a shell/plate mid-surface or thickness distribution of structures. For the curve definition we have adopted one dimensional B-splines. Each curve is formed by an assembly of subsegments passing through certain key points. The positions of key points are randomly generated so that in the generation process it is possible to fulfill the required set of equality or inequality constraints. It is necessary to emphasize that the proposed method is very general and can be applicable to a very broad class of optimization problems. The generality of the approach is confirmed by the proof of the direct equivalence and mapping between discrete fiber orientations and continuous angle ply orientations. The evolution strategy is proposed herein as the optimization algorithm. Similarly as classical ones (e.g. ACO, SS, PS or ISM) it combines all features and advantages of evolution algorithms. It is worth to note that in the evolution strategy the number of children produced in one generation is not limited and it is not necessary to conduct mutation operations as in genetic algorithms. It simplifies significantly the effectiveness of numerical procedures. Then, two numerical examples have been solved to demonstrate the effectiveness of the proposed formulations and the optimization algorithm. They deal with thickness and stacking sequence optimization problems for circular cylindrical shells subjected to various dynamic and static constraints, respectively.

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“High-order free vibration analysis of sandwich beams with a flexible core using dynamic stiffness method”, Composite Structures, Vol. 94, No. 5, pp 1503-1514, April 2012,
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ABSTRACT: In this paper, high-order free vibration of three-layered symmetric sandwich beam is investigated using dynamic stiffness method. The governing partial differential equations of motion for one element are derived using Hamilton’s principle. This formulation leads to seven partial differential equations which are coupled in axial and bending deformations. For the harmonic motion, these equations are divided into two ordinary differential equations by considering the symmetrical sandwich beam. Closed form analytical solutions of these equations are determined. By applying the boundary conditions, the element dynamic stiffness matrix is developed. The element dynamic stiffness matrices are assembled and the boundary conditions of the beam are applied, so that the dynamic stiffness matrix of the beam is derived. Natural frequencies and mode shapes are computed by use of numerical techniques and the known Wittrick–Williams algorithm. Finally, some numerical examples are discussed using dynamic stiffness method.

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ABSTRACT: Results of an experimental study of the buckling and postbuckling behaviour until the collapse of a cylindrical stiffened composite panel are presented. The specimen is subjected to a uniform pressure on one of its faces using a combination of gas and liquid inside a hermetic box. The present analysis shows the postbuckling load carrying capacity of elements of this kind without developing failure mechanism. Due to the high sensitivity to geometric imperfections of these structures, a simple procedure to obtain their measurements once the specimen is placed in the experimental device is set out. The data registered in these tests will be used for the subsequent validation of the numerical model in order to develop more accurate solutions. This will produce a significant increment in the fidelity of those predictions, making possible a reduction in the number of tests to be performed in real applications.


ABSTRACT: Numerical simulations of the experimental tests performed with a pressurized composite stiffened panel are presented in this paper. As a consequence of the high slenderness of this structural typology, pressure caused the panel to enter the postbuckling regime. Previous experimental tests showed that the panel had a large safe postbuckling range, the experimental collapse pressure being over four times the first buckling load. Due to the relevant influence of the geometric imperfections on the global response, a procedure for taking into account actual imperfections in the development of the models is proposed. This procedure can be used as a tool to facilitate the modeling of the actual geometry of the panel, mainly the zone of the skin located between the stringers. A satisfactory agreement with experimental results has been reached using the proposed procedure.

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ABSTRACT: This paper studies the four-point bending response and failure mechanisms of sandwich panels with corrugated steel faces and either plain or fibre-reinforced foamed concrete core. Mechanical properties of both plain and polyvinyl alcohol fibre-reinforced foamed concrete were obtained, which are needed for the design of sandwich panel and numerical modelling. It is found that the fibre-reinforcement largely enhances the mechanical behaviour of foamed concrete and composite sandwich panels. Finite element code Abaqus/Standard was employed to investigate the influence of face/core bonding and fastening on the four-point bending response of the sandwich panels. It was found that face/core bonding plays a crucial role in the structural performance while the influence of fastening is negligible.

ABSTRACT: In the present investigation, the axial static crush response of circular cell, filled honeycombs is studied. Polycarbonate honeycombs with circular cells are used as the base material. Polyurethane, a soft elastomer is used as the filler material. Filled 3-cell, 7-cell and 19-cell honeycombs were subjected to uniaxial, quasi-static, out-of-plane compressive loading. The experimental results show a synergistic energy absorption event, leading to an amplification of crush energy absorption in the filled honeycombs due to a change in the deformation mode (in comparison against unfilled honeycombs). Moreover, it is seen that the initial failure is a stable collapse unlike the abrupt first failure seen in unfilled honeycombs. An explicit finite element solver is used to quantitatively understand the experimental results, thus validating its usefulness as an engineering design tool.

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ABSTRACT: An isogeometric finite element method based on non-uniform rational B-splines (NURBS) basis functions is developed for natural frequencies and buckling analysis of thin symmetrically laminated composite plates based upon the classical plate theory (CPT). The approximation of the solution space for the deflection field of the plate and the parameterization of the geometry are performed using NURBS-based approach. The essential boundary conditions are formulated separately from the discrete system equations by the aid of Lagrange multiplier method, while an orthogonal transformation technique is also applied to impose the essential boundary conditions in the discrete eigen-value equation. The accuracy and the efficiency of the proposed method are thus demonstrated through a series of numerical experiments of laminated composite plates with different boundary conditions, fiber orientations, lay-up number, eigen-modes, etc. The obtained numerical results are then compared with either the analytical solutions or other available numerical methods, and excellent agreements are found.


ABSTRACT: Static response characteristics and failure load of laminated composite shallow cylindrical and conical panels subjected to internal/external lateral pressure are investigated using continuum damage mechanics approach considering geometric nonlinearity and damage evolution. The damage model is based on a generalized macroscopic continuum theory within the framework of irreversible thermodynamics and enables to predict the progressive damage and failure load. Damage variables are introduced for the phenomenological treatment of the state of defects and its implications on the degradation of the stiffness properties. The analysis is carried out using finite element method based on the first order shear deformation theory. The nonlinear
governing equations are solved using Newton–Raphson iterative technique coupled with the adaptive displacement control method to efficiently trace the equilibrium path. The detailed parametric study is carried out to investigate the influences of geometric nonlinearity, evolving damage, span-to-thickness ratio, lamination scheme and semi-cone angle on the static response and failure load of laminated cylindrical/conical panels. It is revealed that the membrane forces due to geometric nonlinearity significantly influence the damage distribution and failure load.

ABSTRACT: In this article, the free vibration and dynamic response of simply supported functionally graded piezoelectric cylindrical panel impacted by time-dependent blast pulses are analytically investigated. Using Hamilton’s principle, the equations of motion based on the first-order shear deformation theory are derived. Also, Maxwell’s electricity equation is taken as one of the governing equations. Three sets of electric surface conditions including closed circuit and two mixtures of closed and open circuit surface conditions are considered. By introducing an analytical approach and using the Fourier series expansions, the Laplace transform and Laplace inverse method, the solution of unknown variables are obtained in the real time domain based on a combination of system frequencies. Finally, the effects of various electric surface conditions, geometric parameters and the material power law index on the free vibration and transient response of functionally graded piezoelectric cylindrical panels subjected to various impulsive loads are examined in detail.

ABSTRACT: The improved third order zigzag theory and its smeared counterpart (without the zigzag effect), recently developed by the authors for static analysis of piezoelectric laminated cylindrical shells, are extended to dynamics. The piezoelectric layers are considered as radially polarized to make use of the extension actuation mechanism that is best suited for effective actuation and sensing. The zigzag theory accounts for the layerwise variation of inplane displacements and includes the transverse normal extensibility under electric field, and also satisfies the conditions on transverse shear stresses at the layer interfaces and at the inner and outer surfaces of the shell. Yet, the number of primary displacement variables is only five, same as its smeared counterpart. The two theories are critically assessed for their accuracy by direct comparison with the three dimensional piezoelectric solutions for free and forced vibration response of simply supported smart angle-ply infinite-length and cross-ply finite-length shells, with a variety of heterogeneous composite and sandwich laminates. It is shown that the zigzag theory, in spite of being computationally efficient, is very accurate even for shells with highly inhomogeneous laminates. In contrast, the smeared third order theory is grossly inadequate for smart shells made of inhomogeneous composite and sandwich substrates.

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ABSTRACT: In the present article, axial crushing behavior of circular aluminum/glass–epoxy hybrid tubes is studied experimentally and analytically. 48 quasi-static axial crushing experiments are carried out on bare metal and hybrid tubes to evaluate the effect of different parameters such as metal and composite wall thicknesses and stacking sequence of composite layers on the crashworthiness characteristics. The specimens are made in two types of layups including angle ply pattern \([\pm \theta]\), and multi angle ply pattern (different ply angles). The experimental results reveal that stacking sequence has a considerable effect on crashworthiness characteristics, for example for layup \([90/0/0/90]\), the absorbed energy is more than three times of aluminum tube with the same aluminum wall thickness. Also the aforementioned layup has better energy absorption compared to \([90/90/90/90]\) which has been previously proposed as the best layup. According to considerable effect of stacking sequence on the axial crushing behavior of hybrid tubes, an analytical model is developed by including fiber ply orientation of each composite layer and an expression is derived for the mean crushing load and fold length in terms of thicknesses of metal and composite walls and material properties of metal and composite. This model shows reasonably good agreement with experimental results.

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ABSTRACT: The present work deals with the postbuckling behavior of an infinitely long plate consisting of laminated composites with symmetrical, balanced lay-up. Along the longitudinal edges the plate is elastically clamped with torsional springs. As loading situation combinations of biaxial compression and shear are accounted for. Aiming at high computational efficiency the problem is solved by variational methods employing a shape function with only few variables. Inserting the shape function into the compatibility condition of in-plane strains, a closed-form solution for the Airy stress function can be obtained. The resulting equilibrium condition is then used to derive the load–deflection relationship by means of the Galerkin procedure. All other state variables such as displacements and stresses can then be calculated. Comparative finite element analyses reveal that apart from the cases involving transversal compression, where the application should be handled with care, the present solution procedure can serve to obtain good approximations of the stability behavior in the early postbuckling region with negligible computational effort.

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“A high-order theory for the analysis of circular cylindrical composite sandwich shells with transversely compliant core subjected to external loads”, Composite Structures, Vol. 94, No. 7, pp 2129-2142, June 2012, 
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ABSTRACT: A new model based on the high order sandwich panel theory is proposed to study the effect of external loads on the free vibration of circular cylindrical composite sandwich shells with transversely compliant core, including also the calculation of the buckling loads. In the present model, in contrast to most of the available sandwich plate and shell theories, no prior assumptions are made with respect to the displacement field in the core. Herein the displacement and the stress fields of the core material are determined through a 3D elasticity solution. The performance of the present theory is compared with that of other sandwich theories by the presentation of comparative results obtained for several examples encompassing different material properties and geometric parameters. It is shown that the present model produce results of very high accuracy, and it is suggested that the present model, which is based on a 3D elasticity solution for the core material, can be used as a benchmark in future studies of the free vibration and buckling of circular cylindrical composite sandwich shells with a transversely compliant core.


ABSTRACT: In this paper, the finite element method is employed to investigate the effects of delamination on free vibration characteristics of graphite–epoxy pretwisted shallow angle-ply composite conical shells. The generalized dynamic equilibrium equation is derived from Lagrange’s equation of motion neglecting Coriolis effect for moderate rotational speeds. The theoretical formulation is based on the Mindlin’s theory and the multi-point constraint algorithm is considered for an eight noded isoparametric plate bending element. The standard eigenvalue problem is solved by applying the QR iteration algorithm. The mode shapes are also depicted for a typical laminate configuration. Non-dimensional natural frequencies obtained are the first known results for the type of analyses carried out here.

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ABSTRACT: Dual-phase functionally graded materials are a particular type of composite materials whose properties are tailored to vary continuously, depending on its two constituent’s composition distribution, and which use is increasing on the most diverse application fields. These materials are known to provide superior thermal and mechanical performances when compared to the traditional laminated composites, exactly because of this continuous properties variation characteristic, which enables among other advantages smoother stresses distribution profile. In this paper we study the influence of different homogenization schemes, namely the schemes due to Voigt, Hashin–Shtrikman and Mori–Tanaka, which can be used to obtain bounds estimates for the material properties of particulate composite structures. To achieve this goal we also use a set of finite element models based on higher order shear deformation theories and also on first order theory. From the studies carried out, on linear static analyses and on free vibration analyses, it is shown that the bounds estimates are as important as the deformation kinematics basis assumed to analyse these types of multifunctional structures. Concerning to the homogenization schemes studied, it is shown that Mori–Tanaka and Hashin–Shtrikman estimates lead to less conservative results when compared to Voigt rule of mixtures.

ABSTRACT: In this paper, a mixed numerical–experimental identification procedure for characterising the storage and loss properties in sandwich structures with a relatively stiff core is developed. At the computational level, the proposed method is based upon an original structurally damped shell finite element model derived from the higher-order shear deformation theory and, at the experimental level, upon an accurate contact-free measurement setup with a loudspeaker-based excitation and a scanning laser interferometer for capturing the time responses. From the modal information extracted from two specimens with different geometries, the procedure allows the simultaneous estimation of the skin and core constitutive parameters through adequate objective functions measuring the discrepancy between the experimental data and the numerical predictions. For validation purposes, the method is then applied to two test cases for which all the influent properties could be estimated with a fairly good accuracy.


ABSTRACT: In this study, the non-linear vibration of truncated conical shells made of functionally graded materials (FGMs) has been investigated using the large deformation theory with von Karman–Donnell-type of kinematic non-linearity. The material properties of FGMs are assumed to vary continuously through the thickness of the shell. The fundamental relations, the non-linear motion and compatibility equations of the FGM truncated conical shell are derived. By using Superposition method, Galerkin method and Harmonic balance method, the non-linear vibration of an FGM truncated conical shell is analyzed. Finally, the influences of compositional profiles and variation of shell geometry on the dimensionless non-linear frequency parameter and the variation of ratio of the non-linear frequency to the linear frequency are investigated. The present results are compared with the available data for a special case.

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ABSTRACT: The out-of-plane crushing behaviour of four types of aluminium hexagonal honeycombs was extensively investigated over a wide range of strain rates where each test was conducted at a constant compressive velocity. The effects of specimen dimensions, relative density, strain rate and honeycomb cell size on the mechanical properties of honeycombs were studied. It was demonstrated that the mean plateau force was
linearly related to the specimen dimensions. However, the calculated plateau stress varied with specimen dimensions and a minimum of $9 \times 9$ cells should be used in order to represent the bulk properties of honeycombs. A large strength enhancement of honeycombs was observed when the relative density and strain rate increased. The tangent modulus also increased towards the end of the crushing process, especially for those honeycombs with small values of wall thickness to edge length ratio ($t/l$). Semi-empirical relations were obtained to describe the effects of relative density ($t/l$ ratio) and strain rate on the plateau stress. The difference in deformation patterns for honeycombs between quasi-static and dynamic loading conditions was also discussed.

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ABSTRACT: This research concentrates on the evaluation of crashworthiness characteristics of natural silk/epoxy composite square tubes energy-absorbers. Composite laminate specimens were subjected to static axial compression load and experimental evaluation of the energy absorption capability of silk/epoxy composite. Specimens were in the form of square cross-sections with the dimension of $80 \times 80$ mm and a radius curvature of 5 mm. The variables in the experiment were the length of the tubes built 50, 80 and 120 mm. Meanwhile, the thickness of the walls, consisting of laminates of silk/epoxy of 12, 24 and 30 plies, correspond to equivalent wall thickness of 1.7 mm, 3.4 mm and 4.2 mm, respectively. The parameters measured were the total absorbed energy ($E_{\text{total}}$), and the crash force efficiency (CFE). $E_{\text{total}}$ is the measure of the amount of energy that the structure can withstand without failure and thus is a measure of its strength, while CFE gives a quantitative indication of the mode of failure of the composites. The mode of failure was observed using photography.

References listed at the end of the paper:
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ABSTRACT: Based on the classical shell theory with the geometrical nonlinearity in von Karman–Donnell sense and the smeared stiffeners technique, the governing equations of motion of eccentrically stiffened functionally graded cylindrical panels with geometrically imperfections are derived in this paper. The characteristics of free vibration and nonlinear responses are investigated. The nonlinear dynamic buckling of cylindrical panel acted on by axial loading is considered. The nonlinear dynamic critical buckling loads are found according to the criterion suggested by Budiansky–Roth. Some numerical results are given and compared with the ones of other authors.

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ABSTRACT: The static, dynamic, and free vibration analysis of a functionally graded material (FGM) doubly curved panel are investigated analytically in the present paper. The FGM Panel is originated from a rectangular planform and its principle curvatures are considered to be constant. All mechanical properties of the FGM panel are assumed to vary continuously through the thickness according to a power law formulation except Poisson’s ratio, which is kept constant. A Pasternak-type elastic foundation containing damping effects is considered to be in contact with the panel during deformation. The elastic foundation reacts in both compression and tension. Equations of motion are established based on the first order shear deformation and the modified Sanders shell theories. Following the Navier type solution, the established equations are reduced to time-dependent ordinary differential equations. Using the Laplace transform, the time-dependency of the problem is eliminated. The solutions are obtained analytically in the Laplace domain and then are inverted to the time domain following an analytical procedure. Finally, the analytical results are verified with those reported in the literature.

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ABSTRACT: The dynamic responses and blast resistance of all-metallic sandwich-walled hollow cylinders with graded aluminum foam cores are investigated using finite element simulations, and compared with those of conventional ungraded ones. After validating the numerical approach and introducing the computational model, sandwich-walled hollow cylinders with various graded aluminum foam cores are analyzed under air blast loading. It is demonstrated that the radial deflection of graded cylinders is smaller than and the blast resistance superior to that of ungraded ones when subjected to identical air blast loading. This can be further improved by
optimizing the foam core arrangement. Finally, the influence of face-sheet arrangements on the dynamic behavior of graded cylinders is explored.


ABSTRACT: This paper introduces a generalized 5 degrees of freedom (DOF) higher-order shear deformation theory (HSDT) to study the bending and free vibration of plates and shells, which may be used to create other HSDTs. It also introduces a new HSDT for shells that is more accurate than many available HSDTs despite having the same 5DOF, and which is also able to reproduce the well-known Soldatos’ HSDT as special case. The governing equations and boundary conditions of the generalized formulation are derived by employing the principle of virtual work. These equations are solved via Navier-type closed-form solutions. Static and dynamic results are presented for plates and cylindrical and spherical shells with simply supported boundary conditions. Panels are subjected to sinusoidal, distributed and point loads. Results are provided for thick to thin as well as shallow and deep shells. Results from the new and well-known HSDTs introduced and reproduced based on the present generalized 5DOF HSDT are compared with the exact three-dimensional elasticity solution. The present new HSDT for plates and shells is found to be more accurate than the well-known HSDTs developed by other authors, for analyzing the static and free vibration of isotropic and multilayered composite plates and shells.


ABSTRACT: This investigation presents an optimization of laminated cylindrical panels based on fundamental natural frequency. Also, trends of change in optimum stacking sequence while the proportions of structures vary, are studied which can be insightful for design purposes. A displacement based finite element model is used, in order to extract fundamental natural frequencies of T300/5208 Carbon/Epoxy cylindrical panels. To obtain optimum designs, the Globalized Bounded Nelder–Mead (GBNM) algorithm is employed. Predictions are compared with the results of Genetic Algorithm (GA) method and show faster and more accurate convergence to the global optimum, while variables are continuous in GBNM and discrete in GA. Moreover, verification of novel convergence criteria to ameliorate local searcher in GBNM is examined.


ABSTRACT: A method for reducing vibration of a sandwich structure using the antiresonance technique is presented. It is found that with appropriate resonators, the motion of the sandwich structure due to disturbances with certain frequencies can be effectively suppressed. A simple two-degree-of-freedom system consisting of an absorbing mass connected by springs to a drive mass is introduced and used to interpret the vibration behavior of the sandwich structure with resonators.

ABSTRACT: Stiffness tailoring of laminated composite structures using steered fibre tows is a design method that maximally uses the directional properties of composite materials. Cylindrical structures usually have circular cross sections while some application, geometric or aerodynamic requirements can necessitate other cross sections, e.g. elliptical. Circumferential tailoring can increase the buckling load of thin cylinders by compensating for non-uniform sectional loading such as bending and/or varying radius of curvature in general cylinders. Here, strength constraints are considered in maximum buckling load design, to ensure that the failure load is greater than the buckling load. A two-step optimisation framework is used to separate the theoretical and manufacturing issues in design. A computationally cheap semi-analytical finite difference method is used to solve the linear static and buckling problems. Conservative failure envelopes based on Tsai-Wu failure criterion are used for strength evaluation. To avoid repetitive analyses, successive convex approximation method is used. For demonstration, circumferential tailoring framework is applied to a circular cylinder under bending and an elliptical cylinder under axial compression. The improvements in buckling capacity of variable over constant stiffness designs are shown and verified using nonlinear buckling analysis in the commercial FEM software Abaqus, and the mechanisms of improvements are investigated.

Ali A. Yazdi (Department of Mechanical Engineering, Quchan Institute of Engineering and Technology, P.O. Box 94717-84686, Quchan, Iran), “Flutter of delaminated cross-ply laminated cylindrical shells”, Composite Structures, Vol. 94, No. 9, pp 2888-2894, September 2012, https://doi.org/10.1016/j.compstruct.2012.03.042

ABSTRACT: In this study, the instability of delaminated cross-ply thin laminated cylindrical shells and panels when subjected to supersonic flow parallel to its length edge is investigated. The delamination is parallel to the shell reference and it extends along the entire length of the cylindrical shell. The Love’s shell theory and Von-Karman–Donnell type of kinematic relations along with first-order potential theory have been employed to construct the aeroelastic equations of motion. The effects of several parameters such as length to radius ratio, delamination position, size and thickness on the critical values are discussed in the details. The results indicate that the presence of delamination reduced the overall stiffness of the structure and thereby decreases the flutter critical boundaries.


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear static and dynamic unsymmetrical responses of functionally graded shallow spherical shells under external pressure incorporating the effects of temperature. Governing equations for thin FGM spherical shells are derived by using the classical shell theory taking into account von Karman–Donnell geometrical nonlinearity. Approximate solutions are assumed and Galerkin procedure is applied to determine explicit expressions of static critical buckling loads of the shells. For the dynamical response, motion equations are numerically solved by using Runge–Kutta method and the criterion suggested by Budiansky–Roth. A detailed analysis is carried out to show the effects of material
and geometrical parameters, boundary conditions and temperature on the stability and dynamical characteristics of FGM shallow spherical shells.


ABSTRACT: The concept of variable angle tow (VAT) placement is explored for enhancing the buckling resistance of composite plates subjected to axial compression loading. The problem is relatively difficult to solve because of varying stiffness properties and requires prior prebuckling analysis to determine the non-uniform stress variation followed by the buckling analysis of VAT plates. A stress function formulation for in-plane analysis and displacement formulation for buckling analysis was employed to derive the governing differential equations of VAT plates based on classical laminated plate theory. The Differential Quadrature Method (DQM) is applied to solve the differential equations. The novel aspect of the present work is the use of Airy’s stress function to model the prebuckling analysis of VAT plates which considerably reduces the problem size, computational effort and provides generality to model pure stress and mixed boundary conditions. DQM was applied first to solve the prebuckling problem of VAT plates subjected to cosine distributed compressive load/ uniform end shortening. Then, DQM was applied to solve the buckling problem of rectangular VAT plates subjected to axial compression under different plate boundary conditions. Results were validated with detailed finite element analysis and the relative accuracy and efficiency of the DQM approach is discussed.


ABSTRACT: The early time, through-thickness stress wave response of a foam-core, composite sandwich cylindrical shell under external blast is examined in this paper. Solutions for the transient response of the facesheets were derived as stress waves propagated through an elastic–plastic, crushable foam core. These solutions were found to be in good agreement with results from finite element analysis. The blast response of the composite sandwich cylindrical shell was shown to be affected by the magnitude and duration of the pressure pulse. High amplitude, low duration (impulsive) pressure pulses induced the greatest energy absorption. Low amplitude, long duration pressure pulses caused minimal energy absorption. The amount of energy absorbed increased and the failure load decreased with increasing core thickness. Sandwich shells with foams of varying density, compressive modulus and crushing resistance were also examined. The sandwich shells with the foam of the highest density, compressive modulus and crushing resistance (Divinycell HCP100) were found to be the most blast resistant to failure even though no energy was absorbed by them. Per unit weight, however, the shells with a lighter, less stiff and strong, Divinycell H200 foam core were more blast resistant to failure than shells with a Divinycell HCP100 foam core.

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ABSTRACT: The bending, buckling and free vibration of annular microplates made of functionally graded materials (FGMs) are investigated in this paper based on the modified couple stress theory and Mindlin plate theory. This microplate model incorporates the material length scale parameter that can capture the size effect in FGMs. The material properties of the FGM microplates are assumed to vary in the thickness direction and are estimated through the Mori–Tanaka homogenization technique. The higher-order governing equations and boundary conditions are derived by using Hamilton’s principle. The differential quadrature (DQ) method is employed to discretize the governing equations and to determine the deflection, critical buckling load and natural frequencies of FGM microplates. A parametric study is then conducted to investigate the influences of the length scale parameter, gradient index and inner-to-outer radius ratio on the bending, buckling and vibration characteristics of FGM microplates with hinged–hinged and clamped–clamped supports. The results show that the size effect on the bending, buckling and vibration characteristics is significant when the ratio of the microplate thickness to the material length scale parameter is smaller than 10.

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ABSTRACT: The higher-order gradient continuum theory is employed to study the structural parameters and elastic properties of single-walled carbon nanocones (SWCNCs), where the higher-order Cauchy–Born rule is used to link the deformation of the carbon atomic structure to that of the continuum level. Unlike single-walled carbon nanotubes (SWCNTs), mechanical properties of SWCNCs vary along its side edge’s direction, owing to the monotonically increasing radius. In the constitutive model, a representative cell in an initial graphite sheet is selected to study the mechanical property of this domain of SWCNCs. By minimizing the potential energy of the representative cell in the undeformed SWCNC, structural parameters and elastic properties of the domain are obtained. The varying chiralities seem to have a large impact on mechanical properties of SWCNCs. Five kinds of SWCNCs are chosen in our study to test the influence of the apex angle on mechanical properties. The computational results demonstrate that mechanical properties of SWCNCs trend to the constant of graphite sheet when the radius is extremely large but this trend becomes mild as the apex angle increases.

ABSTRACT: The paper is focused on the development of a validated procedure for modelling, by means of Finite Element tools, the post-buckling behaviour of stiffened composite flat panels subjected to compression loads. The experimental data for model validation were collected during a test campaign on two sets of CFRP flat stiffened panels. Tests are briefly described and selected experimental results, used for the validation phase, are presented. A detailed description of modelling strategies and analysis set up for post-buckling simulation is provided and some results of the sensitivity studies, which helped in fine-tuning the model of the test specimens, are reported as well. Finally, a thorough comparison of the model results with the experimental data is presented and commented. The final validation is accomplished not only by qualitatively comparing the buckled shape of the panels numerically predicted with those observed in the experiments, but also by quantitatively evaluating the differences between predicted and measured strains and out-of-plane displacements. The comparison between numerical and experimental results highlights the substantial effectiveness of the FEM approach in predicting the structural response of the panels in terms of buckling occurrence and of their post-buckling behaviour.


ABSTRACT: This research present the development of geometrically nonlinear NURBS isogeometric finite element analysis of laminated composite plates. First-order, shear-deformable laminate composite plate theory is utilized in deriving the governing equations using a variational formulation. Geometric nonlinearity is accounted for in Von-Karman sense. A family of NURBS elements are constructed from refinement processes and validated using various examples. $k$-refined NURBS elements are developed to study thin plates. Isotropic, orthotropic and laminated composite plates are studied for various boundary conditions, length to thickness ratios and ply-angles. Computed center deflection is found to be in an excellent agreement with the literature. For thin plate analysis, linear and $k$-refined quadratic NURBS element is found to remedy the shear locking problem. $k$-refined quadratic NURBS element provide stabilized response to distorted, coarse meshes without increasing the order of the polynomial, owing to the increased smoothness of solution space.

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ABSTRACT: The crushing behaviour and energy absorption capacity of frustrated conical shells made-up of bare aluminium (AC) and E-glass fibre/epoxy resin composite overwrapped aluminium (CWAC) was studied under quasi-static axial compression condition. Using spinning process, the hollow frustrated conical specimens were fabricated with the help of wooden conical shaped mandrill with semi apical angles of 16° and 21°. Thin commercial aluminium sheets of average thickness 0.87 mm were obtained for making aluminium conical specimen. CWAC frusta were fabricated by wrapping glass fibre/epoxy resin over aluminium conical shell to form hybrid composite with required thickness by hand layup process. Quasi-static axial compression load was applied over top end of the specimen with cross head speed as 2 mm/min using Universal Testing Machine
From the experiment results, the load–deformation characteristics of different AC and CWAC frusta were investigated. Energy absorption capacities or crashworthiness and mode of collapse of all models of AC and CWAC are determined from load–deformation curve and the same was validated with finite element analysis package ABAQUS.


ABSTRACT: This work investigates the aeroelastic stability boundary of flutter in aircraft composite panels, curved or flat, subject to the effect of stress stiffening caused by the piezoelectric actuator (PZT). Hamilton’s principle is used for the formulation of the energy functional and to obtain the equilibrium equations and boundary conditions of the problem. The finite element method is employed to numerically solve the equations. The aeroelastic behavior of panels manufactured in composite material (boron–epoxy) or conventional material (aluminum 2024-T3) are assessed. Two layers of piezoelectric material (ACX QP10N) are attached to the panels: one on the top surface one on the bottom surface of the panels. Prescribed voltages are statically applied to the piezoelectric actuators, inducing a prestress field which is responsible for the stress stiffening effects when coupled with the nonlinear strain components. Different geometric configuration, laminate stacking sequence, boundary conditions and curvatures are investigated. The study shows that mechanically strain-induced piezoelectric effect increases the rate of occurrence of flutter, stabilizing the plate. This stiffening of the structure is related to the voltage applied on the actuators and the geometrical parameters of the plate. Thus, one can control the occurrence of flutter speed by controlling the voltage applied and the proper design of the geometric properties of the panel and tailoring of the composite laminate.


ABSTRACT: Skewed modes in geometrically nonlinear forced vibrations of angle-ply laminated circular cylindrical shells are investigated in the present study by using the Amabili–Reddy higher-order shear deformation theory. An harmonic force excitation is applied in radial direction and simply supported boundary conditions are assumed. The equations of motion are obtained by using an energy approach based on Lagrange equations that retains dissipation. Numerical results are obtained by using the pseudo-arclength continuation method and bifurcation analysis.


ABSTRACT: The paper presents the large deformation flexural response of composite laminated skew plates subjected to uniform transverse pressure. Third order shear deformation theory (TSDT) and von-Karman’s nonlinearity is used for the analysis. Skew domain is mapped into a square domain and finite degree double Chebyshev series is used to discretize the space domain. No grid generation is required in the present solution technique. The nonlinear equations are linearized using quadratic extrapolation technique and the behavior of moderately thick laminated composite skew plates is studied. The effects of geometric nonlinearity, transverse...
shear, boundary conditions, aspect ratio and modular ratio on the behavior of laminated composite skew plates are discussed in detail.

Erasmo Viola, Luigi Rossetti Nicholas Fantuzzi (Department of Civil, Environmental and Material Engineering – DICAM, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy), “Numerical investigation of functionally graded cylindrical shells and panels using the generalized unconstrained third order theory coupled with the stress recovery”, Composite Structures, Vol. 94, No. 12, pp 3736-3758, December 2012, 
https://doi.org/10.1016/j.compstruct.2012.05.034

ABSTRACT: A 2D Unconstrained Third Order Shear Deformation Theory (UTSDT) is presented for the evaluation of tangential and normal stresses in moderately thick functionally graded cylindrical shells subjected to mechanical loadings. Eight types of graded materials are investigated. The functionally graded material consists of ceramic and metallic constituents. A four parameter power law function is used. The UTSDT allows the presence of a finite transverse shear stress at the top and bottom surfaces of the graded cylindrical shell. In addition, the initial curvature effect included in the formulation leads to the generalization of the present theory (GUTSDT). The Generalized Differential Quadrature (GDQ) method is used to discretize the derivatives in the governing equations, the external boundary conditions and the compatibility conditions. Transverse and normal stresses are also calculated by integrating the three dimensional equations of equilibrium in the thickness direction. In this way, the six components of the stress tensor at a point of the cylindrical shell or panel can be given. The initial curvature effect and the role of the power law functions are shown for a wide range of functionally cylindrical shells under various loading and boundary conditions. Finally, numerical examples of the available literature are worked out.


ABSTRACT: An idea for generating a pumping action with high pumping potential is proposed and evaluated. The pumping potential is defined as the amount of relative volume reduction engendered by an applied load (relative input stroke). The idea is based on the hypothesis that upon twisting a single-ply flexible-matrix-composite (FMC) hyperbolic shell-of-revolution structure, with rigid fibers and negligible matrix stiffness, a considerable volume reduction ensues. A mathematical model governing the large deformation of a hyperbolic shell-of-revolution FMC structure using the energy approach is presented. The response of a specific structure due to an angular twist is computed using a B-spline based technique. In addition, a crude single-ply carbon/polyurethane hyperbolic shell-of-revolution structure is built and tested. The analytical results are compared with a corresponding ANSYS simulation and the experimental ones. The results demonstrate that the proposed idea is viable. The results also suggest that the B-spline based approach is an attractive method for solving large deformation structural boundary value problems.

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“Coupled dynamic buckling of thin-walled composite columns with open cross-sections”, Composite
ABSTRACT: In this paper an analysis of dynamic response of thin-walled composite columns with opened stiffened cross-sections was described. The columns were subjected to an in-plane pulse loading and three different stability criteria were applied: the Budiansky–Hutchinson, the Kleiber–Kotula–Saran and the phase-plane one. A pulse loading of rectangular shape was concerned. The columns were assumed to be simply supported at the ends. Additionally, an attention was paid to an influence of the tracking time of dynamic response on critical values of dynamic load factors. A plate model was adopted in the analysis. Differential equations of motion were obtained from the Hamilton’s Principle, taking into account all components of inertia forces. The discussed problem of dynamic buckling was solved with a numeric method. Special attention was given to a coupled buckling of various global buckling modes.

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ABSTRACT: In this work, we present an optimization methodology used in order to optimize laminated composite shell structures with variable stiffness. Considering the maximization of the structural global rigidity measured by the compliance, a topology optimization problem of the anisotropy fields for thin laminated plates as well as the associated optimization algorithm are extended to thin laminated shells. Numerical examples with quasi-homogeneous angle-ply stacking sequences showing the optimization methodology feasibility are presented.

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ABSTRACT: A reduced-order finite-element model suitable for Progressive Failure Analysis (PFA) of composite structures under dynamic aeroelastic conditions based on a Thin-Walled Beam (TWB) formulation is presented. Validation of the PFA-TWB against an integrated PFA model based on a shell formulation and implemented in the commercial software tool GENOA is conducted for static load conditions. A helicopter blade made from composite material and previously used in literature for the discussion of damage propagation is used as the reference case. The failure criteria for the different layers of the composite material used in the PFA-TWB model have been formulated in analogy with the corresponding criteria implemented in the shell formulation. Comparisons between the predictions of both models for progressively increasing load have been conducted in terms of the cumulative overall damage volume in the thin-walled structure, the layer-resolved
cumulative damage volume, as well as through spatially resolved damage maps for both models. A strikingly similar damage topology has been found from both models up to load values close to final failure, in spite of the restraining assumptions of the TWB formulation. In terms of damage volume the PFA-TWB models predicts slightly higher values which can be traced back to the inevitable differences in the failure criteria formulation in the one-dimensional and the shell model, respectively. It is shown that a good agreement with the predictions of the shell model in terms of the cumulative damage volume is obtained if the strength values of the composite material are adjusted upwards in a uniform manner by about 10%. Considering the common safety factors usually applied in the design process of composite material the agreement of the TWB and the shell model in terms of damage propagation is considered excellent, allowing for the PFA-TWB to be used in systematic design studies.

R. Ansari, A. Shahabodini and H. Rouhi (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Prediction of the biaxial buckling and vibration behavior of graphene via a nonlocal atomistic-based plate theory”, Composite Structures, Vol. 95, pp 88-94, January 2013, https://doi.org/10.1016/j.compstruct.2012.06.026

ABSTRACT: The present article is concerned with the applicability of an elastic plate theory incorporating the interatomic potentials for biaxial buckling and vibration analysis of single-layer graphene sheets (SLGSs) and accounting for the small scale effects. For this purpose, the relations based on the interatomic potential and Eringen’s nonlocal equation are incorporated into the classical plate theory. The former relations are obtained through constructing a linkage between the strain energy induced in the continuum and the potential energy stored in the atomic bonds using the Cauchy–Born rule. The nonlocal governing equations of motion for buckling and vibration of the SLGSs with simply-supported boundary conditions are exactly solved and explicit formulae for the frequencies and critical buckling load are derived. The results generated from the present model are compared with those of molecular dynamic (MD) simulations and the other previously reported ones and a good agreement is achieved. The model developed herein is independent of Young’s modulus which is of an ambiguous definition in the literature. It is found that the small scale effect on buckling and vibrational response of the SLGSs is profound and it becomes more prominent when the side length is low.


ABSTRACT: The 11-variable global–local theory (GLT) was proposed in 1997 with the purpose of accurately predicting transverse stresses in laminated structures directly from the constitutive equations. However, the theory has so far been tested only for composite laminates made of a single material. This study critically examines the accuracy of the GLT for static and dynamic response of plates for a variety of laminate configurations. The recently developed zigzag-local theory (ZLT), with nine primary variables, which also has the capability to calculate transverse shear stresses from constitutive equations, is extended for dynamic analysis and assessed. The comparison with the exact 3D elasticity solutions reveals that the GLT is good only for laminates with upto three layers. For multi-material composite laminates and sandwich laminates with more than three layers, its prediction is poor and even worse than the existing five-variable zigzag theory (ZIGT), not only for transverse shear stresses, but also for displacements and natural frequencies. The ZIGT, on the other hand, yields very accurate results for displacements, inplane stresses and natural frequencies for all laminate configurations. The ZLT is even better with the ability of predicting transverse shear stresses directly from the constitutive equations with good accuracy for any laminate lay-up.
ABSTRACT: The application of the sampling surfaces (SaS) method to laminated composite plates is presented in a companion paper (Kulikov GM, Plotnikova SV. Exact 3D stress analysis of laminated composite plates by sampling surfaces method. Compos Struct 2012;94:3654–3663). In this paper, we extend the SaS method to shells to solve the 3D elasticity problems for cylindrical and spherical laminated composite shells. For this purpose, we introduce inside the n-th layer $I_n$ not equally spaced SaS parallel to the middle surface of the shell and choose displacements of these surfaces as basic kinematic variables. Such choice of displacements allows the derivation of strain–displacement equations, which are invariant under all rigid-body shell motions in any convected curvilinear coordinate system. This gives in turn the opportunity to find the 3D elasticity solutions for laminated composite shells with a prescribed accuracy utilizing a sufficiently large number of SaS, which are located at Chebyshev polynomial nodes and layer interfaces as well.

Yegao Qu, Hongxing Hua and Guang Meng (State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “A domain decomposition approach for vibration analysis of isotropic and composite cylindrical shells with arbitrary boundaries”, Composite Structures, Vol. 95, pp 307-321, January 2013, https://doi.org/10.1016/j.compstruct.2012.06.022

ABSTRACT: An efficient domain decomposition method is proposed for solving the free, harmonic and transient vibrations of isotropic and composite cylindrical shells subjected to various combinations of classical and non-classical boundary conditions. Multi-segment partitioning strategy is adopted to accommodate the computing requirements of high-order vibration modes and responses. The continuity constraints on the segment interfaces are incorporated into the system potential functional by means of a modified variational principle and least-squares weighted residual method. An arbitrarily laminated version of Reissner–Naghdi’s shell theory is employed to formulate the theoretical model. Double mixed series, i.e., the Fourier series and orthogonal polynomials, are used as admissible displacement functions for each shell segment. The utility and robustness of the method for the application of various basis functions are evaluated with the following four sets of orthogonal polynomial series, i.e., the Chebyshev orthogonal polynomials of first and second kind, Legendre orthogonal polynomials of first kind and Hermite orthogonal polynomials. To test the convergence, efficiency and accuracy of the present method, free and forced vibrations (including the harmonic and transient vibrations) of isotropic and composite laminated cylindrical shells are examined under different combinations of free, shear-diaphragm, simply-supported, clamped and elastic supported boundaries. The theoretical results are compared with those previously published in literature, and the ones obtained by using the finite element program ANSYS. Very good agreement is observed.

Ernesto Guades and Thiru Aravinthan (Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, Queensland 4350, Australia), “Residual properties of square FRP composite tubes subjected to repeated axial impact”, Composite Structures, Vol. 95, pp 354-365, January 2013, https://doi.org/10.1016/j.compstruct.2012.08.041

ABSTRACT: In this paper, the residual properties of square composite tubes under axial impact were experimentally investigated. The effects of damage factors such as the mass of the impactor, incident energy,
and number of impacts on their post-impact behaviour were emphasised. Low-velocity impact tests were performed by repeatedly impacting a 100 mm square FRP pultruded tube with energy levels up to 742 J using a drop-weight apparatus. Coupons were then taken from the impacted tubes and tested statically to determine the residual compressive, tensile, and flexural properties. Results show that the levels of impact energy, number of impacts, and the mass of the impactor significantly influenced the residual strength degradation of the impacted tubes. Their effects, however, are almost negligible in the residual modulus property. It was found that the maximum reductions of residual compressive, tensile, and flexural strengths of the impacted tubes are 6.8%, 0.3%, and 10%; respectively. It was also found that effect of impact damage on the reduction of residual compressive strength of the tube is concentrated only in region closer to the impact point.

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ABSTRACT: An advanced variable-kinematics trigonometric Ritz formulation built in the extended framework of the Carrera Unified Formulation (CUF) is developed to cope with free vibration response of anisotropic composite plates in a thermo-mechanical pre/post-buckled state. By using the CUF it is not only possible to introduce different expansion orders for each displacement unknown, but also to retain or discard a particular term with respect to its effectiveness and independently form its location in the displacement field generating the so-called mixed axiomatic/asymptotic theories. The proposed formulation is based on Ritz fundamental primary and secondary stiffness, mass and initial stress nuclei which are built in a unified framework that allows them to be invariant regarding to the used kinematic description, the expansion order adopted for each displacement component and the chosen trial functions. Refined equivalent single layer, zig-zag and layer-wise models are assessed by comparison with the 3D elasticity solution. Convergence and accuracy of the presented formulation are critically examined. Several in-plane mechanical load conditions combined with temperature variations are applied and their influence upon the free vibration response is studied. The effects of significant parameters such as stacking sequence, orthotropic ratio and length-to-thickness ratio on the circular frequency parameters are deeply investigated.


ABSTRACT: The analytical modelling of the local buckling failure mode for composite anisogrid lattice cylindrical shells with the typical system of hexagonal cells is here discussed. The aim is to complement the set of constraint equations that are associated with the preliminary design phase of such structures under axial compressive loads, and to prospectively improve the final solutions. The basic constraint equations for anisogrids without the skin are focused on the global buckling of the shell, the local buckling of helical ribs, and the material failure of these ribs. However, the local buckling of helical ribs is normally based on a simplified and qualitative approach. Conversely, the developed modelling, which is based on the Ritz method, accounts for
the helical angle of the periodic cell, the stiffness of intersecting hoop and helical ribs, and the positive effect of the prebuckling tensile force in hoop ribs. This model has been verified with the aid of finite-element analysis, demonstrating a noteworthy accuracy. Thanks to the comparison with the parallel study on anisogrid shells with triangular cells, the effect of hoop rib positioning on the local buckling strength (i.e., hexagonal or triangular system of cells) is finally assessed.

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ABSTRACT: The conditions of test obtained experimentally were simulated using Dytran a non-linear finite element explicit analysis software implemented to the simulation since this mimics the characteristics of the behaviour of the crashworthiness. Results from the finite element analysis were validated against the experimental results and a good agreement between two approaches was observed i.e. the average errors of total absorbed energy ($E_{\text{total}}$) (6.1%) and crush force efficiency (CFE) (9%) were obtained. The simulation depicted catastrophic failures similar to experimental results i.e. local buckling and mid length buckling failure in the specimens in the resulting geometries. This agreement builds confidence in the future use of non-linear finite element for the design of silk/epoxy composite structure subjected to crash loading in energy-absorbing applications such as in the automotive as well as in the aircraft industries.

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ABSTRACT: The paper is concerned with the buckling analysis of the composite orthotropic cylindrical shell with clamped edges subjected to inertia loading. The problem is characterised by a non-uniform pre-buckling stress state. To address this, the relevant governing system of differential equations with variable coefficients has been derived and solved using Galerkin method. As a result, the problem of determining the critical acceleration causing the buckling of shell is reduced to the solution of the corresponding generalised eigenvalue problem. Using the proposed approach, the critical accelerations are calculated for the glass-fibre reinforced shells with various dimensional and stiffness parameters. Results of calculations are compared with those based on finite-element modelling and analysis.

ABSTRACT: Corrugations are provided for metallic containers used to carry liquefied hydrogen to relieve thermal stresses generated due to large temperature difference between the room temperature and its liquefaction temperature. However, the corrugations of stainless steel (SUS) are vulnerable to failure due to the low pressure resisting capability of the corrugation when subjected to outside cavitation pressure. Since the pressure resisting capability of the corrugations has not been measured accurately due to the unavailability of test equipment, in this work, new test equipment has been developed, which can measure the pressure resisting capabilities of the SUS corrugations with the same boundary conditions of the actual system. The pressure resisting capabilities of the SUS corrugations reinforced with the aluminum anti-buckling structures were estimated with the finite element analysis, and compared to the measured ones. Also, anti-buckling glass fiber epoxy composite structures were developed and their pressure resisting capabilities were measured. Finally, the anti-buckling composite structure was optimized with respect to stacking sequence.


ABSTRACT: Flutter analyses of composite lifting surfaces are presented in this paper. Results were obtained through an advanced aeroelastic formulation based on higher-order 1D structural models coupled with the doublet lattice method. The g-method was used to compute flutter conditions. The Carrera Unified Formulation (CUF) was exploited to build 1D structural models. Refined theories were obtained by using Taylor-like expansions of the cross-section displacement field. In the CUF framework, the order (N) of the expansion is considered as a free-parameter, this means that N can be considered as an input of the analysis. Convergence studies on N can be straightforwardly conducted in order to establish the proper 1D theory for a given problem. Flutter analyses were conducted on several structural configurations. The effect of the stacking sequence and the effect of the sweep angle were analyzed. Results show the enhanced capabilities of CUF 1D in dealing with the flutter analysis of typical composite lifting surfaces with plate-like accuracy and low computational costs.


ABSTRACT: The main aim of this paper is to provide a general framework for the formulation and the dynamic analysis computations of moderately thick laminated doubly-curved shells and panels. A 2D higher-order shear deformation theory is also proposed and the differential geometry is used to define the arbitrary shape of the middle surface of shells and panels with different curvatures. A generalized nine-parameter displacement field suitable to represent in a unified form most of the kinematical hypothesis presented in literature has been introduced. Formal comparison among various theories have been performed in order to show the differences between the well-known First-order Shear Deformation Theory (FSDT) and several Higher-order Shear Deformation Theories (HSDTs). The 2D free vibration shell problems have been solved numerically using the Generalized Differential Quadrature (GDQ) technique. The GDQ rule has been also used to perform the numerical evaluation of the derivatives of the quantities involved by the differential geometry to completely describe the reference surfaces of doubly-curved shell structures. Numerical investigations concerning four types of shell structures have been carried out. GDQ results are compared with those presented
in literature and the ones obtained using commercial programs such as Abaqus. Very good agreement is observed.


ABSTRACT: In present study, a new inverse hyperbolic shear deformation theory is proposed, formulated and validated for a variety of numerical examples of laminated composite and sandwich plates for the static and buckling responses. The proposed theory based upon shear strain shape function yields non-linear distribution of transverse shear stresses and also satisfies traction free boundary conditions. Principle of virtual work is employed to develop the governing differential equations assuming the linear kinematics. A Navier type closed form solution methodology is also proposed for cross-ply simply supported plates which limits its applicability. However, it provides accurate solution which is free from any numerical/computational error. It is observed that the present theory can be more accurately applied for the modeling of laminated composite and sandwich plates at the same computational cost as that of other shear deformation theories.

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ABSTRACT: The dynamic instability of longitudinally stiffened panels having rectangular internal cutouts under parametric in-plane loading is studied by using a developed finite strip method (FSM). The loading is considered as uniform stresses throughout the whole area. The effects of perforations on the instability load frequency regions are investigated using the Bolotin’s first order method and a negative stiffness modeling approach. In order to demonstrate the capabilities of the developed methods in predicting the structural dynamic behavior, some representing results are obtained and compared with those in the literature wherever available.

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ABSTRACT: An exact finite strip for the buckling analysis of moderately thick symmetrically cross-ply laminated composite plates and plate structures is presented in this paper by using First-order Shear Deformation Theory (FSDT). Based on the concept that the so-called strip is effectively a plate, the critical buckling load and out-of-plane deflection mode shape are obtained by solving the Von-Karman’s equilibrium equation exactly. A transcendental stiffness matrix is obtained for an individual strip. The overall stiffness matrix for the whole section is obtained by assembling the individual stiffness matrices. Since the overall
stiffness matrix is transcendental, it is not possible to identify a separate geometric stiffness matrix. In this paper a secure method i.e. bisection method is used to find the buckling load and the corresponding buckling mode of the plate structure.

Shaikh Akhlaque-E-Rasul and Rajamohan Ganesan (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, Canada H3G 1M8), “Compressive response of tapered curved composite plates based on a nine-node composite shell element”, Composite Structures, Vol. 96, pp 8-16, February 2013, https://doi.org/10.1016/j.compstruct.2012.07.037

ABSTRACT: Tapered laminated structures have considerable potential for creating significant weight savings in engineering applications. The objective of the present work is to investigate the compressive response of curved composite plates with longitudinal internal ply-drop-off configurations. A nine-node tapered curved composite finite element is developed based on six well-established first-order shear deformation shell theories. The buckling loads obtained using Finite Element Method (FEM) are compared with that of the existing analytical and experimental results. A comprehensive parametric study is carried out and design guidelines for the tapered curved plates are established based on this study.


ABSTRACT: Glass fiber reinforced polymer (GFRP) composites are used extensively to strengthen and/or to rehabilitate infrastructures. The current study focuses on the use of GFRP for enhancing local buckling behaviour of wide flange steel beams. The study is conducted numerically using a nonlinear finite element model developed in-house. In the numerical model, consistent shell elements are used to simulate the flanges and web of the steel beams as well as the GFRP plates. The interface between the steel and GFRP plates is simulated using a set of continuous linear spring systems representing both the shear and peel stiffness of the adhesive based on values obtained from a previous experimental study. The numerical model is validated using test results and numerical predictions available in literature. Various failure modes, including GFRP rupture, adhesive shear failure, and local buckling of the flanges of beams are included in the model. The effect of geometric imperfection and residual stresses are also included. The model is then used to conduct a parametric study to assess the effect of bonding GFRP plates on enhancing the local buckling behaviour of wide flange steel beams. The results reveal that the effectiveness of this approach especially for the case of slender beams.

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ABSTRACT: A dynamic stiffness approach for the prediction of the vibratory response of thick laminates and sandwich panels is hereby proposed. Initially, the wave dispersion characteristics of a two dimensional periodic medium are numerically predicted using a Wave Finite Element Method (WFEM). The effects of layer coupling...
on wave propagation within the laminate are therefore captured through a full three dimensional Finite Element (FE) modeling for a wide frequency range. The computed dispersion characteristics are used in order to update classical plate theories and calculate a dynamic stiffness matrix for the modeled laminate. The resulting updated Equivalent Single Layer (ESL) modeling proves to be time efficient and accurate for a wide frequency range. An experimental validation of the presented approach is also conducted. The response of a honeycomb orthotropic sandwich panel is measured and is successfully compared to the prediction of the ESL model. The WFEM computed wavenumbers are also validated by experimental measurements. The accuracy and the computational efficiency of the WFEM homogenization are discussed and compared to the ones of modern refined shell theories. The approach proves to be computationally efficient, numerically simple and accurate in a broadband frequency range.

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ABSTRACT: The out-of-plane crushing properties of rhombic and kagome honeycombs are studied in this paper by dividing the whole structure into basic angle elements: corner elements and X-shaped elements. Two theoretical models are presented to analyze the energy absorption mechanisms for inextensional mode of corner elements and one of collapse modes of X-shaped elements respectively. Expressions are derived to predict the mean crushing force of the angle elements. Numerical simulations are also carried out for angle elements under out-of-plane crushing by using nonlinear finite element code LS-DYNA. Crush resistance of angle elements with different geometric configurations including angle, width and thickness is analyzed. A comparison between theoretical predictions and numerical results shows that the theoretical models can effectively predict the mean crushing force of angle elements with a very good accuracy.

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ABSTRACT: In the present work a non-linear dynamic response of a continuous sandwich beam with SMA hybrid composite face sheets and flexible core is analyzed taking into account the phase transformation and also the material non-linearity effects, for every point along the face sheets. The one-dimensional constitutive equation of SMA proposed by Brinson is employed. Equations of motion are derived using Hamilton’s principle and a new finite element is proposed based on a higher order sandwich panel theory. Due to the phase transformation, the equations of motion are coupled with the phase transformation’s kinetic equations of SMA
wires. A new finite-element-based approach along with an iterative incremental method is developed to study the dynamic response of sandwich beam with SMA hybrid composite face sheets and flexible core. A damped response of the sandwich beam is observed, which is due to the hysteresis behavior of SMA wires. The influence of the SMA wires on the vibration suppression related to the resonance phenomena of a sandwich beam as well as the effect of the through thickness location of the SMA wires inside the composite face sheets and also the effect of different boundary conditions on the dynamic response are analyzed.


ABSTRACT: An exact dynamic stiffness method based on higher order shear deformation theory is developed for the first time using symbolic computation in order to carry out free vibration analysis of composite plate assemblies. Hamilton’s principle is applied to derive the governing differential equations of motion and natural boundary conditions. Then by imposing the geometric boundary conditions in algebraic form the dynamic stiffness matrix is developed. The Wittrick–Williams algorithm is used as solution technique to compute the natural frequencies and mode shapes for a range of laminated composite plates and stepped panels. The effects of significant parameters such as thickness ratio, orthotropy ratio, step ratio, number of layers, lay-up and stacking sequence and boundary conditions on the natural frequencies and mode shapes are critically examined and discussed. The accuracy of the method is demonstrated by comparing results with those available in the literature.


ABSTRACT: In recent years, vulnerability against high-velocity impact loads has become an increasingly critical issue in the design of composite aerospace structures. The effects of Hydrodynamic Ram (HRAM), a phenomenon that occurs when a high-energy object penetrates a fluid-filled container, are of particular concern in the design of wing fuel tanks for aircraft because it has been identified as one of the important factors in aircraft vulnerability. The projectile transfers its momentum and kinetic energy through the fluid to the surrounding structure, increasing the risk of catastrophic failure. In the present paper, the commercial finite-element code ABAQUS/Explicit has been used to simulate an HRAM event due to the impact of a steel spherical projectile into a water-filled woven CFRP square tube. In order to simulate the fluid–structure interaction, the Coupled Eulerian Lagrangian (CEL) approach is used. Experimental tests which indicate the pressure at different points of the fluid, strains of the walls and cavity evolution for different impact velocities are compared with the numerical results in order to assess the validity and accuracy of CEL technique in reproducing such a complex phenomenon. Also, several numerical impacts at different initial projectile velocities are performed to study its influence in the HRAM phenomenon.

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ABSTRACT: This paper presents the results of an experimental and numerical study on the low-velocity impact behavior of foam-core sandwich panels. Panels with polyurethane foam core and plain weave carbon fabric laminated face-sheets were subjected to low-velocity impact with hemispherical steel impactors of different diameters at various energy levels. Digital image correlation technique (a non-contact measuring system) was used to measure the real-time displacement and velocity of the impactor, and the back surface out-of-plane panel deflection time-history. A load sensor was used to record the contact force time-history. Non-destructive inspection and destructive sectioning methods were used to evaluate the internal and external damage on the sandwich panels after impact. The effects of impact variables such as impactor diameter, impact energy, and sandwich panel configuration parameters, such as face-sheet thickness and foam core thickness on the impact behavior and resulting impact damage states were studied. Based on the generalized Schapery theory, a progressive damage model is developed to describe the nonlinear behavior of plain weave carbon laminates during impact. The foam core was modeled as a crushable foam material. Coupon tests were conducted to determine the input parameters for the progressive damage model and the foam crushing properties. Three-dimensional finite element models were implemented to analyze the impact response incorporating the progressive damage model. Results from the numerical models were found to agree well with experimental observations.

ABSTRACT: Local denting caused by low-velocity heavy mass impact is one of the active failure mechanisms of sandwich structures, which is important for the structural integrity assessment of sandwich structures. The objective of this work is to investigate the low-velocity impact response of metal foam core sandwich beams incorporating local denting effect. Analytical and numerical solutions are obtained for the structural response of fully clamped sandwich beams struck by a heavy mass with low velocity. The effects of local denting and foam core strength on the overall deformation of the sandwich beams are considered in theoretical analysis. Comparisons of the analytical and numerical results are presented and good agreement is achieved between the predictions and numerical results. It is seen that the load-carrying capacity of sandwich structures may be overestimated if the effect of local denting is neglected in theoretical analysis.

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ABSTRACT: This paper presents a semi-analytical approach to investigate the nonlinear dynamic of imperfect eccentrically stiffened functionally graded doubly curved thin shallow shells taking into account the damping subjected to mechanical loads. The functionally graded shallow shells are simply supported at edges and are reinforced by transversal and longitudinal stiffeners on internal or external surface. The formulation is based on the classical
thin shell theory with the geometrical nonlinearity in von Karman–Donnell sense and the smeared stiffeners technique. By Galerkin method, the equations of motion of eccentrically stiffened imperfect functionally graded shallow shells are derived. Dynamic responses are obtained by solving the equation of motion by the Runge–Kutta method. The nonlinear critical dynamic buckling loads are found according to the Budiansky–Roth criterion. Results of dynamic analysis show the effect of stiffeners, damping, pre-loaded compressions, material and geometric parameters on the dynamical behavior of these structures.

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ABSTRACT: In this work, the structural response of a doubly curved orthotropic shell is tailored to achieve tristable geometries. This is done by varying both material properties and the Gaussian curvature of the surface profile. Tristability is predicted analytically, verified with finite element analysis and, for the first time, demonstrated experimentally. Predicted geometries of the tristable states are shown to compare well with experiment.

Ali A. Yazdi (Department of Mechanical Engineering, Quchan Institute of Engineering and Technology, P.O. Box 94717-84686, Quchan, Iran), “Applicability of homotopy perturbation method to study the nonlinear vibration of doubly curved cross-ply shells”, Composite Structures, Vol. 96, pp 526-531, February 2013, https://doi.org/10.1016/j.compstruct.2012.09.040

ABSTRACT: The objective of this paper is to study nonlinear vibrations of doubly curved cross-ply shells with simply supported boundary conditions. The governing equations of the system are constructed using the von-Karman geometric nonlinear theory with Donnell’s shell equations. The Galerkin procedure is used to reduce the nonlinear partial differential equations to a nonlinearly second-order ordinary differential equation. The homotopy perturbation method (HPM) is employed to analysis the present nonlinear ordinary equation. Based on the results of this study, the first order approximation of the HPM leads to highly accurate solutions for geometrically nonlinearity vibration of doubly curved cross-ply shells. Moreover, HPM in comparison with other traditional analytical methods (e.g. perturbation methods) has excellent accuracy for the whole range of oscillation amplitude and initial conditions.

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ABSTRACT: Functionally graded materials are composite materials wherein the composition of the constituent phases can vary in a smooth continuous way with a gradation which is function of its spatial coordinates. This characteristic proves to be an important issue as it can minimize abrupt variations of the material properties which are usually responsible for localized high values of stresses, and simultaneously providing an effective thermal barrier in specific applications. In the present work, it is studied the static and free vibration behaviour of functionally graded sandwich plate type structures, using B-spline finite strip element models based on different shear deformation theories. The effective properties of functionally graded materials are estimated according to Mori–Tanaka homogenization scheme. These sandwich structures can also consider the existence of outer skins of piezoelectric materials, thus achieving them adaptive characteristics. The performance of the models, are illustrated through a set of test cases.


ABSTRACT: Geometrically nonlinear forced vibrations of thick, deep laminated circular cylindrical panels are studied via multi-modal energy approach based on Lagrange equations. It is assumed that the panel is subjected to a steady harmonic concentrated force acting in the radial direction. Simply supported movable boundary conditions are considered and the energy functional is reduced to a system of nonlinear ordinary differential equations with cubic and quadratic nonlinear terms using admissible eigenfunctions. A code based on pseudo arc-length continuation and collocation method is used to carry out a bifurcation analysis and obtain numerical solutions. Several internal resonances are detected. Direct time integration of the equations of motion has also been performed to obtain the bifurcation diagrams and Poincaré maps. It is shown that the panel exhibits complex nonlinear dynamics including quasi-periodic, intermittency and chaos in the vicinity of internal resonances. Moreover, it is illustrated that the choice of Amabili–Reddy higher-order shear deformation theory could be recommended for studying deep and thick panels.

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ABSTRACT: This study aims to use optimization to increase the design load of composite sandwich cylinders under external hydrostatic pressure. Unlike other studies that only consider buckling, this study took into account both buckling and material failure. MSC.NASTRAN was used for the finite element analysis, while a micro-genetic algorithm was used for the optimization. The finite element model was validated by comparison with the experiment results, and the result of the optimization using the finite element method was validated by comparison with the result of the feasible region analysis. Based on the optimization, as the thickness of the sandwich increases, the buckling load becomes larger than the material failure. Consequently, the optimum point is determined by material failure. The current results suggest that both the buckling and the static material failure should be considered in the design of the composite sandwich cylinder.
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ABSTRACT: The dynamic deformation modes, plateau stresses and energy absorption performance of multi-layer regularly arranged circular honeycombs are investigated numerically under the in-plane crushing loadings at the impact velocities 3–250 m/s, with aim to disclose the influences of configuration parameters and impact velocity on them. The numerical results are presented in the forms of diagrams, curves and tables. With increasing impact velocities, the double “V”-shaped (quasi-static homogeneous mode), “V”-shaped (transition mode) and “I”-shaped (dynamic mode) collapse bands are observed in turn. A simplified energy absorption model is put forward and employed to describe the energy absorption performance. It is shown that the optimal energy absorption per unit volume is related to dynamic plateau stress and dynamic densification strain and that the optimal energy absorption efficiency is the reciprocal of dynamic densification strain. From physical analysis and discussion, the empirical formulas of critical velocity of mode transition, plateau stress and dynamic densification strain are given based on the numerical results.

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ABSTRACT: We formulate in situ parameter identification techniques for multistable spring models of compressed CNT bundles, which capture the sequential buckling through the height of the bundle, as well as the overall mechanical response. The proposed techniques are validated against a SEM-assisted compression experiment on a CNT pillar [1]. Using multi-spring models, we propose a ‘microscopic’ identification technique based on the determination of stress–strain curves of vertical segments of the tested structure (featuring few micron height). We show that the in situ identified models can effectively reproduce the experimentally-observed stress–strain response (single-spring models), and strain localization effects (multi-spring model), within a simple 1D framework.

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ABSTRACT: Two multi-scale techniques will be applied in this paper to analyze buckling and wrinkling phenomena in sandwich structures. The first one is a Fourier-related analysis, where the unknowns are slowly variable Fourier coefficients of the basic fields. As shown in [19], it permits to describe the coupling between global and local buckling without describing the details of the spatial oscillations. This leads to a macroscopical model similar to Landau-Ginzburg envelope equations, but the latter is not able to account for local-global
coupling and it is accurate only near the bifurcation. Nevertheless it is sometimes difficult to associate boundary conditions with this Fourier-related approach because the assumption of a nearly periodic response of the structure is not always valid near the boundary. In [17] it has been proposed to apply the initial model near the boundary, the macroscopical model in the bulk and to relate them by the Arlequin method. In this paper, we associate the Fourier-related analysis and the Arlequin method to study the instability of sandwich structures.


ABSTRACT: Based on third-order shear deformation plate theory of Reddy, this paper presents thermoelastic response of a 2-D functionally graded open cylindrical shell (2-D FGM OCS) with temperature-dependent material properties. Taking into account temperature-dependent properties, the material properties of 2-D FGM OCS are assumed to be graded in radial and axial directions simultaneously according to a brand-new 2-D power-law distribution. Using the 2-D power-law distribution, it is possible to consider various kinds of two directional volume fraction profiles including sigmoidal radial variation as well as symmetrical or classical variation in axial direction. The non-linear steady-state heat conduction equation is solved using an iterative solution procedure along with generalized differential quadrature method (GDQM). In the mechanical analysis, the temperature field obtained from the thermal analysis is entered into the governing equations of the 2-D FGM OCS as a thermal loading. Detailed parametric studies shed new light on the influences of both various volume fraction profiles and variation of the material properties with temperature on temperature field and thermal stresses of 2-D FGM OCS. The present realistic study makes it a useful tool that will enable engineers to develop 2-D FGM OCSs with superior properties.

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ABSTRACT: This study is concerned with an actual collapse testing under the flap-wise loading for a large full-scale composite wind turbine blade, and a discussion is conducted to assess and evaluate the structural response of the blade during loading and after collapse by correlating experimental findings with numerical model predictions. A videometrics technique is adopted to measure the integral deformation and the local deformation of the wind turbine blade under the flap-wise loading. The measured results show that the displacement of the blade tip is up to 11 m at the ultimate load which is 160% of the extreme design load for the tested blade. A simple method is proposed to identify the exact failure location of the blade based on the deformation data. The thorough analysis results indicate that the aerodynamic shells debonding from the adhesive joints is the initial failure mechanism causing a progressive collapse of the blade structure.

Fuhong Dai, Hao Li and Shanyi Du (Center for Composite Materials and Structures, Harbin Institute of Technology, Harbin 150001, China), “A multi-stable lattice structure and its snap-through behavior amoung
This paper develops a multi-stable lattice structure consisting of tri-stable lattice cell which is made by bistable laminates. The multi-stable lattice structure with N tri-stable lattice cells, which can exhibit $2^N$ stable states, is successfully designed and fabricated. The critical loads snapping lattice structure are investigated by the experimental and finite element techniques. The method to simulate the behaviors of contact and constraint between the neighboring bistable laminates are presented. The snap through process of multi-stable lattice structures among multiple states are numerically simulated and experimentally validated. The multiple stabilities highlight the potential to achieve a smooth shape variation in the large area multi-stable structures.

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ABSTRACT: The paper deals with the analytical solutions on geometrical and mechanical properties of ultra-thin-walled lenticular collapsible composite tube (LCCT) in fold deformation for understanding the phenomenon of actual fold deformation and for improving the structural behaviours in engineering application. The LCCT in fold deformation was idealized as the curved thin-walled beam with a biaxially-symmetrical lenticular cross-section described by concave and convex tangential circular arcs and with a longitudinal path depicted by using multinomial shape function. New geometrical equations were established for predicting the in-plane strain of the LCCT in fold deformation (consisting of flattening and curling deformation modes) based on apt geometrical approximations and deformation assumptions, and analytical solution was derived for calculating the interlaminar shear stress on the bonding interface of the LCCT by means of equilibrium equation and linear-elastic constitutive equation founded on micromechanics. In order to validate the model, experiments were performed to determine respectively the load–displacement and in-plane strains of the ultra-thin-walled LCCT in the flattening and curling deformation modes and the comparison between the theoretical predictions and the experiments was conducted. It is shown that the predictions from the new models correlate well with the experiments within small deflection range. These efforts are argued to be successful in predicting the fold deformation of ultra-thin-walled LCCT, but limited to small deflection range only.


ABSTRACT: The investigations are concerned with a comparison of the semi-analytical method (SAM) and the finite element method (FEM) applied to the local post-buckling analysis of thin-walled composite structures with closed cross-sections, in the second order approximation based on the linear analysis. A ‘lower bound’ approach by Koiter and Pignataro [6] improved in [9], enables us to determine the overall flexural stiffness of an isotropic beam–column after its local buckling. The presented paper verifies the semi-analytical method and
the FEM for thin-walled composite structures. The theoretical basis of the present approach is discussed and some typical examples are considered.


ABSTRACT: The influences of centrifugal and Coriolis forces in combination with the other geometrical and material parameters on the free vibration behavior of rotating functionally graded (FG) truncated conical shells subjected to different boundary conditions are investigated. The initial dynamic equilibrium equations and the free vibration equations of motion around this equilibrium state and also the related boundary conditions are derived based on the first-order shear deformation theory (FSDT) of shells. The material properties are assumed to be graded in the thickness direction. The differential quadrature method (DQM) as an efficient and accurate numerical tool is adopted to discretize the governing equations and the related boundary conditions. The convergence behavior of the method is demonstrated and in the limit cases, comparison studies with the available solutions in the literature are performed. Finally, the effects of angular velocity, Coriolis acceleration, material property graded index and geometrical parameters on the frequency parameters of the rotating FG truncated conical shells with different boundary conditions are studied.


ABSTRACT: Series of impact tests were conducted to investigate the behaviour of fibre reinforced polymer (FRP) composite tubes under axial impact. The effects of damage parameters such as the mass of the impactor, incident energy and number of impacts on their behaviour were studied. The tests were performed by axially impacting 100 mm square FRP pultruded tubes to 130 repeated impacts or up to collapse using a drop-weight type impact apparatus. Impact masses and drop heights were varied to produce incident energies ranging from 158 to 635 J. The results showed that the peak load degradation of collapsed tubes is more rapid when it is impacted by higher incident energy. Heavier impactors caused more damage to the tubes at lower incident energies as reflected by their lower number of impacts to collapse, however, its effect gradually decreases at relatively higher energies. The incident energy is a major damage factor in the collapse of the tubes for lower number of impacts. However, the number of impacts becomes the key factor when the value of the incident energy decreases.

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“An analytical study of the non-linear vibrations of functionally graded cylindrical shells subjected to thermal and axial loads”, Composite Structures, Vol. 97, pp 261-268, March 2013,
ABSTRACT: An analytical method and a new simplifying model of FG (functionally graded) cylindrical shells are presented based on Hamilton’s principle, Von Kármán non-linear theory and the first-order shear deformation theory, and subjected to thermal and axial loads. The coupled non-linear partial differential vibration equations are discretized based on a series expansion of linear modes and a multiterm Galerkin’s method. Neglecting the membrane inertias and rotary inertias, the equation of motion is transformed into a reduced equation in the generalised transverse displacement. Adopting multiple scales method, the amplitude frequency dependence and the non-linear forced frequency response are obtained in the case of a single mode assumption. The good agreement found was very satisfactory, in comparison with previous theoretical approaches. The purpose of this approach was to provide engineers and designers with an easy method for determining the non-linear vibration behaviour of FG cylindrical shells.

Hui-Shen Shen (School of Ocean and Civil Engineering; State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200030, People’s Republic of China), “Boundary layer theory for the nonlinear vibration of anisotropic laminated cylindrical shells”, Composite Structures, Vol. 97, pp 338-352, March 2013, https://doi.org/10.1016/j.compstruct.2012.10.027

ABSTRACT: A boundary layer theory for the nonlinear flexural vibration of anisotropic shear deformed laminated cylindrical shells is developed. The shell may be embedded in an elastic medium that is modeled as a Pasternak elastic foundation. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. Two kinds of fiber reinforced composite (FRC) laminated cylindrical shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The motion equations are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity and including the extension-twist, extension-flexural and flexural-twist couplings. The thermal effects are also included, and the material properties of FRCs are estimated through a micromechanical model and are assumed to be temperature dependent. The equations of motion are solved by a singular perturbation technique to determine the linear and nonlinear frequencies of the FRC laminated cylindrical shells. The effects of material property gradient, the temperature change, shell geometric parameter, stacking sequence, foundation stiffness as well as the end conditions on the vibration characteristics of FRC shells are discussed in detail through a parametric study. The results show that a functionally graded reinforcement has a moderately effect on the linear and nonlinear vibration characteristics of FRC shells.

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ABSTRACT: In [1] an Equivalent Single Layer (ESL) approach resulting in an efficient and accurate prediction of the response of layered flat panels was presented and validated using experimental results. The application of this approach to curved and cylindrical shells is hereby discussed. The difficulties encountered when attempting to directly apply the Wave Finite Element (WFE) homogenization procedure to curved structures are initially described. Subsequently, an approach accounting for the curvature of the panel within the formulation of the ESL is given. The results of the presented approach for a thick sandwich cylindrical shell are compared to the results of a full three-dimensional FE modelling. The accuracy and the efficiency of the approach are eventually
ABSTRACT: The interaction between fiber kink banding and splitting in the compressive response of fiber composites is investigated by adopting a micromechanics based 2D finite element representation of the composite. The effect of scaling of the computational model (size of model) on the compressive strength and post critical response is also studied. The size of the computational model is scaled in a systematic manner by increasing the number of fibers in the model, but maintaining a fixed aspect ratio and fiber volume fraction. The response of the model changes with change in model size, and therefore, a converged model size (baseline) for predicting compressive strength is first established. Since the strains experienced within the kink band are very large, the baseline model is extended to account for splitting as a potential mode of failure by adopting a discrete cohesive zone model. A parametric study is carried out to investigate the interaction between kinking and splitting in limiting the compressive strength of the composite.

ABSTRACT: This paper investigates the vibration analysis of thick laminated composite cylindrical shells by a continuous element constructed from the dynamic stiffness matrix. Based on the analytical solutions of the differential equations of thick composite cylindrical shell taking into account the shear deflection effects, the dynamic stiffness matrix has been built from which natural frequencies are easily calculated. A computer program is developed for performing the numerical calculations and results from specific case studies are presented. Results on natural frequencies and harmonic responses of this work are compared to published analytical and Finite Element Method (FEM) results. Numerical examples demonstrate that the proposed model can be used to solve efficiently the vibration analysis of thick cross-ply composite cylindrical shell with many advantages: size of model reduced, time of computing saved, higher precision, direct acquisition of harmonic response and suitable for the analysis of medium and high frequency range.

ABSTRACT: The present paper deals with the small free vibration of functionally graded piezoelectric material (FGPM) beams with rectangular cross sections in pre/post-buckling regimes. The in-plane mechanical boundary conditions are considered to be immovable and various out-of-plane boundary conditions are considered. The Beam is assumed to be under in-plane thermal and electrical excitations. Each thermo-electro-mechanical property of the beam is graded across the thickness based on a power law model. The von-Karman type geometrical non-linearity is implemented to account the large deflection behavior of the beam under in-plane
loadings. A Ritz-based finite element formulation is developed to discrete the motion equations. The resulted system of non-linear equations is solved via the iterative Newton–Raphson scheme. Plots of frequency in terms of loading parameter reveals the existence of bifurcation or critical states in some cases. Vibration of the beam in both pre-buckling and post-buckling states are validated with the available data in the open literature. The effects of boundary conditions, beam geometry, composition rule of constituents, actuator voltage, and thermal environment are examined through the various parametric studies.

Yegao Qu, Xinhua Long, Shihao Wu and Guang Meng (State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “A unified formulation for vibration analysis of composite laminated shells of revolution including shear deformation and rotary inertia”, Composite Structures, Vol. 98, pp 169-191, April 2013, https://doi.org/10.1016/j.compstruct.2012.11.001

ABSTRACT: This paper introduces a variational formulation for predicting the free, steady-state and transient vibrations of composite laminated shells of revolution subjected to various combinations of classical and non-classical boundary conditions. A modified variational principle in conjunction with a multi-segment partitioning technique is employed to derive the formulation based on the first-order shear deformation theory. Double mixed series, i.e., Fourier series and polynomials, are used as admissible functions for each shell segment. The versatility of the formulation is illustrated through the application of four sets of polynomials, i.e., the Chebyshev orthogonal polynomials of first and second kind, the Legendre orthogonal polynomials of first kind and the ordinary power polynomials. A considerable number of numerical examples are given for the free vibrations of cross-ply and angle-ply laminated cylindrical, conical and spherical shells with various geometric and material parameters. Different combinations of free, shear-diaphragm, simply-supported, clamped and elastic-supported boundary conditions are considered. The comparisons established in a sufficiently conclusive manner show that the present formulation is capable of yielding highly accurate solutions with little computational effort. With regard to the steady-state and transient vibration analyses, laminated hemispherical and annular spherical shells subjected to different external forces are examined. Effects of structural damping, shell thickness, layer number, stacking sequence, and boundary conditions on the forced vibration responses of the composite spherical shells are also discussed. The present formulation is general in the sense that it allows to apply any linearly independent and complete polynomials as admissible functions for composite shells of revolution, and permits to analyze most of the linear vibration problems for shells having arbitrary boundary conditions and dynamic loads.


ABSTRACT: In this work, we extend a previously developed four-node quadrilateral element for laminated plates based on an efficient layerwise theory, called the zigzag theory (ZIGT), to laminated shallow shells. The accuracy of the new element is assessed for static and free vibration responses, by comparing with the available 3D elasticity solutions as well as the 2D analytical and FE solutions for various singly- and doubly-curved composite and sandwich shallow shells. The comparison with other available finite elements shows that the present element with seven degrees of freedom per node, gives by far the best performance in terms of accuracy, computational efficiency and simplicity. The results are more accurate than even the three-layer higher order layerwise theories, which have been developed specifically for sandwich shells. The equivalent single layer theories with the same or even higher number of primary variables yield extremely poor
predictions, particularly for sandwich shells.

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ABSTRACT: For the composite stiffened laminated cylindrical shells, a layerwise/solid-element (LW/SE) method was established based on the layerwise theory and the finite element method (FEM). In the present LW/SE method, the layerwise theory was used to model the behavior of the composite laminated cylindrical shells, and the eight-noded solid element is employed to discrete the stiffeners. And then, based on the governing equations of the shells and stiffeners, governing equation of the composite stiffened laminated cylindrical shells was assembled by using the compatibility conditions to ensure the compatibility of displacements at the interface between shells and stiffeners. To demonstrate the excellent predictive capability of this LW/SE method, several numerical examples were carried out to investigate the problem of static analysis and free vibration analysis for the composite stiffened laminated cylindrical shells. Good agreement had been achieved between the predictions and the results of finite element code MSC.Nastran. Furthermore, an analysis model for the composite shells structural systems reinforced by complex stiffeners, which is similar to the geometric form of the aircraft semi-monocoque fuselage structure, was developed based on the present coupling method. And the static response, natural frequencies and vibration modes were obtained.

ABSTRACT: In this paper, the performance of the active constrained layer damping (ACLD) treatment for active control of thin laminated cylindrical shells conveying fluid has been investigated. The constraining layer of the ACLD treatment has been considered to be made of vertically or obliquely reinforced 1–3 piezoelectric composite (PZC) materials. A three-dimensional finite element model has been developed for the laminated shells integrated with the patches of ACLD treatment to describe the coupled hydroelastic behavior of the shells. Velocity feedback control law has been implemented to activate the patches. Symmetric and antisymmetric cross-ply and antisymmetric angle-ply shells have been considered for evaluating the numerical results. Emphasis has also been placed on investigating the effect of the variation of the piezoelectric fiber orientation angle in the PZC constraining layer on the performance of the patches.

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ABSTRACT: In this paper, a new set of models in the framework of Carrera’s Unified Formulation (CUF) is presented for the static analysis of sandwich plates. Concerning the study of multilayered structures, it is
important to fulfill the interlaminar continuity conditions for the transverse stresses. For this aim, the CUF has been conceived by allowing to handle in a unified manner many theories that can differ by the order of expansion and the variables description in the thickness direction. This last can be Equivalent-Single-Layer (ESL), if the variables are assumed for the whole laminate, or Layer-Wise (LW), if the variables are described independently for each layer. The models considered in this work are derived from the Reissner Mixed Variational Theorem (RMVT) in order to model a priori the transverse shear and normal stresses. If sandwich plates with composite faces are considered, the transverse stresses are described as ESL in the faces and LW at sandwich level (faces + core). This procedure permits to save degrees of freedom, preserving the same accuracy of a full layer-wise description. The new formulation is implemented in the framework of finite element analysis. Comparisons are made with 3D results.


ABSTRACT: Sandwich panels with honeycomb cores are used for aerospace frames where mass efficient structures are needed; however the structural integrity of these panels is reduced by low velocity impacts. Their behaviour on impact is investigated in this paper by means of refined numerical Finite Elements simulations. The sandwich panels considered are made of a Nomex™ honeycomb core and thin Al 2024-T3 aluminium alloy skins. A highly detailed FE model (micro mechanical level) has been built by using data obtained from flatwise compressive tests of honeycomb cores and a calibration of the constitutive law and ductile failure of aluminium skins. Numerical results are compared in terms of damage shapes and failure onset with an experimental campaign, carried out using a free-fall apparatus and a spherical steel impactor. The impact phenomena, including the failure of the skin, have been reproduced by means of numerical models with an elevated grade of similarity to a real impact scenario. Discussion and perspective are reported.

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ABSTRACT: Experiments were conducted to study the effect of plate curvature on the blast response of 32 layered carbon composite panels. A shock tube apparatus was utilized to impart controlled blast loading on carbon fiber panels having three different radii of curvatures; infinite (Panel A), 305 mm (Panel B), and 112 mm (Panel C). These panels with dimensions of 203 mm × 203 mm × 2 mm were held under clamped boundary conditions during the blast loading. A 3D Digital Image Correlation (DIC) technique coupled with high speed photography was used to obtain out-of-plane deflection and velocity, as well as in-plane strains on the back face of the panels. There were two types of dominant failure mechanisms observed in all the three panels: fiber breakage and inter-layer delamination. Energy loss analysis was also performed which showed that Panel C had the best energy dissipation property. Macroscopic postmortem analysis and DIC results showed that Panel C can mitigate higher intensity blast waves without initiation of catastrophic damage in the panel. Panel B could sustain the least blast intensity and exhibited catastrophic failure. Panel A exhibited intermediate

ABSTRACT: This paper deals with the vibration and buckling behavior of exponentially graded material (EGM) sandwich plate resting on elastic foundations under various boundary conditions. New functions for midplane displacements are suggested to satisfy the different boundary conditions. The elastic foundation is modeled as Pasternak’s type which can be either isotropic or orthotropic and as a special case it converges to Winkler’s foundation if the shear layer is neglected. The present EGM sandwich plate is assumed to be made of a fully ceramic core layer sandwiched by metal/ceramic EGM coat. The governing equations of the dynamic response of non-homogeneous composite plates are deduced by using various shear deformation plate theories. Numerical results for the natural frequencies and critical buckling loads of several types of symmetric EGM sandwich plates are presented. The validity of the present solution is demonstrated by comparison with solutions available in the literature. The influences of the inhomogeneity parameter, aspect ratio, thickness ratio and the foundation parameters on the natural frequencies and critical buckling loads are investigated.


Corrigendum to “Nonlinear dynamic response of imperfect eccentrically stiffened FGM double curved shallow shells on elastic foundation” [Compos. Struct. 99 (2013) 88–96]

Composite Structures, Volume 102, August 2013, Pages 306-314

ABSTRACT: This paper presents an analytical investigation on the nonlinear dynamic response of eccentrically stiffened functionally graded double curved shallow shells resting on elastic foundations and being subjected to axial compressive load and transverse load. The formulations are based on the classical shell theory taking into account geometrical nonlinearity, initial geometrical imperfection and the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation. The non-linear equations are solved by the Runge-Kutta and Bubnov-Galerkin methods. Obtained results show effects of material and geometrical properties, elastic foundation and imperfection on the dynamical response of reinforced FGM shallow shells. Some numerical results are given and compared with ones of other authors.

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ABSTRACT: Scaling effects in the impact behaviour of foam-based sandwich structures have been investigated using an instrumented drop-weight impact tower. Four scaled sizes of sandwich panel, manufactured by
bonding a woven carbon fibre reinforced epoxy composite to a PMI (polymethacrylimide) foam core, were investigated. Low velocity impact tests on the sandwich structures resulted in a localised mode of fracture in all scale sizes at all energies. The resulting load–displacement traces were normalised by their appropriate scaling factors to highlight potential size effects in the impact response of the structures. Additional indentation tests were conducted at quasi-static and dynamic rates of loading to investigate scaling effects in the contact response of the sandwich panels. Size effects were observed in the load–displacement traces of the smaller samples following indentation tests at both quasi-static and dynamic rates of loading, most likely due to the relative size of the radius of the impactor and the weave dimensions of the composite skins. However, for all scale sizes, both the level and type of damage were similar in polished cross-sections microstructural effects do not play a significant role, simple scaling laws can be used to predict the low velocity impact response of sandwich panels of this type.

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ABSTRACT: Deformation/failure modes, blast resistance and energy absorption of metallic cylindrical sandwich shells with closed-cell aluminum foam cores were investigated in this paper. A brief of experimental result on the dynamic response of blast-loaded sandwich shells was firstly reported. Based on the experiments, corresponding finite element simulations have been undertaken by employing the LS-DYNA software. Numerical simulation results show a good agreement on the deformation/failure modes and back face-sheet center-point deflection of specimens, with those of experimental results. Results indicate that the deformation/failure, deflection response and energy absorption of sandwich shells are sensitive to the loading intensity and geometric configuration. Energy absorption capability of specimens is monotonically increasing and decreasing with the increase of impulse level and core relative density, respectively. However, it does not change monotonically with the face-sheet thickness of specimens. These simulation findings are worthy of the theoretical study and optimal design of metallic sandwich structures under air blast loading.

ABSTRACT: In this paper, the effect of a functionally graded (FG) interlayer on the non-linear stability of three-layered truncated conical shells surrounded by an elastic medium is investigated. The properties of functionally graded material (FGM) of the interlayer are assumed to be graded in the thickness direction according to a simple power law distribution. The Pasternak model is used to describe the reaction of the surrounded elastic medium on the truncated conical shell. The basic equations of the truncated conical shell with a FG interlayer resting on the Pasternak elastic foundation are derived using the Donnell shell theory with von Karman-type of kinematic non-linearity. The basic equations are solved by using Superposition and
Galerkin methods. The numerical results reveal that variations of three-layered shell characteristics, Winkler foundation stiffness, shear subgrade modulus of the foundation and the compositional profiles of the FG layer have significant influences on the non-linear critical axial load. The results are verified by comparing the obtained values with those in the existing literature.

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ABSTRACT: In this paper, a non-uniform rational B-spline based iso-geometric finite element method is used to study the static and dynamic characteristics of functionally graded material (FGM) plates. The material properties are assumed to be graded only in the thickness direction and the effective properties are computed either using the rule of mixtures or by Mori–Tanaka homogenization scheme. The plate kinematics is based on the first order shear deformation plate theory (FSDT). The shear correction factors are evaluated employing the energy equivalence principle and a simple modification to the shear correction factor is presented to alleviate shear locking. Static bending, mechanical and thermal buckling, linear free flexural vibration and supersonic flutter analysis of FGM plates are numerically studied. The accuracy of the present formulation is validated against available three-dimensional solutions. A detailed numerical study is carried out to examine the influence of the gradient index, the plate aspect ratio and the plate thickness on the global response of functionally graded material plates.

Samir A. Emam (Department of Mechanical Engineering, Faculty of Engineering, United Arab Emirates University, Al Ain, P.O. Box 17555, United Arab Emirates and Department of Mechanical Design and Production, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt), “Approximate analytical solutions for the nonlinear free vibrations of composite beams in buckling”, Composite Structures, Vol. 100, pp 186-194, June 2013, https://doi.org/10.1016/j.compstruct.2012.12.044

ABSTRACT: We present approximate analytical solutions for the nonlinear free vibrations of symmetrically or asymmetrically laminated composite beams in prebuckling and postbuckling. Simply supported and clamped–clamped boundary conditions are considered. Galerkin’s discretization is used to obtain the nonlinear ordinary differential equations governing the large-amplitude vibrations of composite beams in prebuckling and postbuckling, which are found to be of the same form. The variational method of He [20,21] is used to derive an approximate analytical solution for the nonlinear natural frequency and the nonlinear load–deflection relation. Results obtained by using the proposed analytical solution is compared with the finite element results available in the literature and a good agreement has been obtained. Numerical results to show the variation of the nonlinear natural frequency with the applied axial load for a variety of composite laminates are presented. The contribution of the amplitude of vibration on the nonlinear load–deflection response and the nonlinear natural frequency is found to be significant.
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ABSTRACT: The article presents results of experimental investigations of thin-walled columns made with carbon fibre composite. Experimental studies were conducted to confirm results obtained from numerical calculations, which was performed using finite element method and proposed analytical–numerical method. The studies consisted of axially compressed thin-walled channel section columns.

Feng-Ming Li and Guo Yao (School of Astronautics, Harbin Institute of Technology, P.O. Box 137, Harbin 150001, China), “1/3 Subharmonic resonance of a nonlinear composite laminated cylindrical shell in subsonic air flow”, Composite Structures, Vol. 100, pp 249-256, June 2013, https://doi.org/10.1016/j.compstruct.2012.12.035

ABSTRACT: The 1/3 subharmonic resonance of a composite laminated circular cylindrical shell with clamped boundary conditions at both ends in subsonic air flow under radial harmonic excitation is investigated. The equation of motion of the composite cylindrical shell is derived from the Donnell’s nonlinear shell theory and the Galerkin’s method is adopted to transform the equation of motion of the shell into a nonlinear ordinary differential equation. The 1/3 subharmonic resonance of the shell is analyzed by using the method of multiple scales and the sufficient and necessary conditions for the stability of the steady-states of the 1/3 subharmonic resonance is obtained by solving the eigenvalue problem of the linearized equations. The influences of the subsonic air flow on the 1/3 subharmonic resonance of the shell are discussed for different modes and the effects of the ply angles are analyzed for the fundamental mode. The numerical results of the threshold curves and the amplitude–frequency relations of the 1/3 subharmonic resonance are illustrated. From the results it can be seen that the existence region for the 1/3 subharmonic resonance is reduced and the amplitude of the subharmonic resonance is dropped with the flow velocity increasing. The composite shell with 45° ply angle exhibits better dynamic characteristic than that with other ply angles. The interval of the frequency ratio for the instability of the steady-state of the subharmonic resonance is broader when the ply angle is chosen as 45° than that of other ply angles for given amplitude of the external excitation.

R. Ansari, A. Shahabodini and H. Rouhi (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “A thickness-independent nonlocal shell model for describing the stability behavior of carbon nanotubes under compression”, Composite Structures, Vol. 100, pp 323-331, June 2013, https://doi.org/10.1016/j.compstruct.2013.01.005

ABSTRACT: In this article, a nonlocal Flügge shell model incorporating interatomic potentials is developed to study the buckling behavior of an axially loaded single-walled carbon nanotube (SWCNT). The theory incorporates the relations resulting from establishing a linkage between the strain energy induced in the continuum and the potential energy stored in the atomic bonds, using the so-called Cauchy–Born rule, into the constitutive relations of Eringen’s nonlocal elasticity theory. An exact solution is implemented to solve the set of coupled field equations. In comparison to classical models, the present model provides a much better fit to
molecular dynamics (MDs) simulations results and proposes the appropriate value of nonlocal parameter for SWCNTs with simply-supported end conditions. Furthermore, the model developed herein is independent of the nanotube wall thickness and Young’s modulus whose values are scattered in the literature.

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ABSTRACT: In this study, the behaviour of two different types of cores, short flax fibre reinforced and continuous flax fibre reinforced polymeric cores, is investigated under low velocity out-of-plane impact loading. The fibre-reinforced corrugations were manufactured by using matched-die compression moulding and the resulting cells were bonded using ultrasonic methods to form recyclable honeycomb cores. A drop weight impact tester, Imatek IM10T-20 ITS, capable of producing velocities up to 20 m/s coupled with a high-speed camera (Phantom), was used to capture video images of the impact. The displacement of the impactor was recorded with a digital displacement transducer and the force was recorded with a digital force transducer. The effects of reinforced material type, the core height and the presence of face sheets including all their interactions on the energy absorption are determined by using statistical analysis based on the Taguchi method. The impact results reveal a better energy absorption when honeycombs with cell walls reinforced with continuous fibres are used; the presence of face-sheets plays an important role in energy absorption only at lower core height. This is confirmed by the results of the statistical analysis revealing antagonistic interaction between the core height and face sheets.


ABSTRACT: In this paper, the pyramidal truss core sandwich structures consisting of carbon fiber reinforced polymer (CFRP) facesheets and aluminum alloy cores were manufactured based on the slot-fitting method. This hybrid concept is to maximize the specific bending stiffness/strength as well as obtain excellent energy absorption ability. Quasi-static compression tests were conducted to get the stress–strain curves and to evaluate the energy absorption mechanism. Low velocity impact tests were carried out to investigate the damage resistance of such structures. The compressive measurements show that the low density aluminum alloy pyramidal truss cores have superior energy absorption ability compared with other lightweight lattice cores. In the impact tests, the failure of matrix cracking, fiber breakage, delamination of CFRP facesheets and buckling of truss members occurred and the extent of damage was significantly affected by the impact site. In addition to experimental testing, finite element models for compression and impact simulations have been developed using ABAQUS software. The numerical results were validated compared with the experimental tests.

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ABSTRACT: This paper presents quasi-static crushing performance of empty and polyurethane foam-filled E-glass/vinylester composite tubes with different geometrical characteristics to use in sacrificial cladding structures. Some empty and foam-filled tubes were compressed laterally between two rigid plates. The effects of polyurethane foam-filler on the crushing characteristics and the corresponding energy absorption by the composite tubes are investigated. Composite tubes with three different fiber fabric layers were considered to study the influence of polyurethane foam on the crushing performance. Also, effects of different geometrical characteristics on energy absorption by different tubes are studied. Experimental results show that the presence of polyurethane foam inside the composite tubes suppresses the circumferential delimitation process and fiber fracturing; consequently, it increases the specific absorbed energy by the composite tubes during the flattening process. Also, it is resulted that injection of the polyurethane foam in the tubes causes the more regular deformation mode, comparing with the empty tubes. Finally, experimental results of the present work are compared with some of the previous articles that were investigated the foam-filled composite structures under the different loadings to suggest an optimized energy absorber.

Hoang Van Tung (Faculty of Civil Engineering, Hanoi Architectural University, Ha Noi, Viet Nam), “Postbuckling behavior of functionally graded cylindrical panels with tangential edge constraints and resting on elastic foundations”, Composite Structures, Vol. 100, pp 532-541, June 2013, https://doi.org/10.1016/j.compstruct.2012.12.051

ABSTRACT: This paper presents an analytical approach to investigate the effects of tangential edge constraints on the buckling and postbuckling behavior of functionally graded flat and cylindrical panels subjected to thermal, mechanical and thermomechanical loads and resting on elastic foundations. Material properties are assumed to be temperature independent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Governing equations are derived basing on the classical shell theory incorporating von Karman–Donnell type nonlinearity, initial geometrical imperfection and Pasternak type elastic foundations. Approximate solutions are assumed and Galerkin procedure are applied to obtain explicit expressions of buckling loads and load–deflection relations. The effects of in-plane edge restraint, elastic foundation, temperature and imperfection on the nonlinear response of the panels are graphically analyzed.


ABSTRACT: This paper investigates the static analysis of doubly-curved laminated composite shells and panels. A theoretical formulation of 2D Higher-order Shear Deformation Theory (HSDT) is developed. The middle surface of shells and panels is described by means of the differential geometry tool. The adopted HSDT is based on a generalized nine-parameter kinematic hypothesis suitable to represent, in a unified form, most of the displacement fields already presented in literature. A three-dimensional stress recovery procedure based on the equilibrium equations will be shown. Strains and stresses are corrected after the recovery to satisfy the top and bottom boundary conditions of the laminated composite shell or panel. The numerical problems connected
with the static analysis of doubly-curved shells and panels are solved using the Generalized Differential Quadrature (GDQ) technique. All displacements, strains and stresses are worked out and plotted through the thickness of the following six types of laminated shell structures: rectangular and annular plates, cylindrical and spherical panels as well as a catenoidal shell and an elliptic paraboloid. Several lamination schemes, loadings and boundary conditions are considered. The GDQ results are compared with those obtained in literature with semi-analytical methods and the ones computed by using the finite element method.

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https://doi.org/10.1016/j.compstruct.2013.01.018
ABSTRACT: The hierarchical trigonometric Ritz formulation (HTRF) developed in the framework of the Carrera unified formulation (CUF), for the first time, is extended to shell structures in order to cope with the free vibration response of doubly-curved anisotropic laminated composite shells. The HTRF is the outcome of the combination of advanced shell theories hierarchically generated via the CUF with the trigonometric Ritz method. It is based on so-called Ritz fundamental primary nuclei obtained by virtue of the principle of virtual displacements (PVD). The PVD is further used to derive the governing differential equations and natural boundary conditions. Donnell–Mushtari’s shallow shell-type equations are given as a particular condition. Several shell geometries accounting for thin and thick shallow cylindrical and spherical shells, deep cylindrical shells and hollow circular cylindrical shells, with cross-ply and angle-ply staking sequences are investigated. CUF-based refined shell models are assessed by comparison with the 3D elasticity solution. Convergence and accuracy of the presented formulation are examined. The effects of significant parameters such as stacking sequence, length-to-thickness ratio and radius-to-length ratio on the circular frequency parameters are discussed.

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“Equivalent analysis and failure prediction of quasi-isotropic composite sandwich cylinder with lattice core under uniaxial compression”, Composite Structures, Vol. 101, pp 180-190, July 2013,
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ABSTRACT: Sandwich cylindrical shells are the major components of aerospace structures. In this paper, an analytical investigation was carried out to examine the response of carbon fiber reinforced composite (CFRC) sandwich cylinders with lattice cores. An equivalent monocoque shell theory, was developed in this paper to predict mechanical behaviors of the quasi-isotropic sandwich cylinder, including the deformation and the multi-mode failure criterion. Five failure modes were suggested for the sandwich cylinder, including global buckling, face sheet mono-cell buckling/dimpling, face sheet local buckling, lattice rib crippling and strength failure. Using the suggested criterion, failure mode maps of the sandwich cylinder were acquired to instruct the design
of the hierarchical sandwich cylinder with five geometrical variables. The method also correctly predicted the failure modes of the tested sandwich cylinder within acceptable errors.

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ABSTRACT: The optimisation of board packages often rely on their load bearing capacity. Then it seems attractive to measure how such thin-walled structures deform using for instance kinematic field measurement techniques, and to incorporate, at least partially, the gained kinematic information within mechanical models. Digital Image Correlation (DIC) can provide a vivid description of the buckling of box panels, e.g. during box compression tests. Therefore, we propose an analytical plate model to predict the elastic post-buckling behaviour of corrugated board box panels where the kinematic boundary conditions emanate from DIC measurements. Comparing experimental and calculated strain fields on the outer liner of board panels as well as box compression force lend some confidence to the model. Further results reveal the heterogeneity of in-plane forces, bending and twisting moments the box panels have to withstand as well as strain fields in usually inaccessible regions of the panels such as the inner liner. Thereby an improvement of the structure of box panels can be envisaged.

Changcheng Du and Yinghui Li (School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu 610031, PR China), “Nonlinear resonance behavior of functionally graded cylindrical shells in thermal environments”, Composite Structures, Vol. 102, pp 164-174, August 2013, https://doi.org/10.1016/j.compstruct.2013.02.028

ABSTRACT: This paper deals with the nonlinear vibrations of functionally graded cylindrical shells in thermal environments. The equivalent properties of functionally graded materials are described as a power-law distribution in the thickness direction and are considered to be temperature-dependent. A typical case with a primary resonance excitation and a 1:2 internal resonance between two modes is analyzed. The energy approach and the Lagrangian formulation are employed to derive the reduced low-dimensional nonlinear ordinary differential equations of motion based on Donnell’s nonlinear shell theory. The dynamic behaviors of system are investigated by means of the so-called multiple scale method. The amplitude–frequency curves and the bifurcation behavior of the system are analyzed using numerical continuation method. The effects of temperature and volume fractions of constituent material on the amplitude response of the system are fully discussed.


ABSTRACT: In this paper, active control and dynamic analysis of shallow doubly curved functionally graded material (FGM) panels integrated with sensor/actuator piezoelectric layers are presented, analytically. Properties of the FGM panel are dictated using a simple power law model across the thickness. Based on the
modified Sander’s shell theory combined with first order shear deformation theory, total potential energy of the system is derived. Five mechanical equilibrium equations and two electrical equations are established as the governing equations. The classical negative velocity feedback controller rule is implemented to suppress the vibration response of the panel. For both the active and passive cases, established equations are reduced into new five equations in terms of displacements and rotations. Employing the combined analytical Fourier–Laplace transformation, consistent with the panels with movable simply-supported edges, an accurate closed-form solution is resulted for response of the panel in both active and passive cases in real time domain.

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ABSTRACT: Thermal buckling and postbuckling behavior are presented for fiber reinforced composite (FRC) laminated cylindrical shells embedded in a large outer elastic medium and subjected to a uniform temperature rise. The surrounding elastic medium is modeled as a Pasternak foundation. Two kinds of fiber reinforced composite laminated shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The governing equations are based on a higher order shear deformation shell theory that includes shell-foundation interaction. The thermal effects are also included, and the material properties of FRC laminated cylindrical shells are estimated through a micromechanical model and are assumed to be temperature dependent. Numerical illustrations are carried out for perfect and imperfect, UD and FG fiber reinforced metal matrix composite laminated cylindrical shells with different values of shell parameters and stacking sequence. The numerical results show that the buckling temperature as well as thermal postbuckling strength of the FRC shells can be increased as a result of functionally graded fiber reinforcements. The results reveal that the thermal postbuckling equilibrium path of the FRC shells with metal matrix may be stable or weakly unstable due to the different values of shell parameter and stacking sequence.


ABSTRACT: Thin walled tubes are often used as impact absorbing elements in automobiles and other transport vehicles. Round cylindrical and conical shells made of composite material prove to be popular energy absorber as they provide reasonably constant operating force, which is the primary characteristics of an ideal absorber. Based on experimental observations, a theoretical procedure is established to predict the post collapse load-compression characteristics of the composite shells. Analytical expressions were obtained to predict the average crush load and the crush length in a crush cycle for the composite conical shells as well as for the cylindrical tubes. The results so obtained were compared with the experimental values available from the literature.

ABSTRACT: Analytical solutions of a general third-order plate theory that accounts for the power-law distribution of two materials through thickness and microstructure-dependent size effects are presented. The Navier solution technique is adopted to derive analytical solutions to simply supported rectangular plates. The modulus of elasticity and the mass density are assumed to vary only through thickness of plate and a single material length scale parameter of a modified couple stress theory captures the microstructure-dependent size effects. Examples of bending, buckling, and vibration problems are presented to show effects of the power-law distribution of two materials and the microstructure-dependent size parameter.

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ABSTRACT: Nonlinear vibration and dynamic response of simply supported piezoelectric functionally graded material (FGM) shells under combined electrical, thermal, mechanical and aerodynamic loading are studied in this paper. The material properties of the shell are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of volume fractions of the constituents. The third-order piston theory is employed to evaluate the aerodynamic pressure. The governing equations are derived using improved Donnell shell theory ignoring the shallowness of cylindrical shells and kinematic nonlinearity and the physical neutral surface concept are taken into consideration. The Galerkin method, Volmir’s assumption and the multiple time scales perturbation methods are used for the nonlinear dynamical analysis of shells to give the expression of natural frequencies, the nonlinear dynamic responses and the primary resonance phenomena. The influences of the shell geometry and piezoelectric thickness, temperature change, external constant electric voltage and aerodynamic loads on the nonlinear dynamic behavior of the piezoelectric functionally graded shells through a comprehensive parametric study are discussed in details.

References listed at the end of the paper:
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ABSTRACT: Nonlinear vibration and dynamic response of the simply supported piezoelectric functionally graded material (FGM) shells under combined electrical, thermal, mechanical and aerodynamic loading are studied in this paper. The material properties of the shell are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of volume fractions of the constituents. The third-order piston theory is employed to evaluate the aerodynamic pressure. The governing equations are derived using

improved Donnell shell theory ignoring the shallowness of cylindrical shells and kinematic nonlinearity and the physical neutral surface concept are taken into consideration. The Galerkin method, Volmir’s assumption and the multiple time scales perturbation methods are used for the nonlinear dynamical analysis of shells to give the expression of natural frequencies, the nonlinear dynamic responses and the primary resonance phenomena. The influences of the shell geometry and piezoelectric thickness, temperature change, external constant electric voltage and aerodynamic loads on the nonlinear dynamic behavior of the piezoelectric functionally graded shells through a comprehensive parametric study are discussed in details.

References listed at the end of the paper:

ABSTRACT: This paper presents a numerical and experimental investigation into the detection of defects in composite T-stiffened panels using vibration modal analysis. The analysis was performed on carbon fibre/epoxy laminate panels containing a delamination crack or porosity. Experimental testing revealed that vibrational excitation of the defective panels altered the vibration mode response, which was measured using scanning laser vibrometry. Testing showed that changes to the mode shape curvature of the lower order vibrational wave modes was the most reliable indicator of damage within the stiffened panel whereas high order modes were less sensitive to the presence of damage. This was confirmed with vibrational analysis of T-stiffened panels using finite element modelling. Modelling also revealed that damage detection using vibration mode shape curvature analysis was dependent on defect location with the technique less likely to find damage in regions of high damping such as the web.


ABSTRACT: The present paper provides a general formulation of a 2D higher-order equivalent single layer theory for free vibrations of thin and thick doubly-curved laminated composite shells and panels with different curvatures. The theoretical framework covers the dynamic analysis of shell structures by using a general displacement field based on the Carrera’s Unified Formulation (CUF), including the stretching and zig-zag effects. The order of the expansion along the thickness direction is taken as a free parameter. The starting point of the present general higher-order formulation is the proposal of a kinematic assumption, with an arbitrary number of degrees of freedom, which is suitable to represent most of the displacement field presented in literature. The main aim of this work is to determine the explicit fundamental operators that can be used not only for the Equivalent Single Layer (ESL) approach, but also for the Layer Wise (LW) approach. Such fundamental operators, expressed in the orthogonal curvilinear co-ordinate system, are obtained for the first time by the authors. The 2D free vibration shell problems are numerically solved using the Generalized Differential Quadrature (GDQ) and Generalized Integral Quadrature (GIQ) techniques. GDQ results are compared with recent papers in the literature and commercial codes.

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ABSTRACT: Isogeometric analysis (IGA) can represent general double-curved geometries very well, as opposed to the classic finite element method (FEM). A composite shell is introduced for a third-order shear deformation theory (TSDT) that achieves the \( C^2 \) required continuity by the use of higher-order NURBS through a \( k \)-refinement strategy. The TSDT is therefore an approach that can be easily implemented in view of the IGA
advantages. Numerical locking is moreover avoided by the use of higher-order NURBS. Here, linear static and dynamic analyses are performed and compared with some known analytical and FEM solutions to demonstrate the efficiency of isogeometric analysis for TSDT and for the most widely used equivalent single layer theories (ESL), that is, classical laminate theory (CLT) and first order shear deformation theory (FSDT).

ABSTRACT: This work investigates the free axisymmetric vibrations of a closed spherical nano-shell using the Eringen nonlocal elasticity theory. The motion equations are properly formulated considering the hypotheses of thin shells and the solution is obtained using the classical separation of variables method. The effect of the nonlocal parameter on the natural frequencies and modal shapes are discussed in comparison to their local counterparts. This study could be useful in biomedical and bioengineering applications as well as in other fields related with the nanotechnology.

ABSTRACT: Local facesheet buckling of a curved sandwich panel subjected to external pressure pulse loading was investigated in this paper. Equations of motion for the facesheet transient deformations in the sandwich shell were derived from Lagrange’s equations of motion, and solutions using this approach compared well with FEA results from ABAQUS Standard. Both facesheet fracture during stable deformation response and local dynamic pulse buckling of facesheets were considered as possible modes of failure in the curved sandwich panel. Parametric studies indicated that local facesheets buckling is more likely to occur than facesheet fracture in thin and deep curved sandwich panels. The facesheet laminate layup can also be adjusted to improve the local buckling resistance of the curve panel.

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ABSTRACT: The free vibration analysis of functionally graded (FG) cylindrical panels with a cut-out and under thermal environment is studied using the three-dimensional Chebyshev–Ritz method. The material properties are assumed to be temperature-dependent and graded in the thickness direction. The formulation is based on the elasticity theory, which includes the effects of initial thermal stresses induced by the thermal environment. Chebyshev polynomials in conjunction with suitable boundary functions are used as admissible functions of the Ritz method. The convergence behavior of the method is demonstrated and to validate the results, comparisons are made with the available solutions for isotropic homogeneous and FG curved panels without cut-out. In addition, the solution for homogeneous panels with cut-out are compared with those
obtained via the commercial finite element package ‘ABAQUS’. Then, the effects of volume fraction index, different types of temperature distributions through the panel thickness, dimensions of the cut-out and the geometrical parameters of the panels on their free vibration behaviors are studied.

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ABSTRACT: In this work, a group of metallic aluminum foam-cored sandwich panels (AFSPs) were used as vehicle armor against blast loading. The dynamic responses of the AFSPs with various combinations of face-sheet materials were analyzed using LS-DYNA. It was found that the AFSP with an aluminum (AA2024 T3) front face and a Rolled Homogeneous Armor (RHA) steel back face (labeled T3-AF-RHA) outperformed the other panel configurations in terms of maximum back face deflection (MaxD) and areal specific energy absorption (ASEA). It was also found that boundary conditions and the standoff distance (SoD) between an explosive and a target surface both have a remarkable influence on the blast response of the AFSPs. Using artificial neural network (ANN) approximation models, multi-objective design optimization (MDO) of the T3-AF-RHA panel was performed both with and without variations in blast load intensity. The optimization results show that the two objectives of MaxD minimization and ASEA maximization conflict with each other and that the optimal designs must be identified in a Pareto sense. Moreover, the Pareto curves obtained are different for varied blast impulse levels. Consequently, it is concluded that loading variation should be considered when designing such sandwich armors to achieve more robust blast-resistant performance.

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ABSTRACT: Solution of the buckling problem for a uniformly compressed rectangular composite sandwich plate having two parallel edges simply supported, one edge clamped and the remaining edge free (the SSCF sandwich plate) is presented in the paper. A variational buckling equation is derived based on the Lagrange principle and first-order shear deformation theory (FSDT). The Kantorovich procedure is applied to reduce the original equation to a one-dimensional form. Subsequent application of the generalised Galerkin method leads to an analytical formula for the critical load which is verified by using finite-element analysis. Efficiency of the analytical formula derived is demonstrated for design cases in which constraints are imposed on the value of critical load.

ABSTRACT: This paper deals with the analysis of active damping of geometrically nonlinear vibrations of doubly curved smart sandwich shells integrated with a patch of active constrained layer damping (ACLD) treatment. The substrate sandwich shell is composed of orthotropic laminated composite faces separated by a thick flexible core. The constraining layer of the ACLD treatment is made of the vertically/obliquely reinforced 1–3 piezoelectric composites (PZCs). The constrained viscoelastic layer is modeled using the Golla–Hughes–McTavish (GHM) method in the time domain. A three dimensional finite element (FE) model has been developed to study this coupled nonlinear electro-elastic problem. The numerical results indicate that the ACLD patch significantly improves the damping characteristics of the paraboloid and hyperboloid sandwich shells with laminated cross-ply and angle-ply facings for suppressing their geometrically nonlinear vibrations. Particular emphasis has been placed on investigating the effect of the variation of piezoelectric fiber orientation angle on the performance of the ACLD treatment. Unlike the doubly curved laminated composite shells, the performance of the ACLD treatment becomes maximum for causing active damping of geometrically nonlinear vibrations of doubly curved sandwich shells with laminated composite facings if the constraining layer of the treatment is made of obliquely reinforced 1–3 PZC.


ABSTRACT: A combined experimental and numerical study is conducted to assess the effects of impact energy, impact site and core density on the compression-after-impact (CAI) strength of pyramidal truss core sandwich structures. It is found that the severity of impact damage highly depends on the impact site. The CAI tests show that the local buckling occurs for both the un-impact specimens and the specimens impacted under lower energy, while debonding is observed for the specimens impacted under higher energy. In case of the specimens impacted on the middle point of the four adjacent nodes, only a crack appears in the impact-damaged facesheet, which propagates transversely across the facesheet. It is observed that the CAI strength of specimens impacted on the middle point of four adjacent nodes drop much more than that of specimens impacted on the node, and that the specimens with higher density cores have slightly lower normalized CAI strength reduction. Moreover, it is found that the CAI strength of specimens impacted on the node decreases with the impact energy increasing. In addition to experimental tests, the numerical simulation performs well in capturing the failure modes for impact-damaged specimens under compressive load.

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ABSTRACT: The main key performance factors of honeycombs are represented by the ability to withstand through-thickness compression and to absorb energy by plastic deformation of the cell walls. The knowledge of the constituent material properties, including the sensitivity of these structures to material defects, and of the folding mechanism occurring during the crushing mode represents a basic step to perform reliable finite element
analyses able to accurately reproduce the behavior of such structures. The present paper reports a comprehensive study of the compressive response of hexagonal honeycomb structures made of phenolic resin-impregnated aramid paper (Nomex®); the compressive response is numerically investigated and compared with experimental results. A shell model of a representative single cell made of expanded Nomex has been created using the implicit ABAQUS finite element solver. Imperfections due to the manufacturing process are taken into account including material imperfections (elastic modulus variability) and geometrical defects (thickness variability). Imperfections are included in the model by defining different material and thickness properties for each element according to a pre-defined statistical distribution. The effects of imperfections on the honeycomb structure behavior are investigated. The predicted structural response, numerically obtained using different sets of imperfections, shows a good correlation with experimental results.


ABSTRACT: A generalized layerwise displacement base higher order shear deformation theory and its finite element formulation for the bending analysis of symmetric laminated and sandwich composite plates are presented. New layerwise HSDTs are presented for the first time. The proposed generalized layerwise HSDT have limited DOFs, because they are independent of the number of layers, and it accounts for non-linear and constant variation of in-plane and transverse displacement respectively through the plate thickness. Results shows that some of the new non-polynomial layerwise HSDTs, having the same or even less DOFs, are more accurate than well-known non-polynomial layerwise HSDTs available in the literature.


ABSTRACT: This paper is concerned with the transient response of fibre metal laminated (FML) shallow spherical shells with interfacial damage subjected to the unsteady temperature field. An exact displacement field which satisfies the boundary conditions on the outer and inner surfaces and stress continuity conditions at interfaces is presented. The nonlinear governing equations of motion for FML shallow spherical shells including the transverse shear deformation are established using the Hamilton’s principle. The transient temperature is determined from the heat conduction equation by using the finite difference method. The collocation point method and Newmark method are adapted to solve the governing equations of motion numerically. The present model provides an effective method for nonlinear dynamic analysis of composites laminated structures with interfacial damage subjected to transient temperature fields. In the numerical examples, the transient temperature, thermal deformation and stresses of FML shallow spherical shells are presented. The transient temperature will increase from initial value with time to a steady state. The displacements and stresses of the shell increase with time and remain unchanged when the temperature is in a steady state. And the effects of interfacial damage on the mechanical behaviours of FML shallow spherical shells are also discussed.

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ABSTRACT: This paper is concerned with the mechanical buckling load of an eccentrically stiffened truncated conical shells made of functionally graded materials and subjected to axial compressive load and external uniform pressure by analytical method. Shells are reinforced by stringers and rings. The change of spacing between stringers in the meridional direction is taken into account. Material properties of shell are graded in the thickness direction according to a volume fraction power-law distribution. The equilibrium and linearized stability equations for stiffened shells are derived based on the classical shell theory and smeared stiffeners technique. The resulting equations which they are the couple set of three variable coefficient partial differential equations in terms of displacement components are investigated by Galerkin method and the closed-form expression for determining the buckling load is obtained. The effects of stiffeners, material and dimensional parameters are analyzed in detail.


ABSTRACT: A unified and exact solution method is developed for the free vibration analysis of composite laminated cylindrical shells with general elastically restrained boundaries and arbitrary lamination schemes. Each of the shell displacements, regardless of boundary conditions, is constructed as a standard Fourier cosine series supplemented with auxiliary functions introduced to eliminate all the relevant discontinuities with the displacement and its derivatives at the edges and accelerate the convergence of series representations. Mathematically, such series expansions are capable of representing any functions (including the exact displacement solutions). Rayleigh–Ritz procedure is employed to obtain the exact solution based on the energy functions of the shell. The current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations. Several numerical examples are presented to validate the excellent accuracy and reliability of current solutions, and the effects of boundary restraining stiffnesses and lamination schemes on frequency parameters are illustrated. New results for different lamination schemes with elastically restrained edges are presented, which may serve as benchmark solutions.


ABSTRACT: Static analysis of laminated composite and sandwich shell is presented by developing a C0 finite element (FE) formulation based on higher order zigzag theory (HOZT) using Sander’s approximations. The proposed model satisfies the inter-laminar shear stress continuity at the interfaces; and zero transverse shear stress conditions at shell top and bottom. This is the first finite element implementation of the HOZT to solve the problem of shells incorporating cross curvature effects in shells. The present HOZT predicts transverse shear stresses more accurately than FE results previously published in literature. Numerical results show that the present 2D model is very efficient in predicting the static response of laminated composite and sandwich shallow shell very close to 3D elasticity solutions.
ABSTRACT: Composite sandwich structures are widely used in the high-performance applications where weight reduction is one of the most attractive design parameters. However, structural sandwich components have low resistance to out-of-plane impact due to the thin outer composite skins and the highly deformable cores. The present paper deals with a finite element study on the impact response of sandwich panels, obtained combining phenolic resin-based glass fiber reinforced plastics as skins and phenolic resin-impregnated aramid paper honeycomb structure (Nomex) as core. The numerical analysis has been performed using the LSDYNA software enabling to account for the main sandwich failure modes occurring during impact. The honeycomb core structure and composite skins have been modeled by means of solid and shell elements respectively. The properties of the finite element model have been calibrated on a series of experimental outcomes in order to achieve numerical parameters for both composite facesheet and orthotropic honeycomb material models. The major concerns are related to damage mechanisms, influence of strain-rate effects and energy absorbing capability. The model is validated using the results from experimental impact tests performed on different initial impact conditions. Good agreement was obtained between numerical and experimental results in terms of impact damage and force–displacement trend.

ABSTRACT: A unified and exact solution method is developed for the free vibration analysis of composite laminated shallow shells with general elastic boundary conditions, a class of problem which is of practical interest and fundamental importance but rarely attempted in the literature. Under the current framework, each of the shell displacements, regardless of boundary conditions, is expanded as a standard Fourier cosine series supplemented with closed-form auxiliary functions introduced to eliminate all the relevant discontinuities with the displacement and its derivatives at the edges and accelerate the convergence of series representations. Mathematically, such series expansions are capable of representing any functions (including the exact displacement solutions). Rayleigh–Ritz procedure is employed to obtain the exact solution based on the energy functions of the shell. The current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations. The excellent accuracy and reliability of the current solutions are validated by numerical examples, and the effects of boundary restraining stiffnesses and lamination schemes on frequency parameters are illustrated. New results for various shell curvatures including spherical, cylindrical and hyperbolical paraboloidal shells with elastically restrained edges are presented, which may serve as benchmark solutions.

ABSTRACT: Compressive response and energy absorption of a composite honeycomb is studied. The base
material is a circular cell hexagonally packed thin-wall polycarbonate honeycomb. Polydimethylsiloxane (PDMS) elastomer is used as the filler material. Filled honeycomb specimens are quasi-statically loaded under controlled displacement along an inplane direction. Synergistic energy absorption in the filled specimen is observed, as its load response is much greater than the sum of the individual load responses of unfilled honeycomb and the filler material, respectively. Analysis of the crush response is conducted using two methods: (a) Digital image correlation (DIC) to monitor strains and displacement fields in the sample during initial stages of loading and in the vicinity of first failure. (b) Finite element (FE) modeling of the filled honeycomb using the ABAQUS/Explicit finite element code, accounting for the hyperelastic compression response of the PDMS filler. The smeared crack approach (SCA) is implemented in the honeycomb to simulate the longitudinal tearing of the cell wall and to subsequently capture the localization failure in the model. Good agreement between experiment and analysis is reported.

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ABSTRACT: A numerical investigation was conducted into a perturbation-based analysis approach for assessing the imperfection sensitivity of composite cylindrical shells buckling under compression loading. The Single Perturbation Load Analysis (SPLA) approach was applied, which uses a single lateral load to introduce a realistic, worst-case and stimulating imperfection pattern. Finite element analysis was conducted for cylinders of both monolithic composite laminate and sandwich construction, with and without small and large cutouts. It was found that using a perturbation displacement equal to the shell thickness provides a suitable technique for estimating the reduction in buckling load caused by imperfections. Predictions of buckling knockdown factors using the SPLA approach showed advantages over the use of eigenmodes as the SPLA approach provides a clear design point and does not require experimental data for calibration. The effect of small and large cutouts was analogous to the effect of small and large perturbation loads. The location of the perturbation load influenced the buckling knockdown factors for both small and large cutouts, and worst-case locations were identified for both configurations.

References listed at the end of the paper:


ABSTRACT: The vibration and damping performances of hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face sheets were investigated in this paper. Hybrid carbon fiber composite pyramidal truss sandwich panels containing different thickness of viscoelastic layers were manufactured using a hot press molding method. Analytical models based on modal strain energy approach were developed using ABAQUS software to estimate the damping property of the hybrid sandwich structures. A set of modal tests were carried out to investigate the vibration and damping characteristics of such hybrid sandwich panels with or without viscoelastic layers. The damping loss factors of composite slender beams with different fiber orientations were tested to determine the constitutive damping properties of parent materials for such hybrid sandwich panels. The numerical simulation results showed good agreement with the experimental tests. The damping loss factors of hybrid sandwich panels increased distinctly compared with previous sandwich panels due to the viscoelastic layer embedded in the face sheets.


ABSTRACT: This paper first time presents an analytical investigation on the nonlinear postbuckling for imperfect eccentrically stiffened FGM double curved thin shallow shells on elastic foundation using a simple power-law distribution (P-FGM) in thermal environments. The formulations are based on the classical shell
theory taking into account geometrical nonlinearity, initial geometrical imperfection, temperature-dependent properties and the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation. By applying Galerkin method and using stress function, explicit relations of thermal load–deflection curves for simply supported curved eccentrically stiffened FGM shells are determined. Effects of material and geometrical properties, temperature, elastic foundation and eccentrically stiffeners on the buckling and postbuckling loading capacity of the imperfect eccentrically stiffened P-FGM double curved shallow shells in thermal environments are analyzed and discussed.

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ABSTRACT: The aerothermoelastic characteristics of the supersonic laminated cylindrical shell are analyzed, and the active flutter control of the aeroelastic structure is also investigated using the piezoelectric material. In the structural modeling, the influences of the in-plane thermal load on the transverse deformation are taken into account. The aerodynamic pressure is evaluated using the supersonic piston theory. Hamilton’s principle and the Galerkin’s method are used to establish the equation of motion. The proportional feedback and LQG control methods are applied to design the controller. The aerothermoelastic analysis for the laminated cylindrical shell is carried out using the frequency- and time-domain methods. The influences of the ply angle on the flutter and thermal buckling properties are investigated. The active flutter control effects of different controllers are compared. Numerical simulation shows that the LQG controller is more accurate and effective than the LQR and proportional feedback controllers.


ABSTRACT: Following the analytical modeling, the first experimental verification of the local buckling failure mode of anisogrid lattice structures with the system of hexagonal cells is here discussed. Such verification is based on a test-article extracted from the composite cylindrical prototype that was designed and manufactured at CIRA for a lightweight launch vehicle interstage. Therefore, the test-article consists of a curved anisogrid lattice panel (without skin) including multiple hexagonal cells (but with a limited cell periodicity) and subjected to an axial compressive load. Complementary mechanical tests on specimens of helical ribs extracted from the same prototype are conducted in order to evaluate the effective flexural stiffness (and strength) properties which are relevant in the bending mechanism. Finite-element models simulating the lattice cylindrical shell and the panel are constructed in order to corroborate the analytical buckling prediction. Finally, the axial compressive test on the panel demonstrates the buckling mode under investigation and the complete correspondence with theoretical and numerical evaluations.

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ABSTRACT: The Refined Zigzag Theory (RZT) belongs to the zigzag class of approximations for the analysis of laminated composite and sandwich structures. This paper presents the derivation of the non-linear equations of motion and consistent boundary conditions of RZT for multilayered plates. Subsequently, the equations are specialized to the linear boundary value problem of bending and the linear eigenvalue problems of free vibrations and buckling. In order to assess the accuracy of RZT, results concerning the static response, the free vibration frequencies and modal shapes, and the buckling loads of symmetric and unsymmetric sandwich plates, both simply supported and clamped and subjected to several loading conditions, are compared to the three-dimensional exact elasticity solution, high-fidelity FEM solutions, classical and zigzag theories, and accurate layer-wise models or solutions obtained in the open literature by means of other methods. The numerical investigation shows that RZT is highly accurate in predicting the static response, the natural frequencies and the buckling loads of sandwich plates without requiring any shear correction factors. In virtue of its accuracy and of the C0-continuity requirement for shape functions, RZT can be adopted to derive reliable and computationally efficient finite elements suited for large-scale analyses of sandwich structures.

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ABSTRACT: A single-wall carbon nanocone (SWCNC) is treated as a tailored graphite sheet rolled up into a seamless hollow tapered form where its two sides are connected together. As either the top radius or height increases, the difference between the potential of a SWCNC and a graphite sheet becomes increasingly smaller. A quasi-continuum approach is adopted to investigate buckling and post-buckling behaviors of the formed SWCNCS, upon bending. It is found that both the height and top radius result in a decreasing critical bending angle. Only one pit develops at the top-centre of the SWCNC, irrespective of its height, and moves towards the bottom as the bending angle continues to increase. At the stage of post-buckling, two tiny symmetrical fins arise near the bottom, accompanying a slight jump in the average strain energy.

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ABSTRACT: The dynamic response of peripherally clamped cylindrical sandwich shells with two aluminum face-sheets and an aluminum foam core has been experimentally investigated using an improved loading
technique. The resistance to impact loading is assessed by using the permanent transverse deflection at central point of back face-sheet of the sandwich shell. The comprehensive deformation and failure modes of specimens were classified and analyzed in term of face-sheets and core, and then the failure mode map of specimens was presented. Effects of impulse, face-sheet thickness, core thickness and relative density of core on the resistance to impact loading were discussed in detail. Deformation mechanism of sandwich shells subjected to projectile impact was explored based on the results of strain gauges adhered on the face-sheets. Results indicate that both the deformation/failure modes and back face-sheet deflection of sandwich shells are sensitive to impulse and their geometrical configurations, and the curved sandwich structures have an evident advantage on the resistance to deform, to the flatted sandwich panels. The experimental results have important reference value to the further study and engineering application of metallic sandwich structures.


ABSTRACT: In this paper, an analytical solution is presented for free vibration and dynamic behavior of doubly curved laminated shell consisting of a functionally graded core layer and surface attached functionally graded piezoelectric layers. Shell through-thickness kinematics is based on higher order shear deformation theory of shells, whereas a quadratic variation is assumed for electric potential. Using Hamilton’s principle and Maxwell’s equation, the governing equations of motion under mechanical loads are derived as seven highly coupled partial differential equations. Implementing Laplace transformation, doing few mathematical operations and using Laplace inverse method, time dependencies of displacement components are expressed in explicit phrases. Besides numerical results for shell natural frequencies, effects of different material properties and shell geometries on the transient response are discussed in details. In particular the influence of shell curvature on the spectra of maximax response has been studied. It is found that, these parameters play major roles on determining the time-histories of the electric potential and displacement components.

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ABSTRACT: The dynamic response of an aerospace layered structure composed of a combination of conical and cylindrical shells is hereby modeled. In the low and the mid-frequency ranges a WFEM derived ESL approach implemented within a FEM is used in order to predict the response of the shell. Furthermore, in the high frequency range the CLF of the connected subsystems are calculated using a WFEM/FEM approach. These CLF are implemented within a SEA approach in order to predict the structural response. The accuracy and robustness of the developed approaches are exhibited by comparisons to experimental measurements on a layered conical-shell-conical configuration.

A.H. Sofiyev (Department of Civil Engineering, Suleyman Demirel University, 32260 Isparta, Turkey), “The influence of non-homogeneity on the frequency-amplitude characteristics of laminated orthotropic truncated
conical shell”, Composite Structures, Vol. 107, pp 334-345, January 2014, 
https://doi.org/10.1016/j.compstruct.2013.08.002

ABSTRACT: In this study, the non-linear vibration of laminated non-homogenous orthotropic truncated conical shell is investigated. It is assumed that the Young’s moduli, shear modulus and density of the layers of the shell vary exponentially through the thickness direction. The basic equations of laminated non-homogenous orthotropic truncated conical shells are derived using the large deformation theory with von Karman–Donnell-type of kinematic non-linearity. The non-linear basic equations are reduced to the non-linear differential equation depending on the time using the superposition principle and Galerkin method. This equation is solved using semi-inverse method and is found the frequency–amplitude relationship. Finally, carrying out some computations, the effects of non-homogeneity, number and ordering of layers, and conical shell characteristics on frequency–amplitude characteristics have been studied.


ABSTRACT: Based on theory of elasticity, static analysis of a simply supported sandwich panel with functionally graded material (FGM) core subjected to thermo-mechanical mechanical load is carried out. The thermo-elastic constants of the FGM core layer are assumed to be graded in the radial direction according to the power-law of constituents while the Poisson’s ratio is assumed to be constant. Analytical solutions for the temperature, stress and displacement fields for the sandwich panel with simply-supported edges are derived by using the Fourier series expansions along the axial and circumferential direction and state-space technique along the radial direction. Accuracy and convergence of the presents approach are validated by comparing the numerical results with those found in literature. In addition, the effects of surface boundary conditions, gradient index, span angle, facing layers thickness and axial length to mid radius ratio on the behavior of the sandwich panel are studied.


ABSTRACT: The manufacture of advanced composite panels with variable fibre angles can lead to laminates with a flat profile on one side and a smooth, curved profile on the other. When modelling these laminates in two-dimensional form the flat plate assumptions may no longer accurately capture the structural behaviour. In this paper the buckling behaviour of laminates with one-dimensional fibre variations and symmetric stacking sequences is investigated. The assumptions of modelling the three-dimensional profile as a flat plate or a cylindrical panel are assessed, taking into account the effects of transverse shear deformation. The governing differential equations are solved in the strong form using the Differential Quadrature method and validated by 2D finite element models. The validity of the two modelling approaches is assessed by comparing the solutions to a 3D finite element model capturing the actual shape of the laminate. It is suggested that the buckling event of these variable angle tow, variable thickness laminates is characterised more accurately by “shell-like” than by “plate-like” behaviour. The idea of investigating the effects of two-dimensional fibre orientations with their associated doubly curved topologies is proposed.

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carried out displacement field representation are arbitrary. The development of the governing equations for the theory is a general, single scale description of the displacement field expressed in terms of arbitrary expansion functions through the thickness of the shell. The functional forms and orders for the expansion functions in the displacement field representation are arbitrary. The development of the governing equations for the theory is carried out using the general nonlinear equations of continuum mechanics referenced to the initial configuration.
within the context of general coordinate systems. The equations of motion and the lateral surface boundary conditions for the theory are derived using the method of moments over the domain of the expansion functions. The (arbitrary) top and bottom surface boundary conditions (BCs) are satisfied exactly. The interfacial constraints (continuity of tractions and (dis) continuity of displacements) are also satisfied exactly. Delamination effects are incorporated into the theory through the use of arbitrary functions relating the displacement jumps to appropriate state variables. These functions can be changed without the need for reformulation of the governing equations. The theory is formulated in a sufficiently general fashion that any type of history-dependent material model can be used to describe the history-dependent behavior of the material composing a layer without the need to reformulate the theory. The theoretical framework is unified in the sense that any type of desired single scale shell (smear/equivalent single layer (ESL), discrete layer, or zig-zag) theory can be obtained through suitable specialization of the framework. In the case of a smeared or ESL representation the domain of the displacement representation applies across the entire thickness of the shell. To generate a zig-zag theory within the context of the proposed framework is simply a matter of carrying out the interfacial analysis appropriate to the zig-zag assumptions and substituting the resulting displacement representation into the framework and then proceeding as with a smeared/ESL theory. In the case of a discrete layer analysis the displacement representations applies across each of the individual domains. The domains may correspond to several layers, a lamina, or a sublamina. Thus, the framework represents a comprehensive approach to modeling shells. The predictions of the theory are compared with the results obtained from an exact elastic solution for the static response of a sphere and the exact elastic solution for the dynamic response of monolithic sphere. Both exact solutions are based on the assumptions of spherically symmetric boundary conditions. It is shown that the theory is capable of providing accurate predictions for the pointwise (displacement, strain, and stress) fields distributions in laminated and monolithic shells. Furthermore, it is shown that the behavior of the theory is self-convergent and thus increasing the order of the analysis always converges the predictions to the correct answer.


ABSTRACT: The longitudinal wave propagation in multiwalled carbon nanotubes is investigated using the nonlocal elasticity theory. A multiwalled rod model is proposed in the formulation. The van der Waals force is considered in the axial direction. The effect of various parameters like the radius of nanotubes, van der Waals forces and nonlocal parameters on the longitudinal wave propagation in multiwalled carbon nanotubes is discussed. It is obtained that different axial relative motion may exist in doublewalled carbon nanotubes. The present results can be useful in the design of nanoscale linear motors, oscillators and similar nanoscale electromechanical systems.

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ABSTRACT: The present paper investigates the static behavior of doubly-curved laminated composite shells and panels. A two dimensional General Higher-order Equivalent Single Layer (GHESL) approach, based on the
Carrera Unified Formulation (CUF), is proposed. The geometry description of the middle surface of shells and panels is computed by means of differential geometry tools. All structures have been solved through the generalized differential quadrature numerical methodology. A three dimensional stress recovery procedure based on the shell equilibrium equations is used to calculate through-the-thickness quantities, such as displacements components and the strain and stress tensors. Several lamination schemes, loadings and boundary conditions are considered in the worked out applications. The numerical results are compared with the ones obtained with commercial finite element codes. New profiles, concerning displacements, strains and stresses, for doubly-curved multi-layered shell structures are presented for the first time by the authors.


ABSTRACT: Layerwise plate theory of Reddy, extended for the analysis of delaminations, has served as a basis for development of enriched finite elements. The proposed model assumes layerwise linear variation of in-plane displacements and constant transverse displacement through the plate thickness. Jump discontinuities in displacement field in three orthogonal directions are incorporated using Heaviside step functions, depending on delamination position through the plate thickness. Equations of motion are derived using Hamilton’s principle. Using the proposed model laminated composite and sandwich plates were analyzed. All numerical solutions are obtained using originally coded MATLAB programs. Proposed model is verified using existing results from the literature. Results for natural frequencies, mode shapes and critical buckling loads for intact and damaged plates are compared. Effects of plate geometry, lamination scheme, degree of orthotropy and delamination size or position on dynamic characteristics of the plate are presented. Excellent agreement is obtained and a family of new results is presented as a benchmark for future investigations.


ABSTRACT: This paper presents an analytical approach to investigate the mechanical buckling load of eccentrically stiffened functionally graded truncated conical shells surrounded by elastic medium and subjected to axial compressive load and external uniform pressure. Shells are reinforced by stringers and rings in which material properties of shell and stiffeners are graded in the thickness direction according to a volume fraction power-law distribution. The elastic medium is assumed as two-parameter elastic foundation model proposed by Pasternak. The change of spacing between stringers in the meridional direction is taken into account. The equilibrium and linearized stability equations for stiffened shells are derived based on the classical shell theory and smeared stiffeners technique. The resulting equations which they are the couple set of three variable coefficient partial differential equations in terms of displacement components are investigated by Galerkin method and the closed-form expression for determining the buckling load is obtained. Four cases of stiffener arrangement are analyzed. Carrying out some computations, effects of foundation, stiffener and input factors on stability of shell have been studied. The effectiveness of FGM stiffeners in enhancing the stability of cylindrical shells comparing with homogenous stiffener is shown.

ABSTRACT: The Hierarchical Trigonometric Ritz Formulation (HTRF) has earlier been successfully developed for plates [1–4] and shells [5] using the Principle of Virtual Displacements (PVD). In this paper the HTRF is significantly extended with the help of Reissner’s Mixed Variational Theorem (RMVT) so as to deal with the free vibrations of doubly-curved anisotropic laminated composite shells. The interlaminar equilibrium of the transverse normal and shear stresses is fulfilled a priori by exploiting the use of Lagrange multipliers. The transverse normal and shear stresses thus become primary variables within the formulation and are always modeled with a Layer-Wise kinematics description. Equivalent Single Layer, Zig-Zag and Layer-Wise approaches are instead efficiently used for the displacement primary variables. Appropriate expansion orders for each displacement or stress unknown are selected depending on the required accuracy and the computational cost. Axiomatic/asymptotic shell theories are then developed by virtue of a deep study on the effectiveness of each term both in the displacements and in the transverse stresses fields. Next exact and/or accurately approximated curvature descriptions are taken into account. Cylindrical, spherical and hyperbolic paraboloidal shells are investigated. The proposed advanced quasi-3D shell models are assessed by comparison with 3D elasticity solutions.

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ABSTRACT: Currently, imperfection sensitive shell structures prone to buckling are designed according to the NASA SP-8007 guideline, from 1968, using its conservative lower bound curve. In this guideline the structural behavior of composite materials is not appropriately considered, since the imperfection sensitivity and the buckling load of shells made of such materials depend on the lay-up design. In this context a numerical investigation about the different methodologies to characterize the behavior of imperfection sensitive composite structures subjected to compressive loads up to buckling is presented in this paper. A comparative study is addressed between a new methodology, called “Single Perturbation Load Approach”, adopted by the European project DESICOS, and some classical approaches such as non-linear analyses considering geometric and thickness imperfection obtained from real measurements. An extension of the Single Perturbation Load Approach called “Multiple Perturbation Load Approach” is also introduced in this paper to investigate if one perturbation load is enough to create the worst geometrical imperfection case. The aim of this work is to validate these numerical methodologies with experimental results and point out their limitation, advantage and disadvantage, to calculate less conservative knock-down factors than the obtained with the NASA SP-8007 guideline for unstiffened composite cylinders.

ABSTRACT: In this paper, the polyurethane foam filled pyramidal lattice core sandwich panel is fabricated in order to improve the energy absorption and low velocity impact resistance. Based on the compression tests, a synergistic effect that the foam filled sandwich panels have a greater load carrying capacity compared to the sum of the unfilled specimens and the filled polyurethane block is found. Moreover, the energy absorption efficiency of foam filled sandwich panels with higher relative density (2.58% and 3.17%) lattice cores is lower than that of the unfilled specimens when the compressive strain is small, while it exhibits superior when the compressive strain arrives at about 0.25, and the superiority enlarges as the strain increase. However, the energy absorption of foam filled sandwich panels owning lower relative density (1.83%) lattice cores is inferior to that of the unfilled specimens. During the low velocity impact tests, it is found that the contact duration between the impactor and the sandwich specimens is shorter and the impact peak load has a slight increase for the foam filled specimens.

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ABSTRACT: A solution is proposed to the buckling problem formulated for a rectangular sandwich plate having all the edges fully clamped (CCCC plate) and subjected to a uniaxial compressive loading. The analysis of the out-of-plane deformation of the buckled plate is based on the equations of the first order shear deformation theory (FSDT). Galerkin method has been employed to solve the problem. Variations of the plate deflection and angles of rotation between the unloaded edges have been approximated using the solution to the bending problem for the shear deformable beam with clamped ends. The approximation of these variables between the loaded edges has been performed using trigonometry series. The solution to the problem is reduced to the calculation of the eigenvector of corresponding homogeneous system of linear equations and determination of its least component. Verification of the solution obtained has been performed using finite-element analysis.

ABSTRACT: Nonlinear dynamic behaviors of a simply supported 3D-Kagome truss core sandwich plate subjected to the transverse and the in-plane excitations are investigated in this paper. The truss core sandwich plate is equivalent to a laminated plate with three laminas according to the equivalent sandwich plate method. The governing equation of motion for the truss core sandwich plate is derived by using the von Karman type equation for the geometric nonlinearity and the Reddy’s third-order shear deformation plate theory. The nonlinear governing partial differential equation is reduced to the ordinary differential equation by applying the Galerkin’s approach. The four-dimensional averaged equation is obtained by using the method of multiple scales. The frequency–response curves are obtained under consideration of strongly coupled of two modes. The results indicate that there are the hardening and softening nonlinearities in the truss core sandwich plate under the specific resonant case. The influences of the amplitudes for the in-plane and transverse excitations on the frequency–response curves are investigated. The results of numerical simulations for the two-degree-of-freedom
nonlinear equation exhibit the existence of the period, multi-period and chaotic responses with the variation of the excitations, which demonstrate that those motions appear alternately.

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ABSTRACT: The parametric instability regions of laminated composite plate and cylindrical shells subjected to non-uniform in-plane axial end-loadings are studied. The static as well as varying parts of the end-loading assumed to vary according to parabolic distribution in the width of the panel. The dynamic instability of panels has been investigated by using a developed finite strip method (FSM). The problem has been formulated on the basis of principle of virtual work. The effects of loading distribution as well as boundary conditions and static loading on the instability regions of load frequency are studied by applying Bolotin’s first order approximation. In order to demonstrate the capabilities of the developed formulations and methods in predicting the structural parametric dynamic behavior, some representative results are obtained and compared with those in the literature wherever available.

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ABSTRACT: The postbuckling response and the collapse of composite specimens with a co-cured hat stringer are investigated experimentally. The specimens are designed to evaluate the postbuckling response and the effect of an embedded defect on the collapse load and the mode of failure. Tests were performed using controlled conditions and instrumentation that included pre-test ultrasonic inspections and measurement of initial geometric imperfections, strain and displacement measurement through strain gauges, LVDTs and three-dimensional digital image correlation system, as well as high-speed video cameras. The test results reveal that minor imperfections due to manufacturing and residual thermal strains can result in large differences in the postbuckling responses. In addition, an embedded delamination can cause a reduction of the collapse load of about 17% for a 20-mm Teflon insert and about 28% for a 40-mm Teflon insert. Using a high speed camera, it was also observed that the collapse initiates as a skin/stringer delamination, which induces an immediate crippling of the stringer. The results obtained with these inexpensive-to-manufacture panels indicate that these test specimens can be useful for the evaluation of damage tolerance of postbuckled structures and could therefore fill the gap between test coupons and multi-stringer panels in the building block approach to the design and certification of aerospace structures.

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ABSTRACT: The first order shear deformation theory (FSDT) is used to present the buckling and initial post-buckling characteristics of symmetrically cross-ply laminated plates. In the buckling phase the Von-Karman’s equilibrium equation is solved exactly for the FS DT to obtain out-of-plane mode shapes and critical loads. The current post-buckling study is effectively a single-mode analysis, which is attempted by utilizing the so-called semi-energy method. The Von-Karman’s compatibility equation is solved exactly in the post-buckling phase with the assumption that the deflected form immediately after buckling is the same as that obtained for buckling. The Principle of Minimum Potential Energy is invoked to solve for the unknown coefficients in the assumed out-of-plane deflections and rotation functions.

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ABSTRACT: The quasi-static axial compression of thin-walled E-glass fibre/epoxy resin reinforced (GFRP) composite conical frusta was carried out to study the crashworthiness of conical shells. The hollow frustrated E-glass fibre reinforced polymer (GFRP) conical specimens having semi-apical angle ranging from 15° to 27° were fabricated using random ply chopped, plain woven roving cross ply [0/90], and uni-directional angle ply [±60°] oriented mats to the required dimensions by hand layup process. Quasi-static axial compression load was applied over the small end of the conical specimen with a crosshead speed of 2 mm/min using Universal Testing Machine (UTM). From the experiment results, the load deformation characteristics of thin GFRP composite conical shells were analyzed and the results were validated through finite element analysis package ABAQUS®. Further, the influence of ply orientation and the laminate wall thickness towards the energy absorbing capability of each GFRP conical specimen was studied. The buckling mode of collapse and the crushed zones of GFRP composite conical shells were also investigated to identify the collapse mechanisms involved in thin fibre/resin composite laminated conical specimens under quasi-static axial compression.

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ABSTRACT: With the introduction of composite materials to industrial aerospace applications, the research for innovative panel stiffening methods has gained significant interest. Possible candidates are grid-stiffened structures comprising of parallel and intersecting stiffeners forming regular polygonal patterns of skin fields. Since these thin-walled structures are critical to buckling, the structural stability is one of the driving criteria for
minimum weight design. The present study investigates the local skin buckling of grid-stiffened structures known as orthogrid, isogrid, diamond grid and kagome grid with a semi-analytical Ritz energy method based on sets of trigonometric shape functions. The influence of the aspect ratio (stiffener angle), curvature and material orthotropy is shown for uni- and biaxial in-plane compression and shear. A self-stiffening effect of the grid-stiffened structures due to interaction with adjacent skin fields is identified, significantly increasing the buckling resistance of such structures. The presented results and trends support preliminary design tasks and the verification of detailed finite element analyses.

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ABSTRACT: This paper describes the experimental and numerical studies carried out on delaminated fiberglass epoxy resin laminates made-up by different fabrication methods, namely by vacuum infusion and prepreg. While the tested specimens were originally intended for the assessment of buckling behavior of composite laminates of wind turbine blades, results were found valuable for the marine industry as well, because similar laminates are used for the hull shell and stiffeners. Systematic calculations were carried out to assess the effects of an embedded delamination on the buckling load, varying the size and through thickness position of the delamination. Different finite element modeling strategies were considered and validated against the experimental results. The one applying the 9 nodes MITC shell elements was found matching the experimental data despite failure modes were different for the two fabrication methods.

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ABSTRACT: Carbon fiber reinforced polymer (CFRP) composite sandwich panels with hybrid foam filled CFRP pyramidal lattice cores have been assembled from a carbon fiber braided net, 3D woven face sheets and various polymeric foams, and infused with an epoxy resin using a vacuum assisted resin transfer process. Sandwich panels with a fixed CFRP truss mass have been fabricated using a variety of closed cell polymer and syntactic foams, resulting in core densities ranging from 44–482 kg m⁻³. The through thickness and in-plane shear modulus and strength of the cores increased with increasing foam density. The use of low compressive strength foams within the core was found to result in a significant reduction in the compressive strength contributed by the CFRP trusses. X-ray tomography led to the discovery that the trusses develop an elliptical cross-section shape during pressure assisted resin transfer. The ellipticity of the truss cross-sections increased, and the lattice contribution to the core strength decreased as the foam density was reduced. Micromechanical modeling was used to investigate the relationships between the mechanical properties and volume fractions of the core materials and truss topology of the hybrid core. The specific strength and moduli of the hybrid cores lay between those of the CFRP lattices and foams used to fabricate them. However, their volumetric and
gravimetric energy absorptions significantly exceeded those of the materials from which they were fabricated. They compare favorably with other lightweight energy absorbing materials and structures.

ABSTRACT: We investigated the web crippling behaviour of pultruded GFRP sections under concentrated loading, employing four square hollow sections of different sizes. End-two-flange (ETF) and interior-two-flange (ITF) loading conditions were adopted, with specimens seated on a bearing plate. Specimens were also placed on the ground with end or interior bearing load to simulate the loading conditions of floor joist members. The observed failure initiated at web–flange junctions and was followed by buckling or crushing in the webs, and these modes were quite different from metallic sections. Correspondingly, two load limits were defined according to the progressive failure process. The effects of the loading positions (end loading or interior loading) as well as the supporting conditions (on a bearing plate or on the ground) on the web crippling behaviour are discussed. An effective web area in the pultrusion direction is identified to characterize the load transfer path within the web. Finally, a simple mechanism based design equation is proposed to estimate the strength of such pultruded GFRP sections subjected to web crippling.

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ABSTRACT: The effect of moisture concentration and the thermal gradient on the free flexural vibration and buckling of laminated composite plates are investigated. The effect of a centrally located cutout on the global response is also studied. The analysis is carried out within the framework of the extended finite element method. A Heaviside function is used to capture the jump in the displacement and an enriched shear flexible 4-noded quadrilateral element is used for the spatial discretization. The formulation takes into account the transverse shear deformation and accounts for the lamina material properties at elevated moisture concentrations and temperature. The influence of the plate geometry, the geometry of the cutout, the moisture concentration, the thermal gradient and the boundary conditions on the free flexural vibration is numerically studied.

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ABSTRACT: The three-dimensional (3D) free vibration of laminated cylindrical panels with finite length and functionally graded (FG) layers is presented. The cylindrical panels with two opposite axial edges simply supported and arbitrary boundary conditions at the curved edges can be analyzed via the present approach. The
material properties vary continuously through the layers thickness. In order to accurately model the variation of the displacement components through the panel thickness, a layerwise-differential quadrature method (LW-DQM) is employed in this direction. Also, the in-plane variations of the displacement components are approximated using the trigonometric series in the circumferential direction and the DQM in the axial direction. The fast rate of convergence and accuracy of the method are demonstrated through different examples. As applications of the present approach, the free vibration of two common types of sandwich cylindrical panels, i.e. sandwich panels with FG face sheets and ceramic core and sandwich panels with FG core and ceramic/metal face sheets, and also bi-layered FG cylindrical panels are studied. The effects of geometrical and material parameters together with the boundary conditions on the frequency parameters of these types of panels are investigated.

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ABSTRACT: An efficient Smoothed Particle Hydrodynamics method is developed in this paper for bending and buckling analysis of laminated composite plates and shells. The governing differential equations of thin structures is based on the First-order Shear Deformation Theory considering the geometrically nonlinear behavior. The Total Lagrangian Formulation is employed to avoid tensile instabilities, which represents one of the major defects of the original SPH method. Another drawback called boundary deficiency is alleviated by developing a Corrective Smoothed Particle Method, which combines with the Taylor series expansion. In order to demonstrate the effectiveness of the present shell-based SPH method, several numerical applications involving geometrically nonlinear behavior are carried out using the explicit dynamics scheme for the time integration. The results are compared with reference solutions and Finite Element results obtained using ABAQUS© commercial software. It has been shown, through the numerical applications that the shell-based SPH method using only one layer of particles is suitable for the study of laminated composite structures undergoing large transformations and therefore may constitute a good alternative to the FE method.


ABSTRACT: Nonlinear forced vibrations of water-filled, laminated circular cylindrical shells are studied by using the Amabili–Reddy nonlinear higher-order shear deformation theory and energy approach in the Lagrangian description. The fluid is modeled by potential flow. It is assumed that the shell is subjected to a steady harmonic concentrated force acting in the radial direction. Pseudo arc-length continuation and collocation technique is used to carry out bifurcation analysis and to obtain nonlinear frequency–amplitude responses. Direct time integration of the equations of motion has also been performed by using Gear’s backward differentiation formula (BDF) to obtain time histories, phase space diagrams and Poincaré maps. The effect of internal fluid and lamination angle on the frequency–amplitude response in the neighborhood of the resonance frequency, traveling wave solution and internal resonances of simply supported shells are investigated. It is shown that water-filled composite shells may exhibit complex nonlinear dynamics including a rare and intricate 1:1:1:1 internal resonance.

ABSTRACT: This paper presents a blast experiment to investigate the blast-resistance of square sandwich panels with hexagon aluminum honeycomb cores. Different heights and cell side length s for honeycomb core were considered in the experiment. The impulse loading on the panel was calculated by using the displacement history of ballistic pendulum. The interaction between the shockwave and panel, as well as the deformation/failure modes of face sheet and core, were discussed. Finite-element simulation was also conducted to investigate the dynamic response of the sandwich panel. The simulation captured most of the details of the deformation patterns. The velocity, displacement, strain history and energy absorption of the sandwich panel was analyzed.

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ABSTRACT: This paper aims to evaluate the potential use of closed-cell aluminium alloy integral-skin foams as stiffening elements for aluminium alloy thin-walled structures that are main basic components in the concept and design of automotive body parts. Foam specimens were prepared using the powder metallurgical route, inserted into empty thin-walled tubes and subjected to quasi-static and dynamic bending loading conditions. The effect of introducing foam into tubes was evaluated using the infrared thermography during the three-point bending tests. The foam-filled tubes, empty tubes and foams are compared in terms of the maximum load carrying capacity, crash energy absorption, specific energy absorption and deformation modes. Results showed that the foam filling leads due to interaction between the tube wall and foam filler, causing an increased bending response of the filled tubes which exceeds the sum of the bending response for the individual components. Their deformation mode is a combination between the modes of the individual components.

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“A method to analyze the pure bending of tubes of cylindrically anisotropic layers with arbitrary angles including 0 deg. or 90 deg.”, Composite Structures, Vol. 109, pp 57-67, March 2014, https://doi.org/10.1016/j.compstruct.2013.10.038

ABSTRACT: A method is proposed to analyze the pure bending of composite tubes made up of layers of angle 0° or 90° together with other arbitrary angles. It is found that in an earlier approach some of the parameters are singular for a few layer orientations even though the stresses and displacements are nonsingular. These singular terms cannot be simply eliminated as the conventional technique for the singular terms in the stresses in the
form of polar coordinates. Otherwise, the continuity conditions at the interface between special and ordinary layers cannot be satisfied. Therefore, the new unified coefficients as well as their nonsingular parameters are introduced and an approach is suggested which is efficient for any case. Several composite tubes are provided to illustrate the proposed method. Besides, the results by NASTRAN are employed for comparison. They are in good agreement to each other.

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ABSTRACT: In this study a numerical investigation is presented for initial buckling response of laminated composite plates and shells under the combined in-plane loading using a modified 8-ANS method. The finite element, based on a modified first-order shear deformation theory, is further improved by the combined use of assumed natural strain method. We analyze the influence of the shell element with the various location and number of enhanced membrane and shear interpolation. Using the assumed natural strain method with proper interpolation functions, the present shell element generates neither membrane nor shear locking behavior even when full integration is used in the formulation. The effect of various types of lay-ups, materials and number of layers on initial buckling response is discussed. In addition, the effect of direction of shear load on the initial buckling response is studied. The interaction curves (between in-plane compression and shear for different parameters of the laminates) are presented. The numerical results obtained are in good agreement with those reported by other researchers.


ABSTRACT: A unified modified Fourier solution based on the first order shear deformation theory is developed for the vibrations of various composite laminated structure elements of revolution with general elastic restraints including cylindrical, conical, spherical shells and annular plates. Regardless of boundary conditions, each displacement and rotation component of the structures is invariantly expressed as the superposition of a Fourier cosine series and two supplementary functions introduced to remove any potential discontinuous of the original displacements and their derivatives. On the basis of energy functional of structure elements, the exact series solutions are obtained using the Rayleigh–Ritz procedure. The accuracy and convergence of the proposed modified Fourier series solution are demonstrated by the comprehensive numerical examples. A variety of new vibration results including frequencies and mode shapes for composite laminated cylindrical, conical, spherical shells and annular plates with classical and elastic restraints as well as different geometric and material parameters are presented, which may serve as benchmark solution for future researches. The effects of the elastic restraint parameters, layout orientations, number of layers, conical angles and degrees of anisotropic on the vibration frequencies of the structures are illustrated.

ABSTRACT: In this paper, a simple yet accurate solution procedure based on the Haar wavelet discretization method (HWDM) is applied to the free vibration analysis of composite laminated cylindrical shells subjected to various boundary conditions. The Reissner–Naghdi’s shell theory is adopted to formulate the theoretical model. The initial partial differential equations (PDE) are first converted into system of ordinal differential equations by the separation of variables. Then the discretizations of governing equations and corresponding boundary conditions are implemented by means of the HWDM, which leads to a standard linear eigenvalue problem. Accuracy and reliability of the current solutions are validated by comparing the results with those available in the literature. The effects of several significant aspects including boundary conditions, length to radius ratios, lamination schemes and elastic modulus ratios on natural frequencies are discussed. The advantages of the current solutions consist in its simplicity, fast convergence, low computational cost and high accuracy.

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ABSTRACT: A single-walled carbon nanotube (SWCNT) is treated as a tubular Bernoulli–Euler beam and the higher-order deformation gradients are involved to establish a higher-order multiscale beam model. The higher-order Cauchy–Born rule is used to calculate the deformation of bond vectors in the representative cell and the strain energy density is equivalent to the energy per unit surface area, calculated from the Brenner potential. On the basis of the classical Bernoulli–Euler beam theory, the second-order deformation gradients with respect to the axial direction are also considered. The total strain energy is expressed as an integral equation, in which all parameters are obtained by calculating the constitutive response around the circumference. The physical meaning of these parameters is discussed in detail. The global buckling of SWCNTs is studied, and the critical buckling force is obtained as the analytical formula for different boundary conditions. The critical buckling force is plotted against the tube chirality, tube radius and tube length, and it is discovered that the contribution of the higher-order terms rapidly becomes large when the tube radius or length is small enough.


ABSTRACT: In this paper, postbuckling behavior of laminated composite plates is investigated using NURBS-based isogeometric analysis (IGA). A Green strain tensor with small rotations is proposed. Both von-Karman strain tensor and the proposed strain tensor are formulated. Governing equations are derived in the framework of first-order shear deformation theory (FSDT). Finite elements based on NURBS show the robustness in performing a laminate with intentional imperfections as well as deformed mode shapes. Quadratic NURBS elements (Q9Nurbs) are used to construct physical meshes in $C^1$ continuity. Newton–Raphson scheme is
adjusted to geometric imperfections and employed for non-linear analysis procedure. In numerical examples, the postbuckling paths of laminated composite plates in sense of von-Karman strain theory and the proposed strain theory are presented. The obtained results of isotropic, symmetric, antisymmetric angle-ply and cross-ply laminates are verified with those available in literature.

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ABSTRACT: The influence of foam infill on the blast resistivity of corrugated steel core sandwich panels was investigated experimentally using a shock tube facility and high speed photography and numerically through Finite Element Methods (FEM). After verifying the finite element model, numerical studies were conducted to investigate the effect of face sheet thickness (1, 3 and 5 mm), corrugated sheet thickness (0.2 mm, 0.6 mm and 1 mm), and boundary conditions (Simple Supported and Encastre Supported on the back sides) on blast performance. Experimental and FEM results were found to be in good agreement with $R^2$ values greater than 0.95. The greatest impact on blast performance came from the addition of foam infill, which reduced both the back-face deflections and front-face deflections by more than 50% at 3 ms after blast loading at a weight expense of only 2.3%. However, increasing face sheet thickness and corrugated sheet thickness decreased the benefit obtained from foam filling in the sandwich structure. Foam infill benefits were more prominent for Simple Supported edge case than Encastre Supported edge case.

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ABSTRACT: To develop reliable and physically based models for the crash behaviour of composite laminates, a thorough understanding of the failure mechanisms is crucial. Compression tests of corrugated Non-Crimp Fabric (NCF) laminates, made of carbon fibre unidirectional (UD) fabric with a [0/90]$_3$s stacking sequence and epoxy, have been performed to study the energy absorbing damage mechanisms. Samples from the specimens have been studied with optical microscopy and Scanning Electron Microscopy (SEM) to identify the mechanisms involved in the crushing process. The specimens tested fail partly in bending and partly in pure compression with a mode I delamination separating these two regions. In the region failing in pure compression, the main damage mechanisms are kink band formation and matrix cracking of transverse bundles, whereas in the part failing in bending mixed mode delaminations, intralaminar shear fracture of axial bundles and kink band formation through parts of bundles are identified.

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ABSTRACT: In this paper, a constitutive model is proposed for analysis of bimodular composite laminated structures. In case of already existing Bert’s model, the material properties are assigned according to the nature (tensile/compressive) of only fiber direction strain. In the proposed model, the material properties are assigned according to the nature of fiber direction and transverse to fiber direction normal strains. The proposed model is used for free vibration analysis of cylindrical and conical panels. First order shear deformation theory based finite element is employed to obtain the free vibration frequencies and through the thickness modal stress distributions. The free vibration frequencies predicted from the two models for the parameters considered are found to be very close to each other but transverse to the fiber direction normal stress distribution using both the models is significantly different.

ABSTRACT: In this paper, an analytical approach is presented to investigate the nonlinear static buckling and post-buckling for imperfect eccentrically stiffened functionally graded thin circular cylindrical shells surrounded on elastic foundation with ceramic–metal–ceramic layers (S-FGM) and subjected to axial compression. The Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation, stress function and Bubnov-Galerkin method are applied. Numerical results are given for evaluating effects of material and geometrical properties, elastic foundations and eccentrically outside stiffeners on the buckling and post-buckling of the S-FGM shells. The obtained results are validated by comparing with those in the literature.

ABSTRACT: This paper focuses on the free vibration analysis of composite laminated conical, cylindrical shells and annular plates with various boundary conditions based on the first order shear deformation theory, using the Haar wavelet discretization method. The equations of motion are derived by applying the Hamilton’s principle. The displacement and rotation fields are expressed as products of Fourier series for the circumferential direction and Haar wavelet series and their integral along the meridional direction. The constants appearing from the integrating process are determined by boundary conditions, and thus the equations of motion as well as the boundary condition equations are transformed into a set of algebraic equations. Then natural frequencies of the laminated shells are obtained by solving algebraic equations. Accuracy, stability and reliability of the current method are validated by comparing the present results with those in the literature and very good agreement is observed. Effects of some geometrical and material parameters on the natural frequencies of composite shells are discussed and some representative mode shapes are given for illustrative
purposes. Some new results for laminated shells are presented, which may serve as benchmark solutions.

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ABSTRACT: The analysis of flexural strength and free vibration of carbon nanotube reinforced composite cylindrical panels is carried out. Four types of distributions of uniaxially aligned reinforcements are considered, i.e. uniform and three kinds of functionally graded distributions of carbon nanotubes along thickness direction of the panels. Material properties of nanocomposite panels are estimated by employing an equivalent continuum model based on the Eshelby–Mori–Tanaka approach. The governing equations are developed based on the first-order shear deformation shell theory. Detailed parametric studies have been carried out to reveal the influences of volume fraction of carbon nanotubes, edge-to-radius ratio and thickness on flexural strength and free vibration responses of the panels. In addition, effects of different boundary conditions and types of distributions of carbon nanotubes are examined.

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ABSTRACT: Variable angle tow (VAT) laminates have previously shown enhanced buckling performance compared to conventional straight fibre laminates. In this study, an analytical method is developed for the buckling analysis of a novel blade stiffened VAT panel to allow this potential to be more fully exploited. The prebuckling and buckling analysis, performed on a representative section of a blade stiffened VAT panel, are based on a generalised Rayleigh–Ritz procedure. The buckling analysis includes a first order shear deformation theory by introducing additional shape functions for transverse shear and is therefore applicable to structures with thick skins relative to characteristic length. Modelling of the stiffener is achieved with two approaches; idealisation as a beam attached to the skin’s midplane and as a rigidly attached plate. Comparing results with finite element analysis (Abaqus) for selected case studies, local buckling errors for the beam model and plate model were found to be less than 3% and 2% respectively, whilst the beam model error for global buckling was between 3% and 10%. The analytical model provides an accurate alternative to the computationally expensive finite element analysis and is therefore suitable for future work on the design and optimisation of stiffened VAT panels.

References listed at the end of the paper:

ABSTRACT: A unified accurate solution procedure for free vibration analysis of arbitrary functionally graded spherical shell segments with general end restraints is presented. The material properties of the spherical shells are assumed to change continuously in the thickness direction and two different four-parameter power-law distributions are considered. The proposed method is formulated by the Ritz procedure on the basis of the first-order shear deformation shell theory. Each of admissible functions, regardless of boundary conditions, is composed of a standard Fourier cosine series and several auxiliary functions introduced to ensure and accelerate the convergence of series representations. The accuracy and reliability of the current solution are validated by comparing the results with existing results and those generated from the finite element analyses, and numerous new results for functionally graded shells subjected to elastic restraints are presented, which can serve as the benchmark solutions for other computational techniques in the future research. The effects of the boundary conditions, power-law exponents, and shell segments on the free vibrations of the spherical shells are also investigated, and some interesting insights into the parameter effects on frequency behaviors are illustrated.

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ABSTRACT: This paper investigates the large amplitude vibration behavior of nanocomposite cylindrical panels resting on elastic foundations in thermal environments. Two kinds of carbon nanotube-reinforced composite (CNTRC) panels, namely, uniformly distributed and functionally graded reinforcements, are considered. The material properties of FG-CNTRC panels are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The motion equations are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The panel-foundation interaction and thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. The equations of motion are solved by a two-step perturbation technique to determine the nonlinear frequencies of the CNTRC panels. Numerical results demonstrate that the natural frequencies of the CNTRC panels are reduced but the nonlinear to linear frequency ratios of the CNTRC panels are increased as the temperature rises. In contrast, natural frequencies are increased but the nonlinear to linear frequency ratios are decreased by increasing the foundation stiffness. The results reveal that the natural frequencies are increased by increasing the CNT volume fraction, whereas the CNTRC panels with intermediate CNT volume fraction do not necessarily have intermediate nonlinear to linear frequency ratios.

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ABSTRACT: Nonlinear free vibration and parametric resonance analysis for a geodesically-stiffened anisotropic laminated thin cylindrical shell of finite length subjected to static or periodic axial forces using the boundary layer theory is presented. The shell is embedded in an elastic medium which is modeled as a Pasternak elastic foundation. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The equations of motion are developed using the Donnel shell theory with a von Kármán-type of kinematic nonlinearity, and the shell-foundation interaction and the extension-shear, extension-flexural and flexural-twist couplings are included. A two-step perturbation technique is employed to determine the linear and nonlinear frequency and parametric resonance of the geodesically-stiffened anisotropic laminated cylindrical shells. The numerical analysis involves the nonlinear vibration behavior of laminated composite cylindrical shells with respect to the material properties and the influences of initial stress, geometric shell characteristics (i.e., radius, length and thickness, including geodesic, axial and ring stiffeners), and stacking sequence. The results reveal that the shell geometric parameters, elastic medium, and periodic axial excitation have a significant effect on the nonlinear vibration behavior of anisotropic laminated composite cylindrical shells.
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ABSTRACT: A design approach is presented for the multi-objective optimal design problem of aeroelastic laminated doubly curved shallow shells. The design objective is the maximization of weighted sum of the critical aerodynamic pressures under different probability density function of flow orientations. The design variable is the fiber orientations in the layers of the symmetrically angle-ply shells. Four typical probability density functions of flow orientations are considered. Hamilton’s principle with the first-order shear deformation theory (FSDT) is used in the flutter analysis of supersonic doubly curved shallow shells. The multi-objective optimal design problem of symmetrical alternating angle-ply sequence \([\theta/\theta/\theta/\theta]\) and symmetrical arbitrary angle-ply sequence \([\theta_1/\theta_2/\theta_3/\theta_4]\), laminated shell structure are investigated. Finally, using a layerwise optimization approach (LOA), the optimal fiber orientation angles of supersonic laminated shells are determined to obtain the maximum design objective.

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ABSTRACT: Buckling analysis of orthotropic plates with two opposite edges simply supported and the other two opposite edges rotationally-restrained (RR) and under combined uniform in-plane shear and linearly varying axial loads is presented, and its application to web local buckling of composite structural shapes is illustrated. A new plate buckled displacement shape function is proposed, and the approximate solution is obtained by the Rayleigh–Ritz method. The accuracy of analytical solution is validated with the numerical finite element analysis, and excellent agreements are achieved. A parametric study is conducted to evaluate the influence of loading ratio and rotational restraint stiffness. By introducing generic non-dimensional parameters, the buckling formulas of long plates under uniform in-plane compression, pure in-plane bending and uniform in-plane shear are obtained using the curve fitting technique. Interaction curves between the uniform in-plane shear and pure in-plane bending for the simply supported (SS) and clamped-simply supported (CS) plates are established, and it is found that the interaction curve is only related to the material orthotropic parameter of \(\beta\). Finally, the proposed discrete restrained plate solution is applied to predict the web local buckling of FRP shapes by adopting the proper rotational restraint stiffness.

Hee Chul Kim, Dong Kil Shin, Jung Ju Lee and Jun Beom Kwon (Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daehak-ro 291, Daejeon 305-701, Republic of Korea), “Crashworthiness
ABSTRACT: Crashworthiness characteristics and axial collapse with damage propagation behavior of an aluminum/CFRP hybrid square hollow section beam were investigated under dynamic axial crushing load for crash box application. The low speed impact test referred to the RCAR regulations was performed with five different lay-up sequences and two different laminate thicknesses. Both tip ends of hybrid specimen were clamped by a specially designed jig to assign a similar boundary condition with an auto-body crash test model. Each different direction of carbon fibers offers respective crashworthiness characteristics, and the characteristics from each direction were mixed when stacked together. The specific energy absorbed and crush force efficiency were improved simultaneously up to 38% and 30%, respectively in the Al/CFRP hybrid SHS beam with a [0°/90°]_n lay-up sequence, and they were slightly improved by increasing the thickness of the CFRP laminate.

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ABSTRACT: New aircraft fuselage concepts have to prove equivalent crashworthiness standards compared to conventional metallic fuselages for certification. Brittle failure mechanisms of CFRP structures make the verification of equivalent crashworthiness for novel CFRP fuselage concepts challenging since conventional metal fuselages absorb a significant part of the kinetic energy by plasticization. In this context, the damage initiation and failure of twin-walled fuselage panels were investigated under crash relevant bending–compression loads. Since the sandwich failure is initiated by core failure, a trigger concept for CFRP composite sandwich panels was developed based on local modifications in the fold pattern of the core for controlled failure initiation. By locally adjusting the collapse strength of the core in normal direction, the failure position and failure load can be adapted according to the defined kinematic hinge requirements. The core trigger concept was validated in experiments with triggered and untriggered sandwich panels under identical loading conditions.

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ABSTRACT: The dynamic characteristics of composite thin cylindrical shells are examined through a systematic order-of-magnitude analysis. The analysis is used to eliminate terms of secondary importance, while retaining the dominant terms in the dispersion relation and boundary conditions. This results in analytical expressions that can describe the vibration of composite cylindrical shells with high accuracy for a wide range of frequencies. Furthermore, the asymptotic analysis is carried out in such a way that the dynamic edge effect is accounted for when determining the vibration mode shapes and the associated internal stresses. Numerical examples are also presented. It is shown that the proposed methodology gives closed-form and analytical results that are in close agreement with numerical solutions of the equations of motion.
Erasmo Viola, Luigi Rossetti, Nicholas Fantuzzi and Francesco Tornabene (DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy), “Static analysis of functionally graded conical shells and panels using the generalized unconstrained third order theory coupled with the stress recovery”, Composite Structures, Vol. 112, pp 44-65, June 2014, https://doi.org/10.1016/j.compstruct.2014.01.039

ABSTRACT: This study focuses on the static analysis of functionally graded conical shells and panels and extends a previous formulation by the first three authors. A 2D Unconstrained Third order Shear Deformation Theory (UTSDT) is used for the evaluation of tangential and normal stresses in moderately thick functionally graded truncated conical shells and panels subjected to meridian, circumferential and normal uniform loadings. To investigate the behavior of the functionally graded structures at issue, a four parameter power law function is considered. The initial curvature effect is discussed and the role of the parameters in the power law function is shown. The conical shell problem described in terms of seven partial differential equations is solved by using the generalized differential quadrature (GDQ) method. Transverse and normal stresses are also calculated by integrating the three dimensional equations of equilibrium in the thickness direction. The stress recovery is worked out to reconstruct the correct distribution of transverse stress components. Accurate stress profiles for general loading combinations applied at the extreme surfaces are obtained. The influence of the semi vertex angle is pointed out.


ABSTRACT: This paper aims at investigating the influence of some typical manufacturing geometric imperfections on the pre-buckling behavior of transversally loaded GFRP I-beam. One dimensional mechanical approach is proposed by modelling each panel of the cross section as a Timoshenko rectangular beam. In addition to the usual displacement and rotational degrees of freedom used in conventional beam models, few extra degrees of freedom are introduced in order to account for sectional distortions. The model is based on the common assumptions of linear elasticity with small strains and moderate rotations. Two kinds of manufacturing imperfection are taken into account: minor axis out-of-straightness and web/flange planes non-orthogonality the latter representing a particular feature of the present model. Numerical analyses, developed via finite elements, show that such kind of imperfections can significantly influence the pre-buckling behavior making deformability requirements a fundamental design rule.

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ABSTRACT: This paper presents an improved finite element computational model using a flat four-node element with smoothed strains for geometrically nonlinear analysis of composite plate/shell structures. The von-
Karman’s large deflection theory and the total Lagrangian approach are employed in the formulation of the element to describe small strain geometric nonlinearity with large deformations using the first-order shear deformation theory (FSDT). The element membrane-bending and geometric stiffness matrices are evaluated by integration along the boundary of smoothing elements which can give more accurate numerical integrations even with bad shape distortions. The predictive capability of the present model is demonstrated by comparing the present results with analytical/experimental and other numerical solutions available in the literature. Numerical examples show that the present formulations can prevent loss of accuracy in distorted or coarse meshes, and therefore, are superior to those of other bilinear quadrilateral elements.


ABSTRACT: A geometrically nonlinear finite element (FE) model based on large rotation shell theory is developed for static and dynamic analysis of piezoelectric integrated thin-walled structures with cross-ply or angle-ply laminates. The implemented large rotation theory has six kinematic parameters expressed by five nodal degrees of freedom (DOFs) based on first-order shear deformation (FOSD) hypothesis. An eight-node shell element with five mechanical DOFs and one electrical DOF is employed. Due to the assumption of small strains and weak electric potential, linear constitutive equations and constant electric field through the thickness are considered. The large rotation piezoelectric coupled FE model is validated by one static benchmark problem and afterwards applied to the static and dynamic analysis of piezoelectric integrated smart plates and shells composed of cross-ply or angle-ply laminates.

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ABSTRACT: Anti-symmetric cylindrical shell as a novel bistable composite structure, offers wide applications in many fields. The entire snap-through and snap-back processes of the anti-symmetric cylindrical shell are systematically studied through experimental investigation and numerical simulation. The experimental and numerical results are also compared with the analytical predictions. The parameters used to characterize the bistable performances of the shells, including coiled-up radii, stress distributions of the shell in the second stable state, and snap load are measured. Load–displacement curves and buckling phenomena in the snapping process are successfully captured. The influences of the geometrical sizes and layup conditions on the bistable performance of anti-symmetric cylindrical shells are discussed in detail. Comprehensive experimental and numerical results indicate that the initial mid-plane transverse radius and ply angle are two key factors that affect bistable behaviors in the same environmental conditions, which is accordant with theoretical predictions, whereas the number of plies and longitudinal length of the shell only influence on the snap load and stress distribution. The angle of embrace is demonstrated of no influence on bistable performance of anti-symmetric cylindrical shells.
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ABSTRACT: This paper presents a semi-analytical procedure for solving linear vibration problems of composite laminated and sandwich hollow bodies of revolution with arbitrary combinations of boundary constraints in the framework of the three-dimensional theory of elasticity. Multilevel partitioning hierarchy, viz., multilayered body of revolution, individual layer and layer segment, is adopted in the theoretical analysis. The appropriate continuity constraints on common interfaces are imposed by means of a modified variational principle combined with the least-squares weighted residual method. The displacement field of each layer segment is characterized by a mixed series of basis functions, i.e., Fourier series and orthogonal polynomials. Numerical examples concerning the free vibrations of composite laminated and sandwich hollow cylinders, cones, and spheres, are presented to show the performance of the method, and comparisons of the present results are made with solutions available in the literature and those obtained from finite element analyses. With regard to the forced vibration problems, steady-state vibration responses of a sandwich hollow cylinder under a uniformly distributed normal harmonic pressure are analyzed, and time-domain solutions of composite laminated and sandwich hollow spheres subjected to various impulsive loads, including a rectangular pulse, a triangular pulse, a half-sine pulse and an exponential pulse, are also examined. Numerical experiments show that the present method is accurate, efficient and reliable for predicting the full spectrum of vibration behaviors of multilayered hollow bodies of revolution.

ABSTRACT: An improved structure mechanical modeling with excellent accuracy is developed for single-cell thin-walled closed-section composite beams based on previous work. Both axial warping effect and the effect of material anisotropies on the shell wall mid-surface shear strain are considered. The shear strain is calculated directly from the general constitutive law of the shell wall. Closed form expressions are obtained of one-dimensional global beam stiffness matrix. Numerical comparisons with ABAQUS simulations are performed for box and cylindrical beams with a variety of lamina layups under various loading conditions and excellent agreements are observed. The effect of material anisotropies on the shell wall mid-surface shear strain has significant influence on the accuracy of modeling. In contrast, the axial warping effect has a negligible influence in cases considered. Significant deficiency of some existing models is revealed.

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ABSTRACT: This paper presents an exact three-dimensional free vibration solution for sandwich cylindrical panels with functionally graded core. Material properties of the FGM core are assumed to be graded in the radial direction, according to a simple power-law distribution in terms of volume fractions of the constituents. Poisson’s ratio is assumed to be constant. The governing equation of motions is formulated based on the 3D-theory of elasticity and displacement fields are expanded in Fourier series along the in-plane coordinates which satisfy the simply supported edges boundary conditions. The state space technique is used to obtain natural frequencies analytically. Accuracy and convergence of the present approach are examined by comparing the analytical results with the existing values in literature. The parametric study is carried out to discuss the effects of gradient index, geometrical properties such as span angle, facing layers thickness and axial length to mid radius ratio on the frequency behavior of the sandwich panel. The obtained exact solution shows that the FGM core has significant effects on the vibration behavior of sandwich cylindrical panel. This first known exact solution serves as a benchmark for assessing the validity of numerical methods or two-dimensional theories used to analyses of sandwich cylindrical panels.


ABSTRACT: The methodology used in part 1 (Zhang and Wang, submitted for publication) of the work for single-cell thin-walled closed-section composite beams is extended to multi-cell thin-walled closed-section composite beams. The effect of material anisotropies is fully considered on the mid-surface shear strain of all the cross sectional members including skin walls and internal members. Numerical comparisons with ABAQUS finite element simulations are performed for three-cell box and elliptical beams with a variety of laminate layups under various loading conditions and excellent agreements are observed. Significant deficiency of some existing models are shown.

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ABSTRACT: The aim of this paper is to develop a modified 1D structural dynamics model for aeroelastic analysis of a composite wing under large deformations. To attain this goal, an accurate available mechanical beam model of a composite wing was considered and improved to simulate large deformation behavior. Also, in aerodynamic aspect of view, a semi-experimental unsteady aerodynamic (ONERA dynamic stall) model has been incorporated to construct the aeroelastic model. To set up a flutter determination tool based on the eigenvalue analysis, Finite Element Method (FEM) has been implemented to discretize the aeroelastic equations. Also, a finite element cross-sectional analysis code VABS (Variational Asymptotical Beam Sectional
Analysis) has been applied to determine composite cross-sectional properties across the wing span. Because of the existence of nonlinear terms in the aeroelastic equations, due to the large deformation behavior, the perturbed dynamic equations have been established about the nonlinear static equilibrium to capture the flutter boundaries. The obtained results are in good agreement with the available experimental data. It is found that the present aeroelastic model is appropriate for analysis of composite wings with arbitrary cross-sections.

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“On the influence of the magnetic field on the eigenmodes of thin laminated cylindrical shells containing magnetorheological elastomer”, Composite Structures, Vol. 113, pp 186-196, July 2014,
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ABSTRACT: Laminated cylindrical sandwich shells composed by embedding magnetorheological elastomers (MREs) between elastic layers is the subject of this investigation. Physical properties of the magnetorheological (MR) layers are assumed to be functions of the magnetic field induction and curvilinear coordinates. A system of differential equations with complex variable coefficients depending upon the magnetic field and based on both the assumptions of the generalized kinematic hypothesis for the whole sandwich and experimental data for MREs is used as the governing one. To analyze damping capabilities of adaptive materials, free vibrations of a three-layered circular cylinder containing MRE core layer are studied at different levels of the magnetic field. Using the asymptotic approach, eigenmodes of free vibrations of a laminated cylindrical shell with variable physical characteristics of MRE are constructed in the form of functions decaying far from the weakest plot on the shell structure. It has been shown that applying constant magnetic field may result in localization of eigenmodes corresponding to low-frequency spectrum of three-layered circular thin cylinder with embedded nonuniform MRE layer. Dependencies of natural frequencies, damping decrement and parameter characterizing the power of the eigenmode localization on the intensity of applied magnetic field are analyzed.

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“Application of higher-order structural theory to bending and free vibration analysis of sandwich plates with CNT reinforced composite facesheets”, Composite Structures, Vol. 113, pp 197-207, July 2014,
https://doi.org/10.1016/j.compstruct.2014.03.007

ABSTRACT: In this paper, the bending and free flexural vibration behavior of sandwich plates with carbon nanotube (CNT) reinforced facesheets are investigated using QUAD-8 shear flexible element developed based on higher-order structural theory. This theory accounts for the realistic variation of the displacements through the thickness, and the possible discontinuity in slope at the interface, and the thickness stretch affecting the transverse deflection. The in-plane and rotary inertia terms are considered in the formulation. The governing equations obtained using Lagrange’s equation of motions are solved for static and dynamic analyses considering a sandwich plate with homogeneous core and CNT reinforced face sheets. The accuracy of the present formulation is tested considering the problems for which solutions are available. A detailed numerical study is
carried out based on various higher-order models deduced from the present theory to examine the influence of the volume fraction of the CNT, core-to-face sheet thickness and the plate thickness ratio on the global/local response of different sandwich plates.

Hui-Shen Shen (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China), “Nonlinear thermal bending of FGM cylindrical panels resting on elastic foundations under heat conduction”, Composite Structures, Vol. 113, pp 216-224, July 2014, https://doi.org/10.1016/j.compstruct.2014.03.034

ABSTRACT: Nonlinear thermal bending analysis is presented for a simply supported functionally graded cylindrical panel resting on an elastic foundation. Material properties of functionally graded materials (FGMs) are assumed to be temperature-dependent, and graded in the thickness direction based on Mori–Tanaka micromechanics model. The formulations are based on a higher order shear deformation shell theory with a von Kármán-type of kinematic nonlinearity and include shell panel-foundation interaction and the thermal effects. A two-step perturbation technique is employed to determine the thermal load–deflection and thermal load-bending moment curves induced by heat conduction. The numerical illustrations concern nonlinear thermal bending response of FGM cylindrical panels with two constituent materials resting on Pasternak elastic foundations from which results for Winkler elastic foundations are obtained as a limiting case. The effects of the volume fraction index, foundation stiffness, the panel geometric parameters as well as the character of in-plane boundary conditions are also examined.

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ABSTRACT: The present paper deals with the onset of local buckling of compressively loaded thin-walled beams made of orthotropically laminated composite materials using discrete plate analysis. The analysis model focusses on the buckling of webs and flanges of composite beams with arbitrary cross-sections under uniform longitudinal compressive load. In order to account for transverse shear deformations as they are typical for moderately thick to thick laminated composite materials made of e.g. carbon fibre reinforced plastics, the present analysis is based on first-order shear deformation theory, thus employing the classical Reissner–Mindlin plate theory for the analysis of laminated composite structures. The idealisation consists of modelling the webs as being simply supported at all four edges, while at the longitudinal unloaded edges an elastic clamping is assumed which is represented by a clamping stiffness that takes material, geometry and layups of the adjacent flanges of the beams into account. Accordingly, the flanges are treated as plates with three simply supported edges and one free edge, wherein the unloaded simply supported edge is elastically clamped in order to represent the rotational support by the adjacent web. The analysis of the web and flange buckling loads is performed using the Rayleigh–Ritz-method employing specifically chosen shape functions for the out-of-plane displacements and the rotations of the cross-sections. The accuracy of the employed approaches is established by comparison with accompanying finite element simulations of actual thin-walled composite beams. It is revealed that the presented methodology is highly efficient in terms of computational effort and yet performs
with satisfying accuracy which makes it very attractive for actual practical applications whenever the local stability behaviour of composite beams is to be considered.

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ABSTRACT: In this paper, a first-known dynamic stability analysis of carbon nanotube-reinforced functionally graded (CNTR-FG) cylindrical panels under static and periodic axial force by using the mesh-free kp-Ritz method is presented. The cylindrical panels are reinforced by single-walled carbon nanotubes (SWCNTs) with different types of distributions, i.e. uniform and three kinds of functionally graded distributions of carbon nanotubes along thickness direction of the panels. Eshelby–Mori–Tanaka approach is employed to estimate effective material properties of the resulting nanocomposite panels. By applying the Ritz minimization procedure to the energy expressions, a system of Mathieu–Hill equations is formulated. Then the principal instability regions are analyzed through Bolotin’s first approximation. Detailed parametric studies have been carried out to reveal the influences of volume fraction of carbon nanotubes, edge-to-radius ratio and radius-to-thickness ratio. In addition, effects of different boundary conditions and types of distributions of carbon nanotubes are examined in detail.


ABSTRACT: Thin-walled composite deployable structures are an attractive solution for many aerospace missions, especially when large configurations are required. This paper investigates the feasibility of coiling an ultra-thin composite boom into a small deployment system. Detailed simulation of the coiling process of a C-section boom made from a two-ply laminate of carbon fiber reinforced plastic was performed using non-linear explicit dynamic analysis. A complete description of the analysis parameters that control the numerical stability of the simulation, and of the boundary conditions and loads adopted to perform the folding process are reported within this paper. The simulation is divided into two consecutive stages: the flattening of the boom, and the coiling inside the deployment device. The accuracy of the results is verified using energy balance assessments, and the structural strength of the boom is evaluated via three specific failure criteria. A parametric analysis of geometrical parameters was carried out in order to find out the slot configuration allowing the boom to fold without reaching its failure.

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ABSTRACT: In this paper, we present some advanced shell models for the analysis of multilayered structures in which the mechanical and physical properties may change in the thickness direction. The finite element method showed successful performances to approximate the solutions of the advanced structures. In this regard, two variational formulations are available to reach the stiffness matrices, the Principle of Virtual Displacement (PVD) and the Reissner Mixed Variational Theorem (RMVT). Here we introduce a strategy similar to MITC (Mixed Interpolated of Tensorial Components) approach, in the RMVT formulation, in order to construct an advanced locking-free finite element. Moreover, assuming the transverse stresses as independent variables, the continuity at the interfaces between layers is easily imposed. We show that in the RMVT context, the element exhibits both properties of convergence and robustness when comparing the numerical results with benchmark solutions from literature.


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear stability of clamped functionally graded material (FGM) shallow spherical (SS) shells and circular plates resting on elastic foundations, subjected to uniform external pressure and exposed to thermal environments. Material properties are assumed to be temperature dependent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Formulations for axisymmetrically deformed SS shells are based on the first order shear deformation theory taking geometrical nonlinearity, initial geometrical imperfection and interaction of Pasternak type elastic foundations into consideration. Approximate solutions are assumed to satisfy clamped immovable boundary conditions and Galerkin method is applied to derive expressions of buckling loads and load–deflection curves for FGM SS shells. Specialization of these expressions gives corresponding relations of FGM circular plates, and an iterative algorithm is adopted to obtain buckling temperatures and postbuckling temperature–deflection curves for thermally loaded FGM circular plates. The effects of material, geometry and foundation parameters, imperfection and temperature dependence of material properties on the nonlinear response of FGM SS shells and circular plates are analyzed and discussed in detail.

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ABSTRACT: Nanoporous materials functionalized (NMF) liquid has high energy absorption efficiency which holds great promise in advanced protective and damping devices. In this work we incorporate the NMF liquid into hollow microtruss structures to construct a superior energy absorption system. The compressive deformation map of hollow microtruss is given, and then the yielding criterion of NMF liquid filled microtruss is proposed. The quasi-static crush behavior is systematically studied through FEM simulation, then the plastic deformation of the microtruss and NMF liquid are analyzed in detail. By filling NMF liquid into the microtruss the plastic buckling of the microtruss is effectively suppressed, so as to improve the load capacity as well as energy absorption efficiency more than two times for relative thin microtruss ($t/R < 0.02$). The origin of the energy absorption enhancement comes from two parts: one is the volumetric plasticity of NMF liquid and the other part is plastic deformation enhancement of the microtruss. Furthermore, the strain hardening effect of the materials of microtruss can further improve the energy absorption of NMF liquid filled microtruss as the microtruss can hold larger infiltration pressure and reduce the plastic strain localization in the wrinkles of the microtruss to avoid the leaking of NMF liquid.


ABSTRACT: This paper focuses on the implementation of the method of sampling surfaces (SaS) for three-dimensional (3D) exact solutions of the steady-state problem of thermoelasticity for laminated composite shells. The SaS method is based on selecting inside the $n$th layer $I_n$ not equally spaced SaS parallel to the middle surface of the shell to choose temperatures and displacements of these surfaces as basic shell variables. This permits the presentation of the proposed thermoelastic shell formulation in a very compact form. The SaS are located inside each layer at Chebyshev polynomial nodes improving the convergence of the SaS method significantly. As a result, the SaS method can be applied efficiently to 3D exact solutions of thermoelasticity for laminated composite shells with a specified accuracy by using the sufficient number of SaS.

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ABSTRACT: In this paper, crushing force and energy absorption of foam-filled conical tubes with fiber reinforced layer between two metal walls under axial loading have been studied by means of an analytical method. Based on the axially crushing models, a simplified analytical solution for the static crushing of foam-filled fiber reinforced conical tubes is presented. The influences of fiber reinforced orientation, fiber layer thickness and base angle of conical tube on energy absorption capability were studied in examples. A validated finite element method was introduced to simulate the collapse of foam filled metal conical tubes and indirectly verified the feasibility of the simplified analytical model proposed in this paper.

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ABSTRACT: Buckling of composite laminates with delaminations is studied based on a proposed isogeometric layerwise approach. The isogeometric approach employs the NURBS basis functions of the geometry’s description to approximate the physical response in an isoparametric sense. Layerwise theories provide an accurate prediction of the three-dimensional structural responses of composite laminates while maintaining a two-dimensional data structure. Usually, to model the delaminations through thickness, the displacement field is enriched with a unit step Heaviside function which allows for discontinuities at the delamination interfaces. An improved implementation of a displacement-based layerwise theory based on the isogeometric paradigm is proposed. The delaminated and undelaminated regions of the laminate are modeled as separate patches. For the undelaminated and delaminated patches respectively, the C0-contintuity and discontinuity conditions of the displacement field at the ply interfaces can be easily facilitated within the isogeometric framework. More reliable and accurate buckling loads are obtained by considering a contact analysis across the delamination interfaces to avoid physically inadmissible buckling modes. The proposed model is verified using laminated composite beam plates. The results are compared to a classical layerwise approach. The numerical results confirm the accuracy of the proposed isogeometric model.


ABSTRACT: In this article, an analytical solution is presented for the size dependent nonlinear vibration behavior of micro-pipes conveying fluid made of functionally graded materials (FGMs). On the basis of the Euler–Bernoulli beam model, the strain gradient theory and von Kármán geometric nonlinearity, the mathematical formulations are developed in terms of three length scale parameters. The material properties of the functionally graded (FG) micro-pipes vary continuously across the thickness according to the power law distribution. The Hamilton’s principle is employed to obtain the differential equation of motion and the corresponding boundary conditions. Without loss of generality, simply supported pipes are considered. The governing equation is written in the form of duffing equation by using Galerkin method. Subsequently, a powerful analytical technique called the homotopy analysis method (HAM) is employed to determine the explicit expressions for nonlinear fundamental frequency for different fluid velocities and power law gradient indices. Comprehensive comparison studies between linear and nonlinear theories using the strain gradient, the couple stress and classical theories are conducted. The results show that the length scale parameter and the FG power law index have significant effect on the fundamental frequency of the FG micro-pipes and the fluid critical velocity.

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ABSTRACT: A mixed, quadrilateral, 3D plate element is proposed for static linear and buckling analysis of folded laminated composite structures. Numerical results show accuracy, comparing to analytical and numerical references, and convergence rate measured using an $s$-norm. These characteristics are due to the self-equilibrated, isostatic state of stress in the element, and to the element kinematics leading to element compliance and compatibility matrix calculations based solely on the interpolation along the element edges. For folded plates, the drilling rotations do not require penalty functions or non-symmetric formulations, thus avoiding spurious energy modes. Buckling analysis is achieved by a corotational formulation, which is possible thanks to the accuracy of rotation approximations. Benchmarking for laminated composite plates includes convergence of displacements and stress-resultants, global error measures, and comparison with literature results.

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ABSTRACT: Conventional composite materials offer high specific stiffness and strength, but suffer from low failure strains and failure without warning. This work proposes a new design for sandwich structures with symmetrically-wavy composite skins and a crushable foam core, aiming to achieve large strains (due to unfolding of the skins) and energy absorption (due to crushing of the foam core) under tensile loading. The structure is designed by a combination of analytical modelling and finite element simulations, and the concept is demonstrated experimentally. When loaded under quasi-static tension, wavy-ply sandwich specimens with carbon–epoxy skins and optimised geometry exhibited an average failure strain of 8.6%, a specific energy dissipated of 9.4 kJ/kg, and ultimate strength of 1570 MPa. The scope for further developing the wavy-ply sandwich concept and potential applications requiring large deformations and energy absorption are discussed.

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ABSTRACT: The magnetoelastic behavior of heterogeneous thick-walled cylinder with cellular material layers and enduring a dynamic and spatially varying eigenstrain is studied in this paper. The electrically conducting cylinders under plane strain or plane stress condition are subjected to a constant magnetic field. An efficient methodology is developed for the time-harmonic and transient response of multilayered cylinders. The developed methodology is then employed to model the functionally graded cellular cylinders with an arbitrary profile of the relative density distribution via the piecewise homogeneous layer technique. The results are first verified with those available in literature. Then, the effect of relative density, non-homogeneity index, and
ABSTRACT: A method for performing reliability analysis of a composite stiffened panel subjected to axial compression using the finite element method is discussed. Three-dimensional shell and brick element models are utilized for baseline response prediction, and comparison with experimental results. Owing to the multiscale nature of composite materials, microscale and macroscale design parameters are identified for the panel. The microscale parameters consist of fiber/matrix properties and the volume fraction. The macroscale parameters consist of structural dimensions, layup definition, and an imperfection scale factor. The fiber and matrix properties are estimated utilizing a micromechanics model in conjunction with an optimization method. Thereafter, parameterized finite element models are used to generate an approximation model. Utilizing the Monte Carlo method, design parameters were subject to variation and the variation in response was predicted using the approximation model along with the probability of failure measured against experimental results and baseline finite element responses.

ABSTRACT: A postbuckling analysis is presented for a functionally graded composite cylindrical shell reinforced by single-walled carbon nanotubes (SWCNTs) subjected to torsion in thermal environments. The multi-scale model for functionally graded carbon nanotube-reinforced composite (FG-CNTRC) shells under torsion is proposed. A singular perturbation technique along with a two-step perturbation approach is employed to determine the buckling load and postbuckling equilibrium path. The numerical illustrations concern the torsional buckling and postbuckling behavior of perfect and imperfect, FG-CNTRC cylindrical shells under different sets of thermal environmental conditions. The results for uniformly distributed CNTRC shell, which is a special case in the present study, are compared with those of the FG-CNTRC shell. The results show that the linear functionally graded reinforcements can increase the buckling torque as well as postbuckling strength of the shell under torsion when the reinforcement has a symmetrical distribution. The results reveal that the carbon nanotube volume fraction has a significant effect on the buckling load and postbuckling behavior of CNTRC shells under torsion.

ABSTRACT: Free vibration of laminated functionally graded (FG) spherical shells with general boundary conditions and arbitrary geometric parameters is studied in this paper. The study is based on the three-dimensional shell theory of elasticity and the energy based Rayleigh–Ritz procedure. It is assumed that the material properties of the laminated FG spherical shells vary continuously through the thickness direction.
according to power law distribution of the volume fraction of the constituents. Under the current framework, regardless of boundary conditions, each displacement variations of the laminated FG spherical shell is invariantly expanded as a modified Fourier series in which several supplementary terms are introduced to ensure and accelerate the convergence of the expansion and all the expanded coefficients are determined by the Rayleigh–Ritz procedure. The modified Fourier series results are presented and compared with the available accurate solutions to verify the validity of the current formulation. Detailed parametric investigation is carried out to examine the influences of boundary conditions, geometric parameters and material distributions on the natural frequencies of the spherical shells. Numerous vibration results for several laminated FG spherical shells with various boundary conditions are presented for different geometric parameters and power-law exponents, which may serve as benchmark solutions for future researches to evaluate the new 2-D shell theories and to compare results obtained by approximate numerical methods.

Wei Li, Guangyan Huang, Yang Bai, Yongxiang Dong and Shunshan Feng (State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China), “Dynamic response of spherical sandwich shells with metallic foam core under external air blast loading – Numerical simulation”, Composite Structures, Vol. 116, pp 612-625, September-October 2014,
https://doi.org/10.1016/j.compstruct.2014.05.038

ABSTRACT: The dynamic response of spherical sandwich shells with aluminum face sheets and aluminum foam core under external air blast loadings were investigated numerically by employing the LS-DYNA. To calibrate the numerical model, the experiments of cylindrical sandwich shells were modeled. And the numerical results have a good agreement with the experiment data. The calibrated numerical model was used to simulate the dynamic response of spherical sandwich shells subjected to the external air blast loadings. It is found that the spherical sandwich shells have a better performance than that of the cylindrical sandwich shells in resisting the blast loadings. The structural dynamic response process has been divided into three specific stages and the deformation modes have been classified and discussed systematically. According to parametric studies, it is concluded that with the decrease of radius of curvature, increase of the thickness of foam core and face sheets and decrease of blast intensity, the blast-resistance is increasing obviously; keeping the thickness summation of front and back face sheet almost constant, a big thickness of front face sheet will improve the blast-resistance performance. These simulations findings can guide well the theoretical study and optimal design of spherical sandwich structures subjected to external blast loading.

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https://doi.org/10.1016/j.compstruct.2014.05.048

ABSTRACT: Thermo-electro-mechanical vibration of piezoelectric cylindrical nanoshells is studied using the nonlocal theory and Love’s thin shell theory. The governing equations and boundary conditions are derived using Hamilton’s principle. An analytical solution is first given for the simply supported piezoelectric nanoshell by representing displacement components in the double Fourier series. Then, the differential quadrature (DQ) method is employed to obtain numerical solutions of piezoelectric nanoshells under various boundary conditions. The influence of the nonlocal parameter, temperature rise, external electric voltage, radius-to-thickness ratio and length-to-radius ratio on natural frequencies of piezoelectric nanoshells are discussed in...
detail. It is found that the nonlocal effect and thermoelectric loading have a significant effect on natural frequencies of piezoelectric nanoshells.

Francesco Tornabene, Nicholas Fantuzzi and Michele Bacciocchi (DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy), “The local GDQ method applied to general higher-order theories of doubly-curved laminated composite shells and panels: The free vibration response”, Composite Structures, Vol. 116, pp 637-660, September-October 2014, https://doi.org/10.1016/j.compstruct.2014.05.008

ABSTRACT: This paper presents a general two-dimensional approach for solving doubly-curved laminated composite shells using different kinematic expansions along the three orthogonal directions of the curvilinear shell model. The Carrera Unified Formulation (CUF) with different thickness functions along the three orthogonal curvilinear directions is applied to completely doubly-curved shells and panels, different from spherical and cylindrical shells and plates. Furthermore, the fundamental nuclei for doubly-curved structures are presented in their explicit form for the first time by the authors. These fundamental nuclei also allow to consider doubly-curved structures with variable thickness. In addition, the theoretical model includes the Murakami’s function (also known as zig-zag effect). For some problems it is useful to have an in-plane kinematic expansion which is different from the normal one. The 2D free vibration problem is numerically solved through the Local Generalized Differential Quadrature (LGDQ) method, which is an advanced version of the well-known Generalized Differential Quadrature (GDQ) method. The main advantage of the LGDQ method compared to the GDQ method is that the former can consider a large number of grid points without losing accuracy and keeping the very good stability features of GDQ method as already demonstrated in literature by the authors.

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ABSTRACT: The effects of high temperature exposure on the low velocity impact behaviors and damage mechanisms of all-composite pyramidal truss core sandwich panel after high temperature exposure”. The composite sandwich panels were manufactured from unidirectional carbon/epoxy prepreg and exposed to different temperatures for 6 h. The impact tests of exposed specimens were performed at three different energy levels, and the effects of exposure temperature and impact energy level on the damage mechanism, absorbed energy and maximum impact force were analyzed. The impact-damaged specimens were subsequently subjected to in-plane compressive tests in order to investigate the effect of exposure temperature and impact energy level on the compressive failure load. The results have shown that the high temperature exposure has a significant effect on impact properties and damage mechanisms of specimens. The fiber fracture, node failure, delamination and buckling were observed during low velocity impact tests and the extent of damage area was significantly affected by exposure temperature. In addition, the absorbed energy increased with increasing exposure temperature, while the maximum impact force and compressive failure load after impact decreased with increasing exposure temperature due to the degradation of the matrix properties and fiber–matrix interface properties at higher temperatures.

ABSTRACT: Free vibration analysis of open conical panels made of through-the-thickness functionally graded materials (FGMs) is analyzed in this research. Mechanical properties of the shell are distributed across the thickness based on the power law function. First order shear deformation theory of shells accompanied with the Donnell type of kinematic assumptions are used to establish the general motion equations and the associated boundary conditions. Considering the Lévy type of conical shells, which are simply supported on straight edges, a semi-analytical solution based on the trigonometric expansion through the circumferential direction combined with generalized differential quadrature (GDQ) discretization in meridional direction is developed. Due to the special configuration of the conical panel, free vibration of flat rectangular plates, flat annular and circular sectoral plates, and singly curved cylindrical panels may also be studied. Solution method is useful for any arbitrary type of free, clamped, and simply supported boundary conditions along the two other curved edges of the shell. After establishment of eigenvalue problem, a series of comparison studies are conducted to assure the validity and accuracy of the present solution. Afterwards, parametric studies are developed to examine the influences of boundary conditions, semi-vertex angle of the cone, subtended angle of the panel, power law index, and thickness to radius ratio. Influences of the aforementioned parameters on natural frequencies and the associated mode shapes are discussed.

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ABSTRACT: A study on the bending response of a composite curved panel with pyramidal metallic truss cores suitable for functional applications is presented using a combination of analytical modeling, three-point bending experiments and finite element (FE) based simulations. The aluminum pyramidal cores were constructed using an interlocking method before curing with composite face sheets to fabricate the final structure. A theoretical model was developed to analyze the experiments and develop failure criteria. Three failure modes: (i) face wrinkling, (ii) face crushing, and (iii) debonding between face sheet and truss cores, were considered and theoretical relationships for predicting the collapse load associated with each mode were developed. The experiments were carried out on two sets of specimens with differing face sheet thickness which clearly indicated the important role played by core debonding in determining the peak load of the structure. Localized buckling instabilities were also reported for samples with thinner face sheets. The role of debonding in determining strength was further highlighted by a comparison with FE simulations with suppressed debonding.

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ABSTRACT: Braided composites tubes have been reported to have a great potential in crash energy absorption applications. However, previous works were limited to thermoset braided composite tubes. In this study, we are interested in the crash energy absorption performance of 2.5D braided thermoplastic composite tubes. The sensitivity to materials, fiber orientation and geometry was investigated. Three crushing modes have been observed. The splaying and progressive folding were reported for glass/polypropylene tubes and fragmentation mode was observed in carbon/polyamide tubes. The last mode has the highest specific energy absorption of 61 kJ/kg. The progressive folding mode has higher specific energy absorption (36 kJ/kg) than the splaying mode. Moreover, the specific energy absorption increases with increasing braiding angle and decreasing length-to-diameter ratio, for glass/polypropylene tubes. On the opposite, the specific energy absorption decreases with braiding angle for carbon/polyamide tubes.

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ABSTRACT: This paper aims to explore the failure modes and crashworthiness characteristics of double hat shaped tubes made of weave carbon fiber reinforced plastic (CFRP) subjected to quasi-static axial crushing and transverse bending. Experimental investigations were carried out into three different thicknesses of the composite tubes fabricated by the bladder molding process. Three distinct failure modes, classified as progressive end crushing (I), unstable local buckling (II) and mid-length collapse (III), were observed in the axial crushing tests, whereas only one similar progressive collapse mode was observed in transverse bending tests. It is shown that the thickness is a critical parameter affecting the failure mode and energy absorption capability, leading to the increase in the peak load and specific energy absorption (SEA) during the tests. The SEA of the tested double hat shaped tubes under axial crushing ranges from 60 to 90 J/g, which is marginally higher than that of regular sectional CFRP tubes but over 2 times of that of conventional metallic tubes. By comparison, the load bearing and energy absorption capabilities of the tubes under transverse bending are much lower than those of the axially compressed tubes (less than 10% and 1%, respectively).

A.H. Sofiyev (Department of Civil Engineering, Faculty of Engineering, Suleyman Demirel University, 32260 Isparta, Turkey), “The vibration and buckling of sandwich cylindrical shells covered by different coatings subjected to the hydrostatic pressure”, Composite Structures, Vol. 117, pp 124-134, November 2014, https://doi.org/10.1016/j.compstruct.2014.06.025

ABSTRACT: The vibration and buckling of sandwich cylindrical shells covered by different types of coatings, such as functionally graded (FG), metal and ceramic coatings and subjected to a uniform hydrostatic pressure using first order shear deformation theory (FOSDT) is discussed. Four types of sandwich cylindrical shells are
considered. The volume fraction of FG coatings varies according to a simple power law function of thickness coordinate, while that of the core equals unity. The effective material properties of FG coatings are assumed to be graded in the thickness direction according to an exponential law distribution. The equations of motion of FG sandwich cylindrical shells are deduced using the FOSDT. The closed-form solutions for non-dimensional frequencies and critical hydrostatic pressures are obtained. The influences of compositional profiles of coatings, shear stresses and sandwich shell characteristics on the non-dimensional frequencies and critical hydrostatic pressures for FG and homogeneous sandwich cylindrical shells are discussed.

Huaiwei Huang and Qiang Han (School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510640, PR China), “Elastoplastic buckling of axially loaded functionally graded material cylindrical shells”, Composite Structures, Vol. 117, pp 135-142, November 2014, https://doi.org/10.1016/j.compstruct.2014.06.018

ABSTRACT: In this paper, elastoplastic buckling behaviors of functionally graded material cylindrical shells under axial compression are investigated with Donnell shell theory and $J_2$ flow constitutive relation of functionally graded materials. The nonlinear material properties vary smoothly through the thickness, and a multi-linear hardening elastoplasticity is considered in the analysis. The buckling government equations are solved by Galerkin method, and the semi-analytical solution of the critical load is given. Numerical results from the present theory are derived by an iterative procedure. The theoretical elastoplastic critical loads are well verified by those of ABAQUS code, which includes both the material and geometrical nonlinearities. The elastic, elastoplastic, and plastic buckling regions of functionally graded cylindrical shells can be effectively distinguished through the present method, and various effects of the material nonlinearity, the dimensional parameters and the power law exponent are investigated.


ABSTRACT: This paper presents the free vibration analysis of functionally graded open shells including cylindrical, conical and spherical ones with arbitrary subtended angle and general boundary conditions. The material properties of the open shells have continuous and smooth variation in the thickness direction based on general four-parameter power-law distributions in terms of volume fractions of the constituents. The formulation is derived by the modified Fourier series in conjunction with Rayleigh–Ritz method according to the first-order shear deformation shell theory. The modified Fourier series is expressed in the form of the linear superposition of a double cosine series and auxiliary functions which are introduced to ensure and accelerate the convergence of the series representations. The comprehensive investigations concerning the convergence and accuracy of the present method are performed by a number of numerical tests and comparisons. Some new results of FGM open shells with elastic restraints are presented. Parametric studies are carried out for FGM open shells with respect to the boundary conditions, material profiles and geometrical parameters.

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ABSTRACT: The influences of centrifugal and Coriolis forces on the free vibration behavior of rotating carbon nanotube reinforced composite (CNTRC) truncated conical shells are examined. The material properties of functionally graded carbon nanotube-reinforced composites (FG-CNTRCs) are assumed to be graded in the thickness direction and are estimated through a micromechanical model. The governing equations are derived based on the first-order shear deformation theory (FSDT) of shells using Hamilton’s principle. The initial mechanical stresses are obtained by solving the dynamic equilibrium equations. The differential quadrature method (DQM) is adopted to discretize the equations of motion and the related boundary conditions. After demonstrating the convergence and accuracy of the presented approach, the effects of angular velocity, Coriolis acceleration, geometrical parameters, type of distribution and volume fractions of carbon nanotubes on the frequency parameters of the CNTRC truncated conical shells are studied. The results reveal that the influences of the type of carbon nanotube distribution and its volume fraction on the frequency parameters depend on the semi vertex angle and angular velocity of the shells and the frequency parameters of the shell with FG asymmetric carbon nanotube distribution can become greater than those of the case with FG symmetric distribution ones.

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“Secondary instability and mode jumping analysis of deep hygrothermally buckled cross-ply laminated plates”, Composite Structures, Vol. 117, pp 244-254, November 2014, https://doi.org/10.1016/j.compstruct.2014.06.037
ABSTRACT: An analytical investigation is performed to study the secondary instability and dynamic aspects of the mode jumping in hygrothermally buckled cross-ply laminated plates. The governing partial differential equations (PDEs) and constitution relations are derived rigorously from an asymptotically correct, geometrically nonlinear theory. A novel and relatively simpler solution approach is developed to solve the two coupled fourth-order PDEs, namely, the compatibility equation and the dynamic governing equation. The von Kármán plate equation, namely, the coupled nonlinear governing equation, is reduced to a system of nonlinear ordinary differential equations (ODEs) by expressing the transverse deflection as a series of linear buckling modes. The ODEs, combined with the non-linear algebraic constraint equations obtained from in-plane boundary conditions, are then solved numerically under the parametric variation of the temperature and moisture. The comparison between the present method and the FEA shows that the secondary bifurcation point of the hygrothermally loaded plate is far beyond the primary buckling point, and the jump behavior cannot be predicted correctly without sufficient assumed modes, while the present method has the capability of exploring deeply into the post-secondary buckling realm and capturing the mode jumping phenomenon for various combinations of plate configurations boundary conditions. Furthermore, by monitoring free vibration along the stable primary postbuckling and the jumped equilibrium paths, we find that a mode shifting phenomenon (the exchange of vibration modes) exists in the primary post-buckling regime.

ABSTRACT: In this work, a new trigonometric zigzag theory is proposed for the analysis of laminated composite and sandwich plates. The theory is based upon shear strain shape function assuming non-linear distribution of transverse shear stresses. It satisfies the necessary conditions of inter-laminar stress continuity at the layer interfaces as well as the condition of zero transverse shear stresses at the top and bottom surfaces of the plates. The theory has the same number of unknown field variables as that of FSDT and the number of unknowns is layer independent which makes the solution computationally more efficient. A C⁰ continuous isoparametric serendipity element is employed to solve the discrete eigenvalue equations arising in both the problems. The accuracy and the efficiency of the theory are thus demonstrated through numerical experiments on the free vibration and stability analysis of laminated composite and sandwich plates with different modular ratio, aspect ratio, span to thickness ratio, loading and boundary conditions, ply orientations, lay-up number, eigen modes, etc. Higher modes with corresponding mode shapes of vibration and buckling are also represented for laminated composite and sandwich plates. An elegant performance of the proposed theory is observed when it is validated with relevant numerical examples.


ABSTRACT: The vibration and damping characteristics of free–free composite sandwich cylindrical shell with pyramidal truss-like cores have been conducted using the Rayleigh–Ritz model and finite element method. The predictions for the modal properties of composite sandwich cylindrical shell with pyramidal truss-like cores showed good agreement with the experimental tests. The influences of fiber ply angles on the natural frequency and damping loss factor were investigated. Three types of such composite sandwich cylindrical shells were manufactured using a hot press molding method and the relevant modal characteristics of various sandwich cylindrical shells could be obtained by modal tests. It can be found that modal strain energy approach was effective to estimate the structural damping loss factors and the variation of damping for each vibration modes could be explained suitably through the contributions of each strain energy components. Results showed that the structural damping loss factors not only depended on inherent material damping, but also relied on the vibration modes. The natural frequencies of composite sandwich cylindrical shell increased with the increasing of the ply angle of the inner and outer curve face sheets, whereas the damping loss factors of present shells did not increase monotonically.


ABSTRACT: Numerical simulations of composite structures are generally performed using multi-layered shell elements in the context of the finite elements method. This strategy has numerous advantages like a low computation time and the capability to reproduce the comportment of composites in most of cases. The main restriction of this approach is that they require an approximation of the comportment in the thickness. This approximation is generally no more valid near the boundary and loading conditions and when non linear
phenomena like delamination occurs in the thickness. This paper explores an alternative to shell computation using the framework of the Proper Generalized Decomposition that is based on a separated representation of the solution. The idea is to solve the full 3D solid problem separating the in-plane and the out-of-plane spaces. Practically, a classical shell mesh is used to describe the in-plane geometry and a simple 1D mesh is used to deal with the out-of-plane space. This allows to represent complex fields in the thickness without the complexity and the computation cost of a solid mesh which is particularly interesting when dealing with composite laminates.

ABSTRACT: Scaling effects in thin walled glass reinforced epoxy filament wound cylindrical tubes with [±55°] layup subjected to indentation load are presented in this work. Buckingham PI theorem is used to scale input and output parameters for four different scales \((n = 1/4, 1/2, 3/4 \text{ and } 1)\). Scaling laws are investigated for force, energy dissipation and damage propagation when tubes are resting on a flat surface. Damage propagation is captured with a video camera, by recording damage reflection on an upward facing mirror placed inside the tubes. The threshold force causing onset of delamination is identified and used for calculation of mode II energy release rate \(G_{IIc}\) with already established relation between the two. The scaling laws have been found effective in estimating quite a few parameters, including force displacement, energy displacement relation and peak load. Damage growth is found to obey scaling law and it is presented with respect to force applied, energy dissipated, indentation displacement and time.

Huaiwei Huang, Biao Chen and Qiang Han (School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510640, PR China), “Investigation on buckling behaviors of elastoplastic functionally graded cylindrical shells subjected to torsional loads”, Composite Structures, Vol. 118, pp 234-240, December 2014, [https://doi.org/10.1016/j.compstruct.2014.07.025](https://doi.org/10.1016/j.compstruct.2014.07.025)
ABSTRACT: In the present work, a semi-analytic solution is presented to analyze buckling behaviors of elastoplastic functionally graded circular cylindrical shells under torsional loads. The material properties vary smoothly through the shell thickness according to the power law distribution and a multi-linear hardening elastoplasticity of materials is included in the analysis. The Ritz energy method and both the flow and deformation constitutive theories help to develop the buckling government equation and the buckling critical condition. An iterative algorithm is resorted to derive the critical load and the buckling mode parameters. Numerical results reveal various effects of the constituent distribution of FGMs, dimensional parameters, and elastoplastic material properties. Meanwhile, the influences of material flow effect on buckling of elastoplastic FGM cylindrical shells are discussed.

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ABSTRACT: Semi-analytical models for the linear buckling analysis of unstiffened laminated composite cylinders and cones with flexible boundary conditions are presented. The Classical Laminated Plate Theory and the First-order Shear Deformation Theory are used in conjunction with the Donnell’s non-linear equations to derive the buckling equations. Axial, torsion and pressure loads can be applied individually or combined in the proposed models. The stiffness matrices are integrated analytically and for the conical shells an approximation is proposed to overcome non-integrable expressions. Comparisons with the literature show that the classical base functions available for axial compression cannot capture the buckling modes for non-orthotropic laminates. For torsion loads these classical shape functions do not catch the buckling modes even when applying the assumption of pure orthotropy, and it is shown how the proposed models correlate well with experimental data from the literature and finite element results. The use of elastic constraints at the boundaries allows the simulation of different boundary conditions in a versatile way and it is shown how those constants can be adjusted in order to change from one type of boundary condition to another.

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ABSTRACT: This paper presents a new triangular composite shell element with damping capability. Formulation of the composite triangular shell element is based on stacking individual homogeneous triangular shell elements on top of each other. The homogeneous shell element is an assembly of a triangular membrane element with drilling degrees of freedoms and a plate element. Damping capability is provided by means of complex element stiffness matrix of individual flat layers of the composite element. These elements with damping capability allow modelling general structures with damping treatments. A few test cases are modelled using triangular finite element developed here and the results of the complex eigenvalue analyses are compared with those of the quadrilateral shell elements proposed recently. The results obtained using the presented triangular and previous quadrilateral composite elements are also compared with those based on modal strain energy method and experimental results. Comparisons of the experimental and the theoretical results confirm that the modal properties including modal damping levels of structures with damping treatments can be predicted with high accuracy using the proposed finite element.

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ABSTRACT: In the present paper a generalization of the Refined Zigzag Theory (RZT) to doubly-curved multilayered structures is proposed. The displacement field characteristic of Naghdi’s shell model is enriched with RZT kinematics and a four-node shell finite element is formulated. Assumed Natural Strain (ANS) strategy is employed to overcome shear locking and Enhanced Assumed Strain (EAS) technique is applied to alleviate membrane locking and bending locking. For efficiency purpose, a one-point quadrature rule is used for the in-plane integration and hourglass stabilization is introduced. Finally, several numerical examples, involving static analysis of thick as well as thin shells, are performed to demonstrate the efficiency and accuracy of the proposed shell finite element.

ABSTRACT: In the present work, a three-dimensional vibration analysis of thick functionally graded conical, cylindrical shell and annular plate structures with arbitrary elastic restraints is presented. The last two structures are obtained as special cases of the conical shell. The effective material properties of functionally graded structures vary continuously in the thickness direction according the general four-parameter power law distributions in terms of volume fraction of constituents, and are estimated by Voigt’s rule of mixture. The exact solution is obtained by means of variational principle in conjunction with modified Fourier series which is composed of a standard Fourier series and some auxiliary functions. Validity and accuracy of the current method are demonstrated by comparing the present solutions with existing results. Numerous new results are given for functionally graded conical, cylindrical shells and annular plates with various boundary conditions including classical and elastic boundary conditions. Parametric investigations are carried out to study the effects of geometrical parameter, boundary conditions and material profiles on free vibration of functionally graded structures.

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ABSTRACT: The present paper develops nonlinear thermo electro elastic analysis of a thick spherical functionally graded piezoelectric materials. The assumed structure is loaded under thermal, electrical and mechanical loads. The mechanical, thermal and electrical properties are graded along the radial direction based on a power function. Primarily, the non homogenous heat transfer equation was solved by applying the general boundary conditions, individually. Geometric nonlinearity has been considered in strain displacement relations using Von-Karman equation. Substitution of nonlinear stress, strain, electrical displacement and material properties in equilibrium and Maxwell equations presents two nonlinear and non homogenous differential equation of order two. The main objective of the present study is considered to improve the relations between mechanical and electrical loads using a nonlinear analysis in spherical shells especially for functionally graded piezoelectric materials. The effect of employed nonlinear analysis can be studied on the results by a
comprehensive comparison between them and corresponding linear results. The percentage of improvement of the nonlinear results rather than linear results can justify necessity of this nonlinear analysis. This improvement is important in design and calibration of sensors in order to receive more accurate results.


ABSTRACT: This work shows a possible implementation of the refined zigzag theory in elements based on Simo’s shell theory. Refined zigzag theory can deal with composite laminate economically, adding only two nodal degrees of freedom, with very good accuracy. Two existing elements are considered, a four-node bi-linear quadrilateral and a six-node linear triangle. This geometry is enhanced with a hierarchical field of in-plane displacement expressed in convective coordinates. The objective is to have simple and efficient elements to analyze composite laminates under large displacements and rotations but small elastic strains. General aspects of the implementation are presented, and in particular the assumed natural strain technique used to prevent transverse shear locking. Several examples are considered to compare on the one hand with analytical static solutions and natural frequencies of plates, and on the other hand to observe the buckling loads and non-linear behavior with large displacement in double curved shells. In these latter cases comparisons are against numerical solutions obtained with solid elements. The results obtained are in a very good agreement with the targets used.


ABSTRACT: The postbuckling and failure behavior of stiffened composite panels subjected to hydro/thermal/mechanical coupled environment is investigated in this paper. The degradation in material properties due to moisture and temperature is taken into account using a micromechanical model. An effective model based on ABAQUS software has been established to evaluate the postbuckling load and failure load of stiffened composite panels. Excellent agreement between experimental data and numerical results is observed. Based on the model, the effects of temperature rise and moisture concentration on buckling and postbuckling response of the plate are presented.

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ABSTRACT: This work deals with the problem of the optimum design of a sandwich panel. The design process is based on a general two-level optimisation strategy involving different scales: the meso-scale for both the unit cell of the core and the constitutive layer of the laminated skins and the macro-scale for the whole panel. Concerning the meso-scale of the honeycomb core, an appropriate model of the unit cell able to properly
provide its effective elastic properties (to be used at the macro-scale) must be conceived. To this purpose, in this first paper, we present the numerical homogenisation technique as well as the related finite element model of the unit cell which makes use of solid elements instead of the usual shell ones. A numerical study to determine the effective properties of the honeycomb along with a comparison with existing models and a sensitive analysis in terms of the geometric parameters of the unit cell have been conducted. Numerical results show that shell-based models are no longer adapted to evaluate the core properties, mostly in the context of an optimisation procedure where the parameters of the unit cell can get values that go beyond the limits imposed by a 2D model.

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ABSTRACT: This work deals with the problem of the optimum design of a sandwich panel. The design strategy that we propose is a numerical optimisation procedure that does not make any simplifying assumption to obtain a true global optimum configuration of the system. To face the design of the sandwich structure at both meso and macro scales, we use a two-level optimisation strategy: at the first level we determine the optimal geometry of the unit cell of the core together with the material and geometric parameters of the laminated skins, while at the second level we determine the optimal skins lay-up giving the geometrical and material parameters issued from the first level. The two-level strategy relies both on the use of the polar formalism for the description of the anisotropic behaviour of the laminates and on the use of a genetic algorithm as optimisation tool to perform the solution search. To prove its effectiveness, we apply our strategy to the least-weight design of a sandwich plate, satisfying several constraints: on the first buckling load, on the positive-definiteness of the stiffness tensor of the core, on the ratio between skins and core thickness and on the admissible moduli for the laminated skins.

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ABSTRACT: The formulation of an enriched macro element suitable to analyze the free vibration response of composite plate assemblies is presented in this article. Based on the Trigonometric Shear Deformation Theory (TSDT) and the use of Gram–Schmidt orthogonal polynomials as enrichment functions a finite macro element is developed. In the TSDT framework, shear stresses are vanished at the top and bottom surfaces of the plates and shear correction factors are no longer required. The Principle of Virtual Work is applied to derive the governing equations of motion. A special connectivity matrix is obtained; so that hierarchically enriched global stiffness matrix and mass matrix of general laminated plate structures are derived, allowing to study generally
coplanar plate assemblies by combining two or more macro elements. This procedure gives a matrix-eigenvalue
problem that can be solved with optimum efficiency. Results of free vibration analysis for symmetric laminated
plates of different thickness ratios, geometrical planform shapes and boundary conditions are presented. The
accuracy of the formulation is ensured by comparing some numerical examples with those available in the
literature.

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“Stress and strain recovery for functionally graded free-form and doubly-curved sandwich shells using higher-
order equivalent single layer theory”, Composite Structures, Vol. 119, pp 67-89, January 2015,
https://doi.org/10.1016/j.compstruct.2014.08.005
ABSTRACT: We investigate recovery of through-the-thickness transverse normal and shear strains and stresses
in statically deformed functionally graded (FG) doubly-curved sandwich shell structures and shells of
revolution using the generalized zigzag displacement field and the Carrera Unified Formulation (CUF). Three
different through-the-thickness distributions of the volume fractions of constituents and two different
homogenization techniques are employed to deduce the effective moduli of linear elastic isotropic materials.
The system of partial differential equations for different Higher-order Shear Deformation Theories (HSDTs) is
numerically solved by using the Generalized Differential Quadrature (GDQ) method. Either the face sheets or
the core is assumed to be made of a FGM. The through-the-thickness stress profiles are recovered by integrating
along the thickness direction the 3-dimensional (3-D) equilibrium equations written in terms of stresses. The
stresses are used to find the strains by using Hooke’s law. The computed displacements and the recovered
through-the-thickness stresses and strains are found to compare well with those obtained by analyzing the
corresponding 3-D problems with the finite element method and a commercial code. The stresses for the FG
structures are found to be in-between those for the homogeneous structures made of the two constituents of the
FGM.

A.D. Shaw, I. Dayyani and M.I. Friswell (College of Engineering, Swansea University, Swansea SA2 8PP,
United Kingdom), “Optimization of composite corrugated skins for buckling in morphing aircraft”, Composite
ABSTRACT: Morphing aircraft aim to increase the performance of aircraft over multiple flight conditions, by
enabling shape changes in flight in order to optimise their aerodynamic properties for the current conditions.
The skin of a morphing aircraft is a critical component. It must be compliant in degrees of freedom that are
required for actuation, to minimise the actuation loads. However, it must also carry structural loads, and
therefore be stiff in load bearing degrees of freedom. This leads to a requirement for extremely anisotropic
material systems. A common solution is the use of a corrugated panel. However, previous work on corrugations
has not addressed the problem of compressive buckling loads. This work analyses the performance of
corrugated panels under buckling loads, and optimises corrugation patterns for the objectives of weight,
buckling performance, and actuation compliance. Simplified analytical models that derive properties equivalent
to conventional plates are used to obtain approximate estimates of the buckling loads. Furthermore a new mode
of buckling, that occurs entirely in-plane and is unique to panels with extreme anisotropy is analysed. The
simple models allow optimisation to be performed, and both a single-objective and a multi-objective approach
are demonstrated. The results are compared to Finite Element Analysis.

ABSTRACT: A comprehensive study on the hydrostatic implosion of carbon fiber reinforced epoxy composite tubes is conducted experimentally to examine the failure and damage mechanisms of collapse. Experiments are performed in a pressure vessel designed to provide constant hydrostatic pressure through the collapse. Filament-wound, braided, and roll-wrapped carbon-fiber/epoxy tubes are studied to explore the effect of geometry and reinforcement architecture on the modes of failure. 3-D Digital Image Correlation technique, which is first calibrated for the underwater environment, is used to capture the full-field deformation and velocities during the implosion event. Dynamic pressure transducers are employed to measure the pressure pulses generated by the event and evaluate its damage potential. The results show that composites with braided fabric reinforcements are found to have more damage potential to adjacent structures than those containing unidirectional reinforcements, as they release pressure waves with significantly greater impulse.

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ABSTRACT: Reinforced thermoplastic pipes (RTPs) are considered as prospective alternatives to traditional steel pipes in different offshore oil and gas applications due to their attractive properties. The spoolable versions of these pipes can be efficiently installed by the reel-lay method with relative ease. Nonlinear flexural behaviour of RTPs composed of a liner made of pipe grade polyethylene (PE), aramid fibre reinforced PE layers and a PE outer cover is modelled and analysed using finite-element analysis (FEA) considering the material nonlinearity. The pipe is modelled as a cylindrical shell in Abaqus/Standard. Numerical algorithms reflecting strain-dependent mechanical characteristics of PE are employed to perform simulations. Advantages of the proposed modelling approach are demonstrated with numerical examples. The minimum allowable bend radii of RTPs with different ply angles are determined. The effects of diameter-to-thickness ratios and the material nonlinearity on the spoolability of RTPs have been investigated. It is shown that the spoolability of RTPs can be improved by employing a certain two angle-ply reinforcing layer system, which could reduce the installation costs.

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ABSTRACT: In this paper, theoretical expressions of the mean crushing force of the three different square multi-cell tubes were derived by applying the Simplified Super Folding Element (SSFE) theory. The profiles of three square multi-cell tubes were divided into several basic angle elements: right corner, T-shape, 3-panel, criss-cross, and 4-panel angle element. Numerical simulations and multi-objective crashworthiness optimization were also performed for the three tubes. A Pareto sets were obtained by the linear weighted average method. Deb and Gupta method was utilized to find out knee points from the Pareto frontiers for multi-cell tubes. The simulation results showed that the multi-cell tube type I with right corner, T-shape and criss-cross angle elements was the best one among the three tubes in the aspect of specific energy absorption (SEA). For all the tubes, the stable and progressive folding deformation patterns were developed. Finally, the theoretical predictions well coincided with the numerical results, and also validated the efficiency of the numerical optimization design method.

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ABSTRACT: This paper presents a new one-dimensional finite elements’ family for the analysis of wrinkling in stiff thin films resting on a thick elastic substrate. Euler–Bernoulli’s theory is used for the thin film, whereas the substrate is ideally divided into two parts: 1. a core layer in the neighbourhood of the film where the displacement field presents high gradients (where an higher-order approximation is required) and 2. the remaining part of the substrate or bottom layer where displacements change very slowly. Low-order models allow an accurate yet efficient description of this latter part. Due to its versatility and generality, Carrera’s Unified Formulation is used to develop the proposed elements’ family. Governing equations’ weak form is derived by means of the principle of virtual displacements and discretised in a finite element sense. The asymptotic numerical method is used to solve the resulting non-linear equations’ system. Numerical investigations show that the proposed one-dimensional elements are able to capture the instability phenomena in film-substrate systems. In order to validate the proposed finite element models, the critical loads and half-wave numbers predicted by the one-dimensional elements are compared with those obtained via two-dimensional finite element analyses and a very good agreement is found.

Bo Zhang, Yuming He, Dabiao Liu, Lei Shen and Jian Lei (Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China), “Free vibration analysis of four-unknown shear deformable functionally graded cylindrical microshells based on the strain gradient elasticity theory”, Composite Structures, Vol. 119, pp 578-597, January 2015, https://doi.org/10.1016/j.compstruct.2014.09.032
ABSTRACT: In this paper, we present a four-unknown shear deformation theory and then develop a shear deformable functionally graded cylindrical microshell model using the strain gradient elasticity theory. Unlike the existing shear deformable cylindrical shell models, the present one contains four independent displacement functions only and introduces three material length scale parameters. In addition, the trapezoidal shape factor \((1 + z/R)\) of a shell element is taken into account in the expressions of classical and non-classical stresses to obtain the accurate stress-resultants over the thickness. The material properties of the microshell are estimated through the Mori–Tanaka homogenization technique. By using Hamilton’s principle, the equations of motion and boundary conditions are obtained. Closed-form solutions are derived for the free vibration problem of cylindrical microshells with simply supported ends and fixed ends respectively. Comparison studies are performed to establish the validity of the derived formulation. Finally, some illustrative examples are presented to investigate the influences of the material length scale parameter, gradient index, thickness-to-radius ratio, thickness-to-length ratio and boundary conditions on the vibration characteristics of cylindrical microshells. Numerical results indicate that both the frequency and higher-order mode shapes exhibit significant size-dependence when the thickness of the microshell approaches to the material length scale parameter.

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“The effects of non-uniform temperature distribution and locally distributed anisotropic properties on thermal buckling of laminated panels”, Composite Structures, Vol. 119, pp 610-619, January 2015,
https://doi.org/10.1016/j.compstruct.2014.09.011

ABSTRACT: The present paper is concerned with the optimal design problem of thermal buckling for fiber reinforced laminated panels. The effects of non-uniform temperature fields and locally distributed anisotropic properties on the thermal buckling behavior are studied. In this analysis, based on the classical lamination theory in conjunction with the Hamilton’s principle, the critical thermal buckling temperature difference is deduced. The numerical results show that under the non-uniform thermal loads the isotropic panel performs as anisotropic structure and it also show that the center of panel is more sensitive to the thermal effects than the edges. The effects of thermal load on panels with different boundary conditions are also investigated and it is found that the panel edges with loose constraint are more sensitive to temperature effect than with strict constraint. In the optimal fiber design problem for thermal buckling, by comparing the critical thermal buckling temperature difference of nine types of panels with different fiber distribution, it is found that the short fiber distribution can largely improve the critical thermal buckling temperature difference of fiber reinforced laminated panels. Finally, using the genetic algorithm the optimal fiber distribution is obtained for an eight-layer symmetrical panel.

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ABSTRACT: Free vibrations of a cantilever composite circular cylindrical shell are considered in this paper. The edge of the shell is fully clamped at one end of the cylinder and is free at the open section of the other end.
Variational equations of free vibrations are derived based on Hamilton’s principle and the problem is solved using the generalised Galerkin method. Analytical formulas enabling calculations of the fundamental frequency are obtained and verified by comparison with the results of a finite element modal analysis. The efficiency of the analytical solution is demonstrated using numerical examples including the design analysis of composite shells subject to constraints imposed on the fundamental frequency.

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ABSTRACT: The buckling and postbuckling analysis for an anisotropic laminated thin cylindrical shell of finite length subjected to combined loading of external pressure and axial compression using the boundary layer theory is presented. The material of each layer in the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The governing equations are obtained utilizing classical shell theory and von Kármán–Donnell strain displacement relations. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfection of the shell, is extended to the case of anisotropic laminated thin cylindrical shells under combined loading cases. A singular perturbation technique is employed to determine interactive buckling loads and postbuckling equilibrium paths. Postbuckling response of perfect and imperfect, anisotropic laminated cylindrical shells with respect to the material and geometric properties and load-proportional parameters under different sets of thermal environmental conditions is numerically illustrated. The analytical model developed can be used as a versatile and accurate tool to study the buckling and postbuckling behavior of composite structures.

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ABSTRACT: There is a renewed interest in grid-stiffened composite structures; they are not only competitive with conventional stiffened constructions and sandwich shells in terms of weight but also enjoy superior damage tolerance properties. In this paper, both global and local buckling is investigated for orthogrid- and isogrid-stiffened composite panels. Homogenized properties corresponding to classical lamination theory are obtained by matching the strain energy of stiffened and equivalent unstiffened cells, and then used in global buckling analysis. Bloch wave theory is adopted to calculate the local buckling load, where the interaction of adjacent cells is fully taken into account. Instead of considering skin buckling and stiffener crippling separately, the skin and stiffeners are assembled together at the level of a characteristic cell. The critical instabilities can be captured whether they are related to the skin, stiffener or their interaction. The proposed combination of
global/local models can also be used to predict the material failure. Numerical examples of isotropic panels show that the local buckling loads predicted by the proposed method match detailed finite element calculations well for eccentric or symmetrically located stiffeners with different torsional stiffness. The proposed method is further validated using typical composite configurations of flat panels and circular cylinders.


ABSTRACT: An alternative finite element (FE) formulation for the analysis of fiber reinforced laminated plates and shells developing small and large deformations is presented. Kinematic relations that ensure the adherence of fibers nodes to the continuum medium are used to introduce long and short fibers immersed in any positions of the laminate. The proposed formulation does not increase the number of degrees of freedom of the analyzed shell and do not require the necessity of matching nodes in the discretization of fibers and matrix. Following this procedure, it is possible to model spatially oriented or random fibers at any voshow its potential are presented.

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ABSTRACT: This paper presents a comprehensive review of the various methods employed to study the static, dynamic and stability behavior of Functionally Graded Material (FGM) plates. Both analytical and numerical methods are considered. The review is carried out with an emphasis to present stress, vibration and buckling characteristics of FGM plates predicted using different theories proposed by several researchers without considering the detailed mathematical implication of various methodologies. The effect of variation of material properties through the thickness, type of load case, boundary conditions, edge ratio, side-to-thickness ratio and the effect of nonlinearity on the behavior of FGM plates are discussed. The main objective of this paper is to serve the interests of researchers and engineers already involved in the analysis and design of FGM structures.


ABSTRACT: Bi-stable response of cross-ply composites is modelled when snap processes are trigged by a vertical force and the laminate is supported at four points. The model is based on the Rayleigh–Ritz technique. Non-linear von
Kármán strains, non-uniform curvatures and uniform through-the-thickness normal strain are included in the analysis. The analysis has been carried out step by step, by small increments of the applied load. Experiments in four \([0/90]_T\) carbon/epoxy laminates have been carried out for comparison in a test configuration that fulfils the requirements of the model. The multi-event snap-through and intermediate equilibrium positions have been experimentally observed and recorded. The initial snap-through and snap-back load–displacement curves have been experimentally determined and compared to those corresponding to the proposed model.

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ABSTRACT: In this paper, size-dependent equations of motion for functionally graded cylindrical shell were developed using shear deformation model and rotation inertia. Material properties of the shell were assumed as continuously variable along thickness, and consistent with the variation in the component’s volume fraction based on power law distribution. To consider the size effect, modified couple stress theory in conjunction with first order shear deformation shell model were used, and general equations of motion and classical and non-classical boundary conditions were derived based on Hamilton’s principle. Finally, in the special case, using the Navier procedure, the free vibrations of simply supported functionally graded cylindrical nanoshell were obtained, and the effects of parameters such as dimensionless length scale parameter, distribution of FG properties, thickness, and length on the natural frequency were identified and was compared with the classical theory. Results obtained through the modified couple stress theory are indicative of the considerable effect of the size parameter, particularly in bigger thicknesses and shorter lengths of nanotubes, on the natural frequency.

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ABSTRACT: We use the Mindlin plate theory and the finite element method to delineate the effect of fixing points on a transverse normal to the mid-surface of the plate on the localization of buckling modes in clamped–clamped rectangular plates made of linear elastic, homogeneous and either isotropic (monolithic) or orthotropic (fiber-reinforced composite) materials. The in-plane loads considered on the bounding edges are: (i) normal tractions on the length, (ii) normal tractions on the width, (iii) equal normal tractions on the length and the width (equal biaxial loading), (iv) shear (tangential), and (v) combined same normal and shear tractions on all sides. It is found that clamping points on a transverse normal passing through the mid-point of a line parallel to the short side increases the critical buckling load of plates of only low aspect ratios over that of the corresponding plates unconstrained at interior points. However, for plates of all aspect ratios (thickness/length) fixing points on a transverse normal divides it into two regions with negligible transverse deflections in only one of the two regions. Only for loads (i)–(iii) the dividing line is parallel to the short side of the plate. For both
thin and thick isotropic plates the slope of the dividing line is found to monotonically increase with an increase in the aspect ratio of a plate until it reaches a saturation value. A parameter based on the modal strain energy is used to quantify the degree of localization of a buckling mode. For an isotropic plate the degree of localization is found to increase with the increase in the aspect ratio for load cases (i)–(iii) but is found to be moderate for load cases (iv) and (v). For an orthotropic layer the degree of localization with an increase in the aspect ratio of the plate increases more for the 90° lamina than that for the 0° and the 45° laminae. Also, the mode localization in the (45°, \(-45°\)) laminate is stronger than that in the (0°, 90°) laminate for the five load cases. However, moderate degree of mode localization is found in symmetric and anti-symmetric cross-ply and angle-ply laminates.

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ABSTRACT: Research activities related to functionally graded materials (FGMs) have increased rapidly in recent years. The superlative properties of carbon nanotubes, i.e. high strength, high stiffness, high aspect ratio and low density have made them an excellent reinforcement for composite materials. Inspired by the concept of FGMs, the functionally graded (FG) pattern of reinforcement has been applied for functionally graded carbon nanotube reinforced composite (FG-CNTRC) materials. This paper attempts to identify and highlight topics relevant to FG-CNTRC and reviews the recent research works that have been reported in these topics. The present review includes: (i) a brief introduction of carbon nanotube reinforced composite (CNTRC) material; (ii) a review of mechanical analysis of FG-CNTRC; and (iii) a detailed discussion on the recent advances of FG-CNTRC and its prospect.


ABSTRACT: This paper presents a semi-analytical method for the buckling analysis of composite panels reinforced with omega stiffeners and subjected to combined loading conditions of biaxial loads and shear. The approach is based on the representation of the panel as an assembly of plate elements, allowing to capture local buckling modes involving skin and stiffener deflections. The panel model includes also the possibility of accounting for the stiffener foot. Trigonometric shape functions are introduced to describe the buckling patterns, while the buckling equations are derived through the application of the minimum potential energy principle. The comparison with Abaqus finite element analyses is presented, demonstrating, for a wide variety of test cases, percent differences below 9% and a good accuracy of the computed buckling modes. The computational speed up is of the order of 100, suggesting the use of the formulation in the context of preliminary design loops, sensitivity analyses or design optimizations.
ABSTRACT: The purpose of this paper was to study the effect of I-shape stiffener stiffness on the buckling and post-buckling behavior of stiffened composite panels – Experimental investigation. Six stiffened composite panel configurations, which were orthogonally designed with two skin configurations and three I-shape stiffener configurations, were taken into account in the experimental investigation. Three specimens for each configuration (18 specimens in total) were manufactured for test. Before tests, the key dimensions of I-stiffener and skin were measured. Furthermore, all the specimens were also inspected visually and detected by the ultrasonic C-scan system. No initial delamination or debonding area was found on all the specimens according to their C-scan images. The experimental results show that the equivalent compression stiffness of I-shape stiffener has great influence on the buckling load and failure mode of stiffened panel, but a little effect on the failure load of stiffened panel. The skin thickness has great impact on the buckling load and the final failure load.

ABSTRACT: The nonlinear thermal instability of moving sandwich plates subjected to a constant moving speed is investigated. The sandwich plates are made of a shape memory alloy (SMA) fiber reinforced composite core and two functionally graded (FG) face sheets (FG/SMA/FG). The Brinson model is used for modeling of SMA behavior, and the geometrically nonlinear third-order shear deformation theory is used for modeling of sandwich plates. Thermomechanical properties of the sandwich plate are assumed to be temperature-dependent. Two types of in-plane boundary conditions are considered. The nonlinear instability is treated by the Galerkin technique. The results show that the initial equilibrium configuration of the sandwich plate becomes unstable at a critical moving speed. Results examine the effect of axial moving speed, SMA volume fraction, pre-strain of SMA fiber, core thickness, imperfection, in-plane boundary conditions, and thermal loading on the stability characteristics of the sandwich plates. It is found that a proper application of SMA fibers postpone the thermal buckling and critical moving speed. Furthermore, the induced tensile recovery stress of SMA fibers could also stabilize geometrically imperfect plates during the reverse martensite transformation.

ABSTRACT: The initial equilibrium configuration of the sandwich plate becomes unstable at a critical moving speed. Results examine the effect of axial moving speed, SMA volume fraction, pre-strain of SMA fiber, core thickness, imperfection, in-plane boundary conditions, and thermal loading on the stability characteristics of the sandwich plates. It is found that a proper application of SMA fibers postpone the thermal buckling and critical moving speed. Furthermore, the induced tensile recovery stress of SMA fibers could also stabilize geometrically imperfect plates during the reverse martensite transformation.

ABSTRACT: The present research aims to investigate the vibration characteristics of stiffened composite cylindrical shells using experimental, numerical and analytical techniques. The specimens are fabricated from continuous glass fiber (GFRP) using a specially-designed filament winding setup. The theoretical formulation is established based on Sanders’ thin shell theory. In the analytical approach, a smeared method is employed to superimpose the stiffness contribution of the stiffeners with those of shell in order to obtain the equivalent stiffness parameters of the whole panel. Using the Ritz method, the governing eigenvalue equations are obtained and will then be solved for evaluating the natural frequencies of the GFRP-stiffened composite shells.

In order to validate the analytical achievements, experimental modal analysis is conducted on a stiffened cylinder. A 3-D finite element model is built for a further validation. This model takes into account the exact geometric configuration of the stiffeners and the shell. Results confirm the accuracy of the analytical method. Furthermore, the influences of changes in the skin thickness and boundary condition are analyzed.

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ABSTRACT: There is evidence that glass fibre reinforced polymer (GFRP) pultruded profiles are particularly susceptible to transverse compressive loads, owing to the much lower mechanical properties in the direction transverse to the pultrusion axis. Although very relevant, the understanding about the web-crippling phenomenon in GFRP pultruded profiles is still very limited, as attested by the lack of information available in design codes and guidelines. This paper reports an experimental study about the web-crippling phenomenon in GFRP pultruded profiles with I-section. The experimental programme included comprehensive material characterization tests (tension, compression, flexure and shear), and full-scale web-cripping tests on four different I-profiles, with heights ranging from 100 mm to 400 mm, thus covering the vast majority of structural profiles currently available in the market. In the web-cripping experiments, two load configurations were tested: interior two flanges (ITF); and end two flanges (ETF). In addition, tests were performed with three different bearing lengths: 15 mm, 50 mm, and 100 mm. The experimental results confirmed the susceptibility of GFRP pultruded profiles to transverse compressive loads, outlining the influence of both the load configuration and the bearing length on the web-cripping phenomenon in terms of strength, stiffness, and failure modes.

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ABSTRACT: The part 1 [1] of this two-part paper presented an experimental study concerning the web-crippling phenomenon on GFRP pultruded I-shaped profiles and showed that they are very sensitive to transverse compressive loads (lower mechanical properties in the transverse direction) and web-crippling failure. This part 2 reports numerical and analytical results aiming at a better understanding of the web-crippling phenomenon and providing enough data to complement the observations made in the experimental campaign. The scope of these studies was to predict and replicate the behaviour exhibited by the four different GFRP profiles tested (I100, I120, I200 and I400) when subjected to different transverse loading configurations (ETF and ITF) and bearing lengths (varying from 15 to 100 mm). Shell finite element (SFE) models with the Tsai Hill failure criterion were developed in ABAQUS, aiming at simulating the experimental tests performed in part 1. This procedure enabled the comparison of the numerical results with the experimental data, as well as the observation of the stress fields and damage evolution. In general, these models presented good agreement with the test results. An analytical formula was also developed to predict the web-crippling load of GFRP profiles and presented very good agreement with the test results.


ABSTRACT: An analytical approach on the nonlinear response of thick functionally graded circular cylindrical shells with temperature independent material property surrounded on elastic foundations subjected to mechanical and thermal loads is presented. Material properties are graded in the thickness direction according to a Sigmoid power law distribution in terms of the volume fractions of constituents (S-FGM). The formulations
are based on the third order shear deformation shell theory taking into account von Karman nonlinearity, initial geometrical imperfection and Pasternak type elastic foundation. By applying Galerkin method and using stress function, explicit relations of thermal load–deflection curves of the S-FGM shells are determined. Detailed parametric studies are carried out to investigate effects of volume fraction index, material properties and geometrical shapes, axial compressions and thermal load, foundation stiffness and imperfection on nonlinear buckling behaviors of S-FGM thick circular cylindrical shells. The present analysis is validated by comparing results with other publications.

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“Characterisation of aluminium alloy tubes filled with aluminium alloy integral-skin foam under axial compressive loads”, Composite Structures, Vol. 121, pp 154-162, March 2015,
https://doi.org/10.1016/j.compstruct.2014.11.003

ABSTRACT: Novel ex-situ foam-filled tubes (FFTs) were prepared by inserting an integral-skin foam filler into an empty aluminium alloy tube. The aluminium alloy foam filler is prepared by powder compact foaming technique allowing to combine the Al-alloy integral-skin filler with an Al-alloy tube which has not been studied yet. Axial compressive crush performance of the individual components (empty tubes and integral-skin foams) and FFTs was studied and evaluated using uniaxial compression tests, exploring their deformation and failure mechanisms. The FFTs deform by axisymmetric axial crushing mode (concertina mode) with the formation of a single visible concertina fold, but with the formation and propagation of longitudinal cracks. The results confirm an improved crush performance under axial compressive loads by introducing the integral-skin foam as a filler in empty tubes.

Mine Uslu Uysal and Ugur Guven (Yildiz Technical University, Mechanical Engineering Department, 34349 Besiktas, Istanbul, Turkey), “Buckling of functional graded polymeric sandwich panel under different load cases”, Composite Structures, Vol. 121, pp 182-196, March 2016,
https://doi.org/10.1016/j.compstruct.2014.11.012

ABSTRACT: In the present paper, the buckling behaviors of adhesively bonded sandwich plates subjected to in-plane shear force, in-plane normal compression force, and out-of-plane distributed load were studied for both point supported concept and linear supported concept. The functionally gradient polymeric adherends and elastic, homogeneous adhesive were used in the assembly. The epoxy resin was used and two types of graphite powder materials were selected PAM96/98 and PV60/65 as filler. The graphite powders were added to the epoxy resin as 3%, 6%, 9%, and 12% vol. The structure and graphite distribution were investigated by light microscope and the elasticity modulus of adherends were predicted based on the image processing program. The influences of the type and volume of graphite powders on the buckling behavior were studied by finite element analyses. The critical buckling loads were predicted and their mode shapes were presented. The highest critical buckling load was determined in PV60/65 structure panels for three different load cases due to the fact that the PV60/65 graphite powder was compatible with epoxy resin.

ABSTRACT: Free vibration and thermal stability analyzes of functionally graded (FG) sandwich plates are carried out by using the advanced Hierarchical Trigonometric Ritz Formulation (HTRF). Refined higher-order kinematics plate models accounting for through-the-thickness deformation are developed within the framework of Carrera’s Unified Formulation (CUF). The Principle of Virtual Displacements (PVD) is used as variational statement to develop the HTRF. Uniform, linear and non-linear temperature rises through-the-thickness layer plate direction are considered. The non-linear temperature distribution is given in different forms: (i) power law through-the-thickness variation; (ii) solution of the one-dimensional Fourier heat conduction equation; (iii) sinusoidal. The effect of initial thermal stresses on the free vibration behavior of the FG sandwich plates is investigated. Accuracy of the presented formulation is discussed in details. Moreover, the effects of volume fraction index, aspect ratio, boundary conditions, length-to-thickness ratio, sandwich plate type and temperature distributions through-the-thickness plate direction, for both natural frequencies and critical temperatures are thoroughly investigated.

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ABSTRACT: Due to the involvement of large number of design variables, it is still one of the key concerns to build an efficient optimization algorithm for the stacking sequence design of composite laminates with various constraints. In this work, the flexural stiffness parameters are expressed in terms of the ply orientations, which helps to formulate the maximum of buckling load factor as a problem of identifying the optimum ply orientation at stacking positions. Afterwards, we suggest a permutation search (PS) algorithm to reduce the evaluations in stacking sequence optimization of composite laminates. In the first stage, permutation operations are sequentially performed for each permutation position, and in the second stage a repair strategy is adopted for overcoming the violation of constraints while maximizing the value of the objective function. A comparison has been performed between the PS and three genetic algorithm (GAs) methods. It has been demonstrated that the number of process analyses for stacking sequence optimization are greatly reduced by the PS algorithm. The novel PS algorithm combined with the modified repair strategy outperforms the studied GA methods for constrained stacking sequence optimization of composite laminate both in computational performance and finding the optimal objective value with high reliability.


ABSTRACT: A formulation applicable to free, periodic, geometrically non-linear vibrations of thin shallow shells made of composite layers with curvilinear fibres is presented. The modes of vibration of this type of
Variable Stiffness Composite Laminated (VSCL) shallow shells are examined in the non-linear regime. Due to the membrane effects and their coupling with bending, the modes of vibration of VSCL shells are more affected by alterations in the curvilinear fibre paths than what was previously found to occur in plates. Indeed, it is discovered that by changing one of the parameters that defines the fibre path – keeping all other properties of the shells unaltered – the degree of softening can be changed, hardening can become softening, the vibration displacement amplitude at which turning points occur can change and the amplitudes of harmonics vary. A significant deduction, which results from the numerical tests, is that modes of vibration that have mode shapes with more half-waves are less likely to experience softening. A geometric explanation for this behaviour, which does not apply only to VSCL shells, is given.

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ABSTRACT: An approximate analytical solution of the buckling problem formulated for a composite sandwich cylindrical shell subjected to a uniform external lateral pressure is presented in the paper. Both ends of the shell of finite length are fully clamped. The problem is solved using the Galerkin method. The analytical formula for the critical load has been obtained and verified by comparison with a finite-element solution. Based on this formula buckling analyses of sandwich pipes with different types of core materials normally used in underwater applications have been performed. Applications of the formula to the solutions of design problems have been demonstrated for the clamped–clamped sandwich pipes considering constraints imposed on the value of critical pressure.

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ABSTRACT: This paper deals with the transient response of a glass–epoxy composite submersible hull subjected to underwater explosive bubble. The boundary-element method (BEM) is used to simulate the physical process of the explosion bubble growth, contraction and collapse while the finite element method (FEM) is used to calculate the glass–epoxy composite structure response to the high pressure induced by the underwater explosion bubble. The coupled BEM–FEM is used to handle the interaction of the composite structures and the underwater explosion bubble. With the coupled code, the mutual effects of relative location between the bubble and the composite submersible hull are investigated; and also the transient responses (such as stresses and internal energy densities) of the composite submersible hull to the underwater explosive bubble can be predicted for different charge weights and charge distances. From the results obtained, some insights to the dynamical problem of the interaction between underwater explosion bubbles and composite structures are deduced.
ABSTRACT: A semi-analytical model to predict the non-linear behavior of unstiffened cylinders and cones considering initial geometric imperfections and various loads and boundary conditions is presented. The formulation is developed using the Classical Laminated Plate Theory (CLPT) and Donnell’s equations, solving for the complete displacement field. The non-linear static problem is solved using a modified Newton–Raphson algorithm with line-search. A numerical integration scheme for the non-linear matrices is proposed and details regarding the implementation of the proposed method are given. Two methods to include measured imperfections into the analyses are presented and for one method the effect of using different approximation levels for the imperfection field on the non-linear response is investigated, and a minimum approximation accuracy that should be used is determined. The semi-analytical results are verified using finite elements and previous models from the literature. The implemented routines are distributed on-line and are based on a matrix notation simply applicable to other problems.

ABSTRACT: A computationally efficient framework is presented to design fibre steered laminates in cylindrical shells, stiffened with longitudinal stiffeners, optimally. The framework is comprised of a semi-analytical analysis approach and a multi-step optimisation framework, and is applied for maximum buckling capacity design of fibre steered laminates of two stiffened cylinders, with different thickness to radius ratios, under bending moment. If the maximum buckling capacity designs are material failure critical, strength is imposed as a constraint in the optimisation problem. Comparisons of buckling capacity of steered fibre laminates with those of straight fibre laminates are shown and validated. Finally, to gain in-depth understanding of the way buckling capacity is improved by fibre steering, the axial section load and the critical buckling modes of straight and steered fibre laminates are compared.
Free vibration of anti-symmetric angle-ply laminated conical shells is studied including shear deformation using spline function approximation. The equilibrium equations are formulated in terms of displacement and rotational functions. These functions are approximated using Bickley-type splines to obtain the generalised eigenvalue problem with suitable boundary conditions. Parametric studies are made to analyse the effects of circumferential node number, length ratio and cone angle on the frequency parameter for different number of layers and materials with different ply orientations under two types of boundary conditions.

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ABSTRACT: Using first-order shear deformation theory (FSDT) and multilayer method (MLM), a semi-analytical solution has been performed for the purpose of elastic analysis of rotating thick truncated conical shells made of functionally graded materials (FGMs) under non-uniform pressure. Material properties of cone are assumed to change along the axial direction according to a power law form. It is also assumed that the Poisson’s ratio is constant. In the multilayer method, the functionally graded (FG) truncated cone is divided into \( n \) homogenous disks, and \( n \) sets of differential equations are given. This set of equations is solved by applying the boundary conditions and continuity conditions between the layers. The problem is also solved, using the finite element method (FEM), the results of which are compared with those of the MLM method. Finally, some numerical results are presented to study the effects of applied pressure, non-homogeneity index, and power law index of FGM on the mechanical behavior of the truncated conical shells.

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ABSTRACT: An experimental and numerical study on the buckling and post-buckling behaviors of hat-stringer-stiffened composite curved panel under axial compression load was carried out. Several influence factors, such as skin thickness, panel radius, and distance between two adjacent stringers were studied. Three groups of stiffened curved panel buckling and postbuckling behaviors were obtained. An engineering approach was proposed to predict the initial buckling load of curved panel. Finite element analysis was used to investigate these tests and the FE models were performed by ABAQUS. The experiment results compared with that of numerical are presented. The capability and feasibility of numerical predictions in post-buckling field was assessed by comparing with experimental data. Good agreement between experimental and numerical results was observed.
ABSTRACT: Variable-stiffness shells are thin composite structures in which the reinforcement direction is a function of its surface co-ordinates. This paper presents a numerical investigation into the buckling and post-buckling of two variable-stiffness cylinders under axial compression. Both shell walls are made from unidirectional carbon fiber slit tapes that are steered to give them a piecewise-continuous fiber-angle variation around the circumference. Dynamic analyses of the complete loading and unloading cycles are computed using a time-integrated finite element model (Abaqus). The numerical results generated herein are compared with test data and are found to be in good agreement, in terms of axial force versus end-shortening and global displacement fields. The analyses provide significant new insight into the mechanisms underpinning collapse behavior of the shells. For example, the development of the initial nonlinear buckle, its dynamic snap-through, and the formation of a post-buckled configuration are clearly visible. One effect elucidated by this investigation is the symmetry-breaking mechanism of the circumferential stiffness variation. In contrast to a constant-stiffness cylinder, in which the total strain energy is invariant to the translation of a dimple of fixed dimensions, the present structures exhibit a single dominant post-buckling mode that are associated with the formation of ‘trapped’ surface dimples. In one case, this dominant mode is found to be stable over a significant amount of further end shortening.

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ABSTRACT: Based on the Reddy’s high-order shear deformation theory, buckling behaviors of the FGM cylindrical shells subjected to an axial compression in thermal environment are investigated analytically. Considering the temperature-dependent FGMs properties, the constituent distribution across the shell thickness is assumed to follow the volume fraction rule of mixture. Through the variational principle, basic equations are derived for shear deformable FGM cylindrical shell with the initial geometric imperfection. Method of separation of variables and Galerkin’s solving process are employed in dealing with the stability governing equations of perfect and imperfect shells, respectively. By changing the boundary conditions, material types, composition distributions, thermal load and temperature fields, the effect of the transverse shear deformation is evaluated by comparing with the results of the classical Donnell’s theory. Meanwhile, imperfection sensitivity for buckling of the shear deformable FGM cylindrical shell is discussed in detail.

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ABSTRACT: The present paper deals with static coupled buckling of thin-walled columns with trapezoidal and square cross-sections, which are made of functionally graded materials (FGMs). An Al–TiC, metal-ceramic material is applied. The discussion assumed that the columns were axial compressed and simple supported at their ends. In addition, the material is subject to Hooke’s law. The effect of temperature is neglected. The classical laminate plate theory (CLPT) has been used to describe properties of the functionally graded structures. The problem of the non-linear buckling was solved by using a variational method for the asymptotic analytical–numerical method (Koiter’s theory). Static interaction of the global buckling mode with the two local buckling modes has been taken into account. In order to derive the equilibrium equations of functionally graded structures, the full Green’s strain tensor and the second Piola–Kirchhoff’s stress tensor has been adapted. The presented problem is particularly important as the authors have found no earlier studies on coupled buckling of thin-walled functionally graded structures with closed cross-sections.

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ABSTRACT: In this study, the buckling of functionally graded (FG) truncated conical shells subjected to external pressures under mixed boundary conditions is investigated. The mixed boundary conditions are as follows: at one end of FGM truncated conical shell is a sleeve that prevents its longitudinal displacement and rotation, and the other end is a free support. The basic equations of FG truncated conical shells are derived using Donnell shell theory. To solve of this problem is used new approximation functions and basic equations are solved using the Galerkin method for the two cases of mixed boundary conditions. The results are compared and validated with the results available in the literature. The influences of truncated shell characteristics, material compositions and boundary conditions on the critical lateral and hydrostatic pressures are investigated.

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ABSTRACT: Fiber reinforced composites (FRPs) with light weight did not exhibit the ductile failure mechanism which was related to metals. FRPs absorb lots of energy through progressive crushing modes by a
combination of multi micro-crack, bending, delamination and friction. FRPs with half weight of traditional metals while absorb more than doubled energy. But FRPs we re not used as energy absorption components in wide range; one of the most important reasons is their high manufacturing cost. In this study, carbon fiber and aramid fiber were chosen as reinforcements and common epoxy resin was chosen as matrix to manufacture five types of different structures and raw materials of carbon/aramid and carbon/carbon fiber reinforced composite tubes through high productive and low cost winding method. Then specimens were dealt under 100 °C condition for 100 h, 200 h and 400 h treatment respectively. After that, energy absorption ability was tested by quasi static compression tests and microscope observation of cross section was taken to analyze the mechanism of failure. By optimizing different hybrid method, ratio and reasonable geometry shape of composites, low cost and high energy absorption components whose specific energy absorption ($E_s$) were near 100 kJ/kg could be manufactured to put to use on vehicles.

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ABSTRACT: A novel column consisting of steel, concrete and fiber-reinforced polymer (FRP) is presented and assessed through experimental study. The sectional form of steel–concrete–FRP–concrete (SCFC) columns has a square steel tube as the outer layer and a circular filament-wound FRP tube as the inner layer, and concrete is filled between these two layers and within the FRP tube. Thus the column can be regarded as a concrete-filled square steel tube (CFST) with a FRP-confined concrete core (FCCC). In comparison to existing composite column sections, several advantages are achieved such as ease of connection to beams, the stronger confinement of core concrete, ductile response, and residual load capacity. 18 SCFC stub columns are tested with different concrete strengths, FRP tube thickness and steel tube thickness in comparison to four traditional composite columns. The distinctive behaviors of SCFC columns, including significant post-yield stiffness, ductile failure, and stable residual bearing capacity are found. Test results show that the strengths of concrete, FRP, and steel are effectively utilized at different stages, including the initial linear stage, the secondary linear stage (hardening stage), and the post-peak stage. The influences of key design parameters on the mechanical characteristics of initial compressive stiffness, peak strain, residual load-bearing capacity, and ductility are also clarified.

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ABSTRACT: This paper presents an investigation on the thermal postbuckling behavior of nanocomposite cylindrical panels resting on elastic foundations and subjected to a uniform temperature rise. The cylindrical panels are made of carbon nanotube reinforced composite (CNTRC) material with the carbon nanotube reinforcement being distributed along the thickness of the panels either uniformly (UD) or functionally graded
A micromechanical model together with molecular dynamics simulation results is employed to obtain the material properties of the FG-CNTRC panels. The governing equations for the cylindrical panels are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The panel–foundation interaction and thermal effects are also included. The material properties of CNTRCs are assumed to be temperature-dependent and an iterative scheme is developed to obtain numerical results. The results reveal that the nanotube volume fraction, foundation stiffness, and the panel curvature ratio have a significant effect on the thermal postbuckling behavior of CNTRC cylindrical panels. It is found that in most cases the CNTRC panel with intermediate nanotube volume fraction does not necessarily have intermediate thermal postbuckling strength.

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ABSTRACT: The aim of this paper is to study the quasi-static and dynamic compressive crush performance of newly developed in-situ foam-filled tubes (FFTs) made of light aluminium alloys prepared by powder compact foaming technique. By this method, the aluminium alloy empty tube is filled with an aluminium alloy foam during its formation. An extruded precursor of aluminium alloy and titanium hydride powder (0.5 wt.%) has been used for this purpose. The axial mechanical crushing behaviour and the failure mechanisms were assessed by uniaxial compression tests coupled with infrared thermography. The axial crush performance of in-situ FFTs was compared with performance of the individual components (integral-skin foam and empty tubes) submitted to the same heat treatment used to prepare the FFTs. Results confirm that the in-situ FFTs have a more stable axial crush performance. The results also demonstrate that heat treated aluminium alloy structures ensure high ductility and very good crashworthiness since they deform without formation of cracks during compression, which is a pre-requisite for good and reliable crashworthiness behaviour.

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ABSTRACT: Anti-symmetric cylindrical shells with two stable configurations have been proved to offer novel morphing structures in advanced engineering fields. The bistable behaviour of anti-symmetric composite shells under thermomechanical loading is analysed herein theoretically combined with a finite element modelling. The properties of the composite material in current study are considered to be functions of temperature. The shell is subjected to two different thermal load, i.e. the uniform temperature field and through-thickness thermal gradient. The influence of this two temperature field on the shell’s stable shapes was predicted analytically, which thereafter is determined by finite element results. This provides a feasible approach of controlling the
deformation of the bistable shell through adjusting the applied temperature field. For this purpose, a superposition of uniform temperature field and through-thickness thermal gradient is imposed and its influence on the bistable shapes of bistable shells is therefore investigated, which is of great importance to the design and application of morphing structures manufactured from bistable composite shells.

ABSTRACT: Layerwise theories provide an accurate prediction of the three-dimensional stress state of composite structures which is in many cases a prerequisite for a successful prediction of failure mechanism. We focus on such a model for laminate composite plate and shell models in the framework of isogeometric analysis. We apply an exact but dimensionally reduced geometry description based on a computer-aided design (CAD) derived mid-surface NURBS model and a layerwise through-thickness B-spline description. Using the unique and characteristic refinement capabilities of isogeometric analysis we simplify the modeling process while keeping the higher order and higher continuity properties of NURBS. Trimmed geometries, as common in CAD models are efficiently handled by an embedded domain method which treats trimmed areas as a fictitious extension domain in the computational model. We verify our approach with several examples for moderately thick laminate plate and shell models and compare our results to existing 3D solutions.

ABSTRACT: The present work illustrates a general formulation for higher-order layer-wise (LW) theories. It aims to analyze doubly-curved laminated shells and panels when soft-core properties are selected. The present approach has its own roots in the Carrera Unified Formulation (CUF) for which the stretching effect of each layer is not neglected. CUF allows to take the kinematic expansion order as a free parameter for the representation of any higher order formulation. This paper shows the explicit fundamental operators for the LW approach when static analysis is investigated. The mathematical problem is solved using a strong formulation approach, termed Generalized Differential Quadrature (GDQ) method. Moreover, the so-called Generalized Integral Quadrature (GIQ) method is used for evaluating the through-the-thickness quantities of the theory such as the stiffness constants, computed layer by layer. Numerical applications are related to the recovery of the inter-laminar stresses and strains that have been compared to reference solutions obtained by a commercial three-dimensional (3D) FEM code.

ABSTRACT: Nonlinear dynamic analysis and vibration of imperfect functionally graded materials (FGM) thick double curved shallow shells with piezoelectric actuators on elastic foundations subjected to the combination of electrical, thermal, mechanical and damping loading are investigated in this paper. Material properties of FGM
Shells are assumed to be temperature dependent and graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The governing equations are established based on Reddy’s higher order shear deformation theory that includes thermo-piezoelectric effects and are solved by the stress function, the Galerkin method and fourth-order Runge–Kutta method. In numerical results, the effects of geometrical parameters; the material properties; imperfections; elastic foundations; electrical, mechanical, thermal and damping loads on the nonlinear dynamic analysis and nonlinear vibration of the FGM hybrid double curved shallow shells are discussed.

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ABSTRACT: The dynamic and parametric instabilities of single-walled carbon nanotubes (CNTs) conveying pulsating and viscous fluid embedded in an elastic medium are modeled and numerically investigated. The partial differential equation of motion based on the nonlocal elasticity theory, Euler Bernoulli beam’s model and fluid–tube interaction is given. Based on the differential quadrature method, complex eigenmodes and associated eigenfrequencies are investigated with respect to the flow velocity as well as to the other considered physical parameters. Multimodal formulation based on real and complex eigenmodes are presented in the frequency and time domains. Models are elaborated for dynamic instabilities such as divergence and flutter as well as for parametric instability behaviors. The influences of the nonlocal parameter, the fluid pulsation and viscosity, the viscoelastic CNT parameter and the thermal effects on the dynamic behaviors of the CNT-fluid system are analyzed. Instability boundaries and interaction between the dynamic and parametric instabilities are investigated.


ABSTRACT: Free vibration response of functionally graded material (FGM) shell structures is studied by using an efficient 3d-shell model based on a discrete double directors shell element. With this element, the vanishing of transverse shear strains on top and bottom faces is considered in a discrete form. The mechanical properties of the shell structure are assumed to vary continuously in the thickness direction according to the general four-parameter power-law distribution in terms of the volume fractions of the constituents. The fundamental equations for the FGM shell structures are derived using principle of virtual work. Performance and accuracy of the present discrete double directors shell model (DDDSM) are confirmed by comparing the present solutions obtained from finite element analyses with the existing results in the literature.

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ABSTRACT: A novel numerical/analytical approach to study geometrically nonlinear vibrations of shells with variable thickness of layers is proposed. It enables investigation of shallow shells with complex forms and different boundary conditions. The proposed method combines application of the R-functions theory, variational Ritz’s method, as well as hybrid Bubnov–Galerkin method and the fourth-order Runge–Kutta method. Mainly two approaches, classical and first-order shear deformation theories of shells are used. An original scheme of discretization regarding time reduces the initial problem to the solution of a sequence of linear problems including those related to linear vibrations with a special type of elasticity, as well as problems governed by non-linear system of ordinary differential equations. The proposed method is validated by the investigation of test problems for shallow shells with rectangular planform and applied to new vibration problems for shallow shells with complex planforms and variable thickness of layers.

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ABSTRACT: In this article, geometrically nonlinear transient analysis of moderately thick laminated composite shallow shells is performed using generalized differential quadrature method. First-order shear deformation theory of doubly curved shells is used to consider transverse shear effect and Von-Karman nonlinear strain–displacement relationships are used to consider geometric nonlinearity due to large displacements. Virtual work principle is used to derive the equation of motion. Partial derivatives in the equation of motion is expressed with generalized differential quadrature method and time integration is carried out using Newmark average acceleration method. Several laminated composite plate, cylindrical and spherical panel problems from the literature are solved with the proposed method. Transient responses are compared with those obtained with other methods in the literature.

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ABSTRACT: Polymeric foams are new materials which prefer special mechanical and thermal properties for mechanical designers. The best mathematical model for polymeric and metallic foams is functionally graded viscoelastic (FGV) materials. So, this paper has concentrated on presenting a reliable and accurate method for free vibration of FGV panels. For this purpose, Levy-type circular cylindrical panel consisting of FGV material is modeled based on Sanders first order shear deformation type theory, as geometrical model, and linear Zener model with variable properties through the thickness, as the best constitutive relation for FGV materials. Validity and accuracy of present method are approved by comparing it with finite element in different tables. Also, effects of various geometrical and material parameters on natural frequencies and decay rate are studied.

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ABSTRACT: Based on first-order shear deformation, this paper investigates the nonlinear dynamic analysis and vibration of shear deformable imperfect eccentrically stiffened functionally graded thick cylindrical panels, taking into account the damping when subjected to mechanical loads. The volume fractions of metal and ceramic are applied by Sigmoid-law distribution for functional graded material (S-FGM) with metal–ceramic–metal layers. The panels are assumed to be resting on elastic foundations and are reinforced by eccentric longitudinal and transversal stiffeners made of full metal. The nonlinear equations are solved by the Galerkin method and fourth-order Runge–Kutta method. The influences of inhomogeneous parameters, dimensional parameters, stiffeners, elastic foundations, boundary conditions and mechanical loads on the nonlinear dynamic analysis and nonlinear vibration of thick S-FGM cylindrical panels are examined in detail. The results are compared with known results in the literature.

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ABSTRACT: In the present study, free vibrations and stability of rotating single walled carbon nanotubes (SWCNT) is investigated by nonlocal theory of elasticity; while the CNT is partially resting on an elastic foundation. The governing equations of motion are presented by using Love’s shell assumptions. An exact series expansion method of solution is employed and very accurate results are obtained. Some parameter studies including the effects of rotating speed, foundation stiffness, slenderness ratio and nonlocal parameter on the natural frequency and stability margins of the current model are studied. The studies show that rotation rates and foundation elasticity can contribute significantly in the dynamic characteristics of rotating MEMS devices.

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ABSTRACT: The important role of imperfections on decreasing the buckling load of structural cylinders has been investigated by scientists and engineers for the past century, yet there is currently no method that is able to stochastically replicate the full range of realistic imperfections for a full account of possible buckling loads. This drawback impairs optimised design as designers are restrained to using an outdated and conservative design philosophy which dates from 1968. Modern manufacturing methods and materials such as composites require new, optimised design measures to take full advantage of their efficiencies. Stochastic analyses can optimise and improve the reliability of such cylinders through accurate prediction of the range of conceivable buckling loads by realistic simulation and sensitivity analyses. A stochastic procedure which realistically models imperfection sensitive composite shells is investigated in this paper. Monte-Carlo simulations of axially compressed cylinders with the full range of imperfection types are performed to show that the stochastic methods described here are able to accurately capture the scatter in the buckling load introduced from the imperfections. The results from a sensitivity analysis indicate that loading imperfections play the largest role in reducing the buckling load knockdown factors of the shell.

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“Results on best theories for metallic and laminated shells including layer-wise models”, Composite Structures,
The abstract text is as follows:

ABSTRACT: This paper deals with Best Theory Diagrams (BTDs) for metallic and laminated shells. The BTD is a curve that is defined over a 2D reference frame in which the horizontal axis indicates the error of a shell model with respect to a reference solution whereas the vertical axis indicates the number of displacement variables of the model. The best reduced model is a refined model that offers the lowest possible error for a given number of variables. The relevant terms of a model are detected by means of the axiomatic/asymptotic method (AAM), and the error is related to a given variable with respect to an exact or quasi-exact solution. In this work, a genetic algorithm has been used to obtain the BTD. The Carrera Unified Formulation (CUF) has been employed to build the refined models. The CUF makes it possible to generate automatically, and in a unified manner, any plate or shell models. Equivalent Single Layer (ESL) and Layer Wise (LW) refined models have been considered. The governing equations for shells have been obtained through the Principle of Virtual Displacements (PVD), and Navier-type closed form solutions have been considered. BTDs have been constructed by considering the influence of several parameters, such as various geometries, material properties, layouts, different displacement/stress components and loadings. The accuracies of some well-known theories have been evaluated and compared with BTD reduced models. The results suggest that, since the BTD depends on the problem characteristics to a great extent, the systematic adoption of the CUF and the AAM can be considered as a powerful tool to evaluate the accuracy of any structural theory against a reference solution for any structural problem.
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ABSTRACT: The free and forced vibration characteristics of bimodular cross-ply laminated clamped–clamped circular cylindrical shells are studied using Bert’s and a recently proposed model considering first order shear deformation theory. The free vibration frequencies in positive and negative half cycles are found to be same for all asymmetric modes and for axisymmetric modes with even number of axial half waves, and different for axisymmetric modes with odd number of axial half waves. However, the negative half cycle amplitude is significantly greater than the positive half cycle amplitude due to the local stiffness of bimodular cylindrical shells being different for positive and negative half cycles even though the natural frequencies are same for positive and negative half cycles of asymmetric vibrations. The relative difference of positive and negative half cycle frequencies is very less for single layer orthotropic shells, and it is significant for cross-ply shells for axisymmetric mode of vibration. The vibration characteristics predicted using proposed and Bert’s constitutive models are quite close except for the transverse to the fiber direction normal stress.

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ABSTRACT: In this work a new device has been developed to estimate compression-after-impact (CAI) strength. This device allows the testing of laminates thinner than those recommended by CAI test standards. The proposed device is composed of a support structure, with a set of vertical ribs that stabilize the specimen during the test, increasing the buckling load. A numerical analysis was made to ensure that global buckling does not occur in the laminate during the CAI test, and that there is no interference with the damage area. Laminate specimens were tested with the proposed device and the ASTM device. For specimens 4.416 mm thick (thickness according to ASTM D7137 standard), the test results were similar with both devices. For thinner laminates, higher CAI strength was estimated with the proposed device than with the ASTM device, showing that the global buckling was delayed.

ABSTRACT: The present study deals with numerical and experimental investigations on free vibration behavior of woven fiber Glass/Epoxy laminated composite shells subjected to hygrothermal environments. A composite doubly curved shell model based on first order shear deformation theory (FSDT) is considered for free vibration of shells subjected to elevated temperatures and moisture concentrations. A quadratic eight-noded isoparametric element is used for the analysis. Series of experiments is conducted to obtain natural frequencies of vibration for woven fiber Glass/Epoxy laminated composite shells using B&K FFT analyzer with PULSE software. Parametric study is carried out varying the curvature ratios, number of layers of laminate and lamination sequences on fundamental natural frequencies of laminated composite shells for different
temperature and moisture concentration under different boundary conditions. The numerical and experimental results show that there is a reduction in natural frequency of laminated composite shells with the increase in temperature and moisture concentrations.

ABSTRACT: A formulation of a smart shell finite element for laminated curved structures with piezoelectric layers working under either the d31 or d33 effects has been developed in order to simulate dynamic tests. The electrical domain was modeled using a first order theory for the electrical field and a layer-wise approach. The mechanical domain is modeled using a degenerated shell theory with implicit curvature, considering a first order shear deformation theory and an equivalent single layer approach. The final formulation was implemented within Abaqus™ commercial finite element analysis package using its User Element (UEL) subroutine. First, some results provided by the proposed formulation were compared to numerical analyses shown by the literature. Second, the implemented finite element was evaluated using modal and frequency domain experiments for a cantilever aluminum beam with two piezoelectric transducers working under the d31 effects, and a free-free curved composite plate with four piezoelectric transducers working under the d33 effects. Comparisons between the natural frequencies and the frequency response functions amplitudes obtained from the experiments and the computational analyses were performed in order to discuss the limitations and potentialities of the proposed formulation.

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ABSTRACT: Experimental studies and numerical simulations are performed to investigate the structural response of adhesively bonded CFRP cylindrical splice-joint panels subjected to axial compression. Splicer joints used in aerospace composite structures need to sustain the design ultimate loads in the presence of flaws due to manufacturing (debonds), in order to demonstrate compliance with flightworthiness. CFRP cylindrical splice-joint specimens with and without debonds are subjected to compression load. Experimental data reveals that the load-carrying capacity of splicer joint decreases in the presence of debonds. Numerical simulations are carried out in line with experimental observations using finite element analysis. Good correlations with experimental results are obtained both in terms of buckling load capacity and load–displacement responses. Non-destructive methods, pulsed thermography and acoustic emission, are employed to detect and monitor the response of debond respectively. Parametric studies are also performed using finite element analysis to assess the influence of bi-directional loading and the effect of the physical gap provided between basic panels in the splicer joints.

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ABSTRACT: In this paper, the supersonic flutter characteristics of doubly curved sandwich shell panels, viz., cylindrical and spherical shells, with carbon nanotube (CNT) reinforced facesheets are investigated using QUAD-8 shear flexible shell element developed based on higher-order structural theory. The formulation accounts for the nonlinear variation of the in-plane and transverse displacements through the thickness, and abrupt discontinuity in slope of the in-plane displacement at the interface. The strain–displacement relation is accurately introduced in the formulation. The first-order high Mach number approximation to linear potential flow theory is employed for evaluating the aerodynamic pressure. The solutions of the complex eigenvalue problem, developed based on Lagrange’s equation of motion, are obtained by QR algorithm. The accuracy of the present formulation is validated considering the problems for which solutions are available in the literature. A detailed numerical study is conducted to highlight the significance of the higher-order model over the first-order theory and also to examine the influence of the volume fraction of the CNT, core-to-face sheet thickness, the shell thickness and the aspect ratio, radius-to-thickness ratio, and temperature on the flutter boundaries.

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ABSTRACT: The paper proposed a coupled numerical method for the static and fundamental frequency optimization of folded laminated composite plates. In the optimization schemes, the objective function is to minimize the strain energy for static problems and to maximize the fundamental frequency for free vibration problems. The fiber orientations are taken as design variables which are discrete integer values between −90° and 90°. For analyzing effectively the behavior of folded laminated composite plates, a recently proposed smoothed triangular plate element, named the cell-based smoothed discrete shear gap method (CS-DSG3), is applied. For searching the optimal solution which contains discrete integer values, an adjusted Differential Evolution (aDE) algorithm is proposed by integrating the conventional Differential Evolution (DE) for searching the optimal continuous solution with a novel technique for handling discrete integer variables and a mutation strategy. The reliability and effectiveness of the proposed aDE are verified by comparing its numerical results with those of other algorithms in literature such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), etc.

Huu-Tai Thai and Seung-Eock Kim (Department of Civil and Environmental Engineering, Sejong University, 98 Gunja Dong Gwangjin Gu, Seoul 143-747, Republic of Korea), “A review of theories for the modeling and
ABSTRACT: In this paper, a comprehensive review of various theories for the modeling and analysis of functionally graded plates and shells is presented. The review is devoted to theoretical models which were developed to predict the global responses of functionally graded plates and shells under mechanical and thermal loadings. This review mainly focuses on the equivalent single layer theories including the classical plate theory, first-order shear deformation theory, higher-order shear deformation theories, simplified theories and mixed theories since they were widely used in the modeling of functionally graded plates and shells. In addition, a thorough review of the literature related to the development of three-dimensional elasticity solutions and a unified formulation is also presented.

Chenghu Li and Zhi Wu (School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China). “Buckling of 120-degree stiffened composite cylindrical shell under axial compression – Experiment and simulation”, Composite Structures, Vol. 128, pp 199-206, September 2015, https://doi.org/10.1016/j.compstruct.2015.03.056

ABSTRACT: Typical specimens (with a central angle of 120°) of stiffened composite cylindrical shell structure and the experimental clamp tools are designed in the experiment. As the experiment results show, in compression, the upper and the lower part of the specimens concave inward and the middle part bulges outward. The buckling destruction of specimens is observed in the middle part and the transverse stiffeners debond from the skin in compression. The compression buckling experiment is simulated with three methods: linear buckling, eigenvalue-based nonlinear buckling, and implicit nonlinear buckling. As the finite element simulation results show, when the border has no side stiffeners or the side stiffeners are inadequately intensified, the model buckles first at the border; when the side stiffeners are adequately intensified, the model buckles first in the middle. The simulation results of the three methods fit the experiment results properly.

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ABSTRACT: Sizing of hat-stiffened composite panels presents challenges because of the broad design hyperspace of geometric and material parameters available to designers. Fortunately, design tasks can be simplified by performing parameter sensitivity analysis a priori and by making design data available in terms of a few select parameters. In the present study, we describe parametric modeling and design sensitivity analyses performed on hat stiffener elements for both single and multiple-hat-stiffened panels using parametrically defined scripting finite element analysis (FEA) models and an idealized analytical solution. We fabricated a composite skin panel and 4 hat stiffeners using out of autoclave (OoA) and vacuum bag only (VBO) techniques. The stiffeners were subsequently bonded to the skin to form a multi-hat-stiffened panel. To validate the FEA and analytical solutions, multi-point deflections were measured using different loading conditions. The analytical solution provided upper and lower bounds for the center-point deflections of the panels, values potentially useful for hat-stiffened composite panels. The detailed FEA results accurately revealed the design sensitivities of relevant geometric parameters of hat-stiffened composite panels. The findings constitute a first step towards a structural and scripted FEA framework to speed the development and qualification of composite
aircraft structures. The framework has the potential to reduce design cost, increase the possibility of content reuse, and improve time-to-market.

ABSTRACT: A geometrically nonlinear theory is developed for shells of generic shape allowing for third-order shear deformation and rotary inertia by using five parameters: in-plane and transverse displacements and the two rotations of the normal; geometric imperfections are also taken into account. The novelty is that geometrically nonlinear strain–displacement relationships are derived retaining full nonlinear terms in all the five parameters. These relationships are presented in curvilinear coordinates, ready to be implemented in computer codes. Higher order terms in the transverse coordinate are retained in the derivation so that the theory is suitable also for thick laminated shells. The theory is applied to laminated composite circular cylindrical shells complete around the circumference and simply supported at both ends. Initially static finite deformation and buckling due to lateral pressure is studied. Finally, large-amplitude forced vibrations under radial harmonic excitation are investigated by using the new theory and results are compared to another third-order shear deformation theory that neglects nonlinear terms in rotations of the normal.

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ABSTRACT: This paper presents a method for the determination of the buckling loads of symmetrically laminated composite plates under uniaxial compressive load with explicit consideration of bending–twisting-coupling (BTC). The plates under consideration are assumed to be thin and balanced with a symmetric stacking sequence and consist of layers with ply orientations of \{0°/±45°/90°\}, but otherwise arbitrary lamination schemes. The characteristic laminate quantities are described in a non-dimensional notation in order to capture all combinations of material and stacking sequences that are physically possible. Plates with rectangular planforms in the framework of Classical Laminate Theory (CLT) under several different sets of boundary conditions are considered, and the buckling problem of such composite laminated plates is solved in an approximate manner by using the classical Rayleigh–Ritz method. Several combinations of the boundary conditions ‘simply supported’ and ‘clamped’ are analyzed, and the obtained results are compared with finite-element simulations for verification purposes. Based on the computed data, two different design equations for sufficiently long plates are developed which allow for a rapid and closed-form analytical assessment of the buckling behavior of symmetrically layered composite plates under explicit consideration of bending–twisting coupling. It is found that the closed-form analytical analysis equations are simple in their application and yet still work with very satisfying accuracy which makes them very suitable for use in practical engineering work.
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“Load carrying capacity of functionally graded columns with open cross-sections under static compression”, Composite Structures, Vol. 129, pp 1-7, October 2015, https://doi.org/10.1016/j.compstruct.2015.03.072

ABSTRACT: The nonlinear problems of static interactive buckling of thin-walled columns with a top hat cross-section and a lip channel cross-section, which are made of functionally graded materials (FGMs), are considered. The FG structures are subjected to static compression. The effect of temperature is neglected. It is assumed that functionally graded materials are subject to Hooke’s law. An interaction of different modes has been analyzed in detail. Numerous different combinations of buckling modes have been computed. In all cases the theoretical value of load carrying capacity has been determined. In order to obtain the equilibrium equations of thin-walled structures from Hamilton’s Principle for the asymptotic analytical–numerical method. The classical laminate plate theory (CLPT) which has been modified in such a way that it additionally accounts for the full Green’s strain tensor and the second Piola–Kirchhoff’s stress tensor has been applied. The study is based on the numerical method of the transition matrix using Godunov’s orthogonalization. Distortions of cross-sections and a shear-lag phenomenon are examined. This paper is a continuation of the study described in the work of the authors entitled: “Static interactive buckling of functionally graded columns with closed cross-sections subjected to axial compression” Composite Structures 123, 2015, 257–262.

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ABSTRACT: The present article reviews the recent research done on the free vibration analysis of multilayered laminated composite and sandwich plates using various methods available for the analysis of plates. Displacement fields of various displacement based shear deformation theories have been presented and compared. Also, some numerical results related to fundamental flexural mode frequencies of laminated composite and sandwich plates are presented using a trigonometric shear and normal deformation theory. The theory involves six unknown variables and does not require problem dependent shear correction factor. Governing differential equations and associated boundary conditions of the theory are derived by employing the dynamic version of the principle of virtual work. Navier-type closed-form solutions are obtained for simply supported laminated composite and sandwich plates. The present results are compared with exact elasticity solution and other higher order shear deformation theories wherever applicable. This article cites 391 references.

ABSTRACT: In this article, large amplitude flexural behaviour of functionally graded doubly curved shell panel is investigated numerically under the thermomechanical load. The nonlinear mathematical model of doubly curved shell panel is developed first time based on higher-order shear deformation theory and Green–Lagrange geometrical nonlinearity. In order to achieve the exact flexure of the structure, all the nonlinear higher order terms are included in the mathematical model. The effective material properties of functionally graded material (metal/ceramic) have been obtained based on Voigt’s micromechanical model. The continuous gradation of metal and ceramic is achieved through the power-law distribution. The governing equation of the panel structure is obtained using the variational principle and a direct iterative method is employed to compute the desired responses numerically. The convergence behaviour of the proposed numerical analysis has been checked and validated through different comparisons to that available literature. Wide variety of examples is solved to reveal the effect of different geometrical parameters, material properties, constraint conditions and thermal and/or mechanical loads on the linear and nonlinear flexural behaviour of functionally graded curved panels.

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“Axial energy absorption of CFRP truncated cones”, Composite Structures, Vol. 130, pp 18-28, October 2015,  
https://doi.org/10.1016/j.composites.2015.04.026

ABSTRACT: Truncated cones made of composite materials, intended for structural applications in the automotive industry, have been studied from the point of view of their energy absorption capability when submitted to axial loading. The study has been developed at first applying quasi-static loads and then dynamic impact ones. The material used for this research is a fabric prepreg obtained by high-strength carbon fibers embedded in an epoxy resin. Three different geometrical parameters of the cones have been considered: the wall thickness (3 different values), the cone angle (3 different values) and the minor internal diameter (3 different values) and a total amount of 25 tests have been performed for each loading conditions. Results are shown in terms of load–displacement and current crushing stress–displacement diagrams; characteristic trends are compared and discussed. Finally SEA and average crushing stress are analyzed and their dependency on the above mentioned geometrical parameters are evaluated.

A. Sabik and I. Kreja (Department of Structural Mechanics, Gdańsk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland), “Thermo-elastic non-linear analysis of multilayered plates and shells”,  
Composite Structures, Vol. 130, pp 37-43, October 2015,  
https://doi.org/10.1016/j.compstruct.2015.04.024

ABSTRACT: Geometrically nonlinear FEM analysis of multilayered composite plates and shells is performed in order to resolve the stability problem of the structures being under the influence of temperature field. The Riks–Wempner–Ramm algorithm with a specially modified multi-choice unloading condition has been implemented in authors’ numerical code. As the representation of multilayered medium the Equivalent Single Layer approach with the First Order Shear Deformation kinematics is employed. The effectiveness of the proposed model is examined in numerical examples with reference solutions available in the literature. Presented study proves that the proposed approach can be very effective in the analysis of stability of thin-walled thermally loaded panels.

ABSTRACT: Hybrid square tubes made from S2 glass/epoxy composites and 304 stainless steel with different fiber orientation, stacking sequence, and thickness are tested under quasi-static loading. The thickness of composite section is identified as an important parameter that can change the crushing mode of stainless steel tubes and also, in some cases, lower its energy absorption due to change in plastic deformation. In addition, a new triggering design is introduced that can increase the crushing load efficiency (ratio of mean crushing to maximum load) up to 13% compared to a chamfered trigger.


ABSTRACT: In this paper, an accurate solution is developed for the vibration and damping characteristics of a three-layered passive constrained layer damping (PCLD) cylindrical shell with general elastically restrained boundaries. In this formulation, characteristic equations of the system are derived by using the modified Fourier–Ritz method in conjunction with Donnell shell assumptions and linear viscoelastic theory. Regardless of boundary conditions, the displacements of each layer are expanded as the linear combination of a standard Fourier series and closed-form functions introduced to eliminate all the relevant discontinuities with the displacements and derivatives at the edges. This method can be universally applicable to all classical boundaries, elastic boundaries and their combinations without any special change in the solution procedure. It provides an effective way to investigate the influence of restraints from different directions on the vibration and damping performance of PCLD shells. New results for elastic restraints and intermediate ring supports are presented, which may serve as benchmark solutions. Furthermore, the detailed effects of thickness of layers and shear parameter on natural frequencies and loss factors are also illustrated.

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ABSTRACT: The work is devoted to the non-linear dynamic stability of heterogeneous orthotropic truncated conical shells subjected to the combined static and time-dependent axial loads. The basic equations are derived using the finite deflection theory with von Karman–Donnell-type of kinematic non-linearity and reduced to a non-linear differential equation with the time variable coefficient using the superposition principle and Galerkin method. The resulting equation is solved numerically using Runge–Kutta method for variety of an axial loading speed, heterogeneity of features, orthotropic material properties and conical shell characteristics to obtain the non-linear critical time parameters. Finally, the influences of the axial loading speed, non-linearity, heterogeneity and orthotropy on the dimensionless critical time parameters are discussed in detail.
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ABSTRACT: Despite the abundance of studies investigating the performance of composite structures under crush loading, disagreement remains in the literature regarding the effect of increased strain rate on the crush response. This study reports an experimental investigation of the behaviour of a carbon–epoxy composite energy absorber under static and dynamic loading with a strain rate of up to 100/sec. Consistent damage modes and measured force responses were obtained in samples tested under the same strain rate. The energy absorption was found to be independent of strain rate as the total energy absorption appeared to be largely associated with fibre-dominated fracture, which is independent of strain rate within the studied range. The results from this study are beneficial for the design of energy absorbing structures.

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ABSTRACT: Due to a lack of statistical data, unstiffened cylindrical lightweight structures are designed following a knockdown factor (KDF) approach described in the NASA SP-8007 (Weingarten and Seide, 1965). This approach aims at a lower-bound, conservative design. The basis for the proposed KDFs are a number of tests with different, partially unknown boundary conditions and imperfection patterns for metallic cylinders that do not resemble the imperfection patterns achieved by state-of-the-art manufacturing methods for cylinders made of carbon fibre reinforced plastics (CFRP). Within this work, two CFRP tubes are manufactured using the filament winding method and are cut into a total of 12 cylinders from which optical measurements are taken to analyse characteristics of the corresponding imperfection patterns. 11 cylinders are tested in axial compression until buckling occurs and tests are accompanied by high speed displacement measurements, thermography and measurements of occurring load imperfections. Four different FE-models, which differ in the parameters considered, are set up for prediction of the buckling load of each cylinder. Model response showed the highest sensitivity to load imperfections. Negligence of this parameter lead to a 15% increase of the corresponding model bias while geometric imperfections made up for only 3%.

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ABSTRACT: In this work, the combined effect of moisture and temperature on the bending behavior of simply supported anisotropic cylindrical shells has been investigated. Initially three dimensional equilibrium equations of thermoelasticity, simplified to the case of a generalized plane strain deformations in the axial direction are solved analytically for an anisotropic cylindrical shell strip under thermal loading. Based on the realistic variation of displacements from the elasticity approach, a new 13 term higher order shear deformation theory HSDT13 was proposed for the analysis of an anisotropic cylindrical shell strip under hygrothermal and mechanical loading. The zigzag form of the displacement is incorporated via the Murakami zigzag function. Results are presented for mechanical and thermal loading for various layups and they are validated against the derived elasticity solution. The significance of retaining various higher-order terms in the present model HSDT13, in evaluating the stresses and deflection for composite laminates is brought out clearly through parametric study. Useful results for combined hygrothermal loading are presented in tabular and graphical form. It is expected that the numerical results presented herein will serve as benchmark in future.

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ABSTRACT: This paper details the theory and implementation of a composite damage model, addressing damage within a ply (intralaminar) and delamination (interlaminar), for the simulation of crushing of laminated composite structures. It includes a more accurate determination of the characteristic length to achieve mesh objectivity in capturing intralaminar damage consisting of matrix cracking and fibre failure, a load-history dependent material response, an isotropic hardening nonlinear matrix response, as well as a more physically-based interactive matrix-dominated damage mechanism. The developed damage model requires a set of material parameters obtained from a combination of standard and non-standard material characterisation tests. The fidelity of the model mitigates the need to manipulate, or “calibrate”, the input data to achieve good agreement with experimental results. The intralaminar damage model was implemented as a VUMAT subroutine, and used in conjunction with an existing interlaminar damage model, in Abaqus/Explicit. This approach was validated through the simulation of the crushing of a cross-ply composite tube with a tulip-shaped trigger, loaded in uniaxial compression. Despite the complexity of the chosen geometry, excellent correlation was achieved with experimental results.

Amir Nasirmanesh and Soheil Mohammadi (High Performance Computing Lab, School of Civil Engineering, University of Tehran, Tehran, Iran), “XFEM buckling analysis of cracked composite plates”, Composite Structures, Vol. 131, pp 333-343, November 2015, https://doi.org/10.1016/j.compstruct.2015.05.013

ABSTRACT: Linear eigenvalue buckling analysis for cracked uni-layer composite plates is performed in the
framework of the extended finite element method (XFEM). The geometry of the problem is discretized using the 8-noded degenerated shell element, which includes transverse shear deformation effects. The effects of several parameters such as crack lengths and angles, fiber directions and boundary conditions on the buckling behavior of cracked composite plates are comprehensively investigated for different loading conditions including compressive, tensile and shear loadings. Also, the accuracy and efficiency of the proposed method are discussed and compared with the available results.


ABSTRACT: The stochastic nonlinear snap-through response of a clamped composite panel under the combination of a severe acoustic excitation and a steady thermal effect has been investigated through the single-mode Fokker–Planck distribution function. The snap-through is a post-buckling behavior, which results in large amplitude vibration between two equilibrium configurations. A novel parameter, which is deduced from the single-mode Fokker–Planck distribution function and the depth of the potential energy well, is proposed to predict the transition from no snap-through to a persistent stochastic snap-through. The effects of the excitation, damping, the stiffness and the temperature variation on the stochastic dynamic snap-through response boundary have been given by a parametric analysis. Results from the single-mode analysis have been validated extensively by the explicit finite element numerical simulation for a heated clamped composite panel under the overall sound pressure (OASPL) of 120–176 dB.

S. Sahmani, M.M. Aghdam and M. Bahrami (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “On the postbuckling behavior of geometrically imperfect cylindrical nanoshells subjected to radial compression including surface stress effects”, Composite Structures, Vol. 131, pp 414-424, November 2015, https://doi.org/10.1016/j.compstruct.2015.05.031

ABSTRACT: The main objective of the present study is to investigate the effect of surface stress on the nonlinear buckling and postbuckling behavior of cylindrical nanoshells with initial geometric imperfection subjected to radial compressive load. Gurtin–Murdoch elasticity theory is implemented into the classical shell theory to develop a size-dependent shell model which is capable to capture surface stress effects efficiently. In order to satisfy balance conditions on the surfaces of nanoshell, a linear variation through the thickness is considered for the normal stress component of the bulk. The principle of virtual work is put to use in order to formulate the non-classical governing differential equations. Afterwards, a boundary layer theory is employed including the nonlinear prebuckling deformations, initial geometric imperfection and large postbuckling deflections. Finally, a two-stepped singular perturbation methodology is utilized to obtain the size-dependent critical buckling loads and the postbuckling equilibrium paths of imperfect nanoshells corresponding to both lateral and hydrostatic pressure loading cases. It is found that for the positive and negative values of surface elastic constants, the both critical buckling load and critical end-shortening of nanoshell increase and decrease, respectively.

Francesco Tornabene, Nicholas Fantuzzi, Michele Bacciocchi and Erasmo Viola (DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy), “A new approach for treating concentrated loads in doubly-curved composite deep shells with variable radii of curvature”, Composite Structures, Vol. 131, pp 433-452, November 2015, https://doi.org/10.1016/j.compstruct.2015.05.049
ABSTRACT: The point load static problem for structural components is a classic numerical test that can be found in several finite element benchmarks throughout the literature. In finite element analysis, since the solution is found in integral form within each element, concentrated forces can be applied at every mesh node. On the contrary, collocation methods do not admit to apply concentrated forces at their collocation points, since only smooth and continuous functions can be discretized. Exploiting a mixed approach of integral and differential quadrature it is possible to treat concentrated loads using Dirac-delta function. Thus, this paper shows convergence, stability and accuracy of the present approach when applied to beams, plates and doubly-curved thin and thick shells. The GDQ method is considered, in particular the best grid point collocation is found in order to achieve the best accuracy using Dirac-delta function. In addition, an alternative approach is presented for the first time, simulating a point load using a continuous and smooth normalized Gaussian distribution.

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ABSTRACT: Reinforced thermoplastic pipes (RTPs) are promising design solutions for deep-water riser applications due to their light weight, high performance and good spoolability. For such applications, RTPs experience significant ambient pressure and sustain bending and/or tension loads during the installation and operation phases. Normally an RTP is composed of an inner Polyethylene (PE) liner, reinforced layers made from fibre-reinforced PE composites and an outer PE cover. The mechanical behaviour of such an RTP when it has been subjected to combined external pressure and bending has been studied through finite-element analysis (FEA). The nonlinear mechanical behaviour of both PE and the fibre-reinforced PE composites has been modelled by developing numerical algorithms that reflect the strain-dependent mechanical characteristics of PE. These algorithms are implemented in the analysis tool used, Abaqus/Standard, with the user subroutine, UMAT. The proposed FE model could accurately simulate the buckling and post-buckling response of the RTP and predict its failures under the combined external pressure and bending. Rotation-pressure interaction collapse envelopes of the RTP in different loading paths are generated. Additionally, the effects of ply angles, loading paths and diameter-to-thickness (D/t) ratios on the performance of the RTP under this loading case are investigated. The results obtained could be used to improve the design of RTPs for deep-water riser applications in the offshore oil and gas industry.

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ABSTRACT: Geometrically non-linear forced vibrations of cylindrical shells with variable stiffness are
analysed. The ordinary differential equations of motion are derived by the principle of virtual work in conjunction with a $p$-version finite element formulation. The shells are in composite laminates with curvilinear fibres, hence the stress–strain relation varies in space, leading to variable stiffness. External harmonic excitations are applied to the shell and periodic responses are sought, therefore, the solution can be expressed in a Fourier series. Distinctively, the harmonic balance method is applied via a procedure in the complex domain, with which one can employ as many harmonics as one wishes without manual changes in the algorithm or on its expressions. The resulting algebraic equation is solved by an arc-length continuation method. Studies of the convergence with the number of shape functions and with the number of harmonics are presented. The influence of the curvilinear fibre paths and of the curvature of the shells on the forced response are analysed.

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ABSTRACT: This paper presents the quantification of rotational and ply level uncertainty of random natural frequency for laminated composite conical shells by using surrogate modeling approach. The stochastic eigenvalue problem is solved by using QR iteration algorithm. Sensitivity analysis is carried out to address the influence of different input parameters on the output natural frequencies. The sampling size and computational cost is reduced by employing the present approach compared to direct Monte Carlo simulation. The stochastic mode shapes are also depicted for a typical laminate configuration. Statistical analysis is presented to illustrate the results and its performance.

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ABSTRACT: In this study, an improved high-order theory is presented for temperature-dependent buckling analysis of sandwich conical shell with thin functionally graded (FG) facesheets and homogenous soft core. First shear deformation theory (FSDT) is used for the facesheets and cubic functions are assumed for the transverse and in-plane displacements of the core. The nonlinear Von-Karman type relations are used to obtain the strain components. The equilibrium equations are derived via principle of minimum potential energy. Analytical solution for static analysis of simply supported sandwich conical shells under axial in-plane compressive load and in the temperature environments is performed using Galerkin’s solution. Numerical modeling is made by ABAQUS finite element (FE) code. The comparison shows that the present results are in good agreement with the results in the literature and the present FE results.
ABSTRACT: In this paper, we study the buckling characteristics of curvilinear fibre composite laminates exposed to hygrothermal environment. The formulation is based on the transverse shear deformation theory and it accounts for the lamina material properties at elevated moisture concentrations and thermal gradients. A 4-noded enriched shear flexible quadrilateral plate element is employed for the spatial discretization. The effect of a centrally located cut-out, modelled within the framework of the extended finite element method, is also studied. A detailed parametric investigation by varying the curvilinear fibre angles at the centre and at the edge of the laminate, the plate geometry, the geometry of the cut-out, the moisture concentration, the thermal gradient and the boundary conditions on the buckling characteristics is numerically studied.


ABSTRACT: Application of large-scale composite lattice cylinders in aeronautic and astronautic engineering is an effective way to reduce structure mass and achieve high mass efficiency. In this paper, structural stiffness and critical axial force of the lattice cylinder are analyzed theoretically by equivalent continuum method. For the lattice cylinder under axial compression, there are four failure modes, which are global buckling, out-of-plane strut buckling, in-plane strut buckling and strength failure. Curves of load capacity and failure maps related to the variation of non-dimensional variables are plotted respectively. According to the failure maps, failure of the large-scale lattice cylinder is generally dominated by global buckling due to relatively small strut thickness of the lattice cylinder. Based on finite element simulations, influence of four key geometrical parameters on stiffness and critical buckling force of the large-scale lattice cylinder under axial compression is discussed. Strut thickness and number of oblique strut rows have relatively great effects on the stiffness and critical buckling force, while number of horizontal strut rows should maintain a relatively small value in order to achieve high mass efficiency. Aimed to minimize mass of a specific Kagome lattice cylinder in practical engineering, a multi-parameter optimization model is built in MATLAB Optimization Toolbox™ and successfully applied to optimize the four geometrical parameters of the large-scale lattice cylinder under axial compression.

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ABSTRACT: This paper presents an investigation on the nonlinear behaviors of nanocomposite cylindrical panels subjected to the combined action of uniform lateral pressure and compressive edge loads. The panels may rest on elastic foundations and be in a varying temperature environment. The nanocomposite consists of reinforcing carbon nanotubes either uniformly distributed (UD) or functionally graded (FG) along the thickness direction of the panels. The two cases of nonlinear bending of initially compressed cylindrical panels and postbuckling of initially pressurized cylindrical panels are considered. A high-order shear deformation shell theory in association with von Kármán nonlinear strain–displacement relationships is applied to derive the governing equations for the carbon nanotube reinforced composite (CNTRC) panels. Furthermore, the effects of the panel-foundation interaction and the temperature variation are also included in the analysis and the material properties of CNTRC panels are assumed to be temperature-dependent. Numerical results are presented to illustrate the nonlinear bending responses and the postbuckling behaviors of CNTRC cylindrical panels resting on the Pasternak-type elastic foundations. The present solutions also highlight the effects of the CNT volume fraction, temperature rise, foundation stiffness as well as initial stress on the nonlinear behaviors of CNTRC cylindrical panels.

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ABSTRACT: Morphing shells are nonlinear structures that have the ability to change shape and adopt multiple stable states. By exploiting the concept of morphing, designers may devise adaptable structures, capable of accommodating a wide range of service conditions, minimising design complexity and cost. At present, models predicting shell multistability are often characterised by a compromise between computational efficiency and result accuracy. This paper addresses the main challenges of describing the multistable behaviour of thin composite shells, such as bifurcation points and snap-through loads, through the development of an accurate and computationally efficient energy-based method. The membrane and the bending components of the total strain energy are decoupled by using the semi-inverse formulation of the constitutive equations. Transverse displacements are approximated by using Legendre polynomials and the membrane problem is solved in isolation by combining compatibility conditions and equilibrium equations. This approach provides the strain energy as a function of curvature only, which is of particular interest, as this decoupled representation facilitates efficient solution. The minima of the energy with respect to the curvature components give the multiple stable configurations of the shell. The accurate evaluation of the membrane energy is a key step in order to correctly capture the multiple configurations of the structure. Here, the membrane problem is solved by adopting the Differential Quadrature Method (DQM), which provides accurate results at a relatively small computational cost. The model is benchmarked against three exemplary case studies taken from the literature.

References listed at the end of the paper:

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ABSTRACT: In this paper, the buckling behavior of functionally graded material (FGM) structures is investigated using the enhanced assumed strain (EAS) solid-shell element based on first-order shear deformation concept. Thus, a computational algorithm, for any type of laminates composites and/or FGM, is proposed for the shear correction factors estimation. Material properties are varied continuously in the thickness direction according to different distributions. This finite element is used to study the buckling behavior of FGM structures and to investigate the influence of same parameters on the buckling load. Comparisons of numerical results among existing ones show the performance of the developed elements.

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ABSTRACT: In this work we investigated the stability behavior and the folding capability of an ultrathin tubular composite boom with C-cross section to be used in nanosatellites applications. A nonlinear buckling analysis was performed using the Riks method, adopting a perturbed finite element model to study the influence of the unavoidable geometrical variations of the boom thickness, arising from the composite manufacturing processes, on the stability behavior of the tubular structure. The effect of several levels of geometrical imperfection on the buckling behavior was analyzed. The minimum coil radius that can be used for a safe storage the boom was determined by quasi-static explicit analysis. The boom folding process was considered as formed by two sequential steps, the flattening and the coiling. The stress fields associated with both steps were investigated.

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ABSTRACT: In this paper the results of a comprehensive numerical investigation regarding the axial–flexural–torsional response of pultruded slender beams is presented. The goal is to propose GFRP standard cross-sections of such proportions and shapes that would possess improved strength, stability and deformational characteristics compared to the corresponding existing sections whose proportions are generally based on standard steel sections. As GFRP sections are thin-walled but are significantly less stiff than similar steel sections, the study focuses on enhancing their appropriate stiffness and buckling strength. The novel and efficient numerical model used in this investigation was developed by the writers and can be used to trace the complete pre-buckling geometrically nonlinear response of any GFRP or steel thin-walled member with open or closed cross-section. The buckling load is computed by the asymptotic value of the load–displacement curve. Members with I-, L-, T- and box sections are analyzed, considering different loading and boundary conditions. It is demonstrated that due to their unsuitable proportions, available standard GFRP sections do not have adequate stiffness and buckling strength. Consequently, recommendations are made for new sectional proportions and modified shapes, and some graphical results are presented to demonstrate how the results of the proposed method could be utilized in practical design situations. The superiority of the proposed sections is quantified by an efficiency factor, defined in terms of ratio of strength gain to material volume increase.

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ABSTRACT: The foam-filled thin-walled composite structures have proven an ideal energy absorber in automotive engineering for its extraordinary energy absorption ability and lightweight features. Unlike existing uniform foam and thickness (UFT) structure, this paper introduces functionally graded foam (FGF) to fill into functionally graded thickness (FGT) thin-walled structure, named as double functionally graded (DFG) tube, where different configurations of foam and wall thickness gradients are taken into account. To systematically explore the crashworthiness of DFG structures, first, experimental results were performed to validate finite element (FE) models. Second, a comparison of crashworthiness was carried out for (1) four different DFG structures, (2) four single functionally-graded (SFG) structures and (3) one traditional UFT structure. The results showed that the DFG structures have better energy absorption capacity than the SFG and UFT structures, especially with a convex gradient configuration. In addition, the specific energy absorption (SEA) values of these four DFG structures are fairly close to each other, while their loading responses highly depend on the combination of gradients. Of these DFG structures, Ascending–Ascending configuration exhibits best overall crashworthiness characteristics. Finally, parametric studies were performed and the results indicated that widening the ranges of foam density and tube wall thickness can improve the energy absorption of the Ascending–Ascending DFG structures without increasing the initial peak load. Therefore, the DFG structure of Ascending–Ascending gradient is recommended for a potential absorber.
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ABSTRACT: Control and analyze the nonlinear dynamic stability of single layered graphene sheets (SLGSs) integrated with zinc oxide (ZnO) actuators and sensors are the main contributions of present work. In order to present a realistic model, the material properties of system are assumed viscoelastic using Kelvin–Voigt model. The surrounding elastic medium is simulated with nonlinear orthotropic visco-Pasternak foundation. Considering refined zigzag theory (RZT), a new formulation is developed through the Gurtin–Murdoch elasticity theory in which the effects of surface stress are incorporated. A novel numerical procedure namely as differential cubature (DC) method is applied for solution. A proportional-derivative (PD) controller is used for the active control of the system dynamic stability. The detailed parametric study is conducted, focusing on the combined effects of the nonlocal parameter, magnetic field, viscoelastic foundation, surface stress, applied voltage, controller and structural damping on the dynamic instability region (DIR) of system. The accuracy of the proposed method is verified by comparing its numerical prediction with other published works as well as solution of system with differential quadrature (DQ) and harmonic differential quadrature (HDQ) methods. Results depict that the magnetic field and external voltage are effective controlling parameters for DIR of system.

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“Mechanical and thermal stability of eccentrically stiffened functionally graded conical shell panels resting on elastic foundations and in thermal environment”, Composite Structures, Vol. 132, pp 597-609, November 2015, https://doi.org/10.1016/j.compstruct.2015.05.072
ABSTRACT: Conical shell panels made of functionally graded materials (FGMs) are rather commonly used by structural engineers. However, due to their complex geometric shape, there are only a few studies on conical shell panels made from FGMs. This paper investigates the linear stability analysis of eccentrically stiffened FGM conical shell panels reinforced by mechanical and thermal loads on elastic foundations. The FGM conical shell is in thermal environment and both the panel and the stiffeners are deformed under temperature. The material properties of both the panels and stiffeners are assumed to be temperature-dependent. Classical shell theory and Lekhnitsky’s smeared stiffeners technique are used to set the balance equations and linear stability. Shells are reinforced by stringers and rings. The effects of stiffeners, material, and mechanical and temperature loads on stability of the eccentrically stiffened FGM conical shell panels are analysed and discussed.

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ABSTRACT: In this paper, a first order shear deformation theory is proposed for cylindrical sandwich pipes subjected to undersea water pressure. The new model examines the change of the circumferential radius due to the radial deflection of the cylindrical sandwich shell and its effect on the bending moments. Differential equations of equilibrium for the non-shallow cylindrical sandwich shell are derived and are expressed in terms of the components of displacement and the rotation angles of the middle planes of the face sheets with respect to the neutral surface. The proposed theory is applied to investigate the buckling of a thermal insulating sandwich pipe laid on the seabed with fully constraint ends. Numerical analyses are conducted by developing MATLAB program to obtain the buckling pressures as well as the corresponding half wave numbers in circumferential direction for cylindrical sandwich pipes for different slenderness ratio, radius-to-thickness ratio and core-to-facesheet thickness ratio. The efficiency and accuracy of the presented theory is confirmed by comparing the analytical solutions with finite element results from ABAQUS, both showing a good agreement with each other.

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ABSTRACT: Many studies reveal that the dynamic compressive strength of metallic honeycombs is higher than the quasi-static one, but the reasons for that are still debatable. This paper aims to study the strain rate effect of parent materials on the out-of-plane dynamic compressive behavior of metallic honeycombs. Quasi-static and dynamic tests on aluminum honeycombs were performed with universal testing machine and Split Hopkinson Pressure Bar, respectively. The velocity values of dynamic tests were from about 6 to 19 m/s. The present and existing measures of plateau stress are evaluated by both the rate-independent (R-I) and rate-dependent (R-D) shock theories. It is shown that the R-D shock theory proposed in our previous study provides more accurate predictions at low, medium and high impact velocities. Based on the R-D shock theory, the influences of strain rate effect are analyzed quantitatively and the change tendencies of measured plateau stresses with impact velocities are explained reasonably. The analysis indicates that the strain rate effect has a large contribution to the dynamic enhancement of metallic honeycombs in a wide velocity range.

A.H. Sofiyev (Department of Civil Engineering of Engineering Faculty of Suleyman Demirel University, Isparta, Turkey), “Buckling analysis of freely-supported functionally graded truncated conical shells under external pressure”, Composite Structures, Vol. 132, pp 746-758, November 2015, https://doi.org/10.1016/j.compstruct.2015.06.026

ABSTRACT: This article presents a method to study the buckling of freely-supported functionally graded (FG) truncated and complete conical shells under external pressures in the framework of the shear deformation theory (SDT). The basic relations, modified Donnell type stability and compatibility equations have been obtained on the basis of SDT. The material properties of truncated conical shells are functionally graded in the thickness
direction according to a volume fraction power law distribution. To solve this problem is used an unknown parameter $\lambda$ in the approximation functions. One of innovations is to achieve closed-form solutions for critical lateral and hydrostatic pressures of freely-supported FG truncated and complete conical shells in the framework of the SDT. The parameter $\lambda$ which is included in the obtained expressions is get from the minimum conditions of critical external pressures. Finally, influences of shear stresses, volume fraction index and shell characteristics on the critical lateral and hydrostatic pressures are investigated.


ABSTRACT: In this paper, the deformation of cylindrical composite structures employing piezoelectric actuators is investigated. It specifically addresses radial deformations of a composite cylinder generated by macro fibre composites (MFC). The purpose is to experimentally characterise the shape as well as the magnitude of the composite cylinder’s deformation using an optical full-field 3D measurement system. Besides cylinder expansion and contraction under operating conditions, shell bending appeared to contribute significantly to the overall deformation behaviour. With the data provided the development of an adaptive primary aircraft structure is conceivable.


ABSTRACT: The present study is concerned with an analysis of load and frequency interaction effects in the dynamic buckling of sandwich plates and shells with a soft, transversely flexible core. The analysis is based of a general geometrically nonlinear soft-core sandwich model presented and a corresponding extended Galerkin solution strategy presented earlier. In the present study, the formalism is adopted and transformed into an eigenvalue problem. Assuming large transverse average displacements but small amplitudes for the vibration problem, a partially decoupled problem is obtained where in a first step the static buckling and face wrinkling problems can be addressed without consideration of the dynamic problem. In a second step, the dynamic eigenvalue problem can be solved, using the static solution as input parameters. The model is applied in parametric studies on the vibration response of plane and doubly curved sandwich panels with rectangular projection. In all cases, strong interaction effects between the external static preload and the natural frequencies are observed. The development of overall buckling or local face wrinkling instabilities enabled due to the transverse flexibility of the core result in distinct drops of the first natural frequency.

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ABSTRACT: This study investigates the problem of limit states of composite lipped channel columns under quasi-static compression. The numerical simulations based on the finite element method were made. The limit states corresponding to the loss of load-carrying capacity of the tested structures were described by the Tsai–Wu failure criterion. The stress components were determined numerically. The authors described a research methodology for macroscopic assessment of failure of the tested composite columns based on analysis of stress components in individual laminate plies. The FE-models were verified in experimental stand tests performed on real thin-walled structures. The columns were produced by the autoclave technique. The thin-walled structures were made of carbon–epoxy composite – a laminate consisting of 8 plies symmetrically oriented.

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ABSTRACT: The present work focuses on the quasi-static axial crush performance of the thin-walled tubes filled with hollow metal spheres (TWT-HMS) and their individual components (thin-walled tubes and hollow metal spheres) under axial compressive loads. All structures were compared in terms of the load–displacement and/or load–strain curves, energy absorption and energy absorbing efficiency curves. The results indicate that hollow metal spheres and thin-walled tubes are promising energy absorbing materials. The hollow metal spheres improve the axial bearing capability of thin-walled tube, and the biggest improvement scale can be 300%; due to the superimposed effect, TWT-HMS has more excellent properties than the hollow metal sphere and thin-walled tube. Thus, TWT-HMS is an energy absorbing structure with excellent properties and it has a promising application prospect.


ABSTRACT: The kink behavior of non-slender glass fiber-reinforced epoxy prismatic specimens of variable length and fiber volume fraction at temperatures ranging from 25 °C to 125 °C was investigated. Splitting failure occurred at the glassy state while kinking failure was observed at the glass transition state and buckling with subsequent post-peak kinking at the rubbery state. Kink initiation was caused by the initial imperfections, i.e. the waviness of the unidirectional fibers. Initiation occurred through fiber microbuckling caused by combined compressive and shear stresses at the glass transition state and predominant shear stresses at the rubbery state due to the preceding buckling. The kink band width was narrow at the glass transition state due to the significant compressive stresses and corresponded to the wavelength of the initial fiber waviness. The kink band width at the rubbery state was much wider and corresponded to the band width of the maximum shear stresses at the inflexion points of the buckling shape. The kink band angle depended on the ratio of compressive to shear stresses. The different specimen slendernesses and fiber volume fractions did not influence the kink initiation and kink band formation mechanisms.

ABSTRACT: In this paper, the modified Fourier series method is applied to study the vibration behavior of composite laminated doubly-curved shells of revolution with elastic restraints. The theoretical formulation is based on the first order shear deformation shell theory considering the effects of the rotary inertia and initial curvature. In summary, the shell energy functional, written in terms of stress resultants and mid-surface strains, is expressed as a function of five displacement components by using the constitutive and kinematic relationships. Each displacement of the shell is then expanded as a superposition of the standard cosine Fourier series and several auxiliary functions introduced to remove any potential discontinuous of the original displacement and its derivatives at the ends. The desired solutions are obtained by using the variational operation. The convergence and accuracy of the presented solutions are validated, with good agreement observed. A systematic parametric study is also performed regarding the effects of the boundary conditions, lamination schemes, material and geometrical parameters. Finally, a variety of new vibration results including frequencies and mode shapes for circular toroidal, elliptical, paraboloidal and hyperbolical shells with classical and elastic boundary conditions as well as different geometric and material parameters are also presented, which may serve as benchmark solutions for the future researches.

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ABSTRACT: Elliptic geometries appear to be important components in engineering practices. The purpose of the present study is to examine the free vibration nature of laminated composite thick and moderately thick elliptic cones, cylinders and plates. A strong form approach, such as the generalized differential quadrature (GDQ) method is employed to carry out the numerical analyses. The geometric description of the structures under consideration is performed through the differential geometry which is a convenient and general mathematical tool to have parametric description of curved structures. Reference solutions are presented for laminated composite thick elliptic shells. 3D finite element models are used for proving the validity and the advantages of the present methodology. Since laminated composite structures are investigated, higher-order theories are considered to capture the nonlinear behavior of the material fibers through the shell thickness. In particular, a hierarchical expansion order of the kinematic displacements is adopted. The expansion order is a function of a free parameter. The numerical solution is found discretizing the dynamic equilibrium equations, written as functions of the displacement parameters, with GDQ method. This technique proved to have several advantages such as stability, accuracy and easy implementation as also demonstrated by the authors in the provided literature.

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ABSTRACT: Corrugation has long been seen as a simple and effective means of forming lightweight structures with high anisotropic behaviour, stability under buckling load and energy absorption capability. This has been exploited in diverse industrial applications and academic research. In recent years, there have been numerous innovative developments to corrugated structures, involving more elaborate and ingenious corrugation geometries and combination of corrugations with advanced materials. This development has been largely led by the research interest in morphing structures, which seek to exploit the extreme anisotropy of a corrugated panel, using the flexible degrees of freedom to allow a structure’s shape to change, whilst bearing load in other degrees of freedom. This paper presents a comprehensive review of the literature on corrugated structures, with applications ranging from traditional engineering structures such as corrugated steel beams through to morphing aircraft wing structures. As such it provides an important reference for researchers to have a broad but succinct perception of the mechanical behaviour of these structures. Such a perception is highly required in the multidisciplinary design of corrugated structures for the application in morphing aircraft.

ABSTRACT: This paper presents a layerwise finite element formulation for dynamic analysis of functionally graded material (FGM) sandwich shell in thermal and non-thermal environments. The layerwise theory used in this work is based on the first-order shear deformation theory (FSDT) for each layer satisfying the displacement continuity at layer interface. Two configurations of FGM sandwich shells are considered, the first with FGM facesheet and homogenous core, and the second having homogenous facesheets and FGM core. Effective material properties of the FGM are estimated according to two micromechanical models, namely, Voigt’s rule of mixture (ROM) and Mori–Tanaka (MT) scheme. For the shells in thermal environment, a nonlinear temperature distribution in thickness direction is considered and the elastic properties are assumed to be temperature dependent. The results obtained from the proposed formulation are validated with those available in the literature. Natural frequencies obtained from Sanders’, Love’s and Donnell’s shell theories for different geometric and boundary conditions are compared to assess the performance of different shell theories for FGM sandwich shells under non-thermal environment. The effects of volume fraction index, core thickness and temperature gradient on natural frequencies of FGM sandwich shells are investigated. The present formulation is simple, accurate and computationally efficient.

ABSTRACT: Crashworthiness optimization of aircraft and automotive structures has become one the main research targets for their respective leading industries. The following research proposes a new design of an aircraft’s vertical strut. The design consists of a hollow aluminum square tube with a glass-fiber reinforced polymer honeycomb-shaped inner structure. Size and shape surrogate-based optimization techniques are used, with the thicknesses of both materials, cell size and cell shape as design variables. The objective function chosen for the single-objective optimization is the specific energy absorption, while the metrics for the multi-
objective optimization are the peak force, mass, absorbed energy and the specific energy absorption. An improvement of 22% of the specific energy absorption with low peak force values is obtained from the single-objective optimization by significantly changing all design variables. Two Pareto fronts have been obtained from the multi-objective optimization confronting, the specific energy absorption against the peak force and the mass against the energy absorbed. When compared to the baseline model, the optimized models show substantial improvement, increasing the specific energy absorption by 65% or reducing the peak force by over 55%. It has been observed an important effect of the cell shape on the model’s performance.

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ABSTRACT: The present study consists on experimental analyses of composite cylinders made by filament winding process, which are under transverse impact loading. The results are shown and discussed considering the influence of the stacking sequence as well as the total thickness of the cylinders. Thus, the results are normalized regarding the stiffness of each cylinder, and there are discussions based on identified damages, different graphics (force, displacement and strain vs. time), energy balance between impactor and coupons, as well as elastic and dissipated energy ratios and response delays for different strain gauges positions on the cylinders. Finally, guidelines for designing composite cylinders are presented considering the aspects addressed by the experimental analyses.

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ABSTRACT: Free vibrations of a cantilever composite lattice cylindrical shell with the rigid disk attached to its free end are considered in the paper. The filament-wound lattice cylinder is modelled as a continuous shell characterised by the effective stiffness parameters. The governing equations of motion are derived using the semi-membrane theory of orthotropic cylindrical shells. The free vibration problem formulated based on these equations is reduced to a transcendental equation. The solution of this equation yields the fundamental frequency of the composite lattice cylinder under consideration. The results of calculations are verified by comparison with a finite-element solution. The effect of the angle of orientation of unidirectional helical ribs on the magnitude of fundamental frequency is studied using a parametric analysis.

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ABSTRACT: A nonlinear analytical model for investigating localized interactive buckling in simply supported thin-face plate sandwich struts with weak cores is extended to account for local deformations in both face plates, which have been observed in experiments and finite element simulations. The original model is based on potential energy principles with large displacement assumptions. It assumes Timoshenko shear deformable theory for the core and approximates the overall mode as a half-sine wave along the length of the strut while the local face plate displacements are initially unknown and are found as solutions of the governing equations. The extended model is able to capture measurable local face plate displacements in the less compressed face plate, beyond the secondary bifurcation which leads to localized interactive buckling, for the case where overall buckling is critical. Moreover, the allowance of local displacements in both face plates allows the extended model to predict the post-buckling behavior better in cases where local buckling is critical. The results from this model compare very well with nonlinear finite element simulations with respect to both the equilibrium paths and panel deformations.

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ABSTRACT: This paper presents an investigation into the development of a design procedure for Pultruded Fibre Reinforced Polymers (PFRP) beams failing by the elastic buckling mode of Lateral–Torsional Buckling (LTB). The design procedure is based on the European design approach for uniform members in bending of structural steel. In particular, the calibration method adopts the general case ‘resistance’ formula in Eurocode 3 (EN 1993-1-1:2005), and follows a standard design from testing procedure given in Eurocode 0 (EN 1990:2002) when calibrating the ‘design model’ to determine the partial factor, gamma-sub-M, for a member instability check. The test population for calibration has 114 LTB buckling resistances using four PFRP section sizes of I and channel shapes. The non-dimensional slenderness parameter is defined using the local flange buckling strength instead of the yield strength. An imperfection factor of 0.34 and partial factor of 1.3 are shown to be appropriate for calculation of the LTB moment of resistance.

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ABSTRACT: The paper deals with post-buckling experimental investigation on stiffened composite panels with pre-damage. Two panels with four equally spaced stiffeners were manufactured and tested. The damage was implemented at the vulnerable stiffener edge. Attempts were made to obtain the buckling load, ultimate carrying capacity and other wanted structure properties. A numerical methodology for the post-buckling behavior
analysis of pre-damaged panels was also presented. The load-shortening curves of numerical results were
compared with that of experimental results, and it gave a good prediction up to the onset of buckling and the
collapse load. Experimental strain analysis indicated that the outer sublaminate at the damage location was
buckling before the global buckling occurred, and the post-failure views also showed that the multiple
delaminations and the unstable buckling took place at the damage site firstly and transversely propagated. It was
validated by the simulated damage patterns which showed that the compression matrix failure and the shear
failure in the impact site led to the collapse of the panel.

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“Experimental investigation of failure process in compressed channel-section GFRP laminate columns assisted
with the acoustic emission method”, Composite Structures, Vol. 133, pp 921-929, December 2015,
https://doi.org/10.1016/j.compstruct.2015.08.023
ABSTRACT: The experimental investigations of thin-walled channel section columns subjected to static
compression are described. The columns under consideration were made of eight layers of a glass/epoxy
unidirectional prepreg tape, with the autoclaving technique. Six different symmetrical layer arrangements were
taken into account. The tests were performed on a Zwick Z100/SN3A universal testing machine with special
self-aligning grips. The columns under investigation were loaded with the force values from zero to the
maximal load destroying the profile, which allowed one to observe the column behaviour till its collapse. The
strain gauges measurement technique was employed to determine the equilibrium paths, the buckling loads and
the post-buckling behaviour. During all the tests, AMSY-5 AE equipment made by the Vallen company was
applied to detect acoustic emission phenomena. The acoustic emission method allowed to investigate the
behaviour of composite structures in the phase prior to their collapse. The results of the experimental
investigations were employed to validate the proposed FE model in order to analyse the post-buckling
behaviour and to determine the failure load with the well-known failure criteria.

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“Plateau lower-bounds to the imperfection sensitive buckling of composite shells”, Composite Structures, Vol.
133, pp 979-985, December 2015, https://doi.org/10.1016/j.compstruct.2015.08.018
ABSTRACT: The buckling of thin FRP laminated shells are sensitive to initial geometric imperfections. A large
number of geometric and material variables prohibit the traditional experiment-based lower-bound design
method for metallic shells from being extended to composite ones. As an alternative, the so-called reduced
stiffness method (RSM) has been applied to the lower bound buckling of FRP laminated shells. It has been
shown for shorter shells the method predicted excellent lower bounds to the nonlinear buckling loads. This
paper aims to extend the study to longer shells. It is shown for longer composite shells the lower-bound
buckling modes generally occur in the long axial wave mode having one axial halfwave but require
imperfection amplitudes of impractical largeness. Further studies of the geometric parameters identify the
existence of intermediate and significant plateaus to the lower bounds. These plateau lower-bounds demonstrate the importance of the short axial wave modes having more than one axial halfwave, associated with the imperfection amplitudes of practical smallness. Using the plateau values and modes to predict lower bounds is suggested to provide an important alternative for improving shell buckling design.

Grzegorz Juszkiewicz and Tomasz Nowak (ABB Corporate Research, Starowislna 13A Street, Cracow, Poland), “Comparative study on thin and thick walled cylinder models subjected to thermo-mechanical loading”, Composite Structures, Vol. 134, pp 142-146, December 2015, https://doi.org/10.1016/j.compstruct.2015.08.085
ABSTRACT: This paper gives a theoretical background and compares two analytical approaches, thin- and thick-walled models, analyzing composite cylindrical tubes under thermo-mechanical loadings. First, a theoretical background is introduced, and a lamination theory and an elasticity theory for thick-wall tubes are recalled. A systematic parametric study for various geometrical, material and load settings was performed to find out the difference between analyzed calculation approaches. It was generally observed, that the Classical Lamination Theory can be successfully applied for pressure loads, however this plane-stress assumption may generate remarkable errors if thermal loads are introduced. It is especially the case for highly orthotropic cylinders. The generalization of the achieved results allowed to recommend a new criterion for the selection of an appropriate calculation model. The proposed measure incorporates simple forms of tubes’ geometrical parameters ($D/t$) and material factor ($C_{22}/C_{33}$). Thanks to the applied approach the importance of through-thickness stresses can be quickly assessed.

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ABSTRACT: The buckling and postbuckling response of the FML profile/column investigated experimentally and determined analytically and numerically is compared. Real dimension specimens of 3/2 FML open cross-section profiles subjected to axial compression in laboratory buckling tests have been modelled in finite element method and examined analytically based on Koiter’s asymptotic theory. Buckling load obtained experimentally on the basis of strains is juxtaposed with those determined on the basis of deflection measurement and compared to analytical and numerical result values. Numerical model was improved with respect to the experimental findings.

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ABSTRACT: The aim of this paper is to study the uniaxial-compressive crush performance of thin-walled structures filled with Advanced Pore Morphology (APM) foam elements, exploring their deformation and failure mechanisms. The APM-foam elements are integral-skin closed-cell foams of near spherical shape fabricated through the Powder-Compacting-Foaming method by heating precursor in a continuous belt furnace. Two lightweight structures using the APM-foam elements were assembled, tested and evaluated: (i) Al-alloy tube filled with non-bonded APM-foam elements and (ii) Al-alloy tube filled with polyamide-bonded APM-foam elements. Non-bonded APM-foam filled tubes were prepared by pouring the APM-foam elements into an empty Al-alloy tube (without any bonding). Polyamide-bonded APM foam filled tubes were prepared by pouring the APM-foam elements coated with polyamide into an empty Al-alloy tube and then submitted to a heat treatment curing the polyamide. The axial crush performance of the APM foam filled tubes was compared to that of the empty tubes (with and without heat treatment) and tubes filled with conventional closed-cell foam. The results show a significant influence of the adhesive bonding on the compressive behaviour of polyamide-bonded APM foam filled tubes, which exhibit controlled deformation behaviour without appearance of cracks and show superior specific energy absorption per mass unit.

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ABSTRACT: An innovative design of the space offset mirror antenna made of composite material is presented in the paper. The antenna body is designed in the form of a composite sandwich conical shell with a cutout made on the side surface. The body geometry is selected to conform to and accommodate the signal transmitting zone. The antenna reflector is located at the bottom part of the sandwich cone and the feed is placed at the top creating a compact antenna configuration. A full-size prototype of the antenna has been designed, built and tested. Design parameters of the sandwich structure have been determined based on the results of finite-element modal analysis. The experimental results of vibration and thermal cycling testing of the prototype provide a proof of concept and evidence of the design feasibility. It is shown that the stiffness characteristics of the proposed integral sandwich antenna ensure efficient applications of such composite structures in the space antennas designed for various ranges of radio wave transmission.

Yegao Qu and Guang Meng (State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “Vibro-acoustic analysis of multilayered shells of revolution based on a general higher-order shear deformable zig-zag theory”, Composite Structures, Vol. 134, pp 689-707, December 2015, https://doi.org/10.1016/j.compstruct.2015.08.053

ABSTRACT: This paper presents a semi-analytical approach for predicting the vibration and acoustic responses of an arbitrarily shaped, multilayered shell of revolution immersed in a light or heavy unbounded fluid. A higher-order shear deformable zig-zag shell theory with general shape functions is proposed to describe the displacement field of a multilayered shell with arbitrary curvatures, which provides a theoretical unification of most thin and shear deformable shell theories in the literature. Based on the higher-order zig-zag theory, the structure model of the multilayered shell is formulated by using a modified variational method combined with a
multi-segment technique, whereas a Chebyshev spectral Kirchhoff–Helmholtz integral formulation is employed to model the exterior acoustic fluid. The displacement field of the shell and the sound pressure of the fluid are expanded by Fourier series and Chebyshev orthogonal polynomials. Such a treatment reduces the size of the problem and permits a semi-analytical solution for the displacement and acoustic variables. A set of collocation nodes distributed over the roots of Chebyshev polynomials are used to establish the algebraic system of the acoustic integral equations, and the non-uniquness solution is eliminated by means of interior CHIEF points. Numerical examples are given for vibration and acoustic radiation analyses of multilayered spherical, cylindrical and conical shells. Comparison studies are performed to evaluate the accuracy of various shell theories. The validity of the present method for acoustic analyses of multilayered shells is demonstrated by comparing the results with exact solutions and those obtained from the coupled finite element/boundary element method. Individual contributions of circumferential modes to the radiated sound of multilayered shells are examined.


ABSTRACT: The paper describes a modeling strategy for multi-scale analysis and optimization of stiffened panels, made of three-dimensional woven composites. Artificial neural network techniques are utilized to generate an approximate response for the optimum structural design in order to increase efficiency and applicability. The artificial neural networks are integrated with genetic algorithms to optimize mixed discrete-continuous design variables for the three dimensional woven composite structures. The proposed procedure is then applied to the multi-objective optimal design of a stiffened panel subject to buckling and post-buckling requirements.

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ABSTRACT: The effect of plate curvature, plate thickness, and thickness distribution on the response of curved composite plates subjected to far field underwater explosion (UNDEX) loading has been studied through computational simulations. In this study five panels with increasing radii of curvature are considered. Furthermore, the effect of plate thickness is considered by investigating three plate thicknesses for a given radii of curvature. Finally, a comparison is made between a plate with a uniform thickness and a plate with equal mass but a thicker outer boundary and thinner midsection. The effects are assessed using the plate center point deflection, full field deformation evolution, and fluid structure wave interaction. The results show that when subjected to shock pressure loading the deformation mechanics of the plate is significantly affected by the amount of curvature, thickness, and thickness distribution.

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ABSTRACT: Space launcher vehicle structures are designed as thin walled cylindrical and conical structures which are prone to buckling and are sensitive towards geometrical imperfections. Small deviations in dimensions, which still are within manufacturing tolerances, may lead to a tremendous decrease in load carrying capacity. Thus, imperfections have to be considered during the design phase and this is commonly done using empirical knock down factors. Besides this approach, imperfections can be considered by applying numerical or analytical structural models. Composite materials are used to exploit the light weight potential of unstiffened thin walled structures. For this type of shell structure, the buckling load of the geometrically perfect shell and the imperfection sensitivity are significantly influenced by the laminate stacking sequence. In this paper, the influence of the laminate stacking sequence of composite shells with rotational symmetric imperfections on the buckling behavior is studied and laminate stacking sequences leading to the highest buckling loads of an imperfect shell structure are identified. These stacking sequences are evaluated further by applying non-rotational symmetric imperfections and localized imperfections and the stacking sequences leading to optimum designs of the geometrical perfect shell structure are considered as reference structures.

Xuyuan Song, Qingkai Han and Jingyu Zhai (School of Mechanical Engineering, Dalian University of Technology, Dalian 116023, PR China), “Vibration analyses of symmetrically laminated composite cylindrical shells with arbitrary boundaries conditions via Rayleigh–Ritz method”, Composite Structures, Vol. 134, pp 820-830, December 2015, https://doi.org/10.1016/j.compstruct.2015.08.134

ABSTRACT: In this paper, the free vibrations of the symmetrically laminated composite cylindrical shells with arbitrary boundaries are analyzed by employing a set of artificial springs. Firstly, by employing a set of orthogonal polynomials as the admissible function, the Rayleigh–Ritz method is used to derive the equations of motion of the composite cylindrical shells with classical boundary conditions. Then, the equivalent elastic constraint is imposed on cylinder edges and to be used to simulate the arbitrary boundary conditions of the symmetrically composite cylindrical shell, and so as to formulate the frequency equations of it, in which the potential energy of the artificial springs is considered. Several comparisons are carried out to validate the approach method in current study, and the convergence investigations are checked at the same time. At last, the influence of boundary stiffness and lamination schemes on natural frequencies of the symmetrically laminated composite cylindrical shells is investigated. The results indicate that the present method is powerful to analyze the vibrations of the shells subjected to various boundaries including the classical constraints, elastic constraints and the combination of them efficiently.

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ABSTRACT: Snap-through phenomenon due to a uniform lateral pressure in a thermally post-buckled sandwich beam is analyzed in this research. It is assumed that material properties of the core and face sheets are temperature dependent. Face sheets are reinforced with carbon nanotube whose distribution may be uniform or functionally graded. Thermomechanical properties of the face sheets are obtained using a refined rule of mixtures approach. To capture the large deflections, geometrical nonlinearity in von-Kármán sense is taken into account. Chebyshev polynomial based Ritz method is implemented into the virtual displacement principle to construct the matrix representation of the equilibrium equations. A successive displacement control strategy is used to trace the temperature dependent post-buckling equilibrium path. Due to the possibility of snap-through phenomenon, cylindrical arch-length technique is used to trace the equilibrium path of a pressurized thermally post-buckled sandwich beam beyond the limit loads. It is shown that, upper limit load of the beam increases as the temperature gradient increases. Furthermore, volume fraction of CNTs affects the snap-through load and snap-through intensity of the beam, meanwhile, the influence of graded profile of CNTs on snap-through features is almost negligible.

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ABSTRACT: In this paper, we present a two-phase optimization method for designing the shape and thickness of shell structures consisting of orthotropic materials. We consider a multi-objective in terms of the compliances under multi boundary conditions, and use the weighted sum compliance as the objective functional and minimize it under the volume and the state equation constraints. The 1st phase is shape optimization, in which a shell structure is varied in the out-of-plane direction to the surface to create its optimal shape. In the 2nd phase, thickness optimization is implemented after shape optimization to decrease the compliance further. A free-form shape and thickness optimization problem is formulated in a distributed-parameter system based on the variational method. The shape and thickness sensitivities are theoretically derived and applied to the H¹ gradient method for shape and size optimization. The optimal multi-objective free-form of a shell structure with an orthotropic material can be determined using the proposal method, and the influence of the orthotropic angle to the optimal shape and thickness distribution is investigated in detail.


ABSTRACT: Innovative manufacturing technology has led to the fabrication of complex shape and multi-functional structures by using the concept of integrated and bonded unitized structural components. To study the stability behavior of such structural designs, this paper presents an efficient finite element buckling analysis of unitized stiffened composite panel stiffened by arbitrarily shaped stiffeners. A first-order shear-deformation theory is employed for both the panel and the stiffeners. Displacement compatibility conditions are imposed at the panel-stiffeners interfaces. To obviate remeshing when the stiffener shape changes, the stiffeners’ geometry and displacement are expressed in terms of those of the panel middle surface through compatibility conditions.
that make use of the interpolation polynomials employed in the finite element method. To accommodate any shaped stiffeners, a generalized geometry parametrization tool is developed to parameterize the shape of the stiffeners including the stiffener placement and the stiffener geometric curvature. Convergence and validation studies using the present method for the buckling analysis of stiffened isotropic and composite panels are conducted to illustrate the accuracy of the present method. Parametric studies show that the stiffener placement, the stiffener geometric curvature, the stiffener depth ratio (height-to-width ratio) and laminates fiber ply orientation influence both the plate bucking load and the correspond buckling mode shape. The tailoriability of the stiffeners shape and the laminates fiber ply orientation provides an enhanced design space in the structural design for improving the structural stability.

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ABSTRACT: Low velocity axial impact crush behaviours and energy absorption characteristics of thin-walled aluminium conical (AC) and E-glass/epoxy composite over-wrapped aluminium conical hybrid frustrated shells (CWAC) have been studied through experimental and numerical procedures. In this regard, 15°–24° semi-apical angled aluminium and hybrid conical test specimens of required thickness and fibre ply orientations were fabricated through hand layup method. The axial impact tests were performed at different strain rates on each AC and CWAC samples with the help of low velocity impact test setup in order to assess the energy absorption capacity of each specimen against impact loading. The influence of inertia, strain rate, addition of GFRP laminates over aluminium shell and GFRP fibre ply orientation towards the crashworthiness performances of various categories of conical frusta were analyzed. The low velocity impact tests were also simulated with the help of finite element analysis (FEA) techniques of ABAQUS® software in order to predict and compare the crashworthiness of each category of specimen model with experimental results. The obtained crashworthiness test results and collapse behaviours of FEA analysis are found in good agreement with the experimental results.

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ABSTRACT: On the basis of the dynamic version of linear Donnell type equations and with deformations before instability taken into account, the dynamic instability of simply supported, functionally graded (FG) truncated conical shells under static and time dependent periodic axial loads is analyzed. Applying Galerkin’s method, the partial differential equations are reduced into a Mathieu-type differential equation describing the dynamic instability behavior of the FG conical shell. The domains of principal instability are determined by using Bolotin’s method. Validation of numerical results was done with those available from previous researches. The influences of various parameters like static and dynamic load factors, volume fraction index, FG profiles and shell characteristics on the domains of dynamic instability of conical shell were investigated.
ABSTRACT: Truss-based lattice materials are cellular materials with an outstanding potential for multifunctional use. This is owing to properties of high compressive strength to density ratios combined with a periodic and open structure. However, such structures at low relative densities are particularly vulnerable to elastic buckling failure. Fibre-reinforcement that increases the buckling strength of lattice materials is proposed and the behaviour of unit cells that are tessellated within the lattice is investigated. A two-dimensional square orientated unit cell and a three-dimensional tetrahedron-shaped unit cell are both modelled discretely using energy principles with the nonlinear interactive buckling behaviour being analysed. The analytical approach, based on a perturbation method, exhibits excellent agreement for the mechanical response when compared to results from numerical continuation for moderately large displacements. A fundamental understanding of the mechanical behaviour of a unit cell can be upscaled in future work. It is postulated that this will enable the determination of the constitutive behaviour of such lattice materials.

ABSTRACT: This paper deals with the accurate description of the multiple delaminations and transverse cracks in double-curved laminated composite shells by using the extended finite element method (XFEM) and layerwise theory (LWT), and develops an extended layerwise method (XLWM) which had been applied to the laminated beams in our previous work (Li et al., 2015 [1]). In the displacement assumption of XLWM, the discontinuous function along the thickness direction is adopted to simulate the displacement discontinuous resulted from multiple delaminations. While the transverse cracks are modeled in in-plane displacements discretization by XFEM. The level set method (LSM) is employed in the present method to track the interfaces resulted from the transverse cracks. The interaction integral method and maximum circumferential tensile criterion are used to calculate the stress intensity factor (SIF) and crack growth angle, respectively. In order to ensure the accuracy of Gauss integral when certain nodes are very close to the crack surface as the crack grows, a local remeshing scheme is developed to shift these nodes without scarifying the mesh quality. In the numerical examples, spherical shells, cylindrical shells and plates with/without multiple delaminations and/or transverse crack are considered to the problems of static responses analysis, SIF calculation and transverse crack arbitrary growth.
ABSTRACT: This paper is devoted to the static analysis of laminated beams with both compact and thin-walled cross-sections. The kinematic models are obtained by means of the Carrera Unified Formulation (CUF), which is a hierarchical formulation leading to very accurate and computationally efficient finite element (FE) models. According to the latest developments in the framework of CUF, it is possible to easily adopt both equivalent-single-layer and layer-wise approaches, by expanding the unknown kinematic variables on the beam cross-section with either Taylor-like or Lagrange-like polynomials, respectively. A number of laminated beam structures are analysed and particular attention is given to laminated single- and multi-cell cross-section beams with open and closed contours. Moreover, in order to demonstrate the effectiveness of the proposed refined elements, the results in terms of displacements and stresses are compared with solid FE solutions and, when possible, with the results available from the research literature.

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ABSTRACT: This paper presents an experimental investigation on the cyclic behaviour of short steel tubes filled with rubberized concrete (RuC), a composite material that mixes concrete with rubber particles. A brief literature review on the cyclic behaviour of CFST columns, the mechanical properties of RuC and recent research on RuC-filled steel tubes (RuCFSTs) is presented. Then, the tested specimens are characterized, comprising three cross-section shapes (square, rectangular, circular), three steel grades (S235, S275, S355), three concrete mixes (0%, 5%, 15% of rubber particles content) and two axial load levels (10%, 20% of axial plastic load). After that, the loading protocol, test rig and experimental procedure are described in detail. The experimental results are extensively discussed, focusing on the columns’ cyclic strength, failure modes, hysteretic and envelope curves, as well as on the energy-based ductility factors. Finally, conclusions are drawn regarding all these parameters. The most relevant achievement is that a concrete mix with a low content (5%) of rubber particles leads simultaneously to the lowest decrease (5%) in the cyclic strength and the highest increase (52%) in the ductility of RuCFST columns, thus being the most suitable mix to use in seismic areas, where ductility and energy dissipation requirements are mandatory.

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ABSTRACT: A new design of composite corrugated horn of the spacecraft antenna is presented in this paper. The horn is made of carbon fibre reinforced plastic and is 2.4 times lighter and 1.3 times stiffer than its metal counterpart having the same antenna gain. The thickness of the horn shell is determined using the results of the finite-element modal analysis. A full scale physical prototype of the horn was built and tested. The structure has
successfully passed stringent operational, vibration and thermal tests. The manufacturing technology and the test results are discussed in detail. It is demonstrated that the composite horn prototype has good dimensional stability and is capable of withstanding the dynamic loads and cyclic orbital thermal changes.

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“A two-way loose coupling procedure for investigating the buckling and damage behaviour of stiffened composite panels”, Composite Structures, Vol. 136, pp 513-525, February 2016,  
https://doi.org/10.1016/j.compstruct.2015.09.056

ABSTRACT: This paper is concerned with the development of a novel FE-based two-way loose coupling approach for the analysis of stiffened composite panels. The aim of this numerical strategy is to investigate the global postbuckling behaviour as well as the local damage progression of composite structures using separated FE models with different levels of fidelity: (i) a relatively simple global model of the complete structure, and (ii) more complex local models of certain details that incorporate damage capabilities to simulate damage events. In the coupling process, information is exchanged between these diverse models to simulate the overall structural behaviour including geometrical as well as material nonlinearities. The two-way loose coupling character of the methodology allows, firstly, a direct interaction between the global and the local levels along the solution process and, secondly, a highly versatile adaption with regard to the definition of the local models. In addition, the separation of the models and analyses in the approach enables the use of standard FE software without complex implementations or modifications of the source code. The developed coupling procedure is assessed through two applications: (i) an academic composite stiffened panel, and (ii) a real stiffened panel taken from literature. The results of the proposed coupling approach are compared with the numerical and experimental reference data, exhibiting a satisfactory level of accuracy.

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ABSTRACT: A layerwise shear deformation theory for functionally graded (FGM) sandwich shells and laminated composite shells is discretized using a differential quadrature finite element method (DQFEM). The DQFEM is a weak-form differential quadrature method that can provide highly accurate results using only a few sampling points. The layerwise theory proposed by Ferreira is based on an expansion of Mindlin’s first-order shear deformation theory in each layer. The combination of the DQFEM with Ferreira’s layerwise theory allows a very accurate prediction of the field variables. Effective material properties of the FGM are estimated according to both Voigt’s rule of mixture (ROM) and Mori-Tanaka (MT) scheme. The DQFEM solutions were compared with various models in literature and especially showed very good agreements with results based on layerwise theories. The analysis of FGM sandwich and laminated composite shells based on Ferreira’s layerwise theory indicates that the DQFEM is an effective method for high accuracy analysis of large-scale problems.
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ABSTRACT: A post-buckling behaviour analysis and an ultimate load estimation of thin-walled composite channel columns under a constant rate of end shortening are presented. The columns with C-sections were made of a carbon-epoxy composite – a laminate consisting of eight symmetrically oriented plies. Four different layer arrangements were taken into consideration. The main objective of the study was to investigate the behaviour of the considered columns under quasi-static compression to achieve their collapse. The experimental tests were performed under standard conditions on a universal ZWICK Z100 testing machine. To collect the experimental data, strain gauges for strain measurements, a laser gauge for deflections and acoustic emission testing equipment were employed. A numerical analysis was conducted with the Abaqus commercial FEM software package. The experimental results were then used to develop FEM models that allowed one to describe the post-buckling behaviour and to estimate the ultimate load-carrying capacity of the composite channels under investigation.

Dongyun Ge, Yuming Mo, Boling He, Yiting Wu and Xuzhen Du (School of Aerospace Engineering, Tsinghua University, Beijing 100084, China), “Experimental and numerical investigation of stiffened composite curved panel under shear and in-plane bending”, Composite Structures, Vol. 137, pp 185-195, March 2016, https://doi.org/10.1016/j.compstruct.2015.09.049
ABSTRACT: An experiment was carried out to study the buckling and post-buckling behavior of stiffened composite curved panel under shear and in-plane bending. A test fixture was designed uniquely which was suitable for curved panel subjected to shear or shear and in-plane bending. The results showed that this kind of fixture was feasible. The strain data were recorded by strain gauges. The out-of-plane displacement field was characterized by a 3D digital speckle system. The stability of stiffened composite curved panel subjected to shear and in-plane bending was analyzed by the obtained data. Finite element method (FEM) was used. The influence of transverse frames on the stability of stiffened curved panel was further studied by FEM. Good correlation between experimental and FEM analysis was obtained. The fixture and test method used in this paper provide a reference to the study of curved panel subjected to shear or shear and in-plane bending.

ABSTRACT: In this paper, an analytical modeling of thin-walled open-section beams with functionally graded materials (FGMs) is presented, regarding mono-symmetric I- and channel-sections. The mechanical properties
of beam such as Young’s modulus and shear modulus are assumed to continuously vary in the thickness
direction based on the power law distribution of volume fraction of metal or ceramic. The locations of center of
gravity and shear center for FG beams are derived. The proposed theory considers restrained warping applicable
to the thin-walled FG beam based on Vlasov’s assumptions. General governing equations are derived and
directly solved, therefore, exact solutions can be achieved. In addition, the effects of gradual law and thickness
ratios of ceramic or metal on behavior of various thin-walled FG beams are investigated.

Tiejun Zhang, Shulin Li, Fei Chang, Xiaopeng Shi and Lekun Li (Aeronautics and Astronautics Engineering
College, Air Force Engineering University, Xi’an, China), “An experimental and numerical analysis for
stiffened composite panel subjected to shear loading in hygrothermal environment”, Composite Structures, Vol.
ABSTRACT: This paper presents a detailed experimental and numerical investigation on absorption and shear
behaviors of stiffened composite panel subjected to hygrothermal environment. Due to the special and complex
configurations of stiffened composite panel, water diffusion process should be divided to two absorption phases.
Compared to conventional single equation by Fick’s law, two absorption equations in this model could describe
the absorption curve of experimental result perfectly. The combination of empirical formulae and finite element
model is used to study buckling and postbuckling behavior for stiffened composite panel subjected to shear
loading in hygrothermal environment. The buckling loads and failure loads of unaged specimens decreased
approximately 10% and 25%. Good agreement between experimental data and numerical results is observed.
According to experimental and numerical results, failure modes of the hygrothermal specimens include panel
cracks and debonding of stiffeners.

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“Buckling and delamination growth behaviour of delaminated composite panels subject to four-point bending”,
ABSTRACT: Buckling behaviour and delamination growth have been investigated in Carbon Fibre-Reinforced
Plastic (CFRP) laminates with artificial and impact-induced delaminations when subject to four-point bending.
The energy of the impact was such that the induced damage, observed using ultrasound, did not extend across
the entire width of the laminates and was barely visible on the impacted face. Stereoscopic digital image
correlation was used to measure the evolution of the deformation of the laminate during bending to structural
failure; and the resulting full-field displacement maps and observations of failure modes from Scanning
Electron Microscopy (SEM) were used to conclude that appropriately shaped and located artificial
delaminations could be employed to represent damage-induced delaminations. This enabled the development of
a non-linear Finite Element Analysis (FEA) incorporating a fibre/matrix constitutive model, a modified
fibre/matrix failure criterion and a delamination growth criterion to examine the interaction between the
buckling behaviour and delamination growth. The predictions of the surface displacements in bending were
validated, with the aid of image decomposition, using the measured data fields for a crossply laminate. The
model reliably predicted the load–displacement curve and the propagation of damage in laminates with a low
level impact damage, which did not extend across the width of laminates, unlike in prior reported models.

ABSTRACT: The purpose of this paper was to investigate the effect of low velocity edge impact damage on the damage tolerance of wing relevant composite panels stiffened with both T-shaped and I-shaped stiffeners under uniaxial compression load. Six stiffened composite panel configurations, including four specimens for each configuration, were manufactured and tested. Before Compression-After-Impact (CAI) tests, the key dimensions of specimens were measured and a vertical drop-weight testing device was used to impact on critical locations such as the skin and the free edge of a stiffener. Different damage types and shapes were discovered from different locations of impact after careful inspection by visual and ultrasonic C-scan. The experimental results reveal the compression failure mechanism that local buckling, subsequent damage propagation and final fracture of the edge impacted stiffener are triggers of the final failure of a stiffened composite panel, which as well determine the ultimate load carrying capacity. In addition, under identical edge impact levels, the damage tolerance behavior of T-stiffened composite panel is distinctly superior to that of I-stiffened composite panel, which results in more cautious design regarding edge impact damage tolerance of the panel stiffened with I-stiffeners.

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ABSTRACT: The nonlinear buckling and post-buckling of ceramic–metal–ceramic layers (S-FGM) toroidal shell segment surrounded by elastic foundation under thermo-mechanical loads are investigated with an analytical approach in this paper. Based on the classical thin shell theory with geometrical nonlinearity in von Karman–Donnell sense, Stein and McElman assumption and Pasternak foundation model, the governing equations of nonlinear buckling of S-FGM toroidal shell segment are analyzed. The static critical buckling loads and the post-buckling analyses in two cases – movable and immovable boundary conditions including temperature effects are obtained. Furthermore, the effects of geometry ratios, characteristic of materials, elastic foundation and thermal environment on the nonlinear buckling of shells are presented.


ABSTRACT: Similarly to the post-buckling behavior of steel girder webs, the post-wrinkling behavior of glass fiber-reinforced polymer (GFRP) cell-core sandwich webs can increase their ultimate shear strength. Post-wrinkling is, however, different from post-buckling since wrinkling is a local buckling instability mode that can occur in any part of the web. Furthermore, all the previously presented theories or models have been limited to isotropic web plates, while the fiber architecture of orthotropic plates can greatly influence post-wrinkling behavior. Based on biaxial compression–tension experiments on GFRP web-core sandwich panels, the redistribution of the strain field during post-wrinkling was examined for two different fiber architectures, [90/0]
and [±45] stacking sequences. The results proved that fiber architecture greatly influences the wrinkling loads and wrinkling mode as well as post-wrinkling behavior. During post-wrinkling, the ultimate shear strength of the sandwich structure and the redundancy of the system can be increased, thus enhancing the safety, functionality and reliability level of this type of structure.


ABSTRACT: In this paper, using third-order shear deformation theory (TSDT) and modified strain gradient theory (MSGT), bending, buckling and free vibration behaviors of microcomposite plate reinforced by functionally graded single-walled carbon nanotube (FG-SWCNT) under hydro-thermal environments are investigated. The generalized rule of mixture is employed to predict mechanical, moisture and thermal properties of micro composite plate. The governing equations of motion are obtained using energy method and Hamilton’s principle, and solved by differential quadrature method (DQM). There is a good agreement between the obtained results and the other results. The influences of the material length scale, elastic foundation parameters and temperature and moisture changes for various boundary conditions on the natural frequency, critical buckling load and deflection of the micro composite plate reinforced by FG-SWCNT are presented. The obtained results show that critical buckling load and natural frequency for MSGT are more than that of for classic theory (CT) and modified coupled stress theory (MCST), and vice versa for the deflection. The material length scale parameters lead to increase the stiffness of system. Also the effect of moisture on microcomposite plate reinforced by SWCNT is similar to thermal effect; furthermore, with increasing of moisture change reduces the natural frequency and critical buckling load and increases the deflection of micro composite plate. Considering the environmental conditions and temperature results are closer to reality.


ABSTRACT: Unstiffened cylindrical shells are very sensitive to geometric imperfections such as production-related deviations from the ideal geometry (conventional imperfections) as well as imperfect boundary conditions, material and wall thickness imperfections (non-conventional imperfections). The load carrying capability of unstiffened shells is reduced significantly by those imperfections. The NASA SP-8007 design guideline from 1968 is currently used for shell design. This guideline provides knock-down factors for the buckling loads and is based on experimental data of isotropic and orthotropic test specimen. Therefore the structural behavior of composite material is not considered adequately. Based on the single-perturbation load approach (SPLA), this paper introduces a new physical based approach, to determine a lower bound for the buckling load of unstiffened composite cylindrical shells with respect to conventional and non-conventional imperfections, the constant single-buckle imperfection (CSBI) principle. The CSBI principle is based on the theory of the metastability of the geometric imperfect cylindrical shell which is introduced within this paper. The results indicate that the CSBI principle has the potential to provide an improved shell design in order to reduce weight and cost of thin-walled shells.
ABSTRACT: Carbon Fiber Reinforced Composites (CFRPs) with light weights absorbed a large quantity of energy through the progressive crushing modes by a combination of multi micro-crack including fiber fracture and matrix fracture, bending, delamination, splitting, friction and so on. High manufacturing cost of CFRPs was one of the most important reasons for not being used as energy absorption components in wide range. In this study, five types of tubes were manufactured by filament winding method and crashworthiness performance was investigated experimentally. The effects of crushing speed, temperature treatment, raw material and structure including hybrid ratio, fiber orientation and thickness of tube wall on energy absorption capabilities were investigated through quasi-static and dynamic compression tests. Optical microscope observation of cross sections was taken to analyze the mechanism of failure. A hybrid carbon/aramid FRP tube after temperature treatment exhibited the highest $E_s$ in quasi-static test (98 kJ/kg in average) and dynamic tests (82 kJ/kg in average), which have excellent energy absorption management.

ABSTRACT: So far thermally induced bistable flat plates and shells have been studied separately. Combination of these elements together introduces a new set of bistable structures. This paper presents a Rayleigh–Ritz model to study the thermal deformation of connected curved composite plates. In this work, the initially curved plate model (Eckstein et al., 2014) is extended to account for the continuity of displacements and strains on the connection line. The model is compared with experimental data and finite element for two and three connected curved plate geometries. Effect of different layups other than $[0/90]$ can be examined by this model. As an example, a $[-45/45]$ layup is studied. The accuracy of the presented model is good away from the boundaries but inaccuracies occur close to the edges, i.e. giving reasonable accuracy overall. As a new result, combining different layups and initial curvatures can lead into more than two stable configurations. Compared to previous analytical models which are focused on single flat or curved plates, in this work a more general model is developed that can take into account various initial shapes. Finally, the combined effect of initial shape and temperature variation on the existence of bistability is demonstrated.
“Buckling behavior of variable-stiffness composite laminates manufactured by the tow-drop method”


ABSTRACT: The current investigation deals with the buckling behavior of variable-stiffness composite panels manufactured by the automated fiber placement (AFP) process. In order to minimize the occurrence of AFP-inherent defects as gaps and overlaps, the so-called tow-drop method was adopted. Compression-buckling tests were performed on large panels containing gaps or overlaps under simply-supported boundary conditions. The specific responses of the out-of-plane deflections, which were tracked by four laser sensors focused on the axial centerline of the panels during compression loading, were explained by the measured initial geometric curvatures, which were characteristic of variable-stiffness panels. The tracking of the in-plane strains using sixteen strain gauges located strategically on the panels confirmed that the presence of gaps and overlaps does not affect the symmetry of variable-stiffness panels. Finally, it was established that the tow-drop method significantly improved the structural performance in terms of the pre-buckling stiffness, buckling load, and the failure load while keeping minimal geometric disturbances.

References listed at the end of the paper:
The use of experimental data, obtaining a satisfactory agreement along the loading procedure, is of particular interest for the analysis of composite stiffened panels in postbuckling regimes subjected to uniform pressure loading. The numerical results are corroborated with experimental data, obtaining a satisfactory agreement along the loading procedure.
ABSTRACT: The design of glass fibre reinforced polymer (GFRP) pultruded members is often governed by deformability and buckling phenomena, preventing the full exploitation of the material potential. Hybridization – the partial replacement of the glass reinforcement with (stiffer) carbon fibres – is a possible approach to improve the performance of GFRP thin-walled profiles. This paper presents an experimental study on the structural behaviour of I-section hybrid fibre reinforced polymer (FRP) pultruded columns made of glass and carbon fibres (GF and CF) embedded in a polyester resin. A bare GFRP reference profile and four series of hybrid C-GFRP profiles, with different types and architectures of CF reinforcement, were designed, manufactured and tested under compression in three different lengths – short, intermediate and long. Particular attention was given to the buckling behaviour of the columns and to the delamination at the interface between GFRP and CFRP layers. In terms of serviceability performance, results obtained confirm the hybridization’s effectiveness in increasing the axial stiffness of GFRP compressive members. In terms of ultimate limit states behaviour, hybridization increased the load carrying capacity of the long columns, which exhibited global buckling. In opposition, for the short and intermediate columns, which failed respectively due to local buckling and a combination of global and local buckling, the load carrying capacity of the hybrid columns was lower than that of the reference profile; such worse performance seems to have been caused by the delamination of the CF layers, owing to the relatively high axial strains that developed in those columns. In a companion paper (Part 2), the experimental data presented and discussed herein is compared with predictions from numerical models and analytical formulae, which also provide further information about the delamination and progressive failure of the hybrid columns.

ABSTRACT: The structural behaviour of hybrid fibre reinforced polymer (FRP) pultruded members under concentric compression is studied in this paper (Part 2) through the use of numerical models – the experimental characterisation was presented in preceding paper (Part 1, Nunes et al., 2015). The hybridization of glass-FRP (GFRP) profiles is made through the partial replacement of the glass reinforcement with (stiffer) carbon fibres. First, a brief literature review shows the absence of available finite element (FE) models that take into account all the nonlinearities (material and geometrical) that influence the FRP column behaviour, and indicates the need to develop reliable and consistent models. Then, the FE model developed in this paper is described in detail. The elastic buckling behaviour of the columns tested in Part 1, with similar I-section shape but different configurations of carbon fibre reinforcement and different lengths, is evaluated. Three failure criteria for composite materials (Maximum Stress, Tsai–Hill and Hashin) are presented, implemented and their differences...
discussed. Using the Hashin criterion associated with a material damage model, progressive failure analyses were performed to simulate the nonlinear behaviour and failure of the hybrid columns. The numerical results comprise load–displacement curves, ultimate loads, stress–strain curves and failure modes, which are validated by comparison with the experimental results. Finally, the available design procedures for FRP columns are critically reviewed and applied to evaluate the columns’ ultimate loads. In this regard, it is shown that buckling prevails over material strength and that existing standards do not predict accurately the ultimate load of short columns or laterally braced columns.

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ABSTRACT: Flutter in aeronautical panels is a type of self-excited oscillation which can occur during supersonic flights. At the flutter point the vibrations of the panel become unstable and increase significantly in time. This manuscript presents a semi-analytical model taking into account the stiffener’s base effects, in order to predict the aeroelastic response of laminated composite stiffened panels under supersonic flow. Krumhaar’s modified supersonic piston theory, which considers the radius effect, is adopted to model the aerodynamic loading. The proposed model has been validated against results available in the literature for various configurations. A parametric study considering different panels and stiffener configurations is also presented. The numerical results indicate that the stiffener base significantly affects the panel aeroelastic behavior. Preliminary studies also indicate that redistributing the laminate plies from the stiffener’s flange to its base significantly increases the torsion stiffness of the panel locally, opening new design possibilities that may lead to a better flutter performance when the airflow is transverse to the longitudinal stiffener direction.

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ABSTRACT: Experimental investigations were conducted to study the axial crushing behaviour of aluminium honeycomb-filled square carbon fibre reinforced plastic (CFRP) tubes. Axial compressive loads were applied to both hollow and honeycomb-filled CFRP tubes at constant velocities of 0.05 mm/s, 0.5 mm/s, 5 mm/s and 50 mm/s, respectively. Experimental results show that the deformation mode of hollow CFRP tubes with 100 mm length was a catastrophic failure mode. However, experimental deformation modes of hollow and aluminium honeycomb-filled CFRP tubes with 50 mm length were found to be a combination of splaying
progressive failure and transverse shearing failure. The mean crushing force (MCF) and energy absorbed (EA) by honeycomb-filled CFRP tubes were larger than those of corresponding hollow CFRP tubes and, in general, these parameters were found to decrease with an increase in a crushing velocity. However, the specific energy absorption (SEA) of aluminium honeycomb-filled CFRP tubes was found to be less than that of a hollow CFRP tube. The effects of using adhesive and different gaps between the honeycomb core and CFRP tube walls were also examined. The energy absorption and specific energy absorption of hollow CFRP tubes, aluminium honeycomb-filled CFRP tubes and metal tubes were also compared.

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ABSTRACT: This paper reports an experimental and numerical investigation of the effects of gaps and overlaps on the buckling behavior of variable-stiffness composite laminates. In the experimental study, variable-stiffness composite laminates with a constant-curvature fiber path were manufactured and tested under uniaxial compression to failure with simply supported edges. The tested panels were optimized to simultaneously maximize the in-plane stiffness and the buckling load. Two manufacturing strategies – complete overlaps and complete gaps – were adopted to allow the independent effect of each type of defect to be investigated in isolation. In the numerical study, a two-dimensional finite element model was built using the commercial software Abaqus through a Python input script. A MATLAB routine was also implemented to localize the gaps and overlaps within the studied variable-stiffness laminates. A linear buckling analysis was performed to calculate the pre-buckling strength and the critical buckling load for each tested composite laminate. Thereafter, a nonlinear analysis using the Riks method was performed to predict the load–displacement relationship, considering the geometric imperfections of cured composite laminates. A good correlation was observed between the results obtained from the finite element simulations and from the experiments.


ABSTRACT: Corrugated panels are widely used as structural elements in engineering fields because of their high stiffness and light weight. Moreover, corrugated composite laminates have attracted much attention as a candidate for morphing aircraft wing that need to have different behaviors in different directions due to their extremely anisotropic behavior. The simple model is required to investigate the mechanical behavior of these structures in design process. On this demand, the equivalent homogenization method of corrugated panels has been used during last decades. This homogenization model is usually treated a corrugated panel as an orthotropic panel that has different material properties in two perpendicular directions. This paper presents an analytical homogenization model for corrugated composite laminates that can be applied easily to any corrugation geometry. This paper gives explicit expressions to calculate not only the effective extensional and
bending stiffness but also the effective transverse shear stiffness for a composite corrugated panel. The effective stiffness of the trapezoidal corrugation shape which is the most common corrugation geometry is evaluated and compared with those of the flat composites. To validate the proposed approach, the obtained results are compared with the previously published results.


ABSTRACT: The paper presents a theoretical formulation for the computation of temperature-dependent nonlinear response of shallow shells with single and double curvatures subjected to transverse mechanical loads while being exposed to through-depth non-uniform heating regimes such as those resulting from a fire. The material nonlinearity arises from taking into consideration the degradation of the material elastic behaviour at elevated temperatures under quasi-static conditions. Two types of boundary conditions are considered, both of which constrain the transverse deflections and allow the rotations about the edge axis to be free. One of the boundary conditions permits lateral translation (laterally unrestrained) and the other one does not (laterally restrained). A number of examples are solved for shallow shells under different types of loading conditions including: an exponential “short hot” fire leading to a high temperature over a relatively short duration; and an exponential “long cool” fire of lower temperature over a longer duration. The limits of the shallow shell equations are investigated through comparison studies. Results show that while current numerical approaches for analysis of laterally restrained shallow shells are often computationally intensive, the proposed approach offers an adequate level of accuracy with a rapid convergence rate for such structures.

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ABSTRACT: This paper presents an aeroelastic analysis of carbon nanotube (CNT) reinforced functionally graded composite panels in supersonic airflow using a higher-order shear deformation theory. There are four types of CNT distributions considered in this investigation. Since the panel studied here is relatively thick, Reddy’s third-order shear deformation theory is applied to evaluate the displacement fields of the panel. Applying Hamilton’s principle, the equation of motion of the structural system is formulated. The CNT reinforced functionally graded composite panels investigated in this study are simply-supported on two opposite edges and therefore, in order to solve the coupling set of differential equations of motion, the state-space Levy method is applied. Based on the Levy solution, the aeroelastic properties of the CNT reinforced composite panels are analyzed using the frequency-domain method. The effects of CNT distributions and boundary conditions on the aeroelastic stabilities of the CNT reinforced functionally graded panels are researched. Different types of aeroelastic instability under different boundary conditions are observed. Moreover, vacuo and fluttering mode shapes of the CNT reinforced functionally graded panels are presented.
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ABSTRACT: Fibre kinking is one of the main failure modes of composite laminates under compression loading. In this paper, the role of kinking in the failure of quasi-isotropic composites subjected to a bearing load is investigated. High-resolution CT scans show that kinking is largely involved in the events leading to laminate collapse, notably by triggering other damage modes such as delamination. Kink bands develop progressively, leading to the formation of a wide localization zone (or FPZ, failure process zone). Such behaviour calls for a non-local modelling approach. Local damage models would lead to overly conservative sizing. A simple model, based on Hashin failure criteria and non-local effective stresses is confronted to experiments, and its limits are highlighted. It will be shown that proper modelling of the bearing failure requires the characteristic behaviour of kink bands to be taken into account.

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ABSTRACT: An accurate buckling analysis for piezoelectric fiber-reinforced composite (PFRC) cylindrical shells subjected to combined loads comprising compression, external voltage and thermal load is presented in this paper. Based on Reddy’s higher-order shear deformation theory, the governing equations for the coupled displacement field and induced piezoelectric field are established. Considering two different kinds of fiber-reinforced configurations, i.e. uniformly distributed (UD) and functionally graded (FG) reinforcements, the buckling solutions of perfect and imperfect PFRC cylindrical shells are obtained by applying separation of variables and Galerkin’s method. The influence of geometric parameters, piezoelectric effect, external electric voltage, temperature field and fibers distribution configurations on buckling characteristics and imperfection sensitivity are discussed in detail. The formulation system thus developed is suitable to other shell theories and to account for the coupled electro-magneto-thermo-elastic effects.

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ABSTRACT: A solution of the free vibrations problem formulated for a composite lattice cylindrical shell with clamped edges is presented in this paper. The lattice shell is composed of a large number of helical and hoop ribs and modelled as a continuous orthotropic thin cylinder with effective stiffness parameters. A solution of the equations of motion of the shell is based on the Fourier decomposition and the Galerkin method and yields an analytical formula for the calculation of a fundamental frequency. It is demonstrated that starting from a certain density of the lattice structure the value of fundamental frequency does not depend on the number of helical ribs. This result is verified and confirmed using finite-element analysis. Applications of this formula to the determination of the parameters of lattice structures and design of composite lattice shells with required fundamental frequencies are demonstrated using numerical examples. It is shown that the analytical formula presented in this article provides an efficient tool for rapid calculation of the fundamental frequency which can be used for the assessment of the structural stiffness of the composite lattice shells in the design analysis.


ABSTRACT: Cutout can be commonly found in Carbon Fiber Reinforced Polymer (CFRP) composite structures such as wing box of aircraft and may lead to significant reduction in structural stability and strength. In this study, experimental and numerical studies are conducted to investigate the bearing behavior and failure characteristic of multidirectional CFRP composite laminate involving different shaped cutouts under shearing load. The stress concentration, buckling behavior, postbuckling bearing capacity as well as the progressive failure mechanisms of specimens with different shaped cutout are analyzed in detail. The effect of cutout size on global response is also discussed. Finally, the effectiveness of reinforcement by inserting sub-merged co-curing layer is evaluated by both numerical modeling and experimental testing. There are two parts to this work. The first part focusing on experiment is presented in this paper.


ABSTRACT: In part I of this work, the mechanical performance of carbon fiber reinforced polymer (CFRP) laminate with cutout of three different shapes (circular, curved-diamond, rounded-rectangular) subjected to shear load was investigated experimentally. This part describes the finite element (FE) simulations of the problem investigated. An efficient laminate-leveled computational model is employed to provide an insight on the failure mechanisms of specimens. The load bearing procedures of specimens, both at pre-buckling and post-buckling stage, are simulated. The characteristics of post-buckling progressive damage undergoing within specimens obtained from modeling are compared with the experimental observations in detail. It is found that the damage model is capable of reproducing the post-buckling progressive damage with complicated coupling effects within thin-walled composite structure costing low computational resources, and good agreement is in
general obtained between the numerical simulations and experimental results. Through this comparative study, the progressive damage events within the structure with different shaped cutout help reader in better understanding the bearing performance and underlying failure mechanisms of CFRP laminate with cutout.


ABSTRACT: In this study, the transient responses of a composite laminated plate and cylindrical shells subjected to low-velocity impacts were investigated numerically. The shear deformation theory of a doubly curved shell and von Karman’s large deflection theory were used to develop a geometrically nonlinear finite element program. It is well-known that in the case of a flat plate with fixed boundary edges, a geometrically nonlinear analysis yields larger contact forces and smaller deflections than a corresponding linear analysis. However, in the case of cylindrical shells, an opposite result was found in this study; a geometrically nonlinear analysis exhibited smaller contact forces and larger deflections than a corresponding linear analysis. The reason for this opposite result is described in this study. Conversely, with a plate and shells that have the same size, shells with a larger curvature exhibited smaller deflections and larger contact forces. The strain distribution at the bottom surface of the plate/shells using the geometrically nonlinear analysis exhibited markedly or only marginally larger tensile areas than those produced using the linear analysis.


ABSTRACT: This paper presents an advanced approximate technique for the vibration and buckling analysis of variable stiffness plates. The formulation is based on a variable-kinematic approach and is developed in the context of a variational framework together with the method of Ritz. Any set of boundary conditions can be accounted for, while loading conditions of pure axial compression are assumed. Results are validated against finite element predictions and solutions available in the literature, demonstrating the accuracy of the proposed method in terms of eigenvalues and modal shape descriptions. A novel set of vibration and buckling results is provided for moderately thick variable stiffness plates, including monolithic and sandwich configurations.


ABSTRACT: This paper investigates the non-linear free vibration of functionally graded (FG) orthotropic cylindrical shells taking into account the shear stresses. The formulation is based on the shear deformation theory (SDT) and von Karman-type strain displacement relationships. The material properties of FG orthotropic cylindrical shell are assumed to vary exponentially through the thickness. The equations of motion of the FG orthotropic cylindrical shells are derived from the Donnell’s non-linear shell theory, and then the superposition and Galerkin methods are adopted to convert the equation of motion into a non-linear ordinary differential equation. The expressions for the non-linear frequency parameters and non-linear to linear frequency ratios depending on the amplitude within the SDT are obtained in the form of Jacobian elliptic function. In addition,
the non-linear ordinary differential equation is solved using the homotopy perturbation method (HPM) and one
another expressions for the non-linear frequency parameters and non-linear to linear frequency ratio are
obtained. The results are compared and validated with the results available in the literature. The influences of
non-linearity, shear stresses, FG profiles as well as the cylindrical shell characteristics on the non-linear
frequencies depending on the amplitude of vibration are investigated through a comprehensive parametric
study.

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“Free vibration of functionally graded carbon nanotube reinforced composite cylindrical panels”, Composite
ABSTRACT: In this study, free vibration characteristics of composite plates reinforced with single walled
carbon nanotubes is investigated. Distribution of the carbon nanotubes through the thickness of the panel may
be uniform or functionally graded. Properties of the composite media are obtained according to a refined rule of
mixtures approach which contains the efficiency parameters. First order shear deformation shell theory and
Donnell-type kinematic assumptions are used. To establish the eigenvalue problem of the system, the energy
based Ritz method with Chebyshev polynomials as the basis functions is implemented. The resulting eigenvalue
problem is solved to obtain the natural frequencies of the system as well as the associated mode shapes. After
performing comparison studies for the simpler cases, numerical results are given for vibration characteristics of
carbon nanotube reinforced cylindrical panels. Numerical results reveal that, frequencies of the panel are
dependent to both, volume fraction of carbon nanotubes and their distribution pattern across the thickness.
Increasing the volume fraction of carbon nanotubes increases the frequencies of the panel.

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“Pre-buckling and buckling analyses of functionally graded microshells under axial and radial loads based on
the modified couple stress theory”, Composite Structures, Vol. 142, pp 226-237, May 2016,
https://doi.org/10.1016/j.compstruct.2016.01.083
ABSTRACT: In the present paper, the pre-buckling and buckling behaviors of a simply supported functionally
graded (FG) microshell under a combined action of axial and radial loads are investigated. The size effects in
the mechanical behavior of the microshell are captured by using the modified couple stress theory. The first
order shear deformable shell theory together with the von Karman’s geometric nonlinearity is adopted to
describe its deformation behavior. Based on these assumptions and the Hamilton’s principle, the equilibrium
equations and associated boundary conditions for the microshell are derived. By applying the Galerkin method
to the equilibrium equations, the pre-buckling deformation is obtained. The critical buckling load is then
derived with the effect of the pre-buckling deformation taken into consideration. Furthermore, the effects of the
material length scale parameter to thickness ratio, the power law index and the radial load to axial load ratio on
the pre-buckling and buckling behaviors of the FG microshell are discussed in detail.
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ABSTRACT: This study presents vibration and lateral buckling optimisation of thin-walled laminated composite beams with channel sections. While flanges’ width, web’s height, and fibre orientation are simultaneously treated as design variables, the objective function involves maximising the fundamental frequency and critical buckling moment. Based on the classical beam theory, the beam element with seven degrees of freedom at each node is developed to solve the problem. Micro Genetic Algorithm (micro-GA) is then employed as an optimisation tool to obtain optimal results. A number of composite channel-section beams with different types of boundary conditions, span-to-height ratios, and lay-up schemes are investigated for the optimum design. The outcomes reveal that geometric parameters severely govern the optimal solution rather than the fibre orientation and it is considerably effective to use micro-GA compared with regular GA in term of optimal solution and convergence rate.

ABSTRACT: A comprehensive review is conducted on the performed investigations in the field of mechanical behaviour of glass-fibre reinforced thermosetting-resin (GFRP) pipes. Classified into six categories of stress/strain analysis, failure evaluation, environmental issues, viscoelastic behaviour and creep analysis, fatigue analysis and impact analysis, the main streamline of the performed and on-going studies in current years have been outlined. The recent trend and challenges in conducted researches are highlighted and discussed. Performing a gap analysis, new perspectives which are still required to be developed more deeply for their industrial applications or have not been addressed in literature are nominated.

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ABSTRACT: This paper presents a finite element based method to investigate the hygrothermal effects on the transient dynamic response of delaminated composite pretwisted conical shells with initial twist impacted at arbitrary locations by multiple spherical impactors. An eight-noded shell element has been used in the present analysis based on the Mindlin’s theory. The generalized dynamic equilibrium equation is derived from Lagrange’s equation of motion neglecting Coriolis effect for moderate rotational speeds. The multi-point
constraint algorithm has been incorporated to ensure the compatibility of deformation and equilibrium of resultant forces and moments at the delamination crack front. The indentation laws as proposed by Hertz have been implemented to compute the contact force and displacement arising from each impact on specific locations of delaminated conical shells already prestressed by residual thermal or moisture strains. Results have been presented to depict the influence of important parameters like, twist angle, size and location of delamination, velocity and mass of the impactors and the time-delay between the impactors on the multiple impact response of delaminated composite conical shells in hygrothermal environment.


ABSTRACT: A simple mechanical model for buckling behavior of boron nitride nanotube (BNNT) surrounded by an elastic matrix is presented. A nonlocal-continuum model is proposed for BNNT using the Euler–Bernoulli beam theory on an elastic matrix. The elastic matrix surrounded of the BNNT is modeled via linear spring model using the Winkler and Pasternak elastic foundation models. The equation is obtained by variational approach for buckling and has been solved by two different approaches. Separation of variables and method of discrete singular convolution are used for computations. The influences of some geometric parameters of BNNT on buckling behavior are investigated in detail. The effect of mode numbers and nonlocal parameter on buckling behavior of BNNT has also been investigated. Finally, some parametric results are presented for BNNT buckling. It is noticed that the present DSC approach can predict accurately the buckling loads for nano-scaled structures.

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ABSTRACT: Hierarchical materials are widely observed in nature, and have been credited with superior mechanical properties and weight efficiency. In the present work, fractal-appearing self-similar regular hexagonal hierarchical honeycombs (HHHs) are constructed by iteratively replacing each three-edge vertex of a base hexagonal network with a smaller regular hexagon up to second order. The cell wall thickness is adjusted so that the two fractal configurations have identical density as the base honeycomb. To investigate the out-of-plane crashworthiness of this new class of hexagonal hierarchical honeycomb concept, finite element modeling is carried out and validated using experiment results. By comparing the results of three traditional corrugated hexagonal honeycombs (0th order HHH) with those pertinent to two novel 1st and 2nd order HHHs, it can be concluded that hierarchical organization of different cells can enhance the material/strength distribution across the network, resulting in improved crush strength and crush force efficiency. In addition, parametric studies are carried out to explore two further strategies to improve out-of-plane crashworthiness by altering the material distribution, namely changing relative cell sizes and cell wall thickness. The results suggest that further improvement can be realized through optimum designs of the fractal geometries.
ABSTRACT: Anti-symmetric laminated \([+\alpha/-\alpha]_n\) cylindrical shell (ALCS) is a type of bistable composite structures that can deform between two stable shapes under an external loading. The maximum snap loads and shape deformations in varying thermal environments play a significant role in their bistable characteristic. This paper presents an experimental study on the bistable behaviour of ALCSs at 20 °C, 40 °C, 60 °C, and 80 °C. The load–displacement curves are obtained by using a testing machine with a thermal chamber. The effect of the temperature variation on the shell’s curvatures is also investigated by digital image processing technique. The obtained experimental results show the same trend as the analytical and numerical results. The thermal influence on the bistable behaviour in a local temperature field is also studied in detail. The experimental investigations presented in this paper is of great importance in the engineering design and applications of morphing structures manufactured from ALCSs.

ABSTRACT: In this paper a computational two-scale model for sandwich composites with a comb-like core structure is proposed. On the global scale the sandwich panel is modeled with homogenized finite shell elements, while on the local scale a representative volume element (RVE) describes the microstructure of the sandwich through the full thickness. The local model is implemented as a constitutive law for the shell elements on the global scale. As the material response is updated in each iteration step of a nonlinear simulation, local effects of nonlinearity such as face sheet buckling or plastic flow can be described by the model.

ABSTRACT: A novel numerical methodology is used to investigate the behavior of an all-composite wing-box under a compressive load taking into account the presence of concurrent inter-laminar damages such as delaminations and skin-stringer debonds and their propagation. The proposed numerical methodology, based on linear structural analyses, is computationally inexpensive if compared to the VCCT and CZM based numerical techniques, hence, it appears to be particularly suitable for the preliminary design phase of complex structure. The presented linear approach is an evolution of a previous technique developed specifically for delaminations.
Indeed, in this paper the linear approach has been enhanced to predict the propagation of inter-laminar damages with open crack surfaces such as skin-stringer debonds and it has been implemented in a commercial Finite Element platform. The effectiveness (in terms of computational cost and accuracy of results) of the suggested linear numerical methodology, in predicting the compressive behavior of complex composite structures with inter-laminar damages, has been confirmed by cross-comparisons with the standard non-linear VCCT technique. Finally, comparisons in terms of critical propagation load and Energy Release Rate distribution along the damage tip predictions, for several examined structural configurations with different damage extension and depth, have allowed to assess the field of applicability of the propose novel numerical methodology.


ABSTRACT: A physical–mathematical interpretation of the alternative first-order shear deformation concept proposed by the author is first presented to get rid of an intuitive aspect of its basic premise that the total deflection $w$ can be assumed as the sum of the bending and transverse shear deflections $w_b$ and $w_s$. Then, on the basis of several beam and plate illustrative examples, the qualitative theoretical framework of the alternative concept is clarified by comparing with the traditional Timoshenko beam and Mindlin–Reissner plate theories. In addition, a new first-order shear deformation cylindrical shell theory is developed based on the alternative concept and Hamilton’s principle to obtain a frequency formula for in-plane vibrations of a thick ring. Finally, the physical–mathematical position of the present theory among the conventional thin-walled structure analysis models is deliberated. The result shows that the present theory is regarded as a refined mathematical generalization of the so-called corrected classical theory and it could lead to a reduction in the number of fundamental variables and governing equations in the modeling of the transverse shear deformable composite structures.


ABSTRACT: This study presents a numerical analysis for aerothermoelastic behavior of functionally graded (FG) curved panels in hypersonic airflow regime. The classical plate theory is used to model the structural treatment and the von Karman strain–displacement relations are utilized to involve the structural nonlinearity. To incorporate the applied hypersonic aerodynamic loads, third-order piston theory is employed to model unsteady aerodynamic pressure in this flow regime. The material properties of a FG panel are supposed to be temperature-dependent and vary continuously through the thickness direction according to power-law distribution of the volume fraction of the constituents. The temperature distribution in the thickness direction is calculated by the solution of one-dimensional steady-state heat conduction equation. The Generalized Differential Quadrature (GDQ) method in conjunction with the fourth order Runge–Kutta method is implemented for discretization and solution of the equations. The effects of several significant parameters including Mach number, curvature, dynamic pressure, surface temperature and volume fraction index on the FG curved panel aerothermoelastic behavior and route to chaos are examined. Comparison of the obtained results with those available in the literature demonstrates the accuracy and reliability of the GDQ method to analyze the aerothermoelastic behavior of FG curved panels in hypersonic flow.
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“Axial deformability of the composite lattice cylindrical shell under compressive loading: Application to a load-
carrying spacecraft tubular body”, Composite Structures, Vol. 146, pp 201-206, June 2016,
https://doi.org/10.1016/j.compstruct.2016.03.021
ABSTRACT: Analysis of axial deformability of filament-wound composite anisogrid lattice tubular body of the
spacecraft subjected to compressive loading is presented in the paper. The axial compressive load is applied to
the lattice cylinder through the rigid ring attached to its end. The lattice structure is modelled using a continuum
model of the orthotropic cylindrical shell. Based on this model, an analytical formula providing the value of the
axial deformation of the rigid ring and assessment of the shell’s axial stiffness is derived. This formula is
verified by the finite-element analysis and employed to investigate the effects of the length, number of helical
ribs and their angle of orientation on the axial deformability of the lattice cylinder. Using these results the full
size physical prototype of the spacecraft body was designed, manufactured and tested. The axial displacement
predicted by the analytical formula is correlated well with that measured in the experiment. Thus, the analytical
formula proposed in this work can be utilised by design engineers in the efficient design analyses of similar
composite lattice structural components.

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“Buckling of axially compressed CFRP truncated cones: Experimental and numerical investigation”, Composite
ABSTRACT: Thin-walled conical structures are widely used in aerospace, offshore, civil and other engineering
fields. Parts of space launcher transport systems are one example for the application of conical shells. Buckling
of such thin-walled imperfection sensitive structures is a very important phenomenon to be considered during
design phase. Nowadays, the analysts still use empirically based lower-bound methods such as the NASA
SP-8007 for cylinders and SP-8019 for cones to calculate the required knock-down factors (KDFs), which do
not include important mechanical properties of laminated composite materials, such as the stacking sequence.
New design approaches that allow taking full advantage of composite materials are therefore required. The
study deals with the buckling experiments on axially compressed, unstiffened carbon fiber–reinforced polymer
(CFRP) truncated cones performed by DLR for validation of high-fidelity numerical models. Three
geometrically identical cones with different layup were designed, manufactured and tested. Before testing, the
thickness of the cones was measured with ultrasonic inspection and the geometry was measured utilizing a 3D
scanning system based on photogrammetry. During testing, a digital image correlation system was employed to
monitor deformations, strain gage readings and load–shortening data were taken. Modeling of shape mid-
surface, thickness and ply piece imperfections are included into the Finite Element Analysis (FEA) of the test
structures, and the experimental results are compared with the FEA results.

ABSTRACT: The paper is to present an overview of various semi-analytical numerical methods for quasi-three-dimensional (3D) analyses of laminated composite and multilayered (or sandwiched) functionally graded elastic/piezoelectric materials (FGEMs/FGPMs) plates and shells with combinations of simply-supported, free and clamped edge conditions. This review introduces the development of various semi-analytical numerical methods incorporating 3D analytical approaches (i.e., the state space and asymptotic ones) with numerical techniques (i.e., the differential quadrature, meshless reproducing kernel and finite element ones), and their applications to the analyses of plates and shells made of advanced materials, such as the fiber-reinforced composite materials, FGEMs and FGPMs, and carbon nanotube-reinforced composite materials. Two micromechanical schemes (i.e., the rule of mixtures and Mori–Tanaka scheme) used to estimate the effective material properties of functionally graded structures are presented. The strong and weak formulations of the 3D piezoelectricity theory and their corresponding possible edge conditions for circular hollow cylinders are presented for the illustration purposes. A comparative study of the results obtained by using assorted semi-analytical numerical methods is undertaken.

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ABSTRACT: In this paper, in order to select a better material between aluminum alloy and composite for the connective parts which is on a folded omega stringers stiffened composite panel under an axial compression, numerical investigation is conducted. The axial compression is divided into two stages which are buckling and post-buckling. By using software ABAQUS, 9 models were analyzed respectively. By comparing among the 9 models, firstly, composite joints have the highest collapse load with the same T stringer or without T stringer and next are aluminum alloy joints. Secondly, aluminum alloy T stringer has the highest buckling load and collapse load than composite one with the same joints or without joints and the composite T stringer the second. Thirdly, the joints and the T stringer are compulsory, because either the joints or the T stringer or both of them can enhance buckling load and collapse load remarkably. An important question for future studies is that the failure mechanisms occurring at the connective parts including their surrounding areas and choosing reasonable failure criterion for the material of these sections have to be researched by numerical methods and experimental tests.

Hassan Sayyaadi, Farhad Rahnama and Mohammad Amin Askari Farsangi (School of Mechanical Engineering, Sharif University of Technology, Tehran 11155-9567, Iran), “Energy harvesting via shallow cylindrical and spherical piezoelectric panels using higher order shear deformation theory”, Composite Structures, Vol. 147, pp 155-167, July 2016, https://doi.org/10.1016/j.compstruct.2016.03.035

ABSTRACT: In this article an analytical solution is presented for power output from a piezoelectric shallow shell energy harvester using higher order shear deformation theory (HSDT). The energy harvester is made of an
elastic substrate layer coupled with one or two surface bonded piezoelectric layers. Mechanical equations of motion with Gauss’s equation are derived on the basis of HSDT and solved simultaneously for simply-supported mechanical boundary conditions. The electromechanical frequency response functions that relate the power output and circuit load resistance are identified from the exact solutions. Using Rayleigh damping the influence of structural damping is taken into account. Also performance of the system is analyzed extensively for different parameters such as type of energy harvester including unimorph and bimorph panel in series or parallel connections of piezoelectric layers, circuit load resistance, geometrical parameters and material properties of core and piezoelectric layers.

Mehdi Darabi and Rajamohan Ganesan (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Blvd. W., Montreal, Quebec, Canada), “Non-linear dynamic instability analysis of laminated composite cylindrical shells subjected to periodic axial loads”, Composite Structures, Vol. 147, pp 168-184, July 2016, https://doi.org/10.1016/j.compstruct.2016.02.064

ABSTRACT: The dynamic instability of thin laminated composite cylindrical shells subjected to harmonic axial loading is investigated in the present work based on nonlinear analysis. The equations of motion are developed using Donnell’s shallow-shell theory and with von Karman-type of nonlinearity. The nonlinear large deflection shallow-shell equation of motions are solved by using Galerkin’s technique that leads to a system of nonlinear Mathieu–Hill equations. Both stable and unstable solutions amplitude of the steady-state vibrations are obtained by applying the Bolotin’s method. The nonlinear dynamic stability characteristics of both symmetric and antisymmetric cross-ply laminates with different lamination schemes are examined. A detailed parametric study is conducted to examine and compare the effects of the magnitude of both tensile and compressive axial loads, aspect ratios of the shell including length-to-radius and thickness-to-radius ratios, and different circumferential wave numbers as well on the parametric resonance particularly the steady-state vibrations amplitude. The present results show good agreement with that available in the literature.

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ABSTRACT: The aero-thermo-elastic stability of layered cylindrical shells with viscoelastic cores is investigated. The Donnell’s shell theory for the outer layers and the first order shear deformation theory for the viscoelastic layer are employed in conjunction with the von Karman–Donnell kinematic nonlinearity to construct the model. The pre-stresses and pre-deformations arisen from the temperature rise and static aerodynamic pressure are first determined by solving the nonlinear thermo-elastic equilibrium equations using an exact analytical method. The results are then used in the linear aeroelastic stability equations and analyzed with the Galerkin’s procedure to determine the supersonic flutter boundaries of the structure. Numerical studies are performed to illustrate the effects of viscoelastic damping, geometrical parameters and temperature rise on the flutter stability margins. Special attention is put on the effect of pre-deformation on the aeroelastic stability of the shell. It is found that the pre-deformation could significantly alter the flutter boundaries for sufficiently high temperatures.
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ABSTRACT: Several natural fibres such as hemp, flax, sisal, kenaf and jute have been used in different industrial applications. Recently, natural fibres have drawn the interest of researchers, engineers and scientists as substitute reinforcements for fibre reinforced polymer (FRP) composites tubes. Due to their fairly good mechanical properties, low cost, high specific strength, environmentally-friendliness and bio-degradability, ease of fabrication, and good structural rigidity, these materials can be used in an extensive range of applications, including aerospace and the automotive industry. Previous studies focused on how to introduce the natural fibres into industrial applications and the replacement of synthetic fibres with natural fibre materials. The tensile properties of natural fibre reinforce polymers are mainly influenced by mechanical properties such as tensile properties, flexural properties, and impact strength are strongly affected by fibre content. Furthermore, the overall tensile and flexural properties of natural fibre-reinforced polymer hybrid composites are highly dependent on the aspect ratio, moisture absorption. The geometric designs such as geometry and shapes and triggering and non-triggering and filled and non-filled was found that significantly affected the crashworthiness parameters and specific energy absorption of natural fibre reinforced polymer composite tubes. Furthermore, the compressed data, which is based on the maximum values, reported in the literature, it can be observed that the woven flax fabric circular tube exhibits high energy absorption capability and CFE. This result contributes to the increased ability to use natural fibres in vehicle manufacture and thus increases the sustainability of this industrial sector. This paper presents an overview of the developments made in the area of natural fibres reinforced composites, in terms of their physical and mechanical properties, and crashworthiness properties. Several uncertainties affecting the experimental results were discussed.

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ABSTRACT: This paper presents an analytical approach to investigate the nonlinear axisymmetric response of functionally graded (FG) shallow spherical shells (SSSs) resting on elastic foundations, exposed to thermal environment and subjected to uniform external pressure. Material properties are assumed to be temperature-independent, and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Formulations are based on the first order shear deformation shell theory taking geometrical nonlinearity, initial geometrical imperfection, Pasternak type elastic foundations and tangential edge restraints into consideration. Approximate solutions are assumed to satisfy clamped boundary conditions and Galerkin method is applied to derive explicit expressions of buckling loads and load–deflection relations.
The effects of material and geometrical properties, foundation stiffness parameters, degree of tangential restraint, temperature field and imperfection on the buckling behavior and load carrying capacity of FG SSSs are analyzed and discussed.


ABSTRACT: This paper aims to propose an alternative approach for response of viscoelastic cross-ply laminated shallow spherical shell. In the proposed approach, the governing differential equations of cross-ply laminated shallow spherical shell are derived using the dynamic version of the principle of virtual displacements. Following this Laplace transform is employed in the transient analysis of laminated shell problem. In the transformed domain damping can be incorporated very easily. The transformed time-independent problem in spatial coordinate is solved numerically by Gauss elimination. Inverse transformation of the results into the time domain is performed by the modified Durbin’s method. Verification of the presented method is carried out by comparing the results with those obtained by Newmark method and ANSYS finite element software. Materials of the shell laminates are assumed to be linear elastic or viscoelastic. The novelty of the present study lies in the fact that a combination of Laplace transform and Navier method is employed in the analysis of damped response of laminated shells. The numerical sample results have proved that the presented method constitutes a highly accurate and efficient solution and it can be easily applied to the laminated composite shell problems.

Wu Yuan, Hongwei Song, Lingling Lu and Chenguang Huang (Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, No. 15 Beisihuanxi Road, Beijing 100190, China), “Effect of local damages on the buckling behaviour of pyramidal truss core sandwich panels”, Composite Structures, Vol. 149, pp 271-278, August 2016, https://doi.org/10.1016/j.compstruct.2016.04.031

ABSTRACT: Truss core sandwich panels have been widely investigated due to their superior mechanical performances. However, local defects or damages during preparation and service may reduce the strength significantly. The objective of this paper is to examine the imperfection sensitive of this kind of structures under in-plane compression. The elastic and plastic buckling behaviour of pyramidal truss core sandwich panels with local damages under in-plane compression are studied experimentally and numerically. Local damages including unbound nodes between lattice truss and the facesheet, missing lattice cells and holes in the facesheet are considered. In-plane compression tests of truss core sandwich panels with prefabricated local damages are conducted, and then a finite element model in conjunction with random number is developed to simulate the buckling behaviour of the panel with randomly distributed damages in a specific region. Experimental and numerical results show that, besides the damage extent, the location of unbound nodes and missing lattice cells have significant effect on the buckling strength of the pyramidal truss core sandwich panel. In addition, the local damage sensitiveness of sandwich panel with round holes in the facesheet is lower than that with square holes.

ABSTRACT: Foam-filled circular composite tube has been widely used in safety design of automobile, spacecraft recovery and so on due to its advantage of high energy absorption, light weight and anti-corrosion. But the axial crush behavior and energy absorption capability of foam-filled composite tubes are threatened by elevated and high temperatures. In practice, the effects of high temperatures cannot be ignored because composites and foam are sensitive to temperature. In this paper, an experimental investigation was carried out to evaluate the effectiveness of energy absorption of foam-filled circular glass fiber reinforced plastic (GFRP) tube under elevated and high temperatures. The temperature range was from 20 °C to 110 °C, covered the glass transition temperature (92 °C). In the meantime, the effects of high environmental temperatures on failure mode, crush force efficiency, energy ductility coefficient and specific energy absorption were also studied. The test results demonstrated that the axial crush behavior and energy absorption capacity of foam-filled GFRP tubes were determined by the environmental temperature. The foam-filled GFRP tubes can achieve top crashworthiness performance when the environmental temperature was less than 70 °C.

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ABSTRACT: The nonlinear dynamic response of functionally graded material (FGM) shallow shells subjected to thermal and harmonic loads is studied using finite element method. The material properties vary continuously in the thickness direction based on a simple power law distribution. The equations of motion are obtained using modal reduction method based on the third order shear deformation theory. The shooting method is used to obtain appropriate initial conditions for having only steady state response. The effects of thickness ratio and radii of curvature on the dynamic response of FGM shallow shells are studied. Buckled equilibrium positions (BEPs) are obtained for thermally loaded FGM shallow shells with immovable middle or physical neutral surfaces. It is shown that there exist one stable and two unstable BEPs. Then the behavior of an FGM shallow shell subjected to harmonic excitation in thermal environment is investigated. It is seen that the thermally loaded FGM shallow shell has different responses for the same frequency and amplitude of excitation depending on its initial conditions.

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ABSTRACT: Based on three-dimensional theory of elasticity, semi-analytical solutions for free vibration of cross-ply laminated cylindrical panels are derived applying the state space approach (SSA) and discrete singular convolution (DSC) algorithm. One pair of opposite edges are assumed to be with simply supported and the other pair of edges arbitrary boundary conditions. The thickness direction of panels is chosen as the transfer direction in SSA, and the DSC is employed to discretize the axial direction of panel. Hence, the original partial differential equations are transformed into a state equation consisting of first-order ordinary differential equations. The application of DSC can deal with various boundary conditions, which cannot be solved in the
conventional SSA. Accuracy and convergence for laminated cross-ply panels are validated through numerical examples.

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ABSTRACT: This paper presents a numerical investigation on the ductility and strength of short steel tubes filled with Rubberized Concrete (RuC), which is a composite material that mixes concrete with rubber particles. This research concerns the enhancement of both ductility and energy absorption of CFST by considering a core of RuC instead of normal concrete (NC). First, a brief literature review on the topic is presented. Then, based on an experimental programme conducted by the authors, numerical models of CFST and RuCFST columns are developed. The results of non-linear analyses (ultimate strengths, load-shortening curves and failure modes) are validated using experimental data, and good agreement is shown. Finally, a numerical study on the properties of confined NC and RuC is conducted. It is concluded that the concrete damaged plasticity model can be used to simulate RuC. The dilation angle plays a key role in RuC and its lower value (compared to that of NC) influences the concrete confinement. Taking into account the RuC dilation angle, steel yield stress and tube local slenderness, a new formula is proposed to predict the concrete core confinement of the studied CFST and RuCFST columns with circular sections.

ABSTRACT: This paper proposes some advanced plate theories obtained by expanding the unknown displacement variables along the thickness direction using trigonometric series, exponential functions and miscellaneous polynomials. The used refined models are Equivalent Single Layer (ESL) theories. They are obtained by means of the Unified Formulation by Carrera (CUF), and they accurately describe the displacement field and the stress distributions along the thickness of the multilayered plate. The governing equations are derived from the Principle of Virtual Displacement (PVD), and the Finite Element Method (FEM) is employed to solve them. The plate element has nine nodes, and the Mixed Interpolation of Tensorial Components (MITC) method is used to contrast the membrane and shear locking phenomenon. Cross-ply plates with simply-supported edges and subjected to a bi-sinusoidal load, and sandwich plates with simply-supported edges and subjected to a constant transverse uniform pressure are analyzed. Various thickness ratios are considered. The results, obtained with different theories within CUF, are compared with the elasticity solutions given in the literature and the layer-wise solution. It is shown that refined kinematic theories employing trigonometric or exponential terms are able to accurately describe the displacement field and the mechanical stress fields. In some cases, the reduction of computational costs is particularly relevant respect to the layer-wise solution.
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ABSTRACT: Automated fiber placement (AFP) machines have made it possible to tailor the material stiffness properties in a laminated composite structure by fiber steering. The so-called variable stiffness (VS) laminate can be designed to improve the structural performance of a composite component. Herein, using a metamodeling based design optimization (MBDO) method, elliptical composite cylinders with VS laminate are designed and optimized for maximum axial buckling capacity. The effect of cross-sectional aspect ratio of the elliptical cylinders on the potential improvement of the buckling capacity is also investigated. As the baseline for comparison, for each cross-sectional aspect ratio, the buckling capacity of elliptical cylinders with quasi-isotropic (QI) and optimum constant stiffness (CS) laminates are also calculated. It is found that the buckling capacity of an elliptical composite cylinder can be improved by fiber steering up to 118% compared with its best CS counterpart.

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“Bending of the composite lattice cylindrical shell with the midspan rigid disk loaded by transverse inertia forces”, Composite Structures, Vol. 150, pp 181-190, August 2016, https://doi.org/10.1016/j.compstruct.2016.05.015
ABSTRACT: Bending deformation of a composite lattice cylindrical shell with the rigid disk attached at the midspan is studied in this paper. The shell with the disk is subjected to a transverse inertia load. The problem is solved using a continuum model of the lattice structure and equations of the semi-membrane theory of orthotropic cylindrical shells. The shells with two variants of the end supports are analysed. Analytical formulas providing the tools for fast and accurate calculations of the transverse disk displacement are derived. Based on these solutions, a parametric study of the effects of the shell length, angle of orientation of helical ribs of the lattice structure and their number on the disk displacement is performed. The results of calculations have been successfully verified using a finite-element analysis. The analytical formulas proposed in this work can be efficiently employed by design engineers to perform analyses of composite lattice cylindrical shells in aerospace applications.

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ABSTRACT: In this paper we present a finite element model for the dynamic analysis of sandwich laminated plates with a soft core and composite laminated face layers, as well as piezoelectric sensor and actuator layers.
The model is formulated using a mixed layerwise approach, by considering a higher order shear deformation theory (HSDT) to represent the displacement field of the compressible core and a first order shear deformation theory (FSDT) for the displacement field of the adjacent laminated face layers and exterior piezoelectric layers. Control laws are implemented and the model is validated for free and forced vibrations with results from the literature and the effect of the core transverse compressibility is assessed on modal damping and frequency response.

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ABSTRACT: In this paper, a new 12-parameter shell finite element for large deformation analysis of composite shell structures is developed using third-order thickness stretch kinematics. The continuum shell element is utilized in the numerical simulations of laminated composite and functionally graded materials, using a high-order spectral/hp approximations. The results obtained from the 12-parameter shell element are compared with those obtained from the 7-parameter shell element to bring out the differences. Deflections and maximum stresses are computed using the two models. The results show that the responses predicted by the two formulations (and models) are consistent with each other, with the 12-parameter model showing slight difference from those predicted by the 7-parameter model.

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ABSTRACT: In this paper, the size-dependent formulation of shear deformable functionally graded piezoelectric (FGP) cylindrical nanoshells is developed based on a new modified couple stress theory. After the general formulation, the buckling of FGP cylindrical nanoshells under pressure is investigated by using the first order shear deformable shell model. The material properties are assumed to be varied along thickness direction according to the power law distribution. The equilibrium equations and boundary conditions are obtained by using the minimum potential energy principle. A buckling analysis of simply-supported FGP cylindrical nanoshells under uniform lateral external pressure is carried out and the effects of different parameters on the critical pressure are examined. The effects of geometrical, electrical and material properties, such as material length scale parameter, length, thickness, external electric voltage and material property gradient index, on the critical pressure are illustrated. It is indicated that the critical pressure is significantly size-dependent.

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ABSTRACT: Buckling behavior of carbon nanotube reinforced functionally graded (CNTR-FG) composite laminated plate is studied. The first-order shear deformation theory (FSDT) is employed to incorporate the effects of rotary inertia and transverse shear deformation, and the meshless kp-Ritz method is used to obtain the buckling solutions. Using the kernel particle approximation in the field variables and minimizing the energy functional via the Ritz procedure, a discretized eigenvalue equation of the problem is derived. The numerical stability and accuracy of the kp-Ritz method is validated through convergence and comparison studies. Besides, parametric studies are conducted for various types of CNTs distributions, CNT volume fraction, plate aspect ratio and plate length-to-thickness ratio under different boundary conditions. Moreover, the effects of number of layers and lamination angle are also investigated.

ABSTRACT: The present study is one of first attempts to closed-form solutions of the thermoelastic stability problem of functionally graded (FG) conical shells subjected to the thermal loading within the first-order shear deformation theory (FSDT). The material properties of FG truncated conical shells vary continuously in the thickness direction. The governing thermoelastic stability equations of FG truncated conical shells under thermal loadings within the FSDT using Donnell shell theory have been derived and for freely supported boundary conditions are reduced to a set of linear algebraic equations using the Galerkin’s method. The expressions for critical temperature differences of freely supported FGM truncated conical shells based on the FSDT subjected to the uniformly and linearly distributed temperatures across the thickness are obtained by solving the linear algebraic equations. The appropriate formulas for FG cylindrical shells based on the SDT are found, as a special case. In order to assure the accuracy of the results, present study are compared and validated with the known data available via literature. Finally, some parametric studies are conducted to investigate the influences of the shear stresses, volume fraction index, FG profiles and the conical shell characteristics on the critical temperature differences are discussed in detail.

ABSTRACT: A novel semi-analytical finite strip method is presented for buckling analysis of composite plate structures with boundary edges elastically supported. A set of unique Fourier series functions is introduced to represent the longitudinal variation of deflection along a strip, and they are capable of handling elastic edges with translational and rotational spring supports. The proposed hybrid method overcomes limitation of classical finite strip method only capable of handling simple end boundary conditions of structures, and it avoids the ill-conditioning when a set of standard Fourier series functions is used for buckling analysis. Accuracy and validity of the proposed method are demonstrated by the convergence and comparative studies in comparison with the numerical finite element method. As an example, the present method is applied to buckling analysis of a composite Z-stiffened panel under pure shear, and its capability and efficiency of treating different edge conditions in the panel skin and stiffeners are illustrated.


ABSTRACT: Functionally graded materials are multi-phase composites which are characterized by continuous and smooth variation of the volume fractions of two or more constituents within the structure domain. In this study, geometrically nonlinear analysis of functionally graded power-based (FGMs) and carbon-nanotubes reinforced composites (FG-CNTRCs) is performed using a fully integrated first-order solid shell finite element. This formulation relies on the alternative parametrization of the so-called 7-parameter shell model. The central aspects that motivate the use of this formulation are: (i) the use of unmodified three-dimensional constitutive laws, and (ii) the consideration of the thickness variation of the shell along the deformation process. Locking treatment is carried out by means of the combination of the Enhanced Assumed Strain (EAS) and the Assumed Natural Strain (ANS) methods. This solid shell element is numerically implemented into the commercial FE code ABAQUS through the user subroutine UEL. Several numerical examples are conducted with the aim of examining the effects of different material parameters on the structural response. These applications show the applicability of the current formulation for FG composite simulations undergoing geometrically nonlinear effects.

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ABSTRACT: A mixed quadrilateral 3D finite element, obtained from the Hellinger–Reissner functional, is presented for linear static and buckling analyses of variable-angle tow (VAT) composite plates. Variable-angle tows describe curvilinear fiber paths within composite laminae and are a promising technology for tailoring the buckling and post-buckling capability of plates. Due to the variable stiffness across the planform of the VAT plates, pre-buckling stresses can be tailored and redistributed towards supported edges, thereby greatly improving the buckling load. A linear mixed element called MISS-4 is used as starting point for this work. The element presents a self-equilibrated and isostatic state of stress. The kinematics lead to element compatibility matrix calculations based solely on the interpolation along element edges. The drilling rotations do not require penalty functions or non-symmetric formulations, thus avoiding spurious energy modes. The buckling analysis
is reliably performed via a co-rotational formulation. In this work VAT plates with linear fiber angle variation in one direction, and constant stiffness properties in the orthogonal direction are studied. Numerical examples of VAT plates subjected to different loads and boundary conditions are investigated herein. The convergence of displacements, stress resultants and buckling loads are presented, and comparisons with numerical results, obtained using the S4R finite element of Abaqus and the pseudo-spectral Differential Quadrature Method, are shown.

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ABSTRACT: In this paper, the post-buckling behavior of laminated nanocomposite plates subjected to biaxial and uniaxial compression is investigated. In each layer, carbon nanotubes (CNTs) are axially aligned within the polymer matrix, and are distributed either uniformly or in a functionally graded pattern in the thickness direction. Discretized governing equations are derived based on the first-order shear deformation theory (FSDT) via the IMLS-Ritz method. In this study, the post-buckling paths are traced using an algorithm that combines the arc-length iterative procedure with the modified Newton–Raphson method. In order to validate the method, comparison studies are performed on the functionally graded material laminated plates, where results are available in the literature. Several example problems are considered including cross-ply and angle-ply laminated nanocomposite plates. The effects of number of layers, lamination scheme, plate geometry, CNT volume fraction ratio, CNT distribution, and boundary conditions on the post-buckling behavior of the plates are presented.

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ABSTRACT: Throughout this report, the collapse behaviors of steel strip reinforced thermoplastic pipe (SSRTP) subjected to external pressure are investigated experimentally and numerically. A hyperbaric chamber is utilized to conduct the full-scale laboratorial tests of SSRTP, and the commercial software ABAQUS is used to simulate its collapse behavior. The results obtained from the experiment and the simulations are in good coincidence with each other, which further prove the reliability and accuracy of the proposed finite element model. Also, a simplified estimation is presented to calculate the collapse pressure of SSRTP, which can be regarded as its lower limit value. In addition, a series of parametric studies were performed to investigate the influential factors on the collapse pressure of the pipe, such as the initial imperfection, the geometrical
configurations, the friction coefficient between contact surfaces, etc. The relative results may be of interest to the manufacture factory engineers.

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ABSTRACT: In this paper, two different types of unstiffened and lozenge grid-stiffened E-glass/epoxy composite cylindrical shells are experimentally investigated under lateral compression. The composite shells are compressed in two different loading conditions: between two rigid flat platens and between a rigid flat platen and a rigid cylindrical indenter which is aligned perpendicular to the shell axis. The effects of the grid stiffeners on the stiffness, contact force and energy absorption capacity of the composite cylindrical shells are investigated in the two mentioned loading conditions. Incorporation of grid stiffeners in the composite cylindrical shells leads to an increase in the structural stiffness, contact force and energy absorbing capacity in both loading conditions. Furthermore, it is observed that the effect of the stiffeners on the structural stiffness is dominant in the elastic deformation stage of the compression processes. The results show that stiffening the composite cylindrical shells with lozenge grid stiffeners can increase the specific energy absorption almost twice in comparison with the unstiffened composite shells; and among all of the specimens, the grid-stiffened structures compressed between two rigid flat platens have the highest specific energy absorption, while the unstiffened structures compressed by the cylindrical indenter have the least capacity to absorb energy.

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ABSTRACT: With regard to future heavy-lift launch vehicles, the buckling analysis and optimization of large-scale stiffened shells by finite element method (FEM) suffer from unbearable computational cost. In spite of the high analysis efficiency, the traditional smeared stiffener method (SSM) is still not accurate enough owing to the assumptions of analytical derivations. In this study, an effective and efficient numerical-based smeared stiffener method (NSSM) is proposed for the buckling analysis of stiffened shells. Firstly, the representative unit cell of stiffened shell is divided, and then it is equivalent using a novel numerical implementation of asymptotic homogenization (NIAH) method. The equivalent stiffness coefficients can be obtained accurately. Then, the buckling load is calculated by means of Rayleigh–Ritz method. Comparing with the prediction results of SSM and FEM, the high prediction accuracy and efficiency of NSSM are observed. Then, the effectiveness of NSSM for different loading conditions and model scales are discussed. Finally, numerical examples illustrate the high prediction accuracy and widespread applicability of NSSM for various grid-patterns, and the advantage of the rotated triangle grid-pattern in load-carrying capacity among various grid-patterns is demonstrated.
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ABSTRACT: In this paper, nonlinear buckling responses of functionally graded (FG) thin-walled open section beams based on Euler–Bernoulli–Vlasov theory is presented. The finite element incremental equilibrium equations are developed by updated Lagrangian formulation using the non-linear displacement cross-section field that accounts for large rotation effects. Young’s modulus of FG beams are varied continuously through the wall thickness based on the power-law distribution. Numerical results are obtained for thin-walled FG beams with symmetric and mono-symmetric I-section and channel-section for various configurations such as boundary conditions, geometry, skin-core-skin ratios and power-law index to investigate the flexural–torsional and lateral buckling loads and post-buckling responses. The accuracy and reliability of proposed model are proved by comparison with previous research and analytical solutions. The importance of above-mentioned effects on buckling results is demonstrated on benchmark examples.

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ABSTRACT: Thin-walled structures have been more and more extensively used as energy absorbing components in industry. It however remains challenging to decide best possible structural configurations. This paper compares the crashworthiness of empty circular CFRP (Carbon Fiber Reinforced Plastics) with CFRP/aluminum/steel tubes filled with aluminum foam or aluminum honeycomb under axial quasi-static crushing. The effects of the following factors on crashworthiness are studied: length-to-diameter ratios ($R = 2, 3, 5$) and ply numbers ($5, 7, 9$) of CFRP tube, the material of tube wall such as CFRP, aluminum and steel, the density of foam filler and the structural parameters of honeycomb filler. The experimental tests exhibit that all of empty circular CFRP specimens undergo a progressive end collapse subject to axial crushing. With the increase in $R$ of CFRP tubes, both the energy absorption and loading capacities increase, with specific energy absorption ($SEA$) increasing from 48.60 J/g to 60.37 J/g. Most of the foam-filled tubes collapse in a progressive mode, exhibiting noticeable advantages in crashworthiness, attributable to the interaction between tubal wall and foam filler. Interestingly, the $SEAs$ of foam-filled CFRP tubes are lower than that of the empty CFRP tube, while the $SEAs$ of foam-filled metal tubes are higher than their empty counterparts. It is noted that in most cases, $SEAs$ of the foam-filled CFRP tubes are higher than those of the metallic counterparts. The CFRP/aluminum/steel specimens filled with honeycomb also crushed in a more stable progressive manner, exhibiting certain advantages over the corresponding empty counterparts. Again, it is noted that the $SEAs$ of
CFRP tubes filled with honeycomb are slightly lower than the empty counterparts but far better than those of all metal specimens.

L.W. Ying, F.P. Yang and X. Wang (School of Naval Architecture, Ocean and Civil Engineering (State Key Laboratory of Ocean Engineering), Shanghai Jiaotong University, Shanghai 200240, PR China), “Analytical method for the axial crushing force of fiber-reinforced tapered square metal tubes”, Composite Structures, Vol. 153, pp 222-233, October 2016, https://doi.org/10.1016/j.compstruct.2016.05.108

ABSTRACT: An analytical method is presented to solve the energy absorption behavior of fiber-reinforced tapered square metal tubes under axial loading. Based on the axial collapse model of square metal thin-walled structures by Wierzbicki and the finite element simulate to fiber-reinforced tapered square metal tubes, a simplified collapse model of fiber-reinforced tapered square metal tubes is presented, and the corresponding analytical solution is given based on an empirical equation getting the proportionality coefficient from finite element simulation. Experiment data and finite element simulation are utilized for validating the rationality of the analytical method proposed in this paper. The influences of fiber wrapped orientation, wall thickness of fiber layer and basic angle of tapered square tubes on the axially crushing force and energy absorption capability of fiber-reinforced tapered square metal tubes are described and discussed.

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ABSTRACT: In the present paper, the post-buckling behavior of a simply supported piezoelectric hybrid microplate subject to thermal, electrical and mechanical loads is studied. The size effect in the mechanical behavior of the microplate is captured by using the modified couple stress theory. The Mindlin plate theory is adopted to describe its deflection behavior with the von Karman’s geometric nonlinearity taken into account. Based on these assumptions and the principle of minimum potential energy, the equilibrium equations of the microplate and associated boundary conditions are derived. By applying the Galerkin method to the equilibrium equations, closed-form solutions for the critical thermal/mechanical buckling load and the load–displacement relation in the post-buckling stage are obtained. Furthermore, the effects of the material length scale parameter to thickness ratio, the applied electric field and in-plane boundary conditions on the buckling and post-buckling behavior of the piezoelectric hybrid microplate are discussed in detail.

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ABSTRACT: The collapse characteristics and energy absorption capability of G827/5224 composite tubes with different fiber orientation and wall thickness were studied under axial quasi-static and impact crushing conditions. The effects of fiber orientation, wall thickness and loading conditions on the crushing mode and energy absorption capability were discussed in detail. The experimental results showed that all tubes deform in a similar brittle fracturing crushing mode. In impact tests, smaller debris were generated and ejected from tube wall as compared to quasi-static tests. The fiber orientation and wall thickness were found to have significant influences on energy absorption performance. This demonstrated that the energy absorption capability could be improved by selecting proper fiber orientation and wall thickness. The energy absorption capability was also found to reduce remarkably under impact crushing condition in comparison with quasi-static crushing condition.

ABSTRACT: A brief review of the laminated shell analyses is presented. The related literatures demonstrate that most previous studies deal with the quadrilateral or flat triangular elements and not the curved triangular element. Based on the continuum mechanic’s theory, a 6-node triangular isoparametric element is formulated for geometrically nonlinear analysis of laminated shells. To prevent the membrane and shear locking effects, the suggested scheme uses assumed strains for in-plane and transverse shear strains. Large displacements and rotations in the nonlinear analysis are included via the total Lagrangian description. Several popular benchmark problems are solved by the Generalized Displacement Control Method. The numerical results obtained are in good agreement with those published by other investigators.

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ABSTRACT: In this paper, modal behaviors of composite thin-walled lenticular tubes (CTLTs) in free vibration and cantilever vibration are performed by comparing experimental with numerical outcome. Then, a linear and nonlinear buckling analysis of CTLTs subjected to axial compression are proposed to compare their numerical critical buckling loads with corresponding experimental results. The numerical method to simulate buckling behaviors of CTLTs under axial compressions is also verified. As the flattened and wrapped CTLTs need to be deployed completely in space engineering application, the flattening and wrapping process of CTLTs should be studied by using numerical simulation method due to complexity of composite materials. To explore the change rules of mechanical characteristics of CTLTs and facilitate design of CTLTs, the design parameters of CTLTs in vibration analysis, buckling analysis and flattening and wrapping process are all evaluated.
Pham Toan Thang and T. Nguyen-Thoi (Division of Computational Mathematics and Engineering, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Viet Nam and Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam), “Effect of stiffeners on nonlinear buckling of cylindrical shells with functionally graded coatings under torsional load”, Composite Structures, Vol. 153, pp 654-661, October 2016, https://doi.org/10.1016/j.compstruct.2016.06.073

ABSTRACT: Stiffened cylindrical shells are widely used in modern engineering structures, especially in aircraft, oil transmitting pipeline, spacecraft industry and ocean engineering. Due to the increasing demands for high structures performances, this paper presents the effect of stiffeners on the nonlinear buckling of cylindrical shells with functionally graded (FG) coatings under torsional load. The cylindrical shell is reinforced with external axial stiffeners. The material properties are assumed to vary continuously through the thickness direction. Equilibrium and stability equations for cylindrical shells are derived by using the classical shell theory (CST) with von-Karman nonlinear kinematic relations. Using analytical approach, Galerkin procedure, and the Airy stress function, the resulting equations are employed to obtain the closed-form expression for the critical buckling loads and load–deflection relation. The influences of the number of stiffeners, volume fraction exponent, the thickness of the metal layer, and geometric parameters on the nonlinear buckling behavior of the cylindrical shell with FG coatings are examined in details.


ABSTRACT: It is shown that Force-Induced-Dimple (FID), initial geometric imperfection leads to a far worse deterioration of buckling strength (for up to four times) than currently used modulated eigenshape(s) or lower bound increased-radius shape deviations from perfect geometry. The FID approach provides not only safer estimates of buckling resistance but also it is efficient in terms of computing time for a range of shell geometries. The physics behind the FID-concept is closer to reality than in the other two approaches.

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ABSTRACT: This paper investigates the effects of both size-dependency and material-dependency on the nonlinear static behavior of carbon nanotubes (CNTs). The energy-equivalent model (EEM) derived on the basis of molecular mechanics is exploited to describe the size-dependence of mechanical properties of CNTs, such as, Young’s modulus, shear modulus and Poisson’s ratio. Carbon nanotube is modeled as modified nonlocal Euler-Bernoulli and Timoshenko nanobeams with mid-plane stretching. To include the size-dependency and length scale effect of nanostructure, a nonlocal differential form of Eringen’s model is proposed. The governing equilibrium equations for proposed beam theories are derived using the principle of virtual displacements, wherein the modified nonlinear von Karman strains are considered. A finite element
model is developed to solve the nonlinear equilibrium equations. Numerical results are presented to show the effects of chirality angle, nonlocal parameter, moderate rotation, and boundary conditions of CNTs. These findings are helpful in mechanical design of high-precision devices and structures manufactured from CNTs.

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ABSTRACT: The predictive capability of high fidelity finite element modelling, to accurately capture damage and crush behaviour of composite structures, relies on the acquisition of accurate material properties, some of which have necessitated the development of novel approaches. This paper details the measurement of interlaminar and intralaminar fracture toughness, the non-linear shear behaviour of carbon fibre (AS4)/thermoplastic Polyetherketoneketone (PEKK) composite laminates and the utilisation of these properties for the accurate computational modelling of crush. Double-cantilever-beam (DCB), four-point end-notched flexure (4ENF) and Mixed-mode bending (MMB) test configurations were used to determine the initiation and propagation fracture toughness in mode I, mode II and mixed-mode loading, respectively. Compact Tension (CT) and Compact Compression (CC) test samples were employed to determine the intralaminar longitudinal tensile and compressive fracture toughness. V-notched rail shear tests were used to measure the highly non-linear shear behaviour, associated with thermoplastic composites, and fracture toughness. Corresponding numerical models of these tests were developed for verification and yielded good correlation with the experimental response. This also confirmed the accuracy of the measured values which were then employed as input material parameters for modelling the crush behaviour of a corrugated test specimen.

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ABSTRACT: The aeroelastic flutter characteristics of a functionally graded carbon nanotube reinforced composite (FG-CNTRC) truncated conical shell under simultaneous actions of a hydrostatic pressure and yawed supersonic airflow are scrutinized. The nonlinearity in geometry of the conical shell is considered in Green–Lagrange sense and the model is derived according to the Novozhilov nonlinear shell theory. The aerodynamic pressure is modeled based on the quasi-steady Krumhaar’s modified supersonic piston theory by considering the effect of the panel curvature and flow yaw angle. Parametric studies are conducted to investigate the effects of boundary conditions, semi-vertex angle, distribution and volume fraction of CNT, Mach number and airflow yaw angle on the stability boundaries and flutter characteristics. The results show that the semi-vertex angle and CNT distribution may alter the stability boundaries. It is also found that the aeroelastic flutter responses of the structure can be significantly improved through a functionally graded distribution of CNT in a polymer matrix.
Moreover, the aeroelastic characteristics of the FG-CNTRC truncated conical shell are found to be very sensitive to geometrical parameters and the airflow yaw angle. The results of this study shed a light into developing and using ultra-high-strength and low-weight composites reinforced with CNT for aerospace applications.


ABSTRACT: The paper deals with buckling and postbuckling behaviour of short columns of channel cross section subjected to uniform axial compression. Considered columns are made as 8 layers GFRP laminate with different layer arrangement and as FML with different laminate layers configurations. The comparison of buckling load, postbuckling behaviour and failure load for column made with hybrid composite and GFR laminate have been made. The experimental test and numerical calculation have been performed. The experimental buckling tests were conducted using universal machine equipped with special self-aligning grips. Additionally the digital image correlation system (Aramis) has been used for non-contact 3D displacement measurement. Numerical analysis were conducted using ANSYS software. The numerical model was prepared with boundary conditions corresponding to the laboratory test stand. The linear buckling analysis and then nonlinear analysis have been performed. Thus the buckling load with corresponding buckling mode and postbuckling behaviour have been determined. Applying failure criteria and employing progressive damage analysis the failure load have been estimated as well. The results for real structures and ideal model have been compared. The advantage and disadvantage of the type of material used for columns according to structure behaviour have been presented. Additionally, the difficulties and differences in FE modelling of postbuckling behaviour and failure phenomenon of columns made of FML and GFRP laminate have been discussed.


ABSTRACT: A numerical procedure based on the Generalized Differential Quadrature (GDQ) method is presented to solve the strong form of the differential equations that govern the free vibration equations of some structural elements. The dynamic behavior of several laminated composite doubly-curved shells with arbitrary shape is investigated comparing the results achieved through different Higher-order Shear Deformation Theories (HSDTs) based on an Equivalent Single Layer (ESL) approach. The theoretical framework of the well-known Carrera Unified Formulation (CUF) represents the starting point to develop easily different higher-order models. Starting from regular domains described in principal curvilinear coordinates, a completely arbitrary shape is obtained by means of Non-Uniform Rational B-Splines (NURBS) due to the advantages shown in the well-known isogeometric analysis (IGA). The mapping technique based on the use of blending functions is illustrated to twist the original domain into the distorted one without subdividing the reference domain into sub-elements or finite element (FE). The procedure is extremely general and allows to deal with different boundary condition combinations and stacking sequences. Its validity is proven by the comparison with the results available in the literature concerning arbitrarily shaped plates or obtained through three-dimensional FE models.
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ABSTRACT: The aim of this paper is to evaluate the quasi-static and dynamic compressive crush performance of integral-skin closed-cell aluminium alloy foam with and without radial constraints. The foam specimens were prepared by the powder compact foaming method. The behaviour under different loading conditions (loading velocity and radial constraints) has been determined by an extensive experimental program. The results show a significant increase in the collapse stress of the integral-skin closed-cell aluminium foam under quasi-static loading when radial constraints are applied. The radial constraint induces a significant strain hardening of the foam, where the densification occurs at lower strains, consequently enhancing the energy absorption per unit volume of the deformed foam. The strain hardening is also sensitive to the foam density, increasing with the density.


ABSTRACT: In this paper we propose a powerful tool for the evaluation of the initial post-buckling behavior of multi-layered composite shells and beams in both bifurcation and limit load cases, including mode interaction and imperfection sensitivity. This tool, based on the joint use of a specialized Koiter asymptotic method and a mixed solid-shell finite element model, is accurate, simple and characterized by a computational cost far lower than standard path-following approaches and many advantages with respect to asymptotic analysis performed with shell elements. The method is very simple and easy to include in existing FE codes because it is based on the same ingredients of a linearized buckling analysis, with very light formula due to the presence of displacement degrees of freedom only. Due to its efficiency it is suitable for layup design when geometrical nonlinearities have to be considered.

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ABSTRACT: This paper focuses on developing and exploiting the potential of miscellaneous through-the-thickness approximating functions for FEM analysis of laminated composite plates/shells. Considering the theory of series expansion, Taylor series, trigonometric series, exponential functions, and miscellaneous expansions are implemented in the equivalent single layer models of Carrera Unified Formulation (CUF). Their performances in obtaining a good approximation of stress distribution through the thickness of the plate/shell are investigated by performing several static mechanical studies, and the inclusion of Murakami’s zig-zag
function is also evaluated. The results are compared with layer-wise theories in the framework of CUF by adopting as thickness functions both Legendre polynomials and Lagrange interpolations on Chebyshev nodes (Sampling-Surfaces method, SaS). The governing equations are derived from Principle of Virtual Displacement (PVD) and Finite Element Method (FEM) is adopted to get the numerical solutions. Nine-node 2D elements for plates and shells are employed, using Mixed Interpolation of Tonsorial Components (MITC) method to contrast the membrane and shear locking phenomenon. Simply-supported cross-ply plate and shell structures with various lay-ups and span-to-thickness ratios subjected to transverse bi-sinusoidal pressure load are analyzed. The results show that all the refined kinematic theories are able to capture the exact solution if a sufficient number of expansion (number of terms in the expansion of the displacement field) is taken, but the maximum computational cost can change for the different types of models. In some cases, combinations of different expansion theories (miscellaneous expansions) can show a significant reduction of computational costs.

ABSTRACT: One of the important topics in impact engineering was lateral crushing behaviour of thin-walled tube. In this study, crushing behaviours of rectangular and square tubes are investigated through lateral crushing testing and theoretical analysis. The average crushing force of the rectangular tube is smaller than that of the square tube. These two types of tubes have identical crushing mechanism, including two crushing stages. Plastic models are built based on the observed crushing behaviour. Theoretical solution for each stage is developed to predict the average crushing force of rectangular and square tubes.

ABSTRACT: The purpose of the paper is to compute the dynamic behavior of functionally graded material (FGM) shell structures subjected to time-varying excitation using 3D-shell model based on a discrete double directors shell element. The third-order shear deformation theory is introduced in the present method to remove the shear correction factor and improve the accuracy of transverse shear stresses. Material properties of the shell are assumed to be graded in the thickness direction by varying the volume fraction of the ceramic and the metallic constituents using general four-parameter power-law distribution. The transient excitation is defined in the time domain and known at each time. The damping material is neglected and the time derivative is approximated by Newmark method. Numerical results for deflection and stresses are presented for plates and spherical caps. The effect of an imposed force on the response of the FGM shell is discussed. The numerical examples prove a good accuracy and reliability compared to the few results available in literature.

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ABSTRACT: The paper shows the free vibration investigation of simply supported functionally graded material (FGM) shells. Spherical and cylindrical shell geometries are investigated for two different material configurations which are one-layered FGM structures and sandwich structures embedding an internal FGM core. A three-dimensional (3D) exact shell model and different two-dimensional (2D) computational models are compared in terms of frequencies and vibration modes. The proposed numerical solutions are typical 2D finite elements (FEs), and classical and advanced generalized 2D differential quadrature (GDQ) solutions. High and low frequency orders are investigated for thin and thick simply supported shells. Vibration modes are fundamental to compare the 3D exact shell model and 2D numerical solutions. The 2D finite element results based on the classical Reissner–Mindlin theory are calculated using a typical commercial FE software. Classical and advanced GDQ 2D models use the generalized unified formulation. The 3D exact shell model uses the differential equations of equilibrium written in general orthogonal curvilinear coordinates and developed in layer-wise (LW) form. The differences between 2D numerical results and 3D exact results depend on the thickness ratio and geometry of the structure, the considered mode and the frequency order, the lamination sequence and materials.

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ABSTRACT: Tailoring composite materials by fibers of spatially varying orientation angles has been realized with the advent of automated tow-placing machine. In order to use these variable stiffness composite materials as structural components, their responses to multiple external loads should be investigated. In this study, a truncated composite conical shell structure subjected to inflating pressure and surface shear traction force is considered. A mathematical model that predicts strain and stress distributions on the conical shell is developed. Based on the model, numerical examples are given for various fiber paths defined on the truncated conical shell that is subjected to inflating pressure and spatially varying shear traction force on the inner and outer surfaces, respectively. Numerical examples show that, under these external loads, the meridional strain and stress components are very sensitive to the type of fiber path definitions and value of semi-vertex angle of the cone. Boundary conditions have, also, shown remarkable effects on strain and stress distributions. To verify the adequacy of the mathematical model, the truncated composite conical shell of variable stiffness is simulated using finite element based ABAQUS commercial software.

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ABSTRACT: The use of variable thickness can help the designers and researchers reduce the weight of the functionally graded (FG) panel structures. For cases where reduction of weight is of high importance, such as space structures, ocean engineering, this type of panel is the best choice. Hence, this paper analyzes the effect of the variable thickness on nonlinear buckling of imperfect cylindrical panels made of sigmoid-functionally graded material (S-FGM) under combined axial compression and external pressure. The governing equations are in nonlinear form based on the classical shell theory with the von Karman assumption. By applying Galerkin procedure and the Airy stress function, the resulting equations are solved to obtain closed form expressions for critical buckling load and load–deflection curves. In numerical results, effect of variable thickness, the volume fraction index, imperfection size, loading as well as the geometric parameters on the load–dimensionless deflection curves are discussed in details.

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ABSTRACT: Effect of impact damage positions on the buckling and post-buckling behaviors of stiffened composite panels under axial compression were investigated in this paper. Barely visible impact damage (BVID) was introduced to three different positions on the smooth sides at impact energy 50 J. Impact crater depths and damage are as were measured and relationships between the two parameters were affirmed. Compression after impact (CAI) experiments were conducted both on the damaged and undamaged specimens to achieve the effect of impact damage on buckling and post-buckling behaviors. The results show that only local buckling in skin bay occurs without global buckling appearing for both damaged and undamaged specimens, which contains four half waves. The buckling load of damaged and undamaged specimens varies little. However, the failure loads of damaged specimens decrease to different extent according to their impact positions, with a maximum decrease of 10% compared to the undamaged specimens. Failure modes of the damaged and undamaged specimens are similar and complex, which contain the debonding of skin to stiffeners, breaking of stiffeners as well as tearing and splitting of skin.

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ABSTRACT: The cross-sectional behaviour of laminated glass (LG) is characterised by a significant zigzag effect owing to the large stiffness mismatch between the glass and polymer layers. The approach incorporated in current glass design standards is based on the use of a monolithic model with an effective thickness, which suffers several sources of inaccuracy and limitations. In this paper, laminated shell elements with an alternating
stiff/soft lay-up are enhanced and used to model LG structures, so as to accurately reproduce the through-thickness behaviour of LG with a minimal number of zigzag displacement parameters per node. In order to consider the influence of loading rate and temperature on the response of LG, a linear viscoelastic material model is adopted to simulate the polymer interlayer, which is formulated based on a recursive formula for stress calculation. Finally, several applications of the proposed modelling approach for two-ply and multi-ply LG structures are presented, considering typical deflection, stability and creep problems, where the benefits of the proposed approach are demonstrated through comparisons against monolithic shell models based on an effective thickness as well as 3D continuum models.

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ABSTRACT: In engineering, the amount of complex geometrical problems, which needs to be solved by using plates and shells theories, is remarkable. This is the reason why there are so many theories, which attempt to simplify three-dimensional problems into simpler ones. Additionally, the current increasing use of laminated and sandwich structures demands a minimum of accuracy from two-dimensional formulations. In the literature, one can find a variety of bi-dimensional theories and solution methods to solve these problems. Laminated and sandwich structure formulations are mainly classified according to the treatment of the variables in the normal direction of the plate/shell surface: equivalent single layer, Zig-Zag and layer-wise theories. The contribution of this paper is to set the stage for new theories and solution methods for laminated and sandwich structures by reviewing over 100 papers. To show the importance of the coupling between plate/shell theories and the respective solution method, a detailed review on theories and the respective solution methods is firstly given to update the current state of art. After that, solution methods based on the Finite Element Method are explained to exhibit how particular and/or complex an approach can get. In fact, this review gives a clearer picture on plate/shell theories.

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ABSTRACT: In the present study buckling loads are computed for carbon nanotubes subject to a combination of concentrated and axially distributed loads. Distributed axial loads are taken as uniformly distributed and triangularly distributed. Carbon nanotubes are modeled as nonlocal Euler–Bernoulli beams. Variational formulation of the problem is derived and variationally consistent boundary conditions are obtained. The Rayleigh quotients for the distributed axial loads are formulated. Numerical solutions are obtained by Rayleigh–Ritz method and employing orthogonal Chebyshev polynomials. Results are given in the form of counter plots
for a combination of simply supported, clamped and free boundary conditions. It is observed that the sensitivity of the buckling loads to small scale parameter depends on the specific boundary conditions.

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ABSTRACT: This paper investigates the periodic global buckling and wrinkling of sandwich struts subjected to uniaxial loads. An exact elasticity solution is obtained in the plane strain setting for selected benchmark problems and serves as reference for a systematic assessment of several displacement-based sandwich plate models. The Sublamine Generalized Unified Formulation is used to generate the algebraic two-dimensional governing equations of the variable kinematics models, for which a Navier-type solution is adopted.

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ABSTRACT: In this work a finite element model is extended for geometrically nonlinear analysis of sandwich plate–shell structures, to study the nonlinear static response of sandwich plates or curved shells which can have a hard or soft core sandwiched between stiff elastic layers. The finite element is obtained by assembling all element-layers through the thickness using specific assumptions on the displacement continuity at the interfaces between layers, but allowing for different behavior of the layers. The stiff elastic layers are modeled using the classic plate theory and the core is modeled using the Reddy’s third order shear deformation theory. Using the Newton–Raphson incremental–iterative method, the equilibrium path is obtained, and in case of snap-through occurrence the automatic arc-length method is used to track the full load displacement distribution. This simple and fast element model is a non-conforming triangular flat plate/shell element with 24 degrees of freedom for the generalized displacements. It is benchmarked in the solution of some illustrative plate–shell examples and the results are presented and discussed with numerical and experimental alternative models.

ABSTRACT: The present investigation concludes the triad of papers by the first three authors concerning the 2D-unconstrained third order shear deformation theory for shell-like structures. Here, the static behavior of functionally graded spherical shells and panels subjected to uniform loadings at the extreme surfaces is studied. The material properties are graded in the thickness direction according to a four parameter power law. The structural model involves the a posteriori stress and strain recovery procedure. The obtained governing equations are solved by means of the GDQ numerical technique. An extensive numerical investigation is carried out to characterize the effect of material parameters on the stress, strain and displacement profiles along the thickness direction. The second order equilibrium operators, of the fundamental system of equations for functionally graded spherical shells and panels, are reported in the extended form.

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ABSTRACT: The main purpose of this work is to perform the free vibration analysis of several laminated composite doubly-curved shells, singly-curved shells and plates, characterized by a continuous thickness variation. Variable thickness could affect the design of shell structures since it allows to tailor the stiffness features in the most stressed areas within the domain, keeping the weight constant. As a consequence, an improved dynamic behavior may be exhibited. The governing equations are solved numerically by the Generalized Differential Quadrature (GDQ) method, which has proven to be an accurate, stable and reliable numerical tool. Its accuracy is tested by means of several comparisons with analytical and semi-analytical results available in the literature, and with the solutions obtained by a three-dimensional finite element (FE) model. The theoretical approach considered in the current paper is general and allows consideration of many higher-order structural theories in a unified manner, in which the order of the kinematic expansion can be chosen arbitrarily.

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ABSTRACT: We manufactured sandwich-walled cylinders with longitudinal and circumferential corrugated cores from carbon fiber reinforced composites using a sequential hot press moulding method. As the first step for manufacturing these structures, we fabricated the integral corrugated cores using assembled steel moulds. Then a set of curved sheets was bonded to the corrugated cores to form cylindrical sandwich shells. Axial compression tests were performed on specimens with different geometries to investigate the failure behavior of these structures. For the cylindrical shells with longitudinal cores, both local buckling and face crushing were
observed during the experiments with face crushing being the dominant failure mode. For the cylindrical shells with circumferential cores, local buckling was found to be the dominant failure mode. In addition, analytical models pertaining to Euler buckling, shell buckling, face crushing and local buckling failure modes were presented. The models were used to construct failure maps for different specimen geometries. Finally, energy absorption calculation showed that cylindrical shells with longitudinal cores have better energy absorption ability than those with circumferential cores.

ABSTRACT: The goal of this paper is to develop a computational model for the free vibration analysis of laminated composite shells with embedded delaminations. Laminated composite shells of different shape are modeled using the assembly of layered plate finite elements based on the Generalized Laminated Plate Theory of Reddy. Discontinuities in the displacement field are implemented using the Heaviside step functions. The material is assumed as orthotropic and linearly elastic. The solver is coded in MATLAB. For the generation of models and the visualization of results, GiD Pre/Post Processor is used. After the verification of the proposed model for the intact composite shells using the existing data from the literature, the effect of delamination size on the fundamental frequencies is investigated numerically. A variety of new results for delaminated shells is presented as a benchmark for future investigations.

ABSTRACT: This paper describes a method for lightweight design of composite laminated structures using optimization technique. The lightweight design optimization model aims to minimize the mass of the composite laminated structures with the fundamental frequency constraint. The design variables are the fibre volume fractions and fibre orientations of the layers. The first derivatives of the weight and frequencies with respect to design variables are computed. The lightweight design optimization model is converted into a series of linear constrain optimization problems using the interior point penalty function method. The sensitivity of the penalty function is calculated using the sensitivity information of the weight and frequencies. An optimization procedure based on the gradient projection algorithm is proposed. Finally, the lightweight designs of two composite laminated plates are performed by using the proposed optimization procedure. The merits of the proposed procedure are also discussed.

ABSTRACT: This work deals with the maximization of the fundamental frequency of laminated plates and cylinders by finding the optimal stacking sequence for symmetric and balanced laminates with neglectable bending–twisting and torsion–curvature couplings are considered. Instead of using the angle at each ply the so-called lamination parameters are used as design variables. Results for the plate problem are compared to those
using analytical expressions found in the literature. The cylinder problem is solved for a large number of thickness and radius-to-length ratio combinations. Values of the optimal stacking sequence are given considering the angle can take any value between 0 deg. and 90 deg. or the case when the angle can only take a discrete set of values.

ABSTRACT: Analytical and numerical study of buckling of imperfect cylindrical shells made by functionally graded materials (FGM) are presented. Critical bending moment is determined in presence of internal pressure. In the analytical solution, the eigenvalue method is used and the buckling equation of defective shell is derived based on the generalized Donnell shallow shell theory. Three types of geometrical imperfections in longitudinal and circumferential directions and also their combinations are considered. The effects of some parameters such as internal pressure, shell dimensions, amplitude and shape of the imperfections and degree of the material grading are investigated. Results show that the defects greatly decrease the critical bending moment and change the buckling mode. Increasing the percentage of ceramic content, radius and thickness increase the buckling load while the cylinder length has not considerable effects in perfect shells. Symmetric defect reduces considerably the buckling moment versus skew-symmetric one. Small skew-symmetric defects (in size of the thickness) have little effects on the shells with small radii. For imperfect shells, the buckling moment increases versus radius and length less than the thickness.

ABSTRACT: The minimum mass designs of state of the art helical circumferential grids are compared to axial helical grids. Analytical models based on the classical laminate theory deliver optimization results in less than one second. Using finite element models the obtained results are validated and adjusted in a second optimization step. Studies on the influence of rib heights and Young’s modulus show potential to create lighter grids in axial helical design than in helical circumferential design. This is shown for medium length cylinders from relatively low up to very high load levels.

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ABSTRACT: An analytical solution of the buckling problem for a uniaxially compressed composite lattice plate with the clamped edges is presented in this paper. The compressive load acting in-plane and applied to the two opposite sides of the plate induces compression in the orthogonal direction due to Poisson effect. The lattice plate composed of the diagonal and transverse ribs is modelled as an equivalent orthotropic plate with effective
stiffness parameters. The deflection of buckled plate is approximated using the mode shape functions of a clamped-clamped beam. A formula providing fast and reliable way of calculation of the critical buckling load is derived and applied to the analyses of the plates with various parameters of lattice structures. The results are verified using a finite-element method. Based on these calculations, the significance of the allowance for Poisson effect is demonstrated. An estimation of the mass efficiency of the lattice plates designed for a required critical load is presented. The solution obtained in this work provides an efficient analytical tool for the design and analysis of prismatic shells composed of composite lattice panels and subjected to axial compressive loading.

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ABSTRACT: This paper presents the results of an experimental investigation into the behaviour of braided CFRP tubes subjected to quasi-static and dynamic axial crushing. Tubes of six different geometries, with round, rectangular or square cross-sections, with 2–4 plies of triaxial braids, were tested. Two types of square tubes were also tested with a plug initiator. Comparisons were made by examining the failure modes, load-displacement curves, specific energy absorption (SEA), and the ratio of the peak load to the average progressive crush load. When tested without a plug initiator, the crush characteristics of these tubes differed significantly under the two loading rates. Under quasi-static crush, tubes showed a greater tendency to fail in an unstable manner, characterized by global buckling, folding of the walls and crushing at both ends of the tube. Therefore, quasi-static crush testing should be used with caution when evaluating dynamic response of a structure. In dynamic testing, seven out of the eight configurations failed in a stable manner, with damage initiating at the bottom and propagating up the length of the tube in a splaying type failure mode. The smaller square and the round tubes performed the best, displaying higher SEA and lower load ratio values.

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ABSTRACT: This paper is aimed at studying the free vibration and thermal buckling behavior of moderately thick functionally graded material (FGM) structures including plates, cylindrical panels and shells under thermal environments. A numerical investigation is performed by applying the finite element method (FEM). A formulation based on the first-order shear deformation theory (FSDT) is proposed for the purpose, which considers the effects of the transverse shear strain and rotary inertia. A graded concept is employed to allow the material property to vary gradually inside the elements. The proposed FGM structures are characterized by two constituents (ceramic and metal) whose material properties are dependent on the temperature and vary
continuously throughout the thickness according to a power law distribution proportional to the volume fraction of the constituents. Two different sets of power law distribution are used to describe the volume fraction of the constituents, based on a single, or four parameters. Based on a parametric analysis, we demonstrate the potentials of the proposed method through its comparison with results available from the literature and by means of a convergence study. Several numerical examples are further presented to investigate the effects of material compositions, geometrical parameters, specified thermal loading and boundary conditions on the free vibration and thermal buckling behavior of these structures. The effect of initial thermal stresses on the vibration behavior is also investigated for plate and shell structures.

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ABSTRACT: Thin-walled aluminum alloy (Al alloy) structure, carbon fiber reinforced plastics (CFRP) tube, aluminum foam (Al foam) and polyurethane foam (PU foam) all can be used as good energy absorbers in automobile, aviation and other industries for their light weight and high energy absorption capacity. In order to clarify the advantages of the design modes, this article studies the crushing behaviors of circular, hexagonal and square CFRP and Al alloy tapered tube and their foam-filled structures subjected to quasi-static axial compression, analyzes and compares the collapse modes and force–displacement curves of these investigated structures as well as calculates the energy absorption (EA) and the specific energy absorption (SEA) of these investigated structures. Experimental results show that the CFRP tapered tubes have higher SEA than that of the Al-alloy tapered tubes and the circular CFRP tubes filled with PU foam have better energy absorption capacity than that of the square and hexagonal structures. In addition, the SEA of the CFRP tube filled with PU foam is 30% higher than that of the Al alloy tube filled with Al foam. Therefore this article leads to a conclusion that PU foam-filled CFRP tapered tube is a potential structure for energy absorber and light weight design.

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ABSTRACT: Buckling analysis of axially-compressed functionally graded carbon nanotube-reinforced composite (FG-CNTRC) conical panels is presented employing the variational differential quadrature (VDQ) method. The material properties of nanocomposite conical panel are assumed to be graded along the thickness direction and are estimated through the micromechanical model. To present the energy functional of the structure, the first-order shear deformation theory is utilized. Applying the generalized differential quadrature (GDQ) method in axial and circumferential directions, the discretized form of energy functional is obtained. Then, based on Hamilton’s principle and matrix relations, the reduced form of stiffness matrices is derived. A
comparison between the obtained results and those given in the literature shows the accuracy of the present approach. Numerical results indicate that volume fractions and distribution patterns of CNTs have significant effects on the buckling load of FG-CNTRC conical panels.

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ABSTRACT: Truncated thin-walled conical shells are often used as transition parts between cylinders of different diameters. Parts of space launcher transport systems are one example for the application of conical shells. Buckling of such thin-walled imperfection sensitive structures is a very important phenomenon to be considered during their design phase. Existing design guidelines, NASA SP-8007 for cylinders and NASA SP-8019 for cones, dated from the late 1960’s are currently used in the aerospace industry and employ conservative lower-bound knock-down factors. These empirically based lower-bound methods do not include important mechanical properties of laminated composite materials, such as the stacking sequence. New design approaches that allow taking full advantage of composite materials and take into account specific manufacturing methods are therefore required. The Single Perturbation Load Approach (SPLA) is an alternative proposal for a deterministic procedure for the design of thin-walled cylinders and cones under axial compression that accounts for geometric imperfections. The study deals with the buckling experiments on axially compressed, unstiffened carbon fiber-reinforced polymer (CFRP) truncated cones with an additional lateral load, performed by DLR for validation of the SPLA applied to this type of structure. Three geometrically identical cones with different layup were designed, manufactured and tested. During testing a digital image correlation system was employed and load-shortening data is extracted. The experimental results are compared with the FEA results.

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ABSTRACT: Honeycomb-filled thin-walled square tube (HFST) structure is a new outstanding energy absorption component, which has attracted great attention in recent years. This paper aims to present a comprehensive investigation by means of both experiments and numerical simulations. Detailed mechanical and energy absorption properties have been determined for kinds of HFST structures with different geometric configurations. Matching relationships between inside honeycomb core and outside metallic thin-walled structures have been observed. Parametric simulations by means of cell expansion numerical simulation methodology have been carried out to further understand the matching effect. The deformation mode evolution of filling has been determined, together with key influence factors on such a matching effect. Results show that
the geometric configuration, the matrix material properties as well as the impact velocity have significant influence on the matching relationships.

Yong Bai (1), Shuai Yuan (1), Peng Cheng (1), Peihua Han (1), Weidong Ruan (1) and Gao Tang (1,2) (1) Institute of Structural Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, PR China (2) College of Materials Science and Engineering, China Jiliang University, Hangzhou, PR China “Confined collapse of unbounded multi-layer pipe subjected to external pressure”, Composite Structures, Vol. 158, pp 1-10, December 2016, https://doi.org/10.1016/j.compstruct.2016.09.007

ABSTRACT: If a leakage exists on the outer sheath of an unbounded multi-layer pipe, external hydrostatic pressure will be applied on the surface of the internal sheath inducing the possibility of a confined collapse. Also, when the pipe bore is depressurized at a fast rate, the pressure remaining in the pipe wall can cause the similar collapse of the internal sheath. The present paper uses a flexible pipe with multi-layer structure to examine the mechanical response of the internal cylinder confined by outer cylinders under external pressure. The previous related researches mainly focus on the rigid or almost rigid confinement conditions. However, this study emphasizes on structural elastic stability in terms of the different confinement levels and D/t ratios of the internal cylinder. The initial investigation is numerical and employs two-dimensional models to obtain the nonlinear pressure-deformation equilibrium paths using a Riks algorithm. The results are fitted as uniform formulas for the prediction to the critical pressure and corresponding collapse modes. The simplified analytical model followed is developed through the principle of virtual work to compare with the fitting formulas. Experimental tests of an unbounded flexible pipe with simple construction are also conducted to validate and agree with the theoretical estimations.

Idris Karen (1), Murat Yazici (2) and Arun Shukla (3) (1) Bursa Orhangazi University, Engineering Faculty, Mechanical Engineering Department, Yildirim Campus 16310, Bursa, Turkey (2) Uludag University, Engineering Faculty, Automotive Engineering Department, 16059 Bursa, Turkey (3) The University of Rhode Island, Dynamic Photomechanics Laboratory, Department of Mechanical Industrial and Systems Engineering, 92 Upper College Road, Kingston 02881, RI, USA “Designing foam filled sandwich panels for blast mitigation using a hybrid evolutionary optimization algorithm”, Composite Structures, Vol. 158, pp 72-82, December 2016, https://doi.org/10.1016/j.compstruct.2016.07.081

ABSTRACT: Developing sandwich structures with high energy absorption capability is important for shock loading applications. In the present study, a hybrid evolutionary optimization technique based on Multi-Island Genetic Algorithm and Hooke-Jeeves Algorithm is used in the design stage of the sandwich structures to obtain effective results. Optimum parameters of cell geometry were investigated using the hybrid optimization algorithm to design foam filled sandwich panels for three main boundary conditions. Shock tube experiments were conducted in order to simulate the shock load effects along with 3D and 2D finite element analysis. Using the experimental results, a simulation-based design optimization approach was prepared and used to develop the designs of new sandwich structures. Promising results were obtained for all three different boundary conditions. In the simply supported case, 21% improvement of shock absorption was achieved by using 57% less volume of foam with respect to the original fully foam filled sandwich panel. In the clamped-clamped case, 16% improvement of shock absorption with 52% less volume was obtained. In the rigid base case study, 6%
improvement of shock absorption with 38% less volume usage was achieved. The structures developed in this study will be of use in the defense, automotive and other industries.

ABSTRACT: A new effective smeared stiffener method is developed to compute the global buckling load of grid stiffened composite panels. This method gives appropriate consideration of the skin-stiffener interactions based on a proposed improved mechanical hypothesis. The stiffness contribution of the stiffeners is evaluated through the force and moment effect analysis of the stiffener network on a general unit cell, and resultant stiffness matrix is applicable to different types of grid network on such unit cell by introducing a stiffener configuration parameter vector. The equivalent global stiffness matrix is then formulated by superimposing the stiffness contribution of the stiffeners and attached skin. Combined with Rayleigh-Ritz method, a general eigenfunction was derived for computing global buckling load, which fully considered the effect of the coupling stiffness and can solve the global buckling loads for a grid stiffened panel under combined in-plane forces. Finally, various test examples with different grid patterns were analyzed and results were compared with results obtained by finite element methods and those obtained with existing smeared methods. It is shown that the developed approach has better accuracy and can give highly computational efficiency for the global buckling analysis of grid stiffened composite structures.

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ABSTRACT: The active vibration control of carbon nanotube (CNT) reinforced functionally graded composite cylindrical shell is studied in this investigation using piezoelectric materials. Piezoelectric patches are bonded onto the outer and inner surfaces of the cylindrical shell to act as the actuator and sensor, respectively. Thermal effects are taken into account. Reddy’s high-order shear deformation theory is used in the structural modeling. The displacement fields of the piezoelectric actuator and sensor are given, according to the geometrical deformation relationship. The equation of motion of the CNT reinforced composite cylindrical shell is formulated by way of Hamilton’s principle, the solution of which is derived using the assumed mode method. In the research surrounding active vibration control, the controller is designed using velocity feedback and LQR methods. Influences of thickness on the vibration control effects of the cylindrical shell are analyzed. The control results gained by way of different control methods are compared. The active control effects of cylindrical shells with different placements of piezoelectric patches are also researched.

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ABSTRACT: In this work, we develop a facet shell element for deep laminated shells, by extending a successful four-node quadrilateral element for laminated plates based on the efficient third order zigzag theory. The obstacle course test comprising of three standard problems is undertaken to examine its performance for various modes of shell behavior. The absence of shear and membrane locking problems is established through the analysis of ultra thin shells. The accuracy of the element is assessed for the static and free vibration responses of composite and sandwich shells in comparison with the three dimensional elasticity solutions. In terms of accuracy, computational efficiency and robustness, the present element is shown to give better performance than various classical and recent finite elements considered in this study. In the case of sandwich shells, for which the equivalent single layer theories showed a high level of error, the present element is shown to yield more accurate results than even the higher-order sandwich shell theories that have been developed specifically for the three-layer sandwich shells.

ABSTRACT: This article describes the development of closed form polynomial equations for compression and shear buckling to assess the effect of Bending-Twisting coupling on infinitely long laminated plates with simply supported edges. The equations are used to generate contour maps, representing non-dimensional buckling factors, which are superimposed on the lamination parameter design spaces for laminates with standard ply orientations. The contour maps are applicable to two recently developed databases containing symmetric and non-symmetric laminates with either Bending-Twisting or Extension-Shearing Bending-Twisting coupling. The contour maps provide new insights into buckling performance improvements that are non-intuitive and facilitate comparison between hypothetical and practical designs. The databases are illustrated through point clouds of lamination parameter coordinates, which demonstrate the effect of applying common design heuristics, including ply angle, ply percentage and ply contiguity constraints.

ABSTRACT: Carbon fiber reinforced plastic (CFRP) composite materials demonstrate significant promise to further improve weight to performance in automotive engineering. Nevertheless, design of CFRP components for crashworthiness criteria remains rather challenging and typically requires laborious trial-and-error processes. This study aims to promote computational design of CFRP structures by establishing effective constitutive model that is implemented in the commercial finite element code Abaqus/Explicit. Two different numerical models (namely, the single layer shell model and the stacked shell model) were developed to simulate experimental crushing tests on the square CFRP tube. The effects of key parameters for these two FE models were analyzed, respectively. The comparisons of numerical results with experimental data indicated that the 9 layers stacked shell model is capable of reproducing experimental results with relatively higher accuracy. Based
on the validated modeling approach, crushing behaviors of several CFRP thin-walled structures with different cross sectional geometries and thicknesses were further explored. The failure modes and key indicators in relation to the structural crashworthiness were investigated for identifying a best possible sectional configuration. It is found that the circular tube shows superior specific energy absorption capacity of all different tubal configurations with the same wall thickness, meaning that the tube with circular section is of good potential as a crashworthy CFRP structure.


ABSTRACT: The deflection responses of the damaged doubly curved shallow shell panels under the combined thermomechanical loading are investigated numerically in this article. The debonded layered structures are modeled mathematically using two higher-order displacement kinematic theories and solved via finite element method. The separation between the consecutive layers is included using two sub-laminate approaches in the current model including the intermittent displacement continuity conditions. Further, the weak form of the equilibrium equation for the deflected shell panel structure under the combined action of loading is achieved via two-dimensional nine noded isoparametric Lagrangian elements. The responses are obtained by minimising the total potential energy expression with the help of an original computer code (MATLAB) in association with the currently developed mathematical models. The consistency of the present numerical solutions is demonstrated by conducting the convergence test and the validity of the models checked through the proper comparison test. Lastly, some new examples are solved using the current models to show the consequence of the delamination (size and position) including the other structural parameters (the side to thickness ratio, the length to width ratio, the curvature ratio and the boundary condition) on the deflection responses under the influence of thermomechanical loading.

Mohammad Rouhi, Hossein Ghayoor, Jeffrey Fortin-Simposn, Torn T. Zacchia, Suong V. Hoa and Mehdi Hojjati (Department of Mechanical and Industrial Engineering, Concordia Center for Composites, Concordia University, Montreal, Quebec H3G 1M8, Canada), “Design, manufacturing, and testing of a variable stiffness composite cylinder”, Composite Structures, Vol. 184, pp 146-152, 15 January 2018, https://doi.org/10.1016/j.compstruct.2017.09.090

ABSTRACT: Fiber steering is one of the promising capabilities of Automated Fiber Placement (AFP) technology in manufacturing of advanced composite structures with spatially tailored properties. The so-called variable stiffness (VS) composites have considerable scope to outperform their traditionally made constant stiffness (CS) counterparts. However, there are several design and manufacturing challenges to be addressed before practically using them as structural components. In this work we demonstrate the design, manufacturing and testing procedure of a variable stiffness (VS) composite cylinder made by fiber steering. The improved bending-induced buckling performance is the objective of the VS cylinder to be compared with its CS counterpart. The experimental results show that the buckling capacity of the VS cylinder is about 18.5% higher than its CS counterpart.

ABSTRACT: Effect of stiffener damage caused by Low Velocity Impact (LVI) on compressive buckling and failure load of the three T-stiffened composite panel was studied by experiment in this paper. Stiffener damages were introduced at four impact energy levels with the impact position located on the panel side over the middle stiffener. The impact experimental results show that the impact energy inducing the initial damage of the stiffened panel is about 34 J. With the increase of impact energy, the damage of the panel is slighter than Barely Visible Impact Damage (BVID), while the stiffener damage and stiffener/panel debonding are serious. The panel dent will not be visible until the stiffener is completely fractured under a higher energy impact. Compression after Impact (CAI) experimental results show that although the initial compression stiffness of the stiffened panel is not affected by the stiffener damage, the compressive stiffness decreases with the increase of compressive load due to the damage propagation of the impacted stiffener and buckling of panel. The failure loads decrease significantly when the damage of stiffener and the stiffener/panel debonding occur as the result of LVI, with a maximum drop of 44% compared to the undamaged specimen.


ABSTRACT: This paper presents, for the first time, a simple first-order shear deformation shell theory (SFSDST) for free and transient vibration analysis of composite laminated open cylindrical shells with general boundary conditions. By partitioning the radial displacement into bending and shear components, the present theory contains only four unknowns and can be regarded as an enhanced classical shell theory with the consideration of the effects of shear deformation and rotary inertia terms. The governing equations and appropriate boundary conditions are derived from Hamilton’s principle. To obtain natural frequencies and transient responses accurately, the method of reverberation ray matrix (MRRM) is employed based on the obtained exact closed-form solutions. The artificial spring technology is adopted to achieve the general boundary conditions. Accordingly, the scattering matrix is redefined in MRRM to make it suitable for different boundary cases. The excellent accuracy, reliability and efficiency of the present theory and approach are verified by examining the free and transient vibrations of composite laminated open cylindrical shells under various combinations of classical and non-classical boundary conditions. Meanwhile, a variety of new parameter studies regarding the influence of the boundary conditions, geometry parameters, lamina number, material properties and loading forms are performed in detail.


ABSTRACT: In this paper, a size-dependent nonlinear higher order refined beam model is developed based on modified couple stress theory. Then, it is applied to investigate post-buckling behavior of multi-phase nanocrystalline silicon nanobeams with geometrical imperfection. Nanocrystalline materials (NcMs) are multi-phase composites with the contribution of nanopores, nanograins and interface phase. Because of experimental observation of strain gradients near interface phase, the nanobeam is modeled via strain gradient based couple stress theory. A micromechanical model based on Mori-Tanaka scheme is employed to incorporate the size of
nanograins/nanopores and their surface energies. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin’s method needless of any iteration process. New results show the importance of porosity percentage, nanograins size, geometrical imperfection, couple stress parameter, foundation parameters and surface phase of nanograins/nanopores on nonlinear buckling behavior of NcM nanoscale beams.


ABSTRACT: In this paper, a new mathematical model for doubly curved singly ruled functionally graded material moderately thick and deep cone is presented. The mathematical model includes a cubic variation of thickness coordinate along with the inclusion of curvature effect in in-plane displacement fields. Due to second degree polynomial transverse shear strain deformation along the thickness of doubly curved singly ruled functionally graded material cone, shear correction factor need is eliminated. The zero-transverse shear strain at upper and lower surface of doubly curved singly ruled functionally graded material cone is imposed in the formulation. The new feature in the present mathematical model is incorporation of normal curvatures in deformation field and twist curvature inclusion in strain expressions. Due to this new feature, the present 2D model can solve problems of moderately thick doubly curved singly ruled functionally graded material cone. The proposed new mathematical model is coded in finite element code and its results are compared with previous published suitable results. After comparison, the present new mathematical model is used to solve many new static problems of doubly curved singly ruled functionally graded material cone considering different volume fraction indices, boundary conditions, geometric parameters.


ABSTRACT: In this paper, the nonlinear vibrations and energy exchange of single-walled carbon nanotubes (SWNTs) are analysed. The Sanders-Koiter shell theory is used to model the nonlinear dynamics of the system in the case of finite amplitude of vibration. The SWNT deformation is described in terms of longitudinal, circumferential and radial displacement fields. Simply supported, clamped and free boundary conditions are applied. The resonant interaction between radial breathing (axisymmetric) modes (RBMs) is analysed. An energy method, based on the Lagrange equations, is considered in order to reduce the nonlinear partial differential equations of motion to a set of nonlinear ordinary differential equations, which is then solved applying the implicit Runge-Kutta numerical method. The present model is validated in linear field comparing the RBM natural frequencies numerically predicted with data reported in the literature from experiments and molecular dynamics simulations. The nonlinear energy exchange between the two halves along the SWNT axis in the time is studied for different amplitudes of initial excitation applied to the two lowest frequency resonant RBMs. The influence of the SWNT aspect ratio on the numerical value of the nonlinear energy beating period under different boundary conditions is analysed.

ABSTRACT: In the present work, vibration analysis of curved nanobeams is investigated using nonlocal elasticity approach based on Eringen formulation coupled with a higher-order shear deformation theory accounting for through thickness stretching effect. The formulation developed here is general in the sense that it can be deduced to examine the influence of different structural theories and analyses of nanobeams. The governing equations derived are solved employing finite element method by introducing a 3-nodes curved beam element. The formulation is validated considering problems for which solutions are available. A comparative study is made using various structural models. The effects of various structural and material parameters such as thickness ratio, beam length, rise of the curved beam, boundary conditions, and size-dependent or nonlocal parameter are brought out on the vibration behaviours of curved nanobeams.


ABSTRACT: In the present article, a nonlocal strain gradient plate model is developed for damping vibration analysis of viscoelastic graphene sheets under hygro-thermal environments. For more accurate analysis of graphene sheets, the proposed theory contains two scale parameters related to the nonlocal and strain gradient effects. Graphene sheet is modeled via a two-variable shear deformation plate theory needless of shear correction factors. Governing equations of a nonlocal strain gradient graphene sheet on viscoelastic substrate are derived via Hamilton’s principle. Differential Quadrature Method (DQM) is implemented to solve the governing equations for different boundary conditions. Effects of different factors such as temperature rise, nonlocal parameter, length scale parameter, elastic foundation and aspect ratio on vibration characteristics a graphene sheets are studied.


ABSTRACT: The post-buckling behavior and nonlinear vibration of a fluid-conveying pipe composed of a functionally graded material were analytically studied. The power-law material property was considered as continuously varying across the direction of the pipe wall thickness. A nonlinear governing equation for the pipe and relevant boundary conditions were derived based on Hamilton’s principle. The post-buckling configurations of the pipe were analytically predicted. The closed-form expression of the nonlinear free vibration of the pipe was determined using the homotopy analysis method. Numerical results are presented to display the dependence of the flow velocity, fluid density, and the initial stress on the post-buckling configurations. It was concluded that the statics and dynamics are significantly changed by the material properties, which suggests that the dynamic behavior of pipes may be tailored by use of man-made functionally graded materials.

Pham Hong Cong, Nguyen Duy Khanh, Nguyen Dinh Khoa and Nguyen Dinh Duc (primarily from: Advanced Materials and Structures Laboratory, VNU-Hanoi, University of Engineering and Technology (UET), 144 Xuan Thuy, Cau Giay, Hanoi, Viet Nam), “New approach to investigate nonlinear dynamic response of sandwich...

ABSTRACT: Nonlinear dynamic behavior of double curved shallow shells with negative Poisson’s ratios in auxetic honeycombs on elastic foundations subjected blast, mechanical and damping loads is investigated in the present article. This study considers double curved shallow shells with auxetic core which have three layers in which the top and the bottom outer skins are isotropic aluminum materials; the central layer has honeycomb structure using the same aluminum material. Based on the analytical solution, Reddy’s third order shear deformation theory (TSDT) with the geometrical nonlinear in von Karman and Airy stress functions method, Galerkin method and the fourth-order Runge-Kutta method, the resulting equations are solved to obtain expressions for nonlinear motion equations. The effects of geometrical parameters, material properties, elastic foundations, imperfections, blast loads, mechanical and damping loads on the nonlinear dynamic analysis of double curved shallow shells with negative Poisson’s ratios in auxetic honeycombs are studied.


ABSTRACT: Public concerns about the environment, climate change, energy consumption and greenhouse gas emissions have placed increasing demands for the use of sustainable materials in the built environment. Natural fibres such as flax, jute and hemp have recently been considered for fibre-resin composites, with a major motivation for their implementation being their notable sustainability attributes. However, many studies have noted the relatively modest mechanical properties of natural fibre composites. Despite this, a recent paper by the author demonstrated that the compression strength of flat plates and plain channel sections may be suitable for light structural applications. This paper presents the geometric optimisation of channel sections via the inclusion of complex web, flange-edge and flange-interior stiffeners. It is demonstrated that the inclusion of geometric stiffeners restricts the development of local buckling, creating less slender channel sections with greater compression strength. Compression strengths are compared with steel and timber wall stud strengths and shown to be suitable for residential building applications. The combined plain channel and stiffened channel experimental data covers a broad range of section slenderness values, and design models are developed to predict their compression strength.


ABSTRACT: A numerical approach is adopted for the multiscale analysis of vibrations of single-walled carbon nanotubes (SWCNTs). The SWCNT is modeled by a hyperelastic membrane whose kinematics is described using the higher-order Cauchy-Born rule. The constitutive model is formulated exclusively in terms of the interatomic potential, so, it inherits the atomistic information and involves no other phenomenological input. The variational differential quadrature (VDQ) method is employed in which the continuum model is discretized using DQ, and a weak form of equation of motion is obtained via a variational approach. VDQ is computationally advantageous since it has a fast rate of convergence and can reproduce the results of molecular dynamics simulations. Detailed investigations into frequencies and mode shapes of SWCNTs with different geometrical parameters, boundary conditions and chiralities are carried out. It is found that short nanotubes display a coupling between the axial/torsional and bending modes. Also, as the tube diameter or length
increases, mode transitions are made at several critical points. If the edge supports are more flexible and tube length is longer, the critical diameters are larger. Eventually, the vibration characteristics of axially strained nanotubes are analyzed, and it is concluded that SWCNTs with smaller radii have higher strain sensitivity.


ABSTRACT: A general approach for the vibration and aeroelastic stability of the functionally graded cylindrical shell with arbitrary boundary conditions is firstly presented. The Sanders' shell theory, a steady-state heat transfer equation and the piston theory are employed to establish the motion equation, where the thermo-mechanical properties of material are set to be location- and temperature- dependent. The orthogonal polynomials series generated by employing the Gram–Schmidt process are taken as the admissible functions to express the general formulations of displacement. Moreover, the artificial spring technique is introduced to simulate the elastic constraints imposed on the cylinders' edges. The frequency equations are derived considering the strain energy of artificial springs during the Rayleigh–Ritz procedure, and the motion equation of cylindrical shells subjected to combined thermal and aerodynamic loads is established based on the Hamilton principle. A few comparisons for the frequency and critical flutter pressure are performed to validate the proposed approach. The influences of the volume fraction, thermal gradient, boundary conditions and spring stiffness on the flutter characteristics are highlighted. This paper overcomes the limitations of previous vibration and flutter studies which are confined to the structure under simply supported or clamped boundaries.

Ashraf M. Zenkour (Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia and Department of Mathematics, Faculty of Science, Kafrelsheikh University, Kafrelsheikh 33516, Egypt), “A novel mixed nonlocal elasticity theory for thermoelastic vibration of nanoplates”, Composite Structures, Vol. 185, pp 821-833, 1 February 2018, https://doi.org/10.1016/j.compstruct.2017.10.085

ABSTRACT: This paper develops a nonlocal theory of elasticity for the thermoelastic vibration of nanoplates. A mixed variational formula based upon Hamilton’s principle is extended to deal with nanoplates. The present nonlocal first-order shear deformation theory does not need any shear correction factors. Equations of motion and boundary conditions are obtained simultaneously through the mixed variational formula. Governing equations of a mixed nonlocal smart nanoplate are obtained and their solutions are given. The accuracy of the present results is investigated through many comparison examples in the literature. The influences of different factors such as nonlocal parameter, aspect ratio, side-to-thickness ratio, and mode numbers on the natural vibration characteristics of nanoplates are studied.


ABSTRACT: This paper proposes a novel numerical optimization procedure with mixed integer and continuous design variables for optimal design of laminated composite plates subjected to buckling loads. In the present optimization problem, the objective function is to maximize the buckling load factor. The design variables are fibre orientation angles and thickness of layers, in which the fibre orientation angles are integer variables and thickness are continuous variables. The constraints include the limitation of variables and the total thickness of
the plate. For analyzing the buckling behavior of laminated composite plates, a recently proposed smoothed finite element method named the cell-based smoothed discrete shear gap method (CS-DSG3) is employed. For solving the current optimization problems which contain both integer and continuous variables, an improved different evolution algorithm, named mixed-variable different evolution (mDE) is proposed. In the mDE, the mutation and selection phases of the original DE are replaced by an adaptive mutation mechanism and an elitist selection technique, respectively. These improvements not only help balance effectively the global and local search abilities of the DE, but also help deal with integer and continuous design variables. The reliability and effectiveness of the proposed optimization procedure are investigated through some numerical examples for optimal design of laminated composite plates with 2, 3, 4 and 10 layers subjected to buckling loads. Additionally, the influence of different loading and boundary conditions on the optimal solution is also investigated.

References listed at the end of the paper:


End of many papers published in the journal, Composite Structures (2012-2016).


**ABSTRACT:** An edge-based smoothed stabilized discrete shear gap method (ES-DSG3) based on the first-order shear deformation theory (FSDT) was recently proposed for static and dynamic analyses of Mindlin plates. In this paper, the ES-DSG3 is extended and incorporated with a layerwise theory for static and free vibration analyses of composite and sandwich plates. In the layerwise theory, the behavior of each layer follows the first-order shear deformation theory and the condition of displacement continuity is imposed at the interfaces of layers. This hence does not require shear correction factors and improves significantly the accuracy of transverse shear stresses. The stiffness formulation of the ES-DSG3 is performed by using the strain smoothing technique over the smoothing domains associated with edges of elements for each layer. The accuracy and reliability of the proposed method are confirmed in several numerical examples.

References listed at the end of the paper:

[82] Pandit MK, Sheikh AH, Singh BN. An improved higher order zigzag theory for the static analysis of laminated sandwich plate
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ABSTRACT: The objective of this paper is to study stability and failure of a composite laminate with a centrally placed cutout of various shapes (i.e., circular, square, diamond, elliptical-vertical and elliptical-horizontal) under combined action of uniaxial compression and in-plane shear loads. The FEM formulation based on the first order shear deformation theory and von Karman’s assumptions has been utilized. Newton–Raphson method is used to solve nonlinear algebraic equations. Failure of a lamina is predicted by the 3-D Tsai–Hill criterion whereas the onset of delamination is predicted by the interlaminar failure criterion. The effects of cutout shape, direction of shear load and composite lay-up on buckling and postbuckling responses, failure loads and failure characteristics of the laminate has been discussed. An efficient utilization of material strength is observed in the case of laminate with circular cutout as compared to the laminate with other shaped cutouts. In addition, it is also concluded that although the buckling strength of the $(0/90)_4$ laminate is lower than that of the $(+45/-45/0/90)_2$ and $(45/-45)_4$ laminates, but its strength is increased in the advanced stage of postbuckling deformation.

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ABSTRACT: Axial buckling analysis of double-walled Boron Nitride nanotubes (DWBNNTs) embedded in an elastic medium under combined electro-thermo-mechanical loadings is presented in this article. Virtual displacement method based on nonlocal cylindrical piezoelasticity continuum shell theory is employed to derive the equilibrium equations. Boron Nitride nanotube (BNNT) is assumed to be surrounded by a bundle of carbon nanotubes (CNTs) as elastic medium for reinforcement. The elastic medium is simulated as Winkler–Pasternak...
The effects of parameters such as electric and thermal loads, elastic medium and small scale are investigated on the buckling behavior of the DWBNNTs. The electric field and its direction are found to have affected the magnitude of the critical buckling load. Moreover, an analysis is carried out to estimate the nonlocal critical electro-thermo-mechanical load for the axial buckling of embedded DWBNNTs.

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ABSTRACT: Buckling of composite annular plates under uniform internal and external radial edge loads have been investigated using energy method. Trefftez rule is used in the stability equations. The symmetric buckling of symmetric cross-ply laminates is considered. In this paper, buckling behavior for the three laminates (90/0)_{2s}, (90/0_{2}/90), and (90_{2}/0_{2}), are studied. Influence of some parameters such as thickness, stacking sequence, type of supports and the ratio of hole to sheet radius on buckling loads and modes are investigated. The results of the energy method are compared with the results of numerical method. Based on the results, in the plates with clamped boundary conditions the symmetric buckling assumption is not accurate, contrary to other boundary conditions.

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ABSTRACT: This paper focuses on natural silk/epoxy composite square tube energy absorption and failure response. The tested specimens were featured by a material combination of different lengths and same numbers of natural silk/epoxy composite layers in form of reinforced woven fabric in thermosetting epoxy resin. Tubes were compressed in INSTRON 5567 with a loading capacity of 30 kN. This research investigates the influence of the wall lengths on the compressive response and also failure mode of the tested tubes are analysed. The load–displacement behaviour of square tubes recorded during the test. Since natural woven silk has been used as textile in centuries but due to rare study of this fabric as reinforcement material for composites, the results of this paper can be considerable. Outcomes from this paper might be helpful to guide the design of crashworthy structures.

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ABSTRACT: In this paper we present a new application for Carrera’s unified Formulation (CUF) to analyse functionally graded plates. In this paper the authors present explicit governing equations of a sinusoidal shear deformation theory for functionally graded plates. It addresses the bending and free vibration analysis and accounts for through-the-thickness deformations. The equations of motion are interpolated by collocation with radial basis functions. Numerical examples demonstrate the efficiency of the present approach.

Shaikh Akhlaque-E-Rasul and Rajamohan Ganesan (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 De Maisonneuve W., Montreal, QC, Canada H3G 1M8), “Non-linear buckling analysis of tapered curved composite plates based on a simplified methodology”, Composites Part B: Engineering, Vol. 43, No. 2, pp 797-804, March 2012, https://doi.org/10.1016/j.compositesb.2011.11.010

ABSTRACT: Very large number of load steps is required to determine the buckling load based on the non-linear analysis in which the stability limit load is calculated from the non-linear load–deflection curve. In the present work, a simplified methodology is developed to predict the stability limit load that requires the consideration of only two load steps. The stability limit loads of the tapered curved plates are calculated using this methodology. Based on the first-ply failure analysis and the simplified non-linear buckling analysis, the critical sizes and parameters of the tapered curved plates that will not fail before global buckling are determined. The stability limit loads calculated using the present simplified methodology are shown to have
good agreement with that calculated based on the non-linear load–deflection curve using the conventional non-linear buckling analysis methodology.

ABSTRACT: Thermal postbuckling analysis is presented for nanocomposite cylindrical shells reinforced by single-walled carbon nanotubes (SWCNTs) subjected to a uniform temperature rise. The SWCNTs are assumed to be aligned and straight with a uniform layout. Two kinds of carbon nanotube-reinforced composite (CNTRC) shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRCs are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The governing equations are based on a higher order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. Based on the multi-scale approach, numerical illustrations are carried out for perfect and imperfect, FG- and UD-CNTRC shells under different values of the nanotube volume fractions. The results show that the buckling temperature as well as thermal postbuckling strength of the shell can be increased as a result of a functionally graded reinforcement. It is found that in most cases the CNTRC shell with intermediate nanotube volume fraction does not have intermediate buckling temperature and initial thermal postbuckling strength.

ABSTRACT: In this work, the buckling behavior of the cross-ply laminated non-homogeneous orthotropic truncated conical shells in the large deformation under the uniform axial load is studied. Firstly, the basic relations of the cross-ply laminated non-homogeneous orthotropic truncated conical shells are derived using the large deformation theory. Then modified Donnell type non-linear stability and compatibility equations are obtained and solved. A computer program called Maple 14 has been used in the numerical solution. Finally, the influences of the degree of non-homogeneity, the number and ordering of layers and the variations of the conical shell characteristics on the non-linear axial buckling load are investigated. The comparison with available results is satisfactorily good.

ABSTRACT: A closed-form solution is obtained to determine the buckling and post-buckling behavior of elastically restrained composite panels under compressive loading. The approach allows to study the response of stiffened panels undergoing local buckling modes, taking into account the restraints provided by the
stiffeners to the rotation of the skin edges. The panels are modeled as thin plates referring to Marguerre type
equations together with classical lamination theory. The equations are written in non-dimensional form,
allowing for the study of a wide class of orthotropic laminates. The problem is formulated in terms of out of
plane displacement, represented with a single-mode approximation, and Airy stress function. The compatibility
equation is solved exactly, while the method of Galerkin is applied to impose the equilibrium. The buckling
load, the out of plane displacement at different load levels, and the post-buckling stiffness are derived and
compared with finite element analyses, revealing good accuracy. Sensitivity analyses are also performed
obtaining design charts.

J.L. Mantari, A.S. Oktem and C. Guedes Soares (Centre for Marine Technology and Engineering (CENTEC),
Technical University of Lisbon, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal), “A
new higher order shear deformation theory for sandwich and composite laminated plates”, Composites Part B:
ABSTRACT: A new shear deformation theory for sandwich and composite plates is developed. The proposed
displacement field, which is “m” parameter dependent, is assessed by performing several computations of the
plate governing equations. Therefore, the present theory, which gives accurate results, is relatively close to 3D
elasticity bending solutions. The theory accounts for adequate distribution of the transverse shear strains
through the plate thickness and tangential stress-free boundary conditions on the plate boundary surface, thus a
shear correction factor is not required. Plate governing equations and boundary conditions are derived by
employing the principle of virtual work. The Navier-type exact solutions for static bending analysis are
presented for sinusoidally and uniformly distributed loads. The accuracy of the present theory is ascertained by
comparing it with various available results in the literature.

K.M. Liew, X. Zhao and Y.Y. Lee (Department of Building and Construction, City University of Hong Kong,
Tat Chee Avenue, Kowloon, Hong Kong), “Postbuckling responses of functionally graded cylindrical shells
under axial compression and thermal loads”, Composites Part B: Engineering, Vol. 43, No. 3, pp 1621-1630,
April 2012, https://doi.org/10.1016/j.compositesb.2011.06.004
ABSTRACT: This paper presents a postbuckling analysis of functionally graded cylindrical shells under axial
compression and thermal loads using the element-free kp-Ritz method. The formulation is developed to handle
problems of small strains and moderate rotations, based on the first-order shear deformation shell theory and
von Kármán strains. The effective material properties of the shells are assumed to be continuous along their
thickness direction, and are obtained using a power-law distribution of the volume fractions of the constituents.
The approximations of the two-dimensional displacement fields are expressed in terms of a set of mesh-free
kernel particle functions. The system bending stiffness is evaluated using a stabilized conforming nodal
integration method and the membrane and shear terms are estimated using direct nodal integration to eliminate
shear locking. The postbuckling path is traced using a combination of the arc-length and mesh-free kp-Ritz
methods. The proposed formulation is validated by comparing the results of the proposed method with those in
the literature. The postbuckling responses of two types of functionally graded conical shells, one composed of
Al/ZrO$_2$ and the other of SUS304/Si$_3$N$_4$, are investigated and the effects of volume fraction, boundary condition,
and length-to-thickness ratio on postbuckling behavior are discussed in detail.

Dae-Yong Park (1) and Sang-Youl Lee (2)
ABSTRACT: This study deals with parametric effects on buckling behaviors of laminated composite structures containing an embedded rectangular delamination using the enhanced assumed strain (EAS) three-dimensional element. The three-dimensional finite element (FE) formulation based on the EAS method for composite structures shows excellence from the standpoints of computational efficiency, especially for distorted element shapes. Using the EAS FE formulation developed for this study, the effects of embedded delamination sizes and ply orientations on the elastic buckling behaviors for various aspect ratios and width-to-thickness ratios are studied. The numerical results obtained are in good agreement with those reported by other investigators. Furthermore, the new results reported in this paper show the progression of local buckling and its influence on global buckling and vice versa. Key observation points are discussed and a brief design guideline is given.

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ABSTRACT: A model for the prediction of the vibroacoustic performance of composite shells of various geometries within a statistical energy analysis (SEA) approach is developed hereby. The dispersion characteristics of composite orthotropic shell structures of a range of geometries, namely curved panels and cylindrical shells are predicted by a Wave Finite Element (WFE) Method. The mass and stiffness matrices of a structural segment are computed by a conventional finite element (FE) modelling and the wave propagation characteristics are derived by forming a polynomial eigenproblem whose eigenvalues correspond to structural wavenumbers. The numerical issues concerning the formation and the solution of this non-linear eigenproblem are discussed. The modal density and the radiation efficiency of the structure are then evaluated using its numerically extracted wave propagation characteristics. The broadband vibroacoustic response of each configuration under a reverberant field excitation can then be computed within an SEA approach.

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ABSTRACT: In this paper, natural frequencies characteristics of a continuously graded carbon nanotube-reinforced (CGCNT) cylindrical panels based on the Eshelby–Mori–Tanaka approach is considered. The volume fractions of oriented, straight single-walled carbon nanotubes (SWCNTs) are assumed to be graded in the thickness direction. In this research work, an equivalent continuum model based on the Eshelby–Mori–Tanaka approach is developed.
Tanaka approach is employed to estimate the effective constitutive law of the elastic isotropic medium (matrix) with oriented, straight carbon nanotubes (CNTs). The CGCNTR shell is assumed to be simply supported at one pair of opposite edges and arbitrary boundary conditions at the other edges such that trigonometric functions expansion can be used to satisfy the boundary conditions precisely at simply supported edges. The 2-D generalized differential quadrature method (GDQM) as an efficient and accurate numerical tool is used to discretize the governing equations and to implement the boundary conditions. The novelty of the present work is to exploit Eshelby–Mori–Tanaka approach in order to reveal the impacts of the volume fractions of oriented CNTs, different CNTs distributions, various mid radius-to-thickness ratio, shell angle, length-to-mean radius ratio and different combinations of free, simply supported and clamped boundary conditions on the vibrational characteristics of CGCNTR cylindrical panels. The interesting and new results show that continuously graded oriented CNTs volume fractions can be utilized for the management of vibrational behavior of structures so that the frequency parameters of structures made of such material can be considerably improved than that of the nanocomposites reinforced with uniformly distributed CNTs.


ABSTRACT: In this paper, the mechanical buckling of a functionally graded nanocomposite rectangular plate reinforced by aligned and straight single-walled carbon nanotubes (SWCNTs) subjected to uniaxial and biaxial in-plane loadings is investigated. The material properties of the nanocomposite plate are assumed to be graded in the thickness direction and vary continuously and smoothly according to two types of the symmetric carbon nanotubes volume fraction profiles. The material properties of SWCNT are determined according to molecular dynamics (MDs), and then the effective material properties at a point are estimated by either the Eshelby–Mori–Tanaka approach or the extended rule of mixture. The equilibrium and stability equations are derived using the Mindlin plate theory considering the first-order shear deformation (FSDT) effect and variational approach. The results for nanocomposite plate with uniformly distributed CNTs, which is a special case in the present study, are compared with those of the symmetric profiles of the CNTs volume fraction. A numerical study is performed to investigate the influences of the different types of compressive in-plane loadings, CNTs volume fractions, various types of CNTs volume fraction profiles, geometrical parameters and different types of estimation of effective material properties on the critical mechanical buckling load of functionally graded nanocomposite plates.

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ABSTRACT: Elastic stability of fibers in fiber-reinforced composite materials subject to compressive loading is studied. The transversal buckling mode is considered, and two limiting cases, the dilute and non-dilute composites are analyzed. In the case of a non-dilute composite, the cylindrical model and the lubrication approximation are applied. The original problem is reduced to a problem of stability of a rod on elastic foundation. Through the solution of this problem a simple formula for the buckling load is obtained. In the case of a dilute composite, the solution of a problem of stability of a compressed rod in elastic plane is used. On the
basis of the obtained solutions in two limiting cases the interpolation formulae are derived. These formulae describe buckling of fiber in the fiber-reinforced composite for any value of the fiber volume fraction. Comparison with known numerical and experimental results is carried out, and the sufficient accuracy of the derived formulae is demonstrated.

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ABSTRACT: This paper is focused on the transient dynamic and free vibration analysis of functionally graded (FG) axisymmetric truncated conical shells with non-uniform thickness. Two numerically efficient and accurate solution methods are presented to study the transient dynamic responses of FG shells subjected to either internal or external mechanical shock loading. Employing the displacement-based layerwise theory in conjunction with the Hamilton’s principle, the transversely discretized equations of motion are obtained. The differential quadrature method (DQM) is used to discretize the resulting equations in the axial direction. To solve the developed time-dependent equations, either DQM (named LWDQ) or Newmark’s time integration scheme (named LWDQN) is employed. The material properties are graded continuously in the thickness direction according to a volume fraction power-law distribution. The developed results are successfully compared with those obtained by ANSYS and also with the available results in the literature. The comparisons demonstrate the accuracy and effectiveness of the aforementioned methods on achievement of fast convergence rate with relatively low computational cost. Finally, the effects of different geometric and material parameters on the dynamic behavior of the FG shells are investigated. Due to high accuracy of the method, the results can be used as benchmarks for future research.

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ABSTRACT: This paper describes an experimental investigation on the response of composite sandwich structures with tubular inserts to quasi-static compression. The performance parameters, namely the peak load, absorbed crash energy, specific energy absorption; average crushing load and crush force efficiency were evaluated. The composite sandwich specimens were fabricated from glass fiber, polystyrene foam and epoxy resin. The primary mode of failure observed was progressive crushing with the composites exhibiting high energy absorption capabilities and high crushes force efficiency. The mechanism of progressive crushing of the sandwich structures and its relation to the energy absorption capabilities was deliberated. Furthermore, a statistical analysis was performed to investigate the effects of the design variables and also to determine if there were interactions between these variables. Such information is vital in the design of polymer composite sandwich structures as energy absorbers.

ABSTRACT: The present study deals with the “dynamic buckling” of a laminated composite stringer-stiffened curved panel. The “dynamic buckling”, in the present study, is concerned with the unbounded lateral response of the panel, which is subjected to an axial impact load. In reinforced panels with widely spaced adequately stiff stringers, the structure may pass through two major states before its total collapse: buckling of the panel skin between stiffeners and buckling of the stiffeners themselves. This study focuses on the lowest buckling load of the stringer-stiffened panel, which is, buckling of the panel skin between stiffeners. The analysis of the laminated composite stringer-stiffened cylindrical panel was performed by using the commercial ANSYS finite element software. The model simulates the structure and its associated boundary conditions. The boundary conditions simulate the stringer-stiffened cylindrical panel as a part of a fuselage. The static buckling analysis was performed using the eigenvalue buckling approach to determine the static critical load. Modal analysis was used to calculate the first natural frequency and corresponding mode shape of the structure. Nonlinear transient dynamic analysis was used to determine the dynamic critical load. In the transient dynamic analysis the Newmark method with the Newton–Raphson scheme were used. In the present study, the equation of motion approach was applied. By this approach, the equations of motion were numerically solved for various load parameter values (loading amplitude and loading duration) to obtain the system response. Special attention was given to the neighborhood of loading durations corresponding to the period of the lowest bending frequency of the skin. For each load duration, the dynamic buckling load was calculated using a load versus lateral displacement curve generated by the ANSYS code. The results were plotted on a dynamic load amplification factor (DLF) graph. The DLF is defined, as the ratio of the dynamic buckling to the static buckling of the panel. For loading periods in the neighborhood of the lowest natural frequency of the panel, the DLF was less than unity. It means that, for those particular loading periods, the dynamic buckling load is lower than the static one.


ABSTRACT: In this paper, an analytical model for perforation of composite sandwich panels with honeycomb core subjected to high-velocity impact has been developed. The sandwich panel consists of an aluminium honeycomb core sandwiched between two thin composite skins. The solution involves a three-stage, perforation process including perforation of the front composite skin, honeycomb core, and bottom composite skin. The strain and kinetic energy of the front and back-up composite skins and the absorbed energy of honeycomb core has been estimated. In addition, based on the energy balance and equation of motion the absorbed energy of sandwich panel, residual velocity of projectile, perforation time and projectile velocity have been obtained and compared with the available experimental tests and numerical model. Furthermore, effects of composite skins and aluminium honeycomb core on perforation resistance and ballistic performance of sandwich panels has been investigated.

Leon Pickett and Vinay Dayal (Department of Aerospace Engineering, Iowa State University, 1200 Howe Hall, Ames, IA 50011, USA), “Effect of tube geometry and ply-angle on energy absorption of a circular glass/epoxy

ABSTRACT: The superior specific energy absorption characteristics of long fiber composite structures as compared to aluminum and steel are well established. Due to cost and time involved in testing of composites, it is imperative to develop numerical solution of the crushing phenomenon. The work presented here reports work to better understand the energy absorption characteristics of glass–fiber circular crush tubes. The effect of tube diameter and ply orientation on the energy absorption has been extensively investigated. Numerical results are compared with experiments performed elsewhere and the correlation between the two is encouraging.

R. Ansari, R. Gholami and H. Rouhi (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Vibration analysis of single-walled carbon nanotubes using different gradient elasticity theories”, Composites Part B: Engineering, Vol. 43, No. 8, pp 2985-2989, December 2012, https://doi.org/10.1016/j.compositesb.2012.05.049

ABSTRACT: The present work aims at investigating the vibrational characteristics of single-walled carbon nanotubes (SWCNTs) based on the gradient elasticity theories. The small-size effect, which plays an essential role in the dynamical behavior of nanotubes, is captured by applying different gradient elasticity theories including stress, strain and combined strain/inertia ones. The theoretical formulations are established based upon both the Euler–Bernoulli and the Timoshenko beam theories. To validate the accuracy of the present analysis, molecular dynamics (MDs) simulations are also conducted for an armchair SWCNTs with different aspect ratios. Comparisons are made between the aforementioned different gradient theories as well as different beam assumptions in predicting the free vibration response. It is shown that implementation of the strain gradient elasticity by incorporating inertia gradients yields more reliable results especially for shorter length SWCNTs on account of two small scale factors corresponding to the inertia and strain gradients. Also, the difference between two beam models is more prominent for low aspect ratios and the Timoshenko beam model demonstrates a closer agreement with MD results.


ABSTRACT: Bending and free vibration analysis of multilayered plates and shells by using a new accurate higher order shear deformation theory (HSDT) is presented. It is one of the most accurate HSDT available in the literature, mainly because new non-polynomial shear strain shape functions (combination of exponential and trigonometric) used in the present theory are richer than polynomial functions, and free surface boundary conditions can be guaranteed a priori. The present HSDT is able to reproduce Touratier’s HSDT as special case. The governing equations and boundary conditions are derived by employing the principle of virtual work. These equations are then solved via Navier-type, closed form solutions. Bending and dynamic results are presented for cylindrical and spherical shells and plates for simply supported boundary conditions. Panels are subjected to sinusoidal, distributed and point loads. Results are provided for thick to thin as well as shallow and deep shells. The present results are compared with the exact three-dimensional elasticity theory and with several other well-known HSDT theories. The present HSDT is found to be more precise than other several existing ones for analyzing the bending and free vibration of isotropic and multilayered composite shell and plate structures.
ABSTRACT: In this paper, we present the initial buckling and post-buckling responses of axial loaded advanced grid stiffened (AGS) composite cylindrical shells with reinforced cutouts. The AGS cylindrical shells were reinforced by various local grid configurations near the cutout areas. The effects of different reinforcing grid configurations on critical loads were then examined and compared to those of different skin-reinforcing designs using Finite Element Analysis (FEA) simulations. A high-fidelity non-linear analysis procedure was proposed to predict the non-linear buckling response of the shell structures. The simulation results indicated that the grid reinforcements can reduce or eliminate the risk of local buckling response near the cutout areas and increase the critical load of the shell more effectively than the skin reinforcements. Furthermore, those results showed that an optimum grid reinforcement configuration exists, which significantly improved the initial buckling and post-buckling resistance of the cylindrical shells under axial loading. The above findings can potentially be useful to the analysis and optimum design of AGS composite cylindrical shells with cutouts.

ABSTRACT: In this paper a C° four node flat facetted shell element with drilling rotational degrees of freedom based on a first order shear deformation shell theory is developed to study the transient response of initially stressed composite sandwich folded plates. The new shell element contains three translations, two rotations of the normals about the shell mid-plane, and one drilling rotational degree of freedom per node. A consistent mass matrix formulation is employed to evaluate the total kinetic energy of the system. A generic validation study is carried out to evaluate the performance of the present finite element formulation. New results are presented for the transient analysis of initially stressed composite sandwich folded plate structures.

ABSTRACT: In this paper the nonlocal buckling of double-nanoplate-systems under biaxial compression is studied. A nonlocal shell theory is used to formulate the governing equations of the nanoplate system. The problem is solved using the finite element method. The results show that the nonlocal effects can significantly influence the buckling behavior of these structures.
ABSTRACT: This paper reports an analytical study on the buckling of double-nanoplate-system (DNPS) subjected to biaxial compression using nonlocal elasticity theory. The two nanoplates of DNPS are bonded by an elastic medium. Nonlocal plate theory is utilized for deriving the governing equations. An analytical method is used for determining the buckling load of DNPS under biaxial compression. Difference between nonlocal uniaxial and biaxial buckling in DNPS is shown. Both synchronous and asynchronous buckling phenomenon of biaxially compressed DNPS is highlighted. Study shows that the small-scale effects in biaxially compressed DNPS increases with increasing values of nonlocal parameter for the case of synchronous modes of buckling than in the asynchronous modes of buckling. The buckling load decrease with increase of value of nonlocal parameter or scale coefficient. In biaxial compression higher buckling modes are subjected to higher nonlocal effects in DNPS. Further the study shows that the increase of stiffness parameter brings uniaxial and biaxial buckling phenomenon closer while increase of aspect ratio widen uniaxial and biaxial buckling phenomenon.

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ABSTRACT: In the present study, nonlinear dynamical behavior and stability of an embedded fluid conveying smart composite micro-tube under imposed electric potential and thermal loadings have been investigated. The composite matrix is the poly-vinylidene fluoride (PVDF) reinforced by double-walled boron nitride nanotubes (DWBNNTs). Composite structure is modeled based on piezoelectric fiber reinforced composite (PFRC) theory and a representative volume element has been considered for predicting the elastic, piezoelectric, dielectric and thermal properties of the smart composite tube. The fluid flow is assumed to be inviscid, irrotational and incompressible. Formulation presented here is based on Euler–Bernoulli beam model with von-Kármán geometric nonlinearity and nonlocal elasticity theory. The interactions between smart composite micro-tube and surrounding elastic media are simulated by Pasternak foundation model. The discretized governing equations of motion are directly obtained by minimizing the energy of the system. As a result, the eigen-values and eigenvectors (mode shapes) are to be obtained by the state-space matrix which is then solved by an iterative method to obtain nonlinear frequencies of smart composite tube. The results significantly show that imposing positive electric potential increases nonlinear stability of the system. In addition, it is concluded that applying electric and thermal loadings can be used as well as controlling parameters to improving stability of the smart composite micro-tube.

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ABSTRACT: In this paper the authors derive a higher-order shear deformation theory for modeling functionally graded plates accounting for extensibility in the thickness direction. The explicit governing equations and boundary conditions are obtained using the principle of virtual displacements under Carrera’s Unified Formulation. The static and eigenproblems are solved by collocation with radial basis functions. The efficiency of the present approach is assessed with numerical results including deflection, stresses, free vibration, and buckling of functionally graded isotropic plates and functionally graded sandwich plates.

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ABSTRACT: Nonlinear buckling response of a composite cylindrical shell made of polyvinylidene fluoride (PVDF), is investigated. A two-dimensional smart model surrounded by an elastic foundation subjected to combined electro–thermo-mechanical loading is considered. The nonlinear strain terms based on Donnell’s theory are taken into account using the first shear deformation theory. The Hamilton’s principle is employed to obtain coupled differential equations, containing displacement and electric potential terms. Harmonic differential quadrature method (HDQM) is applied to obtain the critical buckling load for clamped supported mechanical and free electric potential boundary conditions at both ends of the smart cylinder. Results indicate that the critical buckling load increases when piezoelectric effect is considered.

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ABSTRACT: Electro-thermo nonlinear vibration and instability of embedded double-walled Boron Nitride nanotubes (DWBNNTs) conveying viscose fluid is studied in this article based on nonlocal piezoelasticity theory and Euler–Bernoulli beam (EBB) model. Boron Nitride nanotube (BNNT) is surrounded by elastic medium which is simulated as Pasternak foundation. The van der Waals (vdW) forces between the inner and the outer DWBNNTs are taken into account based on the Lennard–Jones model. Using von Kármán geometric nonlinearity, Hamilton’s principle and considering charge equation for coupling of electrical and mechanical fields, the nonlinear higher order governing equations are derived. The differential quadrature method (DQM) is applied to discretize the motion equations, which are then solved to obtain the nonlinear frequency and critical fluid velocity of fluid-conveying DWBNNTs. Results indicated that the small scale parameter, elastic medium,
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“Effects of flexural boundary conditions on failure and stability of composite laminate with cutouts under combined in-plane loads”, Composites Part B: Engineering, Vol. 45, No. 1, pp 657-665, February 2013,  
https://doi.org/10.1016/j.compositesb.2012.08.016  
ABSTRACT: In the present study, an investigation on the effects of flexural boundary conditions on prebuckling and postbuckling responses, failure loads and characteristics of a quasi-isotropic [i.e., (+45/−45/0/90)_s] square laminate with and without a central cutout of various shapes is carried out under combined in-plane loads [i.e., uni-axial compression combined with in-plane shear (positive and negative)] using finite element method. The finite element formulation is based on the first order shear deformation theory in conjunction with the von Karman’s assumptions to incorporate geometric nonlinearity. The 3-D Tsai-Hill criterion is used to predict the failure of a lamina while the onset of delamination is predicted by the interlaminar failure criterion. It is observed that under combined loading conditions, buckling and postbuckling strengths and failure loads of the laminate are reduced by the introduction of a cutout at the center of the laminate, irrespective of boundary conditions. It is also noted that the laminate with and without cutout has maximum buckling, first-ply failure and postbuckling strengths (at a particular value of transverse deflection) for BC3 (i.e., clamped on all edges) boundary conditions whereas these values are minimum for BC1 (i.e., simply-supported on all edges) boundary conditions, for both directions of shear load.

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https://doi.org/10.1016/j.compositesb.2012.09.052  
ABSTRACT: Critical local and global buckling loads of grid-stiffened carbon-fiber thin-shell structures, such as advanced grid-stiffened (AGS) conical shells relevant to aviation and aerospace applications, under uniform external transverse pressure were determined analytically using an equivalent stiffness model considering the influence of non-uniform grid distribution and the minimum potential energy principle. Experiments and finite-elements analysis have been carried out to assess the reliability of this analytical model. To maximize the buckling resistance for optimal design of the AGS conical shells, a hybrid genetic algorithm combining the genetic approach with a simulated annealing algorithm was developed, which considers the characteristics of multi-constraints and mixed discrete–continuous design variables. Comparisons between the benchmark results from the traditional genetic algorithm and simulated annealing algorithm confirmed the validity and efficiency of the hybrid genetic algorithms. Numerical examples show that the local-buckling constraint is a key factor for weight optimization of the AGS carbon-fiber conical.

Hsuan-The Hu and Hung-Wei Peng (Department of Civil Engineering and Sustainable Environment Research Center, National Cheng Kung University, Tainan 701, Taiwan, ROC), “Maximization of fundamental frequency
ABSTRACT: Free vibration analyses of laminated curved panels with central circular cutouts and subjected to axial compressive forces are carried out by employing the Abaqus finite element program. The fundamental frequencies of these composite laminated curved panels with a given material system are then maximized with respect to fiber orientations by using the golden section method. Through parametric studies, the significant influences of the panel aspect ratio, the panel curvature, the cutout size and the compressive force on the maximum fundamental frequencies, the optimal fiber orientations and the associated fundamental vibration modes of these panels are demonstrated and discussed.


ABSTRACT: Optimization methods are close to become a common task in the design process of many mechanical engineering fields, specially those related with the use of composite materials which offer the flexibility in the design of both the shape and the material properties and so, are very suitable to any optimization process. While nowadays there exist a large number of solution methods for optimization problems there is not much information about which method may be most reliable for a specific problem. Genetic algorithms have been presented as a family of methods which can handle most of engineering problems. However, starting from a common basic set of rules many algorithms which differ slightly from each other have been implemented even in commercial software packages. This work presents a comparative study of three common Genetic Algorithms: Archive-based Micro Genetic Algorithm (AMGA), Neighborhood Cultivation Genetic Algorithm (NCGA) and Non-dominate Sorting Genetic Algorithm II (NSGA-II) considering three different strategies for the initial population. Their performance in terms of solution, computational time and number of generations was compared. The benchmark problem was the optimization of a T-shaped stringer commonly used in CFRP stiffened panels. The objectives of the optimization were to minimize the mass and to maximize the critical buckling load. The comparative study reveals that NSGA-II and AMGA seem the most suitable algorithms for this kind of problem.

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ABSTRACT: Bistability of cross-ply [0(n)/90(n)] laminates has already been examined in detail by researchers. Another kind of bistable composite shell manufactured from carbon-fiber/epoxy prepreg with anti-symmetric layup, such as [30°/−30°/0°/30°/−30°], is investigated in this paper using analytical, experimental and numerical methods. A new experimental method named two points loading method is presented to capture the bistable behavior of the manufactured specimens. The coiled-up radius and the snap loads, including snap-through and snap-back load used to induce the bistable composite shell to snap between two stable shapes are measured. The factors affecting the bistable performance of the anti-symmetric composite shell, including structure sizes and
layup conditions, are discussed by comparing experimental test results and analytical solutions. Good agreement was found between analytical predictions and measured results. The finite element results are approximately in accord with experimental results. Possible reasons of differences between numerical simulation and experimental results are given.

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ABSTRACT: A series of experimental investigations and numerical analyses is presented into the compression response, and subsequent failure modes in corrugated-core sandwich panels based on an aluminium alloy, a glass fibre reinforced plastic (GFRP) and a carbon fibre reinforced plastic (CFRP). The corrugated-cores were fabricated using a hot press moulding technique and then bonded to face sheets based on the same material, to produce a range of lightweight sandwich panels. The role of the number of unit cells and the thickness of the cell walls in determining the overall deformation and local collapse behaviour of the panels is investigated. The experiments also provide an insight into the post-failure response of the sandwich panels. The results are compared with the numerical predictions offered by a finite element analysis (FEA) as well as those associated with an analytical model. Buckling of the cell walls has been found to be initial failure mode in these corrugated systems. Continued loading resulted in fracture of the cell walls, localised delamination as well as debonding between the skins and the core. The predictions of the FEA generally show reasonably good agreement with the experimental measurements. Finally, the specific compressive properties of the corrugated structures have been compared to those of other core materials where evidence suggests that these systems compare favourably with their more conventional counterparts.


ABSTRACT: This paper presents a free vibration and a stability analysis of three-dimensional sandwich beams. Several higher-order displacements-based theories as well as classical models (Euler–Bernoulli’s and Timoshenko’s ones) are derived assuming a unified formulation by a priori approximating the displacement field along the cross-section in a compact form. The governing differential equations and the boundary conditions are derived in a nucleol form that corresponds to a generic term in the displacement field approximation. The resulting fundamental nucleo does not depend upon the approximation order $N$ that is a free parameter of the formulation. A Navier-type, closed form solution is used. Simply supported beams are, therefore, investigated. Slender up to very short beams are considered. As far as free vibrations are concerned, the fundamental natural frequency as well as natural frequencies associated to torsional and higher modes such as sheet face bending and twisting (typical of sandwich structures) are investigated. The stability analysis is carried out in terms of critical buckling stress in the framework of a linearised elastic approach. Results are assessed towards three-dimensional FEM solutions. It is shown that upon an appropriate choice of the approximation order, the proposed models are able to match the three-dimensional reference solutions.

ABSTRACT: A study on buckling phenomena in pultruded Fiber Reinforced Polymer (FRP) beams, based on two mechanical models recently formulated by the authors with regard to composite thin-walled beams, is presented in this paper. Global buckling behavior is analyzed by means of a one-dimensional model in which cross-section torsional rotation is divided into two parts: the first one, associated with Vlasov’s axial warping, the second one, associated entirely with shear strains. The study of local behavior is based on the individual buckling analysis of the components of FRP profile, assumed as elastically restrained transversely isotropic plates. Both mechanical models take into account, within the field of small strains and moderate rotations, the contribution of shear deformation in the kinematic hypotheses. Design charts suitable to evaluate the buckling load of FRP “I” beams with either narrow or wide flanges are obtained and presented in this paper.


ABSTRACT: In the present paper, a consistent power series solution is proposed for dynamic behaviors analysis of circular sandwich plates with functionally graded face sheets/cores, for the first time. The proposed solution is a combination of the finite Taylor’s transform and the fourth-order Runge–Kutta procedure. The extension-bending coupling and the higher-order inertias are considered in the present research. The formulation guarantees continuity of the transverse stress components at the interfaces between layers. Another novelty is proposing a zigzag formulation whose results are corrected on the basis of the dynamic three-dimensional theory of elasticity. An interesting discussion for defining explicit/implicit layerwise shear correction factors is also presented. Furthermore, results reveal that using functionally graded face sheets or cores with transition variations of the material properties may lead to very smooth through-the-thickness stress distributions. Consequently, some of the failure modes may be prevented at the interfaces between the layers.

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ABSTRACT: A free vibration analysis of sandwich plates with laminated anisotropic face sheets in thermal environment is carried out by means of the hierarchical trigonometric Ritz formulation (HTRF) built in the framework of Carrera’s unified formulation (CUF). CUF is presented in its generalized version allowing to produce hierarchically a wide range of advanced equivalent single layer, zig-zag and layer-wise plate theories including the capability to choose the desired expansion order for each unknown in the displacement field. The global–local free vibration response of the sandwich plates subjected to environment temperature variations is accurately described by the employed plate models accounting for through-the-thickness deformations. The
effects of significant parameters such as length-to-thickness ratio, face-to-thickness ratio, number of layers and stacking sequence on the circular frequency parameters and on the modal displacements are examined.


ABSTRACT: In this paper, nonlinear dynamic response of rectangular laminated composite plate resting on nonlinear Pasternak type elastic foundations is investigated. First-order shear deformation theory (FSDT) is used for modeling of moderately thick plates. The plate formulation is based on the von Karman nonlinear equation. The resulting nonlinear governing equations for transient analysis of laminated plates on elastic foundation are integrated using the discrete singular convolution-differential quadrature coupled approaches. The nonlinear governing equations of motion of plate are discretized in space and time domains using the discrete singular convolution and the differential quadrature methods, respectively. The validity of the present method is demonstrated by comparing the present results with those available in the open literature. The effects of the foundation parameters, boundary conditions and geometric parameters of plates on nonlinear dynamic response of laminated thick plates are investigated.


ABSTRACT: In this study buckling analysis of a functionally graded conical shell integrated with piezoelectric layers that is subjected to combined action of thermal and electrical loads is presented. The material properties of functionally graded conical shells are assumed to vary continuously through the thickness direction based on a power law form. The governing equations, including the equilibrium and stability equations, are obtained based on the classical shell theory and the Sanders nonlinear kinematics relations. The case of uniform temperature distribution through the shell domain is considered. The prebuckling forces are obtained considering the membrane solutions of linear equilibrium equations. Minimum potential energy criterion is employed to establish the stability equations. The single-mode Galerkin method is used to obtain the critical buckling temperature difference. The results are compared with the known data in the open literature. Finally, some numerical results are presented to study the effects of applied actuator voltage, shell geometry, and power law index of FGM on thermal buckling behavior of the conical shell.

Yegao Qu, Xinhua Long, Guoqing Yuan and Guang Meng (State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China), “A unified formulation for vibration analysis of functionally graded shells of revolution with arbitrary boundary conditions”, Composites Part B: Engineering, Vol. 50, pp 381-402, July 2013, https://doi.org/10.1016/j.compositesb.2013.02.028

ABSTRACT: This paper describes a general formulation for free, steady-state and transient vibration analyses of functionally graded shells of revolution subjected to arbitrary boundary conditions. The formulation is derived by means of a modified variational principle in conjunction with a multi-segment partitioning procedure on the basis of the first-order shear deformation shell theory. The material properties of the shells are assumed to vary continuously in the thickness direction according to general four-parameter power-law distributions in terms of volume fractions of the constituents. Fourier series and polynomials are applied to expand the displacements and rotations of each shell segment. The versatility of the formulation is demonstrated through
the application of the following polynomials: Chebyshev orthogonal polynomials, Legendre orthogonal polynomials, Hermite orthogonal polynomials and power polynomials. Numerical examples are given for the free vibrations of functionally graded cylindrical, conical and spherical shells with different combinations of free, shear-diaphragm, simply-supported, clamped and elastic-supported boundary conditions. Validity and accuracy of the present formulation are confirmed by comparing the present solutions with the existing results and those obtained from finite element analyses. As to the steady-state and transient vibration analyses, functionally graded conical shells subjected to axisymmetric line force and distributed surface pressure are investigated. The effects of the material power-law distribution, boundary condition and duration of blast loading on the transient responses of the conical shells are also examined.

ABSTRACT: Size-dependent dynamic stability response of higher-order shear deformable cylindrical microshells made of functionally graded materials (FGMs) and subjected to simply supported end supports is investigated. Material properties of the microshells vary in the thickness direction according to the Mori–Tanaka scheme. The modified couple stress elasticity theory in conjunction with the classical higher-order shear deformation shell theory is utilized to develop non-classical shell model containing additional internal length scale parameter to interpret size effect. The differential equations of motion and boundary conditions are derived by using Hamilton’s principle. The governing equations are then written in the form of Mathieu–Hill equations and then Bolotin’s method is employed to determine the instability regions. Selected numerical results are given to indicate the influences of internal length scale parameter, material property gradient index, static load factor and axial wave number on the dynamic stability behavior of FGM microshells. It is found that the width of the instability region for an FGM microshell increases with the decrease of the value of dimensionless length scale parameter. Moreover, it is shown that the classical shell model has an overestimated prediction for the width of instability region corresponding to the FGM microshells especially with lower values of material property gradient index.

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ABSTRACT: In this study, the free vibration behavior of circular graphene sheet under in-plane pre-load is studied. By using the nonlocal elasticity theory and Kirchhoff plate theory, the governing equation is derived for single-layered graphene sheets (SLGSs). The closed-form solution for frequency vibration of circular graphene sheets under in-plane pre-load has been obtained and nonlocal parameter appears into arguments of Bessel functions. The results are subsequently compared with valid result reported in the literature. The effects of the small scale, pre-load, mode number and boundary conditions on natural frequencies are investigated. The results are shown that at smaller radius of circular nanoplate, the effect of in-plane pre-loads is more importance.

ABSTRACT: Electro-thermo-torsional buckling response of a double-walled boron nitride nanotube (DWBNNT) has been investigated based on nonlocal elasticity and piezoelasticity theories. The effects of surrounding elastic medium such as the spring constant of the Winkler-type and the shear constant of the Pasternak-type are taken into account. The van der Waals (vdW) forces are considered between inner and outer layers of nanotube. According to the relationship between the piezoelectric coefficient of armchair boron nitride nanotubes (BNNTs) and stresses, the first order shear deformation theory (FSDT) is used. Energy method and Hamilton’s principle are employed to obtain coupled differential equations containing displacements, rotations and electric potential terms. The detailed parameter study is conducted to investigate the effects of nonlocal parameter, elastic foundation modulus, temperature change, piezoelectric and dielectric constants on the critical torsional buckling load. Results indicate that the critical buckling load decreases when piezoelectric effect is considered.


ABSTRACT: This paper is presented to solve the nonlinear buckling and post-buckling problem of functionally graded stiffened thin circular cylindrical shells only under torsion by the analytical approach. The shells are reinforced by rings and stringers attached to their inside and the material properties of shell and the stiffeners are assumed to be continuously graded in the thickness direction. Theoretical formulations based on the smeared stiffeners technique and the classical shell theory with the geometrical nonlinearity in von Karman sense are derived. Approximate three-term solution of deflection is chosen more correctly and the explicit expression to finding critical load and post-buckling torsional load–deflection curves are given. The effects of various parameters and the effectiveness of stiffeners on the stability of shell are shown.


ABSTRACT: In this study, the response of a FG (functionally graded) coated truncated conical shell subjected to an axial load is investigated by means of non-linear equations governing the finite deformations of the shell. In the solution of non-linear basic equations in the finite deflection the Superposition and Galerkin methods have been used. The effects of material property of FG composite coatings and geometrical parameters on the non-linear critical axial load are discussed in detail through a parametric study. The results are verified by comparing the obtained values with those in the existing literature.
ABSTRACT: An analytical method and a new simplifying model of smart FG (functionally graded) laminated cylindrical shells with thin piezoelectric layers are presented based on Hamilton’s principle, Von Kármán nonlinear theory and constant-gain negative velocity feedback approach. The thin piezoelectric layers embedded on inner and outer surfaces of the smart FG laminated cylindrical shell are acted as distributed sensor and actuator, which is used to control nonlinear vibration of the smart FG laminated cylindrical shell. The coupled nonlinear partial differential equations are discretized based on a series expansion of linear modes and a multiterm Galerkin’s method. The coupled nonlinear equations of motion are then solved by Runge–Kutta numerical method.

S. Maleki and M. Tahani (Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran), “Non-linear analysis of fiber-reinforced open conical shell panels considering variation of thickness and fiber orientation under thermo-mechanical loadings”, Composites Part B: Engineering, Vol. 52, pp 245-261, September 2013, https://doi.org/10.1016/j.compositesb.2013.04.026
ABSTRACT: Non-linear bending analysis of moderately thick laminated conical panels under various thermo-mechanical loadings and boundary conditions is presented using the generalized differential quadrature (GDQ) method together with the Newton–Raphson iterative scheme. The stiffness coefficients are assumed to be functions of the meridional and circumferential coordinates in panels for the realistic applications. In the first case of orthotropic open conical shell panels, the orientation of fibers are assumed to be in the meridional and circumferential directions. The stiffness coefficients of this type of fiber-reinforced panel are usually assumed to be constant. It is shown that due to the geometry of the conical surface, thickness of laminate will be changed along the meridional direction. The effect of stiffness variation on the non-linear response of panel is considered for the first time. In the second type, open conical shell panel can be made by cutting from a filament wound circular conical shell. In this case, thickness and ply orientation are functions of the shell coordinates. In this paper, different path definitions for variable stiffness filament wound shells are considered. The inclusion of this geometric complicating effect in large deformation analysis will add considerably to the complication and cost of a solution scheme. Paper presents some results to show when these assumptions have a significant effect on the end result. Assuming the effects of shear deformation and initial curvature, based on the first-order shear deformation theory (FSDT) and von Kármán-type of geometric non-linearity, the governing system of equations is obtained. Comparisons of the predictions with those available in the literature and finite element analyses show very good agreement. More results for panels with particular boundary conditions and thermo-mechanical load are presented for future references. For the sake of brevity, numerical results which presented in this paper are limited to deflection responses only.

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ABSTRACT: A postbuckling analysis is presented for nanocomposite cylindrical shells reinforced by single-walled carbon nanotubes (SWCNTs) subjected to combined axial and radial mechanical loads in thermal environment. Two types of carbon nanotube-reinforced composite (CNTRC) shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRCs are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The governing equations are based on a higher order shear deformation shell theory with a von Kármán-type of kinematic nonlinearity. The thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. A boundary layer theory and associated singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations concern the postbuckling behavior of perfect and imperfect, FG-CNTRC cylindrical shells under combined action of external pressure and axial compression for different values of load-proportional parameters. The results for UD-CNTRC shell, which is a special case in the present study, are compared with those of the FG-CNTRC shell.

Togay Ozbakkaloglu (School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia), “Behavior of square and rectangular ultra high-strength concrete-filled FRP tubes under axial compression”, Composites Part B: Engineering, Vol. 54, pp 91-111, November 2013, https://doi.org/10.1016/j.compositesb.2013.05.007

ABSTRACT: This paper presents results of an experimental program undertaken to investigate the behavior of square and rectangular ultra high-strength concrete-filled fiber reinforced polymer (FRP) tubes (UHSCFFTs) under axial compression. The effects of the amount of confinement, cross-sectional aspect ratio and corner radius were investigated experimentally through the tests of 24 concrete-filled FRP tubes (CFFTs) that were manufactured using unidirectional carbon fiber sheets and UHSC with 108 MPa average compressive strength. As the first experimental investigation on the axial compressive behavior of square and rectangular UHSCFFTs, the results of the study reported in this paper allows a number of significant conclusions to be drawn. Of primary importance, test results indicate that sufficiently confined square and rectangular UHSCFFTs can exhibit highly ductile behavior. The results also indicate that confinement effectiveness of FRP tubes increases with an increase in corner radius and as sectional aspect ratio approaches unity. It is found that UHSCFFTs having tubes of low confinement effectiveness may experience significant strength loss along the initial portions of the second branches on their stress–strain curves. Furthermore, it is observed that the behavior of UHSCFFTs at this region differs from their normal-strength concrete counterparts and is more sensitive to the effectiveness of confining tube. The second half of the paper presents the performance assessment of the existing FRP-confined concrete models in predicting the ultimate conditions of the HSC and UHSCFFTs. The results of this assessment demonstrate that the existing models provide unconservative estimates for specimens with higher concrete strengths. To address this, a new model that was developed on the basis of a comprehensive experimental test database and is applicable to both NSC and HSC of strengths up to 120 MPa is proposed. The model comparisons demonstrate that the proposed model provides significantly improved predictions of the ultimate conditions of FRP-confined HSC compared to the existing models.
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“Time discretization effect on the nonlinear vibration of embedded SWBNNT conveying viscous fluid”,  
Composites Part B: Engineering, Vol. 54, pp 298-306, November 2013,  
https://doi.org/10.1016/j.compositesb.2013.05.031

ABSTRACT: In this study, the effect of time discretization on the nonlinear transverse vibration and instability of single-walled boron nitride nanotube (SWBNNT) conveying viscous fluid is investigated based on the nonlocal piezoelasticity theory. SWBNNT is considered as an Euler–Bernoulli beam and is subjected to combined mechanical loading, thermal changes and electrical field. The elastic medium is simulated as Winkler and Pasternak foundation. The interaction between the inner viscous fluid and SWBNNT is obtained using Navier–Stokes equation. The axial inertia is neglected and a new approach is introduced to decouple the mechanical and electrical fields considering charge equation. Motion equations are derived by Hamilton’s principle using the Von–Kármán nonlinearity theory. In the first approach, time and space domains are discretized using the method of multiple scale (MMS) and Galerkin procedure respectively, and in the second one differential quadrature method (DQM) is utilized to space discretization. Good agreement is shown between the results of first and second approach. Numerical results indicate the significant effects of aspect ratio, elastic medium and nonlocality on the frequency and instability of the SWBNNT.

T.-P. Chang (Department of Construction Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan), “Stochastic FEM on nonlinear vibration of fluid-loaded doule-walled carbon nanotubes subjected to a moving load based on nonlocal elasticity theory”, Composites Part B: Engineering, Vol. 54, pp 391-399, November 2013, https://doi.org/10.1016/j.compositesb.2013.06.012

ABSTRACT: This paper adopts stochastic FEM to study the statistical dynamic behaviors of nonlinear vibration of the fluid-conveying double-walled carbon nanotubes (DWCNTs) under a moving load by considering the effects of the geometric nonlinearity and the nonlinearity of van der Waals (vdW) force. The Young’s modulus of elasticity of the DWCNTs is considered as stochastic with respect to the position to actually characterize the random material properties of the DWCNTs. Besides, the small scale effects of the nonlinear vibration of the DWCNTs are studied by using the theory of nonlocal elasticity. Based on the Hamilton’s principle, the nonlinear governing equations of the fluid-conveying double-walled carbon nanotubes under a moving load are formulated. The stochastic finite element method along with the perturbation technique is adopted to study the statistical dynamic response of the DWCNTs. Some statistical dynamic response of the DWCNTs such as the mean values and standard deviations of the non-dimensional dynamic deflections are computed and checked by the Monte Carlo Simulation, meanwhile the effects of the nonlocal parameter, aspect ratio and the flow velocity on the statistical dynamic response of the DWCNTs are investigated. It can be concluded that the nonlocal solutions of the dynamic deflections get larger with the increase of the nonlocal parameters due to the small scale effect, and as the flow velocity increases, the maxima non-dimensional dynamic deflections of the DWCNTs get larger.

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ABSTRACT: This paper derives new analytical solutions for thermal bifurcation buckling of cylindrical shells made of functionally graded materials (FGMs) with temperature-dependent material properties. The Donnell’s shell theory is adopted and a symplectic solution methodology is established through the Hamiltonian variational principle. The fundamental buckling problem is then converted into the solving for the symplectic eigenvalues and eigenvectors. The solutions reveal that boundary conditions and temperature-dependent FGM properties have significant influence on thermal buckling behavior. It is also concluded that temperature field conditions cannot be neglected for FGCSs being rich in thermal sensitive compositions.

ABSTRACT: The buckling analysis of cross-ply laminated conical shell panels with simply supported boundary conditions at all edges and subjected to axial compression is studied. The conical shell panel is a very interesting problem as it can be considered as the general case for conical shells when the subtended angle is set to $2\pi$ and also cylindrical panels and shells when the semi-vertex angle is equal to zero. Equations were derived using classical shell theory of Donnell type and solved using generalized differential quadrature method. The results are compared and validated with the known results in the literature. The effects of subtended angle, semi-vertex angle, length, thickness and radius of the panel on the buckling load and mode are investigated.

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ABSTRACT: The energy absorption of circular pultruded composite tubes subjected to axial crush load, transmitted by a small attached mass accelerated by means of an explosive load is presented in this paper. Different masses of explosive are used to provide a range of transmitted impulse and crushed distance of the pultruded composite tubes. The influence of the mass of the explosive on the tube response is investigated with regard to crushed distance, the average crushing force and the specific energy absorption (SEA). The crushing distance increases with increasing transmitted impulse. The results and failure mode are also compared with compression tests carried out on a servo-hydraulic machine (type: MTS-309).
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ABSTRACT: The aim of this work is the application of Radial Basis Function (RBF) method to a General Higher-order Equivalent Single Layer (GHESL) formulation for the free vibrations of doubly-curved laminated composite shells and panels. The theoretical development of the present paper is based on the well-known Carrera Unified Formulation. In particular, the fundamental nuclei of a multi-layered doubly-curved shell structure are deducted and explicitly defined. The Differential Geometry (DG) tool has been used to geometrically define each of the structures under consideration: doubly-curved, singly-curved and degenerate shells. The 2D free vibration shell problems are numerically solved using RBFs, where the shape parameters have been optimized using two different algorithms. In fact, the shape parameters of RBFs depend not only on the choice of the radial basis functions, but also on how the points are located on the given computational domain. Modifying the positions of such points, the shape parameters change too. It has been discovered that, once the shape parameters have been optimized for a given grid distribution, they can be rounded off and used for every kind of structure. This is a very important aspect because when, using a fixed parameter, the RBF method becomes a “parameter free” numerical technique. In order to demonstrate the accuracy, stability and reliability of the present methodology, many comparisons are presented with reference to literature results, that are obtained by using Generalized Differential Quadrature method. The above numerical applications of this study are also compared with finite element method solutions.


ABSTRACT: This paper presents some significant research results about velocity sensitivity of aluminum honeycomb under high-speed axial impact in a velocity range from 20 to 80 m/s. Series experiments were carried out with the help of self-developed high-speed impact system. Afterwards, corresponding numerical simulation works as well as some parametric studies were conducted. The resultant comparison told out that the plateau stress increases markedly when impact below 30 m/s, but slowly when impact at a velocity various from 30 to 80 m/s. Before the parametric studies, inertial effect in various impact masses was investigated. Comparison between parametric results showed that the promotion on Specific Load and energy-absorbing capability increases with the impact velocity for various honeycombs. Density also has a great influence on Specific Load. The higher honeycomb density is, the greater amplitude performs. The energy absorption diagram for honeycomb with different geometric configurations reveals the relationship between dynamic plane stress and energy per unit volume, and also proves the promotion with increasing of impact velocity.


ABSTRACT: The optimization of the sinusoidal higher order shear deformation theory (HSDT) for the bending analysis of functionally graded shells is presented in this paper for the first time. The HSDT includes the stretching effect and their shear strain shape functions ($\sin(mz)$ and $\cos(nz)$) contain the parameters “$m$” and “$n$” that need to be selected by providing displacements and stresses which produce close results to 3D elasticity solutions. The governing equations and boundary conditions are derived by employing the principle of virtual work. A Navier-type closed-form solution is obtained for functionally graded plates and shells subjected to transverse load for simply supported boundary conditions. Numerical results of the optimized sinusoidal HSDT are compared with the FSĐT, other quasi-3D hybrid type HSDTs, reference solutions, and 3D solutions. The key conclusions that emerge from the present numerical results suggest that: (a) the optimization procedure is beneficial in terms of accuracy; and (b) it is possible to gain accuracy keeping the unknown’s constant by performing the optimization procedure shown in this paper.

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ABSTRACT: In this paper, we investigate the vibration analysis of functionally graded material (FGM) and laminated composite structures, using a refined 8-node shell element that allows for the effects of transverse shear deformation and rotary inertia. The properties of FGM vary continuously through the thickness direction according to the volume fraction of constituents defined by sigmoid function, but in this method, their Poisson’s ratios of the FGM plates and shells are assumed to be constant. The finite element, based on a first-order shear deformation theory, is further improved by the combined use of assumed natural strains and different sets of collocation points for interpolation the different strain components. We analyze the influence of the shell element with the various location and number of enhanced membrane and shear interpolation. Using the assumed natural strain method with proper interpolation functions the present shell element generates neither membrane nor shear locking behavior even when full integration is used in the formulation. The natural frequencies of plates and shells are presented, and the forced vibration analysis of FGM and laminated composite plates and shells subjected to arbitrary loading is carried out. In order to overcome membrane and shear locking phenomena, the assumed natural strain method is used. To validate and compare the finite element numerical solutions, the reference solutions of plates based on the Navier’s method, the series solutions of sigmoid FGM (S-FGM) plates are obtained. Results of the present theory show good agreement with the reference solutions. In addition the effect of damping is investigated on the forced vibration analysis of FGM plates and shells.

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ABSTRACT: A comprehensive review is conducted on the modeling and simulation of isolated carbon nanotubes (CNTs) concentrating on all mechanical, buckling, vibrational and thermal properties. Three different approaches consisting of atomistic modeling, continuum modeling and nano-scale continuum modeling are firstly explained and their applications toward understanding behavior of CNTs are discussed. Different investigations available in literature focusing on mentioned behaviors are reviewed and their results are compared to show the applicability and efficiency of employed/developed technique. Taking into account both runtime and accuracy of modeling, advantages and disadvantages of introduced methods are nominated and analyzed.

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ABSTRACT: In this paper, the mechanical buckling properties of a zigzag double-walled carbon nanotube (DWCNT) with both chirality and small scale effects are studied. Based on the nonlocal continuum theory and the Timoshenko beam model, the governing equations are derived and the critical buckling loads under axial compression are obtained. The DWCNTs are considered as two nanotube shells coupled through the van der Waals interaction between them. The equivalent Young’s modulus and shear modulus for zigzag DWCNT are derived using an energy-equivalent model. The results show that the critical buckling load can be overestimated by the local beam model if the small-scale effect is overlooked for long nanotubes. In addition, significant dependence of the critical buckling loads on the chirality of zigzag carbon nanotube is confirmed. These findings are important in mechanical design considerations of devices that use carbon nanotubes.

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ABSTRACT: This work presents the static and dynamic analyses of laminated doubly-curved shells and panels of revolution resting on the Winkler–Pasternak elastic foundation using the generalized differential quadrature (GDQ) method. The analyses are worked out considering the first-order shear deformation theory (FSDT) for the aforementioned moderately thick structural elements. The solutions are given in terms of generalized displacement components of points lying on the middle surface of the shell. Several types of shell structures such as doubly-curved and revolution shells, singly-curved and degenerate shells are considered in this paper. The main novelty of this paper is the application of the differential geometry within GDQ method to solve
doubly-curved shells resting on the Winkler–Pasternak elastic foundation. The discretization of the differential system by means of the GDQ technique leads to a standard linear problem for the static analysis and to a standard linear eigenvalue problem for the dynamic analysis. In order to show the accuracy of this methodology, numerical comparisons between the present formulation and finite element solutions are presented. Very good agreement is observed. Finally, new results are presented to show effects of the Winkler modulus, the Pasternak modulus, and the inertia of the elastic foundation on the behavior of laminated doubly-curved shells.


ABSTRACT: A study has been made to determine the critical time parameters of truncated conical shells with functionally graded coatings (FGCs) and subjected to a time dependent axial load in the large deformation. The method of solution utilizes Superposition principle and Galerkin procedure. Donnell–Karman type non-linear differential equations for the truncated conical shell with FGCs are derived and reduced to ordinary differential equation with the time dependent coefficient. The Runge–Kutta method and modified Budiansky–Roth criterion are then used to solve this non-linear differential equation with the time dependent coefficient. Finally, effects of compositional profiles of coatings, variation of truncated conical shell parameters and loading speed on the dimensionless linear and non-linear critical time parameters have been studied. Comparing the results of this study with those in the literature validates the present analysis.

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ABSTRACT: In this paper, the development of a rational and comprehensive equation to determine the strength of glass fiber reinforced polymer (GFRP) pultruded square tube columns under concentric compression is presented. Material characterization and compression tests on stubs and columns were carried out in order to establish in situ properties. Square tube columns having different lengths and sections, resulting in a range of combinations of global and sectional slenderness, were tested. Material properties, critical loads, compressive strengths and failure modes are reported and comments are made on observed post-buckling behavior and interaction between crushing, local and global buckling. Column and wall imperfections are estimated and used as inputs to the proposed equation. The strength curve is plotted along with the test results, showing good agreement. Finally, a step-by-step example is presented.

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“Buckling and post-buckling of a composite C-section with cutout and flange reinforcement”, Composites Part
ABSTRACT: This paper presents an investigation into the effect of cutout and flange reinforcement on the buckling and post-buckling behaviour of a carbon/epoxy composite C-section structure. The C-section having a cutout in the web is clamped at one end and subjected to a shear load at the other free end. Three different stiffener reinforcements were investigated in finite element analysis by using MSC Nastran. Buckling load was predicted by using both linear and nonlinear FE analysis. Experiments were carried out to validate the numerical model and results. Subsequently post-buckling analysis was carried out by predicting the load–deflection response of the C-section beam in nonlinear analysis. Tsai-Wu failure criterion was used to detect the first-play-failure load. The effect of circular and diamond cutout shape and effective flange reinforcements were investigated. The results show that the cutout and reinforcement have little effect on the buckling stability. However an L-shape stiffener to reinforce the C-section flange can improve the critical failure load by 20.9%.

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ABSTRACT: A simplified theoretical analysis is developed to predict the dynamic response of clamped cylindrical sandwich shells with aluminum foam cores under air blast loading. In this analytical solution, the whole response of the sandwich shell is split into three sequential stages, similar with the existing three-stage theoretical framework of sandwich structures. In the first stage the blast impulse is assumed to only transfer to the velocity of the front face-sheet. The metallic foam core is considered approximately to be a progressive compressive mode in the second stage, while the back face-sheet is still stationary. In the final stage, the classical monolithic shell theory based on an energy dissipation rate balance approach is employed; and the “upper” and “lower” bounds of the maximum back face-sheet central point deflections and response time are obtained by incorporating a comprehensive circumscribing and inscribing yield loci. A reasonable agreement between the theoretical predictions and experimental results is found for the maximum back face-sheet central point deflection of sandwich shells. The proposed theoretical consideration is significant to guide the engineering applications of cellular metal sandwich structures subjected to air blast loading.


ABSTRACT: This paper investigates the large amplitude vibration behavior of a shear deformable FGM cylindrical panel resting on elastic foundations in thermal environments. Two kinds of micromechanics models, namely, Voigt model and Mori–Tanaka model, are considered. The motion equations are based on a higher order shear deformation shell theory that includes shell panel-foundation interaction. The thermal effects are also included and the material properties of FGMs are assumed to be temperature-dependent. The equations of motion are solved by a two step perturbation technique to determine the nonlinear frequencies of the FGM cylindrical panel. Detailed parametric studies are carried out to investigate effects of volume fraction index,
temperature variation, panel curvature ratio, foundation stiffness and in-plane boundary conditions on nonlinear vibration behaviors of FGM cylindrical panels. The results confirm that in most cases Voigt model and Mori–Tanaka model have the same accuracy for predicting the vibration characteristics of FGM cylindrical panels.

ABSTRACT: This paper presents test results for Pultruded FRP (PFRP) beams failing by elastic Lateral-Torsional Buckling (LTB) under various loading and displacement boundary conditions. Beams are simply supported at both ends for major-axis flexure. Results are presented for 114 tests, comprising 19 beams of four PFRP sections at four or five spans, and six groups for mid-span load applied at three heights, with or without end fixity of lateral flexure. Buckling resistance is established either by the Southwell plot method or from the peak load. Measured LTB loads are compared with predictions obtained using closed form equations to show that these expressions will provide a safe resistance for design when the moduli of elasticity are those taken directly from pultruder’s design manual.

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ABSTRACT: In this paper, a simple and innovative foam-filled lattice composite panel is proposed to upgrade the peak load and energy absorption capacity. Unlike other foam core sandwich panels, this kind of panels is manufactured through vacuum assisted resin infusion process rather than adhesive bonding. An experimental study was conducted to validate the effectiveness of this panel for increasing the peak strength. The effects of lattice web thickness, lattice web spacing and foam density on initial stiffness, deformability and energy absorbing capacity were also investigated. Test results show that compared to the foam-core composite panels, a maximum of an approximately 1600% increase in the peak strength can be achieved due to the use of lattice webs. Meanwhile, the energy absorption can be enhanced by increasing lattice web thickness and foam density. Furthermore, by using lattice webs, the specimens had higher initial stiffness. A theoretical model was also developed to predict the ultimate peak strength of panels.

ABSTRACT: Composite materials, in most cases fiber reinforced polymers, are nowadays used in the aerospace and transportation, in which high specific energy absorption (SEA) and strength are critical issues. Aimed at the improvement of SEA and the peak impact load (P), the structure optimization of composite tape sinusoidal specimen and corresponding experiments are investigated in this paper. Firstly, the finite element
model of composite tape sinusoidal specimen is constructed and is validated by experiments. Then, both the single-objective and multi-objective optimizations are performed for composite tape sinusoidal specimen under axial impact loading. At last, the optimal results are validated by experiments. The optimal results show that the SAE increases 67.8% (from 51.3666 kJ/kg to 88.887 kJ/kg) and the $P$ decreases 42.9% (from 34.9936 kN to 20.178 kN). This work lays a foundation for structural design of crashworthiness using fiber reinforced polymers materials.

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ABSTRACT: This paper introduced a simple and innovative hollow sandwich columns with GFRP skins and a paulownia wood core (GSW columns), which were manufactured by vacuum assisted resin infusion process. Four full-scale GSW columns were fabricated and tested under axial compression loading to validate the effectiveness of this column. The ultimate axial load capacity, displacement ductility, failure mode and axial force distribution between GFRP skins and wood core were investigated. Meanwhile, the finite element analysis was conducted to extend to investigate the effects of wood density, GFRP skin thickness and hollow ratio on the axial strength which were not considered in the tests. The numerical results revealed that increasing GFRP skin thickness and decreasing the hollow ratio can enhance the ultimate axial load capacity of the columns. Furthermore, increasing the wood density can improve the initial stiffness significantly. The corresponding calculation formulae were also derived to predict the ultimate axial load capacity of sandwich columns.

Tanish Dey and L.S. Ramachandra (Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, India), “Buckling and postbuckling response of sandwich panels under non-uniform mechanical edge loadings”, Composites Part B: Engineering, Vol. 60, pp 537-545, April 2014,
https://doi.org/10.1016/j.compositesb.2013.12.072
ABSTRACT: The buckling and postbuckling responses of cylindrical sandwich panels, subjected to non-uniform in-plane loadings are investigated in this paper by analytical method. A fourth and fifth order expansions are used respectively for the transverse and tangential displacement of the core to model the core compressibility effect. The stress distribution within the panels due to the applied non-uniform in-plane edge loadings are determined by prebuckling analysis. The governing partial differential equations describing the buckling and postbuckling behavior of cylindrical sandwich panels are derived using the principle of minimum total potential energy. Galerkin’s method is used to reduce the governing partial differential equations to a set of non-linear algebraic equations. Newton–Raphson method in conjunction with Riks approach is employed to solve the algebraic equations. Numerical results are presented for both flat and cylindrical sandwich panels subjected to various non-uniform in-plane edge loadings. The sandwich panels used in the present investigation are made up of isotropic and composite materials.

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ABSTRACT: The weight reduction has become a key driver in the automotive design. The study and the simulations of non-conventional materials has become very important. This work is focused on the numerical crashworthiness design of carbon fibres reinforced plastics (CFRP) structures. After a literature research on the currently numerical models specifically used for CFRP, two different numerical models were developed in order to reproduce experimental crush test on CFRP tube previously made. The influence of several different parameters on the final results was analysed. The work put in evidence the advantages of crushing zone modelling compared to a stacked shell one.

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ABSTRACT: Based on a modified couple stress theory, a model for sigmoid functionally graded material (S-FGM) nanoplates on elastic medium is developed. The two main advantages of the modified couple stress theory over the classical couple stress theory are the inclusion of asymmetric couple stress tensor and the involvement of only one material length scale parameter. Analytical solution for buckling analysis of S-FGM nanoplates on elastic medium is presented. The present models contain one material length scale parameter and can capture the size effect, and two-constituent material variation through the plate thickness. The governing equations are derived from minimum total potential energy principle based on a modified couple stress theory, and the power law variation of the material through the thickness of the plate. Material properties of functionally graded plate are assumed to vary according to two power law distribution of the volume fraction of the constituents. It is assumed that the elastic medium is modeled as Pasternak elastic medium. Buckling response of rectangular S-FGM nanoplates is derived, and the obtained results are compared well with reference solutions. The effects of power law index, small scale coefficient, aspect ratio, side-to-thickness ratio, loading types, and elastic medium parameter on the buckling load of S-FGM nanoplates have been discussed.

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ABSTRACT: Compressive behavior of composite materials has received significant attention in recent years. In the present work, a recently developed strain based fiber kinking model and stress based ones for unidirectional laminated composites are compared with experimental results. These models are implemented into a finite element code and the obtained results for glass/epoxy (Type C) ASNA 4197 unidirectional composites are presented and discussed in detail. Experimental investigations on compressive strength and kink band formation
were also performed for several specimens with various dimensions and off-axis angles made of the same glass/epoxy prepreg composite material. A special compressive fixture was also fabricated in order to ensure that the specimens are in full contact with the loading machine elements and also to eliminate the potential bending moments. Comparison between the experimental and analytical results indicated that the proposed fiber kinking model and the developed code can be used to predict the compressive strength of laminated composites due to fiber kinking mode.

ABSTRACT: Presented in this paper is analysis of buckling of double-orthotropic nanoplates based on nonlocal elasticity theory. It is assumed that two nanoplates are bonded by an internal elastic medium and surrounded by external elastic foundation. Three characteristic types of buckling are considered. Governing equations are derived based on nonlocal theory, while the expressions for the buckling load are given in explicit form for a nanoplate with all edges simply supported. Explained in detail is the influence of small scale coefficient, aspect ratio, and stiffness of internal elastic media and external elastic foundation, on the nondimensional buckling load.

ABSTRACT: The free vibration analysis of Single-Walled Carbon NanoTubes (SWCNTs) is proposed in the present paper. A continuum approach (based on an exact elastic three-dimensional shell model) is used for natural frequency investigation of simply supported SWCNTs. In order to apply this continuum model, carbon nanotubes are defined as isotropic cylinders with an equivalent thickness and Young modulus. Preliminary remarks are proposed concerning the possible use of a continuum approach and the most convenient definitions of the equivalent thickness and Young modulus. Subsequently, the 3D shell method is compared with different beam analyses to show the limitations of 1D beam models. Finally, zigzag, armchair and general chirality SWCNTs (with various lengths and geometries) are analyzed via the 3D shell model to calculate their vibration modes.

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ABSTRACT: Fluted-core sandwich composites consist of integral angled web members spaced between laminate facesheets, and may have the potential to provide benefits over traditional sandwich composites for
certain aerospace applications. However, fabrication of large autoclave-cured fluted-core cylindrical shells with existing autoclaves will require that the shells be fabricated in segments, and joined longitudinally to form a complete barrel. Experiments on two different fluted-core longitudinal joint designs were considered in this study. In particular, jointed fluted-core-composite panels were tested in longitudinal compression because this is the primary loading condition in dry launch-vehicle barrel sections. One of the joint designs performed well in comparison with unjointed test articles, and the other joint design failed at loads approximately 14% lower than unjointed test articles. The compression-after-impact (CAI) performance of jointed fluted-core composites was also investigated with test articles that had been subjected to 6 ft-lb impacts from a 1/2-in. hemispherical indenter. It was found that such impacts reduced the load-carrying capability by 9–40%. This reduction was dependent on the joint concept.

ABSTRACT: A family of 2D refined equivalent single layer models for multilayered and functionally graded smart magneto–electro–elastic plates is presented. They are based on variable kinematics and quasi-static behavior for the electromagnetic fields. First, the electromagnetic state of the plate is determined by solving the strong form of the electromagnetic governing equations coupled with the corresponding interface continuity conditions and external boundary conditions. The electromagnetic state is then condensed into the plate kinematics, whose governing equations can be written using the generalized principle of virtual displacements. The procedure identifies an effective elastic plate kinematically equivalent to the original smart plate. The effective plate is characterized by inertia, stiffness and loading properties which take the multifield coupling effects into account through their definitions, which involve the electromagnetic coefficients appearing in the smart materials constitutive law. The proposed model extends the techniques and tools available for the assessment of the mechanical behavior of multilayered composite plates to smart laminates. Additionally, finite elements for the proposed single layer models are formulated and validated against available benchmark 3D solutions.

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ABSTRACT: A mixed formulation, four node, flat shell element is proposed for the geometrically nonlinear analysis of laminated composite plates. The element is based on the linear analysis of isotropic folded plates, which is then generalized for nonlinear analysis by using a corotational formulation and Koiter’s asymptotic method. Numerical results are presented for buckling and post-critical analysis. The equilibrium paths compare well with those obtained by continuation methods but at a fraction of the computational cost.

A.H. Sofiyev (Department of Civil Engineering of Suleyman Demirel University, 32260 Isparta, Turkey), “The combined influences of heterogeneity and elastic foundations on the nonlinear vibration of orthotropic truncated conical shells”, Composites Part B: Engineering, Vol. 61, pp 324-339, May 2014,
ABSTRACT: The aim of the present paper is to study the nonlinear vibration of heterogeneous orthotropic truncated conical shells resting on the Winkler–Pasternak elastic foundations. The formulation is based on the Donnell shell theory, exponential-law distribution of orthotropic material properties and von Karman geometric nonlinearity. The basic equations are reduced to a time dependent geometrical nonlinear differential equation and solved using homotopy perturbation method (HPM). Finally, the influences of elastic foundations, heterogeneity, material orthotropy and shell characteristics on the nonlinear vibration of the truncated conical shell are studied.


ABSTRACT: In this study, the large-amplitude vibration of non-homogenous orthotropic composite truncated conical shell is investigated. It is assumed that the Young’s moduli and density of orthotropic materials vary exponentially through the thickness direction. The basic equations of non-homogenous orthotropic truncated conical shell are derived using the finite deflection theory with von Karman–Donnell-type of kinematic non-linearity. Then, foregoing equations are solved using the Superposition principle, Galerkin and Semi-inverse methods and the frequency- amplitude relationship is found. Finally, carrying out some computations, the effects of non-homogeneity, orthotropy and conical shell characteristics on the nonlinear vibration characteristics have been studied.

Hessameddin Yaghoobi and Abdolhossein Fereidoon (Faculty of Mechanical Engineering, Semnan University, Semnan, Iran), “Mechanical and thermal buckling analysis of functionally graded plates resting on elastic foundations: An assessment of a simple refined nth-order shear deformation theory”, Composites Part B: Engineering, Vol. 62, pp 54-64, June 2014, https://doi.org/10.1016/j.compositesb.2014.02.014

ABSTRACT: In present study, a refined nth-order shear deformation theory is proposed, formulated and validated for a variety of numerical examples of functionally graded (FG) plates resting on elastic foundation for the mechanical and thermal buckling responses. The present refined nth-order shear deformation theory is based on assumption that the in-plane and transverse displacements consist of bending and shear components, in which the bending components do not contribute toward shear forces and, likewise, the shear components do not contribute toward bending moments. The most interesting feature of this theory is that it accounts for a parabolic variation of the transverse shear strains across the thickness and satisfies the zero traction boundary conditions on the top and bottom surfaces of the plate without using shear correction factors. Governing equations are derived from the principle of minimum total potential energy. A Navier type closed form solution methodology is also proposed for simply supported FG plates resting on elastic foundation which provides accurate solution. The accuracy of the present theory is verified by comparing the obtained results with those predicted by classical plate theory (CPT), first-order shear deformation theory (FSDT), higher-order shear deformation theory (HSDT) and refined plate theory (RPT). Moreover, results show that the present theory can achieve the same accuracy of the existing higher-order shear deformation theories which have more number of unknowns.

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ABSTRACT: The effects of local damage on the natural frequencies and the corresponding vibration modes of composite pyramidal truss core sandwich structures are studied in the present paper. Hot press molding method is used to fabricate intact and damaged pyramidal truss core sandwich structures, and modal testing is carried out to obtain their natural frequencies. A FEM model is also constructed to investigate their vibration characteristics numerically. It is found that the calculated natural frequencies are in relatively good agreement with the measured results. By using the experimentally validated FEM model, a series of numerical analyses are conducted to further explore the effects of damage extent, damage location, damage form on the vibration characteristics of composite pyramidal truss core sandwich structures as well as the influence of boundary conditions. The conclusion derived from this study is expected to be useful for analyzing practical problems related to structural health monitoring of composite lattice sandwich structures.


ABSTRACT: An exact free vibration analysis of doubly-curved laminated composite shallow shells has been carried out by combining the dynamic stiffness method (DSM) and a higher order shear deformation theory (HSDT). In essence, the HSDT has been exploited to develop first the dynamic stiffness (DS) element matrix and then the global DS matrix of composite cylindrical and spherical shallow shell structures by assembling the individual DS elements. As an essential prerequisite, Hamilton’s principle is used to derive the governing differential equations and the related natural boundary conditions. The equations are solved symbolically in an exact sense and the DS matrix is formulated by imposing the natural boundary conditions in algebraic form. The Wittrick–Williams algorithm is used as a solution technique to compute the eigenvalues of the overall DS matrix. The effect of several parameters such as boundary conditions, orthotropic ratio, length-to-thickness ratio, radius-to-length ratio and stacking sequence on the natural frequencies and mode shapes is investigated in details. Results are compared with those available in the literature. Finally some concluding remarks are drawn.

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ABSTRACT: In this research, empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes were fabricated using a hand lay-up process. These circular flax/epoxy tubes were laterally crushed under quasi-static compression. The effects of tube thickness (2, 4 and 6 plies), tube inner diameter (64 and 86 mm) and the foam filler on the crushing characteristics and energy absorption capacity of these tubes
were investigated. The progressive crushing of these tubes were analysed from photography. In addition, the energy absorption capacities of these empty and foam filled tubes were compared with the existing circular empty and/or foam filled tubes made of metallic materials (i.e. aluminium, brass, and titanium) and synthetic fibre reinforced composites (i.e. glass and carbon). The test results indicate that under lateral compression, the foam filled flax/epoxy tubes deformed showing a capability of spreading the deformation. The use of polyurethane-foam suppressed the fibre fracturing and eventually enhanced the energy absorption of the tubes during flattening process. The foam filled tubes with more fabric plies exhibited better crashworthiness compared to the empty tubes. The comparison with the existing tubes shows that the specific energy of natural flax/epoxy tube can be designed comparable to that of conventional aluminium tube and the glass/carbon composite tube as energy absorbers. It also was found that the specific energy of the empty and foam filled flax/epoxy tubes in lateral crushing were significantly lower than those in axial crushing.


ABSTRACT: A finite element modeling methodology was developed to study the crushing behavior and energy absorption characteristics of graphite/epoxy laminated circular tubes. Laminated tubes were modeled using multiple layers of shell elements with layers being tied together using tiebreak contact. A progressive damage model was used to simulate the process. Simulation results compared very well with the experiments in terms of the load–displacement behavior, specific energy absorption, and surface strain distribution, and provided a good depiction of the failure process.

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ABSTRACT: Crushing of composite tubes under impact loading has been studied very intensively over the last few decades. On the contrary, the energy absorption of composite tubes under blast loading is much less studied, and very limited public literature is available. This paper presents the experimental testing of a sacrificial cladding structure, composed of glass/polyester tubes, under blast loading. The composite tubes show stable and progressive crushing and the peak force transferred to the non-sacrificial structure is compared for different configurations of the composite tubes. The results also show that the diffraction of the pressure wave and the skin panel that distributes the blast pressure are critical issues in the set-up of the experiments.

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ABSTRACT: A new inverse trigonometric shear deformation theory is proposed for the static, buckling and free vibration analyses of isotropic and functionally graded (FG) sandwich plates. It accounts for an inverse trigonometric distribution of transverse shear stress and satisfies the traction free boundary conditions. Equations of motion obtained here are solved for three types of FG plates: FG plates, sandwich plates with FG core and sandwich plates with FG faces. Closed-form solutions are obtained to predict the deflections, stresses, critical buckling loads and natural frequencies of simply supported plates. A good agreement between the obtained predictions and the available solutions of existing shear deformation theories is found to demonstrate the accuracy of the proposed theory.

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ABSTRACT: In recent years, nonlocal elasticity theory is widely used for the analytical and computational modeling of nanostructures. This theory, developed by Eringen, has shown to be practical for the vibration and buckling analysis of nanoscale structures and reliable for predesign procedures of nano-devices. This paper considers buckling and dynamic analysis of multi-nanoplate systems. This type of system can be relevant to composite structures embedded with graphene sheets. Exact solutions for the natural frequencies and buckling loads of multi-nanoplate systems have been proposed by considering that the multi-nanoplate system is embedded within an elastic medium. Nonlocal elasticity theory is utilized for the mathematical establishment of the system. The solutions of the homogenous system of differential equations are obtained using the Navier’s method and trigonometric method. An asymptotic analysis is proposed to show the influence of increasing number of nanoplates in the system. Analytical expressions are validated with existing results in the literature for some special cases. Numerical results based on the analytical expressions is shown to quantify the effects of the change in nonlocal parameter, stiffness coefficients of the elastic mediums and the number of layers on the natural frequencies and buckling load.

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“Vibrational analysis of advanced composite plates resting on elastic foundation”, Composites Part B:
ABSTRACT: This paper presents a free vibration analysis of functionally graded plates (FGPs) resting on elastic foundation. The displacement field is based on a novel non-polynomial higher order shear deformation theory (HSDT). The elastic foundation follows the Pasternak (two-parameter) mathematical model. The governing equations are obtained through the Hamilton’s principle. These equations are then solved via Navier-type, closed form solutions. The fundamental frequencies are found by solving the eigenvalue problem. The degree of precision of the current solution can be noticed by comparing it with the 3D and other closed form solutions available in the literature.

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ABSTRACT: Composite laminates are prone to delamination. Implementation of delamination in the Carrera Unified Formulation frame work using nine noded quadrilateral MITC9 element is discussed in this article. MITC9 element is devoid of shear locking and membrane locking. Delaminated as well as healthy structure is analyzed for free mode vibration. The results from the present work are compared with the available experimental or/and research article or/and the three dimensional finite element simulations. The effect of different kinds and different percentages of area of delamination on the first three natural frequencies of the structure is discussed. The presence of open-mode delamination mode shape for large delaminations within the first three natural frequencies is discussed. Also, the switching of places between the second bending mode, with that of the first torsional mode frequency is discussed. Results obtained from different ordered theories are compared in the presence of delamination. Advantage of layerwise theories as compared to equivalent single layer theories for very large delaminations is stated. The effect of different kinds of delamination and their effect on the second bending and first torsional mode shape is discussed.

ABSTRACT: The non-dimensional frequencies for symmetric and anti-symmetric cross-ply laminated heterogeneous composite circular cylindrical shells are analyzed by taking into account the effects of first-order deformations such as transverse shear deformations and rotary inertia. By using the Donnell-type shell theory, a set of fundamental dynamic equations of laminated circular cylindrical shells made of heterogeneous orthotropic materials is derived through Hamilton’s principle. The basic equations are reduced to the six-order algebraic equation. One of the lowest positive roots of the algebraic equation represents the fundamental frequency. Attention is focused on the case of cross-ply laminated heterogeneous orthotropic cylindrical shells, from which solution for homogenous and heterogeneous orthotropic monolayer cylindrical shells follows based on classical shell theory (CST) and shear deformation theory (SDT), as a special case. Moreover, further detailed numerical results dealing with non-dimensional frequencies and corresponding mode shapes of
laminated heterogeneous cylindrical shells having symmetric or anti-symmetric cross-ply lay-up are discussed. Furthermore, some comparisons are made to show the reliability and accuracy of the study.

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ABSTRACT: We present a comprehensive modeling and numerical study focusing on the energy quasi-static crushing behavior and energy absorption characteristics of hollow tube microlattice structures. The peak stress and effective plateau stress of the hollow microlattice structures are deduced for different geometrical parameters which gives volume and mass densities of energy absorption, $D_v$ and $D_m$, scale with the relative density, $\rho$, as $[\text{math}]$ and $[\text{math}]$, respectively, fitting very well to the experimental results of both 60° inclined and 90° predominately microlattices. Then the strategies for energy absorption enhancement are proposed for the engineering design of microlattice structures. By introducing a gradient in the thickness or radius of the lattice members, the buckle propagation can be modulated resulting in an increase in energy absorption density that can exceed 40%. Liquid filler is another approach to improve energy absorption by strengthening the microtruss via circumference expansion, and the gain may be over 100% in terms of volume density. Insight into the correlations between microlattice architecture and energy absorption performance combined with the high degree of architecture control paves the way for designing high performance microlattice structures for a range of impact and impulse mitigation applications for vehicles and structures.

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ABSTRACT: This paper presents a postbuckling analysis of carbon nanotube-reinforced composite (CNTRC) cylindrical panels resting on elastic foundations and subjected to axial compression in thermal environments. The cylindrical panels are reinforced by aligned single-walled carbon nanotubes (SWCNTs) which are assumed to be functionally graded (FG) through the thickness direction with different types of distributions. The material properties of FG-CNTRC panels are estimated through an extended rule of mixture micromechanical model. The governing equations are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The panel–foundation interaction and thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. A singular perturbation technique along with a two-step perturbation approach is employed to determine the buckling loads and postbuckling equilibrium paths. Numerical results reveal that the CNT volume fraction, temperature rise, foundation stiffness, and the panel geometric parameters have a significant effect on the buckling load and postbuckling behavior of CNTRC
cylindrical panels. The results for uniformly distributed (UD) CNTRC cylindrical panels are compared with those of FG-CNTRC cylindrical panels. The results also confirm that for an CNTRC cylindrical panel with immovable unloaded straight edges, the postbuckling path of the panel is no longer the bifurcation type.

ABSTRACT: Layer-wise and equivalent single layer plate models for magneto-electro-elastic multiphysics laminates are presented in a unified framework. They are based on variable kinematics and quasi-static behavior of the electromagnetic fields. The electromagnetic state of each single layer is preliminary determined by solving the corresponding governing equations coupled with the proper interface continuity and external boundary conditions. By so doing, the electromagnetic state is condensed into the plate kinematics and the layer governing equations are inferred by the principle of virtual displacements. This approach identifies effective mechanical layers, which are kinematically equivalent to the original smart layers. These effective layers are characterized by stiffness, inertia and load properties which take the multifield coupling effects into account as their definitions involve the electromagnetic coupling material properties. The layers governing equations are finally assembled enforcing the mechanical interface conditions. This allows to obtain the smart plate resolving system, which involves primary mechanical variables only. Results for thick simply-supported multilayered plates are obtained by an exact closed-form Navier-type solution and compared with benchmark 3D solutions to investigate the features and accuracy of the proposed modeling approach.

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ABSTRACT: This study focused on the bending behavior of an innovative sandwich panels with GFRP face sheets and a foam-web core (GFW panels), manufactured by vacuum assisted resin infusion process. An experimental study was carried out to validate the effectiveness of this panel for increasing the ultimate bending strength. Compared to the control specimen, a maximum of an approximately 410% increase in the ultimate bending strength can be achieved. The influences of web thickness, web height and web spacing on failure mode, initial bending stiffness and mid-span deflection were also investigated. Test results demonstrated that the ultimate bending strength and initial bending stiffness can be enhanced by increasing web thickness and web height. In the meantime, the indentation failure and local wrinkling failure did not occur due to the presence of the GFRP webs. Furthermore, an analytical model was proposed to predict the mid-span deflection and initial bending stiffness of GFW panels. A comparison of the analytical and experimental results showed that the analytical model accurately predicted the ultimate bending strengths and min-span deflections of the GFW panels loaded in four-point bending.

A. Gilioli, C. Sbarufatti, A. Manes and M. Giglio (Politecnico di Milano, Dipartimento di Meccanica, Via la Masa 1, 20156, Milano, Italy), “Compression after impact test (CAI) on NOMEX honeycomb sandwich panels...
ABSTRACT: Sandwich panels are used in industrial fields where lightness and energy absorption capabilities are required. In order to increase their exploitation, a wide knowledge of their mechanical behavior also in severe loading conditions is crucial. Light structures such as the one studied in the present work, sandwich panels with aluminum skins and Nomex™ honeycomb core, are exposed to a possible decrease of their structural integrity, resulting from a low velocity impact. In order to quantitatively describe the decrease of the sandwich mechanical performance after an impact, an experimental program of compression after impact tests (CAI) has been performed. Sandwich panel specimens have been damaged during a low velocity impact test phase, using an experimental apparatus based on a free fall mass tower. Different experimental impact energies have been tested. Damaged and undamaged specimens have been consequently tested adopting a compression after impact procedure. The relation between the residual strength of the panel and the possible relevant parameters has been statistically investigated. The results show a clear reduction of the residual strength of the damaged panels compared with undamaged ones. Nevertheless, a reduced dependency between the impact energy and the residual strength is found above a certain impact energy threshold.

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ABSTRACT: To satisfy the requirements for passive safety protection during railway vehicle collisions, a front-end energy absorbing structure for a certain railway vehicle was designed with its collision performance evaluated based on integral analysis of the characteristics of a thin-walled metal structure and an aluminium honeycomb structure. A finite element model of the energy absorbing structure was established in ANSYS/LS-DYNA, and structures using three types of aluminium honeycomb (Honeycombs 1, 2, and 3, respectively) were assessed by numerical analysis. The results indicated that the entire structure generated orderly and stage-by-stage deformation according to the process by which energy dissipation had been designed. The larger the plateau stress acting on the honeycomb, the greater the contribution made by the honeycomb to the overall energy dissipation of the structure. The total energy dissipation was also improved with increased honeycomb structure plateau stress.


ABSTRACT: The theoretical framework of the present manuscript covers the dynamic analysis of doubly-curved shell structures using the generalized displacement field of the Carrera Unified Formulation (CUF), including the Zig-Zag (ZZ) effect given by the Murakami’s function. The partial differential system of equations is solved by using the Generalized Differential Quadrature (GDQ) method. This numerical approach has been proven to be accurate, reliable and stable in several engineering applications. The current paper...
focuses on Functionally Graded (FG) doubly-curved shells and panels using various higher-order equivalent single layer theories, introduced and applied for the first time by the authors to completely doubly-curved shell structures, and different through-the-thickness volume fraction distributions, such as four-parameter power law, Weibull and exponential distributions. Moreover, the classic theory of mixtures is compared to the Mori–Tanaka scheme for the calculation of the mechanical properties of the materials. In particular, the numerical applications presented in this work are related to particular FG configurations in which it is possible to model a soft-core structure using a continuous variation of the mechanical properties of the materials at hand. The natural frequencies and mode shapes of several structures are presented and compared to numerical solutions taken from the literature.


ABSTRACT: A detailed investigation of the weight of each nonlinear term of the Green–Lagrange strain displacement equation is presented, with reference to the buckling of orthotropic, both flat and prismatic, Mindlin plates. Usually in the literature, in buckling analysis only the second order terms related to the out-of-plane displacement are considered. Such heuristic simplification, known as von Kármán hypothesis, starts by the consideration that the buckling mode of a flat plate is described by dominant out-of-plane displacement and disregards the non-linear terms of the Green–Lagrange strain tensor depending on the in plane displacement components, whose role is confined to first order, say pre-critical, deformation. The present paper shows that disregarding the non linear terms related to the in-plane strain–displacement is equivalent to neglect shear induced rotation. In the work, the governing equations are derived using the principle of strain energy minimum and the differential equations solution is gained by using the general Levy-type method. The obtained results show that the von Kármán model overestimates the critical load when, in buckling mode, magnitudes of shear rotation, in-plane and out-of-plane displacements are comparable.

Yongqiang Zhang, Huaiwei Huang and Qiang Han (School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510640, PR China), “Buckling of elastoplastic functionally graded cylindrical shells under combined compression and pressure”, Composites Part B: Engineering, Vol. 69, pp 120-126, February 2015, https://doi.org/10.1016/j.compositesb.2014.09.024

ABSTRACT: Buckling behaviors of elastoplastic functionally graded material cylindrical shells under combined axial compression and external pressure are investigated with classical shell theory. The material properties vary smoothly through the thickness, and a multi-linear hardening elastoplasticity is used in the analysis. By extending TTO model of functionally graded materials into $J_2$ deformation theory, the elastoplastic constitutive relation of FGMs is founded. The buckling governing equations are solved by Galerkin method, and the expression of the critical condition under combine in-plane loads is given. Numerical results are given through an iterative procedure between the prebuckling state and the critical condition. Numerical results give the interactive curves of the stability regions and the exact elastoplastic interface of the materials. It is interesting to find that, material plastic flow is of significant effects on the stability region, and the effects of the constituent distribution and the elastoplastic material properties are discussed as well.

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ABSTRACT: The bending-induced buckling improvement in a variable stiffness (VS) composite cylinder (made by fiber steering) is studied. For such a cylinder, the effect of the variation of the direction of the load on its buckling performance of the cylinder is also examined. Compromise programming, as a multi-objective optimization method, is used to design for buckling of the VS cylinder subjected to bending load in either of the two opposite directions. Different combinations of weight factors for the structural performance in the two opposite directions were also applied to obtain the Pareto frontier as the main decision making tool for the designers in a multi-objective design problem.

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ABSTRACT: The main aim of this paper is to investigate the nonlinear buckling and post-buckling of functionally graded stiffened thin circular cylindrical shells surrounded by elastic foundations in thermal environments and under torsional load by analytical approach. Shells are reinforced by closely spaced rings and stringers in which material properties of shell and the stiffeners are assumed to be continuously graded in the thickness direction. The elastic medium is assumed as two-parameter elastic foundation model proposed by Pasternak. Based on the classical shell theory with von Karman geometrical nonlinearity and smeared stiffeners technique, the governing equations are derived. Using Galerkin method with three-term solution of deflection, the closed form to find critical torsional load and post-buckling load–deflection curves are obtained. The effects of temperature, stiffener, foundation, material and dimensional parameters are analyzed.


ABSTRACT: This paper presents the Kriging model approach for stochastic free vibration analysis of composite shallow doubly curved shells. The finite element formulation is carried out considering rotary inertia and transverse shear deformation based on Mindlin’s theory. The stochastic natural frequencies are expressed in terms of Kriging surrogate models. The influence of random variation of different input parameters on the output natural frequencies is addressed. The sampling size and computational cost is reduced by employing the present method compared to direct Monte Carlo simulation. The convergence studies and error analysis are carried out to ensure the accuracy of present approach. The stochastic mode shapes and frequency response function are also depicted for a typical laminate configuration. Statistical analysis is presented to illustrate the results using Kriging model and its performance.

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ABSTRACT: This paper presents a theoretical approach to solve vibration problems of functionally graded (FG) truncated conical shells under mixed boundary conditions. The material properties of FG shell are assumed to vary continuously through the thickness of the conical shell. The fundamental relations, motion and strain compatibility equations of FG truncated conical shells are derived by means of the Airy stress function method. Two cases of mixed boundary conditions are investigated. The basic equations are solved by using Galerkin method and fundamental cyclic frequencies of FG truncated conical shells are obtained. The results are compared and validated with the results available in the literature. The detailed parametric studies are carried out to investigate the influences of radius-to-thickness ratio, lengths-to-radius ratio, material composition and mixed boundary conditions on the fundamental cyclic frequencies of truncated conical shells.


ABSTRACT: The free vibration characteristics of FGM cylindrical shells partially resting on elastic foundation with an oblique edge are investigated by an analytical method. The cylindrical shell is partially surrounded by an elastic foundation which is represented by the Pasternak model. An edge of an elastic foundation lies in a plane that is oblique at an angle with the shell axis. The motion of shell is represented based on the first order shear deformation theory (FSDT) to account for rotary inertia and transverse shear strains. The functionally graded cylindrical shell is composed of stainless steel and silicon nitride. Material properties vary continuously through the thickness according to a four-parameter power law distribution in terms of volume fraction of the constituents. The equation of motion for eigenvalue problem is obtained using Rayleigh–Ritz method and variational approach. To validate the present method, the numerical example is presented and compared with the available existing results.


ABSTRACT: In this paper, a numerical study on skin–stringer debonding growth in stiffened composite panels has been carried out. A novel numerical methodology is proposed here to investigate the compressive behaviour of a stiffened composite panel in the presence of skin–stringer partial separation. The novel numerical methodology, able to overcome the mesh size and time increment dependency of the standard Virtual Crack Closure Technique (VCCT), is an evolution of a previously developed and tested numerical approach for the circular delaminations growth. The enhancements, with respect to the previously developed approach, rely mainly in the capability to deal with the different defect shapes characterising a skin–stringer debonding. The proposed novel methodology has been implemented in a commercial finite element platform and tested over single stiffener composite panels. The effectiveness of the suggested numerical methodology, in predicting the
compressive behaviour of stiffened panels with skin stringer debondings, has been preliminary confirmed by comparisons, in terms of load versus applied displacement and debonding size at failure, with literature experimental data and numerical results obtained with the standard VCCT approach.


ABSTRACT: The focus of the present study is on energy absorption capability ($E_a$) of carbon nanotubes (CNTs) dispersed in thermoset epoxy resin under compressive high strain rate loading. Toward this objective, high strain rate compressive behavior of multi-walled carbon nanotube (MWCNT) dispersed epoxy is investigated using a split Hopkinson pressure bar. The amount of MWCNT dispersion is varied up to 3% by weight. Calculation methodology for the evaluation of $E_a$ of individual CNTs and CNTs dispersed in resins/composites is presented. Quantitative data on $E_a$ of individual CNTs and CNTs dispersed in resins under quasi-static and high strain rate loading is given.

Luigi Ascione, Valentino Paolo Berardi, Antonella Giordano and Saverio Spadea (Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II, 84084 Fisciano (SA), Italy), “Pre-buckling imperfection sensitivity of pultruded FRP profiles”, Composites Part B: Engineering, Vol. 72, pp 206-212, April 2015, https://doi.org/10.1016/j.compositesb.2014.12.014

ABSTRACT: This paper presents a geometrically non-linear one-dimensional model suitable for analyzing thin-walled fiber-reinforced polymer profiles, which accounts for the effect of manufacturing imperfections. The kinematic model is developed under the hypotheses of small strains and moderately large rotations of the cross-sections, and is able to take into consideration the contribution of shear strains and the effects related to warping displacements. The aim of the study is to develop a proper tool to analyze the pre-buckling behavior of such beams, since current approaches based on two-dimensional finite element method analysis demand significant computational efforts to be applied to real structures. The numerical results underline the effectiveness of the proposed mechanical model in analyzing case studies of technical interest in Civil Engineering, and the relevant influence of geometrical imperfections on the structural performance of FRP components with regard to serviceability design requirements.


ABSTRACT: Transverse vibrations of doubly orthogonal slender single-walled carbon nanotubes (SWCNTs) at the vicinity of each other are of interest. The van der Waals (vdW) forces play an important role in dynamic interactions between two adjacent nanotubes. Using Lennard-Jones potential function, such a phenomenon is appropriately modeled by a newly introduced vdW force density function. By employing Hamilton’s principle, the equations of motion are obtained based on the nonlocal Rayleigh beam theory. In fact, these are integro-partial differential equations and seeking an exact or even analytical solution to them is a very difficult job. Therefore, an efficient numerical solution is proposed. The effects of the intertube distance, slenderness ratio, small-scale parameter, aspect ratio, and elastic properties of the surrounding medium on the free vibration of the
nanosystem are addressed. The obtained results could be regarded as a pivotal step for better realizing of dynamic behaviors of more complex systems consist of multiple orthogonal networks of nanotubes.

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ABSTRACT: The behaviour of luffa and luffa-filled tubes under uniaxial compression was investigated numerically using finite element analysis (FEA) and analytically by theoretical models. The FEA models were validated against experimental data. Parametric study was carried out using the validated FEA models to examine the effects of the density of luffa, the thickness to diameter ratio of tube and the cross-sectional topology of luffa core. It was found that the optimal density of the luffa as filler for the luffa-filled tubes was closely related to the optimal density of the luffa sponge. It increased with the increase of the thickness to diameter ratio of the tube. The cross-sectional topology of the filler material had a negligible effect on the specific energy absorption per unit mass even when the deformation pattern of the luffa-filled tube was changed from the diamond mode to the concertina one.

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ABSTRACT: An analytical solution is presented to predict the mean axial collapse forces of fiber reinforced conical shells under thermal loading, in which the fibers wrapped orientation is arbitrary; Analytical method and finite element simulate; The influences of thermal loading, fibers wrapped orientations, geometrical eccentricity factor and proportionality coefficient on the axial collapse force of fiber reinforced conical shells are given. The collapse loading Pm of fiber-reinforced conical shells appears in the maximum value under different thermal environment when the fibers wrapped direction equals 45°. By optimizing the wrapping orientation of fiber layers, the capability of energy absorption of fiber-reinforced conical shells can be enhanced.

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ABSTRACT: This paper deals with analysis of biaxial buckling behavior of double-orthotropic microplate system including in-plane magnetic field, using strain gradient theory. Two Kirchhoff microplates are coupled by an internal elastic medium and also are limited to the external Pasternak elastic foundation. Utilizing the principle of total potential energy, the equilibrium equations of motion for three cases (out-of-phase buckling, in-phase buckling and buckling with a plate) are acquired. In this study, we assumed boundary conditions of all the edges are simply supported. In order to get exact solution for buckling load of system, Navier approach which satisfies the simply supported boundary conditions is applied. Variations of the buckling load of double-microplate system subjected to biaxial compression corresponding to various values of the thickness, length scale parameter, magnetic field, stiffness of internal and external elastic medium, aspect ratio, shear stiffness of the Pasternak foundation and biaxial compression ratio are investigated. Furthermore, influence of higher modes on buckling load is shown. By comparing the numerical results, it is found that dimensionless buckling load ratio for in-phase mode is more than those of out of phase and one microplate fixed. Also it is shown that the value of buckling load ratio reduces, when non-dimensional length scale parameter increases. However, we found when properties of plate are orthotropic the buckling load ratio is more than isotropic state. Also, by considering the effect of magnetic field, non-dimensional buckling load ratio reduces.

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ABSTRACT: This paper proposes a new higher-order shear deformation theory for buckling and free vibration analysis of isotropic and functionally graded (FG) sandwich beams. The present theory accounts a new hyperbolic distribution of transverse shear stress and satisfies the traction free boundary conditions. Equations of motion are derived from Lagrange's equations. Analytical solutions are presented for the isotropic and FG sandwich beams with various boundary conditions. Numerical results for natural frequencies and critical buckling loads obtained using the present theory are compared with those obtained using the higher and first-order shear deformation beam theories. Effects of the boundary conditions, power-law index, span-to-depth ratio and skin-core-skin thickness ratios on the critical buckling loads and natural frequencies of the FG beams are discussed.


ABSTRACT: This study investigated the energy absorption response and load carrying capability of woven natural silk/epoxy–triggered composite rectangular tubes subjected to an axial quasi-static crushing test. The rectangular composite tubes were prepared by hand lay-up technique. The tubes consisted of 12, 24, and 30 layers of natural woven silk/epoxy laminate and were 50, 80, and 120 mm long. The crashworthiness of the
tubes was evaluated by measuring the specific energy absorption in quasi-static axial compression. Specific energy absorption was obtained from the load–displacement curve during testing. The failure mode of the tubes was analyzed from high resolution photographs obtained. Overall, the tube with 50 mm length and 30 layers showed the best crashworthiness among the tubes. The failure morphology showed that the specimens failed in two distinct modes: local and mid-length buckling. The triggered composite tubes exhibited progressive failure.

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ABSTRACT: This paper presents the details of experimental and numerical research study on web crippling property of pultruded GFRP I-section under concentrated web crippling loadings. A total of 12 pultruded GFRP I-section with different loading conditions and bearing lengths was tested. The experimental scheme, failure modes and load–displacement curves were also presented. The investigation was focused on the effects of different loading condition and bearing length on web crippling ultimate capacity and ductility of pultruded GFRP I-section. The failure mode comprised longitudinal bending main crack, bending wrinkling cracks and shear cracks. Specimens with interior bearing load had slightly higher ultimate strength and greater deformation capacity than those of specimens with end bearing load. The ultimate strengths usually decreased with the increase of the bearing length except IG condition. Finite element models were developed to numerically simulate the tests performed in the experimental investigations by using commercial ABAQUS software. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of pultruded GFRP I-section under four loading and boundary conditions by using single parameter analysis.

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“FEM modeling of multilayered textile composites based on shell elements”, Composites Part B: Engineering, Vol. 77, pp 46-51, August 2015, https://doi.org/10.1016/j.compositesb.2015.03.023
ABSTRACT: The paper presents a shell element based unit cell approach for numerical homogenization of fiber reinforced textile laminates. The modeling strategy is set up within the framework of the Finite Element Method. Multilayer laminates comprising equal weaves are considered and the constituents, i.e. the tows as well as the unreinforced matrix pockets are discretized by shell elements only which are coupled appropriately. A study on the effective extensional laminate-shell stiffnesses is presented, the results are discussed, and are compared to approaches found in the literature. Additionally, geometrically nonlinear simulations are conducted and the results are compared with experimental tests from literature.

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“Free vibration of four-parameter functionally graded spherical and parabolic shells of revolution with arbitrary boundary conditions”, Composites Part B: Engineering, Vol. 77, pp 59-73, August 2015, 
https://doi.org/10.1016/j.compositesb.2015.03.016

ABSTRACT: The objective of this work is to present a Haar Wavelet Discretization (HWD) method-based solution approach for the free vibration analysis of functionally graded (FG) spherical and parabolic shells of revolution with arbitrary boundary conditions. The first-order shear deformation theory is adopted to account for the transverse shear effect and rotary inertia of the shell structures. Haar wavelet and their integral and Fourier series are selected as the basis functions for the variables and their derivatives in the meridional and circumferential directions, respectively. The constants appearing in the integrating process are determined by boundary conditions, and thus the equations of motion as well as the boundary condition equations are transformed into a set of algebraic equations. The proposed approach directly deals with nodal values and does not require special formula for evaluating system matrices. Also, the convenience of the approach is shown in handling general boundary conditions. Numerical examples are given for the free vibrations of FG shells with different combinations of classical and elastic boundary conditions. Effects of spring stiffness values and the material power-law distributions on the natural frequencies of shells are also discussed. Some new results for the considered shell structures are presented, which may serve as benchmark solutions.

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“Web crippling behavior of pultruded GFRP rectangular hollow sections”, Composites Part B: Engineering, Vol. 77, pp 112-121, August 2015, https://doi.org/10.1016/j.compositesb.2015.03.037

ABSTRACT: This paper presents an experimental investigation on the web-crippling behavior in glass fiber reinforced polymer (GFRP) pultruded profiles with rectangular hollow section. There is evidence that GFRP pultruded profiles are particularly susceptible to transverse compressive loads, owing to the much lower mechanical properties in the direction transverse to the pultrusion axis. Although very relevant, the understanding about the web-crippling behavior in GFRP pultruded profiles is still very limited, as attested by the lack of information available in design codes and guidelines. End-two-flange (ETF) and interior-two-flange (ITF) loading conditions were adopted, with specimens seated on a bearing plate. Specimens were also placed on the ground with end (EG) or interior (IG) bearing load to simulate the loading conditions of floor joist members. The effects of the loading positions (end loading or interior loading) as well as the supporting conditions (on a bearing plate or on the ground) on the web crippling behavior are discussed. In addition, tests were performed with three different bearing lengths: 50 mm, 100 mm and 150 mm. Finite element models were developed to numerically simulate the tests performed in the experimental investigations in the terms of ultimate loads and failure modes. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of pultruded GFRP rectangular hollow sections under four loading and boundary conditions.

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“Buckling failure analysis of cracked functionally graded plates by a stabilized discrete shear gap extended 3-
ABSTRACT: We present new numerical results in buckling failure analysis of cracked composite functionally graded plates subjected to uniaxial and biaxial compression loads. An accurate extended 3-node triangular plate element in the context of the extended finite element method (XFEM) is developed, integrating the discrete shear gap method (DSG) to eliminate shear-locking. The plate kinematics is based on the Reissner–Mindlin theory, and material properties are assumed to vary through thickness direction, obeying a power law distribution. The developed DSG-XFEM is found to be effective and accurate as it owns many desirable advantages: conveniently representing crack geometry which is independent of the mesh; shear-locking effect is no longer valid; mesh distortion is insensitive and controllable; thin plates is possible; triangular elements are easily generated for problems even with complex geometries; and high accuracy. All these arisen features are demonstrated through numerical examples and the effects of crack-length, material gradation, mesh distortion, inclined angles of cracks, boundary conditions, width-to-thickness ratio, length ratio, etc. on the critical buckling coefficient (CBC) are analyzed. Numerical results reveal that the material gradation, crack-length, thickness, length ratios, etc. have a strong effect on the behavior of CBC. This phenomenon is mainly attributed to the plate stiffness degradation due to the presence of local defects and material composition. Also, the boundary conditions greatly alter the CBC whereas the inclination of cracked angle is found to be insignificant.

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ABSTRACT: In this paper, analysis of free vibration of carbon nanotube (CNT) reinforced functionally graded rotating cylindrical panels is presented. The analysis is performed by using the element-free kernel particle Ritz method or in short the kp-Ritz method. The rotating cylindrical panels are reinforced by single-walled carbon nanotubes (SWCNTs) with different types of distributions along thickness direction of the panels. Extended rule of mixture is selected to estimate the effective material properties of the resulting nanocomposite rotating panels. Two-dimensional displacement fields of the plates are approximated by a set of mesh-free kernel particle functions. The discretized governing eigen-equations are developed via the Ritz procedure. This kp-Ritz method enforces essential boundary conditions through the full transformation method. Detailed parametric studies have been carried out to reveal the influences of volume fraction of carbon nanotubes, edge-to-radius ratio and rotation speed on the frequency characteristics, with mode shape visualization provided. In addition, effects of different boundary conditions and types of distributions of carbon nanotubes are examined in detail.

A.H. Sofiyev (Department of Civil Engineering of Engineering Faculty of Suleyman Demirel University, Isparta, 32260, Turkey), “Influences of shear stresses on the dynamic instability of exponentially graded sandwich cylindrical shells”, Composites Part B: Engineering, Vol. 77, pp 349-362, August 2015, https://doi.org/10.1016/j.compositesb.2015.03.040
ABSTRACT: The aim of present study is to investigate the dynamic instability of exponentially graded (EG)
sandwich cylindrical shells under static and time dependent periodic axial loadings using the shear deformation theory (SDT). The modified Donnell-type dynamic instability equations of EG sandwich cylindrical shells based on the SDT are deduced. Then are reduced to Mathieu-Hill equation and by solving the expressions for the boundaries of instability regions of EG sandwich cylindrical shells are obtained. The similar expressions for EG single-layer shell, ceramic-rich shell and metal coated sandwich cylindrical shell on the basis of SDT and classical shell theory (CST) are obtained in a special case. The numerical illustrations concern the influences of compositional profiles of coating layers, shear stresses and geometrical parameters of sandwich cylindrical shells on the boundaries of instability regions. As a check on the accuracy of the present study, the values of the lower and upper boundaries of instability regions are compared with those in the literature.

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“Multiobjective design of viscoelastic laminated composite sandwich panels”, Composites Part B: Engineering, Vol. 77, pp 391-401, August 2015, https://doi.org/10.1016/j.compositesb.2015.03.025  

ABSTRACT: The optimal design of laminated sandwich panels with viscoelastic core is addressed in this paper, with the objective of simultaneously minimizing weight and material cost and maximizing modal damping. The design variables are the number of layers in the laminated sandwich panel, the layer constituent materials and orientation angles and the viscoelastic layer thickness. The problem is solved using the Direct MultiSearch (DMS) solver for multiobjective optimization problems which does not use any derivatives of the objective functions. A finite element model for sandwich plates with transversely compressible viscoelastic core and anisotropic laminated face layers is used. Trade-off Pareto optimal fronts are obtained and the results are analyzed and discussed.

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ABSTRACT: The conventional strong form collocation approach known as Differential Quadrature (DQ) method has been applied in the past to a vast type of engineering problems. It is well-known that its application is strictly limited to regular regions where derivatives are approximated along mesh lines. Generally, its accuracy increases when the number of collocation points is large and the method tends to be stable. However, for some numerical problems several points are needed in order to obtain an accurate solution. Changing the basis functions another numerical technique was developed called Radial Basis Functions (RBFs) method, which has the advantage of approximating derivatives using irregular point distributions and the basis functions depend on the mutual radial distance of the grid points. In order to extend the idea of DQ method to a general case a Radial Basis Function based on Differential Quadrature (RBF-DQ) method has been recently developed. This method merges the advantages of both techniques. Furthermore, this work proposes the application of RBF-DQ when a domain decomposition technique is considered. In this way it will be shown that, using some
kind of basis functions the number of grid points per element can be reduced compared to other classical approaches. Furthermore, once the shape parameter is fixed for one case, it is not needed to calculate it again for other applications.

ABSTRACT: Nonlinear and linear free vibration of symmetrically laminated magneto-electro-elastic doubly-curved thin shell resting on an elastic foundation is studied analytically. The shell is considered to be simply-supported on all edges and the magneto-electro-elastic body is poled along the z direction and subjected to electric and magnetic potentials between the upper and lower surfaces. To obtain the equations of motion, the Donnell shell theory in the presence of rotary inertia effect is used. Moreover, Gauss’ laws for electrostatics and magnetostatics are used to model the electric and magnetic behavior. The nonlinear partial differential equations of motion are reduced to a single nonlinear ordinary differential equation by introducing a force function and using the single-term Galerkin method. The resulting equation is solved analytically by Lindstedt-Poincare perturbation method. After validation of the present study, several numerical studies are done to investigate the effects of foundation parameters, geometrical properties of the shell, and electric and magnetic potentials on the linear and nonlinear behavior of these smart shells.

Hui-Shen Shen (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China), “Nonlinear bending and postbuckling of FGM cylindrical panels subjected to combined loadings and resting on elastic foundations in thermal environments”, Composites Part B: Engineering, Vol. 78, pp 202-213, September 2015, https://doi.org/10.1016/j.compositesb.2015.03.078
ABSTRACT: A nonlinear analysis is presented for FGM cylindrical panels resting on elastic foundations subjected to the combined actions of uniform lateral pressure and compressive edge loads in thermal environments. The two cases of postbuckling of initially pressurized FGM cylindrical panels and of nonlinear bending of initially compressed cylindrical panels are considered. Heat conduction and temperature-dependent material properties are both taken into account. Material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction based on Mori-Tanaka micromechanics model. The formulations are based on a higher order shear deformation theory and von Kármán strain displacement relationships. The panel-foundation interaction and thermal effects are also included. The governing equations are solved by a singular perturbation technique along with a two-step perturbation approach. The numerical illustrations concern the postbuckling behavior and the nonlinear bending response of FGM cylindrical panels with two constituent materials resting on Pasternak elastic foundations. The effects of volume fraction index, temperature variation, foundation stiffness as well as initial stress on the postbuckling behavior and the nonlinear bending response of FGM cylindrical panels are discussed in detail.

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ABSTRACT: High speed dynamic loadings such as small engine fragments, bird strike, tyre impact or ice debris are a concern for many aeronautical structures, as they can create severe damages raising safety issues. A strategy to develop dedicated mechanisms for energy absorption of high speed dynamic impact debris at sub-component level is therefore proposed by means of several reinforced foam-woven composite structures. Among the tests for evaluating the mechanical performances, dynamic crushing tests were performed on a slice of such reinforced composite structures to evaluate their energy absorption. Using simultaneously load signal and fast camera imaging, the tests were analyzed to provide important informations such as damage mechanisms and displacement-load-energy absorption values. At the end, quantitative criterions are presented in order to distinguish the designs that have a good potential for absorbing shock energy and for getting a better understanding for designing reinforced composite structures.

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ABSTRACT: The present paper deals with the lightweight design and the crashworthiness analysis of a composite impact attenuator for a Formula SAE racing car, in order to pass homologation requirements. The analysed impact attenuator is manufactured by lamination of prepreg sheets in carbon fibres and epoxy matrix, particularly used for sporting applications, and has a very similar geometry to a square frusta, so as to obtain a progressive and controlled deformation. During the design, attention was focused on the material distribution and gradual smoothing, but also on the lamination process, which can heavily affect the energy absorption capability. To reduce the development and testing costs of a new safety design, computational crash simulations for early evaluation of safety behaviour under vehicle impact test were carried out. The dynamic analysis was therefore conducted both numerically, using an explicit finite element code such as LS-DYNA, and experimentally, by means of an appropriately instrumented drop weight test machine, in order to validate the model in terms of deceleration values during crushing. To assess the quality of the simulation results, a comparative analysis was initially developed on simple CFRP composite tubes subjected to dynamic axial loading. The numerical analysis was conducted using both shell and solid elements, in order to reproduce not only the brittleness of the composite structure but also the effective delamination phenomenon. Both the analyses show a good capacity to reproduce the crushing process; this is confirmed by the fact that model estimated displacements and accelerations are in close agreement with observed values for these variables. This confirms the quality of the methodology and approach used for the design of a racing car impact attenuator.

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ABSTRACT: A finite element (FE) model using coupling continuum shell elements and cohesive elements is proposed to simulate the compression after impact (CAI) behaviour and predict the CAI strength of stitched composites. Continuum shell elements with Hashin failure criterion exhibit the composite laminate damage behaviour; whilst cohesive elements using traction-separation law characterise the laminate interfaces. Impact-induced delamination is explicitly modelled by reducing material properties of damaged cohesive elements. Computational results have demonstrated the trend of increasing CAI strength with decreasing impact-induced delamination area. Spring elements are introduced into the model to represent through-thickness stitch thread in the composite laminates. Results in this study validate experimental finding that CAI strength is improved when stitching is incorporated into the composite structure. The proposed FE model reveals good CAI strength predictions and indicates good agreement with experimental results, making it a valuable tool for CAI strength prediction of stitched composites.

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ABSTRACT: This paper presents buckling analysis of a two-dimensional functionally graded cylindrical shell reinforced by axial stiffeners (stringer) under combined compressive axial and transverse uniform distributive load. The shell material properties are graded in the direction of thickness and length according to a simple power law distribution in terms of the volume fractions of the constituents. Primarily, the third order shear deformation theory (TSDT) is used to derive the equilibrium and stability equations. Since there is no closed form solution, the numerical differential quadrature method, (DQM), is applied for solving the stability equations. Initially, the obtained results for an isotropic shell using DQM were verified against those given in the literature for simply supported boundary conditions. The effects of load, geometrical and stringer parameters along with FG power index in the various boundary conditions on the critical buckling load have been studied. The study of results confirms that, stringers have significant effects on critical buckling load.


ABSTRACT: Composite materials allow all the benefits which a high specific strength involves, in a design process their application involves many critical problems. Currently, these problems, such as environmental conditions, notch sensitivity, damaging under low velocity impacts, are taken into account by means of the application of conservative design safety factors regarding the ultimate tensile strength. In order to try to reduce these safety factors, this work aimed to study and to understand the impact damage growing mechanisms due to compression loads. To this purpose, compression tests have been experimentally performed on composite
panels, which have been previously subjected to low velocity impact phenomena, considering impact energies of 6 J, 10 J and 13 J respectively. Moreover, numerical model able to simulate Low Velocity Impacts (LVI) and Compression After Impacts (CAI) onto CFRP panels is proposed. A single explicit finite element analysis has been carried out by using the Abaqus® finite element code; the need to build a numerical model, which allows simulation in only one analysis both LVI and CAI steps, depends on the difficulty to import the impact damage distribution into a separate compression analysis. In fact, in only one analysis the compression step can occur directly onto the impacted plate, which allows to consider the effective impact damage distribution as the starting configuration for quasi static analysis under operating loads.

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ABSTRACT: This paper aims to explore the dynamic responses and crashing characteristics of double hat shaped tubes made of weave carbon fiber reinforced plastic (CFRP). Experimental investigations were carried out into three different thicknesses and lengths of the composite tubes fabricated by the bladder molding process. Three distinct failure modes, classified as progressive end crushing, mid-length collapse and overlap opening, were observed in the dynamic crushing tests. Unlike continuous splaying fronds observed in the quasi-static tests, dynamic tests exhibited a number of fragment segments in the progressive end crushing mode. It is shown that the ply number was a critical parameter affecting the failure mode and energy absorption capability. The increase in ply number led to increases in the peak load and specific energy absorption (SEA); whereas the tubal length seemed insensitive to energy absorption capability. Compared to the quasi-static cases, the dynamic impact tests resulted in the higher peak load (increased from 46 % to 125 %) and lower SEA (reduced from 21 % to 33 %) for the tested tubes.

Keivan Kiani (Department of Civil Engineering, K.N. Toosi University of Technology, Valiasr Ave., P.O. Box 15875-4416, Tehran, Iran), “Nonlocal and shear effects on column buckling of single-layered membranes from stocky single-walled carbon nanotubes”, Composites Part B: Engineering, Vol. 79, pp 535-552, September 2015, https://doi.org/10.1016/j.compositesb.2015.04.030

ABSTRACT: Axial buckling behavior of single-layered membranes from vertically aligned single-walled carbon nanotubes is studied in the context of the nonlocal continuum theory of Eringen. To this end, useful discrete models based on the nonlocal Rayleigh, Timoshenko, and higher-order beam theories are developed to evaluate critical buckling loads associated with both in-plane and out-of-plane buckling modes. In discrete models, the size of the eigenvalue equations to be solved drastically magnifies for highly populated membranes. Thereby, development of models whose computational efforts do not affected by the population of the membrane is of great advantageous. To bridge this scientific gap, appropriate nonlocal continuous models are established based on the developed discrete models. The accuracy of the proposed discrete and continuous models is checked and remarkable results are achieved. Subsequently, the roles of the influential factors on both in-plane and out-of-plane axial buckling loads are addressed. The obtained results can be regarded as a basic
step in examining of axial buckling mechanisms of more complex systems consist of multi-layered membranes from parallel or even orthogonal single-walled carbon nanotubes.

S. Sahmani, M.M. Aghdam and M. Bahrami (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “Nonlinear buckling and postbuckling behavior of cylindrical nanoshells subjected to combined axial and radial compressions incorporating surface stress effects”, Composites Part B: Engineering, Vol. 79, pp 676-691, September 2015, https://doi.org/10.1016/j.compositesb.2015.05.006
ABSTRACT: In the present study, the Gurtin-Murdoch elasticity theory, as a theory capable of capturing size effects, is implemented to predict the nonlinear buckling and postbuckling response of cylindrical nanoshells under combined axial and radial compressive loads in the presence of surface stress effects. For this purpose, a size-dependent shell mode containing geometric nonlinearity is proposed within the framework of the classical shell theory. Because it is necessary to satisfy balance conditions on the surfaces of nanoshell, it is assumed that the normal stress component of the bulk varies linearly through the shell thickness. On the basis of a variational formulation using the principle of virtual work, the non-classical governing differential equations are derived. Subsequently, a boundary layer theory is employed including the nonlinear prebuckling deformations and the large deflections in the postbuckling regime. Then a two-stepped perturbation methodology is utilized to obtain the size-dependent critical buckling loads and the postbuckling equilibrium paths of nanoshells corresponding to the axial dominated and radial dominated loading cases. It is revealed that in the radial dominated loading case, a positive value of surface elastic constants leads to increase the critical buckling load but decrease the critical end-shortening of nanoshell. However, in the axial dominated loading case, surface elastic constants with positive sign causes to increase the both critical buckling load and critical end-shortening of nanoshell.

A.H. Sofiyev (Department of Civil Engineering of Engineering Faculty of Suleyman Demirel University, 32260 Isparta, Turkey), “On the vibration and stability of shear deformable FGM truncated conical shells subjected to an axial load”, Composites Part B: Engineering, Vol. 80, pp 53-62, October 2015, https://doi.org/10.1016/j.compositesb.2015.05.032
ABSTRACT: The aim of present study is to investigate the vibration and stability of functionally graded (FG) conical shells under a compressive axial load using the shear deformation theory (SDT). The basic equations of shear deformable FG conical shells are derived using Donnell shell theory and solved using Galerkin's method. The novelty of this study is to achieve closed-form solutions for the dimensionless frequencies and critical axial loads for freely-supported FG truncated conical shells on the basis of the SDT. Parametric studies are made to investigate effects of shear stresses, compositional profiles and conical shell characteristics on the critical parameters. Some comparisons with the various studies have been performed in order to show the accuracy of the present study.

Francesco Tornabene, Nicholas Fantuzzi, Michele Bacciocchi and Erasmo Viola (DICAM, Department, School of Engineering and Architecture, University of Bologna, Italy), “Higher-order theories for the free vibrations of doubly-curved laminated panels with curvilinear reinforcing fibers by means of a local version of the GDQ method”, Composites Part B: Engineering, Vol. 81, pp 196-230, November 2015, https://doi.org/10.1016/j.compositesb.2015.07.012
ABSTRACT: The aim of this paper is to investigate the dynamic behavior of singly and doubly-curved panels reinforced by curvilinear fibers. The Variable Angle Tow (VAT) technology allows the placement of fibers
along curvilinear paths with the purpose of improving dynamic performance of plates and shells. The effect of the variation of constants which define analytically the fiber orientation is also investigated by several parametric studies. The Carrera Unified Formulation (CUF) with different thickness functions along the three orthogonal curvilinear directions is the basis of the present theoretical model. Various doubly curved laminated panels reinforced by curvilinear fibers are analyzed using several structural theories. The Local Generalized Differential Quadrature (LGDQ) method is employed to solve numerically free vibration problems. Compared to the well-known GDQ method from which it descends, the LGDQ is characterized by banded matrices instead of full ones, since the current technique considers only few points of the whole domain. Therefore, the solution of the equation system needs a lower computational effort.

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ABSTRACT: The present paper shows a comparison between classical two-dimensional (2D) and three-dimensional (3D) finite elements (FEs), classical and refined 2D generalized differential quadrature (GDQ) methods and an exact three-dimensional solution. A free vibration analysis of one-layered and multilayered isotropic, composite and sandwich cylindrical and spherical shell panels is made. Low and high order frequencies are analyzed for thick and thin simply supported structures. Vibration modes are investigated to make a comparison between results obtained via the FE and GDQ methods (numerical solutions) and those obtained by means of the exact three-dimensional solution. The 3D exact solution is based on the differential equations of equilibrium written in general orthogonal curvilinear coordinates. This exact method is based on a layer-wise approach, the continuity of displacements and transverse shear/normal stresses is imposed at the interfaces between the layers of the structure. The geometry for shells is considered without any simplifications. The 3D and 2D finite element results are obtained by means of a well-known commercial FE code. Classical and refined 2D GDQ models are based on a generalized unified approach which considers both equivalent single layer and layer-wise theories. The differences between 2D and 3D FE solutions, classical and refined 2D GDQ models and 3D exact solutions depend on several parameters. These include the considered mode, the order of frequency, the thickness ratio of the structure, the geometry, the embedded material and the lamination sequence.

M.H. Mansouri and M. Shariyat (Faculty of Mechanical Engineering, Center of Excellence in Smart Structures and Dynamical Systems, K.N. Toosi University of Technology, Tehran 19991-43344, Iran), “Biaxial thermo-mechanical buckling of orthotropic auxetic FGM plates with temperature and moisture dependent material properties on elastic foundations”, Composites Part B: Engineering, Vol. 83, pp 88-104, December 2015, https://doi.org/10.1016/j.compositesb.2015.08.030
ABSTRACT: Thermo-mechanical buckling analysis of the orthotropic auxetic plates (with negative Poisson ratios) has not been performed so far, especially, in the hygrothermal environments. The complexity increases when the auxetic plate is fabricated from functionally graded orthotropic materials and surrounded by an elastic foundation. The aforementioned analyses are carried out in the present research, for the first time. The buckling loads may be uniaxial or biaxial ones. Moreover, temperature and moisture dependent material properties are considered. The pre-buckling effects are also considered in the paper. The high-order shear-deformation
governing differential equations are solved based on a new differential quadrature method (DQM). The resulting solution may cover many practical simpler applications. A comprehensive parametric study is accomplished for a wide range of geometric and material properties parameters and various boundary conditions. Results reveal that the hygrothermal conditions lead to degradations in the material properties and buckling strengths, especially for higher gradation exponents, the elastic foundation may enhance the buckling behavior through monitoring the buckling pattern, the buckling load decreases as the orthotropy angle increases, and the auxeticity has reduced the buckling strength for the employed material and environmental information.

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ABSTRACT: Finite conductivity, surface energy and nonlocal effect can influence the electromechanical performance of micro/nano-electromechanical systems (MEMS/NEMS). However, these factors are yet ignored on stability analysis of MEMS/NEMS fabricated from functionally graded materials (FGM). In this paper, dynamic stability of double-sided NEMS fabricated from non-symmetric FGM is investigated incorporating finite conductivity, surface energy and nonlocal effect. The Gurtin–Murdoch model and Eringen's elasticity are employed to consider the surface energy and nonlocal effect, respectively. Effect of finite conductivity of FGM on electrostatic and Casimir attractions is incorporated via relative permittivity and plasma frequency of the material. The stability analysis of the nanostructure is conducted by plotting time history and phase portraits. Moreover, bifurcation analysis is conducted to investigate the stability of the fixed points of the nano-structure. The validity of the proposed model is examined by comparing the results of the present study with those reported in the literature. The impact of various parameters i.e. finite conductivity, nonlocal parameter, surface stresses and material characteristics on the dynamic instability of the NEMS are addressed.

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ABSTRACT: The closed-form solution of a generalized hybrid type quasi-3D higher order shear deformation theory (HSDT) for the bending analysis of functionally graded shells is presented. From the generalized quasi-3D HSDT (which involves the shear strain functions “f(ξ)” and “g(ξ)” and therefore their parameters to be selected “m” and “n”, respectively), infinite six unknowns hybrid shear deformation theories with thickness stretching effect included, can be derived and solved in a closed-from. The generalized governing equations are also “m” and “n” parameter dependent. Navier-type closed-form solution is obtained for functionally graded shells subjected to transverse load for simply supported boundary conditions. Numerical results of new optimized hybrid type quasi-3D HSDTs are compared with the first order shear deformation theory (FSDT), and other quasi-3D HSDTs. The key conclusions that emerge from the present numerical results suggest that: (a) all non-polynomial HSDTs should be optimized in order to improve the accuracy of those theories; (b) the optimization procedure in all the cases is, in general, beneficial in terms of accuracy of the non-polynomial hybrid type quasi-3D HSDT; (c) it is possible to gain accuracy by keeping the unknowns constant; (d) there is
not unique quasi-3D HSDT which performs well in any particular example problems, i.e. there exists a problem dependency matter.

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ABSTRACT: This paper deals with modelling the effect of low-velocity impact damage upon the vibration response of CFRP laminates through a micro-mechanical description of the induced internal damage. The serial-parallel (SP) continuum approach is used to estimate the map of induced internal damage by considering the micro-structural interaction between the composite constituents and modifying their constitutive performance through a continuum damage formulation. An eigenvalue analysis is then done to determine the modal response of impacted laminates. The validity of the modelling approach to successfully reproduce the vibration response of impacted coupons is assessed through a comparison with an experimental test series conducted on a set of 48 CFRP laminated coupons. The results confirm the ability of the described approach in comparison to competing ones used to reproduce the experimentally observed behaviour.

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ABSTRACT: In the present paper free vibrations of embedded single-walled carbon nanotubes based on local Euler–Bernoulli beam theory are investigated. The surrounding elastic medium is described as the Winkler and Pasternak models, defined by the $k_w$ and $k_p$ coefficients. The Hamilton principle is applied to derive the governing equations and boundary conditions, which are solved by using the well-known Differential Quadrature Method (DQM). The influence of the elastic medium coefficients, nonlocal parameter and end supports on the free vibrations characteristics of the single-walled carbon nanotube (SWCNT) is described. Numerical examples are performed to show the accuracy of the proposed method.

S. Sahmani, M. Bahrami and M.M. Aghdam (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “Surface stress effects on the nonlinear postbuckling
characteristics of geometrically imperfect cylindrical nanoshells subjected to torsional load”, Composites Part B: Engineering, Vol. 84, pp 140-154, January 2016, https://doi.org/10.1016/j.compositesb.2015.08.076
ABSTRACT: The prime aim of the current investigation is to predict the nonlinear torsional buckling and postbuckling behavior of geometrically imperfect cylindrical nanoshells including surface stress effects. To this end, the size-dependent governing differential equations of cylindrical nanoshell based on von Karman–Donnell-type of kinematic nonlinearity are derived using a combination of Gurtin–Murdoch elasticity theory and the classical shell theory, and employing the principle of virtual work. Subsequently, by considering the transverse displacement and Airy stress function as independent variables, a boundary layer theory is put to use which takes surface stress effects into account in conjunction with the nonlinear prebuckling deformations, large postbuckling deflections and initial geometric imperfection. Finally, an efficient solution methodology based on a two-stepped singular perturbation technique is conducted to obtain the size-dependent postbuckling equilibrium paths of nanoshells. It is revealed that after the minimum point of postbuckling load, by increasing the value of applied torsional load, the difference between postbuckling load-deflection curves corresponding to the perfect and imperfect nanoshells tends to decrease.

A.H. Sofiyev (Department of Civil Engineering of Engineering Faculty of Suleyman Demirel University, 32260 Isparta, Turkey), “Buckling of heterogeneous orthotropic composite conical shells under external pressures within the shear deformation theory”, Composites Part B: Engineering, Vol. 84, pp 175-187, January 2016, https://doi.org/10.1016/j.compositesb.2015.08.058
ABSTRACT: The main objective of this work is to demonstrate a convenient and efficient way to get a closed-form solution for buckling of heterogeneous orthotropic truncated conical shells under external pressures. The first-order shear deformation shell theory (FOSDT) is adopted to formulate the theoretical model. The basic equations of shear deformable heterogeneous orthotropic truncated conical shells are derived using Donnell shell theory. To solve this problem is used an unknown parameter $\lambda$ in the approximation functions. The partial differential equations are transformed into algebraic equations using unknown $\lambda$ parameter and Galerkin's method. The expressions for non-dimensional external pressures of heterogeneous orthotropic truncated conical shells are obtained by solving algebraic equations. The parameter $\lambda$ which is included in the obtained expressions is get from the minimum conditions of the critical external pressures. The accuracy and reliability of the current solutions are validated by numerical examples and comparison with the results available in the literature. The influences of variations of the semi-vertex angle, radius-to-thickness ratio, orthotropy ratio and heterogeneity factor on the non-dimensional critical external pressures of truncated conical shells within the CST and SDT are also discussed.

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ABSTRACT: Web crippling is the major failure mode of galvanized steel tube members when they are subjected to concentrated loads or reactions. Carbon fibre-reinforced polymer (CFRP) sheets were found to be promising for strengthening metallic structural members. This paper presents a test program on strengthening of high strength galvanized steel tubular structural members using externally bonded CFRP sheets. The results of 16 web crippling tests were presented, with 8 tests conducted on galvanized steel square hollow sections
without CFRP sheets strengthening and 8 tests conducted on galvanized steel square hollow sections with CFRP sheets strengthening. The experimental scheme, failure modes and load–displacement curves were also presented. The investigation was mainly focused on the effects of boundary condition, loading condition and CFRP sheets layers for the strengthening of galvanized steel square hollow sections against web crippling. Significant increase in web crippling ultimate capacity was obtained due to CFRP sheets strengthening. Enhancement of web crippling ultimate capacity was not obvious when CFRP sheets layers exceeds 3 layers. Finite element models were developed to numerically simulate the experimental results. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of galvanized steel tubular sections strengthened by CFRP sheets under four loading and boundary conditions.

Yuming Mo, Dongyun Ge and Boling He (School of Aerospace Engineering, Tsinghua University, Beijing, 100084, China), “Experiment and optimization of the hat-stringer-stiffened composite panels under axial compression”, Composites Part B: Engineering, Vol. 84, pp 285-293, January 2016, https://doi.org/10.1016/j.compositesb.2015.08.039

ABSTRACT: The buckling and post-buckling behavior of hat-stringer-stiffened composite flat panel subjected to axial compression was investigated in this paper. The influence of test fixtures was taken into account. In the test, panels were tested with and without test fixtures. The stability and deformation process of the stiffened panel and the hat-stringer were analyzed based on the experimental data. Several models based on ABAQUS software were established to explore the proper cross section of the hat-stringer tested in this paper. Based on the built-in NLPQL algorithm in iSIGHT and MATLAB codes, optimization of the hat-stringer was done to get an optimal cross section. To help engineers to design an optimal hat-stringer, an engineering method was presented based on the optimization results and an example was used to show how the method worked.


ABSTRACT: Dynamic behavior of Voronoi cellular materials with density gradient subjected to constant velocity impact was simulated and analyzed by employing the Ls-dyna 971. The introduction of density gradients may significantly influence the global performance of cellular materials, so in order to probe the failure mechanism and stress transmission, firstly, deformation modes of graded Voronoi models are investigated in details. The approach of capturing the first critical velocity of the deformation mode transformation in uniform cellular materials was extended to the graded cases. Meanwhile, a new method based on the local strain was developed to determine the second critical velocity. Afterwards, the variations of the crushing stress and the plateau stress at both the impact and stationary sides were taken into consideration in the study. Furthermore, the density gradient was introduced into the shock wave theory based on R-P-P-L model to predict the response of the graded cases. Additionally, the feasibility to use the graded materials as a protective coating and the variation of densification strain were sketched. This research may provide valuable insight into engineering applications of the graded cellular materials.

Yin Fan and Hai Wang (School of Aeronautics & Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China), “Nonlinear bending and postbuckling analysis of matrix cracked hybrid
ABSTRACT: The nonlinear bending and postbuckling behaviors of a hybrid laminated plate resting on a Pasternak elastic foundation in thermal environments are investigated in this paper. The plate is composed of conventional fiber reinforced composite (FRC) layers and carbon nanotube reinforced composite (CNTRC) layers. The CNTRC layer consists of reinforcing carbon nanotubes either uniformly distributed (UD) or functionally graded (FG) along the thickness direction. Transverse matrix cracking is introduced in the FRC and UD CNTRC layers and modeled by a refined self-consistent method. The governing equations of the plate are based on a higher order shear deformation plate theory with a von Kármán-type of kinematic nonlinearity and solved by a two-step perturbation technique. The plate-foundation interaction and thermal effects are also included. The material properties of both CNTRC and FRC layers are assumed to be temperature-dependent and are estimated by a micro-mechanical model. A parametric study is conducted to investigate the effects of matrix crack density, foundation stiffness, temperature rise and in-plane boundary conditions on the nonlinear bending and postbuckling behaviors of antisymmetric hybrid laminated plates containing CNTRC layers.

ABSTRACT: Non-linear analysis of two-directional functionally graded annular sector plates has not been performed yet. The present paper focuses on the non-linear bending analysis of variable thickness two-directional functionally graded circular/annular sector plates resting on the non-linear elastic foundation using the generalized differential quadrature (GDQ) and the Newton–Raphson iterative methods. The material properties vary simultaneously along transverse and radial directions according to a power-law distribution of the volume fraction of the constituents. Based on higher-order shear deformation theory (HSDT) with nine degree of freedom in the displacement field and von Kármán's non-linearity, the equilibrium equations are derived using the principle of minimum total potential energy. The concept of physical neutral surface is applied to the HSDT. The elastic foundation is modeled as shear deformable with hardening/softening cubic non-linearity. Rectangular plates are also analyzed based on the HSDT by a proper change in the geometry of annular sector plates. The results of present study are compared with those available in the literature and close agreement is observed. The effects of power-law indices, thickness variation, coefficients of foundation, various boundary conditions and geometrical parameters on linear and non-linear static behaviors of circular/annular sector plates under uniform and non-uniform loading are comprehensively investigated. Predictions of the first-order shear deformation theory are also obtained and compared with those of the HSDT.

ABSTRACT: The crashworthiness testing of carbon/epoxy composite tubes is conducted in this study, and the corresponding energy-absorbing parameters and failure morphology are discussed. Considering the anisotropic constitutive relationships of composites, a stiffness degraded model that involves the extended Hashin failure criterion and damage evolution law based on the continuum damage mechanics is proposed to analyze the...
progressive failure of G803/5224 composite tubes. The progressive failure user subroutine is developed based on the transient dynamics software. The progressive failure numerical analysis combined with the failure criterion is also discussed. The relative error of specific energy absorption and average load is less than 6% compared that of the experimental results. This result indicates that the proposed method can be applied to estimate the energy-absorbing characteristics of composite tubes.

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“Non-linear transient dynamic analysis of sandwich plates with composite face-sheets embedded with shape memory alloy wires and flexible core-based on the mixed LW (layer-wise)/ESL (equivalent single layer) models”, Composites Part B: Engineering, Vol. 87, pp 59-74, February 2016,
https://doi.org/10.1016/j.compositesb.2015.10.008
ABSTRACT: In this study, a nonlinear dynamic analysis of sandwich plate with flexible core and laminated composite face sheets embedded with shape memory alloy (SMA) wires is investigated using the mixed LW/ESL models in the framework of Carrera's Unified Formulation. The instantaneous phase transformation effects are considered for every point on the face sheets. Since, this research deals with the transient nonlinear problem and the structure is thick plate with flexible core, employing a model with high accuracy and low computational cost is vital in this work. For this aim, the new mixed LW/ESL models proposed are employed in this study. The constitutive equation proposed by Brinson is used for modeling the nonlinear behavior of SMA wires. The governing equations are derived employing the Reissner Mixed Variational Theorem (RMVT) in order to satisfy the interlaminar continuity of transverse stresses between the layers. The nonlinear governing equations are solved based on the transient finite element along with the iterative incremental method. Some parametric studies such as intensity of impulsive pressure, location of SMA wires, plate aspect ratio, ratio of face sheet's thickness to the total thickness, volume fraction of the SMA wires and also boundary conditions upon the loss factor are investigated.

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ABSTRACT: In this paper, we study the free vibration characteristics of curvilinear fibre composite laminates exposed to hygrothermal environment. The formulation is based on the transverse shear deformation theory and it accounts for the lamina material properties at elevated moisture concentrations and thermal gradients. A 4-noded shear flexible quadrilateral plate element based on extended finite element approach is employed for the spatial discretization. The effect of a centrally located cut-out, modelled within the framework of the extended finite element method, is also studied. A detailed parametric investigation by varying the curvilinear fibre angles at the centre and at the edge of the laminate, the plate geometry, the geometry of the cut-out, the moisture concentration, the thermal gradient and the boundary conditions on the vibration characteristics is
numerically studied and it is hoped that this detailed study will help the designers in optimizing such structures under dynamic situations.

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ABSTRACT: Buckling behaviors of shear deformable grid-stiffened functionally graded cylindrical shells are investigated under the combined compressive and thermal loads. The governing equations are established on the basis of Reddy’s higher-order shear deformation theory. For the perfect grid-stiffened cylindrical shells, separation of variables is employed to obtain the accurate buckling solutions. Then, according to the derived mode functions, Galerkin's solving procedure is conducted for shells including the initial geometric imperfection. The effects of geometric parameters, properties of FGMs and temperature fields on the anti-buckling performances of grid-stiffened shells are concerned under the clamped boundary condition. Besides, imperfection sensitivities for various reinforced grids are discussed in detail.

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ABSTRACT: This paper presents a static analysis of functionally graded (FG) single and sandwich plates using Carrera Unified Formulation with five new displacement fields of the non-polynomial form. In particular, trigonometric, exponential and hyperbolic displacement fields are employed. The simply supported FG single and sandwich plates are subjected to a bi-sinusoidal load. The governing equations for the static bending analysis are obtained employing the Principal of Virtual Displacement (PVD) under CUF and solved using Navier type solutions. The results show that non-polynomial thickness functions are accurate although, in a few cases, the influence of some non-polynomial terms may be detrimental.

Francesco Tornabene, Nicholas Fantuzzi, Michele Bacciochi and Erasmo Viola (DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy), “Effect of agglomeration on the natural frequencies of functionally graded carbon nanotube-reinforced laminated composite doubly-curved shells”,

Composites Part B: Engineering, Vol. 89, pp 187-218, March 2016,
https://doi.org/10.1016/j.compositesb.2015.11.016
ABSTRACT: This paper aims at investigating the effect of Carbon Nanotube (CNT) agglomeration on the free vibrations of laminated composite doubly-curved shells and panels reinforced by CNTs. The great performances of doubly-curved structures are joined with the excellent mechanical properties of CNTs. Several laminations schemes and various CNT exponential distributions along the thickness of the structures are considered. Thus, it is evident that the shell dynamic behavior can be affected by many parameters which characterize the reinforcing phase. A widespread parametric study is performed in order to show the natural frequency variation. The general theoretical model for shell structures is based on the so-called Carrera Unified Formulation (CUF) which allows to consider several Higher-order Shear Deformations Theories (HSDTs). In addition, a complete characterization of the mechanical properties of CNTs is presented. The governing equations for the free vibration analysis are solved numerically by means of the well-known Generalized Differential Quadrature (GDQ) method due to its accuracy, stability and reliability features.

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“A unified solution for the vibration analysis of FGM doubly-curved shells of revolution with arbitrary boundary conditions”, Composites Part B: Engineering, Vol. 89, pp 230-252, March 2016,
https://doi.org/10.1016/j.compositesb.2015.11.015
ABSTRACT: This paper describes a unified solution for the vibration analysis of functionally graded material (FGM) doubly-curved shells of revolution with arbitrary boundary conditions. The solution is derived by means of the modified Fourier series method on the basis of the first order shear deformation shell theory considering the effects of the deepness terms. The material properties of the shells are assumed to vary continuously and smoothly along the normal direction according to general three-parameter power-law volume fraction functions. In summary, the energy functional of the shells is expressed as a function of five displacement components firstly. Then, each of the displacement components is expanded as a modified Fourier series. Finally, the solutions are obtained by using the variational operation. The convergence and accuracy of the solution are validated by comparing its results with those available in the literature. A variety of new vibration results for the circular toroidal, paraboloidal, hyperbolical, catenary, cycloidal and elliptical shells with classical and elastic boundary conditions as well as different geometric and material parameters are presented, which may serve as benchmark solution for future researches. Furthermore, the effects of the boundary conditions, shell geometric and material parameters on the frequencies are carried out.

A.H. Sofiyev (Department of Civil Engineering of Engineering Faculty of Suleyman Demirel University, Isparta 32260, Turkey), “Parametric vibration of FGM conical shells under periodic lateral pressure within the shear deformation theory”, Composites Part B: Engineering, Vol. 89, pp 282-294, March 2016,
https://doi.org/10.1016/j.compositesb.2015.11.017
ABSTRACT: In recent years, the parametric vibrations of FG shells have received more attention because of their importance in the modern aerospace industry, missile technology and mechanical engineering. The parametric vibration of shear deformable functionally graded (FG) truncated conical shells subjected to static and time dependent periodic uniform lateral pressures is studied. This study is one of the first attempts on the parametric vibration of freely supported FG truncated conical shells based on the first order shear deformation theory (FSDT). The material properties of FG truncated conical shells vary continuously through the thickness
according to a power-law distribution in terms of the volume fractions of the constituents. Initially, the governing relations and equations are derived within first order FSDT using the Donnell shell theory. To solve the governing equations is used an unknown parameter, $\lambda$, that will be determined from the minimum conditions of critical parameters for freely supported boundary conditions. Employing Galerkin's method, these partial differential equations are reduced into a Mathieu type differential equation describing the parametric vibration behavior of the FG truncated conical shells. Following Bolotin's method, the dimensionless excitation frequencies are determined. Numerical results are also presented to bring out the effects of shear stresses, volume fraction index, FG profiles, static and dynamic load factors and truncated conical shell characteristics on the instability regions. The expressions and results that obtained in current study can be used in the development stage, testing and exploitation of FG conical shells in the constructions.


ABSTRACT: The present article proposes a mixed displacements/transverse stresses approach for the free vibration analysis of laminated composite and FGM doubly-curved shells. The theoretical formulation is derived by combining Reissner's Mixed Variational Theorem (RMVT), Carrera's Unified Formulation (CUF) and the Ritz method. With the application of the RMVT the interlaminar equilibrium of the transverse normal and shear stresses is fulfilled a priori by exploiting the use of Lagrange multipliers. The transverse normal and shear stresses become primary variables within the formulation and are modelled with a Layer-Wise (LW) kinematics description. However, on the other hand, displacement variables, which describe the kinematics of the shell structures, are defined using Equivalent Single Layer (ESL), Zig-Zag (ZZ) and LW shell theories. The Mixed Hierarchical Trigonometric Ritz Formulation (MHTRF) is then used as solution technique to compute the natural frequencies of laminated composite and FGM doubly-curved shells. Several study-cases are addressed and the proposed RMVT-based shell models are assessed by comparison with both 3D elasticity and 3D Ritz solutions. The effect of significant parameters such as orthotropic ratio, stacking sequence, aspect ratio, lamination angle, length-to-thickness and radius-to-length ratios as well as volume fraction index on the dimensionless frequency parameters is discussed.

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ABSTRACT: In this paper, carbon nanotube (CNT) reinforced functionally graded rotating laminated cylindrical panels are considered, and a parametric analysis of frequency is presented using the element-free kp-Ritz method. The rotating cylindrical panel is composed of perfectly bonded CNT-reinforced functionally graded layers and, in each layer, the CNTs are assumed to be uniformly distributed or functionally graded in the
thickness direction. The extended rule of mixture is selected to obtain the effective material properties of the resulting nanocomposite rotating laminated panels. The two-dimensional displacement fields of the panels are approximated by a set of mesh-free kernel particle functions, and the discretized governing eigen-equations are developed via the Ritz procedure with the essential boundary conditions enforced through the full transformation method. Detailed parametric studies have been carried out to reveal the influences of the volume fraction of CNTs, types of distribution of CNTs, edge-to-arc ratio, boundary conditions and rotation speed on the frequency characteristics. In addition, the effects of number of layers and lamination angle are examined in detail.

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ABSTRACT: This paper presents an analytical solution procedure for the nonlinear postbuckling analysis of piezoelectric functionally graded carbon nanotubes reinforced composite (FG-CNTRC) cylindrical shells subjected to combined electro-thermal loadings, axial compression and lateral loads. The carbon nanotubes are assumed to be aligned and straight with uniform and functionally graded distributions in the thickness direction. The kinematics and constitutive relations are written on the basis of the classic theory and the von Kármán nonlinear strain–displacement relations of large deformation. Applying the Ritz energy approach, analytical solutions are proposed for the nonlinear critical axial load, lateral pressure as well as the load-shortening ratio of the piezoelectric FG-CNTRC shell. Numerical results are presented to study the effects of dimensional parameters, CNT volume fraction, distribution type of the reinforcement and piezoelectric thickness on the nonlinear buckling behavior of the piezoelectric nanocomposite shell. It is revealed that the carrying capacity of the structure increases as the shell is integrated by the piezoelectric layers and reinforced by higher CNT volume fraction. Furthermore, FGX- and FGO-CNTRC piezoelectric shells are indicated to have higher and lower carrying capacities compared to UD-CNTRC piezoelectric shells, respectively.

Tomasz Kubiak, Zbigniew Kolakowski, Jacek Swiniarski, Mariusz Urbaniak and Adrian Gliszczynski (Lodz University of Technology, Department of Strength of Materials, 1/15 Stefanowskiego St, 90-924 Lodz, Poland), “Local buckling and post-buckling of composite channel-section beams – Numerical and experimental investigations”, Composites Part B: Engineering, Vol. 91, pp 176-188, April 2016, https://doi.org/10.1016/j.compositesb.2016.01.053

ABSTRACT: Local buckling and post-buckling of thin-walled composite channel-section beams under pure bending are described. Profiles were subject to bending in the plane of the lowest second moment of area. Thin-walled beams were made of an eight-layer GFRP composite with six different arrangements of plies. An asymptotic analytical–numerical method was used in the investigations, whereas the ANSYS software based on the finite element method and the experimental test results were employed in the numerical simulations. The analytical–numerical method is based on asymptotic Koiter's theory for conservative systems, modified by Byskov and Hutchinson. Two different finite element models were prepared: the first one with boundary conditions closer to the analytical–numerical method model and the second one with boundary conditions close to those present on the test stand. A four-point bending test was used in the experimental test. The results
obtained in the above-mentioned numerical methods are compared to these obtained experimentally. The advantages and disadvantages of the applied methods and models are presented and discussed.


ABSTRACT: Carrera Unified Formulation (CUF) is used for free vibration analysis of Levy-type thick rectangular porous–cellular plates. The variation of porosity through the thickness causes mechanical properties to change along the thickness. Properties are modeled by a simple cosine rule. The equations of motion are solved analytically for Levy-type rectangular porous–cellular plates using state space method. The correctness of this approach is confirmed through comparison studies with published results based on highly accurate approaches. Different orders of model are used to enhance the accuracy of the method in order to obtain the exact frequencies of thick and very thick porous–cellular plates. The effects of the coefficient of plate porosity and the thickness–length ratio as well as the aspect ratio, on the frequencies are investigated for Levy-type boundary conditions. It is found that natural frequencies of the porous–cellular thick plates decrease as the coefficient of plate porosity increases in all studied boundary conditions.


ABSTRACT: The present paper aims to evaluate the natural frequencies of several doubly-curved shells with variable thickness. The general theoretical formulation allows to take into account various higher-order Equivalent Single Layer (ESL) theories in a unified manner, including the Murakami’s function to capture the zig-zag effect. Such approach is able to study very well the dynamic behavior of a laminated composite shell, even in the presence of a soft-core. A general expression, which is able to combine different kinds of variations (such as linear, parabolic, exponential, sine-wave, Gaussian and elliptic shapes), is introduced to define the thickness profiles. In addition, the same formulation can be employed to localize such variations and to define, consequently, ribbed structures. Since the adopted structural model is two-dimensional, the shell reference surface represents the physical domain in which the governing equations are written. Thus, the differential geometry is necessary to define accurately the doubly-curved surfaces at issue. The fundamental system is solved numerically by means of a local approach of the well-known Generalized Differential Quadrature (GDQ) method. The matrices that allow to solve the problem in hand are banded, since only a part of the discrete grid points is considered. As a consequence, the computational effort is lower, if compared to the corresponding global version. The accuracy, reliability and stability of the present approach are proved by the comparison with the results available in the literature and the solutions obtained through three-dimensional FEM models.

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ABSTRACT: Foam-filled thin-wall structures have exhibited considerable advantages in energy absorption with light weight and have been widely used as energy absorber in engineering. Unlike existing uniform or mono-gradient structures, this paper introduces a novel dual functionally graded structure with changing both foam density and wall thickness along the transverse direction, namely transverse functionally graded foam-filled and functionally graded wall thickness (FGF-FGT) structures. According to different combinations of gradient directions in foam density and wall thickness, four different patterns are considered here. Based on the established surrogate models, the surface plots of crashworthiness criteria indicate that the combination of gradient patterns and the gradient exponents have significant effect on overall crashing performances. The multiobjective particle swarm optimization (MOPSO) algorithm is then adopted to seek optimal gradients of wall thickness and foam density, aiming to simultaneously improve the specific energy absorption (SEA) and reduce the maximum force ($F_{\text{max}}$). The optimization results indicate that the transverse FGF-FGT structures with ascending grading patterns in both FGF and FGT is superior to the uniform counterparts and other graded structures, providing the designer with the promising optima in a Pareto sense.

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ABSTRACT: The major goal of this research was to obtain a closed form of the solution for critical combined loads (combined effects of the axial load and lateral pressure or the axial load and hydrostatic pressure) of functionally graded (FG) truncated conical shell in the framework of the shear deformation theory (SDT). The basic equations of FG truncated conical shell shells subjected to the combined loads are derived in the framework of the SDT. By using the Galerkin method to basic equations are obtained the expressions for critical combined loads of FG truncated conical shell in the framework of the SDT. In particular, similar expressions in the framework of the classical shell theory (CST) are obtained, also. Our numerical experiments reveal that the proposed solution may offer accurate critical combined loads for the FGM shells as compared with reference solutions available in the literature. Finally, the calculation and presentation of the effects of many parameters included in the analysis conclude the goals to be reached in the study.

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ABSTRACT: In the present paper a numerical model for predicting the crushing behaviour of semi-hexagonal E-glass/polyester composite structures has been developed. Qualitative and quantitative analysis have shown
that the results of the simulation are accurately predicted comparing with the experimental data. The peak force has been predicted with 7.5% of error while the mean force of the crushing process, the total amount of absorbed energy and the specific energy absorption capability have been simulated within 1% of error. Moreover the effect of the wall angle of the semi-hexagonal section and the effect of the overall size of the semi-hexagonal section have been numerically analyzed. The crushing process becomes stable when the wall angle is higher than 50° and the highest specific energy absorption values are obtained using the wall angle of 60° and wall length of 10 mm. Higher wall angles and wall lengths increases the stress concentration in the edges of the semi-hexagonal section and in consequence, the load carrying capability of the structure decreases dissipating less energy.

ABSTRACT: The present study deals with buckling analysis of simply supported conical panels based on the Donnell's shell theory. Different material properties have been considered such as isotropic, composite laminated and functionally graded (FG). The governing differential equation for buckling of laminated conical panel is derived. These equations are discrete using method of discrete singular convolution (DSC). Shannon's delta kernel is used for trial functions. To check the presented DSC method and computer program, the critical buckling loads for isotropic and composite conical panels are calculated which compare very well with earlier available results. The effect of some geometric parameters and material parameters on critical buckling of panels is also investigated. It is noticed that the present DSC methodology can predict accurately the buckling loads of conical panels.

ABSTRACT: The size-dependent torsional buckling behavior of functionally graded (FG) cylindrical shell is investigated on the basis of modified couple stress theory using the shell model. The material properties of FG nanoshell are considered change through thickness direction according to power law distribution. The modified couple stress shell theory with the von Karman geometrical nonlinearity is utilized to establish theoretical formulations. The governing equations and boundary conditions are derived using the minimum potential energy principle. As a special case, the torsional buckling of simply supported and clamped FG cylindrical shell is examined using the GDQ method. Afterwards, the influences of geometrical parameters, such as length scale parameter, length, and thickness, as well as material property gradient index of the FG cylindrical shell on the critical torsional buckling moment are studied.

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ABSTRACT: In present study, the buckling and crushing behavior of foam-filled glass-fiber reinforced sandwich composite column under edgewise compression were investigated by experimental, theoretical, and finite element analysis (FEA) methods. Various ratios of slenderness columns were manufactured by the vacuum assisted resin injection (VARI) process. A simple theoretical model was introduced to predict the critical collapse load taking into account the various failure modes. A user subroutine VUMAT were implemented in commercial Abaqus software based on the Hashin failure criteria. The geometrical imperfection was considered in FEA model. The experimental results revealed that the critical collapse load would be significantly reduced with the increase of slenderness, especially for the columns with the same length. Through the observing of failure morphologies and the analysis of buckling, it can be found that the first- and second-order buckling mode would play a dominant role in the crushing failure process. The FEA results simulated by present model were in good agreement with the experimental results. The results obtained in present study will be useful for the design and application of foam-filled sandwich composite.

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A. Raimondo and A. Riccio (Second University of Naples, Department of Industrial and Information Engineering, Via Roma n 29, 81031, Aversa, Italy), “Inter-laminar and intra-laminar damage evolution in composite panels with skin-stringer debonding under compression”, Composites Part B: Engineering, Vol. 94, pp 139-151, June 2016, https://doi.org/10.1016/j.compositesb.2016.03.058

ABSTRACT: In this paper, a numerical investigation on the inter-laminar and intra-laminar damage mechanisms, characterising the skin-stringer debonding growth in stiffened composite panels subjected to compressive load, has been carried out. A novel numerical methodology for inter-laminar damage growth
simulation, based on VCCT technique and able to overcome mesh and time step sensitivity issues, has been adopted in conjunction with a User Material Subroutine (USERMAT), based on Instantaneous Degradation Models (IDM), to investigate the influence of the intra-laminar damages, in terms of fibers and matrix failures, on skin-stringer debonding evolution. The proposed numerical model has been applied to two configurations of single stiffener composite panels with different geometry and debonding size. The numerical results, in terms of compressive load as a function of applied displacements and debonding evolution up to failure, have been compared to experimental data to assess the effectiveness of the implemented methodology. A further comparison with a previously developed numerical model, taking into account only the inter-laminar damage growth, has allowed assessing the influence of the intra-laminar damage on the skin-stringer debonding propagation and the benefit of the proposed integrated inter-laminar intra-laminar numerical model.

M. Mohammadimehr and M. Mostafavifar (Department of Solid Mechanics, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran), “Free vibration analysis of sandwich plate with a transversely flexible core and FG-CNTs reinforced nanocomposite face sheets subjected to magnetic field and temperature-dependent material properties using SGT”, Composites Part B: Engineering, Vol. 94, pp 253-270, June 2016, https://doi.org/10.1016/j.compositesb.2016.03.030

ABSTRACT: In this research, the free vibration analysis of a sandwich plate with a transversely flexible core and functionally graded – carbon nanotubes (FG-CNTs) reinforced nanocomposite face sheets subjected to magnetic field and temperature-dependent material properties is presented based on high-order sandwich plate theory (HSAPT). The governing equations of motion are derived using Hamilton's principle. Classical plate theory (CPT) is used for modeling the face sheets and the effective properties of them are defined based on the extended mixture rule. Mechanical properties of the core such as Young's and shear moduli are assumed to be function of temperature. The influences of aspect and side ratios, temperature changes, core-to-face sheet thickness ratio, distribution types and volume fraction of carbon nanotubes are presented. The size-dependent mathematical formulation of the face sheets is developed based on the strain gradient theory (SGT). The results show that with increasing the aspect ratio, the non-dimensional natural frequency increases, however the side ratio has a reverse effect. As the temperature of the system increasing, the non-dimensional natural frequency decreases while by applying the magnetic field, the frequency parameter increases. Also it is concluded that the sandwich plate with X distribution type of carbon nanotubes in the face sheets, has higher frequency compared with the other types. Finally it is observed that by considering the size effect and introducing the material length scale parameters, the frequency of the sandwich plate increases. Employing FG-CNTs in face sheets, magnetic field, and size dependent effect leads to increase stiffness of nanostructures, thus the use of this sandwich plate has a prominent role in modern engineering applications.


ABSTRACT: The present study is concerned with free vibration of thin-walled functionally graded (FG) open-section beams. The mechanical properties of thin-walled beam are assumed to vary smoothly through the wall thickness according to a power law distribution of volume fraction of constituent phases. Governing differential equations are derived by means of Hamilton's principle. A finite element method is developed to formulate the problem. The theory accounts for warping of cross-section and all the structural coupling coming from anisotropy of material. The natural frequencies and corresponding vibrational modes are obtained for thin-
walled FG mono-symmetric I- and channel-sections beams with several types of material distributions. A numerical comparison is carried out to show the validity of the proposed theory with available results in the literature. Furthermore, effects of gradual law and thickness ratio of ceramic on the natural frequencies of beams are also studied.

Reza Ansari and Jalal Torabi (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Numerical study on the buckling and vibration of functionally graded carbon nanotube-reinforced composite conical shells under axial loading”, Composites Part B: Engineering, Vol. 95, pp 196-208, June 2016, https://doi.org/10.1016/j.compositesb.2016.03.080

ABSTRACT: An efficient numerical method within the framework of variational formulation is employed to study the buckling and vibration of axially-compressed functionally graded carbon nanotube-reinforced composite (FG-CNTRC) conical shells. The effective material properties of functionally graded composite conical shell are estimated based on the extended rule of mixture. To derive the governing equations, the matrix form of Hamilton's principle is first presented on the basis of the first order shear deformation theory. Then, employing the generalized differential quadrature (GDQ) method in axial direction and periodic differential operators in circumferential direction, the numerical differential and integral operators are introduced to perform the discretization process. The comparison study is carried out to verify the accuracy and efficiency of the proposed method. Numerical results indicate that the volume fraction and types of distribution of CNTs have considerable effects on the buckling and vibration characteristics of FG-CNTRC conical shells subjected to axial loadings.

Shih-Yao Kuo (Department of Air Transportation Management, Aletheia University, Tainan City 721, Taiwan, ROC), “Flutter of thermally buckled angle-ply laminates with variable fiber spacing”, Composites Part B: Engineering, Vol. 95, pp 240-251, June 2016, https://doi.org/10.1016/j.compositesb.2016.04.009

ABSTRACT: This study presents the first aerothermoelastic analysis of angle-ply laminates with variable fiber spacing. Based on the Von Karman large deflection assumptions and quasi-steady supersonic aerodynamic theory, the effects of fiber distribution and temperature gradient on the thermal postbuckling, vibration, and flutter behaviors of angle-ply laminates subjected to aerodynamic force and thermal stress are discussed using the finite element method. The numerical results reveal that fiber redistribution can efficiently increase the critical buckling temperature, natural frequencies and flutter boundary. A new boundary along which the eigenvalue drops to zero is observed, and the chaotic phenomenon is eased due to temperature gradient.

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ABSTRACT: The present study deals with the nonlinear postbuckling and free vibration of third-order shear deformable rectangular nanoplate with various edge supports in the pre- and post-buckling regimes incorporating the surface effects. The Gurtin–Murdoch surface stress elasticity theory in conjunction with the third-order shear deformation plate theory is used for the size-dependent mathematical modeling of the
nanoplates. The von Kármán-type kinematic nonlinearity is used to consider the nonlinear behavior of the nanoplate subjected to the in-plane loadings. The normal stress is assumed to be changed cubically through the thickness direction of nanoplate to satisfy the equilibrium conditions between on the surfaces and bulk layers. The size-dependent coupled in-plane and out-of-plane governing differential equations of motion and corresponding boundary conditions are derived by means of an energy method based on Hamilton's principle. The generalized differential quadrature (GDQ) method and pseudo-arc length continuation are employed to obtain the postbuckling load-deflection curves of nanoplates with various edge supports. A time-dependent small disturbance around the buckled configuration is considered to analyze the free vibration of postbuckled nanoplates. The effects of thickness and surface parameters on the postbuckling path and free vibration characteristics of nanoplates in the pre- and post-buckling regimes are studied. Also, a comparison is made between the results based upon the surface stress elasticity and classical continuum theories so as to show the significance of surface effects.

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ABSTRACT: In this study, the nonlinear vibration and dynamic buckling of eccentrically stiffened functionally graded toroidal shell segments surrounded by an elastic medium in thermal environment are presented. The governing equations of motion of eccentrically stiffened functionally graded toroidal shell segments are derived based on the classical shell theory with the geometrical nonlinear in von Karman-Donnell sense and the smeared stiffeners technique. Furthermore, the dynamical characteristics of shells as natural frequencies, nonlinear frequency–amplitude relation, nonlinear dynamic responses and the nonlinear dynamic critical buckling loads evaluated by Budiansky-Roth criterion are considered. The effects of characteristics of functionally graded materials, geometrical ratios, elastic foundation, pre-loaded axial compression and temperature on the dynamical behavior of shells are investigated.

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ABSTRACT: The behavior of foam-filled core composite is vastly superior as a material in terms of its mechanical and physical properties. The present paper describes the performance of polyurethane (PU) foam as an internally-reinforced filler material on pultruded composite square cross-section tubes made of E-glass/polyester resin and subjected to axial and oblique loading. In this research study, foam-filled core composites of three different wall thicknesses and densities were examined experimentally. The capacity of a structure to absorb large amounts of energy during crush regimes is a major concern in the design of
crashworthy structures. Various loads were applied to different angle cross-head platens to assess their energy absorption capacity based on quasi-static load–displacement curves. In addition, the interaction properties of the composite and the foam core sheets during the loadings were discussed. Experimental results indicated that the crashworthy structure of the polyurethane (PU) foam-filled specimen enhanced the specific and quasi-static absorbed energies more than the empty composite tubes.


ABSTRACT: Shear buckling behavior of sandwich panels with an incompressible and a compressible core is presented. The mathematical formulation includes various formulations for layered sandwich panel such as: Ordinary Sandwich Panel Theory (OSPT), High-Order Sandwich panel Theory (HSAPT) without in-plane core rigidity and with in-plane rigidity (HSAPT-A) Theory. The various models are based on a variational approach that yields the non-linear field equations and the appropriate boundary conditions. The high-order model that takes into account the in-plane rigidity through the depth of the core, denoted as HSAPT-A, uses the accurate solution of the 3D elasticity problem involved. Linearization is achieved using a perturbation technique which yields equations for the pre-buckling and buckling stages along with the appropriate boundary conditions. A Galerkin solution type is adopted for all models and a closed-form solution through the depth of the core is used for the high-order case where the core rigidity is considered. A numerical study of a simply-supported panel with various layouts and dimensions and subjected to in-plane shear load is conducted. The results include bifurcation loads and mode shapes (3D or contour plots) of the displacements, internal stress resultants and interfacial stresses at face–core interfaces.


ABSTRACT: Transient response of rotating multi-layered FG truncated conical shells subjected to thermal shock with temperature dependent properties is studied. In order to consider the finite speed of heat propagation, the non-Fourier heat transfer equation is employed. Based on the linear theory of elasticity, the initial dynamic equilibrium equations are derived. The equations of motion of each layer around this equilibrium state and also the related boundary and compatibility conditions are obtained using Hamilton's principle. A layerwise-differential quadrature method in conjunction with the mapping technique is applied to discretize the resulting equations in the spatial domain. This converts the governing partial differential equations to a system of ordinary differential equations in the time domain. Then, to obtain solution of the resulting system of differential equations, a new general multi-step method based on the Bézier curves is implemented. Verification of the formulation and the method of solution are shown using benchmark solutions available for particular problems in the literature. Eventually, the influence of different parameters on the transient analysis of the shells subjected to thermal loading is also examined.

ABSTRACT: In this paper, thermal buckling of double-layered graphene sheets (GSs) with various boundary conditions is analyzed. The new first-order shear deformation theory (NFSDT) is reformulated using nonlocal differential constitutive relations of Eringen. Unlike the conventional first-order shear deformation (FSDT), NFSDT contains only two unknowns. It is assumed that two GSs are bonded by an internal elastic medium and surrounded by external elastic foundations. The equations of equilibrium of the nonlocal model have been derived by using the virtual displacement method. Analytical solutions for the thermal buckling of double-layered GSs under various boundary conditions are presented. The analytical expression is given for the three types of temperature distribution as uniform, linear, and nonlinear temperatures rise through the thickness of the plate. Two comparison studies are carried out to demonstrate the high accuracy of the presented nonlocal NFSDT. The influences of nonlocal parameter, plate aspect ratio, elastic foundation parameters, boundary conditions on critical buckling temperature, and critical temperature ratio are investigated.

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ABSTRACT: The sandwich structures with metallic facesheets and PVC foam cores subjected to water-based impulsive loads are investigated experimentally. The blast resistance in terms of dynamic deformation, failure modes and associated mechanisms is evaluated in relation to the effect of load intensity, core density and core height under air-backed and water-backed conditions. The plates are subjected to underwater impulsive loads of different intensities with a lab-scaled underwater explosive simulator. 3D digital imaging correlation and postmortem analysis are used to investigate the deformation and failure of individual components, focusing on the effects of loading intensities, structural properties and loaded conditions. The primary failure modes of cores transfer from core crushing and inelastic deformation to cracks and fragmentation with the increasing applied impulse and core density. The distinct trends of deflection shown by front faces and back faces are influenced by the effect of core density significantly. Unlike the air-backed condition, water-backed condition affects the damage and deflection of the sandwich structure in a different way because of the critical intensity of impulsive loads. Quantitative structure-loading-performance relation is carried out to provide guidance for structural design.


ABSTRACT: The state-space approach in conjunction with the Levy's method is used to solve exactly the free vibration problem of specially orthotropic multilayered cylindrical and spherical panels. A hierarchical
formulation is presented to build the matrices of the method from small elementary blocks which are invariant with respect to the order and typology of the kinematic shell theory. As a result, the analytical effort to derive the governing equations is minimized and a large number of Levy-type solution based on low to high order, equivalent single-layer or layerwise theories, can be generated within the same mathematical framework. Thereby, the refinement of the two-dimensional shell model can be tailored according to the thickness ratio and the degree of anisotropy of the problem under study and the desired accuracy. Some illustrative results on both thin and thick, laminated and sandwich panels with various boundary conditions are presented and discussed to show the potential of the formulation.


ABSTRACT: Hygrothermal effects on free vibration of woven fiber glass/epoxy laminated composite cylindrical shallow shells are investigated both numerically and experimentally. In the present finite element analysis a composite doubly curved shell model based on first order shear deformation theory (FSDT) is used for free vibration of cylindrical shell panels in hygrothermal environment. B&K FFT analyzer is used to determine the natural frequencies of vibration experimentally by conducting non-destructive testing. The effects of curvature ratios, lamination sequences and boundary conditions on natural frequencies of vibration under hygrothermal loading are investigated. The frequency of vibration decreases with increase of temperature and moisture.

A.H. Sofiyev (Department of Civil Engineering, Faculty of Engineering, Suleyman Demirel University, 32260 Isparta, Turkey), “Large amplitude vibration of FGM orthotropic cylindrical shells interacting with the nonlinear Winkler elastic foundation”, Composites Part B: Engineering, Vol. 98, pp 141-150, August 2016, https://doi.org/10.1016/j.compositesb.2016.05.018

ABSTRACT: The study intends to investigate the large amplitude vibration of functionally graded material (FGM) orthotropic cylindrical shells interacting with the nonlinear Winkler elastic foundation in the framework of the Donnell’s shell theory is investigated. To derivation of basic equations of FGM orthotropic cylindrical shells interacting with the nonlinear elastic foundation is used von-Karman type geometric nonlinearity. The superposition and Galerkin methods are used to convert the above equations into a nonlinear ordinary differential equation. The frequency-amplitude characteristics of functionally graded (FG) orthotropic cylindrical shell interacting with the nonlinear elastic foundation are obtained using the semi-inverse method. The accuracy of the current study is verified by comparing it other solutions available in the literature. Moreover, some new results are also presented for the nonlinear frequency parameters of the cylindrical shells to study the effects of the nonlinear elastic foundation, vibration amplitude, FG orthotropic profiles and shell characteristics.

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ABSTRACT: In this paper, the static compression and progressive crush properties of carbon fiber reinforced epoxy cross-ply laminates with different stacking sequence [(0/90)_s], and [(90/0)_s], and with different kind of 0° plies were investigated experimentally. Unidirectionally Arrayed Chopped Strand (UACS) plies with highly aligned slits of bi-angle pattern and staggered pattern were used as 0° ply, respectively, instead of conventional continuous fiber ply to study the effects of UACS ply on the compression and progressive crush responses of cross-ply laminates. Effects of stacking sequence [(0/90)_s], and [(90/0)_s], and UACS 0° plies on the compressive strength and the progressive crush properties, such as the maximum peak load, energy absorption, crush mean load, and crush force efficiency are clarified. Experimental results showed that the [(90/0)_s] laminate with UACS 0° plies of bi-angle slit pattern improves about 49% of energy absorption and the [(90/0)_s] laminate with UACS 0° plies of staggered slit pattern improves about 30% energy absorption compared to conventional cross-ply laminate.

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ABSTRACT: This paper aims to explore the failure mechanism and crashworthiness characteristics of carbon fiber reinforced plastic (CFRP) square tubes filled with aluminum honeycomb subjected to quasi-static axial crushing. The crushing characteristics between the honeycomb-filled CFRP tubes and the bare CFRP tubes were compared. The influence of the cell width of aluminum honeycomb on the failure mechanism and crashworthiness characteristics of the filled CFRP tubes was further analyzed. Three distinct failure modes, classified as stable progressive end-crushing (I), unstable local buckling (II) and collapse in the mid-length (III), were observed during the crushing tests. By comparison, the peak load and absorbed energy of the filled tubes increased by more than 10% as compared to those of the bare CFRP tubes, ranging approximately from 12.41% to 27.22% and from 10.49% to 21.83% respectively. It has been shown that the cell width was a critical parameter affecting crashworthiness characteristics. Moreover, with the decrease in the cell width, the peak load and absorbed energy increased whilst the specific energy absorption (SEA) decreased.

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ABSTRACT: A Moving Least Squares Differential Quadrature (MLSDQ) method based on Radial Basis Functions (RBFs) is employed in this paper for solving doubly-curved shells made of composite materials. DQ
method can easily approximate partial derivatives of any order by choosing proper basis functions. RBFs are functions that vary according to the radial distance from a current point and its neighborhood. The MLS method is implemented for the approximation of the shape functions used as basis functions. These shape functions depend on some weight functions that in this case are chosen as RBFs. Generally, numerical approaches based on the radial distance work very well on flat surfaces, such as plates, and on curves with constant curvature, such as spheres and cylinders, because the distance between two points can be easily measured. On the contrary, doubly-curved structures with variable radii of curvature which are defined by parametric curvilinear lines do not have a one-to-one (mutual) relationship between a curvilinear distance (defined by using curvilinear coordinates $s_1, s_2$) and the location of two points on the same surface (identified by two parameters $\alpha_1, \alpha_2$).
Therefore, this work aims to show when it is possible to apply the MLSDQ method for solving doubly-curved laminated composite structures.

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ABSTRACT: A semi-analytical approach is presented for the analysis and optimization of laminated panels with non-symmetric lay-ups, and with the possibility of introducing requirements on the buckling load, the postbuckling response and the eigenfrequencies. The design strategy relies on the combined use of semi-analytical techniques for the structural analysis and genetic algorithms for the optimization. The structural analysis is performed with a highly efficient code based on thin plate theory, where the problem is formulated in terms of Airy stress function and out of plane displacement, expanded using trigonometric series. Eigenvalue analyses are performed to determine eigenfrequencies and buckling load, while an arc-length method is adopted for the postbuckling computation. The genetic algorithm is implemented with proper alphabet cardinalities to handle different steps for the angles of orientation, while specific mutation operators are used to guarantee good reliability of the optimization. To show the potentialities of the proposed optimization toolbox, two examples are presented regarding the design of balanced non-symmetric laminates subjected to linear and nonlinear constraints. The accuracy of the semi-analytical predictions is demonstrated by comparison with finite element results and benchmark cases taken from the literature.

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ABSTRACT: Based on the three-dimensional elasticity theory, the investigation of the free vibration response of a carbon nanotube-reinforced cylindrical panel resting in elastic foundation in thermal environments is presented. The response of the elastic medium is formulated by the Winkler/Pasternak model. The cylindrical panel has been reinforced by carbon nanotube in the radial direction and the material properties are temperature dependent and estimated by the extended rule of mixture. Dynamic Young’s modulus of single-walled carbon
nanotubes can be expressed as a function of loading rate and environmental temperature. Differential quadrature method is being utilized and natural frequencies of cylindrical panel are obtained. An accuracy of the present solution is confirmed by comparing with some available results in the article. A detailed numerical study is conducted to examine the effects of temperature rise, carbon nanotube volume fraction, elastic foundations and the geometrical parameters on the deflection of the cylindrical panels.

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ABSTRACT: This paper investigates the nonlinear dynamic buckling response of axisymmetric carbon nanotubes reinforced composite sandwich spherical caps subjected to suddenly applied pressure. To solve this problem, a finite element approach is adopted using an axisymmetric shear flexible shell element, free from spurious constraints causing shear and membrane locking especially for the case of thin shells. The geometric nonlinearity is accounted for in the formulation using von Karman’s strain-displacement relations. Newmark’s integration technique along with the modified Newton-Raphson iteration scheme is employed to solve the nonlinear governing equations. The critical dynamic pressure value is considered as the pressure load beyond which the maximum average displacement response shows instant growth in the time history of the shell structure. The obtained results are validated against the available analytical solutions for the case of isotropic spherical caps. A detailed parametric study is carried out to bring out the effects of shell geometry parameter, volume fraction of the CNT, core-to-face sheet thickness, temperature, boundary conditions and different types of pulse on the dynamic snap-through characteristics of spherical shells.

ABSTRACT: In this comparative study to estimate the values of critical buckling temperatures of carbon nanotubes, modelled as Timoshenko beam, two new nonlocal elasticity models based on Trefftz and Kounadis approaches are addressed. The previous results obtained from literature are compared with those obtained from two new models under simple boundary conditions. The comparative results reveal that the differences between critical buckling temperatures obtained from three nonlocal elasticity models is more pronounced, especially at the high modes and for the short nanotubes.

A. Rabiee and H. Ghasemnejad (Centre for Structures, Assembly and Intelligent Automation, Cranfield University, MK43 0AL, UK), “Effect of multi-stitched locations on high speed crushing of composite tubular
ABSTRACT: The present paper experimentally investigates progressive energy absorption of fibre-reinforced polymer (FRP) composite tubular structures under high speed loading conditions. Various multi stitched locations are studied to find a correlation between single and multi-locations of stitches and energy absorption capabilities of composite absorbers. The through-thickness reinforcements are applied into locations of 10 mm, 20 mm, 30 mm, 10–20 m, 10–30 mm, 10–20–30 mm and 10–15–20–25–30–35 mm from top of the tubes. It is shown that multi-stitched location can cause several increase of crushing load and consequently increase of energy absorption of composite tube absorbers. The idea would be expanded to other designs which are followed by increase of stitched locations and reduction of the distance between stitches to improve the mean force with a smooth and progressive pattern of crushing load.

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“Effects of multiple delaminations on the compressive, tensile, flexural, and buckling behaviour of E-glass/epoxy composites”, Composites Part B: Engineering, Vol. 100, pp 186-196, September 2016,
https://doi.org/10.1016/j.compositesb.2016.06.069
ABSTRACT: The goal of this study is to investigate the effect of multiple delaminations on the compressive, tensile and flexural strength of E-glass/epoxy composites and to evaluate their effects on the first critical buckling and re-buckling loads. Artificial delaminations of different sizes were inserted into four interlayers of [45°/0°/−45°/90°]s oriented E-glass/epoxy composite using a hand lay-up method and a hot press. The effects of through-the-width strip, circular and peanut shaped delaminations and triangle and inverted triangle patterned delaminations through the thickness direction were investigated experimentally. According to the results, the presence of multiple large delaminations influences the compressive and flexural strength and critical buckling load significantly. However, tensile strength is less affected by multiple delamination.

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“Vibration analysis of the embedded piezoelectric polymeric nano-composite panels in the elastic substrate”, Composites Part B: Engineering, Vol. 101, pp 64-76, September 2016,
https://doi.org/10.1016/j.compositesb.2016.06.077
ABSTRACT: In the present study the vibrations of a smart thin micro panel of polymeric nano-composite reinforced by the Single-Walled Boron-Nitride Nano-Tubes (SWBNNTs) and the matrix Poly-Vinylidene Fluoride (PVDF) on an elastic substrate is studied. Using the micromechanics method, the nano-composite structural equations are obtained for a sample volume element and by considering a unidirectional electric field and stress in the field. The stress-strain relationships that include mechanical and electric terms are obtained for the micro-tubes. The micro-panel is considered as the thin wall shell and Donnell’s non-linear theory is used for the strain-displacement relations. To obtain the equations of motion, the minimum energy method or Hamilton’s principle is used. The external work is caused by the elastic environment as well as the magnetic field energies. Given that the work has been in small micro scale the strain gradient, modified coupled stress and classic
Theories are used to consider the small-scale effect in the equations. The results showed stiffness of the panel is reduced by increasing length and reducing volume fraction of BNNT and lower frequencies are obtained. Angling nanotubes is reduced panel frequency and the severity of this reduction is increased at higher volume percentages. The maximum frequency is happened in the full cylinder sector.


ABSTRACT: The fibre-reinforced epoxy composite materials, thanks to their high specific strength, have found many applications in the last decades, especially in the transportation field. However, even though this great advantage allows having a lightweight and strong structure, their application is limited by many critical aspects. Some of these depend on the fact that the composite materials are prone to a large range of defects and damages if subjected to some types of loads. Such defects and damages can be very critical for composites structures, because they may be invisible and cause a significant decrease of the residual strength. In these circumstances, if a structure is not designed under a damage tolerance philosophy it might fail under an unexpected load value, also because the presence of defects can promote the arising of unexpected instability phenomena, as for example buckling under compressive loads. For this reason, one of the most critical aspects to consider during a design process is the structural behaviour of a component under compression load. In fact, fibre and matrix failures and delaminations could reduce the residual strength of a structural component and decrease the buckling load limit. So, defects and damages which could be due either to a critical phenomenon that has previously affected the structure, such as a Low Velocity Impact (LVI), or due to voids and defects caused by manufacturing and production processes, have to be taken into account during the design process. In particular, among different defects and damages, which can affect a composite material, both delamination and fibre failures are the most dangerous. In order to assess the residual strength of damaged composite structures, compression tests are usually performed on such structures. For example, compressive tests are experimentally carried out on damaged structural components, which have been affected to an LVI in a previous phase. With the aim of studying and better understanding the structural behaviour of composites panel under compressive loads, some experimental tests and the respective numerical simulations, based on finite elements theory, have been performed and presented in the paper. The compressive test is numerically reproduced by using the finite element code Abaqus, which, thanks to its implemented algorithms, has allowed considering different failure modes. Moreover, the progressive damage of fibre reinforced composites has been modelled by using Hashin's criteria which allowed considering two different laws for damage initiation and propagation. In particular, the paper deals with structural behaviour of both undamaged and damaged aircraft panels, with omega stiffeners, made of fibre-reinforced composite materials subjected to static compression tests. A comparison between the structural behaviours of both types of panels has been performed and presented in the paper. Moreover, with numerical model validation purpose, also a correlation between numerical and experimental results has been performed and shown in the paper.

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“Winkler-Pasternak foundation effect on the frequency parameter of FGM truncated conical shells in the framework of shear deformation theory”, Composites Part B: Engineering, Vol. 104, pp 57-70, November 2016,
ABSTRACT: This work focuses on the vibration behavior of functionally graded (FG) truncated conical shells interacting with the Winkler–Pasternak elastic foundation in the framework of the first-order shear deformation theory (FOSDT). The eigenvalue problem is solved by using Galerkin method. The formulas of the frequencies of FGM truncated cones resting on elastic foundations in the framework of FOSDT are found. Finally, the combined effects of shear strains, material gradient and elastic foundations on the non-dimensional frequency parameters of conical shells with various geometric characteristics in the framework of FOSDT are studied.

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“Experimental study on the dynamic response of foam-filled corrugated core sandwich panels subjected to air blast loading”, Composites Part B: Engineering, Vol. 105, pp 67-81, November 2016,
https://doi.org/10.1016/j.compositesb.2016.08.038
ABSTRACT: Effective approaches to enhance the blast resistance of sandwich structures with corrugated cores were developed by adopting three different strategies to fill the spaces within cores with polymeric foam. The baseline unfilled panels and foam-filled panels were designed and fabricated, and finally subjected to air blast loading generated by detonating cylindrical explosive. Deformation modes and failure mechanisms of tested panels were investigated. Experimental results demonstrated that the panels with back side filling strategy did not show better blast performance compared with the unfilled panels, even though extra weight was expended due to the addition of foam fillers. The panels with front side filling and fully filling strategies encouragingly appeared to possess desirable blast resistance to prevent severe fracture under high intensity blast loading. This benefit should be attributed to the sufficient crushing deformation of foam fillers and the enhanced buckling resistance of core webs. In addition, a preliminary study has been conducted to investigate the effects of front face thickness on the blast performance of foam-filled panel. Attempts of allocating component mass and filling different material have been made to explore the potential of performance improvement.

ABSTRACT: Shear buckling response of carbon nanotube reinforced composite (CNTRC) rectangular plates in thermal environment is investigated in this research. Distribution of CNTs across the plate thickness may be uniform or graded via a mid-plane symmetric pattern. Properties of the CNTRC plate are obtained using the modified rule of mixtures approach by introduction of efficiency parameters. First order plate theory is adopted to construct the basic equations of the plate. A two-dimensional Ritz formulation with Chebyshev basis polynomials is implemented to obtain the elastic and geometric stiffness matrices of the plate. The proposed solution method may be used for arbitrary in-plane and out-of-plane edge supports. After performing convergence and comparison studies to show the effectiveness and accuracy of the proposed method, parametric studies are conducted to examine the influences of boundary conditions, volume fraction of CNTs, graded pattern of CNTs, thermal environment and plate geometry. It is shown that, shear buckling capacity of
the plate may be enhanced through functionally graded distribution of CNTs. Besides, enrichment of matrix with CNTs enhances the shear buckling loads of FG-CNTRC plates.

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ABSTRACT: The present computational study investigates on stochastic natural frequency analyses of laminated composite curved panels with cutout based on support vector regression (SVR) model. The SVR based uncertainty quantification (UQ) algorithm in conjunction with Latin hypercube sampling is developed to achieve computational efficiency. The convergence of the present algorithm for laminated composite curved panels with cutout is validated with original finite element (FE) analysis along with traditional Monte Carlo simulation (MCS). The variations of input parameters (both individual and combined cases) are studied to portray their relative effect on the output quantity of interest. The performance of the SVR based uncertainty quantification is found to be satisfactory in the domain of input variables in dealing low and high dimensional spaces. The layer-wise variability of geometric and material properties are included considering the effect of twist angle, cutout sizes and geometries (such as cylindrical, spherical, hyperbolic paraboloid and plate). The sensitivities of input parameters in terms of coefficient of variation are enumerated to project the relative importance of different random inputs on natural frequencies. Subsequently, the noise induced effects on SVR based computational algorithm are presented to map the inevitable variability in practical field of applications.

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ABSTRACT: An innovative sandwich structure with auxetic re-entrant cell honeycomb cores was proposed in this paper, and the dynamic responses and blast resistance of the honeycomb sandwich structures under blast loading were investigated numerically by employing the LS-DYNA. The honeycomb structures with thicker walls have a higher plateau force and specific energy absorption (SEA) under the compression loading. Deformation modes and deflections distribution along the axis direction caused by plastic stretching and bending were investigated in detail to have a better understanding of the deformation mechanism. Results show that the sandwich structures have a higher ability of resisting deformation along the longitudinal(Y)-direction than the transverse(X)-direction. In addition, the dynamic responses of honeycomb sandwich structures with different stand-off distances, graded cores and arranged orientations were studied. Results show that both the graded honeycomb cores and cross-arranged honeycomb cores can significantly improve the resistance ability of the sandwich structures under blast loading, compared with the ungraded honeycomb cores and regular-
arranged cores. Comprehensively, the cross-arranged graded honeycomb cores with higher density of the upper layer performs the best under the blast loading compared with the other configurations, taking the effects of graded cores and arranged orientations into consideration. This work provides a reliable basis to design the sandwich structures with auxetic re-entrant cell honeycomb cores under compression and blast loading.

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ABSTRACT: As a first endeavor, the vibration behavior of functionally graded carbon nanotubes reinforced composite (FG-CNTRC) truncated conical panels is studied. Panels with the elastically restrained against rotation edges under thermal environment are analyzed. The governing equations are derived based on the first-order shear deformation theory (FSDT) of shells, and are solved using the differential quadrature method (DQM). In addition to the temperature dependence of material properties, the influences of initial thermal stresses are considered. After validating the present approach, the effects of the carbon nanotubes (CNTs) distribution in thickness direction, the geometrical parameters, the elastic coefficients of the edge restraints, the temperature rise, and the initial thermal stresses on the frequency parameters are investigated. It is shown that the initial thermal stresses have significant effects on the natural frequencies and cannot be neglected. The results prove that the panels with (FG-X) and (FG-O) CNTs distributions have the largest and the smallest natural frequencies, respectively. Moreover, the critical buckling temperature rise of the panels can be extracted from the presented diagrams of the fundamental frequency parameters versus the temperature rise.

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ABSTRACT: Static and vibration analysis of isotropic and functionally graded sandwich plates using a higher-order shear deformation theory is presented in this paper. Lagrangian functional is used to derive the equations of motion. The mixed interpolation of tensorial components (MITC) approach and edge-based-strain technique is used to solve problems. A MITC3 three-node triangle element with 7 degree-of-freedoms per nodes that only requires the $C^0$-type continuity is developed. Numerical results for isotropic and functionally graded sandwich plates with different boundary conditions are proposed to validate the developed theory and to investigate
effects of material distribution, side-to-thickness ratio, thickness ratio of layers and boundary conditions on the deflection, stresses and natural frequencies of the plates.

Stanislaw Burzynski, Jacek Chroscielewski, Karol Daszkiewicz and Wojciech Witkowski (Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Department of Mechanics of Materials, 80-233 Gdańsk, Gabriela Narutowicza 11/12, Poland), “Geometrically nonlinear FEM analysis of FGM shells based on neutral physical surface approach in 6-parameter shell theory”, Composites Part B: Engineering, Vol. 107, pp 203-213, December 2015, https://doi.org/10.1016/j.compositesb.2016.09.015

ABSTRACT: The paper presents the formulation of the elastic constitutive law for functionally graded materials (FGM) on the grounds of nonlinear 6-parameter shell theory with the 6th parameter being the drilling degree of freedom. The material law is derived by through-the-thickness integration of the Cosserat plane stress equations. The constitutive equations are formulated with respect to the neutral physical surface. The influence of the power-law exponent, micropolar characteristic length is evaluated in geometrically nonlinear FEM analyses. The results obtained with the neutral physical surface approach are compared with those computed with the middle surface approach. The influence of choice of the reference surface is observed especially in nonlinear stability analysis.


ABSTRACT: This work presents a novel design, additive manufacturing and modeling approach of three dimensional voronoi-based composite structures that closely mimics nacre’s multilayer composite. Hierarchical structure of natural nacre is mimicked to produce multilayer composite laminates assembled from three dimensional polygonal tablets bonded with organic adhesives. Furthermore, various complex geometries of the nacreous shells observed from the nature, such as the dome-shaped structure, are developed into three dimensional mimicked designs. A novel mapping algorithm is developed to design complex structures of nacre-like composites readily to be fabricated by the unique dual-material 3D printing technology. Preliminary 3D-printed prototypes with complex shapes and material combinations are presented. A novel numerical model of nacreous composite is proposed including the tablet cohesive bonds and interlaminates adhesive layers to mimic the soft organic polymer matrix. The nacreous model is validated against the natural nacre platelet under uniaxial loading. To exemplify a potential application, a scaled model of nacre-mimetic composite made of Aluminum tablets and Vinylester adhesive are constructed and assessed against blast-induced impulsive loading. Performances of nacre-like composite panels are investigated in terms of deformation and energy dissipation.

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ABSTRACT: This paper presents a performance-based comparison of quadratic shell elements with shear deformation and 3-D quadratic solid elements for modeling geometrically non-linear coupled in-plane and out-of-plane deflection of thin-film compliant microelectromechanical systems. A mesh density study of a single out-of-plane torsional compliant element indicates that a relatively coarse shell element mesh can produce force, displacement, and stress results very similar to those predicted by a much larger and computationally costly 3-D solid element model for out-of-plane loading. Shell and 3-D solid element models of a macro-scale prototype of a MEMS compliant lamina emergent constant-force mechanism are shown to agree very well with experientially acquired force displacement data, and to agree well in their estimates of Von Mises stresses. Close agreement of shell element and 3-D solid element models is also demonstrated for models of a thin-film MEMS constant-force mechanism and a thin-film MEMS cellular lance mechanism. Both of these mechanisms exhibit highly non-linear mechanism stiffness, and large, coupled in and out-of-plane displacements. Together, these results strongly suggest that quadratic shell elements with shear deformation can be used to model the coupled in-plane and out-of-plane motion of thin-film compliant mechanisms.

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ABSTRACT: A finite element formulation is derived for the structural analysis of functionally graded hollow cylinders. The power-law distribution model is used for the composition of the constituent material in the thickness direction. According to property variation in FG cylinders, it is difficult to analyze them using the conventional element formulation. In order to facilitate the process of modeling and analyzing the FG cylinders, the finite element formulation is based on a newly designed cylindrical element. The new cylindrical element allows for property variations along the thickness, which results in considerable reduction of the required elements and eliminates the need to mesh the cross section of the FG cylinder. In this study static as well as modal analysis of FG cylinders are performed and the deformations and natural frequencies are compared with those obtained from conventional elements and previous studies. The results indicate high accuracy and good agreement with previous studies and conventional FEM.

S.C. Pradhan (Department of Aerospace Engineering, Indian Institute of Technology, Kharagpur, West Bengal 721 302, India), “Nonlocal finite element analysis and small scale effects of CNTs with Timoshenko beam

ABSTRACT: In the present work, finite element formulations for nonlocal elastic Euler–Bernoulli beam theory and Timoshenko beam theory have been reported. Nonlocal differential elasticity theory is considered. Galerkin finite element technique has been employed. For CNTs, weak forms of governing equations are derived and energy functionals are obtained. With present finite element analysis bending, buckling and vibration for nonlocal beams with clamped–clamped, hinged–hinged, clamped–hinged and clamped–free (C–C, S–S, C–S and C–F, respectively) boundary conditions are computed. These results are in good agreement with those reported in the literature. Further, bending, buckling and vibration analyses are extended to tapered beams. Present formulation will be useful for structural analyses of nanostructures with complex geometries, material properties, loadings and boundary conditions.


ABSTRACT: In recent years, solid-shell elements with the absence of the rotational degrees of freedom have considerable attentions in analyzing thin structures. In this paper, the non-linear formulation of a co-rotational 8-node degenerated thin-walled element with no rotational degrees of freedom is presented to demonstrate the solutions of linear and geometrically non-linear analysis for plate and shell structures. The assumed natural strain (ANS) and enhanced assumed strain (EAS) are used to overcome various locking problems, while the co-rotational formulation is employed to remove rigid body rotations for solving geometrically non-linear problems. In addition, the element formulation here uses plane stress condition in order to fit to thin-walled and shell applications, and the global, local and natural coordinate systems are employed to conveniently model the thin-walled geometry. Several numerical examples are presented to demonstrate the performance of the present element and the results are in good agreement with the references.

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ABSTRACT: A generalized multi-objective optimization method making use of genetic algorithm (GA) is introduced, in order to simultaneously improve the riding comfort and the durability of run-flat tire by optimally tailoring the shape and stiffness of the sidewall insert rubber. The sensitivity analysis invoking the CPU time-consuming finite element analyses is replaced with the genetic evolution and the fitness of each genome in the population is evaluated by utilizing the response surfaces of objective functions approximated by ANN. It is confirmed through the numerical experiment that a number of Pareto solutions of the shape and stiffness of the sidewall insert rubber for different combinations of weighting factors can be successfully obtained. As well, the reliability of the Pareto solutions has been justified from the comparison with the direct finite element analysis.

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ABSTRACT: A super-convergent finite element is developed for the steady state analysis of circular cylinders under general harmonic forces based on thin shell theory. Simplifying assumptions in previous thin-shell formulations for straight cylinders are avoided. The resulting model is capable of capturing general in-plane and out-of-plane cross sectional distortions including ovalization, warping, radial extensibility, etc. A series of shape functions are then developed based on the exact solution of the field equations and used to formulate a cylindrical finite element capable of capturing thin shell behaviour with very few degrees of freedom. Through examples, the element is shown to efficiently model cylinders subject to in-phase and out-of-phase harmonic loading and support excitation.


ABSTRACT: This paper presents the effect of rotational speeds on free vibration characteristics of delaminated twisted graphite–epoxy cross-ply composite conical shells employing finite element method. Theoretical formulation is based on Mindlin's theory considering an eight noded isoparametric plate bending element. A generalized dynamic equilibrium equation is derived from Lagrange's equation of motion neglecting the Coriolis effect for moderate rotational speeds. The multi-point constraint algorithm is utilized to ensure the compatibility of deformation and equilibrium of resultant forces and moments at the delamination crack front. The QR iteration algorithm is used for solution of standard eigenvalue problem. Finite element codes are developed to obtain the numerical results concerning the combined effects of twist angle and rotational speed on the natural frequencies of cross-ply composite shallow conical shells. The mode shapes for a typical laminate configuration are also depicted. Numerical results obtained for cross-ply laminates with delamination are the first known non-dimensional frequencies for the type of analyses carried out here.

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ABSTRACT: In this paper, the bending and the free flexural vibration behaviour of sandwich functionally graded material (FGM) plates are investigated using QUAD-8 shear flexible element developed based on higher order structural theory. This theory accounts for the realistic variation of the displacements through the thickness. The governing equations obtained here are solved for static analysis considering two types of sandwich FGM plates, viz., homogeneous face sheets with FGM core and FGM face sheets with homogeneous hard core. The in-plane and rotary inertia terms are considered for vibration studies. The accuracy of the present formulation is tested considering the problems for which three-dimensional elasticity solutions are available. A
A detailed numerical study is carried out based on various higher-order models to examine the influence of the gradient index and the plate aspect ratio on the global/local response of different sandwich FGM plates.

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ABSTRACT: The purpose of this paper is to show a practical implementation of a genetic algorithm for minimizing membrane stresses discrepancies between the actual assembled equilibrium and the specified design state. The method prevents the surface wrinkle problems in membrane structures under service loading and determines an optimum cutting pattern, which accounts for the designed stresses of the membrane structures. Using the displacements of the 3-D surface as the key variables, the proposed method utilizes a geometrically nonlinear finite element analysis based upon the improved stress-adapted numerical form finding of prestressed surfaces by the updated reference strategy. The model of genetic algorithm and the genetic operators are then designed to solve numerically the optimization problem. The method is validated through examples and compared with the available data. The analysis results show no significant differences between the assumed designed stresses and the actual stresses in the membrane.

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“On the modeling and design of composite multilayered structures using solid-shell finite element model”, Finite Elements in Analysis and Design, Vols. 70-71, pp 1-14, August-September 2013,
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ABSTRACT: In this investigation a coupling between a 3D solid-shell element for the analysis of multilayered composite shell structures and a specific response surface method is proposed. The first part of the paper is dedicated to the finite element formulation of a developed composite 8-node solid-shell element called SCH8gamma7, based only on translational degrees of freedom. The basis of the present finite element formulation is the standard 8-node brick element with trilinear shape functions. A particular attention is given to alleviate shear, trapezoidal and thickness locking, without resorting to the classical plane-stress assumption. Assumed natural strain method and enhanced assumed strain method are used to improve the relative poor element behavior of a standard hexahedral displacement element. The anisotropic material behavior of layered shells is modeled using a fully three dimensional elastic orthotropic material law in each layer, including the thickness stress component. The second part of the paper will focus on an adaptive response surface method for the structural optimization problem. The response surfaces are built using moving least squares approximations and design of experiments by means of a specific method called Diffuse Approximation. Several numerical applications to composite multilayered shell structures are studied to show the applicability and effectiveness of the proposed procedure. Good results of analysis and optimization using the developed SCH8gamma7 solid-shell element have been obtained in comparison with reference analytical solutions and with those obtained using the SC8R solid-shell finite element available in ABAQUS code.
ABSTRACT: Aeroelastic flutter is a dangerous failure mode, and aircraft structural components are designed under a deterministic flutter margin. Meeting this safety factor may result in overly-conservative structures, however, an alternative approach incorporates uncertainties into the computational models, and imposes a maximum allowable flutter probability during the optimization process. This technique is demonstrated for the variable-thickness design of an elastic panel subjected to supersonic flow. A performance measure approach based on the first-order reliability method incorporates probabilistic flutter constraints during the search for a minimum-mass panel. Optimization results are given for uncertainties in the panel's boundary conditions, and for non-deterministic thickness design variables.

ABSTRACT: In this paper we use a numerical procedure to analyse bifurcation and postbifurcation of inflated hyperelastic thick-walled cylinders based on the modified Riks method. In particular, the bulging mode of bifurcation is exploited in the context of aneurysm formation with cylindrical geometry in cardiovascular diseases. We focus here on orthotropic materials with two preferred directions which are mechanically equivalent and are symmetrically disposed. Arterial wall tissue is modeled with this class of constitutive equation showing significant stiffening behaviour. The onset of bulging is considered to give aneurysm formation. Analytical solutions can be found in the literature for very particular conditions involving specific material models and loads applied as well as, usually, a perfect geometry. Here, we provide a unified approach to both the prediction of bifurcation and postbifurcation propagation that can be applied to more general conditions. Furthermore, we show that bulging instability under the conditions at hand propagates axially in agreement with the propagation of aneurysms in arterial wall tissue.

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ABSTRACT: Many problems in structural mechanics involve complex principal stress fields that are not orthogonal to the geometric axis of the structure. Such problems are often analysed with finite elements, but the quality of a finite element solution may be sensitive to the orientation of the mesh with respect to the principal axes of stress. This paper presents the outline of a procedure to generate well-structured inclined quadrilateral finite element meshes for the analysis of thin plate and shell structures. The procedure was developed using the commercial FE pre-processor ABAQUS CAE and the Python script language, though it may readily be applied in any pre-processor which supports an external scripting functionality. A set of mesh convergence studies
using linear buckling analyses are presented on four benchmark problems with known analytical solutions to illustrate the effect of inclined meshes on the accuracy of the computed solution. These illustrations are intended to raise an awareness of the subtle but important relationship between mesh and stress field orientation and are presented for the benefit of practising finite element analysts in structural engineering.

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ABSTRACT: We address in this paper an isogeometric finite element approach (IGA) in combination with the third-order deformation plate theory (TSDT) for thermal buckling analysis of functionally graded material (FGM) plates. TSDT accounts shear deformation effect without requiring any shear correction factors. The IGA utilizes non-uniform rational B-spline (NURBS) as basis functions, resulting in both exact geometric representation and high order approximations. It enables to achieve easily the smoothness with arbitrary continuous order. The present method hence fulfills the $C^1$-requirement of TSDT model. The material properties of FGM plates are assumed to vary according to power law distribution of the volume fraction of constituents. The temperature field through the plate thickness is described by a polynomial series. The influences of length to thickness ratio, aspect ratio, boundary conditions and material property on the temperature critical buckling are investigated. Numerical results of circular and rectangular plates are provided to validate the effectiveness of the proposed method.

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ABSTRACT: In the present paper, a three-dimensional elasticity approach is employed to investigate buckling of heterogeneous functionally graded plates under biaxial compression, shear, tension-compression, and shear-compression load conditions. In this regard, a formulation that employs a full compatible three-dimensional Hermitian element with 168 degrees of freedom and guarantees continuity of the strain and stress components is used. It is known that all of the available famous commercial finite element softwares and the proposed series solutions satisfy continuity conditions of the displacement rather than the stress components. Buckling occurrence is detected based on checking both the instability onset and equilibrium criteria. Results are extracted based on a Galerkin-type orthogonality. Therefore, they are more accurate than those obtained based on the traditional Ritz method. The presented three-dimensional finite element analysis and the extracted results are quite new. A vast variety of results including results of biaxial compression, compression-tension, shear, and shear-compression load cases is considered and discussed in detail.

ABSTRACT: A continuum finite element model for the nanoscale plates considering the surface effect of the material is developed. Governing equations for Kirchoff and Mindlin nanoplates are derived by using the Galerkin finite element technique. The model is verified by comparing the results with available analytical solutions. The results indicate that, depending on the boundary conditions, the deflections and frequencies of the plate have a dramatic dependence on the residual surface stress and surface elasticity of the plates. The present model is an efficient tool for the analysis of the static and dynamic mechanical behaviors of nanoscale plates with complex geometry, boundary and loading conditions and material properties.


ABSTRACT: A robust reduced integration solid-shell finite element in irreducible variational formulation is demonstrated in this paper. To enable shell element-like performance using a single through-shell-thickness element layer, we apply element technologies isotropically, introducing local tri-quadratic hierarchical displacement modes thereafter systematically projected to the global coordinate frame. We also enforce uniform, bilinear and linear ANS interpolations to all local normal and shear strains respectively, imposing identical in-plane and out-of-plane element response for robust 3D thin shell deformation behaviour in non-regular, trapezoidal-shaped meshes. The hierarchical strains realised improve the element performance by complementing the locking alleviating actions of the ANS-modified membrane and shear strain fields in reduced numerical integration scheme performed along the designated shell thickness. We restrict our initial numerical investigations to geometrically linear beams, plates and shell problems solely for preliminary assessment of the element's in-plane and out-of-plane behaviour in response to the uniform modification of strains and hierarchical displacement modes introduced. To this end, the results indicate robust behaviour and comparable accuracy in comparison to mixed variational, enhanced assumed strain elements in full and in reduced integration in all structural problem classes undertaken.

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ABSTRACT: In this paper, the effect of initial geometric imperfections on the buckling load of steel tubes (relatively thick cylindrical shells) under axial load and lateral pressure is investigated. The geometric imperfections are modeled as a 2D-1V non-homogeneous Gaussian stochastic field simulated using the spectral representation method. The evolutionary power spectrum of the non-homogeneous field is derived from available experimental measurements using the recently proposed method of separation. For the determination of the limit load variability of the tubes, a stochastic formulation based on Monte Carlo simulation is
implemented. It is shown that the imperfections can lead to a substantial reduction of the buckling load and thus should be taken into account via a realistic description through stochastic field modeling.


ABSTRACT: A computationally efficient C0 finite element model is developed for laminated composite and sandwich plates by implementing the inverse hyperbolic shear deformation theory recently developed by the authors. This model is used to determine responses of general laminates subjected to various combinations of boundary conditions. The present formulation has been generalized for all existing shear deformation theories involving shear strain function. An eight noded serendipity element with 56 degrees of freedom is used to discretize the plate domain. Influences of lamination sequence (cross ply and angle ply), span to thickness ratio, and boundary conditions are investigated for the flexural behavior of laminated composite and sandwich plates. Further, the stability behavior of plates subjected to in-plane loads (uni-axial and bi-axial) is investigated for a variety of examples. Effects of boundary conditions and applied loads on the critical buckling loads and buckling mode shapes are also assessed for a class of laminates in order to show the efficacy of the present mathematical technique to predict the buckling mode shapes.

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ABSTRACT: This paper presents a synthesis approach to address the problem of uncertainty in the impact force identification. The effects of material uncertainty on dynamic responses of the structure are studied by using Monte Carlo simulation. Six parameters, including mechanical properties and thermal coefficients, are considered as independent random variables. A parametric study is conducted to select four parameters as the optimization variables in the following step of model updating. The technique of model updating is used to correct the modeling errors caused by material uncertainty. Then, an improved inverse analysis technique based on the finite element method and mode superposition method is taken for impact force identification. In this study, the present method is performed on a composite stiffened panel, and the effect of noise on the performance of identification is also discussed. The results of the study show that the developed approach is capable of identifying the impact location and reconstructing the force history accurately by reducing material uncertainty through the modal updating procedure.

ABSTRACT: A hybrid finite element formulation is developed by using the Hellinger–Reissner functional which is obtained from the complementary energy functional for pre-buckling and buckling analysis of thin-walled beams by introducing element equilibrium and force boundary conditions as auxiliary conditions. Comparison to the complementary energy based formulation the current hybrid formulation is advantageous because it does not require the satisfaction of inter-element force equilibrium a-priori and therefore it is easily adaptable within the existing displacement-based thin-walled beam finite-element analysis codes for which the assemblage procedure is relatively easy. Comparison to the displacement-based formulations the current hybrid formulation has the advantage of incorporating the shear deformation effects easily by using the strain energy of the shear stress field without modifying the basic kinematic assumptions of the thin-walled beam theory. In the current formulation, the effects of load position can also be easily captured by virtue of the freedom provided in the beam axis selection. Comparisons with solutions from literature and those based on shell element models are presented and an example is designated to illustrate the significance of shear deformation effect.

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ABSTRACT: An element has been developed for the analysis of laminated composite plates. The element is capable of representing high orders of displacement using very few degrees of freedom. The respective orders of deflection, rotation, moment and shear have been preserved through scrupulous choice of field variables. The element is found to have a correct rank and is free from shear locking. Performance of the element has been tested in a wide range of problems which indicate that combining all these features can help to achieve great accuracy at reduced computation cost.

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ABSTRACT: Sandwich panels designed to resist blasts and high-velocity impacts usually dissipate most of the delivered energy through inelastic deformation of solids. A concept is explored in this study to improve the energy absorption of such structures by the addition of a viscous mechanism. The mechanism relies on the fact that when a viscous liquid is forced through narrow passages at high speeds, it undergoes high shear rates that cause viscous energy dissipation. A simple test specimen in the form of a steel tube with capillaries attached at both ends was chosen for study. Both empty and liquid-filled test specimens were subjected to experimental and simulated drop-weight impact tests and simulated blast load tests. Fluid structure interaction analyses in the form of Coupled-Eulerian–Lagrangian simulations were performed to assess the energy dissipated both by solid plastic deformation and liquid viscous dissipation in the drop-weight and blast simulations. The liquid flow
speeds generated by the applied loads were found to be a critical factor in determining the contribution of the viscous mechanism. The moderate liquid flow speeds generated by the drop-weight impacts resulted in negligible viscous energy dissipation. The simulated blast loads generated much higher liquid flow speeds and as a result the viscous energy contribution to the total absorbed energy in the test specimens approached 30%. The viscosity of the liquid has a major effect on the fraction of energy absorbed in the form of viscous dissipation. Results of this study support the viability of the concept of viscous-assist for improving the ability of protective panels and structures to withstand high-speed impact and blast loads.

ABSTRACT: The post-buckling analysis of laminated plates under combined shear and compression is presented using the nonlinear finite strip method. Similar to the end shortening strain for compression, the skewed angle strain is uniquely proposed for in-plane shear action. The nonlinear governing equations under the skewed angle and end shortening are solved numerically using the Newton-Raphson method. The numerical finite element analysis is conducted to validate the proposed method, and a parametric study is performed to show the post-buckling behavior of composite plates. It is noted that the resulting average longitudinal and transverse section forces induced by the out-of-plane deflection or so called the non-linear strains cannot be ignored when compared to the average shear section force for the case of pure shear action. Also, when the out-of-plane deflection becomes large enough under combined compression and shear action, the average compression section force will transit to the average tensile section force in the longitudinal direction. The present analysis is capable of simulating the post-buckling behavior under the combined shear and compression action.

ABSTRACT: The present contribution deals with the question how structures with softening material behavior can be controlled in a numerical analysis beyond limit points, when conventional path following schemes fail. For nonlinear problems with localized cracks, adaptive path following schemes that increase numerical robustness, minimize user interference and avoid nonphysical (artificial) unloading are presented. In the methods proposed, a control region is identified where control parameters are evaluated. This control region adapts with the continuation of the crack tip. Robustness and applicability of the schemes are illustrated by numerical examples.

ABSTRACT: This paper proposes a three-node triangular flat shell element based on the assumed natural deviatoric strain (ANDES) formulation. The free parameters included in the ANDES formulation are presented.
for better use of the proposed element in curved shell geometries. In order to further enhance the element behavior, a strain smoothing technique is applied to the derivation of the membrane stiffness of the proposed element. Furthermore, in order to avoid the drill rotation locking that is typically induced by the drilling degrees of freedom, a simple modification factor is introduced. Various benchmark examples are tested in order to verify the performance of the proposed element.

PARTIAL ABSTRACT: A mixed 8-nodes quadrilateral 16 dof membrane finite element, called HQ8-13β, is proposed. It is developed within the Hellinger–Reissner variational framework: the assumed stress is self-equilibrated and based on Airy stress solution and the kinematics includes drilling rotations handled à la Allman. It is particularly suitable for recovering constant bending solution accurately with less sensitivity to mesh distortion. On the whole, it shows accuracy also for very coarse meshes and convergence of order O (h 2) O (h 2). Its ...

Frederic Druesne, Mohamed Bader Boubaker and Pascal Lardeur (Roberval Laboratory, UMR 7337, University of Technology of Compiègne, France), “Fast methods based on modal stability procedure to evaluate natural frequency variability for industrial shell-type structures”, Finite Elements in Analysis and Design, Vol. 89, pp 93-106, October 2014, https://doi.org/10.1016/j.finel.2014.05.004
ABSTRACT: This paper proposes a set of parametric numerical methods to predict the effect of uncertainties in the input parameters on the natural frequencies of structures. The first method, called MCS–MSP, involves the Monte Carlo simulation (MCS) and the modal stability procedure (MSP). Here the weak sensitivity of the mode shape to variations in the input parameters of the model is exploited. A single finite element analysis is required for the MCS–MSP, leading to a fast Monte Carlo simulation. Next, two first order methods are presented that rely on the calculation of frequency sensitivity to random variables using either the finite element method (FÔFE) or the MSP (FOMSP). These first order methods require only as many finite element or MSP analyses as the number of random variables. These fast and non-intrusive methods are intended to be used with industrial-size models with a large number of degrees of freedom and a large number of random variables. Finally, two applications are presented: a spot welded plate assembly and a car body in white. The stochastic results obtained (mean value, standard deviation, coefficient of variation, statistical distribution) with the three presented methods are compared to those obtained using the direct MCS as a reference. For both examples, the quality of the results obtained with these fast methods is satisfactory. Moreover, the gains are very valuable: the computation time involved in the proposed approaches based on MSP assumption is lower than the computation time needed for six deterministic finite element analyses.

ABSTRACT: Bulging/necking motion in doubly fiber-reinforced incompressible nonlinearly elastic tubes subject to axial loading and internal pressure is examined using a numerical procedure based on the modified Riks method. In particular, the materials under consideration are neo-Hookean models augmented with two
functions, each one of them accounting for the existence of a unidirectional reinforcement. The functions endow the material with its anisotropic character and each one is referred to as a reinforcing model. We consider two cases for the nature of the anisotropy: (i) reinforcing models that have a particular influence on the shear response of the material and (ii) reinforcing models that depend only on the stretch in the fiber direction.

Bifurcation and postbifurcation results show a very different qualitative behavior for the reinforcing models. Necking and bulging motions are captured. In general, localized bulging occurs first. Nevertheless, we find necking solutions during inflation in thin-walled cylinders under axial loading and internal pressure, although both highly elongated and inflated. We show that necking, under the conditions at hand, propagates both axially and radially, i.e. it is a combination of both axial and radial stretches. Furthermore, axial stretch at the necking zone is smaller than outside the necking region. In addition, necking motion is related to a decrease of pressure beyond the onset of necking. These features are easily identified with the necking solutions found during deflation from a highly inflated tube.


ABSTRACT: This paper develops a method based on genetic algorithm (GA) for reliability-based optimization (RBO) of structures through a software application. This method employs GA as an optimization technique in which reliability constraints of RBO problem are evaluated using finite element reliability analysis modules offered by OpenSees. Since Tcl is a programmable and interpreted language, the proposed method is implemented using Tcl scripting language together with OpenSees software framework. Developing the RBO method through this software application leads to the important advantage of utilizing new advanced structural reliability methods implemented in OpenSees without compiling the source code. In the RBO problem, the cost of design is defined as an objective function and a number of design requirements are defined as reliability constraints. This method is also able to deal with RBO problems with discrete and continuous design variables. Six numerical examples are provided to investigate the strengths of the method through the software application. Results illustrate the advantages of this application in RBO of structures. Since OpenSees is used for finite element reliability analysis, this application is readily extendable to nonlinear structures.


ABSTRACT: Fuel efficiency and occupant safety are two of the most important concerns in the automotive industry nowadays. Encouraged by the importance of this field of study, this research attempts an improvement in the crashworthiness of a vehicle crash absorber. This component consists in a square hollow steel tube filled with a honeycomb structure made of glass-fiber reinforced polyamide. Surrogate-based optimization techniques are used. The three objective functions chosen — mass, absorbed energy and peak load — are approximated by two different models: multivariate adaptive regression splines and Gaussian process (kriging). The thickness of both parts, the shape of the honeycomb and its height are selected as design variables. Two preliminary analyses of the specimen are performed: the computation of the interaction effect and a comparison of a hollow tube with the specimen. From the results of multi-objective crashworthiness optimization two Pareto frontiers are
obtained, one for the absorbed energy and mass, and another one for the absorbed energy and peak load. The results achieved show great improvements on all objective functions compared to the original design. The peak load is reduced by 37% on a specimen with similar mass and absorbed energy, and the specific energy absorbed is increased by 39.5% for a specimen with a similar peak load to the one from the initial model.

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ABSTRACT: This paper evaluates various Finite Element (FE) models for the static and dynamic analyses of single- and multi-bay metallic box structures. Load factors are considered in the static response, whereas free vibration analyses are addressed to compare the dynamic performances. Different FE models able to include cross-sectional deformations are compared. These comprise solid (3D) and plate/shell (2D) models, which are obtained by using a general-purpose commercial software. Results related to a hierarchical variable kinematic beam (1D) formulation, which opportually degenerates into classical beam theories with rigid-cross section assumptions (e.g. Euler–Bernoulli and Timoshenko), are also addressed. Displacements as well as axial and shear stress fields are compared for various loading cases. Regarding dynamic analyses, fundamental and higher-order natural frequencies by various models are computed and the Modal Assurance Criterion is used to compare the eigenmodes. It is concluded that refined models are mandatory to accurately describe the static and dynamic characteristics of thin-walled box structures. Classical and lower-order refined beam models show severe limitations in capturing localized stress/strain fields as well as local mode shapes. Nevertheless, the accuracy of lower-order models is improved as a consequence of the adoption for transverse ribs, which lead to more rigid cross-sections.


ABSTRACT: In this study, an effective p-version two-node mixed finite element is newly presented for predicting the free vibration frequencies and mode shapes of isotropic shells of revolution. The present element considering shear strains is based on Reissner–Mindlin shear deformation shell theory and Hellinger–Reissner variational principle. To improve the accuracy and resolve the numerical difficulties due to the spurious constraints, field-consistent stress parameters are employed corresponding to displacement shape functions with high-order hierarchical shape functions. The elimination of stress parameters and the reduction of the nodeless degrees by the Guyan reduction yield the standard stiffness and mass matrix. Results of the proposed element are compared with analytical, experimental and numerical solutions found in the literature. We can confirm a very satisfactory numerical behavior of the present p-version mixed element.

ABSTRACT: This paper presents a novel approach based on isogeometric analysis (IGA) and a simple first-order shear deformation plate theory (S-FSDT) for geometrically nonlinear analysis of homogeneous and non-homogeneous functionally graded plates. Owing to many advantages such as (a) the S-FSDT is free of shear-locking, (b) less one unknown for the S-FSDT as compared with the conventional FSDT, (c) the awkward $C^1$ continuity required for the generalized displacements is treated straightforwardly because of the nature of the higher-order continuity IGA method, the new formulation is thus effective in modeling the geometrical nonlinearities of plates. The S-FSDT is associated with the von Kármán strain for dealing with small strain and moderate rotation. Numerical validation is analyzed and numerical applications are considered. The obtained results are compared with reference solutions to show the accuracy and the effectiveness of the present approach. The effects of different boundary conditions, gradient index, length-to-thickness ratio, geometric shape, etc. on the geometrically nonlinear mechanical responses of functionally graded plates are investigated.

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ABSTRACT: This paper revisits the buckling analysis of a benchmark cylindrical panel undergoing snap-through when subjected to transverse loads. We show that previous studies either overestimated the buckling load and identified a false buckling mode, or failed to identify all secondary solution branches. Here, a numerical procedure composed of the arclength and branch switching methods is used to identify the full postbuckling response of the panel. Additional bifurcation points and corresponding secondary paths are discovered. Parametric studies of the effect of the rise, thickness, and boundary conditions of the panel on the buckling and postbuckling responses are also performed.

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ABSTRACT: This work presents a finite strain quadrilateral element with least-squares assumed in-plane shear strains (in covariant/contravariant coordinates) and classical transverse shear assumed strains. It is an alternative
to enhanced-assumed-strain (EAS) formulation and, in contrast to this, produces an element satisfying ab initio the Patch-test. No additional degrees-of-freedom are present, unlike EAS. Least-squares fit allows the derivation of invariant finite strain elements which are both in-plane and out-of-plane shear-locking free and amenable to standardization in commercial codes. With that goal, we use automatically generated code produced by AceGen and Mathematica to obtain novel finite element formulations. The corresponding exact linearization of the internal forces was, until recently, a insurmountable task. We use the tangent modulus in the least-squares fit to ensure that stress modes are obtained from a five-parameter strain fitting. This reproduces exactly the in-plane bending modes. The discrete equations are obtained by establishing a four-field variational principle (a direct extension of the Hu–Washizu variational principle). The main achieved goal is coarse-mesh accuracy for distorted meshes, which is adequate for being used in crack propagation problems. In addition, as an alternative to spherical interpolation, a consistent director normalization is performed. Metric components are fully deduced and exact linearization of the shell element is performed. Full linear and nonlinear assessment of the element is performed, showing similar performance to more costly approaches, often on-par with the best available shell elements.

ABSTRACT: The objective of the present manuscript is to describe a new architecture of the nonlinear multiphysics finite element code in object oriented Fortran environment hereafter referred to as FOOF. The salient features of FOOF are reusability, extensibility, and performance. Computational efficiency stems from the intrinsic optimization of numerical computing intrinsic to Fortran, while reusability and extensibility is inherited from the support of object-oriented programming style in Fortran 2003 and its later versions. The shortcomings of the object oriented style in Fortran 2003 (in comparison to C++) are alleviated by introducing the class hierarchy and by utilizing a multilevel programming style.

ABSTRACT: In the conventional isogeometric analysis, a topologically complex shell structure is required to be modeled using multiple NURBS patches. In the CAD industry, however, the topologically complex shell structure is conveniently and efficiently created via trimming techniques rather than constructing multiple untrimmed NURBS patches. With this feature, the isogeometric analysis which enables to handle the topologically complex shell structure with a single NURBS patch is presented in this paper. In the present method, the information of the topologically complex shell structure composed of the untrimmed surface and trimming curves is directly utilized into isogeometric shell analysis. For numerical integration, a special integration scheme is adopted considering the inside or the outside of the trimmed boundaries which are described by the trimming curves. For the shell formulation, the degenerated shell element based on the Reissner–Mindlin theory is employed. The exact surface normal vectors and their analytic derivatives are adopted into the formulation. The shell formulation is validated with linear elastic benchmark problems. Then linear elastic problems of topologically complex shell structures are dealt with using the proposed procedures, and the effectiveness is illustrated.
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ABSTRACT: A finite element study based on 1D beam element model is performed in order to investigate the mechanical behavior of an elasto-plastic beam loaded in axial compression over its buckling limit. The mode of loading is related to the damage of truss-cored beams in truss-cored laminates. The analysis takes into account the effects of geometry and material properties. The results of the FEM analysis are used for developing a simple mechanical model based on the basic Euler–Bernoulli beam theory and accounts for the beam compressibility. The model uses phenomenological functions containing parameters related to the basic material and geometrical properties. The presented model is developed in the form of closed solution which does not require complex numerical methods or extensive parametric studies. Predictions of the compressive stiffness degradation of truss-cored composites are made with the proposed model and compared with the results of FEM simulations. The error of the stiffness prediction with respect to the FEM results is within 10% over a 5 fold range of stiffness.

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ABSTRACT: This paper presents a new simple four-node quadrilateral shell element with 24-dof which can be used to analyze thick and thin shell problems. This element which is developed from DKMQ plate element using the Naghdi/Mindlin/Reissner shell theory can take into account warping effects and coupling bending-membrane energy. This element, called DKMQ24, passed patch tests for membrane, bending and shear problems. It has also successfully passed benchmark tests in the case of thick and thin shells without shear locking. Moreover, the numerical results obtained with DKMQ24 converge toward the reference solution.


ABSTRACT: In this work, we propose a new enhancement strategy that can be applied to the calculated strain field in the analyses of shells by the unconstrained-vector finite element approach, a Solid-Shell-like formulation. This new enhancement is proposed to satisfy the continuity of the shear and normal stresses fields in the transverse direction. The kinematic enhancement is based on the in-plane longitudinal stress equilibrium that is associated with maintaining the elastic strain energy potential in the transverse direction of the shell or plate. No additional degrees of freedom are introduced, and a coherent continuous stress distribution is achieved.
from the enhanced strain field. Moreover, in contrast to typical elastoplastic procedures, we propose an alternative plastic flow rule, which includes a new concept of the hardening parameter that depends on the orthotropic directions of the material and a general failure surface that degenerates into the von-Mises or Drucker–Prager criteria for isotropic materials. The resulting alternative position-based finite element and the enhanced field strategies are tested for elastic and elastoplastic situations by comparing the results with other solutions and known benchmarks.


ABSTRACT: Dynamic elasticity solution for a clamped, laminated cylindrical shell with two orthotropic layers bounded with a piezoelectric layer and subjected to exponential dynamic load distributed on inner surface is presented. The piezoelectric layer serves as sensor/actuator. The governing elasticity partial differential equations are reduced to ordinary differential equations by means of Legendre polynomial expansion for displacement and electric potential in axial direction. The resulting equations are reduced to a system of ODE with constant coefficients by means of Galerkin’s integral method and finally the governing equations are solved by using linear finite element in radial direction. The static and dynamic results are presented for [0/90/Piezo] lamination. The ratio effect of the radius to thickness on dynamic behaviour is studied. The results are compared for different thickness ratios and applied electric loads with simply-supported shell results. Time responses for sensor and actuated shell are presented.

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ABSTRACT: Multi-cell thin-walled structures have proven fairly effective in energy absorption and have been extensively used in vehicle engineering. However, the effects of multi-cell configurations and oblique loads on the crashworthiness performance have been understudied. This paper aims to investigate the crash behaviors of different multi-cell hexagonal cross-sectional columns under axial and oblique loads comprehensively. The modeling results are first validated by comparing with the theoretical and experimental data. It is found that for the same cell number, the number of corners plays a significant role in enhancing energy absorption. Second, a multicriteria decision-making method, namely complex proportional assessment (COPRAS), is used to select the best possible sectional configuration under multiple loading angles. Finally, the Kriging modeling technique and multiobjective particle optimization (MOPSO) algorithm are employed to optimize the dimensions of such a cross-sectional configuration. The results exhibit that an optimized multi-cell sectional tube is more competent in crashworthiness for multiple load cases (MLC).
ABSTRACT: In tires, cracks usually nucleate at the belt edge and grow along the belt–rubber interface. Therefore, to assess the durability of a tire a method of analysis that can accurately simulate the belt is needed. However, in previous studies, a belt cord model that could represent both tension and bending well was not used. Therefore, in this study, to simulate the behavior of the cords in the belt, a wire cord finite element model was developed to accurately model the geometry of cords, and the validity of the model was verified through comparisons of tensile and bending simulation results with test results. However, the configuration of the wire cord model was too complicated and involved too many elements to be used to model the whole tire. Therefore, two equivalent cord models capable of simulating the behavior of the wire cord model were proposed. One was a cord model with solid and truss elements, and the other was a cord model with solid elements that have bilinear material property. Global–local analyses were conducted using a solid element cord model, a rebar element cord model, and the equivalent cord models to obtain the strains at the belt edge. The comparison of the results demonstrated that more appropriate strains could be obtained using the equivalent cord models than the solid element cord model or the rebar element model.

ABSTRACT: This paper aims to extend the evolutionary methods of topology optimization to free vibration problems of acoustic–structure systems. The interacting fluid and structure fields are governed by the acoustic wave equation and the linear elasticity, respectively. Both domains are solved with the finite element method. The coupling conditions are the equilibrium and kinematic compatibility at the acoustic–structure interfaces. The proposed bi-directional evolutionary structural optimization (BESO) method seeks to maximize the first natural frequencies of the acoustic-structural model by switching elements into solid, fluid or void condition. It allows the acoustic–structure boundaries to be modeled and modified straightforwardly, addressing design-dependent loads on the topology optimization problem with simple finite element formulations. The proposed methodology extension is justified by various possible applications to free vibration of acoustic–structure systems such as tanks/reservoirs, acoustic-structural devices, passengers compartments in automobiles and aircrafts and pipelines. Numerical results show that the evolutionary methods can be applied to this kind of multiphysics problem effectively and efficiently.
ABSTRACT: Simulating concrete cracking requires nonlinear modeling applied on a refined mesh if a correct evaluation of crack properties needs to be achieved. Therefore, it is rather costly and even sometimes impossible when large reinforced concrete structures are considered. Alternative solutions have therefore to be proposed. This contribution presents a structural zooming method for the simulation of large reinforced concrete structures with localized nonlinearities. Our method is based on static condensation (Guyan [1]) and provides an adaptive framework for performance-oriented use of this method in nonlinear simulations. In particular, it only simulates the behavior of nonlinear interesting zones (detected by adapted criteria). The areas where refined modeling is not required are replaced by their equivalent stiffnesses. The linearity criteria, depending on the chosen mechanical models, are also used to activate new interesting zones during the simulation. This method substantially decreases the computational cost on both presented test cases (a two-dimensional concrete beam and a three-dimensional reinforced concrete building).

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ABSTRACT: In this paper, 4-node quadrilateral and 3-node triangular solid-shell elements are applied to drape simulations. With locking issues alleviated by the assumed natural strain method and plane-stress enforcement, static and dynamic drape problems are attempted by the quadrilateral element. If the drape i is deep and the mesh density is inadequate, non-realistic sharp folds are predicted due to the non-physical interpenetration of top and bottom element surfaces. To avoid the interpenetration, a reversible adaptive subdivision based on the 1–4 splitting method is developed. To ensure displacement compatibility among elements at different subdivision levels, macro-transition elements are formed by quadrilateral and triangular solid-shell elements. To reduce the dynamic oscillation induced by newly inserted nodes, the discrete Kirchhoff condition is employed to determine the related nodal variables. Dynamic drape examples using adaptive meshing are presented. It can be seen that the predictions look realistic and deep drapes can be predicted with the interpenetration avoided yet the required number of nodes can be kept relatively small.

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ABSTRACT: In the present paper, a detailed description of the formulation of the new SSH3D solid-shell element is presented. This formulation is compared with the previously proposed RESS solid-shell element [1,2]. Both elements were recently implemented within the LAGAMINE in-house research finite element code. These solid-shell elements possess eight nodes with only displacement nodal degrees of freedom (DOF). In
order to overcome various locking pathologies, the SSH3D formulation employs the well known Enhanced Assumed Strain (EAS) concept originally introduced by Simo and Rifai [3] and based on the Hu-Veubeke-Washizu variational principle combined with the Assumed Natural Strain (ANS) technique based on the work of Dvorkin and Bathe [4]. For the RESS solid-shell element, on the other hand, only the EAS technique is used with a Reduced Integration (RI) Scheme. A particular characteristic of these elements is their special integration schemes, with an arbitrary number of integration points along the thickness direction, dedicated to analyze problems involving non-linear through-thickness distribution (i.e. metal forming applications) without requiring many element layers. The formulation of the SSH3D element is also particular, with regard to the solid-shell elements proposed in the literature, in the sense that it is characterized by an in-plane full integration and a large variety in terms of (i) enhancing parameters, (ii) the ANS version choice and (iii) the number of integration points through the thickness direction. The choice for these three parameters should be adapted to each problem so as to obtain accurate results and to keep the calculation time low. Numerous numerical examples are performed to investigate the performance of these elements. These examples illustrate the reliability and the efficiency of the proposed formulations in various cases including linear and non-linear problems. SSH3D element is more robust thanks to the various options proposed and its full in-plane integration scheme, while RESS element in more efficient from a computational point of view.

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ABSTRACT: Dimpled steel products are produced from the combination of an innovative dimpling process and a traditional forming process such as cold-roll forming or press-braking. The wider use of cold-formed dimpled steel members has promoted considerable interest in the local instability and strength of these members. Of particular interest is their buckling behaviour and ultimate strength capacity in columns under compressive loading. However, the dimpling process produces cold-formed sections with a complex ‘dimpled’ surface topography and the ‘dimpled’ material is non-uniformly work hardened through the entire thickness. Owing to these complex issues, there are no existing analytical and design methods to calculate the buckling strength of dimpled products and validate against physical measurements. This paper presents the analysis of the compressive behaviour of cold-formed channel and lipped channel dimpled steel columns using Finite Element techniques. True stress–strain data obtained from physical tests were incorporated into nonlinear simulations of dimpled steel columns. It was found that the predicted buckling and ultimate loads correlated well with the experimental results. Based on the validated Finite Element results for different geometries, standard design formulae for determining buckling and ultimate loads of channel and lipped channel dimpled columns were developed. It is demonstrated that the Finite Element Analysis can therefore be used to analyse and design cold-formed dimpled steel columns.

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ABSTRACT: In this paper we analyze bifurcation and postbifurcation of a finite deformation boundary-value problem for a residually-stressed elastic body using the finite element method. In particular, the torsion of a circular cylindrical tube subject to radial and circumferential residual stresses is studied. The material model is given by a residual-stress dependent nonlinear elastic constitutive law in terms of invariants. Firstly, the numerical methodology able to capture the elastic stability of tubes under torsion is developed without including residual stress. The bifurcation point is initially estimated reducing the original problem to an algebraic eigenvalue problem. A nonlinear analysis is performed to capture the postcritical behavior. Secondly, prestress is introduced. The residual-stress dependent nonlinear elastic constitutive law is implemented in a finite element code. The dependence of bifurcation and postbifurcation behavior of tubes under torsion on residual stresses is illustrated and compared with results when there is no residual stress. Analytical solutions involve a complicated mathematical machinery that deals with specific material models and loads as well as, usually, a perfect geometry. Here, we provide a highly flexible approach that is implemented in a commercial finite element code, which allows this methodology to be easily used on other problems under different loading conditions and geometries. The numerical results obtained for the (thin) tubes are compared with the (analytical) solution for the torsion of an infinitely long circular cylindrical membrane to validate the methodology.

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ABSTRACT: The Koiter–Newton approach is a novel reduced order modeling technique for buckling analysis of geometrically nonlinear structures. The load carrying capability of the structure is achieved by tracing the entire equilibrium path in a stepwise manner. At each step a reduced order model generated from Koiter’s asymptotic expansion provides a nonlinear prediction for the full model, corrected by a few Newton steps. The construction of the reduced order model requires derivatives of the strain energy with respect to the degrees of freedom up to the fourth order, which is two orders more than traditionally needed for a Newton based nonlinear finite element technique. In this paper we adopt the co-rotational formulation to facilitate these complex differentiations. We extend existing co-rotational beam and shell element formulations to make them applicable for the high order derivatives of the strain energy. The geometrical nonlinearities are taken into account using derivatives of the local co-rotational frame with respect to global degrees of freedom. This is done outside the standard element routines and is thus independent of the element type. We utilize three configurations and the nonlinear rotation matrix to describe finite rotations of the shell accurately, and profit from the automatic differentiation technique to optimize the programming of high order derivatives. The performance of the proposed approach using the co-rotational formulation is demonstrated using benchmark examples of isotropic and laminated composite structures.
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ABSTRACT: In the present research, the isogeometric topology optimization of shell structures is proposed. There have been lots of successful studies on the shape optimization using isogeometric analysis (IGA). However, it is not straightforward to apply the conventional IGA to topology optimization. Topological changes of a domain are hard to be represented due to the tensor-product form of a Non-Uniform Rational B-Spline (NURBS) surface. Since only quadrilateral domains can be handled in the conventional IGA, a topologically complex domain which frequently appears during the optimization process should be built by introducing multiple untrimmed NURBS patches for analysis. Trimmed surface analysis (TSA) is the IGA where trimming techniques are employed, and it can handle a topologically complex domain with a single NURBS patch effectively. In the present work, the basic concept of the two-dimensional TSA is appropriately adapted to shell structures in order to handle the complex topologies. The whole optimization process includes the topological change step and the shape optimization step. The criteria based on the topological derivatives are used for the judgement of new hole creation and the decision of the hole position. Holes are represented by introducing NURBS trimming curves. The trimming curve control points as well as the surface control points are set as design variables for the shape optimization. In the optimization process, updating of the trimming curves is performed in adaptive manners to maintain smooth boundary representation and robust convergence. With numerical examples, it is shown that the proposed method gives appropriate and acceptable shell structure designs. By the inner or outer boundaries of a domain which are described by trimming curves, the smooth material layout is derived without gray scales or checkerboard patterns. Since the same IGES standard is used throughout the process, the final design derived by the present method can be directly communicated with CAD systems without any additional treatments.


ABSTRACT: A moving bounds strategy is proposed to implement simultaneous shape optimization of curved shell structures and openings. Design variables related to the hole shape are constrained in a planar reference domain by the moving bounds whose values are adaptively updated as functions of design variables related to the surface by an arc-length rule. It is shown that this strategy is essential not only to ensure the geometric consistence in the simultaneous design process but also to hold the shape-preserving of the mapped FE mesh from reference domains. Numerical results are presented to validate the proposed method.

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ABSTRACT: Recent studies analyze the behavior of advanced shell structures, like foldable, multistable or morphing shell structures. Simulating a thin foldable curved structure is not a trivial task: the structure may go through many snapping transitions from a stable configuration to another. Then, one could claim arc-length methods or use a dynamic approach to perform such simulations. This work presents a geometrically exact shell model for nonlinear dynamic analysis of shells. An updated Lagrangian framework is used for describing kinematics. Several numerical examples of folding a thin dome are presented, including creased shells. The triangular shell finite element used offers great flexibility for the generation of the unstructured curved meshes, as well as great results.

ABSTRACT: Modal analysis of frequency dependent visco-elastic sandwich structures with finite element models leads to a non-linear eigenvalue problem. Many methods have been proposed so far to solve this problem. The present paper compares the asymptotic numerical method to some representative algorithms such as non-linear Arnoldi method, non-linear Jacobi–Davidson method, inverse iteration and iterative shift-invert method. Three mesh refinement levels 1 (~5000 dofs), 2 (~20000 dofs) and 3 (~45000 dofs) have been used. Computational times and accuracy are compared on relevant use cases with frequency dependent visco-elastic materials. Three layered laminated sandwich plates with visco-elastic layers are considered as test cases and two different frequency and temperature dependent materials (ISD112 and PVB) are employed. It is shown that the non-linear Arnoldi method provides the best results in terms of accuracy and CPU time, inverse iteration being the most efficient method for small size problems. Moreover, it is shown that fractional derivative models commonly used to model frequency dependent viscoelastic materials are more CPU intensive than generalized Maxwell models when performing modal analysis of frequency dependent viscoelastic sandwich structures.


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ABSTRACT: In this contribution a new geometrically nonlinear, discontinuous solid-like shell finite element is presented for the simulation of cracking phenomena in thin shell structures. The discontinuous shell element is based on the solid-like shell element, having a layout similar to brick elements but better performance in
bending. The phantom node method is employed to achieve a fully discontinuous shell finite element, which incorporates a discontinuity in the shell mid-surface, director and in thickness stretching field. This allows the element to model arbitrary propagating cracks in thin shell structures in combination with geometrical non-linearities. The kinematics of the discontinuous shell element as well as the detailed finite element formulation and implementation are described. Several numerical examples are presented to demonstrate the performance of the element.

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ABSTRACT: This paper investigates the large amplitude vibration behavior of nanocomposite cylindrical shells reinforced by single-walled carbon nanotubes (SWCNTs) in thermal environments. The SWCNTs are assumed to be aligned and straight with a uniform layout. Two kinds of carbon nanotube-reinforced composite (CNTRC) shells, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRC shells are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The motion equations are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. The equations of motion are solved by an improved perturbation technique to determine the nonlinear frequencies of the CNTRC shells. Numerical results demonstrate that in most cases the natural frequencies of the CNTRC shells are reduced but the nonlinear to linear frequency ratios of the CNTRC shells are increased as the temperature rises. It is found that the natural frequencies are increased by increasing the CNT volume fraction, whereas the CNTRC shells with intermediate CNT volume fraction do not have intermediate nonlinear to linear frequency ratios.


ABSTRACT: This paper analyses dynamic response and vibration characteristics of long microtubules. Mechanical aspects of material properties are described based on an atomistic-continuum model and the use of a higher-order Cauchy–Born rule that bridges the scale between microstructures and continuum description. Long microtubules are simulated with one-dimensional strips, which include microscale interaction among protein molecules and can be dealt with using continuum mechanical approaches under higher-order gradient continuum scheme. Based on Hamilton’s principle, the differential equation of motion is established and is incorporated in the higher-order gradient continuum mesh-free framework. The performances of structures of microtubules are determined by direct numerical integration in time domain and applying the Fourier transform technique in frequency domain. Time-histories and frequency spectrums are obtained to determine vibration
characteristics. Curved shapes of microtubules are involved in the study. Different cases are considered and compared, and the results are presented and discussed.

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ABSTRACT: The higher-order Cauchy–Born rule is applied to predict the mechanical response of single-walled carbon nanotubes (SWCNTs). As second-order deformation gradients can describe the bending effect of C–C bond vectors involved in the theoretical scheme of the higher-order gradient continuum, the established constitutive model accords extremely well with physical behavior. From the constitutive relationship constructed, a novel computational method is proposed for numerical simulation of buckling behaviors of SWCNTs. In this study, a new mesh-free method developed from the moving Kriging (MK) interpolation is employed to implement numerical simulation of mechanical properties of SWCNTs under axis-symmetrical loadings. As the mesh-free shape function constructed using the MK interpolation has the delta function property, the shape functions satisfy the essential boundary conditions automatically. Therefore, the essential boundary conditions can be easily implemented. Several numerical examples of buckling behaviors of SWCNTs are presented to test the effectiveness and efficiency of this method. The numerical results are also compared with those obtained from the full atomistic simulation method, and are found to be in agreement. Moreover, this computational method can largely reduce the degrees of freedom of the system, and thus save a large amount of computational resources. As a result, this is a very attractive approach, which has great potential in the engineering field. This mesh-free method is further applied to the study of post-buckling of SWCNTs. The results are compared with those obtained from full atomistic simulation, and demonstrate that this method is truly effective and efficient.

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ABSTRACT: Based on complex variable theory and moving least-squares (MLS) approximation, the improved complex variable moving least-squares (ICVMLS) approximation is discussed in this paper. Compared with complex variable moving least-squares (CVMLS) approximation, the function in the ICVMLS approximation has an explicit physics meaning. By using a new basis function, the ICVMLS approximation can obtain greater precision and computational efficiency. Based on the ICVMLS approximation, an improved complex variable element-free Galerkin (ICVEFG) method, which belongs to a novel element free Galerkin (EFG) method, is presented for two-dimensional large deformation problems. The Galerkin weak form is employed to obtain the equations, while the penalty method is used to apply the essential boundary conditions. Then the corresponding formulae of the ICVEFG method for two-dimensional large deformation problems are obtained. Compared with
the EFG method, the ICVEFG method has greater precision and efficiency.


ABSTRACT: This paper introduces a structural optimization strategy that combines FE-based parametrization with nonlinear kinematics in order to optimize the shape of thin shell structures. The optimization is based on gradient based strategies where the required derivatives are formulated by the adjoint approach. The applied solution algorithm combines the well known nonlinear path following strategies with the design update procedure of the shape optimization. This results in robust and flexible methods that require only a minimum of system evaluations. The proposed optimization goals improve the load carrying behavior of the structure and minimize displacements and stresses. It is shown that such efficient designs also exhibit an improved limit load. This contribution illustrates the application of the proposed method by several shape optimization problems. The presented results prove the exceptional performance of the optimized designs even if the optimal design is disturbed by unavoidable imperfections. It is shown that the application of nonlinear kinematics in the shape optimization of thin shell structures allows for a much more realistic system response and gradient data. The proposed approach is applicable to all kind of optimization strategies like topology, sizing or material optimization, respectively.


ABSTRACT: This paper discusses the evaluation of quasi-static equilibrium solutions for inflatable space membrane structures. A Mooney–Rivlin hyper-elastic material model, with variable constitutive constants, is considered. A compressible weightless medium is used to introduce within the membrane a one-parametric over-pressure loading compared to an ambient pressure. Analytical instability results are shown for a spherical and derived for a cylindrical case. These are compared to numerical simulations based on a flat linearly interpolated triangular space membrane element. Path-following procedures are used to find generalized equilibrium paths, with different parameterizations. Numerical examples show that the methods developed can give information on the stability of the membranes, but that the medium and means for introducing the internal pressure are of importance for the interpretation of stability.

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ABSTRACT: This paper employs a higher-order gradient continuum theory for studying mechanical properties
of single-walled carbon nanocones (SWCNCs). The SWCNC is constructed by rolling up a fan-shaped graphite sheet and connecting their two sides to form a conical structure. A mesh-free computational framework based on the moving Kriging (MK) interpolation is developed to study the buckling behaviors of SWCNCs under axial compression. Mechanical behaviors of SWCNCs with five different apex angles, i.e. 19.2°, 38.9°, 60°, 84.6° and 112.9°, are studied. Critical strains are predicted with the SWCNC subjects to uniform axial compression on the two ends. Computational results demonstrate that the apex angle has an increasing effect on the critical strain but a decreasing effect on the elastic properties (such as axial Young’s modulus) of SWCNCs. The corresponding buckling patterns reveal that a larger apex angle developed more fins on the side surface of the CNC at critical strain. For some of the CNCs, it is found that the elastic property slightly increases as the cutting tip’s length increases. Besides, a sharp-decrease of the critical strain with an increase number of fins, which approach to ripples, indicates that the CNC becomes unstable.


ABSTRACT: In this work, we revisit the stress resultant elastoplastic geometrically exact shell finite element formulation that is based on the Ilyushin–Shapiro two-surface yield function with isotropic and kinematic hardening. The main focus is on implicit projection algorithms for computation of updated values of internal variables for stress resultant shell elastoplasticity. Four different algorithms are derived and compared. Three of them yield practically identical final results, yet they differ considerably in computational efficiency and implementation complexity, since they solve different sets of equations and they use different procedures that choose active yield surfaces. One algorithm does not provide acceptable accuracy. It turns out that the most simple and straightforward algorithm performs surprisingly well and efficiently. Several numerical examples are presented to illustrate the Ilyushin–Shapiro stress resultant shell formulation and the numerical performance of the presented integration algorithms.


ABSTRACT: In this paper, we present a novel and efficient 3-D Hybrid-EAS solid element formulation to accurately predict interlaminar stresses in thick laminated beams, plates, and shells. The element formulation is based on the mixed three-field Fraeijs de Veubeke–Hu–Washizu (FHW) functional principle. The element is designed to have quadratic C⁰ transverse shear stress field through the thickness direction, while the displacement field remains linear. The continuity of the transverse shear stress at the layer interfaces, together with the vanishing transverse shear stresses at the outer surfaces of the composite structure, are satisfied exactly by using the transverse-shear-stress degrees of freedom (dofs). This method is more elegant than adding the above stress constraints on the FHW functional via a penalty or Lagrange multipliers, and is amenable for implementation in general purpose finite-element codes. Numerical examples show the excellent agreement with Pagano’s exact solution for composite beam/plate problems. The present element satisfies the interlaminar stress continuity, and accurately captures the quadratic variation of the transverse shear stresses in the thickness when compared to other element formulations, in particular the well-known hybrid formulation by Mau, Tong, and Pian (1972) [23]. In addition, the present approach is readily generalizable to the case with large deformation and nonlinear materials.

ABSTRACT: This paper presents a C^1 6-node triangular finite element for multilayered composite plates submitted to mechanical and thermomechanical loads. It is based on the sinus model with layer refinement and includes the transverse normal effect. This kinematics allows to exactly ensure both (i) the continuity conditions for displacements and transverse shear stresses at the interfaces between layers of a laminated structure, and (ii) the boundary conditions at the upper and lower surfaces of the plates. It is important to notice that the number of unknowns is independent of the number of layers. This finite element is able to model both thin and very thick plates without any pathologies of the classic plate finite elements (shear locking, spurious modes, etc.). It is built on the Argyris interpolation for bending and the Ganev interpolation for membrane displacements and transverse shear rotations. The representation of the transverse shear strains by cosine functions allows avoiding shear correction factors. In addition, the transverse normal stress can be accurately recovered from equilibrium equations at the post-processing level, using the high degree of interpolation polynomials. Both mechanical and thermomechanical tests for thin and very thick plates are presented in order to evaluate the capability of this new finite element to give accurate results with respect to exact three-dimensional solutions. Both convergence velocity and accuracy are discussed and this new finite element yields very satisfactory results at a low computational cost. In particular, the transverse shear stresses computed from the constitutive relation are well estimated with regards to other equivalent single layer or even with respect to layerwise models.

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ABSTRACT: An isogeometric Reissner–Mindlin shell derived from the continuum theory is presented. The geometry is described by NURBS surfaces. The kinematic description of the employed shell theory requires the interpolation of the director vector and of a local basis system. Hence, the definition of nodal basis systems at the control points is necessary for the proposed formulation. The control points are in general not located on the shell reference surface and thus, several choices for the nodal values are possible. The proposed new method uses the higher continuity of the geometrical description to calculate nodal basis system and director vectors which lead to geometrical exact interpolated values thereof. Thus, the initial director vector coincides with the normal vector even for the coarsest mesh. In addition to that a more accurate interpolation of the current director and its variation is proposed. Instead of the interpolation of nodal director vectors the new approach interpolates nodal rotations. Account is taken for the discrepancy between interpolated basis systems and the individual nodal basis systems with an additional transformation. The exact evaluation of the initial director vector along with the interpolation of the nodal rotations lead to a shell formulation which yields precise results even for coarse meshes. The convergence behavior is shown to be correct for k-refinement allowing the use of coarse meshes with high orders of NURBS basis functions. This is potentially advantageous for applications
with high numerical effort per integration point. The geometrically nonlinear formulation accounts for large rotations. The consistent tangent matrix is derived. Various standard benchmark examples show the superior accuracy of the presented shell formulation. A new benchmark designed to test the convergence behavior for free form surfaces is presented. Despite the higher numerical effort per integration point the improved accuracy yields considerable savings in computation cost for a predefined error bound.

ABSTRACT: This work presents a computational framework for the transverse compression of microtubules using the Cauchy–Born rule. Atomistic-continuum simulation and mesh-free method are employed in the computation for the theoretical scheme of the higher-order gradient continuum. Elastic properties and mechanical responses of microtubules under transverse compression are intensively studied. Without tracing each atom in large protein structures, a homogenization technique is proposed to evaluate interatomic energy stored among macromolecules. The concept of fictitious bonds is proposed for microtubules to bridge the gap between the atomistic simulation and the continuum approach, which is of great significance for application of the continuum approach to macromolecular structures. To reflect the inhomogeneous deformations of a cylindrical structure, the higher-order Cauchy–Born rule is employed to calculate the fictitious bond vectors emanating from a given evaluation point during the deformation process. By selecting a representative unit, a higher-order gradient continuum constitutive relationship is established to take atomistic interactions into consideration. Elastic modulus and transverse mechanics, including critical hydrostatic pressure and transverse compression-induced structure transitions, are numerically simulated. Example problems are carefully selected and the obtained results are discussed in detail.

ABSTRACT: A hierarchic family of isogeometric shell finite elements based on NURBS shape functions is presented. In contrast to classical shell finite element formulations, inter-element continuity of at least C1 enables a unique and continuous representation of the surface normal within one NURBS patch. This does not only facilitate formulation of Kirchhoff–Love type shell models, for which the standard Galerkin weak form has a variational index of 2, but it also offers significant advantages for shear deformable (Reissner–Mindlin type) shells and higher order shell models. For a 5-parameter shell formulation with Reissner–Mindlin kinematics a hierarchic difference vector which accounts for shear deformations is superimposed onto the rotated Kirchhoff–Love type director of the deformed configuration. This split into bending and shear deformations in the shell kinematics results in an element formulation which is free from transverse shear locking without the need to apply further remedies like reduced integration, assumed natural strains or mixed finite element formulations. The third member of the hierarchy is a 7-parameter model including thickness change and allowing for application of unmodified three-dimensional constitutive laws. The phenomenon of curvature thickness locking, coming along with this kinematic extension, again is automatically avoided by the hierarchic difference vector concept without any further treatment. Membrane locking and in-plane shear locking are removed by two different approaches: firstly elimination via the Discrete Strain Gap (DSG) method and secondly removal of
parasitic membrane strains using a hybrid-mixed method based on the Hellinger–Reissner variational principle. The hierarchic kinematic structure of the three different shell formulations allows a straightforward combination of these elements within one mesh and is thus the ideal basis for a model adaptive approach.

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ABSTRACT: We propose a new isogeometric shell formulation that blends Kirchhoff–Love theory with Reissner–Mindlin theory. This enables us to reduce the size of equation systems by eliminating rotational degrees of freedom while simultaneously providing a general and effective treatment of kinematic constraints engendered by shell intersections, folds, boundary conditions, the merging of NURBS patches, etc. We illustrate the blended theory’s performance on a series of test problems.

ABSTRACT: A computational approach is proposed for the dynamic analysis of complicated membrane systems, such as parachutes and solar sails, which undergo overall motions, large deformations, as well as wrinkles owing to the small membrane resistance to the compressive stress therein. Based on previous studies, a thin shell element of gradient deficient Absolute Nodal Coordinate Formulation (ANCF) is proposed first. Then, the strain energy of the above shell element is derived by using the definition of the Green–Lagrange strain tensor in continuum mechanics. The computationally efficient formulations of elastic forces and their Jacobian for the above shell element are also derived via the skills of tensor analysis. Afterwards, a membrane element of ANCF is proposed by integrating the criterion of wrinkle/slack into the above shell element. To deal with the small compressive stiffness for the membrane element, the Stiffness Reduction Model (SRM) is introduced to the membrane elements. Finally, four case studies including both statics and dynamics of different membrane systems are given to validate the proposed approach. The final example of the spinning deployment of a solar sail shows the efficacy of the proposed approach in the dynamic analysis of complicated membrane system undergoing an overall motion, large deformations and wrinkles.

ABSTRACT: In this paper we propose a multiscale method based on computational homogenization for simulating the mechanical response of a thin-walled porous structure. Due to the inhomogeneous nature of the
porous material in the thickness direction, the length scale of the deformation-field variations in the thickness direction is in the same order of magnitude as in the microstructure. To resolve this issue a higher-order stress-resultant shell formulation (with linear variation of the thickness stretch) based on multiscale homogenization is considered. The microscale is accounted for by calculating the micro-fluctuations from a boundary value problem over the domain of a 3D representative volume element (RVE). The breadth and width of the RVE are determined by the representative microstructure of the porous material, whereas in the thickness direction of the shell the RVE completely resolves the microscopic variation. As a result the macroscopic stress resultants are obtained as volume averages through the entire thickness of the shell. The nested solution scheme is quite computationally demanding and it should only be applied where it is needed. The paper is concluded by a couple of numerical examples that illustrate the method and support the arguments put forward in the paper. Comparison is made to a 2D plane strain reference solution with complete resolution of the microstructure over the domain. Also a 3D case is considered, showing the significance of resolving the microscopic fluctuations.


ABSTRACT: The present communication introduces a non-uniform rational B-splines based isogeometric design framework for thin-walled composite shells. The framework is aimed at optimising the form and the material anisotropy distribution either in separate or simultaneous fashions. Fundamental elements of isogeometric shell design are introduced. Analytical discrete sensitivity calculus is presented and the formulation of convex conservative approximations, utilised to solve the structural shape and sizing optimisation problems, are discussed in great detail. The design approach is verified considering buckling load factor and structural stiffness maximisation problems.


ABSTRACT: This paper extends a previous triangular prism solid element adequate to model shells under large strains to become a solid-shell element, i.e., that discretizations may include just one element across the thickness. A total Lagrangian formulation is used based on a modified right Cauchy-Green deformation tensor (Cbar). Three are the introduced modifications: (a) an assumed mixed strain approach for transverse shear strains, (b) an assumed strain approach for the in-plane components using a four-element patch that includes the adjacent elements, and (c) an enhanced assumed strain approach for the through the thickness normal strain (with just one additional degree of freedom). One integration point is used in the triangle plane and as many as necessary across the thickness. The intention is to use this element for the simulation of shells avoiding transverse shear locking, improving the membrane behavior of the in-plane triangle, alleviate the Poisson effect locking and to handle quasi-incompressible materials or materials with isochoric plastic flow. Several examples are presented that show the transverse shear and Poisson effect locking free behavior, how the improvement in the membrane approach alleviates the volumetric locking and the very good performance of the introduced element for the analysis of shell structures for both geometric and material non-linear behavior.
ABSTRACT: In this work, solid-shell NURBS elements are developed in order to address static problems of slender structures under small perturbations. A single layer of elements is considered through the thickness of the shell, and the degree of approximation in that direction is chosen to be equal to two. A full 3D constitutive relation is assumed. The objective is to obtain highly accurate low-degree elements to be used in coarse meshes. In order to do that, we propose a mixed method from which we derive a Bbar-projection to deal with locking. The main idea is to modify the interpolation of the average stresses and strains through the thickness. More precisely, we develop two finite elements. The first element, which is based on the mixed method or, equivalently, on the Bbar-projection, is extremely accurate, but leads to a fully-populated global stiffness matrix. To improve the efficiency, the second element uses a local least-squares-type procedure to define a new Bbar-projection, leading to a sparse global stiffness matrix. The quality and efficiency of the methods are assessed through several usual test cases and by comparison with other published techniques.

ABSTRACT: We compare isogeometric collocation with isogeometric Galerkin and standard Co finite element methods with respect to the cost of forming the matrix and residual vector, the cost of direct and iterative solvers, the accuracy versus degrees of freedom and the accuracy versus computing time. On this basis, we show that isogeometric collocation has the potential to increase the computational efficiency of isogeometric analysis and to outperform both isogeometric Galerkin and standard Co finite element methods, when a specified level of accuracy is to be achieved with minimum computational cost. We then explore an adaptive isogeometric collocation method that is based on local hierarchical refinement of NURBS basis functions and collocation points derived from the corresponding multi-level Greville abscissae. We introduce the concept of weighted collocation that can be consistently developed from the weighted residual form and the two-scale relation of B-splines. Using weighted collocation in the transition regions between hierarchical levels, we are able to reliably handle coincident collocation points that naturally occur for multi-level Greville abscissae. The resulting method combines the favorable properties of isogeometric collocation and hierarchical refinement in terms of computational efficiency, local adaptivity, robustness and straightforward implementation, which we illustrate by numerical examples in one, two and three dimensions.

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ABSTRACT: Nonlinear transverse vibration response is investigated for bilayer graphene sheets (BLGSs) in thermal environments by using molecular dynamics simulation and nonlocal elasticity. The BLGS is modeled as a nonlocal double-layered plate which contains small scale effect and van der Waals interaction forces. The geometric nonlinearity in the von Kármán sense is adopted. The thermal effects are included and the material properties are assumed to be size-dependent and temperature-dependent, and are obtained from molecular dynamics simulations. The small scale parameter $e_0a$ is estimated by matching the natural frequencies of graphene sheets observed from the molecular dynamics simulation results with the numerical results obtained from the nonlocal plate model. The results show that the stacking sequence has a small effect, while the aspect ratio has a moderate effect on the nonlinear vibration response of BLGSs. In contrast, the temperature change has a significant effect on the nonlinear vibration response of BLGSs. The results reveal that the small scale effect also plays an important role in the nonlinear vibration of BLGSs.


ABSTRACT: We introduce a class of explicit coupling schemes for the numerical solution of fluid–structure interaction problems involving a viscous incompressible fluid and a general thin-walled structure (e.g., including damping and non-linear behavior). The fundamental ingredient in these methods is a (parameter free) explicit Robin interface condition for the fluid, which enables the fluid–solid splitting through appropriate extrapolations of the solid velocity and fluid stress on the interface. The resulting solution procedures are genuinely partitioned. Stability and error estimates are provided for all the variants (depending on the extrapolations), using energy arguments within a representative linear setting. In particular, we show that one of them simultaneously yields added-mass free unconditional stability and optimal (first-order) time accuracy. A comprehensive numerical study, involving different examples from the literature, supports the theory.

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ABSTRACT: This paper presents a postbuckling analysis of carbon nanotube-reinforced functionally graded (CNTR-FG) cylindrical panels under axial compression. Based on kernel particle approximations for the field variables, the Ritz method is employed to obtain the discretized governing equations. The cylindrical panels are reinforced by single-walled carbon nanotubes (SWCNTs) which are assumed to be graded through the thickness direction with different types of distributions. The effective material properties of CNTR-FG cylindrical panels
are estimated through a micromechanical model based on the extended rule of mixture. To eliminate shear locking for a very thin cylindrical panel, the system’s bending stiffness is evaluated by a stabilized conforming nodal integration scheme and the membrane as well as shear terms are calculated by the direct nodal integration method. In the present study, the arc-length method combined with the modified Newton–Raphson method is used to trace the postbuckling path. Detailed parametric studies are carried out to investigate effects of various parameters on postbuckling behaviors of CNTR-FG cylindrical panels and results for uniformly distributed (UD) CNTR-FG cylindrical panel are provided for comparison.

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ABSTRACT: Solid-shell formulations based on reduced integration with hourglass stabilization have several advantages. Among these are the smaller number of Gauss points and the direct modelling of the thickness stretch, a feature which is usually not present in standard degenerated shell elements. The latter issue is especially important for applications where contact is involved, e.g. for almost all relevant systems in production technology. Obviously this makes solid-shell formulations very attractive for their use in industrial design. A major disadvantage in the context of explicit analyses is, however, the fact that the critical time step is determined by the thickness of the solid-shell element which is usually smaller than the smallest in-plane dimension. Therefore, four-node shells (where the critical time step is determined by the in-plane dimensions) are still often preferred for explicit analysis. In the present paper we suggest several techniques to overcome this difficulty, also in the case of problems dominated by nonlinearities such as finite deformations, elastoplasticity and contact. Reference is made to an 8-node hexahedron solid-shell element recently proposed by Schwarze and Reese (2011) [32] in an implicit context. First of all, the time steps in explicit analyses are so small that it may be not necessary to update the hourglass stabilization and the implicit computation of the internal element degrees-of-freedom in every time step. Performing the update in only every hundredth step or computing an explicit rather than implicit update can reduce the computational effort up to about 50%. Another important issue is selective mass scaling which means to modify the mass matrix in such a way that the speed of sound in thickness direction is reduced. This enables the choice of a larger time step. The CPU effort can be finally noticeably decreased without changing the structural response significantly. This makes the presently used solid-shell formulation competitive to four-node shells, also for explicit analysis.

ABSTRACT: A NURBS-based continuum approach of cloth simulation is presented. Cloth geometry is described by NURBS, and the dynamic response is modeled by displacement-only NURBS shell. The shell formulation, including a constitutive description for cloth-like materials and an algorithmic treatment of multi-patch models, is discussed in detail. A fully NURBS based contact/impact update algorithm is presented. Numerical examples are included to demonstrate the performance and the application of the method.
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ABSTRACT: This paper presents the formulation and numerical implementation of the improved complex variable element-free Galerkin (ICVEFG) method for two-dimensional large deformation problems of elastoplasticity in total Lagrangian description. The ICVEFG method is a novel element free Galerkin (EFG) method based on the improved complex variable moving least-squares (ICVMLS) approximation. The ICVMLS approximation has all the advantages inherited from the complex variable moving least-squares (CVMLS) approximation. The function $J$ in the ICVMLS approximation has an explicit physical meaning, compared with the former. The Galerkin weak form is employed to obtain the equations system and the penalty method is used to apply essential boundary conditions. Several numerical examples presented show that the ICVEFG method has greater precision and efficiency compared to the EFG and CVEFG methods.

ABSTRACT: This work applies the framework of a concurrent multiscale approach to the buckling analysis of carbon nanotubes. In particular, the bridging domain method is used to couple a molecular statics model and a continuum mechanics model. The total potential energy of the entire structure is specified by weighted individual energy contributions of overlapping subdomains. In this handshake region, additional kinematics constraints enforce the compatibility between designated atoms and the continuum body. Three different methods are taken into consideration for the kinematics coupling and the corresponding governing equations are presented. The continuum subdomain is handled by means of a finite element approach and the molecular statics is formulated suitable for a common computational implementation. A series of numerical examples investigates the capability of the bridging domain method for its application in the analysis of carbon nanotubes. Initially, the individual approaches for integrating the kinematics constraints into the global equilibrium equations are compared. Then, in the major contribution of the work, the influences of several modelling parameters of the multiscale model on the buckling analysis of a bent single-walled carbon nanotube are numerically studied. In particular, the size of the atomistic section, the extent of the handshake region and the finite element discretisation are varied. Furthermore, the results obtained by the standard and the relaxed variant of the bridging domain method are compared against each other. In addition, the buckling behaviour of a defective carbon nanotube with varying defect locations is presented. The obtained results of the bridging domain multiscale method are persistently validated against full atomistic molecular statics simulations.

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ABSTRACT: An isogeometric continuum shell formulation is proposed in which NURBS basis functions are used to construct the reference surface of the shell. Through-the-thickness behavior is interpolated using a higher-order B-spline which is in contrast to the standard continuum shell (solid-like shell) formulation where a linear Lagrange shape function is typically used in the thickness direction. The present formulation yields a complete isogeometric representation of the continuum shell. The shell element is implemented in a standard finite element code using Bézier extraction which facilitates numerical integration on the reference surface of the shell. Through-the-thickness integration is done using a connectivity array which determines the support of a B-spline basis function over an element. The formulation has been verified using different linear and geometrically non-linear examples. The ability of the formulation in modelling buckling of static delaminations in composite materials is also demonstrated.

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ABSTRACT: The paper presents a complete experimental validation of an advanced computational methodology adapted to the nonlinear post-buckling analysis of geometrically nonlinear structures in presence of uncertainty. A mean nonlinear reduced-order computational model is first obtained using an adapted projection basis. The stochastic nonlinear computational model is then constructed as a function of a scalar dispersion parameter, which has to be identified with respect to the nonlinear static experimental response of a very thin cylindrical shell submitted to a static shear load. The identified stochastic computational model is finally used for predicting the nonlinear dynamical post-buckling behavior of the structure submitted to a stochastic ground motion.

ABSTRACT: This paper focuses on the development of a global–local doubly-curved shell element, suitable for small-deformation implicit and/or explicit dynamic analysis of laminated composite structures. The global–local framework is based on the superposition of a global displacement field, spanning the thickness of the entire laminate, and local (layerwise) displacement fields associated with each layer of the laminate. This approach affords highly-resolved representations in regions of critical interest, and allows a smooth transition from higher to lower resolution zones. Continuity between adjacent layers is enforced by means of discontinuous Galerkin fluxes. Parasitic phenomena characteristic of bilinear shell elements, such as shear locking, are alleviated with the aid of assumed natural strain techniques. Performance characteristics of the proposed finite element are examined with the aid of several numerical examples involving static and dynamic analysis of thick as well as thin shells.
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ABSTRACT: Accurate predictions of the buckling load in imperfection sensitive shell structures requires precise knowledge of the location and magnitude of any geometric imperfections in the shell (e.g. dents). This work describes a non-contact approach to identifying such imperfections in a submerged shell structure. By monitoring the acoustic pressure field at discrete points proximal to a shell structure excited by a cyclic membrane (i.e. in-plane) loading, it is noticed that parameters, describing small scale denting, can be identified. In order to perform the identification, a fluid-structure model that predicts the spatio-temporal pressure field is required. This model is described in detail and includes the predicted effects of the imperfection on the observations. A Bayesian, Markov chain Monte Carlo approach is then used to generate the imperfection parameter estimates and quantify the uncertainty in those estimates. Additionally: for cases involving the occurrence of an unknown number of dents, reversible jump Markov chain Monte Carlo (RJMCMC) methods are employed in this work.

ABSTRACT: In this article, the nonlocal but linear vibrations of carbon nano-tubular shells are analyzed subjected to both internal and external flows. This analysis is addressed for both separate flows as well as concurrent flows by considering slip condition. We observe that both nonlocal parameter and Kn could decrease the eigen-frequency and critical velocity of the first-mode divergence. It is observed that the existence of quiescent fluid does not impress the value of divergence velocity. Nonetheless, the frequencies are declined substantially. Besides, we perceive that CNT subjected to both internal and external flows loses its stability drastically sooner as compared with that subjected to each flow separately. Furthermore, it is observed that an increase in the value of mass density of the external flow results in a greater decrease in the eigen-frequencies as well as the divergence velocity.

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ABSTRACT: We study the spectral approximation properties of finite element and NURBS spaces from a global perspective. We focus on eigenfunction approximations and discover that the Lsquared-norm errors for
finite element eigenfunctions exhibit pronounced “spikes” about the transition points between branches of the eigenvalue spectrum. This pathology is absent in NURBS approximations. By way of the Pythagorean eigenvalue error theorem, we determine that the squares of the energy-norm errors of the eigenfunctions are the sums of the eigenvalue errors and the squares of the Lsquared-norm eigenfunction errors. The spurious behavior of the higher eigenvalues for standard finite elements is well-known and therefore inherited by the energy-norm errors along with the spikes in the Lsquared-norm of the eigenfunction errors. The eigenvalue pathology is absent for NURBS. The implications of these results to the corresponding elliptic boundary-value problem and parabolic and hyperbolic initial-value problems are discussed.

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ABSTRACT: A large deflection geometrically nonlinear behavior of carbon nanotube-reinforced functionally graded (CNTR-FG) cylindrical panels under uniform point transverse mechanical loading is studied. The analysis is carried out using the kp-Ritz method with kernel particle function is employed to construct the shape functions for the two-dimensional displacement approximations. Based on the first-order shear deformation shell theory, nonlinear governing equations are developed with geometric nonlinearity taking the form of von Kármán strains. It is assumed that carbon nanotubes are uniaxially aligned in the axial direction and are functionally graded in thickness direction of the cylindrical panels. The effective material properties of resulting CNTR-FG panels are estimated by employing an equivalent continuum model based on the Eshelby–Mori–Tanaka approach. A stabilized conforming nodal integration scheme is employed to evaluate the system bending stiffness and the membrane as well as shear terms are calculated by the direct nodal integration method to eliminate shear locking, for a very thin cylindrical panel. Several numerical example problems are examined to reveal the influences of volume fraction of carbon nanotubes, span angle, edge-to-radius ratio and thickness on nonlinear responses of the CNTR-FG panels. Moreover, effects of different boundary conditions and distribution type of carbon nanotubes are also investigated.

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ABSTRACT: We present isogeometric shape optimization for shell structures applying sensitivity weighting and semi-analytical analysis. We use a rotation-free shell formulation and all involved geometry models, i.e.,
initial design, analysis model, optimization model, and final design use the same geometric basis, in particular NURBS. A sensitivity weighting scheme is presented which eliminates certain effects of the chosen discretization on the design update. A multilevel design approach is applied such that the design space can be chosen independently from the analysis space. The use of semi-analytical sensitivities allows having different polynomial degrees for design and analysis model. Different numerical examples are performed which confirm the applicability of the proposed method. Furthermore, a shape optimization example with an exact solution is presented which can serve as general benchmark for shape optimization methods.


ABSTRACT: In this contribution a global and linear method for controlling the surface mesh quality during node-based shape optimization is presented. In this method, an artificial stress is applied on the surface mesh and the global linear system of equations is solved for the equilibrium state by finite elements. The applied stress adapts each element towards a desired predefined template geometry and at the end a globally smooth mesh is achieved. In this way both the shape and the size of each element is controlled. Some examples, as well as possible fields of application are shown. At the end, the strength of the method in shape optimization of computational fluid dynamics problems is described.


ABSTRACT: This work presents a framework for the computation of complex geometries containing intersections of multiple patches with Reissner–Mindlin shell elements. The main objective is to provide an isogeometric finite element implementation which neither requires drilling rotation stabilization, nor user interaction to quantify the number of rotational degrees of freedom for every node. For this purpose, the following set of methods is presented. Control points with corresponding physical location are assigned to one common node for the finite element solution. A nodal basis system in every control point is defined, which ensures an exact interpolation of the director vector throughout the whole domain. A distinction criterion for the automatic quantification of rotational degrees of freedom for every node is presented. An isogeometric Reissner–Mindlin shell formulation is enhanced to handle geometries with kinks and allowing for arbitrary intersections of patches. The parametrization of adjacent patches along the interface has to be conforming. The shell formulation is derived from the continuum theory and uses a rotational update scheme for the current director vector. The nonlinear kinematic allows the computation of large deformations and large rotations. Two concepts for the description of rotations are presented. The first one uses an interpolation which is commonly used in standard Lagrange-based shell element formulations. The second scheme uses a more elaborate concept proposed by the authors in prior work, which increases the accuracy for arbitrary curved geometries. Numerical examples show the high accuracy and robustness of both concepts. The applicability of the proposed framework is demonstrated.

ABSTRACT: Dynamic interaction of an inclined stocky single-walled carbon nanotube (SWCNT) and a viscous nanofluid flow in the context of nonlocal continuum theory of Eringen is of concern. The SWCNT is modeled based on the nonlocal Timoshenko and higher-order beam theories. To this end, the governing equations of an inclined SWCNT are constructed for each nonlocal beam by taking into account the applied interaction forces on the inner surface of the SWCNT. By employing a slip-flow model and using Newton’s second law, the governing equations of the viscous nanofluidic flow inside the SWCNT are obtained. Through combining the resulting governing equations of the SWCNT and those of the nanofluidic flow, the dimensionless governing equations of the SWCNT conveying nanofluid flow are established. Using Galerkin method, the discrete form of the governing equations is obtained for each nonlocal beam model. In the case of a SWCNT with simply supported and immovable ends, the resulting sets of ordinary differential equations are solved in the time domain via an efficient scheme. The effects of the slenderness ratio, small-scale parameter, speed and density of the nanofluid flow, inclination angle, and initial axial force within the SWCNT on the maximum values of dynamic longitudinal and transverse displacements as well as maximum values of nonlocal axial force and bending moment within the SWCNT are examined and discussed.

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ABSTRACT: NURBS-based isogeometric analysis was first extended to thin shell/membrane structures which allows for finite membrane stretching as well as large deflection and bending strain. The assumed non-linear kinematics employs the Kirchhoff–Love shell theory to describe the mechanical behaviour of thin to ultra-thin structures. The displacement fields are interpolated from the displacements of control points only, and no rotational degrees of freedom are used at control points. Due to the high order (math) continuity of NURBS shape functions the Kirchhoff–Love theory can be seamlessly implemented. An explicit time integration scheme is used to compute the transient response of membrane structures to time-domain excitations, and a dynamic relaxation method is employed to obtain steady-state solutions. The versatility and good performance of the present formulation are demonstrated with the aid of a number of test cases, including a square membrane strip under static pressure, the inflation of a spherical shell under internal pressure, the inflation of a square airbag and the inflation of a rubber balloon. The mechanical contribution of the bending stiffness is also evaluated.
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“A seven-parameter spectral/hp finite element formulation for isotropic, laminated composite and functionally
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ABSTRACT: In this paper we apply high-polynomial order spectral/hp basis functions in the numerical
implementation of a novel 7-parameter continuum shell finite element formulation using general quadrilateral
finite elements. The implementation is applicable to the analysis of isotropic, functionally graded and laminated
composite shells undergoing fully geometrically nonlinear mechanical response. The shell finite element
formulation is constructed in a purely displacement-based setting such that no mixed variational procedures are
employed and full numerical integration of all quantities appearing in the virtual work statement is performed
using high-order Gauss–Legendre quadrature rules. An efficient procedure for numerically integrating the
discrete weak formulation through the shell thickness is implemented; hence no thin- or shallow-shell type
restrictions are imposed on the element. For the case of laminated composites, we introduce a discrete tangent
vector field, defined on the approximate shell mid-surface, that permits the use of skewed and/or arbitrarily
curved elements in the numerical simulation of complex shell structures. To reduce computer memory
requirements in the numerical implementation we adopt element-level static condensation, wherein, the interior
degrees of freedom of each element are implicitly eliminated prior to assembly of the global sparse finite
element coefficient matrix; an approach that results in storage requirements that are on par with traditional low-
order finite element implementations. The accuracy and overall robustness of the developed shell element are
illustrated through the solution of several nontrivial benchmark problems taken from the literature. These
numerical studies provide evidence that the proposed shell element may be used to obtain accurate locking-free
results and that large load increments can be employed (in the numerical simulation of shell structures
undergoing very large deformations).

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buckling analyses of imperfection sensitive structures”, Computer Methods in Applied Mechanics and
ABSTRACT: The Koiter–Newton approach is a reduced-basis method for nonlinear structural analyses. The
method combines Koiter’s approach as a predictor step and the Newton arc-length technique as a corrector step
to trace the entire load–displacement equilibrium path of a structure in a step by step manner. This
computationally highly efficient and accurate solution method has recently demonstrated a superior
performance in nonlinear analyses compared to standard techniques. In this paper we propose an extension to
buckling imperfection sensitivity analyses exploiting the method’s stability and reliability. We present two
different modeling techniques for imperfection loads that both profit from the Koiter–Newton approach
reducing the initial computation steps to a small fraction thereof. We introduce von Kármán kinematics which
neglect some nonlinear terms of the Green strain–displacement relations to further increase the computational
efficiency of the analysis by an essential reduction of the computation effort required to obtain higher order
derivatives of the strain energy. Using various numerical examples and benchmark tests we demonstrate the
overall high quality and performance of the proposed method.
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ABSTRACT: The paper deals with the computations of so-called geometrically exact shells with scale effects. These type of computations are relevant to thin-walled structures at small scales (e.g. thin films, nanotubes etc.). The shell formulation exhibits higher order gradients and is developed following some author’s recent work on generalised continua. The framework has been modified as to account for two-dimensional surfaces as well. The shell formulation reduces to a standard one upon disregarding the higher gradient terms. The classical part of the formulation is a well known 7-parameter model previously developed by one of the authors which takes thickness change into account. The numerical treatment is based on a meshfree formulation which provides the necessary C1 continuity. As possible applications, dynamic buckling of cylindrical and spherical shells is investigated and some results for various states of loading and scale parameters are presented. The examples include also nanotubes of different dimensions where scale effects matter. The influence of the extra gradients is well demonstrated resulting in different buckling behaviours.

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ABSTRACT: This paper presents a two-dimensional finite element model to investigate global and local instability phenomena in sandwich plates. In particular, global buckling and symmetrical and antisymmetrical wrinkling are studied. The classical plate theory is used to model the mechanics of the skins, whereas a higher-order kinematics is adopted for the core. By imposing the continuity of the displacement field at skin/core interfaces and a linear variation of the through-the-thickness shear stresses, a model with nine field variables, resulting 15 degrees of freedom per node is obtained. The weak form of the governing equations is obtained by the principle of virtual work. The equations are discretized by means of the finite element method. The resulting non-linear system is solved by asymptotic numerical method. Several boundary conditions and loads are considered. The presented results are validated towards analytical models and three-dimensional finite element
solutions. The numerical investigations show that the assumed kinematics permits to accurately yet efficiently predict the critical load of both global and local buckling as well as the post-bifurcation response.


ABSTRACT: We present a global–local finite element formulation for the analysis of doubly-curved laminated composite shells. The proposed formulation is applicable to a wide range of problems, including those involving finite strains/rotations, nonlinear constitutive behavior, and static or dynamic structural response. Moreover, in dynamic analysis applications, it can be combined with either explicit or implicit time integration schemes. The global–local framework is based on the superposition of a global displacement field, spanning the thickness of the entire laminate, and local (i.e. layerwise) displacement fields associated with each layer in the laminate. This approach affords highly-resolved representations in regions of critical interest, and allows a smooth transition from higher to lower resolution zones. Discontinuous Galerkin fluxes are used to enforce interlaminar continuity conditions in perfectly-bonded laminates, and the cohesive-zone methodology is used to represent interfacial delamination. Stresses and surface normals are referred to the initial configuration in the proposed total Lagrangian formulation. Assumed natural strain and enhanced assumed strain techniques are employed to alleviate shear locking and other pathologies that are known to afflict bilinear shell elements. The performance of the proposed finite element is examined with the aid of several numerical examples involving thick as well as thin shells.

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ABSTRACT: B-spline reduced quadrature rules are proposed in the context of isogeometric analysis. When performing a full Gaussian integration, the high regularity provided by spline basis functions strengthens the locking phenomena and deteriorates the performance of Reissner–Mindlin elements. The uni-dimensional B-spline-based quadrature rules, given in a previous paper (part I), are extended to multi-dimensional problems such as plates and shells. The improved reduced integration schemes are constructed using a tensor product of the uni-dimensional schemes. A single numerical quadrature is performed for bending, transverse shear and membrane terms, without introducing Hourglass modes. The proposed isogeometric reduced elements are free from membrane and transverse shear locking. Convergence is first assessed in plate problems with several aspect ratios and then in the shell obstacle course problems. The resulting under-integrated elements exhibit better accuracy and computational efficiency.
ABSTRACT: A large-deformation, isogeometric rotation-free Kirchhoff–Love shell formulation is equipped with a damage model to efficiently and accurately simulate progressive failure in laminated composite structures. The damage model consists of Hashin’s theory of damage initiation, a bilinear material model for damage evolution, and an appropriately chosen Gibbs free-energy density. Four intralaminar modes of failure are considered: Longitudinal and transverse tension, and longitudinal and transverse compression. The choice of shell formulation and modes of failure modeled make the proposed methodology valid in the regime of relatively thin shell structures where damage occurs without significant evidence of delamination. The damage model is extensively validated against experimental data and its use is also illustrated in the context of multiscale composite damage analysis.

ABSTRACT: A new concept called analysis in computer aided design (AiCAD) is proposed for design-through-analysis workflow. This concept uses non-uniform rational B-Splines (NURBS)-based B-Rep models for the entire workflow. Such models consist of trimmed NURBS surfaces and are considered standard in the...
industry, especially for modeling free-form geometries. The newly developed isogeometric B-Rep analysis (IBRA) used in AiCAD is also presented. IBRA can be considered as a generalization of isogeometric analysis (IGA) that uses the boundary representation (B-Rep) of the design model in addition to the same basis functions as in IGA for approximating the solution fields. IBRA provides the framework for creating a direct and complete analysis model from computer aided design (CAD) in a consistent finite-element-like manner. Thus, IBRA allows analyzing a CAD model without remodeling and meshing, even for complex geometries. For the numerical integration of trimmed surfaces, the concept of nested Jacobian approach (NEJA) with NURBS surfaces is introduced. In addition, for enforcing the different types of boundary conditions or mechanical entities, a new finite element type called isogeometric B-Rep element is introduced. Elements of this type permit enforcing, e.g., coupling or Dirichlet boundary conditions. A corresponding formulation based on a penalty approach is presented as well. The proposed workflow is realized exemplarily for surface modeling and the geometrical nonlinear analysis of shell structures. The differences between the standard analysis procedure and the AiCAD workflow are explained in detail. Various numerical examples confirm the accuracy, flexibility, and robustness of the proposed IBRA concept, thus highlighting its advantages for the realization of design-through-analysis workflow with a uniform geometry representation.

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ABSTRACT: This paper presents a hybrid finite-element/boundary-element method for fluid–structure-interaction simulations of inflatable structures. The flow model consists of the steady Stokes equation, which admits a boundary-integral formulation. The structure is represented by a Kirchhoff–Love shell. The boundary-element approximation of the Stokes equation reduces the flow problem to an integral equation on the actual structure configuration, thus obviating the need for volumetric meshing of the strongly deforming fluid domain. The Stokes model moreover exhibits a lubrication effect that acts as an intrinsic mechanism to treat the ubiquitous self-contact that occurs in inflation problems. The aggregated fluid–structure-interaction problem, composed of the boundary-integral equation and the Kirchhoff–Love shell connected by dynamic and kinematic interface conditions, is approximated by means of isogeometric discretizations to accommodate the smoothness requirements on the approximation spaces imposed by the flexural rigidity in the Kirchhoff–Love shell and to provide an accurate and smooth representation of the boundary for the boundary-element method. Auxiliary results presented in this paper are: (1) a parametrization-free Kirchhoff–Love formulation; (2) establishment of a cubic relationship between distance and tractions due to the lubrication effect; and (3) the interpretation of the Lagrange multiplier pertaining to fluid incompressibility as the total excess pressure.

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ABSTRACT: In this work, a recently proposed quadratic NURBS-based solid-shell element based on the Assumed Natural Strain (ANS) method is applied in the analysis of shell-like structures in the geometrical nonlinear regime, together with small strain plasticity. The proposed formulation is based on the additive split of the Green–Lagrange strain tensor, leading to a straightforward implementation of the nonlinear kinematics and to the introduction of a corotational coordinate system, used to integrate the constitutive law, ensuring incremental objectivity. Since the proposed approach is based on Updated Lagrangian formulation combined with a corotational coordinate system, the extension of the ANS methodology is straightforward. Well-known benchmark tests are employed to assess the performance of the proposed formulation and to establish a detailed comparison with the formulations available in the literature. The results indicate that the proposed solid-shell approach based on the NURBS ANS methodology presents good predictability characteristics in the analysis of elasto-plastic thin-shell structures subjected to large deformations.

ABSTRACT: Thin shell structures are widely used in the aerospace, automotive and mechanical engineering industries. They are ideal candidates for the isogeometric analysis paradigm profiting from the smoothness of the geometry model, and the higher order approximation and higher continuity properties of NURBS. To model complex shell structures which need to be assembled from multiple patches, the bending stiffness should be maintained across the patch interfaces. We propose a variationally consistent weak coupling method for thin-walled shell patches. The method overcomes the need for $C^1$-continuity along the patch interface to ensure a corresponding geometric continuity in the deformed configuration and a correct transfer of bending moments across the interface. Importantly, it allows a blended coupling of shells based on different mathematical models, e.g. Kirchhoff–Love and solid-like shell models. The proposed approach retains the high level of accuracy of single patch solutions and reveals its potential for authentic multi-patch NURBS modeling. We illustrate the good performance of the method for pure Kirchhoff–Love shell models and blended shell models with various examples. The presented approach supports local model refinements where e.g. full 3D stress states are of interest, and further opens the door for the coupling of laminated composites belonging to different lamina theories.

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ABSTRACT: Topology optimization often leads to structures consisting of slender elements which are particularly sensitive to geometric imperfections. Such imperfections might affect the structural stability and induce large displacement effects in these slender structures. This paper therefore presents a robust approach to
topology optimization which accounts for geometric imperfections and their potentially detrimental influence on the structural stability. Geometric nonlinear effects are incorporated in the optimization by means of a Total Lagrangian finite element formulation in the minimization of end-compliance. Geometric imperfections are modeled as a vector-valued random field in the design domain. The resulting uncertain performance of the design is taken into account by minimizing a weighted sum of the mean and standard deviation of the compliance in the robust optimization problem. These stochastic moments are typically estimated by means of sampling methods such as Monte Carlo simulation. However, these methods require multiple independent nonlinear finite element analyses in each design iteration of the optimization algorithm. An efficient solution algorithm which uses adjoint differentiation in a second-order perturbation method is therefore developed to estimate the stochastic moments during the optimization. Two applications with structures that exhibit different types of structural instabilities are examined. In both cases, it is demonstrated by means of an extensive Monte Carlo simulation that the deterministic design is very sensitive to imperfections, while the design obtained by means of the proposed method is much more robust.

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ABSTRACT: The intentional or accidental cutting of thin shell structures by means of a sharp object is of interest in many engineering applications. The process of cutting involves several types of nonlinearities, such as large deformations, contact, crack propagation and, in the case of laminated shells, delamination. In addition to these, a special difficulty is represented by the blade sharpness, whose accurate geometric resolution would require meshes with characteristic size of the order of the blade curvature radius. A computational finite element approach for the simulation of blade cutting of thin shells is proposed and discussed. The approach is developed in an explicit dynamics framework. Solid-shell elements are used for the discretization, in view of possible future inclusion in the model of delamination processes. Since a sharp blade can interfere with the transmission of cohesive forces between the crack flanks in the cohesive process zone, standard cohesive interface elements are not suited for the simulation of this type of problems unless extremely fine meshes, with characteristic size comparable to the blade curvature radius, are used. To circumvent the problem, the use of a new type of directional cohesive interface element, previously proposed for the simulation of crack propagation in elastic shells, is further developed and reformulated for application to the cutting of elastoplastic thin structures, discretized by solid-shell elements. The proposed approach is validated by means of application to several cutting problems of engineering interest.

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ABSTRACT: While the 3D elasticity and the available local and zigzag theories encounter inaccuracies for very thin plates, results of the global theories become unreliable for thick plates with severe transverse variations in the material properties. In the present research, a quadratic finite element global–local sandwich
plate theory with elasticity correction (stress recovery) is proposed for static stress and displacement analysis of sandwich plates with orthotropic face sheets and single or dual cores. Since the transverse shear stresses are derived based on the three-dimensional theory of elasticity, the continuity condition of the transverse shear stresses is satisfied at the interfaces between the layers, a priori. The presented theory not only leads to higher accuracies in comparison to the available high-order zigzag theories in some cases (especially, for soft or dual cores) but also it is computationally more economic. Results show that the results of the available zigzag and global–local theories may encounter inaccuracy problems not only for huge numbers of the sub-layers, but also for small numbers of the orthotropic layers.

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ABSTRACT: We present formulations for compressible and incompressible hyperelastic thin shells which can use general 3D constitutive models. The necessary plane stress condition is enforced analytically for incompressible materials and iteratively for compressible materials. The thickness stretch is statically condensed and the shell kinematics are completely described by the first and second fundamental forms of the midsurface. We use $C^1$-continuous isogeometric discretizations to build the numerical models. Numerical tests, including structural dynamics simulations of a bioprosthetic heart valve, show the good performance and applicability of the presented methods.

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ABSTRACT: Computational modeling of thin biological membranes can aid the design of better medical devices. Remarkable biological membranes include skin, alveoli, blood vessels, and heart valves. Isogeometric analysis is ideally suited for biological membranes since it inherently satisfies the $C^1$-requirement for Kirchhoff–Love kinematics. Yet, current isogeometric shell formulations are mainly focused on linear isotropic materials, while biological tissues are characterized by a nonlinear anisotropic stress–strain response. Here we present a thin shell formulation for thin biological membranes. We derive the equilibrium equations using curvilinear convective coordinates on NURBS tensor product surface patches. We linearize the weak form of the generic linear momentum balance without a particular choice of a constitutive law. We then incorporate the constitutive equations that have been designed specifically for collagenous tissues. We explore three common anisotropic material models: Mooney–Rivlin, May Newman–Yin, and Gasser–Ogden–Holzapfel. Our work will allow scientists in biomechanics and mechanobiology to adopt the constitutive equations that have been
developed for solid three-dimensional soft tissues within the framework of isogeometric thin shell analysis.

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ABSTRACT: The finite element implementation of a geometrically exact thin shell model is reported in the present paper. The shell kinematics is based on the Kirchhoff–Love assumption and is characterized by the deformation gradient, which yielded the generalized cross-section strain measures — stretches and curvatures, written in terms of first- and second-order derivatives of displacements. The energetically conjugate quantity, the first Piola–Kirchhoff stress tensor, is used to define the generalized stresses. The shell’s initial geometry is exactly represented using a mapping from a reference configuration. A neo-Hookean material functional, supplemented by the plane stress condition, is incorporated in the constitutive level of the model. Both configuration dependent and independent forces are considered for the domain and boundary loading. The consistent linearization of the rendered weak form is addressed. The TUBA family of plate finite elements is adopted for the discretization of the displacement vector field. These triangular elements, with necessarily straight sides in the reference configuration, provide C1 continuous approximations, a sine qua non property for a consistent discretization of the Kirchhoff–Love model. The family contains 3 pairs of elements (primary and reduced), which provide polynomial approximants of degrees k = 5, 6 and 7, respectively. The reduced elements have a simpler structure and a smaller number of nodes, but still guarantee C1 continuity. The boundary normal derivative of the approximation in these elements is constrained, such that its order is reduced by one unit, from (k-1) at the primary elements to (k-2). Due to complexity of the elements degrees of freedom (which are the function value, its normal, first- and second-order derivatives), the imposition of the essential boundary conditions requires some preliminary analysis of the boundary behavior. Such study is presented for the most common practical cases. Six benchmark examples are presented to demonstrate the model usefulness and efficiency.

ABSTRACT: In this article, based on the most general form of strain gradient theory (MGSGT), a novel extended triangular Mindlin plate element is proposed. To accomplish this aim, first, the quadratic form of energy functional is obtained by vectorizing the higher-order tensors of energy pairs, from which the stiffness and mass matrices of the element are readily derived. In comparison with the standard Mindlin plate element, the new element needs three additional nodal degrees of freedom (DOF) including derivatives of lateral deflection and rotations, which means a total of nine DOFs per node. Also, as compared to the standard Mindlin plate element which requires only Co shape functions, the present one requires C1 continuous smooth shape functions due to second derivatives of deflection and rotations. Hence, cubic polynomials are used to interpolate the displacement components. The new element can be reduced to that based on the modified strain gradient
theory (MSGT) and the modified couple stress theory (MCST). Moreover, the standard Mindlin plate element is recovered when the gradient-based material parameters tend to zero. The Mindlin microplates with different boundary conditions are considered as the problem under study whose free vibration and bending are analyzed. The results are compared with the exact solutions and excellent agreement is achieved.

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ABSTRACT: An improved moving least-squares (IMLS) approximation for the field variables is proposed for geometrically nonlinear large deformation analysis of functionally graded carbon nanotube (FG-CNT) reinforced composite quadrilateral plates. The plate considered is of moderate thickness and, hence, the first-order shear deformation theory (FSDT) and Von Kármán assumption are adopted to incorporate the transverse shear strains, rotary inertia and moderate rotations. The CNTs are assumed to be uniaxially aligned in the axial direction and functionally graded in the plate thickness direction. The discrete nonlinear governing equation is derived based on the IMLS-Ritz method. The modified Newton–Raphson method combined with the arc-length iterative algorithm is employed to solve the nonlinear deformation of the FG-CNT reinforced composite quadrilateral plates. Improvements in computational efficiency and elimination of shear and membrane locking are achieved using a stabilized conforming nodal integration scheme to evaluate the system’s bending stiffness. Through detailed parametric studies, CNT distribution, CNTs volume fraction, aspect ratio and thickness-to-width ratio and different boundary conditions are demonstrated to effect significantly on the large deflection behaviors of the quadrilateral FG-CNT reinforced composite plates.

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ABSTRACT: One of the main properties of cardiovascular stents is to properly bend in order to accommodate the tortuous vascular structure and Finite Element Analyses (FEA) are currently the preferred computational tool to properly evaluate the stent response under bending. Isogeometric Analysis (IgA) has recently emerged as a cost-effective alternative to classical FEA, based on the use of typical CAD basis functions for both geometric
description and variable approximation. This implies the capability to describe accurately the computational domain geometry and, typically, a better approximation of the solution with many fewer degrees of freedom with respect to FEA. Accordingly, this work aims at describing a computational framework based on IgA to evaluate the mechanical performance of endovascular stents. In particular, stent bending analyses involving large deformations are performed using both IgA and classical FEA for two carotid artery stent designs. The results discussed here suggest that for a given level of accuracy IgA attains a better performance with at least one order of magnitude fewer degrees of freedom than classical FEA. Moreover IgA shows an improved capability to reproduce local geometrical instabilities due to buckling.

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ABSTRACT: In this paper, we develop a general framework for the extension of mixed displacement-stress types of formulations to elastoplastic problems under small strains. The difficulty with such formulations is that, contrary to the more usual mixed methods used for incompressible materials, plasticity (which involves the deviatoric part of the stress) is affected by the static unknown. Thus, the plastic flow is not governed by displacement-induced strains alone. The approach followed in this paper consists in choosing the total elastic stress as the static unknown of the mixed formulation. Then, one determines a strain field which is used as input for the plastic projection. We applied this formalism to the mixed NURBS-based solid-shell element of Bouclier et al. (2013, 2015), which led to an efficient extension of the element into the elastoplastic domain. We were able to verify the ability of this element to overcome shell locking problems through several test cases involving a plastic flow rule with linear isotropic strain hardening.


ABSTRACT: The harmonic balance (HB) method is widely used in the literature for analyzing the periodic solutions of nonlinear mechanical systems. The objective of this paper is to exploit the method for bifurcation analysis, i.e., for the detection and tracking of bifurcations of nonlinear systems. To this end, an algorithm that combines the computation of the Floquet exponents with bordering techniques is developed. A new procedure for the tracking of Neimark–Sacker bifurcations that exploits the properties of eigenvalue derivatives is also proposed. The HB method is demonstrated using numerical experiments of a spacecraft structure that possesses a nonlinear vibration isolation device.

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ABSTRACT: Isogeometric collocation methods have been recently proposed as an alternative to standard Galerkin approaches as they provide a significant reduction in computational cost for higher-order discretizations. In this work, we explore the application of isogeometric collocation to large deformation elasticity and frictional contact problems. We first derive the non-linear governing equations for the elasticity problem with finite deformation kinematics and provide details on their consistent linearization. Some numerical examples demonstrate the performance of collocation in its basic and enhanced versions, differing by the enforcement of Neumann boundary conditions. For problems with strong singularities, enhanced collocation is shown to outperform basic collocation and to lead to a spatial convergence behavior very similar to Galerkin, whereas for weaker or no singularities enhanced and basic collocation may give very similar results. A large deformation contact formulation is subsequently developed and tested in the frictional setting, where collocation confirms the excellent performance already obtained for the frictionless case. Finally, it is shown that the contact formulation in the collocation framework passes the contact patch test to machine precision in a three-dimensional setting with arbitrarily inclined non-matching discretizations, thus outperforming most of the available contact formulations and all those with pointwise enforcement of the contact constraints.

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ABSTRACT: In this paper, an efficient computational approach based on refined plate theory (RPT) including the thickness stretching effect, namely quasi-3D theory, in conjunction with isogeometric formulation (IGA) is proposed for the size-dependent bending, free vibration and buckling analysis of functionally graded nanoplate structures. The present novel quasi-3D theory not only possesses 4 variables as refined plate theory but also accounts for both shear deformation and stretching effect without any requirement of shear correction factors (SCFs). The size-dependent effect is taken into account by nonlocal elasticity theory. Isogeometric analysis shows a great advantage in dealing with the high continuity and high order derivative requirements of the displacement fields used in quasi-3D and nonlocal theory. The reliability and accuracy of the present method are ascertained by comparing the obtained results with other published ones. Numerical examples are also performed to show the significance of nonlocal effect, material distribution profile, aspect ratios and boundary conditions on the behaviour of FGM nanoplates.

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ABSTRACT: This paper presents, to the authors’ knowledge, a first known postbuckling analysis of carbon nanotube (CNT) reinforced functionally graded plates with edges elastically restrained against translation and rotation. The plate considered is of moderate thickness and, hence, the first-order shear deformation theory (FSDT) and von Kármán assumption are adopted to incorporate the effects of transverse shear strains, rotary inertia and moderate rotations. The element-free IMLS-Ritz method is employed. The cubic spline weight function and linear basis are utilized in the approximation. In this study, the bending stiffness is evaluated through the nodal integration scheme. The postbuckling path is traced using the arc-length method combined with the modified Newton–Raphson technique. Parametric studies on the postbuckling behavior of CNT reinforced functionally graded plates are conducted to examine the effects of CNT content by volume, plate width-to-thickness ratio and plate aspect ratio by varying the elastically restrained parameters of translation and rotation on the boundaries. The results of the present study are obtained for simplified cases so that comparison studies can be undertaken using the values reported in the literature.

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ABSTRACT: This paper presents an aerothermoelastic analysis of carbon nanotube (CNT) reinforced functionally graded composite panels in supersonic airflow. Meanwhile, the active flutter control of CNT reinforced functionally graded composite panels is also carried out using the piezoelectric actuator and sensor. Reddy’s third-order shear deformation theory is applied in the structural modeling. The equation of motion of the structural system is formulated using Hamilton’s principle and the assumed mode method. The displacement feedback algorithm is used to design the controller. The frequency domain method is applied to investigate the aerothermoelastic properties and active flutter control effects of the panels. The influences of CNT distribution, aspect ratio and thickness-to-length ratio on the aerothermoelastic properties of the CNT reinforced functionally graded composite panels are analyzed. Active flutter control effects under different thicknesses of CNT reinforced functionally graded composite panels are investigated. The optimal area and position of piezoelectric patches are also obtained by the genetic algorithm.

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ABSTRACT: In this paper, the problem of the postbuckling behavior of biaxially compressed straight-sided, functionally graded material (FGM) plates of quadrilateral shape is studied. The plate considered is subjected to in-plane loads on all four edges. A computational framework based on an improved moving least-squares (IMLS) approximation for the field variables is developed for the analysis. The solution procedures involved a transformation from the physical domain to a computational domain and then discrete the nonlinear governing equation using the IMLS-Ritz method. The first-order shear deformation theory (FSDT) with the von Kármán nonlinearity is employed. A nonlinear solution to the postbuckling of quadrilateral FGM plates is computed through the modified Newton–Raphson method combined with the arc-length iterative algorithm. A stabilized conforming nodal integration scheme is employed to improve computational efficiency and eliminate shear and membrane locking. The validity and accuracy of the numerical results are established through convergence studies. To the best of the authors’ knowledge, the problem has not been attempted in the open literature.

ABSTRACT: The development and numerical implementation of a special-purpose constitutive model is described for investigating the structural stability of cylindrical metal shells under axial compression and bending, which buckle in the inelastic range. The model employs von Mises yield surface ($J_2$ plasticity) and the rate form of $J_2$ deformation theory, leading to a non-associated flow rule. Special emphasis is given on plastic flow continuity. The numerical implementation is conducted through both the classical Euler-backward and Euler-forward substitution numerical schemes, where stress and strain tensors are described in curvilinear coordinates, with the extra constraint of zero normal stress through the shell thickness. The numerical results will be compared with available experimental data. The model is implemented within an in-house finite element technique for the nonlinear analysis of relatively thick cylindrical metal shells that uses a “tube-element” discretization, and it is employed for the solution of some benchmark problems.
Furthermore, influence of the Winkler-type elastic foundation on the post-buckling responses of the plate is investigated. In this regard, a full compatible C1-continuous 3D Hermitian element that in contrast to the conventional elements, satisfies the stress continuity condition at the mutual nodes of the adjacent elements, is employed to solve the governing equations of the post-buckling. The full Green’s strain tensor is employed instead of using the approximate von Karman strain–displacement expressions to enable tracing behavior of the plate for quite large deformations. The governing system of equations is solved by a condensation-based incremental under-relaxation Newton–Raphson procedure, due to sensitivity and high numerical compliance of the resulting highly non-linear finite element system of equations. Furthermore, new criteria are proposed for tracing the post-buckling behavior. Results reveal that the elastic foundation significantly affects the post-buckling mechanism and deformation pattern and post-buckling behavior of the plate is enhanced drastically by more negative Poisson’s ratios.

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ABSTRACT: This paper is a revisit of the work [Ladevèze and Pelle, Int. J. Numer. Methods Engrg. 28 (1989)] where the goal here is to acquire guaranteed, accurate and computable bounds of eigenfrequencies through post-processing of conventional finite element results. To this end, a new theoretical quotient is introduced and thereafter, a practical way to deal with the new quotient is developed where the constitutive relation error estimation featured with guaranteed bounding property acts as a key role. Academic numerical examples are performed to check the accuracy of the bounds.

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ABSTRACT: This work is concerned with the development of an efficient and robust isogeometric Reissner–Mindlin shell formulation for the mechanical simulation of thin-walled structures. Such structures are usually defined by non-uniform rational B-splines (NURBS) surfaces in industrial design software. The usage of isogeometric shell elements can avoid costly conversions from NURBS surfaces to other surface or volume geometry descriptions. The shell formulation presented in this contribution uses a continuous orthogonal rotation described by Rodrigues’ tensor in every integration point to compute the current director vector. The rotational state is updated in a multiplicative manner. Large deformations and finite rotations can be described accurately. The proposed formulation is robust in terms of stable convergence behavior in the nonlinear equilibrium iteration for large load steps and geometries with large and arbitrary curvature, and in terms of insensitivity to shell intersections with kinks under small angles. Three different integration schemes and their influence on accuracy and computational costs are assessed. The efficiency and robustness of the proposed isogeometric shell formulation is shown with the help of several examples. Accuracy and efficiency is
compared to an isogeometric shell formulation with the more common discrete rotational concept and to Lagrange-based finite element shell formulations. The competitiveness of the proposed isogeometric shell formulation in terms of computational costs to attain a pre-defined error level is shown.

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ABSTRACT: The present research deals with bifurcation and vibration responses of a composite truncated conical shell with embedded single-walled carbon nanotubes (SWCNTs) subjected to an external pressure and axial compression simultaneously. The distribution of reinforcements through the thickness of the shell is assumed to be either uniform or functionally graded. The equations of motion are established using Green–Lagrange type nonlinear kinematics within the framework of Novozhilov nonlinear shell theory. Linear membrane prebuckling analysis is conducted to extract the prebuckling deformations. The stability equations are derived by applying the adjacent equilibrium criterion to the prebuckling state of the conical shell. A semi-analytical solution on the basis of the trigonometric expansion through the circumferential direction along with the harmonic differential quadrature (HDQ) discretization in the meridional direction is developed. A series of comparison studies are carried out to assure the accuracy and the convergence of the HDQ method. The research indicates that the superb accuracy and efficiency of solutions with few grid points are attributed to the higher-order harmonic approximation function in the HDQ method. Parametric studies are also presented to investigate the influence of boundary conditions, semi-vertex angle of the cone, volume fraction and distribution of CNTs on stability and vibration characteristics of the truncated conical shell. The results show that both volume fraction and distribution of CNTs play a pivotal role in the natural frequencies, buckling mode and buckling loads of the FG-CNTRC truncated conical shell.


ABSTRACT: In this paper a hexahedral solid-shell element with in-plane reduced integration is developed. The element is intended to the analysis of thin/thick elastic–plastic shells with moderate to large strains. Developed within the framework of a total Lagrangian formulation, the element uses as strain measure the logarithm of the right stretch tensor (U) obtained from a modified right Cauchy–Green tensor (Cbar). The modifications, in order to remove transverse shear, Poisson and volumetric locking, are three: (a) a classical assumed mixed shear strain approximation for C13 and C23 (b) an assumed strain approximation for the in-plane components Calphabeta and (c) an enhanced assumed strain for the through the thickness normal component C33 (one additional degree of freedom). The first five components of Cbar are interpolated to the integration points from values at the center of the top and bottom faces. An arbitrary number of integration points is used in the transverse direction and a stabilization scheme is used to avoid spurious modes due to the in-plane sub integration. Several examples are presented that show the locking-free behavior and the very good performance
of the presented element for the analysis of shells with geometric and material nonlinearities, including quasi-incompressible elastic and elastic–plastic with incompressible plastic flow models.

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ABSTRACT: The recently developed Analysis in Computer Aided Design (AiCAD) concept is applied to the integrated design and analysis of structural membranes. This concept allows for a consistent design-through-analysis workflow based on the Isogeometric B-Rep Analysis (IBRA) applied to complete trimmed NURBS surfaces, i.e. unmodified CAD geometry. Structural membranes show very particular characteristics concerning their numerical design and analysis. The arising computational challenges—namely the form-finding of NURBS surfaces, the assembly of trimmed multi-patch NURBS geometries, and the application of cable elements along trimming edges—are treated within this contribution. Formulating a structural membrane element for trimmed NURBS surfaces as well as a cable element that is consistently embedded within the trimmed multi-patch NURBS surface as a B-Rep edge element, these challenges are met. The proposed element formulations are applied to selected numerical examples. In a non-linear structural analysis of untrimmed and trimmed multi-patch geometries, the accuracy, robustness and applicability of the developed element formulations are demonstrated. The example of a minimal surface illustrates form-finding with the formulated elements and is assessed against analytical solutions. Additionally, the “exactness” of NURBS for geometry representation in the context of mechanically motivated structural shapes is discussed with this example.

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ABSTRACT: The micro-damage associated with diffuse fracture processes in quasi-brittle materials can be described by continuum damage mechanics. In order to overcome the mesh dependence of local damage formulations, non-local and gradient-enhanced approaches are often employed. In this manuscript, a higher-order stress-based gradient-enhanced formulation is proposed, which exploits the higher-order continuity of B-spline functions in isogeometric analysis (IGA). The proposed formulation does not require the decomposition of the fourth-order model into two second-order models. Two numerical examples are presented to demonstrate the performance of the formulation and to compare the obtained solutions with results from conventional gradient-enhanced damage formulation.

ABSTRACT: We present a novel design concept for a bi-stable cardiovascular stent in which the device has two fully stable, unloaded configurations: a contracted configuration used for insertion and positioning of the device, and an expanded configuration intended to facilitate blood flow. Once the device is in place, a small trigger force applied in the radial direction induces snap-through, causing the device to snap into its expanded configuration. We model the mechanics of the stent structure using a neo-Hookean hyperelastic formulation, which is discretized using a uniform mesh of solid isoparametric finite elements. Topology optimization is used to obtain the material layout and to tailor the nonlinear response of the baseline structure to achieve bi-stable snap-through behavior. The design domain is defined as a two-dimensional unit cell within the larger mesh pattern that comprises the cylindrical stent structure. We further introduce a novel transverse bracing system, which exerts a containing force that allows snap-through to occur, and that also ensures that the length of the stent does not change due to radial expansion. Optimization results are presented for several two dimensional examples including a benchmark problem based on a bi-stable beam, and a two-dimensional stent patch. Results confirm that topology optimization has been used successfully to achieve bi-stability in both the beam and the stent structures.


ABSTRACT: A finite element formulation for a geometrically linear, shear deformable (Reissner–Mindlin type) shell theory is presented, which exclusively uses displacement degrees of freedom. The total displacement is subdivided into a part representing the membrane and bending deformation, enriched by two extra “shear displacements”, representing transverse shear deformation. This rotation-free approach is accomplished within the isogeometric concept, using C1-continuous, quadratic NURBS as shape functions. The particular displacement parametrization decouples transverse shear from bending and thus the formulation is free from transverse shear locking by construction, i.e. locking is avoided on the theory level, not by choice of a particular discretization. Compared to the hierarchic formulation proposed earlier within the group of the authors (Echter et al., 2013), the method presented herein avoids artificial oscillations of the transverse shear forces. Up to now, a similar, displacement based method to avoid membrane locking has not been found. Thus, in the present formulation the mixed method from Echter et al. (2013) is used to avoid membrane locking.

ABSTRACT: An efficient reduced basis method is proposed for buckling analyses of thin shells subject to large deformations and strains. The thin shells are modeled with the classical Kirchhoff–Love kinematics under the framework of IGA (Isogeometric Analysis), which makes it possible to satisfy the requirement of C1 continuity. The analytically defined geometry of thin shells can be exactly represented by the NURBS (Non-Uniform Rational B-Splines) basis functions. In addition, the critical buckling point can be better pinpointed due to the exact geometric description. For efficient structural analyses, a simplified ROM (Reduced Order Model) is presented by combining the Koiter perturbation technique and the finite element method (FEM). Alternative perturbation forces, based on nonlinear eigenvalue analyses, are also proposed. Embedding three strategies including arc-length control, accompanying eigenvalue analysis and mode injection into the analysis procedure, the proposed method is extended to be applicable to nonlinear buckling analyses. Furthermore, imperfection sensitivity analyses can be conveniently performed with the proposed method. Finally, the effectiveness and efficiency of the proposed method are validated via three benchmark problems.

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ABSTRACT: The basis of this work is a novel symbiosis of mechanics of solids and spherical geometry to quantify and illustrate the variation of the “non-membrane” percentage of the strain energy in the prebuckling region of linear elastic beams, arches, plates and shells, and structures assembled of such one-dimensional and two-dimensional members. The zenith angle of an arbitrary point of a specific curve on an octant of the unit sphere, called buckling sphere, is related to this energy percentage. For the limiting case of buckling from a membrane stress state this curve degenerates to a point, characterized by zero values of both spherical coordinates. For all other stress states the azimuth angle increases with the proportionally increasing load. Its magnitude at the stability limit correlates with a global quantity that depends on both the “non-membrane” deformations and the stiffness of the structure at incipient buckling. The azimuth angle is computed with the help of the so-called consistently linearized eigenproblem, which is solved by means of the Finite Element Method. This eigenvalue problem is the basis for a hypothesis for the “non-membrane” percentage of the strain energy. In the theoretical part of the paper, the concept of the buckling sphere is presented. The subsequent numerical investigation consists of four examples, referring to buckling from a membrane stress state, a pure bending stress state, and a general stress state. The practical motive for this research is the intention to investigate the influence of “non-membrane” action just before buckling on the initial postbuckling behavior of elastic structures.

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ABSTRACT: A new algorithm, denoted by RSRR, is presented for solving large-scale nonlinear eigenvalue problems (NEPs) with a focus on improving the robustness and reliability of the solution, which is a challenging task in computational science and engineering. The proposed algorithm utilizes the Rayleigh–Ritz procedure to compute all eigenvalues and the corresponding eigenvectors lying within a given contour in the complex plane. The main novelties are the following. First and foremost, the approximate eigenspace is constructed by using the values of the resolvent at a series of sampling points on the contour, which effectively circumvents the unreliability of previous schemes that using high-order contour moments of the resolvent. Secondly, an improved Sakurai–Sugiura algorithm is proposed to solve the projected NEPs with enhancements on reliability and accuracy. The user-defined probing matrix in the original algorithm is avoided and the number of eigenvalues is determined automatically by the provided strategies. Finally, by approximating the projected matrices with the Chebyshev interpolation technique, RSRR is further extended to solve NEPs in the boundary element method, which is typically difficult due to the densely populated matrices and high computational
costs. The good performance of RSRR is demonstrated by a variety of benchmark examples and large-scale practical applications, with the degrees of freedom ranging from several hundred up to around one million. The algorithm is suitable for parallelization and easy to implement in conjunction with other programs and software.

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ABSTRACT: An atomistic–continuum approach, in which the constitutive model is derived from the lattice structure of graphene, is developed to simulate the mechanical behaviors of graphene. The chirality of graphene can be reflected by introducing a representative cell and calculated results reveal that the chirality of graphene has little effect on structural parameters and elastic properties. Since the constitutive model has incorporated the information in connection with atomistic structure, the material nonlinearity can be exactly reflected by iteratively updating the constitutive relationship in the present approach. Moreover, geometrical nonlinearity has also been considered under the higher-order gradient continuum theory. The bending deflections of rectangular and circular graphene, with both geometrical and material nonlinearities, having simply supported and clamped constraints are investigated. Based on the constitutive model, the definition of graphene thickness in building the stiffness matrix can be avoided by using the current atomistic–continuum approach. Computational results reveal that the atomistic–continuum approach can accurately capture geometrical and material nonlinearities of graphene and provide a good prediction of the full atomistic simulation even with a small number of nodes.

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ABSTRACT: A layerwise theory within the framework of first-order shear deformation theory is introduced to investigate the postbuckling behavior and the delamination growth of geometrically imperfect composite plates. The Ritz method is adopted and the displacement fields are assumed in a form of polynomial series leading to a reduced computational cost. The proposed method is capable of predicting both the local buckling of the delaminated sublaminates and the global buckling of the plate. Two types of delaminations are considered: through-the-width and edge delaminations. To inhibit the penetration of delaminated domain, contact
constraints are applied. The debonding of adjacent plies is modeled to illustrate the effect of delamination growth on the postbuckling response of the delaminated composite plate. A parametric study is carried out to investigate the influence of size and location of delamination as well as the amplitude of imperfection on the postbuckling behavior with concurrent propagation of delamination. A three dimensional finite element analysis is also implemented. A comparison study is conducted for numerical predictions of the developed theoretical model and implemented finite element simulation. It is found that the snap-back instability can occur during the delamination growth. Moreover, the results show that predictions based upon an analysis without consideration for the delamination growth could not be reliable.

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ABSTRACT: A finite-strain solid–shell element is proposed. It is based on least-squares in-plane assumed strains, assumed natural transverse shear and normal strains. The singular value decomposition (SVD) is used to define local (integration-point) orthogonal frames-of-reference solely from the Jacobian matrix. The complete finite-strain formulation is derived and tested. Assumed strains obtained from least-squares fitting are an alternative to the enhanced-assumed-strain (EAS) formulations and, in contrast with these, the result is an element satisfying the Patch test. There are no additional degrees-of-freedom, as it is the case with the enhanced-assumed-strain case, even by means of static condensation. Least-squares fitting produces invariant finite strain elements which are shear-locking free and amenable to be incorporated in large-scale codes. With that goal, we use automatically generated code produced by AceGen and Mathematica. All benchmarks show excellent results, similar to the best available shell and hybrid solid elements with significantly lower computational cost.

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ABSTRACT: With the theme of fracture of finite-strain plates and shells based on a phase-field model of crack regularization, we introduce a new staggered algorithm for elastic and elasto-plastic materials. To account for correct fracture behavior in bending, two independent phase-fields are used, corresponding to the lower and upper faces of the shell. This is shown to provide a realistic behavior in bending-dominated problems, here
illustrated in classical beam and plate problems. Finite strain behavior for both elastic and elasto-plastic constitutive laws is made compatible with the phase-field model by use of a consistent updated-Lagrangian algorithm. To guarantee sufficient resolution in the definition of the crack paths, a local remeshing algorithm based on the phase-field values at the lower and upper shell faces is introduced. In this local remeshing algorithm, two stages are used: edge-based element subdivision and node repositioning. Five representative numerical examples are shown, consisting of a bi-clamped beam, two versions of a square plate, the Keesecker pressurized cylinder problem, the Hexcan problem and the Muscat-Fenech and Atkins plate. All problems were successfully solved and the proposed solution was found to be robust and efficient.


Many papers published in the journal, Structures (2012-2016):
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Leroy Gardner (Editor in Chief), “Editorial”, Structures, Vol. 1, p 1, February 2015,
ABSTRACT: (none)

Andrew Liew and Leroy Gardner (Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London, UK), “Ultimate capacity of structural steel cross-sections under compression, bending and combined loading”, Structures, Vol. 1, pp 2-11, February 2015,
https://doi.org/10.1016/j.istruc.2014.07.001
ABSTRACT: The Continuous Strength Method (CSM) is a strain based structural steel design approach which allows for the beneficial influence of strain hardening. The method has been previously developed for predicting compression and bending resistances in isolation. This paper describes extension of the method to enable the prediction of the ultimate cross-section resistance of I-sections and box sections under combined loading. At the core of the method is a base curve, which relates the deformation capacity of a cross-section to its cross-section slenderness. Deformation capacity is defined as the ratio of the maximum strain that a cross-section can endure relative to its yield strain. Knowing this limiting strain and assuming plane sections remain plane, the resistance of a cross-section to combinations of axial load and bending moments can be calculated, by integrating the stresses arising from a suitable strain hardening material model over the area of the cross-section. By considering a range of combinations of applied actions, analytical expressions and numerically derived interaction surfaces have been produced, which were then rationalised into simple expressions for use in design. The resulting CSM design predictions for box sections and I-sections have been compared with existing test data, and shown to give additional capacity over current design approaches and a reduction in scatter of the predictions.

Guotao Yang and Mark A. Bradford (Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, UNSW Sydney, NSW 2052, Australia), “Thermoelastic buckling and post-buckling of weakened columns”, Structures (Research Journal of the
ABSTRACT: Structural columns in engineering practice may weaken over time as a result of corrosion, erosion, impact, fatigue cracking or similar effects that reduce their effective cross-section. The effect of the degradation of the cross-section may then lead to premature flexural buckling. This paper presents a solution for the buckling and post-buckling behaviours of such weakened columns under thermal loading. The method of minimum total potential is employed to derive the differential equations for the buckling, as well as those for the post-buckling response, and the boundary value equations with variable coefficients that govern the behaviour are solved using a shooting procedure. The buckling and post-buckling responses of weakened columns are investigated parametrically, and it is found that the weakening of the column may affect the buckling temperature significantly. Comparisons between the solutions of the problem that account for, and do not account for, the axial deformation are also given, and the results indicate that the effects of axial deformation need to be considered under thermal loading. A Rayleigh–Ritz solution for weakened columns is also presented, and it is found that the proposed simplified formulation can predict the buckling and post-buckling responses of weakened columns under thermal loading quite accurately.

ABSTRACT: The paper offers to practitioners economical procedures that can be utilized to optimize the design of built up box sections subject to compression and biaxial bending. Little emphasis appeared in the published literature that addressed this general loading condition. The analysis methodology and structural idealization are first overviewed. Diagrams are presented showing buckling behavior of the section by accounting rotational and lateral restraints. The post-buckling response is also illustrated for various applied stress ratios. A design space concept is then introduced showing interaction of serviceability and strength limit states. These procedures are cost effective and appropriate for industrial implementation to optimize the structural design.

ABSTRACT: Rectangular hollow sections featuring high height-to-width (aspect) ratios have shown to offer improved ultimate capacity due to the effects of the interaction between the elements within the cross-section which are particularly significant for slender cross-sections (Class 4) undergoing local buckling. The European design rules dealing with stainless steel, EN 1993-1-4 [1], utilises the concept of cross-section classification and the effective width method for the design of slender cross-sections susceptible to local buckling neglecting such interaction effects, hence resulting in conservative predictions. This paper examines the benefits of element interaction effects on cold-formed ferritic stainless steel compressed sections on the basis of carefully validated finite element models. Following parametric studies, the applicability of various alternative design approaches accounting for element interaction to ferritic stainless steel is assessed and effective width curves, as well as a Class 3 limiting slenderness equation, are derived herein as an explicit function of the aspect ratio. Comparisons with the loads achieved in the FE models have shown that the proposed effective width equations allowing for the benefits of element interaction improve capacity predictions making design more cost-effective.
Poologanathan Keerthan, Mahen Mahendran and Anand Narsey (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “Shear tests of hollow flange channel beams with real support conditions”, Structures, Vol. 3, pp 109-119, August 2015, https://doi.org/10.1016/j.istruc.2015.03.006

ABSTRACT: This paper presents the details of experimental studies on the effect of real support conditions on the shear strength of hollow flange channel beams, known as LiteSteel beams (LSBs). The LSB has a unique shape of a channel beam with two rectangular hollow flanges, made using a unique manufacturing process. In many applications in the building industry LSBs are used with only one web side plate (WSP) at their supports. The WSPs are also often not full height plates. Past research studies showed that these real support connections did not provide the required simply supported conditions. Many studies have been carried out to evaluate the behaviour and design of LSBs with simply supported conditions subject to pure bending and predominant shear actions. To date, however, no investigation has been conducted into the effect of real support conditions on the shear strength of LSBs. Hence a detailed experimental study based on 25 shear tests was undertaken to investigate the shear behaviour and strength of LSBs with real support conditions. Simply supported test specimens of LSBs with aspect ratios of 1.0 and 1.5 were loaded at mid-span until failure. It was found that the effect of using one WSP on the shear behaviour of LSB is significant and there is about 25% shear capacity reduction due to the lateral movement of the bottom flange at the supports. Shear capacity of LSB was also found to decrease when full height WSPs were not used. Suitably improved support connections were developed to improve the shear capacity of LSBs based on test results. Details of the recommended support connections and shear capacity results are given in this paper.


ABSTRACT: A fundamental aspect of the progressive collapse behaviour of building structures is the response of axially restrained beams following partial or total loss of the load bearing capacity of a supporting member. Owing to the various complex effects involved such as material and geometric nonlinearity, advanced numerical approaches tend to be the most effective tools for modelling performance. Such approaches, however, lack the simplicity needed for common use and may provide only limited capability for understanding structural behaviour. For such purposes, more limited analysis approaches that can address adequately the basic features of performance are likely to be more productive. One such method for modelling the response of axially restrained steel and composite beams following column loss is presented in this paper. The method involves explicit modelling of the connection behaviour and employs conventional structural analysis principles to describe beam performance using accessible spreadsheet calculations. Following careful verification against detailed numerical analyses and validation against available experimental results, the proposed method is deemed capable of modelling the various complex features of response with excellent accuracy. Therefore, it may form a promising advance in studying and understanding the basic mechanics of the problem.

M. Ahmer Wadee and Maryam Farsi (Department of Civil & Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK), “Imperfection sensitivity and geometric effects in

ABSTRACT: An analytical model for axially loaded thin-walled stringer stiffened plates based on variational principles is exploited to study the sensitivity to initial geometric imperfections and the effects of altering geometric properties. Studies on different forms of global and local imperfections indicate that the post-buckling response governs the worst case imperfections. The investigation also focuses on the effect of changing the global and the local slendernesses on the post-buckling behaviour. The parametric space in which the stiffened plates are imperfection sensitive and susceptible to highly unstable cellular buckling is identified.

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ABSTRACT: A finite element analysis (FEA) model is developed to predict the full range response of concrete-encased CFST box stub columns under axial compression. In the model, concrete across the composite section is divided into four regions, i.e. the outer unconfined concrete outside the stirrup, the outer concrete in the web walls, the outer confined concrete in the corners, and the core concrete in the steel tubes. Different material models are used in each region. The analytical results are compared to past experiments, and generally good agreement between the predicted and measured results is obtained. Load-axial strain, loading distribution between the inner CFST and outer RC components and interface stresses between steel and concrete are analyzed. The influence of the web wall slenderness is also investigated. Parameter studies investigate the influence of concrete and steel strength, steel ratio of CFST, longitudinal bar ratio, stirrup spacing and ratio of the diameter of CFST to the sectional width on the ultimate load. A simplified model is proposed to predict the ultimate load of the concrete-encased CFST box stub columns under axial compression.


ABSTRACT: (none)


ABSTRACT: The paper proposes a novel methodology to construct the individual local, distortional, and global buckling modes of a thin-walled structural element under a given loading. The resulting buckling modes form an orthogonal basis of the deformation space, so that any random deformed shape can be expressed as a linear combination of the basic buckling modes. The method is applicable to open branched or unbranched cross sections, as well as cross sections containing closed parts. Examples are provided to illustrate the procedure.

Elizabeth L. Liu and M. Ahmer Wadee (Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK), “Interactively induced localization in thin-walled
I-section struts buckling about the strong axis”, Structures (Research Journal of the Institution of Structural Engineers), Vol. 4, pp 13026, November 2015, https://doi.org/10.1016/j.istruc.2015.08.007

ABSTRACT: A variational model describing the behaviour of a thin-walled I-section strut suffering from local–global buckling mode interaction is presented where global (Euler) buckling about the strong axis is the critical mode. A system of differential and integral equations is derived that describe the equilibrium states from variational principles and are solved numerically using the continuation and bifurcation software Auto-07p for the perfect case. Initially stress relieved out-of-straightness imperfections are subsequently introduced and the nonlinear response is modelled. The modelled interaction is between the critical global buckling mode about the strong axis and local buckling in the flange and web simultaneously, where the flange–web joint is assumed to be free to rotate as a rigid body. The initial eigenmode is shown to be destabilized at a secondary bifurcation where interactive buckling is triggered. A progressive change in the buckling mode is then observed, initially with local buckling localizing at the mid-span of the compression flange, which also triggers sympathetic local buckling in the web. The results from the analytical model have been validated using the commercial finite element (FE) software Abaqus with good comparisons presented for the initial post-buckling behaviour. The strut also exhibits sensitivity to initial out-of-straightness imperfections, with a notable decrease in the ultimate load as the imperfection size increases. The ultimate loads for a range of imperfection amplitudes are found using both analytical models and FE analysis, with very good correlation observed.

References listed at the end of the paper:


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ABSTRACT: This paper provides an overview of the latest developments of the research activity carried out by the authors concerning the non-linear behaviour, ultimate strength and Direct Strength Method (DSM) design of cold-formed steel (plain and stiffened) columns experiencing local–distortional (L–D) interaction. Initially, numerical results obtained by means of Generalized Beam Theory (GBT) elastic post-buckling analyses are presented and their unique modal nature is used to illustrate and provide the main behavioural/mechanics features of this mode coupling phenomenon. Then, both experimental and numerical (obtained from Abaqus shell finite element analyses – SFEA) are presented and discussed, making it possible to provide clear evidence and characterize the column L-D interactive behaviour and failure. Besides reporting on two experimental test series performed by the authors, the paper also presents a critical review of other experimental results available in the literature concerning columns undergoing L–D interaction. The numerical results deal with columns exhibiting different cross-section shapes and fairly extensive parametric studies are carried out, in order to (i) assess the relevance of L–D interaction, as far as the ultimate strength erosion is concerned, and (ii) gather substantial ultimate strength data. Next, after showing the inadequacy of the currently codified DSM column design curves to predict L–D interactive failures, the paper presents and assesses the merits of DSM-based design approaches recently developed specifically to handle such failures.


ABSTRACT: The excellent corrosion resistance presented by all stainless steel grades, together with their appropriate mechanical properties, aesthetic appearance and easy maintenance, makes these metallic alloys perfect for sustainable structural performances. However, their nonlinear stress–strain behaviour, together with their strong strain hardening features, makes them different from carbon steel and makes the development of some specific guidance necessary. Although the compressive and flexural behaviour of stainless steel
Rectangular and Square Hollow Sections (RHS and SHS) has been widely analysed and advanced design approaches considering strain hardening have been developed, more general loading conditions such as combined axial compression and bending moment loading conditions still need to be investigated. Within this scenario, this paper presents an experimental programme on several ferritic RHS and SHS stub column tests subjected to concentric and eccentric compression. The objective is to extend the recent research on austenitic and lean duplex stainless steel RHS under combined loading to ferritic grades by assessing the applicability and accuracy of the interaction expressions currently codified in EN1993-1-4 and those proposed in the literature.

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ABSTRACT: Substantial research has been conducted in recent years into the structural response of stainless steel components, with the focus being primarily on doubly symmetric cross-sections. Limited experimental data exist on non-doubly symmetric stainless steel sections in compression, while there is an absence of such data in bending, despite these sections being widely used in the construction industry as wind posts, lintels and so on. To address this limitation, and to bring an improved understanding of the behaviour of these sections, an experimental study into the flexural response of stainless steel channels bent about their minor axis and angles bent about their stronger geometric axis is described herein. In total, 16 bending tests on austenitic stainless steel beams have been conducted and the obtained results, including the full load-deformation history and observed failure modes have been described. Auxiliary tests on tensile coupons extracted from the tested sections and initial geometric imperfection measurements have also been performed and are reported in detail. The influence of the spread of plasticity and strain hardening on the shift of the neutral axis and the ultimate load carrying capacity is also examined. Based on the obtained test results, the current design provisions of EN 1993-1-4 [1] for these types of cross-sections were assessed and found to be unduly conservative. The effect of strain hardening on the structural response of stocky stainless steel sections and the need to account for it in design has been highlighted.

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“Concrete filled elliptical steel tubular members with large diameter-to-thickness ratio subjected to bending”, Structures, Vol. 5, pp 58-66, February 2016, [https://doi.org/10.1016/j.istruc.2015.08.004](https://doi.org/10.1016/j.istruc.2015.08.004)

ABSTRACT: Concrete filled elliptical steel tubes, hereafter called CFESTs, are elliptical steel tube members filled in with concrete. The CFEST belongs to a family of concrete filled steel tubes, the so-called CFT, having good deformability and large seismic strength due to confined effect between the tube and in-filled concrete. The present study aims to investigate experimentally the characteristics of the CFEST members under pure bending. The selected testing parameters are diameter-to-thickness ratio of elliptical steel tube and loading directions, namely, the minor and major axes directions. From the test results, both local buckling and cracking of the steel tube can be observed in compressive and tensile regions, respectively. Obtained pure bending
strength of the CFEST is strongly affected by diameter-to-thickness ratio. Pure bending capacity of the CFEST is also compared to that of the circular CFT. Methods to predict pure bending strength of the CFEST based on concrete strength, yielding and fracture points of the steel tube and confinement effect are described. Moreover, pure bending strength of the CFEST members is mainly discussed in comparison to that of ordinary CFT members. Additionally, biaxial stress behavior of the steel tube induced by in-filled concrete is also mentioned.


ABSTRACT: This paper investigates the improvement in elastic buckling capacity of pretwisted columns using Linear Perturbation Approach. Three different Universal Column (UC) sections of various lengths were considered in the proposed study assuming fixed–fixed and pinned–pinned end conditions. Linear perturbation analysis was first verified by comparing the critical loads of the simulated straight columns with analytical results. Numerical analysis was then extended to simulate the buckling improvement of pretwisted columns considering four different lengths of 4 m, 5 m, 6 m and 7 m, and a range of twisting angles between 0° and 180°. The results showed that the initial twisting has positively impacted the axial capacity of the pretwisted columns. This noticeable improvement is supported by the significant increase in the buckling capacity for the three UC sections, particularly at angles of twists between 120° and 150°.

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ABSTRACT: In this study, the closed-form solution for the buckling of an inhomogeneous simply supported column that was uncovered by the noted British engineer Duncan in 1937, is first derived in a straightforward manner. It deals with buckling of a centrally compressed inhomogeneous column. It is also found that there are several other columns with variable axial functionally graded material (FGM) that share the same qualities as Duncan's column. It is then shown that the mode postulated by W.J. Duncan (1894–1970), FRS and the newly found modes, have a greater validity, namely the freely vibrating beam, albeit with different flexural rigidity than the centrally compressed one, may possess the same buckling mode. It is demonstrated also that there exists an inhomogeneous beam under axial compression whose vibration mode coincides with the buckling modes in the previous cases.


ABSTRACT: The present work addresses the development of a finite element formulation for handling bending, buckling, and post buckling analysis of composite laminated structures with damage. The inverse hyperbolic shear deformation theory (IHSDT) was applied in the finite element formulation. The effect of
damage is analyzed for thin composite plates. An anisotropic damage formulation was used to simulate the damage, which is based on the concept of stiffness reduction. Computer programming is developed in the MATLAB environment. The excellent agreement of the results obtained in the present method with those from references shows that the technique is effective and precise. Parametric studies in the buckling behavior of a damaged composite plate are presented. Critical buckling temperatures are computed for a damaged plate using the present model. Thermal post buckling equilibrium paths are traced for various parametric variations for composite plates with mild damage and compared the results with that of undamaged cases. The validation of IHSDT has been demonstrated for buckling analysis in thermal environment for composite plates with an internal flaw. The present work is worthwhile compared with previous works due to the choice of finite element method and inverse hyperbolic shear deformation theory for analyzing the influence of damage on buckling and post buckling behavior of laminated plates.

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ABSTRACT: Considering the coupling effect of axial force, bending moment and shear force, the displacement interpolation functions of the spatial beam-column element under axial tension and axial compression are derived respectively based on the differential equilibrium equations of the deformed member. The different displacement interpolation functions of the tension and compression elements are unified by replacing the stability integration functions with the Maclaurin series, and the unified functions are completely equivalent to those expressed by stability integration functions. The second-order element tangent stiffness matrix considering the effect of axial deformation, shear deformation, biaxial bending and torsion is derived. The number of series expansion terms in unified displacement interpolation functions is determined from aspects of calculation accuracy and positive definiteness of the structural general stiffness matrixes. Numerical calculation results by this element model accord well with the experimental data, and it indicates the accurateness of this element. Different element models are used in the analyses of a single layer lattice shell, and calculation results indicate that the geometrical nonlinearity of the structure is well exhibited with good efficiency by the refined spatial beam-column element proposed in this paper.

Vasileios E. Melissianos and Charis J. Gantes (Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, 9 Iroon Polytechniou str., Zografou Campus, GR-15780, Athens, Greece), “Buckling and post-buckling behavior of beams with internal flexible joints resting on elastic foundation modeling buried pipelines”, Structures, Vol. 7, pp 138-152, August 2016, https://doi.org/10.1016/j.istruc.2016.06.007
ABSTRACT: The buckling and post-buckling behavior of axially loaded Winkler beams with flexible internal hinges is addressed, aiming to provide a background for the investigation of upheaval buckling of buried pipelines equipped with flexible joints for their protection against activation of reverse seismic faults. In order to acquire qualitative understanding of the interaction between the hinge stiffness and the soil stiffness for different cases, the beams under investigation are considered as either simply-supported or clamped. At first, elastic critical buckling loads and corresponding eigenmodes are numerically obtained using linearized buckling analysis, and eigenmode cross-over is investigated considering soil and hinge rotational stiffness. Geometrically
nonlinear analyses with imperfections (GNIA) are then performed, indicating for most cases descending post-buckling paths, thus unstable post-buckling behavior, with the exception of cases of very soft soil. The sensitivity of the response to initial imperfection shape and magnitude is also addressed, to identify their impact on the post-buckling behavior. Beam buckling behavior is moreover examined by considering the beam being surrounded by soil exhibiting different stiffness in the upward and the downward direction. The results are compared to the case of a continuous beam, in order to highlight the impact of internal hinges on the beam overall buckling behavior.

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ABSTRACT: Experimental and numerical studies on the bending capacity of cold-formed stainless steel rectangular and circular hollow sections are reported. Eight four-point bending tests were carried out. Material properties, geometric imperfections, bending capacities, moment-curvature curves were obtained in the tests. Finite element models were developed, and were verified using the test data. Material nonlinearity and geometric imperfections were considered in the modeling. Parameter studies were conducted to expand test data with different material properties and section slenderness. Based on the test results and the finite element analysis results, direct strength formulas were proposed for rectangular and circular hollow sections, respectively. Test data were collected from literatures as references, and compared with predictions of the Eurocode, the American code, the Australian/New Zealand code, the Chinese code, and the continuous strength method (CSM). Comparisons show that the Eurocode, the American code, the Australian/New Zealand code, and the Chinese code are generally conservative. The Chinese code provides most conservative predictions, due to the neglect of strain hardening effect and section plasticity, especially for stocky cross sections. The performance of CSM method is better than the design codes. The proposed formulas show better accuracy in predicting bending capacities of cold-formed stainless steel hollow sections.


ABSTRACT: The European stability design rules for steel columns, beams and beam-columns are classically based on Ayrton-Perry formulations that rely on the calibration of imperfection factors in order to estimate the maximum resistance. More recently, “general approaches” have been proposed that combine in-plane and out-of-plane behaviour based on a single reference length. The safety of design rules in modern codes of practice is based on the use of partial factors and the separation of the uncertainty related to loading and resistance. EN 1990 - Annex D [1], for example, contains a procedure for the safety analysis of resistance functions, based on First-Order Reliability Methods. However, its application to stability design rules is not straightforward and several additional assumptions are necessary to ensure that a target probability failure is achieved. Finally, design rules and its accuracy depend on the accuracy of the relevant basic variables such as material properties, geometric properties and imperfections. It is therefore required to appropriately characterize the statistical
distributions of these basic variables in order to comply with the (semi-) probabilistic safety level assessment of design rules. This paper discusses the different approaches for the derivation of design rules for columns, beams and beam-columns and proposes a mechanical consistent general approach. Secondly, a consistent procedure for the probabilistic assessment of the safety level of stability design rules is presented that simplifies the way material and geometrical properties are considered while maintaining its statistical relevance.

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ABSTRACT: This paper examines the response of steel plate shear webs when subjected to in-plane shear loading in the form of applied in-plane shear displacements. The buckling and post-buckling failure capabilities of thin plates subjected to in-plane shear can be substantially eroded through the introduction of openings or cut-outs which can contribute, significantly, towards a less stable structural system. The paper details appropriate suitable finite element modelling strategies and solution procedures to enable the determination of the post-buckled failure response of steel plate shear webs with cut-outs. The results presented in the paper give a detailed account of the complete loading history of the shear webs, illustrating the significant degrading influence on structural performance of the cut-outs and highlighting the importance of the in-plane boundary conditions at the plate edges on the mechanics of structural failure.


ABSTRACT: Spherical dome roofs are widely used on large diameter tanks and silos, as they provide high strength for very limited amounts of material: buckling normally controls the design. Their design is currently based on very simple rules that were devised many decades ago. In particular, existing design is based on very simple boundary condition assumptions that cannot be realised in practice. This paper presents the first thorough study of the influence of realistic boundary conditions, in the form of a ring at the eaves, on the linear bifurcation of these domes. The outcome is a clear documentation of one of the key reference resistances required for a design description in the terminology of the Eurocode on shell buckling EN 1993-1-6. The complete study explored a very wide range of parameters, so only a sample of the findings is presented here. The complete results are expected to form the basis of future rules in the ECCS Recommendations on Buckling of Shells.

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6. Rotter, J.M. Design of shells using reference resistances. in: Amendment AM-1-6-2013-05 to EN 1993-1-6, Approved by CEN TC250 SC3 Steel Structures and NSOs. ; 2015.
ABSTRACT: An imperfection sensitivity analysis of cold-formed steel pallet racks in compression is presented. The analysis is based on Koiter's approach and Monte Carlo simulation on one hand, and the ECBL (Erosion of Critical Buckling Load) approach on the other one. Mode interaction is taken into account and, based on that, the limit load and erosion of critical buckling load are evaluated. The analysis is based on an intensive experimental study carried out at the Politehnica University of Timisoara and extended to other thicknesses of the cross-section in order to highlight the variation of erosion. Thousands of imperfections were analyzed at a very low computational cost and an effective statistical evaluation of the limit performance was carried out.

End of many papers published in the journal, Structures (2012-2016)

http://www.sciencedirect.com/science/journal/00225096
ABSTRACT: Auxetic materials expand when stretched, and shrink when compressed. This is the result of a negative Poisson's ratio $\nu$. Isotropic configurations with $\nu$ close to $-1$ have been designed and are expected to provide increased shear stiffness $G$. This assumes that Young's modulus and $\nu$ can be engineered independently. In this article, a micropolar-continuum model is employed to describe the behavior of a representative auxetic structural network, the chiral lattice, in an attempt to remove the indeterminacy in its constitutive law resulting from $\nu = -1$. While this indeterminacy is successfully removed, it is found that the shear modulus is an independent parameter and, for certain configurations, it is equal to that of the triangular lattice. This is remarkable as the chiral lattice is subject to bending deformation of its internal members, and thus is more compliant than the triangular lattice which is stretch dominated. The derived micropolar model also indicates that this unique lattice has the highest characteristic length scale $\ell_c$ of all known lattice topologies, as well as a negative first Lamé constant without violating bounds required for thermodynamic stability. We also find that hexagonal arrangements of deformable rings have a coupling number $N=1$. This is the first lattice reported in the literature for which couple-stress or Mindlin theory is necessary rather than being adopted a priori.

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ABSTRACT: A versatile strategy for fabricating stretchable electronics involves controlled buckling of bridge structures in circuits that are configured into open, mesh layouts (i.e. islands connected by bridges) and bonded to elastomeric substrates. Quantitative analytical mechanics treatments of the responses of these bridges can be challenging, due to the range and diversity of possible motions. Koiter (1945) pointed out that the postbuckling analysis needs to account for all terms up to the 4th power of displacements in the potential energy. Existing postbuckling analyses, however, are accurate only to the 2nd power of displacements in the potential energy since they assume a linear displacement–curvature relation. Here, a systematic method is established for accurate postbuckling analysis of beams. This framework enables straightforward study of the complex buckling modes under arbitrary loading, such as lateral buckling of the island-bridge, mesh structure subject to shear (or twist) or diagonal stretching observed in experiments. Simple, analytical expressions are obtained for the critical load at the onset of buckling, and for the maximum bending, torsion (shear) and principal strains in the structure during postbuckling.
Constrained growth processes in living materials result in a complex distribution of residual strains, which in certain geometries may induce a bifurcation in the elastic stability. In this work, we investigate the combined effects of growth and material anisotropy in the epithelial pattern formation of tubular tissues. In order to represent the structural organization of most organs, we adopt a strain energy density which accounts for the presence of a nonlinear reinforcement made of cross-ply fibers distributed inside a ground matrix. Using a canonical transformation in mixed polar coordinates, we transform the nonlinear elastic boundary value problem into a variational formulation, performing a straightforward derivation of the Euler–Lagrange equations for perturbations in circumferential and longitudinal directions. The corresponding curves of marginal stability are obtained numerically: the results demonstrate that both the three-dimensional distribution of residual strains and the mechanical properties of fiber reinforcements within the tissue are fundamental to determine the emergence of a specific instability pattern. In particular, different proportions of axial and circumferential residual strains can model the epithelial formation of mucosal folds in the esophagus and of plicae circulares in the small intestine. The theoretical predictions are compared with morphological data for embryonic intestinal tissues, suggesting that the volumetric growth of the epithelium can also drive the early stages of villi morphogenesis.
(or phase-transition-induced buckling as the localization is caused by the phase transition). Due to the similarities between the development of the Luders band in a mild steel and the stress-induced transformations in a SMA, the present results give a strong analytical evidence that the former is also caused by macroscopic effects instead of microscopic effects. Our analytical results also reveal more explicitly the important roles played by the geometrical parameters.

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ABSTRACT: Via the energy-based analytical and numerical methods, this paper studies the pre- and post-buckling compression behaviors of concentric multi-walled cylindrical shells filled with low-shear-modulus (or fluid like) materials, which are widely observed in biological composites. It is found that if the bulk modulus of the filled materials is on the same order of (or larger than) the Young’s modulus of the shell, the axial compression resistance in the post-buckling stage can be significantly improved. In specific, the tangent stiffness increases quickly with the increase of the compression strain, and finally may become compatible with that for a non-buckled hollow shell. Moreover, it is interesting to note that the compression resistance after buckling is approximately in proportion to the net shell-wall area, and independent of the thickness or the number of shell-walls. These investigations may quantitatively reveal a mechanism adopted by the nature: rolling the flat thin-layered composites into a filled concentric multi-walled cylindrical shell to achieve better compression resistance. The biological concentric shell can also be viewed as a double-leveled hierarchical structure, which is capable to sustain more complex loadings than the bottom leveled structure.

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ABSTRACT: We introduce and study a variational model for the formation of patterns induced by bringing the surface of a rigid plate into contact proximity with the surface of a polymeric film strongly bonded to a substrate. We treat the film as a homogeneous, isotropic, hyperelastic solid and account for both attractive and repulsive van der Waals interactions between the film surface and the proximate contractor. Aside from confirming the intuitive expectation that the presence of a repulsive contribution to the van der Waals potential should stabilize patterns that form on the film surface, we elucidate the role of repulsive interactions at the onset of instability. For a recently proposed van der Waals potential involving two parameters, the Hamaker constant A and the equilibrium spacing d-sub-e, our results include estimates for the critical gap d-sub-c at which undulations appear on the film surface, the corresponding wavenumber k-sub-c of the undulations, and a lower bound f-sub-m for the attractive force needed to induce the undulations. To leading order [math] and [more math] where h and [math] denote the thickness and infinitesimal shear modulus of the film. Correction terms due to repulsive interactions indicate that, while k-sub-c may be influenced by [math] and A, d-sub-c may also be influenced...
by d-sub-e. Granted knowledge of $\mu$ and $A$, our results also suggest a simple experimental protocol for determining d-sub-e.

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ABSTRACT: Wrinkling of thin stiff films on thick compliant elastomeric substrates subject to plane strain compression is considered for cases in which the substrate is pre-stretched prior to film attachment. Advanced wrinkling modes are investigated that evolve as the systems are compressed beyond the onset of the primary sinusoidal wrinkling mode. If the substrate pre-stretch is greater than about 40%, an advanced mode in the form of a series of well-spaced ridges separated by relatively flat film is observed in the simulations. Our experiments reveal a localization mode in the form of alternating packets of large and small amplitude wrinkles, but not ridges, while ridge formation has been observed in other recent experiments. Measurements of undulation amplitudes have been made for wrinkle fields of stiff films formed by oxidation of the surface of pre-stretched PDMS substrates. Simulations have been performed with a finite element model and an analytical film/substrate model. The formation of the ridge mode is a consequence of the altered nonlinearity of the substrate produced by the pre-stretch. The role of the tangential substrate stiffness in suppressing localization at the ridges is also highlighted. If there is no substrate pre-stretch, or if the substrate is pre-compressed, the primary sinusoidal mode gives way to an entirely different sequence of advanced modes usually entailing period doubling followed by folding. The nature of substrate nonlinearity that leads to ridges or folds is discussed.

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ABSTRACT: Nanocomposite structure, consisting of hard mineral and soft protein, is the elementary building block of biological materials, where the mineral crystals are arranged in a staggered manner in protein matrix. This special alignment of mineral is supposed to be crucial to the structural stability of the biological materials under compressive load, but the underlying mechanism is not yet clear. In this study, we performed analytical analysis on the buckling strength of the nanocomposite structure by explicitly considering the staggered alignment of the mineral crystals, as well as the coordination among the minerals during the buckling deformation. Two local buckling modes of the nanostructure were identified, i.e., the symmetric mode and anti-symmetric mode. We showed that the symmetric mode often happens at large aspect ratio and large volume fraction of mineral, while the anti-symmetric happens at small aspect ratio and small volume fraction. In addition, we showed that because of the coordination of minerals with the help of their staggered alignment, the buckling strength of these two modes approached to that of the ideally continuous fiber reinforced composites at large aspect ratio given by Rosen's model, insensitive to the existing “gap”-like flaws between mineral tips.
Furthermore, we identified a mechanism of buckling mode transition from local to global buckling with increase of aspect ratio, which was attributed to the biphasic dependence of the buckling strength on the aspect ratio. That is, for small aspect ratio, the local buckling strength is smaller than that of global buckling so that it dominates the buckling behavior of the nanocomposite; for comparatively larger aspect ratio, the local buckling strength is higher than that of global buckling so that the global buckling dominates the buckling behavior. We also found that the hierarchical structure can effectively enhance the buckling strength, particularly, this structural design enables biological nanocomposites to avoid local buckling so as to achieve global buckling at macroscopic scales through hierarchical design. These features are remarkably important for the mechanical functions of biological materials, such as bone, teeth and nacre, which often sustain large compressive load.

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ABSTRACT: We examine the force needed to extend/compress a bio-filament, a key issue in the study of cytoskeleton mechanics and polymer physics, by considering both the associated stretching and bending deformations. Specifically, closed form relationships are derived to predict the buckling of stiff filaments such as F-actin and microtubules. Our results clearly demonstrate that the maximum force a 2D filament can sustain is higher than the Euler buckling load whereas the force in a 3D filament is always below it, and hence clarify some of the ambiguities in the literature. In addition, analytical expression is also obtained to describe how the extensional force increases when a flexible molecule, like DNA, is stretched close to its contour length, which has been shown to fit a variety of experimental data very well. Our theory provides important corrections/improvements to several well-known existing models.


ABSTRACT: We present a three-dimensional continuum model for layered crystalline materials made out of weakly interacting two-dimensional crystalline sheets. We specialize the model to multilayer graphene materials, including multi-walled carbon nanotubes (MWCNTs). We view the material as a foliation, partitioning of space into a continuous stack of leaves, thus loosing track of the location of the individual graphene layers. The constitutive model for the bulk is derived from the atomistic interactions by appropriate kinematic assumptions, adapted to the foliation structure and mechanics. In particular, the elastic energy along the leaves of the foliation results from the bonded interactions, while the interaction energy between the walls, resulting from van der Waals forces, is parametrized with a stretch transversal to the foliation. The resulting theory is distinct from conventional anisotropic models, and can be readily discretized with finite elements. The discretization is not tied to the individual walls and allows us to coarse-grain the system in all directions. Furthermore, the evaluation of the non-bonded interactions becomes local. We test the accuracy of the foliation model against a previously proposed atomistic-based continuum model that explicitly describes each and every wall. We find that the new model is very efficient and accurate. Furthermore, it allows us to rationalize the rippling deformation modes characteristic of thick MWCNTs, highlighting the role of the van der Waals forces
and the sliding between the walls. By exercising the model with very large systems of hollow MWCNTs and suspended multilayer graphene, containing up to \(10^9\) atoms, we find new complex post-buckling deformation patterns.

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ABSTRACT: We present a combined theoretical and experimental study of the buckling of a thin film wrapped around a sphere under the action of capillary forces. A rigid sphere is coated with a wetting liquid, and then wrapped by a thin film having an approximately cylindrical shape. The equilibrium of the film is governed by the competing effects of elasticity and capillarity: elasticity tends to keep the film developable while capillarity tends to curve it in both directions so as to maximize the area of contact with the sphere. In the experiments, the region of contact between the film and the sphere has cylindrical symmetry when the sphere radius is small, but destabilizes to a non-symmetric, wrinkled configuration when the radius is larger than a critical value. We combine the Donnell equations for near-cylindrical shells to include a unilateral constraint with the impenetrable sphere, and the capillary forces acting along a moving edge. A non-linear solution describing the axisymmetric configuration of the film is derived. A linear stability analysis is then presented, which successfully captures the wrinkling instability, the symmetry of the unstable mode, the instability threshold and the critical wavelength. The motion of the free boundary at the edge of the region of contact, which has an effect on the instability, is treated without any approximation.

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“Giant voltage-induced deformation in dielectric elastomers near the verge of snap-through instability”, Journal of the Mechanics and Physics of Solids, Vol. 61, No. 2, pp 611-628, February 2013,
https://doi.org/10.1016/j.jmps.2012.09.006

ABSTRACT: Dielectric elastomers are capable of large voltage-induced deformation, but achieving such large deformation in practice has been a major challenge due to electromechanical instability and electric breakdown. The complex nonlinear behavior suggests an important opportunity: electromechanical instability can be harnessed to achieve giant voltage-induced deformation. We introduce the following principle of operation: place a dielectric elastomer near the verge of snap-through instability, trigger the instability with voltage, and bend the snap-through path to avert electric breakdown. We demonstrate this principle of operation with a commonly used experimental setup—a dielectric membrane mounted on a chamber of air. The behavior of the
membrane can be changed dramatically by varying parameters such as the initial pressure in the chamber, the volume of the chamber, and the prestretch of the membrane. We use a computational model to analyze inhomogeneous deformation and map out bifurcation diagrams to guide the experiment. With suitable values of the parameters, we obtain giant voltage-induced expansion of area by 1692%, far beyond the largest value reported in the literature.

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ABSTRACT: Light metal sandwich panel structures with cellular cores have attracted interest for multifunctional applications which exploit their high bend strength and impact energy absorption. This concept has been explored here using a model 6061-T6 aluminum alloy system fabricated by friction stir weld joining extruded sandwich panels with a triangular corrugated core. Micro-hardness and miniature tensile coupon testing revealed that friction stir welding reduced the strength and ductility in the welds and a narrow heat affected zone on either side of the weld by approximately 30%. Square, edge clamped sandwich panels and solid plates of equal mass per unit area were subjected to localized impulsive loading by the impact of explosively accelerated, water saturated, sand shells. The hydrodynamic load and impulse applied by the sand were gradually increased by reducing the stand-off distance between the test charge and panel surfaces. The sandwich panels suffered global bending and stretching, and localized core crushing. As the pressure applied by the sand increased, face sheet fracture by a combination of tensile stretching and shear-off occurred first at the two clamped edges of the panels that were parallel with the corrugation and weld direction. The plane of these fractures always lay within the heat affected zone of the longitudinal welds. For the most intensively loaded panels additional cracks occurred at the other clamped boundaries and in the center of the panel. To investigate the dynamic deformation and fracture processes, a particle-based method has been used to simulate the impulsive loading of the panels. This has been combined with a finite element analysis utilizing a modified Johnson–Cook constitutive relation and a Cockcroft–Latham fracture criterion that accounted for local variation in material properties. The fully coupled simulation approach enabled the relationships between the soil-explosive test charge design, panel geometry, spatially varying material properties and the panel's deformation and dynamic failure responses to be explored. This comprehensive study reveals the existence of a strong instability in the loading that results from changes in sand particle reflection during dynamic evolution of the panel's surface topology. Significant fluid–structure interaction effects are also discovered at the sample sides and corners due to changes of the sand reflection angle by the edge clamping system.

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ABSTRACT: We study the stability of magnetorheological elastomers (MREs) undergoing finite deformations in the presence of a magnetic field and derive a general condition for the onset of macroscopic instabilities. In particular, we focus on anisotropic MREs with magnetoactive particles that are aligned along a particular direction, forming chain-like structures. We idealize the microstructure of such anisotropic magnetosensitive elastomers as a multilayered structure and derive an analytical model for the behavior of these materials. The analytical model, together with the derived condition for the onset of instabilities, is used to investigate the influence of magnetomechanical finite deformations on the stability of the anisotropic MREs. While the formulation is developed for generic hyperelastic magnetosensitive elastomers, the results are presented for a special class of soft materials incorporating a neo-Hookean hyperelastic response. The influence of material properties and loading conditions is investigated, providing a detailed picture of the possible failure modes.

Xiaoding Wei, Phuong Tran, Alban de Vaucorbeil, Ravi Bellur Ramaswamy, Felix Latourte, Horacio D. Espinosa (Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111, United States), “Three-dimensional numerical modeling of composite panels subjected to underwater blast”, Journal of the Mechanics and Physics of Solids, Vol. 61, No. 6, pp 1319-1336, June 2013, https://doi.org/10.1016/j.jmps.2013.02.007

ABSTRACT: Designing lightweight high-performance materials that can sustain high impulsive loadings is of great interest for marine applications. In this study, a finite element fluid–structure interaction model was developed to understand the deformation and failure mechanisms of both monolithic and sandwich composite panels. Fiber (E-glass fiber) and matrix (vinylester resin) damage and degradation in individual unidirectional composite laminas were modeled using Hashin failure model. The delamination between laminas was modeled by a strain-rate sensitive cohesive law. In sandwich panels, core compaction (H250 PVC foam) is modeled by a crushable foam plasticity model with volumetric hardening and strain-rate sensitivity. The model-predicted deformation histories, fiber/matrix damage patterns, and inter-lamina delamination, in both monolithic and sandwich composite panels, were compared with experimental observations. The simulations demonstrated that the delamination process is strongly rate dependent, and that Hashin model captures the spatial distribution and magnitude of damage to a first-order approximation. The model also revealed that the foam plays an important role in improving panel performance by mitigating the transmitted impulse to the back-side face sheet while maintaining overall bending stiffness.

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“The study of asymptotically fine wrinkling in nonlinear elasticity using a boundary layer analysis”, Journal of the Mechanics and Physics of Solids, Vol. 61, No. 8, pp 1691-1711, August 2013,
https://doi.org/10.1016/j.jmps.2013.04.003
ABSTRACT: Fine sinusoidal wrinkling on the surfaces of mechanically compressed objects has been observed in many contexts over many years. In this paper we investigate such wrinkling through the application of a boundary layer analysis to an elastostatic problem in nonlinear elasticity. We determine the onset of buckling using a linear-stability analysis, and the leading-order postbuckling behaviour through consideration of higher order terms of the energy. The object is assumed to (initially) ‘preserve’ its shape, so that these equations reduce to ordinary differential equations. We then apply a boundary-layer analysis to this problem, determining (in the asymptotic limit of large wavenumbers) the leading order behaviours of the eigenmode, the critical parameter, and the magnitude of the buckle. We find that, to leading order, the shape of the buckle and the time of buckling are independent of the local geometry, however the magnitude of the buckle is dependent on the local geometry. Indeed we find that the magnitude of a buckle with wavenumbers $\lambda$ and $\mu$ (for fixed $\lambda$ and $\mu$) has leading asymptotic order $[\text{math}]$, for an increment of the critical parameter beyond the critical time of buckling. We provide electronic supplementary material which extends this analysis to that of incompressible elasticity. Finally we confirm the accuracy of our ansatz on a compressed NeoHookean ring.

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ABSTRACT: We present a cylindrical lattice structure that mimics the behaviour of the virus bacteriophage T4 in having two (or more) stable states which differ in their radii and length. While the virus achieves bistability through molecular mechanisms we use composite materials to exploit the interplay between pre-stress, material properties and structural geometry. We demonstrate (computationally) that multi-stability is a robust phenomenon. We also show (analytically) that it is possible to choose the design variables so that the energy is independent of the radius, thus resulting in every state of the structure being stable.

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ABSTRACT: Koiter's nonlinear plate theory is used to simulate the wrinkling patterns observed in stretched thin elastic sheets. The phenomenon considered is associated with wrinkle patterns distributed over the interior of the sheet, in regions where the stretching and bending energies are of the same order of magnitude. Numerical solutions to several equilibrium boundary-value problems are obtained by the method of dynamic relaxation based on a dissipative dynamical system and compared with existing experimental, numerical, and analytical results.

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ABSTRACT: Despite their seemingly delicate appearance, thin biological membranes fulfill various crucial roles in the human body and can sustain substantial mechanical loads. Unlike engineering structures, biological membranes are able to grow and adapt to changes in their mechanical environment. Finite element modeling of biological growth holds the potential to better understand the interplay of membrane form and function and to reliably predict the effects of disease or medical intervention. However, standard continuum elements typically fail to represent thin biological membranes efficiently, accurately, and robustly. Moreover, continuum models are typically cumbersome to generate from surface-based medical imaging data. Here we propose a computational model for finite membrane growth using a classical midsurface representation compatible with standard shell elements. By assuming elastic incompressibility and membrane-only growth, the model a priori satisfies the zero-normal stress condition. To demonstrate its modular nature, we implement the membrane growth model into the general-purpose non-linear finite element package Abaqus/Standard using the concept of user subroutines. To probe efficiently and robustly, we simulate selected benchmark examples of growing biological membranes under different loading conditions. To demonstrate the clinical potential, we simulate the functional adaptation of a heart valve leaflet in ischemic cardiomyopathy. We believe that our novel approach will be widely applicable to simulate the adaptive chronic growth of thin biological structures including skin membranes, mucous membranes, fetal membranes, tympanic membranes, corneoscleral membranes, and heart valve membranes. Ultimately, our model can be used to identify diseased states, predict disease evolution, and guide the design of interventional or pharmacologic therapies to arrest or revert disease progression.

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ABSTRACT: While many uniaxial tension experiments of shape memory alloys (SMAs) have been published in the literature, relatively few experimental studies address their behavior in compression or bending, despite the prevalence of this latter deformation mode in applications. In this study, superelastic NiTi tubes from a single lot of material were characterized in tension, compression, and pure bending, which allowed us to make direct comparisons between the deformation modes for the first time. Custom built fixtures were used to overcome some long-standing experimental difficulties with performing well-controlled loading and accurate measurements during uniaxial compression (avoiding buckling) and large-rotation bending. In all experiments, the isothermal, global, mechanical responses were measured, and stereo digital image correlation (DIC) was used to measure the evolution of the strain fields on the tube's outer surface. As is characteristic of textured NiTi, our tubes exhibited significant tension–compression asymmetry in their uniaxial responses. Stress-induced transformations in tension exhibited flat force plateaus accompanied by strain localization and propagation. No such localization, however, was observed in compression, and the stress “plateaus” during compression always maintained a positive tangent modulus. While our uniaxial results are similar to the
observations of previous researchers, the DIC strain measurements provided details of localized strain behavior with more clarity and allowed more quantitative measurements to be made. Consistent with the tension–compression asymmetry, our bending experiments showed a significant shift of the neutral axis towards the compression side. Furthermore, the tube exhibited strain localization on the tension side, but no localization on the compression side during bending. This is a new observation that has not been explored before. Detailed analysis of the strain distribution across the tube diameter revealed that the traditional assumption of elementary beam theory, that plane sections remain plane, does not hold. Yet when the strain was averaged over a few diameters of axial length, the tensile and compressive responses input into elementary beam theory predicted the global bending response with reasonable accuracy. While it is encouraging that a simple model could predict the moment–curvature response, we recommend that beam theory be used with caution. The averaged strain field can under/over predict local strains by as much as two-fold due to the localized deformation morphology.


ABSTRACT: This paper considers certain aspects of static and dynamic analysis of inflated unstretched and prestretched flat circular hyperelastic membranes. The problem is both geometrically and materially nonlinear. The governing equations of equilibrium, and the equations of small amplitude dynamics are obtained using the variational formulation. The equilibrium configuration of the membrane is obtained by solving a two-point boundary value problem exploiting a scaling symmetry of the equations of equilibrium. Interestingly, in certain cases, beyond a certain inflation of the membrane, the Gaussian curvature flips sign (positive to negative) near the periphery of the membrane leading to neck formation and impending wrinkling condition. The dynamics of perturbations over the static shape have been studied considering both constant pressure and adiabatic conditions. Two remarkable new phenomena, namely a symmetry breaking torsional mode instability via a supercritical pitchfork bifurcation, and a stretch induced softening behaviour of the membrane, are revealed through the analysis.

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ABSTRACT: We consider the elastic deformation of a circular cylindrical sector composed of an incompressible isotropic soft solid when it is straightened into a rectangular block. In this process, the circumferential line elements on the original inner face of the sector are stretched while those on the original outer face are contracted. We investigate the geometrical and physical conditions under which the latter line elements can be contracted to the point where a localized incremental instability develops. We provide a robust algorithm to solve the corresponding two-point boundary value problem, which is stiff numerically. We illustrate the results with full incremental displacement fields in the case of Mooney–Rivlin materials and also perform an asymptotic analysis for thin sectors.
ABSTRACT: Thermomechanical properties of monolayer graphene with thermal fluctuation are studied by both statistical mechanics analysis and molecular dynamics (MD) simulations. While the statistical mechanics analysis in the present study is limited by a harmonic approximation, significant anharmonic effects are revealed by MD simulations. The amplitude of out-of-plane thermal fluctuation is calculated for graphene membranes under both zero stress and zero strain conditions. It is found that the fluctuation amplitude follows a power-law scaling with respect to the linear dimension of the membrane, but the roughness exponents are different for the two conditions due to anharmonic interactions between bending and stretching modes. Such thermal fluctuation or rippling is found to be responsible for the effectively negative in-plane thermal expansion of graphene at relatively low temperatures, while a transition to positive thermal expansion is predicted as the anharmonic interactions suppress the rippling effect at high temperatures. Subject to equi-biaxial tension, the amplitude of thermal rippling decreases nonlinearly, and the in-plane stress-strain relation of graphene becomes nonlinear even at infinitesimal strain, in contrast with classical theory of linear elasticity. It is found that the tangent biaxial modulus of graphene depends on strain non-monotonically, decreases with increasing temperature, and depends on membrane size. Both statistical mechanics and MD simulations suggest considerable entropic contribution to the thermomechanical properties of graphene, and as a result thermal rippling is intricately coupled with thermal expansion and thermoelasticity for monolayer graphene membranes.

ABSTRACT: Due to its atomic scale thickness, the deformation energy in a free standing graphene sheet can be easily released through out-of-plane wrinkles which, if controllable, may be used to tune the electrical and mechanical properties of graphene. Here we adopt a generalized von Karman equation for a flexible solid membrane to describe graphene wrinkling induced by a prescribed distribution of topological defects such as disclinations (heptagons or pentagons) and dislocations (heptagon–pentagon dipoles). In this framework, a given distribution of topological defects in a graphene sheet is represented as an eigenstrain field which is determined from a Poisson equation and can be conveniently implemented in finite element (FEM) simulations. Comparison with atomistic simulations indicates that the proposed model, with only three parameters (i.e., bond length, stretching modulus and bending stiffness), is capable of accurately predicting the atomic scale wrinkles near disclination/dislocation cores while also capturing the large scale graphene configurations under specific defect distributions such as those leading to a sinusoidal surface ruga² or a catenoid funnel.
Abstrakt: It is well-known that for most spherical rubber balloons the pressure versus volume curve associated with uniform inflation is N-shaped (the pressure increases rapidly to a maximum, falls to a minimum, and subsequently increases monotonically), and that somewhere along the descending branch of this curve the spherical shape may bifurcate into a pear shape through localized thinning near one of the poles. The bifurcation is associated with the (uniform) surface tension reaching a maximum. It is previously known that whenever a pear-shaped configuration becomes possible, it has lower energy than the co-existing spherical configuration, but the stability of the pear-shaped configuration itself is unknown. With the use of the energy stability criterion, it is shown in this paper that the pear-shaped configuration is unstable under pressure control, but stable under mass control. Our calculations are carried out using the Ogden material model as an example, but it is expected that the qualitative stability results should also be valid for other material models that predict a similar N-shaped behavior for uniform inflation.

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Abstrakt: Magnetorheological elastomers (MREs) are ferromagnetic particle impregnated rubbers whose mechanical properties are altered by the application of external magnetic fields. Due to their coupled magneto-mechanical response, MREs are finding an increasing number of engineering applications. One such application is in haptics, where the goal is to actively control surface roughness. One way to achieve this is by exploiting the unstable regime of MRE substrate/layer assemblies subjected to transverse magnetic fields. In this work, we study the response of such an assembly subjected to a transverse magnetic field and in-plane stress. The layer is made up of a transversely isotropic MRE material, whose energy density has been obtained experimentally, while the substrate is a non-magnetic isotropic pure polymer/gel. An analytical solution to this problem based on a general, finite strain, 2D continuum modeling for both the MRE layer and the substrate shows that for adequately soft substrates there is a finite-wavelength buckling mode under a transverse magnetic field. Moreover, the critical magnetic field can be substantially reduced in the presence of a compressive stress of the assembly, thus opening the possibility for haptic applications operating under low magnetic fields.

Abstrakt: Bifurcation into a shear band is studied for a porous ductile material subject to a combination of shear loading and tensile or compressive loading in different directions. The material with a periodic array of voids is studied by numerical solutions for a plane strain unit cell model with fully periodic boundary conditions.
The fundamental pre-bifurcation solution has been studied before, with focus on ductile fracture under conditions of low stress triaxiality. In the previous studies it has been shown that voids in shear are flattened out to micro-cracks, which rotate and elongate until interaction with neighboring micro-cracks gives coalescence. These failure mechanisms are included in the present study, but here the focus is on the possibility that failure may occur earlier, if bifurcation leads to a shear band crossing over many cells, where the plastic strains inside the band will grow very large, while the overall strains in the material will not increase any further. The unit cell analysis with full periodicity is used both inside and outside the band to find the average behavior in the two material regions. This does not allow for point-wise satisfaction of compatibility and equilibrium along the interface between the two regions, but these conditions can be satisfied on the average. The bifurcation analysis includes determination of the direction along which a shear band is first critical.


ABSTRACT: Variable-stiffness shells are curved composite structures in which the fibre-reinforcement follow curvilinear paths in space. Having a wider design space than traditional composite shells, they have the potential to improve a wide variety of weight-critical structures. In this paper, a new method for computing the initial post-buckling response of variable-stiffness cylindrical panels is presented, based on the differential quadrature method. Integro-differential governing and boundary equations governing the problem, derived with Koiter's theory (Koiter, 1945), are solved using a mixed generalised differential quadrature (GDQ) and integral quadrature (GIQ) approach. The post-buckling behaviour is determined on the basis of a quadratic expansion of the displacement fields. Orthogonality of the mode-shapes in the expansion series is ensured by a novel use of the Moore-Penrose generalised matrix inverse for solving the GDQ-GIQ equations. The new formulation is validated against benchmark analytical post-buckling results for constant stiffness plates and shells, and compared with non-linear finite-element (FE) analysis for variable-stiffness shells. Stability estimates are found to be in good agreement with incremental FE results in the vicinity of the buckling load, requiring only a fraction of the number of variables used by the current method.

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ABSTRACT: We develop the coarse-grained (CG) potentials of single-walled carbon nanotubes (SWCNTs) in CNT bundles and buckypaper for the study of the static and dynamic behaviors. The explicit expressions of the CG stretching, bending and torsion potentials for the nanotubes are obtained by the stick-spiral and the beam models, respectively. The non-bonded CG potentials between two different CG beads are derived from analytical results based on the cohesive energy between two parallel and crossing SWCNTs from the van der Waals interactions. We show that the CG model is applicable to large deformations of complex CNT systems by combining the bonded potentials with non-bonded potentials. Checking against full atom molecular dynamics calculations and our analytical results shows that the present CG potentials have high accuracy. The established CG potentials are used to study the mechanical properties of the CNT bundles and buckypaper efficiently at minor computational cost, which shows great potential for the design of micro- and nanomechanical devices and systems.


ABSTRACT: Wrinkle networks are ubiquitous buckle-induced delaminations in supported graphene, which locally modify the electronic structure and degrade device performance. Although the strong property–deformation coupling of graphene can be potentially harnessed by strain engineering, it has not been possible to precisely control the geometry of wrinkle networks. Through numerical simulations based on an atomistically informed continuum theory, we understand how strain anisotropy, adhesion and friction govern spontaneous wrinkling. We then propose a strategy to control the location of wrinkles through patterns of weaker adhesion. This strategy is deceptively simple, and can in fact fail in several ways, particularly under biaxial compression. However, within bounds set by the physics of wrinkling, it is possible to robustly create by strain a variety of wrinkle network geometries and junction configurations. Graphene is nearly unstrained in the planar regions bounded by wrinkles, highly curved along wrinkles, and highly stretched and curved at junctions, which can either locally attenuate or amplify the applied strain depending on their configuration. These mechanically self-assembled networks are stable under the pressure produced by an enclosed fluid and form continuous channels, opening the door to nano-fluidic applications.

References listed at the end of the paper:


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ABSTRACT: Convolutions are a classical hallmark of most mammalian brains. Brain surface morphology is often associated with intelligence and closely correlated with neurological dysfunction. Yet, we know surprisingly little about the underlying mechanisms of cortical folding. Here we identify the role of the key anatomic players during the folding process: cortical thickness, stiffness, and growth. To establish estimates for the critical time, pressure, and the wavelength at the onset of folding, we derive an analytical model using the Föppl–von Kármán theory. Analytical modeling provides a quick first insight into the critical conditions at the
onset of folding, yet it fails to predict the evolution of complex instability patterns in the post-critical regime. To predict realistic surface morphologies, we establish a computational model using the continuum theory of finite growth. Computational modeling not only confirms our analytical estimates, but is also capable of predicting the formation of complex surface morphologies with asymmetric patterns and secondary folds. Taken together, our analytical and computational models explain why larger mammalian brains tend to be more convoluted than smaller brains. Both models provide mechanistic interpretations of the classical malformations of lissencephaly and polymicrogyria. Understanding the process of cortical folding in the mammalian brain has direct implications on the diagnostics of neurological disorders including severe retardation, epilepsy, schizophrenia, and autism.

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same stabilizing effect as for fluid instabilities, driving the formation of stable wrinkles, as observed in elastic symmetry break. Moreover, if the surface energy is somewhat comparable to the bulk elastic energy, hexagonal creased patterns, albeit quasi-bifurcation drives the observed wrinkle equations are derived for different superposing linear modes. This study proves that a subcritical pitchfork bifurcation is found to be controlled by a characteristic length, defined by the ratio between capillary energy and bulk elasticity. For the first time, a weakly nonlinear analysis of the wrinkling instability is performed here using the network morphology has recently found several applications in many developing fields, such as scaffolds for biomaterials, stretchable electronics and surface micro-fabrication. Albeit much is known of the pattern initiation at the linear stability order, the nonlinear effects driving the pattern selection in soft materials are still unknown. This work aims at investigating the nature of the elastic bifurcation undertaken by a growing soft layer subjected to a equi-biaxial strain. Considering a skin effect at the free surface, the instability thresholds are found to be controlled by a characteristic length, defined by the ratio between capillary energy and bulk elasticity. For the first time, a weakly nonlinear analysis of the wrinkling instability is performed here using the multiple-scale perturbation method applied to the incremental theory in finite elasticity. The Ginzburg–Landau equations are derived for different superposing linear modes. This study proves that a subcritical pitchfork bifurcation drives the observed wrinkle-to-fold transition in swelling gels experiments, favoring the emergence of hexagonal creased patterns, albeit quasi-hexagonal patterns might later emerge because of an expected symmetry break. Moreover, if the surface energy is somewhat comparable to the bulk elastic energy, it has the same stabilizing effect as for fluid instabilities, driving the formation of stable wrinkles, as observed in elastic bi-layered materials.
ABSTRACT: Surface wrinkling of a cylindrical shell supported by a soft core subjected to axial compression is investigated via combined experimental, computational and theoretical efforts. Our experiments show that the post-bifurcation deformation mode of the system is axisymmetric when the modulus ratio of the surface layer to the core is small while a non-axisymmetric wrinkling pattern appears when the modulus ratio is large. Our nonlinear finite element simulations have confirmed this experimental finding. A theoretical analysis based on Koiter’s elastic stability theory is carried out to reveal the mechanisms underpinning the phenomenon of morphological evolution. The critical buckling analysis shows that the first bifurcation mode is axisymmetric for arbitrary modulus ratios of the shell to the core. Post-bifurcation analysis reveals that the system will evolve into a diamond-like mode when the modulus ratio is large enough but keep the axisymmetric mode if the modulus ratio is smaller than a critical value. The results can guide the creation of controlled surface wrinkles on a cylindrical surface under compression. Besides, the analysis approach presented here may be adopted to understand the wrinkling patterns observed in some natural systems generated by, for instance, differential growth.

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ABSTRACT: A compression-induced buckling delamination test is employed to quantitatively characterize the interfacial adhesion of Ni thin film on steel substrate. It is shown that buckles initiate from edge flaws and surface morphologies exhibit symmetric, half-penny shapes. Taking the elastoplasticity of film and substrate into account, a three-dimensional finite element model for an edge flaw with the finite size is established to simulate the evolution of energy release rates and phase angles in the process of interfacial buckling-driven delamination. The results show that delamination propagates along both the straight side and curved front. The mode II delamination plays a dominant role in the process with a straight side whilst the curved front experiences almost the pure mode I. Based on the results of finite element analysis, a numerical model is developed to evaluate the interfacial energy release rate, which is in the range of 250–315 J/m² with the corresponding phase angle from −41° to −66°. These results are in agreement with the available values determined by other testing methods, which confirms the effectiveness of the numerical model.

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ABSTRACT: Numerically simulating deformations in thin elastic sheets is a challenging problem in computational mechanics due to destabilizing compressive stresses that result in wrinkling. Determining the location, structure, and evolution of wrinkles in these problems has important implications in design and is an area of increasing interest in the fields of physics and engineering. In this work, several numerical approaches previously proposed to model equilibrium deformations in thin elastic sheets are compared. These include standard finite element-based static post-buckling approaches as well as a recently proposed method based on dynamic relaxation, which are applied to the problem of an annular sheet with opposed tractions where wrinkling is a key feature. Numerical solutions are compared to analytic predictions of the ground state, enabling a quantitative evaluation of the predictive power of the various methods. Results indicate that static finite element approaches produce local minima that are highly sensitive to initial imperfections, relying on \textit{a priori} knowledge of the equilibrium wrinkling pattern to generate optimal results. In contrast, dynamic relaxation is much less sensitive to initial imperfections and can generate low-energy solutions for a wide variety of loading conditions without requiring knowledge of the equilibrium solution beforehand.

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ABSTRACT: The mechanics of the formation and propagation of ridges on compressed stiff film/compliant substrate systems is studied theoretically and experimentally. Ridges form on bilayer systems where the elastomeric substrate is subject to a significant pre-stretch prior to attachment of the film. When the bilayer is then subject to increasing overall compressive strain, sinusoidal wrinkles first form and subsequently become unstable giving way to localized ridges with relatively large amplitudes. Two-dimensional plane strain simulations for neo-Hookean film/substrate systems reveal the transition from wrinkles to ridges under increasing compression and the reverse transition from ridges to wrinkles when the overall compression is subsequently reduced. For a significant range of pre-stretch, the two transition strains differ, and a significant hysteresis response is observed in a complete cycle of loading and unloading. The Maxwell equal-energy condition has been identified associated with co-existence of wrinkles and ridges and with the three-dimensional steady-state propagation condition for the ridges. Experiments conducted with a specially designed film/substrate loading system have been performed that confirm the essential features of ridge formation and the hysteretic behavior in loading/unloading cycles that span the two transitions.

References listed at the end of the paper:
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ABSTRACT: Surface wrinkling in thin films on compliant substrates is of considerable interest for applications involving surface patterning, smart adhesion, liquid/cell shaping, particle assembly, design of flexible electronic devices, as well as mechanical characterization of thin film systems. When the in-plane size of the system is infinite, the critical wrinkling strain is known to be governed by the moduli ratio between the film and substrate. Here we show a surprising result that the lateral dimension of the film can play a critical role in the occurrence of surface wrinkling. The basic phenomenon was established through selective UV/Ozone (UVO) exposure of a strain-free PDMS slab via composite copper grids with different meshes, followed by treatment using mixed ethanol/glycerol solvents with different volume fractions of ethanol. To understand the physics behind the experimental observations, finite element (FE) simulations were performed to establish an analytical expression for the distribution of shear tractions at the film–substrate interface. Subsequent theoretical analysis leads to closed-form predictions for the critical growth/swelling strain for the onset of wrinkling. Our analysis reveals that the occurrence of surface wrinkling and post-wrinkling pattern evolution can be controlled by tuning the lateral size of the thin film for a given moduli ratio. These results may find broad applications in preventing surface wrinkling, creating desired surface patterns, evaluating the interfacial shear strength of a film/substrate system and designing flexible electronic devices.


ABSTRACT: This paper explores the critical and post-bulging bifurcation of a cylindrical dielectric elastomer (DE) tube undergoing finite deformation under electro-mechanical coupling loading. Explicit expressions for the critical conditions of electro-mechanical bifurcation are derived by using a simplified mathematical method. The post-bifurcation path is comprehensively investigated by specifying the material model as ideal dielectric elastomer. In the post-bifurcation analysis, we analytically establish conditions for the phase coexistence of steady propagation and analyze the physical implications. We demonstrate a global instability under force or voltage control and a localized instability under volume or charge control. Cylindrical tube experiments have been carried out under electro-mechanical coupling loading to verify the theoretical predictions. Good agreements on the critical conditions as well as the post-bifurcation path are obtained. This work characterizes the bifurcation mechanism of rubber-like materials under complex coupling loading.

ABSTRACT: The limits of reversible deformation in graphene under various loadings are examined using lattice-dynamical stability analysis. This information is then used to construct a comprehensive lattice-stability limit surface for graphene, which provides an analytical description of incipient lattice instabilities of all kinds, for arbitrary deformations, parametrized in terms of symmetry-invariants of strain/stress. Symmetry-invariants allow obtaining an accurate parametrization with a minimal number of coefficients. Based on this limit surface, we deduce a general continuum criterion for the onset of all kinds of lattice-stabilities in graphene: an instability appears when the magnitude of the deviatoric strain $\gamma$ reaches a critical value $\gamma^c$ which depends upon the mean normal strain and the directionality $\theta$ of the principal deviatoric stretch with respect to reference lattice orientation. We also distinguish between the distinct regions of the limit surface that correspond to fundamentally different mechanisms of lattice instabilities in graphene, such as structural versus material instabilities, and long-wave (elastic) versus short-wave instabilities. Utility of this limit surface is demonstrated in assessment of incipient failures in defect-free graphene via its implementation in a continuum finite elements analysis (FEA). The resulting scheme enables on-the-fly assessments of not only the macroscopic conditions (e.g., load and deflection) but also the microscopic conditions (e.g., local stress/strain, spatial location, temporal proximity, and nature of incipient lattice instability) at which an instability occurs in a defect-free graphene sheet subjected to an arbitrary loading condition.

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ABSTRACT: Spatial pattern formation in stiff thin films on soft substrates is investigated from a multi-scale point of view based on a technique of slowly varying Fourier coefficients. A general macroscopic modeling framework is developed and then a simplified macroscopic model is derived. The model incorporates Asymptotic Numerical Method (ANM) as a robust path-following technique to trace the post-buckling evolution path and to predict secondary bifurcations. The proposed multi-scale finite element framework allows sinusoidal and square checkerboard patterns as well as their bifurcation portraits to be described from a quantitative standpoint. Moreover, it provides an efficient way to compute large-scale instability problems with a significant reduction of computational cost compared to full models.

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ABSTRACT: Nowadays, two-dimensional materials due to their vast engineering and biomedical applications have been the focus of many researches. The present paper proposes a large-deformation theory for thin plates with application to one-atom-thick layers (OATLs). The deformation is formulated exactly in the mathematical framework of Lagrangian description. In particular, an exact finite strain analysis is given – in addition to the usual strain tensor associated to the middle surface, the second and third fundamental forms of the middle surface of the deformed thin plate are also maintained in the analysis. Exact closed-form solutions for a uniaxially curved thin plate due to pure bending in one case and due to a combination of vertical and horizontal loading in another are obtained. As a special case of the latter problem, the exact solution for the plane-strain bulge test of thin plates is derived. Subsequently, the approximation of Vlassak and Nix [Vlassak, J.J., Nix, W.D., 1992. J. Mater. Res., 7(12), 3242–3249] for the load–deflection equation is recovered. The given numerical results are devoted to graphene as the most well-known OATL.

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ABSTRACT: Layered crystalline materials, such as graphene, boron nitride, tungsten sulfate, phosphorene, etc., have attracted enormous attentions, due to their unique crystal structures and superior mechanical, thermal, and physical properties. Making use of mechanical buckling is a promising route to control their structural morphology and thus tune their physical properties, giving rise to many novel applications. In this paper, we employ molecular dynamics (MD) simulations and theoretical modeling to study the compressive buckling of a column made of layered crystalline materials with the crystal layers parallel to the compressive direction. We find that the mechanical buckling of the layered crystalline materials exhibits two anomalous and counter-intuitive features as approaching the zero slenderness ratio. First, the critical buckling strain $\varepsilon_{cr}$ has a finite value that is much lower than the material's elastic limit strain. A continuum mechanics model (by homogenizing the layered materials) is proposed for the $\varepsilon_{cr}$, which agrees well with the results of MD simulations. We find that the $\varepsilon_{cr}$ solely depends on elastic constants without any structural dimension, which appears to be an intrinsic material property and thus is defined as intrinsic buckling strain (IBS), $\varepsilon_{crIBS}$, in this paper. Second, below a certain nanoscale length, $l_0$, in the compressive direction (e.g., about 20 nm for graphite), the critical buckling strain $\varepsilon_{cr}$ shows a size effect, i.e., increasing as the column length $L$ decreases. To account for the size effect, inspired by our recently developed multi-beam shear model (Liu et al., 2011), a bending energy term of individual crystal layer is introduced in our continuum model. The theoretical model of $\varepsilon_{cr}$ agrees well with the size effects observed in MD simulations. This study could lay a ground for engineering layered crystalline materials in various nano-materials and nano-devices via mechanical buckling.

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ABSTRACT: We present a combined analytical approach and numerical study on the stability of a ring bound to an annular elastic substrate, which contains a circular cavity. The system is loaded by depressurizing the inner cavity. The ring is modeled as an Euler–Bernoulli beam and its equilibrium equations are derived from the mechanical energy which takes into account both stretching and bending contributions. The curvature of the substrate is considered explicitly to model the work done by its reaction force on the ring. We distinguish two different instabilities: periodic wrinkling of the ring or global buckling of the structure. Our model provides an expression for the critical pressure, as well as a phase diagram that rationalizes the transition between instability modes. Towards assessing the role of curvature, we compare our results for the critical stress and the wrinkling wavelength to their planar counterparts. We show that the critical stress is insensitive to the curvature of the substrate, while the wavelength is only affected due to the permissible discrete values of the azimuthal wavenumber imposed by the geometry of the problem. Throughout, we contrast our analytical predictions against finite element simulations.

References listed at the end of the paper:

Cheng, P., 1996. Weight Optimization of Cylindrical Shells with Cellular Cores (Master of Science manuscript).

ABSTRACT: We study localized bulging of a cylindrical hyperelastic tube of arbitrary thickness when it is subjected to the combined action of inflation and axial extension. It is shown that with the internal pressure $P$ and resultant axial force $F$ viewed as functions of the azimuthal stretch on the inner surface and the axial stretch, the bifurcation condition for the initiation of a localized bulge is that the Jacobian of the vector function $(P, F)$ should vanish. This is established using the dynamical systems theory by first computing the eigenvalues of a certain eigenvalue problem governing incremental deformations, and then deriving the bifurcation condition explicitly. The bifurcation condition is valid for all loading conditions, and in the special case of fixed resultant axial force it gives the expected result that the initiation pressure for localized bulging is precisely the maximum pressure in uniform inflation. It is shown that even if localized bulging cannot take place when the axial force is fixed, it is still possible if the axial stretch is fixed instead. The explicit bifurcation condition also provides a means to quantify precisely the effect of bending stiffness on the initiation pressure. It is shown that the (approximate) membrane theory gives good predictions for the initiation pressure, with a relative error less than 5%, for thickness/radius ratios up to 0.67. A two-term asymptotic bifurcation condition for localized bulging that incorporates the effect of bending stiffness is proposed, and is shown to be capable of giving extremely accurate predictions for the initiation pressure for thickness/radius ratios up to as large as 1.2.


ABSTRACT: Many interesting shapes appearing in the biological world are formed by the onset of mechanical instability. In this work we consider how the build-up of residual stress can cause a solid to buckle. In all past studies a fictitious (virtual) stress-free state was required to calculate the residual stress. In contrast, we use a model which is simple and allows the prescription of any residual stress field. We specialize the analysis to an elastic tube subject to a two-dimensional residual stress, and find that incremental wrinkles can appear on its inner or its outer face, depending on the location of the highest value of the residual hoop stress. We further validate the predictions of the incremental theory with finite element simulations, which allow us to go beyond this threshold and predict the shape, number and amplitude of the resulting creases.

ABSTRACT: Flexible natural armors from fish, alligators or armadillo are attracting an increasing amount of attention from their unique and attractive combinations of hardness, flexibility and light weight. In particular, the extreme contrast of stiffness between hard plates and surrounding soft tissues give rise to unusual and attractive mechanisms, which now serve as model for the design of bio-inspired armors. Despite a growing interest in bio-inspired flexible protection, there is little guidelines as to the choice of materials, optimum thickness, size, shape and arrangement for the protective plates. In this work, we focus on a failure mode we recently observed on natural and bio-inspired scaled armors: the unstable tilting of individual scales subjected to off-centered point forces. We first present a series of experiments on this system, followed by a model based on contact mechanics and friction. We condense the result into a single stability diagram which capture the key parameters that govern the onset of plate tilting from a localized force. We found that the stability of individual plates is governed by the location of the point force on the plate, by the friction at the surface of the plate, by the size of the plate and by the stiffness of the substrate. We finally discuss how some of these parameters can be optimized at the design stage to produce bio-inspired protective systems with desired combination of surface hardness, stability and flexural compliance.

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ABSTRACT: The indentation response of polymer spherical shells is investigated. Finite deformation analyses are carried out with the polymer characterized as a viscoelastic/viscoplastic solid. Both pressurized and unpressurized shells are considered. Attention is restricted to axisymmetric deformations with a conical indenter. The response is analyzed for various values of the shell thickness to radius ratio and various values of the internal pressure. Two sets of material parameters are considered: one set having network stiffening at a moderate strain and the other having no network stiffening until very large strains are attained. The transition from an indentation type mode of deformation to a structural mode of deformation involving bending that occurs as the indentation depth increases is studied. The results show the effects of shell thickness, internal pressure and polymer constitutive characterization on this transition and on the deformation modes in each of these regimes.

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ABSTRACT: Recent interests in curvature- and stress-induced pattern formation and pattern selection motivate the present study. Surface morphological wrinkling of a cylindrical shell supported by a soft core subjected to axial compression is investigated based on a nonlinear 3D finite element model. The post-buckling behavior of core–shell cylinders beyond the first bifurcation often leads to complicated responses with surface mode transitions. The proposed finite element framework allows predicting and tracing these bifurcation portraits from a quantitative standpoint. The occurrence and evolution of 3D instability modes including sinusoidally deformed axisymmetric patterns and non-axisymmetric diamond-like modes will be highlighted according to critical dimensionless parameters. Besides, the phase diagram obtained from dimensional analyses and numerical results could be used to guide the design of core–shell cylindrical systems to achieve the desired instability patterns.

References listed at the end of the paper:


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ABSTRACT: Many soft materials and biological tissues are featured with the tension–compression asymmetry of constitutive relations. The surface wrinkling of a stiff thin film lying on a compliant substrate is investigated through theoretical analysis and numerical simulations. It is found that the tension–compression asymmetry of the soft substrate not only affects the critical strain of buckling but, more importantly, may also influence the wrinkling pattern that occurs in the film–substrate system under specified loading conditions. Due to this mechanism, the thin film subjected to equi-biaxial compression may first buckle into a hexagonal array of dimples or bulges, instead of the checkerboard pattern, and consequently evolve into labyrinths with further loading. Under non-equibi-axial compression, the system may buckle either into a parallel bead-chain pattern or a stripe pattern, depending on the substrate nonlinearity and the loading biaxiality. Phase diagrams are established for the wrinkling patterns in a wide range of geometric and mechanical parameters, which facilitate the design of surface patterns with desired properties and functions.


ABSTRACT: Wrinkling can affect the functionality of thin membranes subjected to various loadings or boundary conditions. The concept of relaxed strain energy was studied for isotropic, hyperelastic, axisymmetric membranes pressurized by gas or fluid. Non-intuitive instabilities were observed when axisymmetric wrinkled membranes were perturbed with angle dependent displacement fields. A linearized theory showed that static equilibrium states of pressurized membranes, modelled by a relaxed strain energy formulation, are unstable, when the wrinkled surface is subjected to pressure loadings. The theory is extended to the non-axisymmetric membranes and it is shown that these instabilities are local phenomena. Simulations for the pressurized cylindrical membranes with non-uniform thickness and hemispherical membranes support the claims in both theoretical and numerical contexts including finite element simulations.

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ABSTRACT: An experimental investigation to understand the mechanisms of dynamic buckling instability in cylindrical structures due to underwater explosive loadings is conducted. In particular, the effects of initial hydrostatic pressure coupled with a dynamic pressure pulse on the stability of metallic cylindrical shells are evaluated. The experiments are conducted at varying initial hydrostatic pressures, below the critical buckling pressure, to estimate the threshold after which dynamic buckling will initiate. The transient underwater full-field deformations of the structures during shock wave loading are captured using high-speed stereo photography coupled with modified 3-D Digital Image Correlation (DIC) technique. Experimental results show that increasing initial hydrostatic pressure decreases the natural vibration frequency of the structure indicating loss in structural stiffness. DIC measurements reveal that the initial structural excitations primarily consist of axisymmetric vibrations due to symmetrical shock wave loading in the experiments. Following their decay after a few longitudinal reverberations, the primary mode of vibration evolves which continues throughout later in time. At the initial hydrostatic pressures below the threshold value, these vibrations are stable in nature. The analytical solutions for the vibration frequency and the transient response of cylindrical shell are discussed in the article by accounting for both (1) the added mass effect of the surrounding water and (2) the effect of initial stress on the shell imposed by the hydrostatic pressure. The analytical solutions match reasonably well with the experimental vibration frequencies. Later, the transient response of a cylindrical shell subjected to a general underwater pressure wave loading is derived which leads to the analytical prediction of dynamic stability.

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ABSTRACT: In this paper, we combine experiments and numerical simulations to investigate the large deformation mechanics of periodically patterned cylindrical structures under uniaxial compression. Focusing on cylinders with a square array of circular pores, we show that their buckling behavior is not only controlled by the porosity (as for the case of the corresponding infinitely large planar structures), but also by the length and thickness of the shell and the number of pores along the full circumference. While infinitely long cylindrical shells only support long wavelength (global) modes, by reducing the length and tuning the thickness, short wavelength (local) modes can be observed. Furthermore, frustrated short wavelength modes are triggered when a local instability is critical, but the buckling pattern is not compatible with the number of pores along the circumference.

Reza Avazmohammadi and Pedro Ponte Castaneda (Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104-6315, USA), “Macroscope constitutive relations for elastomers reinforced with short aligned fibers: Instabilities and post-bifurcation response”, Journal
ABSTRACT: This paper is concerned with the characterization of the macroscopic response and possible development of instabilities in a certain class of anisotropic composite materials consisting of random distributions of aligned rigid fibers of elliptical cross section in a soft elastomeric matrix, which are subjected to general plane strain loading conditions. For this purpose, use is made of an estimate for the stored-energy function that was derived by Lopez-Pamies and Ponte Castañeda (2006b) for this class of reinforced elastomers by means of the second-order linear comparison homogenization method. This homogenization estimate has been shown to lose strong ellipticity by the development of shear localization bands, when the composite is loaded in compression along the (in-plane) long axes of the fibers. The instability is produced by the sudden, collective rotation of a band of fibers to partially release the high stresses that develop in the elastomer matrix when the composite is compressed along the stiff, long-fiber direction. Consistent with the mode of the impending instability, a lower-energy, post-bifurcation solution is constructed where “striped domain” microstructures consisting of layers with alternating fiber orientations develop in the composite. The volume fractions of the layers and the fiber orientations within the layers adjust themselves to satisfy equilibrium and compatibility across the layers, while remaining compatible with the imposed overall deformation. Mathematically, this construction is shown to correspond to the rank-one convex envelope of the original estimate for the energy, and is further shown to be polyconvex and therefore quasiconvex. Thus, it corresponds to the “relaxation” of the stored-energy function of the composite, and can in turn be viewed as a stress-driven “phase transition,” where the symmetry of the fiber microstructures changes from nematic to smectic.

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ABSTRACT: We determine stability boundaries for the wrinkling of highly unidirectionally stretched, finely thin, rectangular elastic sheets. For a given fine thickness and length, a stability boundary here is a curve in the parameter plane, aspect ratio vs. the macroscopic strain; the values on one side of the boundary are associated with stable unwrinkled (flat) states, while stable wrinkled configurations correspond to all values on the other. In our recent work we demonstrated the importance of finite elasticity in the membrane part of such a model in order to capture the correct phenomena. Here we present and compare results for four distinct models: (i) the popular Föppl–von Kármán plate model (FvK), (ii) a correction of the latter, used in our earlier work, in which the approximate 2D Föppl strain tensor is replaced by the exact Green strain tensor, (iii) and (iv): effective 2D finite-elasticity membrane models based on 3D incompressible neo-Hookean and Mooney–Rivlin materials, respectively. In particular, (iii) and (iv) are superior models for elastomers. The 2D nonlinear, hyperelastic models (ii)–(iv) all incorporate the same quadratic bending energy used in FvK. Our results illuminate serious shortcomings of the latter in this problem, while also pointing to inaccuracies of model (ii) – in spite of yielding the correct qualitative phenomena in our earlier work. In each of these, the shortcoming is a due to a deficiency of the membrane part of the model.


ABSTRACT: In this paper, the dynamic instability of a shear deformable composite plate subjected to periodic non-uniform in-plane loading is studied for four sets of boundary conditions. The static component and the dynamic component of the applied periodic in-plane loading are assumed to vary according to either parabolic or linear distributions. Initially, the plate membrane problem is solved using the Ritz method to evaluate the plate in-plane stress distributions within the prebuckling range due to the applied non-uniform in-plane edge loading. Subsequently using the evaluated stress distribution within the plate, the equations governing the plate instability boundaries are formulated via Hamilton's variational principle. Employing Galerkin's method, these partial differential equations are reduced into a set of ordinary differential equations (Mathieu type of equations) describing the plate dynamic instability behaviour. Following Bolotin's method, the instability regions are determined from the boundaries of instability, which represents the periodic solution of the differential equations with period $T$ and $2T$ to the Mathieu equations. The instability regions are determined for uniform, linear and parabolic dynamic in-plane loads using first-order and second-order approximations. Numerical results are also presented to bring out the effects of span to thickness ratio, shear deformation, aspect ratio, boundary conditions and static load factor on the instability regions.

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ABSTRACT: This paper develops a Mindlin microplate model based on the modified couple stress theory for the free vibration analysis of microplates. This non-classical plate model contains an internal material length scale parameter related to the material microstructures and is capable of interpreting the size effect that the classical Mindlin plate model is unable to describe. The higher-order governing equations of motion and boundary conditions are derived using the Hamilton principle. The p-version Ritz method is employed to determine the natural frequencies of the microplate with different boundary conditions. A detailed parametric study is conducted to study the influences of the length scale parameter, side-to-thickness ratio and aspect ratio on the free vibration characteristics of the microplate. It is found that the size effect is significant when the thickness of microplate is close to the material length scale parameter.

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ABSTRACT: Large-amplitude (geometrically nonlinear) forced vibrations of a stainless-steel thin rectangular plate carrying different concentrated masses are experimentally studied. The experimental boundary conditions are close to those of a clamped plate. The plate is vertically and horizontally tested in order to investigate the gravity effect. Harmonic excitation is applied by using electrodynamic exciter and the plate vibration is measured by using a laser Doppler vibrometer with displacement decoder. The harmonic excitation is controlled in closed-loop in order to keep constant the desired force and is increased (or decreased) by very small discrete steps. Numerical simulations on reduced-order models, obtained by using Von Kármán nonlinear plate theory and global discretization, are also carried out and compared to experiments in order to better understand the system. Results show that concentrated masses have no effect on the trend of nonlinearity of the vertical plate, while they play a role in case of horizontal plate due to the static flexural deflection caused by gravity, which reduces the hardening-type nonlinearity. Initial geometric imperfection (deviation from flat surface in vertical position) of the plate is measured and taken into account; it plays a significant role.

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ABSTRACT: This paper presents the theory and application of the generalized polynomial chaos expansion for the stochastic free vibration of orthotropic plates. Specifically, the stochastic analysis of orthotropic plates under the uncertainties in elasticity moduli is investigated. The uncertain moduli, eigen-frequencies and eigen-modes of the plates are represented by truncated polynomial chaos expansions with arbitrary random basis. The expansions are substituted in the governing differential equations to calculating the polynomial chaos coefficients of the eigen-frequencies and the eigen-modes. Distribution functions of the uncertain moduli are derived from experimental data where the Pearson model is used to identify the type of density functions. This realization then is employed to construct random orthogonal basis for each uncertain parameter. Because of available experimental modal analysis data, this paper provides a useful practical example on the efficacy of polynomial chaos where the statistical moments and the probability distributions of modal responses are compared with experimental results.


ABSTRACT: The development of tow-placement technology has made it possible to control fiber tows individually and place fibers in curvilinear distinct paths in each layer of a laminated plate. This paper presents
an analytical method for determining natural frequencies and vibration modes of laminated plates having such curvilinear reinforcing fibers. Spline functions are employed to represent arbitrarily shaped fibers, and Ritz solutions are used to derive frequency equations using series type shape functions. The strain energy is evaluated by numerical integration involving the fiber orientation angle, and is calculated using the derivative of the spline function in minute intervals. The results show that the natural frequencies obtained by the present method agree well with results from finite element analyses. The vibration mode shape contour plots of the plates are seen to reflect clear influences of the fiber shapes.


ABSTRACT: Analysis of free vibration of microtubules, based on an atomistic-continuum model, is presented. The theory bridges the polyatomic structure of microtubules with a macroscopic continuum approach under mesh-free computing scheme. A higher-order gradient continuum constitutive relationship is developed and incorporated into a higher-order Cauchy–Born rule. Instead of considering the atomic interaction between every atom pair in such polyatomic bio-composite textures, interatomic energy between subcomponents in microtubules is evaluated by a homogenization technique, represented by the fictitious bond. Material properties and stiffness matrix are determined, depending on deformation of fictitious bonds. Since the mesh-free approximation automatically satisfies the higher-order continuity and possesses intrinsic nonlocal property, the established quasicontinuum theory takes into consideration both atomic interaction and the size effect for modeling this microscale structure. Natural vibration frequencies of microtubules of different lengths and boundary restrictions are predicted and compared with existing solutions.


ABSTRACT: In this paper, free vibrations of the baffled circular plates with radial side cracks and in contact with water on one side are investigated based on the Rayleigh–Ritz method. The completely free, simply supported and completely clamped boundary conditions are considered. Corner functions are introduced to describe the singularities at the crack tip. The motion of water is expressed by the velocity potential and the interaction between the water and the plate is derived in the form of an integral equation including the dynamic deformation of the cracked plate. The convergence studies are carried out and the numerical results show that the distinctions between the dry and wet mode shapes will be increased obviously excluding the first symmetric and antisymmetric modes when cracks appear. When the approximate methods based on the assumption that the wet modes are identical with the dry modes are adopted to calculate the eigenfrequencies, the errors of the results for cracked circular plates are larger than those for intact ones. The influences of the water on the symmetric and antisymmetric modes are different evidently, and the greatest reduction ratio of eigenfrequency and least difference between dry and wet mode are relative to the first symmetric mode. The verifications based on numerical simulation show that the proposed method is adequate for the investigation of free vibration of baffled circular plates with radial side cracks and in contact with water on one side.

ABSTRACT: Bolted flange joints are widely used in engineering structures; however, the dynamic behavior of this connection is complex in nature. In this paper, a simplified nonlinear dynamic model with bi-linear springs is proposed and validated for pipe structures with bolted flange joints. First, static mechanical properties of the bolted flange joint are investigated. The analytical solution reveals that the axial stiffness of the bolted flange joint is different in tension and compression. Then, nonlinear springs with different stiffness in tension and compression are employed to represent the bolted flange joint. A special type of dynamic behavior, coupling vibration in the transverse and longitudinal directions, is observed in analytical derivation. Finally, relevant physical experiments and numerical simulations are performed. The physical experiments confirm the existence of the coupling vibration behavior. The relationship of longitudinal and transverse vibration frequencies is discussed. The numerical solutions reveal that the simplified nonlinear dynamic model better fits the physical response than conventional reduced linear beam model.


ABSTRACT: A method is presented to predict the root mean square displacement response of an open curved thin shell structure subjected to a turbulent boundary-layer-induced random pressure field. The basic formulation of the dynamic problem is an efficient approach combining classic thin shell theory and the finite element method, in which the finite elements are flat rectangular shell elements with five degrees of freedom per node. The displacement functions are derived from Sanders’ thin shell theory. A numerical approach is proposed to obtain the total root mean square displacements of an open curved thin structure in terms of the cross spectral density of random pressure fields. The cross spectral density of pressure fluctuations in the turbulent pressure field is described using the Corcos formulation. Exact integrations over surface and frequency lead to an expression for the total root mean square displacement response in terms of the characteristics of the structure and flow. An in-house program based on the presented method was developed. The total root mean square displacements of a curved thin blade subjected to turbulent boundary layers were calculated and illustrated as a function of free stream velocity and damping ratio. A numerical implementation for the vibration of a cylinder excited by fully developed turbulent boundary layer flow was presented. The results compared favorably with those obtained using software developed by Lakis and Paidoussis (J. Sound Vib. 25 (1972) 1–27) using cylindrical elements and a hybrid finite element method.

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ABSTRACT: A thin plate, excited by a harmonic external forcing of increasing amplitude, shows transitions from a periodic response to a chaotic state of wave turbulence. By analogy with the transition to turbulence observed in fluid mechanics as the Reynolds number is increased, a generic transition scenario for thin vibrating plates, first experimentally observed, is here numerically studied. The von Kármán equations for thin plates, which include geometric non-linear effects, are used to model large amplitude vibrations, and an energy-conserving finite difference scheme is employed for discretisation. The transition scenario involves two bifurcations separating three distinct regimes. The first regime is the periodic, weakly non-linear response. The second is a quasiperiodic state where energy is exchanged between internally resonant modes. It is observed only when specific internal resonance relationships are fulfilled between the eigenfrequencies of the structure and the forcing frequency; otherwise a direct transition to the last turbulent state is observed. This third, or turbulent, regime is characterized by a broadband Fourier spectrum and a cascade of energy from large to small wavelengths. For perfect plates including cubic non-linearity, only third-order internal resonances are likely to exist. For imperfect plates displaying quadratic nonlinearity, the energy exchanges and the quasiperiodic states are favored and thus are more easily obtained. Finally, the turbulent regime is characterized in the light of available theoretical results from wave turbulence theory.


ABSTRACT: This paper develops a three-dimensional analytical model of a cylinder that contains a longitudinal stiffener. The model begins with the equations of motion for a fully elastic solid that produces displacement fields with unknown wave propagation coefficients. These are inserted into stress and displacement equations at the cylinder boundaries and at the location of the stiffener. Orthogonalization of these equations produces an infinite number of indexed algebraic equations that can be truncated and incorporated into a global matrix equation. Solving this equation yields the solution to the wave propagation coefficients and allows the system's displacements and stresses to be calculated. The model is verified by comparison of the results of a plane strain analysis example to a solution generated using finite element theory. A three-dimensional example problem is formulated and the displacement results are illustrated. The inclusion of multiple stiffeners is discussed.


ABSTRACT: An analytical model of acoustic radiation from shear deformable laminated cylindrical shells with initial axial loadings and doubly periodic rings is presented. The shear deformation and rotary inertia of the rings are taken into account and the rings interact with the cylindrical shell only through the normal forces. The far-field sound pressure is found by using the Fourier wavenumber transform and stationary phase method. High frequency limitation issues of the first-order shear deformation theory are discussed and the effects of the second set of rings, axial initial loadings and multiple external loadings on the far-field acoustic radiation are explored. Further, the helical wave spectra of the radial displacement and sound pressure are used to study the vibrational and acoustic characteristics of the laminated shells. Above the ring frequency, the profile of the helical wave spectra of the far-field sound pressure induced by the cylindrical shell is an ellipse and the patterns of the helical wave spectra of the far-field sound pressure keep unchanged. Moreover, the ellipse distinguishes
the supersonic wavenumbers and subsonic wavenumbers from the helical wave spectra of the radial displacement and surface sound pressure in the wavenumber domain. The bright spots and highlights of the helical wave spectra show that the corresponding waves are dominant.

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Vibration behaviors of a box-type structure built up by plates and energy transmission through the structure”,
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ABSTRACT: The vibration behaviors of a box-type built-up structure and energy transmission through the structure are investigated analytically. The modeling of the structure is developed by employing the improved Fourier series method and treating the structure as four elastically coupled rectangular plates. The general coupling and boundary conditions are accounted for using the artificial spring technique and can easily be obtained by assigning the springs with corresponding values. The exact double Fourier series solutions considering both the flexural and in-plane vibrations are obtained by using the Rayleigh–Ritz approach, which are validated by comparison with the Finite Element Method (FEM) results. Since the modification of any parameter in this analytical model from one case to another is as simple as modifying the material properties, and does not involve any change to the solution procedures, thus this will make a parametric study and further mechanism analysis easier compared to most existing procedures. Subsequently, special attention is focused on the energy transmission and mechanism of the box-type structure by structural intensity analysis. Numerical analyses cover several important parameters including symmetrical and non-symmetrical coupling conditions and the excitations, and three types of models, namely the rigidly, elastically and weakly coupled models are involved. The results of the power flow and structural intensity are presented to obtain a clear physical understanding of the physical mechanisms of energy transmission. It is shown that the energy transmission behaviors can be significantly influenced by the coupling conditions and location of the excitation as well as the excitation frequency. Some unexpected interesting phenomena on the energy transmission were revealed, especially for the non-symmetrical model, and the corresponding mechanisms were interpreted. This study provides new and interesting insights into the vibration behaviors and energy transmission of the class of built-up box-type structure.

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ABSTRACT: An analytical solution is presented in this paper for the vibration response of a ribbed plate clamped on all its boundary edges by employing a traveling wave solution. A clamped ribbed plate test rig is also assembled in this study for the experimental investigation of the ribbed plate response and to provide verification results to the analytical solution. The dynamic characteristics and mode shapes of the ribbed plate are measured and compared to those obtained from the analytical solution and from finite element analysis (FEA). General good agreements are found between the results. Discrepancies between the computational and experimental results at low and high frequencies are also discussed. Explanations are offered in the study to disclose the mechanism causing the discrepancies. The dependency of the dynamic response of the ribbed plate
on the distance between the excitation force and the rib is also investigated experimentally. It confirms the findings disclosed in a previous analytical study [T.R. Lin, J. Pan, A closed form solution for the dynamic response of finite ribbed plates, *Journal of the Acoustical Society of America* 119 (2006) 917–925] that the vibration response of a clamped ribbed plate due to a point force excitation is controlled by the plate stiffness when the source is more than a quarter plate bending wavelength away from the rib and from the plate boundary. The response is largely affected by the rib stiffness when the source location is less than a quarter bending wavelength away from the rib.

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ABSTRACT: In this study, a hybrid approach based on computational fluid dynamics (CFD) was used to investigate the aerodynamic forces associated with vortex-induced vibration (VIV) in a circular cylinder. The circular cylinder and the flow field were considered as two substructures of a system. Circular cylinder motion was produced in a wind tunnel test of the VIV prior to the numerical simulation; this motion was used as a known cylinder boundary condition and applied to the flow field. The flow field with the known moving boundary condition was then numerically simulated by the ANSYS CFX code. The transient aerodynamic coefficients of the circular cylinder with predetermined motion were obtained from the numerical simulation. To verify the feasibility and accuracy of the proposed hybrid approach and to calculate cylinder vibrations, the transient aerodynamic coefficients were applied to a single degree of freedom (SDOF) model of the circular cylinder. The oscillation responses of the circular cylinder from the calculated (SDOF model) and experimental results were compared, and the results indicate that the hybrid approach accurately simulated the transient aerodynamic coefficients of the circular cylinder. For further comparison, a nonlinear aerodynamic coefficient model based on a nonlinear least square technique was applied to the SDOF model. The nonlinear aerodynamic model can predict well the amplitude and lock-in region of the VIV of the circular cylinder model.

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ABSTRACT: Edgewise vibrations with low aerodynamic damping are of particular concern in modern multi-megawatt wind turbines, as large amplitude cyclic oscillations may significantly shorten the life-time of wind turbine components, and even lead to structural damages or failures. In this paper, a new blade design with active controllers is proposed for controlling edgewise vibrations. The control is based on a pair of actuators/active tendons mounted inside each blade, allowing a variable control force to be applied in the edgewise direction. The control forces are appropriately manipulated according to a prescribed control law. A mathematical model of the wind turbine equipped with active controllers has been formulated using an Euler–Lagrangian approach. The model describes the dynamics of edgewise vibrations considering the aerodynamic properties of the blade, variable mass and stiffness per unit length and taking into account the effect of
centrifugal stiffening, gravity and the interaction between the blades and the tower. Aerodynamic loads corresponding to a combination of steady wind including the wind shear and the effect of turbulence are computed by applying the modified Blade Element Momentum (BEM) theory. Multi-Blade Coordinate (MBC) transformation is applied to an edgewise reduced order model, leading to a linear time-invariant (LTI) representation of the dynamic model. The LTI description obtained is used for the design of the active control algorithm. Linear Quadratic (LQ) regulator designed for the MBC transformed system is compared with the control synthesis performed directly on an assumed nominal representation of the time-varying system. The LQ regulator is also compared against vibration control performance using Direct Velocity Feedback (DVF). Numerical simulations have been carried out using data from a 5-MW three-bladed Horizontal-Axis Wind Turbine (HAWT) model in order to study the effectiveness of the proposed active controlled blade design in reducing edgewise vibrations. Results show that the use of the proposed control scheme significantly improves the response of the blade and promising performances can be achieved. Furthermore, under the conditions considered in this study quantitative comparisons of the LQ-based control strategies reveal that there is a marginal improvement in the performances obtained by applying the MBC transformation on the time-varying edgewise vibration model of the wind turbine.

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ABSTRACT: This paper demonstrates the applicability of the Superposition Method for free vibration analysis of doubly curved thin shallow shells of rectangular planform with any possible combination of simply supported and clamped edges. The same building block yields the natural frequencies for 55 combinations of edge conditions. The natural frequency parameters of the shells were obtained using the Superposition-Galerkin Method (SGM) for seven sets of boundary conditions, several different curvature ratios and two aspect ratios. The SGM uses approximate steady state solutions as building blocks but the method proves to be accurate and efficient. It has also been shown that even with approximate building blocks, the monotonic nature of convergence of the natural frequencies with respect to the number of driving coefficients holds, as long as the number of admissible functions in the steady state solution is kept constant. The results for natural frequencies of the seven boundary conditions may be considered as benchmarks.

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ABSTRACT: This paper examines the use of eigenvector orientation method to detect the onset of subsonic and supersonic flutter of panels modeled by finite elements. The accuracy of the eigenvector orientation method for prediction of the flutter boundary (indicated by a gradual loss of orthogonality between two eigenvectors) is demonstrated by using the examples of a swept-back cantilever plate model at subsonic speed and a simply supported plate model at supersonic speed. Piezoelectric layers are assumed to be bonded to the top and bottom surfaces of the simply supported plate in order to provide bending moments to control motions of each finite
element. An approach of optimal control design is presented to actively suppress the possible flutter based on linear quadratic regulator theory and the nonlinear modal equations of motions. To illustrate the applicability and effectiveness of using the piezoelectric layers as controllers, several cases are studied and presented. The effects of varying locations of control moments are studied so as to fulfill the objective of adjusting the flutter speed to be within a desirable range. The results illustrate that the control moment manipulation can offset the flutter occurrence and additionally generate a lead time for possibly executing flutter control.

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ABSTRACT: An analytically nonlocal Euler–Bernoulli beam model for the wave propagation in fluid-filled single-walled carbon nanotube (SWCNT) is established. The governing equations with the nonlocal effects are derived on the variational principle, and used in the wave propagation analysis of the SWCNT beam. Compared with the partially nonlocal Euler–Bernoulli beam models used previously, the analytically nonlocal model presented in the present study predicts well the effects of the stiffness enhancement and the wave damping at the high wavenumber or the strong nonlocal effects area for the fluid-filled SWCNT beam. Though the analytical model is less sensitive than the partially nonlocal model when the moving velocity of the internal fluid is high enough, it simulates more of the high-order nonlocal effecting information than the partially nonlocal model does in many cases.


ABSTRACT: We investigate vibrations of an unloaded and loaded tyre rolling at constant speed without slipping in the contact area. A previously proposed analytical model of a reinforced tyre is considered. The surface of the tyre is represented by flexible tread, combined with parts of two tori (sidewalls of the tyre). The contact between the wheel and the ground plane occurs by the part of the tread. The natural frequencies (NF) and mode shapes (MS) are determined analytically for unloaded tyre and numerically for loaded tyre. The results were compared with experiments for the non-rotating tyre. In the case of loaded rotating tyre, the increasing of the angular velocity of rotation implies that NF decrease. Moreover, a phenomenon of frequency loci veering is visible here: NF as functions of angular velocity approach each other and then veer away instead of crossing. The MS interact in veering region and, as a result, interchange.


ABSTRACT: Hand–arm vibration syndrome (HAVS) is collectively a vasospastic and neurodegenerative occupational disease. One of the major symptoms of HAVS is vibration white finger (VWF) caused by
exaggerated vasoconstriction of the arteries and skin arterioles. While VWF is a very painful and costly occupational illness, its pathology has not been well understood. In this study a small artery is modeled as a fluid filled elastic tube whose diameter changes along the axial direction. Equations of motion are developed by considering interactions between the fluid, artery wall and soft-tissue bed. It is shown that the resulting wave equation is the same as that of the basilar membrane in the cochlea of mammals. Therefore, the artery system shows a spatial resonance as in the basilar membrane, which responds with the highest amplitude at the location determined by the vibration frequency. This implies that a long-term use of one type of tool will induce high-level stresses at a few identical locations of the artery that correspond to the major frequency components of the tool. Hardening and deterioration of the artery at these locations may be a possible cause of VWF.


ABSTRACT: This paper deals with the vibration characteristics of a piezoelectric open-shell transducer which was made by dividing a cylindrical piezoelectric transducer longitudinally into two segments. Two-dimensional governing equations were derived by using the cylindrical membrane theory. Applying mechanical and electrical boundary conditions yielded a characteristic equation for the resonance frequencies of the piezoelectric open-shell transducer. The fundamental frequency and the electromechanical coupling factor were calculated and compared with the results of the finite element analysis and experiment. The fundamental mode shape obtained theoretically was compared with the result of the finite element analysis. The theoretical analysis was verified to provide the vibration characteristics of an open-shell transducer.


ABSTRACT: We solve exactly the equations of in-plane natural vibration for a circular plate whose outer edge is restrained elastically. The mode shapes are represented by trigonometric functions with a number of nodal diameters in the circumferential direction and mode functions in the radial direction. We present the exact frequency equations and mode functions and tabulate the frequency parameters satisfying the frequency equations. The corresponding mode functions and two-dimensional mode shapes are illustrated when both radial and tangential stiffness are zero (free edge), infinity (clamped edge), or medium. Comparisons with previous reported results confirm the accuracy of the present work.

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ABSTRACT: The flexural vibration of a homogeneous isotropic linearly elastic cylinder of any aspect ratio is analysed in this paper. Natural frequencies of a cylinder under uniformly distributed axial loads acting on its
bases are calculated numerically by the Ritz method with terms of power series in the coordinate directions as approximating functions. The effect of axial loads on the flexural vibration cannot be described by applying infinitesimal strain theory, therefore, geometrically nonlinear strain–displacement relations with second-order terms are considered here. The natural frequencies of free–free, clamped–clamped, and sliding–sliding cylinders subjected to axial loads are calculated using the proposed three-dimensional Ritz approach and are compared with those obtained with the finite element method and the Bernoulli–Euler theory. Different experiments with cylinders axially compressed by a hydraulic press are carried out and the experimental results for the lowest flexural frequency are compared with the numerical results. An approach based on the Ritz formulation is proposed for the flexural vibration of a cylinder between the platens of the press with constraints varying with the intensity of the compression. The results show that for low compressions the cylinder behaves similarly to a sliding–sliding cylinder, whereas for high compressions the cylinder vibrates as a clamped–clamped one.


ABSTRACT: In this paper, forced vibrations of a double-walled clamped–clamped carbon nanotube (DWNT) are studied. Two Euler–Bernoulli beams are used to model the inner and outer layers of the DWNT. An electrostatic actuation, which is comprised of DC and AC voltages is applied between the nanotubes and the electrode. In the system model, the nonlinear form of the interlayer van der Waals (vdW) force, and also, the mid-plane stretching are considered. The obtained equations are solved through Galerkin and multiple scales methods for primary and secondary resonances. The frequency response of the system is obtained as a function of some of the system parameters. A stability analysis of the response is conducted and bifurcation points are determined. The results demonstrate that the DWNT shows different behavior by changing the value of DC voltage. It is also observed that both layers of the DWNT vibrate with the same frequency under the primary and secondary resonance conditions.


ABSTRACT: A novel active control method of sound radiation from a cylindrical shell under axial excitations is proposed and theoretically analyzed. This control method is based on a pair of piezoelectric stack force actuators which are installed on the shell and parallel to the axial direction. The actuators are driven in phase and generate the same forces to control the vibration and the sound radiation of the cylindrical shell. The model considered is a fluid-loaded finite stiffened cylindrical shell with rigid end-caps and only low-frequency axial vibration modes are involved. Numerical simulations are performed to explore the required control forces and the optimal mounting positions of actuators under different cost functions. The results show that the proposed force actuators can reduce the radiated sound pressure of low-frequency axial modes in all directions.

Shigeru Yoshikawa, Hiromi Ashiro and Yumiko Sakamoto (Graduate School of Design, Kyushu University, 4-9-1 Shiobaru, Minami-ku, Fukuoka 815-8540, Japan), “Experimental examination of vortex-sound generation

ABSTRACT: Aero-dynamical models of sound generation in an organ pipe driven by a thin jet are investigated through an experimental examination of the vortex-sound theory. An important measurement requirement (acoustic cross-flow as an irrotational potential flow reciprocating sinusoidally) from the vortex-sound theory is carefully realized when the pipe is driven with low blowing pressures of about 60 Pa (jet velocities of about 10 m/s). Particle image velocimetry (PIV) is applied to measure the jet velocity and the acoustic cross-flow velocity over the mouth area at the same phase by quickly switching the jet drive and the loudspeaker-horn drive. The vorticity of the jet flow field and the associated acoustic generation term are evaluated from the measurement data. It is recognized that the model of the “jet vortex-layer formation” is more relevant to the sound production than the vortex-shedding model. The acoustic power is dominantly generated by the flow–acoustic interaction near the edge, where the acoustic cross-flow velocity takes larger magnitudes. The acoustic generation formula on the vortex sound cannot deny the conventional acoustical volume-flow model because of the in-phase relation satisfied between the acoustic pressure at the mouth and the acoustic volume flow into the pipe. The vortex layers formed along both sides of the jet act as the source of an accelerating force (through the “acceleration unbalance”) with periodically alternating direction to oscillate the jet flow and to reinforce the acoustic cross-flow at the pipe mouth.

Farough Mohammadi and Ramin Sedaghati (Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, QC, Canada H3G 1M8), “Vibration analysis and design optimization of viscoelastic sandwich cylindrical shell”, Journal of Sound and Vibration, Vol. 331, No. 12, pp 2729-2752, June 2012, https://doi.org/10.1016/j.jsv.2012.02.004

ABSTRACT: Damping properties of viscoelastic sandwich structure can be improved by changing some parameters such as thickness of the layers, distribution of partial treatments, slippage between layers at the interfaces, cutting and its distribution at the top and core layers. Since the optimization problem may result in a thick core layer, for achieving more accuracy a new higher-order Taylor's expansion of transverse and in-plane displacement fields is developed for the core layer of sandwich cylindrical shell in which the displacement fields at the core layer are compatibly described in terms of the displacement fields at the elastic faces. The presented model includes fewer parameters than the previously developed models and therefore decreases the number of degree of freedom in the finite element modeling. The transverse normal stress in the core layer is also considered. The formulations are developed to consider the slippage between layers at the interfaces. Finally, by combining the finite element method and the optimization algorithms based on the genetic algorithm and sequential quadratic programming technique, a design optimization methodology has been formulated to maximize the damping characteristics using the optimal number and location of cuts and partial treatments with optimal thicknesses of top and core layers.

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ABSTRACT: A new elastic nonlocal stress model and analytical solutions are developed for torsional dynamic behaviors of circular nanorods/nanotubes. Unlike the previous approaches which directly substitute the nonlocal stress into the equations of motion, this new model begins with the derivation of strain energy using the nonlocal stress and by considering the nonlinear history of straining. The variational principle is applied to derive an infinite-order differential nonlocal equation of motion and the corresponding higher-order boundary conditions which contain a nonlocal nanoscale parameter. Subsequently, free torsional vibration of nanorods/nanotubes and axially moving nanorods/nanotubes are investigated in detail. Unlike the previous conclusions of reduced vibration frequency, the solutions indicate that natural frequency for free torsional vibration increases with increasing nonlocal nanoscale. Furthermore, the critical speed for torsional vibration of axially moving nanorods/nanotubes is derived and it is concluded that this critical speed is significantly influenced by the nonlocal nanoscale.


ABSTRACT: Moving from a general plate theory, a modified general classical laminated plate theory (MGCLPT) exhibiting nonlinear curvatures but still allowing for some worth features of linear curvature models (von Karman) is formulated. Starting from MGCLPT partial differential equations, a minimal discretized model suitable for the analysis of resonant finite-amplitude vibrations of symmetric cross-ply laminates, with immovable or movable supports, is obtained via the Galerkin procedure. Periodic responses of a single-mode model and of a 3:1 internally resonant two-mode model excited at primary resonance are obtained via the multiple time scale method. The influence of various system parameters (thickness ratio, plate aspect, number of laminae, kind of material, mode number) is addressed, and the comparison of nonlinear vibration results as obtained with the MGCLPT and the von Karman models for different boundary conditions shows some interesting differences.


ABSTRACT: The method of analysis of stress intensity distribution over vibrating plates is presented. Both the geometrical and physical nonlinearities are taken into account. It is showed that with the help of the small parameter method it is possible to obtain the expression for the transverse normal strain in a form, which is convenient for analytical transformations. The dynamic deflection is expanded into truncated series of eigenmodes and discrete model of the system is derived. The backbone curves of thin rectangular immovably simply supported plate vibrations are obtained. The stress intensity distribution patterns over the plate are analyzed. It is noted that in case of nonlinear vibrations not only the magnitudes of stress intensity depend on the vibration amplitude, but also on the pattern of its distribution.

Aurelien Grolet and Fabrice Thouverez (Ecole Centrale de Lyon, Laboratoire de Tribologie et Dynamique des Systèmes, 36, avenue Guy de Collongue, 69134 Ecully Cedex, France), “Free and forced vibration analysis of a
ABSTRACT: This work program is devoted to studying the nonlinear dynamics of a structure with cyclic symmetry under conditions of geometric nonlinearity, through the use of the harmonic balance method (HBM). In order to study the influence of nonlinearity due to the large deflection of blades, a simplified model has been developed. This approach leads to a system of linearly coupled, second-order nonlinear differential equations, in which nonlinearity appears via cubic terms. Periodic solutions, in both the free and forced cases, are sought by applying HBM coupled with an arc-length continuation method. Solution stability has been investigated using Floquet's theorem. In addition to featuring similar and nonsimilar nonlinear modes, the unforced system is known to contain localized nonlinear modes that arise from branching point bifurcation at certain vibration amplitudes. In the forced case, these nonlinear modes give rise to a complex dynamic behavior. Many bifurcations can take place, thus leading to strong or weak localization that may or may not be stable. In this study, special attention has been paid to the influence of excitation on dynamic responses. Several cases of excitation have been analyzed herein: localized excitation, and low-engine-order excitation. In the case of low-engine-order excitation, sensitivity of the response to a perturbation of this excitation type has been investigated, and it has been shown that for a localized, or sufficiently detuned excitation, several solutions can coexist, some of which are represented by closed curves in the Frequency-Amplitude domain. These various solutions overlap when increasing the force amplitude, leading to forced nonlinear localization. Because closed curves are not tied up with the basic nonlinear solution, they can easily be overlooked. In this study, they have been calculated using a sequential continuation with the force amplitude as a parameter.

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ABSTRACT: This paper presents an analytical study on the forced vibration of electrically actuated micro-switches near resonance region, taking into consideration the intermolecular force, axial residual stress, and geometrical nonlinearity due to mid-plane stretching. The micro-switch is made of either homogeneous material or non-homogeneous functionally graded materials with two material phases and subjected to a time-varying applied voltage consisting of a DC component and a small AC component. The perturbation-based method of averaging is employed to solve the nonlinear partial differential governing equations to obtain the resonance frequency responses of both the vibration amplitude and phase angle. The present analysis is validated through direct comparisons with published experimental results and excellent agreement has been achieved. A parametric study is conducted to show the effects of geometrical nonlinearity, intermolecular Casimir force, the electrostatic force due to DC voltage, the AC voltage induced harmonic force, quality factor, axial residual stress and material composition on the frequency response characteristics.

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ABSTRACT: We study the forced motion and far-field acoustic radiation of an elastic cylinder subject to uniform axial flow and actuated at its upstream end by small-amplitude periodic displacement and rotation. The linearized problem is analysed under subcritical conditions of low nondimensional stream-flow velocity, u less than u(critical), where the unforced cylinder is aligned with the external flow. It is found that the forced motion at subcritical conditions is affected by the properties of the in vacuo system. A resonance is excited when the cylinder is actuated at one of its in vacuo eigenfrequencies, omega(resonance), manifested by relatively large deflections. Fluid flow acts to regularize this behavior by transferring energy from the upstream driver to the fluid. The dynamical description is used as a source term in the formulation of the vibroacoustic problem. Assuming the cylinder is well-streamlined and neglecting the effect of vortex shedding, the far field sound is attributed directly to cylinder vibration. Acoustic radiation of a dipole type is found in the limit where the cylinder is acoustically compact. Following the dynamical description, it is shown that fluid flow reduces the sound level compared to that in the absence of mean flow, when actuation is applied close to omega = omega (resonance). In addition, we demonstrate that far-field sound can be controlled by varying the actuation parameters. Analytical description of the dynamical and acoustic fields is obtained in the limit u ⪡ 1, and found in close agreement with the exact numerical solution up to u O(1). Discrepancies between the approximate and exact solutions are observed close to the resonance frequencies, and rationalized in terms of the strong fluid–structure coupling occurring when omega approaches omega(resonance). At omega = omega (resonance), a qualitative description of the effect of fluid stream flow on the system behavior is supplied.


ABSTRACT: The free vibration analysis of functionally graded annular plates with mixed boundary conditions in thermal environment is carried out by the 3D elasticity theory and the Chebyshev–Ritz method. The material properties are assumed to be temperature dependent and graded in the thickness direction. The mixed boundary conditions which include upper and lower surfaces partially fixed, inner side partially fixed and outer side partially fixed are considered, respectively. The accuracy of the present approach for solving the free vibration of the plates with different boundary conditions is validated by comparing the present numerical results with the results available. The effects of the different mixed boundary conditions, the temperature rise, the material graded index and the geometrical parameters on the eigen-frequencies are studied.


ABSTRACT: The linear 3D elasticity theory in conjunction with the classical method of separation of variables and the translational addition theorem for cylindrical wave functions are employed to investigate the three-dimensional steady-state sound radiation characteristics of an arbitrarily thick eccentric hollow cylinder of infinite length, submerged in an unbounded ideal acoustic medium, and subjected to arbitrary time-harmonic on-surface mechanical drives. The spatial Fourier transform along the shell axis and Fourier series expansion in
the circumferential direction are utilized to obtain a formal integral expression for the radiated pressure field in
the frequency domain. The method of stationary phase is subsequently implemented to evaluate the integral for
an observation point in the far field. The analytical results are illustrated with numerical examples in which air-
filled water-submerged concentric and eccentric steel cylinders are driven by harmonic concentrated radial and
transverse surface loads. Effects of excitation and cylinder eccentricity on the far-field radiated pressure
amplitudes/directivities are discussed and contributions from pseudo-Rayleigh, whispering gallery, and axially
guided waves are examined through selected spatial dispersion patterns. Limiting cases are considered and the
validity of results is established with the aid of a commercial finite element package as well as by comparison
with the data in the existing literature.

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“Free vibration analysis of a hanged clamped-free cylindrical shell partially submerged in fluid: The effect of
external wall, internal shaft, and flat bottom”, Journal of Sound and Vibration, Vol. 331, No. 17, pp 4072-4092,
ABSTRACT: The free flexural vibration of a hanged clamped-free cylindrical shell with various boundary
conditions partially submerged in a fluid is investigated. Specifically, the effects of the boundary conditions
such as the existence of the external wall, internal shaft, and bottom on the natural vibration characteristics of
the partially submerged cylindrical shell are investigated both theoretically and experimentally. The fluid is
assumed to be inviscid and irrotational. The cylindrical shell is modeled by using the Rayleigh–Ritz method
based on the Sanders shell theory. The kinetic energy of the fluid is derived by solving a boundary
value problem related to the fluid motion. The theoretical predictions were in good agreement with the experimental
results validating the theoretical approach developed in this study. The effects of the external wall, internal
shaft, and bottom on the natural vibration characteristics can be neglected when its boundaries are not very
close to the shell structure.

Shupeng Sun, Shiming Chu and Denqqing Cao (School of Astronautics, Harbin Institute of Technology, PO
Box 137, Harbin 150001, People's Republic of China), “Vibration characteristics of thin rotating cylindrical
shells with various boundary conditions”, Journal of Sound and Vibration, Vol. 331, No. 18, pp 4170-4186,
ABSTRACT: An analysis is presented for the vibration characteristics of thin rotating cylindrical shells with
various boundary conditions by use of Fourier series expansion method. Based on Sanders’ shell equations, the
governing equations of motion which take into account the effects of centrifugal and Coriolis forces as well as
the initial hoop tension due to rotating are derived. The displacement field is expressed as a product of Fourier
series expressions which represents the axial modal displacements and trigonometric functions which represents
the circumferential modal displacements. Stokes’ transformation is employed to derive the derivatives of the
Fourier series expressions. Then, through the process of formula derivation, an explicit expression of the exact
frequency equation can be obtained for a thin rotating cylinder with classical boundary conditions of any type.
Once the frequency equation has been determined, the frequencies are calculated numerically. To validate the
present analysis, comparisons between the results of the present method and previous studies are performed and
very good agreement is achieved. Finally, the method is applied to investigate the vibration characteristics of thin rotating cylindrical shells under various boundaries, and the results are presented.

ABSTRACT: A three-dimensional (3-D) method of analysis is presented for determining the free vibration frequencies of joined thick conical-cylindrical shells of revolution with variable thickness. Unlike conventional shell theories, which are mathematically two-dimensional (2-D), the present method is based upon the 3-D dynamic equations of elasticity. Displacement components $u_r$, $u_\theta$, and $u_z$ in the radial, circumferential, and axial directions, respectively, are taken to be periodic in $\theta$ and in time, and algebraic polynomials in the $r$ and $z$ directions. Potential (strain) and kinetic energies of the joined shells are formulated, and the Ritz method is used to solve the eigenvalue problem, thus yielding upper bound values of the frequencies by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies. Natural frequencies are presented for different boundary conditions. Comparisons are made between the frequencies from the present 3-D Ritz method and 2-D thin shell theories by previous researchers.

ABSTRACT: The structural behavior of a shallow arch is highly nonlinear, and so when the amplitude of the oscillation of the arch produced by a suddenly applied load is sufficiently large, the oscillation of the arch may reach a position at its primary unstable equilibrium path or secondary bifurcation unstable equilibrium path, leading the arch to buckle dynamically. This paper presents an analytical study of the nonlinear dynamic in-plane buckling of a shallow circular arch under a uniform radial load that is applied suddenly and with an infinite duration. The principle of conservation of energy is used to establish the criterion for dynamic buckling of the arch, and the analytical solution for the dynamic buckling load is derived. It is shown that under a suddenly applied uniform radial load, a shallow pinned–fixed arch has a unique possible dynamic buckling load, while shallow pinned–pinned and fixed–fixed arches may have two possible dynamic buckling loads: a lower dynamic buckling load and an upper dynamic buckling load. The dynamic buckling loads of a shallow arch under a suddenly applied uniform radial load with infinite duration are found to be lower than their static counterparts, and to increase with an increase of the arch included angle and slenderness. The effect of static preloading on the dynamic buckling of an arch is also investigated. It is found that the pre-applied static load decreases the dynamic buckling load of the arch, but increases the sum of the pre-applied load and the dynamic buckling load.

ABSTRACT: The Generalized Differential Quadrature (GDQ) method is applied to study the dynamic behavior of anisotropic doubly-curved shells and panels of revolution with a free-form meridian. The First-order Shear Deformation Theory (FSDT) is used to analyze the above mentioned moderately thick structural elements. In order to include the effect of the initial curvature in the evaluation of the stress resultants three different approaches, specifically Qatu approach, Toorani–Lakis approach and Reissner–Mindlin approach, are considered and compared. An improvement of the Classical Reissner–Mindlin Theory (CRMT) using a different kinematical model is considered. By so doing a generalization of the theory of anisotropic doubly-curved shells and panels of revolution is proposed. Four different anisotropic shell theories, namely General First-order Shear Deformation Theory by Qatu (GFSDTQ), General First-order Shear Deformation Theory by Toorani–Lakis (GFSDTTL), General First-order Shear Deformation Theory by Reissner–Mindlin (GFSDTRM) and Classical Reissner–Mindlin Theory (CRMT), are compared in order to show the differences and the accuracy of these theories. The solution is given in terms of generalized displacement components of points lying on the middle surface of the shell. Simple Rational Bézier curves are used to define the meridian curve of the revolution structures. Results are obtained taking the meridian and circumferential coordinates into account, without using the Fourier modal expansion methodology. Furthermore, GDQ results are compared with those obtained by using commercial programs such as Abaqus, Ansys, Nastran, Straus and Pro/Mechanica. Very good agreement is observed.

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ABSTRACT: The magnetic properties of carbon nanotubes and their mechanical behaviour in a magnetic field have attracted considerable attention among the scientific and engineering communities. This paper reports an analytical approach to study the effect of a longitudinal magnetic field on the transverse vibration of a magnetically sensitive double-walled carbon nanotube (DWCNT). The study is based on nonlocal elasticity theory. Equivalent analytical nonlocal double-beam theory is utilised. Governing equations for nonlocal transverse vibration of the DWCNT under a longitudinal magnetic field are derived considering the Lorentz magnetic force obtained from Maxwell's relation. Numerical results from the model show that the longitudinal magnetic field increases the natural frequencies of the DWCNT. Both synchronous and asynchronous vibration phases of the tubes are studied in detail. Synchronous vibration phases of DWCNT are more affected by nonlocal effects than asynchronous vibration phases. The effects of a longitudinal magnetic field on higher natural frequencies are also presented. Vibration response of DWCNT with outer-wall stationary and single-walled carbon nanotube under the effect of longitudinal magnetic field are also discussed in the paper.


ABSTRACT: This paper investigates the accuracy capabilities of using variable kinematic modeling in compact and thin-walled beam-like structures with dynamic loadings. Carrera Unified Formulation (CUF) is employed to
introduce refined one-dimensional (1D) models with a variable order of expansion for the displacement unknowns over the beam cross-section. Classical Euler–Bernoulli and Timoshenko beam theories are obtained as particular cases of these variable kinematic models while a higher order expansion permits the detection of in-plane cross-section deformation, since it leads to shell-like solutions. Finite element (FE) method is used to provide numerical results and the Newmark method is implemented as a time integration scheme. Some assessments with closed form solutions are discussed and comparisons with shell-type results obtained with commercial FE software are made. Further analyses address both compact and thin-walled cross-sections. In particular, the case of a deformable thin-walled cylinder loaded by time-dependent internal forces is discussed. The results clearly show that finite elements which are formulated in the CUF framework do not introduce additional numerical problems with respect to classical beam theories. Comparisons with elasticity solutions prove that the present 1D CUF model offers an accuracy in analyzing thin-walled structures which is typical of shell or three-dimensional models with a remarkable reduction in the computational cost required.


ABSTRACT: In the present work, the study of the nonlinear vibration of a functionally graded cylindrical shell subjected to axial and transverse mechanical loads is presented. Material properties are graded in the thickness direction of the shell according to a simple power law distribution in terms of volume fractions of the material constituents. Governing equations are derived using improved Donnell shell theory ignoring the shallowness of cylindrical shells and kinematic nonlinearity is taken into consideration. One-term approximate solution is assumed to satisfy simply supported boundary conditions. The Galerkin method, the Volmir's assumption and fourth-order Runge–Kutta method are used for dynamical analysis of shells to give explicit expressions of natural frequencies, nonlinear frequency–amplitude relation and nonlinear dynamic responses. Numerical results show the effects of characteristics of functionally graded materials, pre-loaded axial compression and dimensional ratios on the dynamical behavior of shells. The proposed results are validated by comparing with those in the literature.


ABSTRACT: Accurate prediction of interlaminar transverse stresses in smart piezolaminated structures through two-dimensional laminate theories that are efficient, directly from the constitutive equations, is a challenging task. In this study, we extend the 11 variable global-local theory (GLT) which was originally proposed for elastic laminated structures with this purpose, to the dynamic analysis of hybrid piezolaminated plates under electromechanical loading. The zigzag-local theory (ZLT), with nine primary displacement variables, which was recently developed for static analysis of hybrid plates and has the ability to calculate transverse shear stresses from constitutive equations, is also extended for dynamic analysis. A two-way electromechanical coupling is considered. A variational formulation is presented for the two theories by using the extended Hamilton's principle, obtaining the governing dynamic field equations, and variationally consistent boundary conditions. The accuracy of the two theories are critically assessed in direct comparison with the exact 3D piezoelectricity solutions for static, free vibration and forced vibration response of hybrid plates for a variety of
lamine configurations. It is revealed that the GLT, in spite of having higher number of primary variables, is unable to yield accurate prediction not only for the transverse shear stresses, but also for global responses like displacements under mechanical loading and natural frequencies. For the latter entities, the prediction is even worse than the five-variable zigzag theory. In contrast, the ZLT predicts with good accuracy all response entities including the transverse shear stresses for all laminates under mechanical as well as potential loading, and is superior to both GLT and the zigzag theory.


ABSTRACT: The nonlinear dynamics for forced motions of an axially moving plate is numerically investigated using Von Kármán plate theory and retaining in-plane displacements and inertia. The equations of motion are obtained via an energy method based on Lagrange equations. This yields a set of second-order nonlinear ordinary differential equations with coupled terms. The equations are transformed into a set of first-order nonlinear ordinary differential equations and are solved via the pseudo-arclength continuation technique. The near-resonance nonlinear dynamics is examined via plotting the frequency–response curves of the system. Results are shown through frequency–response curves, time histories, and phase-plane diagrams. The effect of system parameters, such as the axial speed and the pretension, on the resonant responses is also highlighted.

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ABSTRACT: Vibration control plays a crucial role in many structures, especially in the lightweight ones. One of the most commonly practiced method to suppress the undesirable vibration of structures is to attach patches of the constrained layer damping (CLD) onto the surface of the structure. In order to consider the weight efficiency of a structure, the best shapes and locations of the CLD patches should be determined to achieve the optimum vibration suppression with minimum usage of the CLD patches. This paper proposes a novel topology optimization technique that can determine the best shape and location of the applied CLD patches, simultaneously. Passive vibration control is formulated in the context of the level set method, which is a numerical technique to track shapes and locations concurrently. The optimal damping set could be found in a structure, in its fundamental vibration mode, such that the maximum modal loss factor of the system is achieved. Two different plate structures will be considered and the damping patches will be optimally located on them. At the same time, the best shapes of the damping patches will be determined too. In one example, the numerical results will be compared with those obtained from the experimental tests to validate the accuracy of the proposed method. This comparison reveals the effectiveness of the level set approach in finding the optimum shape and location of the CLD patches.

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ABSTRACT: This work aims to investigate a possibility of non-contact vibration modal testing for bending and torsional motions of cylindrical bodies such as pipes. Here, a transducer operated by the electromagnetic acoustic coupling principle is newly devised. Depending on vibration modes, bending or torsional, different magnetic circuit configurations are employed to fabricate the transducer. The main characteristic of the proposed transducer is non-contact vibration generation in a test specimen without any mechanical movement of the actuating unit. It can be also used as a non-contact sensing unit if necessary. The validity and the performance of the proposed non-contact modal testing method are checked with several experiments.

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ABSTRACT: In this study, the nonlinear dynamic buckling of functionally graded (FG) truncated conical shells subjected to axial compressive load varying as a linear function of time is investigated. The material properties of the FG truncated shell are assumed to vary continuously through the thickness of the shell. The nonlinear pre-buckling deformations of the FG truncated conical shell are taken into account. The fundamental relations and modified Donnell type nonlinear dynamic stability and compatibility equations of the FG truncated conical shell are derived and solved by using the Superposition principle, Galerkin and Runge–Kutta methods. The values of the dimensionless nonlinear critical time parameter have been found numerically. Finally, carrying out some computations, the effects of the compositional profiles, the variation of the truncated conical shell geometric parameters and the axial loading speed on the dimensionless linear and nonlinear critical time parameters have been studied. Comparing the results of this study with those in the literature validates the present analysis.

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ABSTRACT: In this paper a wave and finite element (WFE) post-processing technique is applied to predict the effects of pre-stress on the damping of curved panels. It is seen that pre-stress substantially reduces the global loss factor, especially of those modes of vibration which involve considerable radial displacement. This is particularly significant for aerospace structures since ground-test results typically do not include pre-loads. The WFE approach and its extension to include pre-stress effects are briefly described. Numerical examples concerning a pressurised viscoelastic cylinder and a pre-loaded curved laminated panel are presented.


ABSTRACT: In this paper, a weakly nonlinear equation of motion is derived for the dynamics of a towed, neutrally buoyant flexible slender cylinder. The cylinder is terminated by end-pieces at its two ends and is fastened via a massless towrope to a support rigidly fixed upstream. The motions are considered to take place in a horizontal plane. The equation of motion is obtained via Hamilton's principle after obtaining the Lagrangian of the system and the virtual work associated with the fluid dynamic forces. For convenience, the fluid-related forces are derived separately: inviscid hydrodynamic forces are modelled by an extension of Lighthill's slender-body work to third-order accuracy, and the viscous forces are derived to the same accuracy, by elaboration of Taylor's expressions. The Galerkin method is used to discretize the equation of motion with the free–free Euler–Bernoulli beam eigenfunctions, and the resulting set of first-order equations are solved numerically using a time-integration solver. Numerical results are obtained to illustrate the typical dynamical behaviour of a towed flexible cylinder, generally confirming experimental observations and linear theory predictions made in the past. Also, the effect of the towrope-length to cylinder-length ratio and the effect of the tail end-piece shape on the dynamics and stability of the system are investigated. The results confirm that for a towed flexible cylinder, if the tail end-piece is not blunt and the towrope not too short, both rigid-body and flexural instabilities may develop as the flow velocity is increased. The former occur at low flow velocities, in the form of oscillatory and then static instabilities, whereas the latter generally occur at higher flow velocities in the form of second- and then third-mode flutter. Moreover, it is found that the system becomes less stable and is subject to larger deformations if the towrope is longer. On the other hand, making the tail end-piece sufficiently blunt can effectively suppress all the instabilities; the system then remains stable for apparently all towing speeds.

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ABSTRACT: To control the linear vibrations of structures partially filled with liquids is of prime importance in various industries such as aerospace, naval, civil and nuclear engineering. It is proposed here to investigate a linearized formulation adapted to a rational computation of the vibrations of such coupled systems. Its particularity is to be fully Lagrangian since it considers the fluid displacement field with respect to a static equilibrium configuration as the natural variable describing the fluid motion, as classically done in structural
dynamics. As the coupled system considered here is weakly damped in the low frequency domain (low modal density), the analysis of the vibrations of the associated undamped conservative system constitutes the main objective of this paper. One originality of the present formulation is to take into account the effect of the pressurization of the tank on the dynamics of the system, particularly in the case of a compressible liquid. We propose here a new way of deriving the linearized equations of the coupled problem involving a deformable structure and an inner inviscid liquid with a free surface. A review of the classical case considering a heavy incompressible liquid is followed by an application to the new case involving a light compressible liquid. A solution procedure in the frequency domain is proposed and a numerical discretization using the finite element method is discussed. In order to reduce the computational costs, an appropriate reduced order matrix model using modal synthesis approach is also presented.

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ABSTRACT: The paper presents a review of reduced order modeling (ROM) techniques for geometrically nonlinear structures, more specifically of those techniques that are applicable to structural models constructed using commercial finite element software. The form of the ROM governing equations, the estimation of their parameters, and the selection of the basis functions are reviewed in detail and comparisons of predicted displacements and stresses obtained by the ROM and the full order, finite element models are presented. These ROM methods and validations are extended next to multidisciplinary problems in which the structure is subjected to thermal effects or interacts with the aerodynamics/acoustics. These various applications demonstrate the usefulness and appropriateness of ROMs as computationally efficient alternatives to full finite element models for the accurate prediction of the geometrically nonlinear response of the structures considered.

ABSTRACT: This paper deals with the sensitivity analysis of structural acoustic performance in presence of non-proportional damping and optimal layout design of the damping layer of vibrating shell structures under harmonic excitations. The structural system with a partially-covered damping layer has a non-proportional global damping matrix. Therefore, the method of complex mode superposition in the state space is employed in the dynamic response analysis. The sound pressure is calculated with the structural response solution by using the boundary element method. In this context, an adjoint variable scheme for the design sensitivity analysis of sound pressure is developed. In the optimal design problem, the design objective is to minimize the structural vibration-induced sound pressure at a specified point in the acoustic medium by distributing a given amount of damping material. An artificial damping material model that has a similar form as in the SIMP approach is employed, and the relative densities of the damping material are considered as design variables. Numerical
examples are given to illustrate the validity and efficiency of this approach. The influences of the excitation frequency, the damping coefficients and the locations of the reference point on the optimal topologies are also discussed.

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ABSTRACT: Slender curved structures may experience a loss of stability called snap-through, causing the curvature on part or all of the structure to invert inducing fatigue damage. This paper presents a framework for analyzing the transient responses of slender curved structures. A numerical study of snap-through in a shallow arch-like model under periodic excitations is performed on a simplified model and on a detailed finite element model. The boundaries that separate the snap-through and no snap-through regions in the forcing parameters space are identified. Various post-snap responses are analyzed. The effects of initial conditions on the snap-through boundaries and post-snap responses are examined. Forcing parameters that lead to chaotic response are identified.

ABSTRACT: Viscoelastic damping material attached on the surface of a structure is widely used to suppress the resonance vibration in aerospace, automobiles, and various other applications. A full treatment of damping material is not an effective method because the damping effect is not significantly increased compared to that obtained by an effective partial damping treatment. In addition, the weight of the structure is increased significantly, which can cause poor system performance. Topology optimization is recently implemented in order to find an effective optimal damping treatment. The objective function is maximization of the damping effect (i.e. the modal loss factor) and the constraint is a maximum allowable volume of damping material. In this paper we compare the modal loss factors obtained by topology optimization to the ones obtained by other approaches, in order to determine which approach provides a better damping treatment (i.e. higher value of the modal loss factor). As a result, topology optimization provides about up to 61.14 per cent higher modal loss factor, as confirmed by numerical example. The numerical model for finite element analysis and topology optimization is also experimentally validated by comparing the numerical results to the experimental modal loss factors.

ABSTRACT: Parabolic cylindrical shells are commonly used as key components in communication antennas, space telescopes, solar collectors, etc. This study focuses on distributed modal neural sensing signals on a flexible simply-supported parabolic cylindrical shell panel. The parabolic cylindrical shell is fully laminated with a piezoelectric layer on its outer surface and the piezoelectric layer is segmented into infinitesimal elements (neurons) to investigate the microscopic distributed neural sensing signals. Since the dominant vibration component of the shell is usually the transverse oscillation, a new transverse mode shape function is defined. Two shell cases, i.e., the ratio of the meridian height to the half span distance of a parabola at 1:4 (shallow) and 1:1 (deep), are studied to reveal the curvature effect to the neural sensing signals. Studies suggest that the membrane signal component dominates for lower natural modes and the bending signal component dominates for higher natural modes. The meridional membrane and bending signal components are mostly concentrated on the high-curvature areas, while the longitudinal bending component is mostly concentrated on the relatively flat areas. The concentration behavior becomes more prominent as the parabolic cylindrical shell deepens, primarily resulting from the enhanced membrane effect due to the increased curvature.

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ABSTRACT: Stability analysis of a horizontal cantilevered pipe conveying fluid with an inclined terminal nozzle is considered in this paper. The pipe is modelled as a cantilevered Euler–Bernoulli beam, and the flow-induced inertia, Coriolis and centrifugal forces along the pipe as well as the follower force induced by the jet-flow are taken into account. The governing equations of the coupled bending–torsional vibrations of the pipe are obtained using extended Hamilton's principle and are then discretized via the Galerkin method. The resulting eigenvalue problem is then solved, and several cases are examined to determine the effect of nozzle inclination angle, nozzle aspect ratio, mass ratio and bending-to-torsional rigidity ratio on flutter speed of the system.

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ABSTRACT: In the present study, a theoretical method is developed to investigate free vibrations of circular plates immersed in fluids and a series of experimental tests are presented to validate the model. The coupled governing equations of both hydroelastic vibration of the plate and liquid sloshing are solved by a semi-analytical procedure, simultaneously. The effect of the plate, used as a baffle, on suppression free surface waves is also considered. Plates with two different boundary conditions, free-edge and clamped edge, are studied. The fluid domain is non-convex because of the presence of the plate, which introduces a singularity in the formulation of the fluid velocity potential. Both the least square and Galerkin methods are applied to determine
the unknown coefficients in the velocity potential. Natural frequencies and mode shapes are obtained using the Rayleigh–Ritz method, taking fluid–structure interaction into account. The present approach is validated by comparison to results of modal test on two different steel plates with the free edge and submerged in water, as well as comparison to those of a commercial finite element code. The results obtained from the present method agree with those obtained from modal test and the finite element analysis.


ABSTRACT: In this paper, the nonlinear dynamics of thin circular cylindrical shells with clamped-free boundary conditions subjected to axial internal flow is theoretically analyzed for the first time. The nonlinearity is geometric and is related to the large deformation of the structure. The nonlinear model of the shell is based on the Flügge shell theory; in this model, in-plane inertia terms and all the nonlinear terms due to the mid-surface stretching are retained. The fluid is considered to be inviscid and incompressible, and its modelling is based on linearized potential flow theory. The fluid behaviour beyond the free end of the shell is described by an outflow model, which characterizes the fluid boundary condition at the free end of the shell. At the clamped end, however, it is assumed that the fluid remains unperturbed. The Fourier transform method is used to solve the governing equations for the fluid and to obtain the hydrodynamic forces. The extended Hamilton principle is utilized to formulate the coupled fluid–structure system, and a direct approach is employed to discretize the space domain of the problem. The resulting coupled nonlinear ODEs are integrated numerically, and bifurcation analyses are performed using the AUTO software. Results indicate that the shell loses stability through a supercritical Hopf bifurcation giving rise to a stable periodic motion (limit cycle). The amplitude of this oscillation grows with flow velocity until it loses stability to nonperiodic oscillatory motion, namely, quasiperiodic and chaotic oscillation. The values of the critical flow velocities for various length-to-radius ratios obtained by nonlinear theory agree well with available experimental data.

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ABSTRACT: Free vibration characteristics of single-walled carbon nanotubes (SWCNTs) with various constraints, tube chiralities, lengths and diameters are examined using a higher-order gradient theory. The theory describes deformations of C–C bond vectors at the atomic level and links to the continuum level. The capture of curved effects of C–C bond vectors makes the established constitutive model accords extremely well with physical behaviors. Numerical simulations have been conducted using the mesh-free computational framework based on the moving Kriging interpolation. It reveals that the present method gives a good prediction of atomistic simulation results, especially in the treatment of a larger system. SWCNTs of various types of chirality are investigated and computational results reveal that the fundamental frequency increases as the tube diameter increases, until it reaches a critical diameter beyond which it decreases. As the diameter continues to increase, the change of fundamental frequency becomes smaller and smaller and converges to that
of counterpart graphite sheet. The critical diameter is largely dependent on tube lengths and constraints but independent of chiralities. It is found that the increase of tube length gives rise to an increase of critical diameter. As far as constraints are concerned, the critical diameter of fixed–free style is much larger than that of the fixed–fixed style.

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ABSTRACT: The presented work provides an overview of some commonly used approaches for generating reduced bases for discrete nonlinear dynamic systems. It investigates the performance and the robustness of these bases if they are applied in a reduction-by-projection procedure on different test cases. The bases are created from the Linear Normal Modes, the Ritz-vectors, the Proper and the Smooth Orthogonal Decomposition method, the A Priori Reduction, the Centroidal Voronoi Tessellation and the Local Equivalent Linear Stiffness Method. Second-Order Terms and an Enhanced Proper Orthogonal Decomposition formulation are included as variants. The test cases are small dimensional, locally or entirely nonlinear system subjected to a harmonic or an impulse force excitation. The double objective of this numerical study is, first, to determine which bases are most adequate for a given combination of nonlinearity and excitation and, second, to which extent the bases exhibit an inherent robustness if the parameterisation of the excitation is changed. A specific multicriteria decision analysis score is developed to assess the bases' performance. As a major result, a strong dependence of the performance of the bases on the type of excitation is established and thus some bases become more adequate for a certain situation than others. Also a lack of robustness for all considered bases can be observed. This situation improves in most cases if the basis is generated with the most critical values of the parameter.

ABSTRACT: We consider wavenumbers in in vacuo and fluid-filled isotropic and orthotropic shells. Using the Donnell–Mushtari (DM) theory we find compact and elegant asymptotic expansions for the wavenumbers in the intermediate frequency range, i.e., around the ring frequency. This frequency range corresponds to the frequencies where there is a rapid change in the values of bending wavenumbers and is found to exist in isotropic and orthotropic shells (in vacuo and fluid-filled) for low circumferential orders n only. The same is first identified using the n=0 mode of an orthotropic shell. Following this, using the expression for the intermediate frequency, asymptotic expansions are found for other cases. Here, in order to get compact expansions we consider slight orthotropy (\(\tilde{\nu}_t\)) and light fluid loading (\(\tilde{\nu}_f\)). Thus, the orthotropy parameter and the fluid loading parameter are used as asymptotic parameters along with the non-dimensional thickness parameter. The methodology can be extended to any order of , only the expansions become unwieldy. The expansions are matched with the numerical solutions of the corresponding dispersion relation. The match is found to be good.
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ABSTRACT: The non-symmetry and asymmetric dynamic characteristics of piezoelectric shell structures are studied analytically and numerically. The basic formulations of piezoelectric structures are firstly given in the tensor form. The differential equations for displacements and electric potential are derived from the formulations, which validate that the description in curvilinear coordinates with the electrical and mechanical coupling induces the non-symmetry in generalized stiffness and then the dynamic asymmetry of piezoelectric structures. Also expanding the structural displacements and electric potential with various spatial characteristics can induce the non-symmetry in generalized stiffness matrix of the converted ordinary differential equations. Then, for the multi-degree-of-freedom system with asymmetric stiffness matrix, the conventional right modes or eigenvectors are proved to have not the auto-orthogonality relations with the mass or stiffness weight. However, the left and right eigenvectors have the cross-orthogonality relations with the mass or stiffness weight, which can be used for uncoupling the asymmetric systems. Furthermore, the non-symmetric stiffness matrix is divided into the corresponding symmetric and anti-symmetric stiffness matrices. The algebraic equations for eigenvalues and singular values of the asymmetric, symmetric and anti-symmetric systems are given. It is obtained that the eigenvalues are equal to the corresponding singular values for the symmetric system, the singular values are equal to the products of the unit imaginary number and corresponding eigenvalues for the anti-symmetric system, and the differences of the eigenvalues and corresponding singular values for the asymmetric system depend on the anti-symmetric stiffness. Also the upper limits of the absolute and relative differences of the singular values of the asymmetric system to the corresponding eigenvalues of the symmetric system, and the upper and lower limits of the singular values of the asymmetric system are obtained, respectively. Finally, the spherically symmetric piezoelectric shell described in spherical coordinates is studied in detail to show the asymmetric dynamic characteristics. The differential equations for the radial displacement and electric potential of the shell structure are obtained to illustrate the non-symmetric generalized stiffness involving elastic and piezoelectric constants. Eliminating the electric potential, expanding the displacement in space, and using the Galerkin method yield the ordinary differential equations, which represent a multi-degree-of-freedom dynamic system with the asymmetric generalized stiffness matrix. Numerical results are given to illustrate the eigenvalues and modes of the asymmetric system different from those of the corresponding symmetric system, the relative differences of the eigenvalues of the asymmetric to symmetric system for different piezoelectric constants and geometric parameters, and the non-orthogonality of the left or right eigenvectors for the asymmetric system. The analytical and numerical results on the non-symmetric dynamics of piezoelectric shell structures are useful for accurate analysis and design.


ABSTRACT: The laminar flow of a weakly compressible Newtonian fluid in a pipeline is treated by modal methods, aiming at a theoretical basis for the experimental modal analysis of hydraulic pipelines. For two points located at arbitrary positions along a pipeline, the frequency response function between flow rate excitation and...
pressure response is calculated in closed form, expanded into a modal series including transcendental modal transfer functions, and approximated by finite sums of rational fraction expressions. The preferred modal approximation is recognized as mobility function of a structurally damped mechanical multi-degrees-of-freedom system. Experimental modal analysis procedures for structurally and viscously damped mechanical systems are adapted for hydraulic pipelines and pipeline systems.

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“Control of sound and vibration of fluid-filled cylindrical shells via periodic design and active control”, Journal of Sound and Vibration, Vol. 332, No. 18, pp 4193-4209, September 2013,
https://doi.org/10.1016/j.jsv.2013.03.007
ABSTRACT: The wave propagation, vibration transmission and acoustic emission characteristics in the passive and the active periodic shell systems are investigated. A finite element method (FEM) is utilised to conduct the investigation. In the passive periodic shell, two pivotal frequencies (i.e., the cut-off frequency of the periodic shell, and the resonant frequency of flexural vibration of shell ring), which are existed in an arbitrarily high circumferential mode, are found; the frequency range is divided into three regions by these two frequencies. Various band formation mechanisms and the dynamic properties within the three frequency regions are illustrated, with the aid of a series of vibration deformations. Furthermore, an active periodic shell is constructed. Several control methods, such as inverted displacement-, velocity- and acceleration-feedback control strategies, are explored for the active shell. Under these control strategies, the effects of negative stiffness, damping coefficient and mass modulation, can be produced, thus enabling the band gap generable and its characteristics, such as their bandwidth, location and attenuation coefficient, adjustable. The pressure level of the structure-borne sound is also suppressed along the shell within the band gaps.

S.A. Bochkarev and V.P. Matveenko (Institute of Continuous Media Mechanics RAS, Acad. Korolev Str 1, Perm 614013, Russia), “Stability of a cylindrical shell subject to an annular flow of rotating fluid”, Journal of Sound and Vibration, Vol. 332, No. 18, pp 4210-4222, September 2013,
https://doi.org/10.1016/j.jsv.2013.03.010
ABSTRACT: The paper is concerned with the analysis of dynamic behavior of elastic cylindrical shells of rotation subjected to an annular flow of compressible fluid (gas) having both the axial and tangential velocity components. The behavior of the rotating and flowing fluid is described in the framework of the potential theory. The elastic shell is considered based on the model of the classical shell theory. Numerical simulation is done using a semi-analytical variant of the finite element method. The results of numerical experiments made to analyze the stability of shells with different boundary conditions, geometrical dimensions and widths of the annular gap are discussed. The influence of the fluid rotation on the critical flow velocities and the influence of the axial flow on the critical angular velocities of fluid rotation are estimated with reference to the variants, in which one of the velocity components is not taken into account. The effect of elasticity of the outer shell on the boundary of hydroelastic stability is analyzed.

M. Amabili (Canada Research Chair (Tier 1) Department of Mechanical Engineering, McGill University, Macdonald Engineering Building, 817 Sherbrooke Street West, Montreal, Quebec, Canada H3A 0C3), “A new

ABSTRACT: A consistent higher-order shear deformation nonlinear theory is developed for shells of generic shape allowing for thickness variation by using six variables; geometric imperfections are also taken into account. The geometrically nonlinear strain–displacement relationships are derived retaining full nonlinear terms in the in-plane displacements. They are presented in curvilinear coordinates in a formulation that can be readily implemented in computer codes. This new theory is applied to laminated circular cylindrical shells complete around the circumference and simply supported at the ends. Linear (natural frequencies) and geometrically nonlinear (large-amplitude forced response) vibrations are studied by using the present theory and results are compared to those obtained by using the refined Amabili–Reddy higher-order shear deformation nonlinear shell theory, which neglects thickness variations.


ABSTRACT: The flutter of a stiffened laminate composite panel subjected to nonlinear aerodynamic force is investigated by means of a new analytical model in the present study. The von-Karman large deflection plate theory is used to account for the geometrical nonlinearity of the stiffened composite panel, and the third order piston theory is employed to estimate the nonlinear aerodynamic pressure induced by the supersonic airflow. The interaction between the panel and the stiffener is considered to be a pair of acting force and reacting force. According to the Hamilton principle and the Euler–Bernoulli beam theory, the coupled partial differential governing equations of the panel and the stiffener are established. On the basis of deformation compatibility between the panel and the stiffener, the assumption mode shapes of the panel are introduced into the dynamic partial differential governing equations of the stiffener to calculate the acting/reacting force between the panel and the stiffener. When the expression of the acting/reacting force is substituted into the dynamic differential governing equations of the panel, the fourth-order Runge–Kutta numerical integration method is employed to simulate the dynamic response of the stiffened panel. The effects of various parameters, such as the stiffening scheme and the geometric dimension of the stiffener, on the critical flutter dynamic pressure and the amplitude of the transverse vibration of the panel are studied in details. The simulation indicates that the critical flutter dynamic pressure can be greatly enhanced by introducing a proper stiffening scheme.


ABSTRACT: This paper is concerned with the suppression of vibrations and radiated sound of a ring-stiffened circular cylindrical shell in contact with unbounded external fluid by means of piezoelectric sensors and actuators. The dynamic model of a circular cylindrical shell based on the Sanders shell theory was considered together with a ring stiffener model. The mass and stiffness matrices for a ring stiffener were newly derived in this study and added to the mass and stiffness matrices of the cylindrical shell, respectively. The fluid-added mass matrix, which was derived by using the baffled shell theory, was also added to the mass matrix. Finally,
the equations representing the piezoelectric sensor measurement and piezoelectric actuation complete the theoretical model for the addressed problem. The natural vibration characteristics of the ring-stiffened cylindrical shell both in air and in water were investigated both theoretically and experimentally. The theoretical predictions were in good agreement with the experimental results. An active vibration controller which can cope with a harmonic disturbance was designed by considering the modified higher harmonic control, which is, in fact, a band rejection filter. An active vibration control experiment on the submerged cylindrical shell was carried out in a water tank and the digital control system was used. The experimental results showed that both vibrations and radiation sound of the submerged cylindrical shell were suppressed by a pair of piezoelectric sensor and actuator.

ABSTRACT: The dynamical behaviour of the sidewall has an important influence on tyre vibration characteristics. Nonetheless, it remains crudely represented in many existing models. The current work considers a geometrically accurate, two-dimensional, sidewall description, with a view to identifying potential shortcomings in the approximate formulations and identifying the physical characteristics that must be accounted for. First, the mean stress state under pressurisation and centrifugal loading is investigated. Finite-Element calculations show that, while the loaded sidewall shape remains close to a toroid, its in-plane tensions differ appreciably from the associated analytical solution. This is largely due to the inability of the anisotropic sidewall material to sustain significant azimuthal stress. An approximate analysis, based on the meridional tension alone, is therefore developed, and shown to yield accurate predictions. In conjunction with a set of formulae for the ‘engineering constants’ of the sidewall material, the approximate solutions provide a straightforward and efficient means of determining the base state for the vibration analysis. The latter is implemented via a ‘waveguide’ discretisation of a variational formulation. Its results show that, while the full geometrical description is necessary for a complete and reliable characterisation of the sidewall's vibrational properties, a one-dimensional approximation will often be satisfactory in practice. Meridional thickness variations only become important at higher frequencies (above 500 Hz for the example considered here), and rotational inertia effects appear to be minor at practical vehicle speeds.

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ABSTRACT: UNDerwater EXplosions (UNDEX) can cause severe damage to submarines, ships and offshore infrastructures as well as deep-sea fuel transfer installations, most of which are made of laminated plates and shells. A novel method involving an analytical technique and connected with the elastic dynamic response of laminated plates subjected to UNDEX is proposed here. It is based on the state space method, a numerical inversion of the Laplace transform and the fluid–structure interaction (FSI) theory formulated by Taylor. Two novel algorithms for numerically inverting the Laplace transform are also proposed, and these computations are
apparently more efficient than the algorithms to be found in the related literature. The present method is validated by undertaking a comparison with a semi-analytical method and the experiment results derived from the literature written on the subject, as well as with the finite element analysis (FEA). The cooperation is deemed strong and the present method is apparently more accurate than the semi-analytical method and the FEA. The influence of the FSI is investigated in detail in a case study using both a stiff and a flexible plate. The results show that the FSI significantly influences the reaction of the laminated plate. The present solution may assist in promoting an understanding of the elastic and acoustic responses of submerged structures made of plates, and the results might be used as a benchmark solution in further research.

Qinkai Han and Fulei Chu (Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China), “effects of rotation upon parametric instability of a cylindrical shell subjected to periodic axial loads”, Journal of Sound and Vibration, Vol. 332, No. 22, pp 5653-5661, October 2013, https://doi.org/10.1016/j.jsv.2013.06.013

ABSTRACT: Parametric instability of a rotating cylindrical shell under periodic axial loads has been analyzed based upon Bolotin's method in the literature. However, this method could not be used for gyroscopic systems due to the consideration of rotation. Thus, the parametric instability of the same system is studied utilizing the multiple scales method. Analytical expressions of instability boundaries for various modes are obtained, and verified by numerical analysis. As long as rotation is considered, there are only combination instability regions for the cylindrical shell under periodic axial loads. Moreover, effects of rotational speed, constant axial load and viscous damping on the location and width of various instability regions are also examined in detail. Through comparative analysis some errors in other recent studies are also highlighted.

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ABSTRACT: Aerothermoelastic analysis for composite laminated panels in supersonic flow is carried out. The flutter and thermal buckling control for the panels are also investigated. In the modeling for the equation of motion, the influences of in-plane thermal load on the transverse bending deflection are taken into account, and the unsteady aerodynamic pressure in supersonic flow is evaluated by the linear piston theory. The governing equation of the structural system is developed applying the Hamilton's principle. In order to study the influences of aerodynamic pressure on the vibration mode shape of the panel, both the assumed mode method (AMM) and the finite element method (FEM) are used to derive the equation of motion. The proportional feedback control method and the linear quadratic regulator (LQR) are used to design the controller. The aeroelastic stability of the structural system is analyzed using the frequency-domain method. The effects of ply angle of the laminated panel on the critical flutter aerodynamic pressure and the critical buckling temperature change are researched. The flutter and thermal buckling control effects using the proportional feedback control and the LQR are compared. An effective method which can suppress the flutter and thermal buckling simultaneously is proposed.

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ABSTRACT: Slender curved structures can often be found as components of complex structures in civil, mechanical, and aerospace systems. Under extreme loadings, a curved structure might undergo snap-through buckling, i.e., the structure is forced to its inverted configuration, inducing fatigue. Therefore, it is important to identify the stability boundaries of structures and to obtain an accurate description of their performance if the response moves beyond those boundaries. In this paper, a combined experimental–computational framework is used to analyze the transient behavior of clamped–clamped shallow arches. We examine, both experimentally and using Finite Element Analysis (FEA), the response of shallow arches under harmonic distributed loading. Various types of responses are identified and regions in the forcing parameter space that lead to snap-through and chaotic responses are determined.

ABSTRACT: In this paper the nonlinear planar dynamics of a fluid-conveying cantilevered pipe is investigated. The centreline of the pipe is considered to be extensible; i.e., coupled longitudinal and transverse displacements are considered. The extended version of the Lagrange equations for systems containing non-material volumes is employed to derive the equations of motion, resulting directly in a set of coupled nonlinear ordinary differential
equations. The pseudo-arclength continuation technique along with direct time integration are used to solve these equations. Bifurcation diagrams of the system are constructed as the flow velocity is increased; these diagrams are supplemented by time traces, phase-plane portraits, and fast Fourier transforms for some sets of system parameters. As opposed to the case of an inextensible pipe, an extensible pipe elongates in the axial direction as the flow velocity is increased from zero; depending on the system parameters, this static elongation can be considerable. At the critical flow velocity, the system loses stability via a supercritical Hopf bifurcation, emerging from the trivial solution for the transverse displacement and leading to a flutter.

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ABSTRACT: The nonlinear vibrations of a thin, elastic, laminated composite circular cylindrical shell, moving in axial direction and having an internal resonance, are investigated in this study. Nonlinearities due to large-amplitude shell motion are considered by using Donnell’s nonlinear shallow-shell theory, with consideration of the effect of viscous structure damping. Differently from conventional Donnell’s nonlinear shallow-shell equations, an improved nonlinear model without employing Airy stress function is developed to study the nonlinear dynamics of thin shells. The system is discretized by Galerkin’s method while a model involving four degrees of freedom, allowing for the traveling wave response of the shell, is adopted. The method of harmonic balance is applied to study the nonlinear dynamic responses of the multi-degrees-of-freedom system. When the structure is excited close to a resonant frequency, very intricate frequency–response curves are obtained, which show strong modal interactions and one-to-one-to-one-to-one internal resonance phenomenon. The effects of different parameters on the complex dynamic response are investigated in this study. The stability of steady-state solutions is also analyzed in detail.

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ABSTRACT: The present paper extends the layerwise optimization (LO) procedure to the maximization problem of the fundamental frequencies of sandwich plates with fibrous composites and low stiffness core layers. Frequencies are calculated by the Ritz method based on a refined zigzag theory (RZT). Polynomial functions which satisfy at least geometrical boundary conditions with boundary indexes are employed as displacement functions, and they enable satisfying arbitrary sets of boundary conditions for rectangular plates. Results of the experimental modal analysis validate the accuracy of the present calculations, and a comparison with results of the classical laminated theory (CLPT) and the first order shear deformation theory (FSDT) supports the effectiveness of the present method. Optimized results are compared with other typical sets of lay-up configurations and this shows the LO method as suitable means to the optimization problem for sandwich plates.
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ABSTRACT: Branched pipes of arbitrary shapes are prevalent in pipe systems. Considering fluid–structure interaction (FSI), an absorbing transfer matrix method in frequency domain for fluid-filled pipelines with any branched pipes is proposed in this paper. A dominant chain of pipeline would be selected, and the point transfer matrix of each junction on the dominant chain would be determined. Here, the point transfer matrix, representing the influence of branched pipes at the junction on the dominant pipeline, was “absorbed” by the dominant chain. Based on these, with transfer matrices of other elements, the fluid and structure dynamics problem could be solved following the chain transfer matrix method process. Several numerical examples with different constraints are presented to illustrate the application of the proposed method. Moreover, the experiment of cross-shaped pipes with various boundary conditions was carried out. And results from the present approach were validated by measured and numerical data. Then, the forced vibrations of branched pipes were analyzed by considering the effects of various parameters, which shows the fluid pressure and vibrations can be optimized by changing the branch angles and positions. Through these examples, it is shown that the proposed method is efficient and can be used to calculate branched pipes of any shape.


ABSTRACT: We study the effect of adding localised stiffness, via a spring support, on the stability of flexible panels subjected to axial uniform incompressible flow. Applications are considered that range from the hydro-elasticity of hull panels of high-speed ships to the aero-elasticity of glass panels in the curtain walls of high-rise buildings in very strong winds. A two-dimensional linear analysis is conducted using a hybird of theoretical and computational methods that calculates the system eigen-states but can also be used to capture the transient behaviour that precedes these. We show that localised stiffening is a very effective means to increase the divergence-onset flow speed in both hydro- and aero-elastic applications. It is most effective when located at the mid-chord of the panel and there exists an optimum value of added stiffness beyond which further increases to the divergence-onset flow speed do not occur. For aero-elastic applications, localised stiffening can be used to replace the more destructive flutter instability that follows divergence at higher flow speeds by an extended range of divergence. The difference in eigen-solution morphology between aero- and hydro-elastic applications is highlighted, showing that for the former coalescence of two non-oscillatory divergence modes is the mechanism for flutter onset. This variation in solution morphology is mapped out in terms of a non-dimensional mass ratio. Finally, we present a short discussion of the applicability of the stabilisation strategy in a full three-dimensional system.
ABSTRACT: Corrugated pipes are commonly used because of their local rigidity combined with global flexibility. The flow through such a pipe can induce strong whistling tones, which is an environmental nuisance and can be a threat to the mechanical integrity of the system. This paper considers the use of a composite pipe: a shorter corrugated pipe segment embedded between smooth pipe segments. Such a pipe retains some flexibility, while the acoustical damping in the smooth pipe reduces whistling tones. Whistling is the result of coherent vortex shedding at the cavities in the wall. This vortex shedding is synchronized by longitudinal acoustic waves traveling along the pipe. The acoustic waves trigger the vortex shedding, which reinforces the acoustic field for a critical range of the Strouhal number values. A linear theory for plane wave propagation and the sound production is proposed, which allows a prediction of the Mach number at the threshold of whistling in such pipes. A semi-empirical approach is chosen to determine the sound source in this model. This source corresponds to a fluctuating force acting on the fluid as a consequence of the vortex shedding. The functional form of the Strouhal number dependency of the dimensionless sound source amplitude is based on numerical simulations. The magnitude of the source and the Strouhal number range in which it can drive whistling are determined by matching the model to results for a specific corrugated pipe segment length. This semi-empirical source model is then applied to composite pipes with different corrugated segment lengths. In addition, the effect of inlet acoustical convective losses due to flow separation is considered. The Mach number at the threshold of whistling is predicted within a factor 2.

ABSTRACT: The dynamic stiffness method has been developed by using a sophisticated layer-wise theory which complies with the C0z requirements and delivers high accuracy for the analysis of laminated composite plates. The method is versatile as it derives the dynamic stiffness matrix for plates with any number of layers in a novel way without the need to re-derive and re-solve the equations of motion when the number of layers has changed. This novel procedure to manipulate and solve the equations of motion has been referred to as the L matrix method in this paper. The Carrera unified formulation (CUF) is employed to derive the equations of motion of one single layer in the L matrix form, the system of equations of motion of a laminated plate with any number of layers is generated in an efficient and automatic way. A significant feature of the subsequent work is to devise a method to solve the system of differential equations automatically in closed analytical form and then obtain the ensuing dynamic stiffness matrix of the laminated plate. The developed dynamic stiffness element has been validated wherever possible by analytical solutions (based on Navier's solution for plates simply supported at all edges) for the same displacement formulation. Furthermore, the dynamic stiffness theory is assessed by 3D analytical solutions (scantly available in the literature) and also by the finite element method using NASTRAN. The results have been obtained in an exact sense for the first time and hence they can be used as benchmark solutions for assessing approximate methods. This new development of the dynamic stiffness method will allow
free vibration and response analysis of geometrically complex structures with such a level of computational efficiency and accuracy that could not be possibly achieved using other methods.

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ABSTRACT: This paper presents an analytical solution for the vibration and acoustic responses of a finite stiffened plate that is covered with decoupling layers and subjected to external excitation. The theory of elasticity is used for the decoupling layer, and the stiffened plate is modeled by the plate theory and Euler–Bernoulli beam equation. Equations are constructed by the boundary conditions at the plate/coating and coating/fluid interfaces. The problem can be solved by the proposed method in this paper. Test verification shows that a good correlation exists between theoretical and test results. Thus, the theoretical study in this paper is correct. Numerical results show that shear waves insignificantly affect the structural vibration level difference (VR) under low frequencies. The noise reduction of the stiffened plate covered with decoupling layers is greatly influenced by the decoupling layer loss factor. A failure region of the vibration level difference is present in the low frequency band of the decoupling layer. Furthermore, the thickness of the decoupling layer significantly affects noise reduction.

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ABSTRACT: An analytical model is developed to study the transient lateral sloshing in horizontal cylindrical containers assuming inviscid, incompressible and irrotational flows. The model is derived by implementing the linearized free-surface boundary condition and bipolar coordinate transformation, resulting in a truncated system of linear ordinary differential equations, which is numerically solved to determine the fluid velocity potentials followed by the hydrodynamic forces and moment. The model results are compared with those obtained from the multimodal solution. The free-surface elevation and hydrodynamic coefficients are also compared with the reported experimental and analytical data as well as numerical simulations to establish validity of the model. The capability of the model for predicting non-resonant slosh is also evaluated using the critical free-surface amplitude. The model validity is further illustrated by comparing the transient liquid slosh responses of a partially filled tank subject to steady lateral acceleration characterizing a vehicle turning maneuver with those obtained from fully nonlinear CFD simulations and pendulum models. It is shown that the linear slosh model yields more accurate prediction of dynamic slosh than the pendulum models and it is significantly more computationally efficient than the nonlinear CFD model. The slosh model is subsequently applied to roll plane model of a suspended tank vehicle to study the effect of dynamic liquid slosh on steady-turning roll stability limit of the vehicle under constant and variable axle load conditions. The results suggest that the roll moment arising from the dynamic fluid slosh yields considerably lower roll stability limit of the partly-filled tank vehicle compared to that predicted from the widely reported quasi-static fluid slosh model.
ABSTRACT: Numerical and experimental investigations of the dynamics of micromachined shallow arches (initially curved microbeams) and the possibility of using their dynamic snap-through motion for filtering purposes are presented. The considered MEMS arches are actuated by a DC electrostatic load along with an AC harmonic load. Their dynamics is examined numerically using a Galerkin-based reduced-order model when excited near both their first and third natural frequencies. Several simulation results are presented demonstrating interesting jumps and dynamic snap-through behavior of the MEMS arches and their attractive features for use as band-pass filters, such as their sharp roll-off from pass-bands to stop-bands and their flat response. Experimental work is conducted to test arches realized of curved polysilicon microbeams when excited by DC and AC loads. Experimental data of the micromachined curved beams are shown for the softening and hardening behavior near the first and third natural frequencies, respectively, as well as dynamic snap-through motion.

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ABSTRACT: In this paper, flutter of functionally graded material (FGM) cylindrical shells under distributed axial follower forces is addressed. The first-order shear deformation theory is used to model the shell, and the material properties are assumed to be graded in the thickness direction according to a power law distribution using the properties of two base material phases. The solution is obtained by using the extended Galerkin's method, which accounts for the natural boundary conditions that are not satisfied by the assumed displacement functions. The effect of changing the concentrated (Beck's) follower force into the uniform (Leipholz's) and linear (Hauger's) distributed follower loads on the critical circumferential mode number and the minimum flutter load is investigated. As expected, the flutter load increases as the follower force changes from the so-called Beck's load into the so-called Leipholz's and Hauger's loadings. The increased flutter load was calculated for homogeneous shell with different mechanical properties, and it was found that the difference in elasticity
moduli bears the most significant effect on the flutter load increase in short, thick shells. Also, for an FGM shell, the increase in the flutter load was calculated directly, and it was found that it can be derived from the simple power law when the corresponding increase for the two base phases are known.

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“Disturbance rejection control for vibration suppression of piezoelectric laminated thin-walled structures”,
ABSTRACT: Thin-walled piezoelectric integrated smart structures are easily excited to vibrate by unknown disturbances. In order to design and simulate a control strategy, firstly, an electro-mechanically coupled dynamic finite element (FE) model of smart structures is developed based on first-order shear deformation (FOSD) hypothesis. Linear piezoelectric constitutive equations and the assumption of constant electric field through the thickness are considered. Based on the dynamic FE model, a disturbance rejection (DR) control with proportional-integral (PI) observer using step functions as the fictitious model of disturbances is developed for vibration suppression of smart structures. In order to achieve a better dynamic behavior of the fictitious model of disturbances, the PI observer is extended to generalized proportional-integral (GPI) observer, in which sine or polynomial functions can be used to represent disturbances resulting in better dynamics. Therefore the disturbances can be estimated either by PI or GPI observer, and then the estimated signals are fed back to the controller. The DR control is validated by various kinds of unknown disturbances, and compared with linear-quadratic regulator (LQR) control. The results illustrate that the vibrations are better suppressed by the proposed DR control.

ABSTRACT: In this study, the active vibration control and configurational optimization of a cylindrical shell are analyzed by using piezoelectric transducers. The piezoelectric patches are attached to the surface of the cylindrical shell. The Rayleigh–Ritz method is used for deriving dynamic modeling of cylindrical shell and piezoelectric sensors and actuators based on the Donnel–Mushtari shell theory. The major goal of this study is to find the optimal locations and orientations of piezoelectric sensors and actuators on the cylindrical shell. The optimization procedure is designed based on desired controllability and observability of each contributed and undesired mode. Further, in order to limit spillover effects, the residual modes are taken into consideration. The optimization variables are the positions and orientations of piezoelectric patches. Genetic algorithm is utilized to evaluate the optimal configurations. In this article, for improving the maximum power and capacity of actuators for amplitude depreciation of negative velocity feedback strategy, we have proposed a new control strategy, called “Saturated Negative Velocity Feedback Rule (SNVF)”. The numerical results show that the optimization procedure is effective for vibration reduction, and specifically, by locating actuators and sensors in their optimal locations and orientations, the vibrations of cylindrical shell are suppressed more quickly.
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ABSTRACT: In this paper, the Ritz minimum energy method, based on the use of the Principle of Virtual Displacements (PVD), is combined with refined Equivalent Single Layer (ESL) and Zig Zag (ZZ) shell models hierarchically generated by exploiting the use of Carrera's Unified Formulation (CUF), in order to engender the Hierarchical Trigonometric Ritz Formulation (HTRF). The HTRF is then employed to carry out the free vibration analysis of doubly curved shallow and deep functionally graded material (FGM) shells. The PVD is further used in conjunction with the Gauss theorem to derive the governing differential equations and related natural boundary conditions. Donnell–Mushtari's shallow shell-type equations are given as a particular case. Doubly curved FGM shells and doubly curved sandwich shells made up of isotropic face sheets and FGM core are investigated. The proposed shell models are widely assessed by comparison with the literature results. Two benchmarks are provided and the effects of significant parameters such as stacking sequence, boundary conditions, length-to-thickness ratio, radius-to-length ratio and volume fraction index on the circular frequency parameters and modal displacements are discussed.

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ABSTRACT: A novel damage detection method based on frequency shift curve (FSC) is developed for cylindrical shell structures. The FSC is caused by auxiliary mass containing both the natural frequencies and mode shapes information. According to axis-symmetry, the FSC is flat when there is no damage. However, it shows obvious periodic peaks when localized imperfections or damages occur. Furthermore, for the ±2nd FSC, the trough with minimum value indicates the circumferential location of the damage and the difference between the lowest trough value and the values of the other three troughs represents the severity of the local damage. Through changing the location of the accelerometer, which can be considered as an auxiliary mass itself, around the cylindrical shell circumference, the FSCs can be measured and then the damage can be detected and located. Moreover, the difference between the averages of ±2nd FSCs also reflects the severity of damages. Numerical simulation and experimental tests have confirmed the finding. Compared with other vibration based methods, the proposed method is fast, sensitive and feasible to implement in practice as the measured frequency is more accurate than the mode shapes, and only a single accelerometer is required in the tests.

DISCUSSION: M. Amabili (Department of Mechanical Engineering, McGill University, Macdonald Engineering Building, 817 Sherbrooke Street West, Montreal, PQ, Canada H3A 0C3), Discussion on: “Nonlinear vibration of functionally graded circular cylindrical shells based on improved Donnell equations” by D.H. Bich and N. Xuan Nguyen, Journal of Sound and Vibration, 331(25)(2012) 5588-5501
ABSTRACT: The characteristics of beam-mode stability of fluid-conveying shell systems are investigated in this paper for shells with clamped-free (cantilevered) boundary conditions. An FEM algorithm is developed to conduct the investigation. A periodic shell structure of functionally graded material (FGM), termed as PFGM shell here, is designed so as to enhance the stability for the shell system, and to eliminate the stress concentration problems that exist in periodic structures. Results show that by the introduction of periodic design the critical velocities can be raised over several desired ranges of the dimensionless fluid density $\beta$, and the stress concentration is effectively reduced in the PFGM shell. Finally, the effects of the geometric shape, material parameters and spring supports on the dynamical stability are probed.

ABSTRACT: The dynamic behaviour of thin conical shells can be analysed using a number of numerical methods. Although the overall vibration response of shells has been thoroughly studied using such methods, their physical insight is limited. The purpose of this paper is to interpret some of these numerical results in terms of waves, using the wave finite element, WFE, method. The forced response of a thin conical shell at different frequencies is first calculated using the dynamic stiffness matrix method. Then, a wave finite element analysis is used to calculate the wave properties of the shell, in terms of wave type and wavenumber, as a function of position along it. By decomposing the overall results from the dynamic stiffness matrix analysis, the responses of the shell can then be interpreted in terms of wave propagation. A simplified theoretical analysis of the waves in the thin conical shell is also presented in terms of the spatially-varying ring frequency, which provides a straightforward interpretation of the wave approach. The WFE method provides a way to study the types of wave that travel in thin conical shell structures and to decompose the response of the numerical models into the components due to each of these waves. In this way the insight provided by the wave approach allows us to analyse the significance of different waves in the overall response and study how they interact, in particular illustrating the conversion of one wave type into another along the length of the conical shell.

ABSTRACT: Nonlinear system identification is a challenging task in view of the complexity and wide variety of nonlinear phenomena. The present paper addresses the identification of a real-life aerospace structure possessing a strongly nonlinear component with multiple mechanical stops. The complete identification procedure, from nonlinearity detection and characterization to parameter estimation, is carried out based on

ABSTRACT: Balancing structural and acoustic performance of a multi-layered sandwich panel is a formidable undertaking. Frequently the gains achieved in terms of reduced weight, still meeting the structural design requirements, are lost by the changes necessary to regain acceptable acoustic performance. To alleviate this, a design method for a multifunctional load bearing vehicle body panel is proposed which attempts to achieve a balance between structural and acoustic performance. The approach is based on numerical modelling of the structural and acoustic behaviour in a combined topology, size, and property optimization in order to achieve a three dimensional optimal distribution of structural and acoustic foam materials within the bounding surfaces of a sandwich panel. In particular the effects of the coupling between one of the bounding surface face sheets and acoustic foam are examined for its impact on both the structural and acoustic overall performance of the panel. The results suggest a potential in introducing an air gap between the acoustic foam parts and one of the face sheets, provided that the structural design constraints are met without prejudicing the layout of the different foam types.


ABSTRACT: Parametric resonance of a truncated conical shell rotating at periodically varying angular speed is studied in this paper. Based upon the Love’s thin shell theory and generalized differential quadrature (GDQ) method, the equations of motion of a rotating conical shell are derived. The time-dependent rotating speed is assumed to be a small and sinusoidal perturbation superimposed upon a constant speed. Considering the periodically rotating speed, the conical shell system is a parametric excited system of the Mathieu–Hill type. The improved Hill’s method is utilized for parametric instability analysis. Both the primary and combination instability regions for various natural modes and boundary conditions are obtained numerically. The effects of relative amplitude and constant part of periodically rotating speed and cone angle on the instability regions are discussed in detail. It is shown that for the natural mode with lower circumferential wavenumber, only the primary instability regions exist. With the increasing circumferential wavenumber, the instability widths are reduced significantly and the combination instability region might appear. The results for different boundary conditions are substantially similar. Increasing the constant rotating speed (or cone angle) all lead to the movements of instability regions and the appearance of combination instability region. The former will cause the instability width increasing, while the latter will reduce the instability width. The variation of length-to-radius ratio only causes the movements of instability regions.
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“Low-frequency linear vibrations of single-walled carbon nanotubes: Analytical and numerical models”,
Journal of Sound and Vibration, Vol. 333, No. 13, pp 2936-2957, June 2014,
https://doi.org/10.1016/j.jsv.2014.01.016
ABSTRACT: Low-frequency vibrations of single-walled carbon nanotubes with various boundary conditions are considered in the framework of the Sanders–Koiter thin shell theory. Two methods of analysis are proposed. The first approach is based on the Rayleigh–Ritz method, a double series expansion in terms of Chebyshev polynomials and harmonic functions is considered for the displacement fields; free and clamped edges are analysed. This approach is partially numerical. The second approach is based on the same thin shell theory, but the goal is to obtain an analytical solution useful for future developments in nonlinear fields; the Sanders–Koiter equations are strongly simplified neglecting in-plane circumferential normal strains and tangential shear strains. The model is fully validated by means of comparisons with experiments, molecular dynamics data and finite element analyses obtained from the literature. Several types of nanotubes are considered in detail by varying aspect ratio, chirality and boundary conditions. The analyses are carried out for a wide range of frequency spectrum. The strength and weakness of the proposed approaches are shown; in particular, the model shows great accuracy even though it requires minimal computational effort.

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ABSTRACT: The nonlinear free vibration of carbon nanotubes/fiber/polymer composite (CNTFPC) multi-scale plates with surface-bonded piezoelectric actuators is studied in this paper. The governing equations of the piezoelectric nanotubes/fiber/polymer multiscale laminated composite plates are derived based on first-order shear deformation plate theory (FSDT) and von Kármán geometrical nonlinearity. Halpin–Tsai equations and fiber micromechanics are used in hierarchy to predict the bulk material properties of the multiscale composite. The carbon nanotubes are assumed to be uniformly distributed and randomly oriented through the epoxy resin matrix. A perturbation scheme of multiple time scales is employed to determine the nonlinear vibration response and the nonlinear natural frequencies of the plates with immovable simply supported boundary conditions. The effects of the applied constant voltage, plate geometry, volume fraction of fibers and weight percentage of single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) on the linear and nonlinear natural frequencies of the piezoelectric nanotubes/fiber/polymer multiscale composite plate are investigated through a detailed parametric study.
References listed at the end of the paper:


Gary Han Chang and Yahya Modarres-Sadeghi (Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA), “Flow-induced oscillations of a cantilevered pipe conveying fluid with base excitation”, Journal of Sound and Vibration, Vol. 333, No. 18, pp 4265-4280, September 2014, https://doi.org/10.1016/j.jsv.2014.03.036

ABSTRACT: It is known that a plain cantilevered pipe conveying fluid loses its stability by a Hopf bifurcation, leading to either planar or non-planar flutter for flow velocities beyond the critical flow velocity for Hopf bifurcation. If an external mass is attached to the end of the pipe (an end-mass), the resulting dynamics become much richer, showing 2D and 3D quasiperiodic and chaotic oscillations at high flow velocities. In this paper, a cantilevered pipe, with and without an end-mass, subjected to a small-amplitude periodic base excitation is considered. A set of three-dimensional nonlinear equations is used to analyze the pipe’s response at various flow velocities and with different amplitudes and frequencies of base excitation. The nonlinear equations are discretized using the Galerkin technique and the resulting set of equations is solved using Houbolt’s finite difference method. It is shown that for a plain pipe (with no end-mass), non-planar post-instability oscillations can be reduced to planar periodic oscillations for a range of base excitation frequencies and amplitudes. For a pipe with an end-mass, similarly to a plain pipe, three-dimensional period oscillations can be reduced to planar ones. At flow velocities beyond the critical flow velocity for torus instability, the three-dimensional quasiperiodic oscillations can be reduced to two-dimensional quasiperiodic or periodic oscillations, depending on the frequency of base excitation. In all these cases, a low-amplitude base excitation results in reducing the three-dimensional oscillations of the pipe to purely two-dimensional oscillations, over a range of excitation frequencies. These numerical results are in agreement with the previous experimental work.

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ABSTRACT: Snap-through mechanism is employed to harvest electricity from random vibration through piezoelectricity. The random excitation is assumed to be Gaussian white noise. The snap-through piezoelectric energy harvester possesses the bistability. For small-amplitude vibration in a potential well, the Ito stochastic differential equation of the electromechanical coupling system is derived from the Taylor approximation at a stable equilibrium point. The method of the moment differential equations is applied to determine the statistical moments of the displacement response and the output voltage. The effects of the system parameters on the output voltage and the output power are examined. The approximate analytical outcomes are qualitatively and quantitatively supported by the numerical simulations. For large-amplitude interwell motion, the effects of the parameters on the output voltage and the output power are numerically investigated. Nonlinearity produced by the snap-through improves energy harvesting so that the snap-through piezoelectric energy harvester can outperform the linear energy harvester in the similar size under Gaussian white noise excitations.

ABSTRACT: An imperfect multi-layered acoustic cloak is proposed for a two-dimensional cloaking zone based on feasible material properties. In this model, the matching of sound speed and acoustic impedance has been investigated, and the effects of material and geometric properties on the imperfect cloak have been studied for better design of the imperfect cloak. The imperfect cloak could be improved using appropriate changes in the design parameters. By increasing the thickness of the high density layer and with some changes in the sound speeds between the high density and the low density layers, the imperfect cloaking model showed better cloaking performance than Cummer–Schurig cloak. Also, present results show that the sound speed matching is more important for acoustic cloaking than the impedance matching. These results can be applied as a practical design guide for two-dimensional cloaks using multilayered structures composed of naturally existing materials.


ABSTRACT: Static deflection as well as free and forced nonlinear vibration of thin square plates made of hyperelastic materials are investigated. Two types of materials, namely rubber and soft biological tissues, are considered. The involved physical (material) nonlinearities are described through Neo-Hookean, Mooney–Rivlin, and Ogden hyperelastic laws; geometrical nonlinearities are modeled by the Novozhilov nonlinear shell theory. Dynamic local models are first built in the vicinity of a static configuration of interest that has been previously calculated. This gives rise to the approximation of the plate's behavior in the form of a system of ordinary differential equations with quadratic and cubic nonlinear terms in displacement. Numerical results are compared and validated in the static case via a commercial FE software package: they are found to be accurate for deflections reaching 100 times the thickness of the plate. The frequency shift between low- and large-amplitude vibrations weakens with an increased initial deflection.


ABSTRACT: Much of what is known about co-existing responses in nonlinear systems under both deterministic and random dynamic loading is limited to phenomenological investigations of discrete systems, most commonly, the Duffing equation. From these results alone, it is difficult to extrapolate the behavior of the distributed nonlinear systems more commonly seen in real structures such as buckled beams and curved panels. This is because, beyond the simple increase in dimension, real systems bring with them imperfections and more complex forms of energy dissipation. The possibility of co-existing responses, particularly in the case of simultaneous “safe” and “unsafe” solutions (e.g. snap-through and non-snap-through), poses potential problems for engineers as it multiplies the workload, since one must be very careful to ensure that a particular simulation or experiment has captured the most critical response. Even in the case where random forces dominate the overall loading of a system, a situation in which one might anticipate an equally random response, a very small
harmonic component can have an influence beyond its proportion. This effect, known as stochastic resonance, is quite counterintuitive to the analyst more familiar with linear systems where the principles of superposition and scalar multiplication of solutions make this impossible. In this paper, the effect of the damping and noise level on the number of co-existing responses in nonlinear systems is investigated. Stochastic resonance is also demonstrated, first with a double-well Duffing oscillator, and then it is shown to exist experimentally, we believe for the first time, on a macroscopic structure, that being, an (imperfect) buckled beam.

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ABSTRACT: The sound transmission through an infinite multilayer cylinder composed of orthotropic skins and an isotropic polymer core is calculated analytically. The motions of the two thin orthotropic skins are described with the first-order shear deformation theory while the isotropic core is modeled with the three-dimensional elasticity theory. The polymer core transfer matrix relating the displacements and the stresses at the two common interfaces between the core and the skins is first calculated. The coupling of the two skins is then made using the modal transfer matrix of the core, leading to the global dynamic equilibrium of the multilayer cylinder. The sound Transmission Loss (TL) of the cylinder excited by an acoustic plane wave is finally calculated. Our results are compared with results published recently in the literature. Excellent agreement is observed for thin cores where the three layers vibrate in phase in the radial direction. The usefulness of the three-dimensional model is demonstrated for a thick and soft core in the higher frequency domain where the skins are vibrating out of phase with a relative displacement in the radial direction. Finally, a parametric study is conducted to demonstrate the influence of the damping of each layer and some observations are made on the shear and compressional strain energies of each layer.

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“Debonding detection of honeycomb sandwich structures using frequency response functions”, Journal of Sound and Vibration, Vol. 222, No. 21, pp 5299-5311, October 2014, [https://doi.org/10.1016/j.jsv.2014.05.023](https://doi.org/10.1016/j.jsv.2014.05.023)

ABSTRACT: A vibration-based non-destructive evaluation (NDE) method is proposed to determine the location and size of debonding in honeycomb sandwich beams. Although most of the existing vibration-based NDE methods need many measurement points, the method proposed here only utilizes the frequency response function (FRF) measured at one point. A parameterized damaged Timoshenko beam model is developed with the method of reverberation-ray matrix (MRRM) for the first time, and combined with the genetic algorithm (GA) to inverse the damage parameters from the measured FRF. The detection of a honeycomb sandwich beam can be divided into two steps: (1) identifying the equivalent elastic moduli and other parameters of the intact sandwich beam. (2) Identifying the debonding location and size of the damaged sandwich beam with the
predetermined parameters. It is demonstrated experimentally that the method can inverse damage parameters with acceptable precision.

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ABSTRACT: The dynamic response of circular cylinders can be obtained analytically in very few (and simple) cases. For complicated (thick or anisotropic) circular cylinders, researchers often resort to the finite element (FE) method. This can lead to large models, especially at higher frequencies, which translates into high computational costs and memory requirements. In this paper, the response of axially homogenous circular cylinders (that can be arbitrarily complex through the thickness) is obtained using the wave and finite element (WFE) method. Here, the homogeneity of the cylinder around the circumference and along the axis are exploited to post-process the FE model of a small rectangular segment of the cylinder using periodic structure theory and obtain the wave characteristics of the cylinder. The full power of FE methods can be utilised to obtain the FE model of the small segment. Then, the forced response of the cylinder is posed as an inverse Fourier transform. However, since there are an integer number of wavelengths around the circumference of a closed circular cylinder, one of the integrals in the inverse Fourier transform becomes a simple summation, whereas the other can be resolved analytically using contour integration and the residue theorem. The result is a computationally efficient technique for obtaining the response to time harmonic, arbitrarily distributed loads of axially homogenous, circular cylinders with arbitrary complexity across the thickness.

ABSTRACT: A body insonified by a constant (time-varying) intensity sound field is known to experience a steady ( oscillatory) force that is called the steady-state (dynamic) acoustic radiation force. Using the classical resonance scattering theorem (RST) which suggests the scattered field as a superposition of a resonance field and a background (non-resonance) component, we show that the radiation force acting on a cylindrical shell may be synthesized as a composition of three components: background part, resonance part and their interaction. The background component reveals the pure geometrical reflection effects and illustrates a regular behavior with respect to frequency, while the others demonstrate a singular behavior near the resonance frequencies. The results illustrate that the resonance effects associated to partial waves can be isolated by the subtraction of the background component from the total (steady-state or dynamic) radiation force function (i.e., residue component). In the case of steady-state radiation force, the components are exerted on the body as static forces. For the case of oscillatory amplitude excitation, the components are exerted at the modulation frequency with frequency-dependant phase shifts. The results demonstrate the dominant contribution of the non-resonance component of dynamic radiation force at high frequencies with respect to the residue component, which offers the potential application of ultrasound stimulated vibro-acoustic spectroscopy technique in low frequency
resonance spectroscopy purposes. Furthermore, the proposed formulation may be useful essentially due to its intrinsic value in physical acoustics. In addition, it may unveil the contribution of resonance modes in the dynamic radiation force experienced by the cylindrical objects and its underlying physics.

ABSTRACT: A flow field modified local piston theory, which is applied to the integrated analysis on static/dynamic aeroelastic behaviors of curved panels, is proposed in this paper. The local flow field parameters used in the modification are obtained by CFD technique which has the advantage to simulate the steady flow field accurately. This flow field modified local piston theory for aerodynamic loading is applied to the analysis of static aeroelastic deformation and flutter stabilities of curved panels in hypersonic flow. In addition, comparisons are made between results obtained by using the present method and curvature modified method. It shows that when the curvature of the curved panel is relatively small, the static aeroelastic deformations and flutter stability boundaries obtained by these two methods have little difference, while for curved panels with larger curvatures, the static aeroelastic deformation obtained by the present method is larger and the flutter stability boundary is smaller compared with those obtained by the curvature modified method, and the discrepancy increases with the increasing of curvature of panels. Therefore, the existing curvature modified method is non-conservative compared to the proposed flow field modified method based on the consideration of hypersonic flight vehicle safety, and the proposed flow field modified local piston theory for curved panels enlarges the application range of piston theory.

ABSTRACT: The treatment of ship impacts and collisions takes different approaches depending on the emphasis of each discipline. For example, dynamicists, physicist, and mathematicians are dealing with developing analytical models and mappings of vibro-impact systems. On the other hand, naval architects and ship designers are interested in developing design codes and structural assessments due to slamming loads, liquid sloshing impact loads in liquefied natural gas tanks and ship grounding accidents. The purpose of this review is to highlight the main differences of the two disciplines. It begins with a brief account of the theory of vibro-impact dynamics based on modeling and mapping of systems experiencing discontinuous changes in their state of motion due to collision. The main techniques used in modeling include power-law phenomenological modeling, Hertzian modeling, and non-smooth coordinate transformations originally developed by Zhuravlev and Ivanov. In view of their effectiveness, both Zhuravlev and Ivanov non-smooth coordinate transformations will be described and assessed for the case of ship roll dynamics experiencing impact with rigid barriers. These transformations have the advantage of converting the vibro-impact oscillator into an oscillator without barriers such that the corresponding equation of motion does not contain any impact term. One of the recent results dealing with the coefficient of restitution is that its value monotonically decreases with the impact velocity and not unique but random in nature. Slamming loads and grounding events of ocean waves acting on the bottom of high speed vessels will be assessed with reference to the ship structural damage. It will be noticed that naval architects and marine engineers are treating these problems using different approaches from those used by dynamicists. The problem of sloshing impact in liquefied natural gas cargo and related problems will be
assessed based on the numerical and experimental results. It is important for vessel designers to determine the capacity of ships to resist random slamming loads, sloshing loading impact, grounding accidents and ships collisions.

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ABSTRACT: Modal analysis in finite element packages gives natural frequencies and mode shapes, but not modal damping values. Given a constitutive relation for specific material dissipation, volume integrals of the per cycle dissipation can be used to estimate the modal damping. Here, we adopt a well known power law model for such specific dissipation. We develop a modal damping estimation procedure for thin-walled components using shell elements in a commercial finite element package. We validate our shell element results against both analytical results and a solid elements approach developed elsewhere. Our computational approach allows complex geometries in a study of the effects of shape on damping. Finally, we demonstrate the efficacy of both stress concentrations and small tuned resonant appendages in increasing damping.

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ABSTRACT: Converting vibration energy to useful electric energy has attracted much attention in recent years. Based on the electromechanical coupling of piezoelectricity, distributed piezoelectric zero-curvature type (e.g., beams and plates) energy harvesters have been proposed and evaluated. The objective of this study is to develop a generic linear and nonlinear piezoelectric shell energy harvesting theory based on a double-curvature shell. The generic piezoelectric shell energy harvester consists of an elastic double-curvature shell and piezoelectric patches laminated on its surface(s). With a current model in the closed-circuit condition, output voltages and energies across a resistive load are evaluated when the shell is subjected to harmonic excitations. Steady-state voltage and power outputs across the resistive load are calculated at resonance for each shell mode. The piezoelectric shell energy harvesting mechanism can be simplified to shell (e.g., cylindrical, conical, spherical, paraboloidal, etc.) and non-shell (beam, plate, ring, arch, etc.) distributed harvesters using two Lamé parameters and two curvature radii of the selected harvester geometry. To demonstrate the utility and simplification procedures, the generic linear/nonlinear shell energy harvester mechanism is simplified to three specific structures, i.e., a cantilever beam case, a circular ring case and a conical shell case. Results show the versatility of the generic linear/nonlinear shell energy harvesting mechanism and the validity of the simplification procedures.
ABSTRACT: Flexoelectricity possesses two gradient-dependent electromechanical coupling effects: the direct flexoelectric effect and the converse flexoelectric effect. The former can be used for sensing and energy generation; the latter can be used for ultraprecision actuation and control applications. Due to the direct flexoelectricity and large deformations, theoretical fundamentals of a generic nonlinear distributed flexoelectric double-curvature shell energy harvester are proposed and evaluated in this study. The generic flexoelectric shell energy harvester is made of an elastic double-curvature shell laminated with flexoelectric patches and the shell experiences large oscillations, such that the von Karman geometric nonlinearity occurs. Flexoelectric output voltages and energies across a resistive load are evaluated using the current model in the closed-circuit condition when the shell is subjected to harmonic excitations and its steady-state voltage and power outputs are also calculated. The generic flexoelectric shell energy harvesting theory can be simplified to shell (e.g., cylindrical, conical, spherical, paraboloidal, etc.) and nonshell (beam, plate, ring, arch, etc.) distributed harvesters and the simplification procedures are demonstrated in three cases, i.e., a cylindrical shell, a circular ring and a beam harvester. Other shell and nonshell flexoelectric energy harvesters with standard geometries can also be defined using their distinct two Lamé parameters and two curvature radii.

ABSTRACT: The main aim of this paper is to present a dynamic analysis of toroidal shell structures in free space. The simplified thin shell theory, based on the typical small deflection assumption, but enriched by the transverse shear terms, was used. The constituting material is not isotropic but a multilayer composite angle-ply laminate, with non-uniform thickness. A numerical procedure based on the classical Rayleigh–Ritz method, was utilized. The dynamic independent variables were expressed in terms of a double Fourier series expansion as function of the azimuth and internal meridian circular angle. This allowed to determine easily the strain and kinetic energy expressions, and consequently the stiffness and mass matrices. Then, the numerical problem was simplified to the classical generalized eigenvalue problem relation by differentiating the whole energetic functional, as in the Rayleigh–Ritz method. The solutions were determined by using an appropriate algorithm. The high frequency vibration modes were considered and their peculiarities with respect to the low frequency modes were pointed out. The dependence of the obtained results on the laminate winding angle was also considered. Comparisons with the other authors results were necessary to validate the utilized numerical approach.

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ABSTRACT: The proper orthogonal decomposition (POD) method for analysis of nonlinear panel flutter subjected to supersonic flow is presented. Optimal POD modes are extracted from a chaotic Galerkin mode responses. The aeroelastic equations of motion are constructed using von Karman plate theory, first-order piston
theory and quasi-steady thermal stress theory. A simply-supported plate with thermal loads from a uniformly distributed temperature is considered. Many types of panel behaviors, including stable flat, dynamically stable buckled, limit cycle oscillation, nonharmonic periodic motion, quasi-periodic motion and chaotic motion are observed. Our primary focus is on chaos and the route to chaos. It is found that a sudden transition from the buckled state to chaos occurs. Time history, phase portrait, Poincaré map, bifurcation diagram and Lyapunov exponent are employed to study chaos. The POD chaotic results obtained are compared with the traditional Galerkin solutions. It is shown that the POD method can obtain accurate chaotic solutions, using fewer modes and less computational effort than the Galerkin mode approach; additionally, the POD method converges faster in the analysis of chaotic transients. Effects of length-to-width ratios and thermal loads are presented. It is found that a smaller width for fixed length will produce more stable flutter response, while the thermal loads degrade the flutter boundary and result in a more complex evolution of dynamic motions. The numerical simulations show that the robustness of the POD modes depends on the dynamic pressure but not on temperature.

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ABSTRACT: A new method for free vibration and buckling analysis of rectangular orthotropic plates is presented. The proposed method differs significantly from previously published methods in that it allows obtaining practically exact results for free vibration and buckling of orthotropic plates. By enhancing the method of superposition, the boundary value problem is essentially reduced to an infinite system of linear algebraic equations. Of particular significance of this research is that the existence of bounded solution of the infinite system after elimination of the unknowns has been captured in an elegant, but quantitative way to converge upon any natural frequency or critical buckling load of the orthotropic plate to any desired accuracy. The theory is applied to the particular case of orthotropic plates with clamped edges, but it can be extended to other boundary conditions. Buckling analysis is carried out as a degenerate case of free vibration at zero frequency. Comparisons of computed results from the present theory with those available in the literature are made wherever possible and some noteworthy conclusions are drawn.

ABSTRACT: The active vibration control of a free rectangular sandwich plate by using the Positive Position Feedback (PPF) algorithm was experimentally investigated in a previous study. Four normal modes were controlled by four nearly collocated couples of piezoelectric sensors and actuators. The experimental results of the control showed some limitation, especially in the Multi-Input Multi-Output (MIMO) configuration. This was attributed to the specific type of sensors and their conditioning, as well as to the phase shifts present in the vibration at different points of the structure. An alternative approach is here undertaken by abandoning the configuration of quasi-perfect collocation between sensor and actuator. The positioning of the piezoelectric patches is still led by the strain energy value distribution on the plate; each couple of sensor and actuator is now placed on the same face of the plate but in two distinct positions, opposed and symmetrical with respect to the geometric center of the plate. Single-Input Single-Output (SISO) PPF is tested and the transfer function
The parameters of the controller are tuned according to the measured values of modal damping. Then the participation matrices necessary for the MIMO control algorithm are determined by means of a completely experimental procedure. PPF is able to mitigate the vibration of the first four natural modes, in spite of the rigid body motions due to the free boundary conditions. The amplitude reduction achieved with the non-collocated configuration is much larger than the one obtained with the nearby collocated one. The phase lags were addressed in the MIMO algorithm by correction phase delays, further increasing the performance of the controller.

ABSTRACT: It is a common practice in aerospace and automobile industries to use double wall panels as fuselage skins or in window panels to improve acoustic insulation. However, the scientific community is yet to develop a reliable prediction method for a suitable vibro-acoustic model for sound transmission through a curved double-wall panel. In this quest, the present work tries to delve into the modeling of energy transmission through a double-wall curved panel. Subsequently the radiation of sound power into the free field from the curved panel in the low to mid frequency range is also studied. In the developed model to simulate a stiffened aircraft fuselage configuration, the outer wall is provided with longitudinal stiffeners. A modal expansion theory based on Green’s theorem is implemented to model the energy transmission through an acoustically coupled double-wall curved panel. An elemental radiator approach is implemented to calculate the radiated energy from the curved surface into the free field. The developed model is first validated with various numerical models available. It has been observed in the present study that the radius of curvature of the surface has a prominent effect on the behavior of radiated sound power into the free field. Effect of the thickness of the air gap between the two curved surfaces on the sound power radiation has also been noted.

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ABSTRACT: The delamination phenomena can become of paramount importance when the design of the composite plates is concerned. In the current study, the effect of through-the-width delamination on dynamic buckling behavior of a composite plate is studied by implementing semi-analytical finite strip method. In this method, the energy and work integrations are computed analytically due to the implementation of trigonometric functions. Moreover, the method can lead to converged results with comparatively small number of degrees of freedom. These features have made the method quite efficient. To account for delamination effects, displacement field is enriched by adding appropriate terms. Also, the penetration of the delamination surfaces is prevented by incorporating an appropriate contact scheme into the time response analysis. Some selected results are validated against those available in the literature.

ABSTRACT: This paper presents a modal, time-domain scheme for the nonlinear vibrations of perfect and imperfect plates. The scheme can take into account a large number of degrees-of-freedom and is energy-conserving. The targeted application is the sound synthesis of cymbals and gong-like musical instruments, which are known for displaying a strongly nonlinear vibrating behaviour. This behaviour is typical of a wave turbulence regime, in which the wide-band spectrum of excited modes is observable in the form of an energy cascade. The modal method is selected for its versatility in handling complex damping laws that can be implemented easily by selecting appropriate damping values in each one of the modal equations. In the first part of the paper, the modal method is explained in its generality, and it will be seen that the method is valid for plates with arbitrary geometry and boundary conditions as long as the eigenmodes are known. Secondly, a time-integration, energy-conserving scheme for perfect and imperfect plates is presented, and implementation comments are given in order to treat efficiently the high-dimensionality of the resulting dynamical system. The scheme is run with appropriate parameters in order to produce sound samples. A simple impact law is considered for the excitation, whereas the flexibility of the method is highlighted by showing simulations for free-edge circular plates and simply-supported rectangular plates, together with various damping laws.


ABSTRACT: The vibro-acoustic coupling dynamics of a rotor-bearing-foundation-cylinder system are investigated. Using rotor dynamics, structure dynamics and acoustical theory, the vibro-acoustic coupling equation of a cylindrical shell under rotor-bearing-foundation system’s nonlinear vibration excitations is derived based on variational principle. In order to solve the coupling equation, the influences of the shell’s vibration to the rotor-bearing system are neglected, and then the dynamical equation is reduced. The nonlinear forces transmitted to the cylinder are fitted in the Fourier series by the fast Fourier translation and the harmonic balance method, and then the analytical solution of the vibro-acoustic coupling equation of the cylinder is derived. Based on inherent assumption, the analytical expressions of the acoustic radiation power and the surface velocity are given. Then bifurcation diagrams, phase diagrams, time history diagrams and spectrum graphs are employed to study the nonlinear vibration characteristics and the acoustic radiation characteristics. It is inferred that the present work proposes a semi-analytical and semi-numerical method for the nonlinear vibro-acoustic coupling system. The motions of the forces transmitted to the cylinder are periodic motions, quasi-periodic motions, and so on. The vibro-acoustic characteristics of shell are dominated by the rotation frequency of the rotor, while there are some harmonic components dominating the vibro-acoustic characteristics at resonant frequencies.

ABSTRACT: In this paper, some experiments are described which were designed to illustrate the dynamical behaviour of towed flexible cylinders and to test the theory. A silicone rubber cylinder was manufactured such that it was almost neutrally buoyant when immersed in water. The cylinder was terminated by plexiglas end-pieces and was held in horizontal water flow by a length of nylon thread (towrope). Video capturing along with image processing techniques were used to measure the transverse displacement of the cylinder in the horizontal plane. For the cylinder with relatively streamlined nose and tail end-pieces, non-flexural (rigid-body), as well as flexural instabilities developed as the flow velocity was increased; shortening the towrope was not very effective for stabilizing the system, but a sufficiently blunt tail end-piece had a very significant stabilizing effect. The experimental observations are generally in qualitative agreement with the available nonlinear theory. Quantitative comparison of various quantities, e.g. the instability thresholds, between experiment and theory, based on the estimated values of some of the theoretical nondimensional parameters, is also fairly good.

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ABSTRACT: The nonlinear vibration of a simply supported FGM cylindrical shell with small initial geometric imperfection under complex loads is studied. The effects of radial harmonic excitation, compressive in-plane force combined with supersonic aerodynamic and thermal loads are considered. The small initial geometric imperfection of the cylindrical shell is characterized in the form of the sine-type trigonometric functions. The effective material properties of this FGM cylindrical shell are graded in the radial direction according to a simple power law in terms of the volume fractions. Based on Reddy’s third-order shear deformation theory, von Karman-type nonlinear kinematics and Hamilton’s principle, the nonlinear partial differential equation that controls the shell dynamics is derived. Both axial symmetric and driven modes of the cylindrical shell deflection pattern are included. Furthermore, the equations of motion can be reduced into a set of coupled nonlinear ordinary differential equations by applying Galerkin’s method. In the study of the nonlinear dynamics responses of small initial geometric imperfect FGM cylindrical shell under complex loads, the 4th order Runge–Kutta method is used to obtain time history, phase portraits, bifurcation diagrams and Poincare maps with different parameters. The effects of external loads, geometric imperfections and volume fractions on the nonlinear dynamics of the system are discussed.


ABSTRACT: A new type of hexagonal honeycomb sandwich tube with plateau borders are introduced in this work and the Symplectic analysis with its high computational efficiency and high accuracy is applied to obtain the structural dynamic properties. The effects of material distribution (beta) and relative density (rhobar) on the dynamic properties of the structure are also studied. Based on the definition of the elastic constants and the homogenization method, the independent elastic constants are obtained. By introducing dual variables and applying the variational principle, the canonical equations of Hamiltonian system are constructed. The precise
integration method and extended Wittrick–Williams algorithm are adopted to solve the canonical equations. The dispersion relations of sandwich tubes are obtained, and the effects of material distribution and relative density on the normalized frequencies of the sandwich tubes are investigated. The proposed homogenization method is verified by comparing with other researchers’ works. Dispersion relations of the sandwich tubes are obtained. The material distribution parameter and the relative density have significant effects on the dynamic properties of the structures. This work expects to offer new opportunities for the optimal design of metallic honeycomb sandwich tubes and future applications in the engineering sector.

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ABSTRACT: The parametric vibration of a simply supported composite circular cylindrical shell under periodic partial edge loadings is discussed in this article. Donnell’s nonlinear shallow shell theory considering first order shear deformation theory is used to model the shell. The applied partial edge loading is represented in terms of a Fourier series and stress distributions within the cylindrical shell are determined by prebuckling analysis. The governing equations of the dynamic instability of shells are derived in terms of displacements \((u−v−w)\) and rotations (phi-sub-x, phi-sub-theta). Employing the Galerkin and Bolotin methods the dynamic instability regions are computed. Using the expression for the stress function derived in this paper, the prebuckling stresses in the cylindrical shell due to partial load can be calculated explicitly. Numerical results are presented to show the influence of radius-to-thickness ratio, different partial edge loading distributions and shear deformation on the dynamic instability regions. The linear and nonlinear responses in the stable and unstable regions are presented to bring out the characteristic features of the dynamic instability regions, such as the existence of beats, its dependence on forcing frequency and effect of nonlinearity on the response. The effect of dynamic load amplitude on the nonlinear response is also studied. It is found that for higher values of dynamic loading, the shell exhibits chaotic behavior.

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ABSTRACT: This study uses the Rayleigh–Ritz method to derive a dynamic model for the free vibration analysis of a circular cylindrical shell. In particular, explicit expressions for the mass and stiffness matrices are obtained to easily implement a computer simulation under different shell theories and boundary conditions. The dynamic model is constructed according to the Donnell–Mushtari theory, which is fully discussed herein, and then, dynamic models are constructed by using Sanders theory, Love–Timoshenko theory, Reissner theory,
Flügge theory, and Vlasov theory. This paper also discusses the use of eigenfunctions of a uniform beam as admissible functions that produce compact expressions for the mass and stiffness matrices. The numerical results indicate that the Donnell–Mushtari theory is not sufficiently accurate to calculate the natural frequencies and that there is no discernible difference between the other shell theories considered in this study.


ABSTRACT: Vortex-induced vibration (VIV) of a curved circular cylinder (a quarter of a ring, with no extension added to either end) free to oscillate in the crossflow direction was studied experimentally. Both the concave and the convex orientations (with respect to the oncoming flow direction) were considered. As expected, the amplitude of oscillations in both configurations was decreased compared to a vertical cylinder with the same mass ratio. Flow visualizations showed that the vortices were shed in parallel to the curved cylinder, when the cylinder was free to oscillate. The sudden jump in the phase difference between the flow forces and the cylinder displacement observed in the VIV of vertical cylinders was not observed in the curved cylinders. Higher harmonic force components at frequencies twice and three times the frequency of oscillations were observed in flow forces acting on the vertical cylinder, as well as the curved cylinder. Asymmetry in the wake was responsible for the 2nd harmonic force component and the relative velocity of the structure with respect to the oncoming flow was responsible for the 3rd harmonic force component. The lock-in occurred over the same range of reduced velocities for the curved cylinder in the convex orientation as for a vertical cylinder, but it was extended to higher reduced velocities for a curved cylinder in the concave orientation. Higher harmonic force components were found to be responsible for the extended lock-in range in the concave orientation. Within this range, the higher harmonic forces were even larger than the first harmonic force and the structure was being excited mainly by these higher harmonic forces.

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ABSTRACT: This paper describes the results of dynamic impact testing on externally axially loaded steel rectangular hollow sections (RHSs) and compares the response to that of externally post-tensioned steel RHSs. Both the fundamental natural bending frequency of the beam sections and the corresponding damping ratios have been calculated from the measured dynamic response of the beam to a series of impact hammer strikes. The validity of the “compression-softening” effect for post-tensioned sections is tested. The implications of the research are vast, as currently, there is significant disagreement among researchers about the effect of pre- and post-tensioning loads on the dynamic characteristics of structures. The fundamental bending frequencies have been calculated and corresponding damping ratio have been calculated from dynamic test results for each axial load level. The bending frequencies have been calculated repeatedly while changing the axial load level and the
subsequent changes in both frequency and damping ratio, with increasing axial load level have been analysed to determine if the results are statistically significant. It has been determined that “compression softening” theory is not valid for pre- or post-tensioned sections.

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ABSTRACT: A semi-analytical method is developed to predict the vibration and acoustic responses of submerged coupled spherical–cylindrical–spherical shells stiffened by circumferential rings and longitudinal stringers. The structural model of the coupled stiffened shell is formulated using a modified variational method combined with a multi-segment partitioning technique, whereas a spectral Kirchhoff–Helmholtz integral formulation is employed to model the exterior fluid. The stiffened rings and stringers, which may be few or many in number, non-uniform or uniform in size, and non-uniformly or uniformly spaced, are treated as discrete elements. The displacement and sound pressure variables are expanded in the form of a double mixed series using Fourier series and Chebyshev orthogonal polynomials. This provides a flexible way for the present method to account for the individual contributions of circumferential wave modes to the vibration and acoustic responses of coupled stiffened shells in an analytical manner. The application of the method is illustrated with several numerical examples, and comparisons are made with available solutions obtained from the coupled finite element/boundary element method. The contributions of different circumferential wave modes to the vibration responses, sound power and the directivity of radiated sound pressure for coupled shells bounded by light or heavy fluid are examined. Effects of the rings and stringers on the vibration and acoustic responses of the coupled shells are investigated.

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ABSTRACT: This paper investigates sound transmission through double-walled cylindrical shell lined with poroelastic material in the core, excited by pressure fluctuations due to the exterior turbulent boundary layer (TBL). Biot’s model is used to describe the sound wave propagating in the porous material. Three types of constructions, bonded–bonded, bonded–unbonded and unbonded–unbonded, are considered in this study. The power spectral density (PSD) of the inner shell kinetic energy is predicted for two turbulent boundary layer models, different air gap depths and three types of polyimide foams, respectively. The peaks of the inner shell kinetic energy due to shell resonance, hydrodynamic coincidence and acoustic coincidence are discussed. The results show that if the frequency band over the ring frequency is of interest, an air gap, even if very thin, should
exist between the two elastic shells for better sound insulation. And if small density foam has a high flow resistance, a superior sound insulation can still be maintained.

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ABSTRACT: Damping material is usually applied to steel panels of vehicles to reduce vibration levels. On the other hand, the weight of a vehicle must be reduced to improve the rate of fuel consumption. Therefore, the modal loss factors caused by the treatment of damping material on the steel panels of a vehicle body structure must be maximized within a given volume. In this paper, we propose a practical design method to maximize modal loss factors by optimizing the layout of damping material under a volume constraint. The modal loss factor for an eigenmode can be obtained conventionally by the modal strain energy method as the material loss factor multiplied by the ratio of the strain energy stored in the damping material over the total strain energy in the system under consideration. In the proposed method, we assume that the eigenvectors with damping material are almost identical with the eigenvectors without damping material. The modal loss factor can then be expressed approximately by using a corresponding real eigenvalue, for which the stiffness of the damping material is taken into account but its mass density is set to zero and ignored. Several numerical examples are provided to demonstrate that the proposed method obtains optimal layouts of damping material applied to a flat rectangular panel. Our results indicate that the damping material is mainly distributed in areas where strain energy is stored, which agrees well with the results obtained using conventional design methodologies. Moreover, by applying a design sensitivity filter that was improved recently, the layout of damping material can be unified into a single domain to meet practical requirements for manufacturing.

ABSTRACT: In this discussion, the corrections to the errors found in the derivations and the numerical code of a recent analytical study (Zhou et al. Journal of Sound and Vibration 333 (7) (2014) 1972–1990) on sound transmission through double-walled cylindrical shells lined with poroelastic material are presented and discussed, as well as the further effect of the external mean flow on the transmission loss. After applying the corrections, the locations of the characteristic frequencies of thin shells remain unchanged, as well as the TL results above the ring frequency where BU and UU remain the best configurations in sound insulation performance. In the low-frequency region below the ring frequency, however, the corrections attenuate the TL amplitude significantly for BU and UU, and hence the BB configuration exhibits the best performance which is consistent with previous observations for flat sandwich panels.
ABSTRACT: Free and forced nonlinear radial oscillations of a thick-walled cylindrical shell are investigated. The shell material is taken to be incompressible and isotropic within the framework of finite nonlinear elasticity. In comparison with previous seminal works dealing with the dynamic behaviour of hyperelastic cylindrical tubes, in this paper we have developed a broader analysis on the constitutive sensitivity of the oscillatory response of the shell. In this regard, our investigation is inspired by the recent works of Bucchi and Hearn (2013) [28,29], who carried out a constitutive sensitivity analysis of similar problem with hyperelastic cylindrical membranes subjected to static inflation. In the present paper we consider two different Helmholtz free-energy functions to describe the material behaviour: Mooney–Rivlin and Yeoh constitutive models. We carry out a systematic comparison of the results obtained by application of both constitutive models, paying specific attention to the critical initial and loading conditions which preclude the oscillatory response of the cylindrical tube. It has been found that these critical conditions are strongly dependent on the specific constitutive model selected, even though both Helmholtz free-energy functions were calibrated using the same experimental data.

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ABSTRACT: This paper reports the result of an investigation into the nonlinear vibration frequencies of graphene/piezoelectric sandwich films under electrical loading based on nonlocal elastic theory by utilizing a global residual harmonic balance method. Based on the Galerkin method and global residual harmonic balance method, the nonlinear resonant frequencies of graphene/piezoelectric sandwich films under electric exciting loads are obtained with a set of factors: the ratio of the oscillating amplitude to the thickness of sandwich films, small scale effect, electric loading exerted on piezoelectric layer, mode number and size length. Results indicate that the electric exciting load enhances the nonlinear resonant frequency of graphene/piezoelectric sandwich films, the nonlinear resonant frequency decreases as the scale effect increases, the scale effect has a more significant effect on higher mode resonant frequency and linear resonant frequency, and the effect of scale on the nonlinear resonant frequency is independent on the electric exciting load and the boundary conditions exerted on the sandwich films.

ABSTRACT: The dynamic stiffness matrix of completely free rectangular Mindlin plate element is presented in this paper. The system of three coupled equations of motion is transformed into two uncoupled equations introducing a boundary layer function. The dynamic stiffness matrix is derived by use of the superposition method and the projection method. Using the proposed method natural frequencies of individual plates and plate assemblies with arbitrary boundary conditions are computed and validated against the results available in the literature and the finite element analysis. High efficiency and accuracy of the results are demonstrated.

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ABSTRACT: This paper presents a model for the small oscillations of a pressurized, elastic, spherical shell subject to internal and external fluid effects. The shell has three features: a pressure difference across the skin; a thin, tensioned shell; and a double curved interfacial surface. An analytical solution for the natural frequencies and mode shapes, incorporating the inertia both of the shell and the surrounding fluids, is derived. Two key parameters that quantify the effect of pre-stress and fluid inertia on the shell’s behaviour are identified. When the skin tension is set to zero and the inertial effects of the fluid are removed, the results converge to the analytical solution for an elastic spherical shell, and when the skin elasticity is neglected, the results converge to the constant-tension solution of a bubble. The analytical solution is used to predict the natural frequencies of a small balloon, based on a value for the elastic modulus that is determined using inflation measurements. These predictions are compared to experimental measurements of balloon vibrations using impact-hammer testing, and good agreement is seen.

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ABSTRACT: A mixed “Biot–Shell” analytical model dedicated to the calculation of sound transmission through an infinite sandwich cylinder composed of orthotropic skins and a poroelastic core is proposed in this paper. The motion of the two thin orthotropic skins is described with the first-order shear deformation theory while the poroelastic core is modeled with the full 3D Biot’s theory. The main advantage of this mixed model is that it takes into account the elasticity effects related to the skeleton of the poroelastic material. First, an analytical expression of the displacement and stress fields of the solid and fluid phases in the poroelastic layer is presented in cylindrical coordinates. Then, the poroelastic core transfer matrix relating the displacements and the stresses at the two common interfaces between the core and the skins is calculated. The coupling of the two
skins is then made using the modal transfer matrix of the core, leading to the global dynamic equilibrium of the sandwich cylinder. The proposed model is finally used to calculate the sound Transmission Loss (TL) of infinite cylinders excited by an incident plane wave. Excellent agreement is observed in comparison with a finite element model. The usefulness of Biot’s model in this type of problem is demonstrated by comparing the results with those obtained with equivalent fluid models. The mixed “Biot–Shell” analytical model is finally used to demonstrate the influence of the structural damping of each layer and to study the sound transmission in different configurations.

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ABSTRACT: Based on Euler–Bernoulli beam theory and Hamilton’s principle, the differential equation of a vertical cantilevered pipe conveying fluid is derived when the pipe has deploying or retracting motion. The resulting equation is discretized via the Galerkin method in which the eigenfunctions of a clamped-free Euler–Bernoulli beam are utilized. Then, the dynamic responses and stability are discussed with regard to the deploying or retracting speed, mass ratio, and fluid velocity. Numerical results reveal that the dynamical behavior of the system is mainly affected by the flow velocity, instantaneous length of pipe, gravity, and mass ratio. For the small flow velocity, the fluid and higher mass ratio helps to stabilize the transverse vibration of the cantilevered pipe conveying fluid in both deployment and retraction modes, and the system will lose stability with the further increase of flow velocity. The critical flow velocity is mainly influenced by the instantaneous length of pipe. The additional restoring force due to gravity causes critical flow velocity to be higher for the vertically cantilevered pipe conveying fluid. Therefore, gravity is conducive to the stability the transverse vibration of the system in both deployment and retraction modes.

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ABSTRACT: The vibroacoustic behavior of axisymmetric stiffened shells immersed in water has been intensively studied in the past. On the contrary, little attention has been paid to the modeling of these shells coupled to non-axisymmetric internal frames. Indeed, breaking the axisymmetry couples the circumferential orders of the Fourier series and considerably increases the computational costs. In order to tackle this issue, we propose a sub-structuring approach called the Condensed Transfer Function (CTF) method that will allow assembling a model of axisymmetric stiffened shell with models of non-axisymmetric internal frames. The CTF method is developed in the general case of mechanical subsystems coupled along curves. A set of orthonormal functions called condensation functions, which depend on the curvilinear abscissa along the coupling line, is
considered. This set is then used as a basis for approximating and decomposing the displacements and the applied forces at the line junctions. Thanks to the definition and calculation of condensed transfer functions for each uncoupled subsystem and by using the superposition principle for passive linear systems, the behavior of the coupled subsystems can be deduced. A plane plate is considered as a test case to study the convergence of the method with respect to the type and the number of condensation functions taken into account. The CTF method is then applied to couple a submerged non-periodically stiffened shell described using the Circumferential Admittance Approach (CAA) with internal substructures described by Finite Element Method (FEM). The influence of non-axisymmetric internal substructures can finally be studied and it is shown that it tends to increase the radiation efficiency of the shell and can modify the vibrational and acoustic energy distribution.

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ABSTRACT: This paper investigates the free transverse vibration of a wrinkled annular thin film. The non-dimensional Hamilton motion equation of the wrinkled annular thin film is established, which is solved by using the finite difference method to acquire the vibration frequency and mode. The predicted vibration characteristics are verified by the experimental measurements based on the digital image correlation (DIC) technique. The results show that wrinkles have great effects on the vibration of the annular thin film. Especially for the heavily wrinkled cases, the local–global interactive mode dominates the vibration of the annular thin film. The frequency increases as the wrinkling level increases which is mainly due to the increased nonlinear geometric stiffness. The results provide favorable supports for understanding the role of nonlinear wrinkling on the vibration of thin films.

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ABSTRACT: This paper proposes an extension of the full method to investigate sound transmission through poroelastic cylindrical shell. The “extended full method” is presented based on Biot theory with considering the 3-D wave propagation in a cylindrical shell. Contrary to previous methods, it could be applicable for both poroelastic cylindrical shells and double-walled cylindrical shells lined with poroelastic materials with an excellent accuracy. In the extended full method, the well-known Helmholtz decomposition is used to obtain the displacement fields, solid stresses and the fluid pressure. In order to verify the results of the poroelastic cylindrical shell the porosity goes into zero with eliminating the fluid phase of the poroelastic material. Thus, the results are compared with those of TLs for isotropic shell with high accuracy. The results also indicate that enhancing the porosity of the poroelastic cylindrical shells efficiently leads into decreasing the TL. It is also designated that with doubling the thickness of the poroelastic shell, the TL is improved about 6 dB in a broadband frequency. Also, the present method is investigated for the case of a double-walled cylindrical shell.
composed of isotropic skins and poroelastic core. The first-order shear deformation theory is applied to modeling the isotropic shells. The results indicate that presented method is more accurate than simplified method, particularly in the case of small radius cylindrical shells. Moreover, the results indicate that with increasing the radius of the shell, the double-walled cylindrical shell behaves in a same trend as a double-walled flat plate.


ABSTRACT: We study flow-induced instabilities of axis-symmetric shells of revolution with an arbitrary meridian and non-zero Gaussian curvatures. We consider a fluid–structure interaction (FSI) model based on an inviscid flow model and a thin shell theory. This FSI model is solved using a method that combines the Galerkin technique with the boundary element method (BEM). The present method is capable of investigating the dynamic behavior of doubly-curved shells in contact with flow without the need for an analytical solution of the perturbed flow potential. Shells of revolution with different values of non-zero Gaussian curvatures are investigated and their behavior is compared to shells with zero Gaussian curvature. It is found that the added mass natural frequencies of shells of revolution are larger than those of conical shells with the same inlet, outlet and length. Shells of revolution, with both positive and negative Gaussian curvatures, lose their instability by buckling, however, shells with negative Gaussian curvatures buckle at modes similar to those observed in uniform and conical shells, while shells with positive Gaussian curvatures buckle with localized deformations close to the area with higher local flow velocities.

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ABSTRACT: In this work high Mach number aerodynamic and structural measurements acquired in the CIRA (Italian Aerospace Research Center) transonic wind tunnel and the models used to analyze the response of composite panels to turbulent boundary layer excitation are presented. The two investigated panels are CFRP (Carbon Fiber-Reinforced Polymer) composite plates and their lay-up is similar to configurations used in aeronautical structures. They differ only for the presence of an embedded viscoelastic layer. The experimental set-up has been designed to reproduce a pressure fluctuations field beneath a turbulent boundary layer as close as possible to those in flight. A tripping system, specifically conceived to this aim for this facility, has been used to generate thick turbulent boundary layers at Mach number values ranging between 0.4 and 0.8. It is shown that the designed setup provides a realistic representation of full scale size pressure spectra in the frequency range of interest for the noise component inside the fuselage, generated by turbulent boundary layer. The significant role of the viscoelastic layer at reducing panel’s response is detailed and discussed. Finally, it is demonstrated that at high Mach number the aeroelastic effect cannot be neglected when analyzing the panel response, especially when composite materials are considered.

ABSTRACT: This paper deals with the free vibration analysis of isotropic plate assemblies using the dynamic stiffness method (DSM) based on the Reddy’s higher-order shear deformation theory (HSDT). Using the proposed method, the isotropic rectangular plate assemblies of non-uniform thickness and material properties can be analyzed. The proposed model does not have any restrictions regarding the boundary conditions or the frequency limitations. It enables free vibration analysis of both thin and thick plates, making it advantageous in comparison with the conventional finite element method (FEM) regarding the computational cost and the accuracy of the results. Three coupled Euler-Lagrange equations of motion based on the HSDT have been transformed into two uncoupled equations of motion introducing a boundary layer function. The dynamic stiffness matrix for a completely free rectangular plate element has been derived using the superposition and the projection method. The proposed numerical model has been applied in the free vibration analysis of rectangular plate assemblies. Along with the convergence study, the results for natural frequencies have been validated against the existing data from the literature, the previous results from the authors as well as the results obtained by using the finite element software Abaqus. Excellent agreement has been obtained. Finally, a variety of new results is provided as a benchmark for future investigations.


ABSTRACT: Based on the results of experimental and numerical analyses, the effect of rotation on the tyre dynamic behaviour is investigated. Better understanding of these effects will further improve the ability to control and optimize the noise and vibrations that result from the interaction between the road surface and the rolling tyre. Therefore, more understanding in the complex tyre dynamic properties will contribute to develop tyre design strategies to lower the tyre/road noise while less affecting other tyre performances. The presented work is performed in the framework of the European industry-academia project TIRE-DYN, with partners Goodyear, Katholieke Universiteit Leuven and LMS International. The effect of rotation on the tyre dynamic behaviour is quantified for different operating conditions of the tyre, such as load, air pressure and rotation speed. By means of experimental and numerical analyses, the effects of rotation on the tyre dynamic behaviour are studied.


ABSTRACT: Modal density is an important parameter in Statistical Energy Analysis (SEA) based response estimation. Many space structures use composite cylinders. Modal densities of such structural elements are not reported. In this work an expression for modal density of composite cylindrical shells is derived. Its characteristics and sensitivity to various parameters are discussed. The frequency at which the modal density
has a maximum is derived. Modal densities of typical composite cylinders are obtained. It is shown that computing modal density considering an equivalent isotropic cylinder can lead to significant errors.


ABSTRACT: Noise reduction by structural geometry optimization has attracted much attention among designers. In the present work, we propose a free-form optimization method for the structural–acoustic design optimization of shell structures to reduce the noise of a targeted frequency or frequency range in an open or closed space. The objective of the design optimization is to minimize the average structural vibration-induced sound pressure at the evaluation points in the acoustic field under a volume constraint. For the shape design optimization, we carry out structural–acoustic coupling analysis and adjoint analysis to calculate the shape gradient functions. Then, we use the shape gradient functions in velocity analysis to update the shape of shell structures. We repeat this process until convergence is confirmed to obtain the optimum shape of the shell structures in a structural–acoustic coupling system. The numerical results for the considered examples showed that the proposed design optimization process can significantly reduce the noise in both open and closed spaces.

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ABSTRACT: The aim of the present paper is a deep experimental investigation of the nonlinear dynamics of circular cylindrical shells. The specific problem regards the response of circular cylindrical shells subjected to base excitation. The shells are mounted on a shaking table that furnishes a vertical vibration parallel to the cylinder axis; a heavy rigid disk is mounted on the top of the shells. The base vibration induces a rigid body motion, which mainly causes huge inertia forces exerted by the top disk to the shell. In-plane stresses due to the aforementioned inertias give rise to impressively large vibration on the shell. An extremely violent dynamic phenomenon suddenly appears as the excitation frequency varies up and down close to the linear resonant frequency of the first axisymmetric mode. The dynamics are deeply investigated by varying excitation level and frequency. Moreover, in order to generalise the investigation, two different geometries are analysed. The paper furnishes a complete dynamic scenario by means of: (i) amplitude frequency diagrams, (ii) bifurcation diagrams, (iii) time histories and spectra, (iv) phase portraits and Poincaré maps. It is to be stressed that all the results presented here are experimental.

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ABSTRACT: The bend–twist coupling (BTC) is proven to be effective in mitigating the fatigue loads for large-scale wind turbine blades, but at the same time it may cause the risk of flutter instability. The BTC is defined as a feature of twisting of the blade induced by the primary bending deformation. In the classical flutter, the BTC arises from the aerodynamic loads changing with the angle of attack. In this study, the effects of the structural BTC on the flutter are investigated by considering the layup unbalances (ply angle, material and thickness of the composite laminates) in the NREL 5-MW wind turbine rotor blade of glass fiber/epoxy [0°/+45°/−45]_S laminates. It is numerically shown that the flutter speed may decrease by about 5 percent with unbalanced ply-angle only (one side angle, from 45° to 25°). It was then demonstrated that the flutter performance of the wind turbine blade can be increased by using lighter and stiffer carbon fibers which ensures the higher structural BTC at the same time.


ABSTRACT: Circular cylindrical shells with flexible boundary conditions conveying pulsatile flow and subjected to pulsatile pressure are investigated. The equations of motion are obtained based on the nonlinear Novozhilov shell theory via Lagrangian approach. The flow is set in motion by a pulsatile pressure gradient. The fluid is modeled as a Newtonian pulsatile flow and it is formulated using a hybrid model that contains the unsteady effects obtained from the linear potential flow theory and the pulsatile viscous effects obtained from the unsteady time-averaged Navier–Stokes equations. A numerical bifurcation analysis employs a refined reduced order model to investigate the dynamic behavior. The case of shells containing quiescent fluid subjected to the action of a pulsatile transmural pressure is also addressed. Geometrically nonlinear vibration response to pulsatile flow and transmural pressure are here presented via frequency-response curves and time histories. The vibrations involving both a driven mode and a companion mode, which appear due to the axial symmetry, are also investigated. This theoretical framework represents a pioneering study that could be of great interest for biomedical applications. In particular, in the future, a more refined model of the one here presented will possibly be applied to reproduce the dynamic behavior of vascular prostheses used for repairing and replacing damaged and diseased thoracic aorta in cases of aneurysm, dissection or coarctation. For this purpose, a pulsatile time-dependent blood flow model is here considered by applying physiological waveforms of velocity and pressure during the heart beating period. This study provides, for the first time in literature, a fully coupled fluid–structure interaction model with deep insights in the nonlinear vibrations of circular cylindrical shells subjected to pulsatile pressure and pulsatile flow.

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ABSTRACT: The ability to accurately model engineering systems under extreme dynamic loads would prove a major breakthrough in many aspects of aerospace, mechanical, and civil engineering. Extreme loads frequently induce both nonlinearities and coupling which increase the complexity of the response and the computational cost of finite element models. Dimension reduction has recently gained traction and promises the ability to distill dynamic responses down to a minimal dimension without sacrificing accuracy. In this context, the dimensionality of a response is related to the number of modes needed in a reduced order model to accurately simulate the response. Thus, an important step is characterizing the dimensionality of complex nonlinear responses of structures. In this work, the dimensionality of the nonlinear response of a post-buckled beam is investigated. Significant detail is dedicated to carefully introducing the experiment, the verification of a finite element model, and the dimensionality estimation algorithm as it is hoped that this system may help serve as a benchmark test case. It is shown that with minor modifications, the method of false nearest neighbors can quantitatively distinguish between the response dimension of various snap-through, non-snap-through, random, and deterministic loads. The state-space dimension of the nonlinear system in question increased from 2–to–10 as the system response moved from simple, low-level harmonic to chaotic snap-through. Beyond the problem studied herein, the techniques developed will serve as a prescriptive guide in developing fast and accurate dimensionally reduced models of nonlinear systems, and eventually as a tool for adaptive dimension-reduction in numerical modeling. The results are especially relevant in the aerospace industry for the design of thin structures such as beams, panels, and shells, which are all capable of spatio-temporally complex dynamic responses that are difficult and computationally expensive to model.

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ABSTRACT: This paper is concerned with the elastic waveguide properties of an infinite pipe with circular cross section whose radius varies slowly along its length. The equations governing the elastodynamics of such shells are derived analytically, approximated asymptotically in the limit of slow axial variation, and solved by means of the WKB-method (Wentzel–Kramers–Brillouin). From the derived solution the dispersion relation, modal coefficients, and wave amplification at each location along the structure are extracted, allowing identification of which types of waves are able to propagate along the structure at a given frequency. A key feature in the formulation of the model and the solution is that the radius and its variation are not specified in advance. Two characteristic examples of shells of revolution are presented to illustrate some general features of the waveguide properties, demonstrating how the evolution of the waves depends on the axial variation of the shell radius. It is explained how local resonances can be excited by the travelling waves and how strong amplifications of displacement can be produced. Specifically, for the axial/breathing wave it is shown that a local resonance is excited at the location where the frequency of the travelling wave and the radius of the shell exactly match the ring-frequency.

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ABSTRACT: This paper presents a semi-analytical method for the vibro-acoustic analysis of a functionally graded shell of revolution immersed in an infinite light or heavy fluid. The structural model of the shell is formulated on the basis of a modified variational method combined with a multi-segment technique, whereas a spectral Kirchhoff–Helmholtz integral formulation is employed to model the exterior fluid field. The material properties of the shell are estimated by using the Voigt’s rule of mixture and the Mori–Tanaka’s homogenization scheme. Displacement and sound pressure variables of each segment are expanded in the form of a mixed series using Fourier series and Chebyshev orthogonal polynomials. A set of collocation nodes distributed over the roots of Chebyshev polynomials are employed to establish the algebraic system of the acoustic integral equations, and the non-uniqueness solution is eliminated using a combined Helmholtz integral equation formulation. Loosely and strongly coupled schemes are implemented for the structure-acoustic interaction problem of a functionally graded shell immersed in a light and heavy fluid, respectively. The present method provides a flexible way to account for the individual contributions of circumferential wave modes to the vibration and acoustic responses of functionally graded shells of revolution in an analytical manner. Numerical tests are presented for sound radiation problems of spherical, cylindrical, conical and coupled shells. The individual contributions of the circumferential modes to the radiated sound pressure and sound power of functionally graded shells are observed. Effects of the material profile on the sound radiation of the shells are also investigated.

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ABSTRACT: We propose wave and ray approaches for modelling mid- and high-frequency structural vibrations through smoothly joints on thin shell cylindrical ridges. The models both emerge from a simplified classical shell theory setting. The ray model is analysed via an appropriate phase-plane analysis, from which the fixed points can be interpreted in terms of the reflection and transmission properties. The corresponding full wave scattering model is studied using the finite difference method to investigate the scattering properties of an incident plane wave. Through both models we uncover the scattering properties of smoothed joints in the interesting mid-frequency region close to the ring frequency, where there is a qualitative change in the dynamics from anisotropic to simple geodesic propagation.

ABSTRACT: The present study develops a new size-dependent nonlinear model for the analysis of the behaviour of carbon nanotube-based resonators. In particular, based on modified couple stress theory, the fully
nonlinear equations of motion of the carbon nanotube-based resonator are derived using Hamilton’s principle, taking into account both the longitudinal and transverse displacements. Molecular dynamics simulation is then performed in order to verify the validity of the developed size-dependent continuum model at the nano scale. The nonlinear partial differential equations of motion of the system are discretized by means of the Galerkin technique, resulting in a high-dimensional reduced-order model of the system. The pseudo-arclength continuation technique is employed to examine the nonlinear resonant behaviour of the carbon nanotube-based resonator. A new universal pull-in formula is also developed for predicting the occurrence of the static pull-in and validated using numerical simulations.

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ABSTRACT: In this paper, the nonlinear vibrations and energy exchange of single-walled carbon nanotubes (SWNTs) are studied. The Sanders–Koiter theory is applied to model the nonlinear dynamics of the system in the case of finite amplitude of vibration. The SWNT deformation is described in terms of longitudinal, circumferential and radial displacement fields. Simply supported, clamped and free boundary conditions are considered. The circumferential flexural modes (CFMs) are investigated. Two different approaches based on numerical and analytical models are compared. In the numerical model, an energy method based on the Lagrange equations is used to reduce the nonlinear partial differential equations of motion to a set of nonlinear ordinary differential equations, which is solved by using the implicit Runge–Kutta numerical method. In the analytical model, a reduced form of the Sanders–Koiter theory assuming small circumferential and tangential shear deformations is used to get the nonlinear ordinary differential equations of motion, which are solved by using the multiple scales analytical method. The transition from energy beating to energy localization in the nonlinear field is studied. The effect of the aspect ratio on the analytical and numerical values of the nonlinear energy localization threshold for different boundary conditions is investigated.


ABSTRACT: The nonlinear vibrations of a water-filled circular cylindrical shell subjected to radial harmonic excitation in the spectral neighbourhood of the lowest resonances are investigated experimentally and numerically by using a seamless aluminium sample. The experimental boundary conditions are close to simply supported edges. The presence of exact one-to-one internal resonance, giving rise to a travelling wave response around the shell circumference and non-stationary vibrations, is experimentally observed and the nonlinear
response is numerically reproduced. The travelling wave is measured by means of state-of-the-art laser Doppler vibrometers applied to multiple points on the structure simultaneously. Chaos is detected in the frequency region where the travelling wave response is present. The reduced-order model is based on the Novozhilov nonlinear shell theory retaining in-plane inertia and the nonlinear equations of motion are numerically studied (i) by using a code based on arclength continuation method that allows bifurcation analysis in case of stationary vibrations, (ii) by a continuation code based on direct integration and Poincaré maps that evaluates also the maximum Lyapunov exponent in case of non-stationary vibrations. The comparison of experimental and numerical results is particularly satisfactory.


ABSTRACT: Elastic wave propagation in honeycomb thin layers and sandwiches is investigated theoretically and numerically by using the Bloch wave transform, so the modeling of a unique primitive cell is sufficient to understand the wave propagation phenomena through the whole periodic structure. Both in-plane (with respect to the plane of the honeycomb layer) and out-of-plane waves are analyzed by developing finite element models formulated within the framework of the Mindlin–Reissner theory of plates. The dispersion relations and the phase and group velocities as function of frequency and of direction of propagation are calculated. The anisotropic behaviors and the dispersive characteristics of the studied periodic media with respect to the wave propagation are then analyzed. According to our numerical investigation, it is believed that the existence of bandgaps is probably not possible in the frequency domain considered in the present work. However, as an important and original result, the existence of the “backward-propagating” frequency bands, within which Bloch wave modes propagate backwards with a negative group velocity, is highlighted. As another important result, the comparison is made between the first Bloch wave modes and the membrane and bending/transverse shear wave modes of the classical equivalent homogenized orthotropic plate model of the honeycomb media. A good comparison is obtained for honeycomb thin layers while a more important difference is observed in the case of honeycomb sandwiches, for which the pertinence of finite element models is discussed. Finally, the important role played by the honeycomb core in the flexural dynamic behaviors of the honeycomb sandwiches is confirmed.

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ABSTRACT: This paper presents the results of numerical studies carried out on vibro-acoustic and sound transmission loss behaviour of aluminium honeycomb core sandwich panel with fibre reinforced plastic (FRP) facings. Layered structural shell element with equivalent orthotropic elastic properties of core and orthotropic properties of FRP facing layer is used to predict the free and forced vibration characteristics. Followed by this, acoustic response and transmission loss characteristics are obtained using Rayleigh integral. Vibration and acoustic characteristics of FRP sandwich panels are compared with aluminium sandwich panels. The result
reveals that FRP panel has better vibro-acoustic and transmission loss characteristics due to high stiffness and inherent material damping associated with them. Resonant amplitudes of the response are fully controlled by modal damping factors calculated based on modal strain energy. It is also demonstrated that FRP panel can be used to replace the aluminium panel without losing acoustic comfort with nearly 40 percent weight reduction.


Many papers published in the journal, Procedia Engineering (2012-2016):
http://www.sciencedirect.com/science/journal/18777058

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ABSTRACT: Shell structures in civil engineering are known extremely parameter sensitive, so the aim of computational morphogenesis of free-form shells is to find a rational shape which defines an ideal internal stress state. This paper sets forth a kind of computational method to generate free-form shell structures, which is a synthesis of design modelling, structural analysis and mathematical optimization. At first the design modelling of the shell is completed by non-uniform rational b spline (NURBS), then structural analysis is executed to the initial shape, at last the NLPQL algorithm which is a SQP algorithm is used for the optimization. During the optimization metamodelling is used, which involves sensitivity analysis, design of experiments and regression analysis. Several examples show the power of the approach.

References listed at the end of the paper:

ABSTRACT: The paper deals with the influence of initial imperfections caused by the production process and presents fundamental information about experimental and theoretic-numerical research to determine the load-carrying capacity of thin-walled cold-formed compressed steel members. The investigated members have closed cross-sections made from a homogeneous material. The theoretic-numerical analysis in this paper is oriented towards investigating and modelling initial imperfections effects on the load-carrying capacities of the mentioned members, while the experimental investigation verifies the theoretical results and investigates the behaviour of the members during the loading process.

References listed at the end of the paper:

in its plane, inclusion of special diaphragms was chosen to reduce a local and distortional buckling occurrence in global lateral-torsional buckling modes.

References listed at the end of the paper:

Z. Sadovsky (1), J. Kriváček (1), V. Ivančo (2) and A. Duricová (3)
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ABSTRACT: Two approaches to the choice of the most unfavourable geometric imperfections, represented by the eigenmode shapes, recently developed for GMNIA FEM analysis are studied for lipped channel columns exhibiting significant local/distortional interactions. The approaches are based on alternative imperfection measures: a) the commonly applied amplitude, b) the energy measure defined by the square root of the elastic strain energy hypothetically required to distort the originally perfect structural element into the considered imperfect shape.

References listed at the end of the paper:

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ABSTRACT: During an emergency crash landing, the first requirement translates into the ability of an aeronautical structure to ensure a vital space for the occupants during an impact, and then limiting the accelerations on the occupants in terms of intensity and duration. The aim of this study is about the impact phenomenon, that is generally not addressed to understand if and how the structure is deformed, but if the structures allocate the kinetic energy resulting from the impact and if it is completely able to participate to the absorption of impact, all for the benefit of passive safety occupants. On the basis of this consideration, therefore, it becomes much more significant for the structural designer to try to correlate the paths of energy absorption, and this is obtained studying the composite materials and polymers, and their difference in behavior compared to metallic materials, highlighting the design parameters of the same material as a function of impact behavior. A finite element model of a typical composite fuselage was developed using the nonlinear, explicit transient dynamic code, LS-Dyna. The numerical simulations aided to evaluate the part of the structure able to absorb the energy during the impact, the results allowed to reproduce the similar scenario but on a “scaled” numerical component. The focus of this paper is to evaluate the scaling concept and its possible incorporation into the crashworthiness evaluation of fuselage as a potential crashworthiness evaluation tool.

References listed at the end of the paper:
3. EASA (European Agency Safety Aviation) regulations.

ABSTRACT: Most analyses of sandwich structures consider static loading or dynamic loading in which loads are applied slowly enough so that beam and plate theories are adequate in predicting the overall bending deformation. However, for impulsive loading generated by explosions or impacts, the early phase of the response is not captured by these structural theories as it involves wave propagation through the thickness. Significant damage can be introduced during this early phase.

References listed at the end of the paper:


ABSTRACT: The response of cylindrical composite structures subjected to underwater impulsive loads is analyzed. The analysis focuses on the effect of varying structural attributes and material properties on load-carrying capacity, deflection, energy dissipation and damage. The structural designs studied are monolithic composite structures, and sandwich structures with foam cores of different relative densities and different radii. Underwater impulsive loads are generated using a novel experimental setup, and deflection and core compression are characterized using high-speed digital imaging. The experiments are supported by fully dynamic 3D numerical calculations which account for fluid-structure interactions and damage and failure mechanisms in the materials. For the same applied impulse, the monolithic cylindrical sections experience significant warping, delamination and cracking, while sandwich structures experience significantly lower damage. In sandwich structures, as the core density increases, the transmitted impulse and overall damage also increase. Deflection and warping in the impulsively loaded region are influenced by the radius of curvature and material orientation. Results show that cylindrical sandwich structures have superior blast-resistance than cylindrical monolithic structures of equal mass with only relatively minor increases in wall thickness. The experiments, computations and structure-performance relations offer approaches for improving the blast mitigation capabilities of cylindrical composite sections in critical parts of a ship structure like the keel, hull and pipes.

References listed at the end of the paper:
7. DIAB Inc., S.D., DeSoto, Texas 75115, USA.
ABSTRACT: During the last decades the attention given to vehicle crash energy management has been centred on composite structures. The use of fibre-reinforced plastic composite materials in automotive structures, in fact, may result in many potential economic and functional benefits due to their improved properties respect to metal ones, ranging from weight reduction to increased strength and durability features. Although significant experimental work on the collapse of fibre-reinforced composite shells has been carried out, studies on the theoretical modelling of the crushing process are quite limited since the complex and brittle fracture mechanisms of composite materials. Moreover most of the studies have been directed towards the axial crush analysis, because it represents more or less the most efficient design. A mathematical approach on the failure mechanisms, pertaining to the stable mode of collapse of thin-walled composite structures subjected to axial loading, is investigated. The analysis is conducted from an energetic point of view. The main energy contributions to the absorption (bending, petal formation, circumferential delamination, friction) are identified and then the total internal energy is equated to the work done by the external load. The total crushing process can be seen as a succession of deformation states, each responsible for a partial absorption. The minimum configuration for each impact force in the specific state of deformation, function of several variables and dependent on geometric and material parameters is obtained. A comparison between theory and experiments concerning crushing loads and total displacements is presented, showing how the proposed analytical model is effective in predicting the energy absorption capability of axially collapsing composite shells.

References listed at the end of the paper:

ABSTRACT: Most modern structural system designs rely on a damage tolerance philosophy, which means that a structure can withstand some damage without failure. The residual strength of a structure, i.e. the load that a damaged structure can still carry without failure, can be significantly affected by the presence of a crack or a damaged area and is usually substantially lower than the strength of the undamaged structure [1]. In the study presented in this paper MSC.Nastran sol700 explicit solver has been used to simulate different impact conditions on a stiffened composite panel [2]. This has allowed estimating and analysing the damage effects on the matrix and fibers of the composite panel. The virtual damaged panel has been loaded in a non-linear implicit simulation using MSC.Nastran sol400 solution to predict the residual strength [3–6]. The simulation results were in good agreement with experimental tests.

References listed at the end of the paper:
3. MSC Nastran Composite Seminar Notes – NAS113_Sec06_Advanced_failure_theory_and_prediction.
4. Nonlinear Structural Analysis with MSC Nastran (NAS400).
5. Contact Analysis using MSC Nastran and MSC Patran (NAS133).
6. Advanced Contact Analysis Using MSC Nastran Seminar Notes (NAS134).
typical strength analysis due to non-uniqueness of result, initial imperfection, mesh generation and other reasons. The case studied in this paper is that a heavy attaching equipment was closely connected the main equipment by triangular steel structure instead of typical shirt support for the purpose of space saving. The key point of this project case is that the 240-ton attaching equipment causes significant compress stress in the local regions such as the bottom of nozzle, shirt support of main equipment and triangular steel structure. Regarding the loads, not only weight but also wind, seismic load etc. and their load cases combinations should be considered in the buckling analysis. With this case, the paper introduced the basic principles, implementation procedures and software applications of local buckling analysis of pressure vessel. At the end, this paper proposed some suggestion for the Chinese code of buckling analysis through this typical case study.

References listed at the end of the paper:


ABSTRACT: Although most thin walled cylinders under external pressure are stiffened by rings with the same dimension, it is believed that the combination of large and small stiffening rings is helpful to the lightweight design of structures. In this paper, eigenvalue buckling analysis has been done to study the buckling pattern (BP) and critical pressure $P_{cr}$ of thin walled cylinders with the combination of large and small stiffening rings. It is found that there is a map of buckling patterns for different ring combinations. Three BPs appear as buckling of cylinder together with both large and small stiffening rings (BP-I), buckling of cylinder together with small stiffening rings but without large stiffening rings (BP-II), and finally, buckling of cylinder without both large and small stiffening rings (BP-III). In the region of BP-I and BP-II, values of $P_{cr}$ increase with the size of large and small ring, but remain constant in the region of BP-III. And it indicates a remarkable optimization space for the design of stiffening rings. The large ring location and sizes of both large and small rings are optimized for lightweight design of the example cylinder, which yields a reasonable result satisfying the stability requirement under external pressure.

References listed at the end of the paper:

J. Shen (1,2), Y.L. Wu (1) and Y.H. Liu (2)
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ABSTRACT: Roof is an important part of a storage tank and its buckling failure mode should be examined during design stage. However, some factors that affect buckling may appear after design. For example, the case studied in this paper was damaged by a construction accident on site. A weight hit a pothole on the roof. Obviously, such a construction defect would significantly impact the critical load of buckling. Due to the difficulty of repairing and a possible secondary damage during repairing, a buckling examination was necessary. However, formulas in the code can only be used for the roofs without such serious defect. A comprehensive numerical analysis (e.g. FEA) of buckling for this roof is necessary from a technical and economic point of view. According to the Chinese code JBJ 7-2010Technical Specification for Space Frame Structures, the finite element models under different load cases are built for this kind of storage tank roof. Taking into account the initial defect caused by the structure manufacture, installation deviation and construction damage, the static analysis, linear buckling analysis and geometric nonlinear analysis were performed to track the whole process of load-displacement change, evaluate the critical load of buckling and achieve the reasonable repairing scheme of this tank roof.

References listed at the end of the paper:
1. API 650-2013 Welded steel tanks for oil storage[S].
2. GB50341-2014 Code for design of vertical cylindrical welded steel oil tanks[S].
ABSTRACT: Free span resulting from unevenness and scour of seabed often occurs and endanger the safety of submarine pipeline. Local buckling which is an important failure mode for free span should be considered for the safety assessment of pipeline. In this paper, considering the real service status of submarine pipeline, the structural response of free span under loads induced by vortex shedding, effective axial force, gravity and buoyancy was analyzed with numerical simulation and theoretical analysis method. Local buckling analysis for free span with different length was investigated based on the ULS criterion under load controlled condition given by DNV-OS-F101 standard.

References listed at the end of the paper:
showed acceptable agreement with the bending and flattening test results. However, some available criteria in current standards, without concern for neutral plane shifting, ignored the separation of former from plates and hence gave values lower than the actual strain, which might lead to incorrect assessment. This study is helpful to modify some improper criteria in standards for bending and flattening tests.

References listed at the end of the paper:
10. ASTM A262-14, Standard practices for detecting susceptibility to intergranular attack in austenitic stainless steels.
12. J.H. Huang, “Discussion to some problems about detecting susceptibility to intergranular corrosion of austenitic stainless steel in every standards”, Pressure Vessel Technology, 30 (2013), pp. 54-59
17. GB 24510-2009, 9% Nickel steel plates for pressure vessels with specified low temperature properties.
18. GB 3531-2014, Steel plates for low temperature pressure vessels.
19. ASTM A353/A353M -09, Standard specification for pressure vessel plates, alloy steel, double-normalized and tempered 9% Nickel.

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ABSTRACT: Three-dimensional thermo-mechanical stress analyses of cylindrical shell structures made with laminated Fibre Reinforced Polymer (FRP) composites have been carried out. Brick 8-node 185 layered solid elements have been used in the present finite element simulation. Due to curved geometry and interaction of different coupling modes at the ply-interfaces, stress concentration effects have been realized throughout the domain of the laminated shell structure. Appropriate finite element mesh size obtained through convergence study has been adopted to capture these stress concentration effects. Thermal field induced out-of-plane interlaminar stresses (τ_θθ, τ_rr, τ_rθ) responsible for delamination damage initiations have been analyzed in details. Effect of different stacking sequences on thermo-mechanical dynamic stability of shell structures has also been studied. It has been observed that, structural dynamics of composite shell structures get significantly affected under elevated thermal field.
References listed at the end of the paper:
ABSTRACT: In this paper buckling and free vibration characteristics of an isotropic cylindrical panel subjected to uniform temperature rise has been investigated using finite element method. The procedure involves the determination of critical buckling temperature, which is followed by modal analysis considering pre-stress due to the thermal field in the cylindrical panel. Detailed studies are carried out to analyze the influence of curvature ratio, thickness ratio and aspect ratio on the critical buckling temperature and free vibration behavior of an isotropic cylindrical panel. It has been found that as the curvature ratio and the thickness ratio increases the thermal buckling strength of the cylindrical panel decreases. It has also been found that free vibration frequencies reduce with an increase in temperature and the reduction is more significant for the lowest frequency mode. It is observed that free vibration mode shapes at ambient temperature changes with an increase in temperature.

References listed at the end of the paper:

ABSTRACT: The usual approach to linear vibration analysis of plates and shells may look easier than that of nonlinear ones, but sometimes linear problems may involve geometric nonlinearities or other factors that make the investigation a little harder in order to explore possibilities for an approximate solution. Thus our main objective in this paper is to identify such methods, which are commonly used in such situations.

References listed at the end of the paper:

1. Th. V. Kármán, “Festigketsprobleme im Maschinenbau”, Encyklopädie der Mathematischen Wissenschaften, 4 (1910), pp. 311-385

ABSTRACT: This work investigates the geometrical nonlinear free vibration characteristic of cylindrical composite shell panel embedded with piezoelectric layers. A short circuit configuration (top and bottom layers are grounded i.e. zero potential) has been considered for the present analysis. A general mathematical model has been developed using higher order shear deformation mid-plane kinematics employing Green-Lagrange type of nonlinearity. Numerical solutions are obtained using Hamilton's principle and discretized isoparametric finite element steps. The validity of present model has been checked by comparing the responses to those available in published literature. In order to examine the efficacy and applicability of the present developed model, few numerical examples are solved for different geometrical parameters (fiber orientation, thickness ratio, aspect ratio, curvature ratio, support conditions and amplitude ratio) with and/or without piezoelectric embedded layers and discussed in details.

References listed at the end of the paper:


ABSTRACT: The present article deals with the vibration problem associated with thin carbon fiber reinforced composite (CFRC) shell structures that can be mitigated by addition of carbon nanotubes (CNTs) in the polymer matrix phase of such CFRC structures. Mori-Tanaka in conjunction with strength of material method has been employed to obtain the elastic properties of such hybrid composite. Shell structure is discretized by eight noded shell element having five degree of freedom at each node where stress resultant-type Koiter's shell theory is applied. Impulse response using Duhamel integral and frequency response analysis have been carried out to
analyze the damping phenomena of hybrid composite structure considering Raleigh damping. Results revealed that there are profound influence of carbon nanotube content on the dynamic response of the system. It is also found that the both the damping and stiffness of the structure is increased by the inclusion of carbon nanotubes.

References listed at the end of the paper:

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ABSTRACT: Immersed tube tunnel has been widely used in virtue of its characteristics of shallow burial, good waterproof performance, strong stratum adaptability, etc., however, it is also characterized by enclosed space, prolonged submersion of structure in deep water, complicated surrounding environment, etc., particularly, in case of accident of tunnel structure, inestimable losses will be caused, therefore, the control of structural stability risk in operation period is especially important. This article carries out risk source analysis and identification, scenario design and simulation analysis, risk loss judgment standards and weight research for structural stability of long and large immersed tube tunnel in operation period on basis of extra-large immersed tube tunnel of the fourth lane of Shenzhen-Zhongshan Thoroughfare, based on which and in combination with the relevant domestic and foreign risk assessment and expert research results, the structural stability risk levels and risk scores of structural stability in operation period are obtained by quantitative risk calculation method and the relevant suggestions for risk control are proposed.

End of many papers published in the journal, Procedia Engineering (2012-2016).

http://www.sciencedirect.com/science/journal/09977538

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ABSTRACT: In the present paper, a new improved high-order theory is presented for biaxial buckling analysis of sandwich plates with soft orthotropic core. Third-order plate theory is used for face sheets and quadratic and
cubic functions are assumed for transverse and in-plane displacements of the core, respectively. Continuity conditions for transverse shear stresses at the interfaces as well as the conditions of zero transverse shear stresses on the upper and lower surfaces of plate are satisfied. The nonlinear Von-Karman type relations are used to obtain strains. Also, transverse flexibility and transverse normal strain and stress of the orthotropic core are considered. The equations of motion and boundary conditions are derived by principle of minimum potential energy. Analytical solution for static analysis of simply supported sandwich plates under biaxial in-plane compressive loads is presented using Navier’s solution. Effect of geometrical parameters of face sheets and core and biaxial loads ratio are studied on the overall buckling of sandwich plates. Comparison of the present results with those of the three-dimensional theory of elasticity and some plate theories confirms the accuracy of the proposed theory.


ABSTRACT: This paper deals with the analysis of active control of vibration of thin laminated composite truncated circular conical shells using vertically and obliquely reinforced 1-3 piezoelectric composite (PZC) materials as the constraining layer of the active constrained layer damping (ACLD) treatment. A finite element model of smart truncated conical laminated shells integrated with the patches of such ACLD treatment has been developed to demonstrate the performance of these patches on enhancing the damping characteristics of thin symmetric and antisymmetric cross-ply and antisymmetric angle-ply laminated truncated conical shells. Velocity feedback control loop has been implemented to activate the patches. The effect of variation of semicone angle on the performance of the patches for controlling first few modes of the truncated conical laminated shells has been demonstrated. Emphasis has also been placed on exploring the effect of variation of piezoelectric fiber orientation angle in the constraining layer on the control authority of the ACLD patches.


ABSTRACT: This paper presents a study on the suitability of shell models to assess the buckling behaviour of single-walled carbon nanotubes (CNTs) under torsion. It is shown that the simultaneous use of both well known (i) Donnell shell model and (ii) uniform helix deflected shape (HDS) of CNTs, leads to incorrect values of the critical angle of twist per unit of length, as they do not match the results obtained from molecular dynamic simulations. Conversely, more sophisticated models, like the Sanders shell model (SSM) with non-uniform HDS is found to lead to correct results of critical angle of twist. It is established that there is a transitional aspect ratio (length-to-diameter ratio) that separates the group of short CNTs, mostly influenced by end conditions, from the group of long CNTs, mostly influenced by warping deformation. Based on the SSM with non-uniform HDS, straightforward analytical expressions to calculate the critical angle of twist are proposed for each of these groups. Despite its simplicity, the procedure presented is shown to give rather accurate results for a wide range of CNT lengths, diameter and chirality.

S.D. Akbarov (1,2) and S. Karakaya (3)
ABSTRACT: The 3D approach was employed for investigations of the global stability loss of the hollow circular cylinder made from viscoelastic composite materials. This approach is based on the investigation of the evolution of the initial infinitesimal global imperfection of the cylinder within the scope of 3D geometrically non-linear field equations of the theory of the viscoelasticity for anisotropic bodies. The numerical results of the critical forces and critical time are presented and discussed. To illustrate the importance of the results obtained using the 3D approach, these results are compared with the corresponding ones obtained by employing various approximate beam theories. The viscoelasticity properties of the cylinder material are described by the fractional-exponential operator. The numerical results and their discussion are presented for the case where the cylinder is made of an unidirectional fibrous viscoelastic composite material. In particular, it is established that the difference between the critical times obtained by employing 3D and third order refined beam theories becomes more non-negligible if the values of the external compressive force are close to the critical compressive force which is obtained at $t = \infty$ ($t$ denotes a time).

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https://doi.org/10.1016/j.euromechsol.2011.08.008

ABSTRACT: A refined finite element shell model has been developed in this work using an eight-nodes element with nine degrees of freedom for each node. This model enhances the classical shell approaches by including the transverse normal strain. The three displacement components are quadratically expanded in the thickness direction, therefore the transverse shear and normal strains effects are included in such a model making it suitable for thin and thick multilayered composite structures. The transverse normal strain is linear in the thickness direction $z$ and the related shell theory is free from Poisson locking. Finite element locking mechanisms (shear and membrane locking) have been opportunistically corrected: good convergence rate has been shown for the considered shell problems (with various geometries, thickness ratios and stacking layer sequences). No shear correction factors are requested.

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ABSTRACT: In this paper, we study the elastic buckling of a new class of honeycomb materials with hierarchical architecture, which is often observed in nature. Employing the top-down approach, the virtual buckling stresses and corresponding strains for each cell wall at level $n-1$ are calculated from those at level $n$; then, comparing these virtual buckling stresses of all cell walls, the real local buckling stress is deduced; also, the progressive failure of the hierarchical structure is studied. Finally, parametric analyses reveal influences of some key parameters on the local buckling stress and strength-to-density ratio; meanwhile the constitutive behaviors and energy-absorption properties, with increasing hierarchy $n$, are calculated. The results show the possibility to tailor the elastic buckling properties at each hierarchical level, and could thus have interesting applications, e.g., in the design of multiscale energy-absorption honeycomb light materials.

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ABSTRACT: This paper investigates compressive postbuckling under thermal environments and thermal postbuckling due to a uniform temperature rise are presented of a sandwich plate with carbon nanotube-reinforced composite (CNTRC) face sheets resting on an elastic foundation. The material properties of CNTRC face sheets are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The governing equations of the plate are based on a higher-order shear deformation plate theory that includes plate-foundation interaction. The thermal effects are also included and the material properties of both CNTRC face sheets and homogeneous core layer are assumed to be temperature-dependent. A two-step perturbation technique is employed to determine buckling loads (temperature) and postbuckling equilibrium paths. The numerical illustrations concern the compressive and thermal postbuckling behavior of perfect and imperfect, sandwich plates with functionally graded CNTRC face sheets resting on Pasternak elastic foundations under different thermal environmental conditions, from which results for the sandwich plate with uniformly distributed CNTRC face sheets are also obtained for comparison purposes. The results reveal that the foundation stiffness, the temperature changes, the nanotube volume fraction of face sheet, and the core-to-face sheet thickness ratio have significant effects on the compressive buckling load and postbuckling behavior of the sandwich plate, whereas this effect on the thermal postbuckling behavior is less pronounced for the same sandwich plate.

S.M.R. Khalili (1,2) and Y. Mohammadi (1)

ABSTRACT: Improved high-order sandwich plate theory is used to analyze the free vibration of sandwich plates with functionally graded (FG) face sheets in various thermal environments. The material properties of FG face sheets are assumed to be temperature-dependent by a third-order function of temperature and vary continuously through the thickness according to a power-law distribution in terms of the volume fractions of the constituents. Also, the material properties of the core are assumed to be temperature-dependent by a third-order function of temperature. The governing equations of motion in free natural vibration are derived using Hamilton's principle. A new approach is used to reduce the equations of motion and then solved them for both un-symmetric and symmetric sandwich plates. In-plane stresses of the core that usually are ignored in the vibration characteristics of the sandwich structures are considered in this formulation. The results show that the fundamental frequency parameter increases and decreases with increasing the volume fraction index for soft core and hard core sandwich plates, respectively. The results indicate that as the side-to-thickness ratio, the core-to-face sheet thickness ratio and the temperature are changed, a significant effect on the fundamental frequency parameter is observed. Good agreement is found between the theoretical predictions of the fundamental frequency parameters and the results obtained from other references for simply supported sandwich plates with functionally graded face sheets in the literature.


ABSTRACT: A theory of linearly elastic orthotropic shells is presented, with potential application to the continuous modeling of Carbon NanoTubes. Two relevant features are: the selected type of orthotropic response, which should be suitable to capture differences in chirality; the possibility of accounting for thickness changes due to changes in inter-wall separation to be expected in multi-wall CNTs. A simpler version of the theory is also proposed, in which orthotropy is preserved but thickness changes are excluded, intended for possible application to single-wall CNTs. Another feature of both versions of the present theory is that boundary-value problems of torsion, axial traction, uniform inner pressure, and rim flexure, can be solved explicitly in closed form. Various directions of ongoing further research are indicated.


ABSTRACT: An analytical solution to the static analysis of functionally graded plates and doubly-curved shells, modeled using a higher order shear deformation theory (HSDT), is presented. A solution methodology, based on boundary-discontinuous generalized double Fourier series approach is used to solve a system of five highly coupled linear partial differential equations, generated by the higher order-based laminated shell analysis with the fully simple supported boundary condition prescribed at all edges. The mechanical properties of the
panels are assumed to vary in the thickness direction according to a power-law distribution in terms of the
volume fractions of the constituents. In order to verify the present solution, a comparison of the present results
is made with the finite element solutions to verify the present solution with the homogeneous (isotropic) and
functionally graded plates. Important numerical results are presented to show the effect of inhomogeneities,
thickness and membrane effects, as well as their interactions.

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“Free vibration analysis of functionally graded shells by a higher-order shear deformation theory and radial
basis functions, collocation, accounting for through-the-thickness deformations, European Journal of Mechanics
ABSTRACT: This paper deals with free vibration problems of functionally graded shells. The analysis is
performed by radial basis functions collocation, according to a higher-order shear deformation theory that
accounts for through-the-thickness deformation. The equations of motion and the boundary conditions are
obtained by Carrera’s Unified Formulation resting upon the principle of virtual work, and further interpolated
by collocation with radial basis functions. Numerical results include spherical as well as cylindrical shell panels
with all edges clamped or simply supported and demonstrate the accuracy of the present approach.

Tal Cohen and David Durban (Faculty of Aerospace Engineering, Technion, Haifa 32000, Israel), “Plastic
37, pp 193-199, January-February 2013, https://doi.org/10.1016/j.euromechsol.2012.06.005
ABSTRACT: Plastic instabilities under remote triaxial loading, including cylindrical cavity expansion, are
studied in context of large strain plasticity and constrained plane-strain. Material hardening is taken into
consideration and porosity is incorporated using the Gurson (1977) plasticity model. Spontaneous growth of
central cavity due to constant applied triaxial remote load (cavitation instability) is examined in an infinite
cylindrical medium. It is found that the remote field exhibits instability at a definite value of applied radial
tension which may occur before onset of cavitation. That maximum is proposed as an approximation for field
stability limit while, as shown, cavitation in the porous solid can occur only for relatively low values of initial
porosity and within a limited range of remote loading triaxiality. Analysis is facilitated upon choice of effective
stress as independent time-like parameter.

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System and Vibration, Institute of Vibration, Shock and Noise, Shanghai Jiao Tong University, 800 Dongchuan
Road, Shanghai 200240, China), “A modified variational approach for vibration analysis of of ring-stiffened
ABSTRACT: This work presents a modified variational method for dynamic analysis of ring-stiffened conical–cylindrical shells subjected to different boundary conditions. The method involves partitioning of the stiffened shell into appropriate shell segments in order to accommodate the computing requirement of high-order vibration modes and responses. All essential continuity constraints on segment interfaces are imposed by means of a modified variational principle and least-squares weighted residual method. Reissner-Naghdi’s thin shell theory combined with the discrete element stiffener theory to consider the ring-stiffening effect is employed to formulate the theoretical model. Double mixed series, i.e., the Fourier series and Chebyshev orthogonal polynomials, are adopted as admissible displacement functions for each shell segment. To test the convergence, efficiency and accuracy of the present method, both free and forced vibrations of non-stiffened and stiffened shells are examined under different combinations of edge support conditions. Two types of external excitation forces are considered for the forced vibration analysis, i.e., the axisymmetric line force and concentrated point force. The numerical results obtained from the present method show good agreement with previously published results and those from the finite element program ANSYS. Effects of structural damping on the harmonic vibration responses of the stiffened conical–cylindrical–conical shell are also presented.

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ABSTRACT: Conventionally cylindrical shells are often treated as shallow shells whose governing equation, according to Karman–Donnell’s theory, can be approximated by those of thin plates. In this paper Karman–Donnell’s theory for shallow shells is extended for long cylindrical shells undergoing large, nonlinear flexural deflection. The kinematic relations between the changes of curvature and the displacement are derived and the governing equations are established by considering the influence of the initial curvature of the cylindrical shells. In particular, the extended Karman–Donnell’s theory is applied for the failure analysis of infinitely cylindrical shell under lateral pressure. A regional collapse mode is identified to occur in the shell with a longitudinal span proportional to (radius³/thickness)⁰.⁵ and a transverse profile of dog bone shape. It is found that the buckling pressure of the shell is in proportion to (thickness/radius)³ and converges to the classic solution given by Timoshenko and Gere (1961). A comparison to the previous works indicates that ignoring the effect of the initial curvature will result in an overestimate of the buckling pressure for 33%. It shows that the initial curvature of long cylindrical shells has significant influence on the load carrying capacity and the extended Karman–Donnell’s equations give very accurate predictions.

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ABSTRACT: This study focuses on the buckling of cylindrical shells under external pressure with general axisymmetric thickness imperfections. Firstly, the result of uniform thickness imperfection and recent study result of axisymmetric modal thickness imperfection are reviewed briefly. Secondly, asymptotic formulas of the buckling load, which are in terms of the thickness imperfection parameter up to arbitrary order, are determined through asymptotic analyses. The analyses are based on a system of linearized governing partial differential equations of perfect shells with variable thickness. Thirdly, the effects led by three patterns of thickness imperfections on the buckling of the laterally pressured cylindrical shells, which are uniform, axisymmetric modal and parabolic, are respectively investigated. Buckling loads of uniform and axisymmetric modal thickness imperfections coincide with the known results. In addition to the analytic investigation, numerical analyses and comparisons are also carried out. The analytical study results presented in the paper can be utilized to evaluate the stabilities of cylindrical shells under external pressure with general axisymmetric imperfections in thickness, once the thickness imperfection is known.

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ABSTRACT: This paper considers a functionally graded (FG) shell using a meshless radial point interpolation method (RPIM). The material is assumed to be bidirectional FG, where the variation is present in both the radial and the axial directions. Based on the three-dimensional equations of motion, the frequency equations are stated using RPIM. Numerical results are presented for a thick shell for various boundary conditions. These results illustrate the influence from the material variation concerning eigenfrequencies and eigenmodes. In addition, the study shows that the RPIM is an efficient method to solve dynamical shell problems.


ABSTRACT: This article addresses structural analysis of laminated composite cylindrical panels resting on tensionless foundation under axial compression. The problem is inherently and highly nonlinear. The governing equations are derived based on classical shell theory and principle of minimum total potential energy. Major contributions of this paper consider the effects of curvature and composite material properties in deriving energy-based governing equations. The numerical results show that ignoring initial curvature of reinforcing panels for modeling columns having cross sections of curved boundaries would cause that the buckling load would be estimated less than that of actual value. Further, the influence of tensionless foundation on the unilateral buckling behavior of panels is severely dependent on effective parameters such as central angle, aspect ratio, thickness, and the degree of foundation modulus. In addition, increasing the number of panel layers, keeping the thickness constant, and choosing an appropriate ply angle for fibers, might increase impressively the influence of tensionless foundation on the buckling load. Moreover, the effects of parameters like aspect ratio, thickness, central angle, the number and angle of plies, lamination scheme, material orthotropy and
foundation modulus on buckling load are investigated. The results are compared with case studies, whenever available in the literature.

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ABSTRACT: This article deals with the mathematical modelling of the buckling and post-buckling response of structural systems composed of quasi-brittle materials such as concrete (as found for instance in reinforced concrete columns). More specifically, columns with softening characteristics are of concern in this study. The moment-curvature constitutive law is based on continuum damage mechanics arguments (CDM theory). Then, the instability problem can be referred to as the Elastica problem for the case with a continuum damage mechanics constitutive law, or, for short, it may be referred to as the Continuum Damage Mechanica problem.

It is numerically shown for the parameters of interest, that results from geometrically exact and second-order analyses for small rotations are almost equivalent. The instability of the imperfect softening system is associated with a limit load which decreases with the imperfection considered. Such columns are shown to be typically imperfection sensitive. Furthermore, a load-imperfection relationship is derived (similar to Koiter's power law), that can be useful in structural design contexts. An asymptotic expansion is performed to obtain a closed-form analytical solution of the limit load imperfection rule. A comparison with exact numerical values for the continuous column shows good agreement with the asymptotic expression results. The need for including non-locality formulations in a damage localization zone is finally discussed for post-buckling analysis in the presence of curvature softening. The adopted local bending-curvature constitutive law leads to the unloading Wood's paradox. To cover the propagation phenomenon of localization, some non-locality is included in a generalized formulation of the principle of virtual work. However, non-locality is not necessary for limit load calculations since limit loads occur for curvatures in the local hardening regime.

C.C. Hong (Department of Mechanical Engineering, Hsiuping University of Science and Technology, Taichung 412, Taiwan, ROC), “Thermal vibration of magnetostrictive functionally graded material shells”, European Journal of Mechanics – A/Solids, Vol. 40, pp 114-122, July-August 2013,
https://doi.org/10.1016/j.euromechsol.2013.01.010

ABSTRACT: The functionally graded material (FGM) shell with mounted magnetostrictive layer under thermal vibration was studied by using the generalized differential quadrature (GDQ) method. The FGM shell with/without negative velocity feedback of magnetostrictive position, with different power law index effects subjected to two edges lamed condition was analyzed. With velocity feedback and with suitable control gain value can reduce the amplitudes of displacement and shear stress into a smaller value. The magnetostrictive FGM shell is stable versus the Terfenol-D thickness for all values of FGM power law index. The magnetostrictive FGM shell can stand against the higher heating temperature of environment with some values of power law index.
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ABSTRACT: This paper proposes a bottom-up sequence of modeling steps leading to a nanoscopically informed macroscopic theory of single-walled carbon nanotubes (SWCNTs). We provide a description of the geometry and the mechanics of the two most representative types of SWCNTs, armchair (A-) and zigzag (Z-), of their modules and of their elementary bond units. We believe ours to be the simplest shell theory that accounts accurately for the linearly elastic response of both A- and Z-CNTs; its main novel feature is perhaps the proposition of chirality-dependent concepts of effective thickness and effective radius, whose evaluation is achieved in terms of nanoscopic information; moreover, as shown in the companion paper (Favata and Podio-Guidugli, 2012b), it can be generalized to fit SWCNTs of whatever chirality.
ABSTRACT: In the present paper, an improved high-order theory is used for wrinkling analysis of sandwich plates with soft orthotropic core. Third-order plate theory is used for the facesheets and quadratic and cubic functions are assumed for transverse and in-plane displacements of the core, respectively. Continuity conditions for transverse shear stresses at the interfaces as well as the conditions of zero transverse shear stresses on the upper and lower surfaces of the plate are satisfied. The nonlinear Von-Karman type relations are used to obtain strains. Also, the transverse flexibility and transverse normal strain and stress of the orthotropic core are considered. The equations of motion and boundary conditions are derived by principle of minimum potential energy. Analytical solution for static analysis of simply supported sandwich plates under biaxial in-plane compressive loads is presented using Navier's solution. The effect of geometrical parameters of the facesheets and the core and the biaxial loads ratio are studied on the buckling and wrinkling behavior of sandwich plates. Comparison of the present results with the published results in the literature for the special case, confirms the accuracy of the proposed theory. Results showed that the increase in the biaxial load ratio, cause to change the direction of wrinkling wave propagation.

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ABSTRACT: This paper presents a new inverse tangent shear deformation theory (ITSDT) for the static, free vibration and buckling analysis of laminated composite and sandwich plates. In the present theory, shear stresses are vanished at the top and bottom surfaces of the plates and shear correction factors are no longer required. A weak form of the static, free vibration and buckling models for laminated composite and sandwich plates based on ITSDT is then derived and is numerically solved using an isogeometric analysis (IGA). The proposed formulation requires C1-continuity generalized displacements and hence basis functions used in IGA fulfill this requirement. Numerical examples are provided to show high efficiency of the present method compared with other published solutions.

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ABSTRACT: Two-dimensional (2D) general equations of piezoelectric shells with nano-thickness are presented in an orthogonal curvilinear coordinate system, in which the surface effect is considered by treat the
shell as a bulk core plus two surface layers. The general 2D equations can be directly degenerated into those of particular shells such as flat plates, cylindrical shells and so on by setting the Lamé coefficients and the principal radii of curvature to certain values. Using the derived 2D equations of cylindrical shells, the free vibration of a radially polarized piezoelectric cylindrical shell of finite length is analyzed. Numerical results show that the surface effect has a remarkable influence on the natural frequency of the shell at the nano-scale.

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ABSTRACT: This paper presents a full three-dimensional solid-like shell element for dynamic analysis of isotropic, orthotropic and anisotropic laminated composites. The dynamic variational formulation is based on a degenerated-shell concept which uses a compatible displacement field varying quadratically in the through-the-thickness direction in order to overcome Poisson-thickness locking. Mass discretization schemes for implicit and explicit dynamic analysis are presented. A selective mass scaling scheme is proposed for explicit analysis to avoid the use of extremely small time steps needed to resolve high element eigenfrequencies, introduced by the presence of internal degrees of freedom and a small thickness of the element. It is further explained, that a mid-surface and plane-stress constitutive law assumption lead to inaccurate results compared to realistic cases where the Neumann and Dirichlet boundary conditions are applied at the surface of the plates and shells.

ABSTRACT: In this paper free vibration behavior of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) cylindrical panel embedded in piezoelectric layers with simply supported boundary conditions is investigated by using three-dimensional theory of elasticity. By using Fourier series expansion along the longitudinal and latitudinal directions and state space technique across the thickness direction, state space differential equations are solved analytically. The traction-free surface conditions then give rise to the characteristic equation for natural frequencies. Accuracy and convergence of the present approach are validated by comparing the numerical results with those found in literature. In addition, the effects of volume fraction of CNT, four cases of FG-CNTRC, piezoelectric layer thickness, mid radius to thickness ration and modes number on the vibration behavior of the hybrid cylindrical panel are also examined.

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ABSTRACT: It is shown herein that the bending, buckling and vibration problems of a microstructured beam can be modeled by Eringen's nonlocal elasticity model. The microstructured model is composed of rigid periodic elements elastically connected by rotational springs. It is shown that this discrete system is the finite difference formulation of a continuous problem, i.e. the Euler–Bernoulli beam problem. Starting from the discrete equations, a continualization method leads to the formulation of an Eringen's type nonlocal equivalent continuum. The sensitivity phenomenon of the apparent nonlocal length scale with respect to the bending, the vibrations and the buckling analyses is investigated in more detail. A unified length scale can be used for the microstructured-based model with both nonlocal constitutive law and nonlocal governing equations. The Finite Difference Method is used for studying the exact discrete problem and leads to tractable engineering formula. The bending behaviour of the microstructured cantilever beam does not reveal any scale effect in the presence of concentrated loads. This scale invariance is not a deficiency of Eringen's nonlocality because it is in fact supported by the exact discreteness of the microstructured beam. A comparison of the discrete and the continuous problems (for both static and dynamics analyses) show the efficiency of the nonlocal-based modelling for capturing scale effects. As it has already been shown for buckling or vibrations studies, small scale effects tend to soften the material in this case.

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ABSTRACT: In this paper, the effect of local defects, viz., cracks and cutouts on the buckling behaviour of functionally graded material plates subjected to mechanical and thermal load is numerically studied. The internal discontinuities, viz., cracks and cutouts are represented independent of the mesh within the framework of the extended finite element method and an enriched shear flexible 4-noded quadrilateral element is used for the spatial discretization. The properties are assumed to vary only in the thickness direction and the effective properties are estimated using the Mori-Tanaka homogenization scheme. The plate kinematics is based on the first order shear deformation theory. The influence of various parameters, viz., the crack length and its location, the cutout radius and its position, the plate aspect ratio and the plate thickness on the critical buckling load is studied. The effect of various boundary conditions is also studied. The numerical results obtained reveal that the critical buckling load decreases with increase in the crack length, the cutout radius and the material gradient index. This is attributed to the degradation in the stiffness either due to the presence of local defects or due to the change in the material composition.

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ABSTRACT: A fully coupled thermoelastic formulation is developed to deal with free vibration analysis of anisotropic composite plates and isotropic/sandwich FGM plates. The proposed formulation is developed by combining refined hierarchical plate models and a trigonometric Ritz method. The temperature is considered as a primary variable and allows the evaluation of the temperature field effects in the free vibration analysis. The temperature profile across the plate thickness is always modeled with a layer-wise kinematics description, nevertheless both equivalent single layer and layer-wise approaches are properly and effectively used for the displacement variables. In the 2D and quasi-3D higher-order variable-kinematics plate theories, each displacement variable, in the displacement field, is treated independently from the others. Such artifice allows to select scrupulously each expansion order for each primary variable regarding to the required accuracy and the computational cost. So-called Ritz fundamental primary nuclei related to the coupled thermal and mechanical fields are generated by virtue of an unconventional principle of virtual displacement accounting for the internal thermal virtual work to reproduce the coupling effect. Each fundamental primary nucleus is mathematically invariant with respect to the used kinematics description, the employed expansion orders and the chosen Ritz functions. The thermoelastic coupling is investigated in terms of natural frequencies and the effect of stacking sequence and length-to-thickness ratio for lower and higher modes is discussed.


ABSTRACT: Based on the classical shell theory taking into account geometrical nonlinearity, initial geometrical imperfection and Pasternak type elastic foundation, the nonlinear axisymmetric response of shallow spherical FGM shells under mechanical, thermal loads and different boundary conditions is considered in this paper. Using the Bubnov–Galerkin method and stress function, obtained results show effects of elastic foundations, external pressure, temperature, material and geometrical properties on the nonlinear buckling and postbuckling of the shells. The snap-through behaviors of the FGM spherical shallow shells on elastic foundations also are analyzed carefully in this paper. Some results were compared with the ones of other authors.


ABSTRACT: Based on perturbation analysis, this study investigates surface wrinkling of a gel layer under arbitrary lateral confinements in the equilibrium state of swelling. Gels containing incompressible polymer networks and solvents may incur large deformations and increase the volume by several times after swelling. Owing to the restrictions on lateral expansions and surface imperfections, the instabilities may appear in the form of wrinkling. Wrinkling is strongly governed by the compressibility of swollen gel, confinements and gel
thickness. Additionally, gel compressibility is attributed to the migration of solvent under stress at the confined-swelling state, and can be expressed in terms of a confined-swelling volume ratio. This work also discusses possible gel-solvent systems of wrinkling under different confinements. At equal biaxial confinements, the wrinkle pattern is a combination of plane waves with the same wavelength in all directions. Meanwhile, at non-equal biaxial confinements, the wrinkle pattern may be a sum of plane waves with dissimilar wavelengths and corresponding directions.

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ABSTRACT: In this paper, we propose a characterization of the mechanical response of the linearly elastic shell we associate to a single-wall carbon nanotube of arbitrary chirality. In Favata and Podio–Guidugli (2012), we gave such a characterization in the case of zigzag and armchair nanotubes; in particular, we showed that the orthotropic response we postulated for the associated shells is to become isotropic in the graphene-limit, that is, when the shell radius grows bigger and bigger. Here we give an explicit recipe to construct the generally anisotropic response of the shell associated to a nanotube of any chirality in terms of the response of the shell associated to a related zigzag or armchair nanotube. The expected coupling of mechanical effects that anisotropy entrains is demonstrated in the case of a torsion problem, where the axial extension accompanying twist is determined analytically.

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ABSTRACT: A semi-analytical approach eccentrically stiffened functionally graded circular cylindrical shells surrounded by an elastic medium subjected to external pressure is presented. The elastic medium is assumed as two-parameter elastic foundation model proposed by Pasternak. Based on the classical thin shell theory with the geometrical nonlinearity in von Karman–Donnell sense, the smeared stiffeners technique and Galerkin method, this paper deals the nonlinear dynamic problem. The approximate three-term solution of deflection shape is chosen and the frequency–amplitude relation of nonlinear vibration is obtained in explicit form. The nonlinear dynamic responses are analyzed by using fourth order Runge–Kutta method and the nonlinear dynamic buckling behavior of stiffened functionally graded shells is investigated according to Budiansky–Roth criterion. Results are given to evaluate effects of stiffener, elastic foundation and input factors on the frequency–amplitude curves, natural frequencies, nonlinear responses and nonlinear dynamic buckling loads of functionally graded cylindrical shells.

ABSTRACT: In the present paper, the nonlinear response of eccentrically stiffened FGM cylindrical panels on elastic foundation subjected to mechanical loads is presented. Material properties are graded in the thickness direction of the FGM panel according to a simple power law distribution. By applying Bubnov-Galerkin method, the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation and stress function, explicit relations of load-deflection curves for simply supported eccentrically stiffened FGM panels are determined. Numerical results are given for evaluate effects of material and geometrical properties, elastic foundation and eccentrically outside stiffeners on the buckling and postbuckling of the FGM panels. The obtained results are validated by comparing with those in the literature.


ABSTRACT: The problem of finite inflation of a hyperelastic toroidal membrane under uniform internal pressure is considered in this paper. The work consists of the following two aspects of the inflation problem. Firstly, a formulation for solving the inflation problem efficiently by directly integrating the differential equations of equilibrium without discretization is proposed. The results obtained are compared with those obtained using a discretization method proposed earlier. Secondly, the effects of the geometric and material parameters of the membrane and the internal pressure on the inflation and its stability are studied. The roles of the curvature (specifically, the eigenvalues of the shape operator) of the toroidal geometry and the membrane material parameter on the distortion of the cross-section and occurrence of wrinkling instability are clearly brought out. Based on the Cauchy stress resultants, the limits on the inflation to avoid wrinkling are determined. It is observed that the limit point pressure of the membrane is inversely proportional to the geometric parameter of the torus. The proportionality constant involved is found to vary linearly with the material parameter of the membrane, and involves two universal constants for the toroidal geometry.


ABSTRACT: An analytical approach is presented to investigate the nonlinear dynamic response and vibration of imperfect eccentrically stiffened FGM double curved thin shallow shells on elastic foundation using a simple power-law distribution (P-FGM) in thermal environment. The formulations are based on the classical shell theory taking into account geometrical nonlinearity, initial geometrical imperfection, temperature-dependent properties and the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation. By applying Galerkin method and using stress function, explicit relations of thermal load-deflection curves for simply supported curved eccentrically stiffened FGM shells are determined. Effects of material and geometrical properties, temperature, elastic foundation and eccentrically stiffeners on the dynamic response and vibration of
the imperfect eccentrically stiffened P-FGM double curved shallow shells in thermal environments are analyzed and discussed. The numerical results in this paper are compared with results reported in other publications.

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ABSTRACT: The objective of this paper is to present a new triangular shell element for shakedown analysis. The element is based on a mixed variational formulation with displacement/velocity and stress fields independently interpolated. We also employ the continuum based (CB) approach which allows the definition of the yield function at the continuum level without any approximation in terms of generalized stresses. The formulation of the proposed element is presented in details after a brief review of relevant classical shakedown theory concepts. The performance of the element is assessed by means of a set of selected representative examples. The numerical tests include: (i) analyses of thin and thick-walled straight pipes under combined loads, (ii) the shakedown analysis of a pipe bend under internal pressure and in-plane bending and (iii) limit analysis of a cylinder–cylinder intersection subjected to bending and internal pressure.

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ABSTRACT: The dynamic behavior of elastic coaxial cylindrical shells interacting with two flows of a perfect compressible fluid is investigated by application of the finite element method. The fluid behavior is described by the potential theory, the equations of which are reduced to the integral expressions using the Bubnov–Galerkin method. The pressure exerted by the fluid on the deformable body is determined through the use of the Bernoulli equation. The treatment of elastic shells is accomplished in the framework of the classical shell theory. A mathematical formulation of the problem is based on the principle of virtual displacements. With all things considered, the stated problem reduces to simultaneous solution of 4 sets of equations. For shells with different boundary conditions the numerical investigations have been carried out to explore the effects of the annular gap, the flowing fluid density and physicomechanical properties of the shells on the stability boundary.

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ABSTRACT: Some recent experiments have showed that measured resonant frequencies of multi-walled carbon nanotubes (MWCNTs) were often much lower than the theoretical resonant frequencies predicted by the widely used elastic beam model which defines the whole MWCNTs as a single elastic beam. The present work aims at offering a reasonable explanation of this discrepancy by considering interlayer degrees of freedom of MWCNTs. To this end, vibration of MWCNTs with various outer and inner boundary constraints is studied. MWCNTs are modeled as a coupling beam system in which the outermost tube(s) is simulated as a single beam while all other inner tubes are modeled as another single beam and the two beams are coupled through van der walls interlayer forces. To better fit typical experimental conditions, the outmost tube is assumed to be doubly clamped into the surrounding matrix while all other inner tubes are assumed to be free at their ends. Our results confirmed that the interlayer degrees of freedom of MWCNTs have a substantial effect on reducing natural frequencies and thus offer a plausible explanation for the observed lower natural frequencies as compared to the theoretical predictions of the single beam model which ignored all interlayer degrees of freedom. Typically, the natural frequencies predicted by the present model are about 30% lower than those predicted by the single beam model, in good agreement with a few recently reported experimental data.

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ABSTRACT: Sandwich structures are known to be very sensitive to transverse shear effects when submitted to out-of-plane loads. The use of a Mindlin–Reissner type equivalent plate model is then certainly the simplest way to take into account these transverse shear strains that strongly influence the global deflection in simple bending. Such a model requires the estimation of the transverse shear stiffness or of the so-called shear correction factor. In the case of a traditional sandwich (with homogeneous foam core), this shear correction factor is set to unity, so that the equivalent transverse shear modulus coincides with the shear modulus of the foam core, which is fatally insubstantial. In order to improve the through-thickness properties of sandwiches, which are governed by the core layer, use is made of thin-walled core materials or reinforcements. In these more complicated cases, the equivalent shear modulus of the core material (in a 3D framework) highly depends on the geometry of the reinforcements and may only be calculated numerically. Moreover, the use of this homogenized shear modulus for the heterogeneous core layer and of a shear correction factor of unity does not generally convey to the proper value of the transverse shear stiffness, due to the possible interactions between the reinforcements and the skins. This paper particularly deals with sandwich structures manufactured with polymeric foam core reinforced thanks to the Napco® technology (which is based on transverse needle punching) and is devoted to obtaining their transverse shear stiffness. Bearing in mind the remarks made earlier, a one-step homogenization procedure is employed, involving simultaneously the contribution of the reinforcements to the equivalent shear modulus of the reinforced foam core and the interactions between reinforcements and skins. An analytical (respectively numerical) solution is derived, considering a 2D (respectively 3D) unit cell and using the basic principle of energy equivalence. The transverse shear stiffnesses obtained by these two simplified methods are then compared to the one obtained by a finite element numerical computation on a whole beam-like structure for validation purposes, and finally confronted to the experimental values resulting from 3-point bending tests performed with various volume fractions of reinforcements.

ABSTRACT: Linepipe used in offshore and other operations is often protected from corrosive contents by lining internally a carbon steel carrier pipe with a thin layer of corrosion resistant material. In many applications the lined pipeline can experience bending or compression severe enough for the liner to buckle and collapse inside an intact carrier pipe. This paper presents a solution procedure for establishing the onset of the first bifurcation buckling of such a lined pipe under bending. Bending induced differential ovalization of the two shells causes partial separation of the liner from the carrier pipe. The compressed liner intrado at some stage buckles into periodic wrinkles. This bifurcation check is established numerically using the J_2-deformation theory of plasticity. It is shown to occur at bending strain levels very similar to those of the liner shell bent alone but smaller than those of lined pipe under uniform compression. The post-buckling behavior of the lined pipe under bending was subsequently studied by introducing to the liner initial imperfections in the form of the wrinkling buckling mode. Under increasing bending the wrinkle amplitude grows eventually yielding to a second diamond-type buckling mode that results in local collapse. Collapse, while shown to be imperfection sensitive, occurs at a much higher bending strain than the critical wrinkling bifurcation values and it should thus be the failure mode governing design.


ABSTRACT: Analytical formulations and solutions for the stability analysis of simply supported Functionally Graded Material (FGM) sandwich plates hitherto not reported in the literature based on two higher-order refined computational models available in the literature are presented. These computational models are based on Taylor's series expansion of the displacements in the thickness coordinate and incorporate the realistic parabolic distribution of transverse strains through the plate thickness. One of them with twelve degrees-of-freedom considers the effects of both transverse shear and normal strain/stress while the other with nine degrees-of-freedom includes only the effect of transverse shear deformation. In addition another higher-order model and the first-order model developed by other investigators and available in the literature are also considered for the evaluation purpose. For mathematical modeling purposes, the Poisson's ratio of the material is considered as constant whereas Young's modulus is assumed to vary through the thickness according to the power law function. The governing equations of equilibrium for buckling analysis are obtained using the Principle of Minimum Potential Energy (PMPE). Solutions are obtained in closed form using Navier's technique by solving the eigenvalue problem. The comparison of the present results with the available elasticity solutions and the results computed independently using the first-order and another higher-order theory available in the literature shows that the higher-order refined theory with 12 degrees-of-freedom predicts the critical buckling load more accurately than all other theories considered in this paper. After establishing the accuracy of prediction, extensive numerical results for FGM sandwich plates using all the models are presented which will serve as a benchmark for future investigations.

ABSTRACT: A comprehensive kinematical description with a corotational approach, which is based on exact polar decomposition for solid elements using isogeometric analysis is the main objective of this work. A numerical model using NURBS-based FEM is developed to deal with nonlinear problems in solid mechanics involving large rotations. From the theoretical viewpoint, the rate type form of state equation is formulated within the framework of isotropic infinitesimal elasticity. It is shown in particular that the state equation relates the Jaumann derivative of the Cauchy stress to the Eulerian strain rate. Illustrative examples are analyzed to verify the efficiency in solving a wide variety of strong nonlinear problems.

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ABSTRACT: The heart is not only our most vital, but also our most complex organ: Precisely controlled by the interplay of electrical and mechanical fields, it consists of four chambers and four valves, which act in concert to regulate its filling, ejection, and overall pump function. While numerous computational models exist to study either the electrical or the mechanical response of its individual chambers, the integrative electro-mechanical response of the whole heart remains poorly understood. Here we present a proof-of-concept simulator for a four-chamber human heart model created from computer topography and magnetic resonance images. We illustrate the governing equations of excitation–contraction coupling and discretize them using a single, unified finite element environment. To illustrate the basic features of our model, we visualize the electrical potential and the mechanical deformation across the human heart throughout its cardiac cycle. To compare our simulation against common metrics of cardiac function, we extract the pressure–volume relationship and show that it agrees well with clinical observations. Our prototype model allows us to explore and understand the key features, physics, and technologies to create an integrative, predictive model of the living human heart. Ultimately, our simulator will open opportunities to probe landscapes of clinical parameters, and guide device design and treatment planning in cardiac diseases such as stenosis, regurgitation, or prolapse of the aortic, pulmonary, tricuspid, or mitral valve.

ABSTRACT: A nonlinear bending analysis is presented for a simply supported, functionally graded cylindrical panel resting on an elastic foundation in thermal environments. The panel is exposed to elevated temperature and is subjected to a transverse uniform or sinusoidal load. Material properties of functionally graded materials (FGMs) are assumed to be temperature-dependent, and graded in the thickness direction based on Mori-Tanaka micromechanics model. The formulations are based on a higher order shear deformation shell theory with a von Kármán-type of kinematic nonlinearity and include shell panel–foundation interaction and the thermal effects. A two-step perturbation technique is employed to determine the load-deflection and load-bending moment curves. The numerical illustrations concern nonlinear bending response of FGM cylindrical panels with two constituent materials resting on Pasternak elastic foundations from which results for Winkler elastic foundations are obtained as a limiting case. The effects of the volume fraction index, temperature variation, foundation stiffness as well as the character of in-plane boundary conditions are also examined.

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ABSTRACT: The lateral-torsional buckling of a discrete repetitive elastic beam-like structure, composed of rigid links connected by bending and torsional elastic springs, is investigated herein using discrete and continuum approaches. It is shown that the governing equations of the microstructured model are equivalent to a finite difference formulation of a continuous lateral-torsional buckling problem. The discrete equations are introduced through variational arguments and solved exactly for the hinged–hinged boundary conditions using a finite difference approach. A nonlocal equivalent continuum is sought via a continualization method. It is shown that the equivalent continuum is an Eringen’s based elastic nonlocal continuum, which perfectly fits the exact discrete problem. The length scale effect related to the size of the repetitive cell tends to soften the lateral-torsional buckling limit of the asymptotically local continuum. Prandtl's lateral-torsional buckling solution is a particular case, associated with an infinite number of cells. Warping can also be included into the discrete thin-walled structural model, leading to a microstructured-based nonlocal thin-walled model. Love’s equations augmented by the so-called Vlasov effect (warping bimoment) are used to compare the nonlocal approach with the one arising from the continualization of the discrete equation. It is shown that, in this last case, the length scale effect may depend on the warping stiffness.

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ABSTRACT: A Mindlin microplate model based on the modified strain gradient elasticity theory is developed to predict axisymmetric bending, buckling, and free vibration characteristics of circular/annular microplates made of functionally graded materials (FGMs). The material properties of functionally graded (FG) microplates are assumed to vary in the thickness direction. In the present non-classical plate model, the size effects are captured through using three higher-order material constants. By using Hamilton's principle, the higher-order equations of motion and related boundary conditions are derived. Afterward, the generalized differential quadrature (GDQ) method is employed to discretize the governing differential equations along with various types of edge supports. Selected numerical results are given to indicate the influences of dimensionless length scale parameter, material index and radius-to-thickness ratio on the deflection, critical buckling load and natural frequency of FG circular/annular microplates.


ABSTRACT: A four-node quadrilateral element is developed for the dynamic analysis of doubly curved functionally graded material (FGM) shallow shells, using the refined third order theory. Two micromechanics models, the Voigt's rule of mixtures (ROM) and the Mori–Tanaka model, are considered for computing the effective material properties at a point. The accuracy of the element is examined by comparing with various three dimensional elasticity and two dimensional (2D) analytical and finite element solutions available in the literature for static and free vibration responses of FGM plates and shells. It is shown that the present element, with the least number of degrees of freedom, achieves similar or better accuracy compared to other available 2D finite elements some of which are even based on higher order theories. Using this element, we also make a systematic assessment of the accuracy of the widely used ROM in predicting the behavior of FGM structures, for different values of the inhomogeneity parameter, and different geometrical parameters, boundary conditions, and material combinations. It is revealed that there can be very significant error in the deflection, stresses and natural frequencies predicted by the ROM, depending primarily on the inhomogeneity parameter and the difference in the material properties of the constituents.


ABSTRACT: Based on the continuum approximation and Lennard-Jones (LJ) potential, mechanics of nested spherical fullerenes, known as carbon onions, inside multi-walled carbon nanotubes (MWCNTs) is investigated in this study. To this end, direct method is first utilized to determine van der Waals (vdW) interaction force and potential energy between a carbon onion molecule and a semi-infinite MWCNT. According to this method, the interactions between each pair of shells from carbon onion and CNT are summed up over all of the pairs. Thereafter, the suction and acceptance energies for carbon onions entering semi-infinite MWCNTs are evaluated. On the basis of Newton's second law, an analytical expression is then presented to predict the oscillation frequency of a carbon onion molecule inside a MWCNT of finite length. The effect of geometrical parameters on the nature of suction and acceptance energies, vdw interactions and oscillatory characteristics of carbon onion-MWCNT oscillators is thoroughly examined. For a given carbon onion structure, it is found that
there exists an optimal value for the number of nanotube shells beyond which the maximum oscillation frequency does not increase considerably. Furthermore, the maximum oscillation frequency decreases as the carbon onion gets larger.

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ABSTRACT: The Reissner–Mindlin theory is applied to shallow shells with material properties of orthorhombic quasicrystals (QC). A quasi-periodic arrangement of atoms through the thickness of the shell is considered. Due to the intrinsic characteristics of QC, two excitations need to be described under dynamic loads, namely, phonon (elastic waves) and phason (long wavelength fluctuations) fields. The Bak and elastohydrodynamic models are applied for phason governing equation in the elastodynamic case. The phason displacement for the orthorhombic QC in the first-order shear deformation shallow shell theory depends only on the in-plane coordinates on the mid-surface of the shell. A weak formulation for the set of governing equations in the Reissner–Mindlin theory is transformed into local integral equations on local subdomains on the mid-surface of the shell by using a unit-step test function. Nodal points are randomly spread on the mid-surface of the shell and each node is surrounded by a circular subdomain to which local integral equations are applied. The meshless approximation based on the Moving Least-Squares (MLS) method is employed for the implementation. The influences of the shell curvature and the coupling parameter of quasicrystals on the shell deflection are investigated.

ABSTRACT: Flügge's shell theory and solution for the vibration analysis of a non-homogeneous orthotropic elliptical cylindrical shell resting on a non-uniform Winkler foundation are presented. The theoretical analysis of the governing equations of the shell is formulated to overcome the mathematical difficulties of mode coupling of variable curvature and homogeneity of shell. Using the transfer matrix of the shell, the vibration equations based on the variable Winkler foundation are written in a matrix differential equation of first order in the circumferential coordinate and solved numerically. The proposed model is applied to get the vibration frequencies and the corresponding mode shapes of the symmetrical and anti-symmetrical vibration modes. The sensitivity of the vibration behavior and bending deformations to the non-uniform Winkler foundation moduli, homogeneity variation, elliptical and orthotropy of the shell is studied for different type-modes of vibrations.

ABSTRACT: To increase the thermal resistance of various structural components in high-temperature environments, the present research deals with nonlinear stability analysis of thin annular spherical shells made
of functionally graded materials (FGM) on elastic foundations under external pressure and temperature. Material properties are graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. Classical thin shell theory in terms of the shell deflection and the stress function is used to determine the buckling loads and nonlinear response of the FGM annular spherical shells. Galerkin method is applied to obtain closed – form of load – deflection paths. An analysis is carried out to show the effects of material, geometrical properties, elastic foundations and combination of external pressure and temperature on the nonlinear stability of the annular spherical shells.

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ABSTRACT: This paper studies the thermal stability of an eccentrically stiffened functionally graded truncated conical shells in thermal environment and surrounded on elastic foundations. Both of the FGM shell as well as the stiffeners are deformed under temperature. The formulations are based on the classical shell theory taking into account geometrical nonlinearity, initial geometrical imperfection, temperature-dependent properties and the Lekhnitsky smeared stiffeners technique with Pasternak type elastic foundation. By applying Galerkin method, the closed-form expression for determining the thermal buckling load is obtained. The numerical results show that the critical thermal load in the case of the uniform temperature rise is smaller than one of the linear temperature distribution through the thickness of the shell, and the critical thermal load increases when increasing the coefficient of stiffeners and vice versa. The paper also analyzes and discussed the significant effects of material and geometrical properties, elastic foundations on the thermal buckling capacity of the eccentrically stiffened FGM truncated conical shell in thermal environment. The obtained results are validated by comparing with those in the literature.

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ABSTRACT: In this paper, analytical closed-form solutions in explicit forms are presented to investigate small scale effects on the buckling and the transverse vibration behavior of Lévy-type rectangular nanoplates based on the Reddy's nonlocal third-order shear deformation plate theory. Two other edges of Lévy-type rectangular nanoplates may be restrained by different combinations of free, simply supported, or clamped boundary conditions. Hamilton's principle is used to derive the nonlocal equations of motion and natural boundary conditions of the nanoplate. Two comparison studies with analytical and numerical techniques reported in literature are carried out to demonstrate the high accuracy of the present new formulation. Comprehensive benchmark results with considering the small scale effects on frequency ratios, buckling load ratios, non-
dimensional fundamental natural frequencies and non-dimensional buckling loads of rectangular nanoplates with different combinations of boundary conditions are presented for various values of nonlocal parameters, aspect ratios and thickness to length ratios. It is observed that except for SFSF rectangular nanoplates, as the aspect ratio increases, buckling load and natural frequency decreases, while keeping all other parameters fixed. For SFSF rectangular nanoplates, by increasing the aspect ratio, the values of the buckling load and frequency ratio increase.


ABSTRACT: In this work, a layerwise finite element formulation is presented for the first time for dynamic analysis of two types of functionally graded material (FGM) sandwich plates with nonlinear temperature variation along the thickness and the FGM having temperature dependent material properties. Natural frequencies of sandwich plates made of FGM in thermal environment are presented using a layerwise theory. Two configurations of sandwich plate, one with homogenous facesheets and functionally graded core and the second with functionally graded facesheets and homogenous core are considered. The material properties of both types of FGM sandwich plates are varied according to Mori–Tanaka (MT) scheme and the rule of mixture (ROM). The layerwise theory used in this work is based on the assumption of the first order shear deformation theory in each layer and the displacement continuity is satisfied at each layer interface. In the present investigation, it is seen that the natural frequencies converge with lesser number of elements and the results are found to be accurate. Natural frequencies are presented for FGM sandwich plates with different geometric and elastic properties, thermal load and boundary conditions.

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ABSTRACT: The present study deals with the finite element analysis of parametric instability characteristics of delaminated bidirectional Glass/Epoxy composite panels exposed to hygrothermal field with harmonic in-plane loading based on first order shear deformation theory. An 8-noded isoparametric finite element model was developed which takes account of the influences of area delamination and hygrothermal environment for predicting dynamic instability regions of composite flat panels. Validation of numerical results from finite element analysis was done with those available from previous researches. The influences of various parameters like static load factor, area of delamination, temperature, moisture, fiber orientations, boundary conditions and stacking sequence on the dynamic instability regions of bidirectional Glass/Epoxy flat panels were investigated. Significant effects of these parameters on the dynamic stability characteristics of composite plates were observed and discussed.

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ABSTRACT: The objective of this paper is to investigate the progressive failure behaviour of laminated cylindrical/conical panels under meridional compression considering geometric nonlinearity and evolving material damage. The evolving microscopic damage such as fiber breakage, matrix cracking, fiber matrix debonding etc. is modeled through a generalized macroscopic continuum theory within the framework of irreversible thermodynamics. The analysis is carried out using field consistent finite element approach based on first-order shear deformation theory. The nonlinear governing equations are solved using the Newton–Raphson iterative technique coupled with the adaptive displacement control method to trace the equilibrium path. The damage evolution equations are solved at every Gauss point using Newton–Raphson iterative technique within each iteration of a loading/displacement increment. To accurately model the transverse shear strain energy, shear correction factors are calculated using layers' properties and lamination scheme. The detailed study is carried out to highlight the influences of evolving damage, span-to-thickness ratio, lamination scheme, radius-to-span ratio, boundary conditions and semi-cone angle on the postbuckling response and failure load of laminated panels.


ABSTRACT: Thin membranes are prone to wrinkling under various loading, geometric and boundary conditions, affecting their functionality. We consider a hyperelastic cylindrical membrane with non-uniform thickness pressurized by internal gas or fluid. When pre-stretched and inflated, the wrinkles are generated in a certain portion of the membrane depending on the loading medium and boundary conditions. The wrinkling is determined through a criterion based on kinematic conditions obtained from non-negativity of Cauchy principal stresses. The equilibrium solution of a wrinkled membrane is obtained by a specified combination of standard and relaxed strain energy function. The governing equations are discretized by a finite difference approach and a Newton–Raphson method is used to obtain the solution. An interesting relationship between stretch induced softening/stiffening with the wrinkling phenomenon has been discovered. The effects of pre-stretch, inflating medium, thickness variations and boundary conditions on the wrinkling patterns are clearly delineated.

ABSTRACT: Coupled higher-order layerwise piezoelectric laminate mechanics are presented, applicable to shallow cylindrical composite and sandwich shells subjected to static mechanical loads and/or electric voltages. The current formulation enables efficient prediction of (i) global electromechanical response, (ii) local through-thickness distribution of electromechanical variables and (iii) interlaminar shear stress at the interface between adjacent material layers. Using the developed mechanics, the effects of curvature, thickness and ply angle on the global and local through-thickness response of sandwich composite shells are studied.


ABSTRACT: In this paper, we use the Serendipity basis in the isogeometric Reissner–Mindlin shell formulation to facilitate the fiber vector definition. The Serendipity basis and the NURBS basis are used here to express the shell fiber rotations and the mid-surface translations respectively. Results show that they perform nearly the same with the Lagrange/NURBS formulation, but with savings in the number of rotational degrees of freedom. We also study the transverse shear locking phenomenon and give a modified reduced quadrature scheme. It can improve the efficiency and to some extent relieve the locking without introducing hourglass modes. The linear decreasing, from outer elements to inner elements, quadrature point distribution also prevents the oscillation of the solutions in the coarse meshes.


ABSTRACT: This paper presents an analytical investigation on nonlinear thermal dynamic behavior of imperfect functionally graded circular cylindrical shells eccentrically reinforced by outside stiffeners and surrounded on elastic foundations using the Reddy's third order shear deformation shell theory in thermal environment. Material properties are graded in the thickness direction according to Sigmoid power law distribution (S-FGM) in terms of the volume fractions of constituents with metal–ceramic–metal layers. The shells are affected by mechanical, damping loads and temperature. The stress function and the Bubnov–Galerkin method are applied. Unlike previous publications, we propose a general formulation for forces and moments which allow the non-linear dynamic of shear deformable eccentrically stiffened shell to be studied taking into account the thermal stress in both the shells and the stiffeners. Numerical results are given for evaluating effects of temperature, material and geometrical properties, elastic foundation and eccentrically outside stiffeners on nonlinear dynamic of the shear deformable S-FGM shells. A good agreement is obtained by comparing the present analysis with other available in the literature.

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ABSTRACT: In this research, a size-dependent first-order shear deformable model is developed based on the Mindlin's strain gradient elasticity theory to analyze the free vibration and axial buckling of circular cylindrical micro-/nano-shells. The size-dependent governing equations and corresponding boundary conditions are established through Hamilton's principle. For some specific values of the gradient-based material parameters, the most general form of shell formulation can be reduced to those based on simple forms of the strain gradient elasticity theory such as the modified strain gradient theory (MSGT), modified couple stress theory (MCST) and strain gradient theory (SGT). To illustrate the characteristics of a micro-/nano-shell obtained by the size-dependent shell formulation, the axial buckling and free vibration problems of a simply-supported (SS) microshell are analyzed by employing a Navier-type solution. Selected numerical results are presented to get an insight into the effects of dimensionless material length scale parameters, length-to-radius ratio and circumferential mode number on the non-dimensional natural frequencies and buckling loads. For comparison purpose, the non-dimensional natural frequencies and buckling loads predicted by MSGT, MCST, SGT and classical theory (CT) are also presented. It is shown that the effect of small scale is more prominent for lower values of dimensionless length scale parameter.

ABSTRACT: The polar finite element is utilized to examine the dynamic characteristics of the horizontal cylindrical shells taking into account sloshing effect. The proposed method is developed by integrating the structural shape functions that are derived on basis of exact solution of equations of motion of shell, the polar finite element and the Sander's thin-walled shell theory. Furthermore, a rigorous fluid-structure interaction analysis is carried out based on the simultaneous solving of the governing equations of the solid and the fluid domains. Moreover, the natural frequencies and the mode shapes of the system are obtained, and the numerical results are compared with available experimental outcomes. By this mean, the accuracy of the presented method is examined thoroughly and it is concluded that the proposed method, in comparisons with other theoretical approaches, is much more accurate under all practical conditions.

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ABSTRACT: The flexible electronic structure is based on the buckling of a thin film on a compliant substrate. This paper studies the dynamic stability of this structure under a uniaxial step load. Dynamic equilibrium equation is deduced according to the Euler–Lagrange equation. The dynamic response of the film is solved analytically by using Jacobi elliptic functions. It is a periodic vibration influenced by the step load. The critical
load in dynamic buckling is determined by the characteristics of phase graphs and Budiansky–Roth criterion. It is the same as that in static buckling. In dynamic buckling, the amplitude of vibration is larger than that in static buckling. With the increment of the load and initial amplitude, the period of vibration decreases.

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ABSTRACT: In this present article, the static, free vibration and the transient behavior of the laminated composite flat/curved panels have been investigated. The deflections and the natural frequencies of the laminated composite flat panels have been computed numerically using two higher-order mid-plane kinematics and compared with the available published numerical/analytical results. The results are also validated with the experimentally obtained responses (three point bend test and modal analysis). In addition to that, the transient behavior of the laminated structure is also computed numerically and compared with the results available in the open literature. The static, free vibration and the transient responses of the laminated panel are also computed using the simulation model developed in commercial finite element package (ANSYS) based on the ANSYS parametric design language code and compared with present numerical and experimental results. Finally, the importance of the developed higher-order models and the effect of the different parameters have been shown by computing the responses for different parameters and discussed in details.

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ABSTRACT: The aluminum sandwich structures with hexagonal honeycomb cores subjected to water-based impulsive loading are studied experimentally. The blast resistance in terms of dynamic deformation, failure modes and associated mechanisms is evaluated in relation to the load intensity, core relative density under air-backed and water-backed conditions. 3D digital imaging correlation and postmortem analysis are used to investigate the deformation and failure of individual components, focusing on the effects of loading intensities, core relative density and loaded condition. The failure mode maps of sandwich panels are summarized to study the different regimes of deflection resistance in different experimental cases. The results show that the effect of relative core density significantly influences the blast resistance of sandwich panels under the different loaded conditions. The sandwich panels with denser cores perform better blast resistance at high impulsive loads under air-backed condition. Only slight discrepancy of deflection resistance has been observed under the water-backed condition. The honeycomb sandwich panels suffer significantly smaller backface deflections than solid plates of identical mass per area under air-backed condition, while the discrepancy of deflection is negligible under the water-backed condition.
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ABSTRACT: In this paper, the free vibration characteristics of embedded functionally graded carbon nanotube-reinforced composite (FG-CNTRC) spherical shells are studied based on a numerical approach. The elastic foundation is considered to be Pasternak-type. Moreover, the extended rule of mixture is used so as to obtain the material properties of FG-CNTRC. The shell is also modeled according to the first-order shear deformation shell theory. The energy functional of the structure is obtained first. Using differential operators, the discretized form of the energy functional is derived. By means of the variational differential quadrature (VDQ) method, the reduced forms of mass and stiffness matrices are then obtained. Selected numerical results are given to investigate the effects of different parameters such as elastic foundation coefficients, boundary conditions, CNT volume fraction, thickness-to-radius ratio and type of distribution of CNT on the vibrations of FG-CNTRC spherical shells.

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ABSTRACT: This article deals with the geometrical nonlinear flexural behaviour of laminated composite shell panels integrated with the piezoelectric fibre reinforced composite (PFRC) layer. In this study, the PFRC embedded panel has been modeled mathematically using Green-Lagrange nonlinear kinematics in the framework of the higher-order shear deformation theory. Moreover, the quadratic variation of the electric potential has been considered. The nonlinear finite element steps have been adopted for the discretisation of the domain. Further, the principle of minimum potential energy in conjunction with the direct iterative method is implemented to compute the desired responses. The nonlinear numerical solutions have been validated by comparing the responses with those of the available published results. The actuating capability of the present PFRC layer to suppress the linear and the nonlinear deformations of the smart composite shell panels have been investigated by using the proposed higher-order nonlinear model. Finally, the effect of different geometrical parameters (thickness ratio, aspect ratio, curvature ratio, support constraints, shell geometry and piezoelectric fibre angle) on the nonlinear static behaviour of smart composite panels has been examined by solving various numerical examples.


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ABSTRACT: The use of local numerical schemes, such as finite differences produces much better conditioned matrices than global collocation radial basis functions methods. However, finite difference schemes are limited to special grids. For scattered points, a combination of finite differences and radial basis functions would be a possible solution. In this paper, we use a higher-order shear deformation plate theory and a radial basis function – finite difference technique for predicting the transient behavior of thin and thick composite plates. Through numerical experiments on beams and composite plates, the accuracy and efficiency of this collocation technique is demonstrated.


ABSTRACT: The Green quasifunction method is employed to solve the free vibration problem of clamped thin plates. A Green quasifunction is established by using the fundamental solution and boundary equation of the problem. This function satisfies the homogeneous boundary condition of the problem. The mode shape differential equation of the free vibration problem of clamped thin plates is reduced to Fredholm integral equation of the second kind by Green formula. Irregularity of the kernel of integral equation is overcome by choosing a suitable form of the normalized boundary equation. Two examples demonstrate the validity of the present method. Comparison with both the series solution and ANSYS finite-element solution shows fine agreement. The present method is a novel and effective mathematical one.


ABSTRACT: In the past decades, it has been reported that divergence is the expected form of instability for fluid-conveying pipes with both ends supported. In this paper, the form of instability of supported pipes conveying fluid subjected to distributed follower forces is investigated. Based on the Pflüger column model, the equation of motion for supported pipes subjected concurrently to internal fluid flow and distributed follower forces is established. The analytical model, after Galerkin discretization to two degrees of freedom, is evaluated by analyzing the corresponding eigenvalue problem. The complex frequencies versus fluid velocity are obtained for various system parameters. The results show that either buckling or flutter instabilities could occur in supported fluid-conveying pipes under the action of distributed follower forces, depending on the parameter values of distributed follower forces.
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ABSTRACT: This paper studies the dynamic buckling behavior of multi-walled carbon nanotubes (MWNTs) subjected to step axial loading. A buckling condition is derived, and numerical results are presented for MWNTs under fixed boundary conditions. It is shown that the critical buckling load of MWNTs is of multi-branches and decreases as the time elongates. The associated buckling modes for different layers of MWNTs can be either in-phase or out of phase, which is related to the branch that the critical buckling load belongs to. For MWNTs with the same innermost tube radius, the critical buckling load is decreased when increasing the layers.

ABSTRACT: Based on the Flügge shell theory, equations of motion of ring-stiffened thin-walled cylindrical shells conveying fluid are developed with the aid of the Hamilton's principle. Analysis is carried out on the vibration and stability of the ring-stiffened shells conveying fluid, and the effects of fluid velocity, the Young modulus, the size, and the number of the ring stiffeners on the natural frequency and the instability characteristics are examined. It is found that stiffeners can reduce the number of circumferential waves for the fundamental mode, and increase the shell's natural frequency, and thus the critical fluid velocity. For the number of longitudinal half waves being equal to one, the natural frequency and the corresponding critical fluid velocity are the largest for the internal-ring stiffened shell and are the smallest for the symmetrical-ring stiffened shell. The natural frequencies and the corresponding critical fluid velocity predicted by the established model increase with the increase in the Young modulus, the size, or the number of the stiffeners.

ABSTRACT: This paper explores growth induced morphological instabilities in biological soft materials. In view of that the growth of a living tissue not only changes its geometry but also can alter its mechanical properties, we suggest a refined volumetric growth model incorporating the effects of growth on the mechanical properties of materials. Analogy between this volumetric growth model and the conventional thermal stress model is addressed for both small and finite deformation problems, which brings great ease for the finite element analysis based on the suggested model. Examples of growth induced surface wrinkling behavior in soft composites, including core-shell soft cylinders and three-layered soft tissues, are explored. The results and
discussions foresee possible applications of the model in understanding the correlation between the morphogenesis and growth of soft biological tissues (e.g. skins and tumors), as well as in evaluating the deformation and surface instability behavior of soft artificial materials induced by swelling/shrinkage.

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ABSTRACT: Cylinder hydrogel is simple in geometry and easy to synthesize, therefore was widely used to investigate the swelling/shrinking instability of hydrogel and many instability patterns were accumulated in the literature. The mechanism of instability pattern formation of this unique configuration, nevertheless, is far from being fully understood. We applied and extended the recently developed nonlinear theory of polymer gels into cylindrical coordinates, and performed linear perturbation analysis of swelling-induced stability of a constrained cylinder hydrogel. We derived the incremental formulations of stresses and the associated equilibrium equations. We obtained the critical conditions for the onset of instability and probed in details the effects of various parameters on the stability diagram of the hydrogel. The physical meaning of the variation of stability diagram was also interpreted.

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ABSTRACT: Nonlinear dynamic responses of a laminated hybrid composite plate subjected to time-dependent pulses are investigated. Dynamic equations of the plate are derived by the use of the virtual work principle. The geometric nonlinearity effects are taken into account with the von Kármán large deflection theory of thin plates. Approximate solutions for a clamped plate are assumed for the space domain. The single term approximation functions are selected by considering the nonlinear static deformation of plate obtained using the finite element method. The Galerkin Method is used to obtain the nonlinear differential equations in the time domain and a MATLAB software code is written to solve nonlinear coupled equations by using the Newmark Method. The results of approximate-numerical analysis are obtained and compared with the finite element results. Transient loading conditions considered include blast, sine, rectangular, and triangular pulses. A parametric study is conducted considering the effects of peak pressure, aspect ratio, fiber orientation and thicknesses.

ABSTRACT: In this paper, numerical simulation of impact cases of liquid-filled tube impacted by missiles is conducted with a commercial finite element code LS-DYNA, and the results obtained are compared with the experimental data to verify the validity of the numerical simulation model adopted. With the verified numerical method, the processes of dynamic response of a blunt indenter impacting an empty or liquid-filled three-span continuous tubular beam are studied when the parameter such as the indenter's mass, liquid's density or impact velocity is varied and the other conditions are kept the same. The simulation results indicate that the critical perforation energy and the deformation of the wall of the pipe are significantly influenced by the presence of the liquid and the pressure. The liquid filling the tube provides a ‘foundation’ pressure to resist and localize the deformation, which may affect the perforation process and lead to a reduction of the ballistic limit. The simulation results also indicate that the increase of the fluid density filled in the tube will decrease the ballistic limit, but the fluid density must be in some scope. The relationship between the ballistic limit velocity of the tube and the mass of the impact missile is nonlinear in the Cartesian coordinate while it becomes linear through logarithmic transformation.

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ABSTRACT: The transient wave propagation in the finite rectangular Mindlin plate is investigated by the analytical and experimental methods. The generalized ray method (GRM) which has been successfully applied to study the transient responses of beams, planar trusses, space frames and infinite layered media is extended to investi

gate the transient wave propagation and early short time transient response in finite Mindlin plate. Combining the wave solution, the shock source and the boundary conditions, the ray groups transmitted in the finite rectangular plate can be determined. Numerical simulations and experiments are performed and compared with each other. The results show that the transient wave propagation and early short time transient responses in the finite plate can be studied using the GRM. The early short time transient accelerations are very large for the finite plate subjected to the unit impulse, while the early short time transient displacements are very small. The early short time transient accelerations under the unit impulse are much larger than those under the unit step impulse. The thickness and material characteristics have remarkable effects on the early short time transient responses.

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ABSTRACT: This article studies the stability of a functionally graded clamped-clamped micro-plate subjected to hydrostatic and electrostatic pressures. Equilibrium positions of the micro-plate are determined and shown in the state control space. To study the stability of the equilibrium positions, the motion trajectories are given for different initial conditions in the phase plane. Effects of the electrostatic and hydrostatic pressure changes on the deflection and stability of the micro-plate for some sample value of \( k \) are studied and values of the applied voltage and hydrostatic pressure leading system to unstable conditions by undergoing a saddle node and homoclinic bifurcations are determined.

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ABSTRACT: The nonlinear vibration of a cantilever cylindrical shell under a concentrated harmonic excitation moving in a concentric circular path is proposed. Nonlinearities due to large-amplitude shell motion are considered, with account taken of the effect of viscous structure damping. The system is discretized by Galerkin’s method. The method of averaging is developed to study the nonlinear traveling wave responses of the multi-degrees-of-freedom system. The bifurcation phenomenon of the model is investigated by means of the
averaged system in detail. The results reveal the change process and nonlinear dynamic characteristics of the periodic solutions of averaged equations.

ABSTRACT: Based on the Reissner assumptions, this paper is concerned with the bending analysis of simply supported sandwich plates with functionally graded core and orthotropic face sheets subjected to transverse distributed loadings. First, the expressions of the displacements, stresses and internal forces of the sandwich plate are presented according to the constitutive relations and stress states of the core and face sheets. Then, the solutions of bending equilibrium equations are derived by expanding the deflection w, transverse shearing forces $Q_x$ and $Q_y$ with double trigonometric series that satisfy the simply supported boundary conditions. Finally, the proposed solution is validated by comparing the results with available elasticity solutions for a square sandwich plate with an isotropic core and finite element simulations for one with functionally graded core. The Young's modulus of the functionally graded core is assumed to be graded by a power law distribution of volume fractions of the constituents, and the Poisson's ratio is held constant. And the effects of the core's top-bottom Young's modulus ratio $\gamma$ and volume fraction exponent $n_0$ on the variation of the displacements of the functionally graded sandwich plate are also examined.

ABSTRACT: Based on the classical composite laminate theory, the bending problem of a finite composite plate weakened by multiple elliptical holes is studied by means of the complex variable method. The present work is intended to express the complex potentials in the form of Faber series aided by the use of the least squares boundary collocation techniques on the finite boundaries. As a result, concise and high accuracy solutions are presented for the stress distribution around the holes. Finally, numerical examples are presented to discuss the effects of some parameters on the stress concentration around the holes.

ABSTRACT: Free vibration problems of lattice sandwich beams under several typical boundary conditions are investigated in the present paper. The lattice sandwich beam is transformed to an equivalent homogeneous three-layered sandwich beam. Unlike the traditional analytical model in which the rotation angles of the face sheets and the core are assumed the same, different rotation angles are considered in this paper to characterize the real response of sandwich beams. The analytical solutions of the natural frequencies for several typical boundary conditions are obtained. The effects of material properties and geometric parameters on the natural frequencies are also investigated.
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ABSTRACT: A new model for a smart shell of revolution treated with active constrained layer damping (ACLD) is developed, and the damping effects of the ACLD treatment are discussed. The motion and electric analytical formulation of the piezoelectric constrained layer are presented first. Based on the authors' recent research on shells of revolution treated with passive constrained layer damping (PCLD), the integrated first-order differential matrix equation of a shell of revolution partially treated with ring ACLD blocks is derived in the frequency domain. By virtue of the extended homogeneous capacity precision integration technology, a stable and simple numerical method is further proposed to solve the above equation. Then, the vibration responses of an ACLD shell of revolution are measured by using the present model and method. The results show that the control performance of the ACLD treatment is complicated and frequency-dependent. In a certain frequency range, the ACLD treatment can achieve better damping characteristics compared with the conventional PCLD treatment.

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ABSTRACT: Mode jumping is an instability phenomenon in the post-buckling region, which causes a sudden change in the equilibrium configuration and is thus harmful to structure. The configuration of a partial elastic foundation can directly induce mode coupling from the buckling stage and through the whole post-buckling region. The mode coupling effect due to the configuration of partial foundation on mode jumping is investigated and demonstrated to be an important factor of determining mode jumping. By properly choosing the partial elastic foundation configuration, mode jumping can be avoided.

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ABSTRACT: This study discusses the experimental result of the viscoplastic response and collapse of sharp-notched 316L stainless steel tubes with different notched depths subjected to cyclic bending. The tube bending machine and curvature-ovalization measurement apparatus were used for conducting the symmetric curvature-controlled cyclic bending. To highlight the viscoplastic behavior, three different curvature-rates, 0.0035, 0.035 and 0.35 m⁻¹s⁻¹, were controlled. Observations of a certain curvature-rate reveal that five almost parallel lines
corresponding to five different notch-depth (0.2, 0.4, 0.6, 0.8 and 1.0 mm) tubes were presented in the experimental relationship between the cyclic controlled curvature and the number of cycles needed to produce buckling on a log-log scale. However, the slopes for the three different curvature-rates are different. An empirical formulation was proposed to simulate the aforementioned relationship. When comparing with the experimental findings, the simulation was in good agreement with the experimental data.

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ABSTRACT: The elasto-plastic buckling and postbuckling of fiber metal laminates (FML) are studied in this research. Considering the geometric nonlinearity of the structure and the elastoplastic deformation of the metal layers, the incremental Von Karman geometric relation of the FML with initial deflection is established. Moreover, an incremental elasto-plastic constitutive relation adopting the mixed hardening rule is introduced to depict the stress-strain relationship of the metal layers. Subsequently, the incremental nonlinear governing equations of the FML subjected to in-plane compressive loads are derived, and the whole problem is solved by the iterative method according to the finite difference method. In numerical examples, the effects of the initial deflection, the loading state, and the geometric parameters on the elasto-plastic buckling and postbuckling of FML are investigated, respectively.

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ABSTRACT: The nonlinear vibrational model of a slightly curved single-walled carbon nanotube (SWCNT) resting on a Winkler-type elastic foundation is developed using nonlocal Euler-Bernoulli elastic theory. The SWCNT is assumed to vibrate under an external harmonic electric force field and an analytical solution is proposed to obtain the nonlinear resonant frequencies. The results show good agreement with the numerical simulation and the obtained analytical frequency is completely related to the curvature of the nanotube. Our model predicts that although the model is nonlinear in nature, the curved SWCNT could behave linearly in a certain amount of curvatures and this quasi-linear vibrational behavior of curved SWCNT is a function of aspect ratio, nonlocal parameter, and stiffness of the foundation.

ABSTRACT: In this paper, the nonlinear dynamical behavior of two coupled pipes conveying pulsating fluid is studied. The connection between the two pipes is considered as a distributed linear spring. Based on this consideration, the equations of motion of the coupled two-pipe system are obtained. The two coupled nonlinear partial differential equations, discretized using the fourth-order Galerkin method, are solved by a fourth-order Runge-Kutta integration algorithm. Results show that the connection stiffness has a significant effect on the dynamical behavior of the coupled system. It is found that for some parameter values the motion types of the two pipes might be synchronous.


ABSTRACT: The aim of this paper is to study the free transverse vibration of a hanging nonuniform nanoscale tube. The analysis procedure is based on nonlocal elasticity theory with surface effects. The nonlocal elasticity theory states that the stress at a point is a function of strains at all points in the continuum. This theory becomes significant for small-length scale objects such as micro- and nanostructures. The effects of nonlocality, surface energy and axial force on the natural frequencies of the nanotube are investigated. In this study, analytical solutions are formulated for a clamped-free Euler-Bernoulli beam to study the free vibration of nanoscale tubes.

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ABSTRACT: In this paper nonlinear analysis of a thin rectangular functionally graded plate is formulated in terms of von-Karman's dynamic equations. Functionally Graded Material (FGM) properties vary through the constant thickness of the plate at ambient temperature. By expansion of the solution as a series of mode functions, we reduce the governing equations of motion to a Duffing's equation. The homotopy perturbation solution of generated Duffing's equation is also obtained and compared with numerical solutions. The sufficient conditions for the existence of periodic oscillatory behavior of the plate are established by using Green's function and Schauder's fixed point theorem.

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ABSTRACT: This is a modest contribution on higher-order continuum theory for predicting size effects in small-scale objects. It relates to a preceding article of the journal by the same authors (AMSS, 2013, 26: 9–20)
which considered the longitudinal dynamical analysis of a gradient elastic fiber but, in addition to an internal length, an internal time parameter is also introduced to model delay/acceleration effects associated with the underlying microstructure. In particular, the free transverse vibration of a double-walled carbon nanotube (DWNT) is studied by employing gradient elasticity with internal inertia. The inner and outer carbon nanotubes are modeled as two individual elastic beams interacting with each other through van der Waals (vdW) forces. General explicit expressions are derived for the natural frequencies and the associated inner-to-outer tube amplitude ratios for the case of simply supported DWNTs. The effects of internal length (or scale) and internal time (or inertia) on the vibration behavior are evaluated. The results indicate that the internal length and time parameters of the adopted strain gradient-internal inertia generalized elasticity model have little influence on the lower order coaxial and noncoaxial vibration modes, but a significant one on the higher order modes.

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ABSTRACT: This paper deals with the nonlinear forced vibration of FGM rectangular plate with a boundary of two edges clamped opposite and the other two free. The plate is subjected to transversal and in-plane excitations. The present research treats the material properties of the FGM plates as temperature-dependent and graded continuously throughout the thickness direction, following the volume fraction of the constituent materials according to the power law. The temperature is assumed to be constant in the plane and varied only in the thickness direction of the plate. In the framework of geometrical nonlinearity the plate is modeled and the equations of motion are obtained on Hamilton’s principle. With the help of Galerkin discretization, the nonlinear ordinary differential equations describing transverse vibration of the plate are proposed. By the numerical method, the nonlinear dynamical responses of the FGM plate with two clamped opposite and two free edges are analyzed.

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ABSTRACT: The conventional analytical method of predicting strain in a thin film under bending is restricted to the uniform material assumption, while in flexible electronics, the film/substrate structure is widely used with mismatched material properties taken into account. In this paper, a piecewise model is proposed to analyze the axial strain in a thin film of flexible electronics with the shear modification factor and principle of virtual work. The excellent agreement between analytical prediction and finite element results indicates that the model is capable of predicting the strain of the film/substrate structure in flexible electronics, whose mechanical stability and electrical performance is dependent on the strain state in the thin film.
ABSTRACT: This paper is aimed to propose a three-dimensional model which would be used for investigation on the mechanical behavior of single-layered zinc oxide nanosheets. To develop this model, molecular mechanics is coupled with the density functional theory. Simulating the hexagonal lattices of nanosheets as a hexagonal mechanical structure composed of structural beam elements, the buckling behavior of zinc oxide nanosheets is studied. Effects of different parameters on the stability of armchair and zigzag nanosheets are examined. It is shown that the buckling forces of zigzag nanosheets are slightly greater than those of armchair ones. However, with increasing size of nanosheets the effect of atomic structure on the stability of nanosheets diminishes. By studying the effect of end conditions on the buckling behavior of nanosheets, it is shown the stability of nanosheets is affected significantly by boundary conditions.


ABSTRACT: This paper is concerned with the transient deformation of functionally graded (FG) shallow spherical shells subjected to time-dependent thermomechanical load. Based on Timoshenko-Mindlin hypothesis and von Karman nonlinear theory, a set of nonlinear governing equations of motion for FG shallow spherical shells in regard to transverse shear deformation and all the inertia terms are established using Hamilton's principle. The collocation point method and Newmark-beta scheme in conjunction with the finite difference method are adopted to solve the governing equations of motion and the unsteady heat conduction equation numerically. In the numerical examples, the transient deflection and stresses of FG shallow spherical shells with various material properties under different loading conditions are presented.

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ABSTRACT: The thin stiff films on pre-stretched compliant substrates can form wrinkles, which can be controlled in micro and nanoscale systems to generate smart structures. Recently, buckled piezoelectric/ferroelectric nanoribbons have been reported to show an enhancement in the piezoelectric effect and stretchability, which can be applied in energy harvesting devices, sensors and memory devices instead of polymeric polyvinylidene fluoride (PVDF). This paper studies the buckling and post-buckling process of ferroelectric thin films bonded to the pre-stretched soft layer, which in turn lies on a rigid support. Nonlinear electromechanical equations for the buckling of thin piezoelectric plates are deduced and employed to model the ferroelectric film poled in the thickness direction. Two buckling modes are analyzed and discussed: partially
de-adhered buckling and fully adhered buckling. Transition from one buckling mode to the other is predicted and the effect of piezoelectricity on the critical buckling condition of piezoelectric film is examined.

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ABSTRACT: Vibration characteristics of fluid-filled multi-walled carbon nanotubes are studied by using nonlocal elastic Flügge shell model. Vibration governing equations of an N-layer carbon nanotube are formulated by considering the scale effect. In the numerical simulations, the effects of different theories, small-scale, variation of wavenumber, the innermost radius and length of double-walled and triple-walled carbon nanotubes are considered. Vibrational frequencies decrease with an increase of scale coefficient, the innermost radius, length of nanotube and effects of wall number are negligible. The results show that the cut-off frequencies can be influenced by the wall number of nanotubes.

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ABSTRACT: A multi-resolution rectangular shell element with membrane-bending based on the Kirchhoff-Love theory is proposed. The multi-resolution analysis (MRA) framework is formulated out of a mutually nesting displacement subspace sequence, whose basis functions are constructed of scaling and shifting on the element domain of basic node shape functions. The basic node shape functions are constructed from shifting to other three quadrants around a specific node of a basic element in one quadrant and joining the corresponding node shape functions of four elements at the specific node. The MRA endows the proposed element with the resolution level (RL) to adjust the element node number, thus modulating structural analysis accuracy accordingly. The node shape functions of Kronecker delta property make the treatment of element boundary condition quite convenient and enable the stiffness matrix and the loading column vectors of the proposed element to be automatically acquired through quadraturing around nodes in RL adjusting. As a result, the traditional 4-node rectangular shell element is a mono-resolution one and also a special case of the proposed element. The accuracy of a structural analysis is actually determined by the RL, not by the mesh. The simplicity and clarity of node shape function formulation with the Kronecker delta property, and the rational MRA enable the proposed element method to be implemented more rationally, easily and efficiently than the conventional mono-resolution rectangular shell element method or other corresponding MRA methods.

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ABSTRACT: The wave method is introduced to vibration analysis of the fluid-conveying carbon nanotube. The constitutive relation of carbon nanotube on micro-scale is founded using the nonlocal elastic theory. The governing equation on micro-scale is obtained. And the first five orders of the natural frequency of the carbon nanotube conveying fluid with various speeds are calculated through the wave method. Besides, the critical flow velocity when the carbon nanotube loses stability is obtained. Meanwhile, a contrast is made between the result obtained through the wave method and that in previous researches.

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ABSTRACT: Internal resonance in nonlinear vibration of functionally graded (FG) circular cylindrical shells in thermal environment is studied using the Hamiltonian dynamics formulation. The material properties are considered to be temperature-dependent. Based on the Kármán-Donnell's nonlinear shell theory, the kinetic and potential energy of FG cylindrical thin shells are formulated. The primary target is to investigate the two-mode internal resonance, which is triggered by geometric and material parameters of shells. Following a secular perturbation procedure, the underlying dynamic characteristics of the two-mode interactions in both exact and near resonance cases are fully discussed. It is revealed that the system will undergo a bifurcation in near resonance case, which induces the dynamic response at high energy level being distinct from the motion at low energy level. The effects of temperature and volume fractions of composition on the exact resonance condition and bifurcation characteristics of FG cylindrical shells are also investigated.

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ABSTRACT: An optimal time-delay feedback control method is provided to mitigate the primary resonance of a single-walled carbon nanotube (SWCNT) subjected to a Lorentz force excited by a longitudinal magnetic field. The nonlinear governing equations of motion for the SWCNT under longitudinal magnetic field are derived and the modulation equations are obtained by using the method of multiple scales. The regions of the stable feedback gain are worked out by using the stability conditions of eigenvalue equation. Taking the attenuation ratio as the objective function and the stable vibration regions as constrained conditions, the optimal control parameters are worked out by using minimum optimal method. The optimal controllers are designed to control the dynamic behaviors of the nonlinear vibration systems. It is found that the optimal feedback gain obtained by the optimal method can enhance the control performance of the primary resonance of SWCNT devices.

Wei Li and Yueming Li (State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China), “Vibration and sound radiation of an asymmetric laminated plate in thermal environments”, Acta Mechanica Solida Sinica, Vol. 28, No. 1, pp 11-22, February 2015  
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ABSTRACT: Analytical studies on the vibration and sound radiation characteristics of an asymmetric laminated rectangular plate are carried out in this paper. Theoretical formulations, in which the effects of thermal environments are taken into account, are derived for the vibration and sound radiation based on both first-order shear deformation plate theory and Rayleigh integral. It is found that the natural frequencies, the resonant amplitudes of vibration response and the sound pressure level decrease with the temperature rising. The natural frequencies of asymmetric plates are smaller than those of symmetric plates and the velocity responses of asymmetric plates are larger than those of symmetric plates.

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ABSTRACT: In this paper, a precise transfer matrix method is presented to calculate the structural and acoustic responses of the conical shell. The governing equations of conical shells are written as a coupled set of first order differential equations. The field transfer matrix of the shell and non-homogenous term resulting from the external excitation are obtained by precise integration method. After assembling the field transfer matrixes, the whole matrix describing dynamic behavior of the stiffened conical shell is obtained. Then the structural and acoustic responses of the shell are solved by obtaining unknown sound pressure coefficients. The natural frequencies of the shell are compared with the FEM results to test the validity. Furthermore, the effects of the semi-vertex angle, driving force directions and boundary conditions on the structural and acoustic responses are studied.

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ABSTRACT: Wave propagation in two-dimensional hierarchical honeycomb structures with two-order hierarchy is investigated by using the symplectic algorithm. By applying the variational principle to the dual variables, the wave propagation problem is transformed into a two-dimensional symplectic eigenvalue problem. The band gaps and spatial filtering phenomena are examined to find the stop bands and directional stop bands. Special attention is directed to the effects of the relative density and the length ratio on the band gaps and phase constant surfaces. This work provides new opportunities for designing hierarchical honeycomb structures in sound insulation applications.

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ABSTRACT: Wave propagation in infinitely long hollow sandwich cylinders with prismatic cores is analyzed by the extended Wittrick-Williams (W-W) algorithm and the precise integration method (PIM). The effective elastic constants of prismatic cellular materials are obtained by the homogenization method. By applying the variational principle and introducing the dual variables, the canonical equations of Hamiltonian system are constructed. Thereafter, the wave propagation problem is converted to an eigenvalue problem. In numerical examples, the effects of the prismatic cellular topology, the relative density, and the boundary conditions on dispersion relations, respectively, are investigated.

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ABSTRACT: In this paper, we present classical molecular dynamics (MD) simulations of model polymer/CNT composites constructed by embedding a single wall (10,10) CNT into two different amorphous polymer matrices: poly(methyl methacrylate) and poly{[(m-phenylene-vinylene)-co-[(2,5-dioctoxy-p-phenylene)vinylene]}}, respectively, with different volume fractions. The simulation results support the idea that it is possible to use CNTs to mechanically reinforce an appropriate polymer matrix, especially in the longitudinal direction of the nanotube. The comparison of the simulation results with the macroscopic rule-of-mixtures for composite systems showed that for strong interfacial interactions, there can be large deviations of the results from the rule-of-mixtures. In order to verify this study, results obtained have been compared with those given by Elliott and Han (2007).

Shirong Li, Xuan Wang and Zeqing Wan (Department of Civil Engineering, Yangzhou University, Yangzhou 225127, China), “Classical and homogenized expressions for buckling solutions of functionally graded material Levinson beams”, Acta Mechanica Solida Sinica, Vol. 28, No. 5, pp 592-604, October 2015
https://doi.org/10.1016/S0894-9166(15)30052-5

ABSTRACT: The relationship between the critical buckling loads of functionally graded material (FGM) Levinson beams (LBs) and those of the corresponding homogeneous Euler-Bernoulli beams (HEBBs) is investigated. Properties of the beam are assumed to vary continuously in the depth direction. The governing equations of the FGM beam are derived based on the Levinson beam theory, in which a quadratic variation of the transverse shear strain through the depth is included. By eliminating the axial displacement as well as the rotational angle in the governing equations, an ordinary differential equation in terms of the deflection of the FGM LBs is derived, the form of which is the same as that of HEBBs except for the definition of the load parameter. By solving the eigenvalue problem of ordinary differential equations under different boundary conditions clamped (C), simply-supported (S), roller (R) and free (F) edges combined, a uniform analytical formulation of buckling loads of FGM LBs with S-S, C-C, C-F, C-R and S-R edges is presented for those of HEBBs with the same boundary conditions. For the C-S beam the above-mentioned equation does not hold. Instead, a transcendental equation is derived to find the critical buckling load for the FGM LB which is similar
to that for HEBB with the same ends. The significance of this work lies in that the solution of the critical buckling load of a FGM LB can be reduced to that of the HEBB and calculation of three constants whose values only depend upon the through-the-depth gradient of the material properties and the geometry of the beam. So, a homogeneous and classical expression for the buckling solution of FGM LBs is accomplished.

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https://doi.org/10.1016/S0894-9166(16)30005-2
ABSTRACT: The equation of motion of sandwich beam with pyramidal lattice core in the supersonic flow considering geometric nonlinearity is formulated using Hamilton's principle. The piston theory is used to evaluate aerodynamic pressure. The structural aeroelastic properties are analyzed using frequency- and time-domain methods, and some interesting phenomena are observed. It is noted that the flutter of sandwich beam occurs under the coupling effect of low order modes. The critical flutter aerodynamic pressure of the sandwich beam is higher than that of the isotropic beam with the same weight, length and width. The influence of inclination angle of core truss on flutter characteristic is analyzed.

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ABSTRACT: In the present paper, the dynamic stability of multi-walled carbon nanotubes (MWCNTs) embedded in an elastic medium is investigated including thermal environment effects. To this end, a nonlocal Timoshenko beam model is developed which captures small scale effects. Dynamic governing equations of the carbon nanotubes are formulated based on the Timoshenko beam theory including the effects of axial compressive force. Then a parametric study is conducted to investigate the influences of static load factor, temperature change, nonlocal parameter, slenderness ratio and spring constant of the elastic medium on the dynamic stability characteristics of MWCNTs with simply-supported end supports.

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“Linear and geometrically nonlinear analysis with 4-node plane quasi-conforming element with internal parameters”, Acta Mechanica Solida Sinica, Vol. 28, No. 6, pp 668-681, December 2015
https://doi.org/10.1016/S0894-9166(16)30008-8
ABSTRACT: A linear 4-node quadrilateral quasi-conforming plane element with internal parameters is proposed. The element preserves advantages of the quasi-conforming technique, including an explicit stiffness matrix, which can be applied to nonlinear problems. The weak patch test guarantees the convergence of the element. Then the linear element is extended to the geometrically nonlinear analysis in the framework of Total Lagrangian (TL) formulation. The numerical tests indicate that the present element is accurate and insensitive to mesh distortion.

Yiming Fu, Yang Chen and Xuefei Shao (State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China and College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China), “Analysis of elasto-plastic postbuckling and energy release rate for delaminated fiber metal laminated beams in thermal environment”, Acta Mechanica Solida Sinica, Vol. 28, No. 6, pp 693-705, December 2015, https://doi.org/10.1016/S0894-9166(16)30010-6

ABSTRACT: The elasto-plastic postbuckling of fiber metal laminated beams with delamination and the energy release rate along the delamination front are discussed in this paper. Considering geometrical nonlinearity, thermal environment and geometrical initial imperfection, the incremental nonlinear equilibrium equations of delaminated fiber metal laminated beams are established, which are solved using the differential quadrature method and iterative method. Based on these, according to the J-integral theory, the elasto-plastic energy release rate is studied. The effects of some important parameters on the elasto-plastic postbuckling behavior and energy release rate of the aramid reinforced aluminum laminated beams are discussed in details.

Fei Yang (1,2), Weijing Niu (2), Lin Jing (3), Zhihua Wang (2) and Hongwei Ma (4) (1) School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China (2) Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, 79 West Yingze Street, Taiyuan 030024, China (3) State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China (4) School of Civil Engineering, Qinghai University, Xining 810016, China “Experimental and numerical studies of the anti-penetration performance of sandwich panels with aluminum foam cores”, Acta Mechanica Solida Sinica, Vol. 28, No. 6, pp 735-748, December 2015 https://doi.org/10.1016/S0894-9166(16)30013-1

ABSTRACT: Effects of face-sheet thickness and core thickness of sandwich panels, and shape of projectiles on the penetration resistance of sandwich panels were discussed, while typical penetration failure modes were presented. It was shown that the anti-penetration performance of sandwich panels was enhanced with the increase of face-sheet or core thickness; The penetration resistance of sandwich panels was shown to be strongest to blunt-shaped projectile impacts, weaker to hemispherical-nose-shaped projectile impacts, and weakest to conical-shaped projectile impacts. The corresponding numerical simulation was carried out using the finite element code LS-DYNA V970. Numerical results showed that the penetration time decreased with the increase of projectile impact velocity.

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ABSTRACT: In this paper a new 2D-FGM material model based on Mori-Tanaka scheme and third-order transition function has been developed for a thick hollow cylinder of finite length. Elastic mechanical stress analysis is performed by utilizing the finite element method. The corresponding material, displacement and stress distributions are evaluated for different values of \( n_r \) and \( n_z \). Moreover, the effects of different material property distributions on the effective stress with respect to the metallic phase volume fraction are investigated. It is demonstrated that the increase in \( n_r \) and \( V_m \) leads to a significant reduction in the effective stress. Finally, it is shown that the ceramic phase rich cylinder wall has lower maximum effective stresses of which the lowest value of effective stress has been evaluated for \( n_r = 20 \) and \( n_z = 5 \). This minimum value is about half the maximum effective stress which has been evaluated for the non-FGM cylinder case (\( n_r = n_z = 0.1 \)).

ABSTRACT: This study is directed towards a comprehensive exploration on the deformation mechanism of the thin membrane transducer (TMT) caused by surface stress variation. We stress that the biomolecular interaction has changed the magnitude of the surface stress; and when the surface stress exceeds a critical value the TMT will buckle and deform. Based upon Gurtin's theory of surface elasticity and principle of finite deformation, we abstract the TMT as a nanobeam with two clamped ends, and the close-formed governing equation set is derived accordingly. A computer code via the shooting method is developed to solve the presented two-point boundary value problem. In succession, the nanobeam deflection and critical parameters for buckling are quantitatively discussed. This investigation lays the theoretical foundation of TMTs; and it is also beneficial to gain deep insight into characterizing mechanical properties of nanomaterials and engineering nano-devices.

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ABSTRACT: In this paper, the buckling behaviors of axially functionally graded and non-uniform Timoshenko beams were investigated. Based on the auxiliary function and power series, the coupled governing equations were converted into a system of linear algebraic equations. With various end conditions, the characteristic polynomial equations in the buckling loads were obtained for axially inhomogeneous beams. The lower and higher-order eigenvalues were calculated simultaneously from the multi-roots due to the fact that the derived characteristic equation was a polynomial one. The computed results were in good agreement with those analytical and numerical ones in literature.

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ABSTRACT: The woven textile sandwich composite (WTSC) is a promising lightweight composite. In bending, two competing core shearing failure modes reduce the strength; deflection induced by the core shearing deformation reduces the flexural rigidity. To replace a solid composite laminate, the span of WTSC panel must be greater than a critical value, which was deduced on the condition that the load capacity and flexural rigidity of the WTSC panel are equal to those of the composite laminate. Three WTSC panels were tested in bending, so that the failure modes were observed, and the critical spans were determined. Using the alternative design method, the WTSC based wind deflector with reduced weight has been fabricated and mounted on the CRH (China Railway High-speed).

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ABSTRACT: This work deals with the active control of the vibrations of mechanical structures incorporating magnetorheological elastomer. The damping coefficient and shear modulus of the elastomer increase when exposed to a magnetic field. Compared with the vibration control where the elastomer is permanently exposed to a magnetic field, the control of this process through time reduces vibrations more effectively. The experimental study for the vibrations of a sandwich beam filled with an elastomer is conducted, followed by a numerical study using the Abaqus code. The vibration damping is found to be dependent on the loading rate of micro-size ferromagnetic particles in the elastomer.

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ABSTRACT: To satisfy the interfacial shear force continuity conditions, a new model is proposed for the two-layer composite beam with partial interaction by modifying Reddy's higher order beam theory. The governing differential equations for free vibration and buckling are formulated using the Hamilton's principle, the natural frequencies and axial forces are thus analytically obtained by Laplace transform technique. The analytical results are verified through the comparison with those of several other models common in use; and the presented model is found to be a finer one than the Reddy's. A parametric study is also performed to investigate the effects of geometry and material parameters.
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ABSTRACT: This paper presents an analysis of the active control of random vibration for laminated composite plates using piezoelectric fiber reinforced composites (PFRC). With Hamilton's principle and the Rayleigh-Ritz method, the equation of motion for the resulting electromechanical coupling system is derived. A velocity feedback control rule is employed to obtain an effective active damping in the suppression of random vibration. The power spectral density and mean-square displacements of the random vibration for laminated plates under different control gains are simulated and the validity of the present control strategy is confirmed. The effect of piezoelectric fiber orientation in the PFRC layer on the random vibration suppression is also investigated. The analytical methodology can be expanded to other kinds of random vibration.

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https://doi.org/10.1016/S0894-9166(16)30265-8
ABSTRACT: In this paper, the nonlinear dynamics of a curved pipe is investigated in the case of principal parametric resonance due to pulsating flow and impact with loose supports. The coupled in-plane and out-of-plane governing equations with the consideration of von Karman geometric nonlinearity are presented and discretized via the differential quadrature method (DQM). The nonlinear dynamic responses are calculated numerically to demonstrate the influence of pulsating frequency. Finally, the impact is taken into consideration. The influence of clearance on fretting-wear damage, such as normal work rate, contact ratio and impact force level, is demonstrated.

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ABSTRACT: The in-plane dynamic crushing behavior of re-entrant honeycomb is analyzed and compared with the conventional hexagon topology. Detailed deformation modes along two orthogonal directions are examined, where a parametric study of the effect of impact velocity and cell wall aspect ratio is performed. An analytical formula of the dynamic crushing strength is then deduced based on the periodic collapse mechanism of cell
structures. Comparisons with the finite element results validate the effectiveness of the proposed analytical method. Numerical results also reveal higher plateau stress of re-entrant honeycomb over conventional hexagon topology, implying better energy absorption properties. The underlying physical understanding of the results is emphasized, where the auxetic effect (negative Poisson’s ratio) induced in the re-entrant topology is believed to be responsible for this superior impact resistance.

Farzad Ebrahimi and Mohammad Reza Barati (Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran), “Thermal buckling analysis of size-dependent FG nanobeams based on the third-order shear deformation beam theory”, Acta Mechanica Solida Sinica, Vol. 29, No. 5, pp 547-554, October 2016, [https://doi.org/10.1016/S0894-9166(16)30272-5](https://doi.org/10.1016/S0894-9166(16)30272-5)

**ABSTRACT:** In this paper, the thermal effects on the buckling of functionally graded (FG) nanobeams subjected to various types of thermal loading including uniform, linear and non-linear temperature changes are investigated based on the nonlocal third-order shear deformation beam theory. The material properties of FG nanobeam are supposed to vary gradually along the thickness direction according to the power-law form. The governing equations are derived through Hamilton’s principle and solved analytically. Comparison examples are performed to verify the present results. Obtained results are presented for thermal buckling analysis of FG nanobeams such as the effects of the power-law index, nonlocal parameter, slenderness ratio and thermal loading in detail.

Lin Wang, Yuanzhuo Hong, Huliang Dai and Qiao Ni (Department of Mechanics, Huazhong University of Science and Technology and Hubei Key Laboratory for Engineering Structural Analysis and Safety Assessment, Wuhan 430074, China), “Natural frequency and stability tuning of cantilevered CNTs conveying fluid in magnetic field”, Acta Mechanica Solida Sinica, Vol. 29, No. 6, pp 567-576, December 2016 [https://doi.org/10.1016/S0894-9166(16)30328-7](https://doi.org/10.1016/S0894-9166(16)30328-7)

**ABSTRACT:** This paper investigates the dynamics of cantilevered CNTs conveying fluid in longitudinal magnetic field and presents the possibility of controlling/tuning the stability of the CNT system with the aid of magnetic field. The slender CNT is treated as an Euler-Bernoulli beam. Based on nonlocal elasticity theory, the equation of motion with consideration of magnetic field effect is developed. This partial differential equation is then discretized using the differential quadrature method (DQM). Numerical results show that the nonlocal small-scale parameter makes the fluid-conveying CNT more flexible and can shift the unstable mode in which flutter instability occurs first at sufficiently high flow velocity from one to another. More importantly, the addition of a longitudinal magnetic field leads to much richer dynamical behaviors of the CNT system. Indeed, the presence of longitudinal magnetic field can significantly affect the evolution of natural frequency of the dynamical system when the flow velocity is successively increased. With increasing magnetic field parameter, it is shown that the CNT system behaves stiffer and hence the critical flow velocity becomes higher. It is of particular interest that when the magnetic field parameter is equal to or larger than the flow velocity, the cantilevered CNT conveying fluid becomes unconditionally stable, indicating that the dynamic stability of the system can be controlled due to the presence of a longitudinal magnetic field.

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ABSTRACT: Most existing studies on the vibration analysis of cylindrical shells with structural stress are limited to uniform stress distribution. However, non-uniform stress distributions are encountered in many engineering applications. In this study, a unified solution for the vibration analysis of cylindrical shells with a general stress distribution is presented using the Flügge shell theory and modal orthogonality simplification. The obtained analytical solution can be applied to a structure with arbitrary distributed stress, thus it has a wider range of applications than previous methods. The accuracy and advantage of the proposed method are validated by comparing with the finite element method results.

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ABSTRACT: This paper presents the analysis of dynamic characteristics of horizontal axis wind turbine blade, where the mode coupling among axial extension, flap vibration (out-of-plane bending), lead/lag vibration (in-plane bending) and torsion is emphasized. By using the Bernoulli-Euler beam to describe the slender blade which is mounted on rigid hub and subjected to unsteady aerodynamic force, the governing equation and characteristic equation of the coupled vibration of the blade are obtained. Due to the combined influences of mode coupling, centrifugal effect, and the non-uniform distribution of mass and stiffness, the explicit solution of characteristic equation is impossible to obtain. An equivalent transformation based on Green's functions is taken for the characteristic equation, and then a system of integrodifferential equations is derived. The numerical difference methods are adopted to solve the integrodifferential equations to get natural frequencies and mode shapes. The influences of mode coupling, centrifugal effect, and rotational speed on natural frequencies and mode shapes are analyzed. Results show that: (1) the influence of bending-torsion coupling on natural frequency is tiny; (2) rotation has dramatic influence on bending frequency but little influence on torsion frequency; (3) the influence of bending-bending coupling on dynamic characteristics is notable at high rotational speed; (4) the effect of rotational speed on bending mode is tiny.


ABSTRACT: In this paper, a rotation-free triangle is formulated. Unlike the thin and degenerated shell finite element models, rotation-free triangles employ translational displacements as the only nodal DOFs. Compared with the existing rotation-free triangles, the present triangle is simple and physical yet its accuracy remains competitive. Using a corotational approach and the small strain assumption, the tangential bending stiffness matrix of the present triangle can be approximated by a constant matrix that does not have to be updated regardless of the displacement magnitude. This unique feature suggests that the triangle is a good candidate for fabric drape simulation in which fabric sheets are often flat initially and the displacement is much larger than those in conventional shell problems. Nonlinear shell and fabric drape examples are examined to demonstrate the efficacy of the formulation.


ABSTRACT: This paper presents a versatile low order locking-free mixed solid-shell element that can be readily employed for a wide range of linear elastic structural analyses, that is, from thick isotropic structures to multilayer anisotropic composites. This solid-shell element has eight nodes with only displacement degrees of freedom and few assumed stress parameters that provide very accurate interlaminar stress calculations through the element thickness. These elements can be stacked on top of each other to model multilayer structures, fulfilling the interlaminar stress continuity at the interlayer surfaces and zero traction conditions on the top and bottom surfaces of the laminate. The element formulation is based on the well-known Fraeijs de Veubeke–Hu–Washizu mixed variational principle with enhanced assumed strains formulation and assumed natural strains formulation to alleviate the different types of locking phenomena in solid-shell elements. The distinct feature of the present formulation is its ability to accurately calculate the interlaminar stress field in multilayer structures, which is achieved by the introduction of a constraint equation on the interlaminar stresses in the Fraeijs de Veubeke–Hu–Washizu principle-based enhanced assumed strains formulation. The intelligent computer coding of the present formulation makes the present element appropriate for a wide range of structural analyses. To assess the present formulation's accuracy, a variety of popular numerical benchmark examples related to element convergence, mesh distortion, and shell and laminated composite analyses are investigated and the results are compared with those available in the literature. These benchmark examples reveal that the proposed formulation provides very good results for the structural analysis of shells and multilayer composites.


ABSTRACT: This paper presents a new C0 eight-node quadrilateral finite element (FE) for geometrically linear elastic plates. This finite element aims at modeling both thin and thick plates without any pathologies of the classical plate finite elements (shear and Poisson or thickness locking, spurious modes, etc). A C0 FE was previously developed by the first author based on the kinematics proposed by Touratier. This new FE can be
viewed as an evolution towards three directions: (1) use of only $C^0$ FE approximations; (2) modeling of thick to thin structures; and (3) capability in multifield problems. The transverse normal stress is included allowing use of the three-dimensional constitutive law. The element performances are evaluated on some standard plate tests, and comparisons are given with exact three-dimensional solutions for plates under mechanical and thermal loads. Comparisons are made with other plate models using $C^1$ and semi-$C^1$ FE approximations as well as with an eight node $C^0$ FE based on the Reissner–Mindlin model. All results indicate that the present element is highly insensitive to mesh distortion, has very fast convergence properties and gives accurate results for displacements and stresses.


ABSTRACT: In this paper, enhanced four-node shell elements with six DOFs/node based on the Hu–Washizu (HW) functional are developed for Green strain. The drilling rotation is included through the drilling rotation constraint equation. The key features of the approach are as follows.

1. The shell HW functional is derived from the shell potential energy functional, which is an alternative to the derivation from the three-dimensional HW functional. This method is more versatile as it enables the derivation of the so-called partial HW functionals, with different treatment of the bending/twisting part and the transverse shear part of strain energy.

2. For the membrane part of HW shell elements, a seven-parameter stress, a nine-parameter strain and a two-parameter enhanced assumed displacement gradient enhancement are selected as optimal. The assumed representations of stress and strain are defined in skew coordinates in the natural basis at the element's center. This improves accuracy and has positive theoretical consequences.

3. The drilling rotation constraint equation is treated by the perturbed Lagrange method. The faulty term resulting from the equal-order approximations of displacements and the drilling rotation is eliminated, and one spurious mode is stabilized using the gamma method. The proposed formulation is insensitive to the element's distortions and yields a large radius of convergence in the examples involving in-plane bending.

The performance of 4 four-node shell HW elements, having different bending/twisting and transverse shear parts, is analyzed on several numerical examples. Such aspects are considered as: accuracy, radius of convergence, required number of iterations of the Newton method or the arc-length method and time of computations. The element with 29 parameters (HW29) is selected as the best performer.


ABSTRACT: A membrane stress state may be considered as a general stress state in which mechanical constraints have been imposed. Therefore, it would appear that there are mathematical subsidiary conditions for bifurcation buckling from such a stress state. In this work, such conditions are derived in the frame of the Finite Element Method. The basic condition follows from disintegration of the second derivative of the mathematical formulation of the so-called consistently linearized eigenproblem with respect to a dimensionless load parameter. It is used for deriving another condition, characterized by the vanishing of a particular bilinear form. Linear stability analysis and bifurcation buckling from linear prebuckling paths are two special cases for which
this condition is satisfied. Sensitivity analysis of bifurcation buckling of a two-hinged arch, subjected to a uniformly distributed static load, by varying the geometric form of its axis serves the purpose of non-trivial verification of the derived condition for the special case of a thrust-line arch.


ABSTRACT: The smooth DMS-FEM, recently proposed by the authors, is extended and applied to the geometrically nonlinear and ill-posed problem of a deformed and wrinkled/slack membrane. A key feature of this work is that three-dimensional nonlinear elasticity equations corresponding to linear momentum balance, without any dimensional reduction and the associated approximations, directly serve as the membrane governing equations. Domain discretization is performed with triangular prism elements and the higher order ($C^1$ or more) interelement continuity of the shape functions ensures that the errors arising from possible jumps in the first derivatives of the conventional $C^0$ shape functions do not propagate because the ill-conditioned tangent stiffness matrices are iteratively inverted. The present scheme employs no regularization and exhibits little sensitivity to $h$-refinement. Although the numerically computed deformed membrane profiles do show some sensitivity to initial imperfections (nonplanarity) in the membrane profile needed to initiate transverse deformations, the overall patterns of the wrinkles and the deformed shapes appear to be less so. Finally, the deformed profiles, computed through the DMS FEM-based weak formulation, are compared with those obtained through an experiment on an ultrathin Kapton membrane, wherein wrinkles form because of the applied boundary displacement conditions. Comparisons with a reported experiment on a rectangular membrane are also provided. These exercises lend credence to the feasibility of the DMS FEM-based numerical route to computing post-wrinkled membrane shapes.


ABSTRACT: We present a new shell model and an accompanying discretisation scheme that is suitable for thin and thick shells. The deformed configuration of the shell is parameterised using the mid-surface position vector and an additional shear vector for describing the out-of-plane shear deformations. In the limit of vanishing thickness, the shear vector is identically zero and the Kirchhoff–Love model is recovered. Importantly, there are no compatibility constraints to be satisfied by the shape functions used for discretising the mid-surface and the shear vector. The mid-surface has to be interpolated with smooth $C^1$-continuous shape functions, whereas the shear vector can be interpolated with $C^0$-continuous shape functions. In the present paper, the mid-surface as well as the shear vector are interpolated with smooth subdivision shape functions. The resulting finite elements are suitable for thin and thick shells and do not exhibit shear locking. The good performance of the proposed formulation is demonstrated with a number of linear and geometrically non-linear plate and shell examples.

Dan Wang and Weihong Zhang (Weihong Zhang, Engineering Simulation and Aerospace Computing (ESAC), The Key Laboratory of Contemporary Design and Integrated Manufacturing Technology, Northwestern Polytechnical University, Xi’an, Shaanxi 710072, China), “A bispace parameterization method for shape

ABSTRACT: Simultaneous shape optimization of thin-walled curved shell structures and involved hole boundaries is studied in this paper. A novel bispace parameterization method is proposed for the first time to define global and local shape design variables both in the Cartesian coordinate system and the intrinsic coordinate system. This method has the advantage of achieving a simultaneous optimization of the global shape of the shell surface and the local shape of the openings attached automatically on the former. Inherent problems, for example, the effective parameterization of shape design variables, mapping operation between two spaces, and sensitivity analysis with respect to both kinds of design variables are highlighted. A design procedure is given to show how both kinds of design variables are managed together and how the whole design flowchart is carried out with relevant formulations. Numerical examples are presented and the effects of both kinds of design variables upon the optimal solutions are discussed.


ABSTRACT: This paper analyses the buckling behaviour of single-walled and double-walled carbon nanotubes. The total potential of the atomic structure consists of the bonded energy and the non-bonded energy, both resulting from interatomic potentials, as well as the energy of external contributions. In particular, the influence of the in-layer and inter-layer non-bonded interactions is investigated. These non-bonded interactions are important to avoid the nanotubes from self-intersection or penetration and govern the morphology of the buckled tubes. The simulation model is based on a molecular statics approach embedded in the finite element framework. The search for equilibrium configurations of the structure leads to a non-linear system of equations, which is linearised and solved iteratively. Therefore, the model relies on the fully non-linear description of the interatomic potential and the atomic kinematics. Stability points of the loaded carbon nanotubes are detected by an accompanying eigenvalue analysis in combination with a bisection algorithm. By means of branch switching, the continuation of the non-linear load-deformation path in the postbuckling regime is enabled. With this framework, the buckling characteristics of carbon nanotubes in consequence of different loading conditions is studied. Results of numerical simulations are given for carbon nanotubes under torsion, axial compression and bending.

Ashok V. Kumar and Premdheepak S. Periyasamy (Ashok V. Kumar, Department of Mechanical and Aerospace Engineering, University of Florida, P.O. Box 116250, Gainesville, FL 32611-6250), “Mesh independent analysis of shell-like structures”, International Journal of Numerical Methods in Engineering, Vol. 91, No. 5, pp 472-490, August 2012

ABSTRACT: Mesh independent analysis is motivated by the desire to use accurate geometric models represented as equations rather than approximated by a mesh. The trial and test functions are approximated or interpolated on a background mesh that is independent of the geometry. This background mesh is easy to generate because it does not have to conform to the geometry. Essential boundary conditions can be applied using the implicit boundary method where the trial and test functions are constructed utilizing approximate step functions such that the boundary conditions are guaranteed to be satisfied. This approach has been demonstrated for two-dimensional (2D) and three-dimensional (3D) structural analysis and is extended in this paper to model shell-like structures. The background mesh consists of 3D elements that use uniform B-spline approximations,
and the shell geometry is assumed to be defined as parametric surfaces to allow arbitrarily complex shell-like structures to be modeled. Several benchmark problems are used to study the validity of these 3D B-spline shell elements.


ABSTRACT: This paper presents a novel numerical procedure based on the framework of isogeometric analysis for static, free vibration, and buckling analysis of laminated composite plates using the first-order shear deformation theory. The isogeometric approach utilizes non-uniform rational B-splines to implement for the quadratic, cubic, and quartic elements. Shear locking problem still exists in the stiffness formulation, and hence, it can be significantly alleviated by a stabilization technique. Several numerical examples are presented to show the performance of the method, and the results obtained are compared with other available ones.

References listed at the end of the paper:
52. Rabczuk T, Areias PMA. A meshfree thin shell for arbitrary evolving cracks based on an external enrichment. Computer Methods
70. Ferreira AJM, Batra RC, Roque CMC, Qian LF, Jorge RMN. Natural frequencies of functionally graded plates by a meshfree method. Composite Structures 2006; 75(1-4):593–600.
ABSTRACT: This paper investigates a computational strategy for studying the interactions between multiple through-the-width delaminations and global or local buckling in composite laminates taking into account possible contact between the delaminated surfaces. To achieve an accurate prediction of the quasi-static response, a very refined discretization of the structure is required, leading to the resolution of very large and highly nonlinear numerical problems. In this paper, a nonlinear finite element formulation along with a parallel iterative scheme based on a multiscale domain decomposition is used for the computation of three-dimensional mesoscale models. Previous works by the authors already dealt with the simulation of multiscale delamination assuming small perturbations. This paper presents the formulation used to include geometric nonlinearities into this existing multiscale framework and discusses the adaptations that need to be made to the iterative process to ensure the rapid convergence and the scalability of the method in the presence of buckling and delamination. These various adaptations are illustrated by simulations involving large numbers of DOFs.


ABSTRACT: This paper investigates a computational strategy for studying the interactions between multiple through-the-width delaminations and global or local buckling in composite laminates taking into account possible contact between the delaminated surfaces. To achieve an accurate prediction of the quasi-static response, a very refined discretization of the structure is required, leading to the resolution of very large and highly nonlinear numerical problems. In this paper, a nonlinear finite element formulation along with a parallel iterative scheme based on a multiscale domain decomposition is used for the computation of three-dimensional mesoscale models. Previous works by the authors already dealt with the simulation of multiscale delamination assuming small perturbations. This paper presents the formulation used to include geometric nonlinearities into this existing multiscale framework and discusses the adaptations that need to be made to the iterative process to ensure the rapid convergence and the scalability of the method in the presence of buckling and delamination. These various adaptations are illustrated by simulations involving large numbers of DOFs.


ABSTRACT: Fiber-reinforced layers are very popular in industry but are prone to structural instabilities observed in various experimental and technological environments. Such situations combine global inplane
buckling of the reinforcing fibers and local shearing or compression of the filling material. The purpose of the work is to develop an enriched macroscopic model able to treat both aspects through an adequate kinematic and energetic description of the different components and their coupling. It introduces, in addition to the filling material, a surface density of rods able to resist against inplane and outplane bending. A new finite element model is then developed at macroscopic level and validated in different asymptotic or postbuckling regimes.


ABSTRACT: We present a method for finding solutions of large-scale binary programming problems where the calculation of derivatives is very expensive. We then apply this method to a topology optimization problem of weight minimization subject to compliance and buckling constraints. We derive an analytic expression for the derivative of the stress stiffness matrix with respect to the density of an element in the finite-element setting. Results are presented for a number of two-dimensional test problems.


ABSTRACT: Because of its ability to take into account discontinuities, the discontinuous Galerkin (DG) method presents some advantages for modeling cracks initiation and propagation. This concept has been recently applied to three-dimensional simulations and to elastic thin bodies. In this last case, the assumption of small elastic deformations before cracks initiation or propagation reduces drastically the applicability of the framework to a reduced number of materials. To remove this limitation, a full-DG formulation of nonlinear Kirchhoff–Love shells is presented and is used in combination with an elasto-plastic finite deformations model. The results obtained by this new formulation are in agreement with other continuum elasto-plastic shell formulations. Then, this full-DG formulation of Kirchhoff–Love shells is coupled with the cohesive zone model to perform thin body fracture simulations. As this method considers elasto-plastic constitutive laws in combination with the cohesive model, accurate results compared with the experiments are found. In particular, the crack path and propagation rate of a blasted cylinder are shown to match experimental results. One of the main advantages of this framework is its ability to run in parallel with a high speed-up factor, allowing the simulation of ultra fine meshes.


ABSTRACT: The present paper considers the linear static analysis of composite cylindrical structures by means of a shell finite element with variable through-the-thickness kinematic. The refined models used are grouped in the Unified Formulation by Carrera (CUF), and they permit to accurately describe the distribution of displacements and stresses along the thickness of the multilayered shell. The shell element has nine nodes, and the mixed interpolation of tensorial components method is employed to contrast the membrane and shear
locking phenomenon. Different composite cylindrical shells are analyzed, with various laminations and thickness ratios. The governing equations are derived from the principle of virtual displacement in order to apply the finite element method. The results, obtained with different theories contained in the CUF, are compared with both the elasticity solutions given in the literature and the analytical solutions obtained using Navier's method. From the analysis, one can conclude that the shell element based on the CUF is very efficient, and its use is mandatory with respect to the classical models in the study of composite structures.


ABSTRACT: The paper concerns a well-known two-dimensional nine-node quadrilateral element MITC9, which is based on two-level approximations of strains (assumed strain method). The element has good accuracy, but does not pass the patch test. As the first improvement, we propose a modification of the element's transformations, partly resolving the problem with the patch test. The source of the problem is the use of covariant components in a (local) natural co-basis, different at each sampling point. As the second improvement, we use the corrected shape functions of Celia MA, Gray WG. An improved isoparametric transformation for finite element analysis. International Journal for Numerical Methods in Engineering 1984; 20:1447–1459, extending their applicability to the nine-node element for plane elasticity and the $3 \times 3$ integration. Originally, they are tested for an eight-node element for the heat conduction equation and the $4 \times 4$ integration. The improved element, designated as MITC9i, is based on the Green strain and derived from the potential energy for the plane stress condition. It is subjected to a range of tests, to confirm that it passes the patch test for several types of mesh distortions, to prove its coarse mesh accuracy and the absence of locking as well as to establish its sensitivity to mesh distortions. The improved element MITC9i performs substantially better than the MITC9 element, QUAD9** element, and our previous 9-AS element.


ABSTRACT: Calculations on general point-set surfaces are attractive because of their flexibility and simplicity in the preprocessing but present important challenges. The absence of a mesh makes it nontrivial to decide if two neighboring points in the three-dimensional embedding are nearby or rather far apart on the manifold. Furthermore, the topology of surfaces is generally not that of an open two-dimensional set, ruling out global parametrizations. We propose a general and simple numerical method analogous to the mathematical theory of manifolds, in which the point-set surface is described by a set of overlapping charts forming a complete atlas. We proceed in four steps: (1) partitioning of the node set into subregions of trivial topology; (2) automatic detection of the geometric structure of the surface patches by nonlinear dimensionality reduction methods; (3) parametrization of the surface using smooth meshfree (here maximum-entropy) approximants; and (4) gluing together the patch representations by means of a partition of unity. Each patch may be viewed as a meshfree macro-element. We exemplify the generality, flexibility, and accuracy of the proposed approach by numerically approximating the geometrically nonlinear Kirchhoff–Love theory of thin-shells. We analyze standard benchmark tests as well as point-set surfaces of complex geometry and topology.

ABSTRACT: In this paper a coupled two-scale shell model is presented. A variational formulation and associated linearization for the coupled global–local boundary value problem is derived. For small strain problems, various numerical solutions are computed within the so-called FE^2 method. The discretization of the shell is performed with quadrilaterals, whereas the local boundary value problems at the integration points of the shell are discretized using 8-noded or 27-noded brick elements or so-called solid shell elements. At the bottom and top surface of the representative volume element stress boundary conditions are applied, whereas at the lateral surfaces the in-plane displacements are prescribed. For the out-of-plane displacements link conditions are applied. The coupled nonlinear boundary value problems are simultaneously solved within a Newton iteration scheme. With an important test, the correct material matrix for the stress resultants assuming linear elasticity and a homogeneous continuum is verified.


ABSTRACT: This paper describes an eight-node, assumed strain, solid-shell, corotational element for geometrically nonlinear structural analysis. The locally linear kinematics of the element is separated into in-plane (which is further decoupled into membrane and bending), thickness and transverse shear components. This separation allows using any type of membrane quadrilateral formulation for the in-plane response. Assumed strain fields for the three components are constructed using different approaches. The Assumed Natural Deviatoric Strain approach is used for the in-plane response, whereas the Assumed Natural Strain approach is used for the thickness and transverse shear components. A strain enhancement based on Enhanced Assumed Strain concepts is also used for the thickness component. The resulting element passes well-known shell element patch tests and exhibits good performance in a number of challenging benchmark tests. The formulation is extended to the geometric nonlinear regime using an element-independent corotational approach. Some key properties of the corotational kinematic description are discussed. The element is tested in several well-known shell benchmarks and compared with other thin-shell and solid-shell elements available in the literature, as well as with commercial nonlinear FEM codes.


ABSTRACT: A four-node corotational quadrilateral elastoplastic shell element is presented. The local coordinate system of the element is defined by the two bisectors of the diagonal vectors generated from the four corner nodes and their cross product. This local coordinate system rotates rigidly with the element but does not deform with the element. As a result, the element rigid-body rotations are excluded in calculating the local nodal variables from the global nodal variables. The two smallest components of each nodal orientation vector are defined as rotational variables, leading to the desired additive property for all nodal variables in a nonlinear
incremental solution procedure. Different from other existing corotational finite-element formulations, the resulting element tangent stiffness matrix is symmetric owing to the commutativity of the local nodal variables in calculating the second derivative of strains with respect to these variables. For elastoplastic analyses, the Maxwell–Huber–Hencky–von Mises yield criterion is employed, together with the backward-Euler return-mapping method, for the evaluation of the elastoplastic stress state; the consistent tangent modulus matrix is derived. To eliminate locking problems, we use the assumed strain method. Several elastic patch tests and elastoplastic plate/shell problems undergoing large deformation are solved to demonstrate the computational efficiency and accuracy of the proposed formulation.


ABSTRACT: An isogeometric solid-like shell formulation is proposed in which B-spline basis functions are used to construct the mid-surface of the shell. In combination with a linear Lagrange shape function in the thickness direction, this yields a complete three-dimensional representation of the shell. The proposed shell element is implemented in a standard finite element code using Bézier extraction. The formulation is verified using different benchmark tests.


ABSTRACT: This paper extends hybrid equilibrium formulation concepts, previously used with success for planar problems, to the analysis of folded plates and curved shells. A 2D hybrid equilibrium flat shell quadrilateral element is formulated for linear analysis, where detailed consideration is given to the implication of slope discontinuity when the element is used for non-planar domains. Benchmark plate bending, folded plate and curved shell problems are modelled using equilibrium and conforming elements for comparison. In models of the latter two problems, torsional moments may be released along lines of slope discontinuity, and the effects of this assumption for the folded plate are studied by analysing a third type of model composed of 3D solid brick elements. The comparisons demonstrate an excellent performance from the new hybrid equilibrium analysis method for folded plates and curved shells.

Federica Caselli and Paolo Bisegna (Paolo Bisegna, Department of Civil Engineering and Computer Science, University of Rome ‘Tor Vergata’, 00133 Rome, Italy), “Polar decomposition based corotational framework for triangular shell elements with distributed loads”, International Journal for Numerical Methods in Engineering, Vol. 95, No. 6, pp 499-528, August 2013

ABSTRACT: A polar decomposition based corotational formulation for deriving geometrically nonlinear triangular shell elements is proposed. This formulation is novel in two aspects. (1) Original formulas for the projector operator and its variation are presented, leading to simple algorithms for the computation of the nodal residual vector and of the consistent tangent stiffness tensor. (2) For the first time in the context of a corotational kinematic description, a rigorous treatment of distributed dead and follower loads is performed, thoroughly accounting for the various contributions entailed in the residual vector and in the tangent stiffness.
Numerical simulations of popular benchmark problems are reported, showing the effectiveness of the proposed approach. An accessible and adaptable MATLAB toolkit implementing the present formulation is provided as supplementary material.


ABSTRACT: A new bilinear four-noded quadrilateral element (called quadrilateral linear refined zigzag) for the analysis of composite laminated and sandwich plates/shells based on the refined zigzag theory is presented. The element has seven kinematic variables per node. Shear locking is avoided by introducing an assumed linear shear strain field. The performance of the element is studied in several examples where the reference solution is the 3D finite element analysis using 20-noded hexahedral elements.


ABSTRACT: A new triangular thin-shell finite element formulation is presented, which employs only translational degrees of freedom. The formulation allows for large deformations, and it is based on the nonlinear Kirchhoff thin-shell theory. A number of static and dynamic test problems are considered for which analytical or benchmark solutions exist. Comparisons between the predictions of the new model and these solutions show that the new model accurately reproduces complex nonlinear analytical solutions as well as solutions obtained using existing, more complex finite element formulations.


ABSTRACT: A thin shell finite element approach based on Loop's subdivision surfaces is proposed, capable of dealing with large deformations and anisotropic growth. To this end, the Kirchhoff–Love theory of thin shells is derived and extended to allow for arbitrary in-plane growth. The simplicity and computational efficiency of the subdivision thin shell elements is outstanding, which is demonstrated on a few standard loading benchmarks. With this powerful tool at hand, we demonstrate the broad range of possible applications by numerical solution of several growth scenarios, ranging from the uniform growth of a sphere, to boundary instabilities induced by large anisotropic growth. Finally, it is shown that the problem of a slowly and uniformly growing sheet confined in a fixed hollow sphere is equivalent to the inverse process where a sheet of fixed size is slowly crumpled in a shrinking hollow sphere in the frictionless, quasistatic, elastic limit.

ABSTRACT: Piezoelectric materials are increasingly employed throughout the field of sensor and actuator applications. The physical description leads to a boundary value problem with electromechanically coupled differential equations that can be solved approximatively, for example, by the FEM. As the structures usually are quite thin, piezoelectric shell elements are very well suited for this task. In piezoelectric materials, the mechanical and the electrical fields are coupled by the constitutive relations. Especially for problems dominated by bending, this results in incompatibilities when using element formulations where the mechanical and the electrical DOFs are interpolated with lowest order functions. As a consequence, parasitic approximations and incorrect computation results occur. The present work proposes a concept to avoid these incompatible approximation spaces and the occurring computation errors when dealing with thin structures. The element is based on a mixed variational formulation and uses six mechanical and two electrical nodal DOFs. It employs the Reissner–Mindlin kinematics, considers strains throughout the thickness, and allows for 3D-electromechanical constitutive relations. Numerical examples show that the element formulation is electromechanically consistent and enables to analyze piezoelectric shell structures without parasitic approximations for all typical load cases.


ABSTRACT: The paper is concerned with variational sensitivity analysis of a nonlinear solid shell element, which is based on the Hu–Washizu variational principle. The sensitivity information is derived on the continuous level and discretized to yield the analytical expressions on the computational level. Especially, the pseudo load matrix and the sensitivity matrix, which dominate design sensitivity analysis of shape optimization problems, are derived. Because of the mixed formulation, condensation of the pseudo load matrix on the element level is performed to compute the sensitivity matrix. An illustrative example from the field of geometry-based shape optimization demonstrates the possible application of the presented formulation.


ABSTRACT: A new approach termed the Koiter-Newton is presented for the numerical solution of a class of elastic nonlinear structural response problems. It is a combination of a reduction method inspired by Koiter's post-buckling analysis and Newton arc-length method so that it is accurate over the entire equilibrium path and also computationally efficient in the presence of buckling. Finite element implementation based on element independent co-rotational formulation is used. Various numerical examples of buckling sensitive structures are presented to evaluate the performance of the method. The examples demonstrate that the method is robust and completely automatic and that it outperforms traditional path-following techniques. This improved efficiency will open the door for the direct use of detailed nonlinear finite element models in the design optimization of next generation flight and launch vehicles.

Andreas Apostolatos, Robert Schmidt, Roland Wuechner and Kai-Uwe Bletzinger (Apostolatos: T.U. Munich, Germany), “A Nitsche-type formulation and comparison of the most common domain decomposition methods
ABSTRACT: This paper provides a detailed elaboration and assessment of the most common domain decomposition methods for their application in isogeometric analysis. The methods comprise a penalty approach, Lagrange multiplier methods, and a Nitsche-type method. For the Nitsche method, a new stabilized formulation is developed in the context of isogeometric analysis to guarantee coercivity. All these methods are investigated on problems of linear elasticity and eigenfrequency analysis in 2D. In particular, focus is put on non-uniform rational B-spline patches which join nonconformingly along their common interface. Thus, the application of isogeometric analysis is extended to multi-patches, which can have an arbitrary parametrization on the adjacent edges. Moreover, it has been shown that the unique properties provided by isogeometric analysis, that is, high-order functions and smoothness across the element boundaries, carry over for the analysis of multiple domains.

ABSTRACT: An approach is proposed to incorporate gradient-enhanced damage models in shell elements. The approach is elaborated for a solid-like shell element, which is advantageous because of the availability of nodes at the top and bottom shell surfaces, and the presence of a three-dimensional strain state. Some simple examples are given to demonstrate the versatility and the convergence of the method.

ABSTRACT: Finite element method (FEM) with fixed representative volume element (RVE) encounters some difficulties in simulating the periodical postbuckling behaviors of infinite long beam or infinite large film on soft substrate under compression, because the wavelength and pattern of buckling are not known before simulation and will change with the increase of compression strain. In this paper, an adaptive periodical RVE is constructed in a mapping space to avoid remeshing in the real space, and the mapping coefficients, that is, the dimension and shape of RVE in real space, are treated as variables in average energy density minimization to obtain correct postbuckling configurations. The validness and efficiency of the proposed algorithm have been demonstrated by our numerical examples.

ABSTRACT: A rigorous computational framework for the dimensional reduction of discrete, high-fidelity, nonlinear, finite element structural dynamics models is presented. It is based on the pre-computation of solution snapshots, their compression into a reduced-order basis, and the Galerkin projection of the given discrete high-dimensional model onto this basis. To this effect, this framework distinguishes between vector-valued displacements and manifold-valued finite rotations. To minimize computational complexity, it also differentiates between the cases of constant and configuration-dependent mass matrices. Like most projection-based nonlinear model reduction methods, however, its computational efficiency hinges not only on the ability
of the constructed reduced-order basis to capture the dominant features of the solution of interest but also on the ability of this framework to compute fast and accurate approximations of the projection onto a subspace of tangent matrices and/or force vectors. The computation of the latter approximations is often referred to in the literature as hyper reduction. Hence, this paper also presents the energy-conserving sampling and weighting (ECSW) hyper reduction method for discrete (or semi-discrete), nonlinear, finite element structural dynamics models. Based on mesh sampling and the principle of virtual work, ECSW is natural for finite element computations and preserves an important energetic aspect of the high-dimensional finite element model to be reduced. Equipped with this hyper reduction procedure, the aforementioned Galerkin projection framework is first demonstrated for several academic but challenging problems. Then, its potential for the effective solution of real problems is highlighted with the realistic simulation of the transient response of a vehicle to an underbody blast event. For this problem, the proposed nonlinear model reduction framework reduces the CPU time required by a typical high-dimensional model by up to four orders of magnitude while maintaining a good level of accuracy.

ABSTRACT: Most papers on topology optimization consider that there is a linear relation between the strains and displacements of the structure, implicitly assuming that the displacements of the structure are small. However, when the external loads applied to the structure are large, the displacements also become large, so it is necessary to suppose that there is a nonlinear relation between strains and displacements. In this case, we say that the structure is geometrically nonlinear. In practice, this means that the linear system that needs to be solved each time the objective function of the problem is evaluated is replaced by an ill-conditioned nonlinear system of equations. Moreover, the stiffness matrix and the derivatives of the problem also become harder to compute. The objective of this work is to solve topology optimization problems under large displacements through a new optimization algorithm, named sequential piecewise linear programming. This method relies on the solution of convex piecewise linear programming subproblems that include second order information about the objective function. To speed up the algorithm, these subproblems are converted into linear programming ones. The new algorithm is not only globally convergent to stationary points but our numerical experiments also show that it is efficient and robust.

ABSTRACT: In the present paper, a meshless generalized multiple fixed least squares implementation of the geometrically exact Kirchhoff–Love shell theory is described. The material time derivative of the deformation gradient and the first Piola–Kirchhoff stress tensor are considered as basic conjugate quantities to evaluate the internal power. The shell's initial geometry is reproduced exactly by the predefined mapping from a reference plane configuration. As a constitutive model, a neo-Hookean material, whose functional is altered in compliance with the plane stress condition, is chosen. The augmented weak form, suitable for both interpolative and non-interpolative approximations thanks to the imposition of the essential boundary conditions through Lagrange multipliers, is consistently linearized, and the resultant bilinear form proved to be symmetric. The appearance of the corner reactions, related to the jumps of the pseudo-torsion boundary moment, requires the inclusion of additional pointwise displacement constraints at the essential boundary corners. The importance of
these quantities is demonstrated in the numerical tests, revealing its positive influence on the displacements and, particularly, their derivatives (up to 3rd order) in both linear and nonlinear problems. The possibility of incorporation of drilling boundary moment for nonlinear problems was successfully assessed.

ABSTRACT: The use of solid-shell elements in explicit dynamics has been so far limited by the small critical time step resulting from the small thickness of these elements in comparison with the in-plane dimensions. To reduce the element highest eigenfrequency in inertia dominated problems, the selective mass scaling approach previously proposed in [G. Cocchetti, M. Pagani and U. Perego, Comp. & Struct. 2013; 127:39-52.] for parallelepiped elements is here reformulated for distorted solid-shell elements. The two following objectives are achieved: the critical time step is governed by the smallest element in-plane dimension and not anymore by the thickness; the mass matrix remains diagonal after the selective mass scaling. The proposed approach makes reference to one Gauss point, trilinear brick element, for which the maximum eigenfrequency can be computed analytically. For this element, it is shown that the proposed mass scaling can be interpreted as a geometric thickness scaling, obtaining in this way a simple criterion for the definition of the optimal mass scaling factor. A strategy for the effective computation of the element maximum eigenfrequency is also proposed. The considered mass scaling preserves the element translational inertia, while it modifies the rotational one, leading to errors in the kinetic energy when the motion rotational component is dominant. The error has been rigorously assessed for an individual element, and a simple formula for its estimate has been derived. Numerical tests, both in small and large displacements and rotations, using a state-of-the-art solid-shell element taken from the literature, confirm the effectiveness and accuracy of the proposed approach.

ABSTRACT: In this work, we develop an isogeometric non-uniform rational B-spline (NURBS)-based solid-shell element for the geometrically nonlinear static analysis of elastic shell structures. A single layer of continuous 3D elements through the thickness of the shell is considered, and the order of approximation in that direction is chosen to be equal to two. A complete 3D constitutive relation is assumed. The objective is to develop a highly accurate low-order element for coarse meshes. We propose an extension of the mixed method of Bouclier et al. [11] to deal with locking in the context of large rotations and large displacements. The main idea is to modify the interpolation of the average through the thickness of the stress components. It is also necessary to stabilize the element in order to avoid the occurrence of spurious zero-energy modes. This was achieved, for the quadratic version, through the adjunction of artificial elementary stabilization stiffnesses. The result is an element of order 2, which is at least as accurate as standard NURBS shell elements of order 4. Linear and nonlinear test calculations have been carried out along with comparisons with other published NURBS and classical techniques in order to assess the performance of the element.

ABSTRACT: A continuum shell element based on the isogeometric analysis concept is extended to model propagating delaminations that can occur in composite materials and structures. The interpolation in the thickness direction is carried out using a quadratic B-spline, and delamination is modelled by a double-knot insertion to reduce the inter-layer continuity. Within the discontinuity, the traction is derived from the relative displacement between the layers by a cohesive relation. A range of examples, including delamination propagation in straight and curved planes and buckling-delamination, illustrate the versatility and the potential of the approach.


ABSTRACT: This paper presents a generalized FEM based on the solution of interdependent coarse-scale (global) and fine-scale (local) problems in order to resolve multiscale effects due to fine-scale heterogeneities. Overall structural behavior is captured by the global problem, while local problems focus on the resolution of fine-scale solution features in regions where material heterogeneities may govern the structural response. Fine-scale problems are accurately solved in parallel, and, to address the intrinsic coupling of scales, these solutions are embedded into the global solution space using a partition of unity approach. This method is demonstrated on representative heat transfer examples in order to examine its accuracy, efficiency, and flexibility.


ABSTRACT: Computational structural dynamics plays an essential role in the simulation of linear and nonlinear systems. Indeed, the characteristics of the time integration procedure have a critical impact on the feasibility of the calculation. In order to go beyond the classical approach (a unique time integrator and a unique timescale), the pioneer approach of Belytschko and co-workers consisted in developing mixed implicit–explicit time integrators for structural dynamics. In a first step, the implementation and stability analyses of partitioned integrators with one time step have been achieved for a large class of time integrators. In a second step, the implementation and stability analyses of partitioned integrators with different time steps were studied in detail for particular cases. However, stability results involving different time steps and different time integrators in different parts of the mesh is still an open question in the general case for structural dynamics. The aim of this paper is to propose a state-of-the-art of heterogeneous (different time schemes) asynchronous (different time steps) time integrators (HATI) for computational structural dynamics. Finally, an alternative approach based on energy considerations (with velocity continuity at the interface) is proposed in order to develop a general class of HATI for structural dynamics.


ABSTRACT: We demonstrate the potential of collocation methods for efficient higher-order analysis on standard nodal finite element meshes. We focus on a collocation method that is variationally consistent and geometrically flexible, converges optimally, embraces concepts of reduced quadrature, and leads to symmetric stiffness and diagonal consistent mass matrices. At the same time, it minimizes the evaluation cost per
quadrature point, thus reducing formation and assembly effort significantly with respect to standard Galerkin finite element methods. We provide a detailed review of all components of the technology in the context of elastodynamics, that is, weighted residual formulation, nodal basis functions on Gauss–Lobatto quadrature points, and symmetrization by averaging with the ultra-weak formulation. We quantify potential gains by comparing the computational efficiency of collocated and standard finite elements in terms of basic operation counts and timings. Our results show that collocation is significantly less expensive for problems dominated by the formation and assembly effort, such as higher-order elastostatic analysis. Furthermore, we illustrate the potential of collocation for efficient higher-order explicit dynamics. Throughout this work, we advocate a straightforward implementation based on simple modifications of standard finite element codes. We also point out the close connection to spectral element methods, where many of the key ideas are already established.


ABSTRACT: A numerical model to deal with nonlinear elastodynamics involving large rotations within the framework of the finite element based on NURBS (Non-Uniform Rational B-Spline) basis is presented. A comprehensive kinematical description using a corotational approach and an orthogonal tensor given by the exact polar decomposition is adopted. The state equation is written in terms of corotational variables according to the hypoelastic theory, relating the Jaumann derivative of the Cauchy stress to the Eulerian strain rate. The generalized-α method (Gα) method and Generalized Energy-Momentum Method with an additional parameter (GEMM+ξ) are employed in order to obtain a stable and controllable dissipative time-stepping scheme with algorithmic conservative properties for nonlinear dynamic analyses. The main contribution is to show that the energy–momentum conservation properties and numerical stability may be improved once a NURBS-based FEM in the spatial discretization is used. Also it is shown that high continuity can postpone the numerical instability when GEMM+ξ with consistent mass is employed; likewise, increasing the continuity class yields a decrease in the numerical dissipation. A parametric study is carried out in order to show the stability and energy budget in terms of several properties such as continuity class, spectral radius and lumped as well as consistent mass matrices.


ABSTRACT: In this contribution, a mortar-type method for the coupling of non-conforming NURBS (Non-Uniform Rational B-spline) surface patches is proposed. The connection of non-conforming patches with shared degrees of freedom requires mutual refinement, which propagates throughout the whole patch due to the tensor-product structure of NURBS surfaces. Thus, methods to handle non-conforming meshes are essential in NURBS-based isogeometric analysis. The main objective of this work is to provide a simple and efficient way to couple the individual patches of complex geometrical models without altering the variational formulation. The deformations of the interface control points of adjacent patches are interrelated with a master-slave relation. This relation is established numerically using the weak form of the equality of mutual deformations along the interface. With the help of this relation, the interface degrees of freedom of the slave patch can be condensed out of the system. A natural connection of the patches is attained without additional terms in the weak form. The proposed method is also applicable for nonlinear computations without further measures. Linear and
ABSTRACT: A description is given of the development and use of the Reproducing Kernel Particle Finite Strip Method for the buckling and flexural vibration analysis of plates with intermediate supports and step thickness changes. The generalized 1-D shape functions of the Reproducing Kernel Particle Method replace the spline functions in the conventional spline finite strip method in the longitudinal direction. The structure of the generalized Reproducing Kernel Particle Method makes it a suitable tool for dealing with derivative-type essential boundary conditions, and its introduction in the finite strip method is beneficial for solving buckling and vibration problems for thin plates in which a number of the essential boundary conditions can include the first derivatives of the displacement function. Moreover, the modified corrected collocation method is further developed for the buckling and free vibration analysis of plates with abrupt thickness changes. This provides a versatile and powerful analysis capability which facilitates the analysis of problems including plate structures with abrupt thickness changes of its component plates. The application of the proposed technique for the treatment of discontinuities and the enforcement of the internal support conditions are illustrated with a series of numerical examples.

ABSTRACT: In this paper, a framework for computational homogenization of shell structures is proposed in the context of small-strain elastostatics, with extensions to large displacements and large rotations. At the macroscopic scale, heterogeneous thin structures are modeled using a homogenized shell model, based on a versatile three-dimensional seven-parameter shell formulation, incorporating a through-thickness and pre-integrated constitutive relationship. In the context of small strains, we show that the local solution on the elementary cell can be decomposed into six strains and six-strain gradient modes, associated with corresponding boundary conditions. The heterogeneities can have arbitrary morphology but are assumed to be periodically distributed in the tangential direction of the shell. We then propose an extension of the small-strain framework to geometrical nonlinearities. The procedure is purely sequential and does not involve coupling between scales. The homogenization method is validated and illustrated through examples involving large displacements and buckling of heterogeneous plates and shells.

ABSTRACT: In this paper, a novel reduced integration eight-node solid-shell finite element formulation with hourglass stabilization is proposed. The enhanced assumed strain method is adopted to eliminate the well-known volumetric and Poisson thickness locking phenomena with only one internal variable required. In order to alleviate the transverse shear and trapezoidal locking and correct rank deficiency simultaneously, the assumed natural strain method is implemented in conjunction with the Taylor expansion of the inverse Jacobian.
matrix. The projection of the hourglass strain-displacement matrix and reconstruction of its transverse shear components are further employed to avoid excessive hourglass stiffness. The proposed solid-shell element formulation successfully passes both the membrane and bending stiffness tests. Several typical examples are presented to demonstrate the excellent performance and extensive applicability of the proposed element.


ABSTRACT: We show both theoretically and numerically a connection between the smoothed finite element method (SFEM) and the virtual element method and use this approach to derive stable, cheap and optimally convergent polyhedral FEM. We show that the stiffness matrix computed with one subcell SFEM is identical to the consistency term of the virtual element method, irrespective of the topology of the element, as long as the shape functions vary linearly on the boundary. Using this connection, we propose a new stable approach to strain smoothing for polygonal/polyhedral elements where, instead of using sub-triangulations, we are able to use one single polygonal/polyhedral subcell for each element while maintaining stability. For a similar number of degrees of freedom, the proposed approach is more accurate than the conventional SFEM with triangular subcells. The time to compute the stiffness matrix scales with the [math] in case of the conventional polygonal FEM, while it scales as [math] in the proposed approach. The accuracy and the convergence properties of the SFEM are studied with a few benchmark problems in 2D and 3D linear elasticity.


ABSTRACT: A principal issue in any co-rotational approach for large displacement analysis of plates and shells is associated with the specific choice of the local reference system in relation to the current deformed element configuration. Previous approaches utilised local co-rotational systems, which are invariant to nodal ordering, a characteristic that is deemed desirable on several fronts; however, the associated definitions of the local reference system suffered from a range of shortcomings, including undue complexity, dependence on the local element formulation and possibly an asymmetric tangent stiffness matrix. In this paper, new definitions of the local co-rotational system are proposed for quadrilateral and triangular shell elements, which achieve the invariance characteristic to the nodal ordering in a relatively simple manner and address the aforementioned shortcomings. The proposed definitions utilise only the nodal coordinates in the deformed configuration, where two alternative definitions, namely, bisector and zero-macrospin definitions, are presented for each of quadrilateral and triangular finite elements. In each case, the co-rotational transformations linking the local and global element entities are presented, highlighting the simplicity of the proposed approach. Several numerical examples are finally presented to demonstrate the effectiveness and relative accuracy of the alternative definitions proposed for the local co-rotational system.


ABSTRACT: A degenerated shell element with composite implicit time integration scheme is developed in the present paper to solve the geometric nonlinear large deformation and dynamics problems of shell structures. The degenerated shell element is established based on the eight-node solid element, where the nodal forces,
mass matrices, and stiffness matrices are firstly obtained upon virtual velocity principle and then translated to the shell element. The strain field is modified based on the mixed interpolation of tensorial components method to eliminate the shear locking, and the constitutive relation is modified to satisfy the shell assumptions. A simple and practical computational method for nonlinear dynamic response is developed by embedding the composite implicit time integration scheme into the degenerated shell element, where the composite scheme combines the trapezoidal rule with the three-point backward Euler method. The developed approach can not only keep the momentum and energy conservation and decay the high frequency modes but also lead to a symmetrical stiffness matrix. Numerical results show that the developed degenerated shell element with the composite implicit time integration scheme is capable of solving the geometric nonlinear large deformation and dynamics problems of the shell structures with momentum and energy conservation and/or decay.


ABSTRACT: This paper proposed a rotation-free thin shell formulation with nodal integration for elastic–static, free vibration, and explicit dynamic analyses of structures using three-node triangular cells and linear interpolation functions. The formulation is based on the classic Kirchhoff plate theory, in which only three translational displacements are treated as the filed variables. Based on each node, the integration domains are further formed, where the generalized gradient smoothing technique and Green divergence theorem that can relax the continuity requirement for trial function are used to construct the curvature field. With the aid of strain smoothing operation and tensor transformation rule, the smoothed strains in the integration domain can be finally expressed by constants. The principle of virtual work is then used to establish the discretized system equations. The translational boundary conditions are imposed same as the practice of standard finite element method, while the rotational boundary conditions are constrained in the process of constructing the smoothed curvature filed. To test the performance of the present formulation, several numerical examples, including both benchmark problems and practical engineering cases, are studied. The results demonstrate that the present method possesses better accuracy and higher efficiency for both static and dynamic problems.


ABSTRACT: In this paper, a continuum membrane theory and its subsequent finite element approximation for the description of arbitrary shell-like nanostructures such as graphene-based nanostructures is presented. This is carried out by applying a multiscale approach where the continuum membrane is linked to the underlying atomistic lattice. This linkage is performed by the exponential generalization of the Cauchy–Born hypothesis, because the classical Cauchy–Born hypothesis is restricted to three-dimensional bulk structures and is thus not applicable to shell-like structures. However, the approximations of the exponential Cauchy–Born hypothesis published so far are limited to structures with a planar reference configuration. In this paper, we present an extended approximation, which does not require the reference configuration to be planar and is thus applicable to arbitrarily shaped shell-like nanostructures. A detailed elaboration of the related finite element implementation with important computational aspects is presented. Finally, the accuracy of the proposed method and its implementation is verified with several numerical examples.
ABSTRACT: The investigation aims to formulate ground-structure based topology optimization approach by using a higher-order beam theory suitable for thin-walled box beam structures. While earlier studies use the Timoshenko or Euler beams to form a ground-structure, they are not suitable for a structure consisting of thin-walled closed beams. The higher-order beam theory takes into an additional account sectional deformations of a thin-walled box beam such as warping and distortion. Therefore, a method to connect ground beams at a joint and a technique to represent different joint connectivity states should be investigated for streamlined topology optimization. Several numerical case studies involving different loading and boundary conditions are considered to show the effectiveness of employing a higher-order beam theory for the ground-structure based topology optimization of thin-walled box beam structures. Through the numerical results, this work shows significant difference between optimized beam layouts based on the Timoshenko beam theory and those based on a more accurate higher-order beam theory for a structure consisting of thin-walled box beams.

ABSTRACT: Model Order Reduction (MOR) methods are extremely useful to reduce processing time, even nowadays, when parallel processing is possible in any personal computer. This work describes a method that combines Proper Orthogonal Decomposition (POD) and Ritz vectors to achieve an efficient Galerkin projection, which changes during nonlinear solving (online analysis). It is supported by a new adaptive strategy, which analyzes the error and the convergence rate for nonlinear dynamical problems. This model order reduction is assisted by a secant formulation which is updated by the Broyden-Fletcher-Goldfarb-Shanno (BFGS) formula to accelerate convergence in the reduced space, and a tangent formulation when correction of the reduced space is needed. Furthermore, this research shows that this adaptive strategy permits correction of the reduced model at low cost and small error.

ABSTRACT: The equations that govern Kirchhoff-Love plate theory are solved using quadratic Powell-Sabin B-splines and unstructured standard T-splines. Bézier extraction is exploited to make the formulation computationally efficient. Because quadratic Powell-Sabin B-splines result in C1A-continuous shape functions, they are of sufficiently high continuity to capture Kirchhoff-Love plate theory when cast in a weak form. Unlike non-uniform rational B-splines (NURBS), which are commonly used in isogeometric analysis, Powell-Sabin B-splines do not necessarily capture the geometry exactly. However, the fact that they are defined on triangles instead of on quadrilaterals increases their flexibility in meshing and can make them competitive with respect to NURBS, as no bending strip method for joined NURBS patches is needed. This paper further illustrates how unstructured T-splines can be modified such that they are C1A-continuous around extraordinary points, and that the blending functions fulfil the partition of unity property. The performance of quadratic NURBS, unstructured T-splines, Powell-Sabin B-splines and NURBS-to-NURPS (non-uniform rational Powell-Sabin B-splines, which are obtained by a transformation from a NURBS patch) is compared in a study of a circular plate.
ABSTRACT: Linear buckling constraints are important in structural topology optimization for obtaining designs that can support the required loads without failure. During the optimization process, the critical buckling eigenmode can change; this poses a challenge to gradient-based optimization and can require the computation of a large number of linear buckling eigenmodes. This is potentially both computationally difficult to achieve and prohibitively expensive. In this paper, we motivate the need for a large number of linear buckling modes and show how several features of the block Jacobi conjugate gradient (BJCG) eigenvalue method, including optimal shift estimates, the reuse of eigenvectors, adaptive eigenvector tolerances and multiple shifts, can be used to efficiently and robustly compute a large number of buckling eigenmodes. This paper also introduces linear buckling constraints for level-set topology optimization. In our approach, the velocity function is defined as a weighted sum of the shape sensitivities for the objective and constraint functions. The weights are found by solving an optimization sub-problem to reduce the mass while maintaining feasibility of the buckling constraints. The effectiveness of this approach in combination with the BJCG method is demonstrated using a 3D optimization problem.

ABSTRACT: This paper proposes a first step towards a framework to develop shell elements applicable to any deformation regime. Here, we apply it to the large and moderate deformations of, respectively, plates and shells, showing with standard benchmarks that the resulting low-order discretization is competitive against the best elements for either membrane-dominated or bending-dominated scenarios. Additionally, we propose a new test for measuring membrane locking, which highlights the mesh-independence properties of our element. Our strategy is based on building a discrete model that mimics the smooth behavior by construction, rather than discretizing a smooth energy. The proposed framework consists of two steps: (i) defining a discrete kinematics by means of constraints and (ii) formulating an energy that vanishes on such a constraint manifold. We achieve (i) by considering each triangle as a tensegrity structure, constructed to be unstretchable but bendable isometrically (in a discrete sense). We then present a choice for (ii) based on assuming a linear strain field on each triangle, using tools from differential geometry for coupling the discrete membrane energy with our locking-free kinematic description. We argue that such a locking-free element is only a member of a new family that can be created using our framework (i) and (ii).

ABSTRACT: In this paper, a mixed variational formulation for the development of energy–momentum consistent (EMC) time-stepping schemes is proposed. The approach accommodates mixed finite elements based on a Hu–Washizu-type variational formulation in terms of displacements, Green–Lagrangian strains, and conjugated stresses. The proposed discretization in time of the mixed variational formulation under consideration yields an EMC scheme in a natural way. The newly developed methodology is applied to a high-


performance mixed shell finite element. The previously observed robustness of the mixed finite element formulation in equilibrium iterations extends to the transient regime because of the EMC discretization in time.


ABSTRACT: Thin-walled structures, when compressed, are prone to buckling. To fully utilize the capabilities of such structures, the post-buckling response should be considered and optimized in the design process. This work presents a novel method for gradient-based design optimization of the post-buckling performance of structures. The post-buckling analysis is based on Koiter's asymptotic method. To perform gradient-based optimization, the design sensitivities of the Koiter factors are derived, and new design optimization formulations based on the Koiter factors are presented. The proposed optimization formulations are demonstrated on a composite square plate and a curved panel where the post-buckling stability is optimized.


ABSTRACT: In this paper, a four-node quadrilateral flat shell element is proposed for geometrically nonlinear analysis based on updated Lagrangian formulation with the co-rotational kinematics concept. The flat shell element combines the membrane element with drilling degrees of freedom and the plate element with shear deformation. By means of these linearized elements, a simplified nonlinear analysis procedure allowing for warping of the flat shell element and large rotation is proposed. The tangent stiffness matrix and the internal force recovery are formulated in this paper. Several classic benchmark examples are presented to validate the accuracy and efficiency of the proposed new and more proficient element for practical engineering analysis of shell structures.


ABSTRACT: This paper presents an eight-node nonlinear solid-shell element for static problems. The main goal of this work is to develop a solid-shell formulation with improved membrane response compared with the previous solid-shell element (MOS2013), presented in [1]. Assumed natural strain concept is implemented to account for the transverse shear and thickness strains to circumvent the curvature thickness and transverse shear locking problems. The enhanced assumed strain approach based on the Hu–Washizu variational principle with six enhanced assumed strain degrees of freedom is applied. Five extra degrees of freedom are applied on the in-plane strains to improve the membrane response and one on the thickness strain to alleviate the volumetric and Poisson's thickness locking problems. The ensuing element performs well in both in-plane and out-of-plane responses, besides the simplicity of implementation. The element formulation yields exact solutions for both the membrane and bending patch tests. The formulation is extended to the geometrically nonlinear regime using the corotational approach, explained in [2]. Numerical results from benchmarks show the robustness of the formulation in geometrically linear and nonlinear problems.
End of many papers published in the journal, International Journal for Numerical Methods in Engineering [2012-2013; (2014-2018 were transferred to Part 2 in order not to exceed 10000 pages for this file)].

Many papers published in the journal, International Journal of Structural Stability and Dynamics (2012-2013) (2014 – 2016 were transferred to Part 2 in March 2019 in order to avoid exceeding 10000 pages in this file from including lists of references for each paper cited.)


ABSTRACT: Web crippling is the major failure mode of thin-walled members when they are subjected to concentrated loading. Carbon fiber-reinforced polymer (CFRP) is found to be promising for strengthening metallic structural members. This paper reports improved web-crippling capacity of sharp-corner aluminum tubular sections: rectangular hollow section (RHS) and square hollow section (SHS), by attaching CFRP to their webs. Twenty four specimens were tested with four CFRP strengthening configurations applied on each of six different aluminum RHS and SHS sections. Significant increase in load-carrying capacity was obtained. Further comparison is made between CFRP strengthened aluminum tubular sections and cold-formed steel counterparts in respect of strengthening efficiency. Underlying mechanism of different failure modes and strengthening efficiencies of various strengthening configurations are discussed with the assistance of FEM simulation.

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ABSTRACT: This paper presents a novel way of strengthening thin-walled steel cylindrical shells against buckling during axial compression in which a small amount of fiber-reinforced polymer (FRP) composite, coated from both sides can increase the buckling strength effectively. The effects of the reinforcement and the angle of fiber orientation as well as initial geometric imperfections on the buckling load-carrying capacity have been made clear through the three kinds of analytical procedures; the conventional linear eigen value buckling analysis, the reduced stiffness (RS) buckling analysis and the fully nonlinear numerical experiments. These multiple treatments suggest obtaining valuable information for the design of FRP-based hybrid structural elements and discusses influence of FRP to increase the load-carrying capacity of the thin-walled metallic
structures having complex buckling collapse behavior. This paper also discusses how the angle of fiber orientation affects on the buckling strength and the associated buckling modes of the thin-walled shells. References listed at the end of the paper:

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ABSTRACT: Fiber-reinforced polymer (FRP) strengthening technique to improve buckling resistance of steel members is presented in concept and experimental demonstration. The conceptual design of this method is introduced through the preliminary experiments on three specimens. Then, another 14 specimens are tested under axially compressive loading, by which the compressive behavior and the strengthening effects are investigated considering different design parameters and configuration, including the slenderness ratio, the confinement detail, the filled materials and the end connection. The strengthening effects are analyzed by the comparison of both theoretical and test results, which show that the overall buckling failure of steel members
can be prevented by FRP strengthening and the ultimate loading capacity and deformation capacity of steel members are enhanced considerably. The maximum load-bearing capacity of strengthened members is 2.86 times of the nonstrengthened ones, and the failure maintains a ductile behavior. In addition, the load-bearing capacity of the members strengthened in this way is compared with the Euler loads of the original steel member and the composite member.

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ABSTRACT: In order to have a good understanding of the failure mechanism of single-layer cylindrical reticulated shells under earthquake motions, two failure modes, that is, dynamic instability and dynamic strength failure, are studied of single-layer cylindrical reticulated shells under earthquake motion. The accumulation of material damages that may accelerate failure of these shells under dynamic actions is
considered. The relationships between the structural responses under the ultimate loads are investigated through a systematic simulation study that covers different parameters. A method is proposed for classification of failure modes of the shells, using the fuzzy synthetic evaluation theory and the structural responses of different sample studies. The effectiveness of the proposed method is proved through applications to some examples. Finally, a damage model is established for identification of different structural damage levels and for determination of the ultimate load for strength failure.

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**ABSTRACT:** Based on an inextensional two-parameter analytical model for cylindrical shells, bi-stable analyses were carried out on laminated functionally graded material (FGM) shells with various layups of fibers. Properties of FGM shells are functionally graded in the thickness direction according to a volume fraction power law distribution. The effects of constituent volume fractions of FGM matrix are examined on the curvature and twist of laminated FGM shells. The results reveal that the optimum combination of constituents of FGM matrix can be obtained for the maximum twist of FGM shells with antisymmetric layups, which helps the design of deployable structures. The effects of Young’s modulus of fibers and the symmetry of layups on bi-stable behaviors are also discussed in detail.

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ABSTRACT: The effectiveness of the measures provided in the 2005 American Institute of Steel Construction (AISC) Specification for elastic distortional buckling of doubly symmetric I-shaped flexural members with slender webs was evaluated in a previous study. It was demonstrated that the code equations generally provide conservative estimates for the slender-web I-beams, and the amount of the conservatism was found to be rather dramatic for some cases. As a continuation of this effort, the effectiveness and accuracy of the 2005 AISC code provisions as well as predictions for elastic distortional buckling of slender-web singly symmetric I-shaped members is investigated in this paper. Comparisons are made with the finite strip analysis results for distortional buckling and the two design equations for elastic distortional buckling proposed by other researchers. It is demonstrated that the code predictions are by and large conservative, and even overly conservative in some cases, which does not seem to be justifiable economically.

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ABSTRACT: This paper presents a one-dimensional (1D) finite element formulation for the nonlinear stability analysis of framed structures with semi-rigid (SR) connections. By applying the updated Lagrangian incremental formulation and the nonlinear displacement field of thin-walled cross sections, the equilibrium equations of a straight beam element are first developed. Force recovering is performed according to the external stiffness approach. Material nonlinearity is introduced for an elastic-perfectly plastic material through the plastic hinge formation at finite element ends. To account for the SR connection behavior, a special transformation procedure is developed. The effectiveness of the numerical algorithm discussed is validated through the test problems.

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ABSTRACT: An energy–balance-based analytical method and finite element (FE) simulations were developed in this paper to study the dynamic response of metallic sandwich panels subject to blast loadings. The analytical model can be used to predict approximately the deflection of the panels, while the FE model can take into account fluid–structure interactions and the effect of strain rate. Both models were validated by comparing their predictions with the test results available in the literature. Parametric studies were then carried out to assess various factors that are influential in characterizing the dynamic behavior of sandwich panels subject to blast loads.

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ABSTRACT: The dynamics and stability of rotating circular cylindrical shells partially filled with liquid is analyzed. The structural dynamics of the shell is modeled by using the first-order shear deformable shell theory and the flow inside the cylinder is simulated by a quasi 2D model based on the Navier–Stokes equations for ideal liquid. The fluid and structural models are combined using the nonpenetration condition of the flow on the wetted surface of the cylinder and the fluid pressure on the flexible shell. The obtained fluid–structure
model is employed for the determination of the stable regions of the spinning frequency of the cylinder. A series of case studies are performed on the governing parameters of the instability of the cylinder and some conclusions are outlined.

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ABSTRACT: This paper presents a numerical investigation of the feasibility of condition monitoring of unternched pipelines at seabed through ambient vibration measurements. A finite element (FE) model is developed to calculate the dynamic responses of pipelines to ambient wave forces. The model takes into consideration the interaction between the ocean waves, submarine pipeline, and seabed. The fluid around the pipeline is simulated using the acoustic fluid elements, while soil is simulated by springs and dashpots. The ambient hydrodynamic force in the marine environment is simulated based on the Joint North Sea Wave Observation Project (JONSWAP) spectrum. The transfer function from the wave surface elevation to the wave force is used to get the wave force spectrum. The dynamic responses of the pipe structure with different assumed damage conditions to the ambient wave forces are calculated. The calculated dynamic responses are assumed as measured ambient vibration data in condition monitoring to extract the pipeline vibration properties, which in turn are used in the FE model updating calculation to identify the pipeline conditions. Different noise levels are introduced into the calculated dynamic responses to simulate uncertainties that may arise from measurement and ambient hydrodynamic environment. The effect of noise levels on the extraction of pipeline vibration properties, and on the identification of the pipeline conditions is investigated.

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ABSTRACT: The property of free movement of particles allows for most meshless particle methods to be efficiently used for simulation of solid problems involving large deformation as it removes the necessity of remeshing, which is one of the time-consuming parts of the traditional finite element method based on an updated Lagrangian formulation. One of the main sources of instabilities in meshfree particle methods, which approximate the strong form of partial differential equations, is the existence of extra high frequency vibrations. They are induced into the solution due to the use of truncated Taylor series expansions. The cumulative effect of the extra vibrations makes the solution to be polluted by zero energy modes and tensile instabilities. In this paper, the CSPM particle method is used to solve elastodynamic large deformation problems based on an updated Lagrangian procedure. A field smoothing approach, recently proposed for reduction of instabilities that arise from excessive high frequency vibrations, is further extended to large deformation problems. Also, the phenomenon of particles penetration can be prevented without the requirement of any additional artificial damping forces. Another major advantage of the new approach is its generality which allows for its implementation into other particle methods and its application for solving other physical problems. A variety of large deformation problems are solved by the proposed approach and the results are compared with other available results.

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ABSTRACT: Advanced lightweight laminated composite shells are increasingly being used in modern aerospace structures, for enhancing their structural efficiency and performance. Such thin-walled structures are susceptible to buckling when subjected to static and dynamic compressive stresses. In this paper, details of a numerical (FEM) and an experimental study on buckling of carbon fiber reinforced plastics (CFRP) layered composite cylinders under displacement and load controlled static and dynamic axial compression are reported. The effects of different types of loadings, geometric properties, lamina lay-up and amplitudes of imperfection on the strength of the cylinders under compression are studied. Accurate measurement of imperfections in the cylindrical surface is carried out in the specimens tested. It is shown that the buckling behavior of thin-cylindrical shells can be evaluated accurately by modeling measured imperfections and material properties in FEM.

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ABSTRACT: A semi-analytical approach for the buckling analysis of symmetrically laminated rectangular plates under arbitrary constrains is presented. In the proposed method, the out-of-plane displacement field is assumed to be of a multiplicative form containing two vectors of functions, one being prescribed and the other to be determined, depend on separate variables. As a consequence, one may solve the equilibrium equation analytically, and obtain exact buckling loads for the biaxial compression and different boundary constrains. Several cases of plate buckling under different load combinations are studied, in order to demonstrate the applicability of the proposed approach. The results obtained are compared with the existing ones, where available in analytical form, and approximate results obtained by other numerical methods.
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ABSTRACT: In this paper, the nonlinear instability of dished shallow shells under a uniformly distributed load is investigated. The dimensionless governing differential equations for the problem are derived and the equations solved by using the Free-Parameter Perturbation Method with the Spline Function Method. By analyzing the instability modes of dished shallow shells, we obtain the variation rules of the maximum deflection area of initial instability of the uniformly loaded dished shallow shell, and discuss the relationship between the initial instability area and the maximum deflection area of initial instability. These results provide some theoretical basis for engineering design and instability prediction and control of shallow shell structures.

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ABSTRACT: In this paper, explicit local buckling analysis of orthotropic plates subjected to uniaxial compression with two loaded edges simply-supported and two unloaded edges supported by combined vertical and rotational restraining springs is presented. Based on the total potential energy function, the eigenvalue problem is formulated by treating the buckled shape functions as the admissible functions that satisfy the boundary conditions of the rectangular plates. Closed-form and approximate local buckling solutions of the combined rotationally- and vertically-restrained orthotropic plates, as well as explicit formulas for the critical buckling load and critical aspect ratio under the uniform compression, are obtained. By adjusting the stiffness of the rotational and vertical restraining springs, explicit local buckling solutions are established for eight simple cases of boundary conditions. To verify the explicit solutions, numerical analyses of orthotropic plates using the exact transcendental and finite element methods are conducted, for which reasonable agreement has been obtained between the explicit and numerical solutions, particularly for the simplified cases. The explicit solution obtained in this study can be used to facilitate the buckling analysis of composite laminated structures with different boundary conditions or joint connections as parts of stiffened and thin-walled structures by treating them as discrete plates with restrained boundary conditions.

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dynamic instability of the disk. The corresponding nonconservative eigenvalue problem is formulated based on the modal expansion theory for traveling waves and direct discretization technique. The brake pad or stator is modeled as a second order viscoelastic subgrade that reacts to both transverse and shearing motion of the disc brake rotor. The instability behavior of the disk is investigated by examining the resulting complex eigenvalues under various combinations of the system parameters such as frictional traction, geometry of the disk, and viscoelastic properties of the pad lining. In order to assess the effects of shear deformations and rotary inertia of the disk model under such loading conditions, results are compared with those from the classical Kirchhoff–Love's thin disk model. Based on the phase angle information of the eigenvalues, it is found that there exists a critical value of friction, slenderness ratio of the disk, and the size of pad lining at which the transverse amplitude growth rates of high circumferential vibration modes drastically increase. Unless damping is present in the disc brake rotor or pad lining, vibration modes with repeated eigenvalues are found to be always unstable either by means of divergence or flutter even for a very small nonconservative traction load.

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ABSTRACT: A theoretical analysis is presented for determining the free vibrational and buckling characteristics of the nonhomogeneous, orthotropic, thin-walled, circular cylindrical and conical shells under a hydrostatic pressure and resting on a two-parameter elastic foundation. The basic relations have been obtained for the orthotropic truncated conical shell, the Young’s moduli and density of which vary continuously in the thickness direction. By applying the Galerkin method, the buckling hydrostatic pressure and dimensionless frequency parameter of the homogeneous and nonhomogeneous orthotropic truncated conical shells with or without elastic foundations are obtained. Finally, the effects of the Winkler and Pasternak-type elastic foundations, the variations of shell characteristics, the effects of the nonhomogeneity and orthotropy on the critical parameters have been studied. The results are presented in tables, figures and compared with other works.

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actuators is investigated under various axial loads, at various actuation frequencies. Both analytical and finite
proven that PBP actuators are capable of generating deflections three times higher than conventional bimorph
piezoelectric actuators while maintaining full force and moment generating capabilities. Past research has
ABSTRACT: Post
https://doi.org/10.1142/S0219455412500423
International Journal of Structural Stability and Dynamics, Vol. 12, No.. 5, 1250042, October 2012
Georgios Giannopoulos, Mark Groen, Roelof Vos and Ron Barrett (various, including Delft University of
International Journal of Structural Stability and Dynamics, Vol. 12, No.. 5, 1250042, October 2012,
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ABSTRACT: Post-buckled precompressed (PBP) piezoelectric elements have recently been used to enable a
new class of actuators that are able to provide far higher deflections compared to the traditional bimorph
piezoelectric actuators while maintaining full force and moment generating capabilities. Past research has
proven that PBP actuators are capable of generating deflections three times higher than conventional bimorph
actuators. In this paper, this work has been extended to the dynamic response realm and the performance of PBP
actuators is investigated under various axial loads, at various actuation frequencies. Both analytical and finite
element models have been developed in order to evaluate the performance of the actuator regarding the natural frequency shift under increased axial loads. Experimental verification has shown that the overall damping ratio of the structure is a function of the axial forces. Values derived from experiments have been used in the Finite Element model to predict the displacement output, phase angle shifting and end rotation. Numerical and analytical results correlate very well with the experiments and thus give credit to the formulation presented in this work.

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D. Quinn, A. Murphy and C. Glazebrook (School of Mechanical and Aerospace Engineering, Queen’s University Belfast, Ireland, UK, etc.), “Aerospace stiffened panel initial sizing with novel skin sub-stiffening features”, International Journal of Structural Stability and Dynamics, Vol. 12, No. 5, 1250060, October 2012, https://doi.org/10.1142/S0219455412500605

ABSTRACT: The introduction of skin sub-stiffening features has the potential to modify the local stability and fatigue crack growth performance of stiffened panels. Proposed herein is a method to enable initial static strength sizing of panels with such skin sub-stiffening features. The method uses bespoke skin buckling coefficients, automatically generated by Finite Element analysis and thus limits the modification to the conventional aerospace panel initial sizing process. The approach is demonstrated herein and validated for prismatic sub-stiffening features. Moreover, examination of the generated buckling coefficient data illustrates the influence of skin sub-stiffening on buckling behavior, with static strength increases typically corresponding to a reduction in the number of initial skin longitudinal buckle half-waves.

References listed at the end of the paper:

constantly increase. It increases for beam the number of nanotube walls. For slender MWCNTs, the buckling strains fluctuate as the number of walls vary inversely proportional to MWCNTs. Moreover, it is observed that the buckling strains of short MWCNT vary inversely proportional to the number of nanotube walls. For slender MWCNTs, the buckling strains fluctuate as the number of walls increase. It increases for beam-like buckling mode, decreases for shell-like buckling mode and is approximately constant for the shell-beam-like buckling mode. The increase in the length of MWCNT has also led to a

ABSTRACT: We investigate the buckling behaviors of short multi-walled carbon nanotubes (MWCNTs) under axial compression by using molecular mechanics (MM) simulations. The effects of the number of walls, length and chiral angle of MWCNTs on the buckling behaviors are examined. The results show that the buckling behaviors of short MWCNTs are rather different from single walled carbon nanotubes (SWCNTs) and slender MWCNTs. Moreover, it is observed that the buckling strains of short MWCNTs vary inversely proportional to the number of nanotube walls. For slender MWCNTs, the buckling strains fluctuate as the number of walls increase. It increases for beam-like buckling mode, decreases for shell-like buckling mode and is approximately constant for the shell-beam-like buckling mode. The increase in the length of MWCNT has also led to a
significant decrease of the buckling strain for short MWCNTs. However, chirality does not have a significant effect on the buckling strain of MWCNTs nor alter the buckling mode of short MWCNTs.

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ABSTRACT: Chaotic vibrations of functionally graded doubly curved shells subjected to concentrated harmonic load are investigated. It is assumed that the shell is simply supported and the edges can move freely in in-plane directions. Donnell's nonlinear shallow shell theory is used and the governing partial differential equations are obtained in terms of shell's transverse displacement and Airy's stress function. By using Galerkin's
procedure, the equations of motion are reduced to a set of infinite nonlinear ordinary differential equations with cubic and quadratic nonlinearities. A bifurcation analysis is carried out and the discretized equations are integrated at (i) fixed excitation frequencies and variable excitation amplitudes and (ii) fixed excitation amplitudes and variable excitation frequencies. In particular, Gear's backward differentiation formula (BDF) is used to obtain bifurcation diagrams, Poincaré maps and time histories. Furthermore, maximum Lyapunov exponent and Lyapunov spectrum are obtained to classify the rich dynamics. It is revealed that the shell may exhibit complex behavior including sub-harmonic, quasi-periodic and chaotic response when subjected to large harmonic excitations.

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ABSTRACT: A Timoshenko beam element for large displacement analysis of planar beam and frame structures is formulated in the context of the co-rotational method. The shallow arch expression is adopted for the local strain, and cubic and quadratic polynomials obtained from the field consistence approach are respectively employed to interpolate the transversal displacement and rotation. The numerical examples show that the proposed element is capable of furnishing accurate results with a smaller number of elements as compared to the elements previously used in the examples. It has also shown that the nonlinear term in the expression of the local strain plays an important role in the accuracy of the element in the large displacement analysis of beam and frame structures.

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Saroj Kumar Sarangi and M.C. Ray (First author is from: Mechanical Engineering Department, I.T.E.R., SOA University, Bhubaneswar, India), “Smart Control of Nonlinear Vibrations of Laminated Plates Using Active Fiber Composites”, Journal of Structural Stability and Dynamics, Vol. 12, No. 6, 1250050, December 2012, https://doi.org/10.1142/S0219455412500502

ABSTRACT: This paper deals with the geometrically nonlinear dynamic analysis of smart laminated composite plates integrated with the patches of active constrained layer damping (ACLD) treatment. The constraining layer of the ACLD treatment is made of active fiber composite (AFC) materials. The von Kármán type nonlinear strain–displacement relations and the first-order shear deformation theory (FSDT) are adopted in deriving the coupled electromechanical nonlinear finite element (FE) model. The Golla–Hughes–McTavish (GHM) method is implemented to model the constrained viscoelastic layer of the ACLD treatment in time domain. Symmetric/antisymmetric cross-ply and antisymmetric angle-ply laminated substrate plates are considered in the numerical analyses. The results indicate that the ACLD patches significantly improve the damping characteristics of the plates for suppressing the geometrically nonlinear transient vibrations of the plates. The effects of variation of piezoelectric fiber orientation in the AFC constraining layer on the control authority of the ACLD patches have also been investigated.

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\text{References listed at the end of the paper:} \\
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ABSTRACT: An efficient time-integration algorithm for nonlinear dynamic analysis of structures is presented. By adopting the temporal discretization for time finite element approximation, very large time steps can be used by the algorithm. With an accuracy of fourth order, this technique requires only displacements and velocities to be made available at the start of the current time step for integration in state space. Using the weighted momentum principle, the problem of discontinuity caused by impulsive loads is resolved after time-integration of the applied load in external momentum. Since no knowledge is required of acceleration at the current time step, the errors caused by estimation of acceleration by previous finite-difference methods are circumvented. Moreover, an iterative proceeding is included for each time step, involving the three phases of predictor, corrector, and error-checking. The effectiveness and robustness of the proposed algorithm in solving nonlinear dynamic problems is demonstrated in the numerical examples.

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ABSTRACT: Some types of rigid origami possess specific geometric properties. They have a single degree of freedom, and can experience large configuration changes without cut or being stretched. This study presents a numerical analysis and finite element simulation on the folding behavior of deployable origami structures. Equivalent pin-jointed structures were established, and a Jacobian matrix was formed to constrain the internal mechanisms in each rigid plane. A nonlinear iterative algorithm was formulated for predicting the folding behavior. The augmented compatibility matrix was updated at each step for correcting the incompatible strains. Subsequently, finite element simulation on the deployable origami structures were carried out. Specifically, two types of generalized deployable origami structures combined by basic parts were studied, with some key parameters considered. It is concluded that, compared with the theoretical values, both the solutions obtained by the nonlinear algorithm and finite element analysis are in good agreement, the proposed method can well predict the folding behavior of the origami structures, and the error of the numerical results increases with the increase of the primary angle.

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Ji-Hong Ye and Wei Chen (Concrete and Prestressed Concrete, SouthEast University, Nanjing, China), “Elastic restrained distortional buckling of steel-concrete composite beams based on elastically supported column method”, International Journal of Structural Stability and Dynamics, Vol. 13, No. 1, 1350001, February 2013, https://doi.org/10.1142/S02194455413500016
ABSTRACT: Restrained distortional buckling (RDB) is different from overall buckling and distortional buckling, and it usually occurs in the hogging moment region of composite beams. It may govern the member design for some cases, and should be taken into consideration. The present paper investigates the elastic RDB of composite beams based on elastically supported column method. First, Svensson’s elastically supported column model is improved by including the participation of the web as part of the buckling column. The corresponding theoretical expressions for the improved elastically support column subjected to a varying axial force are derived by the potential energy expression and equilibrium differential equation, respectively. Then, the precision of several elastically supported column methods for the RDB problem is discussed, based on the finite element method (FEM). The results show that elastically supported columns subjected to a negative uniform moment or a triangular moment have a good agreement with FEM results, but they are not valid for the cases of nonlinear moment distributions. In order to consider the complicated load conditions of composite beams, the equivalent moment assumption is introduced and proved to be suitable for the RDB problem. However, there is an applicable range of the length of the hogging moment region. Thus, a critical length formula of equivalent moment assumption of RDB is put forward and verified by FEM. Furthermore, a three-step simplified method is presented which can solve the elastic RDB problem of continuous composite beams. The proposed method, in which values of elastically supported column methods can be tabulated previously, is simple and suitable for design purposes.

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ABSTRACT: Free vibration analysis of functionally graded elastic, rectangular, and simply supported (diaphragm) plates is presented based on a higher-order shear and normal deformation theory (HOSNT). Although functionally graded materials (FGMs) are highly heterogeneous in nature, they are generally idealized as continua with mechanical properties changing smoothly with respect to the spatial coordinates. The material properties of functionally graded (FG) plates are assumed here to be varying through the thickness of the plate in a continuous manner. The Poisson ratios of the FG plates are assumed to be constant, but their Young's
moduli and densities vary continuously in the thickness direction according to the volume fraction of constituents which is mathematically modeled as a power law function. The equations of motion are derived using Hamilton's principle for the FG plates on the basis of a HOSSNT assuming varying material properties. Numerical solutions are obtained by the use of Navier solution method. The accuracy of the numerical solutions is first established through comparison with the exact three-dimensional (3D) elasticity solutions and the present solutions are then compared with available solutions of other models.

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Abstract: In this paper, we investigate the buckling capacity of a hybrid grid shell, which is made of quadrangular meshes diagonally stiffened by pre-tensioned thin cables. The eigenvalue buckling, geometrical nonlinear elastic buckling and elasto-plastic buckling analyses of the hybrid structure were carried out. Then the influences of the shape and scale of imperfections on the elasto-plastic buckling loads were discussed. Also, the effects of different structural parameters, such as the rise-to-span ratio, cross-section of beams, area and pre-stress of cables and boundary conditions, on the failure load were investigated. The results show that the buckling capacity is reduced when taking into account the material nonlinearity. Furthermore, the hybrid structure is highly imperfection sensitive and the reduction of the failure load due to imperfections can be considerable. The proper shape and scale of the imperfection are also important. It is also shown that there exists an optimal rise-to-span ratio resulting in a relatively high buckling capacity for a specific span. Moreover, the enlarging of the cross-section of steel beams notably improves the stability performance of the structure. However, the area and pre-stress of cables pose small effect on the structural stability.

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Abstract: In this study, a mixed-finite element method for free vibration analysis of cross-ply laminated composite beams is presented based on the "Euler–Bernoulli Beam Theory" and "Timoshenko Beam Theory". The Gâteaux differential approach is employed to construct the functionals of laminated beams using the variational method. By using these functionals in the mixed-type finite element method, two beam elements CLBT4 and FSDT8 are derived for the Euler–Bernoulli and Timoshenko beam theories, respectively. The
CLBT4 element has four degrees of freedom (DOFs), containing the vertical displacement and bending moment as unknowns at the nodes, whereas the FSDT8 element has eight DOFs, containing the vertical displacement, bending moment, shear force and rotation as unknowns. A computer program is developed to execute the analyses for the present study. The numerical results of free vibration analyses obtained for different boundary conditions are presented and compared with results available in the literature, which indicates the reliability of the present approach.

References listed at the end of the paper:


ABSTRACT: This paper deals with the free vibration of tapered Timoshenko beams. The simultaneous differential equations governing the free vibration of tapered Timoshenko beams are derived by decomposing the deformations of the beam into components as transverse deflection, bending rotation and shear distortion. The governing differential equations are first integrated by the Runge–Kutta method and then solved by the determinant search method, combined with the Regula–Falsi method, to obtain the natural frequencies of the beam along with their corresponding mode shapes. In the numerical examples, the effects of various parameters on the frequencies and mode shapes of the beam are extensively discussed.
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ABSTRACT: This paper presents the results of the experimental studies conducted on the buckling behavior of 420 MPa high strength steel, hot-rolled, equal angle columns, numbering a total of 66 specimens with a wide range of column slenderness and section sizes. Based on the test results, the buckling modes and capacities were analyzed and the nondimensional buckling strengths were obtained and compared with the design strength predicted from Eurocode 3, ANSI/AISC 360-10 and Chinese standards GB50017-2003. The experimental results in previous studies were also employed in the comparison. The effect of width to thickness ratio of legs of an angle on buckling modes and strengths were investigated. It was found that the buckling strengths from test results were much higher than the corresponding design values and current design approaches were too conservative. Based on present and previous experimental results, a new design approach is suggested for the design of angle columns with 420 MPa high strength steel.

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ABSTRACT: This paper is concerned with the nonlinear damped vibration of prestressed orthotropic membranes with viscous damping. The Krylov–Bogolubov–Mitropolsky (KBM) perturbation method is employed for solving the governing equations of large amplitude nonlinear vibration of rectangular orthotropic membranes with viscous damping. Presented herein are asymptotic analytical solutions for the frequency and displacement function of large amplitude nonlinear damped vibration of rectangular orthotropic membranes with four edges simply supported or fixed. Through the computational example, we compared and analyzed the frequency results. Meanwhile, the vibration mode of the membrane and the displacement and time curve of each feature point on the membrane surface were analyzed. The results obtained herein provide a simple and convenient approach to calculate the frequency and lateral displacement of large amplitude nonlinear vibration of rectangular orthotropic membranes with low viscous damping. In addition, the results provide some computational basis for the vibration control and dynamic design of membrane structures.

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**ABSTRACT:** This study examines the dynamic stability regions of damped columns on a Winkler foundation that are subjected to sub-tangentially distributed follower forces. A nondimensionalized equation of motion for the column subjected to linearly distributed follower forces is firstly derived based on the extended Hamilton's principle. A finite element procedure, using Hermitian interpolation functions, is employed to develop the mass matrix, Rayleigh damping matrix, Winkler foundation matrix, elastic and geometric stiffness matrices due to distributed axial forces, and a load correction stiffness matrix to account for sub-tangential follower forces. Subsequently, a time history analysis using the Newmark-β method and an evaluation method for the flutter and divergence loads of the nonconservative system are presented. Finally, the dynamic stability characteristics of the nonconservative system that display the jumping phenomenon in the second flutter load are explored through a parametric study. In particular, how the stable and unstable regions of the undamped and damped Leipholz columns translate with changes in the Winkler foundation stiffness is demonstrated and discussed.

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ABSTRACT: The uncertainty of geometric imperfections in a series of nominally equal I-beams leads to a variability of corresponding buckling loads. Its analysis requires a stochastic imperfection model, which can be derived either by the simple variation of the critical eigenmode with a scalar random variable, or with the help of the more advanced theory of random fields. The present paper first provides a concise review of the two different modeling approaches, covering theoretical background, assumptions and calibration, and illustrates their integration into commercial finite element software to conduct stochastic buckling analyses with the Monte–Carlo method. The stochastic buckling behavior of an example beam is then simulated with both stochastic models, calibrated from corresponding imperfection measurements. The simulation results show that for different load cases, the response statistics of the buckling load obtained with the eigenmode-based and the random field-based models agree very well. A comparison of our simulation results with corresponding Eurocode 3 limit loads indicates that the design standard is very conservative for compression dominated load cases.

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ABSTRACT: Fatigue life, stability and performance of majority of the structures and systems depend significantly on dynamic loadings applied on them. In many engineering cases, the dynamic loading is random vibration and the structure is a plate-like system. Examples could be printed circuit boards or jet impingement cooling systems subjected to random vibrations in harsh military environments. In this study, the response of thin rectangular plates to random boundary excitation is analytically formulated and analyzed. In the presented method, closed-form mode shapes are used and some of the assumptions in previous studies are eliminated; hence it is simpler and reduces the computational load. In addition, the effects of different boundary conditions,
modal damping and excitation frequency range on dynamic random response of the system are studied. The results show that increasing both the modal damping ratio and the excitation frequency range will decrease the root mean square acceleration and the maximum deflection of the plate.

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Vipulkumar Ishvarbhai Patel, Qing Quan Liang and Muhammad N.S. Hadi (First author is from: College of Engineering and Science, Victoria University, PO Box 14428, Melbourne VIC 8001, Australia), “Numerical analysis of circular concrete-filled steel tubular slender beam-columns with preload effects”, International Journal of Structural Stability and Dynamics, Vol. 13, No. 3, 1250065, April 2013, https://doi.org/10.1142/S0219455412500654

ABSTRACT: This paper presents a new numerical model for the nonlinear analysis of circular concrete-filled steel tubular (CFST) slender beam-columns with preload effects, in which the initial geometric imperfections, deflections caused by preloads, concrete confinement and second order effects are incorporated. Computational algorithms are developed to solve the nonlinear equilibrium equations. Comparative studies are undertaken to validate the accuracy of computational algorithms developed. Also included is a parametric study for examining the effects of the preloads, column slenderness, diameter-to-thickness ratio, loading eccentricity, steel yield stress and concrete confinement on the behavior of circular CFST slender beam-columns under eccentric loadings. The numerical model is demonstrated to be capable of predicting accurately the behavior of circular CFST slender beam-columns with preloads. The preloads on the steel tubes can affect significantly the behavior of CFST slender beam-columns and must be taken into account in the design.

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pressure, but an amount of injected gas can be calculated from pressure and enclosed volume. The uniqueness expression chosen has some limitations for large strains. Simulations are parameterized by int reference system. The hyper material models are used in the local plane element expressions. Numerical experiments show that either geometric n inflation processes. By separating rigid body motion and deformational displacement, the major part of very thin structures subjected to pressure loadings from compressible media, aiming primarily at simulations of ABSTRACT: Co rotational triangular space membrane elements, International Journal of Structural Stability and Dynamics, Vol. 13, No. 3, 1250067, April 2013. doi:10.1142/S02194554125000678

ABSTRACT: Co-rotational triangular space membrane elements are developed for the quasi-static analysis of very thin structures subjected to pressure loadings from compressible media, aiming primarily at simulations of inflation processes. By separating rigid body motion and deformational displacement, the major part of geometric nonlinearity is treated by a co-rotational filter. With the formulation, hyper-elastic and linear elastic material models are used in the local plane element expressions. Numerical experiments show that either material model can be used in the present context, but that the linearly elastic model demands an optimal reference system. The hyper-elastic form is useful also for very large expansions, but the neo-Hookean expression chosen has some limitations for large strains. Simulations are parameterized by internal over-pressure, but an amount of injected gas can be calculated from pressure and enclosed volume. The uniqueness


ABSTRACT: Co-rotational triangular space membrane elements are developed for the quasi-static analysis of very thin structures subjected to pressure loadings from compressible media, aiming primarily at simulations of inflation processes. By separating rigid body motion and deformational displacement, the major part of geometric nonlinearity is treated by a co-rotational filter. With the formulation, hyper-elastic and linear elastic material models are used in the local plane element expressions. Numerical experiments show that either material model can be used in the present context, but that the linearly elastic model demands an optimal reference system. The hyper-elastic form is useful also for very large expansions, but the neo-Hookean expression chosen has some limitations for large strains. Simulations are parameterized by internal over-pressure, but an amount of injected gas can be calculated from pressure and enclosed volume. The uniqueness
and stability in the response of the structures must be seen as a function of either pressure or amount of gas, dependent on the precise mechanism for inflation.

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ABSTRACT: A family of new explicit time-integration method is proposed herein, which inherits the numerical characteristics of any existing implicit Runge–Kutta algorithms for a linear conservative system. Based on an exact derivation of the increment of mechanical energy, the method proposed is demonstrated to be unconditionally stable. Also, the stability condition of the proposed method is derived when applied to solving a nonlinear system. The characteristics of the proposed method are investigated by observing the mechanical-energy time history of a nonlinear conservative system. The numerical results can be explained by the stability condition derived in the nonlinear regime. Finally, the computational accuracy and efficiency between the Newmark time integration method and the proposed explicit method are compared in solving the dynamic response of a couple of linear oscillators.

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ABSTRACT: In-plane bending loads occur in many thin-walled structures, including web core sandwich panels (foam-filled panels with interior webs) under transverse loading. The design of such structures is limited in part by local buckling of the thin webs and the subsequent impact on stiffness and strength. However, the core material can have a significant impact on web buckling strength and thus must be considered in design. This paper presents solutions for the buckling strength of simply supported plates under in-plane bending loads. The location of the neutral bending axis is allowed to vary and is characterized by a load parameter. A Pasternak model is used to account for the resistance of the foundation to compression and shear. Using the principle of minimum potential energy, buckling solutions are developed for infinitely long plates and representative foundation materials. The solutions match known results for two special cases: Uniform loading with variable foundation, and bending loads with no foundation. An order of magnitude increase in buckling strength is possible, depending on loading and foundation stiffness. The results suggest an important avenue for future development of lightweight structures, including sandwich panels and structures such as plate girders that are not typically associated with the use of foam filling.

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ABSTRACT: This paper presents numerical simulation studies on buckling and free vibration characteristics of isotropic plates under arbitrarily varying temperature distributions using finite element method (FEM). First the critical buckling temperature is obtained, followed by modal analysis considering pre-stress due to the thermal field in the plate, with the critical buckling temperature as a parameter. It is found that anti-nodal position of the fundamental buckling mode appears away/near to the free edge when the free edge is exposed to
minimum/maximum temperature of the variation. The nodal and anti-nodal lines of free vibration modes moves towards the high temperature exposed plate and nodal lines becomes a nodal area for longer plates.

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- W. L. Ko, Thermal buckling analysis of rectangular panels subjected to humped temperature profile heating, NASA/TP 2120241 (NASA, 2004).
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ABSTRACT: In this study, experimental tests were performed to investigate the load capacities of tubular steel adjustable shores used in construction. The test results show that the overlap length between the connecting tube and base tube of the shore does not affect substantially the load capacity. Additionally, the load capacity of a 3-section tubular steel adjustable shore is lower than that of a 2-section shore. The load capacity of tubular steel adjustable shores decreases when No. 3 steel bars, instead of tube locks, are used. As for the combined systems, the reinforcing effect for a tubular steel adjustable shoring system with less than 16 shores is negligible when reinforced horizontally. For a tubular steel adjustable shoring system with four shores, the reinforcing effect is obvious when reinforced both horizontally and diagonally. This study also introduces the novel concept of upper and lower limit values of load capacity, which embrace the maximum and minimum strengths of all tested shoring members randomly selected for testing at the construction site. This concept can be potentially applied in shoring design.

References listed at the end of the paper:
ABSTRACT: Surface effect often plays a significant role in the pull-in performance of nano-electromechanical systems (NEMS) but limited works have been conducted for taking this effect into account. Herein, the influence of surface effect has been investigated on instability behavior of cantilever nano-actuator in the presence of van der Waals force (vdW). Three different methods, i.e. an analytical modified Adomian decomposition (MAD), Lumped parameter model (LPM) and numerical solution have been applied to solve the governing equation of the system. The results demonstrate that surface effect reduces the pull-in voltage of the system. Moreover, surface energy causes the cantilever nano-actuator with the assigned parameter to deflect as a softer structure. It is found that while surface effect becomes important for low values of the cantilever nano-actuator thickness, vdW attraction is significant for low initial gap values. Surprisingly, the increase in the initial gap, enhances the contribution of surface effect in pull-in instability of the system while reduces the contribution of vdW attraction. Furthermore, the minimum initial gap and the detachment length of the cantilever nano-actuator that does not stick to the substrate due to vdW force and surface effect has been approximated. A good agreement has been observed between the values of instability parameters predicted via these three methods. Whilst compared to the instability voltage predicted by numerical solution, the pull-in voltage obtained by MAD series and LPM method is overestimated and underestimated, respectively.

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“Effect of geometric nonlinearities on nonlinear vibrations of closed cylindrical shells”, International Journal of Structural Stability and Dynamics, Vol. 13, No. 4, 1250078, May 2013,
https://doi.org/10.1142/S0219455412500782

ABSTRACT: Geometrically nonlinear free vibrations of closed isotropic cylindrical shells are investigated through an analytical–numerical model. The method developed is a combination of Sanders–Koiter nonlinear shell theory and the finite element method. The cylindrical shell is subdivided into cylindrical finite elements and the displacement functions are derived from exact solutions of Sander's equations for thin cylindrical shells. Expressions for the mass, linear and nonlinear stiffness matrices are determined by exact analytical integration. Various boundary conditions of shell and in-plane effects are considered. Nonlinear responses are analyzed using the Runge–Kutta numerical method. The nonlinear frequency ratio is determined with respect to the amplitude thickness ratio of the motion for different study cases. Detailed numerical results are presented for several parameters for a closed isotropic shell, indicating either hardening or softening types of nonlinear behaviors, depending on the structure data. The present results show good agreement with the published ones for several cases of shells. This research clarifies the current disagreement about various types of cylindrical shells with geometric nonlinearities.

References listed at the end of the paper:

REFERENCES listed at the end of the paper:


ABSTRACT: In this paper, higher continuity p-version finite element, in particular two-dimensional C2 elements are utilized in studying vibrational characteristics of rectangular Flexural Micro-Plates based on the "gradient elasticity theory". In order to verify the computational procedure, results obtained from the finite element framework are compared to the classical plate theory results and to those of the micro-plate and classical plate investigations that are available in literature. Results indicate that the proposed framework, yields highly accurate results. Moreover, it is concluded that, under certain boundary conditions and length scale effects, the differences in predictions are so gross that the validity of classical theory in predicting micro-plates vibrational characteristics can be ruled out completely.

References listed at the end of the paper:

ABSTRACT: A displacement-based, novel curved beam element is proposed for efficient and reliable analysis of frames composed of curved members. The accuracy of the proposed element is not controlled by the subtended angle of the element with the angle up to \( \pi \). In contrast to the conventional method, the interpolation function for displacement is based on the infinitesimal straight beam sections extracted from the curved element. Consequently, the strain energy of the curved beam element can be integrated by the infinitesimal straight beam sections along the element length. The relationship between the displacements and the corresponding strains in the straight beam is simpler than that in the curvilinear co-ordinate description widely adopted by many researchers in their element derivations. This technique is formulated to avoid couplings between the tangential and radial displacement variables in the strain field and its successful utilization is also demonstrated herein. Furthermore, the relation between displacements and strains of the infinitesimal straight beam section is equivalent to that of the curved beam in the curvilinear co-ordinate description. Finally, the analysis results of several bench marked examples by the proposed curved beam element are presented. The results show the high accuracy and efficiency of the proposed element against the classical curved beam element.

References listed at the end of the paper:

ABSTRACT: This paper presents the snap-through and bifurcation elastic stability analysis of nano-arch type structures with the Winkler foundation under transverse loadings by the strain gradient and stress gradient (nonlocal) theories. The equations of equilibrium are derived by using the variational method and virtual displacement theorem of minimum total potential energy. In the elastic stability analysis, von Karman's nonlinear strain component is included, with the deformation represented by a series solution. It is concluded that in general, the strain gradient theory pushes the system away from instability as compared to the classical theory. However, the nonlocal theory does the reverse and causes the system to experience instability earlier than that of the classical theory. Moreover, theories with different small-size considerations change the mechanism of instability in different ways. For example, in similar conditions, the strain gradient theory causes the system to reach a snap-through point, while the nonlocal theory causes the system to stop at a bifurcation critical point.

References listed at the end of the paper:


ABSTRACT: The buckling of higher-order shear plates is studied in this paper with a unified formalism. It is shown that usual higher-order shear plate models can be classified as gradient elasticity Mindlin plate models,
by augmenting the constitutive law with the shear strain gradient. These equivalences are useful for a hierarchical classification of usual plate theories comprising Kirchhoff plate theory, Mindlin plate theory and third-order shear plate theories. The same conclusions were derived by Challamel [Mech. Res. Commun. 38 (2011) 388] for higher-order shear beam models. A consistent variational presentation is derived for all generic plate theories, leading to meaningful buckling solutions. In particular, the variationally-based boundary conditions are obtained for general loading configurations. The buckling of the isotropic or orthotropic composite plates is then investigated analytically for simply supported plates under uniaxial or hydrostatic in-plane loading. An analytical buckling formula is derived that is common to all higher-order shear plate models. It is shown that cubic-based interpolation models for the displacement field are kinematically equivalent, and lead to the same buckling load results. This conclusion concerns for instance the plate models of Reddy [J. Appl. Mech. 51 (1984) 745] or the one of Shi [Int. J. Solids Struct. 44 (2007) 4299] even though these models are statically distinct (leading to different stress calculations along the cross-section). Finally, a numerical sensitivity study is made.

References listed at the end of the paper:


ABSTRACT: In this study, the instability of spinning cylindrical shells partially filled with viscous liquid is investigated. Based on the Navier–Stokes equations for the incompressible flow, a 2D model is developed for liquid motion at each section of the cylinder. The governing equations of the cylinder vibrations are obtained based on the first-order shear deformable shell theory. The nonpenetration and no-slip boundary conditions of
the flow on the wetted surface of the cylinder relate the liquid motion to the shell vibrations. Also the liquid pressure exerted on the cylinder wall combines the vibrations of the rotary cylinder to the liquid motion. By using the obtained coupled liquid-structure model, the instability conditions of the system are determined. The governing parameters of the rotor vibrations are introduced and their influence on the stability boundaries of the rotor is studied.

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Chun-Sheng Chen, Chih-Wen Chen and Wei-Ren Chen (First author is from: Department of Mechanical Engineering, Lunghwa University of Science and Technology, Guishan Shiang 33306, Taiwan), “Dynamic stability characteristics of functionally graded plates under arbitrary periodic loads”, International Journal of Structural Stability and Dynamics, Vol. 13, No. 6, 1350026, August 2013, 
https://doi.org/10.1142/S0219455413500260

ABSTRACT: The dynamic instability of functionally graded material (FGM) plates under an arbitrary periodic load is studied. The properties of the functionally graded plates (FGPs) are assumed to vary continuously across the plate thickness according to a simple power law. With the derived Mathieu equations, the dynamic instability regions of the FGP s are determined by using the Bolotin’s method. The in-plane periodic load is taken to be a combination of periodic axial and bending stress in the example problems. The influences of the volume fraction index, layer thickness ratio, static and dynamic load on the dynamic instability of ceramic-FGM-metal plates are discussed. The results reveal that the excitation frequency, instability region and dynamic instability index of these plates are significantly affected by the static load, dynamic load, volume fraction index and layer thickness.

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Colloquium on Computation of Shell & Spatial Structures
Materials Conference and Exhibition
· Theory and Applications

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ABSTRACT: The bistable characteristics of the irregular anti-symmetric cylindrical shell (IACS), such as \([+\alpha,-\alpha, +\alpha,-\alpha]\) lay-up, are presented using theoretical methodology and finite element (FE) analysis. A novel approach named two points loading method is used to induce a snap-through of the shell in FE analysis. Unlike regular \([+\alpha,-\alpha, +\alpha,-\alpha]\) lay-up anti-symmetric cylindrical shells, two or more different ply angles are included in the irregular anti-symmetric lay-up. Besides ply angles, the bistable characteristics of composite cylindrical shells with irregular anti-symmetric lay-ups are also affected by the sequence of lay-ups. Both analytical and FE results show that IACS with different bistable behaviors can be obtained by changing the ply angles or sequence of the lay-ups. It is very useful for the design and manufacture of the bistable structure. There is a reasonable agreement between analytical and FE predictions; possible reasons of differences between analytical and FE results are given.

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ABSTRACT: This paper is concerned with buckling analyses of rectangular functionally graded plates (FGPs) under uniaxial compression, biaxial compression and combined compression and tension loads. It is assumed that the plate is a mixture of metal and ceramic that its properties changes as a function according to the simple power law distribution through the plate thickness. The fundamental eigen-buckling equations for rectangular plates of functionally graded material (FGM) are obtained by discretizing the plate into some finite strips, which are developed on the basis of the higher order plate theory (HOPT). The solution is obtained by the minimization of the total potential energy. Numerical results fora variety of FGPs are given, and compared with the available results, wherever possible. The effects of thickness ratio, variation of the volume fraction of the ceramic phase through the thickness, aspect ratio, boundary conditions and also load distribution on the buckling load capacity of FGM plates are determined and discussed. It is found that the buckling behavior of FGM plates is particularly influenced by application of HOPT, especially when the plates are thick.

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ABSTRACT: The paper presents an application of the finite strip method to modeling of vibrations of the collecting electrodes, which are shells with large length (up to 16 m), width of 0.5 m and thickness of 0.002 m. The models and computer programs have been worked out and validated. Comparison of results obtained from numerical simulations and experimental measurements is presented and discussed. The equations of motion have been solved using methods for solution of sparse algebraic equations and Newmark method. The strip method has proved to be numerically effective. The programs enable us to carry out calculations for a system with several hundred thousands of degrees of freedom with time of analysis requiring thousand integration steps during less than 90 min on a PC computer. High numerical efficiency enables the geometrical parameters of the collecting electrodes to be selected in order to ensure large accelerations caused by a beater to be spread evenly over the surface of the electrodes. Conclusions concerning the influence of length of the collecting electrodes on the normal and tangenz accelerations are formulated.

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ABSTRACT: Calculations of nonlinear displacements and vibrations of inhomogeneous loaded shells with developable principal surface by means of different analytical methods are represented. It is shown that solutions to these methods are the expansions of exact solution in the Taylor series for an independent variable,
and in the particular case — for the powers of a natural parameter. A method that provides a polynomial asymptotic approximation of the exact solution of the general form and its meromorphic continuation based on 1D and 2D Padé approximations is proposed. Calculations of nonlinear deformation and stability of elastic flexible circular cylindrical shell under uniform external pressures and of free oscillations of simply supported stringer shell demonstrate the efficiency and accuracy of the proposed method.

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J. Awrejcewicz, A.V. Krysko, I.E. Kutepov, N.A. Zagniboroda, M.V. Zhigalov and V.A. Krysko (primarily Engels Institute of Technology, Saratov State Technical University, Saratov Region, Russian Federation), “Analysis of chaotic vibrations of flexible plates of infinite length are studied. The Kirchhoff–Love hypotheses are used to derive the nondimensional partial differential equations governing the plate dynamics. The finite difference method (FDM) and finite element method (FEM) are applied to validate the numerical results. The numerical analysis includes both standard (time histories, fast Fourier Transform, phase portraits, Poincaré sections, Lyapunov exponents) as well as wavelet-based approaches. The latter one includes the so called Gauss 1, Gauss 8, Mexican Hat and Morlet wavelets. In particular, various plate dynamical regimes including the periodic, quasi-periodic, sub-harmonic, chaotic vibrations as well as bifurcations of the plate are illustrated and studied. In addition, the convergence of numerical results obtained via different wavelets is analyzed.

References listed at the end of the paper:

ABSTRACT: Free vibration and buckling of laminated sandwich plate having soft core is studied by using an efficient C₀ continuous finite element (FE) model based on higher-order zigzag theory (HOZT). In this theory, the in-plane displacement field for both the face sheets and the core is obtained by superposing a global cubically varying displacement field on a zigzag linearly varying displacement field with a different slope in each layer. The transverse displacement is assumed to be quadratic within the core while it remains constant in the faces beyond the core. The proposed model satisfies the condition of transverse shear stress continuity at the layer interfaces and the zero transverse shear stress condition at the top and bottom of the plate. The nodal field variables are chosen in an efficient manner to overcome the problem of C⁰ continuity requirement of the transverse displacement. Numerical examples on free vibration and buckling covering different geometric and material features of laminated composite and sandwich plates are presented. Many new results are also presented which should be useful for future research.

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ABSTRACT: This study deals with the thermal buckling behavior of two-layer shear-deformable beams with partial interaction between the layers. The Timoshenko kinematics are considered for both layers and the shear connection is represented by a continuous relationship between the interface shear flow and the corresponding slip. Geometrically nonlinear behavior based on the von Kármán simplification of the Green strain tensor is accounted in the formulation. A set of differential equations is obtained from a general 2D bifurcation analysis using the aforementioned assumptions. The stability equations are obtained on the basis of the adjacent equilibrium criterion. It is shown that, due to the existence of the stretching–bending coupling effect in the composite beams, the bifurcation state occurs only for beams with both edges clamped.

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ABSTRACT: Currently, four grouped 177 m super-large cooling towers, i.e. column-supported hyperboloidal shells, are to be constructed in a typical electric power plant in Southeast China. To this end, simultaneous pressure measurements on 1:200 rigid tower models are carried out in an atmospheric boundary layer (ABL) wind tunnel, aimed at accurately obtaining the external/internal cladding wind loads on these shells. The wind-induced static behavior of the cooling towers is analyzed by applying the wind loads acquired via the pressure model tests, using both linear elastic and nonlinear elastic finite element (FE) analyses. The corresponding responses (structural deformation, internal force and local buckling state) are compared with those obtained by the traditional design approach, focused on the effects of internal suction and external pressure distribution. Besides, the tower group interference effects are studied by comparing the results computed of a freestanding tower, with those of the tower groups during two different construction stages. The main findings about the loading effects on the static performance of the super-large cooling towers are helpful for improving the current Chinese Codes that govern the design of super-large cooling towers.

References listed at the end of the paper:

ABSTRACT: This paper presents the stability analyses of glulam arches subjected to distributed vertical loading. The present analysis employs a strain-based formulation of a nonlinear geometrically exact three-dimensional beam theory. The influence of the relative height of the arch on the lateral buckling load is studied. The buckling load is determined by bisection method with observing the sign of the determinant of the tangent stiffness matrix. The post-critical load deflection path is traced by a modified arc–length method. Such influences are shown for arches with a constant cross-section or constant volume. After determining the most favorable height of the arch, the influence of the number and position of lateral supports is shown. We also compare the deflections, bending, and radial stresses at the lateral buckling states to the limit values which are recommended by European standards.

References listed at the end of the paper:


ABSTRACT: This paper presents the stability analyses of glulam arches subjected to distributed vertical loading. The present analysis employs a strain-based formulation of a nonlinear geometrically exact three-dimensional beam theory. The influence of the relative height of the arch on the lateral buckling load is studied. The buckling load is determined by bisection method with observing the sign of the determinant of the tangent stiffness matrix. The post-critical load deflection path is traced by a modified arc–length method. Such influences are shown for arches with a constant cross-section or constant volume. After determining the most favorable height of the arch, the influence of the number and position of lateral supports is shown. We also compare the deflections, bending, and radial stresses at the lateral buckling states to the limit values which are recommended by European standards.

References listed at the end of the paper:

ABSTRACT: Higher-order multiple scales methods have been developed for a strong nonlinear differential equation modeling the nonlinear transverse dynamic behavior of piezoelectric–elastic–piezoelectric sandwich beams. The proportional and derivative potential feedback controls via sensor and actuator layers are used. Two higher-orders multiple scales methods are developed leading to accurate approximate time-response and frequency and phase-amplitude relationships. As the classical multiple scales method disregards the quadratic nonlinear terms, the developed higher-order multiple scales methods overcame this drawback and lead to more accurate results. Static and dynamic stability criteria are elaborated and tested. Critical bifurcation points and peak amplitudes are characterized in accordance with the excitation amplitude and the feedback parameters.

References listed at the end of the paper:


ABSTRACT: Critical buckling loads of composite laminates are usually calculated using analytical solutions based on the assumption of uniform in-plane loads, despite of the fact that real structures are often subjected to various nonuniform loads. The present work is focused on the buckling behavior of composite laminates, with and without cutouts, subjected to various nonuniform in-plane loads. The effect of the size of the cutouts, on the buckling behavior, has been studied using finite element method. Furthermore, parametric studies on the effects
of plate aspect ratio, location of the cutout and the application of a nonuniform load combined with a shear load have also been studied. Higher buckling loads were observed in pure in-plane bending compared to uniformly/nonuniformly distributed loads. Consequently, it is important to consider nonuniformly distributed loading whenever applicable, to utilize complete strength of the composite laminate and to avoid premature failure of the composite laminate due to structural instability.

References listed at the end of the paper:


ABSTRACT: Free vibrations of straight beams which are partially supported by an elastic foundation are analyzed. For the sake of simplicity, only the Euler–Bernoulli beam model coupled with a Winkler-type elastic foundation is considered. This structural system can be used to study, in a rather accurate way, the dynamic response of partially embedded piles (like those used for telecommunications) when dealing with the problem of identifying their mechanical properties during operative conditions. The study makes clear that different kinds of vibration modes may occur in the part of the beam which is supported by the continuous elastic foundation: indeed apart from the classical modes, corresponding to the dynamics of a free beam, it is possible to have vibration modes which are similar to the static deflection of a beam on an elastic support or even corresponding to rigid-body modes. For the same beam it is shown that transition between these vibration modes can appear when switching from the fundamental natural frequency to subsequent ones. This effect is the focus of the presented numerical examples. In particular, the analytic expression of the transcendental functions governing the vibration modes, and of the coefficients of the eigenfunctions for all occurring cases, are given here — to the best of the author's knowledge — for the first time. From the practical point of view, the reported results allow to define a suitable range of the elastic stiffness parameter such that the behavior of a partially supported beam can be conveniently approximated with that of a single-span beam, having one built-in end and the other free.

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E. Winkler, *Die Lehre von der Elastizität und Festigkeit* (Dominicus, Prag, 1867).


**ABSTRACT:** The effect of random system properties on thermal post-buckling temperature of laminated composite cylindrical shell panel with temperature independent (TID) and dependent (TD) material properties subjected to uniform temperature distribution is examined in this study. System properties such as material properties, thermal expansion coefficients and lamina plate thickness are modeled as independent basic random variables. The basic formulation is based on higher-order shear deformation (HSĐT) theory with von-Karman nonlinearity using modified C⁰ continuity. A direct iterative-based C⁰ nonlinear finite element method (FEM) combined with Taylor series-based mean-centered first-order perturbation technique (FOPT) developed by the authors for composite plate is extended for shell panel with reasonable accuracy to compute second-order statistics of post-buckling temperature of cylindrical shell panel. Typical numerical results for second order statistics (mean and coefficient of variance) of thermal post-buckling temperature of laminated cylindrical shell panel are obtained through numerical examples for various support conditions, amplitude ratios, shell thickness ratios, aspect ratios, lamination lay-up sequences, curvature to length ratios, types of material properties with the effect of random system parameters. The performance of outlined approach has been validated with those results available in the literatures and independent MCS.

References listed at the end of the paper:


are determined analytically. For the substrate exponentially along the length. The buckling load and the buckling mode shapes for the free standing FGM film

ABSTRACT: The instability of a functionally graded material (FGM) strip as a free standing film or a

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ABSTRACT: The instability of a functionally graded material (FGM) strip as a free standing film or a substrate-bound film is studied in this work, in which the stiffness of the film is assumed to change exponentially along the length. The buckling load and the buckling mode shapes for the free standing FGM film are determined analytically. For the substrate-bound film, the substrate is modeled as a Winkler foundation and
the wrinkling load and wrinkling pattern are determined numerically by using a finite difference method and a series solution. In contrast with the wrinkling of homogenous thin films in which the wrinkles propagate in the entire domain, the wrinkles of the FGM films accumulate around the location with the least bending rigidity. The results of this work show that the sensitivity of the wrinkle accumulation around the weak locations of the system with lower stiffness is very high. This work is expected to provide a better understanding for localization of wrinkles around a region of substrate-bounded thin films in thin film technology.

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ABSTRACT: Surface effects, including surface elasticity, surface piezoelectricity and residual stress, on the postbuckling of piezoelectric nanobeams due to an electric field are investigated using an energy method in this paper. The critical buckling voltage and amplitude are obtained analytically in terms of the bulk and surface material properties and geometric parameters. The results show that surface effects play a significant role in the postbuckling of piezoelectric nanobeams. It is found that the influences of surface piezoelectricity and residual surface stress are more prominent than the surface elasticity. These results might be helpful for designing piezoelectric nanobeam-based devices.

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ABSTRACT: This paper is concerned with the bifurcation buckling of nano-rings and nano-arches where the allowance for small scale effect is catered for by using Eringen's nonlocal theory of elasticity. Exact buckling solutions for nano-rings and nano-arches under uniform radial pressure are derived and the influence of small
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ABSTRACT: The exact eigen-equations of pipe conveying fluid with clamped-clamped and simply supported boundary conditions are derived. The simplified forms of the general eigen-equations for some specific cases are determined, and the corresponding dynamic properties are calculated and discussed. These properties provide a better understanding on the relationships between the dynamic stability and the flow velocities of the fluid-conveying components and help to design stable pipeline systems. In addition, the dynamic properties obtained by the exact eigen-equations can also serve as benchmark solutions for verifying results obtained by other approximate approaches.

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ABSTRACT: This paper investigates the nonlinear free vibration of a double layer graphene sheet (DLGS) embedded in a polymer matrix aroused by the nonlinear van der Waals (vdW) interactions based on the classic Kirchhoff plate theory. Harmonic balance method is used to predict the nonlinear relation between deflection amplitudes and resonant frequencies of the DLGS. The embedded DLGS presents a hardening nonlinearity in both in-phase vibration (IPV) and anti-phase vibration (APV) modes. The surrounding polymer medium is found to have significant effect on the resonant frequency, especially for the IPV mode. For example, the variation of the resonant frequencies of an embedded DLGS is less dependent on the graphene aspect ratio and mode numbers as compared with a free-standing one. Uni-axial and bi-axial in-plane load effects upon the vibrational behavior of DLGS are also investigated. It is concluded that due to the influence of the nonlinear interlayer and interfacial vdW forces on the DLGS, prediction on both linear and nonlinear resonant frequencies for the embedded DLGS is quite different from that for a free-standing one. This study is expected to be useful for understanding the nonlinear mechanical behavior of graphenes with their potential applications in nanocomposites.

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ABSTRACT: The complex variable moving least-squares (CVMLS) approximation is discussed in this paper, and the mathematical and physical meaning of the complex functional in the CVMLS approximation is presented. With the CVMLS approximation, the trial function of a two-dimensional problem is formed with a one-dimensional basis function. Then combining the CVMLS approximation and the Galerkin weak form, we investigate the complex variable element-free Galerkin (CVEFG) method for two-dimensional elastodynamics problems. The penalty method is used to apply the essential boundary conditions, and the implicit time integration method, which is the Newmark method, is used for time history analysis. Then the corresponding formulae of the CVEFG method for two-dimensional elastodynamics problems are obtained. For the purposes of demonstration, some selected numerical examples are solved using the CVEFG method. Compared with the EFG method, the CVEFG method has greater precision.

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ABSTRACT: In the present paper, the mechanical behavior of large deformation of a regular equilateral triangular tube under quasi-static axial crushing is reported, which is a polygon with an acute angle and odd number of sides. Based on the results from nonlinear finite element analysis (FEA), a new type of inextensional basic plastic collapse folding element is proposed to describe the plastic progressive collapse. The progressive folding around the stationary horizontal hinges and inclined traveling hinges are involved to develop the new basic folding element. Two types of inextensional deformation modes are discovered, i.e., diamond mode and rotational symmetrical mode. The average crushing load for each mode is predicted from the super-folding element theory, which was proposed from the previous investigation on the axial crushing of square columns. A rigid-plastic material model and a kinematically admissible model are involved in this theory. The results are further validated against experiments. The approximate quasi-static theoretical predictions for the mean crushing loads of triangular tubes provide reasonable agreement with the corresponding experimental results.

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- A. P. Chattopadhyay et al., Thin-Walled Structures 52, 29 (2012).
- W. Hong et al., Thin-Walled Structures 62, 10 (2013).
ABSTRACT: This paper is concerned with a simplified approach of estimating the effects of the impact of a projectile on a circular dome. The procedure to be introduced involves simplifying the impactor (projectile) and the target (the dome) by a two-degree-of-freedom (2DOF) system which is made up of two lumped masses connected by elastic springs. This modeling approach has only been adapted for analyzing the impact response behavior of beams and plates. The original contributions of this paper is the development of equations and charts for estimating the value of the lumped mass and spring stiffness in the 2DOF lumped mass model to emulate the response behavior of circular domes. Linear elastic behavior of the dome is assumed but nonlinear behavior of the impactor has been taken into account. The developed calculation procedure has been validated and illustrated by case studies.

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ABSTRACT: Buckling, free and forced vibration analyses of orthotropic plates are studied numerically using Isogeometric analysis. The present formulation is based on the classical plate theory (CPT) while the NURBS basis function is employed for both the parametrization of the geometry and the approximation of plate deflection. An efficient and easy-to-implement technique is used for imposing the essential boundary conditions. Numerical examples for free and forced vibration and buckling of orthotropic plates with different boundary conditions and configurations are considered. The numerical results are compared with other existing solutions to show the efficiency and accuracy of the proposed approach for such problems.

References listed at the end of the paper:

ABSTRACT: In the present study, an attempt has been made to present the C0 finite element formulation based on third order shear deformation theory for buckling analysis of functionally graded material skew plate under thermo-mechanical environment. Here, prime emphasis has been given to study the influence of skew angle on the buckling behavior of functionally graded plate. Two dissimilar homogenization schemes, namely Mori–Tanaka scheme and Voigt rule of mixture are employed to sketch their influence for the interpretation of data. Temperature-dependent material properties of the constituents of the plate are considered to perform thermal analysis. Numerical examples are solved using different mixture of ceramic and metal plates to generate the new results and relative imperative conclusions are highlighted. The roles played by the different factors like loading condition, volume fraction index, skew angle, boundary condition, aspect ratio, thickness ratio and homogenization schemes on buckling behavior of the FGM skew plates are presented in the form of tables and figures.

References listed at the end of the paper:


end. In addition, it is much easier to lose stability for the external pressurized shell. The effect of the shel
become much lower than others. And the corresponding buckling modes appear as a “bell” shape at the free
boundary conditions. The results indicated that in
loads and buckling modes are converted to solving for the symplectic eigenvalues and eigensolutions,
stability governing equations are transformed into the lower
combined action of axial impact load, torsion and pressure. By introducing the dual variables, higher

ABSTRACT: A symplectic system is developed for dynamic buckling of cylindrical shells subjected to the

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“Symplectic Method For Dynamic Buckling Of Cylindrical Shells Under Combined Loadings”, International
Journal of Applied Mechanics, Vol. 05, No. 04, 1350042, December 2013, DOI: 10.1142/S1758825113500427

ABSTRACT: A symplectic system is developed for dynamic buckling of cylindrical shells subjected to the
combined action of axial impact load, torsion and pressure. By introducing the dual variables, higher-order
stability governing equations are transformed into the lower-order Hamiltonian canonical equations. Critical
loads and buckling modes are converted to solving for the symplectic eigenvalues and eigensolutions,
respectively. Analytical solutions are presented under various combinations of the in-plane and transverse
boundary conditions. The results indicated that in-plane boundary conditions have a significant influence on this
problem, especially for the simply supported shells. For the shell with a free impact end, buckling loads should
become much lower than others. And the corresponding buckling modes appear as a "bell" shape at the free
end. In addition, it is much easier to lose stability for the external pressurized shell. The effect of the shell
thickness on buckling results is also discussed in detail.

References listed at the end of the paper:

ABSTRACT: This paper investigates the buckling and surface wrinkling phenomena of an elastic graded cylinder under axial compression. We develop a semi-analytical finite element model based on elastic stability theory and the work of Lee et al. [Journal of Mechanics and Physics of Solids 56 (2008) 858–868], which enables us to determine the critical compressive strain and corresponding wrinkling wavelength of a soft cylindrical structure with the shear modulus arbitrarily varying along the radial direction. A number of examples of practical interest have been explored to validate the proposed method, including: (i) surface wrinkling a soft cylinder with a hard outer surface, (ii) surface wrinkling of a soft cylindrical tube with a hard inner surface layer, (iii) buckling of a soft cylinder with an embedded hard layer, (iv) surface wrinkling of a soft cylinder covered by a bilayer, and (v) surface wrinkling of an elastic graded soft cylinder covered by a hard layer. The results demonstrate that the proposed method is valid for all these situations. In comparison to conventional finite element method, the discretization and meshing in the present method are much easier and the degrees of freedom involved are much smaller.

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defect on structural mechanics. In this research, the effects of length, radius, loading ratio, and the position of vacancy defects under the transverse and axial compression loading is investigated based on molecular structural mechanics. In this research, the effects of length, radius, loading ratio, and the position of vacancy defect on the buckling behavior of armchair and zigzag single-walled carbon nanotubes are studied. It is found that the position of pinhole-vacancy has a significant effect on the percent of the reduction of the critical buckling force. It is also seen, that the effect of loading kind on the critical buckling forces loses its importance if the length of carbon nanotube (CNT) increases.

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- C. M. Stafford et al., Nature Materials 3, 545 (2004), DOI: 10.1038/nmat1175.
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ABSTRACT: Elastic buckling of single walled carbon nanotubes (SWCNTs) with di-, triple- and pinhole vacancy defects under the transverse and axial compression loading is investigated based on molecular structural mechanics. In this research, the effects of length, radius, loading ratio, and the position of vacancy defect on the buckling behavior of armchair and zigzag single-walled carbon nanotubes are studied. It is found that the position of pinhole-vacancy has a significant effect on the percent of the reduction of the critical buckling force. It is also seen, that the effect of loading kind on the critical buckling forces loses its importance if the length of carbon nanotube (CNT) increases.
AGREEMENT WITH MD SIMULATION. However, the equivalent shell model underestimates the critical twist angle by

Variation of critical twist angle with length of CNT gives good estimate of critical buckling load/strain and critical buckling torque with respect to the MD results.

Young's modulus for a single available software ABAQUS. Based on our MD results, an empirical equation to analyze single

modulus, Poisson's ratio = 0.19 and shell thickness h = 0.066 nm. We show that the equivalent shell model

WALLED STRUCTURES.
30% because the continuum shell model overestimates torsional stiffness of CNT compared to an atomistic model of CNT. The equivalent shell model is less computational intensive to implement as compared with MD. Its accuracy for predicting the buckling states for long carbon nanotubes allows it to be used for moderately long CNTs under compression/torsion, in-lieu of MD simulations.

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ABSTRACT: We study wrinkling instability of a thin elastic film on a pre-stretched soft elastomer induced by the gravity of periodic array of the rods homogeneously clamped on the surface of the film. By using linear perturbation analysis, we show that the periodic array of the rods can drive the wrinkling instability of the film when the gravitational force of the rods attains the threshold, and the film will wrinkle into stripes parallel to the tensile direction of the pre-stretched elastomer. Our calculation results give the stability criterion of the system, and the threshold of the gravitational force and the wavelength of the wrinkling patterns are obtained, which can be controlled by tuning the magnitude of the pre-stretch and properties of the thin film and the soft elastomer. These results may provide a regulating strategy for generating precise surface patterns in similar rod structures.

References listed at the end of the paper:


ABSTRACT: In this paper, free vibration of functionally graded (FG) rectangular plates subject to different sets of boundary conditions within the framework of classical plate theory is investigated. Rayleigh–Ritz method is used to obtain the generalized eigenvalue problem. Trial functions denoting the displacement components are expressed in simple algebraic polynomial forms which can handle any sets of boundary conditions. Material properties of the FG plate are assumed to vary continuously in the thickness direction of the constituents according to power-law form. The objective is to study the effects of constituent volume fractions, aspect ratios and power-law indices on the natural frequencies. New results for frequency parameters are incorporated after performing a test of convergence. Comparison with the results from the existing literature are provided for validation in special cases. Three-dimensional mode shapes are presented for FG square plates having various boundary conditions at the edges for different power-law indices. The present investigation also involves the rectangular FG plate to lay on a uniform Winkler elastic foundation. New results for the eigenfrequencies associated with foundation parameters are also reported here with the validation in special cases after checking a convergence pattern.

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Ali Ghorbanpour Arani, Abdolreza Jalilvand and Reza Kolahchi (University of Kashan, Iran), “Nonlinear strain gradient theory based vibration and instability of boron nitride micro-tubes conveying ferrofluid”, International Journal of Applied Mechanics, Vol. 6, No. 5, 1450060, October 2014, 
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ABSTRACT: Nonlinear vibration and instability of a boron nitride micro-tube (BNMT) conveying ferrofluid under the combined magnetic and electric fields are investigated. Based on Euler–Bernoulli beam (EBB), piezoelectricity strain gradient theory and Hamilton’s principle, high order equations of motion are derived for three boundary conditions namely as clamped–clamped (C–C), simply–simply (S–S) and clamped–simply (C–S). The differential quadrature method (DQM) is applied to discretize the motion equations in order to obtain the nonlinear frequency and critical fluid velocity using a direct iterative method. A detailed parametric study is conducted to elucidate the influences of the various boundary conditions, size diameter and magnetic field on vibrational characteristic of BNMT. Numerical results indicate that the effect of magnetic field appears in higher speed of ferrofluid and increases the critical velocity or enlarges the stability region. The results are in good agreement with the previous researches. The results of this study can be used to manufacture smart micro/nano electromechanical systems in advanced biomechanics applications with magnetic and electric fields as parametric controllers.

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ABSTRACT: A 3D free vibration analysis of multilayered structures is proposed. An exact solution is developed for the differential equations of equilibrium written in general orthogonal curvilinear coordinates. The equations consider a geometry for shells without simplifications and allow the analysis of spherical shell panels, cylindrical shell panels, cylindrical closed shells and plates. The method is based on a layer-wise approach, the continuity of displacements and transverse shear/normal stresses is imposed at the interfaces between the layers of the structures. Results are given for multilayered composite and sandwich plates and shells. A free vibration analysis is proposed for a number of vibration modes, thickness ratios, imposed wave numbers, geometries and multilayer configurations embedding isotropic and orthotropic composite materials. These results can also be used as reference solutions for plate and shell 2D models developed for the analysis of multilayered structures.

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Sadegh Imani Yengejeh, Seyedeh Alieh Kazemi and Andreas Ochsner (University of Technology, Malaysia; The University of Birjand, Iran; Griffith University, Southport, Australia), “On the influence of atomic modifications on the structural stability of carbon nanotube hybrids: numerical investigation”, International Journal of Applied Mechanics, Vol. 6, No. 6, 1450077, December 2014, https://doi.org/10.1142/S175882511450077X

ABSTRACT: Connected carbon nanotubes (CNTs) with parallel longitudinal axes and with bending angles were simulated by a commercial finite element package and their buckling behavior was investigated by performing several computational examinations. In addition, the effect of defects on the structural stability of these heterojunctions was analyzed. For this purpose, two different nanotube hybrids (straight and kink heterojunction) were constructed in their perfect forms. In the second phase, three most likely atomic defects, i.e., impurities (doping with Si atoms), vacant sites (carbon vacancy) and introduced perturbations of the ideal geometry in different amounts to the perfect models, were simulated. To conclude our study, the buckling behavior of imperfect heterojunctions was numerically evaluated and compared with the behavior of the perfect ones. It was concluded that the existence of any type of defects in the configuration of nanotube hybrids leads to a lower critical load and as a result, lower buckling properties. This study provides a better insight into the prediction of straight and kink heterojunction CNTs behavior.

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ABSTRACT: In the present study, the defect was introduced in the form of missing strut for the individual cell. The effect of defect on the compressive response of sandwich structures with carbon fiber pyramidal truss cores, the pyramidal truss has better defect tolerance. The theoretical result calculated by the proposed model was in general agreement with experimental result.

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ABSTRACT: In the present study, the defect was introduced in the form of missing strut for the individual cell. The effect of defect on the compressive response of carbon-fiber pyramidal truss cores sandwich panel was investigated through experimental and theoretical methods. A series of sandwich panel sample with or without defect was fabricated, and compressive tests were performed at ambient temperature. Scanning electron microscopy (SEM) was conducted on the samples to evaluate the carbon-fiber distribution and failure mode. A revised theoretical model was proposed to predict the effect of defect considering the strut bending and shear behavior. Our results revealed that the compressive moduli of sandwich panel decrease linearly with the fraction of missing struts. Comparing with open-cell foams and honeycombs, the pyramidal truss has better defect tolerance. The theoretical result calculated by the proposed model was in general agreement with experimental result.

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H. Zhang, N. Kuang and F. Sun, Composites Science and Technology 102, 145 (2014).


ABSTRACT: In this paper, post-buckled vibration of cross-ply thick laminated cylindrical shell panels subjected to nonuniform (parabolic) uniaxial and biaxial compression is studied. The mathematical model is based on a higher order shallow shell theory incorporating von Kármán-type geometric nonlinearities and initial geometric imperfections. In the first step, the plate membrane problem is solved to evaluate the stress distribution within the plate in the pre-buckling range as the applied in-plane edge load is nonuniform. By using the above stress distributions, the governing shell panel post-buckling equations are derived through Hamiltonian principle. The governing nonlinear partial differential equations are reduced into a set of nonlinear algebraic equations for post-buckling analysis and nonlinear ordinary differential equations in the case of free vibration analysis using Galerkin's method. The equilibrium paths through limit points are traced using Newton–Raphson method in conjunction with Riks approach. The free vibration frequency of pre-buckled and post-buckled cylindrical panels loaded with uniaxial or biaxial nonuniform in-plane edge load are studied. Free vibration frequency for symmetric (0/90/0) cross-ply laminated cylindrical shell panels under uniaxial and biaxial parabolic in-plane load with initial imperfections are presented for different post-buckled deflections. Limit loads and snap-through behavior of shell panels and corresponding free vibration results are co-related for better understanding of the problem.
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**ABSTRACT:** In the present study, a finite element formulation is presented to investigate vibration response of elastic plates in contact with a fluid medium. The fluid is assumed to be incompressible and inviscid, and the impermeability condition of the plate is taken into account. The classical plate theory (CPT), first-order shear deformation plate theory (FSDT), and Reddy third-order shear deformation plate theory (RSDT) are considered for the kinematic description of the solid medium and the simplified Navier–Stokes equations are used as the governing equations for the fluid medium. For each plate theory, a coupled set of finite element equations is derived. The effect of the fluid pressure is considered as an added mass and its effect on natural frequencies and mode shapes is investigated through several numerical simulations by varying the boundary conditions.

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ABSTRACT: The objective of this paper is to study the postbuckling behaviors of unknown-length nanobeams considering the effects of nonlocal elasticity and surface stress. "Some studies and researches related to the hydro-elasticity of steel work," Proceedings of the 122nd Euromech Colloquium on Numerical Analysis of the Dynamics of Ship Structures, Ecole Polytechnique, Paris, pp. 403–406.


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ABSTRACT: The objective of this paper is to study the postbuckling behaviors of an unknown-length nanobeam combined with small-scale effects. The concept of variable-arc-length elastica is firstly applied on the problem of nanobeams. The span length is not changed while the arc length is varied increasingly. The nanobeam is on a clamped support at one end, while the other end is an overhanging part through a frictionless slot subjected to axial compression. At this end, the nanobeam is movable only in a horizontal direction. The governing equation is developed by the moment–curvature relationship based on the classical Euler–Bernoulli beam theory, including the effects of nonlocal elasticity, residual surface stress, and both combined effects. The governing equation is developed by the moment–curvature relationship based on the classical Euler–Bernoulli beam theory, including the effects of nonlocal elasticity, residual surface stress, and both combined effects. The shooting–optimization technique with two-point boundary condition is employed to solve the differential equations in this problem. The results, including nonlocal elasticity, reveal that nanobeams have decreased structural stiffness; meanwhile, the residual surface tension and both combined effects have increased strength. The postbuckling loads decrease as the arc length of nanobeams is increased. The equilibrium configurations are close to an anti-loop for very large deflections. The friction force at the nanoslot is also considered.

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ABSTRACT: A Meshfree Radial Basis Collocation Method (RBCM) associated with explicit and implicit time integration scheme is formulated to study the coupling dynamics of a rotating flexible tube conveying fluid, which involves a partial differential equation (PDE) with variable coefficients. Dispersion studies are performed and they indicate that the proposed RBCM has a very small dispersion error compared with conventional FEM and Galerkin-based meshfree methods. Numerical examples are conducted for the influence of initial flow rate of the fluid, discretization and shape parameter on the dispersion error. The critical time step is obtained from a Von Neumann stability analysis. For the eigenproblem, Hermite-type RBCM is proposed in order to construct square matrices and eigenvalue analysis gives the frequencies of the system. Subsequently, the influence of angular velocity, flow rate of the fluid and the time variation on the fundamental frequencies is studied. Though proposed for studying the dynamics of a rotating flexible tube conveying fluid, this solution scheme is applicable to other dynamical problems which have similar PDEs with variable coefficients.

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Abstract: The vibration and acoustic radiation for an orthotropic composite conical shell in a hygroscopic environment are explored through the wave propagation approach and Galerkin method. Theoretical results of the natural vibration and far field sound pressure are presented with incremental moisture content. The effects associated with the lowest frequency mode reaches the modal index of 15, which increases with the decrease of the semi-vertex angle. It is found that the natural frequencies decrease with incremental moisture content. The wavenumbers associated with the lowest frequency mode reaches the modal indices corresponding to the lowest buckling mode near the critical buckling moisture content. With the increasing moisture content, a shifting of natural frequencies toward lower frequency band could be observed in lower frequency band of the modal density in constant frequency band. The overall sound pressure level (SPL) decreases generally with the moisture content, but shows a marginal increase near the critical buckling moisture content. The modal density and overall SPL decrease with the incremental stiffness generally, which increases with the decrease of the semi-vertex angle.

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Maroua Hammami, Abderrahim El Mahi, Chafik Karra and Mohamed Haddar (First author is from: National School of Engineering of Sfax (ENIS), Sfax University, Laboratory of Mechanic, Modelling and Production (LA2MP), Route de Soukra 3038, Sfax, Tunisia), “Vibration behavior of composite material with two overlapping delaminations”, International Journal of Applied Mechanics, Vol. 7, No. 4, 1550054, August 2015, https://doi.org/10.1142/S1758825115500544

ABSTRACT: The paper presents an analysis of the vibration behavior of glass fiber reinforced composites with two overlapping delaminations. The effect of delamination length on the vibration parameters is studied. Throughout a series of vibration tests, the change of natural frequencies and modal damping due to delaminations is evaluated. A numerical simulation considering finite element analysis allows to predict the change of natural frequencies for a known damage size. Modal damping was established which evaluates the different energies dissipated in the material layers direction of the fiber reinforced composites. A comparison of the different results was performed. Next, strain energy of layers directions were established by a numerical analysis and discussed.

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ABSTRACT: In this paper, we investigate the effect of high modes of buckling on the mechanical behavior of a pre-shaped curved beam. In a first stage, the presented modeling develops further the snapping forces solution and bistability conditions in order to include high modes of buckling. In a second stage, we develop the analytical solution of the stresses inside the beam during deflection between the two sides of buckling. The buckling with or without mechanical conditions on antisymmetric modes, the force characteristics, bistability conditions and stresses are described in this paper based on mathematical approach in order to provide a clear physical understanding of the curved beam behavior and its design parameters. The accurate knowledge of the design parameters is important in order to achieve the best integration of the curved beam in a complete microstructure. The analytical results are compared with and without considering high modes of buckling and have shown to be in excellent agreement with FEM simulations. The results show the importance of the high modes in calculating stresses and snapping forces.

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ABSTRACT: Based on the framework of Flügge’s shell theory, transfer matrix approach and Romberg integration method, we investigated how the thermal gradient affects the vibration behavior of rotating isotropic and orthotropic oval cylindrical shells. The governing equations of orthotropic oval cylindrical shells, under parabolically varying thermal gradient around its circumference, with consideration of the effects of initial hoop tension and centrifugal forces due to the rotation are derived, and they are put in a matrix differential equation as a boundary-value problem. As a semianalytic solution, the trigonometric functions are used with Fourier’s approach to approximate the solution in the longitudinal direction, and also to reduce the two-dimensional problem in to an one-dimensional one. Using the transfer matrix approach, the equations can be written in a matrix differential equation of first-order and solved numerically as an initial-value problem. The proposed model is applied to get the natural frequencies and vibratory displacement of the symmetrical and antisymmetrical vibration modes. The sensitivity of the vibration behavior to the rotational speed, the thermal gradient, the ovality and orthotropy of the shell is studied for different type-modes of vibration. The present method is found to be accurate when compared with the results available in the literature.

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ABSTRACT: Based on the framework of Flügge's shell theory, transfer matrix approach and Romberg integration method, we investigated how the thermal gradient affects the vibration behavior of rotating isotropic and orthotropic oval cylindrical shells. The governing equations of orthotropic oval cylindrical shells, under parabolically varying thermal gradient around its circumference, with consideration of the effects of initial hoop tension and centrifugal forces due to the rotation are derived, and they are put in a matrix differential equation as a boundary-value problem. As a semianalytic solution, the trigonometric functions are used with Fourier's approach to approximate the solution in the longitudinal direction, and also to reduce the two-dimensional problem in to an one-dimensional one. Using the transfer matrix approach, the equations can be written in a matrix differential equation of first-order and solved numerically as an initial-value problem. The proposed
model is applied to get the natural frequencies and vibratory displacement of the symmetrical and antisymmetrical vibration modes. The sensitivity of the vibration behavior to the rotational speed, the thermal gradient, the ovality and orthotropy of the shell is studied for different type-modes of vibration. The present method is found to be accurate when compared with the results available in the literature.

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Boonchai Phungpaingam, Lawrence N. Virgin and Somchai Chucheekpsakul (First author is from: Department of Civil Engineering, Rajamangala University of Technology Thanyaburi, Pathumthani 12110, Thailand),

ABSTRACT: This paper presents the snap-through phenomenon and effect of self-contact of the spatial elastica subjected to mid-length torque. One end of the elastica is clamped while the other end is placed in a sleeve joint. The total arc-length of the elastica can be varied by sliding the end through the sleeve joint. At a certain value of total arc-length, the sleeve joint is clamped and an external torque is applied at the mid-length of the elastica. The system of governing differential equations is derived from the equilibrium of an elastica segment and geometric relations of the inextensible elastica. The transformation matrix formulated in terms of Euler parameters is utilized to avoid the kinematic singularity. To display the behavior of the elastica, the system of differential equations needs to be integrated numerically from one end to the other end. The integration is performed so that the boundary conditions and some constraint conditions of the problem are satisfied, i.e., a shooting method is used. The effect of self-contact is taken into account by considering the contact force as a point load applying at contact point. From the results, the snap-through phenomenon, effect of self-contact and equilibrium configurations are highlighted herein.

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ABSTRACT: In this paper, vibration analysis of tapered magnetostrictive plate (MsP) is studied for the first time. Magnetostrictive material (MsM) is a component of smart material due to magneto–mechanical coupling in stress–strain relations or its reciprocal nature. A feedback control system is utilized in order to investigate the magnetic field intensity using velocity feedback gain parameter. The thickness of rectangular MsP varies linearly in both x- and y-directions. First order shear deformation theory (FSDT) with considering shear correction factor is used to derive the governing equations of tapered MsP including five equations and five unknowns that solved by differential quadrature method (DQM). Results indicate the effect of various parameters such as aspect ratio, thickness ratio, x- and y-taper ratios and the controller effect of velocity.
feedback gain on the frequency of MsP. The results are also compared by those available in the literature. These findings can be used to vibration cancellation systems and utilized for designing the magnetostrictive actuator, motor, transducer and sensors.

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ABSTRACT: Based on a systematic investigation on the experimental, theoretical and numerical results on various tubes under axial compression/impact including our own tests, a set of key performance indicators (KPIs) for assessing and comparing the energy absorbing performance of tubular structures with various configurations is proposed, so as to guide the design of energy absorbers whilst to facilitate parameter optimization. The five KPIs proposed on the basis of mechanical analyses are effective stroke ratio (ESR),
The governing equations are derived from the principle of virtual displacements. The analytical solution for an exponential law distribution, meaning that Lamé coefficients vary exponentially in a given fixed z-direction. The governing equations are derived from the principle of virtual displacements. The analytical solutions are valid for a set of five KPIs to comprehensively assess the performance of various tubular structures used as energy absorbers. References listed at the end of the paper:

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ABSTRACT: The trigonometric shear and normal deformations plate theory is used to study the thermo-mechanical bending analysis of exponentially graded (EG) thick rectangular plates resting on Pasternak elastic foundations. Material properties of the plate are assumed to be graded in the thickness direction according to an exponential law distribution, meaning that Lamé coefficients vary exponentially in a given fixed z-direction. The governing equations are derived from the principle of virtual displacements. The analytical solutions are...
obtained by using Navier technique and the effects of stiffness of the foundations, thermal loading, and gradient index on thermo-mechanical responses of the plates are discussed. Numerical results for the bending response for EG rectangular plates are investigated and some of them are compared with those available in the literature.

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Zengyong An, Mingjiong Xu, Yajun Luo and Chensong Wu (First author is from: State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xianning West Road, No. 28. Xi'an 710049, P. R. China). “Active vibration control for a large annular flexible structure via a macro-fiber composite strain sensor and voice coil actuator”, International Journal of Applied Mechanics, Vol. 7, No. 4, 1550066, August 2015, https://doi.org/10.1142/S1758825115500660

ABSTRACT: Large annular flexible structures (LAFS) are typical antenna structures for satellites. This structure can significantly increase antenna aperture and effectively improve communication accuracy with minimum addition of mass. LAFS have become mainstream for large aperture antenna structures. However, they have disadvantages, such as low natural frequencies, low damping ratio, and low stiffness. They easily suffer from low frequency, longtime and modal responses. Therefore, the vibration control of LAFS is very important. This study proposes a novel active vibration control method using macro-fiber composite (MFC) as a sensing unit, a voice coil actuator and a PD-fuzzy control algorithm. The MFC sensor can measure a minimum strain of $10^8$ m/m. The voice coil actuator generates a displacement and driving force. Based on the feedback signal from the MFC sensor, the PD-fuzzy control algorithm controls the voice coil actuator. A dynamic model
of LAFS was established, and its characteristics analyzed. A theoretical model for the voice coil actuator and MFC sensor were established, and the corresponding governing equations derived. An experimental system was set up. The results demonstrated that the novel active vibration control method has good performance. This active vibration control method can control vibration at ultralow frequencies and requires no additional stiffness.

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ABSTRACT: The innovative stacked-shell modeling approach is investigated in the frame of an explicit finite element method for the prediction of laminated structural elements' static response, focusing on the interlaminar stress calculation. The main advantage of the investigated stacked-shell modeling technique is the lower computational cost compared to conventional methods, for the same accuracy in displacement and stress results. A laminated plate under sinusoidally distributed transverse loading, a laminated strip under three-point bending and a laminated cylindrical shell under cylindrical bending have been used in the assessment of the developed methodology; static results referring to displacement and both in-plane and out-of-plane stresses of the investigated cases have shown that the proposed technique is highly efficient in the calculation of interlaminar stresses of composite structures, which provides the background for an accurate and efficient delamination prediction.

References listed at the end of the paper:
None given.

ABSTRACT: The mechanical properties of Ogden material under biaxial deformation are obtained by using the bubble inflation technique. First, pressure inside the bubble and height at the hemispheric pole are recorded during bubble inflation experiment. Thereafter, Ogden's theory of hyperelasticity is employed to define the constitutive model of flat circular thermoplastic membranes (CTPMs) and nonlinear equilibrium equations of the inflation process are solved using finite difference method with deferred corrections. As a last step, a neuronal algorithm artificial neural network (ANN) model is employed to minimize the difference between calculated and measured parameters to determine material constants for Ogden model. This technique was successfully implemented for acrylonitrile-butadiene-styrene (ABS), at typical thermoforming temperatures, 145°C. When solving for the bubble inflation, the recorded pressure is applied uniformly on the structure. During the process inflation, the pressure is not uniform inside the bubble, thus full gas dynamic equations need to be solved to get the appropriate nonuniform pressure to be applied on the structure. In order to simulate the inflation process accurately, computational fluid dynamics in a moving fluid domain as well as fluid structure interaction (FSI) algorithms need to be performed for accurate pressure prediction and fluid structure interface coupling. Fluid structure interaction solver is then required to couple the dynamic of the inflated gas to structure motion. Recent development has been performed for the simulation of gas dynamic in a moving domain using arbitrary Lagrangian Eulerian (ALE) techniques.

References listed at the end of the paper:
None given.


ABSTRACT: The vibration, sound radiation and transmission characteristics of plates with various functionally graded materials (FGM) are explored and a detailed investigation is presented on the influence of specific material properties on structural–acoustic behavior. An improved model based on a simplified first order shear deformation theory along with a near-field elemental radiator approach is used to predict the radiated acoustic field associated with a given vibration and acoustic excitation. Various ceramic materials suitable for engineering applications are considered with aluminum as the base metal. A power law is used for the volume fraction distribution of the two constitutive materials and the effective modulus is obtained using the Mori–Tanaka homogenization scheme. The structural–acoustic response of these FGM plates is presented in terms of the plate velocity, radiated sound power, sound radiation efficiency for point and uniformly distributed load cases. Increase in both vibration and acoustic response with increase in power law index is observed for the lower order modes. The vibro–acoustic metrics such as root-mean-squared plate velocity, overall sound power, frequency averaged radiation efficiency and transmission loss, are used to rank these materials for vibro–acoustically efficient combination. Detailed analysis has been made on the factors influencing the structural–acoustic behavior of various FGM plates and relative ranking of particular ceramic/metal combinations.

References listed at the end of the paper:
None given.
ABSTRACT: Free vibration analysis of moderately thick laminated functionally graded rectangular plates with elastic restraints is presented using the modified Fourier–Ritz method in conjunction with the first-order shear deformation plate theory. The material properties are assumed to change continuously through the lamina thickness according to a power-law distribution of volume fractions of the constituents. Each of the displacements and rotations of the laminated functionally graded plates, regardless of boundary conditions, is represented by a modified Fourier series which is constructed as the linear superposition of a standard Fourier cosine series and several closed-form auxiliary functions. The accuracy, convergence and reliability of the current solutions are demonstrated by numerical examples and comparison of the present results with those available in the literature. New results for free vibration of laminated functionally graded plates are presented, which may serve as benchmark solutions. The effects of the boundary conditions, volume fractions and lamina thickness ratios on the frequencies of the plates are investigated.

References listed at the end of the paper:
None given.

ABSTRACT: This paper deals with nonlinear response of smart two-phase nanocomposite plates with surface-bonded piezoelectric layers under a combined mechanical, thermal and electrical loading. The governing equations of the carbon nanotube reinforced composite plate are derived based on first order shear deformation plate theory (FSDT) and von Kármán geometric nonlinearity. The material properties of the nanocomposite host are assumed to be graded in the thickness direction. The single-walled carbon nanotubes (SWCNTs) are assumed aligned, straight and a uniform layout. The Galerkin method is employed to derive the nonlinear governing equations of the problem. A perturbation scheme is employed to determine the nonlinear vibration response and the nonlinear natural frequencies of the plates with immovable simply supported boundary conditions. Post-buckling load–deflection and maximum transverse load–deflection relations have been obtained for the plate under consideration. The effects of the applied voltage, temperature change, plate geometry, and the volume fraction and distribution pattern of the SWCNTs on the linear and nonlinear natural frequencies of the smart two-phase composite plates are investigated through a detailed parametric study.

References listed at the end of the paper:
None given.

ABSTRACT: In this paper, a geometrically nonlinear first-order shear deformable nanoplate model is developed to investigate the size-dependent geometrically nonlinear free vibrations of rectangular nanoplates considering surface stress effects. For this purpose, according to the Gurtin–Murdoch elasticity theory and
Hamilton's principle, the governing equations of motion and associated boundary conditions of nanoplates are derived first. Afterwards, the set of obtained nonlinear equations is discretized using the generalized differential quadrature (GDQ) method and then solved by a numerical Galerkin scheme and pseudo arc-length continuation method. Finally, the effects of important model parameters including surface elastic modulus, residual surface stress, surface density, thickness and boundary conditions on the vibration characteristics of rectangular nanoplates are thoroughly investigated. It is found that with the increase of the thickness, nanoplates can experience different vibrational behavior depending on the type of boundary conditions.

References listed at the end of the paper:
None given.


ABSTRACT: In this paper, buckling analysis of thick radially functionally graded circular/annular sector plates with variable thickness resting on two-parameter elastic foundations is studied. The material properties vary along radial direction according to either an exponential or a power-law distribution. The stability equations are derived using the adjacent equilibrium criterion and are based on a higher order shear deformation theory. The generalized differential quadrature method is employed to discretize the stability equations and convert them into a system of algebraic eigenvalue problem. The formulation and method of solution are validated by performing comparison studies with the available results in the open literature. Then, the effects of power-law index, boundary conditions, thickness variation and coefficients of foundation on the critical buckling load of the circular/annular sector plates subjected to different types of in-plane compressions or in-plane shear are investigated in detail.


ABSTRACT: When a structure vibrates immersed in a fluid it is known that the dynamic properties of the system are modified. The surrounding fluid will, in general, contribute to the inertia, the rigidity and the damping coefficient of the coupled fluid-structure system. For light structures, like spacecraft antennas, even when the fluid is air the contribution to the dynamic properties can be important. For not so light structures the ratio of the equivalent fluid/structure mass and rigidity can be very small and the fluid contribution could be neglected. For the ratio of equivalent fluid/structure damping both terms are of the same order and therefore the fluid contribution must be studied. The working life of the spacecraft structure would be on space and so without any surrounding fluid. The response of a spacecraft structure on its operational life would be attenuated by the structural damping alone but when the structure is dynamically tested on the earth the dynamic modal test is performed with the fluid surrounding it. The results thus are contaminated by the effects of the fluid. If the damping added by the fluid is of the same order as the structural damping the response of the structure in space can be quite different to the response predicted on earth. It is therefore desirable to have a method able to determine the amount of damping induced by the fluid and that should be subtracted of the total damping measured on the modal vibration test. In this work, a method for the determination of the effect of the surrounding fluid on the dynamic characteristics of a circular plate has been developed. The plate is assumed to vibrate harmonically with the vacuum modes and the generalized forces matrix due to the fluid is thus computed. For a compressible fluid this matrix is formed by complex numbers including terms of inertia,
rigidity and damping. The matrix due to the fluid loading is determined by a boundary element method (BEM). The BEM used is of circular rings on the plate surface so the number of elements to obtain an accurate result is very low. The natural frequencies of the system are computed by an iteration procedure one by one and also the damping fluid contribution. Comparisons of the present method with various experimental data and other theories show the efficiency and accuracy of the method for any support condition of the plate.

References listed at the end of the paper:


ABSTRACT: This paper deals with thermomechanical bending of functionally graded material (FGM) plates under various boundary conditions and resting on two-layer elastic foundations. One of these layers is Winkler springs with a variable modulus while the other is considered as a shear layer with a constant modulus. The plates are considered of the type having two opposite sides simply-supported, and the two other sides having combinations of simply-supported, clamped, and free boundary conditions. The temperature is obtained by solving the one-dimensional equation of heat conduction. The material properties of the plate are assumed to be graded continuously across the panel thickness. A simple power-law distribution in terms of the volume fractions of the constituents is used for estimating the effective material properties such as temperature-dependent thermoelastic properties. The governing equations are derived based on the sinusoidal shear deformation plate theory including the external load and thermal effects. The results of this theory are compared with those of other shear deformation theories. Various numerical results including the effect of boundary conditions, power-law index, plate aspect ratio, temperature difference, elastic foundation parameters, and side-to-thickness ratio on the bending of FGM plates are presented.

References listed at the end of the paper:


Farhad Alinaghizadeh and Mahmoud Shariati (Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran), “Buckling analysis of variable thickness radially functionally graded annular sector plates subjected to thermomechanical loads by the GDQ method”, International Journal of Applied Mechanics, Vol. 7, No. 6, 1550083, December 2015.
https://doi.org/10.1142/S1758825115500830

ABSTRACT: In this paper, buckling analysis of thick radially functionally graded circular/annular sector plates with variable thickness resting on two-parameter elastic foundations is studied. The material properties vary along radial direction according to either an exponential or a power-law distribution. The stability equations are derived using the adjacent equilibrium criterion and are based on a higher order shear deformation theory. The generalized differential quadrature method is employed to discretize the stability equations and convert them into a system of algebraic eigenvalue problem. The formulation and method of solution are validated by performing comparison studies with the available results in the open literature. Then, the effects of power-law index, boundary conditions, thickness variation and coefficients of foundation on the critical buckling load of the circular/annular sector plates subjected to different types of in-plane compressions or in-plane shear are investigated in detail.

References listed at the end of the paper:


ABSTRACT: Laminated multiple metal or alloy sheets have been widely used in protective structures. However, energy absorption mechanism remains unclear for those laminates with different interface and surface conditions under low-velocity impact. This study investigates the effect of interface and surface modified double aluminum sheets under drop-weight loading. The experimental results showed that epoxy-bonded double sheets did not dissipate more energy than free-contact sample. The simulation results agree well with the experimental data at low cohesive stress of the epoxy adhesive, and friction plays an important role in absorbing impact energy for free-contact sample. However, at high interface cohesive stress as simulated, epoxy-bonded samples absorb more energy than free-contact ones. Further experiments indicated that sample with grease spread front surface is more sensitive in improving energy absorption than sample with grease applied in between two layers. These results are important reference for designing laminated composites to improve impact resistance.

References listed at the end of the paper:


ABSTRACT: This paper deals with the static behavior of an electrostatically actuated bilayered microswitch on the basis of the modified couple stress theory. The beam is modeled using Euler–Bernoulli beam theory and equivalent elastic modulus and length scale parameter are presented for the bilayer beam. Static deflection and pull-in voltage of the beam is calculated using numerical and analytical methods. The numerical method is based on an iterative approach while the homotopy perturbation method (HPM) is utilized for the analytical simulation. Results show that there is a very good agreement between these methods even in the vicinity of the pull-in instability. Moreover, the effects of different parameters such as thicknesses of layers and length scale parameter on the static deflection and instability of the microcantilever are studied. Results show that for the cases with the equivalent length scale parameter comparable to the thickness of beam, the size-dependency plays significant roles in the static behavior of the bilayer microcantilevers.

References listed at the end of the paper:


ABSTRACT: This paper presents an approach to control the fluid-induced vibration of the carbon nanotubes (CNTs) embedded in viscoelastic medium with topology non-uniform magnetic field. Non-local continuum theory and homogenization equivalence are employed to conclude small-scale effects of the carbon nanotube
(CNT) and the nanofluid, respectively. Simply supported, fixed–fixed and fixed–pinned fluid–conveying carbon nanotubes (FCCNTs) with sliding and no-sliding ends are chosen as samples to illustrate the control effect of the magnetic field, and the optimal magnetic field distributions are obtained through genetic algorithm (GA). Dynamic characteristics (the eigen-frequencies and the critical velocities) of different FCCNT models are calculated through differential quadrature (DQ) method. The control effects of the magnetic field can be validated through examining the stiffness enhancement of the Ampere’s force. Results present that the eigen-frequencies and critical velocities of different FCCNTs are all raised by 3–13% through the given magnetic fields. Contrasts between different models illustrate that the dynamic stiffness of simply supported FCCNT with no-sliding ends is enhanced mostly by the magnetic field.

References listed at the end of the paper:


ABSTRACT: It is proposed to investigate in this paper the damped vibrations of an incompressible liquid contained in a deformable tank. A linearized formulation describing the small movements of the system is presented. At first, a diagonal damping is introduced in the reduced equations of the hydroelastic sloshing problem. We obtain a nonclassically damped coupled system with a damping matrix that is not symmetric. Then, by projecting the system onto its complex modes, the frequency and time responses for different type of loads are built. A numerical application is illustrated on a test case.

ABSTRACT: Stainless steel sandwich beams with a corrugated core or a Y-frame core have been tested in three-point bending and the role of the face-sheets has been assessed by considering beams with (i) front-and-back faces present, and (ii) front face present but back face absent. A fair comparison between competing beam designs is made on an equal mass basis by doubling the front face thickness when the back face is absent. The quasi-static, three-point bending responses were measured under simply supported and clamped boundary conditions. For both end conditions and for both types of core, the sandwich beams containing front-and-back faces underwent indentation beneath the mid-span roller whereas Brazier plastic buckling was responsible for the collapse of sandwich beams absent the back face. Three-dimensional finite element (FE) predictions were in good agreement with the measured responses and gave additional insight into the deformation modes. The FE method was also used to study the effect of (i) mass distribution between core and face-sheets and (ii) beam span upon the collapse response of a simply supported sandwich panel. Sandwich panels of short span are plastically indented by the mid-span roller and the panels absent a back face are stronger than those with front-and-back faces present. In contrast, sandwich panels of long span undergo Brazier plastic buckling, and the presence of a back face strengthens the panel.

ABSTRACT: The three-dimensional, dynamic, elastic-plastic response of a right-angle bent cantilever pipe, with an initially uniform, circular cross section, subjected to out-of-plane loading is examined using finite element beam and shell models in ABAQUS. The large-deflection behavior involves both bending and torsional elastoplastic deformations of the pipe, phenomena which have not been previously studied in the context of the dynamic problem of pipe whip. Initially, neglecting ovalization and local collapse (kinking), the bent pipe is modeled as a beam, using spatial beam elements in ABAQUS. This enables the basic three-dimensional kinematic behavior of the pipe to be analyzed. A similar, but potentially more accurate, analysis was then performed using shell elements. It is shown that there is no significant difference in the global dynamic plastic response. However the ovalization of the pipe cross section and formation and movement of the plastic zones (hinges) can be captured by using shell elements. This provides data which could form the basis for examining local failures in the pipe run. Previously unpublished experimental results, obtained in an earlier study by some of the present authors, are compared with the simulated results. Good agreement is observed and it is concluded that a nonlinear dynamic model using finite elements provides a rigorous approach for estimating the hazard zone (HZ) and, also, for treating the kinematics of a whipping pipe for this complex three-dimensional situation.

ABSTRACT: This article describes a mathematical model and two solution methodologies for efficiently predicting the equilibrium paths of an arbitrarily shaped, precurved, clamped beam. Such structures are common among multistable microelectromechanical systems (MEMS). First, a novel polynomial-based solution approach enables simultaneous solution of all equilibrium configurations associated with an arbitrary mechanical loading pattern. Second, the normal flow algorithm is used to negotiate the particularly complex nonlinear equilibrium paths associated with electrostatic loading and is shown to perform exceptionally well. Overall, the techniques presented herein provide designers with general and efficient computational frameworks for studying the effects of loading, shape, and imperfections on beam behavior. Sample problems motivated from switch and actuator applications in the literature demonstrate the methodologies’ utility in predicting the nonlinear equilibrium paths for structures of practical importance.

ABSTRACT: The instability of a self-gravitating fluid cylinder surrounded by a self-gravitating tenuous medium pervaded by transverse varying electric field is discussed under the combined effect of the capillary, self-gravitating, and electric forces. This has been done for all axisymmetric and nonaxisymmetric modes of perturbation. The problem is formulated and solved with excluding the singular solutions, and the stability criterion is derived. Several published works are obtained as limiting cases from the present general case and investigated, and moreover the results are interpreted physically. The model is stable due to the stabilizing effect of the transverse electric field in all modes of perturbation. The destabilizing effect of the capillary and self-gravitating forces is found in small domain in the axisymmetric perturbation. However, the stabilizing effects of the capillary and self-gravitating forces in large axisymmetric domains and in all nonaxisymmetric domains modify and improve the instability of the present model.

ABSTRACT: Many micromachined electroacoustic devices use thin plates in conjunction with electrical components to measure acoustic signals. Composite layers are needed for electrical passivation, moisture barriers, etc. The layers often contain residual stresses introduced during the fabrication process. Accurate models of the composite plate mechanics are crucial for predicting and optimizing device performance. In this paper, the von Kármán plate theory is implemented for a transversely isotropic, axisymmetric plate with in-plane tensile stress and uniform transverse pressure loading. A numerical solution of the coupled force-displacement nonlinear differential equations is found using an iterative technique. The results are verified using finite element analysis. This paper contains a study of the effects of tensile residual stresses on the displacement field and examines the transition between linear and nonlinear behavior. The results demonstrate that stress stiffening in the composite plate delays the onset of nonlinear deflections and decreases the mechanical sensitivity. In addition, under high stress the plate behavior transitions to that of a membrane and becomes insensitive to the composite nature of the plate. The results suggest a tradeoff between mechanical sensitivity and linearity.


ABSTRACT: Wrinkling modes are determined for a two-layer system comprised of a neo-Hookean film bonded to an infinitely deep neo-Hookean substrate with the entire bilayer undergoing compression. The full range of the film/substrate modulus ratio is considered from the limit of a traction-free homogeneous substrate to very stiff films on compliant substrates. The role of substrate prestretch is considered wherein an unstretched film is bonded to a prestretched substrate with wrinkling arising as the stretch in the substrate is relaxed. An exact bifurcation analysis reveals the critical strain in the film at the onset of wrinkling. Numerical simulations carried out within a finite element framework uncover advanced post-bifurcation modes including period-doubling, folding and a newly identified mountain ridge mode.


ABSTRACT: A new one-dimensional high-order theory for orthotropic elastic sandwich beams is formulated. This new theory is an extension of the high-order sandwich panel theory (HSAPT) and includes the in-plane rigidity of the core. In this theory, in which the compressibility of the soft core in the transverse direction is also considered, the displacement field of the core has the same functional structure as in the high-order sandwich panel theory. Hence, the transverse displacement in the core is of second order in the transverse coordinate and the in-plane displacements are of third order in the transverse coordinate. The novelty of this theory is that it allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core and the rotation at the centroid of the core) instead of just one (midpoint transverse displacement) commonly adopted in other available theories. It is proven, by comparison to the elasticity solution, that this approach results in superior accuracy, especially for the cases of stiffer cores, for which cases the other available sandwich computational models cannot predict correctly the stress fields involved. Thus, this theory, referred to as the “extended high-order sandwich panel theory” (EHSAPT), can be used with any combinations of core and face sheets and not only the very “soft” cores that the other theories demand. The theory is derived so that all core/face sheet displacement continuity conditions are fulfilled. The governing equations as well as the boundary conditions are derived via a variational principle. The solution procedure is outlined and numerical results for the simply supported case of transverse distributed loading are produced for several typical
sandwich configurations. These results are compared with the corresponding ones from the elasticity solution. Furthermore, the results using the classical sandwich model without shear, the first-order shear, and the earlier HSAPT are also presented for completeness. The comparison among these numerical results shows that the solution from the current theory is very close to that of the elasticity in terms of both the displacements and stress or strains, especially the shear stress distributions in the core for a wide range of cores. Finally, it should be noted that the theory is formulated for sandwich panels with a generally asymmetric geometric layout.

ABSTRACT: This paper addresses the problem of the aerothermoelastic modeling behavior and analyses of skin curved panels with static and dynamic edge movability effect in high supersonic flow. Flutter and post-flutter behavior will be analyzed toward determining under which conditions such panels will exhibit a benign instability, that is a stable limit cycle oscillation, or a catastrophic instability, that is an unstable LCO. The aerothermoelastic governing equations are developed from the geometrically non-linear theory of infinitely long two dimensional curved panels. Von Kármán non-linear strain-displacement relation in conjunction with the Kirchhoff plate-hypothesis is adopted. A geometrically imperfect curved panel forced by a supersonic/hypersonic unsteady flow is numerically investigated using Galerkin approach. These equations are based on the third-order piston theory aerodynamic for modeling the flow-induced forces. Furthermore, the effects of thermal degradation and Kelvin’s model of structural damping independent of time and temperature are also considered in this model. Computational analysis and discussion of the finding along with pertinent conclusions are presented.

ABSTRACT: A classical nonlinear thermodynamic theory of elastic shells is derived by specializing the three-dimensional equations of motion and the second law of thermodynamics to a very general, shell-like body. No assumptions are made on how unknowns vary through the thickness. Extensional and bending strains are derived from the equations of motion via the principle of virtual power. The Coleman-Noll procedure plus the second law applied to an assumed form of the first law leads to constitutive relations plus reduced forms of the first and second laws. To avoid potential ill conditioning, a Legendre-Fenchel transformation is used to define a mixed-energy density, the logical place to impose the constitutive Kirchhoff hypothesis, if desired, because such an energy density rests, ultimately, on experiments. The Ladevèze-Pécastaings treatment of three-dimensional edge effects to obtain accurate two-dimensional solutions is discussed.

ABSTRACT: The objective of this work is to investigate the quasi-static plastic behavior of a fully clamped metal foam core sandwich beam transversely loaded by a flat punch. A rigid-plastic beam-on-foundation model is extended to study the local denting deformation of a metal foam core sandwich beam. The effects of local denting and core strength on the overall deformation are incorporated in the analysis. Analytical solutions are derived for three different regimes of post-yield deformation mechanisms. Additionally, finite element results
are obtained. Comparisons of the present analytical predictions with numerical, previous experimental, and analytical results are presented, respectively. It is shown that local denting has a significant effect on the finite deflection response of the metal foam core sandwich structure. The load-carrying and energy absorption capacities of sandwich beams may be overestimated if the effect of local denting is neglected in analysis. It is demonstrated that the present analytical model can reasonably predict the behaviors of post-yield deformation of sandwich beams. Moreover, the present analytical method can be extended to predict the low velocity/energy impact problems of sandwich structures.


ABSTRACT: The mechanical deformation of an ideal thin-walled cylindrical shell is investigated in the presence of intersurface interactions with a planar rigid substrate. A Dugdale–Barenblatt–Maugis (DBM) cohesive zone approximation is introduced to simulate the convoluted surface force potential. Without loss of generality, the repulsive component of the surface forces is approximated by a linear soft-repulsion, and the attractive component is described by two essential variables, namely, surface force range and magnitude, which are allowed to vary. The nonlinear problem is solved numerically to generate the pressure distribution within the contact, the deformed membrane profiles, and the adhesion-delamination mechanics, which are distinctly different from the classical solid cylinder adhesion models. The model has wide applications in cell adhesion and nanostructures.


ABSTRACT: The design equations for pipelines subjected to both internal pressure and longitudinal loading are based on the isotropic hardening plasticity model. However, high strength steel (HSS) pipelines exhibit plastic anisotropy, which cannot be incorporated in the traditional isotropic hardening plasticity model. The stress strain behaviors of HSS in the longitudinal and the circumferential directions are different. Thus, it would not be desirable to adopt the same design equations based on the isotropic hardening plasticity model for HSS pipelines. The design equations of HSS steel pipelines have to be developed by solving numerical models incorporating a suitable material plasticity constitutive model for the HSS that can deal with the exhibited plastic anisotropy. In this paper, various plasticity models are studied and an appropriate plasticity model is adopted and calibrated to model the plastic anisotropy exhibited by the HSS.


ABSTRACT: The material model proposed in Part I (Neupane, 2012, “Modeling the Deformation Response of High Strength Steel Pipelines—Part I: Material Characterization to Model the Plastic Anisotropy,” ASME J. Appl. Mech., 79 , p. 051002) is used to study the deformation response of high strength steel. The response of pipes subjected to frost upheaval at a particular point is studied using an assembly of pipe elements, while buckling of pipes is examined using shell elements. The deformation response is obtained using two different material models. The two different material models used were the isotropic hardening material model and the combined kinematic hardening material model. Two sets of material stress-strain data were used for the isotropic hardening material model; data obtained from the longitudinal direction tests and data obtained from
the circumferential direction tests. The combined kinematic hardening material model was calibrated to provide an accurate prediction of the stress-strain behavior in both the longitudinal direction and the circumferential direction. The deformation response of a pipe model using the three different material data sets was studied. The sensitivity of the response of pipelines to the choice of a material model and the material data set is studied for the frost upheaval and local buckling.


ABSTRACT: Statistical knockdown factors for the axial buckling of anisotropic cylinders were derived for practical design purposes. The solution with the least amount of simplification in the linear bifurcation theory was chosen from the previously published solutions, and it was compared with more than 100 experimental results from the open literature. A-basis values (99% probability with 95% confidence level) and B-basis values (90% probability with 95% confidence level) of knockdown factors were obtained by using inferential statistics, i.e., inference concerning unknown aspects of a population by using a small sample.


ABSTRACT: Bifurcation analysis is a theoretical prediction approach to measure the FLD when the localized neck causes development of vertex on subsequent yield surface as was adopted by Storen-Rice. Some analyses lead to solutions for special cases such as zero and minimum extension. They offer an equation which needs to be optimized with respect to the minimum limit strain versus neck orientation for the whole domain of FLD. Moreover, the previous reported results for the left-hand side of FLD are not quite satisfactory. In this paper, a re-investigation into bifurcation analysis adopted by S-R lead to modified equations which significantly improved FLD and could be respected as a more general approach to find FLD theoretically. The derivation and optimization procedure of equations are indicated and discussed in detail. The predicted limit strains are studied for different work hardening coefficients and compared with Storen-Rice, Zhu and some experimental data and the obtained results show more agreement. Furthermore, the present restrictions and the required conditions for validation of the Zhu approach are fully discussed.


ABSTRACT: This paper presents the effect of randomness in material properties on piezolaminated composite geometrically nonlinear conical shell panel subjected to thermoelectromechanical loading acting simultaneously or individually. Material properties such as modulus ratio, Poisson’s ratio, and thermal expansion coefficients are modeled as independent random variables. The temperature field considered is assumed to be a uniform distribution over the shell panel surface and through the shell thickness and the electric field is assumed to be the transverse component $E_z$ only. It is assumed that the mechanical properties do not depend on temperature and electric fields. The basic formulation is based on higher order shear deformation theory (HSDT) with von-Karman nonlinearity. A C0 nonlinear finite element model based on direct iterative approach in conjunction with mean centered first order perturbation technique (FOPT) used by the present author for plate is now extended for conical shell panel to solve a random nonlinear generalized eigenvalue problem. Parametric studies are carried out to examine the effect of amplitude ratios, stacking sequences, cone angles, circumferential length to thickness ratios, piezoelectric layers, applied voltages, change in temperature, types of
thermoelectromechanical loadings, and support boundary conditions on the dimensionless mean and coefficient of variance (COV) of laminated conical shell panels. The present outlined approach has been validated with those available results in literature and independent Monte Carlo simulation (MCS).

ABSTRACT: The coupling of edge debonding and thermal buckling of patched beam-plates possessing initial edge detachment is examined for the case when the structure is subjected to a uniform temperature change. The geometrically nonlinear analytical model employed is that established by the authors in a prior work. The problem is recast in a mixed formulation in terms of the transverse deflection and the membrane force to aid in the analysis and physical interpretation. The interaction of edge-debond propagation and thermal buckling is studied. The phenomenon of buckle-trapping, originally observed by the authors in a congruent study, as well as the phenomenon of sling-shot buckling, is seen to manifest itself in the debonding behavior. The evolution of the structure is predicted as a function of given material and geometric parameters from numerical simulations based on analytical solutions of the nonlinear problem. A (propagating) contact zone adjacent to the bonded region is accounted for, and its presence or absence, as well as its nature, is seen to be highly influential in the global as well as local behavior of the structure.

ABSTRACT: This study deals with the Bubnov-Galerkin method applied to the buckling of clamped-free double-walled carbon nanotubes (DWCNTs) subjected to a concentrated compressive load at the free end. It was found that at least four comparison functions are needed in order to obtain accurate results.

ABSTRACT: This paper proposes the use of a one-dimensional (1D) structural theory to analyze thin walled structures with longitudinal and transverse stiffeners. The 1D theory has hierarchical features and it is based on the unified formulation (UF) which has recently been introduced by Carrera. UF permits us to introduce any order of expansion (N) for the unknown displacements over the cross section by preserving the compact form of the related governing equations. In this paper the latter are written in terms of finite element matrices. The same 1D structural theory is used to model a given thin-walled structure composed of stiffened (longitudinal and transverse) and unstiffened parts. It is shown that an appropriate choice of N permits us to accurately describe strain/stress fields of both transverse and longitudinal stiffeners. Comparisons with available results from open literature highlight the efficiency of the proposed model. Moreover, a set of sample problems are proposed and compared with plate/shell formulations from a commercial finite element (FE) software.

ABSTRACT: The basic physics of the underwater implosion of metal tubes is studied using small scale experiments and finite element simulations. A series of underwater implosion experiments have been conducted with thin-wall aluminum alloy 6061-T6 tubes. The nominal tube dimensions are 2.54 cm outside diameter and 30.48 cm length. Two cylinders collapsed at their natural buckling pressure of 6895 kPa gauge pressure (1000
psig). Two additional cylinders were caused to implode at 6205 kPa gauge pressure (900 psig) using an initiator mechanism. Each of the four cylinders failed with a mode 2 shape (collapsed shape is flat with two lobes). The near field pressure time-history in the water is measured at a radial distance of 10.16 cm (4in.) from the centerline at three points along the cylinder's length. The pressure time-histories show very similar behavior between the cylinders which buckled naturally and those which were mechanically initiated at 90% of the buckling pressure. To aid in understanding the physical implosion phenomena, a computational model is developed with a fluid-structure-interaction finite element code (DYSMAS). This model is validated against the experimental data, and it is used to explain the features of the implosion pressure pulse and how it is physically created.

ABSTRACT: In this study we contrast two competing methodologies for the impact buckling of a column that is clamped at both ends. The initial imperfection is postulated to be co-configurational with the fundamental mode shape of the column without the axial loading. A solution is also furnished for the case when the initial imperfection is proportional to the Filonenko-Borodich “cosinusoidal polynomial”. Probabilistic and interval analyses are conducted for each case; these are contrasted on some representative numerical data.

ABSTRACT: The time-dependent progressive evolution of transverse displacements of an axially impacted, slender, geometrically imperfect, column is studied here. The analysis is concerned with evaluating the time-history associated with the evolution of the buckling response as a function of the initial geometric imperfection amplitude. The exact solution of the axial stress wave propagation is employed to study the physics of the buckling response with the nonuniform axial strain distribution varying in time and space. The responses of axially impacted columns are examined in light of past experimental results and associated numerical solutions. Results in the present paper are limited to elastic column behavior.

ABSTRACT: The buckling of thin films with natural nonlinearity can provide a useful tool in many applications. In the present paper, the mechanical properties of controllable buckling of thin films are investigated by accounting for both geometric nonlinearity and surface effects at nanoscale. The effects of surface elasticity and residual surface tension on both static and dynamic behaviors of buckled thin films are discussed based on the surface-layer-based model. The dynamic design strategy for buckled thin films as interconnects in flexible electronics is proposed to avoid resonance in a given noise environment based on the above analysis. Further discussion shows that the thermal and piezoelectric effects on mechanical behavior of buckled thin film are equivalent to that of residual surface tension.

ABSTRACT: In this paper, the vibrational behavior of double-walled carbon nanotubes (DWCNTs) is studied by a nonlocal elastic shell model. The nonlocal continuum model accounting for the small scale effects
encompasses its classical continuum counterpart as a particular case. Based upon the constitutive equations of nonlocal elasticity, the displacement field equations coupled by van der Waals forces are derived. The set of governing equations of motion are then numerically solved by a novel method emerged from incorporating the radial point interpolation approximation within the framework of the generalized differential quadrature method. The present analysis provides the possibility of considering different combinations of layerwise boundary conditions. The influences of small scale factor, layerwise boundary conditions and geometrical parameters on the mechanical behavior of DWCNTs are fully investigated. Explicit expressions for the nonlocal frequencies of DWCNTs with all edges simply supported are also analytically obtained by a nonlocal elastic beam model. Some new intertube resonant frequencies and the corresponding noncoaxial vibrational modes are identified due to incorporating circumferential modes into the shell model. A shift in noncoaxial mode numbers, not predictable by the beam model, is also observed when the radius of DWCNTs is varied. The results generated also provide valuable information concerning the applicability of the beam model and new noncoaxial modes affecting the physical properties of nested nanotubes.


ABSTRACT: This paper is concerned with a solid shell finite element formulation to simulate the behavior of thin dielectric elastomer structures. Dielectric elastomers belong to the group of electroactive polymers. Due to efficient electromechanical coupling and the huge actuation strain, they are very interesting for actuator applications. The coupling effect in the material is mainly caused by polarization. In the present work, a simple constitutive relation, which is based on an elastic model involving one additional material constant to describe the polarization state, is incorporated in a solid shell formulation. It is based on a mixed variational principle of Hu-Washizu type. Thus, for quasi-stationary fields, the balance of linear momentum and Gauss' law are fulfilled in a weak sense. As independent fields, the displacements, electric potential, strains, electric field, mechanical stresses, and dielectric displacements are employed. The element has eight nodes with four nodal degrees of freedom, three mechanical displacements, and the electric potential. The surface oriented shell element models the bottom and the top surfaces of a thin structure. This allows for a simple modeling of layered structures by stacking the elements through the thickness. Some examples are presented to demonstrate the ability of the proposed formulation.


ABSTRACT: Elastic waves propagating in graphene nanoribbons were studied using both continuum modeling and molecular dynamics simulations. The Mindlin's plate model was employed to model the propagation of interior waves of graphene, and a continuum beam model was proposed to model the propagation of edge waves in graphene. The molecular dynamics results demonstrated that the interior longitudinal and transverse wave speeds of graphene are about 18,450 m/s and 5640 m/s, respectively, in good agreement with the Mindlin's plate model. The molecular dynamics simulations also revealed the existence of elastic edge waves, which may be described by the proposed continuum beam model.

ABSTRACT: Molecular dynamics simulations are performed to investigate the effect of surface energy on equilibrium configurations and self-collapse of carbon nanotube bundles. It is shown that large and reversible volumetric deformation of such bundles can be achieved by tuning the surface energy of the system through an applied electric field. The dependence of the bundle volume on surface energy, bundle radius, and nanotube radius is discussed via a dimensional analysis and determined quantitatively using the simulation results. The study demonstrates potential of carbon nanotubes for applications in nanodevices where large, reversible, and controllable volumetric deformations are desired.

ABSTRACT: Pressurized graphene bubbles have been observed in experiments, which can be used to determine the mechanical and adhesive properties of graphene. A nonlinear plate theory is adapted to describe the deformation of a graphene monolayer subject to lateral loads, where the bending moduli of monolayer graphene are independent of the in-plane Young's modulus and Poisson's ratio. A numerical method is developed to solve the nonlinear equations for circular graphene bubbles, and the results are compared to approximate solutions by analytical methods. Molecular dynamics simulations of nanoscale graphene bubbles are performed, and it is found that the continuum plate theory is suitable only within the limit of linear elasticity. Moreover, the effect of van der Waals interactions between graphene and its underlying substrate is analyzed, including large-scale interaction for nanoscale graphene bubbles subject to relatively low pressures.

ABSTRACT: In this paper we attempt to answer two questions on graphene from a mechanic's viewpoint: why does this one-atom-thick monolayer have finite bending stiffness to ensure its stability? and what is its wrinkle mechanism? As for the first question, it is found that the repulsive residual internal moment in the bond angle can lead to a nonzero bending stiffness, which makes the graphene flat. Together with long-range attraction among atoms, such as van der Waals forces, a graphene prefers to have a self-buckling wrinkled configuration with many waves.

ABSTRACT: The stochastic behavior of a two-dimensional nonlinear panel subjected to subsonic flow with random pressure fluctuations and an external forcing is studied in this paper. The total aerodynamic pressure is considered as the sum of two parts, one given by the random pressure fluctuations on the panel in the absence of any panel motion, and the other due to the panel motion itself. The random pressure fluctuations are idealized as a zero mean Brownian motion. Galerkin method is used to transform the governing partial differential equation to a series of ordinary differential equations. The closed moment equations are obtained by the Itô differential rule and Gauss truncation. The stability and complex responses of the moment equations are presented in theoretical and numerical analysis. Results show that a bifurcation of fixed points occurs and the bifurcation point is determined as functions of noise spectral density, dynamic pressure, and panel structure parameters; the chaotic response regions and periodic response regions appear alternately in parameter spaces, the periodic responses trajectories change rhythmically, and the route from periodic responses to chaos is via doubling-
period bifurcation. The treatment suggested in this paper can also be extended for the other fluid-structure dynamic systems.


ABSTRACT: This paper proposes advanced approaches to the free vibration analysis of reinforced-shell wing structures. These approaches exploit a hierarchical, one-dimensional (1D) formulation, which leads to accurate and computationally efficient finite element (FE) models. This formulation is based on the unified formulation (UF), which has been recently proposed by the first author and his coworkers. In the study presented in this paper, UF was used to model the displacement field above the cross-section of reinforced-shell wing structures. Taylor-like (TE) and Lagrange-like (LE) polynomial expansions were adopted above the cross-section. A classical 1D FE formulation along the wing’s span was used to develop numerical applications. Particular attention was given to the component-wise (CW) models obtained by means of the LE formulation. According to the CW approach, each wing's component (i.e. spar caps, panels, webs, etc.) can be modeled by means of the same 1D formulation. It was shown that MSC/PATRAN® can be used as pre- and postprocessor for the CW models, whereas MSC/NASTRAN® DMAP alters can be used to solve the eigenvalue problems. A number of typical aeronautical structures were analyzed and CW results were compared to classical beam theories (Euler-Bernoulli and Timoshenko), refined models (TE) and classical solid/shell FE solutions from the commercial code MSC/NASTRAN®. The results highlight the enhanced capabilities of the proposed formulation. In fact, the CW approach is clearly the natural tool to analyze wing structures, since it leads to results that can only be obtained through 3D elasticity (solid) elements whose computational costs are at least one-order of magnitude higher than CW models.


ABSTRACT: Some intriguing results are reported in conjunction with closed form solutions obtained for a clamped-free vibrating inhomogeneous column under an axial concentrated load using the semi-inverse method. Fourth order polynomial is postulated for both the vibration mode shape and buckling displacement. Solution is provided for the flexural rigidity and the natural frequency. It is shown that, for each level of axial loading, there may exist up to five flexural rigidities satisfying the governing differential equation and boundary conditions.


ABSTRACT: Recent experiments in which arrays of compliant fibrils are compressed axially against a rigid surface and then released have shown that there is load-displacement hysteresis during this process, accompanied by buckling and unbuckling of the fibrils. Furthermore, the adhesive performance of the system is decreased by such prior buckling. We present a model describing the buckling and postbuckling characteristics of a fibril with an aspect ratio of 10 or greater. The possibility during buckling of partial detachment of the end of the fibril is taken into account. The results are presented and discussed for both load and displacement control and the load-displacement hysteresis is identified. It is found that due to instabilities sudden spreading and shrinkage of the adhered area at the end of the fibril can accompany the hysteresis. Numerical results are
provided to substantiate the findings and possible reasons for the observed influence of buckling on adhesive performance are reviewed.


ABSTRACT: Analytical models have been established to study the lateral buckling of interconnects under shear in a noncoplanar mesh design for stretchable electronics. Analytical expressions are obtained for the critical load and buckling shape at the onset of buckling by solving the equilibrium equations. The postbuckling behavior is studied by energy minimization of the potential energy, including up to fourth power of the displacement. A simple expression of the amplitude characterizing the deformation after buckling is obtained. These results agree well with the finite element simulations without any parameter fitting. The models in this paper may provide a route to study complex buckling modes of interconnects, such as diagonal compression/stretching involving both compression and shear.


ABSTRACT: Most commercial finite element codes, such as ABAQUS, LS-DYNA, ANSYS and NASTRAN, use as the objective stress rate the Jaumann rate of Cauchy (or true) stress, which has two flaws: It does not conserve energy since it is not work-conjugate to any finite strain tensor and, as previously shown for the case of sandwich columns, does not give a correct expression for the work of in-plane forces during buckling. This causes no appreciable errors when the skins and the core are subdivided by several layers of finite elements. However, in spite of a linear elastic behavior of the core and skins, the errors are found to be large when either the sandwich plate theory with the normals of the core remaining straight or the classical equivalent homogenization as an orthotropic plate with the normals remaining straight is used. Numerical analysis of a plate intended for the cladding of the hull of a light long ship shows errors up to 40%. It is shown that a previously derived stress-dependent transformation of the tangential moduli eliminates the energy error caused by Jaumann rate of Cauchy stress and yields the correct critical buckling load. This load corresponds to the Truesdell objective stress rate, which is work-conjugate to the Green–Lagrangian finite strain tensor. The commercial codes should switch to this rate. The classical differential equations for buckling of elastic soft-core sandwich plates with a constant shear modulus of the core are shown to have a form that corresponds to the Truesdell rate and Green–Lagrangian tensor. The critical in-plane load is solved analytically from these differential equations with typical boundary conditions, and is found to agree perfectly with the finite element solution based on the Truesdell rate. Comparisons of the errors of various approaches are tabulated.


ABSTRACT: In this work, two hybrid composite structures were designed, modeled, and tested for improved resistance to impact. They were inspired by bistable composite structures, which are structures composed of two parts: a so-called “main link” and a so-called “waiting link.” These links work together as a mechanism that will provide enhanced damage tolerance, and the structure exhibits a bistable stress/strain curve under static tension. The function of the main link is to break early, at which point the waiting link becomes active and provides a
redundant load path. The goal of the current study was to design, manufacture, and test a similar concept for impact loading and achieve greatly improved impact resistance per unit weight. In the current project, the main link was designed to be a brittle composite material (in this case, woven carbon/epoxy) exposed to impact, while the waiting link was chosen to be made with a highly nonlinear and strong composite material (in this case, polyethylene/epoxy), on the opposite surface. Hence, the structure, if proven successful, can be considered an enhanced hybrid concept. An explicit finite element (FE) commercial code, LS-DYNA, was used to design and analyze the baseline as well as two proposed designs. The simulations' methodology was validated with results published in the literature, which reported tests from linear fiber-reinforced composites. The plots were obtained via the ASCII files generated from the FE code, processed using MATLAB®, and compared to experimental impact tests. An instrumented drop-weight testing machine performed impact tests, and a high-speed camera validated the specimens' displacement under impact. It is shown that the FE model provided qualitative behavior very consistent with the experiments but requires further improvements. Experimentally, it is shown that one of the two enhanced hybrid models leads to up to a 30% increase of returned energy/weight when compared to its baseline and, therefore, is worthy of further investigations.


ABSTRACT: When a buckle is initiated in a pipe subjected to external pressure, it will propagate along the longitudinal direction of the pipe if the external pressure is greater than its buckle propagation pressure. For a steady state condition, the propagation is simply considered as the translation of the buckle along the pipeline. This paper presents a unique approach to determine the length of the transition zone in a buckle propagating pipe by analyzing the mechanism of postbuckling of the pipe subjected to the external pressure. Buckling is considered to occur locally in the shell, spreading over a certain length along the longitudinal axis of the shell. The governing equations are derived from the postbuckling theory. Approximate solutions are obtained from the Ritz method, using a plausible function of the flexural displacement created based on Timoshenko's ring solution of the transverse collapse mode. The postbuckling equilibrium path shows that the pipeline experiences unstable collapse until the two opposite points on the inner surface contact each other. The length of the transition zone is found to be proportional to the ratio of (radius)³/²/ (thickness)¹/² and is hardly affected by the material properties. The analysis is performed by comparing the obtained results with well-established predictions.


ABSTRACT: Creasing in thin shells admits large deformation by concentrating curvatures while relieving stretching strains over the bulk of the shell: after unloading, the creases remain as narrow ridges and the rest of the shell is flat or simply curved. We present a helically creased unloaded shell that is doubly curved everywhere, which is formed by cylindrically wrapping a flat sheet with embedded fold-lines not axially aligned. The finished shell is in a state of uniform self-stress and this is responsible for maintaining the Gaussian curvature outside of the creases in a controllable and persistent manner. We describe the overall shape of the shell using the familiar geometrical concept of a Mohr's circle applied to each of its constituent features—the creases, the regions between the creases, and the overall cylindrical form. These Mohr's circles can be combined in view of geometrical compatibility, which enables the observed shape to be accurately and completely described in terms of the helical pitch angle alone.

**ABSTRACT:** The paper presents a comparison between two existing zigzag functions that are used to improve equivalent single layer (ESL) theories for the analysis of multilayered composite and sandwich beams. ESL theories are easy to implement and computationally affordable but, in order to correctly describe the mechanical behavior of laminated structures (especially those exhibiting high transverse anisotropy or high thickness-to-side length ratios), the displacement field needs to be enriched by a through-the-thickness piecewise linear contribution denoted as “zigzag.” The zigzag term of the displacement field is used to model the local distortion of the cross section in each lamina of multilayered structures and is related to the continuity of transverse stresses. The paper considers two zigzag functions that have been proposed in the open literature (namely Murakami’s zigzag function and the refined zigzag function) and compares their performances when they are used to improve the classical Timoshenko beam theory; both displacement-based and mixed formulations are considered. To the best of the author's knowledge, such a comparative study has never been published. The problem of a simply supported beam subjected to a transverse distributed load is considered as a test case. Several stacking sequences, ranging from monolithic to sandwich-like and from symmetric to arbitrary, are considered. The special case of laminates with external weak layers is also investigated and the effects of these lay-ups on the derivation of the refined zigzag function are analyzed for the first time. The capability of the tested zigzag functions to help evaluate the overall deflection and model the through-the-thickness distribution of the axial displacement and stress is investigated. It has been recognized that the refined zigzag function is more accurate, especially for unsymmetric and arbitrary lay-ups and can be adopted to efficiently introduce zigzag kinematics into any ESL theory.


**ABSTRACT:** This paper presents a one-dimensional analysis for the blast response of a sandwich beam/wide plate with a compressible core. The dynamic version of the recently developed extended high-order sandwich panel theory (EHSAPT) is first formulated. Material, geometric, and loading parameters are taken from blast experiments reported in literature. The novelty of EHSAPT is that it includes axial rigidity of the core and allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core and the rotation at the centroid of the core) instead of just one (shear stress in the core) of the earlier high-order sandwich panel theory (HSAPT). The solution procedure to determine the dynamic response to a general load applied on the top face sheet of a general asymmetric simply supported configuration is outlined. Although the dynamic EHSAPT is formulated in its full nonlinear version, the solution is for the linear problem so the accuracy of EHSAPT, along with the other theories, can be assessed by comparison to an available dynamic elasticity solution. Results show that the EHSAPT is very accurate and can capture the complex dynamic phenomena observed during the initial, transient phase of blast loading.


**ABSTRACT:** A theoretical model is built for a micrometer size cylindrical shell adhering to a rigid surface in the presence of an electrolyte. In the presence of surface electrostatic double layers and van der Waals attraction
according to the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, the shell deforms and settles in either the primary (1min) or secondary (2min) energy minimum depending on whether it has sufficient energy to overcome the repulsive energy barrier. The adhesion-detachment mechanics are constructed and solved computationally, yielding the relations between applied load, deformed profile, and mechanical stress distribution in the shell. The critical compressive load needed for transition from 2min to 1min is found for several repulsive barrier heights. At a critical pull-off tensile force, shell in the 1min detaches spontaneously at a nonzero contact area, but the one in the 2min detaches smoothly with the contact shrinking to a line contact. The model is relevant to bacterial adhesion in environmental engineering and microelectromechanical systems for microfluidics applications.


ABSTRACT: The problem of determining the deformation of a longitudinally corrugated, long cylindrical shell under external pressure is considered. The topics that are covered can be summarized as follows: the formulation of a boundary value problem for the incremental approach as a normal system of differential equations under appropriate boundary conditions, the determination of postbuckling behavior characteristics for cylindrical shells using the discrete orthogonalization method, and an analysis of deformation for both closed and open cylindrical shells. In particular, we consider the stability and postbuckling behavior of both isotropic and composite shells. The solution is based on the relationships for the cubic version of nonlinear Timoshenko-type shell theory. A comparison is made with the well-established quadratic version, as well as analytical solutions where applicable. The necessity for using more precise equations to examine the postbuckling behavior of shells is shown. Using this higher-order approach, it is possible to determine the postbuckling behavior with much greater accuracy.

References listed at the end of the paper:

ABSTRACT: Thin-walled tubes subjected to axial crushing have been extensively employed as energy absorption devices in transport vehicles. Conventionally, they have a square or rectangular section, either straight or tapered. Dents are sometimes added to the surface in order to reduce the initial buckling force. This paper presents a novel thin-walled energy absorption device known as the origami crash box that is made from a thin-walled tube of square cross section whose surface is prefolded according to a developable origami pattern. The prefolded surface serves both as a type of geometric imperfection to lower the initial buckling force and as a mode inducer to trigger a collapse mode that is more efficient in terms of energy absorption. It has been found out from quasi-static numerical simulation that a new collapse mode referred to as the completed diamond mode, which features doubled traveling plastic hinge lines compared with those in conventional square tubes, can be triggered, leading to higher energy absorption and lower peak force than those of conventional ones of identical weight. A parametric study indicates that for a wide range of geometric parameters the origami crash box exhibits predictable and stable collapse behavior, with an energy absorption increase of 92.1% being achieved in the optimum case. The origami crash box can be stamped out of a thin sheet of material like conventional energy absorption devices without incurring in-plane stretching due to the developable surface of the origami pattern. The manufacturing cost is comparable to that of existing thin-walled crash boxes, but it absorbs a great deal more energy during a collision.


ABSTRACT: Small amplitude vibrations of a functionally graded material beam under in-plane thermal loading in the prebuckling and postbuckling regimes is studied in this paper. The material properties of the FGM media are considered as function of both position and temperature. A three parameters elastic foundation including the linear and nonlinear Winkler springs along with the Pasternak shear layer is in contact with beam in
deformation, which acts in tension as well as in compression. The solution is sought in two regimes. The first one, a static phase with large amplitude response, and the second one, a dynamic regime near the static one with small amplitude. In both regimes, nonlinear governing equations are discretized using the generalized differential quadrature (GDQ) method and solved iteratively via the Newton–Raphson method. It is concluded that depending on the type of boundary condition and loading type, free vibration of a beam under in-plane thermal loading may reach zero at a certain temperature which indicates the existence of bifurcation type of instability.

ABSTRACT: Recent endeavors to combine the desirable energy-absorption characteristics of stochastic foams with the comparatively high strengths of pyramidal lattices have shown promise for creating composites that outperform their constituents alone under compressive loading. Herein we employ numerical and analytical models to identify both the mechanisms by which synergistic behavior is obtained in such composites and the constituent mass fractions that yield maximum benefits. We find that the loading boundary conditions play a crucial role. When, for instance, composites are loaded between plates that are well bonded to the composites, their specific strengths invariably exceed those predicted by a rule-of-mixtures; however, these strengths can always be improved through an optimized lattice of equivalent mass. In contrast, when the composites are loaded between frictionless plates, their specific strengths exceed not only rule-of-mixtures predictions but, in many cases, also that of any mass-equivalent pyramidal lattice alone subject to the same (frictionless) conditions. The origin of this behavior is found to arise from foam-stabilization of lattice bending and splaying: deformation modes that govern strength in the absence of foam. In essence, the foam causes a transition from bend-dominated to stretch-dominated behavior in the lattice.

ABSTRACT: In this paper, the stability of a periodic cantilevered pipe conveying fluid is studied theoretically by means of a novel transfer matrix method. This method is first validated by comparing the results to those available in the literature for a uniform pipe, showing that it is capable of high accuracy and displaying good convergence characteristics. Then, the stability of periodic pipes is investigated, with geometric, material-properties periodicity, and a combination of the two, showing that a considerable stabilizing effect may be achieved over different ranges of the mass parameter $\beta$ ($\beta=m_f/(mf+mp)$, where $m_f$ and $m_p$ are the fluid and pipe masses per unit length). The effect of other different system parameters is also probed.

ABSTRACT: A three-dimensional (3D) method of analysis is presented for determining the free vibration frequencies of clamped, complete (not truncated) conical shells of revolution in which the bottom edges are normal to the midsurface of the shells based upon the circular cylindrical coordinate system using the Ritz method. A convergence study is presented. The frequencies from the present 3D analysis are compared with those from other 3D methods and 2D thin shell theory.
ABSTRACT: Structures made of functionally graded materials have attracted much interest recently. The idea is to create a material that fulfills a specified function in accordance to the identified purpose of structure's utilization. In this study, a semi-inverse problem is posed of determining the needed variation of the axial grading of an inhomogeneous column subjected to a central force, generalizing the ungraded column case. Remarkably, it turns out that for a specific combination of parameters, there could exist three different axially graded columns, that possess the same buckling load. Whereas this fact is not immediately apparent, the proposed formulation leads to the design of the axially graded column in such a manner that the buckling load is not less than a prespecified load. Purpose-oriented design demands columns have at least a prespecified buckling load. To solve the problem, a combined analytical-numerical procedure is developed in this study.

ABSTRACT: In this study, we investigate the modal density of double-walled carbon nanotubes. Emphasis is placed on the effect of the utilized theory. Specifically, we compare the modal density obtained via classical Bernoulli–Euler theory with that obtained by employing the refined Bresse–Timoshenko theory with nonlocal and surface effects taken into account. We show that the effect of refinements is dramatic.

ABSTRACT: The objective stress rates used in most commercial finite element programs are the Jaumann rate of Kirchhoff stress, Jaumann rates of Cauchy stress, or Green–Naghdi rate. The last two were long ago shown not to be associated by work with any finite strain tensor, and the first has often been combined with tangential moduli not associated by work. The error in energy conservation was thought to be negligible, but recently, several papers presented examples of structures with high volume compressibility or a high degree of orthotropy in which the use of commercial software with the Jaumann rate of Cauchy or Kirchhoff stress leads to major errors in energy conservation, on the order of 25–100%. The present paper focuses on the Green–Naghdi rate, which is used in the explicit nonlinear algorithms of commercial software, e.g., in subroutine VUMAT of ABAQUS. This rate can also lead to major violations of energy conservation (or work conjugacy)—not only because of high compressibility or pronounced orthotropy but also because of large material rotations. This fact is first demonstrated analytically. Then an example of a notched steel cylinder made of steel and undergoing compression with the formation of a plastic shear band is simulated numerically by subroutine VUMAT in ABAQUS. It is found that the energy conservation error of the Green–Naghdi rate exceeds 5% or 30% when the specimen shortens by 26% or 38%, respectively. Revisions in commercial software are needed but, even in their absence, correct results can be obtained with the existing software. To this end, the appropriate transformation of tangential moduli, to be implemented in the user's material subroutine, is derived.
ABSTRACT: A theoretical model is developed to investigate the mechanical behavior of closely packed carbon nanoscrolls (CNSs), the so-called CNS crystals, subjected to uniaxial lateral compression/decompression. Molecular dynamics simulations are performed to verify the model predictions. It is shown that the compression behavior of a CNS crystal can exhibit strong hysteresis that may be tuned by an applied electric field. The present study demonstrates the potential of CNSs for applications in energy-absorbing materials as well as nanodevices, such as artificial muscles, where reversible and controllable volumetric deformations are desired.


ABSTRACT: Buckling of stiff thin films on compliant substrates enables many new applications, such as stretchable electronics. Song et al. [2008, “Buckling of a Stiff Thin Film on a Compliant Substrate in Large Deformation,” Int. J. Solids Struct., 45(10), pp. 3107–3121] developed a finite deformation theory to explain the buckled amplitude and wavelength very well. This theory not only accounts for finite geometry change, but also the finite strain and a nonlinear constitutive model for the substrate. To provide a better physical insight, this paper investigates those three effects, and shows that finite geometry change dominates in the finite deformation theory and the simplified analysis leads to results that agree well with experiments and the finite element method.


ABSTRACT: Continuation methods are used to examine the static and dynamic postbuckled behavior of a uniaxially loaded, simply supported plate. Continuation methods have been extensively used to study problems in mathematics and physics; however, they have not been as widely applied to problems in engineering. When paired with a Galerkin approximation, continuation methods are shown to be well suited to solving nonlinear buckling problems. In addition to providing a robust solution method for nonlinear equations, the linearized Jacobians from the continuation steps will contain natural frequency and mode shape information for mechanical systems (provided inertia terms are included). Results for the primary buckling branch are compared to previously published results. Using the open-source continuation package AUTO, stable, remote secondary buckling branches were discovered. These secondary stable equilibrium persist even in the presence of geometric imperfections and their existence is confirmed by experiment.


ABSTRACT: A generalized Reissner theory for axisymmetric problems of circular plates is presented. The plate is assumed to be linearly elastic, and large rotations and strains are allowed. Shear deformation and changes in the plate thickness are neglected. Equilibrium equations are formulated, and a shooting method is applied to obtain numerical results for plates subjected to a uniform pressure. The edge of the plate is assumed to be either simply supported or clamped, and is free to move radially. The resulting deflections are compared to those based on the von Kármán theory.

Buckling of compressed flat-end columns loaded by unattached flat platens is shown, theoretically and experimentally, to occur first at the critical load and associated mode shape of a built-in column, followed extremely closely by a second critical load and different mode shape characterized by column end tilt. The theoretical critical load for secondary or end tilt buckling for a column geometry tested is shown to be only 0.13% greater than the critical load for primary buckling, in which the ends are in full contact with the compression platens. The experimental value is consistent with this theoretical one. Interestingly, under displacement control, the first buckling instability is characterized by a smoothly increasing applied load, whereas the closely following second instability causes an abrupt and large load drop (and hence exhibits incremental negative stiffness). The end tilt buckling gives rise to large hysteresis that can be useful in structural damping but that is nonconservative and potentially catastrophic in the context of design of structural support columns.


The paper discusses nonlinear equations of in-plane bending of curved tubes formulated by E. Reissner in terms of two unknown functions and two unknown parameters. To solve the equations, a numerical method based on the finite-difference approximations and Newton–Raphson iteration technique is proposed. Deformations and stresses in tubes of circular and noncircular cross sections are studied for a wide range of geometrical parameters. The accuracy of the equations is evaluated by comparing the numerical results with predictions obtained by a special shell finite element.


This paper presents a general, exact, two-dimensional (2D) elastodynamic analysis of the response of laminated composite panels subjected to transverse impact loading under conditions of planar deformation. The natural frequencies and mode shapes of free vibration are first extracted. Inspired by a transformation technique for solving a special class of partial differential equations, the forced vibration problem of an impacted laminated panel is solved using an eigenfunction expansion technique. Several examples are studied by varying the laminate lay-up and length-to-thickness ratio. The distributions of transverse stresses in the through-the-thickness direction are further compared with two one-dimensional theories, classical lamination theory (CLT) and first-order shear deformation theory (FSDT), showing the inadequacy of these theories and the necessity to establish a benchmark solution for 2D elastodynamics. The 2D elastodynamic theory that is formulated is also applicable for studying other multilayered structures subjected to arbitrary loading profiles.


Subject to a compressive membrane stress, an elastic film bonded on a substrate can become unstable, forming wrinkles, creases or delaminated buckles. Further increasing the compressive stress can induce advanced modes of instabilities including period-doubles, folds, localized ridges, delamination, and coexistent instabilities. While various instabilities in film-substrate systems under compression have been analyzed separately, a systematic and quantitative understanding of these instabilities is still elusive. Here we present a joint experimental and theoretical study to systematically explore the instabilities in elastic film-substrate systems under uniaxial compression. We use the Maxwell stability criterion to analyze the occurrence and evolution of instabilities analogous to phase transitions in thermodynamic systems. We show that the
moduli of the film and the substrate, the film-substrate adhesion strength, the film thickness, and the prestretch in the substrate determine various modes of instabilities. Defects in the film-substrate system can facilitate it to overcome energy barriers during occurrence and evolution of instabilities. We provide a set of phase diagrams to predict both initial and advanced modes of instabilities in compressed film-substrate systems. The phase diagrams can be used to guide the design of film-substrate systems to achieve desired modes of instabilities.


ABSTRACT: We consider the axial buckling of a thin-walled cylinder fitted onto a mandrel core with a prescribed annular gap. The buckling pattern develops fully and uniformly to yield a surface texture of regular diamond-shaped buckles, which we propose for novel morphing structures. We describe experiments that operate well into the postbuckling regime, where a classical analysis does not apply; we show that the size of buckles depends on the cylinder radius and the gap width, but not on its thickness, and we formulate simple relationships from kinematics alone for estimating the buckle proportions during loading.


ABSTRACT: Wrinkles in graphene with desirable morphology have practical significance for electronic applications. Here we carry out a systematic molecular dynamics study of the wrinkling instability of graphene on substrate-supported nanoparticles (NPs). At a large NP dispersion distance, a monolayer graphene adheres to the substrate and bulges out locally to wrap around individual NPs, forming isolated dome-shaped protrusions. At a small NP dispersion distance, tunneling wrinkles form in graphene to bridge the NP-induced protrusions. A critical NP dispersion distance for the onset of tunneling wrinkle instability of graphene is determined as a function of the NP size. The prediction from the modeling study agrees well with recent experimental observations. Results from the present study offer further insights into the formation of desirable wrinkles in graphene deposited on a substrate with engineered protrusions and, thus, can potentially enable novel design of graphene-based electronics.


ABSTRACT: The failure behavior of geometrically asymmetric sandwich beams with a metal foam core is analytically and experimentally investigated. New initial failure modes of the asymmetric sandwich beams are observed under three-point bending, i.e., face yield, face wrinkling, core shear A, core shear AB, core shear A-AB, and indentation. It is shown that the initial failure modes of sandwich beams depend on the span of the beam, the thicknesses of top and bottom face sheets, core height and material properties. We derived the analytical formulae for the initial failure loads and then constructed the initial failure mechanism maps for the geometrically asymmetric sandwich beams. It is shown that the analytically predicted initial failure mechanism maps are in good agreement with the experimental results, which are clearly different from the symmetric sandwich beams. As a preliminary application, the minimum weight designs are presented for asymmetric metal sandwich beams.

**ABSTRACT:** A shell element for analysis of textile composite structures is proposed in this paper. Based on the embedded element method and solid shell concept, the architecture, geometry, and material properties of a repeat unit cell (RUC) of textile composite are embedded in a single shell finite element. Flat and curved textile composite structures are used to apply and verify the present shell element. The deformation and natural frequency obtained by the present shell element are compared against those computed from full three-dimensional finite element analyses. It is shown that the proposed shell element is efficient, simple, and reliable for textile composite structural analysis.


**ABSTRACT:** A state space method is proposed for analyzing surface instability of elastic layers with elastic properties varying in the thickness direction. By assuming linear elasticity with nonlinear kinematics, the governing equations for the incremental stress field from a fundamental state are derived for arbitrarily graded elastic layers subject to plane-strain compression, which lead to an eigenvalue problem. By discretizing the elastic properties into piecewise constant functions with homogeneous sublayers, a state space method is developed to solve the eigenvalue problem and predict the critical condition for onset of surface instability. Results are presented for homogeneous layers, bilayers, and continuously graded elastic layers. The state space solutions for elastic bilayers are in close agreement with the analytical solution for thin film wrinkling within the limit of linear elasticity. Numerical solutions for continuously graded elastic layers are compared to finite element results in a previous study (Lee et al., 2008, J. Mech. Phys. Solids, 56, pp. 858–868). As a semi-analytical approach, the state space method is computationally efficient for graded elastic layers, especially for laminated multilayers.


**ABSTRACT:** When a stiff film is bonded to a compliant layer and meanwhile encapsulated by another compliant layer on top, the film may form wrinkles under applied compressive stress. Inspired by the recent development of foldable circuit sealed in an encapsulating layer to improve bendability, unlike the wide study of surface wrinkling in a bilayer system, this paper presents a study of possible sinusoidal interfacial wrinkling in such sandwich system. The film is assumed to be anisotropic with arbitrary orientation of elastic axis while both layers are isotropic. A linear perturbation analysis is performed to predict critical membrane stress, wave number and equilibrium amplitude for the onset of interfacial wrinkles. The effect of parameters such as elastic axis orientation of the film and moduli, thicknesses, and Poisson's ratios of the layers on the wrinkling is evaluated in detail. The results show that compared to two compliant layers, the stiffer and thinner the film is, the smaller the values of both the critical stress and wave number for wrinkling will be. Especially, we illustrate three limiting cases: two layers both reach thick-layer limit, two layers both reach thin-layer limit and one layer reaches thick-layer limit while the other layer reaches thin-layer limit. Analytical solutions are obtained for first two cases and numerical solutions are plotted for the third case. It is found that as long as the thin-layer is near incompressible, the interfacial wrinkles can be suppressed. In addition, the equilibrium wave modes for the three limiting cases are also given. The resulting solutions for the sandwich system can be reduced to the classic solutions for a bilayer system.

ABSTRACT: This paper describes an analytical tool for the design of thin-wall tubes for passage through minimal radius of curvature trajectory. The design is based on a model of thin-wall tube buckling under pure bending. An extended analytical solution for general initial cross section is found based on Brazier method by energy theory of elastic stability. The model predicts the critical moment, curvature, flattening, and stress and allows choosing the most suitable cross section shape for a specific purpose. For example, tubes with ocular and rounded-ocular cross sections were found suitable for semiflexible applications such as endoscopy, where they elastically cross a sharp corner.


ABSTRACT: We present results from a numerical investigation of the localization of deformation in thin elastomeric spherical shells loaded by differently shaped indenters. Beyond a critical indentation, the deformation of the shell ceases to be axisymmetric and sharp structures of localized curvature form, referred to as “s-cones,” for “shell-cones.” We perform a series of numerical experiments to systematically explore the parameter space. We find that the localization process is independent of the radius of the shell. The ratio of the radius of the shell to its thickness, however, is an important parameter in the localization process. Throughout, we find that the maximum principal strains remain below 6%, even at the s-cones. As a result, using either a linear elastic (LE) or hyperelastic constitutive description yields nearly indistinguishable results. Friction between the indenter and the shell is also shown to play an important role in localization. Tuning this frictional contact can suppress localization and increase the load-bearing capacity of the shell under indentation.

References listed at the end of the paper:

ABSTRACT: Under quasi-static uniaxial compression, inserting aluminum foams into the interstices of a metallic sandwich panel with corrugated core increased significantly both its peak crushing strength and energy absorption per unit mass. This beneficial effect diminished however if the foam relative density was relatively low or the compression velocity became sufficiently high. To provide insight into the varying role of aluminum foam filler with increasing compression velocity, the crushing response and collapse modes of all metallic corrugate-ored sandwich panels filled with close-celled aluminum foams were studied using the method of finite elements (FEs). The constraint that sandwich panels with and without foam filling had the same total weight was enforced. The effects of plastic hardening and strain rate sensitivity of the strut material as well as foam strut interfacial debonding were quantified. Three collapse modes (quasi-static, transition, and shock modes) were identified, corresponding to different ranges of compression velocity. Strengthening due to foam insertion and inertial stabilization both acted to provide support for the struts against buckling. At relatively low compression velocities, the struts were mainly strengthened by the surrounding foam; at high compression velocities, inertia stabilization played a more dominant role than foam filling.

**ABSTRACT:** Although many researches on the dynamic behavior of honeycombs have been reported, the strain rate effect of parent materials was frequently neglected, giving rise to the underestimated plateau stress and energy absorption (EA). In this paper, the strain rate effect of parent materials on the out-of-plane dynamic compression and EA of metallic honeycombs is evaluated by both numerical simulation and theoretical analysis. The numerical results show that the plateau stress and the EA increase significantly if the strain rate effect is considered. To account for the strain rate effect, a new theoretical model to evaluate the dynamic compressive plateau stress of metallic honeycombs is proposed by introducing the Cowper–Symonds relation into the shock theory. Predictions of the present model agree fairly well with the numerical results and existing experimental data. Based on the present model, the plateau stress is divided into three terms, namely static term, strain rate term, and inertia term, and thus the influences of each term can be analyzed quantitatively. According to the analysis, strain rate effect is much more important than inertia effect over a very wide range of impact velocity.


**ABSTRACT:** Three-dimensional finite transient deformations of polycarbonate (PC) panels impacted at low velocity by a hemispherical-nosed rigid cylinder have been studied by using the commercial finite element software LS-DYNA with a thermo–elasto–viscoplastic material model for the PC incorporated in it as a user defined subroutine. The implementation of the subroutine has been verified by comparing analytical and numerical solutions of simple initial-boundary-value problems. The mathematical model of the low velocity impact problem has been validated by comparing the computed and the experimental results for the maximum deflection and time histories of the centroidal deflection. It is found that the initial slope of the reaction force between the impactor and the panel versus the indentation for a curved panel can be nearly 20 times that for the flat panel of the same thickness as the curved panel. For the impact velocities considered, it is found that the maximum effective plastic strain in the PC shell near the center of impact and the dominant deformation mode there strongly depend on the panel curvature, the panel thickness, and the impact speed. Effects of the panel curvature, the panel thickness, and the impact speed on stresses and strains developed in a panel are delineated. This information should help designers of impact resistant transparent panels such as an airplane canopy, automobile windshield, and goggles. However, damage initiation and propagation, and the final indentation induced in the clamped panels have not been computed.


**ABSTRACT:** In this paper, a closed form solution of an arbitrary oriented hollow elastic ellipsoidal shell impacting with an elastic flat barrier is presented. It is assumed that the shell is thin under the low speed impact. Due to the arbitrary orientation of the shell, while the pre-impact having a linear speed, the postimpact involves rotational and translational speed. Analytical solution for this problem is based on Hertzian theory (Johnson, W., 1972, Impact Strength of Materials, University of Manchester Institute of Science and Technology, Edward Arnold Publication, London) and the Vella’s analysis (Vella et al., 2012, “Indentation of Ellipsoidal and Cylindrical Elastic Shells,” Phys. Rev. Lett., 109, p. 144302) in conjunction with Newtonian method. Due to the nonlinearity and complexity of the impact equation, classical numerical solutions cannot be employed. Therefore, a linearization method is proposed and a closed form solution for this problem is accomplished. The
closed form solution facilitates a parametric study of this type of problems. The closed form solution was validated by an explicit finite element method (FEM). Good agreement between the closed form solution and the FE results is observed. Based on the analytical method the maximum total deformation of the shell, the maximum transmitted force, the duration of the contact, and the rotation of the shell after the impact were determined. Finally, it was concluded that the closed form solutions were trustworthy and appropriate to investigate the impact of inclined elastic ellipsoidal shells with an elastic barrier.

ABSTRACT: This study examines the buckling of a single strip of material, modeled as a two-dimensional (2D) micropolar solid. The effects of material microstructure are incorporated by modeling the material using micropolar theory. By setting the micropolar constants to zero, the equations of classical elasticity are obtained and these results are compared to the buckling analysis performed by previous authors on elastic materials. In the limiting case, when the thickness of the strip becomes small in comparison to the overall length, the micropolar beam equations are developed. Because buckling analysis requires the consideration of geometric nonlinearity, nonlinear micropolar equations are derived using a variational procedure, which also results in variationally consistent boundary conditions. Due to the complexity of micropolar theory, its application has been limited to linear analysis with a few exceptions.

ABSTRACT: Wrinkling of thin films resting on compliant substrates has emerged as a facile means to create well-ordered surface patterns. In this paper, both theoretical analysis and numerical simulations are presented to study the surface wrinkling of a film–substrate system with periodic interfacial structures. It is demonstrated that a variety of novel surface wrinkling patterns can be generated through the introduction of interfacial architectures. These surface patterns can be easily tuned by adjusting two geometric parameters: the lengths of the thin films in the thick and the thin regions. A phase diagram is established for the onset of different wrinkling morphologies with respect to the two geometric dimensions. This study offers a promising route for engineering the surfaces of materials endowed with tunable properties and functions.

ABSTRACT: When exposed to an external solvent, a dry polymeric network imbibes the solvent and undergoes large deformation. The resulting aggregate is known as a hydrogel. This swelling process is diffusion driven and thus results in differential swelling during transient swelling. When subjected to external geometrical constraints, such as being rigidly fixed or attachment to a compliant substrate, wrinkles have been shown to appear due to mechanical instabilities. In the case of free swelling, there are no external constraints to induce the instabilities accounting for wrinkling patterns. However, during the transient swelling process, the swelling differential between the gel on the exterior and the interior causes compressive stresses and gives rise to mechanical instabilities. It is also observed that the time dependence of the swelling profile causes the wrinkles to evolve with time. In this work, we investigate this interesting phenomenon of transient wrinkle mode evolution using the finite element and state-space methods. From our simulations and prediction, we find that there is an inverse relation between critical wave number and time, which has earlier been observed in experiments.

ABSTRACT: The mechanisms by which different morphologies of preferentially foam filled corrugated panels deform under planar blast loading, transmit shock, and absorb energy are investigated experimentally and numerically for the purpose of mitigating back-face deflection (BFD). Six foam filling configurations were fabricated and subjected to shock wave loading generated by a shock tube. Shock tube experimental results obtained from high-speed photography were used to validate the numerical models. The validated numerical model was further used to analyze 24 different core configurations. The experimental and numerical results show that soft/hard arrangements (front to back) are the most effective for blast resistivity as determined by the smallest BFDs. The number of foam filled layers in each specimen affected the amount of front-face deflections (FFDs), but did relatively little to alter BFDs, and results do not support alternating foam filling layers as a valid method to attenuate shock impact.


ABSTRACT: Subject to compression, elastic materials may undergo bifurcation of various kinds. A homogeneous material forms creases, whereas a bilayer consisting of a stiff film and a compliant substrate forms wrinkles. Here, we show several new types of bifurcation behavior for bilayers consisting of films and substrates of comparable elastic moduli. Depending on the ratios of moduli and thicknesses of the two materials, the critical strain for the onset of creases can be either smaller or larger than that for the onset of wrinkles. When the critical strain for the onset of creases is lower than that of wrinkles, creases can be subcritical or supercritical. When the critical strain for the onset of wrinkles is lower than that of creases, wrinkles can further channel to creases at a strain much lower than the critical strain for the onset of creases in a homogeneous material. Experiments, conducted with bilayer polydimethylsiloxane (PDMS) structures subject to compressive loading, show that the different types of bifurcation behavior agree with the theoretical predictions.


ABSTRACT: This paper presents the nonlinear large deflection of the thin film and the effect of substrate deformation on the thin film deflection through the shaft-loaded blister test. The blister of thin film can be divided into two parts, namely, the annular contact brim and the central noncontact bulge. A two-coupled line spring model is developed to describe the deformation of the contact part, and Föppl–Hencky equations are employed to study the constitutive relation between the applied load and the central deflection. The analytical and numerical solutions for the constitutive relation between the applied load and the deflection of thin film with considering the deformation of substrate are derived.


ABSTRACT: In this paper, we investigate the asymmetric bifurcation behavior of an initially curved nanobeam accounting for Lorentz and electrostatic forces. The beam model was developed in the framework of Euler–Bernoulli beam theory, and the surface effects at the nanoscale were taken into account in the model by
including the surface elasticity and the residual surface tension. Based on the Galerkin decomposition method, the model was simplified as two degrees of freedom reduced order model, from which the symmetry breaking criterion was derived. The results of our work reveal the significant surface effects on the symmetry breaking criterion for the considered nanobeam.


**ABSTRACT:** The equilibrium equations and boundary conditions in terms of the second Piola–Kirchhoff membrane stress and moment are given in this note, which are necessary for the finite deformation analysis of shells.


**ABSTRACT:** Critical displacements are determined for snap-through of shallow, extensible, and elastic arches that are pushed downward quasi-statically at any point along the span. The initial arch is circular and unstrained, and the ends of the arch are pinned and immovable. When the vertical position at the push-down location reaches a critical value, the arch jumps into an inverted shape (unless the arch is extremely shallow). The critical displacement is given or approximated by an unstable equilibrium configuration of the unloaded arch, for which an analytical formula is derived.


**ABSTRACT:** Under the actions of internal pressure and electric voltage, a spherical dielectric elastomer balloon usually keeps a sphere during its deformation, which has also been assumed in many previous studies. In this article, using linear perturbation analysis, we demonstrate that a spherical dielectric elastomer balloon may bifurcate to a nonspherical shape under certain electromechanical loading conditions. We also show that with a nonspherical shape, the dielectric elastomer balloon may have highly inhomogeneous electric field and stress/stretch distributions, which can lead to the failure of the system. In addition, we conduct stability analysis of the dielectric elastomer balloon in different equilibrium configurations by evaluating its second variation of free energy under arbitrary perturbations. Our analyses indicate that under pressure-control and voltage-control modes, nonspherical deformation of the dielectric elastomer balloon is energetically unstable. However, under charge-control or ideal gas mass-control mode, nonspherical deformation of the balloon is energetically stable.


**ABSTRACT:** Many recently synthesized materials feature aligned arrays or bundles of carbon nanotubes (CNTs) whose mechanical properties are partially determined by the van der Waals interactions between adjacent tubes. Of particular interest in this paper are instances where the resulting interaction between a pair of CNTs often produces a forklike structure. The mechanical properties of this structure are noticeably different from those for isolated individual CNTs. In particular, while one anticipates buckling phenomena in the forked structure, an adhesion instability may also be present. New criteria for buckling and adhesion instabilities in forklike
structures are presented in this paper. The criteria are illuminated with a bifurcation analyses of the response of the forklike structure to applied compressive and shear loadings.


ABSTRACT: Buckling of slender structures is traditionally regarded as a first route toward failure. Here, we provide an alternative perspective on a burgeoning movement where mechanical instabilities are exploited to devise new classes of functional mechanisms that make use of the geometrically nonlinear behavior of their postbuckling regimes. Selected examples are highlighted across length-scales to illustrate some of the exciting opportunities that lie ahead.


ABSTRACT: Based on the classical plate theory (CPT), we derive scaling factors between solutions of bending, buckling and free vibration of isotropic functionally graded material (FGM) thin plates and those of the corresponding isotropic homogeneous plates. The effective material properties of the FGM plate are assumed to vary piecewise continuously in the thickness direction except for the Poisson ratio that is taken to be constant. The correspondence relations hold for plates of arbitrary geometry provided that the governing equations and boundary conditions are linear. When the stretching and bending stiffnesses of the FGM plate satisfy a relation, Poisson's ratio is constant and the boundary conditions are such that the in-plane membrane forces vanish, then there exists a physical neutral surface for the FGM plate that is usually different from the plate midsurface. Example problems studied verify the accuracy of scaling factors.


ABSTRACT: The axisymmetric inflation problem for a wrinkled membrane is solved by means of a simple nonlinear ordinary differential equation. The solution is illustrated in full details. Both the free and constrained cases are addressed, in the limit case where the membrane is fully wrinkled. In the constrained inflation problem, no slippage is allowed between the membrane and the constraining surfaces. It is shown that an actual membrane can in no way reach the fully wrinkled configuration during free inflation, regardless of the membrane's initial configuration and constituent material. The fully wrinkled solution is compared to some finite element results obtained by means of an expressly developed iterative–incremental procedure. When the values of the inflating pressure and length of the meridian lie within a suitable applicability range, the fully wrinkled solution may represent a reasonable approximation of the actual solution. A comparison with some numerical and experimental results available in the literature is illustrated.


ABSTRACT: An analytical model predicting the dynamic local buckling failure of plates with a large dimension in the longitudinal direction compressed at a constant rate was proposed. The model began with the hypothesis that the proposed analytical approach could be an alternative methodology to approximate the dynamic local
plate buckling response of constituent plates of corrugated core sandwich columns. Prior to the model
development, four preliminary finite-element (FE) simulations were conducted to observe the typical dynamic
response of the sandwich columns having thin core web plates or thin face sheets. From the simulations, several
wrinkles with a regular pattern were generated, and then one of the wrinkles grew excessively to a failure.
Accordingly, the proposed model considered an imaginary patch plate on a long plate simulating a face sheet or
a core web plate. The size of the patch plate was predefined so as to encompass the major growing wrinkle, and
the out-of-plane displacement was calculated till load drop. The verification of the proposed model was
followed by comparison with the FE calculations. The model was satisfactory in predicting maximum forces
and times-to-failure, but some discrepancies were found when postcritical behavior and plasticity were
involved. The sources of the discrepancies were discussed.

Shan Tang, Ying Li, Wing Kam Liu, Ning Hu, Xiang He Peng and Zaoyang Guo “Tensile stress-driven surface
December 2015

ABSTRACT: It has been experimentally observed that wrinkles formed on the surface of electrospun polymer
nanofibers when they are under uniaxial tension (Appl. Phys. Lett., 91, p. 151901 (2007)). Molecular dynamics
(MD) simulations, finite element analyses (FEA), and continuum theory calculations have been performed to
understand this interesting phenomenon. The surface wrinkles are found to be induced by the cylindrical core–
shell microstructure of polymer nanofibers, especially the mismatch of Poisson's ratio between the core and
shell layers. Through the MD simulations, the polymer nanofiber is found to be composed of a glassy core
embedded into a rubbery shell. The Poisson's ratios of the core and shell layers are close to that of the
compressible (0.2) and incompressible (0.5) polymers, respectively. The core is twice stiffer than the shell, due
to its highly packed polymer chains and large entanglement density. Based on this observation, a FEA model
has been built to study surface instability of the cylindrical core–shell soft solids under uniaxial tension. The
“polarization” mechanism at the interphase between the core and shell layers, induced by the mismatch of their
Poisson's ratios, is identified as the key element to drive the surface wrinkles during the instability analysis.
Through postbuckling analysis, the plastic deformation is also found to play an important role in this process.
Without the plastic deformation, the initial imperfection cannot lead to surface wrinkles. The FEA model shows
that the yielding stress (or strain rate) can greatly affect the onset and modes of surface wrinkles, which are in
good agreement with experimental observations on electrospun polymer nanofibers. The deformation
mechanism and critical condition for the surface wrinkles are further clarified through a simplified continuum
theory. This study provides a new way to understand and control the surface morphology of cylindrical core–
shell materials.

Enlai Gao and Zhiping Xu “Thin-shell thickness of two-dimensional materials”, J. Appl. Mech. 2015;82(12):121012-
121012-4. doi:10.1115/1.4031568. December 2015

ABSTRACT: In applying the elastic shell models to monolayer or few-layer two-dimensional (2D) materials, an
effective thickness has to be defined to capture their tensile and out-of-plane mechanical behaviors. This thin-
shell thickness differs from the interlayer distance of their layer-by-layer assembly in the bulk and is directly
related to the Föppl–von Karman number that characterizes the mechanism of nonlinear structural deformation.
In this work, we assess such a definition for a wide spectrum of 2D crystals of current interest. Based on first-
principles calculations, we report that the discrepancy between the thin-shell thickness and interlayer distance is
weakened for 2D materials with lower tensile stiffness, higher bending stiffness, or more number of atomic
layers. For multilayer assembly of 2D materials, the tensile and bending stiffness have different scaling
relations with the number of layers, and the thin-shell thickness per layer approaches the interlayer distance as the number of layers increases. These findings lay the ground for constructing continuum models of 2D materials with both tensile and bending deformation.


ABSTRACT: In the context of strain-energy-deployed space structures, material relaxation effects play a significant role in structures that are stowed for long durations, for example, in a space vehicle prior to launch. Here, the deployment of an ultrathin carbon fiber reinforced plastic (CFRP) tape spring is studied, with the aim of understanding how long-duration stowage affects its deployment behavior. Analytical modeling and experiments show that the deployment time increases predictably with stowage time and temperature, and analytical predictions are found to compare well with experiments. For cases where stress relaxation is excessive, the structure is shown to lose its ability to deploy autonomously.


ABSTRACT: The buckling and postbuckling responses of viscoelastic-layered composites are investigated using finite-element simulations. These composites consist of alternating layers of a stiff elastic constituent and of a soft viscoelastic constituent. In response to compressive loads in the layer direction, elastic instabilities significantly affect the finite deformation mechanics of these composites. The dependence of the critical strain and critical wavenumber on strain rate is analyzed. In the postbuckling regime, the wavenumber of the mode of deformation is found to be highly dependent on strain rate and time and can be used to identify three different regimes that depend on the volume fraction of the stiff constituent. Interestingly, a transition from a wrinkling mode to a longwave mode can be observed when the strain rate is varied for moderate volume fractions of the stiff material. Analytical formulae for the buckling and postbuckling of the elastic-layered composites are used to interpret numerical results obtained for viscoelastic-layered composites. Viscoelastic-layered composites exhibit a wide range of rate-dependent mechanical behavior and could have applications in vibration damping and acoustic metamaterials.


ABSTRACT: The nanostructure of biological materials is built with hard mineral crystals embedded in soft protein matrix in a staggered manner. The staggered arrangement of the crystals is assumed to be critically important for the stability of the nanostructure. But the mechanism is not fully understood. In this paper, a mechanical model, considering the effects of overlapping ratio between the crystals, i.e., the staggering position, is developed for analyzing the buckling behaviors of the nanostructure. It is found that the buckling strength increases with the overlapping ratio \( \lambda \) in the range of 0–1/2 and reaches a peak value at \( \lambda = 1/2 \) that is generally adopted by nature's design of the biological materials. The effect of aspect ratio and volume fraction of mineral crystals are further analyzed at various overlapping ratios, and the results are in general consistent with previous studies for the case of \( \lambda = 1/2 \). In addition, the lower and upper limits of the buckling strength are obtained. Finally, we show that the contact between mineral tips can significantly enhance the buckling strength of the nanostructure when the aspect ratio of minerals is small.

ABSTRACT: In two recent papers, the authors investigated the bending collapse load of rectangular tubes consisting of a perfectly elastoplastic material. From these investigations, it is found that the collapse may also occur due to the buckling of web in a rectangular tube under bending, when the tube has a cross section with a large aspect ratio of web to flange b/a. In order to evaluate the collapse load of such tubes under bending, the effective width concept given by Rusch and Lindner for a plate compressed with stress gradient was used to calculate the postbuckling strength of the tube web. However, in the solution of Rusch and Lindner, the plate is supported at only one longitudinal edge with the other longitudinal edge being free. This boundary condition is obviously different from that of the tube web. This paper complements the previous work by addressing the postbuckling strength of the web under stress gradients. The postbuckling strength of the web under stress gradients is also calculated using the effective width concept given in AS/NZS 4600 standard and North American specification (NAS) for a plate compressed with stress gradient and supported at both two longitudinal edges. Moreover, the web slenderness also affects the condition for reaching cross-sectional fully plastic yielding when the web is wider. A new method is proposed to predict the maximum moment considering the effect of web slenderness on the cross-sectional fully plastic yielding. The validity of the collapse load estimation is checked by the results of FEM (finite element method) numerical analysis.


ABSTRACT: Static and dynamic responses of a circular cylindrical shell made of hyperelastic arterial material are studied. The material is modeled as a combination of Neo-Hookean and Fung materials. Two types of pressure loads are studied—distributed radial forces and deformation-dependent pressure. The static responses of the shell under these two loads differ essentially at moderate strains, while the behavior is similar for small loads. The principal difference is that the axial displacements are much larger for the shell under distributed radial forces, while for actual pressure the shell is stretched both in circumferential and axial directions. Free and forced vibrations around preloaded configurations are analyzed. In both cases, the nonlinearity of the single-mode (driven mode) response of the preloaded shell is quite weak, but a resonant regime with both driven and companion modes active has been found with more complicated nonlinear dynamics.

Chi Zhang, Jian Wu, Keh-Chih Hwang and Yonggang Huang “Postbuckling of hyperelastic plates”, Curvature is simply expressed as the second derivative of the plate deflection in prior studies of postbuckling of plates. It is shown in this paper that the higher-order terms in curvature should be retained, consistent with Koiter's postbuckling theory. This paper also solves the dilemma whether the increase of postbuckling load is proportional to the square of the ratio of the post-buckling deflection w to the plate thickness t, (w/t)², as in most prior studies, or to the characteristic in-plane length L of the plate, (w/L)², as discovered in some recent studies.


ABSTRACT: Tensile stability of healthy medial arterial tissue and its constituents, subject to initial geometrical and/or material imperfections, is investigated based on the long wavelength approximation. The study employs existing constitutive models for elastin, collagen, and vascular smooth muscle which comprise the medial layer of large elastic (conducting) arteries. A composite constitutive model is presented based on the concept of the
musculoelastic fascicle (MEF) which is taken to be the essential building block of medial arterial tissue. Nonlinear equations governing axial stretch and areal stretch imperfection growth quantities are obtained and solved numerically. Exact, closed-form results are presented for both initial and terminal rates of imperfection growth with nominal load. The results reveal that geometrical imperfections, in the form of area nonuniformities, and material imperfections, in the form of constitutive parameter nonuniformities, either decrease or increase only slightly with increasing nominal load; a result which is to be expected for healthy tissue. By way of contrast, an examination of a simple model for elastin with a degrading stiffness gives rise to unbounded imperfection growth rates at finite values of nominal load. The latter result indicates how initial geometrical and material imperfections in diseased tissues might behave, a topic of future study by the authors.

ABSTRACT: Blister tests are commonly used to determine the mechanical and interfacial properties of thin film materials with recent applications for graphene. This paper presents a numerical study on snap transitions of pressurized graphene blisters. A continuum model is adopted combining a nonlinear plate theory for monolayer graphene with a nonlinear traction–separation relation for van der Waals interactions. Three types of blister configurations are considered. For graphene bubble blisters, snap-through and snap-back transitions between pancake-like and dome-like shapes are predicted under pressure-controlled conditions. For center-island graphene blisters, snap transitions between donut-like and dome-like shapes are predicted under both pressure and volume control. Finally, for the center-hole graphene blisters, growth is stable under volume or N-control but unstable under pressure control. With a finite hole depth, the growth may start with a snap transition under N-control if the hole is relatively deep. The numerical results provide a systematic understanding on the mechanics of graphene blisters, consistent with previously reported experiments. Of particular interest is the relationship between the van der Waals interactions and measurable quantities in corresponding blister tests, with which both the adhesion energy of graphene and the equilibrium separation for the van der Waals interactions may be determined. In comparison with approximate solutions based on membrane analyses, the numerical method offers more accurate solutions that may be used in conjunction with experiments for quantitative characterization of the interfacial properties of graphene and other two-dimensional (2D) membrane materials.

ABSTRACT: Acoustic radiation force generated by two counterpropagating acoustic waves in a thin layer of soft material can induce large deformation, and hence can be applied to design acoustomechanical actuators. Owing to the sensitivity of wave propagation to material geometry, the change of layer thickness may enhance wave propagation and acoustic radiation force, causing a jumping larger deformation, i.e., snap-through instability. Built upon the basis of strong elliptic condition, we develop a generalized theoretical method to evaluate the acoustomechanical stability of soft material actuators. We demonstrate that acoustomechanical instability occurs when the true tangential stiffness matrix ceases to be positive definite. Our results show that prestresses can not only enhance significantly the acoustomechanical stability of the soft material layer but also amplify its actuation stretch in thickness direction.

ABSTRACT: This paper presents a generalization of the Laplace transform method (LTM) for determining the flutter points of a linear ordinary-differential aeroelastic system—a linear system involving a spatial derivative as well as a time-eigenvalue parameter. Current implementations of the LTM have two major problems: they are unable to solve systems of arbitrary size, order, and boundary conditions, and they require certain key operations to be performed by hand or with symbolic manipulation libraries. Our generalized method overcomes both these problems. We also devise a new method for solving and visualizing the algebraic system that arises from the LTM procedure. We validate our generalized LTM and novel solution method against both the Goland wing model and a large system of high differential order, as a demonstration of their effectiveness for solving such systems.

ABSTRACT: When an elastic thin-film/substrate bilayer is cyclically compressed with a large plane-strain stroke, various surface morphologies develop either reversibly or irreversibly with cyclic hysteresis. Here, we examine the cyclic morphology evolution with extensive finite-element analyses and present a generic irreversibility map on the primary bilayer Ruga-phase diagram (PB-RPD). The term “PB” refers to a system of a film on a substrate, both of which are incompressible neo-Hookean, while the term “Ruga-phase” refers to the classification of corrugated surface morphologies. Our generic map reveals two configurational irreversibility types of Ruga-phases during a loading and unloading cycle. One, localization irreversibility, is caused by unstable crease localization and the other, modal irreversibility, by unstable mode transitions of wrinkle-Ruga configurations. While the instability of crease localization depends mainly on smoothness of the creasing surface or interface, the instability of Ruga-mode transition is sensitive to film/substrate stiffness ratio, film/substrate strain mismatch (\(\varepsilon_{ps}\)), and material viscosity of the bilayer. For small strain mismatches (\(\varepsilon_{ps} \lesssim 0.5\)), PB Ruga structures are ordered; otherwise, for large strain mismatches, the Ruga structures can evolve to ridge configurations. For evolution of ordered Ruga phases, the configurational irreversibility leads to shake-down or divergence of cyclic hysteresis. Underlying mechanisms of the cyclic hysteresis are found to be the unstable Ruga-phase transitions of mode-period multiplications in the loading cycle, followed by either mode “locking” or primary-period “switching” in the unloading cycle. In addition, we found that the primary-period switching is promoted by the strain mismatch and material viscosity. These results indicate that various Ruga configurations can be excited, and thus, diverse Ruga-phases can coexist, under cyclic loading. Our irreversibility map will be useful in controlling reversibility as well as uniformity of Ruga configurations in many practical applications.

ABSTRACT: In the literature, there are various simplifying assumptions adopted in the kinematic relations of the faces and the core when considering a geometrically nonlinear problem in sandwich structures. Most commonly, only one nonlinear term is included in the faces and the core nonlinearities are neglected. A critical assessment of these assumptions, as well as the effects of including the other nonlinear terms in the faces and the core, is the scope of this paper. The comprehensive investigation of all the nonlinear terms is accomplished by deriving and employing an advanced nonlinear high-order theory, namely, the recently developed “extended high-order sandwich panel theory” (EHSAPT). This theory, which was derived as a linear theory, is first formulated in this paper in its full nonlinear version for the simpler one-dimensional case of sandwich wide panels/beams. Large displacements and moderate rotations are taken into account in both faces and core. In
addition, a nonlinear EHSAPT-based finite element (FE) is developed. A series of simplified models with various nonlinear terms included are derived accordingly to check the validity of each of these assumptions. Two sandwich panel configurations, one with a “soft” and one with a “hard” core, loaded in three-point bending, are analyzed. The geometric nonlinearity effects and the relative merits of the corresponding simplifications are analyzed with these two numerical examples. In addition to a relative comparison among all these different assumptions, the results are also compared to the corresponding ones from a commercial FE code.


ABSTRACT: The purpose of this paper is to develop the motion equations of a flexible spherical shell rolling without slip on a flat surface. The motivation for this paper stems from tumbleweed rovers, which are envisioned to roll, deform, and bounce on the Martian surface due to the flexible nature of their thin walls. The motion equations are derived using a constrained Lagrangian approach and capture the rolling without slip nonholonomic constraint. Numerical simulations are performed to validate the dynamic model developed and to investigate the effect of the flexibility of the spherical shell on its trajectory.


ABSTRACT: We study the effect of a dimplelike geometric imperfection on the critical buckling load of spherical elastic shells under pressure loading. This investigation combines precision experiments, finite element modeling, and numerical solutions of a reduced shell theory, all of which are found to be in excellent quantitative agreement. In the experiments, the geometry and magnitude of the defect can be designed and precisely fabricated through a customizable rapid prototyping technique. Our primary focus is on predictively describing the imperfection sensitivity of the shell to provide a quantitative relation between its knockdown factor and the amplitude of the defect. In addition, we find that the buckling pressure becomes independent of the amplitude of the defect beyond a critical value. The level and onset of this plateau are quantified systematically and found to be affected by a single geometric parameter that depends on both the radius-to-thickness ratio of the shell and the angular width of the defect. To the best of our knowledge, this is the first time that experimental results on the knockdown factors of imperfect spherical shells have been accurately predicted, through both finite element modeling and shell theory solutions.

References listed at the end of the paper:

ABSTRACT: Three-dimensional transient deformations of clamped flat and doubly curved polycarbonate (PC) panels impacted by a rigid smooth hemispherical-nosed circular cylinder have been numerically studied by the finite-element (FE) method to delineate effects of the panel radius of curvature to its thickness ratio on their penetration resistance. The PC is modeled as thermoelastoviscoplastic with the effective plastic strain rate depending upon the hydrostatic pressure. The effective plastic strain of 3.0 at failure is ascertained by matching for one set of flat panels the computed and the experimental minimum perforation speeds. It is found that a negative curvature (i.e., the center of curvature toward the impactor) of a panel degrades its penetration performance, and the positive curvature enhances it especially for thin panels with thickness/radius of curvature of 0.01. However, the benefit is less evident for panels with the panel thickness/radius of curvature of 0.04 or more. For positively curved thin panels, an elastic hinge forms around the central impacted area during an early stage of deformations, and subsequent deformations occur within this region. No such hinge is observed for flat plates, negatively curved panels of all the thicknesses, and positively curved thick panels. Furthermore, the maximum effective stress induced in regions surrounding the impacted area is less for positively curved panels than that for flat panels. The dominant failure mechanism is found to be the deletion of failed elements due to the effective plastic strain in them exceeding 3.0 rather than due to plug formation. For an example problem, the dependence of the effective plastic strain rate upon the hydrostatic pressure and the consideration of the Coulomb friction at the contact surfaces exhibited minimal effects on the penetration characteristics. This information should be useful for designers of impact-resistant transparent armor, such as an airplane canopy, automobile windshield, and goggles.


ABSTRACT: The properties and behavior of a surface as well as its interaction with surrounding media depend on the inherent material constituency and the surface topography. Structured surface topography can be achieved via surface wrinkling. Through the buckling of a thin film of stiff material bonded to a substrate of a softer material, wrinkled patterns can be created by inducing compressive stress states in the thin film. Using this same principle, we show the ability to create wrinkled topologies consisting of a highly structured gradient in amplitude and wavelength, and one which can be actively tuned. The mechanics of graded wrinkling are revealed through analytical modeling and finite element analysis, and further demonstrated with experiments.


**ABSTRACT:** This paper is an extension of the previous review, done by the same authors (Mikhlin, Y., and Avramov, K. V., 2010, “Nonlinear Normal Modes for Vibrating Mechanical Systems. Review of Theoretical Developments,” ASME Appl. Mech. Rev., 63(6), p. 060802), and it is devoted to applications of nonlinear normal modes (NNMs) theory. NNMs are typical regimes of motions in wide classes of nonlinear mechanical systems. The significance of NNMs for mechanical engineering is determined by several important properties of these motions. Forced resonances motions of nonlinear systems occur close to NNMs. Nonlinear phenomena, such as nonlinear localization and transfer of energy, can be analyzed using NNMs. The NNMs analysis is an important step to study more complicated behavior of nonlinear mechanical systems. This review focuses on applications of Kauderer–Rosenberg and Shaw–Pierre concepts of nonlinear normal modes. The Kauderer–Rosenberg NNMs are applied for analysis of large amplitude dynamics of finite-degree-of-freedom nonlinear mechanical systems. Systems with cyclic symmetry, impact systems, mechanical systems with essentially nonlinear absorbers, and systems with nonlinear vibration isolation are studied using this concept. Applications of the Kauderer–Rosenberg NNMs for discretized structures are also discussed. The Shaw–Pierre NNMs are applied to analyze dynamics of finite-degree-of-freedom mechanical systems, such as floating offshore platforms, rotors, piece-wise linear systems. Studies of the Shaw–Pierre NNMs of beams, plates, and shallow shells are reviewed, too. Applications of Shaw–Pierre and King–Vakakis continuous nonlinear modes for beam structures are considered. Target energy transfer and localization of structures motions in light of NNMs theory are treated. Application of different asymptotic methods for NNMs analysis and NNMs based model reduction are reviewed.


**ABSTRACT:** Corrugated pipes and tubes are commonly used in many engineering and industrial applications because they offer global flexibility combined with local rigidity. Some of the engineering systems which use the corrugated pipes are Liquefied Natural Gas (LNG) storage systems, risers for offshore oil and gas industries, heat, ventilation, and air conditioning systems (HVAC), aerospace and automobile cabin cooling systems, and certain domestic appliances such as vacuum cleaners. Air flow through a short or a long length of corrugated pipes can cause the pipes to emit loud and clear “tonal” sounds or “whistling” at some critical flow conditions. Interaction and coupling of these acoustic waves with vortex shedding-flow instability can result in severe noise and structural vibration problems. A phenomenon of sound generation in corrugated pipes is also observed in a children's toy called “Hummer,” “Voice of the Dragon,” or “Magic Whistle.” This review paper focuses on the research work carried out to date to study the sound generation mechanism and its reduction methodology in corrugated pipes with air flow. This paper reviews and summarizes the various theoretical, experimental and computational work carried out in relation to acoustics of corrugated pipes.

ABSTRACT: This review aims to complement a milestone monograph by Singer et al. (2002, Buckling Experiments—Experimental Methods in Buckling of Thin-Walled Structures, Wiley, New York). Practical aspects of load bearing capacity are discussed under the general umbrella of “buckling.” Plastic loads and burst pressures are included in addition to bifurcation and snap-through/collapse. The review concentrates on single and combined static stability of conical shells, cylinders, and their bowed out counterpart (axial compression and/or external pressure). Closed toroidal shells and domed ends onto pressure vessels subjected to internal and/or external pressures are also discussed. Domed ends include: torispheres, toricones, spherical caps, hemispheres, and ellipsoids. Most experiments have been carried in metals (mild steel, stainless steel, aluminum); however, details about hybrids (copper-steel-copper) and shells manufactured from carbon/glass fibers are included in the review. The existing concerns about geometric imperfections, uneven wall thickness, and influence of boundary conditions feature in reviewed research. They are supplemented by topics like imperfections in axial length of cylinders, imperfect load application, or erosion of the wall thickness. The latter topic tends to be more and more relevant due to ageing of vessels. While most experimentation has taken place on laboratory models, a small number of tests on full-scale models are also referenced.


ABSTRACT: A survey of several methods under the heading of strong formulation finite element method (SFEM) is presented. These approaches are distinguished from classical one, termed weak formulation finite element method (WFEM). The main advantage of the SFEM is that it uses differential quadrature method (DQM) for the discretization of the equations and the mapping technique for the coordinate transformation from the Cartesian to the computational domain. Moreover, the element connectivity is performed by using kinematic and static conditions, so that displacements and stresses are continuous across the element boundaries. Numerical investigations integrate this survey by giving details on the subject.


ABSTRACT: The achievements occurred in nonlinear dynamics over the last 30 years entail a substantial change of perspective when dealing with vibration problems, since they are now deemed ready to meaningfully affect the analysis, control, and design of mechanical and structural systems. This paper aims at overviewing the matter, by highlighting and discussing the important, yet still overlooked, role that some relevant concepts and tools may play in engineering applications. Upon dwelling on such topical concepts as local and global dynamics, bifurcation and complexity, theoretical and practical stability, attractor robustness, basin erosion, and dynamical integrity, recent results obtained for a variety of systems and models of interest in applied mechanics and structural dynamics are overviewed in terms of analysis of nonlinear phenomena and their control. The global dynamics perspective permits to explain partial discrepancies between experimental and theoretical/numerical results based on merely local analyses and to implement effective dedicated control procedures. This is discussed for discrete systems and reduced order models of continuous systems, for applications ranging from macro- to micro/nanomechanics. Understanding of basic phenomena in nonlinear dynamics has now reached such a critical mass that it is time to exploit their potential to enhance the effectiveness and safety of systems in technological applications and to develop novel design criteria.

ABSTRACT: This study revisits Timoshenko beam theory (TBT). It discusses at depth a more consistent and simpler governing differential equation. The so-called second spectrum is also addressed. Then, we provide the asymptotic justification of the aforementioned differential equation along with detailed discussion of the boundary and initial conditions. The paper also presents remarks of historical character, in the context of other pertinent studies.


ABSTRACT: Bistable composite laminates have received a considerable attention due to their fabulous behavior and potential for morphing and energy harvesting. A bistable or multistable laminate is a type of composite structure that exhibits multiple stable static configurations. The characterization of unsymmetric fiber-reinforced laminated composite plates as a bistable structure is well established and quantitatively determined after about 30 years of research. As predicting cured shapes of unsymmetric composite laminates became well identified, attention was directed to the design of these structures for morphing applications. Bistable composite laminates have attracted researchers as a morphing structure because a bistable structure settles at one of its equilibrium positions without demanding continuous power to remain there. If the structure is triggered to leave an equilibrium position, it will snap or jump to the other equilibrium position. The snapthrough response is highly geometrically nonlinear. With the increased demand for broadband vibration energy harvesters, bistable composite laminates, which are able to gain large-amplitude vibrations in snapthrough motion, have recently attracted attention. This paper aims to summarize, review, and assess references and findings concerned with the response of bistable composite laminates for morphing and energy harvesting to date. It also highlights the remaining challenges and possible future research work as research in bistable composites transitions from phenomena to application.


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ABSTRACT: In this article, a new three-dimensional finite element modeling approach with less computing time and space is introduced to study the buckling behavior of sandwich panels, containing a face–core debond. The finite element model presented in this study relates the motion of the face sheets to the core through constraint equations utilizing the concept of slave and master nodes, thus representing a more realistic model of the sandwich panel. The composite face sheets are modeled with shell elements, and the core is modeled using the 3D structural solid elements capable of taking transverse flexibility into consideration. In order to model the debond, the constraints between the nodes of the face sheet and the core are removed and replaced with contact elements in the debonded region to avoid interpenetration. The model is validated through comparison with experimental results reported in the literature. The validated model is then used to study the effects of the size, shape, aspect ratio of the debond, as well as fiber orientation of the face sheets and the influence of core stiffness on the buckling load of the panel subject to different boundary conditions on the top and bottom face sheets of the panel.

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ABSTRACT: In the present work, a new axisymmetric weak form meshless method is presented for analysis of free vibration of functionally graded material (FGM) cylinders. This method is based on weak form of equilibrium equation and moving least squares (MLS) approximation. Essential boundary conditions are imposed by transformation method. In this method, shape functions that do not satisfy the Kronecker delta condition are corrected, then essential boundary conditions are imposed easily as in the finite element method (FEM). In the present work, the material is assumed to be functionally graded in the radial direction. Variations in the material properties such as Young’s modulus and Poisson’s ratio may be arbitrary functions of the radial coordinate. The FGM cylinder material varies continuously from silicon carbide (SiC) on the inner surface to stainless steel (SUS304) on the outer surface. Free vibration analysis of FGM cylinders with any arbitrary combination of boundary conditions is possible by the proposed model. Natural frequencies obtained from the presented model are in good agreement with results of finite element simulation. Effects of various types of boundary conditions, geometrical parameters, and mechanical properties on the natural frequencies are studied.


ABSTRACT: This experimental study discusses the effects of the tube diameter and the impact energy level on the impact and compression after impact behaviors of [±55]₃ filament-wound glass/epoxy composite tubes. Four different tube diameters were selected as 50, 75, 100, and 150 mm. The composite tubes were subjected to various impact energy levels, 15, 20, and 25 J, using an instrumented impact testing machine at room temperature. Impacted and nonimpacted samples were subjected to axial compression tests. Results indicated that both specimen diameter and impact energy highly affect the impact response and compression-after impact strength of composite tubes.
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ABSTRACT: Hamilton’s principle coupled with the Rayleigh–Ritz technique is used to compute the fundamental frequencies of simply supported thin-walled fiber-reinforced composite cylinders with elliptical cross sections. Owing to the decreased geometric stiffness resulting from less curvature, it is expected that the normal displacement component of the vibratory motion will be larger in the flatter regions of the cross section than that in the more curved regions. Accordingly, in the Rayleigh–Ritz formulation, the normal displacement component of the vibratory motion is modulated with circumferential location to represent this characteristic by using a so-called shape factor. A number of simplifications in the analysis lead to a hierarchy of expressions for the fundamental frequency, including the one termed Lo’s approximation. The so-called large and small cylinders, as measured by cylinder circumference and with wall laminates [±θ/0/90]₁₂ and[±θ/0/90]₁₂, respectively, θ in the range of 0 to 90°, are considered. It is demonstrated that the comparisons with finite element calculations are good, particularly for Lo’s approximation. Then, parameter studies using Lo’s approximation are conducted to illustrate the dependence of the fundamental frequency on fiber angle θ, cross-sectional geometry, cylinder circumference, and cylinder length. It is shown that for cylinders of the same circumference, an elliptical cylinder has a lower fundamental frequency than a circular one and that difference is quantified. However, the dependence of the fundamental frequency on other geometric parameters and fiber angle is much the same for cylinders with elliptical cross sections as for circular cylinders.


ABSTRACT: This study presents the effect of impact energy on the static failure pressures, and fatigue life of composite pipes. The specimens manufactured have inner diameter 100 mm and length 400 mm. Impact tests were realized at three different energy levels 5.0, 7.5, and 10.0 J. Force–deflection curves were plotted. Impacted and non-impacted specimens were subjected to internal pressure statically and dynamically to obtain failure pressure and fatigue life of the composite pipe, respectively. Results indicate that leakage and eruption pressures for static test decrease and perspiration, leakage, and eruption cycles decrease by lateral impact.


ABSTRACT: An analytical solution to the static analysis of a general cross-ply finite-dimensional doubly curved panel of rectangular plan-form, modeled using a higher order shear deformation theory, is presented. A solution methodology, based on boundary-discontinuous generalized double Fourier series approach is used to solve a system of five highly coupled linear partial differential equations, generated by the higher order-based laminated shell analysis, with the fully clamped type 4 (C4) boundary condition prescribed on two opposite
edges, while the remaining two edges are subjected to the simply supported type 4 (SS4) constraint. The numerical accuracy of the solution is ascertained by studying the convergence characteristics of the deflection and moment of a cross-ply spherical panel, and also by comparison with the available results in literature. Additional comparisons were made with the finite element counterparts using commercially available software for distributed load. Hitherto unavailable important numerical results presented include sensitivity of the predicted response quantities of interest to shell geometry (cylindrical and spherical), lamination, lamina material property, thickness and membrane effects as well as their interactions.

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ABSTRACT: The article presents hygrothermally induced buckling of geometrically linear laminated composite plates resting on two parameters Pasternak elastic foundation subjected to moisture and temperature-independent and -dependent material properties with random system properties. System properties such as elastic moduli, shear moduli of the constituent materials, hygroscopic contraction coefficients, thermal expansion coefficients, and foundation stiffness parameters are modeled as independent basic random variables. A computationally efficient C⁰ finite element method combined with Taylor series based mean-centered first-order perturbation technique via higher order shear deformation plate theory is used to solve the random eigenvalue problem. Typical numerical results for dimensional mean and coefficient of variance of hygrothermally induced buckling load of laminated composite plate subjected to uniform hygrothermal loadings are examined with uniform moisture concentration and temperature rise, plate thickness and aspect ratios, total number of plies, fiber orientations, elastic foundations, and different boundary conditions with random system properties. The numerical results obtained by the present solution approach are validated with those available in the literatures and independent Monte Carlo simulation.


ABSTRACT: Shuffled frog-leaping algorithm (SFLA), a memetic meta-heuristic, is proved to be a successful combinatorial optimization algorithm and applied to several engineering problems. However, its potential is not explored in the context of laminate stacking sequence optimization of composite structures. In this article, we propose a hybrid version of SFLA for solving the combinatorial optimization problem associated with lay-up sequence optimization of laminate composite structures. In order to improve the computational performance as well as reliability of the optimal solutions, a customized neighborhood search algorithm and an adaptive search factor are incorporated in to the SFL algorithm to accelerate the convergence characteristics. Apart from this, a crossover operator is suitably incorporated in the proposed hybrid SFLA. Numerical experiments have been carried out by first considering the problem of buckling and failure load optimization of composite plate and later, optimal design of stiffened composite cylindrical shells. Superior convergence characteristics and
robustness of the proposed hybrid SFLA is demonstrated by comparing with other popular meta-heuristic algorithms including genetic algorithms.

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ABSTRACT: In this study, the buckling and compressive failure of adhesively-bonded stepped-lap joints (with/without composite patches) composed of pultruded glass fiber-reinforced polymer composite laminates was investigated experimentally and numerically. Two-component epoxy adhesive was used for bonding purposes. Composite patches were woven glass-epoxy layer. They were added onto the conventional stepped-lap joints so that additional load transfer paths were created and localized stress concentrations near joint edge were reduced. The axial compression tests were performed and the results revealed that the buckling and failure load of new stepped lap composite joints with composite patches were significantly higher than the conventional stepped lap joints. The influence of the overlap length was evaluated. For both types of joints, a small increase was observed in failure loads by increase of the overlap length. Numerical results showed a very good agreement with experimental results.

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ABSTRACT: Dow and Rosen’s work in 1965 formed an intellectual framework for compressive strength of unidirectional composites. Compressive strength was explained in terms of micro-buckling, in which filaments are beams on an elastic foundation. While groundbreaking, the discrepancy between model predictions and observed compressive strength is well known. This study builds on Dow and Rosen’s model specifically with respect to the dominant shear mode instability. A new method that accounts for matrix thermal residual strain, matrix compressive and shear stresses, with associated reductions in tangent modulus due to matrix non-linearity, is proposed. The method is validated using a specific test case, which is conducted to precisely account for microscopic fiber alignment and matrix non-linearity. Accordingly, a method of measuring and accounting for a continuum of fiber misalignment is developed. Predictions are compared to literature values, with variations in fiber modulus, matrix modulus, and volume fraction. Good agreement is shown, both in terms of trend and magnitude. The approach successfully preserves initial in-plane shear stiffness, while showing that in-plane shear stiffness decreases significantly as compressive stress increases.

ABSTRACT: The present work aims at determining the critical material properties that can be used to tailor the crush behaviour of pultruded GFRP (Glass Fibre Reinforced Polymer) box-beams, as can be found in, for example, roadside furniture such as guard-rails. For this purpose, the mechanical behaviour and energy absorption mechanisms of the constituent pultruded box-beam sections subjected to lateral compressive loading, the dominating load case in composite structures when used as roadside furniture, have been studied. The analysed pultruded profiles consist of E-glass fibre reinforcements with two different lay-up configurations in a polyester matrix. The lateral crushing of profile sections is experimentally evaluated and further numerically studied using commercially available tools, applying readily available models incorporated in the software, in analogy to common practice in designing structures, to identify design and material parameters for improving the fracture behaviour of pultruded GFRP profiles. From the analyses, it is shown that the junctions between flanges and webs are the weakest points of box-beam sections: here, high shear stress concentrations in combination with occurring matrix failure lead to further damage such as delamination and tearing. This behaviour is well-described using the Hashin damage model within ABAQUS. Predicted failure behaviour corresponds with observed experimental results, whereas the material stiffness is underestimated. It is shown that the out-of-plane properties (transverse tensile and shear strength) are the dominant parameters affecting the overall performance.

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ABSTRACT: The aim of this study is investigation of the effect of interface crack on lateral buckling load and free vibration response of a sandwich composite beam using experimental methods and finite element solutions. The lateral buckling load and natural frequencies in a thin sandwich composite cantilever beam with crack were considered. The crack was opened between the face sheets and foam core. The length of the crack was selected, such as 100, 150, 200, and 250 mm. Lateral buckling and vibration tests were applied on these samples and then the critical lateral buckling load and natural frequencies were found using experimental and finite element method. In the experimental studies, in-house test mechanisms were used. For the numerical analysis, ANSYS finite element software was used. Close results were obtained between both two methods.

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ABSTRACT: Nonlinear flutter characteristics under the thermal load as well as aerodynamic heating on functionally graded material panels are investigated in the hypersonic flow. Mathematical models are defined such as power-law, sigmoid and exponential functionally graded materials by the volume fractions of the constituents. Further, third-order piston theory of aerodynamics and von Karman strain-displacement relationship is adopted in order to perform the aero-thermoelastic analysis. Applying the principle of virtual work, equations of motion are derived in the matrix form, and then finite element method is used to obtain the
discretized equations. Then, the time domains analysis is performed using Newmark’s time integration method. To check the validity of the present formulation, numerical results are compared with the previous data in the literatures.

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ABSTRACT: Thermal buckling and postbuckling behavior is presented for fiber-reinforced laminated plates subjected to in-plane temperature variation and resting on an elastic foundation. Two kinds of fiber-reinforced laminated plates, namely, uniformly distributed and functionally graded reinforcements, are considered. The material properties of fiber-reinforced laminated plates are based on a micromechanical model and are assumed to be temperature dependent. The governing equations are based on a higher order shear deformation plate theory that includes plate–foundation interaction and the thermal effect. Numerical illustrations are carried out for fiber-reinforced polymer matrix and metal matrix composite laminated plates without or resting on elastic foundations. The numerical results show that the buckling temperature as well as thermal postbuckling strength of the plate can be increased as a result of functionally graded fiber reinforcements. The results reveal that the effect of functionally graded fiber reinforcements on the thermal buckling and postbuckling strength of the plate with polymer matrix is more pronounced compared to the plate with metal matrix.

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ABSTRACT: Conventional wisdom dictates that adding more 0° plies in the load-bearing direction of a laminate will increase its stiffness and strength. While this is true for undamaged laminates, the compression strength of laminates with impact damage may not be as straightforward. In this study, compression after impact strengths of relatively thin laminates with 25%, 33% or 50% of plies aligned in the 0° load-bearing direction were measured for three different damage severity levels. Results show that the increase in compression strength of the laminates with a higher percentage of plies in the 0° direction is lessened as impact damage severity increases indicating that a laminate that is stronger in compression when undamaged may not be stronger in compression when impact damage is accounted for.

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ABSTRACT: Low-velocity dynamic compression tests were performed to reveal the failure mechanism and the energy absorption capacity of the integrated woven sandwich composite. Shear deformations were induced by the tilting of fiber piles in the core of the integrated woven sandwich composite. Ductile load–displacement curves are featured by a long deformation plateau originated from rotations of the core piles. Densification is apparent in the later stage of compression. Stout piles in the core also lead to plastic compression failure mode accompanying with much smaller rotations of core piles. Controlled by the latter failure mode, the dynamic strength and the energy absorption of the panel are stronger. In dynamic compression experiments, the integrated woven sandwich composite panels exhibit similar failure modes with those observed in quasi-static compression tests. The dynamic strength is much greater and the corresponding deformation plateau is much more stable, which leads to greater energy absorption. The dynamic effects of the strength and the energy absorption were explained by the dynamic buckling of the woven struts in the core. The tests suggest that the integrated woven sandwich composite is ideal to serve as a lightweight anti-impact material in engineering structures.


ABSTRACT: Three-point bending tests were conducted to reveal the failure mechanisms of the three-dimensional WTSC. Sixteen groups of experiments were designed and performed based on the orthotropic core structure and different thicknesses of the two skins. Bended along the weft direction, skin yielding and crimping renders WTSC ductile failure mode. Bended along the warp direction, skin cracking renders WTSC brittle–ductile failure mode, while core shearing renders a quasi-brittle mode. After the initial failure, the progression of plastic hinges renders WTSC residual load capacity in a long deformation plateau, while fractures of lower skins lead to complete and abrupt failures. According to the experiments, failure mechanisms of WTSC include skin fracture, skin yielding, skin crimping, tensile failure, indentation, and core shearing. Strength of the skins and the core in the warp and weft directions were predicted. The woven skin and the woven core are stronger in the weft direction. These failure mechanisms lead to six typical styles of flexural deflection curves having different brittle and ductile characteristics.

Development

ABSTRACT: To increase understanding of damage evolution in advanced composite material systems, stereo digital image correlation has been integrated with a compression–bending mechanical loading system to obtain full-field deformations on both compression and tension surfaces throughout the loading process. The integrated system is employed to simultaneously quantify full-field deformations along the length of the specimen. Specifically, the integrated system is employed to experimentally study the progressive failure behavior of thin, woven glass–epoxy composite specimens undergoing both cyclic and monotonic compression–bending loading resulting in large out-of-plane bending deformations with end conditions that allow free out-of-plane rotation. Experimental results obtained using the measurement system for specimens undergoing both linear and highly non-linear deformations during monotonic loading are presented. Results clearly show (a) the presence and magnitude of anticlastic (double) specimen curvature near mid-length for all fiber angles, (b) the distinct differences in the strain fields between the tension and compression surfaces at the critical location, (c) the corresponding disparity in local material failure mechanisms between the tension (e.g. matrix cracking) and compression (e.g. fiber buckling) surfaces in the critical regions and (d) the highly localized character of the strain fields, focused in regions of increased damage.


ABSTRACT: Since train’s frontal nose is the first part of the train which is damaged at the frontal impact, specific attention should be paid to the design of this part. In this study, an effort has been conducted to the design of a nose with light weight which can absorb maximum amount of energy that is possible during a frontal collision. To this aim and with attention to aerodynamic considerations, application of aluminium honeycomb sandwich panel has been studied. This paper includes two main parts. The first part is dedicated to the simulation of aluminium honeycomb sandwich panel, while the frontal collision of nose with different internal layer thicknesses of honeycomb and various nose lengths have been simulated in the second part. Finite element method using LS-DYNA commercial package has been used for the numerical simulation. The results have been validated with available experimental results and an acceptable agreement has been observed.


ABSTRACT: In this article, the nonlinear equations of motion for anti-symmetric angle-ply composite rectangular plates have been derived using the first-order shear deformation theory, including shear deformation and rotary inertia. By using the Galerkin method, five coupled nonlinear partial differential equations of motion are reduced to a nonlinear ordinary differential equation. Then, the multiple time scales method is used to solve the obtained equation and to derive an analytical relation for the nonlinear frequency. Results are compared with the literature and good agreement is achieved. After proving the validity of this study, nonlinear free and forced vibration of a fiber metal laminated rectangular plate have been studied and the effects of some system parameters on the nonlinear behavior of the FML rectangular plate have been investigated.
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ABSTRACT: Composite lattice structures can be regarded as hierarchical when trusses have their own structure (e.g. different stacking sequences are incorporated). In this study, hollow composite pyramidal lattice sandwich structures in end compression were analyzed, measured and evaluated with respect to the designable properties of sandwich cores, such as relative density and truss stacking sequence. Collapse mechanism charts were constructed for both component elements and sandwich columns to illustrate the influence of structural geometries and properties of composite pyramidal lattice cores on failure modes. Operative failure modes were identified and the analytical models were shown to be accurate when compared to the measured response. The minimum weight design for the hollow composite pyramidal lattice sandwich column in end compression was carried out and the structural efficiency was also discussed.

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ABSTRACT: Composite pyramidal lattice structures with hollow trusses afford a convenient means to enable functionality by inserting elements into free volumes within or between trusses. In this study, vibration and low-velocity impact tests were carried out to investigate the dynamic behavior of hollow composite pyramidal lattice structures filled with silicone rubber. Frequencies and the corresponding damping ratios were obtained, which revealed that the damping ratios of space-filled composite pyramidal lattices increased by two times but those of hybrid composite pyramidal lattices decreased by 2% for the first three orders compared with hollow composite pyramidal lattices. Energy absorption capability for rubber-filled structures increased and the rubber filled between trusses can prevent tup penetration. Desired functional potentials can be realized for composite pyramidal lattice structures by serious selection of filling materials and the corresponding geometry.

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ABSTRACT: This work reports the effect of nanotube aspect ratio on the free vibration characteristics of a functionally graded nanocomposite cylinders reinforced by wavy single-walled carbon nanotubes (CNTs) based on mesh-free method. In this simulation, an axisymmetric model is used and axisymmetric natural frequencies of CNT reinforced composite cylinders are presented. The material properties of functionally graded CNT reinforced composites are assumed to be graded in the thickness direction and are estimated by a micromechanical model. The effect of the waviness of the CNTs and its parameters are studied. In the mesh-free analysis, moving least squares shape functions are used for approximation of displacement field in the weak form of motion equation, and the transformation method is used for the imposition of essential boundary conditions. It is observed that the waviness significantly reduces the effective reinforcement of the nanocomposites. The effective moduli and frequency response are very sensitive to the waviness but this sensitivity decreases with the increase of the waviness. The validity of the Young's modulus and the frequency response were assessed by a comparison with available literature data, providing a good agreement.

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ABSTRACT: The traditional approach to mitigate problems resulting from stress concentrations around cutouts for windows and doors in aeronautical structures, either made of metallic or of composite materials, is to locally thicken the structure increasing its weight as well. A more effective solution, without weight penalties, is to reduce the peak stress by redistributing loads to supported regions of the panels such as frames and stiffeners. This can be achieved by means of fibre-steered laminates with variable in-plane stiffness. In this work, the potential of these novel designs for the purpose of stress alleviation around cutouts in composite panels is explored. The optimal configurations in terms of shear buckling and postbuckling failure responses are identified by means of parametric numerical studies. It is predicted that there are steered-fibre configurations that outperform the optimal straight-fibre ones for hole sizes up to two-thirds of the panel width.

References listed at the end of the paper:
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ABSTRACT: There has been an increase in the use of fiber-reinforced composite materials in many areas. In particular, glass-fiber-reinforced composites have gained in popularity owing to their low cost, high-strength properties, durability, ease of repair, and being simple to form. This paper analyzes the buckling load for the glass-fiber-reinforced plywood specifically used for the liquid natural gas cargo tank and carriers, especially the No 96 cargo containment system insulation box. The buckling load of the plywood reinforced with glass fiber composite on both outer surfaces was estimated with various composite thicknesses and compared with the buckling load of unreinforced plywood. The buckling load was also evaluated at various temperatures to verify the temperature dependence of the buckling load. A much higher buckling load for the glass fiber/epoxy-reinforced plywood was obtained as the number of glass fiber/epoxy prepreg composite was increased. However, the rate of increase in the buckling load decreased as the temperature decreased and as the number of glass fiber/epoxy prepreg composite increased.

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ABSTRACT: A number of refined beam theories are discussed in this paper to trace the free vibration response of laminated beams, including thin-walled boxes. By expanding the unknown displacement variables over the beam section axes using Taylor type expansions, trigonometric series, exponential, hyperbolic and zig-zag functions, many new displacement fields were obtained and, for the first time, evaluated for the dynamic analyses of composite structures. The finite element method is used to derive governing equations in weak form. These equations are written using the unified formulation introduced by the first author, in terms of fundamental nuclei, whose forms do not depend on the expansions used. The natural frequencies are compared with results available in the literature or with those obtained by the finite element models related to commercial software. A number of analyses were conducted to compare various theories, including Euler–Bernoulli and Timoshenko models. The advantages/disadvantages of using the different theories are discussed for significant problems related to laminated beams as well as thin-walled boxes. It is shown that refined kinematic theories are able to yield a very accurate evaluation of fundamental as well as higher mode frequencies in a way comparable to three-dimensional analysis, but it is obtained with a strong reduction of computational costs.

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ABSTRACT: This study examines the parametric effects of core density, core thickness, face-sheet stacking sequence, and indentor diameter on the compressive strength of aluminum honeycomb-core sandwich panels stiffened with eight-ply, quasi-isotropic, graphite/epoxy face sheets. The sandwich panels contained damage at the threshold of visual detectability created through quasi-static indentation with 25.4 mm or 76.2 mm-diameter spherical indentors. During compression-after-indentation testing, failure occurred due to: dent deepening followed by localized, compressive micro-buckling of fibers in the 0° plies; localized buckling of the near-free-surface sub-laminates; or unstable dent growth in the direction lateral to the applied compressive load. Regardless of failure mode or face-sheet type, the compression-after-indentation strength increased with increasing core thickness and with decreasing core density. Additionally, panels containing face sheets with the 0° plies near the mid-plane and 45° angle change between subsequent plies exhibited greater undamaged compressive strength and higher compression-after-indentation strength relative to panels containing 90° angle changes between subsequent plies and 0° plies near the free surface. The compression-after-indentation strength was found to be relatively unaffected by the indentor diameter size and the resulting variations in the face sheet and core damage. These results imply that precise representation of the damage state in models to predict the post-indentation response of sandwich panels may not be necessary in order to make accurate average residual strength predictions.

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ABSTRACT: A composite-antenna-structure covering three bands of global positioning system (1.575 GHz), digital multimedia broadcasting (2.62 GHz) and direct broadcast satellite (11.7–13.5 GHz) was designed and fabricated as a part of the structure surfaces. A new concept of antennas integrated into a composite sandwich structure provides a design that is an electrically and structurally effective multi-functional antenna structure. We designed two types of antennas. One is an annular ring patch antenna for global positioning system and digital multimedia broadcasting. The other is a microstrip patch antenna for direct broadcast satellite. In the design process, the effects of the composites and adhesive films are considered for in the design processes, because structural materials affect the antenna performance. Additionally, the composite-antenna-structure was designed by considering the coupling effect in a strict substrate. The measured results of buckling tests have provided useful information regarding not only the compression behavioral characteristics but also its degradation in electrical performance before and after the test. The experimental results have shown good results for compressive tolerance, though the specimens after compression loading returns to their original shape before failure. Additionally, an acoustic emission system is implemented in the buckling test system to study the inner behavior of the composite-antenna-structure for the reliability of secure mechanical performance. The antenna performance, as measured by the return loss and radiation pattern, remained excellent after the compression tests. These electrical performance results suggest that antennas with composite laminates will function well despite damage.

ABSTRACT: An experimental investigation has been carried out on skin delaminations buckling and growth phenomena in stiffened composite panels subjected to compression loading. Optical fibers have been used to monitor the delamination-related phenomena. The optical fibers have been embedded in the skin close to an artificial delamination following paths with minimum length, satisfying the grating sensor locations and direction requirements and fulfilling specific embedding/integrity constraints. The stiffened panel has been also instrumented with back-to-back strain gauges in skin and stringer locations to acquire additional information on delamination and panel buckling and on delamination growth. Finally, a lock-in thermography inspection activity has been performed at different levels of the applied compressive load to acquire information on the delamination buckling and growth shapes. The performed experimental activity was aimed to study the delamination-related phenomena by comparing experimental data obtained from different sources focusing on delamination growth initiation and delamination growth stability.


ABSTRACT: A numerical study has been carried out on stiffened composite panels under compression, focusing on the delamination-related phenomena. A robust numerical finite elements model has been introduced to simulate the compression behavior of the panel, including the delamination buckling and growth, and to provide reasonable predictions of the strain measurements in the delaminated area. The robustness of the novel approach, which adopts an improved (mesh and time step independent) virtual crack closure technique for the simulation of the delamination propagation, has been demonstrated by comparisons with standard commercial FEM (Finite Element Method) codes results and experimental data. Indeed, the numerical results, in terms of strains and delamination size as a function of the applied load, have been compared to experimental strain gauges readings, embedded optical fibers measurements, and thermography images of the delamination taken at different load steps. Actually, the performed numerical activity contributed to improve the knowledge on delamination-related phenomena in stiffened composite panels, focusing on delamination growth initiation and delamination growth stability, by providing reasonable justifications and interpretations of experimental strain measurements and thermography images.


ABSTRACT: A numerical study has been carried out on stiffened composite panels under compression, focusing on the delamination-related phenomena. A robust numerical finite elements model has been introduced to simulate the compression behavior of the panel, including the delamination buckling and growth, and to provide reasonable predictions of the strain measurements in the delaminated area. The robustness of the novel approach, which adopts an improved (mesh and time step independent) virtual crack closure technique for the simulation of the delamination propagation, has been demonstrated by comparisons with standard commercial FEM (Finite Element Method) codes results and experimental data. Indeed, the numerical results, in terms of strains and delamination size as a function of the applied load, have been compared to experimental strain gauges readings, embedded optical fibers measurements, and thermography images of the delamination taken at different load steps. Actually, the performed numerical activity contributed to improve the knowledge on delamination-related phenomena in stiffened composite panels, focusing on delamination growth initiation and delamination growth stability, by providing reasonable justifications and interpretations of experimental strain measurements and thermography images.
ABSTRACT: The effect of introducing semi-circular shear keys in at the skin-core interface of the composite sandwich panels is illustrated numerically in the current study using ABAQUS software. Particularly, the effect of the shear keys orientation (shear grid), namely ±15°, ±30°, ±45°, ±60° and 90/0°, on the shear response of the sandwich panel is introduced. Composite sandwich panels consisting of polyurethane foam core sandwiched between stiff glass fibre reinforced polymer skins were used, while chopped strand glass fibre impregnated with epoxy resin was utilized for the keys. The nonlinear finite element model was built to capture the shear response and the damage mode of the sandwich panel with the shear grid. The finite element model nominated the model with ±60° grid orientation to be the most sustainable one among the other investigated models. In comparison to the model with shear keys in one direction (uni-axial model), the model with shear grid showed a significant reduction in the shear strength.


ABSTRACT: In this study, buckling behavior of adhesively patch repaired composite plates was investigated experimentally and numerically. Unidirectional carbon/epoxy composite plates with circular cutout were repaired with an adhesively bonded patch. Critical buckling loads of composite plates were researched without cutout, circular cutout, single patch-repaired, and double patch-repaired conditions. In addition to circular hole dimensions, patch length and adhesive thickness were used as geometrical parameters. Numerical study was performed in ANSYS finite element software three dimensionally. As a result, the critical buckling loads of single and double patch-repaired composite plates were increased from 96 and 263 ratios higher than circular-cutout composite plates. The percentile errors between experimental and numerical studies were determined from 2 to 11.5.

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ABSTRACT: A new four-node quadrilateral plate that accounts for shear deformation effect and all couplings from the material anisotropy is developed for laminated composite plates. Lagrangian linear interpolation functions are used to describe the primary variables corresponding to the in-plane displacements, while Hermitian cubic interpolation functions are considered for the transverse displacement. Since the present element is derived based on a refined plate theory that has strong similarity with the classical plate theory, it is capable of modeling both thin and very thick plates without shear locking. The accuracy of the present formulation is verified by comparing the results obtained with those available in the open literature. Numerical results are presented to investigate the effects of thickness ratio, lamination angle and lay-up on the shear deformation and response of laminates.
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ABSTRACT: A combination of experimental, analytical and numerical techniques is used to characterise the shear response of lightweight corrugations based on glass fibre and carbon fibre reinforced epoxy resins. The corrugations were manufactured via a compression moulding procedure in which composite prepregs are cured between two serrated mould halves. The properties of the composite corrugations are compared with those offered by a similar aluminium system. Subsequent mechanical testing was undertaken using an Arcan rig capable of generating a range of loading conditions between pure shear and pure compression. As a result of difficulties in accurately measuring the displacement of the cores under mixed-loading conditions, an analytical model was used to predict the stiffness characteristics of the cores as a function of loading angle. The accuracy of the model was assessed using a finite element analysis. The final part of this investigation focused on fitting the measured values of maximum strength to an appropriate failure criterion. An examination of the corrugated structures during combined compression–shear loading indicated that the composite samples failed as a result of buckling in the strands and in certain cases, delamination between the composite plies. Both the analytical model and the finite element analysis indicated that the stiffness of composite and aluminium cores did not vary significantly with loading angle. An analysis of the strength characteristics of the corrugated cores showed that the aluminium corrugations could be accurately represented using a two-dimensional quadratic failure criterion. In contrast, due to the initiation of delamination within the composite struts, an additional component in the failure criterion was required to accurately capture the response of the composite corrugations.

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ABSTRACT: By a domain decomposition method, free vibration characteristics of laminated orthotropic conical shells resting on Pasternak foundations are analyzed. The conical shell is divided into some conical shell segments in the meridional direction and separated from the geometric boundary and Pasternak foundation; the theoretical model is formulated based on a modified variational functional which includes energy of each conical shell segment, interface potentials (including the boundary potentials) and the energy due to the Pasternak foundation. Numerical comparisons with those published results are made to validate the high accuracy of the present method. The variation of the energy contribution of the shell with different thickness-to-radius ratio, cone angle and fibre orientation against various circumferential wave numbers are presented to help better understand the vibrational characteristics. Moreover, the effects of elastic foundation, boundary condition, stacking sequence and the variations in physical parameters of the shells on the natural frequencies are also investigated.
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ABSTRACT: Hybrid lattice cores for sandwich structures containing both solid struts and polymer foam are a recent option available to designers. These cores benefit from a synergistic effect in which the foam supports the slender struts against buckling in addition to carrying a portion of the applied loads directly. This work will optimize these hybrid cores to minimize unit cell density given compressive and shear strength constraints for a variety of unit cell configurations. An analytical model is developed for prediction of failure using the assumption that the foam is an elastic foundation that supports the struts; however, the unit cells are found to be optimal when no polymer foam is used. With the problem thereby simplified, analytical optimization solutions are derived and studied extensively, revealing qualitative insights about efficient lattice core designs. Optimal strut inclination angle, failure mode, and configuration are plotted against loading, which show that, for the large majority of strength constraints, the lowest unit cell density is achieved with tetrahedral cores whose struts fail in compressive yielding.

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ABSTRACT: This article performs an experimental analysis on the E-glass/polyester and vinylester composite tubes with circular cross-section subjected to the lateral compression loading during the flattening process in three different filling conditions: empty, polyethylene, and polyurethane Teflon-filled. Energy absorption behavior and failure response of the composite tubes during the lateral compression tests in the quasi-static condition are studied. The effects of Teflon-type, Teflon-filling, Teflon wall thickness and length, tube inner diameter, fiber fabric layer, and tube length are investigated on the crashworthiness parameters of lateral load, total absorbed energy, and specific absorbed energy (SAE) of the circular composite tubes. The experiments introduce the cylindrical polyethylene Teflon with the large wall thickness as the appropriate filler into the composite tubes, but the experimental measurements show that filling the tubes by the polyurethane Teflon-filler has undesirable effects on the mechanical behavior of the flattened specimens. Also, according to the flattening tests, it is found that in the polyethylene Teflon-filled specimens, the tubes with the vinylester resin have the higher SAE, compared with the corresponding specimens with the polyester resin.

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ABSTRACT: In this paper, refined one-dimensional beam theories are implemented for the free vibration analysis of laminated beams with compact and thin-walled cross-sections. The proposed models are based on the Carrera Unified Formulation, which was formerly introduced for the analysis of plates and shells and recently extended to beam structures by the first author and his co-workers. Carrera Unified Formulation is a hierarchical modelling technique leading to very accurate and computationally efficient finite element theories. According to the latest developments in the framework of Carrera Unified Formulation, refined beam models are implemented using either Taylor-like or Lagrange-like polynomials in order to expand the unknown kinematic variables on the cross-section of the beam. Equivalent single layer models result from the former approach. On the other hand, if Lagrange polynomials are used, layer-wise models are produced. In this work, a classical one-dimensional finite element formulation along the beam length is used to develop numerical applications. A number of laminated beam structures are analyzed and particular attention is given to laminated box beams with open and closed cross-sections. The frequencies and the mode shapes obtained with the present refined beam elements are compared with solid/shell finite element solutions from the commercial code MSC/Nastran and, when possible, with those found in the literature. The modal assurance criterion is used for model-to-model comparisons so as to demonstrate the enhanced capabilities of the proposed formulation in investigating the free vibration characteristics of both compact and thin-walled box laminated beams.

A Alibeigloo (Department of Mechanical Engineering, Faculty of Engineering, Tarbiat Modares University, Tehran, Iran), “Three-dimensional static and free vibration analysis of laminated cylindrical panel with viscoelastic interfaces”, Journal of Composite Materials, Vol. 49, No. 19, pp 2415-2430, August 2015, https://doi.org/10.1177/0021998314547527

ABSTRACT: In this paper, three-dimensional theory of elasticity is employed to investigate bending and free vibration behavior of simply supported cylindrical panel with special emphasis on incorporating viscoelastic interfacial imperfection. Analysis is carried out by using Fourier series along the axial and circumferential directions and state space technique along the radial direction. Time-dependent behavior is investigated by solving first-order differential equation of sliding displacement at the viscoelastic interfaces. Numerical results depict good agreement between the present numerical results and the available published results. In addition, the effects of solid, elastic and viscous interfaces, time, aspect ratio and mid radius to thickness ratio on the bending and vibration behavior of laminated cylindrical panel are discussed.

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ABSTRACT: Low-velocity dynamic compression tests were carried out to reveal the failure mechanism and the energy absorption capacity of multilayered woven lattice sandwich panels. Dynamic compression coupled with
shear deformation results in typical softening deformation after the peak stress. The load–displacement curve is characterized by a long zigzag deformation. Multilayered woven lattice sandwich panels have deformation characteristics of type II structure. Compared with the quasi-static compressed panel, the impacted woven textile sandwich has similar failure mode but excellent energy absorption induced by greater dynamic strength. Strain rate effect of the structure was explained by dynamic buckling theory. Gradient structure, placing the hardest layer as the first impacted layer and the weakest as the last, has great benefits in terms of energy absorption efficiency and should be ideal to serve as an energy-absorbing structure.

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ABSTRACT: In this paper, the influence of foam filling of aluminum honeycomb core on its in-plane crushing properties is investigated. An aluminum honeycomb core and a polyurethane foam with densities of 65, 90, and 145 kg/m³ were used to produce foam filled honeycomb panels, and then experimental quasi-static compression tests were performed. Moreover, finite element model, based on the conducted tests, was developed. In the finite element analyses, three different polyurethane foams were used to fill three different honeycomb cores. The effects of foam filling of aluminum honeycomb core on its in-plane mechanical properties (such as mean crushing strength, absorbed energy, and specific absorbed energy) were analyzed experimentally and numerically. The results showed that the foam filling of honeycomb core can increase the in plane crushing strength up to 208 times, and its specific absorbed energy up to 20 times. However, it was found that the effect of foam filling decreases in heavier honeycombs, producing an increment of the above mentioned properties only up to 36 and 6 times, respectively.

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ABSTRACT: Composite structures such as hull of a ship and wings of aircraft are subjected to compressive loading. The behavior and strength of carbon fiber-reinforced polymer (CFRP) panels subjected to tensile loading has been studied rigorously by various researchers, whereas compressive behavior is not well addressed. In this study, behavior of CFRP panel with multiple interacting holes of various configurations (1H, 2HL, 2HT, and 2HD) under compressive loading is studied. A three-dimensional finite element-based progressive failure analysis (PFA) is used to model the damage progression in CFRP laminates. Damage detection is carried out using both Hashin’s failure and Ye’s-delamination criterions. Using these failure criterions, failure and post failure behavior of CFRP laminate with cutouts are predicted. The material is assumed to behave as linear elastic until final failure. Sudden degradation rule of material property is employed and subsequently PFA is carried out successively. Using digital image correlation (DIC) technique, whole field surface strain is obtained experimentally and is used for validating finite element analysis (FEA) model. Load–
deflection behavior as well as path of damage progression is predicted by both PFA simulation and experiment. They are found to be in good agreement thereby confirming the accuracy of PFA implementation. Among all the configurations, one with two holes along the longitudinal direction (2HL) is recommended for design application as it exhibits low stress concentration factor and sustains higher initiation and final failure load.

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ABSTRACT: While conventional design and manufacturing techniques of fiber-reinforced laminates keep the fiber orientation angle constant within a layer, automated tow-placement technology allows fabricating laminates with curved fibers. This offers more flexibility to tailor the mechanical properties and improve the performance of laminated structures. Exploiting this flexibility requires an efficient method for finding optimal or near-optimal fiber configurations. In this paper, laminated cylindrical shells are studied. Curvilinear variations for the fiber orientations are adopted in the circumferential and longitudinal directions. The computational burden, typical in numerical optimization of complex structures, is reduced using a Kriging model, which substitutes for direct finite element simulation. A sequential quadratic programming algorithm is employed as local optimizer, coupled with a restart strategy to search for the global optimum in the entire design space. Some numerical cases are presented: the maximization of the fundamental frequency of the shell considering different boundary conditions and the minimization of the maximum displacement with a constraint on the buckling load.

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ABSTRACT: Three-dimensionally woven E- and S2-glass fiber textiles have been used in the past to create delamination-resistant corrugated core sandwich panels. During subsequent out-of-plane loading, the E-glass composite core struts and S2-glass composite faces are subjected to either compressive or tension loads. This study has investigated the relationships between the three-dimensional fiber architecture, fiber properties and the mechanical response of representative samples of the core and faces. Using X-ray computed tomography and optical microscopy to characterize the three-dimensional fiber architectures, it is found that the in-plane warp and weft fibers suffer significant off-axis displacement (waviness) due to their interaction with through thickness z-fiber tows. The consequence of this fiber waviness on the relationships of the in-plane tensile and compressive mechanical properties, along with fiber type, fiber volume fraction, and strut aspect ratio are experimentally investigated. The large initial misalignment angle of the warp and weft fiber tows results in a strut compressive strength that is substantially lower than its tensile strength due to compressive failure by either elastic or localized fiber microbuckling. Simple micromechanical models are used to relate the
compressive strength of the three-dimensional woven composite struts to strut aspect ratio, fiber volume fractions in the three directions and the three-dimensional fiber architecture.


ABSTRACT: The effect of configuration of quasi-unidirectional woven fabric on the compressive failure modes of quasi-isotropic composite laminates was investigated in this study. Two kinds of out-of-plane fiber waviness were formed in the composite laminates due to different quasi-unidirectional woven fabrics and measured using a fast Fourier transform method. The compressive failure modes of the composite laminates were identified using experimental and numerical methods. It was found that the compressive strength of a composite laminate fabricated using long-pitch weft fabrics was greater than that fabricated using standard-pitch weft fabrics. The relationship between the compressive strength and the configuration of quasi-unidirectional woven fabrics was investigated in a parametrical study, and four compressive failure modes were found: the axial compressive, normal, bending, and shear failure modes.

References listed at the end of the paper:


ABSTRACT: Thermal bifurcation behavior of cross-ply laminated composite cylindrical shells embedded with shape memory alloy fibers is investigated. Properties of the constituents are assumed to be temperature-dependent. Donnell's kinematic assumptions accompanied with the von-Karman type of geometrical nonlinearity are used to derive the governing equations of the shell. Furthermore, the one-dimensional constitutive law of Brinson is used to predict the behavior of shape memory alloy fibers through the heating process. Governing equilibrium equations are established by employing the static version of virtual displacements principle. Linear membrane pre-buckling analysis is performed to extract the pre-buckling deformations of the shell. Applying the well-known adjacent equilibrium criterion to the pre-buckling state of the shell, stability equations are derived. The governing equations are solved via a semi-analytical solution employing the exact trigonometric function in circumferential direction and the harmonic differential quadrature method in the longitudinal direction. Numerical results cover various cases of edge supports, cross-ply lamination, shape memory alloy fibers volume fraction and shape memory alloy fiber pre-strain. It is shown that, proper usage of shape memory alloy fibers results in considerable delay of the thermal bifurcation type of buckling.

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ABSTRACT: An experimental study of damage tolerance under quasi-static indentation (QSI) was performed for sandwich composite panels consisting of 16-ply carbon–epoxy facesheets bonded to an aluminum honeycomb core. To determine how indentation damage and compression strength after indentation depend on the facesheet layup, three facesheet stacking sequences were used, varying the maximum ply angle change and placement of the outermost 0° ply. Similarly, to determine the effect of core parameters on damage and strength following indentation, three cores with varying density and thickness were studied. Specimens were indented in QSI to the barely visible indentation damage threshold by spherical indenters of 25.4 or 76.2 mm diameters. Damaged specimens were tested to failure in compression to determine the post-indentation compressive strength and resulting failure mode. Compression-after-indentation (CAI) strength is compared to the undamaged strength obtained from edgewise-compression tests of specimens with the same geometry type. Three distinct failure modes were observed in the CAI experiments: compressive fiber failure, delamination buckling and global instability. Post-indentation compressive strength was independent of indenter size and there was no clear propensity for a particular failure mode dependent on a given specimen geometry. Specimens
with a high core density and facesheets with a primary ply angle change of 90° were found to be the most damage resistant. Specimens with facesheets having the outer 0° plies closest to the center of the laminate were found to be the most damage tolerant.

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ABSTRACT: Two finite element models are used to investigate the behavior of aluminum/silicon carbide thin-film layered composites with imperfect internal geometry when subjected to various loadings. In both models, undulating layers are represented by regular waveforms with various amplitudes, wavelengths, and phase offsets. First, uniaxial compressive loading of the composite is considered. The modulus and stress/strain response of the composite is sensitive to both loading direction and frequency of the undulation. Second, the nanoindentation response of the composite is investigated. The derived hardness and modulus are shown to be sensitive to the presence of undulating layers and the relative size of the indenter to the undulation. Undulating layers create bands of tensile and compressive stress in the indentation direction that are significantly different from the flat layers. The amount of equivalent plastic strain in the Al layers is increased by the presence of undulating layers. The correlations between the two forms of loading, and the implications to composite property measurement are carefully examined in this study.


ABSTRACT: This work presents an experimental characterization of the curvature effects on the compression-after-impact strength of laminated composite shells. Curved panels impacted on the outer (convex) face and with normal pressure on the inner (concave) face with three different curvatures at three different impact energy levels were tested. A compression-after-impact testing setup was designed and implemented to evaluate the impact-induced damage tolerance of the composite shells. An analytical modeling methodology for compression-after-impact strength predictions based on the Mar-Lin and Whitney-Nuismer failure criteria is also proposed. The approach proposed herein consists of replacing the damaged area of the impacted coupon by an equivalent hole. The analytical compression-after-impact predictions obtained using the Mar-Lin and Whitney-Nuismer failure criteria were compared with experimental results. A good agreement between analytical predictions and experimental results was found. The experimental results also indicate that the compressive residual strength of the composite shells is significantly affected by the shell curvature and internal pressure effects.

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ABSTRACT: In the present article, the variational energy principle and the Griffith-type fracture criterion are implemented to analyze the speed of through-the-width delamination growth of a buckled composite laminate with clamped edges, subjected to in-plane strains. The inertial effect has been included in the total energy equation. The formulations are based on the first-order shear deformation theory, and the thin film delamination model has been considered. By implementing the local growth condition at the crack tip, the governing equations are obtained through variational principle. The equations are then solved using fourth-order Runge–Kutta method. Subsequently, the results of current study have been compared with those available in the literature. The effects of shear deformation theory and bending extension coupling have been investigated and discussed for different non-dimensional load-geometry parameters.


ABSTRACT: A new kind of higher order analysis model is presented for sandwich plates with flexible core, especially “soft” core. The governing equations derived from equilibrium differential equations of motions are analytically solved for simply supported sandwich plate with a flexible core. The Navier-type solutions for free vibration analysis and static bending are presented for sinusoidal and uniformly distributed loads. The accuracy and convergence of the present theory and solution are ascertained by comparing with various available results, the author considered vary of length-to-width ratios, Young’s modulus ratios between skins and core, thickness ratios between skins and core, and span-to-thickness of sandwich plates. The results show that the present theory can achieve the great accuracy for sandwich plate with flexible core by comparing with existing classical plate theory, first-order shear deformation, higher order shear deformation theory, and finite element software ANSYS.


ABSTRACT: This paper investigates the blast response of a glass fiber reinforced polymer pipeline using explicit finite element analysis. In this study, a fluid-structure interaction methodology was employed to obtain the deformation and damage of pipeline under explosive impact using LS-DYNA. The purpose of this research is to evaluate the influence of the stand-off distance, the tube diameter, the internal pressure of tube and the explosive quantity on dynamic response of composite pipe. Simulations were carried out not only in the case of empty pipe but also in the case of water-filled pipe with different internal pressures. The analysis was performed in two phases; initialization phase, where the pressurization and gravity loads are applied on the pipeline, and the blast phase. Comparing the analysis results, it was proved that the internal pressure influences significantly the deformation of the tube. The results of the present study can serve as a reference guide for the prediction of pipe response under blast loading, since no guidelines exist in pipeline standards for design under blast loading conditions.
References listed at the end of the paper:

10. Lawson A and Hobart L. Glass reinforced plastic (GRP) in the design of a bore water transfer system. Parsons Brinckerhoff, Adelaide, SA.

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ABSTRACT: The metallic airplane structure fuselage design is characterized by skin, frames, stiffeners, and attachments. In most airplanes, the attachments between these components are made by rivets. The influence of the attachments in the panel behavior under diagonal tension can be verified in the metallic Wagner beam. For stiffened composite panels, like metallic Wagner beams, there is insufficient data about attachment design. In order to design and build lightweight composite structures, the analyst must consider different ways in which the skin is connected to the stiffeners and frames. Therefore, the objective of this paper is to investigate different conceptions of a real-reinforced composite panel used in the aeronautical industry. Experimental and numerical results for strains showed good agreement. The finite element model and the criteria used in the failure analysis are also presented. Comparisons between different panel configurations are made, and conclusions are drawn about attachment efficiency.


ABSTRACT: An experimental study on the underwater collapse of composite tubes with polymeric coatings is conducted in an attempt to mitigate the implosion pressure pulse released. Experiments are performed in a pressure vessel designed to provide constant hydrostatic pressure during collapse. Filament-wound carbon-fiber/epoxy tubes are studied with polyurea coatings of different thicknesses on the interior and exterior of the tube to explore the effects of these configurations on implosion pulse mitigation. 3-D Digital Image Correlation (DIC) technique is used to capture the full-field deformation and velocities during the implosion event. Local pressure fields generated by the implosion event are measured using dynamic pressure transducers to evaluate the strength of the emitted pressure pulses. Local pressure data and DIC results are used to obtain a measure of normalized energy released during implosion. Results show that thick interior coatings significantly reduce the energy released in the pressure pulse by slowing the collapse and softening the initial wall-to-wall contact. In contrast, thick exterior coatings increase this energy by suppressing damage, thereby reducing the energy absorption capacity of the structure.


ABSTRACT: This paper reports the compressive behaviors of three-dimensional four-directional and three-dimensional five-directional circular braided composite tubes subjected to quasi-static and impact compressions along longitudinal direction. The compression tests of the three-dimensional four-directional and three-dimensional five-directional carbon fiber/epoxy circular braided composite tubes were tested under strain rates ranging from 0.001 to 884 s⁻¹. The compression stress–strain curves were obtained and the damage morphologies were observed to analyze the damage behaviors. A microstructure model of the braided preform and the braided composite tube was established to calculate the compressive deformation and damage
mechanisms with finite element method. The stress–strain curves, specific energy absorption, deformations, and damage morphologies were sensitive to the strain rate and the braiding structures. The three-dimensional five-directional braided composite tubes have higher compressive strength and specific energy absorptions than the three-dimensional four-directional braided composite tubes.


Many papers published in the journal, Experimental Mechanics (2012-2016):
Google the string: “Experimental Mechanics”, then click on the first entry, “Experimental Mechanics – Springer”, then, on the resulting screen, click on “All Volumes & Issues” (located on the right-hand side of the screen near the top, in blue color)


PAPER:
Sandwich panels made of stiff face sheets and compliant low density core materials result in high stiffness lightweight structures. Over the last few years, the science and technology of sandwich structures and materials has gained an impressive momentum, and the use of such structures and materials in a variety of products covering the range from sporting goods to satellites is on the increase. There is a lot of interest in sandwich structures particularly in applications related to aerospace, energy, and marine technologies. Advances in materials processing and fabrication techniques including digital manufacturing are leading to novel applications. As the range of applications expands, particularly in the area of marine structures such as high speed craft and structures resistant to blast loading, there is increased need to understand the behavior of sandwich structures under a wide range of loading conditions and environments. This poses special challenges to experimental mechanics in characterizing the loading and deformation and failure response of sandwich structures. The International Conference on Sandwich Structures has served as a premier venue over the last two decades for periodically bringing together researchers to discuss progress in this area. The 9th International Conference on Sandwich Structures (ICSS-9) sponsored by the Office of Naval Research, was held on the campus of the California Institute of Technology (Caltech), Pasadena, California, July, 2010. The overall objective of the ICSS-9 was to provide a forum for the presentation and discussion of the latest research and technology on all aspects of sandwich structures and materials. The conference covered a wide range of topics including dynamic effects, experimental aspects, modeling and simulation, fracture, fatigue, instabilities, materials, processing, manufacturing, and applications of sandwich structures. The global interest in these topics was reflected in participation of more than 120 researchers from 20 countries. The papers in this volume represent leading contributions from presentations at ICSS-9 with emphasis on experimental mechanics of marine sandwich structures. The papers are organized into topical areas of mechanical properties, impact damage, air and underwater blast performance, and hull slamming of sandwich structures.

The characterization of mechanical properties of sandwich structures poses special challenges due to their heterogeneity and considerable mismatch in properties between core and face sheet. Furthermore, sandwich structures are finding increasing applications in the sea water environment and extremes of low and high temperatures. There is also a critical need for knowledge of properties for design and analysis of applications
employing sandwich structures. Zhang, Dulieu-Barton, Fruehmann, and Thomsen discuss a new methodology using digital image correlation (DIC) for measuring material properties of polymeric foam core materials at elevated temperatures. They have focused on measuring the compressive and tensile moduli and Poisson’s ratio of the foam in an accurate manner by correcting for the non-uniform strain distribution across the specimen. Aviles, Carlsson, and May-Pat present a shear-corrected formulation for the sandwich twist specimen and have validated this new approach using experiments. This approach accounts for the shear stiffness of the core and is especially important for low density cores. Siriruk, Penumadu, and Sharma present a detailed study of the combined effect of seawater and low temperatures on the behavior of foam cores and overall behavior of sandwich structures. They provide an extensive study of the fracture behavior under complex loading conditions and harsh environmental conditions.

Sandwich structures can experience low velocity impact both during manufacturing of marine craft and during service. It is imperative to characterize and develop models to predict the damage caused by such impact. Daniel, Abot, Schubel, and Luo provide a comprehensive assessment and review of damage tolerance of composite sandwich structures with various core materials subjected to low velocity impact. They use spring-mass and energy balance models to compare with the experimental measurements and finite element simulations to capture the full response of the panel indentation. The high speed naval marine craft can be subjected to air blast and underwater explosive loading. Relatively little is known concerning the blast resistance of sandwich structures and effective strategies to mitigate the blast effects. Shukla and Wang discuss the performance of pre-compressed sandwich panels subjected to blast loading. They use a shock tube to generate blast loading, and 3D DIC and high speed photography to measure the transient deformation of the deforming sandwich structures. Arora, Hooper, and Dear present detailed methodologies for studying the dynamic structural response of sandwich structures and composite tubes. They have conducted field experiments together with high speed instrumentation to study the effects of air blast and underwater explosive loading. They use DIC and high speed photography to obtain the 3D transient response of large panels of sandwich structures subjected to air blast. Avachat and Zhou analyze the response of sandwich structures subjected to underwater blast loading. They provide insights to the effect of various material parameters on energy dissipation and transient deformation, which could lead to optimization of structural design.

High speed marine craft made of sandwich structures are subjected to highly transient periodic loading in the form of hull slamming and infrequent high amplitude wave impact. Battley and Allen present a novel method for studying slamming of sandwich panels on water. They have developed an instrumented servo-hydraulic machine for studying the interaction due to the impact of the hull of a marine craft on water surface. They provide insights regarding the response of sandwich panels under hull slamming conditions. Silva and Ravichandran discuss the development of a mechanical slamming simulator for emulating the loading due to hull slamming. They describe the use of simultaneous DIC and infrared thermography to study damage evolution in sandwich structures under repeated hull slamming using thermoelastic stress analysis.


ABSTRACT: The deformation and failure response of composite sandwich beams and panels under low velocity impact was reviewed and discussed. Sandwich facesheet materials discussed are unidirectional and woven carbon/epoxy, and woven glass/vinylester composite laminates; sandwich core materials investigated include four types of closed cell PVC foams of various densities, and balsa wood. Sandwich beams were tested in an instrumented drop tower system under various energy levels, where load and strain histories and failure
modes were recorded for the various types of beams. Peak loads predicted by spring-mass and energy balance models were in satisfactory agreement with experimental measurements. Failure patterns depend strongly on the impact energy levels and core properties. Failure modes observed include core indentation/cracking, facesheet buckling, delamination within the facesheet, and debonding between the facesheet and core. In the case of sandwich panels, it was shown that static and impact loads of the same magnitude produce very similar far-field deformations. The induced damage is localized and is lower for impact loading than for an equivalent static loading. The load history, predicted by a model based on the sinusoidal shape of the impact load pulse, was in agreement with experimental results. A finite element model was implemented to capture the full response of the panel indentation. The investigation of post impact behavior of sandwich structures shows that, although impact damage may not be readily visible, its effects on the residual mechanical properties of the structure can be quite detrimental.

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ABSTRACT: An experimental investigation was conducted to evaluate the dynamic performance of E-glass Vinyl Ester composite face sheet / foam core sandwich panels when subjected to pre-compression and subsequent blast loading. The sandwich panels were subjected to 0 kN, 15 kN and 25 kN of in plane compression respectively, prior to transverse blast wave loading with peak incident pressure of 1 MPa and velocity of 3 Mach. The blast loading was generated using a shock tube facility. During the experiments, a high-speed photographic system utilizing three digital cameras was used to acquire the real-time 3-D deformation of the sandwich panels. The 3D Digital Image Correlation (DIC) technique was used to quantify the back face out-of-plane deflection and in-plane strain. The results showed that in-plane compressive loading facilitated buckling and failure in the front face sheet. This mechanism greatly reduced the blast resistance of sandwich composites.

References listed at the end of the paper:


ABSTRACT: The resistance of glass-fibre reinforced polymer (GFRP) sandwich panels and laminate tubes to blast in air and underwater environments has been studied. Procedures for monitoring the structural response of such materials during blast events have been devised. High-speed photography was employed during the air-blast loading of GFRP sandwich panels, in conjunction with digital image correlation (DIC), to monitor the deformation of these structures under shock loading. Failure mechanisms have been revealed by using DIC and confirmed in post-test sectioning. Strain gauges were used to monitor the structural response of similar sandwich materials and GFRP tubular laminates during underwater shocks. The effect of the backing medium (air or water) of the target facing the shock has been identified during these studies. Mechanisms of failure have been established such as core crushing, skin/core cracking, delamination and fibre breakage. Strain gauge data supported the mechanisms for such damage. These studies were part of a research programme sponsored by the Office of Naval Research (ONR) investigating blast loading of composite naval structures. The full-scale experimental results presented here will aid and assist in the development of analytical and computational models. Furthermore, it highlights the importance of support and boundary conditions with regards to blast resistant design.


ABSTRACT: The response of sandwich structures to underwater blast loading is analyzed. The analysis focuses on the effect of varying structural attributes on energy dissipation and deformation. The structures analyzed are...
planar sandwich plates with polymer foam cores and fiber-reinforced polymer composite facesheets. The thickness of the facesheets is varied under the conditions of constant material properties and core dimensions. The fully three-dimensional finite-element simulations carried out account for underwater blast loading through the use of the Mie-Gruneisen equation-of-state of a linear Hugoniot form and a modified Drucker-Prager core crushing model. The impulse imparted to the panels is varied from 4 to 42 kPa·s. The results show that there exists an optimal thickness of the facesheets which maximizes energy absorption in the core and minimizes the overall deflection of the structure.


ABSTRACT: Slamming, the impact between a marine craft’s hull and the water surface is a critical load case for structural design of marine vessels. The importance of hull slamming has led to a significant body of work to understand, predict and model these impacts. There is however, a lack of experimental data for validation, particularly for deformable panels and sandwich structures. This paper describes a high-velocity panel slamming test system that enables the generation of comprehensive and reliable experimental data on slamming impacts for both rigid and flexible panel structures. The pressure magnitudes, time-histories and spatial distributions resulting from testing of a nominally rigid panel have been compared with previous analytical, semi-empirical and experimental studies. Slamming impacts of a deformable sandwich panel are shown to cause different pressures to those from a rigid panel impact, resulting in increased transverse shear loading at the panel edge.


ABSTRACT: The effect of repeated loading from mechanically simulated hull slamming on foam core sandwich composites was investigated utilizing a novel technique that simultaneously measured temperature and displacement while cyclic loading occurred. Thermoelastic Stress Analysis (TSA) and Digital Image Correlation (DIC) techniques were combined using a single infrared camera for characterization of the foam core. Improved stress fields with TSA results were found through deformation compensation. Initial work approximating hull slamming conditions mechanically utilizing a custom device were performed. Mechanically loading offers several benefits over water impact investigations, including easy access to the sample during the slamming event, an unobstructed optical path, and accelerated testing. Evolving stress fields under long-duration, repeated simulated hull slamming loading were observed around a growing delamination crack between the foam core and skin.


ABSTRACT: The dynamic behavior of two types of sandwich composites made of E-Glass Vinyl-Ester (EVE) facesheets and Corecell™ A-series foam with a polyurea interlayer was studied using a shock tube apparatus. The materials, as well as the core layer arrangements, were identical, with the only difference arising in the location of the polyurea interlayer. The foam core itself was layered with monotonically increasing wave
impedance of the core layers, with the lowest wave impedance facing the shock loading. For configuration 1, the polyurea interlayer was placed behind the front facesheet, in front of the foam core, while in configuration 2 it was placed behind the foam core, in front of the back facesheet. A high-speed side-view camera, along with a high-speed back-view 3-D Digital Image Correlation (DIC) system, was utilized to capture the real time deformation process as well as mechanisms of failure. Post mortem analysis was also carried out to evaluate the overall blast performance of these two configurations. The results indicated that applying polyurea behind the foam core and in front of the back facesheet will reduce the back face deflection, particle velocity, and in-plane strain, thus improving the overall blast performance and maintaining structural integrity.


ABSTRACT: To characterize the materials parameters and deformation of a convex shell of axial symmetry, a hydrogel contact lens is mechanically deformed by two loading configurations: (a) compression between two parallel plates and (b) central load applied by a shaft with a spherical tip. A universal testing machine with nano-Newton and submicron resolutions is used to measure the applied force, \( F \), as a function of vertical displacement of the plate/shaft, \( w_0 \), while a homemade laser aided topography system records the in-situ deformed shell profile and the contact radius or central dimple, \( a \). A nonlinear shell theory and an iterative finite difference method are used to account for the large elastic deformation, the central buckling for the central load compression, and the interrelationship between the measureable quantities \( (F, w_0, a) \).

References listed at the end of the paper:

Experimental and numerical crashworthiness investigation of empty and foam-filled thin-walled tubes and shallow spherical caps, Experimental Mechanics, Vol. 54, No. 2, pp 115-126, February 2014
ABSTRACT: Thin-walled structures have been extensively used as energy absorbers in crashworthiness applications such as automobile and aeronautical industries to protect passengers from severe injury. This paper investigates the energy absorption responses of empty and foam-filled cylindrical and conical tubes with shallow spherical caps under quasi-static axial loading. Nonlinear dynamic finite element analyses are carried out to investigate the details concerning crushing process. Satisfactory agreements are achieved between the finite element and the experimental results. The numerical and experimental results highlight several effects of foam filling on the crushing behavior of the thin-walled tubes. Finally, the effect of semi-apical angle on the crushing behavior of the empty and foam-filled tubes with shallow spherical caps is investigated. This study provides practical information about using thin-walled tubes with shallow spherical caps as energy absorbers in aerospace applications in order to design reentry sounding rocket based on foam-filled tube with shallow spherical caps.

References listed at the end of the paper:

ABSTRACT: Measurements are presented on the oblique impact of a hollow rubber ball incident on a polished granite surface, and the results are compared with those for a solid rubber superball. The hollow ball had a much higher coefficient of sliding friction than the superball, resulting in significant differences in all bounce parameters, at all angles of incidence. The hollow ball gripped the surface at all observed angles of incidence, resulting in one or two reversals in the direction of the friction force during the impact. The friction force was measured directly, as was the rotation speed of the ball during the impact. The results show that the tangential coefficient of restitution of a ball depends on both the coefficient of sliding friction and the ratio of the tangential to the normal vibration frequency of the ball.

References listed at the end of the paper:

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ABSTRACT: In this paper, we propose a multi-pulsed double exposure (MPDE) acquisition method to quantify in full-field-of-view the transient (i.e., >10 kHz) acoustically induced nanometer scale displacements of the human tympanic membrane (TM or eardrum). The method takes advantage of the geometrical linearity and repeatability of the TM displacements to enable high-speed measurements with a conventional camera (i.e., <20 fps). The MPDE is implemented on a previously developed digital holographic system (DHS) to enhance its measurement capabilities, at a minimum cost, while avoiding constraints imposed by the spatial resolutions and dimensions of high-speed (i.e., >50 kfps) cameras. To our knowledge, there is currently no existing system to provide such capabilities for the study of the human TM. The combination of high temporal (i.e., >50 kHz) and spatial (i.e., >500 k data points) resolutions enables measurements of the temporal and frequency response of all points across the surface of the TM simultaneously. The repeatability and accuracy of the MPDE method are verified against a Laser Doppler Vibrometer (LDV) on both artificial membranes and ex-vivo human TMs that are acoustically excited with a sharp (i.e., <100 μs duration) click. The measuring capabilities of the DHS, enhanced by the MPDE acquisition method, allow for quantification of spatially dependent motion parameters of the TM, such as modal frequencies, time constants, as well as inferring local material properties.

ABSTRACT: This paper proposes a new damage detection method for cylindrical shell structures based on the frequency shift induced by an auxiliary mass. The natural frequency of a cylindrical shell changes when an auxiliary mass is placed at different positions on its surface. In fact, when the auxiliary mass is approaching the damage resulting in a decrease of local stiffness, the natural frequencies will drop drastically. This is because the auxiliary mass increases the local mass. That is, the auxiliary mass can enhance the influence of the damage on the dynamic characteristics of the cylindrical shell, and therefore, it can be used to probe the damage by traversing it over the entire surface of the cylindrical shell. On the other hand, the sudden drop of natural frequencies induced by the auxiliary mass approaching the damage can be considered as an anomaly since the frequencies usually change smoothly under the assumption that intact cylindrical shell is homogeneous and smooth. To detect the anomaly, a new damage index is proposed based on the curvature of frequency shift, which only uses the information from the damaged cylindrical shell. The proposed method is then tested on a
damaged CNG cylinder; it demonstrates that it is more accurate and sensitive compared to other traditional vibration based damage detection methods which depend on mode shape instead.

N.S. Ha, H.M. Vang and N.S. Goo (Smart Microsystems Research Lab, Division of Interdisciplinary Studies, Konkuk University, Gwangjin-gu, Korea), “Modal analysis using digital image correlation technique: An application to artificial wing mimicking beetle’s hind wing”, Experimental Mechanics, Vol. 55, No. 5, pp 989-998, June 2015

**ABSTRACT:** Understanding the dynamic behavior of structures has become increasingly important in the design process of any mechanical system. Therefore, the demands for improved structural performance have motivated the search for an effective method of structural dynamics testing, since the conventional methods are limited to the location of relatively few applied sensors. Due to the state-of-the-art optical technologies, the shape and deformation of a vibrating structure have been measured using 3-dimensional digital image correlation (DIC) technique. Although DIC has been used widely to construct the mode shape of the structure in modal measurement, it has rarely been applied to determine the full modal parameters (natural frequencies, mode shapes, damping factors). Therefore, this study presents an effective method to measure the full modal parameters of an artificial wing that mimics a beetle’s hind wing using the DIC technique. In our measurement, the artificial wing was mounted on a shaker, which was vibrated with a white noise signal. The full-field result as well as the displacement of a single point on the wing over time was then obtained using ARAMIS® software, a DIC technique-based software. From the temporal displacement of a single point signal in the time domain, we performed fast Fourier transform to obtain the frequency response function (FRF). The spectrum averaging technique and Savitzky-Golay filter were used to reduce the noise. Also, the natural frequencies and damping factors were determined from smoothed FRF. Finally, the mode shapes were measured using DIC at the pre-measured natural frequency.


**ABSTRACT:** In recent years, vulnerability against high-speed impact loadings has become an increasingly critical issue in the design of fluid-filled structures. The initial shock waves caused by high-speed impacts were investigated experimentally in this paper. The $600 \times 310 \times 310$ mm water-filled tank with aluminum targets were subjected to impact by projectiles at impact velocity $50 \sim 350$ m/s. Five different nosed projectiles and targets with different thicknesses were considered to study how the strength and decayed characteristics of the initial shock waves were influenced by those factors. In order to compare the pressure time history which was recorded by the pressure transducers positioned in the tank with different distributions, the visualized propagation of shock waves was monitored by a new technique. The failure modes of the targets were investigated to provide the assessment on the shock resistance of metal tanks by comparing with air-back impact tests. This work presents the results of these tests.

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ABSTRACT: This paper is an experimental investigation of the crashworthiness behavior of functionally graded thickness (FGT) thin-walled tubular structures. Aluminum alloy AA6061-T5 was chosen because of its high strength to weight ratio and high stiffness. A series of FGT tubes with thicknesses varying linearly from one end to the other were evaluated in quasi-static crushing and three- and four-point bending tests for the purpose of evaluating their energy absorption characteristics. AA6061-T5 FGT tubes with four thickness distributions were considered, namely: $t_{\text{top}} = 0.6, 0.8, 1.0, 1.2 \text{ mm}$, $t_{\text{bottom}} = 1.5 \text{ mm}$. Specific energy absorption (SEA) and crush force efficiency (CFE) under maximum deformed displacement ($\delta_{\text{max}}$) were measured from the tests to infer crashworthiness of the FGT tubes. It was found that the FGT tubes exhibit superior performance relative to a uniform thickness (UT) counterpart especially at the highest displacements and deformed more stably in overall crushing behaviors or collapsed modes. For example, the CFE of the AA6061-T5 FGT tube with $t_{\text{top}} = 0.6 \text{ mm}$ at $\delta = 80 \text{ mm}$ was ~105 %; however, that for an AA6061-T5 UT counterpart with a 1.5 mm thickness tube is only 62 %. This suggests the possibility that crash energy absorption management in ground transportation vehicles may be enhanced through the use of the FGT tube designs.

References listed at the end of the paper:

ABSTRACT: This work presents a comprehensive set of experimental results on the water entry of compliant cylindrical shells. Free fall experiments are conducted on a flexible thin cylinder varying the drop height. The problem studied here is not representative of a free cylinder as this is held by a sledge, which acts as a concentrated mass. The impact dynamics is analyzed from accelerometers, linear position sensors, and through the analysis of high speed images. Further, an experimental methodology based on the modal decomposition method is developed and utilized to reconstruct the overall structural deformation and the distributed strain field on the base of local strain measurements. Fiber Bragg gratings are utilized for this purpose. Results show that the flexibility of the structure plays an important role on the impact dynamics, which is found to completely differ from the impact of rigid structures. The overall deformation of the shell follows the first mode shape of vibration of a free ring, while the stresses are influenced by the superposition of the higher mode shapes that are excited during the impact.

References listed at the end of the paper:
ABSTRACT: Geometric imperfections play an important role in the strength and behavior of thin-walled metal parts such as those commonly used in cold-formed steel construction. The objective of this paper is to detail a newly developed imperfection measurement platform, where the full three-dimensional (3D) imperfect geometry of a cold-formed steel member can be measured and reconstructed with reasonably high throughput and sufficient accuracy to explore all relevant imperfections. The measurement platform is composed of a two-dimensional laser sensor mounted on rotary and linear stages. Specimens are placed within a rotary ring and along a reference beam. The linear stage provides a means to scan the length of the specimen and the rotary stage a means to scan from any angle. Control of the custom linear and rotary stages are detailed in the paper, and corresponding control accuracies are studied. A procedure for registering the individual scans into the complete 3D model reconstruction (point cloud) is provided by specific calibration tests, from which rotation and translation quantities can be found to transform surfaces measured in local coordinates to a universal global coordinate system. A variety of different imperfection quantities, from basic dimensions and out-of-plane deviations to more advanced spectral and modal-based imperfection magnitudes may be rapidly processed from the 3D model. Accurate understanding of geometric imperfections is critical to the long-term success of cold-formed steel structures.
analysis-based design paradigms for cold-formed steel constructions. The apparatus detailed herein will be used to provide a broad suite of imperfection information to assist in these new efforts.

References listed at the end of the paper:
18. Young B (1997) The behavior and design of cold-formed channel columns. Dissertation, University of Sydney
23. Zhao X, Schafer BW (2014) Laser scanning to develop three-dimensional fields for the precise geometry of cold-formed steel members. In Recent Research and Developments in Cold-Formed Steel Design and Construction, St. Louis


ABSTRACT: A comprehensive investigation on the implosion of composite cylinders subjected to a nearby explosion is performed. Experiments are conducted in a large pressure vessel, designed to provide constant hydrostatic pressure throughout the event. Carbon fiber/epoxy filament-wound tubes are studied with constant hydrostatic pressure and varying charge standoff distances to determine the effect of the explosive loading on the mechanisms of collapse. 3-D Digital Image Correlation (DIC) is used to capture the full-field displacements.
and velocities during the implosion event, and to characterize the initial dynamic response of the tube. Dynamic pressure transducers measure the shock waves generated by the explosive and also the pressure pulse generated by the collapse. Results show that different magnitudes of explosive loading produce drastic differences in the way implosions are initiated, and in the extent of damage to the structure. Experiments with strong explosive loading show immediate collapse of the tube upon the arrival of shock wave. Relatively smaller explosive loading result in collapses due to the additional bubble pulse loading, or after accumulating damage for extended periods of time.

References listed at the end of the paper:

S. Aghdamy, D.P. Thambiratnam and M. Dhanasekar (Civil Eng., Queensland University of Technology, Brisbane, Australia), “Experimental investigation on lateral impact response of concrete-filled double-skin tube

ABSTRACT: This paper presents an experimental investigation on the lateral impact performance of axially loaded concrete-filled double-skin tube (CFDST) columns. These columns have desirable structural and constructional properties and have been used as columns in building, legs of off shore platforms and as bridge piers. Since they could be vulnerable to impact from passing vessels or vehicles, it is necessary to understand their behaviour under lateral impact loads. With this in mind, an experimental method employing an innovative instrumented horizontal impact testing system (HITS) was developed to apply lateral impact loads whilst the column maintained a static axial pre-loading to examine the failure mechanism and key response parameters of the column. These included the time histories of impact force, reaction forces, global lateral deflection and permanent local buckling profile. Eight full scale columns were tested for key parameters including the axial load level and impact location. Based on the test data, the failure mode, peak impact force, impact duration, peak reaction forces, reaction force duration, column maximum and residual global deflections and column local buckling length, depth and width under varying conditions are analysed and discussed. It is evident that the innovative HITS can successfully test structural columns under the combination of axial pre-loading and impact loading. The findings on the lateral impact response of the CFDST columns can serve as a benchmark reference for their future analysis and design.

References listed at the end of the paper:

End of many papers published in the journal, Experimental Mechanics (2012-2016)


ABSTRACT: The present research develops a three-dimensional multi-field formulation of a functionally graded piezoelectric thick shell of revolution by using tensor analysis. An orthogonal curvilinear coordinate system was employed, and basic geometric equations were derived for an arbitrary thick shell of revolution with variable thickness and curvature. Mechanical and electrical properties were assumed to vary along a three-dimensional orthogonal coordinate system with arbitrary functional distribution. The functional of the introduced shell was derived by using kinetic and potential energy of the structure based on three orthogonal displacement components, electric potential and material properties. The final differential equations were derived in general state for every arbitrary structure and material property distributions. The obtained equations were reduced for functionally graded and functionally graded piezoelectric cylindrical shells and the mentioned reduced equations were verified by comparison with the literature. Trueness and generality of the present results can be justified by capability of these equations for different geometries and material properties.

References listed at the end of the paper:

ABSTRACT: An accurate and efficient solution procedure based on the elasticity theory is employed to investigate the thermoelastic behavior of rotating laminated functionally graded (FG) cylindrical shells in thermal environment. The material properties are assumed to be temperature dependent and graded in the thickness direction. In order to accurately model the variation of the field variables across the thickness, the shell is divided into a set of mathematical layers. The differential quadrature method (DQM) is adopted to discretize the governing differential equations of each layer together with the related boundary and compatibility conditions at the interface of two adjacent layers. Using the DQM enables one to accurately and efficiently discretize the partial differential equations, especially along the graded direction, and also implement the boundary and compatibility conditions in their strong forms. After demonstrating the convergence and accuracy of the presented approach, the effects of material and geometrical parameters and also temperature dependence of material properties on the stresses and displacement components of rotating laminated FG cylindrical shells are studied.

References listed at the end of the paper:


ABSTRACT: The large amplitude free vibration of a laminated composite parabolic plate with parabolically orthotropic plies is investigated for the first time. The effects of out-of-plane shear deformations, rotary inertia, and geometrical nonlinearity are taken into account. The geometry of the plate is described, and the analysis performed in the parabolic coordinate system. The problem is solved numerically using a new parabolic hierarchical finite element. The nonlinear equations of free motion are mapped from the time domain into the frequency domain using the harmonic balance method. The resultant nonlinear equations are solved iteratively using the linearized updated mode method. Results for the fundamental linear and nonlinear frequencies are obtained for symmetric and antisymmetric laminates with clamped and simply supported edges. Comparisons are made with the finite element method for clamped and free isotropic parabolic plates and show excellent agreement. The aspect ratio, thickness ratio, moduli ratio, number of plies, layup sequence, and boundary conditions are shown to affect the hardening behavior.

References listed at the end of the paper:

A.H. Sofiyev (1), A.N. Alizada (2), O. Akin (3), A. Valiyev (4), M. Avcar (1) and S. Adiguzel (1)
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ABSTRACT: In this study, the stability analysis of functionally graded material (FGM) cylindrical, truncated and complete conical shells subjected to combined loads and resting on elastic foundations for two boundary conditions is investigated. The functionally graded material properties are assumed to vary continuously through the thickness of the conical shell. At first, the basic relations, the stability and compatibility equations of the FGM truncated conical shell on the Pasternak-type elastic foundation are obtained. By applying the Galerkin method to the foregoing equations, the critical combined loads of clamped–clamped and sliding–sliding FGM shells on the Pasternak-type elastic foundation are obtained. Finally, carrying out some computations, effects of the elastic foundation, boundary conditions, the variation of shell characteristics and material composition profiles on the values of critical combined loads have been studied.

References listed at the end of the paper:
ABSTRACT: The system of three partial differential equations with respect to displacements (Donnell equations) is used to analyze nonlinear vibrations of a cylindrical shell. The Galerkin method is applied to every partial differential equation to obtain a finite-degree-of-freedom model of the shell. The system of ordinary differential equations with respect to the general coordinates of the radial shell displacements is derived. The nonlinear modes of free vibrations are calculated using the harmonic balance method. The stability analysis of periodic motions is performed.

References listed at the end of the paper:


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ABSTRACT: The free vibration and static response of a two-dimensional functionally graded (2-D FGM) metal/ceramic open cylindrical shell are analyzed using 2-D generalized differential quadrature method. The open cylindrical shell is assumed to be simply supported at one pair of opposite edges and arbitrary boundary conditions at the other edges such that trigonometric functions expansion can be used to satisfy the boundary conditions precisely at simply supported edges. This paper presents a novel 2-D power-law distribution for ceramic volume fraction of 2-D FGM that gives designers a powerful tool for flexible designing of structures under multifunctional requirements. Various material profiles in two radial and axial directions are illustrated using the 2-D power-law distribution. The effective material properties at a point are determined in terms of the local volume fractions and the material properties by the Mori–Tanaka scheme. The 2-D generalized differential quadrature method as an efficient and accurate numerical tool is used to discretize the governing equations and to implement the boundary conditions. The convergence of the method is demonstrated, and to validate the
results, comparisons are made with the available solutions for FGM cylindrical shells. The interesting results indicate that a graded ceramic volume fraction in two directions has a higher capability to reduce the mechanical stresses and natural frequency than conventional 1-D FGM. The achieved results confirm that natural frequency and mechanical stress distribution can be modified to a required manner by selecting an appropriate volume fraction profile in two directions.

References listed at the end of the paper:

ABSTRACT: The global bifurcations and multi-pulse chaotic dynamics for high-degree freedom non-autonomous nonlinear dynamical system is directly utilized to an autonomous nonlinear dynamical system. The nonlinear governing equation of the honeycomb sandwich rectangular plate is derived by using the Hamilton’s principle and the Galerkin’s approach. A two-degree-of-freedom non-autonomous nonlinear equation of motion is obtained. It is known that the less simplification processes on the system will result in a better understanding of the behaviors of the multi-pulse chaotic dynamics for high-dimensional nonlinear systems. Therefore, the extended Melnikov method of the non-autonomous nonlinear dynamical system is directly utilized to analyze the global bifurcations and multi-pulse chaotic dynamics of the two-degree-of-freedom non-autonomous nonlinear system for the honeycomb sandwich rectangular plate. The theoretical results obtained here indicate that multi-pulse chaotic motions can occur in the honeycomb sandwich rectangular plate. Numerical simulation is also employed to find the multi-pulse chaotic motions of the honeycomb sandwich rectangular plate. It also demonstrates the validation of the theoretical prediction.

References listed at the end of the paper:


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“Controlling the dynamic behavior of piezoceramic cylinders by cross-section geometry”, Acta Mechanica, Vol. 223, No. 6, pp 1119-1136, June 2012

ABSTRACT: This paper focuses on the possibilities of controlling the dispersion spectra and wave characteristics of cylindrical waveguides by changing their geometry and electro-elastic properties. We consider cylinders with classical circular and hollow cross-sections, and waveguides that have sector cut of arbitrary angular measure in the cross-section. Numerical results are presented for the cylinders of all studied types with different boundary conditions. It is shown that the required wave characteristics can be obtained by a variation of the cross-section geometry of the waveguides.


ABSTRACT: The paper presents an analysis of functionally graded material doubly curved panels with rectangular planform under the action of thermal and mechanical loads. Based on the first-order shear deformation theory of modified Sanders assumptions, five coupled partially differential equations (PDEs) are established as equations of motion. Each thermo-mechanical property of the shell follows the power law distribution across the thickness, except Poisson’s ratio, which is kept constant through the panel. Assuming that four edges of the shell-panel are simply supported, a Navier-based solution is adopted to reduce the PDEs into time-dependent ODEs. Applying the Laplace transformation, the equations of motion are transformed into the Laplace domain. With the aid of analytical Laplace inverse method, solutions of stresses, strains, and displacements are obtained in time domain and expressed in explicit phrases. Dynamic, free vibration, and thermo-mechanical bending analysis of the panel is carried out for various geometries. Obtained results are validated with the well-known available data reported in the literature.

References listed at the end of the paper:
nonlocal parameter together with the other geometrical parameters and also the stiffness parameter of the elastic medium on the natural frequencies are studied.

References listed at the end of the paper:
Seyyed M. Hasheminejad (1), Hessam Mousavi-Akbarzadeh (1) and Yaser Mirzaei (2)
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ABSTRACT: The classical Navier equations of linear elasticity and the Helmholtz equation for the internal/external acoustic domains in conjunction with the translational addition theorem for spherical vector wave functions are employed to present an exact solution for three-dimensional nonaxisymmetric steady-state sound radiation from an eccentric hollow elastic sphere, immersed in and filled with acoustic fluids, and subjected to arbitrary time-harmonic mechanical drives at its internal/external surface. The analytical results are illustrated with numerical examples in which air-filled, water-submerged, thick-walled concentric and eccentric steel spheres are driven by harmonic concentrated or distributed radial internal/external loads. The numerical results reveal the important effects of sphere eccentricity, loading configuration, and excitation frequency on the sound radiation characteristics of the submerged structure. Limiting cases are considered and the validity of results is established with the aid of a commercial finite element package as well as by comparison with the data in the existing literature.

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ABSTRACT: Introducing beads into thin-walled structures for enhancing bending stiffness is a common practice and has been used for many decades. Typically, forms and patterns of such beads are rather based on experience as well as practical results than on analytical or numerical investigations. Recently computational methods have been developed for designing or optimizing beads. The paper at hand contributes to these attempts. It deals with increasing the buckling resistance as well as the fundamental frequency of thin-walled structures by systematic bead design. The design strategy is based on the idea to disturb the buckling mode and the fundamental vibration mode, respectively, of a structure in an efficient way by laying beads along the direction of the occurring maximum principal curvature of the corresponding mode shape. Since the beads influence this mode shape, an incremental approach is required. Numerical investigations into plate and profile structures are performed by applying this new iterative design procedure in combination with the finite element method.

References listed at the end of the paper:

ABSTRACT: The article is concerned with a transversely isotropic homogeneous elastic medium subjected to uniform compression in the isotropy plane. The medium becomes unstable in the sense of Hadamard at a certain level of initial strain. The critical strain is established to be uniquely determined from the system of equations of the equilibrium bifurcation; however, there are many modes of buckling corresponding to this strain. A solution of the system of the bifurcation equations is considered in the form of double periodic functions of the kind \( \sin r_1 x_1 \sin r_2 x_2 \). The uncertainty in the buckling mode implies that the wave numbers \( r_1 \) and \( r_2 \) remain arbitrary. In order to determine the relationship between the wave numbers, we examine the initial supercritical behavior of the material. Only two types of buckling modes (the shear type and the volume type) are possible. It is established that the buckling mode of the volume type is a chessboard-like one, and the mode of the shear type is not chessboard like. The stability of the supercritical equilibrium state is discussed.

References listed at the end of the article:


S. Papargyri-Beskou (1), S.V. Tsinopoulos (2) and D.E. Beskos (3,4)
ABSTRACT: The governing equations of motion for a gradient elastic circular cylindrical thin shell are derived. The basic equations of dynamic equilibrium and strain-displacement relations due to Donnell are combined with the stress–strain equations of the gradient theory of elasticity involving one microstructural and one microinertial elastic constant in addition to the two classical elastic moduli. The shell governing equations of motion are first used to study the propagation of harmonic waves and then free vibrations for the particular case of a circular cylindrical shell simply supported at its two ends. The results of these analyses are compared against those of the classical case in order to assess the microstructural and microinertial effects on the dynamic behavior of the shell.

References listed at the end of the paper:


ABSTRACT: In this paper, the axisymmetric vibration of a fluid-filled spherical membrane shell is studied based on nonlocal elasticity theory. The membrane shell is considered elastic, homogeneous and isotropic. The shell model is reformulated using the nonlocal differential constitutive relations of Eringen. The membrane shell is completely filled with an inviscid fluid. The motion of the fluid is governed by the wave equation. Nonlocal governing equations of motion for the fluid-filled spherical membrane shell are derived. Along the contact surface between the membrane and the fluid, the compatibility requirement is applied and Legendre polynomials, associated Legendre polynomials and spherical Bessel functions are used to obtain the natural frequencies of the fluid-filled spherical membrane shells. The frequencies for both empty and fluid-filled spherical membrane shell are evaluated, and their comparisons are performed to confirm the validity and accuracy of the proposed method. An excellent agreement is found between the present and previous ones available in the literature. The variations of the natural frequencies with the small-scale parameter, density ratio, wave speed ratio and Poisson’s ratio are also examined. It is observed that the frequencies are affected when the size effect is taken into consideration.

References listed at the end of the paper:


ABSTRACT: Nonlinear torsional vibrations of thin-walled beams exhibiting primary and secondary warpings are investigated. The coupled nonlinear torsional–axial equations of motion are considered. Ignoring the axial inertia term leads to a differential equation of motion in terms of angle of twist. Two sets of torsional boundary conditions, that is, clamped–clamped and clamped-free boundary conditions are considered. The governing partial differential equation of motion is discretized and transformed into a set of ordinary differential equations of motion using Galerkin’s method. Then, the method of multiple scales is used to solve the time domain equations and derive the equations governing the modulation of the amplitudes and phases of the vibration modes. The obtained results are compared with the available results in the literature that are obtained from boundary element and finite element methods, which reveals an excellent agreement between different solution methodologies. Finally, the internal resonance and the stability of coupled and uncoupled nonlinear modes are investigated. This study can be a preliminary step in the understanding of complex dynamics of such systems in internal resonance excited by external resonant excitations.

References listed at the end of the paper:


ABSTRACT: The paper is focused on the elastic buckling behavior of piezocomposite elliptical cylindrical shell finite element formulation. The formulation is based on the shear deformation theory, and the serendipity quadrilateral eight-node element is used to study the elastic behavior of elliptical cylindrical shells. The strain-displacement relations are accurately accounted for in the formulation. The contributions of work done by the applied load are also incorporated. A constant gain displacement control algorithm coupling the direct and inverse piezoelectric effect is applied to provide active control of composite non-circular shells in a self-monitoring and self-controlling system. The governing equations obtained using the principle of minimum potential energy are solved through an eigenvalue approach. The influences of elliptical cross-sectional parameter and displacement feedback gain ($G_d$) values on the critical buckling loads of elliptical cylindrical shells are examined.

References listed at the end of the paper:

ABSTRACT: A structural mechanics model is employed for the investigation of the bending buckling behavior of perfect and defective single-walled carbon nanotubes (SWCNTs). The effects of different types of defects (vacancies and Stone–Wales defects) at various locations on the critical bending buckling moments and curvatures are also studied for zigzag and armchair nanotubes with various aspect ratios (length/diameter). The locations of defects are along the length of the nanotube and around the circumference. Moreover, the results of this structural mechanics model are compared with a finite element model. The simple continuum model, especially, could be adopted to predict the critical buckling moments and curvatures of SWCNTs with large aspect ratio. Finally, the results of the present structural model are compared with those from molecular dynamics (MD) simulation, and there is good agreement between our model and the MD model.

References listed at the end of the paper:

ABSTRACT: This paper investigates the large-amplitude free vibration of a double-walled carbon nanotube (DWCNT) surrounded by an elastic medium in the presence of temperature change. Based on continuum mechanics, a nonlocal elastic beam model is employed in which nanotubes are coupled together via the van der Waals (vdW) interlayer interactions. The Pasternak foundation model and a nonlinear vdW model are utilized to describe the surrounding elastic medium effect and the vdW interlayer interactions, respectively. DWCNTs with different boundary conditions are analyzed utilizing the Timoshenko beam theory that considers the shear deformation and rotary inertia effects. The governing equations are derived from Hamilton’s principle; the Galerkin method is utilized to discretize the governing equations. The influences of the nonlocal parameter, spring constant, carbon nanotube aspect ratio, and temperature change on the nonlinear free vibration characteristics of a double-walled carbon nanotube with different boundary conditions are thoroughly investigated. It is deduced that the nonlocal parameter, spring constant, and the aspect ratio play significant roles for the value of the nonlinear frequency. Also, the temperature change and the type of boundary conditions have an effect on the nonlinear frequency.

References listed at the end of the paper:

ABSTRACT: Three-dimensional nonlinear thermo-elastic analysis of a functionally graded cylindrical shell with piezoelectric layers under the effect of asymmetric thermo-electro-mechanical loads is carried out. The strain–displacement relations are based on the nonlinear Lagrangian strain–displacement relations; that is, nonlinear terms containing derivatives of the displacement in the radial direction are included. Material properties of the shell are assumed to be graded in the radial direction according to a power law but the Poisson’s ratio is assumed to be constant. Cylindrical shells are assumed to be under the effect of pressure loading in cosine form, ring pressure loads, electric and temperature fields. Numerical results of stress, displacement, electric and thermal fields are obtained by using two versions of the differential quadrature methods, namely polynomial and Fourier quadrature methods. The convergence of the solution is studied, and results of the axisymmetric loadings are verified with reported results for a cylindrical shell with material properties obeying a power law. Effects of the grading index of material properties, the temperature difference, the ratio of the mean radius to the thickness of the shell, boundary conditions, the thickness of piezoelectric layers and electric excitation on stress, displacement, electric and temperature fields are presented.

References listed at the end of the paper:
References listed at the end of the paper:

ABSTRACT: Vibrations in a poroelastic composite hollow sphere are investigated employing Biot’s theory of wave propagation in poroelastic media. A composite hollow poroelastic sphere consists of two concentric poroelastic spherical layers both of which are made of different poroelastic materials with each poroelastic material being homogeneous and isotropic. The boundaries of the composite hollow poroelastic sphere are free from stress. The frequency equations of both radial and rotatory vibrations are obtained each for pervious and impervious surfaces. The frequency equation of vibrations of a poroelastic composite hollow sphere with rigid core is derived as a particular case. The non-dimensional frequency for propagating modes is computed as a
function of ratio of thickness to inner radius of core. The results are presented graphically for two types of poroelastic composite spheres and then discussed.

References listed at the end of the paper:


ABSTRACT: An application of WKB methods is proposed here for a stretched annular thin plate with piecewise-constant mechanical properties (also known as a bi-annular plate). Unlike the classical scenario involving only a simple annular such plate, in certain cases the neutral stability curve fails to be convex and the critical eigenmodes behave rather differently as the plate becomes progressively thinner (equivalent to $\mu \rightarrow \infty$ in our notations). On one side of this curve, the corresponding eigenmodes are localised near the inner rim of the annulus, while in the remaining part these functions are concentrated along the interface separating the two annular sub-regions. By using the asymptotic reduction technique proposed by Coman and Haughton in (Acta Mech 185:179–200, 2006), the original fourth-order three-point boundary-value problem is formally reduced to a pair of second-order differential equations coupled through a set of matching conditions at the interface. It is shown that for $\mu \gg 1$ the critical eigenvalues for both cases mentioned above can be approximated by solving a couple of simple transcendental equations and that the results predicted compare well with the direct numerical simulations of the original problem.
References listed at the end of the paper:

ABSTRACT: The compressive strengths and dynamic response of corrugated sandwich plates with unfilled and foam-filled sinusoidal plate cores are investigated. The “effective” compressive strengths of the unfilled and foam-filled sinusoidal plate cores are derived and numerically analyzed. Finite element method is employed to analyze the dynamic response of fully clamped metal sandwich plates with unfilled and foam-filled sinusoidal plate cores subjected to impulsive loading. Moreover, a simplified plastic-string model is developed to analytically predict the large deflection and time responses of the clamped sandwich plates under impulsive loading. One can see a good agreement between the analytical and numerical predictions. It can be seen that the present analytical procedure is efficient and simple to evaluate the dynamic response of corrugated sandwich plates.
References listed at the end of the paper:
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ABSTRACT: In this paper, the whirling frequencies of simply supported and clamped rotating cylindrical shells surrounded by an elastic foundation are investigated. The Love’s shell theory is used along with the Winkler foundation to obtain the governing equations of motion. An exact power series solution is obtained for arbitrary boundary conditions and the results are verified with the literature. Several case studies are performed, and the effect of spinning speed, foundation stiffness, and geometrical dimensions of the cylinder on the whirling frequencies are investigated.

References listed at the end of the paper:
ABSTRACT: Thermal buckling analysis of a transversely graded circular plate attached to a centric partial elastic foundation is studied, analytically. Thermomechanical properties of the circular plate are distributed across the thickness based on a power law function. The governing equations of the plate are obtained by means of the classical plate theory. A conventional Winkler-type foundation is assumed to be in contact with the plate which acts in compression as well as in tension. Proper boundary conditions are chosen after pre-buckling analysis of the plate, and stability equations are established via the adjacent equilibrium criterion. To analyze the thermal stability problem, the plate is divided into two sections, a foundation-less domain and an in-contact region. An exact procedure is presented to accurately predict the critical buckling temperature as well as the buckled configuration of the plate. Analysis of various involved parameters including the Winkler parameter, foundation radius, power law index, and loading type is presented. It is concluded that while the loading is symmetric, in many cases, the buckled configuration of the plate is asymmetric.

References listed at the end of the paper:

ABSTRACT: Both divergence (static) and flutter (dynamic) instabilities of carbon nanotubes conveying fluid and modeled as thin-walled beams are investigated in this paper. The effects of boundary conditions, geometric nonlinearity, non-classical transverse shear, and rotary inertia on the static and dynamic instability characteristics are studied. Governing equations and various boundary conditions are derived simultaneously via extended Hamilton’s principle. Numerical analysis is performed using the extended Galerkin method which enables us to obtain solutions even when it is not feasible to find trial functions satisfying all the boundary conditions.
conditions. The variations in critical flow velocity with both geometric parameters and three different boundary conditions of carbon nanotubes are investigated and compared with those of a linear system, and pertinent conclusions are outlined.

References listed at the end of the paper:


ABSTRACT: This paper studies vibration behavior of single-walled carbon nanotubes based on three-dimensional theory of elasticity. To accounting for the size effect of carbon nanotubes, nonlocal theory is adopted to the shell model. The nonlocal parameter is incorporated into all constitutive equations in three dimensions. Governing differential equations of motion are reduced to the ordinary differential equations in thickness direction by using Fourier series expansion in axial and circumferential direction. The state equations obtained from constitutive relations and governing equations are solved analytically by making use of the state space method. A detailed parametric study is carried out to show the influences of the nonlocal parameter, thickness-to-radius ratio and length-to-radius ratio. Results reveal that excluding small-scale effects caused decreasing accuracy of natural frequencies. Furthermore, the obtained closed form solution can be used to assess the accuracy of conventional two-dimensional theories.

References listed at the end of the paper:
ABSTRACT: This study concerns a theoretical analysis on the buckling of cylindrical shells under axial compression, buckling solutions are mainly grouped into two types according to their nature of different buckling modes.
non-uniform buckling with deflection localized at the vicinity of the ends and uniform buckling with deformation waves distributed uniformly along the axial direction, and the complete solving space only consists of the basic eigensolutions. The influence of geometric parameters and boundary conditions on the critical loads and buckling modes is discussed in detail, and some insights into this problem are analyzed.

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Bekir Akgoez and Oemer Civalek (Civil Eng., Akdeniz University, Antalya, Turkey), “Buckling analysis of functionally graded microbeams based on the strain gradient theory”, Acta Mechanica, Vol. 224, No. 9, pp 2185-2201, September 2013

ABSTRACT: The buckling behavior of size-dependent microbeams made of functionally graded materials (FGMs) for different boundary conditions is investigated on the basis of Bernoulli–Euler beam and modified strain gradient theory. The higher-order governing differential equation for buckling with all possible classical and non-classical boundary conditions is obtained by a variational statement. The effects of the power of the material property variation function, boundary conditions, slenderness ratio, ratio of additional material length scale parameters for two constituents, beam thickness-to-additional material length scale parameter ratio on the buckling response of FGM microbeams are investigated. Some comparative results are presented in tabular and graphical form in order to show the differences between the results obtained by the present model and those
predicted by modified couple stress and classical continuum models.

References listed at the end of the paper:
Mohammad Bedroud (1), Shahrokh Hosseini-Hashemi (2) and Reza Nazemnezhad (1)
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ABSTRACT: The present study proposes an analytical solution for the axisymmetric/asymmetric buckling analysis of moderately thick circular/annular Mindlin nanoplates under uniform radial compressive in-plane load. In order to consider small-scale effects, nonlocal elasticity theory of Eringen is employed. To ensure the efficiency and stability of the present methodology, the results are compared with other ones presented in the literature. Further the exact closed-form solution is obtained using three potential functions. In addition, the effect of small scales on buckling loads for different parameters such as geometry of the nanoplate, boundary conditions, and axisymmetric/asymmetric mode numbers, is investigated. It is observed that the buckling mode shape for annular nanoplates, which corresponds to the lowest critical buckling load, may be axisymmetric or asymmetric depending on boundary conditions, inner to outer radius ratios, and thickness of the nanoplate. In other words, for stiffer boundary conditions and smaller inner to outer radius ratios, the mode shape corresponding to the lowest critical buckling load is an asymmetric mode. Also, the difference between axisymmetric and asymmetric buckling loads for higher mode numbers, greater thickness to outer radius ratios and smaller outer radii decreases by increasing the nonlocal parameter.

References listed at the end of the paper:


ABSTRACT: The evaluation of inter-laminar shear stresses in laminated shells using 2D finite element models involves cumbersome post-processing techniques. In this paper, a simple and efficient method has been proposed for accurate evaluation of transverse shear stresses in laminated composite shells by using a displacement-based C^0 FE model derived from higher-order shear deformation theory (HSDT) and a least square error (LSE) method. In order to include the effect of three curvature terms in the strain components of composite shells, Sander’s approximations are followed. In this model, the first derivatives of transverse displacement have been treated as independent variables to overcome the problem of C^1 continuity in the FE implementation associated with the present shell theory (HSDT). The LSE method is applied at the post-processing stage, after in-plane stresses are calculated by using the present FE model based on HSDT. Thus, the proposed method is quite simple compared to the usual method of integrating the 3D equilibrium equations for the calculation of transverse stresses in laminated composite shells. The accuracy of the method is demonstrated in the numerical examples by comparison of the present results with those obtained from different models based on HSDT, exact analytical and 3D elasticity solutions.

References listed at the end of the paper:
ABSTRACT: Free transverse vibrations of elastically supported double-walled carbon nanotubes (DWCNTs) subjected to axially varying magnetic fields are examined. Using nonlocal Rayleigh beam theory, the explicit expressions of the governing equations are obtained and then numerically solved via an efficient numerical scheme. For magnetically affected DWCNTs with simply supported, fully clamped, simple-clamped, and clamped-free ends, the flexural frequencies as well as the corresponding vibration modes are evaluated for different varying magnetic fields. The influences of the small-scale parameter and the magnetic field strength on
the dominant flexural frequencies of the DWCNTs are explained and discussed. The results indicate that the vibration characteristics of DWCNTs can be significantly affected by the axially varying magnetic field. The role of variation of the axial magnetic field on the vibrational mode patterns of both the innermost and outermost tubes is also revealed. For a special applied magnetic field, the alteration from coaxial to noncoaxial vibration pattern is also reported. The obtained results display that the flexural frequencies magnify with the magnetic field strength. Generally, the variation of the magnetic field strength has more influence on the variation of the frequencies of DWCNTs with higher small-scale parameters. This matter is mainly attributed to the incorporation of the size effect into the nonlocal Lorentz forces.

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Aman Zhang, Furen Ming and Zueyan Cao (College of Shipbuilding Engineering, Harbin Engineering University, China), “Total Lagrangian particle method for the large-deformation analysis of solids and curved

ABSTRACT: A high-accuracy smoothed-particle hydrodynamics (SPH) method for a large-deformation solid is developed from two aspects: improving the completeness of the approximation function and deducing the governing equation in the undeformed configuration. On the basis of Combescure’s researches and our previous studies, the SPH shell theory based on the Mindlin–Ressiner plate is detailed, which has overcome the unbridgeable drawbacks of solid modeling of thin structures and pushed forward the engineering applications of solving large-deformation and other nonlinear issues. Afterward, several treatments of SPH solid and shell are carried out, including the hourglass mode, boundary conditions and irregular structures; moreover, the corresponding validations are also conducted to reveal the feasibility and effectiveness of the proposed treatments. Finally, the accuracy of the present SPH program is verified further through two benchmarks of a curved shell.

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ABSTRACT: This paper deals with the linear and nonlinear vibrations of a truncated conical shell; both internal and external surfaces are covered by functionally graded coatings (FGCs). The theoretical formulation is based on the von Karman–Donnell-type nonlinear kinematics. The material properties of FGCs are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The fundamental relations, the modified Donnell-type nonlinear motion, and compatibility equations of the truncated conical shell with FGCs are derived. The basic equations are reduced to the ordinary differential equation depending on time with geometric nonlinearity using the Superposition and Galerkin methods. By applying the homotopy perturbation method to the foregoing equation, the relation between nonlinear frequency parameters with the dimensionless amplitude of a truncated conical shell with FGCs is obtained. Parametric studies are performed to illustrate the effect of different values of thickness and material
composition of the FGCs on the frequency-amplitude relationships. The validity of the present solution is demonstrated by comparison with solutions available in the literature.

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1) Mechanical Eng., Tarbiat Modares University, Tehran, Iran
2) Mechanical Engineering, University of Guilan, Rasht, Iran

ABSTRACT: A unified analytical approach is applied for investigating the vibrational behavior of grid-stiffened composite cylindrical shells considering the flexural behavior of the ribs. A smeared method is employed to superimpose the stiffness contribution of the stiffeners with those of the shell in order to obtain the equivalent stiffness parameters of the whole panel. The stiffeners are modeled as a beam and considered to support shear loads and bending moments in addition to the axial loads. Therefore, the corresponding stiffness terms are taken into consideration while obtaining the stiffness matrices due to the stiffeners. Theoretical formulations are based on first-order shear deformation shell theory, which includes the effects of transverse shear deformation and rotary inertia. The modal forms are assumed to have the axial dependency in the form of Fourier series whose derivatives are legitimised using Stokes’ transformation. In order to validate the obtained results, a 3-D finite element model is also built using ABAQUS CAE software. Results obtained from two types of analyses are compared with each other, and good agreement has been achieved. Furthermore, the influence of variations in the shell thickness and changes of the boundary conditions on the shell frequencies is studied. The results obtained are novel and can be used as a benchmark for further studies.

References listed at the end of the paper:

ABSTRACT: A two-dimensional linearly elastic model of shells made of an anisotropic material described by 21 elastic moduli is developed. For this aim, the generalized Timoshenko–Reissner hypotheses are used. In contrast to the ordinary shell models, the tangential stress-resultants here depend not only on the tangential strains but also on the transverse shear. An asymptotic analysis of the obtained equations is fulfilled. The typical stress-strain states, namely the membrane state, the edge effect state, and the boundary layer, are constructed. The system of the Donnell type is delivered. As an example of general anisotropy, a composite material consisting of a matrix reinforced by the system of fibers inclined to the mid-surface is studied. Certain simple static problems and free vibration problems are solved for a cylindrical shell made of this material.

References listed at the end of the paper:

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ABSTRACT: Modified couple stress theory is a size-dependent theorem capturing the micro/nanoscale effects influencing the mechanical behaviors of the micro- and nanostructures. In this paper, it is applied to investigate the nonlinear vibration of carbon nanotubes under step DC voltage. The vibration, natural frequencies and dynamic pull-in characteristics of the carbon nanotubes are studied in detail. Moreover, the effects of various boundary conditions and geometries are scrutinized on the dynamic characteristics. The results reveal that application of this theory leads to the higher values of the natural frequencies and dynamic pull-in voltages.
References


ABSTRACT: This paper presents an analytical approach to investigate the buckling and postbuckling behavior of functionally graded cylindrical shells subjected to thermal and axial compressive loads. Material properties are assumed to be temperature dependent and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of constituents. The governing equations are established within the framework of classical thin shallow shell theory taking both geometrical nonlinearity in von Kármán–Donnell sense and initial imperfection into consideration. Thermal stability analysis also incorporates the effects of tangential edge constraints. A Galerkin procedure is applied to derive expressions of load-deflection relations from which the thermal buckling loads and postbuckling curves of the shells are obtained by an iteration. Effects played by material and geometrical properties, tangential stiffness, imperfection and buckling modes are discussed.

References listed at the end of the paper:

ABSTRACT: This paper presents the study on natural frequency characteristics of a thin-walled functionally graded material (FGM) cylindrical shell with rings support based on first-order theory subjected to ten boundary conditions”, Acta Mechanica, Vol. 225, No. 7, pp 2085-2109, July 2014

M.R. Isvandzibaei, H. Jamaluddin and R.I. Raja Hamzah (Mechanical Eng., Technological University of Malaysia (UTM), Johor Bahru, Malaysia), “Effects of uniform interior pressure distribution on vibration of FGM cylindrical shell with rings support based on first-order theory subjected to ten boundary conditions”,
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Mohsin Islam (1), Aviit Kar (2) and M. Kanoria (3)  
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ABSTRACT: This paper is concerned with the determination of thermoelastic stresses, strain and conductive temperature in a spherically symmetric spherical shell. The two-temperature three-phase-lag thermoelastic model (2T3P) and two-temperature Green–Naghdi model III (2TGNIII) are combined into a unified formulation. There is no temperature at the outer boundary, and thermal load is applied at the inner boundary. The basic equations have been written in the form of a vector–matrix differential equation in the Laplace transform domain which is then solved by the state-space approach. The numerical inversion of the transform is carried out using Fourier series expansion techniques. Because of the short duration of the second sound effects, small time approximations of the solutions are studied. The physical quantities have been computed numerically and presented graphically in a number of figures. A complete and comprehensive analysis of the results has been presented for the 2T3P and the 2TGNIII models. These results have also been compared with those of the
References listed at the end of the paper:

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ABSTRACT: Aeroelastic properties of two-dimensional panels neglecting and considering the shear deformation in supersonic airflow are analytically investigated. The two types of panel are known as the Kirchhoff and Mindlin panels. A method for estimating the flutter bound of the aeroelastic structural system is proposed. The classical plate theory and the first-order shear deformation theory are used in the structural modeling. The unsteady aerodynamic pressure is evaluated by the supersonic piston theory. The governing equation of motion of the structural system is formulated applying Hamilton’s principle. The exact solution for the partial differential equation of motion of the aeroelastic structural system is calculated, and the aerelastic modes (AEMs) of the panels are obtained and compared with the vacuo natural modes of the structures. The correctness of the present methodology used in the aeroelastic analysis is verified. Aeroelastic characteristics of panels with different boundary conditions are investigated, and the time response history of the panel is calculated using the AEMs obtained in this study. Moreover, the accuracy of the assumed mode method in the aeroelastic analysis is also researched. Some interesting and useful results are obtained and analyzed.

References listed at the end of the paper:


ABSTRACT: Several novel models, based on the nonlocal stress theory, on the lateral buckling of two- and three-dimensional (2D and 3D) ensembles of vertically aligned single-walled carbon nanotubes (SWCNTs) are developed. The existing van der Waals forces between the constitutive atoms of the neighboring SWCNTs are modeled by an elastic layer, and each individual SWCNT is modeled using the nonlocal Rayleigh beam theory. The governing equations for lateral buckling of both 2D and 3D SWCNTs ensembles due to axial compressive loads are derived. These are called discrete models since the lateral deformations of each SWCNT is modeled using the nonlocal Rayleigh beam theory. The resulting models are called continuous models. Based on both discrete and continuous models, the critical axial buckling loads for both 2D and 3D ensembles of SWCNTs for a special case, when the outer SWCNTs are prohibited from any lateral movement, are obtained. A reasonably good agreement between the results of the discrete model and those of the continuous model is reported. Subsequently, the roles of small-scale parameter, intertube distance, and number of SWCNTs on the critical buckling loads are examined. The obtained results and the proposed models in the present work would be very helpful in design and fabrication of 2D and 3D groups of vertically aligned SWCNTs, particularly those whose main duties are to transfer securely the applied axial forces.
References listed at the end of the paper:
ABSTRACT: The global and local buckling of sandwich panels under uniaxial compression is discussed in the framework of classical linearized stability analysis. A refined two-dimensional (2D) plate model is constructed by postulating a layer-wise kinematics within a partially mixed variational statement. The 3D constitutive law is retained, and the interface continuity conditions of both displacements and transverse stresses are exactly satisfied. A Navier-type closed-form solution is adopted for the considered case studies, which solves the 2D equilibrium and compatibility equations in strong form. A comparison against full 3D results obtained by commercial finite element analysis and from open literature shows that the proposed solutions yield quasi-3D accuracy. A comprehensive assessment is given of the geometric and mechanical parameters defining the stability limit of sandwich struts, such as the thickness and stiffness ratios between face sheets and core as well as their orthotropy ratio. Moreover, the effects are discussed of von Kàrmàn’s assumptions and of the definition of the buckling preload in terms of uniform strain or stress.

References listed at the end of the paper:

ABSTRACT: The present paper is devoted to an issue of possible localization of waves propagating within a structure that consists of a film connected to a backing material by a substrate. The substrate is initially damaged. In the first approximation, the film model in the present paper is assumed to be a string on an elastic foundation with a coefficient depending on the substrate damage degree. The elastic foundation imitates the substrate and backing material effects on the film. Initiation of a string delamination resulted from the structure damaged at localized oscillations caused by impact loads has been considered. At loading, the initial damage of the substrate is changing in time and space according to the proposed law of the damage growth. It has been shown that at impact the cause of the string substrate material damage increase can be localized oscillation modes. The localized mode existence depends on the relation between initial substrate rigidity and main material rigidity. The impact energy is redistributed between propagating waves and localized waves in such a way that the latter make the main contribution to the growth of the material damage.

References listed at the end of the paper:
ABSTRACT: Bifurcation behavior of heated conical shell made of a through-the-thickness functionally graded material is investigated in the present research. Properties of the shell are obtained based on a power law form across the thickness. Temperature dependency of the constituents is also taken into account. The heat conduction equation of the shell is solved based on an iterative generalized differential quadrature method (GDQM). General nonlinear equilibrium equations and the associated boundary conditions are obtained using the virtual displacement principle in the Donnell sense. The prebuckling solution of the shell is obtained under the assumption of linear membrane deformations. The stability equations are extracted via the concept of the adjacent equilibrium criterion. A semi-analytical solution employing the GDQM and trigonometric expansion is implemented to solve the stability equations. Numerical results of the present research are compared and validated with the known available data through the open literature. Some parametric studies are conducted to investigate the influences of various involved parameters, such as the cone semi-vertex angle, boundary conditions, power law index of composition rule, length to thickness ratio, and the radius to thickness ratio.

References listed at the end of the paper:

ABSTRACT: This article is mainly focused on accurate solutions for axial impact buckling of functionally graded cylindrical shells in a heated environment. A new analytical methodology is developed, and a rigorous solving procedure is conducted to guarantee the accuracy of the obtained results. Various aspects related to boundary conditions, geometric parameters, material properties and temperature variations are investigated systematically. The numerical results reveal that in-plane boundary conditions have an obvious influence on the shell. If the reflection of stress waves occurs, critical stresses should further decrease with the interaction of incident and reflected waves. The ability of FGCSs in resisting buckling failure can be improved by controlling the material exponent.

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ABSTRACT: This paper is devoted to the geometrically nonlinear analysis of a functionally graded (FG) thick hollow cylinder with Rayleigh damping, Acta Mechanica, Vol. 226, No. 5, pp 1497-1513, May 2015

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ABSTRACT: This paper is devoted to the geometrically nonlinear analysis of a functionally graded (FG) thick hollow cylinder with Rayleigh damping. The hollow cylinder is subjected to axisymmetric mechanical shock loading on its bounding surfaces. First, the meshless local Petrov–Galerkin (MLPG) method is developed for geometrically nonlinear problems based on total Lagrangian approach. During this process, the local integral equations are obtained using the weak formulation on local sub-domains for the set of governing equations by employing a Heaviside test function. The radial point interpolation method is used to approximate the field variables in terms of nodal displacements. The iterative Newmark/Newton–Raphson method is employed to solve the system of resulting nonlinear equations in suitable time steps. Because of large deformations compared to linear elastic materials, the hyper-elastic neo-Hookean model is considered for the problem. The hollow cylinder is supposed to be in plane strain condition. The properties of the FG cylinder are varied in the thickness direction using the volume fraction that is an exponential function of radius. At the end, to prove the robustness of the proposed method, several numerical tests are performed and effects of relative parameters on the dynamic behavior of the cylinder for various kinds of FGMs are discussed in detail. Findings demonstrate the effectiveness of the presented MLPG method for large deformation problems because of vanishing of the mesh distortion. This paper furnishes a ground to develop the MLPG method for dynamic large deformation problems.
References listed at the end of the paper:
ABSTRACT: Hygrothermal influence on the buckling behavior of bidirectional glass/epoxy composite panels having delaminations was studied numerically and verified by conducting several experiments. First-order shear deformation theory was used to develop a finite element model for numerical predictions with an 8-noded quadratic isoparametric element that takes care of the effects of delamination area and hygrothermal conditions of composite panels. Verification of results of the numerical analysis was done by conducting several experiments showing the effects of various parameters like temperature, moisture, area of delaminations, orientations of fibers, stacking sequence and boundary conditions on the buckling characteristics of bidirectional glass/epoxy composite panels. Experimental buckling loads were calculated using an INSTRON 8862 universal testing machine for hygrothermally treated composite panels having delaminations. It was observed that there is a good comparison of predicted and experimental buckling loads. The effects of various parameters on the buckling behavior of composite panels are presented. The buckling results can be utilized as a tool for detection of delamination damage in composite plates subjected to hygrothermal environment.

References listed at the end of the paper:

ABSTRACT: In this article, we investigate the effect of carbon nanotube (CNT) waviness on the active constrained layer damping (ACLD) of the laminated hybrid composite shells. In particular, the effect of CNT waviness has been studied for the case of a novel nano-tailored composite—continuous fuzzy fiber-reinforced composite (FFRC). The distinctive feature of the construction of the FFRC is that the uniformly spaced straight or wavy CNTs are radially grown on the circumferential surfaces of carbon fibers. The constraining layer of the ACLD treatment is considered to be made of vertically or obliquely reinforced 1–3 piezoelectric composite material. A three-dimensional finite element model has been developed to study the damping characteristics of the laminated FFRC shells integrated with the patches of ACLD treatment. Our results reveal that (i) the planar orientation of CNT waviness has a significant influence on the damping characteristics of the laminated FFRC shells, (ii) damping characteristics of the symmetric cross-ply, and antisymmetric angle-ply laminated FFRC shells are improved if CNT waviness is coplanar with the longitudinal plane of the carbon fiber, and (iii) for the antisymmetric cross-ply laminated FFRC shells, the performance of the ACLD patches becomes maximum for attenuating the fundamental mode when CNT waviness is coplanar with the transverse plane of the carbon fiber. 

References listed at the end of the paper:

ABSTRACT: A two-dimensional analytical piezothermoelastic solution for a functionally graded material (FGM) hollow sphere with integrated piezoelectric layers as a sensor and actuator subjected to non-axisymmetric loads is carried out. A feedback gain control algorithm is used for the active control of stress and displacement of an FGM hollow sphere. The material properties of the FGM layer are assumed to be graded in the radial direction according to a power law function. Governing differential equations are developed in terms of the components of the displacement field, the electric potential, and the temperature of each layer of the smart FGM hollow sphere. These equations are solved analytically using the Legendre polynomials and the system of Euler differential equations. The effects of grading index of material properties and feedback gain on the mechanical–electrical responses are demonstrated in detail.

References listed at the end of the paper:


ABSTRACT: The present study portrays the stochastic natural frequencies of laminated composite conical shells using a surrogate model (D-optimal design) approach. The rotary inertia and transverse shear deformation are incorporated in probabilistic finite element analysis with uncertainty due to variation in angle of twist. A sensitivity analysis is carried out to address the influence of different input parameters on the output natural frequencies. Typical fiber orientation angle and material properties are randomly varied to obtain the stochastic natural frequencies. The sampling size and computational cost are exorbitantly reduced by employing the present approach compared to direct Monte Carlo simulation. Statistical analysis is presented to illustrate the results. The stochastic natural frequencies obtained are the first known results for the type of analyses carried out here.

References listed at the end of the paper:
most important feature of the developed element is the evaluation of linear membrane bending and nonlinear

ABSTRACT: This study reports an improved finite element computational model using a flat four-node element for nonlinear bending analysis of plates and cylindrical shells with element distortions. The von Kármán’s large deflection theory and the total Lagrangian approach are employed in the formulation to describe small strain geometric nonlinearity with large deformations using the first-order shear deformation theory. The most important feature of the developed element is the evaluation of linear membrane bending and nonlinear

geometric stiffness matrices based on integration along the boundary of smoothing elements. This technique can give more accurate numerical integrations even with badly shaped elements or coarse meshes when compared to other flat elements using domain integration techniques. The accuracy and predictive capability of the present model is demonstrated by several numerical investigations and comparative studies with analytical/experimental and other numerical solutions available in the literature.

References listed at the end of the paper:

ABSTRACT: This study is concerned with the torsional buckling behavior of chiral multi-walled carbon nanotubes (MWCNTs) based on a molecular mechanics model. An analytical solution is carried out to calculate the elastic critical buckling shear strain of MWCNTs with different types of chirality. To determine the force constants used in the molecular mechanics model, on the basis of quantum mechanics, density functional theory is employed. Through comparison of the results obtained from the present molecular mechanics model and ones from available molecular dynamics simulations, the validity of the present approach is assessed. The influence of chirality on the critical buckling shear strain of nanotubes is then investigated. It is indicated that nanotubes with \((n, n/2)\) chirality buckle at lower values of critical buckling shear strain compared with zigzag and armchair nanotubes.

References listed at the end of the paper:


ABSTRACT: Finite element analysis of functionally graded plates based on a general third-order shear deformation plate theory with a modified couple stress effect and the von Kármán nonlinearity is carried out to bring out the effects of couple stress, geometric nonlinearity and power-law variation of the material composition through the plate thickness on the bending deflections of plates. The theory requires no shear correction factors. The principle of virtual displacements is utilized to develop a nonlinear finite element model. The finite element model requires $C^1$ continuity of all dependent variables. The microstructural effects are captured using a length scale parameter via the modified couple stress theory. The variation of two-constituent material is assumed through the thickness direction according to a power-law distribution. Numerical results are presented for static bending problems of rectangular plates with various boundary conditions to bring out the parametric effects of the power-law index and length scale parameter on the load–deflection characteristics of plates with various boundary conditions.

References listed at the end of the paper:


ABSTRACT: In this study, an asymptotic analytical solution for horizontal shear waves in a confocal piezoelectric elliptic cylinder shell, with poling direction parallel to the axis, is obtained. On the basis of tensor analysis and elastodynamic equations, the field-governing equation in elliptic cylinder coordinates, which is expressed by displacement and electric potential, is deduced. By the separation of variables, the partial differential equations are translated into ordinary differential equations. Considering electrically open boundary conditions, the ordinary differential equations are solved, and the wave functions of horizontal shear waves (SH waves) in a piezoelectric elliptic cylinder are obtained by the Wentzel–Kramers–Brillouin and power series methods. In a numerical example, the relation between the correction coefficient of the wave number and frequency of SH waves in different piezoelectric elliptic cylinder shells is discussed. The waves’ structures for the first three modes are also illustrated. The results reveal that one or more mode SH waves can propagate along the circumference in a confocal piezoelectric elliptic cylinder shell. The correction coefficient of the wave number of the first mode, which depends on the size of the piezoelectric elliptic cylinder shell, is approximately
a constant. The number of modes increases with the frequency and thickness of the shell. For the first mode, the wave energy should concentrate on the convex surface at high frequency. These results should provide theoretical guidance not only for non-destructive evaluation of curved structures but also for the design of novel acoustic devices based on curved structures.

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approximate solution of deflection is chosen more correctly, and the explicit expression to find critical load and post-buckling torsional load-deflection curves is given. The effects of geometrical parameters and the effectiveness of stiffeners on the stability of the shell are investigated.

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ABSTRACT: One of the significant issues in the nanotube research community is buckling behavior. In the present work, the buckling of single-walled nanotubes (SWNTs), double-walled nanotubes (DWNTs) and multi-walled nanotubes (MWNTs) under axial compression is investigated. Buckling analysis for nanotube composite structures is performed by using layer-wise theory based on the nonlinear constitutive relations of Eringen. The governing equations of SWNTs, DWNTs and MWNTs are developed. Then analytical solutions are obtained using the state-space method. The effects of nanotube length, diameter and nonlocal parameter on the buckling loads are studied. The numerical results indicate that the nonlocal parameter is important for the buckling analysis of nanotube composite structures.

References listed at the end of the paper:

References listed at the end of the paper:
ABSTRACT: The nonlinear free vibration of non-prismatic single-walled carbon nanotubes (SWNTs) is studied using a new non-local shear deformable beam $p$-element. The effects of the internal length scale parameter, transverse shear deformation, rotary inertia, and geometrical nonlinearity are taken into account. The principle of virtual displacements and the harmonic balance method are used to derive the nonlinear equations of motion, which are solved iteratively by the linearized updated mode method to obtain the fundamental nonlinear frequencies and mode shapes of H–H, C–H, and C–C SWNTs with uniform, linear, and quadratic radius variation. The convergence and accuracy of the non-local shear deformable beam $p$-element are demonstrated through comparison with other methods. It is shown that the non-uniformity parameters influence significantly the backbone curves and mode shapes of non-prismatic SWNTs.

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ABSTRACT: In the present investigation, the buckling of generally laminated conical shells with various boundary conditions subjected to axial pressure is studied using an analytical approach. The governing equations are obtained using classical shell theory with Donnell assumptions in strain–deformation relations and the principle of minimum potential energy. The differential equations are solved using trigonometric functions in circumferential and power series in longitudinal directions. All types of boundary conditions can be applied in this method. The results are compared and validated with the results available in the literature, and good agreement is observed. Finally, the effects of the length, semi-vertex angle, and lamination sequences on the buckling load and mode shapes of generally laminated conical shells are presented.

References listed at the end of the paper:

ABSTRACT: This paper presents a generalized layerwise higher-order shear deformation theory for laminated composite and sandwich plates. We exploit a higher-order shear deformation theory in each layer such that the continuity of the displacement and transverse shear stresses at the layer interfaces is ensured. Thanks for enforcing the continuity of the displacement and transverse shear stresses at an inner-laminar layer, the minimum number of variables is retained from the present theory in comparison with other layerwise theories. The method requires only five variables, the same as what obtained from the first- and higher-order shear deformation theories. In comparison with the shear deformation theories based on the equivalent single layer, the present theory is capable of producing a higher accuracy for inner-laminar layer shear stresses. The free boundary conditions of transverse shear stresses at the top and bottom surfaces of the plate are fulfilled without any shear correction factors. The discrete system equations are derived from the Galerkin weak form, and the solution is obtained by isogeometric analysis (IGA). The discrete form requires the C1 continuity of the transverse displacement, and hence NURBS basis functions in IGA naturally ensure this condition. The laminated composite and sandwich plates with various geometries, aspect ratios, stiffness ratios and boundary conditions are studied. The obtained results are compared with the 3D elasticity solution, the analytical as well as numerical solutions based on various plate theories.

References listed at the end of the paper:
ABSTRACT: An efficient low-order finite shell element is derived for the thermo-elastic analysis of shell structures made of functionally graded materials. It is based on a one-way coupling between the thermal and the mechanical analysis. The thermal quantities are evaluated using a new iterative scheme that properly accounts for convection boundary conditions and large gradients of the thermal conductivity. The resulting non-constant temperature field with respect to the thickness direction gives nodal forces and couples, which are applied on a shear weak six-parameter shell formulation. Here, drill rotations are included, supplemented with a proper method for calculating effective elastic properties. Numerical results indicate the efficiency and accuracy of the proposed approach.

References listed at the end of the paper:

ABSTRACT: Free vibration analysis of functionally graded sandwich beams with general boundary conditions and resting on a Pasternak elastic foundation is presented by using strong form formulation based on modified Fourier series. Two types of common sandwich beams, namely beams with functionally graded face sheets and isotropic core and beams with isotropic face sheets and functionally graded core, are considered. The bilayered and single-layered functionally graded beams are obtained as special cases of sandwich beams. The effective
material properties of functionally graded materials are assumed to vary continuously in the thickness direction according to power-law distributions in terms of volume fraction of constituents and are estimated by Voigt model and Mori–Tanaka scheme. Based on the first-order shear deformation theory, the governing equations and boundary conditions can be obtained by Hamilton’s principle and can be solved using the modified Fourier series method which consists of the standard Fourier cosine series and several supplemented functions. A variety of numerical examples are presented to demonstrate the convergence, reliability and accuracy of the present method. Numerous new vibration results for functionally graded sandwich beams with general boundary conditions and resting on elastic foundations are given. The influence of the power-law indices and foundation parameters on the frequencies of the sandwich beams is also investigated.

References listed at the end of the paper:
Xiao-Jian Xu (1), Zi-Chen Deng (2), Kai Zhang (2) and Jun-Miao Meng (2)

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(2) Engineering Mechanics, Northwestern Polytechnical University, Xi’an, China


ABSTRACT: Surface effects are responsible for the size dependence and should be taken into account for dielectric structures at nanoscale dimensions. By incorporating the effects of surface stress, surface piezoelectricity, surface elasticity and surface piezomagnetism, this paper investigates the bending, buckling and free vibration of magneto-electro-elastic (MEE) beams based on the Euler–Bernoulli beam theory. The governing differential equation and its corresponding boundary conditions are derived by Hamilton’s principle. The analytical solutions for the magneto-electro-elastic bending deflection, buckling magnetic potentials and frequency equations of MEE beams are obtained. In contrast to the previously published works, the positive surface stress is found to stiffen the MEE beams, as evidenced by the decrease in the deflections, the increase in the buckling magnet potentials and the increase in the resonant frequencies. Numerical studies show the importance of the surface effects, the electric and magnetic potentials and boundary conditions on the static and dynamic behavior of MEE beams. This work may be of special interest in the design and application of smart
References listed at the end of the paper:

buckling load of system is reduced. It is anticipated that the results reported in this work are applied as a benchmark in future microstructure issues.

References listed at the end of the paper:
ABSTRACT: Surface stresses can significantly affect the mechanical behavior of structures when they are dependent behavior of nanostructures due to the surface stress effect in a continuum manner. The Gurtin–Murdoch surface elasticity theory has the capability to capture the size-dependent behavior of nanostructures due to the surface stress effect in a continuum manner. The present work is concerned with the application of Gurtin–Murdoch theory to the nonlinear free vibration analysis of circular cylindrical nanoshells with considering surface stress and shear deformation effects. The nonlinear governing equations of motion together with the corresponding boundary conditions are firstly derived using Hamilton’s principle, the first-order shear deformation shell theory and von Kármán’s assumption. An analytical approach is then presented to solve the nonlinear free vibration problem. Selected numerical results are given to illustrate the effects of surface energy on the nonlinear free vibration behavior of shear deformable nanoshells with different material and geometrical parameters. It is shown that there is a large difference between the results of Gurtin–Murdoch theory and those of its classical counterpart for very thin nanoshells.

References listed at the end of the paper:

A. Farajpour (1), M.R. Haeri Yazdi (2), A. Rastgoo (2) and M. Mohammadi (3)
(1) North Tehran Branch, Islamic Azad University, Tehran, Iran
(2) Mechanical Eng., University of Tehran, Iran
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ABSTRACT: In this paper, a new size-dependent plate model is developed based on the higher-order nonlocal strain gradient theory. The influences of higher-order deformations in conjunction with the higher- and lower-order nonlocal effects are taken into account. The presence of three different kinds of scale parameters in the
formulation results in a theory which is capable of capturing both reduction and increase in the stiffness of structures at nanoscale. The governing differential equations are derived for the buckling of nanoplates resting on a two-parameter elastic foundation using the principle of virtual work. The nanoplate is assumed to be orthotropic with size-dependent material properties. The influence of thermal stress caused by a temperature change is taken into consideration. An exact closed-form solution is obtained for the critical buckling loads of graphene sheets. The higher-order governing differential equation is also solved by the differential quadrature method. The results of the two solution methods are compared with each other. Excellent agreement between the exact and numerical results is observed. For numerical results, three types of graphene sheets with different aspect ratio are considered. The effects of various scale parameters together with the other parameters such as the coefficients of the elastic medium, temperature change and the length of the nanoplate on the buckling behavior of graphene sheets are investigated.

References listed at the end of the paper:
M. Mirzaei (1) and Y. Kiani (2)

(1) Mechanical Eng., University of Qom, Iran
(2) Faculty of Eng., Shahrekord University, Iran


ABSTRACT: In this research, large amplitude free vibrations of a sandwich beam with stiff core and carbon nanotube (CNT)-reinforced face sheets are analysed. The distribution of CNTs across the thickness of the face sheets may be uniform or functionally graded. The equivalent single-layer theory of Timoshenko is used to construct the Hamiltonian of the beam under the von Kármán type of geometrical nonlinearity assumptions. A uniform temperature field through the beam is also included in the formulation. The Ritz method with polynomial basis functions is used to discretize the equations of motion and establish the matrix representation of the governing equations. A nonlinear eigenvalue problem is obtained and solved using a standard continuation procedure. After validating the developed solution method and formulation, parametric studies are conducted to examine the influences of thermal environment, core thickness-to-face sheet thickness ratio, boundary conditions, amplitude of vibrations, CNTs volume fraction and their distribution pattern. It is concluded that an increase in the volume fraction of CNTs results in higher fundamental frequency and decreases the nonlinear-to-linear frequency ratio.

References listed at the end of the paper:


ABSTRACT: The thermally induced vibration of a simply supported single-walled carbon nanotube (SWCNT) subject to thermal stress is investigated by using the models of planar and non-planar nonlinear beams with initial stress, respectively. The dynamic equations of nonlinear stochastic vibration of the SWCNT are established, with the geometric nonlinearity of the large deformation taken into account. The thermal vibration of SWCNT is predicted by numerically integrating both the dynamic equations of the nonlinear beam models via the Runge–Kutta algorithm of fourth order. The root-mean-square (RMS) amplitude and the stationary probability density of the thermal vibration of the SWCNT are obtained via the planar and non-planar nonlinear beam models with simply supported boundary conditions for both pre-buckling case and post-buckling case. The RMS amplitude of the thermal vibration of the SWCNT is given by using the numerical integration of probability density function. The RMS amplitude of thermal vibration of a SWCNT predicted via the non-planar nonlinear model with thermal stress is lower than that predicted via the planar nonlinear beam model, but higher than that predicted via the planar linear model.

References listed at the end of the paper:


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ABSTRACT: Considering initial axial loads, dynamics and stability of an inner functionally graded cylindrical shell conveying swirling fluid (i.e., water) in the annulus between the flexible inner shell and the identical rigid outer shell are investigated by the traveling wave approach. Shell motions are described by Donnell’s thin shell equations. The fluid forces associated with shell motions are treated in the frame of the potential flow theory. The theoretical analysis is conducted by the zero-level contour method. The critical velocities of losing stability are determined. The influences of angular flow on the critical axial velocity and axial flow on the critical annular velocity are studied. Moreover, effects of the magnitude and the direction of initial axial loads on the critical velocities are fully discussed.

References listed at the end of the paper:

ABSTRACT: Using Reddy’s third-order shear deformation plate theory (TSDT) with von Kármán geometrical nonlinearity, this work presents an analytical solution on the buckling and postbuckling behaviors of eccentrically stiffened functionally graded material (ES-FGM) plates on elastic foundations subjected to in-plane compressive loads or thermal loads or thermo-mechanical loads. Plates are reinforced by closely spaced FGM stiffeners. The material properties of the plate and stiffeners are assumed to be temperature-dependent. Theoretical formulations based on the smeared stiffeners technique and TSDT are derived. The expressions of thermal parameters are found in the analytical form. Applying Galerkin method, the expressions to determine the critical buckling load and analyze the postbuckling mechanical and thermal load–deflection curves are obtained. Two iterative algorithms are presented for the case of temperature-dependent plate material properties. The effects of thermal element, FGM stiffeners, geometrical and material parameters, initial imperfection, and foundation are considered and discussed. By comparing the present results with those in references, the accuracy of the present study is affirmed.

References listed at the end of the paper:


Zhencai Zhu (1,2), Lei Zhang (1), Gang Shen (1,2) and Guohua Cao (1,2)
(1) Mechanical and Electrical Eng., China University of Mining and Technology, Xuzhou, China
(2) Mechanical and Electrical Equipment, China University of Mining and Technology, China

ABSTRACT: In this paper, a one-dimensional higher-order theory is presented for both static and dynamic analyses of thin-walled structures with rectangular hollow sections. The formulation has been enriched with four cubic distortional modes, capable of reproducing three-dimensional behavior of thin-walled structures in a very accurate way. Toward this end, a systematic procedure is developed to determine higher-order distortional modes for a rectangular hollow cross section. Then, involved with the application of the modal superposition method, the two- and three-dimensional displacement fields are reduced to one dimension with 11 degrees of freedom. Next, the principle of minimum potential energy and Hamilton’s principle are applied to formulate the static and dynamic governing equations of the thin-walled structure, respectively. At last, the finite element implementation is carried out by employing the \( C^0 \) interpolation function. Numerical examples are also presented to validate the new theory.

References listed at the end of the paper:

ABSTRACT: Vibration characteristics of moderately thick doubly curved functionally graded composite panels reinforced by carbon nanotube are analyzed. Here, special cases of doubly curved shell panels such as spherical,
cylindrical and hyperbolic paraboloid panels and five different distributions of carbon nanotubes through the thickness direction are considered. By utilizing the modified rule of mixture, mechanical properties are estimated. The equations of motion are derived via the first-order shear deformation theory, and non-dimensional frequencies are obtained by the use of Galerkin’s method. The suggested model is justified by a good agreement between the results given by present model and available data in the literature. The influences of volume fraction of carbon nanotubes, thickness ratio, aspect ratio, curvature ratio, and shallowness ratio on the frequencies of moderately thick doubly curved nanocomposite shell panels are also examined. Furthermore, the effect of various boundary conditions on the frequency analysis of doubly curved nanocomposite panels is studied, and the corresponding mode shapes are depicted.

References listed at the end of the paper:
ABSTRACT: The present work considers lamellar (micro) structures of thin, elastic lamellae embedded in a yielding matrix as a stability problem in the context of the theory of stability and uniqueness of path-dependent systems. The volume ratio of the stiff lamellae to the relatively soft matrix is assumed low enough to initiate a symmetric buckling mode, which is investigated by analytical and numerical means. Using a highly abstracted, incompatible model, a first approach is made, and the principal features of the problem are highlighted. Assuming plane strain deformation, an analytic expression for the bifurcation load of a refined, compatible model is derived for the special case of ideal plasticity and verified by numerical results. The effect of lamella spacing and matrix hardening on the bifurcation load is studied by a finite element unit cell model. Some of the findings for the ideal plastic matrix are shown to also apply for a mildly hardening matrix material. Furthermore, the postbuckling behaviour and the limit load are investigated by simulating a bulk lamella array. References listed at the end of the paper:


References listed at the end of the paper:
ABSTRACT: This paper is concerned with a detailed study of the crush behaviour of foam-filled conical frusta using numerical, analytical and experimental techniques. Finite element models of thin-walled frusta with and without metallic foam filler are developed to simulate their progressive collapse behaviour under axial crush loads. The finite element results are compared with a kinematically admissible analytical model developed earlier by the authors as well as experimentally using crush tests. The effect of key design parameters such as taper angle, slenderness ratio, and foam filling are carefully examined and discussed. The results show that introducing a taper angle in a straight column helps to reduce the initial crippling load and increases the resistance to global buckling. Besides, the filling of the metallic foam further increases the specific energy absorption efficiency. This is due to the densification of the filler foam and the reduction of the plastic fold length. This work is intended to provide guidelines for the design of thin-walled metallic energy absorbers.

References listed at the end of the paper:


ABSTRACT: In this study, an analytical method is proposed for the determination of the critical buckling loads of composite corrugated plates under nonlinearly distributed compressive loads. The composite corrugated plate is treated both as an original corrugated plate model and as a simplified anisotropic flat plate model with equivalent stiffness. By means of the equivalent energy and force methods, the equivalent flexural stiffness including the flexural-twist coupling stiffness of the original corrugated plate is obtained. We derive the critical buckling loads of composite corrugated plates under nonlinearly distributed compressive loads accounting for flexural-twist coupling based upon the large deflection equation of an anisotropic plate and the obtained equivalent flexural stiffness. The influence of flexural-twist coupling on the critical buckling loads is investigated for both trapezoidal and sinusoidal composite corrugated plates with different stacking sequences. Numerical examples demonstrate that the critical buckling loads obtained by the proposed method agree well with those calculated by the finite-element method. In addition, it is found that the flexural-twist coupling stiffness should be taken into account in the buckling analysis of composite corrugated plates.

References listed at the end of the paper:


ABSTRACT: This paper aims to study the vibration characteristics of viscoelastic double-walled carbon nanotubes embedded in a viscoelastic medium. In doing this, the governing equations of the system are derived by combining the Euler–Bernoulli beam theory, nonlocal viscoelastic model and Kelvin viscoelastic foundation model. Subsequently, the transfer function method is employed to solve the governing equations, which enables one to obtain the natural frequencies and the corresponding mode shapes in closed form for the DWCNTs with arbitrary boundary conditions. Here, the developed mechanics model is first compared with the existing techniques available in the literature, where excellent agreement is achieved. Also, a detailed parametric study is conducted to examine the effect of boundary conditions, nonlocal parameter, relaxation time, slenderness ratio, stiffness coefficient and damping coefficient on the vibration response of the DWCNTs.

References listed at the end of the paper:


Google the string: “Acta Mechanica Sinica”, then click on the first entry, “Acta Mechanica Sinica – Springer”, then, on the resulting screen, click on “All Volumes & Issues” (located on the right-hand side of the screen near the top, in blue color)

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ABSTRACT: The paper studies the axisymmetric compressive buckling behavior of multi-walled carbon nanotubes (MWNTs) under different boundary conditions based on continuum mechanics model. A buckling condition is derived for determining the critical buckling load and associated buckling mode of MWNTs, and numerical results are worked out for MWNTs with different aspect ratios under fixed and simply supported boundary conditions. It is shown that the critical buckling load of MWNTs is insensitive to boundary conditions, except for nanotubes with smaller radii and very small aspect ratio. The associated buckling modes for different layers of MWNTs are in-phase, and the buckling displacement ratios for different layers are independent of the boundary conditions and the length of MWNTs. Moreover, for simply supported boundary conditions, the critical buckling load is compared with the corresponding one for axial compressive buckling, which indicates that the critical buckling load for axial compressive buckling can be well approximated by the corresponding one for axisymmetric compressive buckling. In particular, for axial compressive buckling of double-walled carbon nanotubes, an analytical expression is given for approximating the critical buckling load. The present investigation may be of some help in further understanding the mechanical properties of MWNTs.

References listed at the end of the paper:

D. Karagiozova (1, 2), X.-W. Zhang (1, 3) and T.-X. Yu (1)
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ABSTRACT: The deformation and snap-through behaviour of a thin-walled elastic spherical shell statically compressed on a flat surface or impacted against a flat surface are studied theoretically and numerically in order to estimate the influence of the dynamic effects on the response. A table tennis ball is considered as an example of a thin-walled elastic shell. It is shown that the increase of the impact velocity leads to a variation of the deformed shape thus resulting in larger deformation energy. The increase of the contact force is caused by both the increased contribution of the inertia forces and contribution of the increased deformation energy. The contact force resulted from deformation/inertia of the ball and the shape of the deformed region are calculated by the proposed theoretical models and compared with the results from both the finite element analysis and some previously obtained experimental data. Good agreement is demonstrated.
References listed at the end of the paper:


S.T. Talebian (1), M. Tahani (1), M.H. Abolbashari (3) and S.M. Hosseini (2)
(1) Mechanical Eng., Ferdowesi University of Mashhad, Iran
(2) Industrial Eng., Ferdowesi University of Mashhad, Iran
(3) Mechanical Eng., Lean Production Engineering Research Center, Ferdowsi University of Mashhad, Iran
“A glance on the effects of temperature on axisymmetric dynamic behavior of multiwall carbon nanotubes”,

ABSTRACT: In this paper the effects of temperature on the radial breathing modes (RBMs) and radial wave propagation in multiwall carbon nanotubes (MWCNTs) are investigated using a continuum model of multiple elastic isotropic shells. The van der Waals forces between tubes are simulated as a nonlinear function of interlayer spacing of MWCNTs. The governing equations are solved using a finite element method. A wide range of innermost radius-to-thickness ratio of MWCNTs is considered to enhance the investigation. The presented solution is verified by comparing the results with those reported in the literature. The effects of temperature on the van der Waals interaction coefficient between layers of MWCNTs are examined. It is found that the variation of the van der Waals interaction coefficient at high temperature is sensible. Subsequently, variations of RBM frequencies and radial wave propagation in MWCNTs with temperatures up to 1 600 K are illustrated. It is shown that the thick MWCNTs are more sensible to temperature than the thin ones.

References listed at the end of the paper:
locking effects. The numeric efficiency of the proposed meshless formulation is illustrated by the numeric examples.

References listed at the end of the paper:

ABSTRACT: Electromechanical carbon nanothermometers are devices that work based on the interactions and relative motions of double-walled carbon nanotubes (DWCNTs). In this paper, the mechanics of carbon nanotubes (CNTs) constituting two well-known configurations for nanothermometer, namely shuttle configuration and telescope configuration are fully investigated. Lennard-Jones (LJ) potential function along with the continuum approximation is employed to investigate van der Waals (vdW) interactions between the interacting entities. Accordingly, semi-analytical expressions in terms of single integrals are obtained for vdW interactions. Acceptance condition and succion energy are studied for the shuttle configuration. In addition, a universal potential energy is presented for the shuttle configuration consisting of two finite CNTs. Also, for the telescope configuration, extensive studies are performed on the distributions of potential energy and interaction force for various radii and lengths of CNTs. It is found that these geometrical parameters have a considerable effect on the potential energy.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: In this work, the stability of a flexible thin cylindrical workpiece in turning is analyzed. A process model is derived based on a finite element representation of the workpiece flexibility and a nonlinear cutting force law. Repeated cutting of the same surface due to overlapping cuts is modeled with the help of a time delay. The stability of the so obtained system of periodic delay differential equations is then determined using an approximation as a time-discrete system and Floquet theory. The time-discrete system is obtained using the semi-discretization method. The method is implemented to analyze the stability of two different workpiece models of different thicknesses for different tool positions with respect to the jaw end. It is shown that the stability chart depends on the tool position as well as on the thickness.


ABSTRACT: In this work, the stability of a flexible thin cylindrical workpiece in turning is analyzed. A process model is derived based on a finite element representation of the workpiece flexibility and a nonlinear cutting force law. Repeated cutting of the same surface due to overlapping cuts is modeled with the help of a time delay. The stability of the so obtained system of periodic delay differential equations is then determined using an approximation as a time-discrete system and Floquet theory. The time-discrete system is obtained using the semi-discretization method. The method is implemented to analyze the stability of two different workpiece models of different thicknesses for different tool positions with respect to the jaw end. It is shown that the stability chart depends on the tool position as well as on the thickness.

References listed at the end of the paper:


Bo Wang (1), Peng Hao (1), Gang Li (1), Jia-Xin Zhang (1), Kai-Fan Du (1), Kuo Tian (1), Ziao-Jun Wang (2) and Ziao-Han Tang (2)
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ABSTRACT: A concept of hierarchical stiffened shell is proposed in this study, aiming at reducing the imperfection sensitivity without adding additional weight. Hierarchical stiffened shell is composed of major stiffeners and minor stiffeners, and the minor stiffeners are generally distributed between adjacent major stiffeners. For various types of geometric imperfections, e.g., eigenmode-shape imperfections, hierarchical stiffened shell shows significantly low imperfection sensitivity compared to traditional stiffened shell. Furthermore, a surrogate-based optimization framework is proposed to search for the hierarchical optimum design. Then, two optimum designs based on two different optimization objectives (including the critical buckling load and the weighted sum of collapse loads of geometrically imperfect shells with small- and large-amplitude imperfections) are compared and discussed in detail. The illustrative example demonstrates the
inherent superiority of hierarchical stiffened shells in resisting imperfections and the effectiveness of the proposed framework. Moreover, the decrease of imperfection sensitivity can finally be converted into a decrease of structural weight, which is particularly important in the development of large-diameter launch vehicles.

References listed at the end of the paper:

ABSTRACT: A new 4-node quadrilateral flat shell element is developed for geometrically nonlinear analyses of thin and moderately thick laminated shell structures. The flat shell element is constructed by combining a quadrilateral area coordinate method (QAC) based membrane element AGQ6-II, and a Timoshenko beam function (TBF) method based shear deformable plate bending element ARS-Q12. In order to model folded plates and connect with beam elements, the drilling stiffness is added to the element stiffness matrix based on the mixed variational principle. The transverse shear rigidity matrix, based on the first-order shear deformation theory (FSDT), for the laminated composite plate is evaluated using the transverse equilibrium conditions, while the shear correction factors are not needed. The conventional TBF methods are also modified to efficiently calculate the element stiffness for laminate. The new shell element is extended to large deflection and post-buckling analyses of isotropic and laminated composite shells based on the element independent corotational formulation. Numerical results show that the present shell element has an excellent numerical performance for the test examples, and is applicable to stiffened plates.

References listed at the end of the paper:


ABSTRACT: Prediction of wrinkling characteristics is strongly correlated with the strain perpendicular to wrinkling direction. In this paper, the strain field of wrinkled membrane is tested by VIC-3D system based on the digital image correlation technique. Experimental results are validated by the tension wrinkling simulation. The experimental strain perpendicular to wrinkling direction is analyzed in depth. The wrinkling strain of a square wrinkled membrane under corner tension is extracted from experimental strain perpendicular to wrinkling direction. A quantitative characterization format of the experimental wrinkling strain is proposed. A modified prediction method of wrinkling amplitude is presented based on the experimental wrinkling strain. The results show that the precision of modified prediction model has improved 13.2% compared with the classical prediction model. The results reveal that the modified model can give an accurate prediction of the wrinkling amplitude.

References listed at the end of the paper:
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(2) Civil Eng., The University of Queensland, St. Lucia, Australia
(3) Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora, Australia


ABSTRACT: In this paper, the free vibration of magneto-electro-elastic (MEE) nanoplates is investigated based on the nonlocal theory and Kirchhoff plate theory. The MEE nanoplate is assumed as all edges simply supported rectangular plate subjected to the biaxial force, external electric potential, external magnetic potential, and temperature rise. By using the Hamilton’s principle, the governing equations and boundary conditions are derived and then solved analytically to obtain the natural frequencies of MEE nanoplates. A parametric study is presented to examine the effect of the nonlocal parameter, thermo-magneto-electro-mechanical loadings and aspect ratio on the vibration characteristics of MEE nanoplates. It is found that the natural frequency is quite sensitive to the mechanical loading, electric loading and magnetic loading, while it is insensitive to the thermal loading.

References listed at the end of the paper:

ABSTRACT: Because of the interaction between film and substrate, the film buckling stress can vary significantly, depending on the delamination geometry, the film and substrate mechanical properties. The Mexican hat effect indicates such interaction. An analytical method is presented, and related dimensional analysis shows that a single dimensionless parameter can effectively evaluate the effect.

References listed at the end of the paper:

ABSTRACT: A theoretical model is proposed in this paper to predict the bi-stable states of initially stressed cylindrical shell structures attached by surface anisotropic piezoelectric layers. The condition for existence of bi-stability of the shell structural system is presented and analytical expressions for corresponding rolled-up radii of the stable shell are given based on the principle of minimum strain energy. The resulting solution indicates that the shell system may have two stable configurations besides its initial state under a combined action of the actuating electric field and initial stresses characterized by the bending moment. If the piezoelectric layer materials act as only sensor materials without the actuating electric field, initial stresses may produce the bi-stable states, but one corresponding to its initial state. For the shell without initial stresses, the magnitude in the actuating electric field determines the number of the stable states, one or two stable configurations besides the initial state. The theoretical prediction for the bi-stable states is verified by finite element method (FEM) simulation by using the ABAQUS code.

References listed at the end of the paper:


ABSTRACT: A kinetics approach is developed for the geometrically nonlinear analysis of photo-induced wrinkling of glassy twist nematic films on soft elastic substrates. In this way, the problem is reduced to finding the steady state of an overdamped evolution system according to a kinetic law, rather than directly solving the coupled nonlinear equations. This enables one to account for the complicated director distribution and obtain the precise wrinkling morphology of the film. Though the approach proposed here is for a twist nematic film, it can be extended to study glassy nematic films with other director distributions.

References listed at the end of the paper:
a Timoshenko nanobeam. The equations of motion of the nanoscale pipe are obtained based on Hamilton’s principle and the Gurtin–Murdock continuum elasticity incorporating the surface stress effect. Afterwards, the generalized differential quadrature method is employed to discretize the governing equations and associated boundary conditions. To what extent important parameters such as the thickness, material and surface stress modulus, residual surface stress, surface density, and boundary conditions influence the natural frequency of nanoscale pipes and the critical velocity of fluid is discussed

References listed at the end of the paper:
ABSTRACT: Self-excited oscillation in a collapsible tube is an important phenomenon in physiology. An
experimental approach on self-excited oscillation in a thin-walled collapsible tube is developed by using a high transmittance and low Young’s modulus silicone rubber tube. The elastic tube is manufactured by the method of centrifugal casting in our laboratory. An optical method for recording the evolution of the cross-sectional areas at a certain position along the longitudinal direction of the tube is developed based on the technology of refractive index matching. With the transparent tube, the tube law is measured under the static no-flow condition. The cross section at the middle position of the tube transfers from a quasi-circular configuration to an ellipse, and then to a dumbell-shape as the chamber pressure is increased. During the self-excited oscillation, two periodic self-excited oscillating states and one transitional oscillating state are identified. They all belong to the LU mode. These different oscillating states are related to the initial cross-sectional shape of the tube caused by the difference of the downstream transmural pressure.

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7. Patterson, S.W., Starling, E.H.: On the mechanical factors which determine the output ventricles. J. Physiol. 48, 357–379 (1914)

ABSTRACT: The free vibration characteristics of fluid-filled functionally graded cylindrical shells buried partially in elastic foundations are investigated by an analytical method. The elastic foundation of partial axial and angular dimensions is represented by the Pasternak model. The motion of the shells is represented by the first-order shear deformation theory to account for rotary inertia and transverse shear strains. The functionally graded cylindrical shells are composed of stainless steel and silicon nitride. Material properties vary continuously through the thickness according to a power law distribution in terms of the volume fraction of the constituents. The governing equation is obtained using the Rayleigh–Ritz method and a variation approach. The fluid is described by the classical potential flow theory. Numerical examples are presented and compared with existing available results to validate the present method.

References listed at the end of the paper:
ABSTRACT: In this paper, a model of topology optimization with linear buckling constraints is established based on an independent and continuous mapping method to minimize the plate/shell structure weight. A composite exponential function (CEF) is selected as filtering functions for element weight, the element stiffness matrix and the element geometric stiffness matrix, which recognize the design variables, and to implement the changing process of design variables from “discrete” to “continuous” and back to “discrete”. The buckling constraints are approximated as explicit formulations based on the Taylor expansion and the thin-walled or thick shell theory. The optimization model is transformed to dual programming and solved by the dual sequence quadratic programming algorithm. Finally, three numerical examples with power function and CEF as filter function are demonstrated the feasibility and efficiency of the proposed method.

References listed at the end of the paper:


ABSTRACT: Based on the nonlocal elasticity theory, the vibration behavior of circular double-layered graphene sheets (DLGSs) resting on the Winkler- and Pasternak-type elastic foundations in a thermal environment is investigated. The governing equation is derived on the basis of Eringen’s nonlocal elasticity and the classical plate theory (CLPT). The initial thermal loading is assumed to be due to a uniform temperature rise throughout the thickness direction. Using the generalized differential quadrature (GDQ) method and periodic differential operators in radial and circumferential directions, respectively, the governing equation is discretized. DLGSs with clamped and simply-supported boundary conditions are studied and the influence of van der Waals (vdW) interaction forces is taken into account. In the numerical results, the effects of various parameters such as elastic medium coefficients, radius-to-thickness ratio, thermal loading and nonlocal parameter are examined on both in-phase and anti-phase natural frequencies. The results show that the thermal load and elastic foundation respectively decreases and increases the fundamental frequencies of DLGSs.

References listed at the end of the paper:
ABSTRACT: A semi-analytical model for determining the equilibrium configuration and the radial breathing mode (RBM) frequency of single-wall carbon nanotubes (CNTs) is presented. By taking advantage of the symmetry characteristics, a CNT structure is represented by five independent variables. A line search optimization procedure is employed to determine the equilibrium values of these variables by minimizing the potential energy. With the equilibrium configuration obtained, the semi-analytical model enables an efficient calculation of the RBM frequency of the CNTs. The radius and radial breathing mode frequency results obtained from the semi-analytical approach are compared with those from molecular dynamics (MD) and ab initio calculations. The results demonstrate that the semi-analytical approach offers an efficient and accurate way to determine the equilibrium structure and radial breathing mode frequency of CNTs.

References listed at the end of the paper:

ABSTRACT: This article presents closed-form solutions for the frequency analysis of rectangular functionally graded material (FGM) thin plates subjected to initially in-plane loads and with an elastic foundation. Based on classical thin plate theory, the governing differential equations are derived using Hamilton’s principle. A neutral surface is used to eliminate stretching–bending coupling in FGM plates on the basis of the assumption of constant Poisson’s ratio. The resulting governing equation of FGM thin plates has the same form as homogeneous thin plates. The separation-of-variables method is adopted to obtain solutions for the free vibration problems of rectangular FGM thin plates with separable boundary conditions, including, for example, clamped plates. The obtained normal modes and frequencies are in elegant closed forms, and present formulations and solutions are validated by comparing present results with those in the literature and finite element method results obtained by the authors. A parameter study reveals the effects of the power law index $n$ and aspect ratio $a/b$ on frequencies.

References listed at the end of the paper:


Google the string: “AIAA Journal”, then scroll down for a list of all issues, each of which you can click on to see authors, titles and abstract of papers.

ABSTRACT (cannot cut and paste abstract nor references)


ABSTRACT: This paper compares early and very recent approaches to the static analysis of reinforced-shell wing structures. Early approaches were those based on the pure semimonocoque theory along with the beam assumptions of the Euler–Bernoulli and Timoshenko type. The recent approaches are based on a hierarchical, one-dimensional formulation. These are obtained by adopting various polynomial expansions of the displacement field above the cross-section of the structure according to the unified formulation which was recently proposed by the first author. Two classes were developed in the unified formulation framework. In the first class, Taylor expansion models were developed by exploiting N-order Taylor-like polynomials; classical beam theories (Euler–Bernoulli and Timoshenko) were obtained as special cases of Taylor expansion. In the second class, Lagrange expansion models were built by means of four- and nine-point Lagrange-type polynomials over the cross-section of the wing. The component-wise approach was obtained by using different four- and nine-point Lagrangian descriptions for different wing components including panels, ribs, spar caps, stringers, and transverse ribs. The finite element method was used to develop numerical applications in the weak form. Finite element matrices and vectors are expressed in terms of fundamental nuclei whose forms do not formally depend on the order and the expansion. A number of typical aeronautical structures were analyzed, and semimonocoque results were compared to classical (Euler–Bernoulli and Timoshenko), refined (Taylor expansion), and component-wise (Lagrange expansion) models. Stress and displacement fields of simple statically determinate, redundant, and open-section wing-box structures were analyzed. Finite element models by a commercial software that make use of solid and shell elements were used for comparison purposes. Results have highlighted the enhanced capabilities of the present refined and component-wise formulations. The present component-wise approach appears to be the natural tool to analyze wing structures because it leads to results that can only be obtained by the use of three-dimensional elasticity (solid) elements whose costs are at least one order of magnitude higher than component-wise cases. Component-wise models in conjunction with finite elements could be seen as a modern way of analyzing reinforced-shell structures by removing classical assumptions of constant shear in the spar webs and panels.

ABSTRACT: A minimum-mass optimization strategy for variable-angle-tow panels subject to buckling and manufacturing constraints is presented. The optimization is performed using a fast-running optimization package that employs infinite-strip analysis for buckling and a gradient-based optimization method. A new variable-angle-tow-panel manufacturing method, continuous tow shearing, providing good quality, is considered in the optimization strategy where variable thickness occurs due to the shear deformation of dry tows. Optimum designs of variable-angle-tow panels are obtained and compared with panels without thickness variation. Different panel boundary conditions are investigated and discussed. The results show that boundary conditions have dramatic effects on optimum fiber paths. Over 20% mass saving is obtained for the optimization strategy with thickness variation compared with the design without thickness variation. The buckling strains are reduced to a practical level when the thickness variation is considered in the optimization. The buckling loads and mode shapes obtained from the infinite-strip method are in a good agreement with finite-element results. The optimization strategy provides structurally efficient solutions with good precision and low computational cost.


ABSTRACT: In the present study, new nonpolynomial shear-deformation theories are proposed and implemented for structural responses of laminated-composite and sandwich plates. The theories assume nonlinear distribution of transverse shear stresses, and also satisfy the traction-free boundary conditions at the top and bottom layers of the laminates. The governing differential equations are derived for a generalized shear-deformation theory by implementing the dynamic version of principle of virtual work and calculus of variations. A generalized closed-form solution methodology of the Navier type is implemented to ensure the validity and efficiency of the present theories for bending, buckling, and free-vibration responses of the laminated-composite and sandwich plates. It is observed that the proposed formulation in conjunction with the solution methodology is capable of handling all existing five-degree-of-freedom-based shear-deformation theories. The comparison of results also shows that the adequate choice of shear deformation leads to an accurate prediction of structural responses. The influence of shear deformation on the type of analysis performed is also observed in this study. The theories are also capable of an efficient prediction of the responses of structures at a similar computational cost as that of other equivalent single-layer theories.


ABSTRACT: This paper presents an experimental and numerical study of the folding, stowage, and deployment behavior of viscoelastic tape springs. Experiments show that during folding the relationship between load and displacement is nonlinear and varies with rate and temperature. In particular, the limit and propagation loads increase with the folding rate but decrease with temperature. During stowage, relaxation behavior leads to a reduction in internal forces that significantly impacts the subsequent deployment dynamics. The deployment behavior starts with a short, dynamic transient that is followed by a steady deployment and ends with a slow creep recovery. Unlike elastic tape springs, localized folds in viscoelastic tape springs do not move during deployment. Finite-element simulations based on a linear viscoelastic constitutive model with an experimentally determined relaxation modulus are shown to accurately reproduce the experimentally observed behavior, and to
capture the effects of geometric nonlinearity, time and temperature dependence.


ABSTRACT: The geometrically nonlinear behavior of modern soft-core sandwich plates is studied. For this purpose, a specially tailored geometrically nonlinear finite element that is based on a high-order sandwich plate theory is developed. The theory uses a von Kármán type of geometrical nonlinearity in the face sheets and account for shear and through the thickness deformability of the core. The conversion of the theory to a specially tailored finite element extends its applicability to a wide range of structural layouts, allows the use of standard numerical techniques, and simplifies the coupling with other elements. Yet it avoids the need for meshing through the thickness of the plate. The application of the specially tailored finite element to the geometrically nonlinear analysis of in-plane and out-of-plane loaded sandwich plates explores many interesting physical phenomena. Among them, the evolution of localized instabilities during a globally stable load-deflection behavior, the development of localized diagonal wrinkling patterns, and their impact on the interfacial stresses are listed. The development of unique load resisting mechanisms and, particularly, the evolution of these mechanisms along the geometrically nonlinear response path are also detected. The paper discusses these effects and their role in the geometrically nonlinear behavior of the soft-core sandwich plate.


ABSTRACT: This paper outlines an architecture for simultaneous analysis, robustness, and reliability calculations in aircraft wing design optimization. Robust design optimization and reliability-based design optimization are unified in a mixed formulation, which streamlines the setup of optimization problems and aims at preventing foreseeable implementation issues in uncertainty-based design while ensuring that the performance hit of robustness/reliability assessments is kept to a minimum. To avoid the extra computation time that would be the result of a direct evaluation approach to nondeterministic optimization, Kriging surrogate models are employed, and an alternative implementation of the reliability subproblem is also proposed. The sigma point method is used to compute statistical moments in the robust objective function. The computational effort of reliability analysis is further reduced through the implementation of a coordinate change in the respective optimization subproblem to solve for the distance from the current iterate to the most probable point of failure. Robustness and reliability-based optimization is tested on both simple analytic problems and more complex wing design problems, across a range of statistical variation, revealing that performance benefits can still be achieved while obeying precise probabilistic constraints.
ABSTRACT: A simplified four-unknown shear and normal deformation plate theory is proposed. It is used to study the response of multilayered angle-ply composite plates due to a variation in temperature and moisture concentrations. The effects of temperature and moisture concentrations on the material properties and the hygrothermal response of multilayered angle-ply composite plates are studied. A number of examples are solved to illustrate the numerical results concerning bending response of multilayered angle-ply composite plates subjected to hygrothermal effects. It is suggested that temperature-dependent and/or moisture-dependent material properties ought to be used in the analysis of laminated plates subjected to hygrothermal loads. Additional comparisons between the present theory and the classical, uniform, and parabolic shear deformation plate theories are made to show how the effect of transverse normal strain is highly significant.

ABSTRACT: A new bilevel optimization strategy for wing design is developed, in which the optimizations of the wing-planform and wing-airfoil shapes are decoupled from each other. The design of the wing-planform shape and the shape of the airfoils in several spanwise positions are considered as the goal of the optimization. In the new approach, the design problem is decomposed into a series of subproblems based on the design variables. The design variables defining the wing-planform shape are optimized in a top-level optimization, and the design variables defining the shape of airfoils in several spanwise positions are optimized in several sublevel optimizations. To take into account the influence of the airfoil shape in a specific spanwise position on the shape of the airfoils in other spanwise positions, a series of design variables are added to the design vector of the top-level optimization. The top-level optimizer is responsible for the consistency of the optimization. Using this approach, the number of design variables in the top-level optimization is reduced; the airfoils in several spanwise positions are optimized in parallel; and, instead of complex three-dimensional aerodynamic and structural solvers, much simpler and faster two-dimensional airfoil analysis tools can be used.

ABSTRACT: An efficient Co continuous two-dimensional finite-element model has been presented in this paper for the control of laminated composite and sandwich plates embedded/surface-bonded with piezoelectric layers and subjected to mechanical loading as well as electric potential. The problem of modeling of smart laminates involves the coupling between mechanical and electrical fields. The structural component is modeled by an efficient equivalent single-layer plate theory, which ensures interlaminar shear-stress continuity and zero transverse shear-stress conditions at the top and bottom of the plate surfaces. Moreover, this theory contains unknowns defined at the reference plane (i.e., midplane) only. The electric field is modeled using layerwise theory, which contains the unknowns at each layer interfaces. The proposed combine model, which may be called a refined hybrid plate model, is implemented to analyze the coupled problem of piezoelectricity in laminated composites and sandwich plates.

ABSTRACT: An aeroelastic model is developed by using multivariable solid-shell elements. Geometrical nonlinearity and the elimination of corresponding locking phenomena are considered accurately in the modeling. Unsteady aerodynamic forces are addressed by solving Euler flow dynamic equations. The computational-structural-dynamics solver is loosely coupled to the computational-fluid-dynamics solver, and the full match of the computational structural dynamics and computational fluid dynamics interfaces is achieved by three-dimensional modeling. An interpolation method using finite-element shape functions is developed to transform forces from aerodynamic grids to structural grids. The aerodynamic mesh deformation is obtained by using radial basis functions combined with the transfinite interpolation method. The aeroelastic model is validated through the study of the flutter and the limit cycle oscillation of a cropped delta wing in transonic flow. Moreover, the establishment of the aeroelastic model using multivariable solid shell elements is compared with other modeling methods. Improved numerical results show that the multivariable finite-element method is an efficient and capable tool for simulating geometrical nonlinearity, and the developed three-dimensional data-exchange method also plays a key role in the nonlinear aeroelastic modeling.


ABSTRACT: This paper proposes a kind of support structure for inflatable deployable reflector. The surface accuracy, which is crucially important to the performance of the reflector, is maintained by support ribs stretched by the tension system. To obtain sufficient surface accuracy, a reverse design algorithm is proposed to design the initial lower-edge shape of the support rib, which is verified by the current experiment. Also, the morphing characteristics of the support rib under different tensions are tested using the Vic-3D whole strain testing system. From the results of the experiments and simulations, some effective control strategies are presented to resist the local buckles of rib. The main approach is to introduce some transverse constraints that are perpendicular to the rib at the local buckling positions. Finally, by comparison between different strategies, an effective control strategy is confirmed to improve the structure accuracy and stability. The results are of great benefit to the design and shape control of inflatable antenna reflectors.


ABSTRACT: A new formulation for corotational nonlinear dynamic analysis of thin-shell structures involving large displacements and finite rotations has been presented in this paper. By introducing the kinematic description of the geometrically exact quasi-static shell model to describe the motion of an arbitrary material point in a triangular shell element, the new expressions for the inertial force vector and tangent inertia matrix were derived systematically. The elastic deformation was handled by using the consistent symmetrizable equilibrated corotational formulation, which is independent with respect to the local finite element modeling. An energy-momentum-conserving algorithm and an energy-decaying/momentum-conserving algorithm were developed for nonlinear dynamic analysis by applying the generalized energy-momentum method in the
corotational formulation. Three classic numerical examples, including the dynamic response, free motion, and dynamic buckling of thin-shell structures, were computed to verify the accuracy and capability of the presented formulation for solving the nonlinear dynamic problems of thin-shell structures with finite rotations. In the relevant numerical example, the conservations of linear momentum and angular momentum of a shell structure due to the time-integration algorithms in the corotational formulation were investigated.


ABSTRACT: This paper presents an experimental study on the thermal buckling behavior of sandwich panels with truss cores. The ultimate goal is to find the critical buckling temperature and examine postbuckling behavior of this newly developed sandwich panel experimentally. A specifically designed fixture, which can introduce in-plane loads to the sandwich panel through thermal expansion mismatch between the specimen and the load frame, is applied in the experiment. High-temperature strain gauges are attached at the center of the sandwich panel face sheets to measure the local in-plane response, and the critical buckling temperature of panels deformed in symmetric mode is determined by using the Southwell method. To obtain the full-field postbuckling mode as well as critical buckling temperature of the sandwich panel deformed in asymmetric mode in high-temperature environments, a noncontact measurement system based on the three-dimensional digital image correlation technique is also developed. The accuracy of the present noncontact measurement technique is validated by the coordinate measurement machine technique, a conventional contact measurement method. It is found that the critical buckling temperature obtained from experiments is lower than that predicted by theoretical and numerical models, due to defects and imperfections of the truss core and sandwich panel during fabrication. Full-field measurement also indicates that local yielding together with overall buckling is the typical deformation mode in the tested specimen.


ABSTRACT: The transient blast response of a sandwich panel that consists of a compressible core with in-plane rigidity using the extended high-order sandwich panel theory is presented and compared with elasticity closed-form solutions. The mathematical formulation of the extended high-order sandwich panel theory for the transient dynamic response of sandwich plates is described along with a numerical investigation. The extended high-order sandwich panel theory formulation takes into account the shear resistance of the core and its compressibility, which is envisaged through nonidentical displacements of the upper and the lower facesheets and its in-plane rigidity. The equations of motion and the appropriate boundary conditions are derived using the Hamilton’s principle. A numerical investigation is conducted on a simply supported sandwich panel, and its results are compared with a benchmark elasticity closed-form solution. The results include deformed shapes at the first millisecond at various time steps; displacements of the various constituents, as well as various stress resultants in the facesheets; and stress distributions within the core and at its interfaces with the facesheets. The extended high-order sandwich panel theory and the elasticity benchmark results correlate very well. Finally, a summary is presented and conclusions are drawn.

ABSTRACT: A computational aeroelastic model is presented for a cantilevered plate rotated from a position with the clamped edge normal to the flow (0 deg) to where the clamped edge is aligned with the flow (90 deg) using a new inextensible plate theory. A large-amplitude limit-cycle oscillation has been observed beyond the linear flutter speed in both the computations and in a wind-tunnel experiment. The computations and experiments for the limit-cycle oscillation response of the several yawed plate aeroelastic models show that the inextensible plate theory produces results in good agreement with the measurements. Also, a comparison with results obtained using von Kármán’s nonlinear plate theory has been made.


ABSTRACT: A finite element method based approach is developed for studying the static, vibration, and buckling behaviors of curvilinearly stiffened plates in the presence of in-plane compressive and tensile stresses. The first-order shear deformation theory is employed for both the plate and the Timoshenko beam modeling. Interpolation functions are used to build the displacement mapping between the stiffener and the plate nodes to allow the stiffener to be placed anywhere within the plate. One of the advantages of the present method is that the plate need not be remeshed while the stiffener configuration is changed; another advantage is that the results obtained by the present method with a much fewer number of elements match well with the results obtained by using a commercial finite element method software. Several numerical examples are solved to study both the static and dynamic behaviors of stiffened plates. The effects of boundary conditions, stiffener eccentricity, stiffener curvature, stiffener-plate geometry parameters, in-plane load condition, stiffener-plate cross-section area ratio, and stiffness ratio on the static and dynamic behaviors of a curvilinearly stiffened plate are investigated. Results have shown that the behavior of the natural frequency parameter as a function of applied in-plane stress could be affected by the plate thickness, in-plane load condition, stiffener-plate cross-section area ratio, and stiffness ratio during compression only, but not when subjected to in-plane tension.


ABSTRACT: The three-dimensional linear dynamic elasticity problem formulation and solution for a generally asymmetric sandwich plate consisting of core and face sheets that are orthotropic, and subjected to blast loading, is presented. Laplace transforms are used to obtain ordinary differential equations in the complex Laplace space (with the variable being the through-thickness coordinate), which are subsequently solved in closed form for a simply supported plate, with the solution involving a cubic characteristic equation with complex coefficients. Subsequently, the time response is obtained by a numerical inverse Laplace transform by use of the Euler method. A realistic material and blast case is used to demonstrate the transient behavior for the displacements and face sheet/core interfacial transverse normal and shear stresses. The elasticity results are compared with the predictions of the first-order shear deformation plate theory as well as a high-order sandwich panel theory. This dynamic elasticity solution can serve as a benchmark in assessing the accuracy of sandwich-plate theories.


ABSTRACT: Tow-steered composites are optimized for use in tailoring the aeroelastic behavior of a simple two-dimensional composite wing, with particular emphasis on improving both flutter/divergence airspeeds and
gust loads. Symmetric layups are considered where the fibers vary in orientation along the wingspan and chord. Tow-steered laminates were found to increase the instability airspeed by up to 7% compared with optimized straight-fiber laminates and by 13% compared with optimized laminates with standard \((0/\pm 45/90\,\text{deg})\) plies. Tow-steered laminates were also found to reduce the peak wing root gust loads (up to 52%) and the correlated gust loads (up to 24%). The lowest gust loads were reached with higher order nonlinear fiber angle variations when either all plies were optimized or when two-dimensional fiber angle variations were used. Optimization strategies that allowed the fiber angles to vary freely in each ply generally performed better than optimizations based on the rotation of \((0/\pm 45/90\,\text{deg})\)-ply stacks along the span of the wing.


ABSTRACT: A boundary-discontinuous generalized double Fourier-series-based solution to the problem of deformation of a finite-dimensional general cross-ply thick, doubly curved panel with negative Gaussian curvature and of rectangular planform, modeled using a higher-order shear deformation theory, is presented. This spectral method is used to solve a system of five highly coupled, linear partial differential equations, generated by the higher-order shear deformation theory-based laminated shell analysis, with the simply supported of type 2 boundary condition prescribed on two opposite edges, whereas the remaining two edges are subjected to the simply supported of type 3 constraint. The hitherto unavailable important numerical results presented include sensitivity of the predicted response quantities of interest to shell geometry (negative or positive Gaussian curvature), lamination and thickness effects, as well as their interactions.


ABSTRACT: In this work, a nonlinear state-space-based identification method is proposed to describe compactly unsteady aerodynamic responses. Such a reduced-order model is trained on a series of signals that implicitly represent the relationship between the structural motion and the aerodynamic loads. The determination of the model parameters is obtained through a two-level training procedure where, in the first stage, the matrices associated to the linear part of the model are computed by a robust subspace projection technique, whereas the remaining nonlinear terms are determined by an output error-minimization procedure in the second stage. The present approach is tested on two different problems, proving the convergence toward the reference results obtained by a computational fluid dynamics solver in linear and nonlinear, aerodynamic, and aeroelastic applications, whereas the aerodynamic reduced-order models are coupled with the related structural mechanical systems, demonstrating the ability of capturing the main nonlinear features of the response. The robustness of the reduced-order model is then tested considering a series of inputs with varying amplitudes and frequencies outside the range of interest and computing aeroelastic responses with nonnull pretwist angles.


ABSTRACT: Variations of manufacturing process parameters, environment aspects, and imperfections may significantly affect the quality and performance of stiffened shells. The reliability-based design optimization (RBDO) of stiffened shells, considering all these uncertainty factors simultaneously, is extremely time-consuming, even if the surrogate-based technology is used. Therefore, a hybrid bi-stage framework for RBDO of stiffened shells is presented to release the computational burden, where two main sources of uncertainties are
considered: variations of material properties and geometric dimensions are described as random variables, while various forms of imperfections of stiffened shells are covered by the single perturbation load approach. The basic idea of the proposed method is to combine the efficiency of smeared stiffener method with the accuracy of finite element method, and then narrow the design window efficiently with little accuracy sacrifice. The adaptive chaos control method is used to ensure the robustness of the search process of the most probable target point. The numerical example illustrates the advantage of the proposed method over other RBDO approaches from the point of view of computational cost, accuracy and robustness of the result.


**ABSTRACT:** The extended high-order sandwich panel theory was formulated in its one-dimensional version for orthotropic elastic sandwich beams. This theory includes the in-plane rigidity of the core, and the compressibility of the soft core in the transverse direction is also considered. The novelty of this theory is that it allows for three generalized coordinates in the core (the axial and transverse displacements at the centroid of the core, and the rotation at the centroid of the core) instead of just one (midpoint transverse displacement) commonly adopted in other available theories. The theory was derived so that all core/face displacement continuity conditions are fulfilled. It is proven, by comparison to the elasticity solution, that this approach results in superior accuracy, especially for the cases of stiffer cores, for which cases of the other available sandwich computational models cannot correctly predict the stress fields involved. In this paper, a linear finite element is formulated based on the extended high-order sandwich panel theory. The element equations are outlined, and numerical results for the simply supported case of transverse distributed loading are produced for several typical sandwich configurations. These results are compared with the corresponding ones from the elasticity solution. The comparison among these numerical results shows that, with a relatively small number of elements, the results are very close to the elasticity ones in terms of both the displacements and stress or strains. Thus, the finite element version of the extended high-order sandwich panel theory constitutes a very powerful analytical tool for sandwich panels.


**ABSTRACT:** A partitioned fluid–structure coupling code for transonic panel flutter has been developed and validated. The Reynolds-averaged Navier–Stokes equations are solved numerically by means of an implicit finite volume method to account for nonlinear aerodynamics, as there are shock waves and a viscous boundary layer at the panel surface. An implicit finite element formulation of the structural equations, as well as a Galerkin solution of the von Kármán plate equation are employed to solve elastic panel deformations with respect to geometric nonlinearities. A detailed validation process has shown good agreement with results from the literature for high subsonic and low supersonic Mach numbers. Thereby, a recent comparison between theory and experiment is confirmed. The validated solver is then used for further studies focusing on the impact of turbulent boundary layers on aeroelastic stability boundaries and instabilities. An increase in aerodynamic damping due to a viscous boundary layer is identified by an increase of the aeroelastic stability boundary. Furthermore, a significant damping on high flutter frequencies and mode shapes is revealed. The application of either a one-equation or two-equation turbulence model did not cause any major deviations in the results.

ABSTRACT: Variable-angle tow describes fibers in a composite lamina that have been steered curvilinearly. In doing so, substantially enlarged freedom for stiffness tailoring of composite laminates is enabled. Variable-angle tow composite structures have been shown to have improved buckling and postbuckling load-carrying capability when compared to straight fiber composites. However, their structural analysis and optimal design is more computationally expensive due to the exponential increase in number of variables associated with spatially varying planar fiber orientations in addition to stacking sequence considerations. In this work, an efficient two-level optimization framework using lamination parameters as design variables has been enhanced and generalized to the design of variable-angle tow plates. New explicit stiffness matrices are found in terms of component material invariants and lamination parameters. The convex hull property of B-splines is exploited to ensure pointwise feasibility of lamination parameters. In addition, a set of new explicit closed-form expressions defines the feasible region of two in-plane and two out-of-plane lamination parameters, which are used for the design of orthotropic laminates. Finally, numerical examples of plates under compression loading with different boundary conditions and aspect ratios are investigated. Reliable optimal solutions demonstrate the robustness and computational efficiency of the proposed optimization methodology.

References listed at the end of the paper:
ABSTRACT: Based on the Carrera unified formulation, this work extends variable kinematic finite beam elements to include load factors and nonstructural masses for the static and vibration analyses of complex, metallic wing structures. According to the Carrera unified formulation, variable kinematic beam theories are formulated in an automatic and hierarchical manner by expressing the displacement field as an arbitrary expansion through generic cross-sectional functions. Both Taylor-like and Lagrange polynomials are used in this paper to develop refined beam kinematics, and the related theories are referred to as Taylor expansion and Lagrange expansion, respectively. The generalized unknowns of Taylor expansion models are the beam axis displacements and the $N$-order displacement derivatives, with $N$ being a free parameter of the analysis. Classical beam theories are clearly particular cases of the linear ($N=1$) Taylor expansion model. On the other hand, Lagrange expansion models have only pure translational displacements as unknowns. By exploiting this characteristic of Lagrange expansion, a componentwise approach is implemented and used for the analysis of multicomponent reinforced-shell structures. Numerical applications are developed by classical finite element procedures, and both static response and free vibration analyses are addressed. Various configurations of a benchmark wing are considered, and the capabilities of the present methodologies when dealing with higher-order effects due to deformable cross sections and geometrical discontinuities (for example, underside windows) are evaluated. The attention is focused on the applicability of the present refined beam models to problems involving complex, external inertial loadings. The results are compared to finite element solutions from commercial tools, including full three-dimensional models and models obtained by assembling two-dimensional shell and one-dimensional finite elements.


ABSTRACT: Advanced structural models, based on variable one-, two-, and three-dimensional kinematics, are proposed in this paper and applied to the analysis of the free vibration of reinforced aircraft shell structures. The used models go beyond classical structural theories, that is, Euler–Bernoulli (for one-dimensional beams) and Kirchhoff (for two-dimensional plates) type assumptions. The order of the expansion of the displacement fields over the cross section (one-dimensional case) and along the plate thickness (two-dimensional case) is, in fact, a free parameter of the problem. In this paper, Lagrange polynomials are used to build such expansions, and as a consequence, only displacements are used as the problem unknowns (no rotations or derivatives of displacements, which are typical of one-dimensional/two-dimensional classical theories, are introduced). The finite-element method is used to provide numerical solutions. The related arrays and the governing dynamical equations are written in terms of a few fundamental nuclei according to the Carrera unified formulation. Classical three-dimensional finite-element solid models are also considered. One-, two-, and three-dimensional finite elements are easily connected to each other to make the most appropriate computational model of the reinforced shell structures. The capability to use the same fundamental nucleus to derive finite-element matrices...
of one-, two-, and three-dimensional elements of the present model is unique because it is usually not available in other finite-element formulations, that is, no ad hoc techniques are required in the present case to couple finite elements with different kinematics. Three main benchmarks have been analyzed: a plate stiffened by means of bidirectional I-stiffeners, a simplified model of a complete aircraft, and a fuselage–wing connection. Comparison with commercial finite-element software (MSC Nastran) is provided for most of the quoted numerical investigations. The modal assurance criterion has been used to compare the free-vibration modes of the different models. The present mathematical models appear closer to reality and cheaper, from the computational point of view, than those of other existing formulations. Carrera unified-formulation-based finite elements do not require the definition of virtual lines (beam axes) or virtual surfaces (plate reference surfaces), and only physical lines/surfaces are therefore used.


ABSTRACT: Experiments on the interaction of a fast-moving oblique shock with an elastic panel in turbulent supersonic flow at Mach numbers of 3 and 4 were conducted to enhance the understanding of coupled flow–structure phenomena and for the validation of coupled simulations. A complex and challenging experimental setup allowed achieving remarkable shock motion, changing the impingement point within a few milliseconds, to excite high-amplitude oscillations of an elastic panel. The flowfield was analyzed by using high-speed pressure transducers and high-speed schlieren photography. The panel deflection was measured by nonintrusive high-speed capacitive and laser distance sensors. Measurements were also conducted on a rigid panel to be used as reference for the elastic case, and to allow a more detailed analysis of the shock-wave/boundary-layer interaction on the panel, yielding insights into the spatial and temporal distribution of frequencies occurring in the interaction area. Oscillations of the elastic panel with an amplitude of about 1 mm were obtained.


ABSTRACT: The efficiency of a modal substructuring method depends on the component modes used to reduce each subcomponent model. Methods such as Craig–Bampton have been used extensively to reduce linear finite-element models with thousands or even millions of degrees of freedom down orders of magnitude while maintaining acceptable accuracy. A novel reduction method is proposed here for geometrically nonlinear finite-element models using the fixed-interface and constraint modes of the linearized system to reduce each subcomponent model. The geometric nonlinearity requires an additional cubic and quadratic polynomial function in the modal equations, and the nonlinear stiffness coefficients are determined by applying a series of static loads and using the finite-element code to compute the response. The geometrically nonlinear, reduced modal equations for each subcomponent are then coupled by satisfying compatibility and force equilibrium. This modal substructuring approach is an extension of the Craig–Bampton method and is readily applied to geometrically nonlinear models built directly within commercial finite-element packages. The efficiency of this new approach is demonstrated on two example problems: one that couples two geometrically nonlinear beams at a shared rotational degree of freedom, and another that couples an axial spring element to the axial degree of freedom of a geometrically nonlinear beam. The nonlinear normal modes of the assembled models are compared with those of a truth model to assess the accuracy of the novel modal substructuring approach.


ABSTRACT: We investigated the natural frequencies and mode shapes of a freely vibrating, integrally stiffened and/or stepped plate. The stiffeners used here were plate-strip stiffeners as opposed to the normally employed rib stiffeners. Both the plate and stiffeners were analyzed using the first-order shear deformation theory. The deflections and rotations were assumed as a tensor product of Timoshenko beam functions, chosen appropriately according to the given boundary conditions. Unlike Navier and Levy solution techniques, the approach used in this paper can also be applied to fully clamped, free, and cantilever supported stiffened plates. The governing differential equations were solved using the Rayleigh–Ritz method. The development of the stiffness and the mass matrices in the Ritz analysis was found to consume a huge amount of CPU time due to recursive integration of Timoshenko beam functions. An approach is suggested to greatly decrease this amount of CPU time, by replacing the recursive integration in a loop structure in the computer program, with the analytical integration of the integrand in the loop. The numerical results were compared with the solutions available in the literature as well as the commercially available finite-element software ABAQUS®, and the results were found to be highly satisfactory.


ABSTRACT: An efficient optimization framework of cylindrical stiffened shells with reinforced cutouts by curvilinear stiffeners is proposed in this study. First, an adaptive method to determine the near field around the cutout and far field away from the cutout is presented. Then, a novel hybrid model is established to reduce the computational efforts of postbuckling analysis; the numerical implementation asymptotic homogenization method is used to smear out the stiffeners in the far field, and curvilinear stiffeners are adopted to improve the loading path and thus local stiffness of the near field, which can provide a type of flexible stiffener configurations for cutout reinforcement. After that, the optimization of curvilinear stiffeners is performed by a novel bilevel strategy based on the hybrid model. In the first level, a stiffener distribution function is used to reduce the number of active variables, and then stiffener layout, stiffener number, and section profile are optimized simultaneously. In the second level, the stiffener number and section profile are held constant, and local optimization is then performed for each curvilinear stiffener location. An illustrative example demonstrates the effectiveness of the proposed framework, when compared with traditional optimizations.


ABSTRACT: Motivated by the need for high-fidelity modeling and accurate control of future hypersonic vehicles subjected to complex aerothermomechanical loads and many other such applications, a novel scheme is proposed to accurately compute higher modes of vibration for one-dimensional structures by coupling the classic Ritz method as a predictor and the linear two-point boundary value problem solver SUPORE as a corrector. The Ritz method is used to compute a preliminary estimate of the natural frequencies for the desired modes. These estimates are then used as initial guesses by SUPORE, which employs superposition and reorthonormalization to accurately solve the governing boundary value problem. Compared to a high-fidelity Ritz approximation or a highly refined finite element modeling procedure, this is a simple, computationally less expensive, and yet highly accurate method to compute mode shapes for applications that require higher modes. This scheme is used to compute mode shapes within an absolute and relative error tolerance of 0.0000001 for the idealized case of a free–free Euler–Bernoulli beam and a typical air-breathing hypersonic vehicle modeled as a thin-walled structure and taking into account deformations due to bending, shear, and torsion.


ABSTRACT: A method for optimizing ply drop locations in composite laminates is developed using ideas from topology optimization. The design is parametrized using a fiber angle and fictitious density distribution for each ply. The solution proceeds using a successive conservative convex approximations strategy. Starting from a feasible point, the algorithm converges to a local minimum. The structural responses are approximated separately in terms of the angle and fictitious density distributions of each ply. Explicit penalization of intermediate densities is used to force the densities to either one for ply coverage or zero for no coverage. Ply drop locations are identified as the boundary between regions having densities near one and those near zero. The ply drop optimization is combined with fiber angle optimization by alternating the optimization between the corresponding sets of variables. Optimized variable-stiffness variable-thickness composite laminates, with a prespecified ply drop order, are obtained. Initial results show that large improvements in the buckling loads of flat plates can be obtained by combining ply drop and fiber angle optimizations.


ABSTRACT: Analytical and experimental results are presented regarding the nonlinear temperature-curvature relationship displayed by composite bimorph shells. Snap-through action, driven solely by temperature change, is demonstrated using fiber–metal hybrid laminates. These laminates exploit the high coefficient of thermal expansion mismatch between composites and metals to yield thermal bimorphs with tailorable properties. To predict the potentially nonlinear response of these laminates, an energy-based multistability model is developed and made available online. The model utilizes experimentally measured one-dimensional thermally induced curvatures as input parameters to predict a corresponding shell’s two-dimensional flexural behavior. Initial curvature is found to be a critical component in enabling snap-through behavior, especially when partnered with highly orthotropic internal moments. Interestingly, the [0\n\90\n]n\ class of unsymmetric laminates popular in the study of thermally induced bistability are shown to be inherently incapable of displaying thermally driven snap-through behavior, regardless of initial curvature. Modeling results compare well with experiments for a square-planform hybrid laminate. The potential impact of this work is the realization of passively controlled, variable geometry structures that can be triggered to change shape at certain temperatures or within specified temperature ranges. Applications include flow and cooling control of gas turbine engines, spacecraft passive
thermal control systems, and bimorph-based micro-electromechanical systems.

ABSTRACT: This paper describes an effort toward characterizing the role of material plasticity on the structural response and operational life of compliant panels in high-speed flow. A fluid–thermal–structural–material interactions framework is used to investigate the response of elastic and elastic-plastic panels subjected to multiple loading cycles. The plastic material response is predicted using a nonlinear strain hardening law that accounts for cyclic loading. A fatigue analysis is conducted using a linear cumulative damage rule. A residual deformation on the order of one panel thickness is found to produce characteristically different responses for elastic and plastic panels. After several loading cycles, the onset of flutter for the permanently deformed panel increased beyond the time responses considered.

ABSTRACT: This paper proposes a numerical approach to estimate the dynamic behavior of a typical aeronautical aluminum box-beam structure liable to buckling. The methodology is based on a nonlinear finite element model and an experimental modal analysis procedure. The finite element model deals with the coupled nonlinear static and dynamic problems in two steps: 1) determining the static equilibrium considering geometrical nonlinearities, and 2) solving for a linear small-amplitude free-vibration problem based on the tangential stiffness matrix from the current static equilibrium. To illustrate the proposed method, a finite element model is built for a simple supported box beam under a uniaxial compression load with different degrees of eccentricity. The numerical results are correlated with an experimental modal analysis procedure in pre- and postbuckling regimes. Based on this comparison, an updated model is proposed for adjusting the shape and magnitude of the initial imperfections based on linear buckling modes. The results are presented in order to illustrate the effect of the buckling phenomenon and initial imperfections on the dynamic behavior of the box-beam structure.


ABSTRACT: In this paper, a triangular planar element is developed for a geometrically nonlinear structural analysis, which includes the drilling degrees of freedom using a corotational framework. Based on the assumptions of a small degree of strain and large displacement, the corotational framework allows an accurate geometrically nonlinear structural analysis. The presently improved corotational framework accommodates in-plane rotational behavior (that is, the drilling degrees of freedom) by using the corotational framework corresponding to a solidlike planar element. It focuses on triangular planar elements that will be useful for three-dimensional analysis using a reduced number of degrees while targeting a structure with a complex geometry, such as a flapping wing. Regarding the present analysis, validation by solving both static and time-transient problems is conducted. The fluid–structure interaction framework is then developed by using the
present structural analysis. During this validation procedure, the present results are compared with those obtained with three-dimensional solid elements provided by the commercial software ANSYS. Finally, a relevant fluid–structure interaction analysis for the flapping wing is conducted and an examination of the usefulness of the present planar element is done through comparisons between experimental results and those obtained in earlier studies.


ABSTRACT: Stress recovery based on results from a two-dimensional plate-theory solution is a common method to estimate the transverse stresses in a plate. The development of a stress-recovery procedure is presented that is based directly on plate-theory finite element solutions applicable to situations in which geometrically nonlinear and inertial effects are important. The key reason for employing the stress-recovery procedure is its computational efficiency compared to three-dimensional finite element analyses. The developed procedure is applied to an example flat plate under the influence of dynamic loading. Results from the developed procedure are discussed; they compare well to those from a benchmark three-dimensional finite element solution. The range of applicability of the procedure, considering plate span-to-thickness ratio and degree of nonlinearity, is illustrated. Finally, a discussion is included in which the computational effort to obtain an accurate transverse-stress distribution by the stress-recovery method is compared to that of the benchmark three-dimensional solution.


ABSTRACT: The free vibration, bending, and transient responses of laminated composite plates have been investigated with delamination in this present study. The laminated, composite, shear deformable plate has been modeled mathematically using two higher-order shear deformation theories in conjunction with finite element steps. The final form of the governing equations of the bending and the free vibration responses are obtained using the variational method and the classical Hamilton’s principle, respectively. In addition, the transient responses are computed using Newmark’s time integration scheme for the discrete coupled second-order ordinary differential equation system of the dynamic equilibrium. The desired free vibration, bending, and transient responses are computed numerically using a homemade computer code developed in the MATLAB environment and compared with those available published numerical and analytical results. Finally, the importance of the developed higher-order models has been studied by analyzing the responses for different structural design parameters and discussed in detail.


ABSTRACT: Longitudinally corrugated shell structure is an appropriate structural element adopted in aerospace, mechanical, naval, nuclear, and weapons engineering. In the present paper, the dynamic expansion of
a longitudinally corrugated shell under nonuniform internal pressure with the restriction of outside rigid bodies was studied with an efficient numerical method without element discretization along the circumferential direction. Furthermore, based on the developed numerical methodology, the authors conducted intensive investigations on the geometric parameters of the corrugated shell and revealed a characteristic configuration parameter that governs the expansion dynamics of the longitudinally corrugated shell. In addition, the type (distribution) and rate of the load, which are other important factors that can influence the dynamic behavior of the corrugated shell, are also discussed. The high computational efficiency of the algorithm and the characteristic deformation behavior of the corrugated shell revealed by our analysis make the present method more favorable than commercial software in treating the expansion system in the engineering field.


ABSTRACT: By adopting advanced beam models, this paper presents free vibration analyses of metallic aircraft structures affected by local damages. Refined theories are developed within the framework of the Carrera unified formulation, according to which any-order two-dimensional and one-dimensional theories of structures can be implemented in a hierarchical and unified manner. By employing Lagrange polynomials to expand the generalized displacement field, component-wise models of aircraft structures are implemented in this work. The component-wise approach provides a detailed physical description of multicomponent structures, since each component can be modeled with its own geometrical and mechanical characteristics; that is, no reference surfaces and axes, as well as no homogenization techniques, are employed. This characteristic allows accurate modeling of global and local damages within the structure. The results show that the proposed refined one-dimensional models can deal with the free vibration analysis of damaged aircraft structures as accurately as the shell and solid models. Moreover, thanks to the computational efficiency of the Carrera unified formulation, component-wise models are good candidates for providing the vibration characteristics of structures for a wide range of damage scenarios in order to create databases able, for example, to train neural network for damage detection.


ABSTRACT: It is known that the aeroelastic stability of elastic plates significantly decreases in low supersonic flow. A further reduction may arise due to compressive in-plane loads, which can be caused by deformations of the adjacent structure. Thus, this is an important subject in the design of supersonic aircraft or rockets. Encouraged by recent studies that have shown an increase in aerodynamic damping due to a turbulent boundary layer, the present study applies three different aerodynamic models coupled with the von Kármán plate equation to show that there is as well a significant enlargement of the static stability regions of a flat plate subjected to quasi-static in-plane loads at Mach 1.2. However, it has also been found that, despite a turbulent boundary layer, the critical dynamic pressure for flutter almost drops to zero if the in-plane load approaches the critical load for Euler buckling. Further analysis on postcritical flutter revealed that a flexible panel subjected to a boundary layer behaves similarly to a panel in inviscid flow at a lower dynamic pressure, leading to the conclusion that the turbulent boundary layer scales down the effective dynamic load. This result further shows that the aeroelastic design of flexible plates based on inviscid flow models is a conservative approach. Representative results have been discussed by means of bifurcation curves, modal participation analysis, frequency spectra,
phase plots, and Poincaré maps.


ABSTRACT: Thin-walled beams exhibit a nonlinear response to bending moments due to the progressive flattening of the cross-section, a behavior commonly referred to as the Brazier effect. Most approaches to model this effect are limited to either circular cross-sections or to cross-sections made of isotropic materials. This article proposes an efficient two-step method of predicting the nonlinear collapse of thin-walled cross-sections of arbitrary geometry with isotropic and orthotropic materials. The procedure relies on representing the cross-section by two-dimensional nonlinear corotating beam elements with imposed in-plane loads proportional to the curvature, combined with a finite strip buckling analysis based on the deformed cross-section. By comparison with existing analytical and numerical modeling approaches, it is demonstrated that the present method can capture the cross-section flattening and critical moment for buckling of thin-walled structures commonly found in the industry.


ABSTRACT: Surrogate models often provide an effective tradeoff between accuracy and efficiency during reliability analysis with expensive physics models. In snap-through buckling reliability analysis, a surrogate model could be built for the critical buckling load, as a function of loading, material properties, geometry, and boundary conditions. However, in the presence of spatiotemporal variability, the response surface of the critical buckling load is often highly nonlinear and irregular, thus rendering commonly used response surface-type surrogate modeling strategies ineffective. This paper proposes a new buckling reliability analysis method based on support vector machines for structures subjected to spatiotemporal variability and in the presence of epistemic uncertainty regarding model inputs and parameters. Bayesian calibration is first used to quantify the epistemic uncertainty in the modeling of spatiotemporal variability under limited data. Upon the modeling of spatiotemporal variability and epistemic uncertainty, a time-dependent reliability analysis method is developed for the snap-through buckling failure by constructing a nonlinear support vector machine classifier. Considering that the computer simulation is computationally expensive and the support vector machine classifier may not be well trained due to limited computational resources, a method is also developed to quantify the uncertainty in the reliability estimate due to classification uncertainty. A curved beam with an uncertain boundary condition, spatially varying cross-section geometry, and spatiotemporally varying loading is used to demonstrate the effectiveness of the proposed method.


Google the string: “International Journal of Offshore and Polar Engineering”; click on one of the volumes/issues in the upper right-hand corner.

ABSTRACT: This paper deals with the buckling behavior of UOE pipes under a bending moment. Full-scale bending tests were performed to evaluate the compressive strain limit (ϵLimit). During the numerical simulation, the pipe was modeled using the measured pipe profile and the material constitutive law newly developed to analyze the orthogonal anisotropy. The test results verified that ϵLimit was not degraded by aging during the anti-corrosion coating, although it declined for pipes with girth welds. The results obtained from the validated models suggest that the conventional method using the isotropic work hardening law may overestimate ϵLimit under high internal pressure.

ABSTRACT: A critical factor for economical design of offshore Arctic pipelines is the burial depth requirement to protect the pipeline from ice-gouge hazards. The current methodology to determine pipeline strain demand due to ice-gouge hazards is based on Winkler-type soil-spring structural models. Due to necessary simplifications and lack of full-scale verification data, this empirical method can be overly conservative and may lead to unrealistic burial depth requirements. This paper presents an advanced 3D continuum modeling approach as an alternative to the current empirical methodology. These advanced models provide more realistic simulation capability for modeling the ice-gouging process, can provide more accurate estimates for pipeline strain demand, and can potentially reduce the required burial depths and costs. Continuum models, once validated using large-scale field tests, can be used to advance the reliability and cost effectiveness of design for offshore pipelines subjected to ice-gouging.

ABSTRACT: This paper presents the results of experimental studies focused on the strain capacity of X80 linepipe. A full-scale bending test of X80 grade, girth-welded 48” high-strain linepipe pressurized to 60% SMYS was conducted to investigate the compressive strain limit and tensile strain limit. The compressive strain limit focused on the critical strain at the formation of local buckling on the compression side of bending. One large developed wrinkle and some small wrinkles on the pipe surface during bending deformation were captured relatively well from observation and strain distribution measurement. The tensile strain limit is discussed from the viewpoint of competition of two fracture phenomena: ductile crack initiation/propagation
from an artificial notch at the HAZ of the girth weld, and strain concentration and rupture in the base material at the tension (opposite) side of the local buckling position. A curved wide plate (CWP) test and full-pipe tension test were also conducted to investigate the tensile strain capacity of the girth-welded joint under tensile load using relatively small diameter X80 pipeline. Crack initiation and propagation behavior was clarified satisfactorily by sectional observation of the surface notch at the HAZ of the welded joint. Tensile fracture limits related to the maximum load are discussed from the viewpoint of the effect of internal pressure by comparing the CWP and full-pipe tension test results.

Zhiyong Pei (Key Laboratory of High Performance Ship Technology of Ministry of Education School of Transportation, Wuhan University of Technology, Wuhan, China), Kazuhiro Iijima and Masahiko Fujikubo (Dept. of Naval Architecture and Ocean Engineering, Graduate School of Engineering Osaka University, Suita, Osaka, Japan), Yoshiteru Tanaka (Structural Analysis Group, National Maritime Research Institute, Mitaka, Tokyo, Japan), Satoyuki Tanaka and Shigenobu Okazawa (Graduate School of Engineering, Hiroshima University, Higashi-hiroshima, Hiroshima, Japan) and Tetsuya Yao (Design Department, Tsuneishi Shipbuilding Co., LTD, Fukuyama, Hiroshima, Japan), “Collapse Behaviour of a Bulk Carrier under Alternate Heavy Loading Conditions”, International Journal of Offshore and Polar Engineering, Vol. 23, No. 3, September 2013, pp. 224–231

ABSTRACT: For a bulk carrier in alternate heavy loading conditions, it is noted that the double bottom of an empty hold is subjected to both longitudinal thrust due to hull girder bending in hogging and local bending caused by high pressure loads on bottom plating. In order to examine the influence of local bending of the double bottom on the ultimate hull girder strength, a series of nonlinear calculations is performed applying three different methods. The first method is Smith’s method using in-house code, HULLST, to evaluate ultimate hull girder strength under pure bending. The second is the application of a new system recently developed by the authors. This method is a combination of load/motion analysis by Singularity Distribution Method and progressive collapse analysis by ISUM/FEM. The third is nonlinear FEM analysis using a commercial code, MSC.Marc. It has been found that bending deformation is produced not only in the double bottom but also in the bilge hopper tank, and the ultimate hull girder strength is reduced by roughly 20% due to this local bending.


ABSTRACT: Trenching is a frequently used method for protection of offshore pipelines against dropped objects and fishery activities. To provide additional protection the trenches are usually back-filled. The backfill material may be soft, partly remoulded clay or sand present at the seabed or sand mix and crushed rock installed after pipe lay. Offshore pipelines may experience large axial forces due to temperature expansion. As a part of the pipeline design, the buckling failure modes must be analysed. In the buckling analyses, an important parameter is the upheaval resistance from the backfill material. To verify the design of a trenched offshore pipeline in the Norwegian Trench, a full-scale test was performed by SINTEF and NTNU. The test program included measurement of uplift resistance in soft clay, sand mix and crushed rock. This paper presents the test setup, the backfill materials and the measured uplift resistances. The measured resistances are compared with theoretical models for uplift resistance for different backfill materials. Recommendations are given regarding the uplift resistance pipes in trenches backfilled with sand mix or crushed rock.

ABSTRACT: Gas transportation over long distances is increasingly needed to gather natural gas from far fields to final market. Pipelines are often required to cross harsh areas where ground hazards are likely to occur. The need to study the strain-based behavior of pipelines under imposed displacement necessitated the development of full-scale testing facilities and numerical/analytical models for buckling prediction. This paper presents a new analytical formulation for the estimate of pipe strain capacity against buckling. Its development has been carried out by taking advantage of an experimental database coming from Eni’s projects.

Erik Levold (Statoil ASA Trondheim, Norway), Andrea Restelli (ENI Exploration and Production San Donato Milanese (MI), Italy), Lorenzo Marchionni and Luigino Vitali (Saipem S.p.A.Fano (PU), Italy), Caterina Molinari (Saipem S.p.A.San Donato Milanese (MI), Italy) and Istemi F. Ozkan (C-FER Technologies Edmonton, Alberta, Canada), “Strength and Deformation Capacity of Corroded Pipe: Laboratory Tests and FEM Analyses”, International Journal of Offshore and Polar Engineering, Vol. 25, No. 3, September 2015, pp. 212–220; http://dx.doi.org/10.17736/ijope.2015.oa05

ABSTRACT: With the future development of offshore pipelines moving toward difficult operating conditions and deep/ultradeep water applications, there is a need to understand the failure mechanisms and better quantify the strength and deformation capacity of corroded pipelines, considering the relevant failure modes (collapse, local buckling under internal and external pressure, fracture/plastic collapse, etc.). A joint industry project sponsored by ENI Exploration and Production and Statoil has been launched with the objective to quantify and assess the strength and deformation capacity of corroded pipes in the presence of internal overpressure.


ABSTRACT: This paper presents a probabilistic method to assess the lateral buckling response of a pipeline. The method is based on a Monte Carlo (MC) simulation in which the lateral buckling response is predicted through the use of a surrogate model that employs artificial neural networks (ANNs) calibrated from nonlinear finite element (FE) analyses. The method presented intends to improve on current industry best practice by directly considering the limit states relevant to global buckling to produce designs with consistent levels of reliability.

ABSTRACT: When using large models, building a comprehensive finite element (FE) numerical model able to simulate the portion of a containership whose extension in length is sufficient to properly evaluate combined loading effects is rather time consuming, and assigning proper boundary conditions representing the distribution of actual forces and moments on the hull girder is a challenging task. In this paper, the effect of shear stress distribution on the structural components of the hull girder is analyzed. At first, finite element (FE) models simulating a suitable length of the hull girder are considered. Later, smaller models of stiffened panels are extracted from the hull girder models and analyzed. The aim of this work is to investigate the shear stress distribution originating in the entire cross section and to build a smaller model extracted from a selected portion of the ship where hull girder collapse is supposed to initiate.


ABSTRACT: This research deals with experimental and numerical axial quasi-static crash tests on end-capped cylindrical and conical tubes. Axial quasi-static crush tests have been generated for end-capped cylindrical and conical tubes. Furthermore, in order to gain more detailed knowledge about the crash process, finite element (FE) simulations of the experiments have been performed. The explicit FE code Abaqus/explicit was used and the results have been validated by experimental data. The elastic–plastic material model was used for the aluminium tubes. In terms of finding more efficient (higher energy absorption) and lighter crash absorbers particularly, the energy absorption, E, and specific energy absorption, SEA, have been considered. The influences of geometrical parameters of the tubes on their collapse response have also been investigated. Finally, a multiobjective optimisation method is used to find the tube geometry which has the maximum energy absorption and specific energy absorption.

References listed at the end of the paper:


ABSTRACT: In the present study, the mechanical behaviour of CSM (chopped strand mat)-based GFRC (glass fibre-reinforced composite) plates with single and multiple hemispheres under compressive loads has been investigated both experimentally and numerically. The basic stress–strain behaviours are identified with quasi-static tests on two-ply coupon laminates and short cylinders, and these are followed up with compressive tests in a UTM (universal testing machine) on single- and multiple-hemisphere plates. The ability of an explicit LS-DYNA solver in predicting the complex material behaviour of composite hemispheres, including failure, is demonstrated. The relevance and scalability of the present class of structural components as ‘force-multipliers’ and ‘energy-multipliers’ have been justified by virtue of findings that as the number of hemispheres in a panel increased from one to four, peak load and average absorbed energy rose by factors of approximately four and six, respectively. The performance of a composite hemisphere has been compared to similar-sized steel and aluminium hemispheres, and the former is found to be of distinctly higher specific energy than the steel specimen. A simulation-based study has also been carried out on a composite 2 × 2-hemisphere panel under impact loads and its behaviour approaching that of an ideal energy absorber has been predicted. In summary, the present investigation has established the efficacy of composite plates with hemispherical force multipliers as potential energy-absorbing countermeasures and the suitability of CAE (computer-aided engineering) for their design.

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Tubes were cut at different lengths of the same circular cross combination of glass fibres in the form of reinforcing direct roving fabric in thermosetting pol geometry. This paper extends the work to hybrid tubes and presents the results of experimental work pertaining numerous studies.

ABSTRACT: The use of tubes as energy absorption structures has been prevalent for many decades and parameters and failure modes of steel and hybrid tube made by steel and GFRP under low velocity impact. Reza Mehryari Lima, Z.N. Ismarrubie, E.S. Zainudin and S.H. Tang, “Effect of length on crashworthiness of steel and hybrid tubes that were subjected to quasi-static axial compressive loading. The hybrid specimens were featured by inner mild steel tube wrapped by a material combination of glass fibres in the form of reinforcing direct roving fabric in thermosetting polyester resin. Tubes were cut at different lengths of the same circular cross-section that encompassed both classical.
progressive buckling and the global bending modes of failure. Particular attention was paid to the investigate
effect of tube length on crashworthiness parameters and critical length to avoid global bending during quasi-
static crushing of thin-walled tubes. At first, similar work was done on steel tubes to compare results obtained
by hybrid tubes with plain counterparts.
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ABSTRACT: Nowadays, there is increasing interest in lightweight automotive structures capable of absorbing
large quantities of energy in case of a crash phenomenon. These requirements are satisfied by composite
devices, provided they are properly designed. The aim of the present paper is the investigation of the
crashworthy behaviour of composite material tubes with woven laminae subjected to dynamic axial
compression. The research was done by combining experimental and numerical analysis; without any
experimental feedback, in fact, engineers might not accurately design an innovative structure. After the
numerical characterisation of the used CFRP (carbon fibre-reinforced polymer) material, different simulations
with the non-linear explicit dynamic code LS-DYNA have been done in order to understand how the structure
absorbs energy by varying its geometrical and material parameters. In particular, circular and square tubes have
been investigated with different resistant section, wall thickness, fibres orientation and staking sequence. The numerical analysis has been carried out taking into account different composite material models present in the LS-DYNA library, where each of them implements a different damage criterion. The choice of model to be used was made only after performing crash tests on the same tubes using a drop tower, appropriately instrumented in order to measure the main impact characteristics. The comparison between numerical and experimental results gave satisfactory outcomes, providing the basis for the design methodology of impact attenuators that are geometrically more complex.

References listed at the end of the paper:


ABSTRACT: Soft body impact tests were conducted using an artificial bird of 0.2 kg with a striking velocity of 150 m·s\(^{-1}\) on three different configurations of metallic wing leading edge (LE) structures. The objective of these experiments is to address the preliminary design of LE wing structures to soft body impact loads. The explicit finite element software PAM-CRASH was selected to simulate these experiments using smoothed particle hydrodynamics (SPH) techniques for modelling the bird. The impact tests were also performed for a velocity of 70–180 m·s\(^{-1}\) on instrumented aluminium and steel flat plates to attain the bird material parameters. The artificial bird material parameters for a hydrodynamic material model (Murnaghan equation of state) and elastic-plastic solids with damage and failure were optimised using iSIGHT and PAM-CRASH coupling technique in conjunction with tests on flat plates. The experimental and numerical correlations of the flat plates suggested that at high velocity the hydrodynamic material model gives good results. Bird-strike simulations on wing LE structures were performed using optimised artificial bird parameters. The load transferred to the support structure and post-test deflection-simulated results showed good conformity with the experiment. The SPH method proved to be very effective for modelling a bird strike on flat plates and LE structures. The deformation behaviour of the SPH bird appears to be in excellent agreement with the video stills, with the flow around the structure and break-up into particles.

References listed at the end of the paper:


ABSTRACT: Preformed structural reinforcements have shown good performance in crash tests, where the great advantage is their weight. These reinforcements are designed with the aim of increasing the rigidity of regions with large deformations, thus stabilising sections of the vehicle that work as load path during impact. The objective of this work is to show the application of structural reinforcements made of polymeric material PA66 in the field of vehicle safety, through finite element simulations. Simulations of frontal impact at 50 km/h and in
ODB (offset deformable barrier) at 57 km/h configurations (standards such as ECE R-94 and ECE R-12) were performed in the software LS-DYNA® and MADYMO. The simulations showed that the use of polymeric reinforcements leads to a 70% reduction in A-pillar intrusion, a 65% reduction in the displacement of the steering column and a 59% reduction in the deformation in the region of the occupant legs and feet. The level of occupant injuries was analysed by MADYMO software, and a reduction of 23.5% in the chest compression and 80% in the tibia compression were verified. According to the standard, such conditions lead to an improvement in the occupant safety in a vehicle collision event.

References listed at the end of the paper:

ABSTRACT: E-glass/polyester composite and layered corrugated aluminium and aluminium foam core sandwich panels were projectile impact tested between 127 m/s and 190 m/s using a hardened steel sphere projectile. The corrugated aluminium cores, constructed from aluminium fin layers and aluminium interlayers
and face sheets, exhibited relatively lower-plateau stresses and higher stress oscillations in the plateau region than aluminium foam cores. The applied brazing process resulted in reductions in the plateau stresses of the corrugated aluminium cores. The sandwich panels with 2- and 3-mm-thick composite face sheets and the epoxy-bonded corrugated aluminium sheet cores were perforated, while the sandwich panels with 5-mm-thick composite face sheets were penetrated in the projectile impact tests. On the other hand, the sandwich panels with aluminium foam cores were only penetrated. A simple comparison between the ballistic limits of the sandwich panels as a function of total weight revealed significant increases in the ballistic limits of the cores with the inclusion of composite face sheets. The determined higher impact resistance of the foam core sandwich panels was attributed to the relatively higher strength of the foam cores investigated and the ability to distribute the incident impulse to a relatively large area of the backing composite plate.

References listed at the end of the paper:
ABSTRACT: A wide range of energy absorbing structures and geometries have been researched upon and proposed for safety applications, particularly for automotive safety. Aluminium pressload panels are being researched to explore the energy absorption capabilities of the unique geometry so as to utilise them for automotive vehicle structures as energy absorbers. Preliminary research outputs describing the deformation of the egg-box under quasi-static loads were presented and the structure was proposed for a commercial vehicle front by the authors. Also the underlying reasons for the specific mode of deformation of the geometry were experimentally explored and research results were published. The current work serves as an extension to the recently published work as a numerical study using HYPERMESH and LS-DYNA software packages and validation against the experiments was carried out. The panel was experimentally tested to further explore the deformation pattern of the egg-box geometry. The effect of natural restraint that occurs due to the existence of the surrounding finite number of peaks/frusta and the flanges surrounding each frustum that comprises the panel's geometry was investigated as three separate cases: (1) single peak with free-free edges, (2) single peak with constrained edges and (3) single-peak in-situ, all tested quasi-statically. The egg-box geometry was modelled numerically and the simulated results were in good agreement with those from the experiment. The specific energy absorption of the single peak cut from the panel and edges left unconstrained was 300 J/kg and that with constrained four corner edges was 700 J/kg. The single peak in-situ absorbed as high as 775 J/kg of specific energy, which is nearly 2.6 times greater than that of for a single peak with free-free edges. This indicates the positive influence of the natural occurring restraint within the egg-box panel geometry to its energy absorption capability.

References listed at the end of the paper:
ABSTRACT: Composite inserts are a well-known and innovative technology in the automotive industry used to improve safety, NVH (noise, vibration, and harshness) and fatigue life of vehicles, as well as to reduce vehicle weight and manufacturing cost. In order to study the crashworthiness performance of composite inserts in a vehicle structure, a three-point bending test of simplified steel-composite combined beam structures is considered. The beam structure in this investigation has a double-hat section. Epoxy-based structural foam and 33% short glass fibre reinforced nylon insert are considered as composite fillers for the two empty beam sections. Four cases, based on the different combination of composite materials inserted in the beam sections, are considered. The test results show that the composite insert greatly contributes to improvement of the energy absorption of beam structure. The force–displacement (F–D) curves of bending tests, the deformation behaviours of beam structures and the failure modes of composite inserts are shown and analysed to understand the effects of composite inserts to the crashworthiness of the beam structure in a bending condition. The numerical study was performed to develop a practical finite element (FE) model of the steel-composite combined structure.

References listed at the end of the paper:


ABSTRACT: A 3-D model of a regional jet fuselage section with central wing box (CWB) was developed for vertical drop crash simulation. The two wings were modelled with a dynamically equivalent system comprising beam and lumped-mass element. Four crashes with differ falling velocity were simulated in the explicit transient-dynamics finite-element code MSC.Dytran, respectively. The acceleration at seat rail is greatly higher than that of the typical fuselage section of the same plane. At high falling velocity, the crash process consists of two impact events due to the involvement in the section bottom and CWB, respectively. The frame and keel beam underneath the CWB are completely crushed. The spanwise beams of CWB are buckled but not collapsed. The longitudinal rib was not appropriately distorted and thus prevented the spanwise beams’ buckling. Energy analysis shows that the deformation energy is mainly attributed to the plastic deformation in high dropping velocity. Finally, some proposals on the improvement of crashworthiness are remarked.

References listed at the end of the paper:
ABSTRACT: Laminated composites with nano fillers are subjected to medium velocity impact. The laminates are prepared by hand lay-up technique followed by compression moulding, for different thicknesses. Laminates are made of glass woven roving mates of 610 gsm, epoxy resin and nano clay. Clay dispersion is varied from 1% to 5% by weight. A piston type gas gun set up is employed to impact the composite laminates. Spherical nose cylindrical projectile, of diameter 9.5 mm and mass 7.6 g, is used for the study. The impact tests are conducted to predict the ballistic limits of the laminates with and without clay. Quasi-static deflection tests and dynamic tests are carried out to find the energy absorbed by the laminates. Dispersion of clay in polymer matrix shows considerable improvement in energy absorption and ballistic limit of the composite laminates.

References listed at the end of the paper:
ABSTRACT: Under 50 km/h frontal collisions, composite cylinders installed in compressed natural gas (CNG) vehicles’ trunks could suffer impact damages caused by luggage modules. The impact damages of cylinders induced by luggage modules were investigated in this paper through undertaking frontal crash sled tests. When
performing falling ball impact experiments, with the composite cylinders impact damage critical value of 25 J, the impact bore by the cylinders’ surface can evaluate the safety of cylinders in crash tests. When the cylinders and luggage modules moved at a different velocity in the same direction, the impact that was obtained by simulation analysis was used to appraise the safety of the composite cylinders in frontal collisions.

References listed at the end of the paper:

ABSTRACT: This paper presents the result of an optimisation study by linear, quadratic, Kriging and radial basis meta-models in order to augment the crashworthiness characteristic of cellular structures. Thin-walled cellular structures (honeycomb) have the ability to absorb impact energy during crashing, thus it is important to enhance the crushing efficiency and optimise the structural reliability. The optimisation carried out in this study is aimed at maximising the energy absorption characteristics using meta-models while considering some limitation on the maximum force as a constraint. Achieving these characteristics is an important factor in crashworthiness analysis, which minimises the damage in dynamic performance. The objective of using various meta-models is to qualify the meta-model in crashworthiness analysis using different point selection schemes and different number of points. The optimisation is performed in two stages; through experimental design methods in which a set of sampling points is selected from design space and polynomial fitting in order to optimise the objective. It is concluded that D-optimal best suits response surface method for model approximation. Kriging performed best by space filling and the best point selection scheme for radial basis surrogate is latin hypercube design. The results show that for optimising the crashworthiness characteristics of honeycomb, Kriging and quadratic response surface (RS) are best, in terms of accuracy and robustness point of view and the radial basis neural network would be the second best. During this optimisation, the RS was
combined with detailed geometrically simplified finite element model of honeycomb cell using ANSYS/LS-DYNA, LS-DYNA and LS-opt packages. Approximated functions combined with the finite element analysis were an effective tool to optimise highly non-linear impact problems. This has led to the development of validated algorithm that enabled the development of the optimised solutions.

References listed at the end of the paper:

ABSTRACT: This paper will investigate how current state-of-the-art structural optimisation algorithms, with an emphasis on topology optimisation, can be used to rapidly develop lightweight body in white (BIW) concept designs, based on a computer aided design envelope. The optimisation models included in the paper will primarily focus on crashworthiness and roof crush scenarios as specified in the Federal Motor Vehicle Safety Standards (FMVSS) 216 standard. This paper is a continuation of a previously published paper, which investigated the potential effects of recently proposed changes to FMVSS 216 upon BIW mass and architecture using topology optimisation. The paper will investigate the possibilities of including buckling considerations of roof members directly into current state-of-the-art topology optimisation algorithms. This paper will also demonstrate the potential for developing a detailed BIW design including cross-sectional properties based on a styling envelope.

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ABSTRACT: In crash simulations of composite aircraft fuselage sections, frame breaking, skin bending and failure of mechanically fastened joints can typically be identified as major contributors to crash energy absorption. In order to generate a database for model validations, corresponding static and dynamic tests have been performed on coupon and structural element level to characterise the rate-dependent failure behaviour and energy absorption. Skin-bending, frame-bending and joint-failure tests under pull-out, bearing and peeling loads were performed on 977-2/HTS carbon fibre/epoxy specimens. On the one hand, effects of loading rate on the frame-bending behaviour could be observed. On the other hand, fastener failure did not appear to be depending on loading rate for the test speeds up to 10 m/s involved in this study. Adequate modelling methods in Abaqus/Explicit were derived and validated, and finally applied to a global aircraft crash simulation model.

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ABSTRACT: Crashworthiness design and certification have been and will continue to be the main concern in aviation safety. The influence of composite skin on crashworthiness of composite fuselage section was investigated in the paper. A finite element model of fuselage section was built, and the dynamic responding characteristics of composite fuselage section subjected to vertical impact velocity of 6.67 m/s were analysed by changing composite ply numbers and ply angles in the explicit finite element code LS-DYNA. The failure modes and acceleration response of fuselage section under different conditions were presented. The results show that the peak overload on the seat can be significantly reduced by selecting appropriate composite ply numbers and ply angles, and the crashworthiness of composite fuselage section can be efficiently improved.

References listed at the end of the paper:

ABSTRACT: In this paper, compression behaviour and energy absorption of aluminium alloy AA7005 and AA7003 tubes were investigated both experimentally and numerically. LS-DYNA software was used for the static and dynamic simulations of AA7005, AA7003, AA6061 and high strength steel (DP800) tubes of equal dimensions. True stress–plastic strain curves at different strain rates from the literature were used in the dynamic simulations of AA7003 and DP800 tubes. Dynamic simulations were done with drop velocity from 7 to 15 m/s to understand the inertia and strain rate effects on energy absorption. The peak loads and energy absorption values between experimental compression results and numerical simulation are found to be in good agreement. The simulation results show the energy absorption characteristics of AA7XXX tubes are better than that of AA6061 and DP800 tubes based on specific energy.

References listed at the end of the paper:


ABSTRACT: Thin-walled structures like crash tubes may be used as energy absorption members in automobile chassis. There have been a lot of investigations into the behaviour of these parts on the frontal crash. The main task of previous researches has been to predict the energy absorption and maximum impact force in shell structure. The energy absorption and maximum impact force depend on many parameters such as boundary conditions, the history of plastic deformation during metalworking, geometry, material, and impact energy (mass and velocity of striker). In this paper, the crash behaviour of a circular tube made of the extruded aluminium alloy EN AW-7108 T6 is studied. In this study, by creating elastic and plastic boundary conditions instead of rigid boundary conditions on the bottom of a crash box, the stress–strain sensitivity effect on box behaviour during a crash is considered. In addition, the effect of elastic and plastic boundary conditions on the energy absorption of circular tubes under impact force is numerically investigated. The ductile failure criterion is employed to accurately obtain crashworthiness simulation results. Results reveal that the use of elastic boundary can change deformation mode and decrease the maximum impact force.

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ABSTRACT: In an effort to increase road vehicles’ structural strength, cellular materials, such as foam, have been utilised and installed in vital parts of the vehicle. The limited structural crush zones in side-impact collisions, when compared to frontal impacts, have shown to cause higher deformation to the passenger compartments that will lead to severe injury to the vehicle occupants. Therefore, the need to further enhance road vehicles’ passive safety system to protect the occupants during side-impact collisions is necessary. In
addition to many passive safety features, cellular materials have been installed in current vehicles to serve as structural reinforcement by absorbing impact energy from transferring to the occupants. This study is aimed at investigating the effect of various cellular materials in enhancing vehicle crashworthiness such as side door's intrusion, interior door's acceleration and the internal energy of the cellular materials. To fulfill the objective of this paper, an existing finite element model of a sedan vehicle is modified to include a cellular material sandwiched in between the door panels. The cellular materials used for this study are IMPAXX, polyurethane foam, micro-agglomerated cork, DAX and CONFOR foams. The mechanical properties of the cellular materials utilised in the computational model are validated. Various dynamic responses of the vehicle structure with the inclusion of the five selected materials are numerically tested and compared against the vehicle structure without the cellular materials. Side-impact simulations in accordance to federal motor vehicle safety standard (FMVSS) No. 214 standard are used to replicate side-impact collisions. This study quantifies the energy absorption and side-door intrusion with different cellular padding. It also shows that the inclusion of cellular materials significantly reduces occupant compartment's intrusion and deceleration of the vehicle by at least 30%. Therefore, the inclusion of cellular materials has shown promising results in improving the crashworthiness of road vehicles.

References listed at the end of the paper:


ABSTRACT: Two major requirements for a vehicular system's crash components are being lightweight and having good crashworthiness. Thin-walled round and conical tubes, which are either empty or foam filled and that can potentially be used as the front rails of a passenger car subjected to oblique impact, are numerically analysed using the finite element method. The conical tube was found to have the best performance in terms of both specific energy absorption and peak crushing force. A maximum of 106.6% increase in the specific energy absorption was observed for the empty conical tube than the foam-filled round tube in the load angle range of 0°–30°. Using the Kriging metamodels with a maximum relative error less than 4%, multi-objective design optimisation of the conical tube was performed with a weight constraint of 0.2 kg. Lightweight and improved crashworthiness were obtained simultaneously for the conical tube through optimisation. It was also found that the optimal tube configurations differ for different impact angles. However, including multiple load angles in the multi-objective design optimisation process is feasible and could result in improved robustness of the tube against oblique impact.

References listed at the end of the paper:


ABSTRACT: For S-shaped frame structures (SFS) in vehicle body, the multi-diagonal reinforced frame (MRF) might bring higher energy absorption than the single-diagonal reinforced frame (SRF). However, the complicated structure of the MRF leads to the requirement of trade-off for multi-geometrical parameters in crashworthiness design. This paper presents a systemic methodology of optimisation design of reinforced SFS under axial dynamic loading. First, the finite element analysis of the crash behaviour and the energy absorption
characteristics of the MRF and the SRF are implemented. Based on the numerical results, it can be found that the specific energy absorption (SEA) of the MRF is about 22% higher than that of the SRF, and the peak crushing force (PCF) of the MRF is reduced by 12% by comparing with the SRF. The simulations show the fact that the thickness of inner stiffener and the thickness of wall frame play significant effects on the SEA and the PCF. Second, a systemic methodology of optimisation design of reinforced SFS under axial dynamic loading is developed. The multi-objective optimisation design is performed by adopting multi-objective practice swarm optimisation (MOPSO) algorithm to achieve maximum SEA capacity and minimum PCF. During the multi-objective design (MOD) process, the response surface method (RSM) is utilised to improve computational efficiency for the complicated design problem in practical engineering. Finally, the optimisation results show the potential advantages of multi-diagonal reinforced frame (MRF) and the proposed method of optimisation design guarantees the feasibility of this type of reinforced SFSs used in passenger vehicles.

References listed at the end of the paper:
ABSTRACT: An accurate prediction of material failure and fracture is essential for a successful crash simulation. A computationally efficient shell modelling is indispensable when simulating large structures. This does not allow for a physically based Gurson fracture model. Many phenomenological fracture criteria were developed, which often challenge experimental material characterisation. In this paper, the description of material failure and fracture for the aluminium alloy EN AW-6082 is carried out with a minimum set of experimental tests. The yield function and the strain hardening function are evaluated with orthotropic tensile tests. In addition, flat shear specimens are tested giving another point on the yield surface. With the experimentally determined strain hardening and yield function, forming limits are calculated with a simulation model and are integrated into LS-DYNA (Livermore Software Technology Corporation LSTC, LS-DYNA Version 971, Revision R6.0.0) as Müschenborn and Sonne forming limit curve. Material fracture is described by the maximum shear stress criterion which is also calibrated with the flat shear specimens. Finally, the material model is verified with three-point bending tests of thin extruded sections showing good agreement between experimental and simulated force-displacement curves as well as in the fracture pattern.

References listed at the end of the paper:


ABSTRACT: Crush can is an automotive part located behind the bumper of automobiles like cars, trucks, jeeps, buses, etc. on each side. The purpose of crush can is to absorb impact energy in smooth way. The ideal requirement for crush can is that it should give a rectangular shape of force–displacement graphs on crush event. In this paper, it is described that the finite element analysis can be taken to assess the performance of conventional crush can. If required, the other large shell deformation mechanism can be plugged into it for improving its performance. Hence individual performance of crush and its combination with mechanism can assess through finite element analysis, which is cheaper than the physical test. The best mechanism of crush can lead towards the ideal requirements that can be chosen from finite element analysis iterations. The experimental verification is done for finite element analysis of individual and mechanism plugged in crush cans.

References listed at the end of the paper:


ABSTRACT: This paper investigates various modelling strategies to identify the most suitable approach for modelling the low-velocity impact response of laminated composite panels. The purpose of this paper is to thoroughly investigate a dropped tool scenario or a ground vehicle impact on an aircraft fuselage panel using detailed numerical models. Three-dimensional meso-scale finite element models have been developed and implemented with user-defined material subroutines in ABAQUS/Standard. The models predict the simultaneous evolution of inter-laminar and intra-laminar damage mechanisms that occur in composite panels during impact. The paper describes the implementation of the combined inter/intra-laminar models and assesses their performance. User-defined material models developed in previous work for quasi-static problems have been further developed in this paper for damage analysis under impact loading. Experimental drop-weight impact tests, representative of low-velocity high-energy rigid-body impacts, have been carried out for model validation. Impact energy levels were varied from 10 to 40 J to evaluate the damage threshold and damage area that develops within the laminate. The results of the combined inter/intra-laminar model are in excellent agreement with experimental data, especially in terms of energy absorbed during impact. Numerical results provide an accurate description of the threshold at which a significant change in laminate stiffness occurs. It is shown conclusively that the combined inter/intra-laminar damage model developed in this work can be employed as an accurate predictive tool for low-velocity impact events.

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ABSTRACT: Tubular forms of crash elements such as crash boxes are widely applied in transportation industries, especially in automobile industry. A crash box is an element used in the frontal crash zones, generally inserted between chassis and bumper to reduce the amount of crash energy that is transmitted to the rest of the front safety zones. In this paper, first, square section crash boxes filled with functionally graded honeycomb (FGH) subjected to oblique impact loading is presented with the objective to improve crashworthiness. Then, some optimisation tools such as the weighted average method, the geometrical average method, and multi-design objective optimisation technique are utilised to optimise the crash box structures. The optimisation results reveal that the crashworthiness of the FGH filled box structures exposed to the oblique impact loading is improved, and also proves its superiority with respect to the uniform honeycomb filled box structures. Finally, the metallic honeycomb density exponent gradient is properly determined.

References listed at the end of the paper:

ABSTRACT: The capability to numerically model the crushing behaviour of composite structures will enable the efficient design of structures with high specific energy absorption capacity. This is particularly relevant to the aerospace and automotive industries where cabin structures need to be shown to be crushworthy. In this paper, a three-dimensional damage model is presented, which accurately represents the behaviour of composite laminates under crush loading. Both intralaminar and interlaminar failure mechanisms are taken into account. The crush damage model was implemented in ABAQUS/Explicit as a VUMAT subroutine. Numerical predictions are shown to agree well with experimental results, accurately capturing the intralaminar and interlaminar damage for a range of stacking sequences, triggers and composite materials. The use of measured material parameters required by the numerical models, without the need to ‘calibrate’ this input data, demonstrates this computational tool’s predictive capabilities.

References listed at the end of the paper:

Crashworthiness performance of the FGT tubes are compared with their UT counterparts at the same weight. Simulated by using the non-linear gradient patterns are introduced to the axial direction of the tubes and then impact with a fixed rigid wall is evaluated. Functionally graded thickness (FGT) enables to obtain variable stiffness throughout the length of a structure; thus, it provides more efficient control of the crashworthiness parameters when compared with traditionally designed uniform thickness (UT) counterparts. In order to investigate the crash behaviour of FGT tubes, different thickness-gradient patterns are introduced to the axial direction of the tubes and then impact with a fixed rigid wall is simulated by using the nonlinear explicit finite element (FE) method. To show the efficiency of FGT tubes, crashworthiness performance of the FGT tubes are compared with their UT counterparts at the same weight.


ABSTRACT: The main objective of this study is to investigate the effects of thickness-gradient patterns on energy absorption characteristics of aluminium-based circular tubes under axial impact loading. Functionally graded thickness (FGT) enables to obtain variable stiffness throughout the length of a structure; thus, it provides more efficient control of the crashworthiness parameters when compared with traditionally designed uniform thickness (UT) counterparts. In order to investigate the crash behaviour of FGT tubes, different thickness-gradient patterns are introduced to the axial direction of the tubes and then impact with a fixed rigid wall is simulated by using the nonlinear explicit finite element (FE) method. To show the efficiency of FGT tubes, crashworthiness performance of the FGT tubes are compared with their UT counterparts at the same weight.
The effects of thickness range and aspect ratio of the tubes on their crash behaviours are also investigated. The simulation results show that the FGT tubes have superior crashworthiness performance than that of their UT counterparts and the crashworthiness parameters of the FGT tubes can be controlled and improved with the appropriate selection of geometric parameters of the tubes.

References listed at the end of the paper:

ABSTRACT: Fibre reinforced plastics are widely used for energy absorbing parts. Due to their superior
strength to density ratio they provide a high performance and are ideal for lightweight design for crashworthiness. For this, it is essential that the mechanical behaviour of fibre reinforced composites be predicted correctly by simulation. However, due to the complex inner structure, this is still a challenging task, in particular in case of highly nonlinear crash loading. In order to provide an alternative in this paper a virtual manufacturing simulation chain is proposed to gather detailed geometrical information about the roving structure of a filament wound tube on meso-scale. In addition effective material properties, based on calibrated models of the individual constituents, for the filament–matrix interaction are derived by micro-scale calculations. Both, combined with a USER MATERIAL model for the roving structure finally provide a complete finite element model which is used for the crash simulation of the filament wound tube. By comparing the numerical results to experimental data, the potential of the approach is shown and occurring differences are discussed as well as possible subsequent investigations are proposed.

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ABSTRACT: In order to assess the crashworthiness of simple magnesium structures, the axial deformation behaviour of different hollow rectangular profiles produced from wrought magnesium alloys Mg–3wt.%.Al–1wt.%Zn–0.3wt.%Mn and Mg–1wt.%Zn–0.4wt.%rare earth mischmetal were investigated under quasi-static compressive loading conditions. Laser beam welding was applied to build the crush configurations from plane rolled sheets; indirect extrusion was used to manufacture seamless profiles. Numerical simulations were conducted to predict and assess the crush behaviour. The simulation results revealed that the material work hardening rates evidenced in uniaxial compression tests together with the cross section influenced the buckling modes as well as the energy dissipation. The performance of the magnesium profiles in terms of dissipated specific energy is better than that of aluminium profiles for small compressive displacements. However, for large displacements, shear-compressive failure limited the crush displacement and hence the energy dissipation. The weld itself did not influence the failure and the energy dissipation of the respective structure. For the alloy and process development of wrought magnesium, prospective improvements towards higher dissipated energy can be realised by increasing not only the strength but also the hardening rate of the material.

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ABSTRACT: This study attempts to establish an experimental–numerical framework to simulate the dynamic response of aluminium foam-based sandwich panels subjected to bird strike. The numerical model is developed with the non-linear dynamic finite element code PAM-CRASH, where the smooth particle hydrodynamics (SPH) algorithm is used to model the bird, an elastic–plastic material model with isotropic damage is used to describe aluminium skin and the Deshpande–Fleck foam model is used to describe the foam core. Mechanical tests of the skin and foam materials as well as bird-strike tests of a double sandwich panel are conducted and the experimental results are used to calibrate the model parameters. The bird-strike simulation results show reasonably good agreement with test data, indicating the simulation method is capable of predicting the dynamic response of aluminium foam-based sandwich panels in the event of bird strike. Finally a series of parametric studies are conducted to examine the effects of foam thickness and arrangement on the deformation behaviour and energy-absorbing ability of the sandwich panels to illustrate the potential application of the numerical model in the design of aluminium foam-based sandwich structures.

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ABSTRACT: Thin-walled structures are major energy-absorbing components on the vehicle for crashworthiness. Most of the past and current research works on such structures are focused on their behaviour under single and simple loading conditions such as axial impact, and their deformation mode/failure under combined and complex loading conditions are much less studied. In this paper, we used numerical models to analyze the structural response and energy-absorbing performance of a novel octagonal thin-walled sandwich tube under oblique impact at various impact angles. The effect of key geometric parameters (internal reinforced plate thickness t₁ and external wall thickness t₂) on the overall structural behaviour (i.e. specific energy absorption and peak crush force) was discussed in detail. Based on the numerical model, a multi-objective optimisation was further performed to enhance its performance. The results indicate that the optimal design would be different based on various impact angles, and the effect of key geometric parameters are also the
functions of impact angle. Specifically, the optimal $t_1$ at the impact angles of 0°, 10°, 20° and 30° are 1.92, 1.93, 2.00 and 0.84 mm, respectively, while optimal $t_2$ are identical, and equal to 2.40 mm at each angle. These findings would provide a valuable guideline for the design of thin-walled energy absorbers under multiple oblique loading.

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ABSTRACT: Trade studies during the preliminary design phase play an important role in the design process of a new aircraft. However, the generation and adaption of appropriate finite element (FE) models still takes a lot of time which in turn may prevent comprehensive trade studies and, therefore, lead to time- and cost-intensive redesign during the detailed design phase. Based on a standardised aircraft description, a fuselage modelling tool was developed to automatically generate global FE models for preliminary sizing purposes using beam elements for the fuselage stiffening structure. To be also used in crash simulations these models can be extended in a way that certain regions – where high plastic deformations or failure is expected – may be modelled much finer by the use of extruded profiles and shell elements. Nevertheless, this fine representation is still based on the same standardised aircraft description. In this paper the crash analysis tool AC-CRASH is presented introducing various modelling options and applications. They range from standard section drops with a pure vertical velocity up to full fuselage models under realistic crash and ditching conditions. As an exemplary application of AC-CRASH a vertical drop of a generic fuselage rear section is evaluated in detail.

References listed at the end of the paper:


ABSTRACT: Aircraft water landing emergency provisions 14 CFR 25.801 demand requirement of ditching in water to both types of impacts are also presented. The dynamic simulation results from this study suggest that the acceleration pulses from the cabin floor are then utilised as input for the occupant simulation performed using the mathematical code, MADYMO 7.5. The occupant model consists of a MADYMO FAA Hybrid-III 50th percentile dummy, a 2-point lap belt and a rigid seat. The lumbar loads experienced by the occupants in relation to both types of impacts are also presented. The dynamic simulation results from this study suggest that the fuselage section in water impact may be less severe than solid surface impact.


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4. P. Bhonge, A methodology for aircraft seat certification by dynamic finite element analysis, Ph.D. diss., Wichita State University, 2008.


ABSTRACT: Hexagonal honeycombs have exhibited significant advantages in energy absorption and they are increasingly used as absorbers under crush conditions. Rather than restating details of the existing traditional regular hexagonal honeycomb, this paper introduces reinforced hexagonal honeycomb. The full-scale elaborator finite-element model created through LS-DYNA is validated by available theoretical solutions and experimental results. Afterwards, the validated simulation model is further applied to do a number of parametric studies on the reinforced hexagonal honeycomb under dynamic impact. The parameters such as stiffener thickness, expanding angle, cell length, cell wall thickness, impact mass, impact velocity and end constraint are employed to determine their relative effects on crushing behaviour of the reinforced hexagonal honeycomb. In the multi-objective crashworthiness optimisation, optimal Latin hypercube design method is used to select the sampling design points from the design space. To obtain a maximum specific energy absorption per mass (SEAm ) capability and minimum initial peak stress (oPeak ), response surface method, which is an accurate surrogate modelling method is adopted. The optimisation results show that the reinforced hexagonal honeycomb has a better energy absorption performance within the same limit of oPeak. This research is hence significant in providing technical support in potential applications of the reinforced hexagonal honeycomb used as crashworthiness structures.

References listed at the end of the paper:
ABSTRACT: Over the last few decades, the fuel efficiency of aircrafts was mainly improved by the application of refined aerodynamics, new materials, structural optimization and enhanced engine performance. A further potential for a greener aircraft is seen in the unconventional blended-wing-body (BWB) design configuration due to its advanced aerodynamic design and its reduced weight. For the certification of novel aircraft configurations, the airworthiness authorities require proof of at least equivalent safety standards compared to the existing conventional transport aircraft. In this context, the BWB configuration has to demonstrate sufficient crashworthiness for emergency landing on rigid surface and on water. Since structural modifications for improved safety should be applied in the early conceptual design phase of an aircraft, explicit simulations have been performed with the objective to estimate the crash behaviour of the BWB configuration. Based on the simulation results, design principles are derived for improved crashworthiness and ditching behaviour for the BWB aircraft configuration.

References listed at the end of the paper:


ABSTRACT: Thin-walled circular tubes are good in energy absorption and also light in weight. Energy absorption and deformation modes of these tubes depend on the geometry of the structure. Energy absorption can further be enhanced by implementing improved geometrical configurations. In the present investigation, an attempt is made to improve the energy absorption of thin concentric cylindrical tubes by replacing the inner tube with half cylindrical shells acting as stiffeners along the circumference of the external tube. The tubes have been tested simulated under impact loading and their deformation and energy absorption is studied in view of bottoming-out and energy absorption effectiveness factor. The total mass of the stiffened and double tubes is kept identical for the purpose of comparison. It is found that energy absorption capacity of the double tube is 1.71 times higher than the single tube and for stiffened tube, it is 1.91 times higher than the single tube configuration. Moreover, energy absorption effectiveness factor is found to be 1.69 times higher for double and 1.89 times higher for stiffened tubes in comparison with the single tube configuration. Further, it is concluded that provision of longitudinal stiffeners results in higher energy absorption with higher energy absorption effectiveness factor for stiffened tube configurations in comparison with the single and double tube configurations. Further, it is found that provision of stiffeners influences the deformation modes considerably.

References listed at the end of the paper:


ABSTRACT: In this paper, effects of solidity and cross-sectional shape on crashworthiness characteristics of thin-walled tubes under dynamic axial impact load are examined. For this purpose, explicit finite element analyses are conducted for tubes having triangular, square, circular, hexagonal, octagonal and multi-cell cross-sectional shapes. The FE model is validated with analytical and experimental results that were reported in literature. It is found that FE solutions agree well with analytical and experimental results presented in the literature. To compare the tubes having different geometric dimensions and shapes on the same ground, the tubes are selected such that they have the same mass and length, and the striker mass and velocity are identical for all tubes as well. By changing solidity of tubes between 0.05 and 0.25, the cross-sectional dimensions of tubes are specified. The crushing force efficiency, crushing strain, total efficiency, structural efficiency and dynamic energy absorbing effectiveness parameters are calculated for various tubes as a function of the solidity parameter. It is concluded that crashworthiness performance of thin-walled tubes is significantly influenced by the solidity and cross-sectional shape. Results about the most effective solidity values and cross-sectional shapes are presented.

References listed at the end of the paper:
4. A. Alavi Nia and M. Parsapour, Comparative analysis of energy absorption capacity of simple and multi-cell thin-walled tubes with triangular, square, hexagonal and octagonal sections, Thin-Walled Struct. 74 (2014), pp. 155–165.


ABSTRACT: The aim of this research is the investigation of foam-filled honeycomb sandwich panels under in-plane impact loading and the analysis of their crashworthiness. This paper presents a finite element analysis of foam-filled honeycomb sandwiches under in-plane impact loading. Three different aluminium honeycombs filled with three different polyurethane foams were considered in the numerical simulation, and results were compared with those obtained for bare honeycomb panels. For what concerns the crashworthiness analysis, the response of the foam-filled honeycomb panels under out-of-plane impacts was compared with those of unfilled honeycomb panels and circular tubes.

References listed at the end of the paper:


ABSTRACT: In this paper, crushing characteristics of small-sized conical tubes called miniature frusta under axial loading have been studied. Finite-element model is developed using non-linear explicit code LS_DYNA to investigate the non-symmetrical fold patterns as well as material and geometrical non-linearity of frusta. Numerical simulation is first validated by confirming the results using experimental test data. Effects of shell thickness, semi-epical angle of cone and frusta's length on energy absorption characteristics are then studied by carrying out a parametric study. Based on the crushing parameters of numerous examples, a simplified analytical model as a meta-model for the mean crushing force of miniature frusta is presented using a Genetic Algorithm optimization for finding the meta-model coefficients. Miniature frusta show promising behaviour in lightweight design and crash analysis as their response results in low peak force and efficient-specific energy absorption. Obtained results from the developed meta-model showed good concurrence with finite elements method (FEM) model.

References listed at the end of the paper:
16. A.G. Mamalis and W. Johnson, The quasi-static crumpling of thin-walled circular cylinders and frusta under axial compression,
ABSTRACT: An important issue that should be considered in accidents, including car, helicopter, and airplane crashes, is the safety of the human occupants. In this research, graded honeycomb structure is primarily introduced as a shock absorber. The amount of energy absorption, and the applied force and acceleration to the passengers have been calculated through numerical simulation in ABAQUS software. In order to validate numerical results, a low velocity experiment has been conducted on the test sample. Results represent an acceptable agreement with empirical ones. Given the occurrence of an emergency helicopter crash, it is of great importance to avoid any potential injurious loading to the passenger. Hence, according to Joint Aviation Regulations part 27, an optimised seat shock absorber has been designed and analysed for a helicopter in crash condition by the means of Genetic and Sequential Quadratic Programming algorithms. The designed shock absorber, which is of graded honeycomb structure, has satisfied complete standard specifications while being applied in the helicopter crash simulation. The applied design and simulation approach could be extended for any other types of shock absorbers.

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7. S.A. Galehdari, M. Kadkhodayan, and S. Hadidi-Moud, Analytical, experimental and numerical study of a graded honeycomb
15. MATLAB software, MathWorks, 2015.


**ABSTRACT:** This paper compares the responses of three-dimensional four-directional (3D4D) and five-directional (3D5D) circular braided composite tubes under transverse impact loading. Transverse impact tests were conducted on a modified Split-Hopkinson pressure bar (SHPB). A finite-element analysis (FEA) model was established based on the microstructure of 3D circular braided preform. Load–displacement curves, specific load and specific energy absorption were obtained for the purpose of comparison between 3D4D and 3D5D samples. It was found that the peak load of the 3D5D tube was about twice that of 3D4D tube. The specific load and the specific energy absorption of 3D5D tubes were averagely about 1.21 times and 1.18 times those of 3D4D tubes, respectively. Due to the existence of straight axial yarns, the deformation of the 3D5D braided tube was smaller than that of the 3D4D braided tube. Stress propagation in the straight axial yarns was observed to be faster than that in the crimped braiding yarns. The damage morphologies were observed and it was found that the damages of the 3D4D braided tubes were severer than those of the 3D5D braided tubes.
References listed at the end of the paper:

ABSTRACT: The aim of this case–control study was to determine if there is an association between vehicle panel damage and AIS3+ thoracic injuries. NASS CDS data from 2001 to 2012 was examined for single vehicle
rollover crashes with occupants receiving serious thoracic injuries (cases) and those without thoracic injuries (controls). Vehicle panel damage for cases and controls were coded and logistic regression performed to determine if there is an association between serious thoracic injury and vehicle panel damage. Furthermore, an investigation into the differences in injury sources and injury outcomes between front-seated near- and far-side occupants was performed with the data. There were two main findings from this study. First, there is an association between the rear left segment, front left upper-half door, and front right upper-half door damage and serious thoracic injury. Second, the sources of thoracic injuries and the thoracic viscera injured are different for near-side and far-side occupants.


ABSTRACT: This paper presents a simple novel crash energy absorbing system made of plain aluminium thin-walled tubes and honeycomb. The proposed tube/honeycomb system is characterized by slightly shorter tubes inserted into the cells of the honeycomb with close fit. The individual tube and honeycomb structures are numerically modelled under low-speed vertical impact loading and compared with experiments conducted in this study. Next, three representative triangular sections, which involve the symmetric boundary conditions of each cell group, are employed to model the tube/honeycomb system. Load-displacement curves and deformation patterns are compared with the experiments. The proposed honeycomb/tube system is found to produce higher energy absorption capacities for both per unit mass and volume, compared to an ordinary deformation of the tubes pushed by the collapsed honeycomb walls. This interaction also enables synchronised deformation throughout the crash. Finally, a parametric study is performed, based on the height difference between the tubes and honeycomb, which is found to be the determiner of the performance for the proposed system.

References listed at the end of the paper:

ABSTRACT: Mechanical responses of quasi-static and dynamic transversely loaded empty/foam-filled braided tubes were investigated with a custom load frame and pneumatic gun/projectile at velocities ranging from 21 to 27 m/s. Braided tubing was woven from AISI 304 wire (wire diameter: 0.51 mm, external diameter: 64.5 mm, length: 330 mm). Foam density ranged between 162 and 520 kg/m³. Localised foam collapse at mid-span under impact resulted in greater energy absorption for foam-filled specimens compared to quasi-static tests. Foam density significantly influenced force efficiency for reduced deflections. For low-density quasi-static tests, the average force efficiency was 58.3% decreasing to 41.9% under impact. Force efficiency for high-density foam under quasi-static loading was 42.8% decreasing to 23.4%. High-density foam cores exhibited minimal foam
crushing as the increased mechanical properties of the foam resulted in braided tube failure. Low/medium-density foam cores yielded both optimal specific energy absorption over the full deflection range and force efficiency for reduced deflections.

References listed at the end of the paper:

End of many papers published in the journal, Crashworthiness (2012-2016).


ABSTRACT: Presented in this paper are the vibration characteristics of single-walled carbon nanotubes (SWCNTs) with different boundary conditions. A nonlocal shell model accounting for the size effect is adopted. The set of governing equations of motion are numerically solved using a semi-analytical finite element method. The effectiveness of the present nonlocal shell model is assessed by molecular dynamics simulations as a benchmark of good accuracy. The significance of the small size effects on the resonant frequencies is indicated to be dependent on the sizes, boundary conditions of nanotubes, and the tube wall thickness varying within 0.066 nm to 0.34 nm.

References listed at the end of the paper:

ABSTRACT: Aiming to increase the accuracy and computational efficiency of shear, flexible, thin-walled beam assemblages with arbitrary cross-section, two $C^0$-finite element models for three-dimensional analysis are developed based on the hybrid/mixed variational principle. To eliminate the shear/warping locking in these $C^0$ elements, the Hellinger-Reissner-variational principle is adopted. In this, both displacement and stress fields are approximated independently. To enhance the accuracy and performance of these models, the stress parameters are chosen to satisfy the equilibrium within the element level in addition to the conventional requirements; i.e., avoid all kinematic deformation modes and enable the resulting element to handle applications with constrained problems. Such stress parameters are of the interelement-independent type and, therefore, can be eliminated on the element level by applying the relevant stationary conditions, thus leading to the standard form of the stiffness equations for implementation. Further, the underlying generalized beam theory employed accounts for all coupled significant modes of deformations including stretching, bending, shear, torsion, as well as warping. The formulation is also valid for both open- and closed-type, thin-walled sections; this is accomplished by using kinematic descriptions accounting for both flexural and warping torsional effects. Despite the effort in selecting the stress field to satisfy equilibrium within the element level, the present models achieved better accuracy, robustness, and fast convergence.

References listed at the end of the paper:

ABSTRACT: In this work, on the basis of a nonlocal elastic plate model, the free vibration of monolayer graphene sheets is studied. An explicit formula for estimating the fundamental frequencies of a monolayer graphene sheet is studied. An explicit formula for estimating the fundamental frequencies of a monolayer graphene sheet is studied. An explicit formula for estimating the fundamental frequencies of a monolayer graphene sheet is studied. An explicit formula for estimating the fundamental frequencies of a monolayer graphene sheet is studied. An explicit formula for estimating the fundamental frequencies of a monolayer graphene sheet is studied.

References listed at the end of the paper:


ABSTRACT: In this paper, a finite element model is proposed for the study of two-dimensional arch structures. Three- and five-node elements are developed irrespective of the shape of the arch and capable of analyzing thick to very thin structures using a modified Mindlin-Reissner theory. A compatibility displacement-based method is used: full integration is introduced to evaluate all energy terms and the convergence pattern is completely independent of the thickness values, even if a coarse mesh is employed. Shear and membrane locking are completely eliminated, shaping shear and membrane strains by means of suitable functions appropriately projected over Gauss integration points. A formulation has been developed which takes into account, in the elastic range, the possibility of working with a more general cross-section conceived as a set of layers. Numerical examples are also given to show the accuracy of the method and comparisons with previous models are made.

References listed at the end of the paper:

ABSTRACT: This study is focused on the structural optimization of an axial flow compressor rotating disk in a more simplistic way. Since optimization involves several runs, performing Finite Element Analysis (FEA) for a disk model in each run increases computational cost. Alternative response surface design models have been developed using the design of experiment (DOE) method to represent the FE disk model. These response equations are validated and used in optimization runs. A constraint nonlinear optimization procedure based on genetic algorithms has been used. FEA is completely avoided during the optimization runs with the help of response equations, resulting in less computational time and cost.

References listed at the end of the paper:

ABSTRACT: This paper investigates the free vibration of multiple delaminated graphite-epoxy cross-ply composite pretwisted rotating conical shells. The generalized dynamic equilibrium equations are derived from Lagrange's equation, neglecting the Coriolis effect for moderate rotational speeds. The formulation is based on Mindlin's theory considering an eight-noded isoparametric plate-bending element. The multipoint constraint algorithm is employed and a QR iteration algorithm is utilized to solve the standard eigenvalue problem. The mode shapes for a typical laminate configuration are also depicted. Numerical results obtained are the first known value, which could serve as reference solutions for future investigators.

References listed at the end of the paper:

ABSTRACT: This paper presents the stochastic post-buckling response of elastically supported FGM plate with random system properties subjected to uniform and nonuniform temperature change with temperature-dependent and -independent material properties. The FGMs plate is supported with two parameters of Pasternak foundation with Winkler cubic nonlinearity. The basic formulation is based on higher-order shear deformation theory (HSDT) with von-Karman nonlinearity using modified C⁰ continuity. A direct iterative-based nonlinear finite element method combined with first-order perturbation technique is used to compute the second-order statistics (mean and coefficient of variation) of post-buckling response of FGM plates.

References listed at the end of the paper:

ABSTRACT: Vibration suppression of a smart thin elastic rectangular plate is considered. The plate is subjected to external disturbances and generalized control forces, produced, for instance, by electromechanical feedback. A nonlinear controller is designed, based on fuzzy inference. The initial-boundary value problem is spatially discretized by means of the time spectral method. The implicit Newmark-beta method is employed for time integration. Two numerical algorithms are proposed. The techniques have been implemented within MATLAB with the use of the Fuzzy Logic Toolbox. Representative numerical results are given.

References listed at the end of the paper:


ABSTRACT: Exact solutions of eigenfrequencies and vibration modes of rectangular cantilever thin plates are derived by using the double finite integral transform method. Since only the basic elasticity equations of the plates are used, the analytical method utilized in this paper eliminates the need to predetermined the deformation function arbitrarily and is hence more reasonable than conventional semi-inverse methods. Numerical results presented in the paper demonstrate the validity of the approach.

References listed at the end of the paper:

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significantly influenced by temperature distribution, thickness, and angular speed of the disk. The numerical results reveal that these quantities are significantly influenced by temperature distribution, thickness, and angular speed of the disk.

References listed at the end of the paper:


ABSTRACT: This paper studies the thermoelastic displacements, stresses, and strains in a thin, circular, functionally graded material (FGM) disk subjected to thermal load by taking into account an inertia force due to rotation of the disk. The material properties of the FGM disk have been assumed to vary exponentially in the radial direction. Based on the two-dimensional thermoelasticity theory, the axisymmetric problem is formulated in terms of a second-order ordinary differential equation, which is solved by employing the finite element method (FEM). The temperature profile has been modeled with the help of a heat conduction equation. The model has been solved numerically to attain stresses, strains, and displacements in an Al$_2$O$_3$/Al FGM circular disk and the computer-simulated results are presented graphically. The effect of Kibel Number on stresses, strains, and displacement has also been discussed. The numerical results reveal that these quantities are significantly influenced by temperature distribution, thickness, and angular speed of the disk.

References listed at the end of the paper:

ABSTRACT: This paper deals with buckling analysis of plates by the charge simulation method, and the effectiveness of an application of this method has been verified. First, the general solution for the deflection is obtained by a combination of two kinds of series of Green's functions. Satisfying the modified boundary conditions at the boundary points, the non-homogeneous simultaneous equations are obtained. The buckling loads are found by using an iterative solution method with varying edge compression. Numerical results are presented for rectangular and isosceles triangular plates under uniform compression, and are in good agreement with the results obtained by other methods.

References listed at the end of the paper:


ABSTRACT: In this paper, we present a study of finite element analysis (FEA) of structural instability by using a switching implicit-explicit algorithm embedded into the finite element method. Snap-through or snap-back buckling problems often cause divergence of the finite element method if arc-length methods are not used. The origin of divergence is often associated with critical points. An alternative to the latter is considered herein, the implicit–explicit FEA. The numerical results showed the effectiveness of this switching technique for solving divergence when simulating structural instabilities such as buckling of an elastic–plastic arch.

References listed at the end of the paper (I do not understand all the extraneous “31”s in the authors’ names):

ABSTRACT: High strain rate experiments performed on multi-walled carbon nanotubes, polycarbonate composites (MWCNT-PC) have exhibited enhanced impact resistance under a dynamic strain rate of nearly 2500/s with composition of only 0.5 to 2.0% multi-walled carbon nanotubes (MWCNTs) in pure polycarbonate (PC). Similarly, hardness and elastic modulus under static loads resulted in a significant increase, depending upon the composition of MWCNTs in PC. The present work aims to analyze these results by correlating the data to fit expressions in generalizing the behavior of MWCNTs composition for MWCNT-PC composites under both static and impact loads. As a result, we found that an optimum composition of 2.1 weight % of MWCNTs exhibits maximum stress resistance within elastic range under strain rates of nearly 2500/s for MWCNT-PC composites. The composition of MWCNTs plays a crucial role in maximizing modification of static and dynamic impact-based mechanical properties of polycarbonates. Further, a simple model based on Lennard–Jones 6–12 atom-atom based potential is formulated and used to compute preliminary estimates of static properties of pure as well as composite PC with the aim to modify this in subsequent approaches.


ABSTRACT: Nonlocal continuum theory is studied for modeling stress distributions in nanocomposites. The second-order approximation in nonlocal theory is considered since the first-order approximation leads to an unacceptable solution. A representative volume element (RVE) of CNT composite is utilized to derive unknown constants in the nonlocal theory model. Stress distributions in RVE using nonlocal theory, classical elasticity, and finite element method are obtained. All three approaches yield the same force, but classical elasticity gives an incorrect value of first moment. Wave propagation studies show that the dispersion curve obtained by nonlocal theory is quite close to the atomic Born-von Karman model.

References listed at the end of the paper:

ABSTRACT: The presence of in-plane loading may cause buckling of stiffened panels. An accurate knowledge of critical buckling load and mode shapes is essential for reliable and lightweight structural design. This paper presents parametric studies on simply supported laminated composite blade-stiffened panels subjected to linearly varying in-plane edge/compressive loading. Studies are carried out by changing the panel orthotropy ratio, stiffener depth, pitch length (number of stiffeners), smeared extensional stiffness ratio of stiffener to that of the plate and load distribution parameter. Based on the studies, a few important parameters influencing the buckling behavior are identified and their significance is discussed. Further, the interaction equations for combined loadings are validated by carrying out numerical studies.

References listed at the end of the paper:


ABSTRACT: This article presents the strong, nonlocal scale effect on the terahertz flexural wave dispersion characteristics of a monolayer graphene sheet (GS), which is embedded in elastic medium. The chemical bonds are assumed to be formed between the GS and the elastic medium. From the spectrum analysis, we found that the elastic matrix highly affects the flexural wave mode and rapidly increases the frequency band gap of
flexural wave. The nonlocal elasticity calculation shows that the wavenumber escapes to infinite at a certain frequency and the corresponding wave velocity tends to zero at that frequency, indicating localization and stationary behavior.

References listed at the end of the paper:

ABSTRACT: The effect of temperature-dependent material properties on the geometric nonlinear flexural response and thermal postbuckling behavior of shear flexible Functionally Graded Material (FGM) beams is investigated under various thermal and thermo-mechanical environments. The important aspects of the thermal and thermo-mechanical bending and thermal post-buckling of FGM beams are studied. The temperature variation across the thickness is obtained analytically and the finite element method (FEM) is used to predict the transverse deflections and stresses in the flexural analysis and the load-deflection paths for the thermal postbuckling analysis. The through thickness continuous variation of the material properties of the FGM beams is considered using the standard power law distribution. The von-Karman-type strain-displacement relations are used to account for the moderately large deflections. The FGM beams, with the classical hinged and clamped boundary conditions, are analyzed considering the axially immovable ends. The numerical results are provided to clearly bring out the importance of including the temperature dependency of the material properties to evaluate the realistic flexural response and thermal postbuckling behavior of the FGM beams subjected to
References listed at the end of the paper:


ABSTRACT: Recently, a two–dimensional, three- and five-node arch element has been developed devoid of shear and membrane locking, even in the extreme thin limit. By following the same approach, but making different choices on the shape functions regarding shear, bending, and membrane strains appropriately projected over Gauss integration points, a family of locking free–shell finite elements has been derived. The undesired locking phenomena are completely suppressed. A range of numerical examples are also given to show the accuracy of the formulation proposed and comparisons with well-known shell finite elements are made in order
to yield insight into the predictive capability of the nine-node shell element studied.

References listed at the end of the paper:

ABSTRACT: The bending analysis of laminated composite and sandwich plates using different radial basis functions and higher-order shear deformation theory is presented. This meshfree technique is insensitive to spatial dimension and considers only a cloud of nodes (centers) for the spatial discretization of both the problem domain and the boundary. Numerical results for simply supported isotropic, symmetric cross-ply composite and sandwich plate are presented. The results are compared with other available results. It is observed that convergence of the polynomial function is faster as compared to other radial basis functions, whereas Gaussian function takes the least solution time. The effect of various types of loadings on sandwich plate is presented.

References listed at the end of the paper:
http://dx.doi.org/10.1080/15502287.2014.882444

ABSTRACT: Most courses on mechanics of materials use a linearized (second-order) buckling analysis of a simple elastic system as an introductory example. We propose to start with a third-order buckling analysis instead, to enable the students to understand the crucial load-response diagrams from the beginning of the course. We present an extensive mathematical discussion of an extended standard introductory example, leading to an easy-to-implement plotting routine for load-response diagrams. The resulting diagrams are interpreted in physical terms. An implementation of the plotting algorithm using Maplesoft Maple™ is attached.

References listed at the end of the paper:
ABSTRACT: This article presents a numerical investigation to predict the behavior of ceramic (Al$_2$O$_3$ 99.5)/metal (Al5083 H116) composite panels under two consecutive high-velocity impacts of 7.62 mm sharp-nosed small projectiles. A numerical model is developed using the advanced nonlinear software AUTODYN. The aim of the study is to predict the impact behavior of ceramic/metals composite panels. The study mainly focuses on the effect of arrangement of front ceramic tiles having collinear and non-collinear joints on the impact damage pattern. The novelty of the study presented in this article is the prediction of high-velocity-impact response under two consecutive and closely spaced hits on composite panels carried out in a more realistic manner. Numerical responses, such as depth of penetration, and deformation in back plate and crack patterns, are found to match well with the experimental results. It is believed that the outcome of this study is helpful in the design of a ceramic tile joint arrangement to minimize damage in the target panel.


ABSTRACT: In this article, compression behavior and energy absorption of aluminum alloy AA6061 tubes are investigated both experimentally and numerically. Static and dynamic simulations are done using LS-Dyna Software for AA6061 tubes. True stress-plastic strain curves from the tensile test are used in the static and dynamic simulations of AA6061 tubes. The energy absorption values between experimental compression results and numeral simulation are found to be in good agreement. Dynamic simulations are done with drop velocity of up to 10 m/s to understand the inertia effects on energy absorption. The deformed modes from the numerical simulation are compared between tubes with and without holes in static and dynamic conditions.

References listed at the end of the paper:
ABSTRACT: The phenomenal damping characteristics of carbon nanotube reinforced polymer composites are attributed to the interfacial stick slip mechanism. In the current work, the interfacial-stick-slip-based damping mechanism is analytically studied for multi-walled carbon nanotube (MWNT) reinforced polymer composites. A theoretical model is proposed to estimate the loss factor for the representative volume element (RVE). An appropriate homogenization procedure is used to calculate the overall loss in the structure undergoing cyclic deformation. Damping experiments are carried out to validate the work. Satisfactory correlations are found to exist between the theory and experiments.

References listed at the end of the paper:
ABSTRACT: The microscale vibration characteristics of microbeams made of functionally graded materials (FGMs) are investigated based on the strain gradient Reddy beam theory capable of capturing the size effect. The non-classical governing differential equations, together with the corresponding boundary conditions, are obtained using Hamilton's principle. Then, the free vibration problem of simply supported FGM microbeams is solved using the Navier solution. The natural frequencies of FGM microbeams are calculated corresponding to a wide range of dimensionless length scale parameters, material property gradient indices, and aspect ratios to illustrate the influences of size effect on the vibrational response of FGM microbeams.

References listed at the end of the paper:

with stress parameters satisfying the equilibrium within the element level in addition to the common requirements; i.e., avoiding all kinematic deformation modes, and enabling the resulting element to handle applications with constrained problems (i.e., thin curved beams). Such stress parameters are of the interelement-independent type, and therefore can be eliminated on the element level by applying the relevant stationary conditions, thus leading to the standard form of the stiffness equations for implementation. The membrane and shear, due to flexure and warping, locking in this C0-element can be eliminated by adopting the Hellinger-Reissner-variational principle in which both displacement and stress fields are approximated independently. Further, the underlying generalized beam theory employed accounts for all coupled significant modes of deformations, including stretching, bending, shear, torsion, as well as warping. The formulation is also valid for both open- and closed-type thin-walled sections. Despite the effort in selecting the stress field to satisfy equilibrium within element, the developed model achieved better accuracy, robustness, and fast convergence.

References listed at the end of the paper:
ABSTRACT: In the present work, an adaptive isogeometric analysis based on a combined r-h strategy is proposed for plane elasticity problems. For performing the r-adaption, the control net is considered to be a network of springs with the individual spring stiffness values being proportional to the error estimated at the control points. While


ABSTRACT: In the present work, an r-h adaptive isogeometric analysis is proposed for plane elasticity problems. For performing the r-adaption, the control net is considered to be a network of springs with the individual spring stiffness values being proportional to the error estimated at the control points.


ABSTRACT: It is known that elastic large deflections of thin plates are governed by von Karman nonlinear equations. The analytical solution of these equations in the general case is unfeasible. Samuel Levy, in 1942, showed that large deflections of the rectangular plate can be expressed as a double series of sine-shaped harmonics (deflection harmonics). However, this method gave no way of creating the computer algorithm of solving the problem. The stress function expression taken in the Levy's method must be revised to find the approach that takes into account of all possible products of deflection coefficients. The algorithm of solving the problem for the rectangular plate with an arbitrary aspect ratio under the action of the lateral distributed load is reported in this paper. The approximation of the plate deflection is taken in the form of double series proposed by Samuel Levy. However, the expression for the stress function is presented in the form that incorporates products of deflection coefficients in the explicit form in distinction to the Levy's expression. The number of harmonics in the deflection expression may be arbitrary. The algorithm provides composing the system of governing cubic equations, which includes the deflection coefficients in the explicit form. Solving the equation system is based on using the principle of minimum potential energy. A method of the gradient descent is applied to find the equilibrium state of the plate as the minimum point of the potential energy. A computer program is developed on the basis of the present algorithm. Numerical examples carried out for the plate model with 16 deflection harmonics illustrate the potentialities of the program. The results of solving the examples are presented in the graphical form for the plates with a different aspect ratio and may be used under designing thin-walled elements of airplane and ship structures.

References listed at the end of the paper:

preserving the boundary control points, relocation of only the interior control points is made by adopting a successive relaxation approach to achieve the equilibrium of spring system. To suit the noninterpolatory nature of the isogeometric approximation, a new point-wise error estimate for the h-refinement is proposed. To evaluate the point-wise error, hierarchical B-spline functions in Sobolev spaces are considered. The proposed adaptive h-refinement strategy is based on using De-Casteljau’s algorithm for obtaining the new control points. The subsequent control meshes are thus obtained by using a recursive subdivision of reference control mesh. Such a strategy ensures that the control points lie in the physical domain in subsequent refinements, thus making the physical mesh to exactly interpolate the control mesh and thereby allowing the exact imposition of essential boundary conditions in the classical isogeometric analysis (IGA). The combined r-h adaptive refinement strategy results in better convergence characteristics with reduced errors than r- or h-refinement. Several numerical examples are presented to illustrate the efficiency of the proposed approach.

References listed at the end of the paper:

ABSTRACT: In this paper, variable kinematic one-dimensional (1D) structural models have been used to analyze thin-walled structures with longitudinal stiffeners and static loads. These theories have hierarchical features and are based on the Carrera Unified Formulation (CUF). CUF describes the displacement field of a slender structure as the product of two function expansions, one over the cross-sectional coordinates, Taylor (TE) or Lagrange (LE) expansions were used here, and one along the beam axis. The results obtained using the refined 1D models have been compared with those from classical finite element analyses that make use of plates/shells and solids elements. The performances of classical and refined structural models have been compared in terms of accuracy and computational costs. The results show that the use of the LE over the cross-section allows the strain/stress fields to be evaluated accurately for all the structural components. The comparisons with the results obtained using the classical models highlight how, the use of 1D refined models, allows the number of degrees of freedom (DOF) to be reduced, meanwhile, the accuracy of the results can be preserved.

References listed at the end of the paper:


ABSTRACT: This article presents the buckling analysis of laminated composite stiffened plates subjected to partial in-plane edge loading. The finite element method is used to carry out the analysis. The eight-noded
isoparametric degenerated shell element with $C^0$ continuity and first-order shear deformation and a compatible three-noded curved beam element are used to model the plate skin and the stiffeners, respectively. The eigenvalue analysis is carried out to track the buckling load. The convergence study is performed for some specific problems and the results are compared with the available results in the literature. It is observed that the convergence of results is very fast for this finite element model. Effect of different parameters like orientation of fibers, number of layers, and loading types are considered in the present investigation. It is also observed that all these parameters have significant effect on the buckling response of the composite stiffened plate.

References listed at the end of the paper:

ABSTRACT: The thermal buckling analysis of nanoplates is based on nonlocal elasticity theory with four-unknown shear deformation theory resting on Winkler–Pasternak elastic foundation. The nanoplate is assumed to be under three types of thermal loadings, namely uniform temperature rise, linear temperature rise, and nonlinear temperature rise through the thickness. The theory involves four unknown variables with small-scale effects, as against five in the case of other higher-order theories and first-order shear deformation theory. Closed-form solution for theory was also presented. Results are presented to discuss the influences of the
nonlocal parameter, aspect ratio, side-to-thickness ratio, and elastic foundation parameters on the thermal buckling characteristics of analytical rectangular nanoplates.

References listed at the end of the paper:
ABSTRACT: This article presents the application of DKMQ24 shell element for twist of thin-walled beams. This element passed the patch tests for membrane, bending and shear problems and gave fine results for plate and shell problems analysis without shear locking. Thin-walled cantilever beams are analyzed using this element. DKMQ24 gives good results for cantilever beams with open cross-section for a very few number of element. Moreover, the comparison of the results obtained with Vlassov analytical solution enables to evaluate the accuracy of the twist rigidity, \( J_d \), which depends on an empirical coefficient in Vlassov theory.

References listed at the end of the paper:

References listed at the end of the paper:
function can be improved by optimizing its scaling parameters.
exponential and spline. The numerical results for three case studies, i.e., cantilever, plate with a hole and pressurized thick cylinder, are presented. Computational results indicate that the performance of Gaussian test function is the best, followed by exponential and spline functions, but the performance of exponential test function can be improved by optimizing its scaling parameters.
References listed at the end of the paper:


ABSTRACT: The smoothness of shape functions computed using moving least-square approximation is affected by the choice of trial function and order of basis function. This paper presents elastostatic analysis using Meshless Local Petrov Galerkin method (MLPG) with three types of test functions, i.e., Gaussian, exponential and spline. The numerical results for three case studies, i.e., cantilever, plate with a hole and pressurized thick cylinder, are presented. Computational results indicate that the performance of Gaussian test function is the best, followed by exponential and spline functions, but the performance of exponential test function can be improved by optimizing its scaling parameters.


ABSTRACT: This paper presents the results of a numerical investigation into the structural behaviour of preloaded tubular members under lateral impact loads by means of finite element method. The lateral load represents a statically modelled impact from collision between tubular member and a solid rectangular indenter. Three different kinds of end conditions have been applied to the model and the effects of boundary conditions are investigated. Also, the effect of preloading on the buckling strength as well as the ultimate strength for laterally impacted tubes is assessed and it will be shown that preloading and position of applying force directly affect these strengths. In other words, by increasing in the amount of preloading, ultimate strength reduces and member tends to collapse under lower amounts of loads. The influence of the position of applying lateral load has also been addressed and relevant results will be discussed. In order to verify the performance of numerical model, the results have been examined against an available experimental test.

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ABSTRACT: This paper provides two convergence criteria to find translational and rotational locations of the neutral axis plane (NAP) for intact and damaged vessels. Definition of three types of asymmetries of a ship section is proposed: material-, load-, and geometry-induced asymmetries. Concept of moment plane (MP) is introduced to define the heeling angle of ship section. It is suggested that force equilibrium and force vector equilibrium criteria are simultaneously necessary to determine new position of NAP due to both translational and rotational shifts. In order to verify the applicability of the convergence criteria, midship section of a VLCC is selected with two types of asymmetries: one is due to heeling of a section and the other due to hull damages. 0° and 30° heeling conditions and collision-induced and grounding-induced damage extents based on ABS
Guides and DNV Ship Rules are taken into account. The various section properties are compared according to the area reduction ratios for each heeling and damage cases. It is shown that ultimate hull girder capacities are closely related to the area reduction due to the damages. Using new convergence criterion, mobility of NAPs and force centroids in elastic and inelastic regimes are visually provided.

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ABSTRACT: Lined pipes are Carbon Manganese pipes (backing steel) with a thin liner of corrosion resistant alloy, mechanically bonded to the backing steel. Lined pipes are cheap to produce compared to clad pipes, where the liner is metallurgically bonded to the backing steel, but they are also more complex to design for. One particularly challenging aspect is to determine load/displacement levels for potential disbondment between the liner and the backing steel. In that context, the strength of the metallurgical bond between the backing steel and the liner in a lined pipe may have an important influence. The metallurgical bond may be characterized by residual stresses in the liner and the friction coefficient between the inner surface of the backing steel and the outer surface of the liner. Current industry testing practice to determine the magnitude of residual stresses is defined in API 5LD, but these tests fail to consider boundary effects and Poisson’s ratio effects which have a substantial impact on the measured stress levels. An analytical formulation for stress levels in the liner close to free boundaries, and interaction between axial and hoop stresses are presented in this paper and validated by detailed finite element analyses. This formulation provides excellent transparency in terms of understanding which physical parameters are important in the surface interaction between the liner and the backing steel, and, among several applications, they are a highly useful tool to reinterpret the test regimes suggested in API 5LD.

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ABSTRACT: The aim of this paper is to investigate the effects of corrosion pits on the ultimate capacity of mild steel rectangular plates under uniaxial compression. For aging ship structures suffering from corrosion deterioration, the normal inspection practice is to measure the pit intensity (DOP) and maximum or average pit depth. A series of nonlinear FEM analysis on plates with partial and through thickness corrosion pits are carried out, changing geometrical attributes of both pits and plates, i.e., the radius, depth and location of pits and the slenderness of plates. The simulation results show that the volume loss dominates the degradation of the compressive capacity of pitted mild steel plates in addition to plate slenderness. This effect can be represented by the DOP and average thickness loss at pits, and the later primarily governs the collapse behavior of the plate itself. It is found that single side distributed pits have slightly severer deterioration on plates than the double sided pits with the same total thickness reduction, which tends to be more evident with increasing DOP and partial depth at pits. Finally, an empirical formula based on FEM results is proposed to predict the ultimate capacity of pitted plates under in-plane compression, which can be used for practical purposes. The comparison between results from the FEM simulation and the formula shows a satisfactory fit.
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ABSTRACT: This paper evaluates the distributions of three slenderness ratios of the plates, the stiffeners, and the stiffened panels, and presents a comparison of the load-shortening behaviors of the stiffened panels. The slenderness ratios, which represent the geometry and material properties of the stiffened panels, are obtained from deck and bottom platings of the midship area of 163 vessels, including 59 tankers, 46 bulkers, 28 product carriers, 15 container carriers, and 12 miscellaneous ships. Under the assumption that each slenderness ratio closely follows a normal distribution, average and upper/lower bound slenderness ratios are derived based on mean and mean plus/minus two times standard deviations. In order to compare the load-shortening capacities of the stiffened panels from simplified formulas of common structural rule (CSR) with those derived from a nonlinear FEA, a new parameter of relative average strain energy is introduced. It is concluded that the CSR formulas may be developed based on the very small initial imperfections of weld-induced initial deflection and residual stress.


ABSTRACT: Throughout the world, ships are continuously being declared as total losses and a significant part of these accidents are collisions between ships. The International Maritime Organization strives towards a more risk-based view on addressing the damage stability of ships. The current study addresses the survivability following a ship collision by the use of a sequential (de-coupled) computational methodology. The methodology is comprised of structural analysis of a collision scenario followed by dynamic damage stability simulations of the struck ship in order to establish the time to capsize of the struck ship. The emphasis of the current investigation is on the structural computations of the collision event; explicit finite element analyses are presented for a case study of a collision scenario. In particular, uncertainties of input parameters in the finite element simulations and their impact on the shape and size of the damage opening area, and time to capsize of the struck ship, are addressed. Material modelling aspects are studied; scatter in material properties within a material class as well as damage modelling. In addition, the effects of using a deformable or rigid striking bow section, the friction coefficient, the collision angle and the speed of the striking ship are studied. On the basis of the results presented, assumptions commonly used in these kinds of analysis are discussed. Recommendations for a sufficient level of simplifications for arriving at reliable results in numerical simulation of ship collisions are made.

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ABSTRACT: In the present paper, a mathematical model which is capable of representing the physics of lateral buckling failure in the tensile armour layers of flexible pipes is introduced. Flexible pipes are unbounded composite steel–polymer structures, which are known to be prone to lateral wire buckling when exposed to repeated bending cycles and longitudinal compression, which mainly occurs during pipe laying in ultra-deep waters. On the basis of multiple single wire analyses, the mechanical behaviour of both layers of tensile armour wires can be determined. Since failure in one layer destabilises the torsional equilibrium which is usually maintained between the layers, lateral wire buckling is often associated with a severe pipe twist. This behaviour is discussed and modelled. Results are compared to a pipe model, in which failure is assumed not to cause twist. The buckling modes of the tensile armour wires can be obtained by the presented method.

Tiago P. Estefen and Segen F. Estefen (Subsea Technology Laboratory, COPPE – Ocean Engineering Department, Federal University of Rio de Janeiro, P. O. Box 68508, 21945-970, Rio de Janeiro, Brazil), “Buckling propagation failure in semi-submersible platform columns”, Marine Structures, Vol. 28, No. 1, pp 2-24, August 2014, https://doi.org/10.1016/j.marstruct.2012.05.003

ABSTRACT: The present paper aims at studying the behavior of stiffened panels from a column segment of a new generation of semi-submersible platforms up to the peak compressive load and in the post-buckling condition. Previous studies have demonstrated a strong influence of the mode and magnitude of initial geometric imperfections, as well as boundary conditions, on the structure's axial load capacity. Numerical–experimental correlation study for small-scale models was performed to define the proper numerical model to be used in more complex numerical simulations of the failure behavior of full-scale column structures. The stiffened panels were assessed to identify the buckling onset in a specific plate and its interaction with longitudinal and transversal stiffeners during the progressive column failure. Measurements of the geometric imperfection distribution of full-scale stiffened panels were collected during construction to better understand the buckling mechanism. Initial geometric imperfections were measured by means of laser-based equipment including a portable measuring system that uses laser technology with sub-millimeter accuracy.

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ABSTRACT: Nonlinear finite element analysis is used to simulate welding of stiffened plates, giving the three-dimensional distribution of welding-induced residual stress and distortion. Load-shortening curves are generated for the welded stiffened plates under axial compression. These curves are then used as input in a hull girder ultimate strength analysis using Smith's method. Results are compared with those of an ultimate strength analysis using load-shortening curves derived from the IACS Common Structural Rules and with published experimental data. The ultimate strength predicted using IACS curves was significantly higher than the experimental result, whereas that determined using load-shortening curves from finite element analysis agreed well with the measured value.
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ABSTRACT: Offshore activities and shipping in arctic regions increased significantly in the past decade due to the expected natural resources and due to the upcoming advantages of the northern sea route. Hence, structural solutions used in arctic conditions need to resist the low temperatures at an adequate safety level. Therefore, this paper analyses the collision resistance of ships exposed to sub-zero temperature (SZT). Further, it assesses the influence of the material properties for 0, −30, −60 and −90 °C of typical shipbuilding steel. Thereby, the theoretical influence of SZT on the collision force will be presented as well as the potential gain from specially selected materials for SZT, arctic materials, compared to standard materials, both with and without the presence of rupture. As a result, the potential increase in crashworthiness of structures under SZT will be presented and thereby a contribution to safe arctic operations and transport.

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ABSTRACT: Ship collisions are increasingly simulated with numerical methods predicting the structural damage, respectively the ships' safety, in such accidental event. The latest analyses techniques can take the non-linear structural behaviour and the motions of the colliding vessels into account, however using time-consuming numerical models. Hence, a single dynamic collision can be analysed with a fair degree of accuracy, but at high computational cost. Therefore, this article presents a combined numerical and analytical procedure to assess ship collision damage with significantly lower computational cost. Numerical quasi-static collision simulations estimate the non-linear structural behaviour for a given vessel colliding at selected vertical locations. This provides the force versus penetration curves, which thus depends on the structural arrangement at the striking location. Hence, the semi-analytical collision analysis is calibrated based on these structural resistance curves in order to estimate the change in available energy for structural deformation considering different longitudinal striking locations and angles. As a result, the collision damage, respectively penetration depth and length, can be estimated for vessels of different dimensions and mass ratio's subjected to various collision situations if the presented procedure is applied.

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ABSTRACT: The present article is concerned with the resistance of a ship during a collision with another ship. The paper is directly related to the so-called super-elements method developed to estimate the capability of a ship to withstand to an impact. This approach consists of dividing the structure into several elements (the so-called super-elements), whose resistance to collision is evaluated individually. At the recent stage of development, the super-elements method is only able to treat the case of perpendicular collision scenarios. The purpose of this paper is to go one step further, by establishing analytical formulations giving the resistance of various super-elements to an oblique impact. As a first step, the paper gives a short description of the original super-elements method. After that, analytical calculations in oblique collision cases are performed for the different super-elements involved in the procedure. Finally, the formulations are validated by comparison with results provided by classical nonlinear finite element method. As a conclusion, some perspectives on the future work are presented.


ABSTRACT: Accidental damage of offshore pipelines in the form of local buckles induced by excessive bending deformation during deepwater installation may severely lead to local collapse of the tube and consequent buckle propagation along the pipeline. The present paper describes experimental and numerical research conducted to predict the magnitude of buckle propagation pressure of offshore pipelines under external pressure. The experiments of buckle propagation for pipe specimens with different initial geometric imperfections using 316 grade stainless steel tubes are carried out under quasi-static steady-state conditions in a sealed hyperbaric chamber. The stress–strain characteristics in the axial tensile test are measured for the tube material, and then used to numerically calculate the buckle propagation pressure of the pipe. The comparisons between experimental and numerical results are conducted to establish the precise numerical simulation technique. Based upon experimental and extensive numerical results, a more reasonable empirical formula for buckle propagation pressure of offshore pipeline with various values of diameter-to-thickness ratio as well as different strain hardening modulus and yield stress is proposed.


ABSTRACT: In a previous study, a new empirical formula for the ultimate strength of the titanium alloy spherical pressure hulls of deep manned submersibles is recommended. This formula is mainly derived from the systematic finite element analyses of ANSYS. This paper introduces the further experimental verification of this new equation. Four small spheres of inner diameters 500 mm are tested to collapse. The collapse load range is predicted before the test and all the four final test results are within the range. The work shows that the predictions by the new equation are in well agreement with the experimental results. This suggests that the new equation can be used as the core equation to update current design rules.

N. Zhang and Z. Zong (School of Naval Architecture Engineering, Faculty of Vehicle Engineering and Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian 116024, PR China), “Hydro-elastic-plastic

ABSTRACT: Dynamic hydro-elastic-plastic response of a floating ship hull girder subjected to an underwater explosion bubble is studied in this paper. A fluid-structure analysis is given to consider the effect of a gas bubble acting on the hull girder. The bubble dynamic equations with the bubble's migration, free surface effect and drag force taken into consideration are numerically solved using Runge–Kutta method. The elastic and plastic responses of a hull induced to a bubble impulsive pressure are calculated using a method presented herein. Resonance mechanism in hull girder's whipping response to an underwater bubble is discussed in detail. The formation of the plastic hinge when the hull girder's longitudinal bending moment exceeds its ultimate bending moment is investigated. Real-scale ship examples are given to discuss the features of the dynamic elastic and plastic response.


ABSTRACT: Experimental tests on two full-scale un-reinforced circular tubular Y-joints and two corresponding chord reinforced ones subjected to brace axial compressive loading are carried out. It is found from experimental measurements that the static strength of a tubular Y-joint can be greatly improved by increasing the chord thickness locally near the weld toe. In addition, finite element models (FEM) are also built to analyze the static strength of the above specimens. The numerical results show a good agreement with the experimental results to prove the accuracy and reliability of the FEM. Using the presented FEM, a parametric study is conducted to investigate the effects of some geometrical ($\alpha$, $\beta$, $\gamma$ and $\theta$) and reinforcing parameters ($T_c/T$, $L_c/d_1$) on improving the static strength. Based on the investigation, a parametric equation is presented for predicting the static strength of the reinforced circular tubular Y-joint subjected to axial loading, and the accuracy of this parametric equation is then verified through error analysis.


ABSTRACT: Five specimens are tested under axial compression until collapse to investigate the ultimate strength of wide stiffened panels with four stiffeners. To avoid the side bays collapse and reduce the influence of the clamped boundary condition on the collapse behaviour, the tests are made on panels with two half bays plus one full bay in the longitudinal direction with simply supported condition at the end edge of loading. Initial loading cycles are used to release the residual stresses of the stiffened panels and the gap between the stiffened panels and the supported steel block. Strain gauges are installed on the plates and the stiffeners to record the distribution of strain. This series of experiments is compared to a series of tests with narrow panels (two stiffeners), which allows analysing the effect of the width on the strength of stiffened panels.

ABSTRACT: The use of lightweight aluminium sandwiches in the shipbuilding industry represents an attractive and interesting solution to the increasing environmental demands. The aim of this paper was the comparison of static and low-velocity impact response of two aluminium sandwich typologies: foam and honeycomb sandwiches. The parameters which influence the static and dynamic response of the investigated aluminium sandwiches and their capacity of energy absorption were analysed. Quasi – static indentation tests were carried out and the effect of indenter shape has been investigated. The indentation resistance depends on the nose geometry and is strongly influenced by the cell diameter and by the skin – core adhesion for the honeycomb and aluminium foam sandwich panels, respectively. The static bending tests, performed at different support span distances on sandwich panels with the same nominal size, produced various collapse modes and simplified theoretical models were applied to explain the observed collapse modes. The capacity of energy dissipation under bending loading is affected by the collapse mechanism and also by the face-core bonding and the cell size for foam and honeycomb panels, respectively. A series of low-velocity impact tests were, also, carried out and a different collapse mechanism was observed for the two typologies of aluminium sandwiches: the collapse of honeycomb sandwiches occurred for the buckling of the cells and is strongly influenced by the cell size, whereas the aluminium foam sandwiches collapsed for the foam crushing and their energy absorbing capacity depends by the foam quality. It is assumed that a metal foam has good quality if it has many cells of similar size without relevant defects. A clear influence of cell size distribution and morphological parameters on foam properties has not yet been established because it has not yet been possible to control these parameters in foam making. The impact response of the honeycomb and foam sandwiches was investigated using a theoretical approach, based on the energy balance model and the model parameters were obtained by the tomographic analyses of the impacted panels. The present study is a step towards the application of aluminium sandwich structures in the shipbuilding.

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ABSTRACT: The corrosive marine environment is a threat to the ultimate strength of steel sandwich structures. Therefore, ultimate strength experiments were carried out in three-point bending for beams with different corrosion exposure times, i.e. one and two years. Standard laser-welded web-core sandwich beams are studied and different corrosion protection systems are considered. The beams experienced general corrosion. The thickness reduction in unprotected plates and laser welds is around the typical 0.1 mm/year. This led to an ultimate strength reduction of 10% and 17% for beams with exposure times of one and two years, respectively. The experimental ultimate strength is in agreement with finite element simulations. The ultimate strength was maintained for the beams protected with coating or closed-cell polyurethane (PU) foam.

Z. Zong, Y. Zhao, and H. Li (School of Naval Architecture Engineering, Faculty of Vehicle Engineering and Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, PR China), “A numerical study of whole ship structural damage resulting from close-in underwater explosion shock,” Marine Structures, vol. 31, pp. 24–43, April 2013.
ABSTRACT: There are quite a few researches on far-field underwater explosion and contact underwater explosion. However, few studied the close-in non-contact underwater explosion. In this paper the numerical simulations on the deformation and rupture of a rectangular plate and a stiffened plate are conducted, respectively. The simulation results are close to the failure modes shown in the tests. The limit of acoustic–structure coupling method is also pointed out. Then a full-scale surface ship subjected to underwater shock is presented using the same method. The damage evolution process is studied and three damage modes of the whole ship are specified according to the standoff distance. All of these results can be reference to the research of close-in non-contact underwater explosion.

Simon Benson, Jonathan Downes and Robert S. Dow (School of Marine Science and Technology, Newcastle University, Armstrong Building, Queen Victoria Road, Newcastle upon Tyne NE1 7RU, UK), “Compartment level progressive collapse analysis of lightweight ship structures”, Marine Structures, Vol. 31, pp 44-62, April 2013, https://doi.org/10.1016/j.marstruc.2013.01.001

ABSTRACT: The continued development of large high speed ships, often constructed from aluminium alloy, has raised important issues regarding the response of lightweight hull girders under primary hull girder bending. In particular, the response of lightly framed panels in compression may be influenced by overall panel buckling over several frame spaces. Therefore, to provide improved ultimate strength prediction for lightweight vessels, an extended progressive collapse methodology is proposed. The method has capabilities to predict the strength of a lightweight aluminium midship section including compartment level buckling modes. Nonlinear finite element analysis is used to validate the extended progressive collapse methodology.


ABSTRACT: Five specimens of wide stiffened panel with four stiffeners under axial compression until collapse are studied with a nonlinear finite element analysis and Common Structural Rules to compare with the experimental results. The stiffened panel models have two longitudinal bays to produce reasonable boundary condition at the end of edges. Tension tests have been conducted to obtain the material properties of the steel that are used in the finite element analysis. Three boundary condition configurations are adopted to investigate their influence on the collapse behaviour of the stiffened panels. A displacement transducer was used to measure the initial geometrical imperfections of the stiffened plates. The collapse behaviour of the stiffened panels is analysed in finite element analysis with the measured initial imperfections and with nominal imperfections. An equivalent initial imperfection is validated for the ultimate strength of stiffened panel under compressive load until collapse for the panels under consideration. With the same imperfection amplitude, the shape of the column-type initial deflection of stiffeners affects significantly the collapse shape, but only slightly the ultimate strength and the mode of collapse of the stiffened panels. The 1/2 + 1 + 1/2 bays model with restrained boundary condition BC3 gives an adequate FE modelling and is possible to be fabricated in experiment.

Sabril Haris and Jorgen Amdahl (Department of Marine Technology, Norwegian University of Science and Technology, Otto Nielsens V.10, Trondheim 7491, Norway), “Analysis of ship-ship collision damage

ABSTRACT: This paper presents a procedure to analyse ship collisions using a simplified analytical method by taking into account the interaction between the deformation on the striking and the struck ships. Numerical simulations using the finite element software LS-DYNA are conducted to produce virtual experimental data for several ship collision scenarios. The numerical results are used to validate the method. The contributions to the total resistance from all structural components of the collided ships are analysed in the numerical simulation and the simplified method. Three types of collisions were identified based on the relative resistance of one ship to the other. They are denoted Collision Types 1 and 2, in which a relatively rigid ship collides with a deformable ship, and Collision Type 3, in which two deformable ships are involved. For Collision Types 1 and 2, estimates of the energy absorbed by the damaged ships differ by less than 8% compared to the numerical results. For Collision Type 3, the results differ by approximately 13%. The simplified method is applicable for right angle ship collision scenario, and it can be used as an alternative tool because it quickly generates acceptable results.

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ABSTRACT: Composite materials have been widely used in modern engineering fields such as aircraft, space and marine structures due to their high strength-to-weight and stiffness-to-weight ratios. However, structural efficiency gained through the adoption of composite materials can only be guaranteed by understanding the influence of production upon as-designed performance. In particular, topologies that are challenging to production including panels stiffened with pi or tophat stiffeners dominate many engineering applications and often observe complex loading. The design of stiffened composite panels against buckling is a key point of composite structures. While a growing number of studies are related to the reliability analysis of composites few of these relate to the local analysis of more complicated structures. Furthermore for the assessment of these structures in a design environment it is important to have models that allow the rapid assessment of the reliability of these local structures. This paper explores the use of a stochastic approach to the design of stiffened composite panels for which typical applications can be found in composite ship structures. A parametric study is conducted using Navier grillage theory and First-order Reliability Methods to investigate any detectable trend in the safety index with various design parameters. Finally, recommendations are made to provide guidance on applications.

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ABSTRACT: Experimental drop weight impact tests are performed to examine the dynamic response of web girders in a one-tenth scaled tanker double hull structure struck laterally by a knife edge indenter. The small
stiffeners of the full-scale prototype are smeared in the small-scale specimen by increasing the thicknesses of the corresponding plates. The plastic response is evaluated at two impact velocities and the impact location is chosen between two web frames to assure damage to the outer shell plating and the stringers. The laboratory results are compared with numerical simulations performed by the LS-DYNA finite element solver. In the simulations, the strain hardening of the material is defined using experimental data of quasi-static tension tests and the strain rate sensitivity is evaluated using standard coefficients of the Cowper–Symonds constitutive model. The experimental permanent deflection and shape of the deformation show a good agreement with the collision simulations. It is found that the crushing resistance of the specimens is determined by the deformation mechanism of the stringers. Thus, the deformation process is described and compared with theoretical deformation modes for web girders subjected to large in-plane quasi-static loads. Additionally, the influence of the stiffeners on the shape of the deformation of the stringers is illustrated through simulations of stiffened structural elements.

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ABSTRACT: This paper provides a new contribution to the simplified analytical treatment of collisions between two ships. It is directly connected to the well-known super-elements method, which is a simplified procedure allowing for a quick estimation of the damages caused to both the striking and struck vessels during such events. In this article, a new analytical formulation is presented for estimating the impact resistance provided by inclined ship side panels. Two different scenarios are treated. We first deal with the case of an impact between the oblique plate and the stem of the striking ship, and then we consider the situation where the inclined panel is impacted by the bulb. For these two scenarios, an analytical formulation relating the force and the penetration is provided and these developments are validated by comparing them to the results of finite elements simulations. Finally, the new inclined plate super-element is integrated in a simplified model of a frigate collided by another ship, and the resistance given by the super-elements method is then compared to the one obtained by a numerical simulation of this collision.

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ABSTRACT: The paper presents results of a numerical study into the buckling resistance of geometrically imperfect mild steel cones subjected to: (a) axial compression only, (b) lateral external pressure only, and (c) axial compression and external pressure acting simultaneously. Buckling strength of axially compressed and imperfect cone is only 55% of geometrically perfect model. Buckling strength of a cone subjected to lateral pressure, on the other hand, amounts to 43% of the corresponding value of perfect model. But it is the shrinkage of stability plot of imperfect cone which was found to be significant. For imperfect cones subjected to combined axial compression and external pressure, the collapse envelope shrinks by 48% with the elastic sub-set being reduced by 51%.
ABSTRACT: Catenary risers can present during installation a very low tension close to seabed, which combined with torsion moment can lead to a structural instability, resulting in a loop. This is undesirable once it is possible that the loop turns into a kink, creating damage. This work presents a numerical methodology to analyze the conditions of loop formation in catenary risers. Stability criteria were applied to finite element models, including geometric nonlinearities and contact constraint due to riser-seabed interaction. The classical Greenhill's formula was used to predict the phenomenon and parametric analysis shows a “universal plot” able to predict instability in catenaries using a simple equation that can be applied for typical risers installation conditions and, generically, for catenary lines under torsion.

ABSTRACT: In deepwater S-lay operations, the combined influences of stinger curvature, axial tension and roller support force can induce very large plastic deformation in the pipe. Dynamic loads from vessel motion and pipe sliding down the stinger lead the cyclic plastic deformation. This paper investigates the cyclic plastic stress history of the overbend pipe subjected to the dynamic pipelaying loading. The dynamic roller support forces are obtained through an innovative large scale hybrid substructure experiment constructed to simulate the pipe-stinger impact behavior. The measured roller forces are used to verify a 3D finite element analysis results developed with ABAQUS/Standard to observe the dynamic pipe stress history. The results confirm that the roller support can induce stress concentration in the pipe and the combined dynamic pipelaying loadings can cause extensive cyclic plastic deformation.

ABSTRACT: As an application to predict and mitigate the out-of-plane welding distortion by elastic FE analysis based on the inherent deformation theory, a panel structure of a pure car carrier ship is considered. The
inherent deformations of different types of welded joints included in this ship panel structure are evaluated beforehand using thermal elastic plastic FE analysis. Applying idealized boundary condition to focus on the local deformation, elastic FE analysis shows that the considered ship panel structure will buckle near the edge and only bending distortion is dominant in the internal region. In order to mitigate out-of-plane welding distortion such as buckling and bending, straightening using line heating is employed. In the internal region, only inherent bending with the same magnitude as welding induced inherent bending is applied on the opposite side of welded joints (fast moving torch). On the other hand, only in-plane inherent strain produced by line heating is introduced to the edge region to correct buckling distortion (slow moving torch). The magnitude of out-of-plane welding distortion in this ship panel structure can be minimized to an accepted level.

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ABSTRACT: A series of finite element analyses are conducted to investigate the influence of boundary conditions and geometry of the model on the predicted collapse behaviour of stiffened panels. Periodic and symmetric boundary conditions in the longitudinal direction are used to calculate the ultimate strength of stiffened panels under combined biaxial thrust and lateral pressure. The calculated ultimate strength of stiffened panels are compared with those by different FEM (finite element method) code and are assessed. The periodic boundary condition in the longitudinal direction for two spans or bays model provides an appropriate modelling to a continuous stiffened panel and can consider both odd and even number of half waves and thus, is considered to introduce the smaller model uncertainty for the analysis of a continuous stiffened panel.

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ABSTRACT: A series of collapse analyses is performed applying nonlinear FEM on stiffened panels subjected to longitudinal thrust. MSC.Marc is used. Numbers, types and sizes of stiffeners are varied and so slenderness ratio as well as aspect ratio of local panels partitioned by stiffeners keeping the spacing between adjacent longitudinal stiffeners the same. Initial deflection of a thin-horse mode is imposed on local panels and that of flexural buckling and tripping modes on stiffeners to represent actual initial deflection in stiffened panels in ship structures. On the basis of the calculated results, buckling/plastic collapse behaviour of stiffened panels under longitudinal thrust is investigated. The calculated ultimate strength are compared with those obtained by applying several existing methods such as CSR for bulk carriers and PULS. Simple formulas for stiffened panels, of which collapse is dominated fundamentally by the collapse of local panels between longitudinal stiffeners, are also examined if they accurately estimate the ultimate strength. Through comparison of the estimated results with the FEM results, it has been concluded that PULS and modified FYH formulas fundamentally give good estimation of the ultimate strength of stiffened panels under longitudinal thrust.

ABSTRACT: This paper describes full-scale measurements of the wave-induced vertical bending moment amidships a 9400 TEU container carrier and focuses on the effect of the hydro-elastic high-frequency vibration on the extreme hogging wave bending moment. One extreme event, where the vertical wave-induced hogging bending moment amidships slightly exceeds the design value, is analysed and the measurements are verified by the use of the relationship between measurements of accelerations and strains and simple beam theory. The measurements are found to be reliable. In the extreme case, the high-frequency vibrations caused by impulsive loads are observed to be of the same magnitude as the rigid-body wave-induced response and thus acts to double the total vertical bending moment amidships. It was also found that even though the ship is sailing in bow quartering seas, only the 2-node vertical vibration mode is apparently excited. Following the extreme event analysis and verification, three hours of strain measurements are used for establishing a Gumbel distribution for the extreme value prediction, and it is found that the probability of exceeding the rule design wave bending moment by 50% in the given sea state is quite significant. Finally, the hydro-elastic behaviour of the hull girder is assessed by simple approximations using the measured statistical properties and closed-form expressions and the agreement with the actual measurements is found to be good.


ABSTRACT: An experimental study is presented of three box girders made of mild steel subjected to pure bending moment, with different spacing between frames. The moment curvature curves are presented, allowing for the analysis of elastic–plastic behaviour until collapse and the evaluation of the ultimate bending moment and post collapse behaviour for each experiment. The residual stress relief during loading and unloading path is also analysed. The effect of the span between transverse frames on the ultimate bending moment of the box girder is studied and thus its dependence on the column slenderness of the panel under compression can be established. The energy dissipated by internal friction during each load cycle is evaluated and compared with elastic potential energy.


ABSTRACT: In this paper, we investigate the damage to offshore platforms subjected to ship collisions. The considered scenarios are bow and stern impacts against the column of a floating platform and against the jacket legs and braces. The effect of the ship–platform interaction on the distribution of damage is studied by modeling both structures using nonlinear shell finite elements. A supply vessel of 7500-ton displacement with bulbous bow is modeled. A comprehensive numerical analysis program is conducted, and the primary findings are described herein. The collision forces from the vessel are compared with the suggested force–deformation
curves in the NORSOK code. For collisions with floating platforms we particularly focus on the crushing behavior and potential penetration of the bulbous bow and stern sections into the cargo tanks or void spaces of semi-submersible platforms. For fixed jacket platforms we investigate whether jacket braces can penetrate into the ship without being subjected to significant plastic bending or local denting. Adequate treatment of the relative strength between the interacting bodies is especially relevant for impacts with high levels of available kinetic energy, for which shared energy or strength design is aimed at. Simplifying one body as rigid quickly leads to overly conservative and/or costly solutions, and is in some cases non-conservative. The numerical analysis is used to develop a novel pressure–area relation for the deformation of the bulbous bow and stern corners of the supply vessel. Procedures for strength design of the stiffened panels are discussed. Refined methods and criteria are proposed for strength design of platforms, including both floating and jacket structures. The adequacy of the NORSOK design guidance for collisions against jacket legs is evaluated. The characteristic strength of a cylindrical column is used to develop a novel criterion for the resistance to local denting from stern corners and bulbous bows.

ABSTRACT: The paper presents finite element simulations of a small-scale stiffened plate specimen quasi-statically punched at the mid-span by a rigid indenter, in order to examine its energy absorbing mechanisms and fracture. The specimen, scaled from a tanker side panel, is limited by one span between the web frames and the stringers. The paper provides practical information to estimate the extent of structural damage within ship side panels during collision accidents. Moreover, the results of this investigation should have relevance to evaluate grounding scenarios in which the bottom sustains local penetration. This is possible since the structural arrangement of the double hull and the double bottom of tanker vessels is very similar. The experimentally obtained force–displacement response and shape of the deformation show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The numerical analysis includes aspects of particular relevance to the behaviour of ship structures subjected to accidental loads which could give rise to difficulties in interpreting finite element calculations. In particular, the paper comments on the material nonlinearities, the importance of specifying the precise boundary conditions and the joining details of the structure. The considerable practical importance of these aspects has been the focus of attention in previous publications of the authors which evaluate the experimental-numerical impact response of simple ship structural components, such as beams and plates. Therefore, this paper uses the definitions proposed in those references to evaluate its applicability in the scaled tanker side panel, as an example of a more complex ship structure.

Mihkel Koergesaar and Jani Romanoff (Aalto University, Department of Applied Mechanics, Otakaari 3, Espoo, Finland), “Influence of mesh size, stress triaxiality and damage induced softening on ductile fracture of large-scale shell structures”, Marine Structures, Vol. 38, pp 1-17, October 2014, https://doi.org/10.1016/j.marstruc.2014.05.001
ABSTRACT: In this investigation, ductile fracture in stiffened and unstiffened panels is simulated employing the fracture criterion, which depends on the mesh size, stress state and damage induced softening. The aim of the study is to show that employed fracture criterion removes mesh size effects more efficiently than traditional fracture criteria adjusted only on the basis of uniaxial tension. Fracture model is implemented into Finite Element software ABAQUS using user-defined material, VUMAT-subroutine, available for shell elements.
Mesh size sensitivity analysis is carried out. Finite element simulation results are validated with experimental measurements available in literature. Comparison of numerical and experimental results shows that simulations effectively capture most of the experimentally observed features, especially when considering different mesh densities. In most cases, mesh size effects are considerably reduced compared with the fracture criteria adjusted on the basis of a uniaxial tension.

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ABSTRACT: The aim of this paper is to present a simplified analytical method for estimating the crushing resistance of an oblique cylinder impacted by the stem of a striking ship. The collision angle of the vessel is arbitrary, i.e. oblique collisions are also considered in this article. The two extremities of the tube are assumed to be clamped. These developments are intended to be used for evaluating the crashworthiness of an offshore wind turbines jacket. To achieve this goal, closed-form expressions are first derived for the particular situations of a horizontal and a vertical cylinder by applying the upper-bound method. An interpolation formula is then proposed to get the resistance opposed by the tube for any inclination angle. In order to validate these theoretical developments, some comparisons are made with the results of numerical simulations. These latter are performed using the finite elements software LS-DYNA. In almost all cases, the analytical prediction of the resistance is found to be in quite good agreement with the numerical ones. Finally, another comparison is made by simulating an OSV collision with a full jacket. In this case, the theoretical model is found to be insufficient for large impact energies and points out the need of further research.

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ABSTRACT: One of the major topics confronted by the designers of naval vessels is to qualify the ship integrity exposed to underwater explosions (UNDEX). The far-field UNDEX & contact UNDEX problems are investigated by a few researchers previously. However, when a ship is subjected to close-in non-contact UNDEX environment, the failure mechanism of structures under the combined effect of shock wave load and bubble pulsations is rarely discussed. Thus, the dynamic response of ship structures subjected to close-in non-contact UNDEX is mainly concerned in this paper. Four UNDEX experimental tests of ship-type box structure (STBS, which can be fundamentally viewed as surface ships) are conducted in the study by using charge explosion. With reasonable finite element models, the coupled acoustic-structure algorithm in ABAQUS/Explicit code is utilized for the simulations. The wet vibration modes, accelerations, acoustic fluid pressure, and velocities from simulation results are compared with experimental data. The numerical simulation results agree well with those of experimental tests. Then, the detailed discussions are given to explore the damage processes of STBS subjected to the shock wave and bubble integrated loadings. The experiment and
numerical simulation results reveal that global longitudinal strength collapse combined with the local wrinkling, the plastic deformation of hull between bulkheads and the plastic deformation of local bottom hull are the mainly three failure modes. And if the UNDEX bubble effects are not incorporated in the analysis, the damage severity will be underestimated. Moreover, other two practical numerical simulation examples are also discussed to illustrate the failure modes in depth.

ABSTRACT: Present article proposes improved assessment of the ultimate bending capacity (ultimate bending moment), i.e. enhancement of the ultimate limit state evaluation in the concept design of the monotonous thin-walled structures predominantly subjected to vertical bending loads during their exploitation. An alternative progressive collapse analysis method is proposed, which incorporates direct consideration of various relevant distributed load effects and consequently enables more sophisticated evaluation of the ultimate bending capacity and more accurate and reliable identification of the critical cross section and its collapse sequence. Relevant aspects of the employed approximate model for the cross sectional warping due to vertical bending are considered and determination of the (longitudinal) warping displacements and strains, shear strains and stresses, as well as the corrected longitudinal strains is described. Influence of the (ultimate) shear capacity on the (ultimate) bending capacity is discussed and detailed description and critical overview of the proposed method is given. Finally, various aspects of the considered problem and accuracy of the proposed approach are discussed and demonstrated on example of the thin-walled box-girder, whereby detailed comparison of the results obtained by the proposed approach and nonlinear finite element method analyses is given.

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“Simulation on progressive collapse behaviour of whole ship model under extreme waves using idealized structural unit method”, Marine Structures, Vol. 40, pp 104-133, January 2015,
https://doi.org/10.1016/j.marstruc.2014.11.002
ABSTRACT: To ensure the safety of navigating ship, working loads and structural load-carrying capacity are two important aspects. In the present paper, a total simulation system combing load calculation and structural collapse analysis is applied to simulate progressive collapse behaviour of a single-hull Kamsarmax type bulk carrier. A three dimensional singularity distribution method is adopted to calculate pressure distribution with time history. A mixed structural model, collapse part simulated by ISUM elements and remaining part by elastic FEM elements with relative coarse mesh, is proposed for collapse analysis. Progressive collapse behaviour obtained by ISUM is good agreement with that by nonlinear software package, MARC. However, the calculation time of ISUM analysis is about 1/70 of MARC analysis. The applicability to structure system, high accuracy and sufficient efficiency of ISUM had been demonstrated.
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“Plastic mechanism analysis of structural performances for stiffeners on bottom longitudinal web girders during a shoal grounding accident”, Marine Structures, Vol. 40, pp 134-158, January 2015,
https://doi.org/10.1016/j.marstruc.2014.11.001

ABSTRACT: A theoretical model is introduced in this paper for structural performance of stiffeners on double-bottom longitudinal girders in a shoal grounding accident. Major emphasis is placed on establishing the characteristic deformation mechanism of stiffeners and identifying major energy dissipation patterns. Numerical simulations using the LS-DYNA nonlinear finite-element program were carried out to examine thoroughly the progressive deformation process during sliding deformation. Stiffener deformations were observed to fall into two categories: stiffeners fully contacted with the indenter, and stiffeners subjected to indirect deformation due to energy transfer from attached girders. Grounding performance of stiffeners is substantially influenced by that of the attached plating, and therefore a review of the existing deformation models of longitudinal girders (i.e. Simonsen 1997, Midtun 2006 and Hong 2008) was included. Hong's model of bottom girders was found not capable of representing the effects of stiffeners, and a new model of girders was thus developed. Based on observation of the numerical deformation process and the new analytical girder model, a kinematically admissible model of stiffeners on bottom longitudinal girders was built. Using the methods of plastic mechanism analysis, simplified analytical expressions for energy dissipation by girder-attached stiffeners, both fully contacted and noncontacted, were formulated, and equations for grounding resistance were subsequently obtained. The theoretical expressions agree favorably with results from nonlinear finite-element simulations and capture two significant characteristics of the problem: that energy varies little with indentation for stiffeners that fully contacting the indenter, and that energy is independent of slope angle for indirectly deformed stiffeners. The proposed theoretical model helps to predict analytically shoal grounding performance of stiffeners on longitudinal girders with reasonable accuracy.

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ABSTRACT: In the deepwater S-lay operations depending on the required stinger radius and rollers configuration, relatively large plastic deformation is induced when the pipe passes over the stinger, under the combined loadings of bending, axial tension, roller reaction force and the pipelay vessel motion. The resulting plastic deformation does not vanish after the pipe leaves the stinger. It accumulates until the pipe reaches the seabed. The inherited residual deformation might reduce the collapse capacity of the pipe under the external pressure loading. The present paper investigates the dynamic loading history of the pipe during the S-lay operation based on a test-verified finite element model, and then calculates the residual plastic deformation of the pipe cross-section after the pipe reaches the seabed. Finally, the nonlinear collapse analysis is implemented
based on the modified RIKS method to evaluate the capacity of the installation-induced deformed pipe. The results confirm that the deepwater S-lay operation will lead to obvious plastic deformation of the pipe, which decreases the pipe collapse capacity to some extent.

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ABSTRACT: Experimental investigations on the laser-welded triangular corrugated core sandwich panels and equivalent solid plates subjected to air blast loading are presented. The experiments were conducted in an explosion tank considering three levels of blast loading. Results show that the maximum deflection, core web buckling and core compaction increased as the decrease of stand-off distance. Back face deflections of sandwich panels were found to be nearly half that of equivalent solid plates at the stand-off distances of 100 mm and 150 mm. At the closest stand-off distance of 50 mm, the panel was found to fracture and fail catastrophically. Autodyn-based numerical simulations were conducted to investigate the dynamic response of sandwich panels. A good agreement was observed between the numerical calculations and experimental results. The model captured most of the deformation/failure modes of panels. Finally, the effects of face sheet thickness and core web thickness on the dynamic response of sandwich panel were discussed.


ABSTRACT: The paper presents a simplified analytical method to examine the energy absorbing mechanisms of intact and damaged small-scale stiffened plate specimens, quasi-statically punched at the mid-span by a rigid wedge indenter. The specimens scaled from a tanker side panel are limited by one span between web frames and stringers. The influence of the initial damage on the impact response is based on the plastic behaviour of an intact specimen. The initial damage is provoked at one-quarter from the support by the same indenter that, afterwards, punches the specimen at the mid-span. In practice, initial imperfections of this type could be due to minor incidents during ship service operation, such as collision of ships with floating objects. To validate the proposed simplified method, experiments and numerical simulations are conducted. The experimentally obtained force-displacement responses and shapes of the deformation show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The analytical method derives expressions to estimate the energy dissipated by the intact and the damaged specimens based on the plastic deformation mechanisms, assuming that both the plate and stiffener structural components absorb the incident energy through the rotation of the plastic hinges at the point of contact and at the supports and the membrane tension over the plastically deforming region between the loading and the supports.
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ABSTRACT: In a Thermal-Elastic-Plastic (TEP) FE analysis to investigate welding induced buckling of large thin plate welded structure such as ship panel, it will be extremely difficult to converge computation and obtain the results when the material and geometrical non-linear behaviors are both considered. In this study, an efficient FE computation which is an elastic FE analysis based on inherent deformation method, is proposed to predict welding induced buckling with employing large deformation theory, and an application in ship panel production is carried out. The proposed FE computation is implemented with two steps: (1) The typical weld joint (fillet weld) existing in considered ship panel structure is conducted with sequential welding using actual welding condition, and welding angular distortion after completely cooling down is measured. A TEP FE analysis with solid elements model is carried out to predict the welding angular distortion, which is validated by comparing with experimental results. Then, inherent deformations in this examined fillet welded joint are evaluated as a loading for the subsequent elastic FE analysis. Also, the simultaneous welding to assemble this fillet welded joint is numerically considered and its inherent deformations are evaluated. (2) To predict the welding induced buckling in the production of ship panel structure, a shell element model of considered ship panel is then employed for elastic FE analysis, in which inherent deformation evaluated beforehand is applied and large deformation is considered. The computed results obviously show welding induced buckling in the considered ship panel structure after welding. With its instability and difficulty for straightening, welding induced buckling prefers to be avoided whenever it is possible.

ABSTRACT: In this paper, structural reliability concepts are used in conjunction with limit state functions proposed in the Recommended Practice DNV-RP-F101 (2010) to evaluate the probability of failure of corroded pipelines during their lifetimes. The model takes into account the natural spread of material properties, geometric and operational parameters, and the uncertainties associated with the sizing of eventual corrosion defects. Bayesian reliability concepts are used to estimate the evolution of a pre-defined distribution of defects obtained, for instance, from an inspection campaign. By comparing the predicted probability of failure with the reliability acceptance criteria, the operator can schedule defect repairs and establish inspection intervals with more confidence. This proposed methodology can provide the basis to develop a risk based maintenance strategy of pipeline systems.

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ABSTRACT: As an increasing number of ships continue to sail in heavy traffic lanes, the possibility of collision between ships has become progressively higher. Therefore, it is of great importance to rapidly and
accurately analyse the response and consequences of a ship's side structure subjected to large impact loads, such as collisions from supply vessels or merchant vessels. As the raked bow is a common design that has a high possibility of impacting a ship side structure, this study proposes an analytical method based on plastic mechanism equations for the rapid prediction of the response of a ship's side structure subjected to raked bow collisions. The new method includes deformation mechanisms of the side shell plating and the stiffeners attached. The deformation mechanisms of deck plating, longitudinal girders and transverse frames are also analysed. The resistance and energy dissipation of the side structure are obtained from individual components and then integrated to assess the complete crashworthiness of the side structure of the struck ship. The analytical prediction method is verified by numerical simulation. Three typical collision scenarios are defined in the numerical simulation using the code LS_DYNA, and the results obtained by the proposed analytical method and those of the numerical simulation are compared. The results correspond well, suggesting that the proposed analytical method can improve ship crashworthiness during the design phase.

ABSTRACT: The paper presents a simplified analytical method to examine the crushing resistance of web girders subjected to local static or dynamic in-plane loads. A new theoretical model, inspired by existing simplified approaches, is developed to describe the progressive plastic deformation behaviour of web girders. It is of considerable practical importance to estimate the extent of structural deformation within ship web girders during collision and grounding accidents. In this paper, new formulae to evaluate this crushing force are proposed on the basis of a new folding deformation mode. The folding deformation of web girders is divided into two parts, plastic deformation and elastic buckling zones, which are not taken into account for in the existing models. Thus, the proposed formulae can well express the crushing deformation behaviour of the first and subsequent folds. They are validated with experimental results of web girder found in literature and actual numerical simulations performed by the explicit LS-DYNA finite element solver. The elastic buckling zone, which absorbs almost zero energy, is captured and confirmed by the numerical results. In addition, the analytical method derives expressions to estimate the average strain rate of the web girders during the impact process and evaluates the material strain rate sensitivity with the Cowper-Symonds constitutive model. These adopted formulae, validated with an existing drop weight impact test, can well capture the dynamic effect of web girders.

ABSTRACT: Helically armored cables or pipes find a wide range of applications as structural members in engineering. An example of this is the increasing use of flexible pipes in the oil offshore production. Although keeping a geometrical similarity with other helically armored structures such as wire ropes and ACSR conductors, and borrowing from them a useful methodology for the structural analysis, some care must be taken in order not to indiscriminately use an approach which was not thought for a flexible pipe: internal and external pressures, for instance, are a great concern in the analysis of flexible pipes, but obviously not for wire ropes. This work aims at giving some additional contribution to the structural response of flexible pipes when
subjected to axisymmetric loads, including the effect of both internal and external pressure in pipe displacements. Derivation of linear operators, relating the stress-resultants to their related displacements or deformations in each of the layers of the pipe, as well as the process of deriving an analogous linear operator to represent the behavior of the pipe as a whole, are clearly presented, highlighting interesting mathematical aspects and their associated physical meaning. A numerical case study of a 2.5” flexible pipe subjected to traction and internal pressure is also presented and discussed.

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ABSTRACT: Rigorous analytical formulations are given to describe the gross slip initiation and progression in tensile armor layers of unbonded flexible pipes. Then two mechanisms are thought to contribute to the decrease of layer stiffness before gross slip begins. The first one considers the micro-slip occurred at the interlayer contact interfaces. The relative displacement between an armor wire and the underlying layer is determined according to the theory of contact mechanics. Shear deformations of the supporting plastic layer are taken into account in the other mechanism where plane sections no longer remain plane. The results of bending moment-curvature relationship from the presented models are compared with the available test data and good correlations are found. The shear model is seen to describe the slip transition better than other models do.

ABSTRACT: This paper presents a set of analytical expressions for the calculation of damage opening sizes in tanker groundings. The simplified formulas were given for the grounding force, longitudinal structural damage and the opening width in the inner and outer plating of a tanker's double bottom. The simplified formulas derived are based on a set of numerical simulations conducted with tankers of different dimensions- 120, 190 and 260 m in length. The simulations were performed for five penetration depths and for several rock/ground topologies. The formula for the horizontal grounding force was derived provided the grounding force is proportional to the contact area and the contact pressure. By use of regression analysis it was shown that the contact pressure for any combination of ship and rock size can be expressed with a single normalized polynomial. The actual contact pressure was found by scaling the normalized pressure with the structural resistance coefficient. Given the formulation for the normalized contact pressure, the actual contact force for a ship can be found as a product of average contact pressure and the contact area. The longitudinal length of the damage was evaluated based on the average contact force and the kinetic energy of the ship. The damage opening widths in the outer and inner bottom of the ship were derived separately for two ranges of relative rock sizes as they have strong influence on the deformation mode. The damage widths were given as a function of rock size, penetration depth and double bottom height. To improve the prediction of the onset of the inner bottom failure, a critical relative penetration depth as a function of the ratio of the rock size and the ship breadth was established. Comparison to the numerical simulations showed that the derived simplified approach describes the horizontal grounding force and the damage length well for the penetration depths above 0.5 m. For the range of specified relative rock sizes, the damage width in the inner and outer bottom deviates from
numerical simulations approximately up to 25%, which was considered sufficient for the analyses where rapid damage assessment is needed. Comparison was also made to real accidental damage data and to the results of several simplified formulas.

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“Laboratory tests and thermal buckling analysis for pipes buried in Bohai soft clay”, Marine Structures, Vol. 43, pp 44-60, October 2015, https://doi.org/10.1016/j.marstruc.2015.05.001
ABSTRACT: Upheaval buckling of submarine pipelines occurs due to relative movement of pipeline and surrounding soil and is often triggered by high operational temperature of the pipeline, initial imperfection of the pipeline, or a combination of both. Since buckling can jeopardize the structural integrity of a pipeline, it is a failure mode that should to be taken into account for the design and in-service assessment of trenched and buried offshore pipelines. In this study, a series of vertical (uplift) and axial pullout tests were carried out on model pipe segments buried in soft clay deposit similar to that present in Bohai Gulf, China. Pipe segments with three different diameters (= 30 mm, 50 mm and 80 mm) were buried in different depth-to-diameter ratios ranging from 1 to 8. Based on the results of laboratory tests, nonlinear force-displacement relations are proposed to model soil resistance mobilized during pipeline movement. The proposed nonlinear soil resistance models are employed in finite element analysis of buried pipelines with different amplitudes of initial geometric imperfections. Thermal upheaval buckling behavior of pipelines operating at different temperatures is studied. Results show that the capacity of pipeline against thermal buckling increases with the burial depth and decreases with the amplitude of initial imperfection.

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ABSTRACT: The application of non-metallic light weight pipeline (LWP) in subsea oil/gas transmission system is subject to subsea pipeline on-bottom stability problem because of their light weight. Additional weight required for the stabilization of subsea LWP is a critical item to consider when decreasing the cost of the pipeline system. This paper presents an effective approach to determine the additional weight by utilizing a reliability-based assessment of subsea LWP against on-bottom stability. In the approach, a dynamic non-linear finite element model (FEM), including a model of fluids-pipe-soil interaction for the subsea pipeline, is used to study the pipeline displacement response. In-place analysis of a flexible pipe is presented as an example of the authors' methodology. Results show that displacements are largely affected with and without considering the lift force. Additionally, the uncertainties of all parameters used in the model are considered. With 145 cases of FEM calculations being the samples, a response surface model (RSM) is developed to predict the pipeline lateral displacement using the software Design-Expert. Combing with the RSM equation, the Monte Carlo simulation method is employed to estimate the probability of exceeding pipeline stability. To calculate the reliability of LWP for different submerged weights, the method introduces a calibrated factor into the serviceability limit state (SLS) function. The proposed approach can be used to determine the additional weight
required for the on-bottom stability of subsea pipelines while considering the uncertainties of all relevant parameters.

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ABSTRACT: An analytical model is given to investigate the behavior of unbounded flexible pipes under biaxial dynamic bending. The stick-slip conditions of each wire are studied in the framework of incremental analysis by an operator splitting of the time step into a stick-state prediction and a slip-state correction step. The tension gradient is calculated using the classical return-mapping algorithm and the obtained tension gradients are integrated numerically to find the axial tension by imposing appropriate boundary conditions. From the axial tension the bending moments with respect to the principal bending axes of the pipe are obtained. Poisson's effect, bending induced tension in the wire, shear deformations of the supporting plastic layer and the changes of the effective torsion and curvature increments of the wire after slip occurs are taken into account in the model. The results of bending moment–curvature relationship from this model are compared with the test data from simple bending and good correlations are found. The comparison of the biaxial bending moment results between this model and the available model also shows good agreement.

ABSTRACT: An experiment of hull girder model subjected to near field underwater explosion at midship is implemented. High-speed photography is applied to achieve the time history of hog displacement of the hull girder model subjected to shock wave of undex. The determination method of hog distortion using these show-motion pictures is presented. The experiment also achieves the local plate distortion of the hull girder model. Based on these works, the damage mechanism and mode of hull girder subjected to near field undex at midship are discovered. Finally, the coupling effect between whole motion of hull girder and distortion of local structure is discussed.

Bing-Chuan Nie, Jia-Chun Li and Hui-Qin Zhang (Key Laboratory for Mechanics in Fluid Solid Coupling System, Institute of Mechanics, Chinese Academy of Sciences, No. 15 Beisihuanxi Road, Beijing 100190, China), “On the regimes of underwater explosion for a submerged slender structure by pulsating bubble”, Marine Structures, Vol. 44, pp 85-100, December 2015, https://doi.org/10.1016/j.marstruc.2015.07.003
ABSTRACT: Three regimes: near-, middle- and far-fields of underwater explosion are proposed in this study aiming at providing an overview on the responses of submerged slender structure by pulsating bubble. In the near-field, the material starts to yield, thus leading to structure breakdown immediately; remarkable structural global elastic deformation occurs in the middle-field as well as substantial movement; and a structure moves as a rigid body with negligible deformation for the far-field. Equivalent dimensionless parameters are obtained by two different dimensional analysis methods, among which a dominant similarity parameter is found out. Thus, a scaling law providing us with a relation between structural global response and the dominant similarity
parameter is yielded, which can be used for demarcating the three regimes quantitatively. To demonstrate, three models corresponding to typical submarine parameters are performed in the case studies. Quantitative criterion of the three regimes is presented along with the regime diagrams. The structural global response features such as the deformation and maximal acceleration/speed of different regimes are provided as well.

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ABSTRACT: A new analytical model to predict the damage of a simplified hull girder (SHG) subjected to underwater explosion (UNDEX) shock wave load and following bubble pulsation load is presented. In the shock wave phase, the rigid-plastic material model and triangular pressure distribution assumption are adopted to build the governing equations. Based on this model, a new damage indicator of a SHG is derived and discussed. In the bubble pulsation phase, damage types and severity are evaluated based on the Vernon bubble model and the modified hydro-plastic series equations. Analytical results are compared with experimental data and numerical simulations. It is shown that the proposed model is able to capture the essential response features and damage types of a SHG both in shock wave phase and in bubble pulsation phase.

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ABSTRACT: This paper focuses on the behaviour of tubular members when subjected to low-velocity mass impact. Particular emphasis is given to the numerical assessment of impact damage and the classification of impact response of tubular members. Damage extents of 12 tubular frame test models were predicted and used for quantifying the modelling uncertainties of the numerical tools. USFOS and ABAQUS software packages were used with beam and shell elements, respectively. Based on the test results and the parametric studies performed, the influence of the geometrical parameters and the interaction between the local shell denting and the global beam deformation modes are discussed. A classification of the impact response of the tubular members based on their relative resistance against shell denting and beam plastic collapse load is proposed. Finally, existing analytical models for each energy dissipation mode are visited and modifications are proposed.

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ABSTRACT: Assessment of the ultimate longitudinal strength of hull girders under combined wave loads can be of particular importance especially for ships with large deck openings and low torsional rigidity. In such
cases the horizontal and torsional moments may approach or exceed the vertical bending moment when a vessel progresses in oblique seas. This paper presents a direct calculation methodology for the evaluation of the ultimate strength of a 10,000 TEU container ship by considering the combined effects of structural non-linearities and steady state wave induced dynamic loads on a mid ship section cargo hold. The strength is evaluated deterministically using non-linear finite element analysis. The design extreme values of principal global wave-induced load components and their combinations in irregular seaways are predicted using a cross-spectral method together with short-term and long-term statistical formulations. Consequently, the margin of safety between the ultimate capacity and the maximum expected moment is established.

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ABSTRACT: Time-variant reliability analysis of a corroded bulk carrier in intact and damage conditions is performed by First-Order (FORM), Second-Order (SORM) Reliability Methods and Importance Sampling simulation. Annual failure probabilities are determined up to 25-year ship lifetime, accounting for time-variant corrosion wastage of structural members contributing to hull girder strength. Statistical properties of hull girder capacity are determined by Monte Carlo simulation, applying three correlation models among corrosion wastages of structural members contributing to hull girder strength, namely no correlation, full correlation and full correlation among wastages of structural members belonging to the same category of compartments. A modified incremental-iterative method is applied, to account for instantaneous neutral axis rotation, in case of asymmetrical damage conditions, as for collision and grounding events. Incidence of intact/damage condition, as well as correlation among corrosion wastages, on annual sagging/hogging time-variant failure probability is investigated and discussed. Time-variant sensitivity analyses for intact and damage conditions are also performed, to investigate the incidence of random variables' uncertainties on the attained failure probability. Finally, the bulk carrier section scheme, benchmarked in the last ISSC Report, is applied as test case.


ABSTRACT: In this paper a new framework for FE simulation of reeling operations that utilizes a Lagrangian–Eulerian description of the beam kinematics is proposed. In contrast to the conventional Lagrangian approach, the material is enabled to flow with an axial velocity through a nearly space-fixed beam mesh. This gives far more effective and robust simulations since the length of the beam model reduces significantly and because the contact geometry undergoes less changes. The main ingredients of the Lagrangian–Eulerian framework and a flexible pipe beam model are presented. An idealized spoolbase-vessel load-out operation is considered in order to gain insight into the torsional failures experienced by subsea contractors in recent years. Here, three different mechanisms were found to provoke torsional failure of the pipe. Strategies to avoid the torsional failures and FE modeling remarks are provided.
ABSTRACT: Design optimization of offshore wind turbine support structures is an expensive task due to the highly-constrained, non-convex and non-linear nature of the design problem. A good depth of detail in the problem formulation can give useful insights in the practical design process, but may also compromise the efficiency. This paper presents an analytical gradient-based method to solve the problem in an effective and efficient way. The design sensitivities of the objective and constraint functions are evaluated analytically, while the optimization procedure is performed in the time domain, subjected to sizing, eigenfrequency, extreme load and fatigue load constraints. A case study on the OC4 and UpWind jacket substructures show that the method was reliable and consistent in delivering superior efficiency and accuracy in the optimization study, as compared with the conventional finite difference approach. The global optimum was probably achieved in the design optimization process, where the large number of design constraints implemented can possibly be the blessing in disguise, as they seem to enable the optimizer to find the global optimum. Both the buckling and fatigue load constraints had significant influence over the design of tubular members and joints, while each component is oriented to maximize the utilization against the prescribed limit state functions.

ABSTRACT: This work studies the combined effect of both geometrical characteristics (opening and initial imperfections) and age related damage (corrosion and cracks) on the local and global responses of thin rectangular steel plates. A series of experimental tests has been conducted for in-service steel plates with a circular opening and subjected to several damage actions and uni-axial compression. Different initial imperfection shapes and amplitudes, corrosion degradation levels and locked crack lengths are considered. Several collapse modes were observed and the reasons for their occurrence are discussed. The experimental results of force-displacement and stress–strain relationships are presented and the relevant dissipated energies, resilience and toughness are estimated. The experimental results are compared with published experimental results, confirming the complexity of the plate behaviour accounting for different damage scenarios.
ABSTRACT: This study intends to characterize numerically the ratcheting behavior of stainless steel pipes subjected to cyclic bending and internal pressure. A cyclic plasticity constitutive model able to simulate the cyclic plastic behavior is first presented in the framework of rate-independent plasticity theory. Validity of the constitutive model is confirmed against the strain- and stress-controlled cyclic loading test data. The verified constitutive model is then applied to parametric studies in which the local (circumferential strain) and global (cross-section diameter change) ratcheting responses of pressurized straight stainless steel pipes under cyclic in-plane bending are scrutinized. The results demonstrate that the shape and degree of the ovalization which occurs during the multiaxial ratcheting are dependent not only on the geometry but also on the applied loads such as the internal pressure and the cyclic in-plane bending.

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ABSTRACT: This paper reports the in-plane plastic collapse moment of cracked circular hollow section (CHS) gap K-joints containing a semi-elliptical surface crack located at the crown position. An in-house 3D finite element (FE) mesh generator is developed to create all the mesh models automatically. Firstly, in-plane plastic collapse moment applied to the uncracked CHS gap K-joints are investigated. Both Lu’s deformation limit and twice elastic compliance are used to determine the in-plane plastic collapse moment. Consequently, an extensive parametric study is carried out to investigate the in-plane plastic collapse moment of the cracked joints. It is found that the crack has a significant influence on the in-plane plastic collapse moment. The decrease of the in-plane plastic collapse moment is up to 30.4% when the crack area $A_{nc}$ reaches up to 25%. The strength reduction factors of all the analyzed cracked CHS gap K-joints are calculated. Finally, a lower bound reduction factor $F_{AR}$ equation is proposed based on the FE results.

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ABSTRACT: Sandwich pipes composed of two relatively thin concentric steel pipes and a thick and flexible core in the annulus, are viewed as a significant potential for deepwater and ultra-deepwater applications in oil and gas transportation because they can simultaneously meet mechanical and thermal requirements. This paper presents a collapse capacity prediction of sandwich pipes with various inter-layer adhesion behaviour under external pressure. The solid polypropylene with favourable thermal insulation capacity and high compressive strength is used as the core layer material. The stress-strain curves of the polypropylene material are measured through the uniaxial tension and compression tests. The tests of simple shear specimen and sandwich pipe section specimen are conducted to evaluate the stick-slip levels of epoxy resin and 3M-DP8005 adhesives in two surface conditions of steel pipe, respectively. Then, the dedicated finite element model is developed and an
extensive parametric study is conducted to explore the influences of geometric configuration, initial imperfection, material property, and inter-layer adhesion behaviour on the pressure capacity and deformability of sandwich pipes. It is observed that the inter-layer adhesion behaviour has a strong influence on the collapse capacity of sandwich pipes.


ABSTRACT: This paper investigated the effect of a 3D simulated metal inert gas (MIG) welding induced heat affected zone (HAZ), residual stress and distortion fields on the behaviour of aluminum stiffened plates under compressive loading. A two-step, thermo-structural finite element model was developed for the simulation of the welding process and the model was verified using the available experimental results. The welding induced HAZ, residual stress and distortion were then studied for tee-bar stiffened aluminum plates of various geometries. The effect of these welding induced imperfections on the load vs. shortening curves, buckling mode, and the post-buckling behaviour of each stiffened plate geometry were investigated. It was found that welding induced tensile and compressive residual stresses ranged from 72 to 77% and 18–36% of the base metal yield stress, respectively. The width of the HAZ around the weld line increased as the plate slenderness increased. The reduction in buckling strength of the tee-bar aluminum stiffened plates due to the presence of the HAZ and residual stress was as much as 10% and 16.5% respectively.


ABSTRACT: Structural damping induced by material viscoelasticity in flexible risers may generate a non-ignorable effect on the global dynamic analyses. This paper presents an analytical model in frequency domain which is capable of predicting the structural viscoelastic behavior of flexible risers subjected to axisymmetric harmonic loads. In this model, the influence of temperature is taken into consideration, as well as the viscoelastic material properties, which are represented by Prony series. Shift factor as a function of temperature is observed through a series of experimental data. The material constants in Prony series are obtained through Levenberg-Marquardt curve-fitting method. This model yields an evident non-linear relationship between force and axial strain, posing a noticeable hysteresis loop. The loop circumscript area can be accurately calculated as the dissipated energy used for obtaining the axial structural damping. A case study is presented to illustrate the model application and it is found that the axial strains are inversely proportional to the frequency regardless of temperature. Furthermore, both axial strain and dissipated energy are seen to be dramatically affected by the interaction of frequency and temperature, but no strict law can be found.

ABSTRACT: The objective of this work is to assess the importance of an accurate prediction of the weld-induced residual stresses and distortion based on numerical simulations and experiments, and to investigate the compressive longitudinal ultimate strength of fillet-welded steel-plated ship structures. The distortions and residual stresses are calculated by a nonlinear thermo-elasto-plastic (TEP) approach considering a range of plate dimensions. The calculations are validated with an experimental program on the effect of welding. The calculated pattern of residual stresses is used to calibrate the size of the idealized model of the residual stress distribution. The obtained ultimate strength is compared with the results of some simplified methods as well as the International Association of Classification Societies (IACS) Common Structural Rules (CSR). The effects of plate and column slenderness on the ultimate strength of the stiffened plates are also included.

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ABSTRACT: The paper re-visits the topic of ultimate bearing capacity of laterally loaded piles in clay. The paper first presents a review of various recommendations made by design guidelines and industry practitioners which illustrates inconsistency and need for further work. A literature study is therefore performed and a generalised recommendation of the ultimate lateral capacity of piles in clay that is self-consistent and flexible for a wide range of conditions is made. The paper further investigates two practical considerations often encountered in design, namely the effect of axial loading and the effect of soil strength anisotropy by means of finite element analyses. Practical methods to account for these effects are proposed.

End of many papers published in the journal, Marine Structures (2012-2016).

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ABSTRACT: This paper deals with the study of the slamming load and response of one complex 3D steel wedge with deadrise angle 22°. The stiffened panels on both sides of the wedge are made up of 9 longitudinal stiffeners and 5 transverse frames. In order to study the effect of flexibility on the elastic responses, the cross sections of the stiffeners and frames on each side were designed with different sizes. It is one segment of an idealized ship structure with V-shaped wedge bottom that was used in a series of free-drop experiments impacting still water. The acceleration, slamming pressures, and stress responses were measured. In this paper, one uncoupled method combining Wagner theory and the finite element method is presented to analyze this
slamming problem for the 3D structure. The matched asymptotic theory is expanded to predict both the motion and the slamming pressure on the free-drop rigid body. Then slamming pressures are added on the finite element model to predict the transient structural responses. The numerical and experimental results of this slamming problem for a 3D structure are compared. Good agreement is achieved and the hydroelastic effects are discussed.

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“Dynamic response of Mindlin plates resting on arbitrarily orthotropic Pasternak foundation and partially in contact with fluid”, Ocean Engineering, Vol. 42, pp 112-125, March 2012,
https://doi.org/10.1016/j.oceaneng.2012.01.010

ABSTRACT: In this study, a method of analysis is presented for investigating the dynamic response behavior of moderately thick plates (Mindlin plates) resting on arbitrarily orthotropic two parameter foundation and partially in contact with a quiescent fluid on its other side. A mixed-type finite element formulation is derived for the Mindlin plate–arbitrarily orthotropic Pasternak foundation interaction by applying the Gâteaux differential. A four nodded isoparametric \( C^0 \) class element is adopted and at each node eight degrees of freedom are assigned. The rotary inertia effect is taken into account through the consistent mass matrix formulation. For calculation of the fluid–structure interaction effects, the boundary element method is adopted. The fluid is assumed to be ideal, i.e., inviscid, incompressible, and its motion is irrotational. The infinite frequency limit condition is applied on the fluid's free surface using a modified fundamental solution implicitly satisfying the appropriate free surface boundary condition. It is assumed that the plate–elastic orthotropic foundation system vibrates in its in vacuo eigenmodes when it is in contact with fluid, and that each mode gives rise to a corresponding surface pressure distribution on the wetted surface of the structure. The fluid–structure interaction forces are calculated in terms of the generalized hydrodynamic added mass coefficients (due to the inertial effect of fluid). To assess the influence of the arbitrarily orthotropic Pasternak foundation and fluid on the dynamic response behavior of moderately thick plates, the natural frequencies and associated mode shapes are presented for rectangular and circular plates with various boundary conditions.


ABSTRACT: In this paper, the ultimate strength of open box girders with crack damage subjected to pure torque, compressive force, bending moment and combined loads is investigated using a commercial FEA program, ABAQUS. The ultimate strength reduction characteristics of the box girders due to cracking damage as a function of crack types, crack sizes and crack locations are studied. Based on the numerical results obtained from the present study, a simple model for predicting the residual ultimate strength of open box girders with crack damage under single load and combined loads is proposed. The suggested model has a simple form yet well represents the lower bounds of the reduced ultimate strength due to crack damage.

Gui-jie Shi and De-yu Wang (State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200030, China), “Residual ultimate strength of cracked box girders under torsional loading”, Ocean
ABSTRACT: In this paper, the ultimate strength of cracked box girders subjected to torsional loading is investigated using a commercial FEA program, ABAQUS. The ultimate strength reduction characteristics of the box girders due to cracking damage as a function of crack sizes and crack locations are studied. Based on the numerical results obtained from the present study, a simple model for predicting the ultimate strength of cracked box beams under torsional loads is proposed.

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ABSTRACT: An elastic model based on the Rayleigh–Ritz approach was proposed by Jang and Ma (2011) for analyzing the lateral-torsional buckling (“tripping”) behavior of permanent means of access (PMA) structures which was introduced by the International Maritime Organization (IMO) for a regular inspection of ship structure. This paper extends the elastic model into the inelastic range, using deformation theory and an iterative and incremental formulation. The effects of cross-sectional distortion and plasticity are included. Results obtained using the method are shown to be in a good agreement with nonlinear finite element analysis results.

ABSTRACT: The paper discusses the results of buckling tests on carefully machined steel cones subjected to combined loading. Two cones were subjected to pure axial compression, further two were loaded by lateral pressure and the remaining six were tested under different combinations of axial load and external pressure. Cones were relatively thick with the radius, \( r_2 \), at the base to wall thickness, \( t \), being \( r_2/t=50 \). The ratio of height, \( h \), to the base radius, \( h/r_2=1.0 \), and the semi-vertex angle was \( \beta=14^\circ \). All numerical predictions of buckling load were found to be higher than the values obtained in experiments. Experimental results were also checked against values recommended by two design codes. Buckling loads recommended by codes show that five out of ten cones would have developed permanent, plastic straining at the recommended load level. Consequences of this, for repeated loading, are also highlighted in the paper. The paper also shows that a large portion of the interactive diagram is affected by plastic strains with the first yield envelope having bi-linear shape while the collapse envelope being quadratic.

ABSTRACT: A sandwich pipe (SP) is an effective design alternative, providing effective load carrying capacity and thermal insulation to pipelines, especially when the pipe is going to be utilized in deep and ultra-deep water applications. However, the design and development of a reliable SP requires an in-depth understanding of the behavior of such a system under various loading conditions. In this paper, the behavior of SPs subject to pure
bending, which is one of the governing loading conditions for offshore pipelines, is investigated. In order to perform this investigation, a series of numerical parametric models, using the finite element (FE) method, was developed. The linear eigenvalue buckling analysis and the nonlinear post-buckling analysis were conducted to explore the systems' response. The influence of several significant structural parameters on the pre-buckling, buckling and post-buckling responses of SPs was investigated. The parameters investigated included various combinations of several geometrical and material properties, as well as the consideration of various possible intra-layer adhesion mechanisms. Moreover, the recent high strength steels used in formation of oil and pipes exhibit certain degree of yield anisotropy; it is therefore crucial to understand the effect of material's yield anisotropy on such system's response. This issue has also been considered in this research.

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“The necessity of applying the common corrosion addition rule to container ships in terms of ultimate longitudinal strength”, Ocean Engineering, Vol. 49, pp 43-55, August 2012,
https://doi.org/10.1016/j.oceaneng.2012.04.012
ABSTRACT: This study explores the ultimate longitudinal strength of five different sizes of container ships to investigate the impact of considering aged corrosion effects throughout a ship's life. The typical design life of double oil tankers and bulk carriers, according to the CSR (Common Structural Rule), is 25 years and approximately 20 years for other commercial ships. In case of container ships, whether corrosion addition is required differs according to classification society with some not stipulating any such requirements. To conveniently define aged corrosion additions for container ships, the corrosion addition requirements for a double hull oil tanker, which has a relatively similar mid-ship the section configuration, were applied in this study as an initial guideline. The ultimate strength of the selected container ship, including their longitudinal strength behavior, is investigated in this study to show the necessity of corrosion addition application to container ships and the relevant predictions regarding decreases in the longitudinal strength of new-building container ships after corrosion. The investigation results regarding longitudinal strength reduction and other findings from this analysis of five container ships will be useful in enforcing corrosion addition as a general guideline. (One of the Key Words is identified by authors as: “Ultimate hull girder strength”)

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ABSTRACT: Ocean-current induced pipeline on-bottom stability on a sloping sandy seabed involves a complex interaction between the hydrodynamic loading, the untrenced pipeline and the neighboring soil. In this study, a newly-designed pipe-soil interaction facility and a flow-structure-soil interaction flume have been utilized for full-scale physical modeling of the pipeline instability on a sloping sand-bed, including the downslope instability and the upslope instability. Unlike the pipeline lateral stability on the horizontal seabed, an initial lateral-soil-resistance is developed and the static-instability might be triggered for the sloping seabed. According to dimensionless analyses, an ultimate lateral-soil-resistance coefficient is proposed to describe the interaction of the pipe with the sloping sand-bed. Experimental results indicate that sand-bed slope angle, pipe
submerged weight and end-constraints have much influence on pipe on-bottom stability. No matter for the upslope instability or the downslope instability, the corresponding lateral-soil-resistance coefficient for a sloping sand-bed is larger than that for a horizontal sand-bed.

ABSTRACT: This paper presents a numerical simulation and simplified methods for estimating the residual strength of a damaged double bottom. A typical double-bottom structure from a shuttle tanker was modelled. The structure was idealised to a small degree. Imperfections were introduced to the whole structure according to design rules. The most severe situation of the fully loaded condition was investigated. Hull girder bending was considered. Damage was caused by a variety of indenters that were specially designed to obtain a desired damage profile. A total of 16 numerical-calculation cases were investigated using the explicit commercial code LS-DYNA 971. A simplified method was derived. This method includes elastic plus rigid-plastic analyses of a 3-span, single-stiffener model. Unlike Smith's method, the present approach takes damaged stiffened panels into account in the residual strength assessment. The elastic and rigid-plastic analyses were combined to provide the load-end shortening curve for the damaged stiffeners. A simplified damage mechanism for the tripping of stiffeners is presented, as is a 3-span single stiffener model with proper boundary conditions. Both the analytical and single stiffener models were used to estimate the residual strength of a damaged double bottom. Both methods were validated with a non-linear, finite-element analysis (NLFEA) simulation carried out using LS-DYNA 971.

Siyuan Ma and Hassan Mahfuz (Florida Atlantic University, Ocean and Mechanical Engineering Department, Boca Raton, FL 33431, United States), “Finite element simulation of composite ship structures with fluid structure interaction”, Ocean Engineering, Vol. 52, pp 52-59, October 2012, https://doi.org/10.1016/j.oceaneng.2012.06.010
ABSTRACT: A finite element tool for structural analysis of a composite multi-hull structure is developed. Two-way fluid structure interaction (FSI) is implemented by coupling finite element analysis (FEA) and computational fluid dynamics (CFD). FEA models have been developed using sandwich construction having composite face sheets and foam core. Fluid domain is modeled using a CFD code, CFX and a wave motion is simulated based on Sea State 5. FSI module is then used to connect FEA with the CFD code. Dynamic response of the hull is generated in time domain. A critical area with high stress gradient is chosen and a sub model is developed with refined mesh. Force and displacement boundary conditions are transported from the global model. Interlaminar stresses and shear stress distributions at the core and girder are then determined. Materials failure criteria for composites and foam are applied on the sub model and structural integrity of each component is checked. An analysis without FSI is also performed on a reference model with identical load and boundary conditions and the result is compared with that of FSI.

ABSTRACT: Energy method is used for tripping analysis of asymmetric stiffeners in stiffened plates.
shape of normalized warping function of stiffener is proposed as a strain distribution for sideways bending and classical plate theory is used for out-of-plane deflection. Strain distribution and elastic tripping stress of different angle bars and permanent means of access structures are calculated and compared with finite element method. It is found that for slender angle bars rigid web or flange assumption for out-of-plane deflection is justified. For angle bars proposed strain distribution based on normalized warping function and previously suggested strain distribution based on bending theory are exactly the same. However, for permanent means of access structures, the proposed strain distribution has better agreement than previously suggested strain distribution. For angle bars and permanent means of access structures with high ratio of web height to length, some discrepancy arises between proposed strain distribution and finite element method due to shear deformation.


ABSTRACT: Corrosion is one of the time dependent detrimental phenomena which reduces strength of structures and leads to catastrophic failures. All rules and regulations concerning strength of corroded plates are based on uniform thickness reduction. To estimate residual strength of corroded structures, typically a much higher level of accuracy is required, since, the actual corroded plate has irregular surfaces. There is little study on strength analysis of corroded plate with irregular surfaces especially as a function of corrosion parameters. It is the main aim of present work to study ultimate strength of corroded steel plates with irregular surfaces under in-plane compression. Nonlinear finite element method is employed to determine ultimate strength of corroded steel plates with irregular surfaces. Comparing the results with ultimate strength of corroded plates with uniform thickness, a reduction factor is introduced. Having done this, ultimate strength of corroded plates could be evaluated easily as a function of corrosion conditions.

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ABSTRACT: Sandwich pipes (SP) can be an effective solution for the ultra-deepwater submarine pipeline, combining high structural resistance with thermal insulation capability. Besides polymer, steel fiber reinforced concrete (SFRC) can be another choice for the annular material, based on the characteristics of high fracture toughness and good adhesion with metal. The purpose of this work was to investigate numerically the ultimate strength of SP filled with SFRC under external pressure and longitudinal bending. The mechanical behaviour of SFRC was simulated using a Concrete Damaged Plasticity (CDP) model whose parameters were estimated by uniaxial tension, compression and four-point bending tests. The applicability of the parameters obtained was verified by simulating the compression and four-point bending tests, where the results showed good correlation between measured and predicted numerical values. Pressure–curvature ultimate strength for SP with perfect adhesion and no adhesion interface condition was obtained. Besides, a parametric study was performed to
investigate the effect of the thickness of each layer on the pressure–curvature collapse envelope of SP. It was found that the adhesion between layers and the lateral confinement effect on SFRC play a dominant role in the ultimate strength behaviour of SP, which lead to the non-monotonicity of the collapse envelope.

Qing Yang, Van Jones and Leigh McCue (Department of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA 24061, USA), “Free-surface flow interations with deformable structures using ans SPH-FEM model”, Ocean Engineering, Vol. 55, pp 136-147, December 2012,
https://doi.org/10.1016/j.oceaneng.2012.06.031
ABSTRACT: A two-dimensional SPH–FEM model is proposed to investigate its application in the fluid–structure interaction (FSI) problem. The fluid model is based on the theory of Smoothed Particle Hydrodynamics (SPH) and the structural dynamics employ a large-deformation Finite Element Method (FEM). This paper describes the basics of both SPH and FEM models and presents the development of a loosely coupled SPH–FEM model. Validation results of two benchmark FSI problems are illustrated. The first test case is flow in a sloshing tank interacting with an elastic body (Souto-Iglesias et al., 2008) and the second one is dam-break flow through an elastic gate (Antoci et al., 2007). The results obtained with the SPH–FEM model show good agreement with published experimental results and suggest that the SPH–FEM model is a viable and effective numerical tool for FSI problems.

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“Nonlinear dynamic response of sandwich plates with FGM face sheets resting on elastic foundations in thermal environments”, Ocean Engineering, Vol. 57, pp 99-110, January 2013,
https://doi.org/10.1016/j.oceaneng.2012.09.004
ABSTRACT: This paper presents an investigation on the nonlinear dynamic response of sandwich plates with FGM face sheets resting on elastic foundations in thermal environments. The material properties of FGM layer are assumed to be graded in the thickness direction according to the Mori–Tanaka scheme. The governing equations of the plate that includes plate–foundation interaction are solved by a two-step perturbation technique. The thermal effects are also included and the material properties of both FGM face sheets and homogeneous core layer are assumed to be temperature-dependent. Two cases of the in-plane boundary conditions are considered. Initial stresses caused by thermal loads or in-plane edge loads are introduced. The numerical illustrations concern the nonlinear dynamic response of sandwich plates resting on Pasternak elastic foundations under different sets of thermal environmental conditions, from which results for single-layer FGM plates are also obtained for comparison purposes. The numerical results show that foundation stiffness and initial stress have a significant effect on the dynamic response of both single-layer and sandwich FGM plates. They also show that the core-to-face sheet thickness ratio has a significant effect on the dynamic response of sandwich FGM plates. The results reveal that the volume fraction distribution of FGM layer has a significant effect on the dynamic response of single-layer FGM plates, whereas this effect is less pronounced for the sandwich plate with FGM face sheets.

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ABSTRACT: In this study maximum deflection and free vibration of quasi-isotropic thin rectangular plates that are clamped or simply supported from four edges were examined. The effects of changes in aspect ratio and orientation angle on the results of statical bending and free vibration problems according to the Classical Lamination Plate Theory were parametrically calculated by utilizing the Galerkin Method and the Least Squares Method among Weighted Residuals Methods. Obtained results were compared with the software package ANSYS that conducts analyses through Finite Elements Method (FEM). It is observed that the Galerkin Method yields reasonable results much more rapidly than FEM. It was determined that the effect of changes in orientation angles and aspect ratios of different combination of plates, which were constituted with the alternative arrangement of the lamination angles, on maximum deflection and fundamental natural frequency values is substantial. It was considered that the optimum plates that will properly satisfy different load conditions on the different parts of the structure can be determined with the use of the nondimensional tables prepared with the Galerkin Method in the preliminary design of composite hulls. It is proposed that savings from materials, labor, testing and time can be achieved by this means.

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ABSTRACT: Wind as a source of energy is being used from very long time. It has gained more significance in the current age of energy crisis. Lots of efforts have been made to develop the horizontal axis wind turbines but vertical axis wind turbines did not get much attention over the past couple of decades. Blade is the most important component of a wind turbine which controls the performance of a wind turbine and design of other components attached to it. A concept for the design of a straight symmetrical blade for a small scale vertical axis wind turbine using beam theories for analytical modeling and a commercial software ANSYS 11.0 for numerical modeling is presented in current research. Design parameters of the blade like solidity, aspect ratio, pressure coefficient etc are determined aiming the 1 kW power output and the blade design was analyzed at extreme wind conditions where maximum values of deflection and bending stresses were determined at peak values of aerodynamic and centrifugal forces. The design was optimized to attain the structural strength i.e. reduction in deflections and bending stresses. This blade design has high strength and lower material consumption to achieve the low cost of complete rotor assembly of the wind turbine which actually covers more than 50% of the overall wind turbine cost.

ABSTRACT: A new analytical method to predict nondestructively the elastic critical pressure of a submerged cylindrical shell which is subjected to external hydrostatic pressure is presented in this paper. The structural-fluid coupling dispersion equation of the system is established considering axial and lateral hydrostatic pressure
based on the wave propagation approach. The data of the natural frequencies of the system under different hydrostatic pressures is obtained by solving the coupled dispersion equation. The curve of the fundamental natural frequency squared versus hydrostatic pressure is then drawn with the data, which is straight approximately. The elastic critical hydrostatic pressure is obtained when the corresponding fundamental natural frequency decreases to zero. The results obtained from the present approach show good agreement with published results.

ABSTRACT: This work deals with the evaluation of the ultimate bending moment of two box girders subjected to different levels of corrosion degradation and experimentally tested under pure vertical bending moment. A series of nonlinear finite element analysis have been conducted. Two models of corrosion degradation have been used representing an average general corrosion thickness reduction, and the real corrosion thickness as it is measured. Based on the real corrosion measurements, experimental ultimate strength and finite element calculations, a relationship has been developed to predict the expected difference in the ultimate strength calculations based on the FE models representing the corrosion degradation as an average thickness reduction or as the real measured corrosion reduction.

ABSTRACT: The aim of present work is to investigate the characteristics of interactions of different buckling modes of flat-bar stiffened panels. Literature-based and rules-based expressions for assessing buckling strength of stiffened plates are studied. Energy method is employed for the analyses of selected buckling modes of stiffened plates including plate buckling, torsional buckling, web buckling and interactions of them when either plate or stiffener or both are under compression. Results are compared with numerical solutions using finite element method and available expressions to identify the applicability and accuracy of selected expressions for certain conditions. It is found that some of the given expressions for buckling analyses of stiffened plates have limited applicability.

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ABSTRACT: Large high-speed wave-piercing catamarans are subject to continuous wave induced hull vibrations during their lifetime of operation. In severe sea conditions, the vessel experiences high load impacts, known as slamming, accompanied by high frequency structural response giving rise to fatigue effects. Classical vibration analysis techniques such as the Fourier Transform fail to identify the exact response frequencies of slamming events due to the transformation to the frequency domain and the loss of temporal information about these transient events which is of great importance to fatigue analysis. The work presented in this paper
introduces, describes, applies and recommends the continuous wavelet transform as an effective means to investigate the wave induced hull vibrations in both the time and frequency domains simultaneously.

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ABSTRACT: A new type of marine flexible pipeline is designed for applications in shallow water at a reduced cost. To investigate the mechanical behavior of the flexible pipeline and to improve the structural design, an analytical model to predict the tension behavior of the flexible pipeline is proposed in which the effect of radial deformation is given more attention. The governing equations for the flexible pipeline are derived, and their solution provides the tension load–deformation relationship. Tension tests of the flexible pipeline were carried out, and there was a good agreement between the analytical model and the experimental results. In addition, a parametric study is conducted to understand the effect of the radial stiffness on the tension stiffness. Finally, suggestions are given for the design of the radial stiffness and the tension stiffness of the flexible pipeline for shallow water applications.

ABSTRACT: The work is devoted to the strength and elastic stability analysis of a barrelled shell loaded with uniform radial pressure. The shell is assumed to be isotropic, homogeneous and of constant thickness. The geometry of the shell is described as well as the field of displacement for which Kirchhoff–Love hypothesis is applied. On the basis of the linear equilibrium equations the relations describing the membrane state of stress in the pre-buckling state are derived. The buckling problem of the barrelled shell is described analytically and solved approximately with the use of Bubnov–Galerkin method. As a result the formula for the critical pressure is obtained. The numerical examples are presented which were solved analytically and with the use of finite element method. The comparison of the results obtained in both ways shows very good agreement as to the values of membrane forces, buckling load and buckling shape. The formulae presented in the paper may help in the design of shell structures in the shape of barrel.

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ABSTRACT: In the offshore industry there are two possible materials for the construction of the hull of any structure: steel and concrete. Steel is being widely used in the shipbuilding industry for merchant ships, warships, etc. Materials such as aluminium, glass reinforced plastic (GRP) or timber are also used in small units with lengths lower than 100 m and with less adverse conditions than in the offshore industry. Nevertheless,
some ships/barges have been built of concrete in the past, but these have been rather isolated cases and have not changed the industry practice. During the First and Second World War concrete was used due to the scarcity of other materials, so the series of barges by Alfred A. Yee were a rare exception. Other floating structures were also made in concrete, but they are almost anecdotal. However, the behaviour of these concrete structures, especially in terms of maintenance, has been excellent. Therefore, the fact that concrete has not had an adequate reception so far in shipbuilding does not mean that it will not be the material best suited to the offshore industry in the future. The extra displacement and associated fuel costs in concrete ships have been found to be prohibitive in the past. However the loss of mobility in a concrete hull compared to a steel hull can be perfectly offset by the advantages offered by concrete, as the shipping and offshore industry now have very different priorities. One of the main differences in these priorities is the importance of maintenance and resistance to fatigue, precisely the areas where concrete performs the better. Ships can easily be dry-docked for maintenance and repair, while in the offshore platforms these works have to be done in situ, so maintenance and fatigue are crucial to them. Besides these aspects, concrete has other advantages, according to a number of findings in several studies. This supports the fact that in recent years concrete offshore units have been built proving that in certain cases the benefits of steel are inferior to those of concrete. Concrete gravity base platforms type Condeep have been building since the first unit became operational in 1976, together with a few floating platforms, that have geometry similar to those made of steel (barges, semi-submersibles and TLP type platforms). Offshore LNG terminals and offshore industrial plants utilise emerging concepts in concrete that are lasting for years. The life of these barges can be designed for up to 200 years, such as the floating Nkossa barge, so they can be a good alternative to the construction of these facilities on land, thus avoiding landfills on the coast that degrade the already punished coastline of industrialized countries. The challenge is precisely to optimize their capital costs to compete for an offshore installation against a shore facility. The environment will undoubtedly benefit from this great challenge that lies ahead in the XXI century.


ABSTRACT: The purpose of the current study is to assess a selection new innovative crashworthy side-shell structures, with respect to their contribution to the crashworthiness of ships, and compare them to a conventional reference structure. Explicit finite element (FE) simulations are used to assess the performance of each structure on a small-scale experimental structure as well as in simulations of large-scale ship collisions. The structures compared are divided into two concepts: the maximization of striking bow-struck ship contact area by allowing for a large intrusion depth of the bow before the watertight integrity is breached (ductile design), and the maximization of energy absorption of the structure and low intrusion depth of the striking bow (strength design). The assessment is made by comparing the intrusion depth before rupture of the inner side-shell of a double-hull structure occurs, energy absorption during the indentation, the final damage opening area as well as the weight and manufacturing costs of each structure. It was found that the strength design concept – the X-core structure – was in favour of the ductile design concept – the corrugated inner side-shell structure. The results provide basis for discussing the potential and challenges related to the implementation of each structure.

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ABSTRACT: This paper aims to compare between ultimate strength of T and Y stiffeners when subjected to lateral load. Two groups of Y and T stiffeners are studied. In the first group, T stiffeners with standard dimensions are compared with Y stiffeners having the same section modulus, attached plate and weight. The plates of both types of stiffeners are subjected to uniform pressure. In the second group, both T and Y stiffeners share the same section modulus with different attached plate and weight, and a pressure load is applied to a small central area of the plate. The results are shown in 2 sets of curves. In the first set, perfect T stiffeners are compared with perfect Y stiffeners. In the second set, imperfect T stiffeners are compared with imperfect Y stiffeners. Also, perfect and imperfect T stiffeners are compared as well as perfect Y and imperfect Y stiffeners. Five perfect models of T and Y stiffeners having different dimensions with three levels of initial imperfections are studied in the two groups. Nine imperfect models branch from each of the five perfect models for both groups; 200 models are obtained and results from the FE analysis are shown in the form of load–displacement curves.

ABSTRACT: In this paper the statistical properties of the slamming impact process are analyzed with the help of experimental data acquired in the towing tank on a high speed ferry model. The physical model is a segmented-hull with a flexible backbone-beam equipped, among other devices, with sensors to measure the wetness of hull sections and strain gauges to estimate the induced vertical bending moment. This setup allows us to analyze the slamming process not only on the basis of the detected slamming events but also on the basis of the whipping response produced by the impacts. Moreover, due to the particular model selected for the present analysis, characterized by a V-shaped hull, bottom as well as bow flare slamming contributions are investigated. One of the major findings is the evidence that the impact statistics are largely affected by the grouping of slams into clusters thus violating the hypothesis of mutual independence between successive impacts that is at the basis of most of the statistical models. The dependence of the whipping response on the impact velocity is also investigated. Finally, the definition of a new criterion for slamming identification based on the evaluation of the whipping bending moment is discussed.

ABSTRACT: This paper deals with the buckling behavior of composite sandwich columns under compressive loading. Namely, finite element (FE) modeling strategies are discussed with the aim to test a suitable and cost effective solution for assessing the buckling behavior of delaminated sandwich laminates. Indeed, pleasure craft industry is now facing the challenge of thinner and thinner skin laminates. Buckling, that in past years was not a governing limit state because of rather high thicknesses and of limited spans of structural elements, should be
now assessed possibly accounting for actual defects, i.e. delaminations, and applying straightforward but cost-effective approaches, easy to implement in the everyday practice of composite hull structural design. A suitable test case, available in open literature, was selected and results of the proposed modeling strategy are compared with experimental ones as well as with other numerical estimates, showing its capabilities and addressing hints for FE application.

ABSTRACT: This paper presents the results of an investigation of the effect of lateral pressure on the progressive hull collapse behaviour of a double-hull oil tanker subject to vertical bending moments in both the sagging and hogging conditions. As an illustrative example, a Suezmax-class double-hull oil tanker designed by the Common Structural Rules (CSR) method is considered. The ANSYS nonlinear finite element method (NLFEM) is employed for the progressive hull collapse analysis. The effects of lateral pressure – static (anchored condition) and dynamic (operating condition) – are investigated in both the full-load and ballast conditions. To check the accuracy of ultimate hull girder strength analysis methods, Dow's test hull is also applied together with Suezmax class oil tanker under conditions of vertical bending moment but without lateral pressure loads. In this regards, the NLFEM method is compared with ALPS/HULL intelligent supersize finite element method (ISFEM) programs and International Association of Classification Societies (IACS) CSR method, which applies the idealized structural unit method (ISUM) (also called the Smith method). The important insights developed from the present study are documented.

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ABSTRACT: Previous studies have been conducted on the structural behavior of dented tubular members. Nevertheless, there is insufficient experimental research on the deformation behavior of locally loaded tubes. In this paper, the behavior of six pre-compressed specimens under local lateral loads was investigated and experimentally evaluated. Relevant finite element simulations and theoretical predictions were considered for the comparison of critical loads, absorbed energy and modes of deformation. Derived results were aimed at using data for dented tubular members in full scale.

ABSTRACT: The design process is becoming increasingly complex with designers balancing societal, environmental and political issues. Composite materials are attractive to designers due to excellent strength to weight ratio, low corrosion and ability to be tailored to the application. One problem with composite materials
can be the low stiffness that they exhibit and as such for many applications they are stiffened. These stiffened structures create a complex engineering problem by which they must be designed to have the lowest cost and mass and yet withstand loads. This paper therefore examines the way in which rapid assessment of stiffened boat structures can be performed for the concept design stage. Navier grillage method is combined with genetic algorithms to produce panels optimised for mass and cost. These models are constrained using design rules, in this case ISO 12215 and Lloyd's Register Rules for Special Service Craft. The results show a method that produces a reasonable stiffened structure rapidly that could be used in advanced concept design or early detailed design to reduce design time.

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ABSTRACT: As offshore oil and gas developments move into ultra-deep water depths, the greater the impact onerous installation procedures will have on pipeline integrity. Current approaches for predicting this impact are mostly based on a global pipeline perspective, using installation analysis tools that model the entire length of suspended pipeline using a string of ‘pipe’ finite elements. While these analysis methods are proven to provide reasonable predictions for moderate installation loadings, they lack sufficient detail for considering the most extreme conditions and do not generally account for material plasticity, residual curvature and pipe twist. This lack of detail could represent a significant shortcoming in future developments where pipe joints will be subjected to more substantial loading during ultra-deep water installation. A detailed local finite element model of the pipe cross-section during installation has been developed that allows for greater insight into the actual as-laid condition of a given pipeline. Numerous installation scenarios are considered and comparisons are made with output from traditional global analysis methods. These comparisons demonstrate potential shortcomings of existing engineering design approaches for ultra-deep water. This ultimately leads to recommendations that will shape on-going developments in design methods.

ABSTRACT: In this paper, a probabilistic framework for performance assessment of ship hulls under sudden damage accounting for different operational conditions is presented. Grounding and collision accidents are considered as sudden damage scenarios. The combined effects of sudden damage and progressive deterioration due to corrosion are investigated. The performance of ship hull is quantified in terms of ship reliability and robustness. The longitudinal bending moment failure is considered as the limit state. The longitudinal bending moment capacities of the intact and damaged ship hulls are assessed using an optimization-based version of incremental curvature method. The wave-induced loads for different ship speeds, headings and sea states are identified based on hydrodynamic analysis and the ship performance under different operational conditions is investigated. The approach is illustrated on an oil tanker. Under different operational conditions the reliability index associated with the intact and damaged ship hull and the robustness index associated with damage scenarios are presented in polar plots. In addition, aging effects on ship reliability are investigated.
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ABSTRACT: The paper presents a method to experimentally characterize the significance of hydroelasticity for slamming loaded marine panels. The methodology is based on a large number of systematical experiments of slamming loaded panels from which semi-empiric expressions for the pressure distributions are derived. Finite element simulations are used to obtain rigid/quasi-static reference solutions. Hydroelastic effects are quantified by comparing deflections and strains from experiments with the corresponding non-hydroelastic reference solutions. The study shows that the largest hydro-elastic effects appear to be a time-lag effect, which however does not seem to affect the structural response magnitudes dramatically. The most significant hydroelastic effects can be expected to be close to the panel supports for very flexible structures or sandwich constructions. The results are also discussed with reference to classification rules which indicate that hydroelastic effects are small in the design of conventional ship hull structures.

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ABSTRACT: Subsea pipelines buckle globally because of their movement relative to surrounding soil. Global buckling is often triggered by high operational temperature of the oil in pipelines, initial imperfections in the pipeline, and/or a combination of both. Pipeline global buckling is a failure mode that must be considered in the design and in-service assessment of submarine pipelines because it can jeopardize the structural integrity of the pipelines. Global buckling is increasingly difficult to control as temperature and pressure increase. Therefore, location prediction and buckling control are critical to pipeline design. Finite element analysis (FEA) is often used to analyze the behavior of pipelines subject to extreme pressures and temperatures. Four numerical simulation methods based on the finite element method (FEM) program ABAQUS, i.e., the 2D implicit, 2D explicit, 3D implicit, and 3D explicit methods, are used to simulate pipeline global buckling under different temperatures. The analysis results of the four typical methods were then compared with classical analytical solutions. The comparison indicates that the results obtained using the 2D implicit and 2D explicit methods are similar and the results obtained using the 2D implicit method are closer to those obtained using traditional analytical solutions. The analysis shows that the results of the 3D implicit and 3D explicit methods are similar, but the results obtained using the 3D methods are significantly different from those obtained using the analytical solution. A novel method to introduce initial pipeline imperfections into the FEA model in global buckling analysis is also presented in this paper.

Mahdi Khorasanchi and Shan Huang (Department of Naval Architecture, Ocean and Marine Engineering,
University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK), “Instability analysis of deepwater riser
with fairings”, Ocean Engineering, Vol. 79, pp 26-34, March 2014,
https://doi.org/10.1016/j.oceaneng.2014.01.003

ABSTRACT: The paper investigates the mechanism of instability of deepwater risers fitted with fairings and
presents an analytical model to predict the instability onset conditions. The simplified case of a two-dimen-
sional (2D) problem was considered. The governing equations were derived, and the hydrodynamic forces were
calculated and the effect of motion in these forces was taken into consideration. The final equations were
linearised and an eigenvalue analysis was employed to systematically examine the stability with the emphasis
on identifying the critical current speed for a given system. This model was validated against the available test
results and showed a good agreement. A parametric study was also carried out. It showed the significant role of
the hydrodynamic coefficients as well as mass distribution in the stability of the system.

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“Nonlinear vibration of anisotropic laminated cylindrical shells with piezoelectric fiber reinforced composite

ABSTRACT: This paper deals with the small and large amplitude flexural vibrations of anisotropic shear
defeatable laminated cylindrical shells with piezoelectric fiber reinforced composite (PFRC) actuators in
thermal environments. Two kinds of fiber reinforced composite (FRC) laminated shells, namely, uniformly
distributed and functionally graded reinforcements, are considered. The motion equations are based on a higher
order shear deformation shell theory with a von Kármán-type of kinematic nonlinearity and including the
extension-twist, extension-flexural and flexural-twist couplings. The thermo-piezoelectric effects are also
included, and the material properties of both FRCs and PFRCs are estimated through a micromechanical model
and are assumed to be temperature dependent. A boundary layer theory and associated singular perturbation
 technique are employed to determine the linear and nonlinear frequencies of hybrid laminated cylindrical shells.
The numerical illustrations concern the cross-ply and angle-ply laminated cylindrical shells with fully covered
or embedded PFRC actuators under different sets of thermal and electric loading conditions. Detailed
parametric studies are carried out to investigate effects of material property gradient, temperature variation,
applied voltage, shell geometric parameter, stacking sequence, as well as the shell end conditions on the linear
and nonlinear vibration characteristics of the hybrid laminated cylindrical shells.

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“Collapse of sandwich pipes with PVA fiber reinforced cementitious composites core under external

ABSTRACT: Sandwich pipes (SP) with steel tubes and a lightweight flexible core are under consideration as a
potential solution for ultra-deepwater submarine pipelines, combining high structural resistance with thermal
insulation. Besides polymeric materials, strain hardening cementitious composites (SHCC) reinforced with polyvinyl alcohol (PVA) fibers, a micromechanically designed material with high tensile ductility, can be an option for the annular material. The purpose of this work was to investigate experimentally and numerically the collapse behavior of SP filled with SHCC under external hydrostatic pressure. The preparation procedure for SHCC and the fabrication process for SP were presented in detail. The full-scale laboratorial tests of SP were performed using a hyperbaric chamber to analyze the collapse pressure subjected to external pressure. The mechanical behavior of SHCC was simulated using a concrete damaged plasticity (CDP) model provided by the commercial finite element package ABAQUS, whose parameters were estimated by tension and compression tests. In addition, a systematic parametric study was performed to analyze the effects of ovality, thickness and outer/inner radius ratio on the collapse pressure of SP with SHCC core.

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ABSTRACT: A trawl gear impact on an underwater pipeline can create a dent that pushes part of the pipe wall inward. External pressure also tends to push the wall inward. Because of that interaction, an impact under external pressure dents the pipeline more severely than the same impact with no external pressure. The interaction has been investigated as part of a wider study of overtrawlability of pipe-in-pipe systems carried out by the National University of Singapore. The problem is important because the need to protect pipelines against trawl gear impact leads to a requirement to trench medium and small-diameter pipelines. Trenching is costly and a frequent source of delays and disputes, and so it is worthwhile to search for ways to eliminate unnecessary trenching. A finite-element model of denting under external pressure for single wall pipe and pipe-in-pipe using hydrostatic fluid element has been established and verified by comparison against published data and current experiment data. Parametric study of different external pressures shows the effect of external pressure on the denting process. The combinations of the internal pressure, external pressure and indentation are considered. The study shows that when the internal pressure of a dented subsea pipe is decreasing, the possibility of buckle propagation for the single wall pipe is higher than it is for the pipe-in-pipe.

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ABSTRACT: The possibility of collision between FPSO and ships exist, and consequences of such collisions can be severe. The crashworthiness of FPSO side structures must be considered in preliminary stage of structure design. In this paper, an analytical method is proposed for rapidly predicting responses of FPSO side structures in case of being struck by a ship with rigid bulbous bow. This method is particularly suitable for use in
preliminary structure design phase because it is built based on a series of close-formed formulae derived using the simplified analytical method and only a few parameters are needed for calculation. The proposed analytical method is developed by combining several primary failure models of major double shell members, including the plate punching model, the plate perforating model, the plate denting model, the plate tearing model, and the X-shaped structure crushing model. Using the proposed method, curves of impact load versus indentation for three typical collision scenarios are obtained. These curves provide a detailed description of the collision process until rupture occurs in inner shell and help to evaluate crashworthiness of FPSO side structures. Accuracy of the analytical method is verified by numerical simulations using code LS_DYNA. The results of numerical simulations and those by the proposed analytical method match well. (“FPSO” means Floating Production, Storage and Offloading”)

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“Minimum cost design of hybrid cross-ply cylinders with uncertain material properties subject to external pressure”, Ocean Engineering, Vol. 88, pp 310-217, September 2014, https://doi.org/10.1016/j.oceaneng.2014.06.010
ABSTRACT: Minimum cost design of hybrid cross-ply cylinders is presented which employ high-stiffness and expensive materials in the surface layers and the low-stiffness and inexpensive layers in the middle layers to combine the advantages of the two materials. Hybrid construction takes advantage of the sandwich effect whereby most of the load is carried by the surface layers. The cylinder is subject to external pressure with the material properties displaying uncertain-but-bounded variations around their nominal values. For a given external pressure, the material cost is minimized by minimizing the thickness of the surface layers. Analysis to determine the worst-case combination of material uncertainties makes use of convex modeling to compute the least favorable solution defined here as the minimum buckling pressure. The minimum cost designs are investigated for various problem parameters such as the wall thickness and the level of uncertainty. The relative sensitivities of the buckling pressure to material properties are also studied by defining sensitivity indices.

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ABSTRACT: The dynamic behaviour of offshore pipeline in the process of deepwater S-lay operations, which is of prime importance in the installation design of the pipeline, has drawn extensive research attention. In this paper, a comprehensive finite element model for S-lay systems within the framework of the commercial computer code OrcaFlex is developed to investigate the dynamic lay effects, including surface waves, ocean currents, pipelay vessel motions, and the clashing contact between the pipeline and stinger rollers. Meanwhile, a non-linear hysteretic soil model is applied to identify the vertical pipe-seabed interaction mechanism. The numerical model is then used to conduct a practical engineering analysis of a 6-inch offshore pipeline being laid to a water depth of 1500 m in LW3-1 gas field in the South China Sea using the HYSY 201 pipelay vessel. The dynamic behaviour of offshore pipeline on aspects of deflection, axial tension, bend moment, stress and strain is estimated in detail. Significant differences between static and dynamic results are observed, which offer very intuitive evidences of dynamic effects concerning deepwater S-lay pipeline.

ABSTRACT: Two independent sets of analytical solutions have been derived for calculation of displacements and stresses in elastic multi-layer cylinders subjected to both pressure and thermal loading. The solutions are computationally efficient and easily implemented, and thus suitable for engineering applications. In particular, the novel solutions are relevant for offshore pipelines and risers, since the impact of internal and external coating layers on the stress state in the pipe wall often is disregarded or assessed by simplified methods in current pipeline engineering practice. Recursive solutions are obtained both for the case of uniform temperature in each cylinder layer and for the case of radially varying temperature in each cylinder layer. Both plane stress and plane strain conditions are considered. In addition, a recursive solution of the heat equation is derived for steady-state conditions. Applicability of the solutions is illustrated by using them on an offshore pipeline with a corrosion-resistant liner and multi-layered thermal insulation coating. It is demonstrated that coating layers, generally disregarded in conventional pipeline design, may have a non-negligible impact on hoop stresses and the true wall axial force.


ABSTRACT: With shear deformation and pre-buckling deformation included, a 2D mathematical model for composite pipes is developed to analyze the collapse of RTP pipe under pure external pressure, pure bending moment, or combined external pressure and bending moment. The models for RTP pipes are developed based on the models of steel pipe proposed by Kyriakides and his co-workers. Theoretical analyses of collapse of RTP pipe under short-term hydrostatic external pressure, bending moment, or combined external pressure and bending moment have been presented in this paper. The effects of radius–thickness ratios, initial ovality and initial stresses, pre-buckling deformation and modulus of elasticity have been discussed. Through data fitting, formulas of RTP collapse under pure external pressure, pure bending moment, or combined external pressure and bending moment have been developed. A good agreement between the calculation based on formulas and finite element analysis verifies the efficiency of the formulas.


ABSTRACT: A global–local analysis methodology based on fluid–structure coupling is used to investigate the mechanical responses of both composite and steel risers. Since the design of the riser system can be a daunting task, involving hundreds of load cases for global analysis, semi-empirical fluid load models are considered for the reduced order computations of full-scale riser models. The structural performance of composite risers under real sea current conditions is investigated systematically and discussed with regard to the practical concerns in full-scale settings. The failure envelops of internal liners are found to be within that of the composite layers,
which reveals that the liner is the weakest link for composite riser design. Results show that the composite risers can be more prone to vortex-induced vibration (VIV) due to their lower structural frequencies. In the present study, the composite riser yields 25.5% higher RMS strains than the steel riser. Placement of buoyancy modules along the riser may be critical for the design against VIV, and our results show that the modules are not recommended at the top region of the riser, especially if a top-sheared current is expected. Instead, it is preferable to implement them at the bottom-half portion of the riser and as a continuously buoyed region rather than short discrete buoys separated with gap spaces. Composite risers with different metallic liners are studied, and the titanium liner riser is found to be favourable over the steel and aluminum liner risers.


ABSTRACT: The responses of boat hull bottom panels under slamming loads are studied analytically using a linear elastic Euler–Bernoulli beam as a representation of the cross section of a bottom panel. The slamming pressure is modeled as a high-intensity peak followed by a lower constant pressure, traveling at constant speed along the beam. The slamming response essentially consists of an initial slamming load arriving phase, followed by a vibration phase. The response of the beam is solved analytically. Deflection and bending moment as functions of time and position for different slamming speeds, bending stiffnesses, etc. are given. The response during the two phases are studied and compared. The maximum deflection and bending moment occur approximately when the time it takes for the slamming load to traverse the beam is comparable to the lowest natural period of the beam. At higher slamming speeds the response is less, and the responses do not peak out until after the slam has traversed the beam (i.e., it occurs during the vibration phase). The importance of the leading high-intensity pressure peak often encountered during slamming is also studied. It is seen that a high peak pressure does not necessarily lead to a large structural response, whereas the total load of the peak of the slam does influence the structural response significantly. For relatively slow moving slamming loads, this influence is limited. However, for faster moving loads it can be substantial.

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ABSTRACT: Marine risers are important components operating in offshore oil and gas industry. The vortex-induced vibration design of marine risers requires accurate knowledge of natural frequencies and mode shapes. Free vibration of marine risers are re-examined in this paper by means of variational iteration method, which is relatively new technique capable of dealing with eigenvalue problems rather efficiently. Solutions from the variational iteration method are compared to approximate solutions previously proposed in literatures via a numerical example. Furthermore, validation of the technique is demonstrated by comparing experimentally measured natural frequencies of model marine riser with the predicted ones.
ABSTRACT: The design of horizontal axis wind turbines (HAWT) has faced limitations in size and uncontrollable wind behaviour. Shape-adaptive wind turbine blades are proposed as one of the solutions to these design constraints, as they can improve the performance of the blades under varying operating conditions without increasing the size of the blades. A novel Differential Stiffness Bend–Twist coupling (DSBT) concept is proposed in this paper to control the deformation behaviour of the blades. The DSBT concept achieves bend–twist coupling in the global structure while allowing the main deformation of the structural sub-components to remain in pure bending. By eliminating the need to design bend–twist coupled parts, this simplifies the material design and potentially enhances the manufacturability. An analytical conceptual model was developed to study the fundamental behaviour of DSBT structures under bending loads. The feasibility analysis demonstrated that the DSBT concept could achieve bend–twist coupling by altering the flexural stiffness distribution of stiffeners attached to the skin of the structure. A preliminary design scheme for the DSBT blades was also developed with the material design of stiffeners identified as an area to be optimised. The genetic algorithm (GA) was coupled with the Finite Element Method to search for the optimal flexure stiffness values. GA was reused to evaluate the required composite layup based on the stiffness requirements. Thus the design satisfies the requirements for strength and stiffness to enable DSBT.

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ABSTRACT: A proper numerical simulation method is developed to simulate structure impact problems that consider the effect of strain rate. High-speed tensile tests were carried out to obtain the stress–strain relationships at different strain rates, and these results were used as material inputs to analyze the dynamic response of laterally impacted stiffened plates. The simulation results are compared with falling weight impact experiments, and good agreement was obtained. The stress–strain relationships obtained from high-speed tensile tests and the Cowper–Symonds constitutive (CS) model were compared. Part of the results shows that the curve obtained from the CS model is higher than that obtained from the high-speed tensile test and that with increasing strain rate, the distance will become more pronounced. The numerical simulation is verified and fits the experimental result well. The failure strain is affected by the mesh size in finite element simulation and will decrease with decreasing mesh size. Different mesh sizes for the model can be simulated accurately, once an appropriate material input is obtained. These conclusions can be very useful for studying large-scale impact problems, such as ship collisions and groundings, and can guide engineering applications.

Kyeong-Hoon Jeong and Jong-Wook Kim (SMART Development Division, Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon 305-353, Republic of Korea), “Free vibration analysis of
ABSTRACT: The analytical method to calculate the natural frequencies of an open rectangular container partially filled with water is suggested. The wet dynamic displacements of the U-shaped container are approximated by combining the orthogonal polynomials. The liquid displacement potentials describing the Laplace equation are deduced so that the liquid boundary conditions can be satisfied. The relationship between the structure and liquid is derived by the compatibility requirement using the finite Fourier transform. An eigenvalue problem based on the Rayleigh–Ritz method is derived to extract the natural frequencies of the wet rectangular container. The predictions from the proposed analytical method show an excellent agreement with the finite element analysis results.


ABSTRACT: Understanding the effect a flexible structure has on the loads and responses during slamming events will improve the design process for high speed marine craft. Design of hulls is typically undertaken on the assumption that the pressures applied are the same as if the hull was rigid. In reality the loads may vary due to the hydroelasticity resulting from the fluid structure interaction during the impact. This work characterises the variations in both applied pressure and panel response due to the hydroelasticity. Impacts have been undertaken using a purpose built servo-hydraulic slam testing system with impact velocities up to 6.0 m/s and a deadrise angle of 10°. The unsupported panel area was set at approx 1000×500 mm with simply supported boundaries along all four edges. Clear trends between a panel’s flexibility and the total force and applied pressure have been observed. The changes in both loads and responses are largest at the centre and chine edge of the panel and can be related to the regions of the most significant changes in local velocity (centre) and deadrise angle (chine). Changes in the loads and responses for sandwich constructions can be attributed to the shear stiffness and shear factor as well as the flexural rigidity.

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ABSTRACT: An upheaval buckling solution is proposed using a preheating method combined with constraints from two segmented ditching constructions, which are scheduled before and after preheating. In this solution, some selected pipe segments along the route were curve-laid and preserved resting on the seabed in the first ditching construction, while other straight segments were trenched. The subsequent hot water flushing operation induced the curve-laid segments to buckle on the seabed, and then these prebuckles were laterally constrained by the second ditching operation carried out during preheating. After preheating, the cooling rebound of these prebuckles was constrained by the new trenches, and axial pretension was induced in the pipe wall to offset the axial compression in service and upgrade the thermal stability of the entire pipeline. A detailed design approach is provided in this paper, and corresponding Finite Element Model (FEM) verification is given for an example pipeline.
ABSTRACT: The development of Arctic oil and gas fields requires high strength structures that can resist critical loads in extreme environment. A novel conical caisson structure constructed by lightweight steel–concrete–steel (SCS) sandwich shell is proposed for withstanding ice pressure imposed thereon by impinging sheet ice in Arctic region. This paper mainly investigates the ultimate strength behaviour of SCS sandwich shell experimentally and analytically. Two pilot quasi-static tests on the lightweight SCS sandwich composite shells subject to patch loading are carried out. The failure mode of composite shell is punching shear. Tests show that the punching shear resistance depends on the control perimeter of punched concrete frustum and shear connectors. The membrane action of the outer steel plates provides post-hardening strength. On the basis of the experimental failure mechanism, an analytical model is developed to explain the force transfer mechanism and predict the punching shear resistance of SCS sandwich composite shell. The verification of the model shows that the predictions are in good agreement with the test results. It is also shown that the SCS sandwich shell, in accord with the ISO ice load design, is capable of resisting the localised contact and punching loads.

ABSTRACT: The paper examines the effect of material modeling behavior on the elastic–plastic buckling of relatively thick unstiffened steel cones subjected to axial compression. Cones are assumed to be made from mild steel with radius-to-thickness ratio, \((r_2/t)\) of 34.3 and cone angle of 26.56°. Three material models were considered: (i) elastic-perfectly plastic, (ii) engineering stress–strain and (iii) true stress true strain. The accuracy of numerical predictions as compared to experimental results was seen to be strongly dependent on the material modeling strategy. Plastic mechanism design approach previously proposed for cones under axial compression was modified to widen the range of its applicability by catering for the effect of excessive plastic deformation. The proposed model utilizes the concept of true stress true strain nature of constitutive equation in determining the squash load. Predictions of collapse load given by the modified constitutive model were compared with initial plastic mechanism design approach and available design codes (API, ECCS, and ASME code case 2286-2) for published experimental data on axially compressed unstiffened steel cones in the elastic–plastic range. Results indicate that the proposed model gives much better predictions of load carrying capacity than both the initial design approach and the available design codes.
“Static and dynamic analysis on upheaval buckling of unburied subsea pipelines” Ocean Engineering, Vol. 104, pp 249-256, August 2015, https://doi.org/10.1016/j.oceaneng.2015.05.019

ABSTRACT: Upheaval buckling is one of the most common problems threatening the safe operation of subsea pipelines, which is triggered by the increasing of temperature and inner pressure. In order to predict the critical buckling temperature and post buckling path of upheaval buckling, ABAQUS is used to build four kinds of numerical models, and they are static and dynamic models both in 2D and 3D. Two analysis procedures which combine the static and dynamic processes are applied to aforementioned models. The results show good agreement with existing test data. For snap upheaval buckling, pipelines have two different buckling modes. Such buckling modes are not found in experiments. In addition, only 3D dynamic model can catch such buckling modes. For bifurcation upheaval buckling, predicted buckling temperatures of those models are all acceptable with an error of 5%.

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ABSTRACT: The widespread application of thin cylindrical shells has motivated many researchers to investigate the buckling behavior of such thin-walled structures. Cylindrical shells strengthened by additional external stiffeners, which are also referred to as stiffened cylindrical shells, have been extensively investigated by researchers. However, shell structures stiffened through corrugation, herein referred to as corrugated shell structures, have remained almost untouched as quite a few experimental studies have been reported in this regard. It is important to note that stiffening of thin-walled shell structures through corrugation may result in considerable conservation of material and favorable performance, and hence further studies are required to investigate the buckling stability as well as performance of corrugated shell structures. This paper presents an experimental study on such corrugated thin-walled structures under uniform peripheral pressure. Test results are compared with theoretical predictions and accordingly satisfactory results are obtained. Moreover, different buckling/failure modes are identified and investigated in the current experimental study.


ABSTRACT: The aim of this paper is to quantitatively evaluate the extent of collapse of a bulk carrier when the ship is subjected to extreme wave loads. A hydro-elastoplasticity theory, which was proposed by the present authors and takes into account the interaction between the large elasto-plastic deformation and the wave load evaluation, is applied to the ship’s structure with the assumption that a plastic hinge is formed in the midship region when the hull girder collapses in extreme wave conditions. The dynamic response of the hinge can be expressed by the relationship between the vertical bending moment and the curvature, which are obtained using nonlinear Finite Element Analysis (FEA). A comparative correct moment–curvature curve and a reasonable
load evaluation are necessary for prediction of the severity of the collapse for the actual ship. A bulk carrier hull model with one frame space is constructed and analysed using an arc-length control method (Riks method). The geometric nonlinearity resulting from large deformations and the material nonlinearity are taken into account. The presence of an initial imperfection is considered using the consistent imperfection mode method in the FEA. A prediction of the extent of collapse for a bulk carrier subjected to an extreme wave load is carried out using the hydro-elastoplasticity approach. This analysis clarifies the extent to which the hull girder may collapse in extreme wave conditions at an exceedance probability of 1/1000 in several short-term sea states.

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ABSTRACT: An important consideration in the safe and efficient manufacture and operation of marine structures is the possible distortion, and consequential induced residual stress, owing to welding. This paper deals with welding simulation of a stiffened plate structure with longitudinal and transverse stiffeners using a thermal elasto-plastic FE method. Shell elements with section integration features are adopted to model the plate and stiffeners and solid elements to model the local detail of the weld line region. Linear constraint equations are established between degrees of freedom of the shell and solid elements. Welding parameters of heat input, welding speed and welding sequence are considered in the analysis. A typical fillet-welded joint is studied and the thermal and mechanical results are compared with experimental values. Six welding sequences are simulated. The results demonstrate the specific influences of the different welding parameters on residual distortion and stress in a stiffened plate structure.

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ABSTRACT: The rapid increase in offshore to onshore hydrocarbon transportation has prompted the expansion of subsea pipeline networks to meet energy demands. In offshore platform, unexpected accidents such as fractional dents or fractures may occur in proximity of subsea pipelines due to transverse loading or external forces during operation and installation. Partial damage may cause leaks and oil spills, and in serious cases, the sequence may lead to fire and severe explosions. Meticulous safety measures should consider safety issues and mitigate different extent of risk to the life, environment and assets. To avoid these undesirable events, this study presents a probabilistic and numerical modelling analysis of accidental scenarios to verify the safety of subsea pipelines under different conditions. An impact analysis of transverse loading on a subsea pipeline is performed using scenario sampling and finite element analysis to assess safety measures and mitigate damage by evaluating the effects of impacts in different possible accidental scenarios.
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ABSTRACT: The ring-stiffened toroidal shell is entirely different from the traditional ring-stiffened cylindrical and spherical shells. It has special structurally beneficial characteristics for underwater engineering. A whole welding steel toroidal model with the ring-stiffened ribs has been manufactured, tested until collapse in pressure chamber and analyzed by nonlinear finite element analyses (FEAs). Then the essential cause and collapse mode of this tested ring-stiffened toroidal model have been studied comprehensively by nonlinear FE method. The experimental and numerical results both reveal that the initial geometric imperfection would mainly determine the model's final failure mode, critical pressure and collapse deformation. Further parametric study is made to study the buckling property of ring-stiffened toroidal shell, including failure mode and critical pressure loading by varying the structural parameters. This investigation will lay a good foundation for deriving a theoretical solution for the buckling of ring-stiffened toroidal shell in the near future.

References listed at the end of the paper:

ABSTRACT: With the development of submarine oil and gas resources, research on global pipeline buckling caused by high temperature and pressure in the process of oil and gas transport is becoming an important issue. Owing to human factors or to uneven seabed conditions, local bends are produced in the process of pipeline manufacturing and laying. Those bends are called geometric initial imperfections whose deformation forms can be divided into a single arch symmetric deformation and a double arch antisymmetric deformation. In this paper, the energy method is introduced to calculate the analytical solution of pipeline lateral buckling with a single arch initial imperfection, and the cause of snap buckling phenomenon is discussed. A FEA model is established, and the difference between the analytical solution and numerical solution is also presented.


ABSTRACT: An analytic method is presented to analyze free and forced vibration characteristics of ring-stiffened combined conical–cylindrical shells with arbitrary boundary conditions, e.g. classical and elastic ones. The combined shell is firstly divided into multiple substructures according to the junctions of shell–shell and shell–plate, and/or the location of driving point. Then, Flügge theory is adopted to describe the motions of the cylindrical and conical segments. Instead of adopting the smeared out method and treating the ring stiffeners as beams, the stiffeners with rectangular cross-section are treated as discrete members and the equations of motion of annular plate are used to describe the motion of stiffeners. Power series, wave functions and Bessel functions are used to express the displacement functions of conical segment, cylindrical segment and annular plate, respectively. Lastly, boundary conditions and continuity conditions between adjacent substructures are used to assemble the final governing equation. Results of present method show good agreement with the results in literature and the results calculated by finite element method (FEM). In addition, the influences of boundary conditions and ring stiffeners on the free vibration are studied. The effects of direction of external force and bulkheads on the forced vibration are also discussed.

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ABSTRACT: An effective new approach to nondestructively predict the elastic critical hydrostatic pressure of a submerged eccentric cylindrical shell is presented in this paper. According to the geometry characteristic of the cross section of eccentric cylindrical shell, the eccentric problem is transformed into the problem of variable
thickness in the circumferential direction. The vibration equations considering hydrostatic pressures of outer fluid are written in the form of a matrix differential equation which is obtained by using the transfer matrix of the state vector of the shell. Depending on wave propagation approach, the data of the fundamental natural frequencies of the shell with various eccentricities under different hydrostatic pressure and boundary conditions are obtained by solving the frequency equation with a Lagrange interpolation method. The curve of the fundamental natural frequency squared versus hydrostatic pressure is then drawn with the data, which is approximately straight line or parabola that depends on the eccentric value. The elastic critical hydrostatic pressure is therefore obtained while the fundamental natural frequency is assumed to be zero according to the curve. The results obtained by the present approach show good agreement with published results and finite element results.

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ABSTRACT: This study is interested in adopting a simple way to analyze a dynamic response of beam-like composite sandwich plates with transversely compressible core under time-dependent impulse pressure. A two dimension (2-D) advanced model was proposed for the beam-like composite sandwich plate consisting of anisotropic skins and transversely compressible isotropic core. For validating the structural model developed in the present paper, the frequencies of sandwich panel predicted by the proposed models are compared with the results calculated from the finite element analysis by ABAQUS and the solution by some papers. Finally, the dynamic responses of the sandwich plate in terms of transverse displacements, deformation and stress of the sandwich plate under three kinds of time-dependent pressures (rectangular, delta and steady-state incentive) are discussed.

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ABSTRACT: This study attempts to investigate the effects that external pressure has on the residual stress behavior in a girth-welded duplex stainless steel pipe. At first, FE simulation of the pipe girth welding is performed to identify the weld-induced residual stresses and depressions using sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. Then, 3-D elastic–plastic FE analysis is carried out to evaluate the residual stress redistributions in the girth-welded pipe under external pressure. The residual stresses and plastic strains obtained from the thermo-mechanical FE simulation are employed as the initial condition for the analysis. The FE analysis results show that the hoop compressive stresses induced by the external pressure significantly alter the hoop residual stresses in the course of the mechanical loading, i.e. the hoop residual stress
distributions on both surfaces of the pipe weld shift downward considerably, whilst the axial residual stresses are little affected by the superimposed external pressure.

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ABSTRACT: Upheaval buckling behavior of submarine pipelines under high temperature and high pressure conditions is a primary concern for structural integrity. The critical axial force is a key factor governing the buckling behavior. There have been already some formulas to calculate critical axial force for some particular initial imperfection shapes. However, there is no universal formula to express the effects of initial imperfection shape and Out-of-Straight (OOS) on the critical axial force. In this paper, the upheaval buckling behaviors of eight groups of pipeline segments with different imperfection shapes and different OOS have been studied using the finite element method. A new parameter is defined to express the differences of imperfection shapes. An approximation and universal formula is proposed to calculate the critical axial force which covers the new parameter and the OOS of pipeline. A case study is presented which illustrates the application of the formula. Finally, comparison between this study and previous research results is conducted, and it manifests that this formula has a greater precision.

ABSTRACT: This paper deals with the shortcomings in current design methods for dynamically loaded composite structures in underwater applications. This is done through an experimental study to evaluate the eigenfrequencies of rectangular plates made from metals as well as composites that are tested in air (dry) and completely submerged under water (fully wetted). The eigenfrequencies are studied using forced vibrations. The test series comprises 19 specimens that are made from various materials including aluminium, steel, glass-fibre, and carbon-fibre with aspect ratios varying from 3.7 to 11.2 and breadth to thickness ratios ranging from 2.7 to 20.5. The test method is based on electro-mechanical excitation by random vibrations as well as stepped sine refinements in the vicinity of the identified eigenfrequency. The results clearly show how differently the specimens are affected by the “added mass” from the water when fully wetted compared to the dry condition. Slender and more lightweight configurations are more profoundly affected by water than heavier and more rigid specimens. The results clearly show that for advanced composite materials and more complex geometries the current rule-of-thumb methods used by the industry today are inadequate in predicting the shift in natural frequency due to the effect of the surrounding water.

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ABSTRACT: When a flexible pipe is subjected to high external hydraulic pressure, the innermost carcass layer serves to resist buckling and collapse. The maximum external pressure that the carcass layer can withstand before buckling collapse must be considered during pipe design. To study this problem, a strain energy equivalence method is proposed to transform a representative volume element (RVE) of the carcass layer, which has a complex geometry, into a homogeneous shell with an equivalent thickness. To obtain the strain energy, a finite element model of the RVE is developed, and the analytical equations for the homogeneous shell are derived for the same uniform-strain boundary conditions. Radial compression tests on three different carcass layer test pieces are performed to verify the safety and effectiveness of the proposed equivalence method. The strain energy equivalence method is found to give conservative results when compared to other equivalence approaches. The advantages of the method for designing a collapse-resistant carcass layer in engineering practice are also discussed.

ABSTRACT: Fiber reinforced plastics (FRP) panels are extensively used in ship structures due to their superior specific stiffness and strength as compared to metals. However, their prolonged use may result in degradation of material properties as well as the boundary conditions; thus, affecting the dynamic performance. Moreover, the changes in material properties are mostly at constituent level, i.e. fiber or matrix. A vibration based inverse identification technique is proposed using finite element model updating to estimate the constituent elastic material parameters of FRP panels having elastically restrained boundary. The objective function is formed from the difference of experimental as well as finite element prediction of dynamic responses. A gradient based optimization viz. the inverse eigensensitivity method is implemented. A set of numerically simulated examples is presented to demonstrate that the prediction of material parameters can be grossly erroneous if the boundary elasticity is overlooked. The algorithm is found to be robust even when the ‘experimental’ data is sparse and contains random noise. The method can be used for condition assessment and damage detection of FRP ship panels. The technique is novel as for the first time constituent level elastic parameters of FRP panels having elastic boundaries are estimated from dynamic responses.

ABSTRACT: The dynamic response of offshore pipelines induced by deepwater S-lay is highly noticeable, and directly dominates the design of such structures and the installation feasibility in practice. A comprehensive finite element model for deepwater S-lay systems using the software OrcaFlex is specially developed to explore the influences of sea state on the pipeline dynamic responses, considering surface waves, ocean currents, pipelay vessel motions, clashing contact between the pipeline and rollers. Meanwhile, a non-linear hysteretic soil model is applied to simulate the vertical pipe–seabed interaction, and the modified Coulomb friction model is used to model the lateral pipe–seabed interaction. The numerical model is then used to carry out an illustrative example analysis of a 12-in. gas export pipeline being laid onto the seabed with a water depth of 1500 m using the HYSY 201 pipelay vessel in the LW3-1 gas field in the South China Sea under various sea
states. The influences of sea state on the pipeline dynamic behaviour on aspects of configuration, lateral displacement, axial tension, bending moment, stress and strain as well as pipeline embedment are estimated quantitatively. The findings show that a strong relevance exists between surface wave and resulting pipelay vessel motions, and pipeline dynamic responses.

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ABSTRACT: Exploration of deeper oceans for oil and gas requires increasingly lightweight solutions. A key enabler in this aspect is the use of fiber-reinforced composite materials to replace metals in risers. However, design synthesis and analyses of composite risers are more challenging than for conventional metals due to the complex behavior and damage mechanisms which composite materials exhibit. Composite risers are predicted to be a high-impact technology that will be mainstream in the medium term but there is still relatively little literature pertaining directly to the behavior of these materials under the complex loading scenarios arising from their use in deep water structures. Therefore there is a need to perform a review and assessment of the available technologies and methodologies in the literature to gain a good understanding of their predictive capabilities, efficiency and drawbacks. This article provides a comprehensive review of published research on manufacture, experimental investigations and numerical analyses of composite risers in deepwater conditions determining the gaps and key challenges for the future to increase their application.

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ABSTRACT: Inflatable Offshore Fender Barrier Structures (IOFBS) are anti-terrorist security structures that function primarily to either stop terror bound vessels from reaching valuable offshore structures, incapacitate its crew or delay the vessel’s progress until secondary security measures can be put in place. In this study, an advanced and efficient modelling method for impact simulation of the structure and similar multi-physics systems is presented. Numerical implementation of this modelling technique, using Abaqus finite element code is described and used in the impact simulation of the inflatable structure based on its current design as well as an alternative design of the structure. Results from the two designs provisions were compared and from these results, recommendation for improvement of the current design is also reported. This is desirable in ensuring high reliability in application of the structure in meeting its design objectives.

ABSTRACT: A three-dimensional nonlinear finite element model was developed to simulate the welding process of extruded and non-extruded aluminum tee-bar stiffened plates joined together by friction stir welding (FSW), metal inert gas (MIG) butt and MIG fillet welding. The three-dimensional residual stress and distortion fields as well as the heat affected zones (HAZ) for all three welding methods were obtained and compared. The load-shortening curves for stiffened plates and the ultimate moment capacity of a hull girder made up of the stiffened plates were analyzed. The results showed that MIG welding resulted in tensile and compressive residual stress of as much as 88% and 30% of the material yield strength, and a considerable level of distortion while residual stresses and distortions formed in the friction stir welding model were negligible. The load-shortening responses showed that extruded stiffened plates joined by FSW attained a 26% higher buckling load than the non-extruded stiffened plates joined by MIG fillet welding, which in turn resulted in a 28% higher ultimate moment capacity of the hull girder fabricated using FSW on extruded elements. The results also indicated that the presence of the residual stress and HAZ had the most significant effect on hull girders fabricated by MIG fillet welding on non-extruded plates where respective reductions of 10.5% and 7.5% in the ultimate moment capacity of the hull girders as a result of residual stresses and HAZ were observed.

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ABSTRACT: Stiffened composite panels are primary structural components in ship, aircraft and aerospace vehicles. The main objective of this study is to investigate the behavior of glass fiber reinforced polymer (GFRP) composite panels with stiffener runout condition and different stiffener configurations such as blade, T and hat under axial compression. A special fixture was designed and fabricated for the compressive testing of GFRP composite stiffened panels. Fabricated specimens were tested until failure and the effect of different stiffener configurations on the load–deformation behavior is compared. Digital image correlation (DIC) was used to measure the deformations and strains on the GFRP composite panels. Test results indicated that T-stiffeners performed well with higher failure load and stiffness as compared to other stiffeners. DIC results show that the presence of stiffeners reduced the out-of-plane displacement in the stiffened panels. As the load level increases, damage initiates and propagates. The surface strain and displacement are sensitive to damages and it can alter their distribution. This could be captured using DIC technique as the damage distribution takes place. The T-stiffeners were found to be effective in resisting bending strains and produced more uniform distribution of compressive strain compared to other stiffener configuration.

ABSTRACT: This work investigates the residual structural capacity of experimentally tested steel plates with a large central ellipsoidal opening with and without locked cracks, subjected to uni-axial compressive load. A series of experimental tests have been carried out. The tested plates were a part of a real box structure, which represents a scaled midship section of single hull tanker ship, exposed to a corrosive seawater environment. A plate with one large opening with different crack lengths is analysed. The influence of the combined effect of the plate opening and different crack lengths on the residual strength is investigated. The experimental results; force–displacements relationships, dissipated energy, stress–strain relationships, resilience and toughness are presented and analysed. The stresses at particular locations along the plate specimens are estimated and analysed. Several collapse modes are observed and discussed. The experimental results of the tested specimens have been compared with other test results for plates with different opening sizes, confirming the significance of the combined effect of an opening with simultaneous locked cracks on the local and global structural behaviour.

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ABSTRACT: Buckling of composite riser assumed beam structure is one of numerous engineering challenges in deep water pipeline design. Thermal postbuckling analysis of shear deformable anisotropic laminated composite beams with tubular cross-section subjected to uniform, linear and non-linear temperature distribution through the thickness resting on a two-parameter elastic foundation is presented. The material of each layer for the composite beam with tubular section is assumed to be linearly elastic and fiber-reinforced. The governing equations are introduced by using high-order shear deformation beam model with a von Kármán-type of kinematic nonlinearity. Composite beams with clamped–clamped, clamped–hinged, and hinged–hinged boundary conditions are considered. A numerical solution for nonlinear partial-integral differential form in terms of the transverse deflection by using Galerkin’s method is employed to determine the buckling temperatures and postbuckling equilibrium paths of anisotropic laminated beams with different types of temperature distribution through the thickness. The numerical illustration concern the thermal postbuckling response of laminated beams with different types of boundary conditions, ply arrangements (lay-ups), geometric and physical properties. The results reveal that the geometric and physical properties, temperature dependent properties, initial geometry imperfection, boundary conditions and elastic foundation have a significant effect on thermal postbuckling behavior of anisotropic laminated composite tubular beams.


ABSTRACT: The aim of present work is to investigate the effects of uniform in-plane loads on vibratory characteristics of symmetrically cross-ply laminated composite plates on elastic foundation and vertically in
contact with fluid based on the first order shear deformation theory. The fluid is assumed to be ideal, incompressible and inviscid with small amplitude motion and the effects of hydrostatic pressure and free surface waves are negligible. The fluid domain is considered to be finite in depth and width but it is infinite in length direction. The Rayleigh–Ritz method is applied to derive the eigenvalue equation of the fluid–plate system and Chebyshev polynomials multiplied by a boundary function are adopted as the admissible functions in the procedure. The accuracy of the proposed method is examined via comparison studies with the available data in the literature. The effects of different parameters on natural frequencies such as, thickness-span ratios, aspect ratios, fluid depth ratios, load intensities, elastic foundation coefficients and various types of in-plane loads and boundary conditions are discussed in tabular and graphical forms.

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ABSTRACT: The ultimate strength of the hull structural plates is degraded due to pitting corrosion on the surface of the plates. This report aims at development of an assessing formula for ultimate strength of hull plate with pitting corrosion damage under combined loading. Firstly, the qualitative expression was deduced in theory. Secondly, the effects of a few factors (such as the shape, the distribution status and the depth of corrosion pits and the element type for finite element method analysis) on the ultimate strength with respect to the corroded volume loss were investigated. The influences of some parameters (such as the plate slenderness ratio, the plate aspect ratio, the linear load factors at the edges, the ratio between the transverse and longitudinal in-plane stresses, the ratio between the shear and longitudinal in-plane stresses and the maximum deflection of the initial geometric imperfection) on the ultimate strength reduction with respect to the corroded volume loss were also discussed. Lastly, the ultimate strength assessment formula based on the corroded volume loss was obtained from the data by non-linear FEM analyses for series of corroded plate models that were in accord with the actual hull plates with pitting corrosion damage.


ABSTRACT: In this paper, a pipe element is developed for a pipe structure with variable wall thickness. The variable wall thickness field t-sub-w can be an arbitrary function about circumferential and axial directions. A local dimensionless cylindrical coordinate system is set up. The displacement expression is defined based on the local dimensionless cylindrical coordinate system. The map from the local dimensionless cylindrical coordinate system to the pipe structure configuration is established. In the circumferential and radial dimensions, the series is used as the displacement basis functions. In the axial direction, Lagrangian interpolation is applied. Furthermore, the referential surface R can also be defined as an arbitrary function about circumferential and axial directions as t-sub-w. Thus, this pipe element has wide applications. The complicated problems with geometrical nonlinearity (large deformation and finite strain) can be analyzed well by this element. The pipe buckle crossover problem is analyzed in this paper. In this problem, the pipe model has an axially variable wall thickness field. The eccentric pipe collapse problem is also analyzed. In this problem, the pipe model has a
circumferential variable wall thickness field. The results are compared with those from other well-established FEM simulations.

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ABSTRACT: This paper studied ultimate strength behaviour of Steel–Concrete–Steel (SCS) sandwich plate under concentrated loads. Eight square SCS sandwich plates were simply supported and tested to failure under concentrated loads. The investigated parameters included strength of the core material, thickness of the steel skin plate, content of the steel fibre in the core, size of the loading area, and different type of the fibre. Test results showed that SCS sandwich plate exhibited two peak resistances that benefited from the tension membrane action of the top steel skin, which behaved differently from reinforced concrete structures. The influences of different parameters on ultimate strength behaviours of SCS sandwich plate have been analysed and discussed. On the basis of the experimental studies, analysis and discussions, theoretical models were developed to predict the ultimate resistances of the SCS sandwich plate under concentrated loads. The developed models considered the punching shear resistance of the top steel skin plate, modified the resistance contributed by the headed studs, adopting proper critical perimeter for the punching cone, and developing formulae for the second peak resistance. The analytical models were observed predicting well the ultimate resistances of the SCS sandwich plates.


ABSTRACT: In the present paper the effect of the nonlinear vertical wave-induced bending moments on the ship hull girder reliability is evaluated. A chemical tanker for which the nonlinearity of the vertical wave-induced bending moments was found to be significant is adopted as case study. The nonlinear effects on the vertical wave-induced bending moments of the chemical tanker are accounted for in the reliability assessment problem through model correction factors, which are estimated using direct calculation methods based on linear and nonlinear strip theory formulations and the most likely response wave method. It is verified that the design formulation presently used to define the hull girder vertical wave-induced bending moments underestimates the magnitude of the nonlinear effects. The more accurate predictions provided by the direct calculations methods show that the actual hull girder reliability in sagging is significantly smaller. Possible modified design solutions for the midship cross-section of the chemical tanker are evaluated in order to demonstrate the impact of the increase of the nonlinear vertical wave-induced bending moment in sagging in terms of structural design criteria.
ABSTRACT: This study proposes the concept of subsea production systems with a seabed storage tank to provide an alternative to conventional floating facilities and performs the reliability, maintainability and availability study for the seabed storage tank. The reliability assessment of the seabed storage tank performs a four-step procedure. A four-step procedure is to define the system boundary, collect the reliability data, construct a fault tree and estimate the reliability. The failure and repair data are obtained from the component of the lowest level of the seabed storage tank because the seabed storage tank is a new system without reliability data. Reliability of the seabed storage tank is estimated with a consideration of critical events. The total failure frequency of the SST is estimated approximately $2.27 \times 10^{-4}$/hour. The maintainability analysis is estimated in accordance with MIL-HDBK 472 Procedure V. The elements of repair time is obtained from the subsea JIP 2000 and RAM study of field data. Active repair time from OREDA 2009 is regarded as the repair/replace of repair time elements. The total repair time is mainly affected by the preparation time of repair time elements. The system availability for the seabed storage tank under normal operation is calculated as approximately 91.8%.

ABSTRACT: This paper numerically deals with the ultimate strength reduction characteristics of steel plate due to crack damage under longitudinal compression. A series of nonlinear finite element analyses was carried out with varying the length, location, and orientation angle of cracks to examine their effects on the ultimate strength of cracked steel plates. Three types of cracks, namely transverse crack, longitudinal crack and inclined crack, are considered in the present study. It was assumed that the cracks are through-thickness, having no contact between their faces and propagation of cracks is not considered in the present study. It is found that the minimum and the maximum ultimate strength values are obtained for the transverse crack and longitudinal crack cases respectively when the crack length is constant. The projected length of the crack normal to loading direction is an influential parameter to the ultimate compressive strength of plate with central inclined crack. Based on the numerical results, simple empirical formula as a function of crack projected length are proposed to predict the ultimate strength of plate with central inclined crack under longitudinal compression.

ABSTRACT: This paper presents a highly efficient small-scale, detailed finite-element modelling method for flexible risers which can be effectively implemented in a fully-nested (FE²) multiscale analysis based on
computational homogenisation. By exploiting cyclic symmetry and applying periodic boundary conditions, only a small fraction of a flexible pipe is used for a detailed nonlinear finite-element analysis at the small scale. In this model, using three-dimensional elements, all layer components are individually modelled and a surface-to-surface frictional contact model is used to simulate their interaction. The approach is applied on a 5-layered pipe made of inner, outer and intermediate polymer layers and two intermediate armour layers, each made of 40 steel tendons. The capability of the method in capturing the detailed nonlinear effects and the great advantage in terms of significant CPU time saving are demonstrated by comparing the results obtained on elements of pipe of different lengths, equal to one pitch length \( L_{\text{sub-p}} \) as well as \( L_{\text{sub-p}/5}, /20 \) and /40.

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ABSTRACT: This paper provides a brief literature review on dynamic behavior of liquid storage containers. Moreover, the free vibration of two-dimensional deformable rectangular tanks fully-filled with a compressible fluid is analytically investigated, and the exact solutions are derived. In this study, the fluid-structure interaction is rigorously considered, and the fluid is assumed to be irrotational, inviscid and compressible. Furthermore, a closed-form expression is introduced for evaluating the fundamental frequency of the flexible 2D rectangular tanks filled with compressible liquid. In addition, an approximate formula is suggested to determine the corresponding pressure distribution on tank walls. Finally, numerical examples are performed to verify the presented closed-form relations. To study the effect of various parameters on natural frequencies and mode shapes of the fluid-structure system, a sensitivity analysis is also conducted.

Rouzbeh Hashemian and Magdi Mohareb (Department of Civil Engineering, University of Ottawa, Ottawa, ON, Canada K1N 6N5), “Finite difference model for the buckling analysis of sandwich pipes under external pressure”, Ocean Engineering, Vol. 122, pp 172-185, August 2016, https://doi.org/10.1016/j.oceaneng.2016.06.003

ABSTRACT: A general eigenvalue buckling solution is developed for the buckling analysis of sandwich pipes with thick cores subjected to internal and external hydrostatic pressure. The formulation accounts for shear deformation effects and involves two destabilizing terms: one is due to the external hydrostatic pressure and incorporates the follower effects, and the other, is due to the pre-buckling stresses undergoing the nonlinear components of strains. Work conjugate triplets consisting the Cauchy stress tensor, the Green-Lagrange strain tensor, and constant constitutive relations are adopted in the formulation. The principle of stationary potential energy is used to formulate the conditions of equilibrium and neutral stability conditions using polar coordinates. A finite difference solution is developed and implemented in MATLAB and then applied to predict the buckling capacity of sandwich pipes consisting of two steel pipes with a soft core. A comprehensive verification study is conducted, and the validity of the formulation is established through comparison with other solutions. A parametric study is then carried out to investigate the effect of internal pressure, the thickness and material properties of the core, internal and external pipe thicknesses, on the buckling of sandwich pipes. Simple design equations are developed to predict the critical pressure of sandwich pipes.

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ABSTRACT: Safety of crew, ship and cargo requires that ships are designed to endure wave load extreme events. Design values are often based on univariate statistical analysis, while actually multivariate statistics is more appropriate for modeling the whole structure. This paper studies extreme stresses simultaneously measured at two different deck locations of a container vessel operating in the North Atlantic between Europe and North America. The focus is placed on the hydroelastic structural response, particularly whipping, which refers to transient vibratory response of the hull girder due to wave impacts occurring mainly in the bow area. It must be noted however that since analysed in this paper vessel hydroelastic response is a on-board measured one, it includes all non-linear effects like both whipping and springing. Due to less than full correlation between stresses in the different ship panels, application of the multivariate, or bivariate in the simplest case, extreme value theory is of interest. Due to non-stationarity and complicated nonlinearities of the wave induced loads, as well as the human factor in the operation of ships, reliable numerical prediction of extreme hydroelastic vessel responses, including whipping, is challenging. Laboratory tests and numerical simulation tools may not fully reproduce all critical conditions that take place during real vessel operation. Therefore, measurements on-board of real ships provide a key insight into the structural responses when the vessel is at sea. This paper focuses on application of the ACER (average conditional exceedance rate) method for prediction of extreme value statistics extended to the case of bivariate time series. Application of bivariate version of ACER method is demonstrated for simultaneously measured stresses at mid and aft deck locations.

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ABSTRACT: A double-wall steel-concrete-steel (SCS) composite vault has been proposed for the “Singapore Cone” Arctic offshore structure. The SCS vault performs well under uniform pressure, but can fail prematurely under partial asymmetric loading. These shells will often experience a punching shear failure or flexural steel plate buckling which is exacerbated by the loss of bond between the steel wall and concrete interface. In this study, a construction friendly method using an array of welded mini studs to improve the steel–concrete interfacial bond is proposed and studied. Two workable Type I Portland cement grout mixes are tested as the bulk material: plain, and fiber reinforced. Studded concrete steel interfaces were tested under mode I interface peeling, and mixed mode shear. The small scale tests were also modeled with the nonlinear finite element analysis software ABAQUS, and the numerical results were compared against the laboratory experimental results. After qualitatively matching the computational results with experimental results, a large scale SCS prototype is modeled and designed, with working stresses limited to the elastic range. Mode I peeling ultimate strength of 0.46[\sqrt{f_{sub-c}}] was used for the prototype analysis, with mixed mode shearing limited by bulk concrete away from the studded bond surface.

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ABSTRACT: Stiffened panels are basic constitutive members of ships and offshore structures, and in practice they often have different mass and stiffness attachments, which significantly influence their dynamic response. In this paper, a numerical procedure is presented for the free vibration analysis of stiffened panels with arbitrary sets of boundary conditions and carrying multiple lumped mass and stiffness attachments. It is based on the assumed mode method, where characteristic orthogonal polynomials having the properties of Timoshenko beam functions and satisfying the specified edge constraints are used as approximation functions. The Mindlin theory is applied for plate and the Timoshenko beam theory for stiffeners. The total potential and kinetic energies of the system are formulated in a convenient manner and further applied to derive an eigenvalue problem by means of Lagrange's equation of motion. Based on the developed numerical procedure, an in-house code is developed and is applied to a free vibration analysis of bare plates and stiffened panels carrying lumped masses and locally supported by pillars or springs. Comparisons of the results with those available in the literature and FEA solutions confirm the high accuracy and practical applicability of the presented procedure.

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ABSTRACT: Thick-walled steel pipes during their installation in deep water are subjected to combined loading of external pressure and bending, which may trigger structural instability due to excessive pipe ovalization. In the case of reeling installation method, prior to deep-water installation the pipe is subjected to cold forming associated with strong cyclic bending on the reel, resulting in the development of initial ovalization and residual stresses, which may affect the pipe structural performance. Using advanced material models and finite element tools, the present study examines the effect of cyclic loading due to reeling on the mechanical behavior of thick-walled seamless steel pipes. In particular, it examines the effects of reeling on cross-sectional ovalization and the corresponding material anisotropy and, most importantly, on pipe resistance against external pressure and pressurized bending. The results show that cyclic bending due to the reeling process induces significant anisotropy and ovalization on the pipe. It is also shown that the mechanical resistance of reeled pipes is lower than the resistance of non-reeled pipes, mainly because of the resulting cross-sectional ovalization at the end of reeling process.

ABSTRACT: A three-dimensional analytical model is presented to calculate the stress and deformation of a sandwich pipe (SP) system subjected to linearly varying external pressures. Based on a stress function method, an analytical solution for a thick-walled pipe was researched, and then an analytical solution for a SP system was obtained according to the boundary and continuity conditions of stress and displacement. Furthermore, the analytical solution of a SP system was verified by comparing with finite element method (FEM). The results indicate that the stresses from present method (PM) are in a good agreement with that from FEM. Finally, our researches provide a benchmark for approximate or numerical solutions, and are beneficial to evaluate the safety and integrality of SP systems.

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ABSTRACT: In this paper we describe and evaluate an isogeometric finite element program, IFEM-FSI, for doing coupled fluid–structure interaction simulations. We investigate the role played by employing higher polynomial orders and higher regularity for solving a well known benchmark problem for flow past a circular cylinder with an attached flexible bar at Reynolds number \( Re = 100 \). Furthermore, we investigate the sensitivity to resolution in the fluid mesh as well as stiffness distribution in the mesh movement algorithm. Mesh quality is also assessed. Our simulations indicate that quadratic and cubic spline elements give better estimation of lift, drag and displacements than linear spline elements.

Luyun Chen, Xiaofeng Liang and Hong Yi (State Key Laboratory of Ocean Engineering, Shanghai Jiaotong University, Shanghai 200240, China), “Vibro-acoustic characteristics of cylindrical shells, with complex acoustic boundary conditions”, Ocean Engineering, Vol. 126, pp 12-21, November 2016, https://doi.org/10.1016/j.oceaneng.2016.08.028

ABSTRACT: The structural–acoustic radiation problem of cylindrical shell structures with complex acoustic boundary conditions is investigated in the present study. The structural–acoustic radiation problem of a cylindrical shell is solved by using the double reflection method, in which the acoustic boundary conditions consist of a free surface and a rigid wall surface. The expression of the acoustic radiation function is also derived for cylindrical shell structures in a quarter-infinite acoustic domain. Finally, the influence of the acoustic radiation power and the acoustic directivity caused by the acoustic boundary characteristics, the acoustic source location, and the radiation frequency in a thin cylindrical shell structure is discussed. Thus, the results provide a new method to analyze the acoustic radiation problem with complex acoustic boundaries.

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ABSTRACT: Vibrations in marine offshore marine structures, due to various environmental loads, can reduce platform productivity, endanger safety, affect serviceability of the structure and have been attributing factors in several major accidents and failures in the marine and offshore industry over the last few decades. Controlling the vibrations in marine offshore structures potentially due to self-excited nonlinear hydrodynamic forces, large deformations and highly nonlinear responses, is challenging. While general vibration control strategies have been investigated and demonstrated to be effective for structural vibration mitigation, there currently is limited research highlighting the specific methods available for design engineers and researchers concerned with vibrations of marine offshore structures. This paper provides a review of vibration control techniques and their application for marine offshore structures. Initially, a review of the general approaches following the conventional categorization of passive, active, semi-active and hybrid is presented. This is then followed by a review of the specific marine offshore vibration control methods and a comparison of the approaches. The marine offshore structures considered in this review include jacket structures, tension leg platforms (TLPs), spar structures, floating production storage and offloading vessels (FPSOs) and riser structures. It can be found that the general trend is progressing towards semi-active and hybrid vibration control from passive or active control, as they provide more practical approaches for implementation, possessing the advantages of passive and active control systems.


ABSTRACT: A semi-analytical method is present to analysis the vibration response of submerged stiffened combined shells. In general, the submarine hull can be modeled as submerged stiffened combined conical-cylindrical-spherical shells. The precise integration method is imported to develop a precise transfer matrix method (PTMM). The dynamic model is established to solve the dynamic responses of the combined shell in vacuo. The fluid load is described by wave superposition method (WSM). Then the structural responses of a submerged stiffened submarine hull can be obtained by coupled PTMM and WSM method. The effectiveness of the present method has been verified by comparing the frequency parameters of the combined shells and the structural responses of the submerged spherical shell with existing results. Furthermore, the effects of the model truncation, stiffness, damping and fluid load on the structural responses of the combined shells are studied.

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ABSTRACT: Offshore platforms in deep seas require extremely long large diameter pipe piles (LDPPs) to support the loads generated from the structure itself, wind and waves. One of the construction issues related to the installation of a LDPP into a seabed is pile running. Unexpected pile running during the LDPP driving process may break the steel wires connected to the heavy hammer or may cause the loss of the hammer into the sea. An analytical method to predict the occurrence of pile running is proposed in this paper. The framework for determining the calculation parameters from a laboratory or field test are established. The dynamic resistance of the surrounding soil during the pile driving process is considered through analysis of the soil sensitivity and the induced excess pore water pressure. Three case studies were conducted to verify the accuracy of the proposed method. Good agreement indicated that the proposed method is capable of predicting pile running during the driving process of LDPPs in layered soil deposits.

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ABSTRACT: This study aims to characterize numerically the ratcheting behavior of a girth-welded straight stainless steel pipe in combined action of internal pressure and cyclic bending loading. Finite element (FE) thermal simulation of the girth butt welding process is first performed to identify weld-induced residual stresses. Three-dimensional (3-D) elastic-plastic FE analyses incorporated with the cyclic plasticity constitutive model capable of describing the cyclic plastic performance are next conducted to scrutinize the local (circumferential strain) and global (cross-section diameter change) ratcheting responses of the girth-welded stainless steel pipe under internal pressure and cyclic bending, which take the residual stresses and plastic strains obtained from the preceding thermal simulation as the initial condition. The analytical results demonstrate that welding residual stresses in combination with the internal pressure have significant effects on the hoop strain rate and the in-plane and out-of-plane diameter changes, and the degree and shape of the ovalization which occurs during the multiaxial ratcheting are dependent on the applied loads.


ABSTRACT: Composites are an attractive material for pressure hulls because of their high strength and low density. This paper presents a history of composite pressure vessel hull development over the last 50 years and uses the lessons learnt, to develop a composite pressure hull concept for a shallow diving hull, or buoyancy device. This is done by evaluating several concepts modelled using Finite Element Analysis for weight and other criteria. A converged solution is developed and further analysed for sensitivity to geometric imperfections. These imperfections are shown to have a significant effect on the collapse depth of the composite pressure hull.

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ABSTRACT: In this paper a linear, closed-form analysis of the buckling behavior of an orthotropic plate with elastic clamping and edge reinforcement under uniform compressive load is presented. This is a typical structural situation found in aerospace engineering for instance as stiffeners in wings or the fuselage. All governing equations are transformed in a dimensionless system using common characteristic quantities to gain good analytical access. The buckling behavior is analyzed and generic buckling diagrams are presented. The solutions show excellent agreement with results from literature and numerical analyses. The minimum bending stiffness of the edge reinforcement needed to withstand buckling is examined and a minimum stiffness criterion is presented. Furthermore an absolute minimum bending stiffness is found which is sufficient to enable the reinforcement to act as a near-rigid support for arbitrarily long plates. These criteria are of interest for optimized lightweight design of stringers and stiffeners.

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ABSTRACT: A deployable space antenna has a deployment mechanism which has high precision and reliability. The articulated mechanism is able to alter its configuration without failure from a compact to deployed shape to meet specific operational requirements. Consequently, the analysis of the dynamic characteristic of the deployment mechanism must be done at an initial design stage. In this paper, the kinematic, dynamic analysis and control methods to predict the deployment motions of the hoop truss deployable antenna are presented. First, the general model of deployment kinematic analysis is established. The model can be applied to carrying out the position, velocity and acceleration analysis of any point on the structure. Second, the dynamic model for the hoop truss deployable antenna is established based on the Lagrange method in multibody dynamic systems and using absolute generalized coordinates, which takes into consideration the dissipative force, torques of torsional springs in hinges and the pretension forces in nets. The force-controlled method is presented to control the deployment motion, and the relation between the driving force and the deployment motion is derived. The variation of the driving force is obtained according to the planned deployment motion. The deployment dynamics of the hoop truss deployable antenna is simulated, and the effects of initial velocity, damping and gravity upon deployment are summarized. Deployment dynamic analysis and control of the hoop truss deployable antenna are carried out taking into account the stiffness of torsional spring, damping in joints, gravity and the pretension forces in nets. The results of simulation experiment validated the proposed method.

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ABSTRACT: In this study, the thermal flutter characteristics of an imperfect cantilever plate under aerodynamic loads are investigated. The plate is assumed to be rectangular and functionally graded (FG). The plate is modeled based on first-order shear deformation theory (FSDT), and the Von-Karman strain-displacement relations are used to model the geometric nonlinearity. Geometric imperfections are modeled as strain energy, which causes a reduction in the structural stiffness. The quasi-steady first-order piston theory is used to model the aerodynamic pressure due to supersonic flows. The effects of geometric imperfections, the volume fraction distribution, the temperature gradient, aerodynamic pressure and the aspect ratio on cantilever plate flutter characteristics are investigated.


ABSTRACT: The severe weight limitations of flapping wing micro air vehicles necessitates the use of thin flexible wings, which in turn requires an aeroelastic modeling tool for proper numerical characterization. Furthermore, due to the unconventional nature of these vehicles, wing design guidelines for thrust and/or power considerations are not generally available; numerical design optimization then becomes a valuable tool. This work couples a nonlinear shell model to an unsteady vortex lattice solver, and then computes analytical design gradients: the derivative of aerodynamic force/power quantities with respect to a large vector of thickness variables. Gradient-based optimization is then used to locate the wing structure that maximizes the thrust, or minimizes the power under a thrust constraint, for a variety of shell boundary conditions. Changes in the topological features of the optimal wing thicknesses highlight important aeroelastic interactions that can be exploited for efficient flapping wings.


ABSTRACT: In this paper, the buckling behavior of thin-walled GFRP cylindrical shells with triangular lattice patterned reinforcements formed by helical and circumferential ribs under axial force is analyzed. In this analysis, various models of composite isogrid stiffened cylindrical shells with outer diameter of 150 millimeters, shell thickness of 0.5 millimeters and height of 280 millimeters, stiffened with 6 helical and 2 circumferential ribs and all with the same material properties of shell and ribs are used. Ribs have constant section areas but different shapes and cross section profiles. The effects of these differences on buckling strengths of structures under axial load are studied. For analysis and modeling of structures, Finite Element Analysis method and ANSYS software were used. The results (elastic buckling load) for each model were derived and based on these results, ratio of buckling strengths to weight parameters were calculated for each model and were compared to results obtained from other models. The effect of profile of the ribs on the buckling of shells under axial loading can be concluded from the results. Results showed that stiffening the shells increased the buckling load from 10% up to 36% while decreased the buckling load to weight ratio to 42% up to 52% of an unstiffened shell.
ABSTRACT: A refined trigonometric shear deformation theory (RTSDT) taking into account transverse shear deformation effects is presented for the thermoelastic bending analysis of functionally graded sandwich plates. Unlike any other theory, the number of unknown functions involved is only four, as against five in case of other shear deformation theories. The theory presented is variationally consistent, does not require shear correction factor, the displacement components are expressed by trigonometric series representation through the plate thickness to develop a two-dimensional theory and gives rise to transverse shear stress variation such that the transverse shear stresses vary parabolically across the thickness satisfying shear stress free surface conditions. The sandwich with homogeneous facesheet and FGM core is considered. Material properties of the present FGM core are assumed to vary according to a power law distribution in terms of the volume fractions of the constituents. The influences played by the transverse shear deformation, thermal load, plate aspect ratio, and volume fraction distribution are studied. Numerical results for deflections and stresses of functionally graded metal–ceramic plates are investigated. It can be concluded that the proposed theory is accurate and simple in solving the thermoelastic bending behavior of functionally graded plates.

ABSTRACT: A method is presented here for modeling and predicting the rolling and yaw behavior of an aircraft tire which is subjected to a strong inflation pressure and a concentrated load on the axle, in contact with a flat, rigid surface. Finite element methods were used to model and simulate the aircraft tire/ground interactions. The incompressibility of the material, the large transformations and the unilateral contact with Coulomb friction law were all taken into account. Imaging methods were used to examine the complex structure of the tire cross-section. Comparisons are made between the data obtained with the model, the experimental data and those provided by the manufacturer. The tire response predictions were found to depend considerably on the material and the geometrical characteristics of the tire.

ABSTRACT: The paper deals with the computationally efficient linear static analysis of cylindrical frame-stringer stiffened fuselage structures. In this regard a special dedicated finite element is proposed, which is a
combination of curved beam elements and shell elements. This element is based on classical beam theory as well as on membrane shell theory. It is derived using approach functions that consider the differential couplings between the approach functions and hence allows for larger element sizes. Therefore an analysis can be carried out with only few degrees of freedom and hence the computational time for structural analyses is significantly reduced. An approximation technique is discussed to enable the analysis of elliptical cross-sections using circular elements. The element aids in a computationally efficient analysis of the entire fuselage, without compromising accuracy compared to other conventional finite element softwares. As an example for illustrating the application of the developed element a numerical analysis of an orthogonally stiffened fuselage structure made of a symmetric orthotropic laminate is presented.

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“Dynamic bending response of thermoelastic functionally graded plates resting on elastic foundations”, Aerospace Science and Technology, Vol. 29, No. 1, pp 7-17, August 2013,  
https://doi.org/10.1016/j.ast.2013.01.003  
ABSTRACT: In this paper, the analyses of dynamic deflection and stresses in functionally graded (FG) plates resting on two-parameter elastic foundations, according to Pasternak’s model, are investigated. The present FG plate is subjected to time harmonic thermal load. Material properties of the plate are assumed to be graded in the thickness direction, from the upper surface which is ceramic-rich to the lower one which is metal-rich, according to a simple exponential law distribution in terms of the volume fractions of the constituents. The governing equations of the dynamic response of a non-homogeneous composite plate are deduced by using various shear deformation theories as well as the classical one. The influences of the time parameter, power-law index, side-to-thickness ratio and the foundation parameters on the dynamic bending are illustrated.

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“Nonlinear finite element analysis of thermal post-buckling vibration of laminated composite shell panel embedded with SMA fibre”, Aerospace Science and Technology, Vol. 29, No. 1, pp 47-57, August 2013,  
https://doi.org/10.1016/j.ast.2013.01.007  
ABSTRACT: Numerical investigation of nonlinear free vibration of thermally post-buckled laminated composite spherical shell panel embedded with shape memory alloy (SMA) fibre is presented. The mathematical model is proposed for the first time by taking the geometric nonlinearity in Green–Lagrange sense and the panel kinematics based on higher order shear deformation theory. In addition to the above the material nonlinearity in SMA fibres due to the temperature field is also considered in the present analysis. The system governing differential equation of the shell panel is obtained using Hamilton’s principle. A direct iterative method in conjunction with nonlinear finite element is used to discretise and solve the system of equations. Effects of various parameters such as curvature ratios, thickness ratios, amplitude ratios, aspect ratios, support conditions, lamination schemes, SMA prestrains and SMA volume fractions on the nonlinear free vibration behaviour on post-buckled laminated panels are examined in detail and discussed. The results obtained are
compared with those available in the literature.

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ABSTRACT: Bi-stable composites have been considered for morphing applications thanks to their ability to hold two statically stable shapes with no energy consumption. In this paper, the modelling of the dynamic response of cantilevered wing-shaped bi-stable composites is presented. To this end, an analytical model approximating the dynamic response about each statically stable shape of wing-shaped bi-stable composites is derived. Theoretical modal properties are obtained to attain or stabilise a desired configuration following a previously introduced resonant control strategy. The resonant control technique is evaluated for a wing-shaped bi-stable composite subject to aerodynamic loads. Wind tunnel experiments are conducted on a wing-shaped specimen showing the ability of the control strategy to stabilise or attain a desired stable shape under aerodynamic loads.

References listed at the end of the paper:

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ABSTRACT: The paper is concerned with direct aeroelastic bifurcation analyses of an airfoil system in which both aerodynamic and structural nonlinearities are considered. Here, structural dynamics is treated in terms of polynomial nonlinearities associated with the pitching stiffness. Two CFD tools are employed in the present work and they are based on the Euler formulation. For Hopf bifurcation analysis, a structured grid CFD code is used and flutter boundaries are found with the inverse power method. Previous work has demonstrated the applicability of such approach for both airfoil and wing configurations with a linear structural model. The novelty of the present effort is the use of this procedure for the investigation of the aeroelastic behavior with structural nonlinearities. Time-marching aeroelastic analysis is also performed and compared with direct calculation of Hopf bifurcation points in order to verify the approach. In the time-marching case, a CFD code solves the flowfield using an unstructured computational domain discretization. The results shown in the present paper are particularly concentrated in the investigation of flutter boundaries and typical limit cycle oscillation nonlinear effects for high-subsonic and transonic flows over a NACA 0012 airfoil-based typical section. The investigation reveals interesting nonlinear dynamics when both aerodynamic and structural nonlinearities interact.

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ABSTRACT: The thermo-mechanical behaviors of functionally graded material (FGM) panels are investigated in hypersonic airflows. Present study deals with the three types of material such as power-law FGM (P-FGM), sigmoid FGM (S-FGM) and exponential FGM (E-FGM) models. Based on the first-order shear deformation theory of plate and von Karman strain-displacement relations are adopted in the formulation. Also, the non-linearity is considered as a model for the aerodynamic loads, and thus the pressure is evaluated using the third-order piston theory. Newton–Raphson iterative method is applied to solve the thermal post-buckling behavior in the numerical analysis. In order to validate the modeling and formulation, present results are compared with the previous data. More works reveal that the thermal or aerodynamic loads exceed a critical value, then the panel snaps to the opposite equilibrium position in this study. Especially, snap-through instabilities are more deeply investigated in the thermal post-buckling behavior of FGM panels in hypersonic regimes.


ABSTRACT: The aircraft fuselage was idealized as a sandwich cylinder and the minimization of the inner sound pressure of the cylinder was studied. Subjected to a point force excitation, the inner sound pressure of the sandwich composite cylinder was predicted using the FEM/BEM. The acoustic transfer vector method was adopted in the numerical model. The predicted results were validated with the experimental results. Using the verified numerical model, the structural parameters including core properties, core thickness, sandwich layup and fiber orientation, were studied for their influences on the inner sound pressure. Finally, an optimization method integrating the genetic algorithm and acoustic transform vector method were developed to minimize the inner pressure of a fuselage section. It has been demonstrated that the optimization method can improve the computation efficiency and give a good compromise between the weight, the mechanical performance and the acoustic properties of the sandwich fuselage.


ABSTRACT: The objective of this article is to analytically investigate the free vibration of shape memory alloy hybrid composite (SMAHC) beams in thermally pre/post-buckled domains. Non-linear equations of motion of SMAHC beams are derived based on the first-order shear deformation theory and von Karman geometrical non-linearity via the extended Hamilton principle. The recovery stress generated by temperature-induced martensitic phase transformation of the pre-strained SMA fibers is computed by means of the Brinson model. Exact closed-form solutions are presented for the buckling temperature, post-buckling deformation and temperature-deformation equilibrium path of symmetric and asymmetric simply supported SMAHC beams under uniform temperature rise. The vibration of the symmetric SMAHC beam around the first buckled configuration is also investigated and an analytical solution for the fundamental frequency and its associated mode shape is obtained. Based on the developed closed-form solutions, extensive numerical results are presented to provide an insight
into the influence of SMA fibers volume fraction, pre-strain in the SMA fibers, location of SMA fibers, temperature rise and geometrical parameters on the static and dynamic responses of the SMAHC beams in the thermally pre/post-buckling regimes. Due to the absence of similar results in the specialized literature, this paper is likely to fill a gap in the state of the art of this problem.


ABSTRACT: The present study is concerned with the elastic/plastic buckling of thin rectangular plates under various loads and boundary conditions. The in-plane loads are placed uniformly and linearly varying in the uniaxial compression and biaxial compression/tension. The equilibrium and stability equations are derived and analyses are carried out based on two theories of plasticity, i.e. deformation theory (DT) and incremental theory (IT). The elastic/plastic behavior of plates is described by the Ramberg–Osgood model. Generalized Differential Quadrature (GDQ) discretization technique is used to solve the buckling of plate equation. To examine accuracy of the present formulation and procedure, several convergence and comparison studies are investigated and new results are presented. The differences between the IT and DT results increase by increasing loading parameter in linearly varying in-plane loading. Some new consequences are achieved regarding the validation range of two theories. Furthermore, effects of aspect, thickness to length and loading ratios, boundary condition, type of plasticity theory and linearly varying in-plane loading on the buckling coefficient are discussed. Contour plots of buckling mode shapes for various loading parameters are also illustrated.


ABSTRACT: In this study, the high velocity impact response of sandwich specimens with FML skins and polyurethane foam was investigated by experimental and numerical approaches. Impact tests were performed using a helium gas gun to identify deformation mechanisms and to check accuracy of finite element model. The 3D finite element code, LS-DYNA was used to model impact of cylindrical projectile with clamped boundary condition. Parametric studies were carried out incorporating different core densities, initial velocities of projectile and layer's stacking sequence. The results show the facesheets have major contribution on energy absorption of the sandwich specimens. Also, increasing core density does not significantly change absorbing energy in comparison with the effects of other parameters. Comparison of different layer sequences of skins indicated that these panels have benefits of both composite sandwiches and metal sandwiches, simultaneously. Examining damaged specimens demonstrated the cracks in front and back facesheet develop in different patterns. Circumferential crack was made in front facesheet, and radial crack was made in back facesheet.

M.M. Alipour and M. Shariyat (Faculty of Mechanical Engineering, Center of Excellence in Smart Structures and Dynamical Systems, K.N. Toosi University of Technology, Tehran 19991-43344, Iran), “Analytical stress analysis of annular FGM sandwich plates with non-uniform shear and normal tractions, employing a zigzag-elasticity plate theory”, Aerospace Science and Technology, Vol. 32, No. 1, pp 235-259, January 2014,
ABSTRACT: Present paper is devoted to stress and deformation analysis of functionally graded annular sandwich plates subjected to non-uniform normal and/or shear tractions. In spite of its wide applications, analytical stress analysis of plates under shear or combinations of normal and shear tractions has not been performed so far, especially for the sandwich plates. Furthermore, it is the first time that a power solution is developed for the annular functionally graded sandwich plates. The governing equations are derived based on principle of minimum potential energy and a double superposition zigzag theory. The transverse shear stresses are determined based on the three-dimensional theory of elasticity. The resulting governing equations may cover symmetric and asymmetric layups, various boundary conditions, and arbitrary non-uniform tractions on the top and bottom face sheets. The obtained results are verified by comparing them with results of the three-dimensional theory of elasticity. While the present approach is accurate, it is computationally more economic than the three-dimensional elasticity approach. Finally, a parametric study including evaluating effects of various parameters on the stress and displacement distributions of the annular sandwich FGM plates is accomplished.


ABSTRACT: A numerical study is presented where tailoring optimization and stitching are applied to improve the structural performances of sandwich plates undergoing static and blast pulse pressure loading. The purpose is to recover the critical interlaminar stresses at the interface with the core and contemporaneously keep maximal the flexural stiffness. Optimized distributions of the stiffness properties for the faces are obtained solving an extremal problem whose target is the minimization of the energy due to transverse shear and bending stresses under spatial variation of the stiffness properties, along with the maximization of the energy due to in-plane stresses. The contribution of stitching is computed through 3D finite element analysis and it is incorporated as modified elastic moduli into the refined, hierarchic zig-zag model employed as structural model to carry out the analysis accurately accounting for the layerwise effects of the out-of-plane transverse shear and transverse normal stresses and deformations. Approximate solutions giving the ply fibre orientation at any point (compatible with the current manufacturing technologies) are considered in the numerical applications. The numerical results show that stitched sandwiches incorporating optimized low-cost glass-fibre plies can achieve the same bending stiffness as sandwiches with uniform stiffness carbon-fibre faces, with a consistent reduction of critical out-of-plane stresses. The amplitude of vibrations under blast pulse loading can be consistently reduced with a proper choice of the curvilinear paths of fibres incorporated in the faces.

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“Bending analysis of FGM plates under hygro-thermo-mechanical loading using a four variable refined plate
ABSTRACT: The bending response of functionally graded material (FGM) plate resting on elastic foundation and subjected to hygro-thermo-mechanical loading is studied. Using a four variable refined plate theory, both a quadratic variation of the transverse shear strains across the thickness and the zero traction boundary conditions on the top and bottom surfaces of the plate are satisfied without using shear correction factors. The number of independent unknowns of present theory is four, as against five in other shear deformation theories. The elastic coefficients, thermal coefficient and moisture expansion coefficient of the plate are assumed to be graded in the thickness direction. The elastic foundation is modelled as two-parameter Pasternak foundation. Numerical results are presented to verify the accuracy of present theory and the influences played by many parameters are investigated. The study is relevant to the simulation of rocket launch pad structures subjected to intense thermal loading.


ABSTRACT: In this work, a new trigonometric zigzag theory is proposed for the static analysis of laminated composite and sandwich plates. This theory considers shear strain shape function assuming the non-linear distribution of in-plane displacement across the thickness. It satisfies the shear-stress-free boundary conditions at top and bottom surfaces of the plate as well as the continuity of transverse shear stress at the layer interfaces obviating the need of an artificial shear correction factor. An efficient displacement based C0 finite element model is employed for the accurate assessment of the static behavior of laminated composite and sandwich plates. Some numerical examples covering various features such as different material properties, loading and boundary conditions of cross-ply composite and sandwich composite plates are solved. Efficiency and applicability of the present model is ascertained by validating the evaluated results not only with three-dimensional elasticity solutions but also with the available published results based on other shear deformation theories.


ABSTRACT: In this article, free vibration of functionally graded (FG) rectangular plates subject to different sets of boundary conditions within the framework of Classical or Kirchhoff's plate theory are investigated. The eigenfrequency equation is obtained by the use of Rayleigh–Ritz method. Displacement components are expressed in simple algebraic polynomial forms which can handle any sets of boundary conditions. Material properties of FG plate are supposed to vary along thickness direction of the constituents according to exponential law. The objective is to study the effects of constituent volume fractions and aspect ratios on the natural frequencies. New results for frequency parameters are incorporated under various sets of boundary conditions after performing a test of convergence. Comparison with the results from the existing literature is provided for validation in special cases. Mode shapes for clamped FG rectangular plates with respect to aspect ratios and constituent volume fractions are also reported. The present study also involves the power-law variation of temperature dependent material properties for the convergence and validation of the results for FG
plate in thermal environment. As such, new results for exponential FG plate under the consideration of thermal conditions are incorporated after checking the convergence of frequencies.

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ABSTRACT: The present investigation is devoted to a development of new optimal design concepts of aircraft lateral wing upper covers made of advanced composite materials. In the first part three rib bays laminated composite panels with T, I and HAT-stiffeners were modeled with ANSYS and NASTRAN finite element codes to investigate their buckling behavior as a function of skin and stiffener lay-ups, stiffener height, stiffener top and root width. Due to the large dimension of numerical problems and large number of optimization tasks to be solved, an optimization methodology was developed employing the method of experimental design, response surface technique and linear buckling analysis. Weight optimization problems were solved for the laminated composite panels with three types of stiffeners, two stiffener pitches and four load levels taking into account manufacturing, repairability and damage tolerance requirements. The composite panel with the best stiffener type was identified for the subsequent nonlinear buckling analysis and optimization presented in the Part II. Optimal results were verified successfully using ANSYS shared-node and NASTRAN rigid-linked models.

ABSTRACT: Thermal postbuckling analysis is presented for FGM cylindrical panels resting on elastic foundations. Heat conduction and temperature-dependent material properties are both taken into account. Material properties of functionally graded materials (FGMs) are assumed to be graded in the thickness direction based on Mori–Tanaka micromechanics model. The formulations are based on a higher order shear deformation theory and von Kármán strain displacement relationships. The panel–foundation interaction and thermal effects are also included. The governing equations are first deduced to a boundary layer type that includes nonlinear prebuckling deformation and initial geometric imperfection of the panel. Thermal postbuckling equilibrium paths are determined by using a singular perturbation technique along with a two-step perturbation approach. The effects of volume fraction index, foundation stiffness, panel curvature ratio on the thermal postbuckling behavior of FGM cylindrical panels are discussed in detail. The results reveal that the thermal postbuckling equilibrium path of FGM cylindrical panels with immovable simply supported edge conditions is no longer the bifurcation type for both uniform and non-uniform temperature variations.

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ABSTRACT: During launch, satellites and their equipment are subjected to vibration loads of random nature
The vibro-acoustic response is an important issue to be analysed, in particular, for structural components such as solar arrays in folded configuration. The modelling of these structures in the low frequency range (low modal density) requires combining models for the air layers, the structural elements and the surrounding air. This work studies different combinations of numerical methodologies (FEM, BEM, SEA) to model the system in order to simulate the modal and the vibro-acoustic responses outlining their advantages and drawbacks. The modal and acoustic simulated responses are determined and analysed to find out the efficiency of the combinations of the numerical methodologies proposed. Two different cases are considered: a simple benchmark case (two structural elements and one air layer) and a real solar wing design (three solar panels and two air layers). For the latter, experimental results on both the modal and vibro-acoustic responses are also presented.

S. Abolghasemi, A.R. Shaterzadeh and R. Rezaei (Faculty of Mechanical Engineering, University of Shahrood, Shahrood, Iran), “Thermo-mechanical buckling analysis of functionally graded plates with an elliptic cutout”, Aerospace Science and Technology, Vol. 39, pp 250-259, December 2014,
https://doi.org/10.1016/j.ast.2014.10.004

ABSTRACT: In this paper, buckling of functionally graded plates (FG plates) with an elliptical cutout under combined thermal and mechanical loads is investigated using Finite Element Method. Unlike other studies in which the plates are exposed to thermal or mechanical loads, in this study it is assumed that the mechanical and thermal loads are applied simultaneously. The material properties are assumed to vary across plate thickness according to power law distribution of the volume fraction of constituents. The plate formulation is based on the First order Shear Deformation Theory (FSDT) and element stiffness matrices are derived based on the principle of minimum potential energy. A flexible mesh generation algorithm is prepared in which the mesh density around the hole can be controlled easily. After validating the results of developed FE code with those available in the literature, the effect of boundary condition, plate aspect ratio and cutout radius ratio on thermo-mechanical buckling behavior of FG plates is studied and stability diagrams are presented. Finally useful conclusions are presented.

Farhad Alinaghizadeh and Mehran Kadkhodayan (Ferdowsi University of Mashhad, Department of Mechanical Engineering, Mashhad, Iran), “Large deflection analysis of moderately thick radially functionally graded annular sector plates fully and partially rested on two-parameter elastic foundations by GDQ method”, Aerospace Science and Technology, Vol. 39, pp 260-271, December 2014,
https://doi.org/10.1016/j.ast.2014.09.014

ABSTRACT: This paper presents an investigation into large deflection analysis of moderately thick radially functionally graded (RFG) annular sector plates fully and partially rested on two-parameter (Pasternak) elastic foundation by employing Generalized Differential Quadrature (GDQ) method. The material properties are graded through the radial direction of plates according to a power-law distribution of the volume fraction of the constituent. Based on the first-order shear deformation theory in conjunction with non-linear von Kármán assumptions, the equilibrium equations are derived. Application of GDQ method to the equilibrium equations leads to a system of non-linear algebraic equations. The set of non-linear algebraic equations are then solved by employing the Newton–Raphson iterative scheme. It is shown that the predictions of GDQ method vis-à-vis other numerical methods reported in the literature, are in a good agreement. Furthermore, effects of change in power law index, geometrical parameters and stiffness of foundation are studied in detail.

ABSTRACT: In this paper, a numerical study on the skin–stringer debonding growth in composite panels under compressive load is presented. A novel numerical procedure, for the selection of proper material parameters governing the traction–separation law in Cohesive Zone Model (CZM) based elements, is introduced and demonstrated. Indeed, the proposed procedure uses Virtual Crack Closure Technique (VCCT) based FEM analyses on Double Cantilever Beam (DCB) and End Notched Flexure (ENF) specimen to characterize the traction–separation law, respectively, for fracture mode I and mode II. The established traction–separation laws are then applied to composite structures containing inter-laminar damages modeled by cohesive elements. To validate the proposed approach, a single stringer panel under compression with an artificial debonding between skin and stringer, has been considered. The numerical results, in terms of displacements and debonding size as a function of applied compressive load, have been compared to experimental data available in literature providing a good numerical–experimental correlation.


ABSTRACT: In this paper, buckling analysis of functionally graded annular sector plates subjected to uniform in-plane compressive loads based on three dimensional theory of elasticity is investigated. Moreover, influence of full or partial Winkler-type elastic foundations is considered. In-plane normal compressive loads have been applied to either radial, circumferential, or all edges of annular sector plates. The material properties vary continuously through the thickness of plate according to a power law distribution while Poisson's ratio is assumed to be constant. The governing equations are developed based on the principle of minimum total potential energy and solved based on finite element orthogonal integral equations. Buckling loads are obtained based on a generalized geometric stiffness concept. In this regard, effects of both pre- and post-buckling modes are considered. The effects of material gradient exponent, different sector angles, aspect ratio, thickness ratio, loading condition, different shapes of partial elastic foundation and foundation stiffness on the buckling loads and mode shapes of movable simply supported FGM annular sector plates have been investigated to draw practical conclusions.


ABSTRACT: Geometrically nonlinear response of a sandwich panel based on elastic–linear plastic (bilinear) shear behavior of the core is presented. The extended high order sandwich panel theory (EHSAPT) is applied to obtain governing equations. The nonlinear Von Karman type relations for strains of face sheets and the core are adopted. The face sheets follow first order shear deformation theory along with the linear elastic assumption. A Ritz based solution which is suitable for any essential boundary condition is implemented. Two types of boundary conditions are considered simply supported and immovable clamped at both edges. In each type of boundary conditions, the effects of plastic shear modulus of bilinear material behavior on transverse shear stress
distribution along with detection of the elastic and plastic regions within the core, force and moment resultants, transverse displacement distributions in the face sheets, in-plane and vertical displacements through the thickness of the core are studied in detail. Besides, all results based on the bilinear material assumption of the core are compared with the linear elastic ones. Finally, for the case study of the simply supported beam, the results of the constitutive model are compared with finite element simulation.


ABSTRACT: The aim of the paper is to investigate active shape control of post-buckled elastic beams subjected to in-plane compressive loadings using surface-bonded shape memory alloy (SMA) layer actuators. A robust macroscopic SMA model is used to simulate main features of the SMA layer under dominant axial and transverse shear stresses during non-proportional thermo-mechanical loadings. The SMA model is able to reproduce martensite transformation/orientation, pseudo-elasticity, shape memory effect and in particular reorientation of martensite and ferro-elasticity effects. Non-linear equations of equilibrium for the moderately thick smart beam are derived by means of the principle of minimum total potential energy based on the first-order shear deformation theory and von Kármán geometrical non-linearity. The governing equations of equilibrium are solved using Ritz based finite element method along with an iterative numerical algorithm. Effects of the pre-strain state, thickness and temperature of the SMA layer actuator are examined, and their implications upon the pre/post-buckling behavior of the smart beam under in-plane compressive loadings are highlighted. The obtained results reveal that installing the SMA layer actuator can play a significant beneficial role toward confining deformation of the smart structure in the post-buckling regime. Due to lack of similar results in the specialized literature, the results of this research are expected to contribute to a better understanding of active shape control capability of the SMA composite beams under in-plane mechanical loadings.


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear dynamic response and vibration of imperfect eccentrically stiffened functionally graded thick circular cylindrical shells surrounded on elastic foundations using both the first order shear deformation theory and stress function with full motion equations (not using Volmir's assumptions). Material properties are graded in the thickness direction according to a sigmoid power law distribution (S-FGM) in terms of the volume fractions of constituents with metal–ceramic–metal layers. The S-FGM shells are subjected to mechanical and damping loads. Numerical results for dynamic response of the shells are obtained by Runge–Kutta method. The results show the influences of geometrical parameters, the volume fractions of metal–ceramic–metal layers, imperfections, the elastic foundations, eccentrically stiffeners, pre-loaded axial compression and damping loads on the nonlinear dynamic response and nonlinear vibration of functionally graded cylindrical shells. The proposed results are validated by comparing with other results reported in the literature.

ABSTRACT: Coupled higher-order layerwise piezoelectric laminate mechanics are presented, applicable to composite and sandwich composite plates subjected to static mechanical loads and/or electric voltages. In the development of these formulations through-thickness compressibility is either considered (3-D) or neglected (2-D). Their advantage compared to linear layerwise theories lies in the efficient prediction of the local through-thickness response by using a gross through-thickness discretization, while retaining simplicity in through-thickness kinematic assumptions. Moreover, they enable prediction of interlaminar shear and transverse normal stress at the interface between discrete layers, which is crucial information for prediction of delamination initiation. Using the developed mechanics, the effects of transverse compressibility and ply angle on the local through-thickness response of composite and sandwich plates are studied.

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ABSTRACT: This paper presents an investigation of free vibration of stiffened doubly curved shallow shells made of functionally graded materials under thermal environment. Two types of temperature rise throughout the shell thickness; namely linear and nonlinear temperature rises are considered in the present investigation. The power law distribution and Mori–Tanaka homogenization scheme are used to describe the material graduation throughout the shell thickness. In order to take into account the significant effects of shear deformation and rotatory inertia of the shell skin and its stiffeners, the first-order shear deformation theory is employed to derive the governing equations used for determining natural frequencies of the stiffened shells. The governing equations can be solved analytically to obtain exact solutions for this problem. The stiffened shells can be specialized into different forms of spherical, cylindrical and hyperbolic shells by setting components of curvature. Several parameters of material volume fraction index, geometrical ratio, temperature change, number of stiffeners, etc. that affect vibration results of the shells are investigated and discussed in detail. Based on the numerical results, it is revealed that increasing number of stiffeners leads to considerable changes in natural frequencies of the stiffened shells.


ABSTRACT: In this work, thermal buckling analysis of functionally graded rectangular nanoplates is investigated. In order to consider the size effects, nonlocal elasticity theory and third-order shear deformation
theory are used. It is assumed that the material properties of functionally graded nanoplates are varied through the thickness of nanoplates according to the power law distribution. Two types of uniform and nonlinear temperature distributions are considered in this paper. To show the accuracy of present methodology, our results are verified with the results available in the literature. Moreover, the influences of different parameters such as nonlocal parameter and piezoelectric layers are studied.


**ABSTRACT:** In this paper, a model of the FGM circular plates is successfully established by physical neutral surface and higher-order shear deformation theory. The primary material properties are assumed to be temperature-dependent and vary along the thickness, while Poisson's ratio depends weakly on temperature change and position and is assumed to be a constant. It is worth noting that the displacements have special forms, there are no stretching–bending couplings in constitutive equations, and governing equations have the simple forms, so the solution procedure is similar to that of the homogeneous isotropic plate. The validity of this new model is confirmed by comparison with related researchers' results. Multi-term Ritz method is novel for nonlinear bending analysis of FGM circular plates, and influences played by different supported boundaries, thermal environmental conditions and volume fraction index are discussed in detail.


**ABSTRACT:** In the present paper, shear buckling analysis of functionally graded annular sector plates is investigated for the first time. A three-dimensional elasticity approach is employed instead of the approximate plate theories. In-plane shear loads have been applied to radial, circumferential, or all edges of annular sector plates. Moreover, buckling of annular sector plates subjected to in-plane shear load at upper/lower surfaces is investigated for the first time. Three different boundary conditions have been examined: (1) Movable simply supported edges. (2) Immovable simply supported radial edges and free circumferential edges. (3) Immovable simply supported circumferential edges and free radial edges. The material properties are assumed to have transverse heterogeneity according to a power law distribution while Poisson's ratio is assumed to be constant. Results are extracted based on the principle of minimum total potential energy and a graded finite element method. Buckling loads are obtained based on a generalized geometric stiffness concept. In addition to different loading and boundary conditions, the effects of material gradient exponent, sector angles, aspect ratio and thickness ratio on the shear buckling loads and mode shapes of FGM annular sector plates have been investigated in detail.


**ABSTRACT:** In the present study, a rotating functionally graded cylindrical shell (FGM) with imperfectly
surface bounded functionally graded piezoelectric material (FGPM) subjected to an axisymmetric hygrothermo-electro-mechanical loading is considered. The shell is simply supported and could be rested on an elastic foundation. The material properties of FGM and FGPM are assumed to be exponentially graded in the radial direction. The Fourier series expansion method through the longitudinal direction and the differential quadrature method (DQM) across the thickness direction are used for solving governing differential equations. To check the validity of the present work, comparisons with the previous results are performed. Finally, numerical results are shown to clarify the effects of important parameters on the behavior of the smart shell.

ABSTRACT: The study is concerned with the elastoplastic buckling of thin-walled beams and stiffened plates, subjected to in-plane, uniformly distributed, uniaxial and biaxial load. The ruling differential equations have been solved analytically by using the Kantorovich technique and the obtained displacement field has been employed in a general procedure that, by using the framework derived by the finite element method, is able to analyze the elastoplastic buckling behavior of prismatic beams and stiffened plates with arbitrary cross-section. The inelastic effect is modeled through a stress–strain law of the Ramberg–Osgood type, and both the incremental deformation theory and the J2 flow theory are here considered. The reliability of the numerical procedure is illustrated for rectangular plates, and the contradicting results obtained by using the two plastic theories are discussed in detail. Finally, the performance of the method is illustrated through the analysis of a C-section and five different closed section columns.

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ABSTRACT: This article demonstrates the effectiveness of acoustic nondestructive inspection methods to monitor the condition of the bond-line in carbon fiber reinforced polymer stiffened panels. In particular, acoustic emission and guided ultrasonic waves were utilized experimentally to identify the onset of debonding in the stiffened panels and track its evolution under constant amplitude fatigue loading. Before testing, numerical simulations of wave propagation were carried out to evaluate the wave characteristics and optimize the placement of sensors along the spar. A damage index based on numerically produced guided waves was developed to estimate the extent of debonding which was tested and proved effective using actual experimental data. The panels were subjected to both quasi-static and fatigue loading conditions, while continuously recording acoustic emission and triggering guided ultrasonic waves at predetermined load levels. The acoustic emission activity associated with debonding was found to have a dual dominant frequency content and a low frequency centroid, which were also confirmed with wavelet analysis. In view of potential aerospace applications of the investigation presented herein, pattern recognition algorithms were also implemented and showed great potential for real-time detection of such damage.
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ABSTRACT: In this work, the experimental and numerical study of induction welding devoted to the fabrication of a composite stiffened panel, representative of a typical aeronautic sub-component, is presented. A thermoplastic matrix composite, polyphenylene sulfide (PPS) reinforced with carbon fibers, is used. The influence of the fundamental process parameters, such as generator power, distance between induction coil and laminate, coil geometry and laminate lay-up on the heating rate and the heat distribution was analyzed applying finite element simulations. The model was validated through the comparison of experimental and model results obtained in static experiments. Optimized parameters for composites welding were found out, and the mechanical properties of the welded joints were evaluated by single lap shear and pull-off experiments. Finally, a prototype panel made of a flat laminate stiffened with four “L” shaped stringers is fabricated by continuous induction welding, exploiting modeling and experimental results. A C-scan of the panel was also performed.


ABSTRACT: The fully coupled thermo-mechanical behavior of bi-directional functionally graded material (FGM) beam structures is studied using a computationally low cost isogeometric finite element model. In the proposed analysis, the temperature is considered as a primary variable. The kinematical equations of the bi-directional FGM beam are described by a refined high order global–local theory. A combination of polynomial and exponential expressions is used to introduce the in-plane displacement field. This representation of the in-plane displacement field allows avoiding shear correction factors. Concerning the thermal part, a high-order temperature field is considered through the thickness direction of the bi-directional graded beam. The capability of this novel formulation has been assessed through various thermal and thermo-mechanical tests. To this aim, the obtained numerical results from the proposed isogeometric formulation have been compared with thermo-elasticity solutions or other available results in open literature. It is found that the results obtained from the present beam formulation agree quite well with the reference results.

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ABSTRACT: This paper presents a detailed investigation on the post-buckling behaviour of adhesively bonded stiffened panels subjected to in-plane shear loading. An experimental programme was carried to determine the buckling load, buckling shape, collapse load and failure modes of two bonded stiffened panels. A nonlinear finite element based modelling approach, accounting for geometrical and material nonlinearities as well as progressive failure in the adhesively bonded interface between the skin and the stiffener is proposed to predict the structural behaviour of the panels up to failure. This approach consists in modelling the bonded interfaces using a newly developed cohesive zone based constitutive damage model. In order to account for damage in the stiffener and the skin a Von Mises based constitutive damage model is also formulated and presented in the paper. Both constitutive models were implemented into ABAQUS/Explicit finite element code as user-defined material models. A very good agreement between experimental results and numerical predictions is obtained using the proposed modelling approach, with deviations smaller than 8% in buckling load and bonded interface failure load onset.


ABSTRACT: This paper reports the systematic development of tape spring hinges for a solar array by an optimization method considering various deployment performances. The nonlinear behavior between the moment and the rotation angle of a tape spring hinge is determined through experimental results rather than through finite element analysis results or theoretical solutions in order to identify the moment–rotation profile accurately. Response surfaces comprising the measured moment–rotation profile and design parameters of a tape spring hinge are generated by a Box–Behnken experimental design. Furthermore, to consider deployment performances such as low latch-up load, latching without overshoot, high deployment stiffness, and high torque margin, the deployment equation is derived by Kane's dynamic equation considering any number of solar panels. The present study proposes a systematic approach for designing tape spring hinges for any number of solar panels; the designed hinges satisfy all design requirements. The approach involves minimizing the cost function including several design requirements and solving the deployment equation containing the response surfaces of the moment–rotation profiles simultaneously. To verify the effectiveness of the proposed approach, several examples are demonstrated.


ABSTRACT: The present paper is devoted to the investigation of the dynamic response of typical aerospace structures subjected to different time-dependent loads. These analyses have been performed using the mode superposition method combined with refined one-dimensional models, which have been developed in the framework of the Carrera Unified Formulation (CUF). The Finite Element Method (FEM) and the principle of virtual displacements are used to compute the stiffness and mass matrices of these models. Using CUF, one has the great advantage to obtain these matrices in terms of fundamental nuclei, which depend neither on the adopted class of beam theory nor on the FEM approximation along the beam axis. In this paper, Taylor-like expansions (TE), Chebyshev expansion (CE) and Lagrange expansion (LE) have been employed in the
framework of CUF. In particular, the latter class of polynomials has been used to develop pure translational displacement-based refined beam models, which are referred to as Component Wise (CW). This approach allows to model each structural component as a 1D element. The dynamic response analysis has been carried out for several aerospace structures, including thin-walled, open section and reinforced thin-shells. The capabilities of the proposed models are demonstrated, since this formulation allows to detect shell-like behavior with enhanced performances in terms of computational efforts.

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ABSTRACT: In this research, linear thermal buckling of a composite conical shell made from a polymeric matrix and reinforced with carbon nanotube fibres is investigated. Distribution of reinforcements across the shell thickness is assumed to be uniform or functionally graded. Thermomechanical properties of the constituents are temperature dependent. Under the assumption of first order shear deformation shell theory, Donnell kinematic assumptions and von Kármán type of geometrical nonlinearity, the complete set of equilibrium equations and boundary conditions of the shell are obtained. A linear membrane analysis is carried out to obtain the pre-buckling thermal stresses of the shell. Adjacent equilibrium criterion is implemented to establish the stability equations associated with the buckling state. The resulting equations are discreted by means of trigonometric expansion through the circumferential direction and discrete singular convolution method through the shell length. The established eigenvalue problem is solved iteratively to obtain the critical buckling temperature and critical mode number. Parametric studies are presented to explore the influences of semi-vertex angle, volume fraction of CNTs, distribution pattern of CNTs and boundary conditions. It is shown that, conical shells with intermediate carbon nanotube volume fraction do not have, necessarily, intermediate critical buckling temperature.

ABSTRACT: In this work, nonlinear dynamic analysis of a cylindrical sandwich panel with embedded SMA wires in the face sheets is performed taking into account the instantaneous and spatial martensite phase transformation. The Boyd and Lagoudas one-dimensional SMA constitutive equation is used to model the pseudoelastic behavior of the shape memory alloy wires. Since the martensite volume fraction depends on the stress distribution, the governing equations and the phase transformation kinetic equations are coupled together and therefore an iterative method is employed to solve the highly nonlinear equations. Moreover, considering that the stress resultants generated by the martensite phase transformation in the wires are path dependent values, an incremental method is used to estimate the increment of the stress resultants at each time step. A new finite-element-based procedure is proposed and Newmark time integration method is used to solve the finite element equations. The results show a gradual decrease in the amplitude of vibration as long as the SMA wires do not reach a fully elastic condition. This feature is of great interest for the vibration suppression of structures especially that which is related to resonance phenomena. Finally, the effect of various parameters such sector angle, operating temperature, wire volume fraction, through the thickness location of the wires and different
boundary conditions on the vibration amplitude and loss factor is investigated.

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ABSTRACT: The buckling of a thin FGM microplate subjected to mechanical and thermal loading is evaluated using the spline finite strip method, based on modified couple stress theory. Regarding thickness, the features of the FGM plate are assumed as being variable according to the law's proposed model. The spline finite strip method are used for calculating the buckling load and critical temperature by solving an eigenvalue problem. The results showed that reduction in size did not affect interaction of forces. Also, the length scale parameter, volume fraction modulus, different boundary conditions and the dimensions of the plate are considered.

S.A. Galehdari, M. Kadkhodayan and S. Hadidi-Moud (Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran), “Low velocity impact and quasi-static in-plane loading on a graded honeycomb structure; experimental, analytical and numerical study”, Aerospace Science and Technology, Vol. 47, pp 425-433, December 2015, https://doi.org/10.1016/j.ast.2015.10.010
ABSTRACT: Through the increasing development of technology in different industries, and the integral requirement of energy absorption, light shock absorbers such as honeycomb structure under in-plane and out-of-plane loads have been in the center of attention. The purpose of this research is to analyze the behavior of graded honeycomb structure (GHS) under low-velocity impact and quasi-static loading. To begin with using the lower-bound theorem, an analytical equation for plateau stress is represented, taking power hardening model into consideration. To compare the acquired analytical equations, empirical tests are conducted on test specimens made of aluminum 6061-O, under previously mentioned loading. Uniaxial tensile tests on each row material are performed to collect data on material properties. The low-velocity and quasi-static tests are conducted with Drop-weight and Santam compression machines, respectively. The quasi-static test is conducted to study the strain rate effect on behavior of the structure. Two experimental tests are simulated in ABAQUS/CAE. Based on the conducted comparisons, the numerical and analytical results indicate a satisfactory agreement with experimental results. Given the performed comparison between experimental and numerical mode shapes, a “V” deformation mode is distinguished for test specimen.

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“Nonlinear vibration of FGM doubly curved panels resting on elastic foundations in thermal environments”,

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ABSTRACT: A large amplitude vibration analysis is presented for a shear deformable doubly curved panel made of functionally graded materials (FGMs) resting on elastic foundations in thermal environments. The effective material properties are evaluated using the Mori–Tanaka micromechanics model. The formulations are based on a higher order shear deformation theory and von Kármán strain–displacement relationships. The panel–foundation interaction and thermal effects are also included. The temperature-dependent material properties of FGMs are assumed to be graded in the thickness direction according to a simple power law distribution. The motion equations are solved by a two-step perturbation approach to determine the nonlinear vibration characteristics of FGM doubly curved panels. The numerical illustrations cover small- and large-amplitude vibration characteristics of FGM doubly curved panels resting on elastic foundations of Pasternak-type. The results obtained from the Mori–Tanaka model are compared with those obtained from the Voigt model. The results confirm that in most cases Voigt model and Mori–Tanaka model have the same accuracy for predicting the vibration characteristics of FGM doubly curved panels. The effects of volume fraction index, temperature variation, foundation stiffness and panel curvature ratio on the nonlinear free vibration behaviors of FGM doubly curved panels are also discussed in detail.


ABSTRACT: In the present work the effects of important parameters such as core thickness, radius of curvature and sector angle on the static and dynamic response of composite cylindrical sandwich panels have been investigated using a higher-order sandwich panel theory (HSAPT). The presented higher-order theory, which applies first-order shear deformation shell theory (FSDT) for the face sheets and the equivalent elasticity theory for the core, is a rigorous approach that includes the higher-order effects incurred by the nonlinearity of the in-plane and transverse displacements of core. Equations of motion along with associated boundary conditions are derived by using Hamilton's principle. For simply-supported panels closed-form solutions can be achieved by Navier techniques. However, for dynamic analysis, the solution is obtained in the time domain by implementing Newmark method. Finally numerical parametric studies are performed to provide some insight into the roles of key variables that influence the static and dynamic response of sandwich panels.

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ABSTRACT: The nonlinear free vibration behaviour of laminated composite spherical shell panel under the elevated hygrothermal environment is investigated in this article. The composite material properties are considered to be the function of temperature and moisture concentration and the effective properties are evaluated using the micromechanics approach. The laminated shell panel model is developed mathematically using Green–Lagrange nonlinear kinematics in the framework of the higher-order shear deformation theory.
The model is discretised using suitable finite element steps and solved numerically through a direct iterative method. The significance of the present nonlinear model is highlighted by solving the wide variety of numerical examples.


ABSTRACT: To improve the reutilization of advanced carbon fiber reinforced composite (CFRC) lattice-core sandwich cylinder (LSC), a severely damaged LSC was retrofitted by CFRC laminate through wrapping and riveting schemes. Free vibration and uniaxial compression experiments were carried out to reveal its mechanical performances. Natural frequencies and vibration modes of the repaired cylinder are close to the intact cylinder. Compared with the stiffness of the intact cylinder, 98.7 kN/mm, stiffness of the repaired cylinder is 138.83 kN/mm, even a little stiffer. Failure of the repaired cylinder locates at the lower end. Initially, the inner skin delaminated from the core and finally fracture of the outer skin made the cylinder out of work. The repaired segment is not damaged. Ultimate load of the repaired cylinder is 377.38 kN, only a little smaller than of the intact cylinder. The retrofitting scheme is effective to re-utilize the severally damaged CFRC LSC.


ABSTRACT: In the present study, an analytical solution is presented to analysis dynamic behavior of FG (functionally graded) thick hollow sphere subjected to thermo-mechanical timed dependent loads. Thermodynamic properties of FG, except for Poisson's ratio, are assumed to vary continuously and smoothly in the radial direction according to power law. Differential transform method (DTM) and Laplace transform method as efficient and accurate methods are used to solve the governing equations analytically for spatial domain and time domain respectively. Comprehensive parametric studies are carried out to show the influences of the power index, thickness and direction of FGM on the dynamic characteristics of the FG thick hollow sphere. The results in Laplace domain are transferred to time domain by employing the fast inverse Laplace transform (FLIT) method. Accuracy of present approach is assessed by comparing the numerical results with the results of published work in the literature.

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ABSTRACT: The present investigation is devoted to a development of new optimal design concepts of aircraft lateral wing upper covers made of advanced composite materials. In the second part a stiffened composite panel with the best weight/design performance obtained from the linear buckling analysis (Part I) is verified by the nonlinear buckling analysis and re-optimized in the case of necessity. Additionally an effect of shear and fuel pressure as well as an effect of skin post-buckling on its performance is investigated. Three rib bays laminated
composite panels with HAT-stiffeners were modeled with ANSYS finite element code to study their buckling behavior as a function of skin and stiffener lay-ups, stiffener height, stiffener top and root width. Due to the large dimension of numerical problems to be solved, an optimization methodology was developed employing the method of experimental design and response surface technique. Weight optimization problems were solved for four load levels, taking into account manufacturing, repairability and damage tolerance requirements. Optimal results were verified successfully using ANSYS shared-node model.


ABSTRACT: A semi-analytical method for the quick and robust solution of guided waves excited in infinite laminated composite strips is presented. In the proposed method, the response of the strip is constructed in time-space domain directly from the governing wave equations, assuming a layerwise variation of the through-the-thickness displacement components. Analytical Fourier transforms, with respect to time and space, provide the transformed response in the frequency-wavenumber domain. Dispersive modal properties for the structure are extracted. Finally, the time transient response of the propagative guided waves is calculated using two inverse Fourier transforms, the first is calculated via the Cauchy's residue theorem, whereas the second is numerically computed. Various numerical results are presented for isotropic, cross-ply composite laminate and sandwich strips and are compared with results from other reported methods as well as with experimental results in composite strips.

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ABSTRACT: In this study, an inverse trigonometric shear deformation theory developed by the authors is extended to assess the flutter behavior of multilayered composite plates subjected to yawed supersonic flow. The shear deformation is considered in terms of an inverse cotangent function which yields non-linear distribution of shear stresses. A generalized finite element formulation is presented to consider the shear strain function based theories. The displacement field is modified by a precise involvement of additional field variables to ensure the implementation of continuous finite element. First order piston theory is employed to consider the aerodynamic load. The applicability, validity and accuracy of the present mathematical treatment are ascertained by performing various numerical tests and comparing the present results with the existing results. The influences of various parameters such as lamination sequences, boundary conditions, material anisotropy, flow angles, etc. on the free vibration and flutter behavior are examined and significant conclusions are made. It is concluded that flow angles, lamination sequence and material anisotropy should be considered as essential design parameters for enhanced flutter boundary of supersonic vehicles.

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ABSTRACT: This work investigates the aeroelastic stability boundary of flutter in Shape Memory Alloy Hybrid Composite laminates (SMAHC). The SMAHC consists of SMAs wires and continuous carbon fibers embedded into a polymeric matrix resulting in a three constituent composite material. The derivation of the effective mechanical properties of the SMAHC is based on micromechanical model which accounts for temperature and fraction of martensite/austenite transformation phases of the shape memory alloy. Hamilton's principle is used for the formulation of the energy functional and to obtain the equilibrium equations and boundary conditions of the aeroelastic problem. The finite element method is employed to numerically solve the equations. Different geometric configuration, laminate stacking sequence, boundary conditions and curvatures are investigated. The study shows that the stiffening effect induced by the changes in the fraction of martensite/austenite transformation phases of the shape memory alloy increases the rate of occurrence of flutter, stabilizing the plate. Thus, one can control the occurrence of flutter speed by controlling the temperature of the SMA wires and the proper design of the geometric properties of the panel and tailoring of the composite laminate.

ABSTRACT: In this present work, improved zigzag theories are developed for the flexural analysis of laminated plates using algebraic, hyperbolic, inverse trigonometric and trigonometric shear strain functions. The governing differential equations and boundary conditions of the structural system are obtained through the principle of virtual work. A generalized Navier closed form solution technique is applied for the flexural analysis of laminated plates. The present theories fulfill the transverse shear stress continuity and in-plane displacement continuity at each layer interfaces. Moreover, the present theories exhibit a constant variation of transverse displacement and parabolic variation of transverse shear stresses across the plate thickness. The tangential stress free boundary conditions are satisfied on the external surfaces of the panel; hence the necessity of artificial shear correction factor is ignored. The present theories consist of 5 unknowns as in the case of FSDT. Several numerical examples are carried out for a broad range of lamination sequence and geometric parameters. To reveal the potency and performance of the present models, numerical comparisons are made with the 3D elasticity solution and other numerical methods and it is observed that the present models perform very well for the static behavior of laminated plates.

ABSTRACT: This paper presents an analytical approach to study the nonlinear dynamic buckling of sigmoid functionally graded material (S-FGM) toroidal shell segments surrounded by elastic foundations subjected to axial compression. Shells are reinforced by closely spaced rings and stringers. The nonlinear dynamic buckling analysis is based on the classical shell theory with von Kármán–Donnell-type of geometrical nonlinearity. By
using the Galerkin method, the closed-form expression of the deflection–time curves is obtained. Numerical solutions are presented in tabular and graphical forms to investigate the deflection–time curves of FGM shells surrounded by elastic foundations. Finally, the influences of geometrical parameters, volume fraction index, elastic foundations, and the effectiveness of stiffeners on the nonlinear dynamic buckling of the S-FGM toroidal shell segments are discussed. The present results are compared with the available data for a special case.


ABSTRACT: The electrostatic forming membrane reflector antenna (EFMRA) is a promising scheme to construct large-size, high-precision and lightweight space deployable reflector antennas. A set of comprehensive structural optimization design procedures is presented for EFMRA in this paper. This procedure consists of four steps: Firstly, a synthesized form-finding method is introduced for the AstroMesh structure which is the structural foundation of the EFMRA. Based on the nonlinear force density method, a fast iterative format is derived, using which we can get a initial state in which the tensions of the front rear cable networks and one electrode membrane are completely uniform, and all the nodes of the front networks are on the ideal paraboloid. Secondly, based on the finite element theory, a structure-electrostatic coupled analysis model is established to take the coupled field problems into consideration. Thirdly, a technique is proposed to optimize the initial reflective membrane geometry. The shape of the membrane is expressed by a set of polynomials, and the polynomial coefficients are optimized to obtain optimal geometry of the reflective membrane. Moreover, the controlling voltage adjustment model is established, which is solved by sensitivity analysis. At length, these proposed methods are applied to the structural optimization design of an EFMRA. The results validate the effectiveness of this comprehensive optimization procedure and the feasibility of designing the EFMRA to compensate the errors introduced from manufacturing process and environmental changes.


ABSTRACT: A procedure for the characterization of low velocity impact damage and its effect on residual tensile and buckling behaviour of composite structures is presented. A simplified analytical method is used to enhance the damage simulation and a degradation model is introduced in the subsequent finite element analysis. Different degradation coefficients are defined for three impact energy stages. Two different types of analysis are performed using MD.Nastran software: the non-linear progressive failure analysis to estimate the residual tensile strength and the linear analysis to predict the critical uniaxial and shear buckling loads after impact. Tensile and buckling experiments are used to validate the present methodology. A good correlation is obtained for all the cases under investigation.

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“Nonlinear buckling analysis of the conical and cylindrical shells using the SGL strain based reduced order model and the PHC method”, Aerospace Science and Technology, Vol. 55, pp 103-110, August 2016
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ABSTRACT: Thin-walled conical and cylindrical shells subjected to axial compression often show a snap-back response in the presence of buckling. Newton iterations based path-following methods cannot trace reliably the snap-back response due to the extremely sharp turning angle near the limit point, and the original Koiter–Newton method also meets difficulties to achieve a complete post-buckling response beyond the limit point. In this paper, the improved Koiter–Newton method is proposed to trace the post-buckling path of cylinders and cones, in the framework of the reduced-order modeling technique. The polynomial homotopy continuation (PHC) method is used to solve the lower-order nonlinear reduced order model reliably and efficiently. The simplified Green–Lagrange (SGL) kinematics which consider the stress redistribution after buckling are implemented into the construction of the reduced order model to produce accurate results for curved shells. The numerical results presented reveal that the improved method is a robust and efficient technology to achieve the entire nonlinear response for the snap-back case.

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“Finite element implementation of Puck’s failure criterion for failure analysis of laminated plate subjected to biaxial loadings”, Aerospace Science and Technology, Vol. 55, pp 227-241, August 2016,
https://doi.org/10.1016/j.ast.2016.05.001
ABSTRACT: The present work proposes a finite element implementation of Puck's failure criterion for ultimate failure analysis of laminated composite plate via well-established higher order shear deformation theory (HSDT). A seven degree of freedom and Co continuity finite element model using nine noded isoparametric elements is developed for precise computation of ply-by-ply stresses of laminated composite plate subjected to various bi-axial loading. The physically based Puck's failure criterion based on Mohr–Coulomb hypothesis and a degradation model proposed by Puck is used in the present failure analysis procedure for computing first-ply failure (FPF) and last-ply failure (LPF) stress. The finite element implementation is carried out through a finite element code developed in MATLAB, where material non-linearity due to material behaviour under in plane loading and post FPF damage, was taken into account. The results obtained by present approach are compared with classical Tsai–Wu, Tsai–Hill, Lee's failure criteria and experimental results available in various literatures. The FPF and LPF stress envelopes for a critical lamina are obtained for various lamination schemes, thickness ratio, modulus ratio and different biaxial loading conditions for symmetric angle-ply and cross-ply laminates.

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ABSTRACT: In this paper, nonlinear transverse vibration characteristics of representative volume element (RVE) of nanocomposites are examined in order to predict the vibration behavior of a nanocomposite beam at macro scale. In this regard, firstly by a bridging method the mechanical properties of nanocomposites in macro scale are determined for different state of dispersions based on the micro scale investigation. For this purpose, RVEs containing nanotubes are used with different length ratios which represent a certain state of dispersion on the macro scale. Then, the vibration equations of volume element are obtained and free vibration behavior of RVE is investigated in different boundary conditions (BCs). The non-dimensional natural frequency of nanocomposites as a function of vibration amplitude showed that the BCs have a great effect on the rate of the system nonlinear behavior. Results indicate that in clamped–pinned condition the nonlinear frequency rate is approximately 20% more than clamped–clamped condition, which shows a more nonlinear behavior. Next, the forced vibration behavior of RVE is determined using the three methods of perturbation theory, least squares and harmonic balance influenced by sinusoidal force and resonance phenomenon and the super harmonic behaviors of the systems are investigated. Results indicate that the methods for the solution of the equation of system are effective in predicting the element's behavior. The harmonic balance method shows results that are almost equal to the average of the two other methods. Moreover, most non-linear behavior is observed in the perturbation theory. The examination of the super harmonic behavior of RVEs indicated that jump phenomena in representative model with pinned–pinned BC for a constant force are more sensitive than other conditions.

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ABSTRACT: In this paper, an analytical solution is developed to investigate the thermal buckling behavior of the imperfect rectangular plates with functionally graded (FG) coatings under uniform temperature rise. Material properties of the FG coatings are assumed to be temperature-dependent and to continuously vary in the thickness direction using the power law distribution of volume fraction of metal and ceramic. Theoretical formulations are based on the classical plate theory with von-Karman nonlinear kinematic relations. The initial geometrical imperfections of plates are also accounted. By using the Galerkin method and the Airy stress function, the resulting equations are solved to obtain the closed form expressions for nonlinear equilibrium paths. Effects of power law index, imperfection, geometric parameters, and temperature distributions on the response of rectangular plates with FG coatings are discussed in details.


ABSTRACT: The response of a stiffened circular composite spar subjected to bending was studied analytically using a modified Brazier approach. The spar caps were placed in the top and bottom sectors of a spar to increase the bending capabilities such as the rigidity and collapse load. The mathematical model to predict the collapse load of the stiffened circular spar was derived using the linear elastic energy method. Numerical simulations were performed to estimate the effect of the spar caps on the failure load and compared with the presented model. A static experimental test was performed on a prototype stiffened spar, and the test results were compared with a mathematical model. The results show that the modified Brazier approach can reasonably predict the collapse load.


ABSTRACT: The dynamic version of the Extended High Order Sandwich Panel Theory (EHSAPT) for a sandwich beam with soft core and carbon nanotube reinforced composite (CNTRC) face sheets is first formulated. Distribution of fibers through the thickness of the face sheets could be uniform or functionally graded (FG). The influences of boundary conditions on dynamic response of the sandwich panel are investigated. In each type of boundary condition the effects of nanotube volume fraction and their distribution pattern, core-to-face sheet thickness ratio, on many essential involved parameters of the sandwich beam with functionally graded carbon nanotube reinforced composite (FG-CNTRC) face sheets are studied in detail. The results for a transient displacement of sandwich beam with isotropic face sheets reveal that the EHSAPT is very accurate during the initial, transient phase of dynamic loading in comparison with conventional high order sandwich panel theory (HSAPT). Finally, it is concluded that the sandwich beam with V distribution figure of face sheets is the strongest and the smallest transverse displacement, followed by the X, UD, O and W-ones, respectively.

Alireza Jahanpour and Farhad Roozbahani (Department of Civil Engineering, Malayer University, Malayer, Iran), “An applicable formula for elastic buckling of rectangular plates under biaxial and shear loads”
ABSTRACT: As thin plates have relatively big thickness ratios, their elastic buckling usually occurs before the yielding. From beginning of the previous century, many researchers have considered various in-plane loading states on thin plates and have strived to find simple equations to predict the buckling load. However, there are few valid equations with negligible errors for a thin plate, when it is under all of in-plane loads. In this paper, using energy method, an applicable formula is suggested for a simply supported rectangular plate, which is under biaxial and shear loads. The biaxial loads can be applied in the compressive/compressive, compressive/tensile, and tensile/tensile states on the plate. Generally, 15-129 examples are considered for this problem. The aspect ratio of plates varies from 1 to 5 and for each case and with the known load ratios, the plate buckling coefficient is calculated. Then, by using the regression techniques and interpolation, it is tried to estimate a simple equation with minimum error to predict the buckling load. The confirmed results show that for the biaxial compression and shear state, the maximum error is 8%, and for the compression–tension–shear and biaxial tension and shear states, it increases until 20%.

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ABSTRACT: This paper presents the study of influence of core geometry on vibration and acoustic response characteristics of sandwich panels which are used as aerospace structures. Sandwich panels considered in this research work are: (a) Honeycomb core, (b) Truss and Z core, (c) Foam core. The present study has found that (i) For a honeycomb core sandwich panel in due consideration to space constraint, the better acoustic comfort can be achieved by reducing the core height and increasing the face sheet thickness. (ii) It is demonstrated that, for a honeycomb core sandwich panel, vibration and acoustic response is not sensitive to the cell size. (iii) It is observed that, triangular core gives better acoustic comfort for the truss core sandwich panel compared to other type of core. (iv) For foam core sandwich panels, it is observed that sandwich panel with carbon-epoxy (high stiffness) face sheet radiates less sound in the lower frequency range (0–100 Hz). While the sandwich panel with Titanium (high density) face sheet radiates less sound at the higher frequencies. In order to reduce the preprocessing time and computational effort throughout the analysis in the present study, equivalent 2D elastic properties are calculated and used to find out the vibration and acoustic response characteristics.


ABSTRACT: Present study deals with the free vibration analysis of skew plates made from functionally graded carbon nanotube reinforced composites. Carbon nanotubes as reinforcements are distributed across the thickness of the plate. Distribution pattern may be uniform or functionally graded. The developed formulation from a Cartesian coordinate system is transformed to an oblique coordinate system to satisfy the boundary conditions. The virtual strain and kinetic energies of the plate are obtained using the first order shear deformation plate theory. Ritz method whose shape functions are developed according to the Gram–Schmidt process is implemented to construct an eigenvalue problem associated to the natural frequencies of the plate.
The developed solution method is general and may be used for arbitrary boundary conditions of the plate. Results are compared for isotropic homogeneous and composite laminated plates in skew shape with the available data in the open literature. Afterwards numerical results are provided for skew plates reinforced with carbon nanotubes. It is shown that volume fraction of carbon nanotubes and their distribution pattern are both influential of natural frequencies of the carbon nanotube reinforced plates. Generally, the higher the volume fraction of carbon nanotubes, the higher the natural frequencies of the skew plate.

ABSTRACT: Flexible hexagonal honeycomb cores exhibit nonlinear elastic properties due to the large geometric deformation. To rapidly and efficiently analyze the mechanical properties of honeycomb sandwich structures, it is standard to replace the actual core structure in analyses with a homogenized core material presenting reasonably equivalent elastic properties. As such, a convenient and efficient method is required to evaluate the equivalent elastic properties of flexible hexagonal honeycomb cores. The present work develops analytical expressions based on a deformable cantilever beam under large deformation. On that basis, the equivalence expressions are improved by including the stretching deformations of the honeycomb structure on an infinitesimal section of a unit cell. Finite element analysis and experimental testing are subsequently performed for two examples of flexible hexagonal aluminium and Nomex® honeycomb cores. Both computational and experimental results indicate that their equivalent elastic moduli have the different variation with high strain in the two characteristic orthogonal directions. The analytical predictions demonstrated that the improved analytical expressions are more suitable to flexible honeycomb cores under conditions of high strain and low elastic modulus. It is further revealed that the structure of Nomex honeycomb cores result in different forms of damage during failure along the different load directions, which lead to differing equivalent properties in the orthogonal directions when the strain limit is reached.

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ABSTRACT: A numerical model is presented in this paper to simulate the aerodynamic behavior of combined conical–cylindrical shells. This class of structures is of great interest due to its extensive use in aeronautical and aerospace applications. Two distinct semi-analytical finite elements are used to model a combined axisymmetric shell for better geometrical consistency. The structural formulation is a combination of the finite element method and classical shell theory. The displacement functions of each finite element are derived from exact solutions of Sanders' shell equilibrium equations. The linearized first-order piston theory formula is applied to take into account the aerodynamic interaction effect. For a liquid contained in the combined shell, the fluid pressure is derived from the velocity potential, Bernoulli equation and from the impermeability condition applied to ensure permanent coupling at the fluid–solid interface. Initial stress stiffening due to axial compression and/or radial pressure is accounted for by generating an additional stiffness matrix. The elementary
matrices of the solid and fluid corresponding to each finite element are calculated using exact analytical integration. Results obtained using the present approach in various conditions such as under vacuum, filled with liquid and subjected to supersonic flow are compared to those in published experimental or numerical works. Good agreement is found.

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ABSTRACT: This paper presents a generalized layerwise higher-order shear deformation theory for static, free vibration and buckling analyses of symmetric laminated composite and sandwich plates using improved meshfree radial point interpolation method (iRPIM). The approach comes from a layerwise model combined with a generalized higher-order shear deformation theory. In other words, we impose the continuity on the interface of each layer for the in-plane displacements and transverse shear stresses. This yields more adequate solution for sandwich structures which present the significant difference of properties between the core sheet and the face ones. As a result, transverse shear stresses are accurately achieved as compared with the analytical ones. The present iRPIM shows stability and high accuracy with respect to the uniquely proposed correlation function. A simple but effective enforcement based on the concept of the rotation-free of essential boundary conditions yields significant advantage of computations. The numerical results are provided and compared well with other published solutions.

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ABSTRACT: This work presents an analysis of the thermo-mechanical behavior of rotating discs made of functionally graded material (FGM) with variable thickness. The solutions are obtained by variable material property (VMP) theory. In this theory, the domain is divided into some finite sub-domains in the radial direction, in which the thermo-mechanical properties are assumed to be constant and the form of the elastic response is used to solve elastic–plastic problems. The results obtained by the VMP method are then compared with the results obtained by the finite element analysis using ANSYS software. In addition, the unloading and reverse yielding behavior of FG rotating disk are investigated and the residual stresses are then calculated with the same values of pressure and temperature by VMP theory and FE analysis. The results reveal that the mentioned methods are in very good agreement in both elastic and elasto-plastic states. Also, the effect of
considering the temperature-dependent material properties is discussed. It is found that the results obtained by ignoring the temperature-dependent material properties lead to high discrepancies in comparison with those by considering that. Subsequently, the effect of various parameters including the disk geometry, temperature distribution, and boundary conditions on the stress behavior of disk is investigated. The results show that unlike the uniform rotating discs in which the yielding necessarily initiates from the inner radius, in the FG rotating discs, plasticity can be initiated from any point.


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ABSTRACT: Considered in this paper is a special case relating to the large deflection of a thin beam. One end of the beam is fixed (i.e., clamped) to a rigid wall, whereas the other end is placed on a flat surface of arbitrary orientation. In previous studies, unique and non-unique solutions to the deflected shape were derived for cases in which the curvature of the beam experiences at least one change in sign. In this paper, a special case is examined in which the curvature of the beam does not change sign. Experimental results from photographs of deflected beams are presented to support the numerical predictions. An excellent agreement was found between the photographed and the predicted shapes.

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ABSTRACT: The present work uses a finite-element approach to study vibration, buckling, and dynamic instability characteristics in damaged cross-ply and angle-ply curved panels. The panels are subjected to nonuniform, centrally, and edge-distributed follower loading. First order shear-deformation theory was used to model the doubly curved panels and was formulated in accordance with Sanders’ first approximation. An anisotropic damage formulation was used to model damage. An analysis was carried out on plate and shallow shells to obtain vibration, buckling, and static instability (i.e., divergence) and dynamic instability (i.e., flutter)
behavior. The effects of load type, load width, damage, and damage location on natural frequency, buckling load, divergence load, flutter load and flutter frequency were studied. The effect of curvature to improve the stability characteristics of panels is discussed. The desirable position of damage on a panel is discussed on the basis of different stability behavior. Results indicate that narrow edge loading is undesirable in most cases.

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ABSTRACT: A failure analysis of composite plates accounting for localized loadings is presented in this work. A unified formulation is adopted to derive classical, higher order, layerwise, and mixed theories. A closed form, Navier-type solution is assumed. Simply supported, cross-ply laminates are investigated. Plates are subjected to a stepwise loading, an off-centric localized one and a localized moment. First-ply failure loading and index are obtained via several failure criteria. The influence of the side-to-thickness ratio is accounted for investigating thin and very thick plates. Symmetric and asymmetric stacking sequences are investigated. The accuracy of the proposed theories is assessed. On the basis of the obtained results, it can be concluded that higher order models are required for a correct failure analysis in which the three-dimensional stress state attributable to the localized loadings is accurately described.

ABSTRACT: In this paper a general solution to the geometrically nonlinear analysis of plates stiffened by arbitrarily placed parallel beams of arbitrary monosymmetric cross sections with a deformable connection subjected to arbitrary loading is presented. The plate-beam structure is assumed to undergo moderate large deflections and the nonlinear analysis is carried out by retaining the nonlinear terms in the kinematical relationships. According to the proposed model, the stiffening beams are isolated from the plate by sections in the lower outer surface of the plate under the hypothesis that the plate and the beams can slip in all directions of the connection without separation, while the arising tractions in all directions at the fictitious interfaces are taken into account. These tractions are integrated with respect to each half of the interface width, yielding two interface lines along which the loading of the beams as well as the additional loading of the plate are defined. Their unknown distribution is established by applying continuity conditions at the interfaces in all directions, taking into account their relationship with the interface slip through the shear connectors’ stiffness. Any distribution of connectors in each direction of the interfaces can be handled. The utilization of two interface lines for each beam enables the nonuniform distribution of the interface transverse shear forces and the
nonuniform torsional response of the beams to be taken into account. Six boundary value problems are formulated and solved using the analog equation method, a boundary element-based method. Application of the boundary element technique leads to a system of nonlinear and coupled algebraic equations that is solved using iterative numerical methods. The adopted model permits the evaluation of the shear forces at the interfaces in both directions; the knowledge of which is very important in the design of prefabricated ribbed plates.

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ABSTRACT: A cable-braced grid shell is a new type of single-layer latticed shell suitable for glass roofs. Compared with traditional single-layer latticed shells, this new type of shell has a unique mesh shape (planar quadrilateral mesh), mesh form (steel and crossing cables), and surface shape (from the translation surface method). The grid shell is a single-layer latticed structure, and therefore stability is one of the key factors in the structural design. Therefore, in this paper, an elliptic paraboloid cable-braced grid shell with imperfections is used as an example with which to determine the formulas for the buckling load based on the continuum analogy. The main contents of this paper include the formula for the linear buckling load of an elliptic paraboloid cable-braced grid shell with imperfections, which is determined based on the continuum analogy. The equivalent rigidity for the cable-braced grid shell is then determined, and the effect of the cables on the shear rigidity is discussed. Finally, the formula for the linear buckling load is verified with numerical examples, and the errors are analyzed and a corresponding correction factor is given.

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ABSTRACT: The finite-element methodology is presented to evaluate the energy absorption performance of staggered triangular honeycombs under in-plane crushing loadings at impact velocities of 50–300 m/s. The minimum dynamic cushioning coefficient is proposed to characterize the maximum energy absorption efficiency of staggered triangular honeycombs. When all configuration parameters are constant, the energy absorption per unit volume is proportional to the square of the impact velocity; for a given impact velocity, the energy absorption per unit volume is related to the ratio of the cell wall thickness to the edge length by a power law and to the expanding angle by complicated analytical equations. The maximum energy absorption efficiency is insensitive to the impact velocity. Only for the smaller ratio of the cell wall thickness to the edge length does the maximum energy absorption efficiency increase with the increasing expanding angle. At a given impact velocity there is a threshold ratio of the cell wall thickness to the edge length. The maximum energy absorption efficiency decreases abruptly when the ratio is larger than the threshold. The threshold ratio is
approximately equal to 0.04.


ABSTRACT: In the current study, a semianalytical closed-form solution is presented for the first time for buckling analysis of two-directional, functionally graded (FG) circular plates with variable thickness supported by both constrained edges and two-parameter elastic foundations. It is assumed that the material properties of the functionally graded material (FGM) vary in the transverse and radial directions, simultaneously. While variations of the elasticity modulus in the transverse direction is described by a power-law, variations of the material properties and the thickness in the radial direction are assumed to obey exponential laws. Mindlin’s shear deformation plate theory and the differential transform technique are employed to develop the governing equations. A sensitivity analysis including evaluation of effects of various edge conditions, geometric parameters, coefficients of the elastic foundation, and material heterogeneity is performed. Results reveal that the strength degradation caused by the radial thickness reduction may be compensated by an appropriate increasing of the elasticity modulus in the radial direction. Furthermore, the elastic foundation may significantly affect the buckling load in some circumstances.


ABSTRACT: Eccentric discharge in slender metal silos is known to be one of the most critical load conditions, responsible for many silo buckling disasters in the past. The high failure rate may be significantly attributed to difficulties in devising a suitable wall pressure representation for this condition. Where the flow of stored solids is eccentric and has partial contact with the wall in a slender silo, the solid exerts much lower pressures than the adjacent stationary solid. This pressure drop leads to very high local axial compression and causes buckling failure. Experimentally measured pressures indicate that a significant rise in pressure may occur just outside the flow channel, but its form and magnitude are not yet well understood because very detailed and expensive instrumentation is needed to obtain data that can define it. This paper explores the nonlinear structural behaviour and buckling of a slender metal silo with and without specific inclusion of an adjacent rise in pressure, to determine whether it is a necessary part of any design pressure representation. To assist this investigation, the mechanics of the nonlinear behaviour of a cylindrical silo under this load condition is explored using the analogy of a propped cantilever slice-beam. Advantage is taken of a particular load condition that leads, by chance, to buckling at the same load factor for both linear and geometrically nonlinear analyses. This special case permits the detrimental effect of wall flattening and the beneficial effect of the changing prebuckling stress pattern to be explored to give a deeper insight into the behaviour. The slice-beam analogy may also be generalised to describe the nonlinear behaviour of any thin-walled cylindrical shell under meridional strip-like loads acting on part of the circumference.

ABSTRACT: A three-dimensional (3D) method of analysis is presented for determining the free vibration frequencies of hemispherical shells of revolution having linearly varying thickness along the meridional direction (\(\phi\)) with and without an axial conical hole fixed at the bottom edge and with the remaining boundaries free based upon a curvilinear coordinate system (\(\phi, z, \theta\)) using the Ritz method. A convergence study is presented. Natural frequencies from the present 3D analysis are also compared with those from other 3D finite methods.

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ABSTRACT: An analytical study of local buckling of discrete laminated plates or panels of fiber-reinforced plastic structural shapes is presented. Two cases of composite plate analyses with two opposite edges simply supported and the other two opposite edges either both rotationally restrained or one rotationally restrained and the other free, are studied. Generic loading cases with combined linearly varying axial and in-plane shear loading are considered. A variational formulation of the Ritz method is used to establish the eigenvalue problem for the local buckling behavior, and explicit expressions for predictions of the plate buckling stress resultants, in terms of the rotationally restrained stiffness, the plate aspect ratio, and the ratios of applied stress resultants, are developed. Based on different boundary and loading conditions, simple and explicit local buckling solutions for several special cases are further reduced. Validity of the explicit solutions presented is demonstrated by a good agreement of comparisons between the present predictions and available solutions in the literature. Parametric studies are further conducted, and the influences of several parameters such as the rotationally restrained stiffness, biaxial loading stress ratio, material flexural orthotropy, and linearly varying axial loading stress gradient on the local buckling stress resultants are discussed.

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ABSTRACT: An analytical pilot model for interactive buckling in sandwich struts with cores made from a functionally graded material based on total potential energy principles is presented. Using a Timoshenko beam approach, a system of nonlinear differential and integral equations is derived that predicts critical and secondary
instabilities. These are validated against numerical simulations performed within the commercial finite-element package *Abaqus*. Good agreement is found, and this offers encouragement for more elaborate models to be devised that can account for face-core delamination—a feature where functionally graded materials are known to offer distinct advantages.

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ABSTRACT: The effect of fiber orientation is studied on the failure load of a laminated curved panel subjected to uniaxial compression for a combination of simply supported and clamped boundary conditions. The failure modes are specified as buckling and first-ply failure, with the failure load defined as the minimum of these two loads. The panel is taken as a shear-deformable symmetrically laminated angle-ply laminate, and the effect of fiber orientation on the failure load is investigated by considering several laminations consisting of 0, 90, and $\theta$ ply angles and by determining the failure load for different aspect ratios and panel thicknesses. The best ply angles for each stacking sequence are determined to maximize the failure load and the stacking sequence giving the highest failure load. The numerical results are obtained using an eight-noded shell finite element that avoids the parasitic shear or shear locking problem. It is observed that the rotational restraints at the curved edges have a major effect on the failure load.


ABSTRACT: This paper presents a study on the thermal postbuckling response of a shear deformable functionally graded cylindrical shell of finite length embedded in a large outer elastic medium. The surrounding elastic medium is modeled as a Pasternak foundation. Two kinds of micromechanics models, namely the Voigt model and Mori-Tanaka model, are considered. The governing equations are based on a higher-order shear deformation shell theory that includes shell-foundation interaction. The thermal effects are also included and the material properties of functionally graded materials (FGMs) are assumed to be temperature dependent. The governing equations are solved by a singular perturbation technique. The numerical results show that in some cases the FGM cylindrical shell with intermediate volume fraction index does not have intermediate buckling temperature and thermal postbuckling strength. The results reveal that Voigt model and Mori-Tanaka model have the same accuracy for predicting the thermal buckling and postbuckling behavior of FGM shells. The results confirm that for the case of heat conduction, the postbuckling equilibrium path for geometrically perfect FGM cylindrical shells with simply supported boundary conditions is no longer of the bifurcation type.

Nuno Silvestre and Dinar Camotim (Dept. of Civil Engineering, Instituto de Engenharia de Estruturas, Território e Construção (ICIST), Instituto Superior Técnico, Technical Univ. of Lisbon, 1049-001 Lisbon, Portugal), “Generalized beam theory to analyze the vibration of open-section thin-walled composite members”,

ABSTRACT: This paper presents the formulation of a generalized beam theory (GBT) to analyze the vibration behavior of composite thin-walled prismatic members displaying straight axis, open-section, and arbitrary orthotropy. It accounts for the effects of (1) the cross section in-plane deformation, (2) geometric and material couplings, (3) primary and secondary warping, and (4) rotary inertia. First, the GBT equilibrium equations and boundary conditions are derived, and their terms are physically interpreted, i.e., related to the member mechanical properties. Then, a few remarks on the cross-section mechanical properties appearing in the linear stiffness and inertia terms are presented. Finally, to clarify the concepts involved in the proposed GBT formulation and illustrate its application and capabilities, an in-depth study concerning the local and global vibration behavior of lipped channel members with (1) simply supported end sections and wall cross-ply orthotropy and (2) fixed (clamped) end sections and wall nonaligned orthotropy are presented and discussed in detail.


ABSTRACT: This paper presents the incorporation of shear deformation effects into a generalized beam theory (GBT) formulation developed to analyze the first-order (linear) and buckling behavior of composite thin-walled members made of laminated plates displaying arbitrary orthotropy, often designated as anisotropic laminates. Unlike other existing beam theories, the proposed GBT formulation incorporates in a unified fashion (1) elastic coupling effects, (2) warping effects, (3) cross-section in-plane deformation, and (4) shear deformation. The main concepts and procedures involved in the currently available GBT are adapted and/or modified to account for the specific aspects associated with shear deformation. In particular, the GBT equilibrium equations and boundary conditions are derived, and their terms are physically interpreted. A lipped channel section is considered to illustrate the performance of a GBT cross-section analysis, namely, the operations required to determine the (additional) set of shear deformation modes. Finally, to clarify the concepts involved in the proposed GBT formulation and illustrate its application and capabilities, two numerical examples are presented and discussed in detail: the first concerns the first-order and buckling behaviors of a lipped channel column exhibiting nonaligned orthotropy; and the second assesses the influence of shear deformation on the buckling behavior of lipped channel columns with cross-ply orthotropy.


ABSTRACT: Based on Eringen’s nonlocal elasticity theory, a new nonlinear, nonlocal constitutive relation in polar coordinates is presented for axisymmetric bending of annular graphene-like nanoplate. Instead of the common strain gradient theory, an iterative procedure is developed to solve the coupled nonlinear constitutive relations and to express the nonlocal stresses asymptotically in stress gradients with increasing orders. Subsequently, the nonlocal strain energy is formulated similarly to that of gradient elasticity, and the potential energy of external forces is obtained. Because analytical solutions are not available to date, a computational
approach is developed to compute the minimum total energy and to establish the bending equilibrium condition of the nonlocal nanoplate. In a mathematically asymptotic manner, the nonlocal bending deflection function is approximated by finite polynomials that satisfy the admissible geometric boundary conditions. A numerical algorithm based on a minimum energy approach is subsequently developed to solve the coefficients of the nonlocal deflection function. To demonstrate the accuracy and computational efficiency, four practical examples with different boundary conditions and external loadings are presented. After verifying numerical convergence with increasing orders of polynomials, the numerical solutions show that the dimensionless maximum deflection decreases with increasing nonlocal effect. The analytical and numerical solutions presented here will assist in behavioral analyses for graphene and graphene-like structures and their performances.

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ABSTRACT: This paper is devoted to the analytical and numerical modeling of the lateral-torsional stability of horizontally layered composite beams. Composite beams are classified as horizontally layered beams with interlayer slip or sandwich beams with a weak shear core. The governing differential equations of the out-of-plane behavior of horizontally layered composite beams are supported by variational arguments. In the theoretical analysis, a distinction is made between the influence of the shear connection at the interface with respect to the in-plane or transversal deformations and to the out-of-plane or lateral deformations, respectively. Some engineering results are presented for a partially composite beam under pure bending moment. In the case of noncomposite in-plane action (orthotropic connection), a simple closed-form solution is derived for the lateral-torsional buckling moment, and it is shown that the exact dimensionless buckling moment depends only on two structural parameters for beams composed of two identical subelements. The results are analogous to those obtained for the in-plane buckling of partially composite or sandwich-type beams, where the buckling moment increases with the stiffness of the shear connection. Prandtl’s valid solution for lateral-torsional buckling of ordinary beams is also found for composite beams in the case of noncomposite action in both the transversal and lateral directions. A generalization of Prandtl’s valid solution for composite beams with partial composite action in the lateral direction and noncomposite action in the transversal direction is derived. It is shown that the lateral-torsional buckling formulas are strongly affected by the kinematics of the connected shear layer. Also, the lateral-torsional buckling of partially composite beams with both in-plane and out-of-plane slip behavior is analyzed using the Rayleigh-Ritz method. This mathematical problem leads to a system of differential equations with nonuniform coefficients. An approximated solution is derived for the isotropic connection with isotropic noncomposite actions, whereas an exact solution is presented for the orthotropic connection with noncomposite in-plane action. Finally, the Rayleigh-Ritz approach is compared with some numerical results associated with the exact resolution of the differential equations with nonuniform coefficients. The Rayleigh-Ritz approach appears to be efficient to capture the main phenomena, including the nonmonotonic dependence of the buckling load to the connection parameter.
ABSTRACT: Wood I-joists are efficient and lightweight structural members that are well suited for long-span floor and rafter applications. However, because of the thin-wall nature of the web and relatively low stiffness, local web buckling of the joist is an issue that must be considered. To increase the buckling capacity of these joists, investigators at West Virginia Univ. and Univ. of Idaho developed web panels with a sinusoidal geometry, instead of the flat web panels commonly used for prefabricated I-joists. This study presents analytical modeling, experimental testing, and finite-element (FE) analysis of the local buckling capacities of these sinusoidal web panels under compression. The flanges and web are not rigidly connected; thus, this problem can be described as the instability of a sinusoidal shell with two rotationally restrained loaded edges under compression. Using an energy method, the critical compression buckling stresses were obtained in terms of the elastic rotational restraint stiffness. The analytical solution was verified by FE analysis. Compression tests were performed for joists with both flat and sinusoidal webs, each at two different heights, to evaluate the elastic rotational restraining effect and illustrate the increase of the buckling capacities for sinusoidal webs compared with flat webs. Finally, a parametric study was conducted to study the core aspect ratio effect on the buckling load. The method described in this paper can be further extended to determine local buckling capacities of other structural shapes with elastic restraints along the loaded edges.

ABSTRACT: The buckling response of symmetric laminates that possess strong flexural-twist coupling is studied using different methodologies. Such plates are difficult to analyze because of localized gradients in the mode shape. Initially, the energy method (Rayleigh-Ritz) using Legendre polynomials is employed, and the difficulty of achieving reliable solutions for some extreme cases is discussed. To overcome the convergence problems, the concept of Lagrangian multiplier is introduced into the Rayleigh-Ritz formulation. The Lagrangian multiplier approach is able to provide the upper and lower bounds of critical buckling load results. In addition, mixed variational principles are used to gain a better understanding of the mechanics behind the strong flexural-twist anisotropy effect on buckling solutions. Specifically, the Hellinger-Reissner variational principle is used to study the effect of flexural-twist coupling on buckling and also to explore the potential for developing closed-form solutions for these problems. Finally, solutions using the differential quadrature method are obtained. Numerical results of buckling coefficients for highly anisotropic plates with different boundary conditions are studied using the proposed approaches and compared with finite-element results. The advantages of both the Lagrangian multiplier theory and the variational principle in evaluating buckling loads are discussed. In addition, a new simple closed-form solution is shown for the case of a flexurally anisotropic plate with three sides simply supported and one long edge free.
ABSTRACT: This paper presents analytical approximate solutions for the initial postbuckling deformation of sandwich beams including transverse shear. The approximate procedure is based on the nonlinear beam equation (with transverse shear included) by coupling the well-known Maclaurin series expansion and orthogonal Chebyshev polynomials; the governing differential equation with sinusoidal nonlinearity can be reduced to form a cubic-non-linear equation. Analytical approximations to the resulting boundary condition problem are established by combining the methods of Newton linearization and harmonic balance. Unlike the classical method of harmonic balance, the linearization is performed prior to proceeding with harmonic balancing thus resulting in a set of linear algebraic equations instead of one of nonlinear algebraic equations, thereby establishing analytical approximate solutions. Illustrative examples are presented for a few typical sandwich construction configurations, and it is shown that the proposed approximate solutions are in excellent agreement with the numerical solution obtained via the shooting method for both small and large angles of rotation.

ABSTRACT: In this paper, the buckling behavior of generic higher-order shear beam models is investigated in a unified framework. This paper shows that most higher-order shear beam models developed in the literature (polynomial, sinusoidal, exponential shear strain distribution assumptions over the cross section) can be classified in a common gradient elasticity Timoshenko theory, whatever the shear strain distribution assumptions over the cross section. The governing equations of the bending/buckling problem are obtained from a variational approach, leading to a generic sixth-order differential equation. Buckling solutions are presented for usual archetypal boundary conditions such as pinned-pinned, clamped-free, clamped-hinge, and clamped-clamped boundary conditions. The results are then extended to general boundary conditions based on generalized linear elastic connection law including vertical and rotational stiffness boundary conditions. Engineering analytical solutions are derived in a dimensionless format. The model valid for macrostructures is generalized for micro- or nanostructures using the nonlocal integral Eringen’s model. The nonlocal framework is also developed in a variational consistent framework. Buckling solutions are finally presented for the nonlocal higher-order beam/column models.
ABSTRACT: The analytical strip method (ASM) is extended in this paper to the buckling analysis of antisymmetric laminated composite plates with bending-extension coupling. A system of three equations of equilibrium governing the buckling response of antisymmetric laminated composite plates is reduced to a single eighth-order partial differential equation, expressed in terms of a displacement function. This equation is then solved analytically to generate the critical value of the in-plane forces (\(N_x, N_y\)) for antisymmetric cross-ply and angle-ply laminated and stiffened composite plates. The effects of various parameters, including plate aspect ratio, plate orthotropy ratio, beam rigidity, and plate bending-extension coupling on the critical values of \(N_x\) and \(N_y\) on antisymmetric laminated composite plates are discussed. The results derived using the ASM are presented in tabular and graphical forms and compare very well with ones derived using finite-element analysis.

M.M. Shokrieh and A. Askari (Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran Univ. of Science and Technology, Narmak, Tehran 16846-13114, Iran), “Similitude study of impacted composite laminates under buckling loading”, ASCE Journal of Engineering Mechanics, Vol. 139, No. 10, October 2013, https://doi.org/10.1061/(ASCE)EM.1943-7889.0000560

ABSTRACT: In this study, critical buckling load of an impacted composite laminate is predicted, using the structural similitude method. Because of impact loading, damaged regions have formed in the laminate. To establish similarity conditions between impacted laminates for buckling loading, the idea of sequential similitude method is introduced. According to the sequential similitude method, similarity conditions can be established for a structure subjected to different loading situations, provided that each loading event is simulated independently. On the basis of this method, to develop similarity conditions for buckling loading of impacted composite laminates, similarity conditions are developed first for impact loading and then for buckling loading separately. Afterward, the obtained conditions are implemented in the commercial finite-element software, ABAQUS, to obtain the critical buckling load. Results show that sequential similitude method can be used as a simple and accurate method for prediction of buckling load of impacted laminates.

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ABSTRACT: In this paper, a new solution method is proposed for investigation of the vibration characteristics of finite-length circular cylindrical shells with a circumferential part-through crack. Four representative sets of boundary conditions are considered: simply supported, clamped-clamped, clamped-simply supported, and clamped-free. The governing equation of the cracked cylindrical shell is derived by integrating the line-spring model with the classical thin shell theory. A computationally efficient numerical solution method for determining the natural frequency of the system of a given mode is proposed. The algorithm calculates the natural frequency from an initial trial through a one-dimensional optimization process. Two initial trial estimation methods are considered: the beam-function method and Soedel’s expression method. On the basis of
the case study results, a recommendation is made on the selection of a suitable initial trial calculation method. The verification of the proposed method is divided into two parts. In the first part, the intact cylindrical shell analysis results obtained from the proposed method are compared with those from the literature and from finite-element (FE) analysis using Ansys. Because relevant cracked cylindrical shell analysis results are not available from the literature, the proposed method’s performance in this case is verified using the FE method alone in the second part. The verification results demonstrate that the proposed method provides a fast and efficient way to calculate the time-domain responses of a cracked cylindrical shell. Furthermore, the case study results indicate that the dynamic characteristics of short shells are more sensitive to circumferential surface cracks than those of long shells. This observation makes it possible to extend the proposed cracked shell modeling method to crack detection following the model-based approach, especially for short shell members.


ABSTRACT: The objective of this paper is to provide the theoretical background and illustrate the capabilities of the constrained finite strip method (cFSM) for thin-walled members with general end boundary conditions. Based on the conventional finite strip method (FSM), cFSM provides a mechanical methodology to separate the deformations of a thin-walled member into those consistent with global, distortional, local, and other (e.g., shear and transverse extension) modes. For elastic buckling analysis, this enables isolation of any given mode (modal decomposition) or quantitative measures of the interactions within a given general eigenmode (modal identification). Existing cFSM is only applicable to simply supported end boundary conditions. In this paper, FSM is first extended to general end boundary conditions, including simply–simply, clamped–clamped, simply–clamped, clamped–guided, and clamped–free. Next, with the conventional FSM for general end boundary conditions in place, the derivation of the constraint matrices for global, distortional, local, and other modes that play a central role in cFSM are summarized. Several bases (i.e., the constraint matrices) are presented for general end boundary conditions involving, in particular, different orthogonalization conditions. For modal identification, normalization schemes for the base vectors as well as the summation method employed for the modal participation calculation are also provided. Numerical examples of modal decomposition and identification are illustrated for a thin-walled member with general end boundary conditions. Recommendations on the choice of basis, orthogonalization, and normalization are provided.


ABSTRACT: In many cases, an arch may have in-plane elastic end restraints provided by the connected structures or elastic foundations, which may influence the elastic lateral-torsional buckling of the arch. However, little research of the lateral-torsional buckling of arches with elastic end restraints has been reported in the open literature. This paper analytically investigates the lateral-torsional buckling of pin-ended circular arches having in-plane elastic rotational end restraints under a uniform radial load. The analytical solutions for the prebuckling behavior of such an arch show that the uniform radial load produces combined axial compressive and bending actions in the arch and that the axial compressive force produced by the uniform
radial load is approximately uniform along the arch axis. It is found that the stiffness of elastic rotational end restraints has significant effects on the magnitude and distribution of the axial compressive forces and bending moments. The axial compressive force decreases with an increase of the stiffness of rotational end restraints. The analytical solution for the lateral-torsional buckling load of the arch is derived, which accounts for the effects of rotational end restraints. It is found that the effects of the stiffness of rotational end restraints on the lateral-torsional buckling load are profound. The buckling load increases with an increase of the stiffness of the end restraints. It is demonstrated by comparisons with the finite-element results that the analytical solution provides good predictions for the lateral-torsional buckling load of both shallow and deep arches having in-plane rotational end restraints.

Yue Huang and Ehab Hamed (Center for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, Univ. of New South Wales, Sydney, NSW 2052, Australia), “Buckling of one-way high-strength concrete panels: Creep and shrinkage effects”, ASCE Journal of Engineering Mechanics, Vol. 139, No. 12, December 2013, https://doi.org/10.1061/(ASCE)EM.1943-7889.0000629

ABSTRACT: A nonlinear theoretical model is developed in this paper for investigating the time-dependent behavior of one-way high-strength RC panels, with particular emphasis on the combined effects of creep and shrinkage on the buckling capacity and its degradation with time. A rheological generalized Maxwell chain model is used for modeling the creep of the concrete including its cracking, tension stiffening, and aging through strain- and time-dependent springs and dashpots. The incremental governing equations of the panel are derived and solved through a step-by-step time analysis that takes into account the variation of the internal stresses and deformations with time. A smeared cracking model is adopted, and an iterative procedure is conducted at each time step for the determination of the unknown rigidities of the cracked section, as well as the length of the cracked region. The capabilities of the proposed model are demonstrated through numerical and parametric studies, which show the important roles of creep and shrinkage in the buckling of high-strength concrete panels and which reveal the sensitivity of the nonlinear response to the magnitude and eccentricity of the sustained load and to the reinforcement ratio.

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ABSTRACT: This paper presents the development and application of a simplified analytical model to analyze the energy response of an idealized composite sandwich panel under blast loads. The model is used to gain insight into optimizing the energy absorption capabilities, and thus blast resistance, of the core of these structures. The analytical predictions calculate spatial and time variations in blast pressure as a result of charge size and location as well as the corresponding structural response based on velocity transfer among the sandwich panel components and discretization of the sandwich panel into a system of single degree of freedom mass-spring systems. The energy absorption mechanisms considered include absorbed strain energy as a result of inelastic deformation of the core and energy dissipation through progressive failure of the core, where the failure criterion is the failure strain where the composite material loses strength. The results demonstrate that energy absorption is maximized when failure of the core is prevented. The accuracy of the program as a result of the simplifying assumptions made in the derivation of the analytical approach is also reviewed.

ABSTRACT: In this paper, buckling delamination around interface inner cracks contained within the simply supported elastic and viscoelastic rectangular sandwich plate under biaxial loading is studied. It is assumed that the materials of the face layers are viscoelastic and the material of the core layer is pure elastic. Moreover, it is assumed that the material of the core layer is stiffer than the materials of the face layers. Within these assumptions it is supposed that between the face and core layers there are rectangular inner cracks, the locations of which are symmetric with respect to the plate geometry. The edge surfaces of the cracks have insignificant initial imperfections before the loading. The evolution of these initial imperfections with the flow of time is investigated within the scope of the three-dimensional (3D) geometrically nonlinear field equations of the theory of viscoelasticity. For determination of the values of the critical parameters (buckling force, time, and buckling mode), the initial imperfection criterion (i.e., the case where the size of the initial imperfection starts to increase and grows indefinitely) is used. Mathematical modeling of the corresponding boundary value problem is formulated within the framework of the piecewise homogeneous body model. To solve the corresponding boundary-value problems, boundary form perturbation techniques, the Laplace transform, 3D FEM modeling and the Schapery method are used. The numerical results related to the influence of the materials or geometrical parameters of the plate on the critical parameters and critical time are presented and analyzed.

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ABSTRACT: This study presents the buckling analysis of a radially loaded, solid, circular plate made of porous material. Properties of the plate vary across the thickness. The edge of the plate is either simply supported or clamped and the plate is assumed to be geometrically perfect. The geometrical nonlinearities are considered in the Love-Kirchhoff hypothesis sense. The equilibrium and stability equations, derived through the variational formulation, are used to determine the prebuckling forces and critical buckling loads. The equations are based on the Sanders nonlinear strain-displacement relation. The porous plate is assumed to be of the form where pores are saturated with fluid. The results obtained for porous plates are compared with the homogeneous and porous/nonlinear, symmetric distribution, circular plates.


ABSTRACT: In this paper, a new quasi-three-dimensional (3D) hyperbolic shear deformation theory for the bending and free vibration analysis of functionally graded plates is developed. By dividing the transverse
displacement into bending, shear, and thickness stretching parts, the number of unknowns and governing
equations of the present theory is reduced, and hence makes it simple to use. The present plate theory approach
accounts for both transverse shear and normal deformations and satisfies the zero traction boundary conditions
on the surfaces of the plate without using shear correction factor. Unlike any other theory, the number of
unknown functions involved in displacement field is only five, as against six or more in the case of other shear
and normal deformation theories. A comparison with the corresponding results is made to check the accuracy
and efficiency of the present theory.

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Laboratory of Digital Manufacture for Thin-Walled Structures, Shanghai Jiao Tong Univ., Shanghai 200240,
China), “Large-amplitude vibration analysis of shear deformable laminated composite cylindrical shells with
initial imperfections in thermal environments”, ASCE Journal of Engineering Mechanics, Vol. 140, No. 3,
March 2014, https://doi.org/10.1061/(ASCE)EM.1943-7889.0000675
ABSTRACT: Large-amplitude vibration analysis for a shear deformable cross-ply laminated composite
cylindrical shell of finite length in thermal environments is presented. The material of each layer of the shell is
assumed to be linearly elastic and fiber reinforced. The motion equations are based on Reddy’s higher-order
shear deformation shell theory with a von Kármán-Donnell–type of kinematic nonlinearity. The thermal effects
and initial imperfections of the shell are both taken into account. A two-step perturbation technique is employed
to determine the linear and nonlinear frequency of the laminated cylindrical shells. The numerical illustrations
concern the nonlinear vibration behavior of laminated composite cylindrical shells with different values of
geometric parameters and different cases of thermal environmental conditions. The results show that the shell
has relatively lower natural frequencies when the temperature-dependent properties are taken into account. The
results reveal that the temperature changes, initial imperfections of the shell, and the shell geometric parameter
have significant effects on the nonlinear vibration behavior of laminated composite cylindrical shells.

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“Ideal location of intermediate ring stiffeners on discretely supported cylindrical shells”, ASCE Journal of
ABSTRACT: Silos in the form of a cylindrical metal shell are commonly elevated to provide access to the
space beneath, permitting the contained materials to be directly discharged. A few discrete column supports at
evenly spaced intervals are commonly used. However, the structural design of discretely supported cylindrical
shells presents a variety of challenges. The presence of discrete supports results in circumferential
nonuniformity in the axial compressive stress as well as a progressive vertical decay above the support. Several
approaches can be adopted in design depending on the severity of the nonuniformity of the stresses. Relevant
research to date has focused mostly on the behavior of cylinders supported on brackets, local forces at the base,
or stiff ring beams. The use of intermediate ring stiffeners to provide circumferential uniformity in the axial
membrane stresses has long been recognized, but few studies have given a clear view of the practical
requirements for such rings. In this paper, a combination of base and intermediate ring stiffeners is explored to
develop a practical and cost-effective solution that leads to more uniformity in the axial membrane stresses
above the intermediate ring stiffener. For the purposes of obtaining a simple analytical solution, the cylindrical
shell is subjected to the fundamental harmonic of the column support and analyzed using membrane theory. It is
shown that an ideal location exists for an intermediate ring stiffener such that the axial membrane stress above
this ring is circumferentially completely uniform. The ideal location of this ring is determined analytically and is expressed in terms of the basic geometric variables. This ideal ring location is then independently verified using many linear finite-element analyses. A further study explores the effect of placing the intermediate ring stiffener below the ideal location. The results are presented in a manner that makes them suitable for direct adoption into traditional design specifications.

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ABSTRACT: The shear lag effect is one of the very important mechanical characteristics of thin-walled box girders and has been studied over several decades. However, the generalized displacement adopted in many papers is not very simple or clear, and the analytical procedure is somewhat complicated. In this paper, a new method for analyzing the shear lag effect in thin-walled box girders is proposed in which the additional deflection induced by the shear lag effect is adopted as a generalized displacement to describe the shear lag deformation state. Based on the generalized moment for shear lag defined in this paper, the shear lag deformation state is separated from the flexural deformation state of the corresponding elementary beam and analyzed as a fundamental deformation state. The governing differential equation and boundary condition for the additional deflection are established by applying the principle of minimum potential energy, and the initial parameter solution to the differential equation is given. A very simple and convenient formula of shear lag warping stress is proposed that has the same form as that of the bending stress of the elementary beam. A finite beam segment element with eight degrees of freedom is developed to analyze the shear lag effect in complex continuous box girders with varying depth. An example of a simply supported concrete box girder is provided in which the results obtained by the present method are compared with those by FEM, finite-strip method, and other existing analytic methods. A three-span continuous box-girder model with varying depth is also analyzed, and the calculated results are in a good agreement with the test results on the whole, which validates the analytical method and the element presented.

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ABSTRACT: A crack in a steel structure will cause a local change in its stiffness. The change in stiffness will lead to a change in buckling loads and a discontinuity in the associated buckling modes. The changes in the buckling characteristics of columns cause a change in the buckling stability of the structure. The effect of cracks on the buckling load of structural systems can be investigated through numerical methods. The FEM is a well-known method for this work. In this paper, a new and innovative finite-element (FE) formulation for the buckling analysis of cracked columns is presented. The method presented is simpler and, at the same time, more accurate and practical than those available in the literature. The proposed FE formulation for cracked columns has the same format as that for intact columns. The formulation is used successfully in efficient and accurate buckling analysis of cracked frames.
ABSTRACT: Buckling and vibration characteristics of thin, symmetrically laminated, elliptical composite plates under initial in-plane edge loads and resting on Winkler-type elastic foundation are presented based on the classical laminated-plate theory. The governing equations were obtained from the variational approach and solved by the Ritz method. Extensive numerical data are provided for the first three natural frequencies as a function of in-plane load, and critical buckling loads as a function of aspect ratio for various classical edge conditions (free, clamped, and simply supported). Moreover, the effects of fiber orientation on the natural frequencies and buckling loads of laminated angle-ply plates, with stacking sequence of $[(\alpha/\beta/\alpha/\beta)]_s$, were studied for chosen foundation parameter. Selected deformation buckling mode shapes are illustrated. The accuracy of calculations was checked by performing good convergence studies, and the correctness of results is established by comparison to existing results in the literature and FEM data.

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ABSTRACT: In this research, a new method and numerical procedure for determining the plastic limit load in shell intersections using elastic-plastic finite-element analysis are presented. The proposed method is based on the maximum criterion of the rate of the change of the relative plastic work. For experimental models of cylindrical vessels with radial nozzles under in-plane moment, the results of comparisons with the twice elastic slope method were considered for determining the plastic limit moment. A parametric study of the nonradial cylindrical shell intersections subjected to in-plane moment on the nozzle was performed to examine the influence of an angular parameter on the plastic limit moment on the basis of the proposed criterion.

https://doi.org/10.1061/(ASCE)EM.1943-7889.0000764
ABSTRACT: The present investigation deals with the nonlinear stability behavior of cross-ply laminated composite circular cylindrical shells subjected to partial and complete edge loading along with uniform external pressure. The shell is modeled using Donnell’s shell theory including the first-order shear deformation theory (FSDT). The analysis uses the simply supported boundary condition (at $x=0$, $L N_{xx}=N_{xx}$, $w=M_{xx}=v=\Phi_{\theta}=0$). The equations governing the nonlinear stability behavior of cylindrical shells are derived in terms of displacements ($u$-$v$-$w$) and rotations ($\Phi_x$, $\Phi_\theta$). The applied partial edge loading is expressed in terms of Fourier series, and stress distributions within the cylindrical shell are determined by prebuckling analysis. The study uses multiterm Galerkin’s method along with the Newton-Raphson method to solve the governing partial differential equations of the shell nonlinear stability. With the help of numerical investigations, the authors present the number of modes required for the postbuckling analysis and the influence of initial
geometric imperfections on the equilibrium path in the presence of partial edge loading. They have developed a simple algorithm based on potential theory to locate the exact location of bifurcation and limit points on the equilibrium path using the bisection method.

ABSTRACT: Stiffeners are used to reduce the probability of local failures in structures. Local stiffening is of interest in civil, mechanical, and aerospace engineering. In this paper, a stiffener is modeled by a massless spring. The spring introduces a fall (inverse jump) in a function of displacement. For example, a torsion spring produces a fall in the tangent to the lateral displacement of a flexural member. The effect of stiffeners on the free-vibration analysis of structural frames is considered, and governing equations are derived. In the case of simple members, the closed-form solution, and in the case of stiffened structural frames, the finite-element formulation, are proposed. The formulation is implemented in a computer program. Through analyses of three examples, the accuracy, efficiency, and robustness of the work are verified.

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ABSTRACT: An approximate solution to the nonlinear problem of an elastic stiffener welded to an elastic plate is obtained in the form of a finite sum of Chebyshev polynomials. To an exact first-order approximation, the deformed length of the stiffener is proved to be greater than its undeformed length. Other conclusions show that the longitudinal force decreases when elongation of the stiffener is included, whereas the concentration coefficient, defined in terms of the singular behavior of the interactive force between the stiffener and the plate that occurs at either end, decreases when the elongation is sufficiently large.

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ABSTRACT: Review of the literature on first-ply failure of composite shells shows that research reports on first-ply failure of moderately thin, laminated composite cylindrical shell panels, using a geometrically nonlinear approach, are not available. The present paper aims to fill this deficiency. It uses a finite-element code developed using eight-noded, doubly-curved elements combined with modified Sanders’ first-approximation theory for thin shells and von Kármán-type nonlinear strains. The accuracy of the present geometric nonlinear and first-ply failure formulations are verified separately through solutions of two benchmark problems. Failure loads, failure modes (for individual stress or strain failure) or tendencies (for interactive stress failures), and the locations from where the failures initiate are reported. The results are discussed critically to formulate design
guidelines, suggesting practical values for factors of safety applicable to failure loads. Such suggestions also consider the serviceability requirements.

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ABSTRACT: The damage to pipelines from submarine landslides or debris flows has been vastly reported. In this paper, the behavior of pipelines is investigated through analytical and numerical analyses. A refined analytical method is first brought forward by improving the tension assumption. The pipeline is divided into different segments based on loading conditions, and the continuity of displacement, inclination angle, bending moment, and shear are all preserved. Then numerical analysis by vector-form intrinsic FEM is carried out by further considering the axial soil resistance at the sliding zone. The numerical analysis demonstrates that the initial negative pipeline displacement is a threat to pipeline safety because of the large increase in bending moment. The axial tension is closely related to the location of the landslide impact and the initial pipeline configuration. The variations in displacement and tension with time are also investigated in the parametric analysis.

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ABSTRACT: For the nonlocal theory of structures, Eringen’s small length-scale coefficient $e_0$ may be identified from atomistic modeling or experimental tests. In this study, Eringen’s small length-scale coefficients are presented for the vibration and buckling of nonlocal rectangular plates with simply supported edges. The coefficients are calibrated by comparing the vibration frequency and buckling loads obtained from a nonlocal plate and a microstructured beam-grid model with the same characteristic length. The beam-grid model is composed of rigid beams connected by rotational and torsional springs. It is found that the small length-scale coefficient $e_0$ varies with respect to the initial stress, rotary inertia, mode shape, and aspect ratio of the rectangular plate.

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ABSTRACT: The governing equations for the stability analysis of stochastic frame structures with small variations of the material and geometry parameters are established for the means and deviations of responses by including first-order terms. Taking advantage of the similarity between these equations and the governing
equations for static analysis, a new Green’s function method based on the fundamental solutions for static problems is proposed for the stability analysis of stochastic structures in conjunction with multidomain techniques. The numerical examples presented show that there is good agreement between the results of the proposed method and those from Monte Carlo simulation for small variation situations, and that the new approach is more efficient than the perturbation stochastic FEM. Based on the numerical results, the effects of the covariance type, correlation scale parameter, coefficient of variation, and discretization of random fields, as well as the location of fictitious loads, are investigated.

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ABSTRACT: A closed-form solution and finite-element formulation are developed for the dynamic analysis of thin-walled members with asymmetric open sections subjected to harmonic forces. The dynamic equations of motion and associated boundary conditions are derived from Hamilton’s principle. The formulation is based on a generalized Vlasov-Timoshenko beam theory and accounts for the effects of shear deformation caused by bending and warping and translational and rotary inertia effects. It also captures the effects of flexural-torsional coupling caused by cross-sectional asymmetry. From this a general closed-form solution is obtained. A family of shape functions is then developed based on the exact solution of the coupled field equations and is used to formulate a beam finite element. The new element has two nodes with six degrees of freedom per node and successfully captures the coupled bending-torsional static and steady-state responses of asymmetric thin-walled members under harmonic forces. Results based on the closed-form solution and finite-element formulation are assessed and validated against other well-established finite-element solutions.

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ABSTRACT: This paper discusses self-supporting sandwich panels, which are used as wall and roof cladding. They consist of two external thin and flat facings and a thick soft core. The panels are subjected to mechanical and temperature actions. The aim of this paper was to find the optimal solution for supports of a multispan sandwich structure. The following support models were considered: rigid support and linear-elastic support, with or without an imposed limit of elastic deflection. The problem was formulated as a two-criterion optimization (i.e., the maximization of the load multiplier and the maximization of the allowable length of the span). The criteria were in mutual exclusion (i.e., the results of the optimization comprise a set of nondominated optimal solutions). It shows that the optimal choice of supporting conditions remarkably improves the capacity of thermally loaded sandwich panels used in civil engineering.
https://doi.org/10.1061/(ASCE)EM.1943-7889.0000860
ABSTRACT: An accurate three-dimensional (3D) elasticity solution is presented for static analysis of flat laminated panels with interlaminar bonding imperfection under arbitrary boundary conditions exhibiting edge effects. The recently developed mixed-field multiterm extended Kantorovich method (MMEKM) for 3D solution of perfectly bonded laminates is generalized to include the interfacial compliance characterized by displacement jumps. A general variationally consistent framework using the Reissner-type mixed variational principle is proposed to treat the imperfect interfacial conditions. It is shown through numerical studies on composite and soft-core sandwich panels under different boundary conditions that, similar to the perfect bonding case, the MMEKM yields accurate results with just two or three terms and in two or three iterations for the weakly bonded laminates also. The roles that the boundary conditions, locations of the imperfect interfaces, and span-to-thickness ratios play on the effect of weak bonding on the response of laminated structures are investigated for a wide range of values for the imperfection compliance.

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ABSTRACT: For exposed subsea pipelines, lateral buckles are usually artificially triggered as an accommodation technique to release thermal expansion by providing temporary flotation with controlled spacing. With the given buoyancy load, the pipeline will be uplifted initially and will then buckle laterally under a certain thermally induced axial load, which is called the bifurcation load. Previous studies have analyzed this problem and modeled the uplifted pipeline as a fixed-fixed end beam, assuming the lateral seabed stiffness is infinite. However, the lateral seabed stiffness is usually low because the seabed is formed from soft soils. Using analytical methods, this paper investigates the buoyancy load required to trigger lateral buckles along a pipeline, considering a seabed with finite elastic stiffness, and provides suggestions for the buoyancy design with an elastic-plastic seabed model using an example of finite-element analysis. It was found that the seabed condition significantly influenced the flotation design.

Farid Mahboubi Nasrekani and Hamidreza Eipakchi (Mechanical Engineering Faculty, Shahrood Univ., P.O. Box 316, 3619995161 Shahrood, I.R. Iran), “Nonlinear analysis of cylindrical shells with varying thickness and moderately large deformation under nonuniform compressive pressure using the first-order shear deformation theory”, ASCE Journal of Engineering Mechanics, Vol. 141, No. 5, May 2015
https://doi.org/10.1061/(ASCE)EM.1943-7889.0000875
Also see: Erratum for this paper in Vol. 141, No. 11
ABSTRACT: In this paper, the displacements of a cylindrical shell with varying thickness and subjected to axial and external pressure are calculated analytically using the first-order shear deformation theory. The kinematics of the problem is defined by von Kármán theory, and the constitutive equation obeys Hooke’s law. The governing equations, which are a system of nonlinear differential equations, are extracted by applying the virtual work principle; the matched asymptotic expansion method of the perturbation technique is used to calculate the analytical solution. The effects of different load profiles and thicknesses on the results are investigated. Also, a comparison with the FEM is performed.

ABSTRACT: A three-dimensional (3D) method of analysis is presented for determining the free-vibration frequencies of complete hollow spherical shells of revolution with variable thickness. Unlike conventional shell theories, which are mathematically two-dimensional (2D), the present method is based on the 3D dynamic equations of elasticity. Displacement components $u_r$, $u_\theta$, and $u_z$ in the radial, circumferential, and axial directions, respectively, are taken to be periodic in $\theta$ and in time, and algebraic polynomials in the $r$- and $z$-directions. Potential (strain) and kinetic energies of the complete hollow spheres are formulated, and the Ritz method is used to solve the eigenvalue problem, thus yielding upper-bound values of the frequencies by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the complete hollow spheres. Comparisons are also made between the frequencies from the present 3D method, a 2D thin-shell theory, and two other 3D analyses.

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ABSTRACT: An analytical approach is presented to investigate the linear buckling of eccentrically stiffened functionally graded thin toroidal shell segments subjected to axial compression, lateral pressure, and hydrostatic pressure. On the basis of classical thin shell theory, the smeared stiffener technique and the adjacent equilibrium criterion, the governing equations of buckling of eccentrically stiffened functionally graded toroidal shell segments are derived. The functionally graded toroidal shell segments with simply supported edges are reinforced by a ring and stringer stiffener system on an external surface. The resulting equations in the case of compressive and pressure loads are solved directly. The obtained results show the effects of stiffeners and input factors on the buckling behavior of these structures. In this paper, the results are also compared with the solutions published in the literature for the specific cases of a toroidal shell.

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ABSTRACT: In this paper, an analytical model is developed to determine the torsional-flexural buckling load of a channel column braced by unevenly distributed batten plates. Solutions of the critical-buckling loads were derived for three boundary cases using the energy method in which the rotating angle between the adjacent
battens was presented in the form of a piecewise cubic Hermite interpolation (PCHI) for unequally spaced battens. The validity of the PCHI method was numerically verified by the classic analytical approach for evenly battened columns and a finite-element analysis for unevenly battened ones, respectively. Parameter studies were then performed to examine the effects of loading eccentricities on the torsional-flexural buckling capacity of both evenly and unevenly battened columns. Design parameters taken into account were the ratios of pure torsional buckling load to pure flexural–buckling load, the number and position of battens, and the ratio of the relative extent of the eccentricity. Numerical results were summarized into a series of relative curves indicating the combination of the buckling load and corresponding moments for various buckling ratios.

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ABSTRACT: Two finite-element formulations are developed for the general distortional analysis of beams with monosymmetric sections. In the first formulation, cubic and linear Hermitian polynomials are adopted to interpolate the nodal displacements; whereas in the second formulation, shape functions that exactly satisfy the governing field equations were used. Because the distortional lateral-torsional and the longitudinal-transverse responses are fully uncoupled, separate finite elements were developed for both types of behaviors. A comparison with other finite-element solutions and a recently developed distortional theory established the validity of the present formulations. A study was then performed on the stability and convergence characteristics of both elements. The new elements were then adopted to solve linearly static analysis of simple beams and beams with overhangs. The formulation is shown to reliably capture the difference in behavior between stiffened and unstiffened beams.

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ABSTRACT: When a beam is subjected to an in-plane linear temperature gradient field, the thermal effects of the temperature gradient field tend to change the curvature of the beam in the transverse direction and to expand the beam in the axial direction. The rotation and expansion of the ends of the beam may be restrained elastically by its supports or by adjacent members such as columns. The restrained thermal actions will produce bending moments and compressive forces in the beam, and when these actions reach critical values the elastically restrained beam may bifurcate from its primary in-plane equilibrium configuration to an out-of-plane buckled equilibrium configuration. This paper investigates the thermoelastic out-of-plane buckling of an elastically restrained beam with a doubly symmetric cross section that is subjected to an in-plane linear temperature gradient field. The analytical solution for the critical temperature gradient for thermoelastic out-of-plane buckling of the beam is derived. It is found that the positions of the effective centroid and shear center of a cross section subjected to a linear temperature field are different from those under mechanical loads. Beams having a doubly symmetric cross section under a linear temperature gradient field behave as beam-columns with a monosymmetric cross section, thereby rendering the thermoelastic out-of-plane buckling of an elastically restrained beam under a linear temperature gradient field more complicated than its counterpart under mechanical loading.
ABSTRACT: In this work, the nonlinear flexural behavior of laminated carbon/epoxy composite panels is investigated numerically using a generalized nonlinear mathematical model based on two higher-order shear deformation midplane kinematics and Green-Lagrange type geometrical nonlinearity. The exact flexural behavior of the laminated panel is computed by considering all the nonlinear higher order terms in the present mathematical model. The nonlinear governing equations are obtained using variational principles and discretized through suitable finite-element steps. The desired nonlinear responses are computed numerically using the direct iterative method. The proposed nonlinear models have been validated by comparing the responses with those available in published literature and the experiment (three-point bend test) as well. In addition, the linear and nonlinear flexural responses of the laminated carbon/epoxy flat panel are also computed using ANSYS 13.0 simulation finite element analysis package. Finally, the efficacy and applicability of the proposed models have been checked by solving some numerical examples for different geometrical parameters (thickness ratio, aspect ratio, curvature ratio, and constraint condition) and discussed in detail. The practical importance of the proposed nonlinear higher-order theory for the laminated structure is highlighted by comparing the linear and nonlinear responses with experimental (three-point bend test) and simulation results.

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ABSTRACT: This paper studies the flexural performance of sandwich panels composed of a soft polyurethane foam core and glass-fiber-reinforced polymer (GFRP) skins. A robust numerical model is developed to predict the full load-deflection and strain responses of the panel. It is based on equilibrium and strain compatibility and accounts for the excessive shear deformation and material nonlinearity of the core. It also accounts for geometric nonlinearity in the form of localized deflection of the loaded skin using the principals of beam-on-elastic foundation and the change in core thickness due to its softness. The model incorporates various failure criteria, namely core shear failure, core flexural tension or compression failure, compression skin crushing or wrinkling, or tensile rupture of skin. The model has the advantage of being able to isolate quantitatively the individual contributions of flexure, shear, and localized skin deformations, to overall deflection. A parametric study is performed to examine the effects of core density and skin thickness on panel behavior. It is shown that as the core density increases from 32 to 192kg/m³, the contribution of shear to overall deflection reduces from about 90 to 10%. It also appears that the optimal core density of the sandwich panels is within 96 to 128kg/m³, which represents the lowest density necessary to achieve the highest ultimate strength and stiffness

E. Lucena Neto, F.A.C. Monteiro and P.T.M.L. Soares (Instituto Tecnológico de Aeronáutica, São José dos Campos 12228-900, SP, Brazil), “Exact solution for buckling of axially compressed cylindrical panels with

ABSTRACT: This paper presents an exact solution for the boundary-value problem which describes the linear buckling of axially compressed circular cylindrical panels with stringers attached to the straight edges. The boundary conditions differ from the classical simply supported ones, often assumed for design purposes, in the sense that the torsion resisted by the stringers are also taken into account. The presence of the stringers makes the results reported herein of practical interest and valuable as benchmark data.

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ABSTRACT: This paper presented new analytical solutions for the elastic buckling of Eringen’s nonlocal columns with allowance for selfweight. A discrete column model on the basis of the central finite difference formulation and the equivalent Hencky bar-chain model also were presented for this buckling problem. The discrete column model allows one to determine the buckling solutions of columns constructed from repetitive cells. In addition, one may use the discrete buckling solutions to calibrate the small-length scale coefficient $e_0$ in the Eringen’s nonlocal column model. It was found that $e_0$ values varied from 0.289 to 0.373 with respect to increasing selfweight for clamped-free column case, from 0.289 to 0.276 for the pinned-pinned column case, and from 0.289 to 0.281 for the clamped-clamped column case.

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ABSTRACT: This paper revisits the nonlinear in-plane analysis of a shallow pin-ended circular arch under a central concentrated load. It is found that the arch may have multiple equilibrium branches and limit points, and a modified slenderness of the arch defined in the paper plays an important role in the number of the limit points and equilibrium branches. The analytical solution for the specific modified slendernesses that switch the number of equilibrium branches and limit points is derived. The analytical solutions for the load, axial force, and radial displacements corresponding to the specific modified slendernesses are also derived. This paper deepens the understanding for the geometric nonlinear analysis of circular arches and their geometric softening and stiffening behavior and provides useful benchmarks for the analyses of shallow arches. In addition, this paper extends the current solutions of nonlinear equilibrium of arches associated with axial compression to those associated with axial tension caused by large deformations.
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ABSTRACT: A three-dimensional (3D) Ritz method of analysis is presented for determining the free vibration frequencies of completely free, toroidal shells of revolution with hollow circular cross-section having variable thickness. Displacement components ur, uθ, and uz in the radial, circumferential, and axial directions, respectively, are taken to be sinusoidal in time, periodic in θ, and ordinary algebraic polynomials in the r and z directions. Strain and kinetic energies of the torus are formulated, and upper bound values of the frequencies are obtained by minimizing the frequencies. As the degree of the polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the torus. Comparisons are made between the frequencies from the present 3D Ritz method, a 3D finite-element method, experimental methods, and thin and thick ring theories.

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ABSTRACT: This study deals with the geometric nonlinear analysis of the plane problem based on the corotational formulation. Both analytical solutions and hybrid stress functional will be utilized in the proposed technique. A quadrilateral four-node element with drilling degrees of freedom is proposed for the finite-element analysis. The corotational method is applied for the nonlinear behavior. In this way, small strains and rigid body motions can be separated. Based on analytical solution, the hybrid stress scheme is used in the local coordinates for small strains. By using Allman’s quadratic displacement, the boundary condition for this element is introduced. In this approach, added drilling degrees of freedom increase the accuracy and robustness of the element. Furthermore, the corotational formulas are written in the local and global coordinates system to derive the nonlinear relations. These equations were solved by using the arc-length algorithm. To investigate the accuracy and capability of the suggested element, several numerical tests are performed. Findings prove the advantage of the proposed element in the geometric nonlinear analysis of plane problems.

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ABSTRACT: The pb2-Ritz method and the homotopy shape function are used for bending, buckling, and vibration analyses of equilateral triangular plates with rounded corners. On the basis of the comprehensive results obtained, it is found that the deflection shape, buckling load, and fundamental frequency vary nonlinearly with respect to the corner roundedness parameter α and Poisson’s ratio for simply supported plates, whereas these aforementioned results vary nonlinearly with respect to α only for clamped plates. The use of the pb2-Ritz method facilitates the development of approximate formulas for the accurate prediction of deflection shapes, buckling loads, and fundamental frequencies for simply supported and clamped rounded-corner equilateral triangular plates. These formulas presented in this paper should be useful for designers working on
such plates.

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ABSTRACT: An analytical framework has been proposed to analyze the effect of random structural irregularity in honeycomb core for natural frequencies of sandwich panels. Closed-form formulas have been developed for the out-of-plane shear moduli of spatially irregular honeycombs following minimum potential energy theorem and minimum complementary energy theorem. Subsequently an analytical approach has been presented for free-vibration analysis of honeycomb core sandwich panels to quantify the effect of such irregularity following a probabilistic paradigm. Representative results have been furnished for natural frequencies corresponding to low vibration modes of a sandwich panel with high length-to-width ratio. The results suggest that spatially random irregularities in honeycomb core have considerable effect on the natural frequencies of sandwich panels.

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ABSTRACT: In nonlinear structural dynamics, direct integration algorithms are used to solve the differential equations of motion after they are temporally discretized. Explicit algorithms do not require iterations and thus avoid numerical problems of convergence by making use of certain approximations. Thus, they are appealing for multi-degree-of-freedom (MDOF) nonlinear dynamic problems. In this paper, the study previously conducted by the authors for nonlinear single-degree-of-freedom systems is extended to MDOF ones to investigate the Lyapunov stability of explicit algorithms. For this purpose, a generic-explicit integration algorithm is formulated for generic MDOF nonlinear systems with softening or stiffening behavior governed by nonlinear functions of the restoring forces. This approach transforms the stability analysis of the formulated nonlinear system to investigating the strictly positive realness of its corresponding transfer function matrix. Furthermore, this is equivalent to a problem of convex optimization that can be solved numerically. Using this approach, a sufficient condition that the bounds where the explicit algorithm is stable in the sense of Lyapunov for the MDOF nonlinear system can be obtained. This approach is applied to two commonly used explicit integration algorithms for a bridge structure and also demonstrated by a generic nonlinear multistory shear building.

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ABSTRACT: The equilibrium governing equations of nonlocal anisotropic thin-walled circular cylindrical shell under combined axial compressive force, torsional load, and external pressure are explicitly derived. This is
accomplished by appropriately combining the equilibrium equations and the strain-displacement relations according to Flügge’s shell theory and the stress-strain equations of Eringen’s nonlocal elasticity theory. An analytical solution for the buckling of the shells is presented by using the complex method. This model is validated by a good agreement between the results given by the present model and available data in the literature. Furthermore, the model is utilized to elucidate the buckling properties for different load combinations.


ABSTRACT: In this paper, we study the static bending and free vibration of cross-ply laminated composite plates using sinusoidal deformation theory. The plate kinematics is based on the recently proposed Carrera Unified Formulation (CUF), and the field variables are discretized with the non-uniform rational B-splines within the framework of isogeometric analysis (IGA). The proposed approach allows the construction of higher-order smooth functions with less computational effort. Moreover, within the framework of IGA, the geometry is represented exactly by the Non-Uniform Rational B-Splines (NURBS) and the isoparametric concept is used to define the field variables. On the other hand, the CUF allows for a systematic study of two dimensional plate formulations. The combination of the IGA with the CUF allows for a very accurate prediction of the field variables. The static bending and free vibration of thin and moderately thick laminated plates are studied. The present approach also suffers from shear locking when lower order functions are employed and shear locking is suppressed by introducing a modification factor. The effectiveness of the formulation is demonstrated through numerical examples.

References listed at the end of the paper:


ABSTRACT: A comprehensive micromechanical model for the analysis of a smart composite piezo-magneto-thermoelastic thin plate with rapidly varying thickness is developed in the present paper. A rigorous three-dimensional formulation is used as the basis of multiscale asymptotic homogenization. The asymptotic homogenization model is developed using static equilibrium equations and the quasi-static approximation of Maxwell’s equations. The work culminates in the derivation of a set of differential equations and associated boundary conditions. These systems of equations are called unit cell problems and their solution yields such coefficients as the effective elastic, piezoelectric, piezomagnetic, dielectric permittivity and others. Among these coefficients, the so-called product coefficients are also determined which are present in the behavior of the macroscopic composite as a result of the interactions and strain transfer between the various phases but can be absent from the constitutive behavior of some individual phases of the composite material. The model is comprehensive enough to allow calculation of such local fields as mechanical stress, electric displacement and magnetic induction. In part II of this work, the theory is illustrated by means of examples pertaining to thin laminated magnetoelastic plates of uniform thickness and wafer-type smart composite plates with piezoelectric and piezomagnetic constituents. The practical importance of the model lies in the fact that it can be successfully employed to tailor the effective properties of a smart composite plate to the requirements of a particular engineering application by changing certain geometric or material parameters. The results of the model constitute an important refinement over previously established work. Finally, it is shown that in the limiting case of a thin elastic plate of uniform thickness the derived model converges to the familiar classical plate model.

ABSTRACT: A comprehensive micromechanical model for the analysis of a smart composite piezo-magneto-thermoelastic thin plate with rapidly varying thickness is developed in Part I of this work. The asymptotic homogenization model is developed using static equilibrium equations and the quasi-static approximation of Maxwell’s equations. The work culminates in the derivation of general expressions for effective elastic, piezoelectric, piezomagnetic, dielectric permittivity and other coefficients. Among these coefficients, the so-called product coefficients are determined which are present in the behavior of the
macroscopic composite as a result of the interactions between the various phases but can be absent from the constitutive behavior of some individual phases of the composite structure. The model is comprehensive enough to also allow for calculation of the local fields of mechanical stresses, electric displacement and magnetic induction. The present paper determines the effective properties of constant thickness laminates comprised of monoclinic materials or orthotropic materials which are rotated with respect to their principal material coordinate system. A further example illustrates the determination of the effective properties of wafer-type magnetoelastic composite plates reinforced with smart ribs or stiffeners oriented along the tangential directions of the plate. For generality, it is assumed that the ribs and the base plate are made of different orthotropic materials. It is shown in this work that for the purely elastic case the results of the derived model converge exactly to previously established models. However, in the more general case where some or all of the phases exhibit piezoelectric and/or piezomagnetic behavior, the expressions for the derived effective coefficients are shown to be dependent on not only the elastic properties but also on the piezoelectric and piezomagnetic parameters of the constituent materials. Thus, the results presented here represent a significant refinement of previously obtained results.


ABSTRACT: The paper proposes a comparison between classical two-dimensional (2D) finite elements (FEs) and an exact three-dimensional (3D) solution for the free vibration analysis of one-layered and multilayered isotropic, composite and sandwich plates and cylinders. Low and high order frequencies are analyzed for thick and thin simply supported structures. Vibration modes are investigated to make a comparison between results obtained via the finite element method and those obtained by means of the exact three-dimensional solution. The 3D exact solution is based on the differential equations of equilibrium written in general orthogonal curvilinear coordinates. This exact method is based on a layer-wise approach, the continuity of displacements and transverse shear/normal stresses is imposed at the interfaces between the layers of the structure. The geometry for shells is considered without any simplifications. The 2D finite element results are obtained by means of a well-known commercial FE code. The differences between 2D FE solutions and 3D exact solutions depend on the considered mode, the order of frequency, the thickness ratio of the structure, the geometry, the embedded material and the lamination sequence.

References listed at the end of the paper:


ABSTRACT: This present paper has a complete and homogeneous presentation of plane stress and plane strain problems using the Strong Formulation Finite Element Method (SFEM). In particular, a greater emphasis is given to the numerical implementation of the governing and boundary conditions of the partial differential system of equations. The paper’s focus is on numerical stability and accuracy related to elastostatic and elastodynamic problems. In the engineering literature, results are mainly reported for isotropic and homogeneous structures. In this paper, a composite structure is investigated. The SFEM solution is compared to the ones obtained using commercial finite element codes. Generally, the SFEM observes fast accuracy and all the results are in very good agreement with the ones presented in literature.

References listed at the end of the paper:


[61] Tornabene F., 2-D GDQ solution for free vibrations of anisotropic doubly-curved shells and panels of revolution, Compos. Struct., 2011, 93, 1854-1876.


ABSTRACT: This paper presents a versatile and efficient modeling and solution framework for free vibration analysis of composite laminated cylindrical and spherical panels modeled according to two-dimensional equivalent singlelayer and layerwise theories of variable order. A unified formulation of the equations of motion is adopted which can be used for both thin and thick structures. The discretization procedure is based on the spectral collocation method and is presented in a compact matrix form which can be directly and easily implemented. The convergence and accuracy of the proposed approach is evaluated for panels having different boundary conditions, thickness and shallowness ratios, and lamination layups.

References listed at the end of the paper:


ABSTRACT: Within a setting where the isogeometric analysis (IGA) has been successful at bringing two different research fields together, i.e. Computer Aided Design (CAD) and numerical analysis, T-spline IGA is applied in this work to frictionless contact and mode-I debonding problems between deformable bodies in the context of large deformations. Based on the concept of IGA, the smooth basis functions are adopted to describe
surface geometries and approximate the numerical solutions, leading to higher accuracy in the contact integral evaluation. The isogeometric discretizations are here incorporated into an existing finite element framework by using Bézier extraction, i.e. a linear operator which maps the Bernstein polynomial basis on Bézier elements to the global isogeometric basis. A recently released commercial T-spline plugin for Rhino is herein used to build the analysis models adopted in this study. In such context, the continuum is discretized with cubic T-splines, as well as with Non Uniform Rational B-Splines (NURBS) and Lagrange polynomial elements for comparison purposes, and a Gauss-point-to-surface (GPTS) formulation is combined with the penalty method to treat the contact constraints. The purely geometric enforcement of the non-penetration condition in compression is generalized to encompass both contact and mode-I debonding of interfaces which is approached by means of cohesive zone (CZ) modeling, as commonly done by the scientific community to analyse the progressive damage of materials and interfaces. Based on these models, non-linear relationships between tractions and relative displacements are assumed. These relationships dictate both the work of separation per unit fracture surface and the peak stress that has to be reached for the crack formation. In the generalized GPTS formulation an automatic switching procedure is used to choose between cohesive and contact models, depending on the contact status. Some numerical results are first presented and compared in 2D for varying resolutions of the contact and/or cohesive zone, including frictionless sliding and cohesive debonding, all featuring the competitive accuracy and performance of T-spline IGA. The superior accuracy of T-spline interpolations with respect to NURBS and Lagrange interpolations for a given number of degrees of freedom (Dofs) is always verified. The isogeometric formulation is also extended to 3D bodies, where some examples in large deformations based on T-spline discretizations show an high smoothness of the reaction history curves.

References listed at the end of the paper:


ABSTRACT: In this paper free vibration behavior of laminated composite stiffened elliptical parabolic shell has been analyzed in terms of natural frequency and mode shape. Finite element method has been applied using an eight-noded curved quadratic isoparametric element for shell with a three noded curved beam element for stiffener. Cross and angle ply shells with different edge conditions have been studied varying the size and position of the cutouts to arrive at a set of inferences of practical engineering significances.

References listed at the end of the paper:

ABSTRACT: Analytical Strip Method is presented for the analysis of the bending-extension coupling problem of stiffened and continuous antisymmetric thin laminates. A system of three equations of equilibrium, governing the general response of antisymmetric laminates, is reduced to a single eighth-order partial differential equation (PDE) in terms of a displacement function. The PDE is then solved in a single series form to determine the displacement response of antisymmetric cross-ply and angle-ply laminates. The solution is applicable to rectangular laminates with two opposite edges simply supported and the other edges being free, clamped, simply supported, isotropic beam supports, or point supports.

References listed at the end of the paper:


ABSTRACT: In this paper, second order statistics of thermally induced post buckling response of elastically supported laminated piezoelectric composite plates using micromechanical approach is examined. A Co finite element has been used for deriving eigenvalue problem using higher order shear deformation theory (HSDT).
References listed at the end of the paper:


ABSTRACT: A hybrid-mixed ANS four-node shell element by using the sampling surfaces (SaS) technique is developed. The SaS formulation is based on choosing inside the nth layer In not equally spaced SaS parallel to the middle surface of the shell in order to introduce the displacements of these surfaces as basic shell variables. Such choice of unknowns with the consequent use of Lagrange polynomials of degree In – 1 in the thickness direction for each layer permits the presentation of the layered shell formulation in a very compact form. The SaS are located inside each layer at Chebyshev polynomial nodes that allows one to minimize uniformly the error due to the Lagrange interpolation. To implement the efficient analytical integration throughout the element, the enhanced ANS method is employed. The proposed hybrid-mixed four-node shell element is based on the Hu-Washizu variational equation and exhibits a superior performance in the case of coarse meshes. It could be useful for the 3D stress analysis of thick and thin doubly-curved shells since the SaS formulation gives the possibility to obtain numerical solutions with a prescribed accuracy, which asymptotically approach the exact solutions of elasticity as the number of SaS tends to infinity.

ABSTRACT: In this paper the free vibrations and buckling analysis of laminated plates is performed using a global meshless method. A refined version of Kant’s theory which accounts for transverse normal stress and through-the-thickness deformation is used. The innovation is the use of oscillatory radial basis functions. Numerical examples are performed and results are presented and compared to available references. Such functions proved to be an alternative to the tradicional nonoscillatory radial basis functions.

References listed at the end of the paper:


ABSTRACT: A review of literature reveals that bending analysis of laminated composite stiffened hypar shells with cutout have not received due attention. Being a doubly ruled surface, a skewed hypar shell fulfils aesthetic as well as ease of casting requirements. Further, this shell allows entry of north light making it suitable as civil engineering roofing units. Hypar shell with cutout subjected to uniformly distributed load exhibits improved performances with stiffeners. Hence relative performances of antisymmetric angle-ply laminated composite stiffened hypar shells in terms of displacements and stress resultants are studied in this paper under static loading. A curved quadratic isoparametric eight noded element and three noded beam elements are used to model the shell surface and the stiffeners respectively. Results obtained from the present study are compared with established ones to check the correctness of the present approach. A number of additional problems of antisymmetric angle-ply laminated composite stiffened hypar shells are solved for various fibre orientations, number of layers and boundary conditions. Results are interpreted from practical application standpoints and findings important for a designer to decide on the shell combination among a number of possible options are
References listed at the end of the paper:

ABSTRACT: In the present manuscript, free vibration response of circular cylindrical shells with functionally graded material (FGM) is investigated. The method of discrete singular convolution (DSC) is used for numerical solution of the related governing equation of motion of FGM cylindrical shell. The constitutive relations are based on the Love’s first approximation shell theory. The material properties are graded in the thickness direction according to a volume fraction power law index. Frequency values are calculated for different types of boundary conditions, material and geometric parameters. In general, close agreement between the obtained results and those of other researchers has been found.

References listed at the end of the paper:


ABSTRACT: In the present manuscript, free vibration response of circular cylindrical shells with functionally graded material (FGM) is investigated. The method of discrete singular convolution (DSC) is used for numerical solution of the related governing equation of motion of FGM cylindrical shell. The constitutive relations are based on the Love’s first approximation shell theory. The material properties are graded in the thickness direction according to a volume fraction power law indexes. Frequency values are calculated for different types of boundary conditions, material and geometric parameters. In general, close agreement between the obtained results and those of other researchers has been found.

References listed at the end of the paper:


ABSTRACT: A Fourier-Ritz method for predicting the free vibration of composite laminated circular panels and shells of revolution subjected to various combinations of classical and non-classical boundary conditions is presented in this paper. A modified Fourier series approach in conjunction with a Ritz technique is employed to derive the formulation based on the first-order shear deformation theory. The general boundary condition can be achieved by the boundary spring technique in which three types of liner and two types of rotation springs along the edges of the composite laminated circular panels and shells of revolution are set to imitate the boundary force. Besides, the complete shells of revolution can be achieved by using the coupling spring technique to imitate the kinematic compatibility and physical compatibility conditions of composite laminated circular panels at the common meridian with theta = 0 and theta=2pi. The comparisons established in a sufficiently conclusive manner show that the present formulation is capable of yielding highly accurate solutions with little computational effort. The influence of boundary and coupling restraint parameters, circumference angles, stiffness ratios, numbers of layer and fiber orientations on the vibration behavior of the composite laminated circular panels and shells of revolution are also discussed.

References listed at the end of the paper:

References...


[34] Jin, G., et al., Three-dimensional exact solution for the free vibration of arbitrarily thick functionally graded rectangular plates...


ABSTRACT: In this paper, the buckling load optimisation is performed on sandwich cylindrical panels. A finite element program is developed in MATLAB to solve the governing differential equations of the global buckling of the structure. In order to find the optimal solution, the genetic algorithm Toolbox in MATLAB is implemented. Verifications are made for both the buckling finite element code and also the results from the
genetic algorithm by comparisons to the results available in literature. Sandwich cylindrical panels are optimised for the buckling strength with isotropic or orthotropic cores with different boundary conditions. Results are presented in terms of stacking sequence of fibers in the face sheets and core to face sheet thickness ratio.

References listed at the end of the paper:

ABSTRACT: One of the main goal in aircraft structures designing is weight decreasing and stiffness increasing. Composite structures recently became popular in aircraft because of their mechanical properties and wide range of optimization possibilities. Weight distribution and lay-up are keys to creating lightweight stiff structures. In this paper we discuss optimization of specific structure that undergoes the non-uniform air pressure at the different flight conditions and reduce a level of noise caused by the airflow-induced vibrations at the constrained weight of the part. Initial model was created with CAD tool Siemens NX, finite element analysis and post processing were performed with COMSOL Multiphysics® and MATLAB®. Numerical solutions of the Reynolds averaged Navier-Stokes (RANS) equations supplemented by k-w turbulence model provide the spatial distributions of air pressure applied to the shell surface. At the formulation of optimization problem the global strain energy calculated within the optimized shell was assumed as the objective. Wall thickness has been changed using parametric approach by an initiation of auxiliary sphere with varied radius and coordinates of the center, which were the design variables. To avoid a local stress concentration, wall thickness increment was defined as smooth function on the shell surface dependent of auxiliary sphere position and size. Our study
consists of multiple steps: CAD/CAE transformation of the model, determining wind pressure for different flow angles, optimizing wall thickness distribution for specific flow angles, designing a lay-up for optimal material distribution. The studied structure was improved in terms of maximum and average strain energy at the constrained expense of weight growth. Developed methods and tools can be applied to wide range of shell-like structures made of multilayered quasi-isotropic laminates.

References listed at the end of the paper:


ABSTRACT: Two type of numerical approach namely, Radial Basis Function and Spline approximation, used to analyse the free vibration of anti-symmetric angle-ply laminated plates under clamped boundary conditions. The equations of motion are derived using YNS theory under first order shear deformation. By assuming the solution in separable form, coupled differential equations obtained in term of mid-plane displacement and rotational functions. The coupled differential is then approximated using Spline function and radial basis function to obtain the generalize eigenvalue problem and parametric studies are made to investigate the effect of aspect ratio, length-to-thickness ratio, number of layers, fibre orientation and material properties with respect to the frequency parameter. Some results are compared with the existing literature and other new results are given in tables and graphs.

References listed at the end of the paper:
End of many papers published in the journal, Curved and Layered Structures
(2012-2016).


Google the string: “ASCE Journal of Structural Engineering”, then click on the entry, “ASCE Journal of Structural Engineering | ASCE Library”, then, on the resulting screen, click on “ALL ISSUES”.


ABSTRACT: This paper deals with the accurate evaluation of complete three-dimensional (3D) stress fields in beam structures with compact and bridge-like sections. A refined beam finite-element (FE) formulation is employed, which permits any-order expansions for the three displacement components over the section domain by means of the Carrera Unified Formulation (CUF). Classical (Euler-Bernoulli and Timoshenko) beam theories are considered as particular cases. Comparisons with 3D solid FE analyses are provided. End effects caused by the boundary conditions are investigated. Bending and torsional loadings are considered. The
proposed formulation has shown its capability of leading to quasi-3D stress fields over the beam domain. Higher-order beam theories are necessary for the case of bridge-like sections. Various theories are also compared in terms of shear correction factors on the basis of definitions found in the open literature. It has been confirmed that different theories could lead to very different values of shear correction factors, the accuracy of which is subordinate to a great extent to the section geometries and loading conditions. However, an accurate evaluation of shear correction factors is obtained by means of the present higher-order theories.

S.F. Darehshouri (1), N.E. Shanmugam (2) and S.A. Osman (1)
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ABSTRACT: This paper is concerned with the ultimate shear capacity of steel-concrete composite plate girders in which one of the flanges of the steel girder is connected to reinforced concrete slab through shear connectors so that the steel girder and the slab act compositely as a single unit. The analysis of such girders becomes complex and it is necessary to have a simple method for design office use. Therefore, an attempt is made in this paper to propose an analytical method to determine the shear strength of a web panel in the girder. The method considers the tension field action in the plate girder web panel and shear failure of concrete slab. The method is approximate and can be applied to composite plate girders at the preliminary stages of design. The predicted results are compared with the corresponding experimental values for girders tested by other researchers and also with finite-element predictions. The predictions are found to be accurate enough for any design office use.

ABSTRACT: The objective of this paper is to provide and verify a general design method for prediction of inelastic bending capacity in cold-formed steel members potentially subject to local, distortional, and/or lateral-torsional buckling modes. An extensive experimental database of tested cold-formed steel beams is collected and indicates that inelastic reserve in the bending capacity of thin-walled cold-formed steel members is more common than typically assumed. Elementary mechanics for inelastic reserve are reviewed and simplified expressions provided for connecting the strain demand to the inelastic bending capacity in the range between the yield moment and the fully plastic moment. The strain capacity that can be sustained in inelastic local and inelastic distortional buckling is investigated through existing experiments coupled with nonlinear finite-element (FE) analysis. The nonlinear FE models provide a comprehensive means to investigate the relationship between cross-section slenderness, normalized strain capacity, and the resulting bending strength. A design approach for inelastic lateral-torsional buckling is provided on the basis of the hot-rolled steel AISC Specification. The resulting relationships for inelastic local, distortional, and lateral-torsional buckling are provided in a Direct Strength Method format for potential adoption in the cold-formed steel American Iron and Steel Institute (AISI) Specification. The provided design method is assessed against available data and shown to be a reliable predictor of inelastic bending capacity in cold-formed steel members.

Yoshiaki Goto, Kosuke Mizuno and Ghosh Prosenjit Kumar (Dept. of Civil Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, 466-8555, Japan), “Nonlinear finite element analysis for cyclic

ABSTRACT: The strength, ductility, and energy dissipation capacity of thin-walled, stiffened rectangular concrete-filled steel columns (thin-walled stiffened RCFT columns) subjected to cyclic loads are significantly upgraded by filling with concrete the internal hollow space of rectangular steel tube with longitudinal stiffeners and diaphragms. However, because of the accumulation of plastic strains and the high tensile stress concentration in thin-walled steel columns, metal fracture sometimes occurs before the columns develop their high strength and ductility. To elucidate the behavior of CFT columns and prevent the premature failure resulting from metal fracture, it is necessary to develop some geometrically and materially nonlinear finite element (FE) models that can accurately take into account important factors such as cyclic local buckling, stress and strain concentrations in the steel tube, confinement of the in-filled concrete, and interface action between steel tube and in-filled concrete. In this paper an accurate and yet, numerically stable FE model, which fully includes these important factors, is proposed. The accuracy of the proposed model is confirmed by comparison with the existing cyclic-loading tests on thin-walled stiffened RCFT columns. By utilizing the numerical results obtained by the proposed FE model, the upgrading mechanism and metal fracture of thin-walled stiffened RCFT columns are discussed in detail.

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ABSTRACT: To enhance the strength and constructability of rectangular (or trapezoidal) tubular compression members, reinforced or unreinforced concrete may be filled in the tube. Longitudinal stiffeners are often attached to increase the local buckling strength of the thin-walled skin. The effect of important design parameters on the minimum required stiffener moment of inertia was investigated numerically in this study by examining the residual stress distributions, initial imperfections, and elastic and inelastic buckling stresses of a number of hypothetical models. Because the thin-walled panel can only buckle (bulge) out from the concrete core, the buckling mode shape of a panel with multiple stiffeners resembles a waffle slab. A series of parametric studies was performed to characterize and quantify the analytically collected data. A new equation for the minimum required moment of inertia for the longitudinal stiffeners was derived. Through the evaluation of a few selected case studies and a design example, the validity and reliability of the proposed equation was demonstrated.

Cao Hung Pham and Gregory J. Hancock (School of Civil Engineering, Univ. of Sydney, Sydney NSW 2006, Australia), “Direct strength design of cold-formed C-sections for shear and combined actions”, ASCE Journal of Structural Engineering, Vol. 138, No. 6, June 2012, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000510

ABSTRACT: The direct strength method (DSM) recently included in the North American Specification and Australian/New Zealand Standard AS/NZS 4600:2005 gives design rules for compression and bending. No rules are presented in this standard for shear or for combined bending and shear. Two series of tests on C-section can be used to develop and calibrate rules for design in shear and for combined bending and shear. These are the University of Missouri Rolla tests of the 1970s and recent tests on high-strength C-sections at the University of Sydney. Both series of tests use a similar test rig, although different levels of tension field action have been observed. Two features researched are the effect of full-section shear buckling (as opposed to web-
only shear buckling), and tension field action. Full-section buckling is a feature of the DSM but requires software that can evaluate full sections for shear. The paper proposes DSM design rules for C-sections in shear and for combined bending and shear both with and without tension field action. The test results are compared with the proposed design rules.


ABSTRACT: The condition of eccentric discharge is known to be one of the most critical for the design of thin-walled cylindrical metal silos. Significant progress has been made in recent years in devising a relatively realistic set of representative pressures for this load case. However, the consequences these may have on the predicted structural behavior of a silo are not yet fully understood. This paper presents a detailed parametric study into the behavior of a custom-designed slender silo under a set of unsymmetrical pressures describing the action of an eccentric parallel-sided pipe flow channel of varying cross-sectional areas. The results are compared with the reference axisymmetric case of concentric discharge. It is found that the predicted behavior is very complex indeed, and that geometric nonlinearity is of much greater significance for cylindrical shells under unsymmetrical load patterns than under symmetrical patterns. Further, it is found that eigenmode-affine imperfections, which are very deleterious under axisymmetric loading patterns, are instead beneficial to the buckling strength of a silo under eccentric discharge, thus making them unsuitable for use in design for this load condition.

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ABAQUS version 6.9 [Computer software]. Dassault Systèmes Simulia, Providence, RI.
obtained directly from the FE analysis. Following that, a model was established, with both material and geometrical nonlinearity, allowing load redistribution across the sections with three different sizes of T web openings and formation of the Vierendeel mechanism. The reduction of the global shear capacities, because of incorporation of the local Vierendeel moments acting on the top and bottom T-sections, was obtained directly from the FE analysis. Following that, a comparison of the global shear-moment (\((V/M)\))
interaction curves of the steel sections with various web opening shapes and sizes was established, and empirical generalized V/M interaction curves were developed. Moreover, the accurate position of the plastic hinges was determined together with the critical opening length and the Vierendeel parameter. This work has shown that the shape of the web opening can also significantly affect the structural behavior of perforated beams, as opposed to the equivalent rectangular shape predominately used so far. In addition, the effect of the position of the web opening along the length of the perforated beam was revealed. The importance of the parameters that affects the structural performance of such beams is illustrated. The thorough examination of the computational results has led to useful conclusions and an elliptical form of a web opening is proposed for further study. The outcomes are considered relevant for practical applications.

ABSTRACT: The compressive strength of cold-formed steel (CFS) lipped channel (LC) members may be governed by yielding, local, distortional, or overall buckling, and any possible interaction among these modes. The direct strength method (DSM) has been advanced recently for evaluating the strength of CFS LC beams and columns. Although the DSM is an improvement over other methods in terms of simplicity and accuracy, further improvement by minor modification to the DSM is possible if all the parameters that affect the strength of such members is properly accounted for and understood. In this study, the DSM equations for evaluating the strength of members that fail after experiencing only local buckling are discussed. The strength of such members, according to the DSM, is a function of only the ratio of yield strength of the section (Py) to the elastic local buckling load (Pcrℓ) (also equal to the reciprocal of square of the nondimensional local buckling slenderness ratio, 1/λ²ℓ). This study indicates that the relative area of the stocky elements of the cross section, which are less vulnerable to elastic local buckling, also influences the strength of such members. Using the experimental results available in the literature and the finite-element analysis data generated in this study, the behavior and strength of stub LC compression members experiencing only local buckling before failure by yielding are evaluated. Simple modifications to the currently available DSM equations are suggested to more accurately evaluate the strength of such members.

ABSTRACT: In order to provide a good understanding of the damage states of single-layer reticulated domes under earthquake loading, a number of increment dynamic analyses are carried out on domes with different spans, rise-span ratios, roof weights, and other parameters. A model is proposed for the quantitative evaluation of damage. The damage states for single-layer reticulated domes are defined based on their structural dynamic performance and corresponding damage factors. The vulnerability of single-layer reticulated domes is shown using fragility curves with different damage states. A model of probability distribution for seismic hazard, structural damage probability, and various losses, including direct and indirect economic loss and maimed and fatality loss, is discussed for assessing risk. The risk assessment of a single-layer reticulated dome is performed for different seismic intensities for its loss or fatality acceptability.
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https://doi.org/10.1061/(ASCE)ST.1943-541X.0000603
ABSTRACT: Dynamic response of composite beams with partial interaction is presented using a one-dimensional finite-element model based on a higher-order beam theory. The proposed model takes into account the effect of partial shear interaction between the adjacent layers, as well as the transverse shear deformation of the beam. A third order variation of the axial displacement of the fibers over the beam depth is taken to have a parabolic variation of shear stress, which vanishes at both the top and bottom fibers of the transverse composite surface, as clearly derived on the free and tangentially unloaded surface of the continua. In the proposed finite-element model, there is no need to incorporate any shear correction factor, and the model is free from the shear locking problem. The proposed numerical model is validated by comparing the results with those available in the literature. Many new results are presented, because there are no published results on vibration and buckling of composite beams based on higher-order beam theory.

Halima Dewanbabee and Sreekanta Das (Dept. of Civil and Environmental Engineering, Center for Engineering Research in Pipelines, Univ. of Windsor, 401 Sunset Ave., Windsor, ON, Canada N9B 3P4), “Structural behavior of corroded steel pipes subject to axial compression and internal pressure: Experimental study”, ASCE Journal of Structural Engineering, Vol. 139, No. 1 January 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000596
ABSTRACT: External corrosion is found in many onshore oil and gas pipelines, and corrosion is a major cause of structural failure of these pipelines. Onshore buried pipelines can be subjected to axial, bending, shear, and other complex loadings as a result of geotechnical movements and temperature variations. In addition, these pipes experience internal pressure from the fluids that they transport. Pipeline industry is concerned about the structural behavior and integrity of corroded pipelines when subjected to various loads and load combinations. Hence, structural behavior and failure conditions of corroded pipelines under various loads and load combinations need to be understood for safe operation of these field pipelines. A literature review did not reveal any studies that determined the structural behavior of corroded steel pipes when subjected to monotonically increasing axial compressive force with constant internal pressure. Therefore, an experimental study was completed to determine the structural behavior of X46 steel line pipe subjected to monotonically increasing axial compression and constant internal pressure as the geometry of corrosion and level of internal pressure change. This study shows that the axial load-carrying capacity reduces as the corrosion depth increases. However, this pipe is highly ductile and does not pose any threat to the structural integrity of the pipe when subjected to monotonically increasing axial deformation and constant internal pressure.

A. Prokic, D. Lukic and I. Milicic (Faculty of Civil Engineering Subotica, Univ. of Novi Sad, 24000 Subotica, Serbia), “Free vibration analysis of cross-ply laminated thin-walled beams with open cross sections: Exact solution”, ASCE Journal of Structural Engineering, Vol. 139, No. 4, April 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000693
ABSTRACT: The objective of the present paper is to analyze the free vibrations of thin-walled beams with
arbitrary open cross section, made of cross-ply laminates with midplane symmetry, by means of an exact solution. The theory of thin-walled composite beams is based on assumptions consistent with Vlasov’s beam theory and classical lamination theory. The governing differential equations for coupled bending-torsional vibrations were obtained using the principle of virtual displacements. To simplify the coupled system of differential equations, an ideal center of gravity and shear center were introduced. In the case of a simply supported thin-walled beam, the closed-form solution for the natural frequencies of free harmonic vibrations was derived. The frequency equation, given in determinantal form, is expanded in an explicit analytical form. To demonstrate the validity of this method, the natural frequencies of nonsymmetric thin-walled beams having coupled deformation modes are evaluated and compared with results available in the literature as well as with FEM results.

Poologanathan Keerthan and Mahen Mahendran (Faculty of Science and Engineering, Queensland Univ. of Technology, Brisbane, QLD 4000, Australia), “New design rules for the shear strength of LiteSteel beams with web openings”, ASCE Journal of Structural Engineering, Vol. 139, No. 5, May 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000563

ABSTRACT: A LiteSteel beam (LSB) is a new cold-formed steel hollow flange channel section produced using a patented manufacturing process involving simultaneous cold-forming and dual electric resistance welding. The LSBs are commonly used as floor joists and bearers with web openings in residential, industrial, and commercial buildings. Their shear strengths are considerably reduced when web openings are included for the purpose of locating building services. However, no research has been undertaken on the shear behavior and strength of LSBs with web openings. Therefore, experimental and numerical studies were undertaken to investigate the shear behavior and strength of LSBs with web openings. In this research, finite-element models of LSBs with web openings in shear were developed to simulate the shear behavior and strength of LSBs including their buckling characteristics. They were then validated by comparing their results with available experimental test results and used in a detailed parametric study. The results showed that the current design rules in cold-formed steel structures design codes are very conservative for the shear design of LSBs with web openings. Improved design equations have been proposed for the shear capacity of LSBs with web openings based on both experimental and parametric study results. An alternative shear design method based on an equivalent reduced web thickness was also proposed. It was found that the same shear strength design rules developed for LSBs without web openings can be used for LSBs with web openings provided the equivalent reduced web thickness equation developed in this paper is used. This is a significant advancement as it simplifies the shear design methods of LSBs with web openings considerably.

Basaglia, C. and Camotim, D. (Dept. of Civil Engineering and Architecture Instituto Superior Técnico, Technical Univ. of Lisbon, 1049-001 Lisbon, Portugal), “Buckling, Postbuckling, Strength, and DSM Design of Cold-Formed Steel Continuous Lipped Channel Beams.” J. Struct. Eng. 139, Special Issue: Cold-Formed Steel Structures, 657–668, 2013, DOI: 10.1061/(ASCE)ST.1943-541X.0000651

ABSTRACT: The work reported in this paper is part of an ongoing numerical investigation aimed at (1) assessing the buckling, postbuckling, strength, and collapse behavior of cold-formed steel continuous beams and simple frames and (2) developing an efficient methodology, based on the direct strength method (DSM) approach, to design such structural systems. The results available at this stage concern two- and three-span lipped channel beams subjected to nonuniform bending, and they include the assessment of how accurately the beam ultimate strengths can be predicted by the current DSM design curves. The numerical results presented and discussed are obtained through analyses based on generalized beam theory (elastic buckling analyses) and
shell finite-element models (all the remaining analyses). Ultimate strength values yielded by geometrically and materially nonlinear shell finite-element analyses are compared with estimates provided by the DSM equations, and on the basis of this comparison, it is possible to identify some features that must be included in a DSM approach applicable to continuous cold-formed steel beams.

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ABSTRACT: The paper presents an attempt to predict the load carrying capacity of perforated rack columns by the direct strength method (DSM). The investigation is focused on two different issues: the prediction of the elastic buckling loads of members with multiple perforations; and the evaluation of the accuracy of the current DSM buckling curves when applied to rack columns. In relation to the first issue, a model for the calculation of the reduced thickness of the perforated strip to be used in finite-strip buckling analysis is developed. Regarding the study of the DSM curves, it is demonstrated that they can be used to accurately determine the strength of rack cross sections whose failure is governed by distortional buckling or global buckling (with no significant participation of local buckling). This is an interesting result because it will allow substituting the distortional buckling tests, that are currently carried out in the process of design of these columns, by a simple and easy to apply calculation procedure.

ABSTRACT: This paper presents procedures for the design of fixed- and pin-ended equal-leg angle columns with short-to-intermediate lengths. First, some remarks concerning the buckling and postbuckling behavior of the angle columns are presented that (1) illustrate the main differences between the fixed- and pin-ended column responses and (2) demonstrate the need for specific design procedures. Then, the paper reports an in-depth investigation aimed at gathering a large column ultimate strength data bank that includes (1) experimental values collected from the literature and (2) numerical values obtained from shell finite-element analyses carried out in the code ABAQUS. The set of experimental results is comprised of 41 fixed-ended columns and 37 pin-ended columns and the numerical results obtained include 89 fixed-ended columns and 28 pin-ended columns; various cross-section dimensions, lengths, and yield stresses are considered. Finally, the paper closes with the proposal of new design procedures for fixed- and pin-ended angle columns based on the direct strength method (DSM). The two procedures adopt modified global and local strength curves, and it is shown that the proposed DSM approach leads to accurate ultimate strength estimates for short-to-intermediate columns covering a wide slenderness range.

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ABSTRACT: Experiments were conducted on cold-formed steel C-section joists with rectangular unstiffened web holes. The presence of holes decreased joist capacity and amplified distortional buckling deformation. Distortional buckling was accompanied by unstiffened strip buckling of the compressed web. When hole depth approached the web depth, sudden buckling of the compressed flange and web above the hole was observed. Critical elastic buckling moments for local, distortional, and global buckling were calculated for each specimen including the influence of holes with recently introduced engineering expressions and finite strip analysis. Forthcoming direct strength method equations for cold-formed steel joists with holes were demonstrated to be viable predictors of flexural capacity for the specimens considered in the experimental program.

Dan Dubina, Viorel Ungureanu and Andrei Crisan (Dept. of Steel Structures and Structural Mechanics, Civil Engineering Faculty, Politehnica Univ. of Timisoara, 300224 Timisoara, Romania), “Experimental evidence of erosion of critical load in interactive buckling”, ASCE Journal of Structural Engineering, Vol. 139, No. 5, May 2013, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000789
ABSTRACT: The paper starts with a selective review of some basic contributions related to local-overall buckling mode interactions in thin-walled steel members. Then, the results of an intensive experimental study carried out at the Politehnica University of Timisoara with the purpose of evaluating the erosion of a theoretical bifurcation load in the distortional-flexural buckling interaction range in pallet rack uprights are presented. Two different sizes of cross sections, with and without perforations, have been studied. To evaluate and quantify the erosion, the erosion of the critical bifurcation load approach is applied. This approach enables one to use the European buckling curves in the Ayrton-Perry format, expressing the imperfection factor ($\alpha$) in terms of the erosion coefficient ($\psi$). It allows estimation of the member’s ultimate capacity, taking into account the interaction of sectional (local or distortional) and member (flexural, torsional, or flexural-torsional) instability modes. Test results and the evaluation procedure for the erosion coefficient ($\psi$) and imperfection factor ($\alpha$), applied on tested specimens, are presented.

ABSTRACT: Stainless steel is gaining increasing use in construction because of its durability, favorable mechanical properties, and aesthetic appearance, with the austenitic grades being the most commonly used. Austenitic stainless steels have a high nickel content (8–11%), resulting in high initial material cost and significant price fluctuations; this, despite its desirable properties, represents a considerable disadvantage in terms of material selection. Ferritic stainless steels, having no or very low nickel content, may offer a more viable alternative for structural applications, reducing both the level and variability of the initial material cost while maintaining adequate corrosion resistance. There is currently limited information available on the structural performance of this type of stainless steel. Therefore, to overcome this limitation, a series of material, cross section, and member tests have been performed, covering both the standard EN 1.4003 grade (similar to the chromium weldable structural steel 3Cr12) and the EN 1.4509 grade (441), which has improved weldability and corrosion resistance. In total, 20 tensile coupon tests, 16 compressive coupon tests, eight stub column tests, 15 flexural buckling tests, and eight in-plane bending tests were carried out. Precise measurements of the geometric properties of the test specimens, including the local and global geometric imperfections, were also
made. The experimental results are used to assess the applicability of the current European (EN 1993-1-4) and North American (SEI/ASCE-8) provisions to ferritic stainless steel structural components. In addition, the relative structural performance of ferritic stainless steel to that of more commonly used stainless steel grades is also presented, showing ferritic stainless steel to be an attractive choice for structural applications.


ABSTRACT: In this paper, the behavior of deep trapezoidal sheeting with perforated webs is studied. The analyzed panel has longitudinal stiffeners both in the webs and flanges, which improves the load-bearing capacity but makes the behavior more complicated. The considered panel is produced with and without web perforations. When web perforation is applied, it is located in the middle part of the web. The primary aim of web perforation is to enhance noise resistance, but it also has an influence on the static behavior. Because reliable design rules for web-perforated trapezoidal sheeting panels are not available, an experimental program is undertaken: panels with and without web perforations are tested in parallel. The test setup and specimens are designed to provide information on all the behavior modes. On the basis of the test results, it is possible to define the degrading effect of web perforation on the rigidity, bending, and shear resistances and on the resistance to direct transverse forces close to and far from the panel end. The experimental results are compared with proposals found in the relevant literature. On the basis of the test results, reduction factors might be proposed to consider the effect of web perforation in the design of the investigated sheeting panel.

Yuanqi Li, Zuyan Shen, Xingyou Yao, Rongkui Ma and Fei Liu (Dept. of Building Engineering, Tongji Univ., State Key Laboratory of Disaster Reduction in Civil Engineering, Shanghai 200092, China), “Experimental investigation and design method research on low-rise cold-formed thin-walled steel framing buildings”, ASCE Journal of Structural Engineering, Vol. 139, No. 5, May 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000720

ABSTRACT: Cold-formed thin-walled steel residential building systems, because of their good environment protection, seismic performance, and high construction efficiency, have been widely used in the United States, Canada, Japan, and Australia, and recently, they also have had good application in China. Although a variety of studies have been carried out all over the world in the last 20 years, there is no related design code for this kind of building in China. For this reason, a series of research has been conducted in China recently, considering the consistency of standard systems in structural design in China and the newest development in the world. The contents of the paper can be divided into two parts. First, the major research works conducted by the authors over the last 5 years and the main findings are reviewed and summarized. Second, based on a Chinese professional standard, a brief summary of the design methods for cold-formed thin-walled steel framing residential buildings developed by the authors and other researchers in China is introduced.


ABSTRACT: The paper summarizes the main new design provisions included in the recently revised Australian standard for steel storage racks. The standard features multitiered analysis provisions ranging from basic linear-
elastic analysis-based provisions to highly advanced integrated design-analysis [geometric and material nonlinear analysis with imperfections (GMNIA)] provisions that allow the analysis and design to be completed in one step. The GMNIA provisions distinguish between beam element–based and shell element–based analysis according to cross section slenderness and provide rules for the imperfections to use for the two types of analysis, including imperfections in the local and distortional buckling modes for the shell element–based analysis. The selection of the system-based reliability (resistance) factor ($\Phi_s$) is discussed. The standard is seen as the most advanced design code of its type currently available for frame-type steel structures. The paper also provides an in-depth discussion about the use of linear and nonlinear elastic analysis methods for the design of steel storage racks and how torsion may be considered in determining design capacities while not in the structural analysis.

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“Cold-formed steel lipped channel columns influenced by local-distortional interaction: Strength and DSM design”, ASCE Journal of Structural Engineering, Vol. 139, No. 6, June 2013
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ABSTRACT: This paper deals with the ultimate strength and design of fixed-ended lipped channel columns experiencing local-distortional buckling mode interaction. First, the paper reports the results of an experimental investigation involving a set of 26 columns with several cross-section dimensions and yield stresses that were tested to determine their failure loads and also to provide experimental evidence of the occurrence of local-distortional mode interaction. These results consist of the column geometries, material properties, initial geometric imperfections, nonlinear equilibrium paths, and ultimate strength values. Then, after comparing the experimental column ultimate loads with the estimates provided by the current direct strength method (DSM) design curves against local and distortional failures, which clearly show that they lead to inaccurate and often very unsafe ultimate strength estimates, the paper presents and assesses the quality of DSM-based design procedures based on approaches providing nominal strengths against local-distortional and distortional-local interactive failures. Next, an in-depth comparison is made between all the experimental ultimate strength results available in the literature and their estimates provided by the preceding DSM design procedures. Finally, the paper closes with design considerations and recommendations, motivated by the conclusions drawn from this investigation.

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ABSTRACT: The strength of thin-walled stainless steel columns has been investigated extensively over the last few years. In European standards, the concept of section classification for determining the cross section capacity is used. In this system, for Class 4 cross sections, the effective width method (EWM) must be used to account for the effect of local buckling. Because of the complexity and limitations of this method, other methods have been developed, such as the direct strength method (DSM) for cold-formed thin-walled profiles and the continuous strength method (CSM), initially established for members made of nonlinear metallic
materials. In the CSM, to take advantage of strain hardening, a deformation-based design approach using a continuous relationship between the cross-sectional slenderness and the cross-sectional deformation capacity is used. To a large extent, the CSM yields accurate predictions, especially in the low slenderness range where the current DSM design procedures for members submitted to pure compression tend to produce conservative predictions for materials with pronounced strain hardening such as stainless steel alloys. The present paper presents an extension of the traditional DSM, which provides accurate design strength predictions in the low slenderness range for stainless steel thin-walled section columns failing by distortional, local, and overall buckling. It contains practical information concerning the reference experimental data and draws conclusions about the justification of the proposed analytical formula. The paper is divided into three main parts: the description of the database, the establishment of the design model, and a reliability analysis of the method.

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ABSTRACT: Composite steel-concrete columns and beam-columns have been shown to provide superior performance when the intrinsic synergistic characteristics of concrete and steel are properly exploited. However, limited test data are available to justify the structural system response factors and comprehensive design equations in current design specifications. This research, through the testing of 18 full-scale, slender concrete-filled steel tube (CFT) beam-columns, addresses these needs by providing comprehensive data to calibrate advanced computational models and assess design equations. The CFT specimens were subjected to complex load protocols that included pure compression, uniaxial and biaxial bending combined with compression, pure torsion, and torsion combined with compression. The results for the pure compression tests reported in this paper indicate that current AISC design provisions provide an accurate estimation of column capacity for both strength and stiffness. The experimental loading response was also contrasted with column curves obtained from advanced, nonlinear fiber analysis models. The experimental and computational column curves are strongly correlated in the elastic critical load range, but showed some differences in the inelastic buckling load range. These differences are attributed to the higher concrete strength assumed in the computational analysis because of the confinement effect of the steel tube; this strength is underpredicted in current design specifications.

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ABSTRACT: This paper presents a new two-dimensional shear-wall and diaphragm model developed as part of a Network for Earthquake Engineering Simulation (NEES) Project entitled NEES-Soft: Seismic Risk Reduction for Soft-Story Woodframe Buildings. A large portion of the older multistory buildings in the California region were constructed with a deficiency that makes them vulnerable to collapse in the first story during earthquakes. This deficiency is referred to as soft-story. The new model presented in this paper was developed using a
corotational formulation, which makes it suitable for modeling the side-sway collapse of wood shear walls under large displacement as well as estimating the in-plane stiffness of floor diaphragms. To achieve high computational efficiency, a nodal condensation technique is used to eliminate the degrees of freedom (DOFs) associated with the nail connections from the global DOFs of the model. To verify the validity of the new model, the model was coded into a computer program and was used to analyze selected shear walls and diaphragms tested by various institutions and research programs. Good agreement was observed between the test and model-predicted backbone and cyclic curves for shear walls with various gravity loads and different anchorage conditions. The model is highly flexible and has been shown to be able to model older shear wall construction with horizontal sheathing boards and diagonal bracings.

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ABSTRACT: Under extreme earthquake loading, light-frame wood building collapse is often caused by excessive interstory drifts at one or more story levels, leading to catastrophic P-Δ failure once the shear walls, and subsequently the entire structure, become unstable. This soft-story collapse mechanism has been observed in numerous earthquakes. Current performance-based seismic design methods for light-frame wood buildings typically uses very conservative drift levels to represent the near collapse deformation of wood frame building systems, such as the 3% drift limit used in ACSE Standard 41 corresponding to a collapse prevention performance target. A series of full-scale collapse loading tests on wood shear walls was conducted in this study to identify the ultimate drift level at which P-Δ collapse will occur and is described in this paper. It was concluded that laterally braced wood shear walls can remain stable up to ∼7–10% interstory drift, depending on the magnitude of the vertical loading. If one considers the typical design range of gravity load commonly seen in multistory light-frame wood construction, assigning a single ultimate drift level of 7% for light-frame wood building collapse limits appears to be justifiable based on the experimental results presented herein.

ABSTRACT: Upon recent research, steel plate shear wall (SPSW) is known as an effective lateral force resisting system in high seismic zones. However, there are still areas of concern in the design and construction of this system with regard to conventional approaches recognized as stiffened and unstiffened types. This paper presents results of research conducted on diagonally stiffened steel plate shear walls as a new type of stiffening method. Four 1/2-scaled single-story test specimens are designed as prototype thin steel plate shear walls for the experimental study. Three of the specimens are diagonally stiffened, and the fourth one is an unstiffened steel shear wall. Testing of the systems is performed under cyclic quasi-static loading. The effects of the edge stiffeners and the type of beam-to-column connections on the seismic behavior of the diagonally stiffened specimens are also investigated. Experimental results show that the specimens tolerate 3.5% to approximately 5% story drifts, and the diagonal stiffeners improve hysteretic behavior of the steel shear walls, especially when the edge stiffeners are used in the panel. The results indicate that the response modification factor (R) of a
diagonally stiffened specimen is approximately 13% greater than the R factor of an unstiffened system. In addition, a formula is developed and proposed for the shear strength estimation of a diagonally stiffened SPSW. The theoretical predictions of the shear strengths are compared with the experimental results, and good agreements are observed between the two methods.

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ABSTRACT: Large-scale shake table tests were performed at E-Defense to examine the out-of-plane stability of buckling-restrained braces (BRBs). Two specimens were subjected repeatedly to a near-fault ground motion with increasing amplification. The test specimens comprised a single-bay, single-story steel frame and a pair of BRBs placed in a chevron arrangement. The specimens were not braced at the brace-to-beam intersection in order to produce a condition where the BRBs were susceptible to out-of-plane instability. Standard BRBs were used in the first specimen, while BRBs with a flexible segment at each end of the steel core were used in the second specimen. A simple stability model predicted the BRBs in the second specimen to fail because of out-of-plane buckling. The first specimen exhibited excellent ductility during the shake table tests, while the second specimen developed severe out-of-plane deformation that compromised the ductility of the BRBs. Based on the experimental observations and the stability model, a methodology is proposed to evaluate bracing requirements at the brace-to-beam intersection.

Cao Hung Pham and Gregory J. Hancock (School of Civil Engineering, Univ. of Sydney, Sydney, NSW 2006, Australia), “Experimental investigation and direct strength design of high-strength, complex C-sections in pure bending”, ASCE Journal of Structural Engineering, Vol. 139, No. 11, November 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000736

ABSTRACT: Plain C- or Z-sections are two of the most common cold-formed steel shapes in use throughout the world. Other shapes are high-strength SupaCee and SupaZed (Bluescope Steel Ltd., Melbourne, Australia) steel sections, which are widely used in Australia as purlins in roof and wall systems. They contain additional return lips and web stiffeners that enhance the bending capacity of the sections. Design methods for these sections are normally specified in the Australian/New Zealand Standard for cold-formed steel structures or the North American Specification for cold-formed steel structural members. In both standards, which include the newly developed direct strength method of design (DSM), the method presented is developed for beams and columns, including the reliability of the method. This paper presents two different test series on both plain C- and SupaCee sections in pure bending (constant moment). They were performed at the University of Sydney for the extension of the DSM to include channel section beams with complex stiffeners. Two different section depths and three different thicknesses of high-strength lipped channel sections were tested in pure bending. Tests with and without torsion/distortion restraint straps screwed on the top flanges in the pure bending region were also considered to allow local and distortional buckling to form in the sections, respectively. Test results
and formulas developed from the DSM are summarized in the paper. Three different cases where moments are
used in association with yield, inelastic, or plastic criteria in the DSM local and distortional strength equations
are compared with the test data. By comparisons between cases, a proposed recommendation for DSM inelastic
buckling strength design in pure bending with extended nondimensional slenderness limit for both local and
distortional buckling is given in the paper.

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“Plate buckling strength of steel wide-flange sections at elevated temperatures”, ASCE Journal of Structural
Engineering, Vol. 139, No. 11, November 2013, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000769
ABSTRACT: At ambient temperature, estimations of the postbuckling strength of steel plates (web and flanges)
in wide-flange beams are based on the assumption that the stress at the edge of the plate equals the yield stress
of the material. However, at elevated temperatures material behaves in a nonlinear manner beginning at very
small strains. The work presented in this paper has shown that at elevated temperatures the ultimate buckling
load occurs when stresses at the plate edge are smaller than the yield stress, which are typically defined at large
strains such as at 2%. Hence, the current expressions for plate buckling strength at ambient temperature cannot
be directly applied at elevated temperature. By taking into account the nonlinear behavior of steel at elevated
temperatures, a new postbuckling strength equation for webs and flanges in wide-flange beams that correlates
well with finite-element studies at elevated temperatures is proposed.

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“Development of an axial load capacity equation for doubly symmetric built-up cold-formed sections”, ASCE
Journal of Structural Engineering, Vol. 139, No. 12, December 2013
https://doi.org/10.1061/(ASCE)ST.1943-541X.0000780
ABSTRACT: This work aims to develop an axial load capacity equation for doubly symmetric built-up cold-
formed sections with a sufficient number of intermediate, symmetrical connections. A numerical parametric
study involving a total of 360 different configurations was conducted, and the numerical results were compared
with the experimental data and specifications from the American Iron and Steel Institute (AISI). In this process,
the axial load capacities and failure modes, which were influenced by out-of-straightness and out-of-flatness,
were thoroughly investigated. To address the issues of an unnecessarily complicated AISI specification for
doubly symmetric members subject to distortional buckling, a simple and reliable axial load capacity equation
was developed based on a regression analysis of a three-dimensional surface fitting and calibration with the
experimental data. This proposed equation exhibited good agreement with the numerically simulated and
experimentally measured capacities, while simultaneously ensuring safety and efficiency.

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“Stability of Z-section purlins used as temporary struts during construction”, ASCE Journal of Structural
ABSTRACT: The stability of Z purlins subject to combined axial force and biaxial bending due to self-weight (a situation that typically arises during construction) is investigated. Single, isolated purlins as well as purlins with one or more lines of bridging are considered. The purlin can thereby be supported at the ends in various ways: (1) a simple cleat plate connection with two bolts, (2) a semicontinuous connection obtained by lapping the purlin with an adjacent span, and (3) a cleat plate connection with fly-bracing. The beneficial effect of the end restraint provided by each of these different support conditions about both a horizontal and a vertical axis was measured experimentally. The experimental data served as input for (1) detailed finite-element models, and (2) a theoretical buckling analysis of Z-section columns. Based on this work, design guidelines are presented for Z purlins subject to combined axial force and biaxial bending.

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ABSTRACT: Concrete-filled tubes (CFTs) have been used in civil engineering practice as piles, caissons, columns, and bridge piers. Relative to conventional structural steel and reinforced concrete components, CFTs have several advantages. The steel tube serves as both reinforcement and formwork, eliminating the need for both, and provides large tensile and compressive capacities; the concrete fill restrains buckling of the steel tube, which increases the strength, stiffness, and deformability of the section. In some cases, internal reinforcement is used to enhance the strength and facilitate connection to adjacent members. Although these properties are well accepted, the use of CFTs in practice is awkward because design provisions among codes vary significantly and previous research has not considered internal reinforcement. An analytical research study was undertaken to evaluate and improve design provisions for CFTs with and without internal reinforcement under combined axial load and bending. A continuum model was developed to simulate prior test results subjected to combined loading and the validated model was used to investigate the strength and inelastic performance of CFTs under combined loading. Current design provisions for CFTs were evaluated using the results of these finite-element analysis and previous test results. The comparisons indicate that current design approach provides good prediction of CFT capacity subjected only to bending or axial demands, but current provisions provide conservative values for the CFTs under general combined loading. An alternative P-M interaction curve for CFTs was proposed.

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ABSTRACT: It is well known that structural glass members are made by assembling thin laminated panels, which can be connected with different bonding techniques; for instance, with steel devices or with structural
adhesives. The latter are very commonly used because they do not reduce the transparency of the member and make it possible to avoid stress concentrations because of the presence of holes. This technique is used to make up columns in glazing structures and different applications of the technique can be found in contemporary architecture. As evidenced by the literature, one of the most important problems in such members is caused by buckling phenomena, resulting from the slenderness of the panels. The great deal of research work conducted in the last 20 years has highlighted the fact that the critical load in laminated glass panels depends not only on the geometrical slenderness, but also, and perhaps above all, on the effective level of connection ensured by the interlayer. Although many studies have focused on the compressive behavior of panels, few are currently available about laminated glass columns. This study presents the results of compressive tests on glass members. Two different series of 12 columns with two different levels of connection were manufactured by assembling laminated glass panels with structural silicone. The specimens had different cross-sectional shapes and different heights. Additionally, compressive tests were performed on single panels with varying slenderness to study buckling behavior, and bending tests were undertaken on laminated and monolithic glass panels to characterize the mechanical properties and the level of connection between the two glass foils.

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ABSTRACT: The primary objective of this paper is to evaluate and compare design methods for locally slender steel columns. Three design methods utilized for such columns in the United States are explored: (1) the Q-factor method; (2) the unified effective width method; and (3) the direct strength method. The design strength formulas for locally slender W-section columns for all methods are provided in a common notation. The expressions highlight the prominent role of elastic local (cross-section) slenderness. A nonlinear shell finite-element analysis parametric study on short, intermediate, and long columns is conducted to explore the divergence in the design methods as a function of local slenderness. Recommendations for advancing the design methods are offered. In particular, based on the parametric study, an effective width method alternative is provided.

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https://doi.org/10.1061/(ASCE)ST.1943-541X.0000867
ABSTRACT: Traditionally, the design of transverse stiffeners in the AISC and AASHTO specifications has been based on two criteria: a moment of inertia requirement to ensure near-zero lateral deflection of the stiffeners at the web shear buckling load, and an area requirement to ensure that the transverse stiffeners can serve as verticals in an effective Pratt truss in the postbuckling condition of the web. However, multiple investigators have found that the transverse stiffener response is dominated by bending actions caused by restraint of the out-of-plane deformation of the web panels. As such, the latest AASHTO and AISC specifications have adopted transverse stiffener sizing rules that focus solely on a transverse stiffener moment
of inertia requirement. This paper summarizes various details of the underlying research leading to the development of these new rules and outlines the proper application of the new specification provisions.

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ABSTRACT: The local buckling restraining behavior of thin-walled circular concrete-filled tubular (CFT) columns is examined under seismic loads by conducting a bidirectional cyclic loading and a bidirectional shaking table test. According to the responses of the deformations and strains measured in the bidirectional cyclic loading test, the axial compressive force acting on the buckled part of a steel tube is reduced with the increase in its local buckling deformation because most of the compressive axial force is transferred from the steel tube to the in-filled concrete. The reduction in the compressive axial force in the steel tube slows the progress of the buckling deformation. In addition, under a cyclic load applied after the occurrence of local buckling, the opening and closing of major horizontal cracks and dilation occur in the in-filled concrete. As a result, a predominant tensile axial force acts repeatedly on the buckled part of the outer steel tube. This tensile force restrains or restores the local buckling deformations by stretching them. The magnitude of the tensile force is enhanced further if a diaphragm is installed on the steel tube at the upper surface of the in-filled concrete. The shaking table test confirms that the local buckling restraining behavior is similar under seismic accelerations. The shaking table test together with the numerical analysis illustrates that the ratio between the residual sway displacement $\delta_r$ and the maximum response sway displacement $\delta_m$, defined as $\delta_r/\delta_m$ for CFT columns, is generally much smaller than that for hollow columns because of the enhanced strength and ductility of CFT columns.


ABSTRACT: The buckling behavior of T-section columns is discussed in detail, followed by a numerical study using geometric and material nonlinear analyses (GMNIA) to produce column strengths for a wide range of geometries of T-sections and column lengths. The T-sections are assumed to be hot-rolled and include residual stresses and geometric imperfections typical of hot-rolled sections. On the basis of the numerical strengths thus produced and the available test strengths for T-section columns, the design provisions of the Australian, European, and American specifications for hot-rolled steel structures are evaluated. It is shown that the Australian standard provides fairly consistent and accurate predictions of strength. However, the design provisions for T-sections of current European and American specifications are conservative and associated with large variability, particularly for T-sections with slender elements. The paper recommends modifications to the European and American specifications that improve the design strength predictions of these specifications for T-section columns.

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ABSTRACT: Previous studies have proposed a cyclic ductile fracture model by applying the void growth model and an established rule in incremental form, in which only a monotonic tensile coupon test is required to calibrate the parameters of the fracture model and the corresponding plasticity models. The model parameters were deduced from small-scale hourglass steel coupons, but not from large-scale specimens. In practice, however, ductile fracture after the occurrence of local buckling has been observed in steel members during recent huge earthquakes. This paper aims to establish a simulation method for the postbuckling cracking process on the basis of formerly proposed fracture and plasticity models. Experimental results demonstrate that the ultimate behaviors of heat-treated square hollow section (SHS) stub columns associated with plate buckling and ductile fracture under cyclic loading can be simulated with favorable accuracy.

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ABSTRACT: Aluminum alloys are used in a wide range of engineering applications and are gaining increasing usage in the construction sector, offering high strength-to-weight ratios and good durability. In this paper, a series of stub-column tests on aluminum alloy box sections with and without internal cross stiffeners is carried out to investigate cross-section capacity and to explore the possible exploitation of strain hardening in design. All existing stub-column test results from the literature were also collected. A database containing the results from 346 tests on aluminum alloy stub columns of box, channel, and angle sections, with a wide range of cross-section slendernesses, was formed. The test strengths were compared with the design strengths predicted by the current American, Australian/New Zealand, and European specifications. Furthermore, the test strengths were compared with those predicted by the deformation-based continuous strength method (CSM). Following reliability analyses, the design strengths predicted by the three current design specifications were found to be generally conservative, whereas the CSM offered improved design capacities, owing to its allowance for strain hardening.

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ABSTRACT: This paper presents selected results from an experimental and computational evaluation on the
behavior of slender concrete-filled steel tubes (CFTs) under combined axial compression and biaxial flexure. A complex loading protocol was used in the experimental program, including monotonic and cyclic loading that allowed detailed evaluation of the complete beam-column response. This paper principally addresses the experimental determination of the maximum stable axial load–bending moment (P–M) interaction strength. The experimental P–M interaction strengths extracted at incipient instability shows that for very slender specimens, the bilinear interaction diagram proposed in the current design provisions of the AISC is somewhat unconservative. This experimental observation is also confirmed by detailed computational results. However, the results also indicate that current AISC provisions provide an accurate and conservative approach for evaluating axial load–flexural interaction for most practical CFT column sizes and lengths (i.e., composite beam columns with low and intermediate slenderness).

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ABSTRACT: A first-order torsion formulation for closed thin-walled (CTW) beam subjected to restrained torsion is developed to consider the warping deformation and restrained shear stresses on cross section and their effect on the behavior of thin-walled (TW) beam. The total torque on closed cross section in the current formulation consists of four component torques. The expressions of various torques and corresponding shear stresses are given. To account for the distribution of true restrained shear stress due to restrained shear rotation in TW cross section, torsion shear coefficient is proposed for CTW beam. Like the transverse shear coefficient in Timoshenko beam theory, the torsion shear coefficient lies at the heart of the first-order torsion theory. The new governing equations of restrained torsion of CTW beam are obtained, which have obvious physical meaning and is easy to be used in engineering and can also be used to solve the torsion problem of open thin-walled beam. The initial parameter method is developed so as to obtain the analytical solution effectively. To demonstrate the accuracy and applicability of the present theory, numerical and closed-form results are compared with those of some other available method. The effects of restrained shear stress on the behavior of open and CTW beams are investigated and verified.

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ABSTRACT: The direct strength method (DSM) simplified the design of cold-formed steel (CFS) beams and columns compared with the traditional effective width method (EWM). In this paper, DSM equations for the distortional buckling (DB) strength are evaluated using the results of the experimental study on channel compression members with edge and intermediate stiffeners as well as nonlinear finite-element analysis (FEA) of the stiffened lipped channel compression members with various configurations, which fail after only DB. A total of 14 fixed-ended stiffened lipped channel compression members with intermediate stiffeners in both the web and flanges were tested, which failed after only DB. Further, additional data on the DB behavior is generated based on a parametric study using the nonlinear FEA, which was initially calibrated with the test data. A study on effect of parameters, such as the type of cross section, the dimensions of the cross section, the lip depth to flange width ratio (d/b), the web height to the flange width ratio (h/b), the yield stress (fy), end
boundary condition (EBC), and the failure modes, shows that the nondimensional ultimate strength, expressed as the ratio of the ultimate strength to yield strength under compression, $Pu/Py$, is adequately addressed through the nondimensional DB slenderness, $\lambda d$, alone as assumed in the DSM. The test and the analysis results show that the DSM equations generally evaluate the strength of stiffened lipped channel members under DB conservatively. Modifications to the DSM equations are suggested to evaluate the DB strength of stiffened lipped channel members more accurately.

Yuner Huang and Ben Young (Dept. of Civil Engineering, Univ. of Hong Kong, Pokfulam Rd., Hong Kong), “Design of cold-formed lean duplex stainless steel members in combined compression and bending”, ASCE Journal of Structural Engineering, Vol. 141, No. 5, May 2015
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001091

ABSTRACT: The structural performance and design of cold-formed lean duplex stainless steel members in combined compression and bending are investigated. A wide range of square and rectangular hollow sections has been performed by finite-element analysis. A finite-element model has been developed and verified against the available test data for lean duplex stainless steel members subjected to axial compression and minor axis bending. An extensive parametric study was conducted using the verified finite-element model, and 150 finite-element analysis results were obtained. A total of 233 data, including the numerical results obtained in this study as well as the experimental and numerical data from the literature, are compared with design predictions from the current American, Australian/New Zealand, and European specifications for stainless steel structures. Reliability analysis was carried out to assess the reliability of these design rules for the lean duplex stainless steel beam-column members. It is shown that the American Specification is capable of providing accurate prediction for the compression and bending capacities, whereas the Australian/New Zealand Standard (AS/NZS) and European Code provide quite conservative predictions. However, the calculation procedure in the American Specification involves tedious iterative processes. Therefore, two modified design methods are proposed for lean duplex stainless steel beam-columns in this study. The two modified design methods in the AS/NZS and direct strength method generally provide better predictions for the cold-formed lean duplex stainless steel beam-columns compared to the current design rules.


ABSTRACT: Due to their typical high slenderness ratios, glass structural elements can be often subjected to buckling phenomena. Major difficulties in a correct estimation of their effective buckling strength and load-carrying behavior are generally given by a combination of multiple mechanical and geometrical aspects, especially in presence of laminated cross sections or interacting applied loads. In this paper, buckling experiments are performed on laminated glass beam-columns eccentrically compressed. Extended numerical and analytical comparisons are performed with test results in terms of Euler’s critical loads or load-displacement paths. As shown, appropriate calibration of numerical and analytical models generally can provide good agreement between buckling predictions and experimental results. Viscoelastic numerical models, in particular, if well-calibrated in terms of mechanical [e.g., creep effects in polyvinyl butyral (PVB)-foils] and geometrical properties (e.g., initial imperfections, load eccentricities) can provide interesting correlation with experiments, both in the form of global load-carrying behavior and ultimate loads. At the same time, simplified analytical methods based on the equivalent thickness concept can be used for rational analytical predictions—
although in well-defined load-time and temperature conditions—and simplified buckling verification procedures.

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ABSTRACT: This paper describes an experimental program investigating the local–global interaction buckling of stainless steel I-section beams. Three alloys were included: austenitic S30401, ferritic S44330, and lean duplex S32101. Extensive coupon tests were conducted to determine the specific properties of stainless steel sheets, including nonlinearity, anisotropy, and strain hardening. The test program encompassed six laterally braced tests and 24 unbraced tests with spans ranging between 1.9 and 4.0 m. The unbraced specimens were tested in a specially designed setup featuring clearly defined loading and support conditions. Interaction buckling was successfully achieved in the tests. The geometric imperfections, bearing capacity, and sectional and global deformations of each specimen were carefully recorded before or during the tests. Key factors affecting the test conditions were identified. The research addressed the lack of experimental data for local–global interaction buckling of stainless steel beams with open cross section and establishes the foundation for further theoretical study, as described in a companion paper.

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“Local-global interaction buckling of stainless steel I-beams. II: Numerical study and design”, ASCE Journal of Structural Engineering, Vol. 141, No. 8, August 2015
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001131
ABSTRACT: The paper presents a detailed finite-element model used to study the local–global interaction buckling of stainless steel I-section beams. The model was constructed with the commercial software package ABAQUS v.6.11 and was verified against the experimental data presented in a companion paper, yielding accurate predictions of interaction buckling behavior and ultimate capacity. Parametric studies were conducted by using the calibrated models to extend the experimental database. The accuracy of the Australia/New Zealand, American, and European standards for stainless steel structures was evaluated by using the available data. It was found that the codes were incapable of capturing the interaction buckling effect, thus affording overly optimistic strength predictions for beams of high section slenderness. Existing direct strength method formulas, as proposed for carbon steel beams and stainless steel columns, were also evaluated to assess their applicability to the stainless steel beams.

ABSTRACT: Analytical models are proposed to predict the compressive resistance of discontinuous bracing members in steel X-braced frames when governed by flexure of the connecting plates at the mid-connections. The connections are bolted single shear splice connections commonly used for HSS bracing members. An incremental analysis procedure is developed to predict the axial load-deformation response of the brace-connection assembly including geometric and material nonlinearities. The buckling strength depends on the thickness of the connecting plates, the length of the connection, the clear distance between the continuous and discontinuous bracing members at the brace intersection, and the length of the discontinuous brace segments. The method is validated against test results from full-scale X-bracing specimens. It is also used to verify the design procedure proposed in the AISC Design Guide 24 for Hollow Structural Section Connections for a series of 17 X-braces covering a wide range of properties. The AISC design procedure generally over-predicts the buckling resistance. A new design procedure is proposed that better reflects the buckling response of discontinuous braces in X-bracing.

Cao Hung Pham, Luciano A. Bruneau and Gregory J. Hancocl (School of Civil Engineering, Univ. of Sydney, Sydney, NSW 2006, Australia), “Experimental study of longitudinally stiffened web channels subjected to combined bending and shear”, ASCE Journal of Structural Engineering, Vol. 141, No. 11, November 2015

ABSTRACT: The direct strength method (DSM) of design of cold-formed sections has been recently extended in the North American Specification for Cold-Formed Steel Structural Members NAS S100:2012 to include shear. The two new features of the DSM rules for shear researched are the effect of full-section shear buckling as opposed to web-only shear buckling and tension field action (TFA). The prequalified sections in the rules include sections with flat webs and webs with small intermediate longitudinal stiffeners. In order to extend the range to larger intermediate stiffeners as occurs in practice, a series of fourteen shear tests have been performed at the University of Sydney for C-sections with rectangular stiffeners of varying sizes. Six different types of stiffeners were tested with an additional preferred plain section. Each type of section was tested twice to ensure accuracy. As the web stiffener sizes increase, the shear buckling and strength of the sections are expected to improve accordingly. However, the tests show that the shear ultimate strengths only increase slightly in association with the respective increases of stiffener sizes. The test results are compared with the DSM design rules for shear and found to be lower than those predicted by the DSM curve for shear with TFA. The test failures were observed mainly due to the combined bending and shear modes. The effect of the bending is therefore significant and starts to govern when the shear capacity is significantly strengthened by adding the large longitudinal web stiffener. The test results are subsequently plotted against the DSM interaction curves between bending and shear, where the interaction is found to be significant. Recommendations for prequalified sections with longitudinally stiffened web channels in combined bending and shear are validated in the paper.

Poologanathan Keerthan and Mahen Mahendran (Science and Engineering Faculty, Queensland Univ. of Technology Brisbane, Brisbane, QLD 4000, Australia.), “Improving the shear capacities of lipped channel beams with web openings using plate stiffeners”, ASCE Journal of Structural Engineering, Vol. 141, No. 11, November 2015

ABSTRACT: Cold-formed steel lipped channel beams (LCBs) are used extensively in residential, industrial, and commercial buildings as load-bearing structural elements. Their shear capacities are considerably reduced when the web openings are included for the purpose of locating building services. Past research has shown that the shear capacities of LCBs were reduced by up to 70% due to the inclusion of these web openings. Hence there is a need to improve the shear capacities of LCBs with web openings. A cost-effective way of eliminating
the detrimental effects of large web openings is to attach suitable stiffeners around the web openings and restore
the original shear strength and stiffness of LCBs. Hence detailed experimental studies were undertaken to
investigate the behavior and strength of LCBs with stiffened web openings subject to shear, and combined
bending and shear actions. Both plate and stud stiffeners, with varying sizes and thicknesses, were attached
to the web elements of LCBs using different screw-fastening arrangements. Simply supported test specimens of
LCBs with aspect ratios of 1.0 and 1.5 were loaded at midspan until failure. Numerical studies were also
undertaken to investigate the strength of LCBs with stiffened web openings. Finite-element models of LCBs
with stiffened web openings under shear, and combined bending and shear actions, were developed to simulate
the behavior of the tested LCBs. The developed models were then validated by comparing their results with
experimental results and were used in further studies. Both experimental and finite-element analysis results
showed that the stiffening arrangements recommended by past research and available design guidelines are not
adequate to restore the original shear strengths of LCBs. Therefore, new stiffener arrangements were proposed
based on screw fastened plate stiffeners. The details of the research reported in this paper are presented.

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“Experimental investigation of aluminum alloy stub columns with circular openings”, ASCE Journal of
Structural Engineering, Vol. 141, No. 11, November 2015
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001265
ABSTRACT: This paper describes a test program on a wide range of aluminum alloy square hollow section
stub columns containing central circular openings. A total of 28 compression tests was conducted by applying
uniform axial load to the specimens, which were fabricated by extrusion of square hollow sections using 6061-
T6 heat-treated aluminum alloys. The column strengths; failure modes (including local buckling failure and
material yielding failure); strain distribution along the quarter of square hollow sections at midheight of the
columns; and load versus axial shortening curves of test specimens were obtained from the experimental
investigation. The test results were compared with the design strengths calculated by using the current design
rules given in the design specifications and design rules proposed by other researchers for perforated carbon
steel structural members. It is shown that most of the current design rules for perforated carbon steel structural
members are generally inappropriate, with comparatively high scatter of predictions for the design of perforated
aluminum alloy stub columns.

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“Simplified approaches to design medium-rise unpraced steel storage pallet racks. I: Elastic buckling analysis”,
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001271
ABSTRACT: The design of steel storage pallet racks is quite complex, despite the fact that these structures are
built with economical components and manufactured from thin coils or sheets. The most advanced approaches
for rack design recommend the use of simplified methods to estimate the key parameters governing both static
and seismic design. In the first case, which is the core of this first part of a two-part paper, an evaluation of the
elastic critical load multiplier for the sway buckling mode (\(\alpha_{cr}\)) is required to select the method of analysis and
check member instability. The term $\alpha_{cr}$ can be predicted through simplified approaches, which have been adequately calibrated for traditional steel structures constructed with members having a double-symmetric cross section. Rack uprights (columns) have, in general, an open cross section, with one axis of symmetry, and thus the overall frame response and member behavior is significantly influenced by Wagner’s coefficients, warping torsion, and shear-center eccentricity. Currently, these effects are neglected in routine rack design, owing to the absence of clear indications in standard provisions and the limited availability and knowledge of appropriate software tools supporting this complex design approach. This paper addresses the applicability of simplified approaches for the static design of medium-rise unbraced pallet racks, whereas the second part companion paper considers seismic approaches. A numerical analysis of several racks composed of different geometries, components, and degrees of stiffness of both beam-to-column and base-plate joints has been completed by using an open source finite-element analysis program for academic use, which is characterized by a refined beam formulation accounting for warping effects. Furthermore, the application to model racks of a traditional beam formulation on the basis of the coincidence between the shear center and the cross section centroid allows a direct appraisal of the warping influence on the prediction methods. Finally, to improve the accuracy of the critical load multiplier prediction, a suitable safety factor has been proposed to be used when beam formulations, including warping, are not available for structural analysis.

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ABSTRACT: This paper concludes a two-part paper, which addresses the reliability of simplified approaches for rack design. The first part presents a parametric study on medium-rise, unbraced racks differing for components, geometry, and flexural stiffness degree of beam-to-column joints and base-plate connections. The evaluation of the elastic critical load multiplier, which is required to select the analysis method and check member instability, is considered through a simplified approach that is adequately calibrated for the more traditional steel structures. This second part focuses on seismic design, which is governed by the value of the fundamental period of vibrations ($T_1$). Simplified approaches from the literature on typical steel frames and recommendations to predict period $T_1$ are applied to two beam formulations differing in the absence or presence of warping. Research outcomes are discussed, considering the limits of the simplified approaches, and improvements to increase the accuracy of fundamental period prediction are proposed. For reproduction purposes, this paper details the data used in the application of the considered simplified approaches and the previously discussed approaches.

ABSTRACT: This research focuses on the strengthening methods used for improving the compression behaviors of plates perforated by slotted holes, as provided in steel bridge pylons for the purposes of access and service. The rectangular plates that were investigated each have a centric slotted hole and are simply supported on four edges in the out-of-plane direction. Three types of strengthening stiffeners, ringed stiffener (RS), flat
stiffener (FS), and longitudinal stiffener (LS), are considered. Uniaxial compression tests are first conducted for 41 specimens, of which seven are unstrengthened plates and 34 are strengthened plates. Stress concentrations, failure patterns, and elasto-plastic ultimate strengths are experimentally investigated. Finite element models are further developed to predict the ultimate strengths of plates with various dimensions. The FE results are validated by the test data. The influences of nondimensional parameters including plate aspect ratio, stiffener slenderness ratio, and stiffener thickness on ultimate strengths are revealed on the basis of numerous parametric studies. Comparisons in strengthening efficiencies of stiffeners are also made by considering stiffener weight. The simplified formulations used for predicting the compression strengths of strengthened plates are proposed. The net cross-sectional area–based strength, including stiffeners, is also recommended for the strength approximation in engineering applications.

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ABSTRACT: A procedure for nonlinear analysis of RC slabs and shell structures is presented. Cracked RC is treated as an orthotropic material governed by a smeared rotating crack procedure and the constitutive formulations of the disturbed stress field model. The analysis procedure is implemented within the framework of a finite-element program employing layered thick-shell elements that consider out-of-plane (through-thickness) shear deformations. A simple modification method employing an effective shear strain concept is introduced to improve the out-of-plane performance of the layered shell element for RC applications. The adequacy of the procedure is verified using test data of RC members controlled by out-of-plane shear failure mechanisms and elements under combined in-plane and out-of-plane loading scenarios. The nonlinear finite-element program is shown to be suitable for elements exhibiting ductile or brittle responses, and the shear modification method introduced is found to be capable of capturing out-of-plane shear failures.

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ABSTRACT: The rigid pressure measurement and aero–elastic vibration measurement were performed to the largest exhaust cooling tower in Asia. Through analyses, the surface wind pressure distribution, multitower proportional coefficient, and wind-induced vibration coefficient of the exhaust cooling towers from the most unfavorable wind direction were obtained. On this basis, finite-element software and self-made reprocessing and postprocessing programs were employed to analyze the ultimate load-carrying capacity and overall and local stabilities of exhaust cooling tower in three conditions, which include (1) no opening, (2) opening without strengthening, and (3) opening with different strengthening schemes, then the ultimate load-carrying capacity of
exhaust cooling tower during construction under different load combinations was also analyzed. For cooling
tower with opening, obvious stress aggregation was found near the opening, and the minimum safety factor for
local stability of the tower throat area was 4.27. An effective strengthening scheme was proposed for such
problem, e.g., the stress aggregation and local instability near the opening were effectively eliminated, and the
critical wind speed for overall destabilization of exhaust cooling tower was increased. During the construction
of exhaust cooling tower, as the constructed height increases, the critical wind speed for overall destabilization
gradually decreases. When 100 template layers are constructed, the critical wind speed is 119.4 m/s, which is
much higher than the designed wind speed of 49.0 m/s; and when the most unfavorable wind speed for
destabilization was applied as regulated wind pressure, the wind speed for overall buckling destabilization is
69.1 m/s. With the consideration of internal suction, the critical wind speed for destabilization decreases by
about 30%. In this paper, some useful conclusions can be used for reference in wind-resistant design of
superlarge exhaust cooling towers.

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142, No. 1, January 2016, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001319
ABSTRACT: Steel concentrically braced frames inherently provide great strength and stiffness, and are widely
used for seismic resisting systems in buildings. These include conventional buckling braced frames and
buckling restrained braced frames. Although the latter can prevent brace buckling and provide ductile behavior,
both types of braces provide no hysteretic damping at small drift levels and offer very limited post-
yielding stiffness. This study proposes a new type of steel brace with a novel mechanism—the naturally buckling brace
(NBB). The design combines high-strength and low-yield steels arranged in parallel with a specified initial
eccentricity along the brace length, providing ductile seismic behavior. Six tests of various NBB models
subjected to cyclic loading were conducted to examine the seismic performance of the proposed NBB. Two
specimens out of the six achieved the characteristics intended for NBB. The test results showed that the NBB
specimens with appropriate design parameters could achieve early yielding, or hysteretic damping, from around
0.11% story drift and prevent local buckling as well as deformation concentration up to a very large story drift
(greater than 3%). A single NBB would provide an asymmetric hysteretic behavior, a large post-yielding
stiffness in tension, and a ductile performance with stable energy dissipation. Further systematic studies of
NBBs are needed to comprehensively evaluate the capacities and limitations of the NBBs, including the
reliability of performance with repeated tests.

Ann E. Jeffers (Dept. of Civil and Environmental Engineering, Univ. of Michigan, Ann Arbor), “Triangular
shell heat transfer element for the thermal analysis of nonuniformly heated structures”, ASCE Journal of
ABSTRACT: This paper presents a triangular shell heat transfer element that is used to simulate the thermal
response of nonuniformly heated structures. The formulation uses a combination of finite-element and control
volume techniques to arrive at a layered shell element that is used to solve the 3D conduction heat transfer
problem in a highly efficient manner. This paper considers a 3-node linear element and a 6-node quadratic element. The element formulation is verified against a converged continuum heat transfer model for a thick steel plate exposed to a concentrated heat flux, a thick steel pipe exposed to a concentrated heat flux, and a concrete slab exposed to a localized fire. The verification studies demonstrate that the linear and quadratic elements consistently converge to the continuum model and require a fraction of the computational cost. The verification study involving the concrete slab exposed to a localized fire demonstrates that the formulation can readily handle steep temperature gradients as well as temperature-dependent material properties.

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ABSTRACT: An experimental and numerical study of ferritic stainless steel tubular cross sections under combined loading is presented in this paper. Two square hollow section (SHS) sizes—SHS 40×40×2 and SHS 50×50×2 made of Grade EN 1.4509 (AISI 441) stainless steel—were considered in the experimental program, which included 2 concentrically loaded stub column tests, 2 four-point bending tests, and 14 eccentrically loaded stub column tests. In parallel with the experimental investigation, a finite-element (FE) study was also conducted. Following validation of the FE models against the test results, parametric analyses were carried out to generate further structural performance data. The experimental and numerical results were analyzed and compared with the design strengths predicted by the current European stainless steel design code EN 1993-1-4 and American stainless steel design specification SEI/ASCE-8. The comparisons revealed that the codified capacity predictions for ferritic stainless steel cross sections under combined loading are unduly conservative. The deformation-based continuous strength method (CSM) has been extended to cover the case of combined loading. The applicability of CSM to the design of ferritic stainless steel cross sections under combined loading was also evaluated. The CSM was shown to offer substantial improvements in design efficiency over existing codified methods. Finally, the reliability of the proposals was confirmed by means of statistical analyses according to both the SEI/ASCE-8 requirements and those of EN 1990.

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ABSTRACT: This paper investigates the global in-plane failure and local web shear failure mechanism and strength of steel I-section circular arches with a sinusoidal corrugated web. In reference to a flat web that can resist both the shear and axial forces, the sinusoidal corrugated web can resist the shear force only. As a result, the sinusoidal corrugated web may fail in an elastic-plastic shear buckling mode. This study considers pin-ended circular steel arches with a sinusoidal corrugated web under a uniform radial load or a uniform vertical load to elucidate numerically their different failure modes. It is found that local web failure occurs suddenly
without warning, and all aspects pertaining to the local web shear failure are investigated thoroughly with an equation for the ultimate shear-carrying capacity of nonuniformly sinusoidal corrugated webs being proposed. It is also found that the effects of the shear deformations of corrugated web on global in-plane buckling and the strength of steel arches are significant. A strength design equation for arches under nominal uniform axial compression and an interaction equation for arches under a uniform vertical load are developed. Strength design procedures for steel arches with a sinusoidal corrugated web against global failure and web shear failure are proposed. All of the equations proposed for global in-plane buckling, local web shear buckling, global in-plane strength, and web shear strength agree with finite-element results.

References listed at the end of the paper:

ABSTRACT: Fire safety plays a vital role in building design because appropriate level of fire safety is important to safeguard lives and property. Cold-formed steel channel sections along with fire-resistive plasterboards are used to construct light-gauge steel frame (LSF) floor systems to provide adequate fire resistance ratings (FRR). It is common practice to use lipped channel sections (LCS) as joists in LSF floor systems, and past research has only considered such systems. This research focuses on adopting improved joist sections such as hollow flange channel (HFC) sections to improve the structural performance and FRR of cold-formed LSF floor systems under standard fire conditions. The structural and thermal performances of LSF floor systems made of a welded HFC, LiteSteel Beams (LSB), with different plasterboard and insulation configurations, were investigated using four full-scale fire tests under standard fires. These fire tests showed that the new LSF floor system with LSB joists improved the FRR in comparison to that of conventional LCS joists. Fire tests have provided valuable structural and thermal performance data of tested floor systems that included time-temperature profiles and failure times, temperatures, and modes. This paper presents the details of the fire tests conducted in this study and their results along with some important findings.

Liping Wang and Ben Young (Professor, Dept. of Civil Engineering, Univ. of Hong Kong, Pokfulam Rd., Hong Kong), “Behavior of cold-formed steel built-up sections with intermediate stiffeners under bending. I: Tests and numerical validation”, ASCE Journal of Structural Engineering, Vol. 142, No. 3, March 2016 https://doi.org/10.1061/(ASCE)ST.1943-541X.0001428
ABSTRACT: An experimental investigation of simply supported built-up section beams with different sectional configurations has been conducted under both four-point bending and three-point bending. Intermediate stiffeners were employed to the webs of built-up sections to improve the buckling strength that is susceptible to local buckling and/or distortional buckling. In this study, the built-up sections were assembled by self-tapping screws from two channels with web stiffeners, which were brake-pressed from high-strength, zinc-coated grades G500 and G550 structural steel sheets with nominal 0.2% proof stresses of 500 and 550 MPa, respectively. The screws were located either at the flanges or webs, and the built-up sections include both open sections and closed sections. The moment capacities and observed failure modes of the beam tests are presented, and no failure was found in the screws. The local and distortional buckling behavior of the built-up section beam specimens were found to be different from the single profiles. Finite-element (FE) models were developed, and numerical analysis that includes material nonlinearity, geometric nonlinearity, and contact nonlinearity was performed. The FE and the experimental results were found in good agreement in terms of ultimate moments and failure modes. The verified FE models are used to perform parametric studies in the companion paper. The structural behavior and design rule for built-up section beams with intermediate stiffeners is then explored and presented.

Liping Wang and Ben Young (Dept. of Civil Engineering, Univ. of Hong Kong, Pokfulam Rd., Hong Kong), “Behavior of cold-formed steel built-up sections with intermediate stiffeners under bending. II: Parametric
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001427

ABSTRACT: Built-up sections were used in a wide range of constructional steel applications. The investigation aims to develop suitable design rules for cold-formed steel doubly symmetric built-up open and closed sections with intermediate stiffeners under bending in this study. These built-up sections have a sufficient number of connections either at the flanges or webs, depending on the sectional configurations. Followed with the experimental investigation and finite-element validation in the first part of this study, a numerical parametric study including a total of 113 different built-up section beams was conducted. The key parameters including the sectional shapes and slenderness as well as the different failure modes and structural behavior were examined. The experimental data, together with the numerical results were compared with the predicted strengths using the current direct strength method (DSM) in the North American Specification. The determination of elastic buckling stresses corresponding to different failure modes, mainly the local and distortional buckling, for beam members is a prerequisite for DSM. Simplified assumptions on the built-up sections were employed in determining the elastic buckling stresses. Furthermore, modified DSM equations for beams with different built-up sectional configurations were calibrated with the experimental and numerical data obtained from this study. The design strengths predicted by the recommended design rules exhibited good agreement with ultimate moments of the built-up open and closed section beams. A reliability analysis was also performed. It is shown that the recommended design rules for cold-formed steel built-up open and closed sections with intermediate stiffeners under bending is reliable.

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ABSTRACT: The direct analysis method is the primary means of assessing system stability within a standard specification. This method, and in particular its use of reduced stiffness, has been thoroughly validated for use in frames consisting of structural steel members. However, appropriate stiffness reductions have not yet been established nor has the method as a whole been validated for frames with steel-concrete composite columns. Through comparisons between second-order inelastic analysis results and results from the design methodology on a parametric suite of small frames, the current design provisions are evaluated in this paper. The results indicate that while the current design provisions are safe and accurate for the majority of common cases, there exist cases in which the current provisions result in high levels of unconservative error. Modifications to the current design provisions are proposed to address these issues.

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ABSTRACT: This paper presents the experimental investigation on the compressive behavior of cold-formed
high-strength steel tubular stub columns. In this paper, the nominal 0.2% proof stress of the high-strength steel was 700, 900, and 1,100 MPa. A total of 25 stub column tests on circular, rectangular, and square hollow structural sections were conducted. Geometric imperfections and load-deformation histories were reported and assessed. The experimental results were compared against the design values calculated from the Australian, European, and North American codes, and the corresponding compactness criteria were assessed. A finite-element model, which incorporated the varying material properties, was described, and the influence of geometric and material imperfections was also evaluated. The finite-element results successfully captured the experimental observations and can be adopted for future parametric studies.


ABSTRACT: A new and advanced beam-column element, namely the curved tapered-three-hinges (TTH) beam-column element, is proposed in this paper. The present element can perform large deformation analysis and explicitly simulate the initial member curvature, which is essential for the second-order direct analysis using one-element-per-member models. Another distinct feature of the element is to analytically express the flexural rigidity of tapered I-sections in the stiffness matrix through a series of tapered stiffness factors such as the $a_i$ and $b_i$ factors. Unlike the conventional models using the approximated distributions (e.g., linear, parabolic, or cubic) or stepped-elements modeling approaches in an analysis, the present study gives an accurate simulation solution on nonprismatic beam-column elements. Herein, the element derivations and formulations are given in detail. To consider the large deflection effect in the analysis, the incremental tangent stiffness method is adopted and the kinematic descriptions are presented. Finally, several examples are employed to validate and verify the reliability and accuracy of the proposed element.

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ABSTRACT: This paper deals with the effects of geometric imperfections on flexural inelastic buckling resistance of axially loaded columns with equally spaced lateral braces and presents a simplified way of forming the critical geometric imperfection for finite-element analyses, which leads to rational results for buckling resistances. First, laterally braced columns with geometric imperfections formed by the traditional single half sine wave or the eigenbuckling modes were analyzed by FEM to illustrate the effect of different imperfection shapes. Second, geometric imperfections of columns acquired from measurements in laboratory tests were adopted, and the statistical characteristic and probability distribution of initial deflections along the column length were obtained; then, extensive numerical results from finite-element analyses were obtained through random imperfection simulations. Last, the comparison was made between statistical results based on the random imperfections and those based on eigenbuckling modes to propose a critical geometric imperfection shape as a linear superposition of a limited number of scaled eigenbuckling modes, making it possible to obtain a rational buckling resistance result by one-time analysis, which is safe but not too conservative. The commonly
used lowest eigenbuckling mode or equivalent sine shape for initial geometric imperfections do not provide a rational prediction for the inelastic buckling resistance of laterally braced columns. The critical geometric imperfection shape presented in this paper can be used in advanced analysis for inelastic buckling resistance of braced columns.

Lavan Sundararagah, Mahen Mahendran and Poologanathan Keerthan (Queensland Univ. of Technology, Brisbane, QLD 4000, Australia), “Experimental studies of lipped channel beams subject to web crippling under two-flange load cases”, ASCE Journal of Structural Engineering, Vol. 142, No. 9, September 2016
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001523
ABSTRACT: Lipped channel beams (LCBs) are commonly used as flexural members such as floor joists and bearers in the construction industry. These thin-walled LCBs are subjected to specific buckling and failure modes, one of them being web crippling. Despite considerable research in this area, some recent studies have shown that the current web crippling design rules are unable to predict the test capacities under end-two-flange (ETF) and interior-two-flange (ITF) load conditions. In many instances, web crippling predictions by the available design standards such as AISI S100, AS/NZS 4600 and Eurocode 3 Part 1-3 are inconsistent, i.e., unconservative in some cases, although they are conservative in other cases. Hence, experimental studies consisting of 36 tests were conducted in this research to assess the web crippling behavior and capacities of high-strength LCBs under two-flange load cases (ETF and ITF). Experimental results were then compared with the predictions from current design rules. Comparison of the ultimate web crippling capacities from tests showed that the design equations are very unconservative for LCB sections under the ETF load case and are conservative for the ITF load case. Hence, improved equations were proposed to determine the web crippling capacities of LCBs based on the experimental results from this study. Current design equations do not provide the direct strength method (DSM) provisions for web crippling. Hence, suitable design rules were also developed under the DSM format using the test results and buckling analyses using finite-element analyses.

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ABSTRACT: Generalized polynomial chaos (gPC) expansion–based simulation technique is used to investigate the influence of input parameter uncertainty, on peak response quantities and fragility curves of base-isolated liquid storage tanks. Unidirectional horizontal sinusoidal base excitation is considered to develop the fragility curves for the base-isolated liquid storage tanks. Extensively used laminated rubber bearing (LRB), with linear force-deformation behavior, is considered as the isolation system. The liquid storage tank is modeled using a widely accepted lumped mass model. The failure of the liquid storage tank is defined corresponding to the elastic buckling of the tank wall. The uncertainties are considered in the isolator parameters and in the base excitation. Considerable difference in the peak response estimation is observed when the input parameters are represented using different probability distributions, especially when the uncertainties are higher. It is also
observed that when the uncertainties in the input parameters increase, probability of failure at given amplitude of the excitation increases. It is demonstrated that the probability of failure estimated using gPC expansion–based simulations closely matches the same obtained through the direct Monte Carlo (MC) simulations. Significant influence of the time period of the isolation system is observed on the fragility curves of the base-isolated liquid storage tanks. However, isolation damping has a marginal effect on the fragility curves of the base-isolated liquid storage tanks.

ABSTRACT: This paper investigates the load-bearing capability of sandwich panels (composed of fiber-reinforced polymer faces and a foam core) connected by aluminum hinges in an origami-inspired deployable structure intended for temporary sheltering. The structure is studied (1) during deployment (loaded under self-weight only), and (2) as both individual and combined modules subjected to uniform pressures emulating wind loads. The measured results are used to validate finite element models, with comparisons focusing on surface strains and displacements at panel centers (to study global behavior), as well as surface strains near connections (to study local behavior). The validated numerical models are used to perform parametric studies investigating design decisions for (1) deployment, including panel reinforcement, location of lifting equipment, and size of lifting equipment, and (2) combined modules, including restraints and connections between modules, gasketing between panels, and panel reinforcement. This research ultimately demonstrates the load-bearing capability of deployable structures composed of hinged sandwich panels and provides design guidelines and recommendations.

ABSTRACT: This paper presents a numerical model developed to predict the response of partially composite load bearing concrete sandwich panels under axial loads applied to the structural wythe at any eccentricity. The model accounts for material nonlinearity, second-order effects, and cracking of concrete and plasticity of steel reinforcement, and can also model fiber-reinforced polymer (FRP) connectors. The analysis uses a bond-slip model to simulate partial composite action between the two wythes resulting from various configurations of insulation and shear connectors. A variety of failure modes can be detected, including concrete crushing, flexural yielding, connectors yielding, pullout or rupture, and stability failures. Progressive failure of connectors is also modeled. The degree of composite action (\(\kappa_u\)) can be calculated for a given design. The model was verified against experimental data and used to conduct a comprehensive parametric study. It was shown that \(\kappa_u\) increases with panel length. Connectors’ diameter and spacing greatly affect \(\kappa_u\) and give similar gains in strength and stiffness at the same connector’s reinforcement ratio (\(\rho_v\)). Connectors inserted at an angle are considerably stronger than those inserted normal to panel face. The insulation bond alone provides a 31% increase without any connectors, but this contribution decreases as \(\rho_v\) increases.

Ou Zhao (1), Leroy Gardner (1) and Ben Young (2)
ABSTRACT: This paper presents a comprehensive experimental study of the buckling behavior of ferritic stainless steel tubular section beam-column structural members subjected to unequal end moments. Testing was carried out on two cold-formed and seam-welded cross sections—one rectangular hollow section (RHS) 100×40×2 and one square hollow section (SHS) 60×60×3 made of grade AISI 410 (EN 1.4003) stainless steel. The experimental investigation included a series of material tensile coupon tests, initial local and global geometric imperfection measurements and 24 beam-column tests under unequal end moments. The experimental setup and procedures are described, and the test observations, including the key test results, the load-deformation histories, and the failure modes, are fully reported. The experimental results were carefully analyzed and then compared with the design strength predictions determined according to the current European code, American specification, and Australian/New Zealand standard for stainless steel structures, enabling the accuracy of each codified method to be evaluated. Generally, the European code resulted in the most conservative and scattered strength predictions among the three codified approaches, owing principally to the use of the same treatment for stainless steel beam-columns under both equal and unequal end moments. The American specification and Australian/New Zealand standard employ an equivalent uniform moment factor to consider the beneficial effects of moment gradient on beam-column strengths. These approaches were shown to offer more accurate and consistent capacity predictions for ferritic stainless steel beam-columns under unequal end moments, though further improvements remain possible.

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ABSTRACT: A new manufacturing process allows for the production of tapered spirally welded steel tubes. This paper describes a series of eight large-scale tests examining the behavior of such tubes in flexure and investigates the impact of imperfections on the flexural strength of the tube. The tests are performed on tapered circular steel tubes with diameters between 0.7 and 1.1 m and maximum diameter-to-thickness ratios between 200 and 350. Specimen geometries are selected to provide flexural test data at slenderness ratios not commonly tested in the literature and to be representative of tapered tubes applied as wind turbine towers. The geometries of the specimens are measured with laser scanners before and during testing to characterize initial imperfections and the evolution of local buckling. Results are compared to design strengths per Eurocode EN 1993 1-6. All specimens meeting Eurocode manufacturing quality requirements exceed predicted strengths. The location and orientation of the local buckling region are correlated with the spiral seam welds on the specimens.


ABSTRACT: The novelty of this paper is the use of a new four-variable refined plate theory for thermal buckling analysis of functionally graded material (FGM) sandwich plates. Unlike any other theory, the present new theory is variationally consistent and gives four governing equations. The number of unknown functions involved is only four, as against five in case of other shear deformation theories. In addition, the theory, which has strong similarity with classical plate theory in many aspects, accounts for a quadratic variation of the transverse shear strains across the thickness and satisfies the zero traction boundary conditions on the top and bottom surfaces of the plate without using shear correction factors. Material properties and thermal expansion coefficient of the sandwich plate faces are assumed to be graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. The thermal loads are assumed as uniform, linear, and nonlinear temperature rises across the thickness direction. The effects of aspect and thickness ratios, gradient index, loading type, and sandwich plate type on the critical buckling are all discussed.


ABSTRACT: In this study, damping characteristics of viscoelastic sandwich cylindrical shell under internal/external pressure and internal temperature are investigated. By implementing finite difference method for irregular grids in the sandwich cylinder, the temperature distribution at each layer is determined. A nonlinear model for displacement fields at the viscoelastic core layer is developed to describe the damping characteristics of sandwich cylinder with thin/thick core layer. The effect of dissipation in a pressurized cylinder under harmonic variation of the pressure is also investigated. As shown, deflection increases with time due to the dissipated energy and consequently loss factor is not unique even at a constant frequency.


ABSTRACT: The localized behavior of sandwich structures with foam core subjected to indentation loading is investigated in this article. Based on the principle of virtual velocities, concisely explicit solutions for the
indentation forces and shape functions of deformation zones of sandwich beams are derived. Both flat and cylindrical indenters are considered. The indentation force varies linearly with the square root of indenter displacement and the surface deformation profiles are proportional to the square of the distance from the contact center along the beam direction. Finite element models have been established using the ABAQUS/Explicit code to verify the validity and applicability of the analytical solutions. The theoretical predictions of the profiles of deformation zones and the denting loads of indenters are in good agreement with those by numerical simulation.


ABSTRACT: Closed-form formulations of two-dimensional refined higher order beam theories and higher order beam theories for the free vibration analysis of simply supported cross-ply laminated composite and sandwich curved beams are presented. The present refined higher order beam theory analysis incorporates a trapezoidal shape factor that arises due to the fact that the stresses through the thickness of the beam are integrated over a curved surface. Therefore, the present theory refines other higher order beam theories established hitherto for free vibration analysis of strongly thick circular curved beams. The stress–strain relationship is derived from an orthotropic lamina in a three-dimensional state of stress. Numerical results are presented for the natural frequencies of laminated composite and sandwich thin/thick straight beams and shallow/deep and moderately/strongly thick curved beams. The closed-form solutions presented herein are compared with the available exact two-dimensional elasticity and analytical solutions in the available literature and excellent agreement is obtained.


ABSTRACT: This paper deals with the failure of compression-loaded sandwich panels with an implanted circular face/core debond. Uniform compression tests were conducted on intact sandwich panels with three different types of core material (H130, H250 and PMI) and on similar panels with circular face/core debonds having three different diameters. The strains and out-of-plane displacements of the panel surface were monitored using the digital image correlation technique. Mixed mode bending tests were conducted to determine the fracture toughness of the face/core interface of the panels. Finite element analysis and linear elastic fracture mechanics were employed to determine the critical buckling load and compression strength of the panels. Modeling approaches and failure criteria are discussed. Numerically determined crack propagation loads in most of the cases show a fair agreement with experimental results, but in a few cases up to 45% deviation is seen between numerical and experimental results. This can be ascribed to several factors such as the large scatter in the measured interface fracture toughness, differing crack tip details and crack growth mechanisms between the panels and the mixed mode bending specimens. Tentative strength reduction curves are presented, but uncertainty concerning the intact strengths of the materials used needs to be removed before these can be utilized with confidence.

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ABSTRACT: An analytical technique is presented for obtaining the large amplitude, damped response of a foam-core composite sandwich panel subjected to uniform pressure pulse loading. The predicted panel response was in agreement with finite element analysis, and it was used to examine the blast resistance of panels with various foam cores. Although blast resistance generally increased with the increasing core density, panels with the densest cores exhibited no energy absorption before panel failure. The panel with the PVC H200 foam also sustained higher failure pressure per unit areal weight density than the denser panels with Klegecell R300 and HCP100 foams.

ABSTRACT: An eight-node assumed stress solid element with rotational degrees of freedom is employed for analyses of sandwich plates consisting of stiff face and a comparatively flexible core material with the aim to accurately and efficiently capture stresses. The element formulation is based directly on an eight-node element. This direct formulation requires fewer computations than a similar element that is derived from an internal 20-node element in which the midside degrees of freedom are eliminated by expressing them in terms of displacements and rotations at corner nodes. The formulation is based on Hellinger-Reissner variational principle. Numerical examples are presented to show the validity and efficiency of the present element.

ABSTRACT: In this article, the static analysis of sandwich plates is performed by radial basis functions collocation, according to the Murakami’s Zig-Zag function theory. The Murakami’s Zig-Zag function theory accounts for through-the-thickness deformation, by considering a Zig-Zag evolution of the transverse displacement with the thickness coordinate. The equations of motion and the boundary conditions are obtained by the Carrera's unified formulation, and further interpolated by collocation with radial basis functions.

ABSTRACT: The dynamic behavior of soft-core sandwich plates is investigated. A high-order finite element concept that has been developed for the dynamic analysis of multi-layered plate structures with stiff and compliant layers is applied to the soft-core sandwich plate. The application to sandwich plates aims to validate the general model through comparison with experimental and analytical benchmarks and to throw light on the unique structural response of the sandwich plate. The model introduces the core’s three-dimensional stress and deformation fields using a high-order kinematic assumption that is based on the closed-form solution of the static governing equations of the core. The first-order shear deformation laminated plate theory is used for the
face sheets. The combination of the high-order theory with the finite element concept aims to extend the application of the theory to more general layouts, to reduce the computation effort needed for a three-dimensional analysis, and to address some of the obstacles due to differences in length scales and elastic properties. The validity and the capabilities of the formulation are examined through comparison with experimental and analytical results taken from the literature. In addition, the static, free vibration, and dynamic behaviors of an ‘L’ shaped sandwich plate subjected to localized loads and boundary conditions are numerically studied. The formulation, the comparison with experimental and analytical benchmarks, and the numerical study highlight the three-dimensional effects and reveal unique aspects of the dynamic response of soft-core sandwich plates.


ABSTRACT: We focus on the description of the stress state of sandwich beams under bending and shear, a non-trivial task if Saint-Venant's principle does not hold, as it is the case if the skins are somewhat stiffer than the core. Each of the analytical structural models available in literature turns out to be accurate for a limited range of relative stiffness between core and skins, or sandwich heterogeneity. For a simply supported sandwich beam subject to uniform transversal load, we evaluate the stress by means of (a) the classical theory relying on the linear cross-section kinematics, appropriate if Saint-Venant's principle holds, (b) the structural theory based on the zig-zag warping (e.g. Krajcinovic D. Sandwich beam analysis. J Appl Mech, Trans ASME 1972; 39(3): 773–778), and (c) the higher-order theory of Frostig et al. (Frostig Y, Baruch M, Vilnay O, et al. High-order theory for sandwich-beam behavior with transversely flexible core. J Eng Mech, Trans ASCE 1992; 118(5): 1026–1043), the latter usually appropriate when the core is much softer than the skins. The results are compared, for several combinations of material and geometrical parameters, with those of finite element simulations in which the sandwich is modelled as a plane stress continuum. This comparison allows us to provide some graphs which can help in selecting the model appropriate for each sandwich heterogeneity. This is accomplished in terms of non-dimensional material and geometrical parameters the sandwich heterogeneity depends on. We identify and discuss two levels of heterogeneity at which one should switch analytical model: one level is related to the validity of Saint-Venant's principle, while the other level is concerned with the definition of antiplane sandwich.


ABSTRACT: This paper presents a crashworthiness robust optimization design of aluminum honeycomb sandwich panel with regular hexagonal core cell based on explicit finite element analysis. First, the crashworthiness of honeycomb sandwich panel and the bare honeycomb core are compared with each other in the aspects of specific energy absorption and peak crushing force. The comparative results show that honeycomb sandwich panel can absorb more energy than the bare honeycomb core, though the peak crushing force of honeycomb sandwich panel is larger. Then the factor screening experiments are carried out to find out variables that have significant effects on the crashworthiness of honeycomb sandwich panel. The ultimate purpose of factor screening experiments is to decrease the computational expense by reducing the number of design variables. Finally, the dual response surface method and the crossed array design are employed to
formulate the complex robust optimization design problem. The regression expressions of specific energy absorption and peak crushing force are defined as the objective and constraint function respectively in the robust design of crashworthiness optimization.

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ABSTRACT: Buckling-induced skin–core debond growth in honeycomb sandwich cantilever beam is demonstrated using a cohesive zone model. The input parameters for the analysis are interfacial bond strength, mode I and mode II interfacial fracture toughness values, obtained from flatwise tension tests, drum-peel tests and three-point end notch flexure tests, respectively. Debonded honeycomb specimens are tested and the acoustic emission technique was used to observe the initiation of the debond growth. The load-displacement response from the cohesive zone model model shows a good agreement with the experimental results. The conventional analysis without cohesive zone model overestimates failure load by 56%. Cohesive zone model is able to predict the coupled debond growth and buckling failure in honeycomb sandwich structures.

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ABSTRACT: In this article, a three-dimensional finite element model is proposed to study the effect of distributed attached mass with thickness and stiffness on the buckling instability of sandwich panels with transversely flexible cores. Unlike the previous works in the literature which have made use of unified displacement theories, the present model uses different types of finite elements to model the core and the face sheets. It utilizes shell elements for the face sheets and three-dimensional solid elements for the core which enables the model to account for the transverse flexibility of the structure. The motions of the face sheets and the core as well as the attached mass are related through defining constraint equations between the nodes of their respective finite elements based on the concept of master and slave nodes which is incorporated into the finite element analysis program ANSYS through a user-defined subroutine. The validated finite element model is then used to study the effects of size, thickness, material property, aspect ratio, and the position of the attached mass on the buckling load of a sandwich panel under different combinations of boundary conditions. The results presented in this study have hitherto not been reported in the literature.

ABSTRACT: This article focuses on dynamic stability of smart sandwich beams resting on Winkler elastic foundation subjected to harmonic axial loads. To increase the dynamic buckling load and the stability region of the beam, an electro-rheological layer is adhered as a core. The finite element method is employed to derive a three layer smart sandwich beam element. By inspecting dynamic response of the beam in different load amplitudes, critical dynamic loads are calculated. Parametric study is done to investigate effects of various parameters such as beam geometry, foundation stiffness, static load, applied voltage and properties of core layer on critical dynamic loads and stability regions of the beam. This study indicates that by applying electric field to the electro-rheological core, dynamic critical load and consequently, dynamic stability of the beam increase efficiently. Furthermore, the elastic foundation reduces the unstable region and increases the critical dynamic load of the smart beam. Proper use of these parameters makes the beam less sensitive to axial harmonic loading by relocating the instability region.


ABSTRACT: In this study, an indentation failure analysis of sandwich composite plates via several higher-order theories is presented. The unified formulation by Carrera is adopted in order to derive displacement based or mixed, refined theories based on an equivalent single layer approach or a layerwise one. In this manner, out-of-plane normal and transverse shear stresses responsible for the indentation failure can be accurately described. A closed form, Navier-type solution is assumed. Simply supported plates made of fibre-reinforced polymeric skins and foam cores are investigated. The side-to-thickness ratio, $a/h$, and the indenter side dimension are considered as analysis parameters. The effect of skins' lamination and thickness is also investigated. Failure indentation is described in terms of failure loading value and failure position. The variation of displacement and stress fields near the indentation area are also presented. The accuracy of the proposed theories is assessed towards Pagano's three-dimensional exact solution. The obtained results show that higher-order models are required to accurately describe the indentation failure of sandwich plates.


ABSTRACT: Experimental blast response and quasi-static material property data were obtained for E-glass and carbon face skin sandwich composite panels with balsa, polyvinyl chloride foam, and TYCOR® cores. The pressure versus impulse ($P-I$) curve methodology enabled the generation of a database of performance envelopes for these sandwich composite panel configurations under different blast loading scenarios. The strength versus deformation properties of various undamaged sandwich composite panels are established numerically and idealized for single-degree-of-freedom modeling. Results show good correspondence between model predictions and experimental results for performance evaluation of the various sandwich composite structural panel configurations that were investigated.

Buket Okutan Baba (Department of Mechanical Engineering, Faculty of Engineering, Celal Bayar University,
ABSTRACT: This article presents experimental results of the impact response and failure characteristics of curved composite sandwich beam with debond. The objective of this study is to determine how the curvature and debond affects the contact force, displacement, absorbed energy, and damage type under impact loading. An instrumented drop-weight impact test are performed on sandwich beams made of carbon/epoxy face sheets and polyurethane foam core material with four different radii of curvature and debonds between the top and bottom interface of face sheet and foam core. Impact energy was kept constant of 4 J. The contact force and displacement histories of curved sandwich composites with debond are measured to determine the impact response. The results are compared with those of flat beams with the same dimensions and no debond. They indicate that the value of the contact force increases as the curvature angle increases for the beam with no debond. Opposed to the beams with no debond, the contact force decreases as the curvature angle increases for the beam with debond. These results show that curvature angle and debond are important mechanical parameters that must be considered in the design of structures.

ABSTRACT: The three-dimensional free vibration analysis of simply supported, functionally graded piezoelectric material sandwich circular hollow cylinders with different surface conditions is presented. The material properties of each functionally graded piezoelectric material layer are regarded as heterogeneous through the thickness coordinate, and obey an exponent-law dependent on this. Pagano's method is modified to be feasible for this study of functionally graded piezoelectric material sandwich cylinders, in which a displacement-based formulation is replaced by a mixed one; a set of the complex-valued solutions of the system equations is transferred to the corresponding set of real-valued solutions using Euler’s formula; a successive approximation method is adopted to approximately transform each functionally graded piezoelectric material layer into homogeneous piezoelectric layers with an equal and small thickness for each layer in comparison with the mid-surface radius, and with the homogeneous material properties determined in an average thickness sense; and a transfer matrix method is developed so that the general solutions of system equations can be obtained layer-by-layer, which is significantly less time-consuming than usual. A parametric study of the influence of the mid-surface radius-to-thickness ratio, open- and closed-circuit surface conditions, the thickness ratio of each layer, and the material-property gradient index on the natural frequencies of functionally graded piezoelectric material sandwich cylinders is carried out.

ABSTRACT: An elastic-plastic model was developed for predicting the blast response of a foam-core, curved composite sandwich panel. A multi-layered approach was used to distinguish facesheets and core deformations. Core compressibility and transverse shear through the thickness were accounted for using linear displacement fields through the thickness. The predicted solution from the elastic-plastic model was shown to compare well
with FEA from ABAQUS Implicit. A parametric study showed that blast resistance of the sandwich shell is increased by allowing cores to undergo plastic crushing. Very thick and shallow shells derive much of their resistance to blast from core crushing. Strong, dense foam cores did not increase the blast resistance of the curved sandwich panel but allowed facesheets to fracture while the core remained elastic.

Saeed Kamarian, Mohammad Hossein Yas and Aminallah Pourasghar, “Free vibration analysis of three-parameter functionally graded material sandwich plates resting on Pasternak foundations”, Journal of Sandwich Structures & Materials, Vol. 15, No. 3, pp 292-308, May 2013, https://doi.org/10.1177/1099636213487363 ABSTRACT: Based on the three-dimensional elasticity theory, this paper focuses on the free vibration characteristics of functionally graded sandwich rectangular plates resting on Pasternak foundations. The two-constituent functionally graded plate consists of ceramic and metal. These constituents are graded through the thickness according to a three-parameter power-law distribution. The benefit of using the considered power-law distribution is to illustrate and present useful results arising from symmetric, asymmetric and classic profiles. In this research work, a detailed parametric study is carried out to highlight the influences of different profiles of fiber volume fraction, three parameters of power-law distribution and two-parameter elastic foundation modulus on the vibration characteristics of the functionally graded sandwich plates.

Alan Nettles (NASA-MSFC Building, 4601 Rideout Rd., Huntsville, AL 35812, USA), “Normalizing impact energy by face sheet thickness for composite sandwich structure compression after impact testing”, Journal of Sandwich Structures & Materials, Vol. 15, No. 3, pp 340-358, May 2013, https://doi.org/10.1177/1099636213484027 ABSTRACT: The amount of impact energy used to damage a composite laminate face sheet of a sandwich structure is a critical parameter when assessing residual compression strength. The compression after impact strength of impacted laminates used as face sheets on honeycomb core sandwich structure is dependent upon how thick the face sheet laminate is and this has traditionally been accounted for by normalizing (dividing) the impact energy by the laminate’s thickness. However when comparing compression after impact strength values for a given lay-up sequence and fiber/resin system, dividing the impact energy by the specimen thickness has been noted by the author to give higher compression after impact strength values for thicker face sheet laminates. A study was thus undertaken to assess the comparability of compression after impact strength data of sandwich structure by normalizing the impact energy by the face sheet thickness raised to a power to account for the higher strength of thicker laminates. Two data sets generated in this study were analyzed by dividing the impact energy by the face sheet thickness to the 1.0, 1.5, 2.0 and 2.5 powers. Results show that raising the face sheet thickness to a power of approximately 2.5 and dividing the impact energy by this quantity yields more comparable compression after impact strength data for comparing 8- and 16-ply face sheet laminates. For comparison of 24-ply face sheet laminates to 8- or 16-ply face sheet laminates, a value closer to 2 was found to give more comparable compression after impact strength data.

numerical investigation are presented in two parts. In the first part compressible core are considered using the elasticity closed-form solution and various high-order computational models such as the high-order sandwich panel theory (HSAPT) and the extended HSAPT model (EHSAPT). The second part is dedicated to incompressible cores and includes classical models, first-order and high-order shear deformable models, and zig-zag displacement pattern model, ordinary sandwich panel theory. The elasticity-based model serving as the benchmark solution (in first part) assumes isotropic, orthotropic, as well as layered core types. The mathematical formulation utilizes Hamilton’s principle to derive the general equations of motion. A closed-form solution of the elasticity model is available only for a simply-supported panel and it is compared with all various models numerically. The numerical investigation includes: eigenfrequencies, displacement modes along the length and through the depth of panel, as well as stress modes through the depth of panel. The results of the various models are compared with the 2D elasticity solution and finite element results of ADINA. In general, the lower mode correlates well for all models while for the higher modes only the EHSAPT and the HSAPT with displacement formulation compared well.

ABSTRACT: The free vibration response of a unidirectional sandwich panel with an incompressible core using shear deformable and layered models is presented. The models considered include the layered model, ordinary sandwich panel theory that uses a zig-zag in-plane displacements distribution in addition to the shear deformations and the first and high-order shear deformable theories that adopt an approach which replaces the layered sandwich panel with a single layer with equivalent properties. The mathematical formulations use Hamilton’s principle to present the general equations of motion and the specific mass and stiffness matrices for a simply-supported panel. The results of the models are compared with the closed-form solution of the 2D elasticity equations of motion and finite element results of ADINA. The numerical comparison is described in terms of eigenfrequencies and eigenmodes of displacements and stresses and reveal a good correlation at the lower modes only.

ABSTRACT: Lattice truss cores are an emerging family of synthetic periodic materials that can add multifunctional capabilities to lightweight sandwich constructions while maintaining high standards of strength and stiffness. Recent strides in prototyping technologies allow efficient monolithic truss cores to be built from advanced metals without the nuisances of assembled constructions. Based on published models for these materials, this paper tackles the optimal design of tetrahedral truss cores for minimum density under prescribed constraints on strength and stiffness. A closed-form, single-pass algorithm is developed, which finds the optimum after a finite number of steps. The method shows that the best tetrahedral truss core depends on the initial conditions, though 45° orientations are most likely to occur and squatter shapes are rarely convenient. A numerical example demonstrates that optimized aluminium tetrahedral cores outperform high-profile polymer foams and compete favourably with commercial-grade aluminium honeycombs of equal density. The general approach disclosed can be applied to the mechanical optimization of other types of truss core (e.g. pyramidal or kagome, single- or multilayered) and classical periodic design (e.g. corrugated cores), which so far have been
analyzed in a less general way.

ABSTRACT: This paper reviews the most significant works in literature about the acoustic behaviour of sandwich panels, starting from the first examples of multi-layered structures, comprising a series of different layers enclosing an air-gap, to the actual configurations in which the opportunities of emerging manufacturing technologies are considered in the design stages. The focus is on presenting an exhaustive list of dedicated and validated models, which are able to predict the sound transmission through sandwich panels according to their specific configuration. Some experimental works, aimed to the model correlations, are reviewed, too.

ABSTRACT: An improved third-order shear deformation theory is employed to investigate free and forced vibration responses of functionally graded plates. A power law distribution is used to describe the variation of material compositions across the plate thickness. The governing equations for vibration analysis obtained using an energy approach are then solved using the Ritz method. Two types of solutions, temperature independent and dependent material properties, are considered. Many effects of the volume fraction index, temperature, material pairs, thickness, plate aspect ratio, etc., which have significant impact on dynamic behaviour of the plates, are considered in the numerical illustrations of free and forced vibration results. At high temperatures, it is observed that the maximum deflections of the functionally graded plates subjected to the dynamic loading increase with the increase of frequency ratio and temperature.

ABSTRACT: The failure modes of open weave (latticed) sandwich skins under biaxial compression load are analysed. Due to the latticed structure of these sandwich face sheets, they are able to transfer loads in both directions. Tests show a distinct non-linear correlation between load and deformation. This non-linear load-deflection-behavior indicates that the failure may be induced by geometrical imperfections. Based on this assumption and measured geometrical imperfections, a mathematical model for the latticed face sheet consisting of beams under compression is derived. Several beams are combined within one or two cells of the honeycomb core to describe the failure modes. Furthermore, biaxial loading is analysed by using the finite element method. Experimental results are in good agreement with failure loads derived by analytical and by finite element method analyses as well.

ABSTRACT: A refined trigonometric higher-order plate theory is presented for bending analysis of simply supported functionally graded ceramic–metal sandwich plates. The effects of transverse shear strains as well as the transverse normal strain are taken into account. The number of unknown functions involved in the present theory is only four as against six or more in case of other shear and normal deformations theories. Several types of the present symmetric and non-symmetric sandwich plates are used. The faces are assumed to be functionally graded through the thickness, while the core layer is still homogeneous and made of an isotropic material. The present refined plate theory is used to derive the field equations of the functionally graded sandwich plates. Numerical results of the present theory are compared with other theories to show the effect of the inclusion of transverse normal strain on the deflections and stresses.


ABSTRACT: In this paper, a new higher-order shear and normal deformation theory for the bending and free vibration analysis of sandwich plates with functionally graded isotropic face sheets is developed. The number of unknown functions involved in the present theory is only five, as against six or more in case of other shear and normal deformation theories. The theory accounts for hyperbolic distribution of the transverse shear strains and satisfies the zero traction boundary conditions on the surfaces of the plate without using shear correction factor. The boundary conditions for the plate are assumed to be simply supported in all edges and in the static analysis, the plate is assumed to be subjected to a sinusoidally distributed load. Both symmetric and non-symmetric sandwich plates are considered. The equations of motion are obtained using Hamilton’s principle. Numerical results of present theory are compared with three-dimensional elasticity solutions and other higher-order theories reported in the literature. It can be concluded that the proposed theory is accurate and efficient in predicting the bending and free vibration responses of sandwich plates with functionally graded isotropic face sheets.


ABSTRACT: The subject of the paper is about sandwich beam-column with a metal foam core. The global buckling phenomenon of an axially loaded member is investigated. Two analytical models of the beam-column are presented. In the first model, a classical one, the mechanical properties of the core are assumed to be linear. In the second model, the non-linear behaviour of the core is taken into account. Solutions of these two models are presented and the formulae for the critical loads are determined. The numerical finite element models of the beam-column are also elaborated and the linear buckling and the non-linear analyses are performed. The results
of experimental tests on the aluminium sandwich beam-columns with aluminium foam core are described. Analytical, numerical finite element model and experimental values of the critical loads are compared.


ABSTRACT: A numerical model has been developed on metallic sandwich structures as an armor for aeronautical applications. Several combinations of AA5086-H111 aluminium skins and aluminium honeycomb core have been studied, considering medium-velocity and high-energy impacts. The aim is to establish links between the sandwich performances and the material and geometrical parameters. An elasto-plastic, strain-rate dependent behavior has been implemented to represent the skins and the core. The sandwich model has been calibrated and validated from the experimental data. Dynamic effects, as well as strong couplings between the skins and the core appear to have a significant effect on the target performance.


ABSTRACT: A new type of 3D composite sandwich structure with foam core reinforced by composite columns, which can be called integrated 3D composite sandwich structure, is designed, fabricated, and studied. The integrated 3D composite sandwich structure inherits the advantages and improves the shortcomings of the traditional foam core composite sandwich structures. All types of the samples with different consisting materials and structural parameters are tested and analyzed under compressive load. The results show that the compressive properties of the integrated 3D composite sandwich structures are obviously better than those of the traditional foam core composite sandwich structures and due to the fact that the composite columns and the foam support each other. Moreover, the support effect is more obvious for the better toughness foam. And the structural parameters have significant influence on the out-of-plane compressive properties, especially the diameter of composite columns and the distance between composite columns. However, the variety of these parameters results in a corresponding change of the mass and then effect the specific compressive properties. Consequently, it is necessary to find a balance among these parameters in order to get the optimal properties.


ABSTRACT: The solution of the buckling problem for a rectangular composite sandwich plate with two parallel simply supported edges and another two edges clamped (SSCC) is presented in the paper. The plate is composed of two identical composite facings and orthotropic core, and subjected to in-plane uniform compressive load applied to the simply supported edges. Buckling equations are derived based on the first-order shear deformation theory. The problem is solved using the Levy and Galerkin methods. The analytical formula for the critical load has been obtained and verified using finite-element analysis. The design analyses have been
performed for the sandwich panels subject to constraints imposed on the value of buckling load.


ABSTRACT: This paper presents an analytical study of the in-plane dynamic crushing and energy absorption of hexagonal honeycombs with density gradients under different impact loading. Explicit dynamic finite element method simulations are carried out by using ANSYS/LS-DYNA. Firstly, under the assumption that the cell wall length is the same, a density-graded honeycomb mode is established by the variation of the cell wall thicknesses along the crushing direction. The effects of density gradient and impact velocity on the crushing deformation modes, plateau stresses and energy absorption characteristics of the specimens are explored in detail. Numerical results show that except for the impact velocity, the dynamic crushing performance and energy absorption abilities of honeycombs also rely on the density/strength gradients. The weakest layer is suggested to be placed at the impact end or the output end, and the strongest layer at the intermediate stage to achieve higher energy absorbing efficiency. According to the one-dimensional shock wave theory, the simple empirical formulae for graded honeycombs to predict the plateau stress are given under high-impact velocities. These results will provide some useful guides in the multi-objective optimization dynamic design and shock energy absorbing control of sandwich structures.


ABSTRACT: This paper analyzes the bending response of functionally graded skew sandwich plates with graded layer as face sheet/core using higher order shear deformation theory in the framework of finite element method considering through-the-thickness variation of displacements. The assumed kinematics field incorporates the quadratic variation of thickness co-ordinate in defining the transverse displacement. The $C_0$ finite element formulation has been done efficiently to overcome the problem of $C_1$ continuity associated with the higher order shear deformation theory. For this, a rectangular isoparametric Lagrangian element with nine nodes and 13 nodal unknowns at each node is developed. Two types of plates are modeled: functionally graded skew plates with graded face sheets and graded layer as core part. By considering the symmetry of the plate, different combinations of bottom-core-top thickness has been considered for the numerical study. Wide variety of numerical problems are presented for functionally graded sandwich plates with various skew angles, thickness schemes, aspect ratio, thickness ratio and boundary conditions. It is noticed that isotropic plates exhibit diverge response in comparison with graded plates. Also, power law exponent and skew angle are vital parameters that dictate the response of the plate under bending.


ABSTRACT: Detailed structural nonlinear finite element modeling of a sandwich panel with corrugated core is performed in this study. A simply supported panel is loaded in uniaxial compression well into the regimes of global panel buckling and local face sheet buckling. The highly nonlinear load versus in-plane and out-of-plane...
displacement responses obtained from finite element analysis agree reasonably well with experimental results, but the model slightly overpredicts the maximum load. The difference between experiments and predictions is attributed to damage of the corrugated paper web introduced during manufacture of the core and corrugated board. Computations of the buckling also result in a slight thickness reduction of the panel for a large range of face and web thicknesses identify lower thickness limits when the web loses its ability to contribute to the compressive strength of the panel. The highly nonlinear response associated with local and global buckling also results in thickness reduction of the panel.

ABSTRACT: In this paper, an efficient and simple refined shear deformation theory is presented for the vibration and buckling of exponentially graded material sandwich plate resting on elastic foundations under various boundary conditions. The displacement field of the present theory is chosen based on nonlinear variations in the in-plane displacements through the thickness of the plate. By dividing the transverse displacement into the bending and shear parts and making further assumptions, the number of unknowns and equations of motion of the present theory is reduced and hence makes them simple to use. Equations of motion are derived from Hamilton’s principle. Numerical results for the natural frequencies and critical buckling loads of several types of symmetric exponentially graded material sandwich plates are presented. The accuracy of the present theory is verified by comparing the obtained results with solutions available in the literature. Numerical results show that the present theory can archive accuracy comparable to the existing higher order shear deformation theories that contain more number of unknowns.

ABSTRACT: High fibre content composite laminate skins use marine grade orthophthalic polyester, POLYLITE® 440-M850 resin and chopped strand mat/woven E-glass for the thin outer face skins and DIVINYCELL® H100 closed-cell linear PVC foam as core. Marine grade hybrid sandwich panels are designed in accordance with BS EN ISO 12215-5:2008 for small craft hull construction, using a wet lay-up and cured under vacuum pressure. Impact damage testing followed ASTM D7766-11 and ASTM D6264-98 procedures A and B for rigidly supported and simply supported sandwich panels. A review of the current state of standard testing procedures of marine sandwich panels is described. Testing using the default hemisphere indenter also included other standard rock geometries – conical, square-based pyramid and flat-faced cylindrical. The damage incurred under each variation of indentation impact is described, in terms of force, absorbed energy and indentation displacement. New contact laws are suggested for the different rock geometries. Destructive sectioning of the panels provides the visual damage incurred through the thin face skins and core and the roles played by all members comprising the sandwich panels.

ABSTRACT: Low weight and high load capacity are remarkable advantages of sandwich panels which make them more considerable by structure designers. In this paper, multi-objective optimization of sandwich panels with corrugated core is carried out using modified Non-dominated Sorting Genetic Algorithm (NSGAII) considering two objective functions: the structure’s weight and deflection. Deflection of the panel as one of the objective functions is calculated using finite element analysis by commercial software ANSYS. To employ this FE model in the multi-objective optimization process, the software products ANSYS and MATLAB have been coupled together during the run time. Finally, nearest to ideal point (NIP) method and technique for ordering preferences by similarity to ideal solution (TOPSIS) method are used to find the some trade-off optimum design points from all non-dominated optimum design points represented by the Pareto fronts.

ABSTRACT: Marine grade hybrid sandwich panels are designed in accordance with BS EN ISO 12215-5:2008 using a wet lay-up and cured under vacuum pressure. The high fibre content composite laminate skins use marine grade orthophthalic polyester, POLYLITE® 440-M850, resin and chopped strand mat (CSM)/woven E-glass; the core is DIVINYCELL® H100 closed cell linear polyvinyl chloride (PVC) foam. Impact damage testing followed American Society for Testing and Materials (ASTM) D7766-11 procedure C and ASTM D7136/D7136M-05. Impact damage was sustained by the default hemispherical indentor and further ‘standard’ geometrical indentor rocks – conical, pyramid and cylindrical. The investigation reviews the current state of affairs in impact sandwich testing procedures. A 50–80% through thickness penetration criteria is proposed following noted shortcomings in the standard originally intended for laminates. It is shown that the panel overall flexural rigidity to thickness ratio better describes the transition between ‘thin’ to ‘thick’ impact response; force measurements indicate that strain rate effects need to be considered; dent indentation can only be assessed through data acquisition; destructive damage observation sectioned specimen observations describe the impact damage sustained under the various indentor conditions, as well as the roles played by both the face composite skins and the core material.

ABSTRACT: The load response and failure behaviour of ‘grid-scored’ sandwich panels used in wind turbine blades have been investigated. This paper presents the results of a combined experimental and numerical investigation of the load response and failure behaviour of a specific grid-scored foam cored composite sandwich panel configuration subjected to multiaxial quasi-static loading conditions that are representative for realistic loading conditions present in wind turbine blades. From the experimental evidence a criterion based on fracture mechanics has been proposed for predicting the onset of fracture in the resin grid. The criterion can be applied directly in conjunction with finite element modelling based on 3D solid elements where the resin grid in situ the core is fully modelled. However, since most full-scale blade models are based on first-order shear deformation theory where the core properties normally are homogenised a strain-based failure criterion is also proposed. The input for this failure criterion is the allowable resin grid strain, which can be obtained from a
simple uniaxial tension test of a grid-scored sandwich beam specimen. The predictions of the criteria have been compared with the experimental observations, and a good correlation has been found.

ABSTRACT: This paper focuses on the free vibration characteristics of functionally graded sandwich cylindrical shells resting on Pasternak elastic foundation. The free vibration analysis is based on three-dimensional elasticity theory and the natural frequencies are obtained by means of generalized differential quadrature method. The two-constituent functionally graded shell consists of ceramic and metal. These constituents are graded through the thickness according to a generalized power-law distribution with four parameters. The benefit of using the considered power-law distribution is to illustrate and present useful results arising from symmetric, asymmetric and classic profiles. A detailed parametric study is carried out in order to reveal the effects of different profiles of ceramic volume fraction, two-parameter elastic foundation modulus, different geometrical parameters such as the mid radius-to-thickness ratio, length-to-mean radius ratio and the thickness of face sheets on the vibrational characteristics of the functionally graded sandwich cylindrical shell.

ABSTRACT: The structural stiffness is explored for box-section beams in three-point bending. Four hollow tubes of various topologies are designed, manufactured and tested. The observed results show that a significant local compliance exists at the centre of the upper tube wall under the loading patch, in addition to the macroscopic bending of the hollow tube. The predicted and measured stiffnesses are in good agreement for a hollow tube with monolithic walls, and a hollow tube with foam-cored sandwich walls. However, the predicted stiffnesses are much greater than the measured values for two hollow tubes with sandwich walls comprising lattice corrugated cores. This can be ascribed to the imperfections introduced by the manufacturing route either by welding or adhesive bonding, and to the local yielding and large plastic deformations of the upper tube walls under the loading patch.

ABSTRACT: This paper presents the impact and compression after impact behavior of PVC foam cored /E-glass reinforced/vinylester sandwiches used in a four-seat amphibian aircraft. The impact damage was sorted in three categories: barely visible impact damage; visible impact damage; and clearly visible impact damage. It was observed that when increasing impact energy, the extension of the damage from barely visible impact damage to visible impact damage corresponds to a significantly high rate of energy absorption as depicted by the absorbed energy/impact energy ratio. Sandwich coupons were modeled with the finite element analysis ANSYS software to predict the critical failure load in presence of damage zones equivalent to those observed
experimentally. The finite element model predicts consistently the compression after impact strength of undamaged coupons and this result confirms the model used to represent the woven fabric by an equivalent cross-ply laminate model. However, the finite element overestimates the compression after impact strength of impacted ones. It is suggested that the induced out-of-plane displacements generate stress concentrations in the tip of cracks located at the borders of the damaged zone.


ABSTRACT: This paper studies the twist behavior of soft-core sandwich plates. The paper adopts a comparative analytical approach, derives a geometrically nonlinear extended high-order sandwich plate theory, and compares this theory with the classical high-order one. The extended theory takes all stiffness components of the core and its Poisson effect into account and considers the direct contribution of the in-plane shear stresses in the core to the twist resistance mechanism. The classical high-order sandwich plate theory, which is presented for comparison, neglects the in-plane shear and normal stiffness of the core and attributes the twist mechanism to the composite action of the face sheets and to the ability of the core to resist out-of-plane shear and out-of-plane normal stresses. Both theories account for large displacements, moderate rotations, and small strains in the face sheets and serve as platforms for the development of specially tailored finite elements. Along with the development of the extended sandwich plate theory, the paper studies the twist behavior, compares the two theories, compares the results with experimental ones taken from the literature, and looks into the impact of the geometrical nonlinearity on the twist response.


ABSTRACT: The increasing application of functionally graded materials in the aerospace structures requires the adoption of accurate modeling strategies. The original formulation of the Refined Zigzag Theory is here extended to the bending and free vibration analysis of sandwich plates embedding functionally graded layers, either as faces or core. Extensive numerical investigation shows the superior predictive capabilities of Refined Zigzag Theory over both First-order Shear Deformation Theory and Third-order Shear Deformation Theory, if compared with the reference three-dimensional elasticity or high-fidelity FEM solutions. In virtue of its accuracy and of the $C^0$–continuity requirement for shape functions, Refined Zigzag Theory can be adopted to formulate reliable and computationally efficient finite elements suited for large-scale analyses of both traditional and functionally graded structures.


ABSTRACT: This study presents the thermal buckling analysis of solid circular plate made of porous material bounded with piezoelectric sensor-actuator patches. The porous material properties vary through the thickness
with specific function. The general mechanical nonlinear equilibrium and linear stability equations are derived using the variational formulations to obtain the governing equations of piezoelectric porous plate. Thermal buckling load is derived for solid circular plates under uniform temperature load for the clamped edge condition. In recent paper the effects of porous plate’s thickness, porosity, porous thermal expansion coefficient, piezoelectric thickness, piezoelectric thermal expansion coefficient, and feedback gain on thermal stability of the plate are investigated.


ABSTRACT: The in-plane dynamic crushing behaviors and energy-absorbed characteristics of honeycombs with negative Poisson’s ratio (NPR) have been studied by means of explicit dynamic finite element analysis (DFEA) using ANSYS/LS-DYNA. First, the honeycomb models filled with different reentrant cells by the variation of micro-cell configuration parameters (cell-wall angle and shape ratio) are established. The respective influences of micro-structure and impact velocities on the deformation behaviors, the dynamic plateau stresses and the absorbed energy of reentrant honeycombs are explored in detail. It is shown that owing to the variation of cell micro-structure, reentrant honeycombs display different macro-/micro-deformation properties during the crushing. For the given impact velocity, the dynamic plateau stresses are related to the shape ratio by a power law and to the cell-wall angle by least-square curves. And they are also proportional to the square of impact velocities for a high impact velocity. Based on the finite element simulated results and one-dimensional shock wave theory, an empirical formula for auxetic honeycomb to predict the dynamic plateau stress is derived in terms of relative density and impact velocity.


ABSTRACT: This paper presents a study on the potential offered by lightweight energy-absorbing foam structures reinforced with aluminium and steel cylindrical tubes subjected to compressive crushing. Initially, attention was focused on establishing the influence of the length as well as the diameter to thickness ratio of the metal tubes on the specific energy absorption (SEA) characteristics. The metal tubes were then embedded in a range of cross-linked PVC foams to investigate how the stiffness of the foam influences the SEA of the tubes and the failure modes. The results show that aluminium tubes offer a superior energy-absorbing capability relative to their steel counterparts and the SEA of the metal tubes remains roughly constant with an increase in the tube length. The energy-absorbing capability of the two types of metal tubes increased with decreasing value of inner diameter/thickness ratio. Small D/t tubes were also embedded into a range of polymer foams and tested at both quasi-static and dynamic rates of strain. It has been shown that that the stiffness of the foam does not modify the energy-absorbing behaviour of the metal tubes. This evidence suggests that it should be possible to predict the response of an energy-absorbing system containing an array of tubes using a simple rule of mixtures approach. The output of this study provides useful data on core materials for sandwich construction.

Payal Desai and Tarun Kant (from institutions in India), “On numerical analysis of axisymmetric thick circular
ABSTRACT: Numerical analysis is carried out in this paper for thick circular cylindrical shells using higher order shell theory. In orthogonal curvilinear coordinate system, all equations are derived with the inclusion of the additional quadratic and cubic terms in the Taylor’s series expansions of the both in-plane as well as the transverse displacement components for the improvement of bending behaviour of the shell. Assuming \((h/R)^2 \ll 1\), a rigorous formulation involving the reduction of a three-dimensional elasticity problem to a two-dimensional one, based partly upon the Reissner’s variational principle, is presented. These equations are algebraically manipulated to be in the form of a coupled system of first-order differential equations in terms of the intrinsic dependent variables. These are then solved by a segmentation method – numerical integration technique for various combinations of material and geometric parameters. The theory is shown to result in a partial differential equation system of sixteenth order.

ABSTRACT: A new design of aluminum foam composite panels with enhanced ribs was proposed, and the energy absorption property of it was analyzed by combining dynamic testing and numerical simulation. The optimization of aluminum foam composite panels with enhanced ribs was investigated assuming that the panels had the same total mass. An Instron drop hammer test machine was used to study the dynamic compressive behavior of the new composite panels and the impact deformation characteristics of the components. Finite element method (FEM) software was employed to simulate the loading process, and the simulation results were compared with the experimental data for validating the reliability of the model. The effect of rib-mass ratio on the energy absorption property was investigated, and the energy absorption capacities of the new composite panels and conventional sandwiches were compared at different impact velocities. The analysis shows that, compared with conventional sandwich panels, aluminum foam composite panels with enhanced ribs have better energy absorption subjected to uniform distributed loading; and both rib-mass ratio and impact velocity have an effect on the normalized energy absorption. The results of this study can be a reference for related academic research and engineering application.

ABSTRACT: Sandwich panels made of metal sheets with unfilled cellular cores are found to exhibit lower deflections compared to an equivalent monolithic plate of same metal and similar mass per unit density. The structures having such sandwich panels are suitable under impact loading due to low deflection. However, the process of localized impact on solid structures is quite complicated involving plastic deformation, high strain rates, temperature effect, material erosion, etc. Further, the sandwich panel having triangular corrugated core depends on various design parameters such as thickness of front plate, thickness of back plate, thickness of core, thickness of webs, and angle of web. The influences of these parameters on the structural performance are studied while designing a triangular corrugated core structure for improved ballistic limit for a given mass per
unit area. In this research, a numerical analysis of impact of empty triangular corrugated core sandwich panels by ogive nose steel rod projectiles is carried out. Design parameters of the corrugated structure; namely web thickness, core thickness, web angle, front and back plate thickness are varied; and residual velocity of projectile is obtained for each case. Impact at webs resulted in higher projectile retardation and deflection than impact at the base of the prism. For base impacts, improvement in ballistic performance at minimum cost of structural weight can be achieved by increasing web angle or front or back plate thickness, while the same can be achieved for web impacts by increasing web thickness. Since web impacts experience higher penetration resistance than base impacts, designing the panel using optimum design parameters for web impacts is desirable.


ABSTRACT: In this work, the functionally graded honeycomb structures with defects are investigated. It is shown how the patterns and locations of defects, as well as the density gradients, can affect the in-plane dynamic crushing behavior of honeycombs. Numerical results show that due to missing vertical cell walls, the deformation process for the transverse-vertical mixing defects is more complicated than that for pure vertical defects. For the honeycombs with negative density gradient, the I-shape deformation band is dominant during the dynamic crushing. However, the honeycombs with positive density gradient are crushed to densification with the combination of the first and second deformation bands. It is revealed that the ability of energy absorption could be improved by introducing the functional graded property. Moreover, under a high impact velocity, the gradient displays a high sensitivity on the energy-absorption capability of the honeycomb structures. At the early stage of crushing, the honeycomb structures with the positive density gradient behave the stronger capacity on energy absorption than those with the negative one. The energy-absorption curves for systems with positive and negative densities are symmetric about the homogeneous structures. As the compression proceeds, for the honeycombs with positive and negative density gradients, the trends of energy- absorptive abilities go into reverse.


ABSTRACT: The paper presents an experimentally based and numerically supported investigation of the collapse behaviour of polymer foam cored sandwich beams subjected to combined mechanical and thermal loading. Recent analytical and numerical modelling results available in the literature have ascertained that collapse may be due to loss of stability induced by nonlinear interactions between mechanical loads and thermally induced deformations, when accounting for the reduction of the polymer foam core mechanical properties with increasing temperature. In the paper, experiments are devised whereby a thermal gradient is introduced into a sandwich beam specimen loaded in three-point bending. The experiments cover a range of temperatures where one face sheet is heated from room temperature (25°C) to just below the glass transition temperature of the polymer foam core (70°C) and the other face sheet remains at room temperature. Digital image correlation (DIC) is used to obtain the local displacement field of the sandwich beam and its temperature is monitored using an infrared detector and thermocouples. The experimental results are compared with the
predictions of both a generally nonlinear finite element model and an analytical so-called high-order sandwich panel theory (HSAPT) model. It is important to note that the HSAPT model has clear limitations as it takes into account only the geometric nonlinearity and thermal degradation of the foam core elastic properties, and it further assumes that the sandwich constituents are linear elastic with infinite straining capability. The HSAPT model predicts the occurrence of a strongly nonlinear load response leading to loss of stability (limit point behaviour). However, the experiments show that for the investigated sandwich beam configuration, it is necessary to include the nonlinear material properties in the modelling, as the nonlinear beam response leading to failure and collapse is significantly influenced by plastic deformations in the constituent materials. Thus, core indentation and extensive plasticity precede the transition to loss of stability driven by geometric nonlinearity and thermomechanical interaction effects. Finite element analyses that include both geometric and material nonlinearities provide results that correlate closely with the experimental observations. The work presented lays the foundation of a methodology for validating complex thermomechanical behaviour in sandwich structures using non-contact full-field measurement systems, and it demonstrates that analytical or numerical models based on the assumption of linear elastic material behaviour (such as the HSAPT model referenced in the paper) generally cannot adequately describe the thermomechanical behaviour of foam-cored sandwich structures.

Dengbao Xiao, Lin Mu and Gulping Zhao (State Key Laboratory for Mechanical Structure Strength and Vibration, School of Aerospace, Xi’an Jiaotong University, Xi’an 710049, P.R. China), “Indentation response of sandwich panels with positive gradient metallic cellular core”, Journal of Sandwich Structures & Materials, Vol. 17, No. 6, pp 597-612, November 2015, https://doi.org/10.1177/1099636215589087
ABSTRACT: This paper deals with the plastic indentation of sandwich panels with positive gradient metallic cellular core under a spherical indenter. The gradient metallic cellular material has an increasing plateau stress. Under quasi-static compression, the crushing stress of gradient metallic cellular material cannot be assumed as a constant like that of homogeneous metallic cellular material before densification. To predict the crushing stress of the gradient metallic cellular material, a novel predicting formula associated with densification strain is presented. And then a gradient analytical model for the sandwich panel with positive gradient metallic cellular core under the spherical indenter is developed based on the analytical model for sandwich panel with homogeneous core. Finite element simulation is carried out in order to verify the analytical results. The influence of positive gradient metallic cellular core on the indentation force of the sandwich panel is further analyzed.

ABSTRACT: This paper presents a new higher-order shear deformation theory for static, buckling and free vibration analysis of functionally graded sandwich beams. In this theory, the axial displacement accounts for a third-order and inverse trigonometric distribution, and the transverse shear stress satisfies the traction-free boundary conditions on the top and bottom surfaces of the beams. Governing equations of motion are derived from the Hamilton’s principle for sandwich beams with homogeneous hardcore and softcore. Navier-type solution for simply-supported beams is developed to solve the problem. Numerical results are obtained to investigate effects of the power-law index, span-to-height ratio and thickness ratio of layers on the displacements, stresses, critical buckling load and frequencies.

ABSTRACT: In the present work, by considering the agglomeration effect of single-walled carbon nanotubes, free vibration characteristics of functionally graded (FG) nanocomposite sandwich beams resting on Pasternak foundation are presented. The carbon nanotubes (CNTs) volume fraction is graded through the thicknesses of face sheets according to a generalized power–law distribution. The material properties of the FG nanocomposite sandwich beam are estimated using the Eshelby–Mori–Tanaka approach based on an equivalent fiber. The equations of motion are derived based on Timoshenko beam theory and employing Hamilton's principle. Generalized differential quadrature technique as an efficient and accurate numerical tool is employed to obtain the natural frequencies of the structure. The verification study represents the accuracy of the solution for free vibration analysis of the nanocomposite sandwich beams resting on elastic foundation. Detailed parametric studies are carried out to investigate the influences of CNTs agglomeration, different profiles of CNT volume fraction such as symmetric, asymmetric, and classic, Winkler foundation modulus, shear elastic foundation modulus, length to span ratio, thicknesses of face sheets, and boundary conditions on the vibrational behavior of the structure. It is shown that the natural frequencies of structure are seriously affected by the influence of CNTs agglomeration. Results also represent the fact that utilizing FG nanocomposite sandwich beams in most agglomeration states improves the fundamental frequencies of the structure, but in some cases has a destructive effect on the vibrational characteristics.


ABSTRACT: In this study, the behavior of vibration of sandwich cylindrical shells covered by functionally graded coatings and resting on the Pasternak elastic foundation considering combined influences of shear stresses and rotary inertia are examined. It is assumed that the effective material properties of functionally graded coatings changes exponentially in thickness direction. The modified Donnell type equations of motion of functionally graded and homogeneous sandwich cylindrical shells on the Pasternak elastic foundation are deduced using the first-order shear deformation theory. Basic equations are reduced to an algebraic equation of the sixth order and numerically solving this algebraic equation gives the dimensionless fundamental frequency. The expressions for the dimensionless fundamental frequencies of functionally graded and ceramic coated sandwich cylindrical shells with and without taking into account the effects of Pasternak elastic foundation and shear stresses obtained in a special case. Calculations, the influences of an elastic foundation, compositional profiles of coatings, shear stresses, rotary inertia, and sandwich shell geometry parameters on the nondimensional fundamental frequency are described. The results are verified by comparing the obtained values with those in the existing literature.

ABSTRACT: This paper presents an analytical solution for vibration and buckling of functionally graded (FG) sandwich beams using various quasi-3D theories, which consider effects of both shear and normal deformation. Sandwich beams with FG skins–homogeneous core and homogeneous skins–FG core are considered. By using the Hamilton’s principle, governing equations of motion are derived. An analytical solution is presented, and the obtained results by various quasi-3D theories are compared with each other and with the available solutions in the literature. The effects of normal strain, power-law indexes, skin–core–skin thickness and slenderness ratios on vibration and buckling behaviour of sandwich beams are investigated.

References listed at the end of the paper:

19. Belabel Z, Houari MSA, Tounsi A, Mahmoud SR, Beg OA. An efficient and simple higher order shear and normal deformation
ABSTRACT: This paper presents the results of an experimental and numerical study on aluminium honeycomb sandwich structures under low-velocity impact loadings. In order to investigate the impact behavior of honeycomb sandwich structures, which is consisted of two identical aluminium facesheets and an aluminium honeycomb core, an experimental study was carried out by using a drop-weight impact test system. Using this system, the contact forces and absorbed energies were measured to determine the influence of impact energy for one configuration of the sandwich structure. According to these results, a numerical model by finite element method of sandwich structures was developed, which is in good agreement with experimental results in terms of contact forces and deformations. Later, the effect of the cell size and the height variation of aluminium honeycomb core on the impact response of sandwich structures were investigated using the improved numerical model. The obtained numerical and experimental results were interpreted in detail.

References listed at the end of the paper:


ABSTRACT: In this article, the free vibration behavior of functionally graded carbon nanotube reinforced composite plate is investigated under elevated thermal environment. The carbon nanotube reinforced composite plate has been modeled mathematically using higher order shear deformation theory. The material properties of carbon nanotube reinforced composite plate are assumed to be temperature dependent and graded in the thickness direction using different grading rules. The effective material properties of the functionally graded plate are introduced in the present model through a micromechanical model under temperature load. The governing differential equation of the functionally graded carbon nanotube reinforced composite plate is obtained using Hamilton’s principle. The domain is discretized using the suitable isoparametric finite element steps and solved numerically through a computer code developed in MATLAB environment. The validity and the convergence behavior of the present numerical results have been checked and a simulation model is also developed in commercial finite element package (ANSYS) using ANSYS parametric design language code. The effect of various geometrical parameters (aspect ratios, support conditions, and thickness ratios), the grading effect, and the temperature variation on the free vibration behavior of functionally graded carbon nanotube reinforced composite are examined and discussed in detail.

ABSTRACT: In the present work, a higher-order zig-zag laminate theory is utilized to investigate the behaviour of sandwich laminates having low-density core materials subjected to thermal loading. The theory satisfies continuity condition of transverse shear stress at the layer interfaces and zero transverse shear stress at the top and bottom surfaces of the laminated plate. The assumed in-plane displacements are having cubic variations through the entire thickness of the plate. On the other hand, the variation of the transverse displacement is taken to be quadratic within the core and constant through the facesheets. In order to reduce the computation effort, an efficient $C^0$ finite element formulation for the above sandwich plate model is adopted. Some examples of laminated composite and sandwich plate with different material properties, core thickness ratios, aspect ratios, boundary conditions, number of layers and ply orientations are considered for the analysis. The efficacy of the present model in predicting various responses is verified by comparing with three-dimensional elasticity solutions along with the available published results.


ABSTRACT: This paper presents an experimental investigation on impact response of sandwich composite panels with different face-sheet thicknesses. A number of low velocity impact tests were performed under various impact energies. The damage process of the sandwich composites consisted of glass/epoxy face-sheets, and foam cores are analyzed from cross-examining some graphs such as load–deflection curves and damaged specimens. The primary damage modes observed are fiber fractures at upper and lower skins, delaminations between adjacent glass-epoxy layers, and core shear fractures.


ABSTRACT: Free vibration of a fiber-reinforced polymer honeycomb sandwich beam with sinusoidal core configuration is studied based on a refined sandwich beam theory. Using a micro/macromechanics approach for face laminates and a mechanics of material approach for honeycomb core, the equivalent elastic properties of face laminates and honeycomb core are obtained. A free vibration model based on the refined sandwich beam theory is formulated using the Hamilton's variational principle. Analytical solutions for a cantilevered sandwich beam are obtained by the Ritz method. Experimental results conducted on the fiber-reinforced polymer honeycomb sandwich beams with different lengths are applied to validate the proposed analytical solutions. As a comparison and further verification, the analytical solutions based on the Timoshenko beam theory and high-order beam theory are also presented. The analytical solutions in term of natural frequencies are compared with the numerical simulation results as well. Good agreements among various comparisons demonstrate the accuracy and capability of the refined sandwich beam theory and its potentials in design applications and health monitoring of fiber-reinforced polymer honeycomb sandwich beams.

Vahid Tahouneh and Mohammad H. Naei (School of Mechanical Engineering, College of Engineering, University of Tehran, Islamic Republic of Iran), “Free vibration and vibrational displacements analysis of thick elastically supported laminated curved panels with power-law distribution functionally graded layers and finite
ABSTRACT: This paper deals with free vibration and vibrational displacements analysis of thick laminated curved panels with finite length resting on two-parameter elastic foundations based on the three-dimensional elasticity theory. Because of using two-dimensional generalized differential quadrature method, the present approach makes possible vibration analysis of cylindrical panels with two opposite axial edges simply supported and arbitrary boundary conditions including free, simply supported and clamped at the curved edges. The material properties vary continuously through the layers’ thickness according to a three-parameter power-law distribution. It is assumed that the inner surfaces of the functionally graded sheets are metal rich, while the outer surfaces of the layers can be metal rich, ceramic rich or made of a mixture of two constituents. The benefit of using the considered power-law distribution is to illustrate and present useful results arising from symmetric and asymmetric profiles. The effects of two-parameter elastic foundation modulus, geometrical and material parameters together with the boundary conditions on the frequency parameters of the laminated functionally graded panels are investigated. The obtained results show that the outer functionally graded material layers have significant effect on the vibration behavior of cylindrical panels. This study serves as a benchmark for assessing the validity of numerical methods or two-dimensional theories used to analysis of laminated curved panels.


ABSTRACT: The free vibration of soft-core sandwich beams is analyzed by using the weak form quadrature element method. An N-node novel weak form quadrature sandwich beam element is established based on the extended high-order sandwich panel theory and the differential quadrature rule. Gauss quadrature is used to obtain the element stiffness and consistent mass matrices numerically. Detailed formulations are given. Convergence study shows the fast rate of convergence. The validity and the capability of the novel beam element are examined through comparison with analytic results based on the same theory and two-dimensional finite element data. It is shown that one proposed beam element can yield very accurate frequencies with a relatively small number of nodal points. New data of soft-core sandwich beams with boundary conditions other than the simply supported one, not available in literature, are provided. These data may be referential with which other researchers can compare their results during developing new numerical methods.


ABSTRACT: This paper presents an analytical approach to investigate the nonlinear dynamic response and vibration of shear deformable imperfect eccentrically stiffened sandwich plate with functionally graded material (FGM) on elastic foundation using both of the first-order shear deformation plate theory and stress function with full motion equations (not using Volmir's assumptions). The thick sandwich plates are assumed to rest on elastic foundation and subjected to mechanical loads in thermal environment. Numerical results for dynamic response of the eccentrically stiffened thick sandwich plates are obtained by Runge–Kutta method. The results show the influences of geometrical parameters, material properties, imperfections, the elastic foundations,
eccentric stiffeners, mechanical loads and temperature on the nonlinear dynamic response and nonlinear vibration of functionally graded sandwich plates. The numerical results in this paper are compared with the results reported in other publications.


ABSTRACT: This paper presents the free vibration analysis of composite thick rectangular plates, based on Reddy’s higher order shear deformation theory (HSDT). The plate theory ensures a zero shear-stress condition at the top and bottom surfaces of the plate and do not requires a shear correction factor. Although the plate theory is quite attractive, it could not be used in the finite element analysis. This is due to the difficulties associated with the satisfaction of the C1 continuity requirement. To overcome this problem associated with Reddy’s HSDT, a new C1-HSDT p-element with eight degrees of freedom per node is developed and used to find natural frequencies of thick composite plates. The formulation is easily implemented into simple and efficient finite element programs in which the trigonometric hierarchical shape functions are used. A fast convergence and excellent agreement with the known results in the literature are obtained using only one element. Besides, the effects of the boundary conditions, core to face sheet thickness ratio, Young’s modulus ratio on the natural frequencies are investigated through the analysis of these numerical results.


ABSTRACT: Two finite element formulations using different laminate plate theories are developed for the elastic-viscoelastic-elastic sandwich plates. A critical comparison and assessment between them are provided. The dynamic characteristics, namely, the natural frequencies and associated loss factors of the elastic-viscoelastic-elastic sandwich plates are calculated using the two finite element models. The two models are validated through the numerical example and experiment results. Comparisons of the accuracy and computational efficiency of the two finite element models are given. The results show that both of the two finite element models have good accuracy in predicting the natural frequencies and the loss factors with different efficiency. The works in this article have instructive significance in the calculation and application of the elastic-viscoelastic-elastic sandwich structures.


ABSTRACT: In this paper, a modified analytical model has been presented for clamped circular composite sandwich panels subjected to low-velocity impact by spherical impactor. The composite sandwich panel is symmetric and its composite face sheets consist of cross-ply laminates. The principle of minimum total potential energy has been used for obtaining the contact force and contact force–indentation relation. In this analytical model, the strain membrane stretching energy and the strain energy due to the bending of face sheet
have been determined and the core considered as rigid perfectly plastic. Also, the two degree-of-freedom spring–mass model has been used for determining the contact force history and deflection of the sandwich panel. The analytical contact force and the deflection of sandwich panel have been compared with published experimental and numerical results and good agreement has been observed.

ABSTRACT: This paper focuses for the first time on the static analysis of sandwich plates with functionally graded faces and homogeneous core by an nth-order shear deformation theory and meshless global collocation method. The meshless global collocation method approximates the solutions of governing differential equations based on the nth-order shear deformation theory using all nodes in the problem domain. The deflection and stress of a simply supported sandwich plates under sinusoidal load are calculated to verify the accuracy and efficiency of the present theory.

ABSTRACT: A simplified three-unknown shear and normal deformations nonlocal beam theory for thermo-electro-magneto mechanical bending analysis of a nanobeam with a functionally graded material core and two functionally piezomagnetic layers is studied in this paper. The assumed structure is subjected to mechanical, thermal, electrical, and magnetic loads. An initial applied voltage and magnetic load is considered on the functionally graded piezomagnetic material layers. Eringen’s nonlocal constitutive equations are considered in the analysis. Governing equations are derived according to the present refined theory using the principle of virtual displacements. The numerical results including the deflection, electric, and magnetic potential distribution are calculated in terms of important parameters of the problem such as applied electric and magnetic potentials, two parameters of temperature distribution, and nonlocal parameter. The numerical results indicate that increase in applied electric potential increases the deflection unlike the applied magnetic potential that decreases the deflection. Furthermore, it can be concluded that increasing the nonlocal parameter leads to increase in the deflection.

ABSTRACT: The crushing of single- and double-layer zig-zag trapezoidal corrugated core sandwiches was investigated experimentally and numerically at quasi-static and dynamic rates. The buckling stress of sandwiches increased when the rate increased from quasi-static to dynamic. The increased buckling stresses were ascribed to the micro-inertial effects, which altered the buckling mode of the core from three plastic hinges to higher number of plastic hinge formations. The initial buckling stress was numerically shown to be
imperfection sensitive when the imperfection size was comparable with the buckling length. The numerical buckling stresses of zig-zag and straight corrugated cores were similar, while higher inertial effects were found in triangular corrugated core.


ABSTRACT: The nonlinear torsional buckling and post-buckling of ceramic functionally graded material (C-FGM-M) stiffened cylindrical shell surrounded by Pasternak elastic foundation in thermal environment are investigated in this paper. The C-FGM-M cylindrical shell is reinforced by ring and stringer stiffeners system in which the material properties of shell are assumed to be continuously graded in the thickness direction. Based on the classical shell theory, theoretical formulations are derived with the geometrical nonlinearity in von Karman sense and the smeared stiffeners technique. The three-term approximate solution of deflection is chosen more correctly and the explicit expression for finding critical load and post-buckling torsional load–deflection curves are given. The effects of geometrical parameters, temperature, stiffeners and elastic foundation are investigated.


ABSTRACT: In this study, the low-velocity impact response of sandwich composites consisting of different foam core configurations is investigated experimentally. Polyvinyl chloride foam core and glass fibers were used as core material and face sheets, respectively. A number of tests under various impact energy levels for three different sandwich composite configurations were conducted with Ceaust 9350 Fractovis Plus impact testing machine in order to improve the energy absorption capacity of sandwich composites panels. Absorbed energies, maximum loads and the maximum deflection of sandwich panels were obtained for each impact energy level. As the impact energy was increased, fiber fractures at face sheets, delaminations between glass-epoxy layers, core fractures, and indentations failures were observed by visual inspection. According to the obtained results, the sandwich composite with proposed new foam core design with two internal face sheets exhibits high energy absorption capacity compared to sandwich panels formed by sandwiching a polyvinyl chloride foam core between glass fabric face sheets. Maximum contact force values decrease by increase of number of core material.


http://pressurevesseltech.asmedigitalcollection.asme.org/issues.aspx
ABSTRACT: In this paper, a developed solution structure theorem has been provided. It can be used to solve the wave equation about the structural response of cylinder under the dynamic pressure. This new approach also can be used to solve a batch of partial differential equations having the similar form. A detailed derivation process has been given to show how the solution is obtained. Finally, a practical example is presented, and the finite element result is also provided to validate the accuracy of methodology proposed in this paper. The result shows that it has a high accuracy for solving the elastodynamic response of the cylinder.


ABSTRACT: A method of calculating soil cover requirements for horizontally bent buried pipelines is described. In sequence, the results of a comprehensive three-dimensional finite element analysis are used to develop regression models for two dependent variables: maximum allowed temperature change and minimum overburden height. Other variables considered include the pipe diameter and thickness, the radius and angle of the bend, the internal pressure, the fluid specific weight, and the material used. Relationships among the different variables are determined. Finally, the results are checked with respect to several buckling modes to consider elastic instability conditions.


ABSTRACT: The elastic analysis of two different kinds of radially heterogeneous pressure vessels is conducted in this paper. As a first kind of heterogeneous pressure vessels, a multilayered pipe with different material properties in different layers is considered. Another kind of heterogeneous pressure vessels is a thick hollow cylinder made of functionally graded material (FGM). On the basis of the finite difference method, the time-dependent deformation, strain and stress distributions of both kinds of heterogeneous pipes are obtained under the different kinds of thermomechanical loadings. In this investigation, it is assumed that the pressure and temperature are symmetrical about the axis of the cylinder. Also, the material properties are considered to be independent of temperature. Results obtained from the present method are compared with the existing data.


ABSTRACT: A methodology is introduced for calculating the allowable buckling stress in equipment operating in the time-dependent (creep) range. Norton's equation coupled with various procedures such as the stationary
stress method, classical creep buckling equations, and the isochronous stress–strain diagrams are utilized to obtain a practical design approach for equipment operating in the time-dependent range. Various components are investigated such as slender columns, cylindrical shells, spherical components, and conical transition sections.

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(This paper received at the Pressure Vessels and Piping Conference in Anaheim in July 2014 the Journal of Pressure Vessel Technology G.E.O. Widera Literature Award for the Outstanding Technical Paper.)
ABSTRACT: The paper provides details about tests on six steel cones. Test models were machined from 250 mm diameter billet. All cones had substantial and integral top and bottom flanges in order to secure well defined boundary conditions. Experimental data were obtained for: (i) two cones subjected to axial compression, (ii) two cones subjected to external pressure, and (iii) the remaining two models subjected to combined action of external pressure and axial compression. Apart from axisymmetric modeling of tested cones, true geometry with true wall thickness was also used in calculations. Theoretical failure loads were obtained for: (i) elastic perfectly plastic, (ii) engineering stress–strain, and (iii) true stress–true strain modelling of steel. The latter approach coupled with measured geometry and wall thickness secured safe predictions of the collapse loads in all cases. Comparisons of experimental collapse loads with estimates given by ASME and ECCS design codes are included. It is seen here that the ASME and ECCS rules provide a safety margin of about 100% against the collapse (except 50% for axial compression in the case of the ECCS).

ABSTRACT: Motivated by the response of industrial piping under seismic loading conditions, the present study examines the behavior of steel process piping elbows, subjected to strong cyclic loading conditions. A set of experiments is conducted on elbow specimens subjected to constant amplitude in-plane cyclic bending, resulting into failure in the low-cycle-fatigue range. The experimental results are used to develop a low-cycle-fatigue curve within the strain-based fatigue design framework. The experimental work is supported by finite element analyses, which account for geometrical and material nonlinearities. Using advanced plasticity models to describe the behavior of elbow material, the analysis focuses on localized deformations at the critical positions where cracking occurs. Finally, the relevant provisions of design codes (ASME B31.3 and EN 13480) for elbow design are discussed and assessed, with respect to the experimental and numerical findings.

ABSTRACT: Assuming very large slide displacement subsequent to tank rock motion to be a possible scenario of tank walk motion, fundamental mechanics of the walk motion of unanchored flat-bottom cylindrical shell model tanks subjected to horizontal base excitation is examined. First, employing a 3DOF model consisting of a set of two masses connected by flexible columns, equations of motion are derived through a variational
The interaction among the translational motion of a harmonic oscillator consisting of the upper mass and the flexible columns, the rock motion of the 3DOF model and the slide motion of it is thoroughly studied. Comparison of the experimental results and their predictions demonstrate applicability of the proposed analysis. A reduction in nominal friction force accompanying the rock motion that plays a primary role in causing the very large slide displacement is also pointed out. Next, drawing an analogy between the mechanics of the walk motion of the 3DOF model and that of an unanchored flat-bottom cylindrical shell model tank, equations of motion for the tank walk motion are derived. Shaker table test and time domain analysis are conducted, employing a model tank whose bottom plate concentrically uplifts for readily evaluating fluid masses contributing to the tank rock motion. Comparison of the experimental and analytical results of the slide displacement and the rotational angle corroborates the applicability of the proposed analysis.


ABSTRACT: During seismic events, buried pipelines are subjected to deformation by seismic ground motion. In such cases, it is important to ensure the integrity of the pipeline. Both beam-mode and shell-mode buckling may occur in the event of compressive loading induced by seismic ground motion. In this study, the beam-mode buckling of a buried pipeline that occurred after the 2007 Niigataken Chuetsu-oki earthquake in Japan is investigated. A simple formula for estimating the critical buckling strain, which is the strain at the peak load, is derived, and the formula is validated by finite-element analysis. In the formula, the critical buckling strain increases with the pipeline diameter and hardness of the surrounding soil. By comparing the critical strain derived in this study for beam-mode buckling with the critical strain derived in a past study for shell-mode buckling, the formula facilitates the selection of the mode to be considered for evaluating the earthquake resistance of a pipeline. In addition to the critical buckling strain, a method to estimate the deformation caused by seismic ground motion is proposed; the method can be used to evaluate the earthquake resistance of buried pipelines. This method uses finite-element analyses, and the soil–pipe interaction is considered. This method is used to reproduce the actual beam-mode buckling observed after the Niigataken Chuetsu-oki earthquake, and the earthquake resistance of a buried pipeline with general properties is evaluated as an example.

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ABSTRACT: New hazmat (hazardous material) transport tanks will be constructed to the rules of the ASME Code Section XII. The criteria and basis to design these tanks have been questioned and a full scale buckling test has been performed to evaluate maximum allowable over-the-road loadings and required design details. This paper summarizes the results of this testing and provides comparisons with classical Code buckling criteria, Code Case 2286 and other methods for such evaluations. The objective is to provide the ASME Section XII committee with a basis for establishing buckling design criteria and shell stiffening details for both hazmat and nonhazmat transport tanks.

ABSTRACT: This study is mainly concerned with the analytical solutions of plastic bifurcation buckling of cylindrical shells under compressive load. The analysis is based on the J2 deformation theory with a linear hardening and proportional loading is adopted in the calculation. A symplectic solution system is established and Hamilton's governing equations are derived from the Hamilton variational principle. The basic problem in plastic buckling is converted into solving for the symplectic eigenvalues and eigensolutions, respectively. The obtained results reveal that boundary conditions have a very limited influence on bucking loads but its influence on buckling modes and plastic borders cannot be neglected. Meanwhile, it is demonstrated that the shell material properties significantly affect the plastic buckling behavior. This proposed symplectic method is shown to be a rigorous approach. It also provides a uniform and systematic way to any other similar problems.

References listed at the end of the paper:
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“A full 3D finite element model for buckling analysis of stiffened steel liners in hydroelectric pressure tunnels”,
ABSTRACT: The availability of tools for safety evaluation of a pressure liner is a relevant issue in both structural and hydraulic engineering. A numerical procedure for assessing the stability of a stiffened steel liner in a hydroelectric pressure tunnel is presented in this paper. First, a review of some analysis methods for steel liners is outlined. Relevant aspects for the critical buckling pressure assessment are considered, specifically boundary conditions and geometric imperfections. General 2D and 3D nonlinear finite element modeling procedures, including large displacements formulation are presented. Some relevant factors in the liner response, such as the annular gap, the stiffeners, and the interaction with the elastic medium surrounding the steel liner are taken into account. As a result, some simple modeling guidelines for thin-walled steel pressure liners are depicted. Also, some conclusions regarding the influence of stiffeners as well as of the surrounding medium are drawn. The procedure is applied to an actual steel tunnel liner which failed by global instability in 2010 in Spain. The aim is to simulate the causes of collapse as well as to draw some design criteria.

ABSTRACT: Buried pipelines may be corroded, despite the use of corrosion control measures such as protective coatings and cathodic protection, and buried pipelines may be deformed due to earthquakes. Therefore, it is necessary to ensure the integrity of such corroded pipelines against earthquakes. This study has developed a method to evaluate earthquake resistance of corroded pipelines subjected to seismic motions. Pipes were subjected to artificial local metal loss and axial cyclic loading tests to clarify their cyclic deformation behavior until buckling occurred under seismic motion. As the cyclic loading progressed, displacement shifted to the compression side due to the formation of a bulge. The pipe buckled after several cycles. To evaluate the earthquake resistance of different pipelines with varying degrees of local metal loss, a finite-element analysis method was developed that simulates cyclic deformation behavior. A combination of kinematic and isotropic hardening was used to model the material properties. The associated material parameters were obtained by small specimen tests that consisted of a monotonic tensile test and a low-cycle fatigue test under a specific strain amplitude. This method enabled the successful prediction of cyclic deformation behavior, including the number of cycles required for the buckling of pipes with varying degrees of metal loss.

George E. Varelis and Spyros A. Karamanos (Dept. of Mechanical Engineering, University of Thessaly, Volos 38334, Greece), “Buckling of High-Strength Steel Cylinders Under Cyclic Bending in the Inelastic Range”,
DOI: 10.1115/1.4026123
ABSTRACT: The present paper examines the structural behavior of elongated steel hollow cylinders, referred to as tubes or pipes, subjected to large cyclic bending, through a rigorous finite element simulation. The bent cylinders exhibit cross-sectional distortion, in the form of ovalization, combined with excessive plastic deformations. Those deformations grow under repeated loading and may lead to structural instability in the
form of local buckling (wrinkling) and, eventually, failure of the loaded member. The study focuses on relatively thick-walled seamless cylindrical members made of high-strength steel, which exhibit local buckling in the plastic range of the steel material. The analysis is conducted using advanced nonlinear finite element models capable of describing both geometrical and material nonlinearities. A cyclic plasticity model that adopts the “bounding surface” concept is employed. The material model is calibrated through special-purpose material testing, and implemented within ABAQUS, using a user-subroutine. The finite element model is validated by comparison with two experiments on high-strength steel tubular members. Special emphasis is given on the increase of ovalization and the gradual development of small-amplitude initial wrinkles with repeated loading cycles. A parametric numerical study is conducted, aimed at determining the effects of initial wrinkles on plastic buckling performance.


ABSTRACT: When a crack-like-flaw is detected in piping during in-service inspection, the limit load criterion given in the codes such as JSME Rules on Fitness-for-Service for Nuclear Power Plants or ASME Boiler and Pressure Vessel Code Section XI can be applied to evaluate the structural integrity of the piping. However, in-service piping is generally subjected to combined tensile, bending, and torsional loading, and a methodology to evaluate the limit moment for torsion has not yet been established because of inadequate experimental validation. In this study, fracture tests were conducted for circumferentially cracked cylinders subjected to torsional moment. The experimental maximum moments were compared with the limit moments, which were evaluated on the basis of the net-section-collapse criterion for torsional moment. The maximum moments can be conservatively predicted by the net-section-collapse criterion.


ABSTRACT: Polyethylene (PE) pipes are widely used in natural gas transportation systems in urban areas nowadays. As landslide caused by earthquake would cause destructive damage to buried pipes, increasing attention is attracted to the safety of buried PE pipes under seismic load. In this paper, the deformation behavior of PE pipe subjected to seismic landslide was investigated and a related failure criterion due to yielding was proposed. Based on extensive uniaxial tensile tests, a rate-dependent constitutive model of PE was applied to simulate the mechanical behavior of PE pipes. The extended Drucker-Prager model was used for surrounding soil. In our proposed finite element model, a quartic polynomial bending deflection displacement normal to the pipeline was loaded along the axial direction of PE pipe. The numerical simulation results revealed that the main failure mode of buried PE pipe subjected to seismic landslide shifted from bending deformation to ovalization deformation with increasing bending deflection. On the basis of deformation behavior analysis, failure criterion curves were put forward, which depicts the maximum relative deflection of the pipe cross-section, and the maximum displacement of the pipe versus pipe length subjected to seismic landslide. The results may be referable for design and safety assessment of PE pipes due to seismic landslide.

ABSTRACT: An internal floating roof is to be installed on an existing large API storage tank. In order to ensure the proper functionality of the roof, the deformation of the shell has been monitored and analysed. The measurements on the shell ovality show that the actual radial deformation is beyond the acceptable limit for installation of a serviceable internal floating roof and corrective actions should be taken. Consequently, a series of tests and analyses were performed to provide a recommended practice to restore the tank to its round shape.


ABSTRACT: Eighteen mild steel cylinders with the length-to-radius ratio, L/R ≈ 2.4 and with the radius-to-wall thickness ratio, R/t ≈ 185 were collapsed by axial compression. Cylinders had variable length at one end of sinusoidal profile. The magnitude of axial imperfection-to-wall thickness ratio, 2A/t, was varied between 0.05 and 1.0. Experimental results show that buckling strength strongly depends on the axial amplitude of imperfection. On average imperfect cylinders, with 2A/t = 1.0, are able to support 49% of experimental buckling load obtained for geometrically perfect model. The largest sensitivity of buckling strength was associated with small amplitude of imperfection in axial length. For example, for axial length imperfection amounting to 25% of wall thickness the buckling strength was reduced by 40%. It appears that the number of sinusoidal waves in the imperfection profile plays a secondary role, i.e., its role in reducing the buckling strength is not a dominant factor. The paper provides experimental details and comparisons with numerical results.


ABSTRACT: In this paper, a convenient modal analysis method for the linear coupled vibration of a container that is partially filled with a fluid is introduced. This problem is important for various reasons, such as stability analysis. The fluid-structure interactions in an elastic tank with an incompressible liquid are assumed to produce small vibrations. Reduced symmetric finite element equations of the system are acquired according to the component mode synthesis method. Considering that the liquid satisfies the same governing equation as steady heat conduction, general programs can be used to calculate the mass matrix and stiffness matrix of the coupled system. Then, modal analysis of the liquid container using general software, e.g., MSC Nastran, that ensures accuracy and stability in the process, is applied to demonstrate that this method can determine the modal frequency in a fluid-structure coupled system.


ABSTRACT: The present study examines the mechanical behavior of steel process piping elbows, subjected to strong cyclic loading conditions. The work is numerical, supported by experimental data on elbow specimens subjected to in-plane cyclic bending, with or without internal pressure, resulting in failure in the low-cycle-fatigue range. The investigation of elbow behavior is conducted using rigorous finite element analysis accounting for measured elbow geometry and the actual material properties. An advanced cyclic plasticity
material model is employed for the simulation of the tests. Emphasis is given on the value of local strain and its accumulation at the critical elbow location where cracking occurs. Based on the cyclic stress–strain curve of the material and the strain-based fatigue curve from the test data, the use of Neuber's formula leads to a fatigue analysis and design methodology, offering a simple and efficient tool for predicting elbow fatigue life.


ABSTRACT: Thermal postbuckling of solid circular plates made of a through-the-thickness functionally graded material (FGM) is analyzed in this paper. Initial imperfection of the plate is also taken into account. Each thermomechanical property of the plate is assumed to be a function of the temperature and thickness coordinate. Equivalent properties of the FGM media are obtained based on three different homogenization schemes, namely, Voigt rule, Mori–Tanaka scheme, and self-consistent estimate. Temperature profile is assumed to be through-the-thickness direction only. The solution of the heat conduction equation is obtained using an iterative central finite difference scheme. Various types of thermal loadings, such as uniform temperature rise, temperature specified at surfaces, and heat flux, are considered. Nonlinear equilibrium equations of the plate are obtained by means of the conventional Ritz method. Solution of the resulting nonlinear equilibrium equations and temperature distribution are obtained simultaneously at each step of heating. It is shown that response of a perfect clamped FGM plate is of the bifurcation type of buckling with stable postbuckling equilibrium branch, whereas imperfect clamped and perfect/imperfect simply supported FGM plates do not reveal the bifurcation type of instability through the nonuniform heating process. Furthermore, amplitude of initial imperfection is an important factor on the equilibrium path of FGM circular plates, especially for simply supported ones.


ABSTRACT: When a crack is detected in a nuclear piping system during in-service inspections, failure estimation method provided in codes such as ASME Boiler and Pressure Vessel Code Section XI or JSME Rules on Fitness-for-Service for Nuclear Power Plants can be applied to evaluate the structural integrity of the cracked pipe. In the current codes, the failure estimation method for circumferentially cracked pipes is applicable for both bending moment and axial force due to pressure. Torsion moment is not considered. Recently, two failure estimation methods for circumferentially cracked pipes subjected to combined bending and torsion moments were proposed based on analytical investigations on the limit load for cracked pipes. In this study, experimental investigation was conducted to confirm the applicability of the failure estimation method for cracked pipes subjected to bending and torsion moments. Experiments were carried out on 8-in. diameter Schedule 80 stainless steel pipes containing a circumferential surface crack. Based on the experimental results, the proposed failure estimation methods were confirmed to be applicable to cracked pipes subjected to combined bending and torsion moments.

T. Hassan, M. Rahman and S. Bari (Dept. of Civil, Constructuion, and Environmental Eng., North Carolina State University, Raleigh, NC, USA), “Low-cycle fatigue and ratcheting responses of elbow piping

ABSTRACT: The objective of this study was to investigate low-cycle fatigue and ratcheting responses of elbows through experimental and analytical studies. Low-cycle fatigue and ratcheting damage accumulation in piping components may occur under repeated reversals of loading induced by earthquake and/or thermomechanical operation. Ratcheting and fatigue damage accumulation can cause failure of piping systems through fatigue cracks or plastic buckling. However, the ratcheting damage induced failures are yet to be understood clearly; consequently, ASME Code design provisions against ratcheting failure continue to be a controversial issue over the last two decades. A systematic set of piping component experimental responses involving ratcheting and a computational tool to simulate these responses will be essential to rationally address the issue. Development of a constitutive model for simulating component ratcheting responses remains to be a challenging problem. In order to develop an experimentally validated constitutive model, a set of elbow experiments was conducted. The loading prescribed in the experiments involved displacement-controlled or force-controlled in-plane cyclic bending with or without internal pressure. Force, displacement, internal pressure, elbow diameter change, and strains at four locations of the elbow specimens were recorded. This article presents and discusses the results from the experimental study. A sister article evaluates seven different constitutive models against simulating these elbow ratcheting and fatigue responses.


ABSTRACT: In the present work, the effects of nanoscale parameter and Coriolis force together are investigated on vibrating eigenvalues of fluid-conveying carbon nanotube (CNT). A nonlocal Timoshenko beam and a plug flow model are implemented to derive fluid–structure interaction (FSI) governing equations of motion. These equations solved by Galerkin to obtain instability pattern, critical fluid velocities (CFVs), frequency and damping at different nanoscale parameter, boundary conditions, and aspect ratios. The results demonstrate existence of multiple types of instabilities and bifurcations, which are deviated from classic FSI buckling and flutters' instabilities, and caused by damping from coalition of nanoscale effect and fluid's Coriolis force, this phenomena are more noticeable in the CNTs with asymmetrical boundary conditions and smaller size.


ABSTRACT: The availability of tools for safety evaluation of a pressure liner is a relevant issue in both structural and hydraulic engineering. A suitable design of a steel liner may involve a significant reduction in the investment cost of a hydropower plant and may also ensure its future integrity, avoiding prolonged stoppages in the operation stage. First, a review of the design methods for steel pressure liners is outlined and certain key aspects for the critical buckling load assessment are pointed out. Second, a numerical modeling and analysis procedure of a steel pressure liner is presented. The methodology is based on 3D nonlinear finite element modeling procedures, involving both liner constraining and the effect of stiffeners. In addition, both large displacements and a surrounding elastic medium are assumed in the model. Besides, some types of geometric imperfections such as weld-induced ones, initial gap, ovality, and wall-thickness loss due to corrosion are taken

ABSTRACT: Sloshing response of a cylindrical liquid storage tank with the double deck type floating roof (DDFR) subjected to seismic excitation is considered in this paper. The aim of the paper is to clarify the significant parameters that should be considered in the seismic design of a DDFR and proposing a practical seismic design procedure for evaluating the dynamic stresses inside a DDFR. A numerical method including fluid–structure interaction and the geometry details of a DDFR tank are established. The geometric nonlinear effects on the seismic behavior of the DDFR as well as the accuracy of common analytical solution suggested in the literature are examined by the numerical model. The numerical results show that the geometric nonlinear effects can considerably reduce the seismic stress in DDFR, but have no significant effect on the liquid hydrodynamic pressure exerted on the DDFR and the roof's vertical displacement. It is also revealed that not only the general displacement of DDFR but also the local effects of liquid hydrodynamic pressure on the bottom plate should be considered for seismic design of a DDFR. Finally, a design procedure for the evaluation of dynamic stress in the DDFR due to the seismic loads is proposed and discussed.


ABSTRACT: Low cycle fatigue tests and finite element (FEM) analysis were conducted using 100A pipe bend specimens made of STPT410 carbon steel with and without local wall thinning. Local wall thinning was machined on the inside of the elbow and was prepared at extrados, crown, and intrados. The parameters of the wall thinning were same (the wall thinning ratio = 0.5, the wall thinning angle = 180 deg, and the wall thinning length = 100 mm) in all test cases. The pipe bend specimens were subjected to the prescribed cyclic in-plane bending displacement with constant internal pressure of 0–12 MPa. Also, low cycle fatigue tests using sound pipe bend specimens were carried out for comparison. According to the test results, low cycle fatigue strength of wall thinned pipe bend specimens was not so different, regardless of location of wall thinning. Low cycle fatigue strength of the pipe bend specimens was beneath the best fit fatigue curve and its reason can be explained quantitatively by a proposed cumulated damage rule introducing ductility exhaustion considering multi-axial stress state. The validity of the new proposed cumulative damage rule was also confirmed by another sample analysis using other reference data obtained by pre-overloaded in-plane cyclic bending tests.


ABSTRACT: The minimum wall thickness required to prevent seismic buckling of a reactor vessel (RV) in a
fast reactor is derived using the system based code (SBC) concept. One of the key features of SBC concept is margin optimization; to implement this concept, the reliability design method is employed, and the target reliability for seismic buckling of the RV is derived from nuclear plant safety goals. Input data for reliability evaluation, such as distribution type, mean value, and standard deviation of random variables, are also prepared. Seismic hazard is considered to evaluate uncertainty of seismic load. Minimum wall thickness required to achieve the target reliability is evaluated, and is found to be less than that determined from a conventional deterministic design method. Furthermore, the influence of each random variable on the evaluation is investigated, and it is found that the seismic load has a significant impact.

ABSTRACT: The effects of imperfections and nonlinearities on the failure mode and the B2 stress index of thin-walled straight pipes are investigated with finite element (FE) analyses. The analyses were performed for pipes made of an ideal elastic–plastic material and the austenitic steel X6CrNiNb18-10. The B2 index is calculated from the instability bending moments obtained by limit load analyses. The effects of initial imperfections as well as the D/t-ratio and the yield stress on the B2 stress index are studied. As a first result, it is noted that thin-walled straight pipes and imperfections fail due to local plastic buckling. Further analyses show that the type of imperfections, the ovality, the D/t-ratio, and the yield stress have significant influences on the B2 index. The obtained B2 indices for thin-walled straight pipes with D/t > 40 and possible technical imperfections are considerably higher than 1.0. The results have been compared with those of other investigations.

ABSTRACT: Piping components in power plants may experience combined bending and torsion moments during operation. There is a lack of guidance for pipe evaluation for pipes with local wall-thinning flaws under the combined bending and torsion moments. ASME boiler and pressure vessel (B&PV) Code Section XI Working Group is currently developing fully plastic bending pipe evaluation procedures for pressurized piping components containing local wall thinning subjected to combined torsion and bending moments. Using elastic fully plastic finite element (FE) analyses, plastic collapse bending moments under torsions were obtained for 4 (114.3)–24 (609.6) in. (mm) diameter pipes with various local wall-thinning flaw sizes. The objective of this paper is to introduce an equivalent moment, which combines torsion and bending moments by a vector summation, and to establish the applicable range of wall-thinning lengths, angles, and depths, where the equivalent moments are equal to pure bending collapse moments.

ABSTRACT: With a purpose of identifying the failure mode and associating the ultimate strength of piping
components against seismic integrity, many kinds of failure tests have been conducted for thick wall piping for light water reactors (LWRs). However, there are little failure test data on thin wall piping for sodium cooled fast reactors (SFRs). In this paper, a series of failure tests on thin wall elbows for SFRs is presented. Based on the tests, the failure mode of a thin wall piping component under seismic loads was identified to be fatigue. The safety margin included in the current design methodology was clarified quantitatively.


ABSTRACT: In this paper, a new methodology for solving response of a spherical shell based on developed solution structure theorem has been proposed. It can be used to solve the wave equation about the structural dynamic response of a spherical shell under the impact pressure. The proposed method can be used to solve a batch of partial differential equations having the similar governing equation with different initial and boundary conditions. A detailed solving procedure has been provided to show how to use this method correctly. Finally, a practical example is provided to show how to use the proposed method to solving the elastodynamic response of a spherical shell under inner impact load.


ABSTRACT: An overview of the mechanical behavior of steel pipe (elbows) is offered, based on previously reported analytical solutions, numerical results, and experimental data. The behavior of pipe bends is characterized by significant deformations and stresses, quite higher than the ones developed in straight pipes with the same cross section. Under bending loading (in-plane and out-of-plane), the main feature of the response is cross-sectional ovalization, which influences bending capacity and is affected by the level of internal pressure. Bends subjected to cyclic in-plane bending exhibit fatigue damage, leading to base metal cracking at the elbow flank. Using advanced finite-element tools, the response of pipe elbows in buried pipelines subjected to ground-induced actions is also addressed, with emphasis on soil–pipeline interaction. Finally, the efficiency of special-purpose finite elements for modeling pipes and elbows is briefly discussed.


ABSTRACT: The effects of the initial geometric imperfections on the buckling response of grade X-100 UOE manufactured pipes are studied through finite element analysis (FEA). The initial geometric imperfections had been previously measured and quantified in terms of deviations in outside radius (OR) and wall thickness. The measurement results are used to develop imperfection models to be incorporated into buckling analysis. The OR deviation is seen to have insignificant effects on the buckling behavior, while the effects of thickness deviation are seen to be profound for both unpressurized and pressurized pipes. The geometric imperfection models are further investigated through a sensitivity study to isolate the most influential imperfection aspects on the
buckling resistance of UOE pipes. A parametric study is carried out using these models and shows that excluding geometric imperfections will always result in overprediction of buckling capacity irrespective of D/t ratios.

ABSTRACT: Many studies focused on casing collapse resistance under uniform load have been done, and API 5C3 and ISO standards have been formed. However, the collapse models presented by API 5C3 and ISO standards are not suitable for calculating and predicting the casing collapse resistance under nonuniform load (NUL), despite it is well known that the NUL has a significant impact on the casing collapse resistance. Hence, based on the elastic theory and new ISO collapse model, the conception of advance coefficient of plastic collapse of casing under NUL is put forward, and the new equations to compute casing collapse resistance under NUL are established, which takes into full account the effect of manufacturing defects (such as ovality and eccentricity) and residual stress on the casing collapse resistance. The influence rule of nonuniform coefficient of load (NCL) on casing collapse resistance has been analyzed. Numerical and experimental comparisons show that the calculation results (CR) of new equations are much closer to the real failure data than the current equations proposed by Han and EI-Sayed (1992, “Resistance of Cemented Concentric Casing Strings Under Nonuniform Loading,” SPE Drill. Eng., 7(1), pp. 59–64). Research results can provide an important theoretical reference for casing design in complicated stratum (such as plastic creep and dipping stratum).

ABSTRACT: In the paper, the efficiency of strengthening of a buried steel pipeline with a composite wrap subjected to an active faults action is analyzed. A three-dimensional numerical model of the pipeline is developed. The pipeline is considered as an elastoplastic steel shell, while the composite wrap is represented as an orthotropic elastic shell. The model takes into account the elastoplastic behavior of soil, contact interaction between the soil and the pipe, large inelastic strains, distortion of the pipeline cross section, and local buckling formation. A normal-slip fault kinematics with large fault offsets is considered in numerical modeling. The effect of the wrap thickness, length, and position relative to the fault plane is analyzed.

ABSTRACT: In order to develop the knowledge base necessary to design deep sea pressure vessels, it is essential to understand the full chain from design and manufacturing through nondestructive testing (NDT) and characterization to long-term behavior under hydrostatic pressure. This paper describes results from European and national research programs focusing on the use of composites for underwater applications over the last 20 years. Initial tests on small glass/epoxy cylinders were followed by large demonstration projects on carbon/epoxy cylinders with implosion pressures of up to 600 bar, corresponding to 6000 m depth. Numerical
modeling has enabled end closures design to be optimized for test performance. Thin and thick wall cylinders have been tested under quasi-static, and long-term loading. Both thermosetting and thermoplastic matrix composites have been tested to failure, and the influence of defects and impact damage on implosion pressure has been studied. These deep sea exploitation and exploration studies were performed for oceanographic, military, and offshore applications, and extensive data are available. The aim of this paper is to indicate existing results, particularly from European projects, in order to avoid costly repetition.


ABSTRACT: An experimental study on the underwater buckling of composite and metallic tubes is conducted to evaluate and compare their collapse mechanics. Experiments are performed in a pressure vessel designed to provide constant hydrostatic pressure through the collapse. Filament-wound carbon-fiber/epoxy, glass/polyester (PE) tubes, and aluminum tubes are studied to explore the effect of material type on the structural failure. Three-dimensional digital image correlation (DIC) technique is used to capture the full-field deformation and velocities during the implosion event. Local pressure fields generated by the implosion event are measured using dynamic pressure transducers to evaluate the strength of the emitted pressure pulse. The results show that glass/PE tubes release the weakest pressure pulse and carbon/epoxy tubes release the strongest upon collapse. In each case, the dominating mechanisms of failure control the amount of flow energy released.


ABSTRACT: In this article, the nonlinear bending behavior of functionally graded (FG) curved (cylindrical, hyperbolic, and elliptical) panel is investigated under combined thermomechanical loading. In this study, two temperature fields (uniform and linear) across the thickness of shell panel are considered. The panel model is developed mathematically using higher-order shear deformation midplane kinematics with Green–Lagrange-type nonlinear strains. The individual constituents of functionally graded material (FGM) are assumed to be temperature-dependent (TD) and graded continuously using the power-law distribution. The effective material properties of FG shell panel are evaluated based on Voigt's micromechanical model. The governing equation of the panel structure is obtained using the variational principle and discretized through suitable finite-element (FE) steps. A direct iterative method is employed to compute the desired responses of the curved panel structure. The efficacy of the present nonlinear model has been shown by comparing the responses with those available published literature and commercial FE tool ANSYS. Finally, the model has been extended to examine the effect of various parameters (volume fractions, temperature, thickness ratios, curvature ratios, aspect ratios, and support conditions) on the nonlinear bending behavior of curved FG panel by solving wide variety of numerical illustrations.

Many papers published in the journal, Advances in Structural Engineering (2012-2016)
Google the string: “Advances in Structural Engineering”, then click on the entry: “Advances in Structural Engineering – All Issues – SAGE Journals”

ABSTRACT: The use of steel elliptical hollow sections (EHS) has grown steadily, but the implementation of EHS has been done without appropriate design guidelines or procedures. A pragmatic objective has been to develop a section conversion method to transform the EHS into an equivalent shape for which design equations and guidelines already exist. This paper further explores the equivalent RHS (rectangular hollow section) approach for member design. By using the equivalent RHS approach to convert the EHS into an equivalent RHS, the validity of existing RHS cross-section classification limits and member design equations are demonstrated for EHS columns subjected to axial compression that buckle about the major axis and the minor axis, and EHS beams subjected to bending about the major axis and the minor axis. The equivalent RHS approach is a single consistent and rational procedure, and it is shown to be a viable method for designing EHS compression members and flexural members.

ABSTRACT: The LiteSteel Beam (LSB) is a new cold-formed steel hollow flange channel beam recently developed in Australia. It is commonly used as a floor joist or bearer in buildings. Current practice in flooring systems is to include openings in the web element of floor joists or bearers so that building services can be located within them. Shear behaviour of LSBs with web openings is more complicated while their shear strengths are considerably reduced by the presence of web openings. However, no research has been undertaken on the shear behaviour and strength of LSBs with web openings. Therefore a detailed experimental study involving 26 shear tests was undertaken on simply supported LSB test specimens with web openings and an aspect ratio of 1.5. This paper presents the details of this experimental study and the results of their shear capacities and behavioural characteristics. Experimental results showed that the current design rules in cold-formed steel structures design codes are very conservative for the shear design of LSBs with web openings. Improved design equations have been proposed for the shear strength of LSBs with web openings based on the experimental results from this study.

ABSTRACT: Innovations in formwork solutions create new possibilities for architectural concrete constructions. Flexible fabric replaces the stiff traditional formwork elements, and takes away a limiting factor for creative designs. Combined with textile reinforcement, the production of a new range of curved and organic shapes becomes possible without the intensive labour for formwork installation. Besides a general introduction about the concepts of fabric formwork and textile reinforcement, this paper focuses on the production and structural evaluation of doubly curved shells. Creating a very interesting type of element from a structural point of view, the shape flexibility of both the fabric formwork and textile reinforcement make a perfect match to overcome practical production issues for thin shell elements. The application of shotcrete and the integration of
non-metallic reinforcement allowed first of all the production of very thin concrete shell elements based on the
design approach of the textile architecture. Comparing a shell structure with traditional reinforcement and one
with textile reinforcement, a case study evaluates furthermore both the design and the structural performance of
such a shell structure.

Niujing Ma, Ronghui Wang and Hao Xin, “A ne approach for the free vibration of steel bridge deck with
stiffeners”, Advances in Structural Engineering, Vol. 15, No. 7, pp 1167-1179, July 2012,
https://doi.org/10.1260/1369-4332.15.7.1167
ABSTRACT: Based on energy principle, the free vibration of orthotropic steel bridge deck is investigated. The
orthotropic steel bridge deck considered to be a stiffened plate. Both longitudinal stiffeners and transverse
diaphragms are considered to be beam elements according to the equivalent principle of mass and rigidity.
Besides, the plate is analyzed according to classic thin plate theory. The mode shape functions are expressed by
the product of two independent beam functions. During the derivation of frequency equation, the lateral flexural
effect of both the plate and stiffeners is considered. Besides, the eccentricity and torsion of stiffeners are taken
into consideration, as well as the membrane strain energy of the plate. The results of the present approach are
validated by the published example. At last, a stiffened plate with three classical boundary conditions is studied.
The results show good agreement with the FE software ANSYS. Besides, it is observed that the eccentricity of
stiffeners has a greater influence on lower frequencies than the higher, and the dynamic rigidity of stiffened
plate can be increased efficiently by increasing the thickness of longitudinal stiffeners or reducing the distance
between neighboring stiffeners. But the latter is more efficient.

Yi Zhou, Yuan-Qi Li and Zu-Yan Shen, “An improved stability matrix for co-rotational formulation”,
Advances in Structural Engineering, Vol. 15, No. 8, pp 1425-1438, August 2012, https://doi.org/10.1260/1369-
4332.15.8.1425
ABSTRACT: Geometrically nonlinear analysis of 3D framed structures has focused on the treatment of the
difficulties associated with finite nodal rotations. The Co-rotational formulation excludes the rigid body rotation
of the element, and to account for this aspect the addition of a stability matrix is required to the natural tangent
stiffness matrix. This spatial beam element stability matrix needs to fully account for the behaviour of the nodal
forces and moments on the rigid body rotation. In the context of the Co-rotational formulation, the correct
stability matrix is used in conjunction with the natural tangent stiffness matrix. The natural finite element
concept used for the numerical analysis of nonlinear structural problems is extended to the Co-rotational
formulation. It is shown through numerical examples that fully account for the rotational behaviour of nodal
moments, that the Co-rotational formulation can accurately predict the flexural-torsional buckling loads for
spatial structures in which the members are not connected collinearly.

M. Fong, Y.P. Liu and S.L. Chan, “Second-order analysis and experiments of semi-rigid and imperfect domes”,
Advances in Structural Engineering, Vol. 15, No. 9, pp 1537-1546, September 2012,
https://doi.org/10.1260/1369-4332.15.9.1537
ABSTRACT: Since the recent introduction of second-order analysis in codes, engineers begin to realize the
advantages of the second-order analysis in enhancing the safety and economy of the design output. The method
is especially useful for design of complex structures like the shallow dome where failure is commonly due to
snap-through buckling with the collapse load difficult to be assessed by the effective length method. In this
paper, the second-order analysis is used to study the behavior and to determine the snap-through buckling load
of the shallow domes. A comparison on the failure loads of a shallow dome between the laboratory test and
second-order analysis is carried out to demonstrate the application of the second-order analysis. Further, the
importance for inclusion of global imperfection in the analysis is demonstrated because the snap-through
buckling load can be greatly reduced if the practically unavoidable and unfavorable global imperfection is included.

ABSTRACT: The behaviour of composite steel-concrete beams subjected to pure flexure and the presence of flexure and shear is fairly well understood and provisions do exist in international codes of practice for their design, however in most instances the influence of the concrete slab is not included in the strength design of the composite beam in shear. Combined internal actions including the presence of torsion and flexure have also been considered of late. These actions combine to occur in edge beams and curved composite beams and thus are of significant practical interest. Of increasing interest has become the presence of axial force and flexure in composite beams. These internal actions need to be considered in the design of raking beams of stadia, elevated approach spans for bridges and interchanges and in the design of integral abutment bridges and cable stayed bridges. Furthermore, composite beams in floor systems for braced multi-storey buildings are often required to resist axial force, flexure and shear force. This paper considers the effects of the presence of axial force in conventional composite beams. The effects of different forms of axial force and flexure combinations are considered in this paper. An analytical treatment, experiments and design approaches are given in this paper which is useful for structural engineers. Furthermore research in this area is also discussed. This paper will also present the results of an extensive experimental series to study the behaviour of high performance steel sections subjected to transverse impact loads which are able to simulate either a collision or blast. The experimental program has considered both mild structural steel and stainless steel hollow sections both filled and unfilled being tested. The purpose of the tests was to identify the potential advantages of using concrete infill to increase the energy absorption capability of steel hollow sections.

ABSTRACT: In cold-formed steel trusses and space frames, angles are commonly used for the members, the load being transferred to the members at both ends through a connection to a gusset plate. Such connections are typically formed through bolts or screws. Since this connection is made through one of the angle legs, the load is therefore eccentric to the centroid of the section. On the other hand, owing to contact with the gusset plate and the bolt-head, the ends of the connection possess partial torsional restraint. When designing cold-formed steel angle sections, an engineer would typically take into account the eccentricity of the connection but ignore the beneficial effect of the partial torsional restraint. This paper describes a non-linear elasto-plastic finite element model of angle sections connected to a gusset plate through a single bolt at each end subjected to axial compressive load. The results of the finite element model are validated against previously published full-scale laboratory test results. A parametric study of both equal and unequal angle sections is presented. From the results of the parametric study, simple design recommendations are proposed.

ABSTRACT: In a composite beam, transverse web stiffeners are often provided to the steel section at regular intervals along the beam span to eliminate local shear buckling as well as to reduce web distortion in the steel section. These transverse stiffeners are also found to be effective in providing intermediate lateral restraints from the stiff concrete slab to the compressive steel flange, forming a ‘discrete inverted U-frame’ action so that
the resistance of the composite beam against distortional lateral buckling is significantly enhanced. In general, the load carrying capacity of a continuous composite beam depends on a number of factors such as initial imperfections, residual stresses, and material nonlinearity. A general design method to evaluate the contribution of transverse web stiffeners to the capacity of a continuous composite beam, is however yet unavailable. This paper presents an advanced numerical investigation into the structural behaviour of composite beams under the discrete inverted U-frame action. Based on a comprehensive finite element study, the following key parameters affecting the load carrying capacity of the beam are studied: i) the flexural stiffness of the concrete slab, ii) the stiffness of the web stiffeners, iii) the ratio of the depth to thickness of the steel web, and iv) the ratio of the spacing of the web stiffeners to the beam span. It has been verified that in the presence of properly designed web stiffeners, the buckling moment resistances of composite beams will be significantly increased while the lateral deflection of the compression flanges is greatly reduced.

ABSTRACT: An investigation of the seismic behaviour and a design method for single-layer reticulated shells with semi-rigid joints is described in this paper. A semi-rigid joint system has some bending and rotational rigidity that lying between that of a rigid-joint and a pin-joint. The seismic capacity of Kiewit reticulated shells with bolt-ball joints is analyzed in detail on the basis of the bending rigidity of the bolt-ball joint reported by others. The change rules of natural frequency and seismic internal force coefficient are reviewed by analyzing of large-scale shells with different span, depth-to-span ratio, bending rigidity, roof load, section size of members and seismic wave parameters. The seismic internal force coefficient (under the influence of bending moment) for shells with a semi-rigid joint system is summarized statistically to provide the maximal seismic response envelop.

ABSTRACT: The Direct Strength Method (DSM) is a recently adopted design approach by the North American Specifications for Cold-Formed Steel Structural Members (AISI S100) for calculating the nominal strength of cold-formed steel (CFS) sections. The critical elastic buckling load shall be obtained in order to employ the DSM in computing the nominal strength of CFS members. The AISI S100 provides simplified methods for determining the critical elastic distortional buckling load. However it is found that the AISI S100 simplified methods are over conservative for the industrial standard C and Z sections in the U.S. This paper presents revised simplified methods for calculating the critical elastic distortional buckling loads of typical CFS C and Z sections in bending and axial compression loading respectively. The new methods yield more accurate results but similar computation cost compared to the existing methods. The new methods can be added to the DSM methodologies for designing CFS members.

ABSTRACT: Cable dome is a new type of spatial structure, consisting of cables and struts. Its properties such as its static, dynamic and stability behavior were widely studied, but the failure of the dome is rarely investigated due to its complexity and the limitation of traditional methods. The Vector Form Intrinsic Finite Element method (VFIFE) is a recently proposed method based on a combination of vector mechanics and
numerical calculation. Without establishing the stiffness matrix, it is easy to solve problems related to rigid body motion, large deformation and large displacement. It is thus used to simulate the whole failure process of cable domes. The fundamentals of VFIFE are first summarized and the formulations for rod elements and prestressed cable elements are presented. Then the failure analysis of a dome due to cable slack or rupture is conducted by taking a Levy cable dome as an example. Numerical results show that the dome can continue to bear load after some cables slack and will fail after some hoop cable rupture. The dynamic effects caused by cable rupture should not be ignored. Numerical results also indicate that the VFIFE method is effective in the full-process analysis of structures involving rigid body motion, large deformation or vibrations.

ABSTRACT: The roof of Dalian Gymnasium, of span 145.4 m ~ 116 m, rise span ratio 1/10, truss height 2.4 m and strut height 10.0 m, is the largest suspended dome structure in Asia. Different tension schemes have an important effect on the performance of a structure. It is necessary to investigate the characteristics and feasibility of different tension schemes. In addition, to check the accuracy of the numerical model and its calculated results and to investigate the mechanical performance when subjected to construction and design loads, as well as safety considerations during construction and when in service, a scale model of the suspended dome with scaling factor 1:10 was constructed and models of some key joints at full scale. The results show that the theoretical strut internal forces and displacements of joints, are in good agreement with test results. Therefore, tension steps in the cable can be controlled by internal forces in the struts. The lifting of struts is a continuous process of adjustment. The size of the cable needed to be accurate during the test, which indicates that the controllability of this method is relatively difficult. However, when tensioning diagonal cables, the diagonal cable force can be an effective control because these is a sufficient number of controllable tension points and a relatively small cable force. More importantly, because the geometrical dome forming accuracy of this method is higher, the latter method is suggested for use during construction. The displacements of the joints in the upper reticulated shell of the suspended dome, the axial forces in the struts and the stresses in the members present, vary linearly with test load which indicates that the vertical stiffness of the overall structure is well maintained when conducting static tests on the model. The test CHS (circular hollow section) joints which were not internally strengthened, failed with a large amount of plastic deformation. However, the ultimate bearing capacity of CHS joints strengthened by inside gusset plates was obviously improved. Some key CHS joints are suggested for strengthening with inside gusset plates, during the construction process. The work of this paper provides a reference for similar structures.

ABSTRACT: The structural behaviour of prestressed stayed columns is investigated through nonlinear finite element modelling. The models were developed using the commercial software ABAQUS and validated against a series of recently conducted experiments. The sensitivity of the load-carrying capacity to the geometry of the stayed column, the initially applied prestress level within the stays and the initial global imperfection is investigated through parametric studies. It is found that there is a substantial increase in load-carrying capacity with increasing cross-arm length, provided the critical buckling mode remains symmetric. Once the critical buckling mode becomes antisymmetric, mode interaction becomes significant and the load-carrying capacity reaches a plateau and the component generally becomes more sensitive to imperfections. It is also found that the relative level of initial prestress required to maximize the load-carrying capacity of a given stayed column tends
to reduce with increasing cross-arm length.

ABSTRACT: Aluminum has been increasingly used in reticulated shell structures for large span applications. The joint configuration in such space structure is essentially important for both architectural and structural performance. A novel cast aluminum joint was introduced in this paper. Full-scale specimens were examined under three loading conditions to study the mechanical performance and failure mechanism. The rotational stiffness, critical sections, and failure modes of the specimens assembled with this novel cast aluminum joint were investigated. Finite element analysis was further performed and validated by the experimental results in order to examine the local stress distributions. Based on the experimental and numerical results, it was found that out-of-plane rotational stiffness of this novel joint was larger than that of in-plane and the joint in both directions was semi-rigid according to Eurocode 3. The cross sections of the joint end and beam end with bolt holes were the critical sections. The comparison of calculated results from elastic FEA and Euler beam theory indicated that reliable safety factors should be considered if the latter is used in design, because of the stress concentration at critical sections.

ABSTRACT: The deployable hybrid grid shell, which can be deformed elastically by bending until the desired form is obtained, is an attractive structural form in the design and construction of long-span transparent glass roof structures. These hybrid structures are very slender and lightweight. Therefore, the structural behavior of the hybrid grid shell needs to be well understood. The mechanical characteristic, static and dynamic behaviors of the grid shell have been investigated in this paper. The effect of the structural parameters, such as rise-to-span ratios, cross-sections of steel beams, areas and pre-stress of cables, on the structural behavior has been studied in detail. Results show that the hybrid grid shell with a good translucence is more efficient than the general single-layer reticulated shell structure. The vertical structural stiffness initially increases with the increase of the rise-to-span ratio and then decreases afterwards. There exists an optimum rise-to-span ratio resulting in an optimum stiffness for the specified span. The optimum value of the ratio is found between 0.15 and 0.20 from the simulation study presented in this paper. Given a specific height-to-span ratio, the increase of the beam section greatly reduces the nodal displacement and member forces and increases the natural frequency. However, it can be found that increasing the areas and pre-stress of cables is not an economical way to improve the structural behavior.

ABSTRACT: In conventional steel-concrete-steel (SCS) construction, the external steel plates are connected to the concrete infill by welded shear connectors. This paper describes an experimental programme in which the response of axially restrained non-composite (without shear connectors) SCS protective panels subject to impulsive loading was studied. A comprehensive parametric study was carried out to investigate the effects of different types of infill materials, amount of impact energy, and the bond between the concrete core and steel faceplates, on the performance of the protective panels. The experimental results showed that the panels developed high load-carrying capacity through the tensile membrane resistance of the steel faceplates at large
deformation. The panels demonstrated a highly ductile response and were able to sustain large deformation up to 18 degrees end rotation without collapse. The high strength and high ductility characteristics of these SCS panels make them an economical alternative to the existing protective barrier structures.


ABSTRACT: A new type of space structure called the double inner and outer latticed shell string structure, which can reduce the space occupied by the roof and be laid easily using a rigid roofing material, is proposed. Numerical algorithm for shape determination of this new space structure is introduced and some suggestions for improvement are put forward. One example is investigated and the results confirm the validity of the above method. Finally, a model experiment based on a practical engineering application is introduced. Experimental results are compared with those of the finite element numerical analysis and results show that the theoretical value and the experimental value match well, which reveals that the model design, loading scheme and measuring plan meets experimental requirements. The internal forces and the structure deformation vary linearly for full span load cases, which reveals that the double inner and outer latticed shell string structure has an excellent load-carrying capacity and structural rigidity, and has broad application prospects.


ABSTRACT: Tensegrities are structures whose integrity is based on a balance between tension and compression. A numerical procedure is presented for the geometrical nonlinear analysis of tensegrity structures. This approach is based on a co-rotational method where the major component of geometrical non-linearity is treated by a co-rotational filter. This is achieved by separating rigid body motions from deformational displacements. The outcomes evince that the efficiency of the co-rotational approach is considerably greater than those using total Lagrangian and updated Lagrangian formulations for space rod elements, which have more rigid body movement modes than deformational modes. Numerical examples illustrate that the displacements of tensegrity systems depend on the applied force density coefficient and external loading values. Furthermore, in the analysis of tensegrity structures, constraints such as the yield strength of all elements and zero stiffness of string elements becoming slack at any equilibrium configuration must be allowed for.


ABSTRACT: The hysteretic behavior of four buckling-restrained braces (BRBs) with H cross section unrestrained segment was tested under cyclic load. The transformation of the unrestrained segment's section from crisscross shape to H shape can improve the moment-resistance capacity of unrestrained segment significantly and avoid buckling instability of unrestrained segment effectively due to evident stiffness enhancement. BRBs were designed according to Chinese codes, the load-carrying elements of BRBs were fabricated with Chinese Q235 steel. In the process of experiment, BRBs did not buckle, BRBs could undergo fully-reversed axial yielding cycles without loss of stiffness and strength, the ductility and energy absorption capacity of BRBs are large enough to withstand major earthquake. The resilience model can be simplified to a symmetrical bilinear resilience model. The ratio of width to thickness of inner core has a little influence on the mechanical behavior and energy-dissipation capacity of BRBs. A suggestion for design improvement of BRBs was proposed according to the failure modes of BRBs.
Chunlin Wang, Tao Li, Quan Chen, Jing Wu and Hanbin Ge, “Experimental and theoretical studies on plastic torsional buckling of steel buckling-restrained braces”, Advances in Structural Engineering, Vol. 17, No. 6, pp 871-880, June 2014, https://doi.org/10.1260/1369-4332.17.6.871

ABSTRACT: A type of partly-welded BRB was proposed in this paper to mitigate the unfavourable effect of the welds on the low-cycle fatigue property of BRBs. Three partly-welded BRB specimens under different strain amplitudes were tested and the plastic torsional buckling of the end portion was observed in two specimens. According to the experimental results, the strain amplitude is an important factor for the torsional buckling of the end portion. The critical stress declines with the increase of the strain amplitude, while the maximum compressive stress increases with the growth of the strain amplitude. Even though the hysteretic behaviour of specimens under large strain amplitudes met the requirement by seismic provisions (AISC 2010), torsional buckling is an undesired failure mode for BRBs, which leads to great torsional deformation of BRBs. Based on the principle of minimum potential energy, a theoretical formula of the critical stress was provided in this paper, which gave a good prediction to the failure mode. Moreover, a recommendation value of the calculated length based on the theoretical equation was given for the design to avoid torsional buckling in the unrestrained part of the BRB’s yielding segment.


ABSTRACT: Single-layer lattice shells (also known as gridshells) are widely used for architecturally innovative structures. When an explosion occurs inside such a structure, confined blast loading on the structural components will be seriously affected by different factors, such as charge locations and weight, structural types and forms. Moreover, slight changes of blast loading perhaps result in various responses for such a complicated structure. In this paper, blast loads on single-layer lattice shell are calculated by AUTODYN software package. The effect of scaled distance, ratio of rise to span and ratio of height to span are investigated. Simplification of blast loading is studied, and the principles of equivalent loading process are validated with a 40 meters single-layer Kiewitt-8 reticulated dome. In order to predict the blast loading, a precise and simple model is derived from numerical results, which is suitable for a wide scope of single-layer lattice shells. Two applications with different charge weight, structural spans and forms are worked out by using the blast prediction model. Good agreements of comparisons are achieved between prediction model and numerical results.


ABSTRACT: An isogeometric-meshfree coupled analysis is presented for Kirchhoff plates. This approach rationally couples the isogeometric basis functions and the meshfree shape functions under the consistency condition, which makes the present method capable of unifying the exact geometry and flexible model refinement properties simultaneously. Moreover, higher order smoothing approximation can be readily constructed in a straightforward way which is very desirable for the Galerkin analysis of Kirchhoff plate problems that necessitates a $C^1$ approximation. Particular attention is placed on the coupling of cubic isogeometric and meshfree approximations which are frequently used for the numerical solutions of Kirchhoff plates. The cubic consistency for the coupled approximation is studied in detail. Subsequently the coupled approximation is introduced to the plate weak form to obtain the coupled discrete equations in which both static and free vibration formulations are considered. The efficacy of the proposed method is demonstrated through a set of benchmark examples in which the deflectional convergence for static analysis and the frequency
convergence for free vibration analysis are measured. The results show that optimal convergence behaviors for Kirchhoff plate problems can be uniformly achieved by the proposed method.


ABSTRACT: Mean/fluctuating wind pressure distributions on an actual large cooling tower (167-meter high) have been obtained and compared to previous results of other cooling towers. The agreement of mean wind pressure distributions is good. But the fluctuating wind pressure coefficients on the large cooling tower are much smaller than those on cooling towers of smaller sizes over the full range. It is assumed that the differences have resulted from the discrepancy of the turbulence intensity of the incoming flow, which is proven true according to wind tunnel model tests. Besides, it is found that most wind pressure signals produced by transducers around the throat section of the actual large cooling tower are of non-Gaussian distributions and they are not likely to be caused by the organized large-scale vortices according to the spatial correlation analyses. The upcoming flow of unsteady speed and direction in the engineering field might be an explanation for the phenomena. Two different methodologies (the traditional Davenport methodology and the complete probability methodology) are adopted to calculate the peak factors, in which the complete probability methodology is appropriate for non-Gaussian distributions. Studies about the spectral characteristics of wind-induced pressures on the actual large cooling tower are also included in this paper, and results show some differences from the previous study.


ABSTRACT: Self-compacting Concrete Filled Square steel Tubes (SCFST) is used to strengthen square RC columns. In order to investigate the eccentric loading behavior of the strengthened columns, a generic fiber element model is proposed. The ultimate strengths and the complete load-deflection response at the mid-height of the strengthened columns are predicted by the model in the aid of computational procedure. To verify the accuracy of the computational results, related experiments have been performed. The obtained experimental results were then compared with the computational results. After finding close agreement between them, the effects of extensive experimental parameters on the behavior of strengthened columns are investigated, including tube wall thickness, concrete compressive strength and initial eccentricity. Furthermore, a simple design formula based on the verified model is proposed to calculate the ultimate strength of eccentrically compressed strengthened columns. The calculation results agree well with the experimental results.


ABSTRACT: Although high strength steel has been applied in many buildings and bridges, the application and researches of 960 MPa high strength steel are still quite limited. In order to investigate the local buckling behavior of 960 MPa high strength steel welded section stub columns under axial compression, an experimental program including 8 box and I-section members was conducted. Based on the test results, the local buckling strength and ultimate strength of each specimen were investigated. A finite element model validated through the test results was used to perform a parametric analysis, including 13 box section stub members and 33 I-section stub members with different width-to-thickness ratios. Compared with the corresponding design methods in GB 50017–2003, ANSI/AISC 360–10 and Eurocode 3, it was confirmed that the design methods about the local buckling behavior of 960 MPa high strength steel welded section stub columns under axial compression need to
be modified.


ABSTRACT: One of the main advantages of using Steel Plate Shear Panels (SPSPs) as lateral load resisting system is the ability to create openings at desired locations within the panels for access and architectural requirements. Stiffeners are used on the infill plate in order to achieve better structural performance and optimum utilization of the system's linear and nonlinear capabilities. Three 1/3rd scale specimens with two openings and with different separations, subjected to cyclic loads, were used to study the structural behavior of SPSPs. The Plate-Frame Interaction (PFI) model, enhanced with additional refinements, was used in theoretical studies to determine the shear stiffness and ultimate shear strength of the SPSPs. The results of the theoretical studies were compared with the experimental and numerical methods. The outcome showed that the new PFI theory predicted the structural behavior of SPSPs with a good agreement.


ABSTRACT: This paper presents an investigation on behaviour and design of composite beams with stiffened and unstiffened web openings. The composite beams were simply supported and had profiled steel sheeting oriented transversely to the steel beams. Nonlinear 3-D finite element models were developed to analyse the inelastic behaviour of composite beam components comprising the steel beam, concrete slab, profiled steel sheeting, headed stud shear connectors, reinforcement bars as well as interfaces among these components. In addition, the load-slip characteristic of the headed stud shear connectors in composite slabs with profiled steel sheeting were carefully incorporated into the finite element models. The finite element models of the composite beams have been validated against published experimental results. The composite beams had different moment-to-shear (M/V) ratios at the openings, stiffened and unstiffened web opening sizes, web opening locations, profiled steel sheeting, shear connections, beam lengths, concrete slab strengths and steel beam strengths. The ultimate loads of the composite beams, load-deflection relationships and modes of failure of the beams were predicted from the finite element analysis and compared well against the test results. Furthermore, the variables that influence the composite beam behaviour and ultimate load comprising different stiffened and unstiffened web opening sizes, M/V ratios at openings, web opening locations, beam lengths, concrete strengths and steel beam strengths, were also investigated in an extensive parametric study. It is shown that the ultimate loads of composite beams with stiffened web openings with horizontal stiffeners located above and below the openings, having an opening height equal to 0.6 the steel beam depth, can be considerably increased compared with that of unstiffened openings. It is also shown that the increase in structural steel strength has a remarkable effect on the composite beam ultimate loads. In addition, the ultimate loads of the composite beams with stiffened and unstiffened web openings predicted from the finite element analysis were compared with the design ultimate loads calculated using the Eurocode 4 and technical report SCI P355 published by the Steel Construction Institute for composite beams with profiled steel sheeting and rectangular stiffened and unstiffened web openings. Generally, it is shown that the design ultimate loads accurately predicted the ultimate loads of the composite beams within an average of 6% difference from the ultimate loads predicted using the finite element analysis.

Weibin Yuan and Changyi Chen, “Nonlinear bending response and buckling of channel section beams of finite length under minor-axis pure bending”, Advances in Structural Engineering, Vol. 18, No. 7 pp 1043-1050, July
ABSTRACT: In this paper, the geometric nonlinear bending response of channel-section beams of finite length is investigated by using energy methods. The basic assumptions used in the present study are that the total strain energy of a channel-section beam subjected to pure bending can be simplified into a two-stage analysis process. One is the local bending response of the web behaving as the plate; the other is the overall bending response as a beam with flattened section. Analytical solutions for both static and dynamic instabilities of channel section beams of finite length subjected to pure bending about its minor axis are derived by applying the minimum potential energy principle. To validate the analytical solution developed, geometric nonlinear finite element analyses are also conducted. Good agreement between the present solution and the FEA results is demonstrated. The effect of beam's length on the critical load is also discussed.

Chungang Wang, Zhuanguan Zhang, Daqian Zhao and Yu Bai, “Experimental and numerical study on perforated channel columns with complex edge stiffeners and web stiffeners”, Advances in Structural Engineering, Vol. 18, No. 8 pp 1303-1318, August 2015, https://doi.org/10.1260/1369-4332.18.8.1303

ABSTRACT: In order to study the influence of web holes on axial compression behaviors of thin-walled columns with different section forms, a total of 10 pin-ended compression specimens with two section forms were tested. One section is channels with complex edge stiffeners and web holes, the other section is channels with complex edge stiffeners and Σ type web stiffeners and web holes. The ultimate load, buckling mode and deformation behavior of these specimens were studied. It was found that the axial compression loading efficiency of perforated Σ-section specimens can increase about 30% to 50%, which compared with channels with complex edge stiffeners and web holes under the same conditions. The tests were simulated by finite element analysis (FEA), and the analysis results agreed well with experimental data. It was shown that the loading efficiency of Σ-section models with holes decreased about 25% compared with the same section models without holes. While channel section models with complex edge stiffeners and holes decreased about 6% average. Furthermore, the direct strength method (DSM) was used to calculate the ultimate loading capacity of perforated channels with complex edge stiffeners. The results indicate that the existing DSM formulas for perforated members, developed mainly based on channel sections with simple edge stiffeners, are also valid for channels with complex edge stiffeners and web holes under axial compression.


ABSTRACT: In the present paper, a developed stepwise regression (SR) model for predicting the member moment capacity of half-through I-section bridges girders has been presented. The reliable database (training and testing data) for SR-based model are generated by a developed Finite Element (FE) model which has been verified by related existing experimental investigations using software ABAQUS. Then based the SR modeling a practical formulae has been presented. To verify the accuracy of the proposed formulae, the FE results of specimens which have not been employed in the SR modeling process are used. The results indicate that SR-based model provide good predictions which are more accurate than those from other available methods. The proposed SR formulation can be used for predicting the RDB capacity of half-through I-section bridges girders with good accuracy.


ABSTRACT: The existence of initial imperfections in manufacturing of double-layer space structures having
thousands of members is inevitable. Many of the imperfections, such as member length imperfections, are all random in nature. In this paper, the probabilistic effect of member length imperfection in the load bearing capacity of double-layer grid space structures with different types of supports have been investigated. First, for the member length imperfection of each member, a random number is generated from a normal distribution. Then, the imperfections are randomly distributed amongst the members of the structure. Afterwards, the ultimate bearing capacity of the structure is determined by using nonlinear analysis and this procedure is frequently repeated using Monte Carlo simulation method. Ultimately, based on the maximum values of bearing capacity, structure's reliability diagrams are obtained. The results show the sensitivity of the collapse behavior of double-layer grid space structures to the random distribution of initial imperfections.

ABSTRACT: This paper presents the results of experimental studies on circular tubed steel-reinforced-concrete (TSRC) short columns subjected to axial and eccentric loading. A total of 12 columns with the key parameters of eccentricity ratio and diameter-to-thickness ratio of the steel tube were tested. The effect of shear studs on the co-work behavior of concrete and shaped steel was studied. The test results indicated that the shear studs affected little on the failure mode, bearing capacity and ductility of the eccentrically loaded circular TSRC short columns. Elastic-plastic analysis for the steel tube showed that the tubes at the compression side began to yield when the load approximately reached 90% of the peak load. Fiber-based numerical models for circular TSRC short columns were established and the results accorded well with the experimental results. Furthermore, the whole section plastic assumption in EC4 was adopted to determine the section capacity interaction diagram for circular TSRC columns.

ABSTRACT: Steel tubular sections are extensively found in many kinds of civil and mechanical engineering structures such as columns and bracing elements, offshore industry, bridge elements, etc. Due to the extensive usage, a considerable amount of research has been carried out on such structural members. Although many studies focused on the bending stability of steel members, very little research can be found on the effect of surface defects, such as dent imperfection, on the bending behavior of such tubular members. This research aimed to evaluate the effect of dent-shaped defects on the flexural capacity of CHS members. The data obtained in this paper can be applied to evaluate the capacity of large scale CHS members with similar D/t ratio when a dent is formed on the tubes during the service life of such members. An interrelation between the capacity and the details of the dent, i.e. size and position of the dent, was proposed.

ABSTRACT: Initial imperfections can cause evident influence on the bearing capacity of lattice shells. In this article, the member initial imperfections including the initial bending and residual stress are considered by the Marshall model which is a phenomenon model based on the hysteresis loop of the real structural imperfect member under cyclic loading. The geometrical initial imperfection of lattice shells resulting from the structure assembly deviation is represented by the normally distributed random variable. The bearing capacities of lattice shells with initial imperfections are assumed to be distributed normally, and then this assumption is proved.
correct by the nonparametric test. The expressions of the mean value and variance estimators of the normally distributed structural bearing capacities are derived by the maximum likelihood method. A new method to calculate the design bearing capacity of the initial imperfect lattice shell at a uniform probability level is proposed, and its error expression at certain confidence level is derived. Numerical analysis indicates that some members of the structure at the ultimate limit state get buckled as a result of the member initial imperfections. The structure bearing capacity can be markedly overestimated if the member initial imperfections are neglected. The nonlinear design bearing capacity of the lattice shell at a uniform probability level cannot be acquired by the methods suggested by the structure design code.


ABSTRACT: This article reviews research on cold-formed steel structures published in 2013 and 2014 in three leading journals: the Journal of Structural Engineering, ASCE, Thin-Walled Structures and the Journal of Constructional Steel Research. It also reviews papers published in the three main conferences in the area over the same period. These are Eurosteel 2014 (Naples, Italy), the 7th International Conference on Thin-Walled Structures (Busan, Korea) and the 22nd International Specialty Conference on Cold-Formed Steel Structures (St Louis, MO, USA). Three research areas which have recently been incorporated in the North American Specification NAS S100:2012 or are being incorporated in the Australian/New Zealand Standard AS/NZS 4600 have been highlighted. These are the works on the semi-analytical finite strip method for sections in shear by the author and his colleagues at the University of Sydney, net section rupture by Associate Professor Lip Teh at the University of Wollongong and fire design by Professor Mahendran at Queensland University of Technology.

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ABSTRACT: As a new type of structure, cable-stiffened single-layer spherical latticed shell generally has an increased load-carrying capacity. In the past, greater emphasis was placed on analysing their stability behaviours using finite element method or approximate formulae. This work conducted experimental investigation into the stability behaviour of cable-stiffened single-layer latticed shells. Three experimental models, including one ordinary single-layer spherical latticed shell and two different types of cable-stiffened single-layer spherical latticed shells under three different types of load distributions, were investigated in this study. Corresponding numerical analyses were conducted to investigate the stability behaviour of the latticed shells as well. Both the experimental study and the numerical analyses indicate that the load-carrying capacity of single-layer latticed shell has been significantly improved by the introduction of the cable-stiffened system. The numerical results also show that the joint stiffness has remarkable effect on the stability of ordinary single-layer latticed shell, whereas the effect on corresponding cable-stiffened single-layer latticed shells is limited.

ABSTRACT: This article derives analytical solutions for steel pipelines subjected to combined bending moments, axial forces, and internal pressure by considering the effect of ovalization on the plastic region. Both lower and upper bound solutions are proposed based on the selection of a general modulus of pipe material. The ultimate bending capacity, as well as the moment–curvature relationship, can be obtained from the analytical solutions. A comparison of the analytical solutions with the experimental and numerical results finds the bending capacities and the moment–curvature curves in good agreement. Therefore, the proposed analytical solutions can be used to study the behavior of steel pipelines subjected to combined loadings.

ABSTRACT: Most finite element models of actual projects established in general finite element software are rigidly connected or connected by hinge joints. Member imperfection cannot be considered in such models, which is inconsistent with the actual situation in most projects. To estimate the influences of joint stiffness and member imperfection on the mechanical behavior of latticed shell structures, double elements and imperfect members were combined in this study. First, the accuracies of double elements and imperfect members were validated. Then, they were combined to establish imperfect elements with semi-rigid joints. The accuracy of imperfect elements with semi-rigid joints was also validated, and the relationship between joint stiffness and that of double elements was deduced. The findings validated that imperfect elements with semi-rigid joints could consider semi-rigid joints and imperfect members simultaneously and with high accuracy. In addition, imperfect elements with semi-rigid joints could be constructed conveniently in general finite element software.

ABSTRACT: This article presents a numerical analysis on the behavior of square recycled aggregate concrete-filled steel tube stub columns with the cold-formed hollow structural steel tube being used. A nonlinear finite element model for the square recycled aggregate concrete-filled steel tube stub column under axial compression has been developed using the general-purpose finite element program. An equivalent stress-strain model is proposed to simulate the behavior of the recycled aggregate concrete confined by a steel tube. The results obtained from the finite element model are compared with the experimental data. The comparison indicates that the finite element model is capable of predicting the mechanical behavior of the square recycled aggregate concrete-filled steel tube stub columns. After the validation of the numerical model, the effects of the recycled aggregate replacement ratio on the behavior of the square recycled aggregate concrete-filled steel tube stub columns are investigated. Furthermore, the applicability of the current design specifications and the proposed empirical formulas by various researchers to predict the ultimate compressive strengths of the recycled aggregate concrete-filled steel tube stub columns are examined. The comparative study shows that the specification Eurocode 4 gives closer prediction of the ultimate compressive strength than the other methods.

ABSTRACT: LiteSteel beam is a hollow flange channel made from cold-formed steel using a patented manufacturing process involving simultaneous cold-forming and dual electric resistance welding. LiteSteel beams are currently used as floor joists and bearers in buildings. However, there are no appropriate design standards available due to their unique hollow flange geometry, residual stress characteristics and initial geometric imperfections arising from manufacturing processes. Recent research studies have focused on investigating the structural behaviour of LiteSteel beams under pure bending, predominant shear and combined actions. However, web crippling behaviour and strengths of LiteSteel beams still need to be examined. Therefore, an experimental study was undertaken to investigate the web crippling behaviour and strengths of LiteSteel beams under end-one-flange and interior-one-flange load cases. A total of 23 web crippling tests were performed and the results were compared with the current AS/NZS 4600 and AISI S100 design standards, which showed that the cold-formed steel design rules predicted the web crippling capacity of LiteSteel beam sections very conservatively under end-one-flange and interior-one-flange load cases. Therefore, suitably improved design equations were proposed to determine the web crippling capacity of LiteSteel beams based on experimental results. In addition, new design equations were also developed under the direct strength method format. This article presents the details of this experimental study on the web crippling behaviour and strengths of LiteSteel beams under end-one-flange and interior-one-flange load cases and the results.

ABSTRACT: Reinforced concrete conical tanks are used in municipalities and industrial applications as liquid containing vessels. These tanks can be ground supported tanks or elevated on a supporting shaft. Although most design codes provide guidelines for rectangular and cylindrical tanks, no guidance is provided in these codes for conical tanks. This study focuses on assessing the accuracy of a design approach based on the provisions of Portland Cement Association Circular Concrete Tanks without Pre-stressing code for cylindrical tanks combined with an equivalent cylinder approach provided by the American Water Works Association-D100. Several reinforced concrete conical tanks with different geometric configurations are analyzed under the effect of hydrostatic loading using this approach. The internal forces obtained according to code provisions are
compared with those predicted by a linear finite element analysis model developed for all studied tanks. The finite element analysis model is based on a degenerated consistent sub-parametric triangular shell element developed in-house. The results of this comparison show that Portland Cement Association Circular Concrete Tanks without Pre-stressing approach leads to larger hoop tension and smaller meridional moment compared to those obtained from the finite element analysis. Therefore, the Portland Cement Association Circular Concrete Tanks without Pre-stressing provisions combined with the equivalent cylinder approach lead to an inadequate design if applied to conical-shaped tanks.


ABSTRACT: The behaviour of composite frames with castellated steel beams at elevated temperatures is investigated, and the results obtained were compared with the companion results of simply supported composite castellated steel beams. Overall, it is aimed to investigate the effect of axial and rotational restraining of the steel beam via rigid connections with protected steel columns at elevated temperatures. A previously reported finite element model for the analysis of composite beams in fire was extended to perform the nonlinear analyses of composite frames at elevated temperatures. The finite element model has accounted for the frame geometries and boundary conditions, nonlinear material properties of steel, concrete, profiled steel sheeting, longitudinal and lateral reinforcement bars as well as shear connection behaviour at ambient and elevated temperatures. The thermal properties at the steel beam top flange/profiled steel sheeting and profiled steel sheeting/concrete elements interfaces were considered in the thermal heat transfer analysis that allowed the temperatures to be accurately predicted in the composite slab during fire exposure. The comparison of composite frames and composite beams behaviour has shown that if the columns were sufficiently protected and the connection maintained its rigidity during fire exposure, such that it can restrain the composite beam thermal expansions, this would result in considerable reduction in fire resistances of the composite frames compared with that of simply supported composite beams. This is attributed to the premature failure at elevated temperatures due to local buckling at the bottom flange of the steel beams in the frame connections. Furthermore, the variables that influence the fire resistance and behaviour of the composite frames comprising different load ratios during fire, different fire curves, presence of web openings and different steel grades were investigated by parametric studies. It is shown that the strength of steel and the fire scenarios have a considerable effect on the time–displacement behaviour and fire resistances of the composite frames.


ABSTRACT: A novel spherical lattice shell composed of six-bar tetrahedral units whose horizontal projections are quadrilaterals is proposed. The lattice shell provides an advantage in industrialized production and prefabricated construction by comprising a plurality of similarly shaped modular units. Kinematic analysis for the lattice shell, based on which several strengthening structures and joint rigidity arrangements are proposed, is carried out. The structural behavior of a basic structure of the lattice shell, whose chord and web members are designed as beam and bar elements, respectively, is studied systematically. Construction details of the nodal joints and six-bar tetrahedral modular units are suggested, followed by a discussion about the construction scheme. A tool called A-shaped installing frame is designed to realize the prefabricated construction without scaffold. A test model of 10-m span was built to verify the feasibility of the nodal joint construction as well as the prefabricated construction scheme.

ABSTRACT: A linear elastic model constituted by two interacting concentric arches is developed. The sensitivity of the behaviour of the system to its mechanical and geometrical parameters is studied to individuate the fundamental ones. The analysis is extended to the nonlinear field by means of computational finite element models. Another objective of the research is to specifically analyse the interaction between the two arches when there is a large difference in stiffness. A practical case is represented by the retrofitting of a masonry vault with a single curvature (barrel vaults) with a reinforcing concrete layer that, in several cases, resulted in the detachment of some masonry blocks. Finally, on the basis of the results of the nonlinear analyses, which qualitatively confirmed the results of the linear ones, a slightly innovative approach to the use of the reinforcing layers is proposed.


ABSTRACT: Reinforced concrete column confined using two layers of stirrups is a new kind of column form recently proposed by the authors. The concrete of the column is under three different levels of confinement, namely unconfined concrete cover, singly confined, and doubly confined concrete core. This column form provides a simple but effective solution for reinforced concrete columns located in seismic hazard zones and/or reinforced concrete columns with large axial load ratio, where large amount of transverse reinforcement is necessary to achieve a ductile response. This study aims to investigate the axial compressive behavior of square reinforced concrete columns confined using two layers of stirrups. In total, 15 columns were prepared and tested under axial compression. Two different stirrup configurations were investigated. The axial responses and the failure modes of the columns were examined in detail, and the average stress–strain curve of the singly confined and doubly confined concrete core was derived. A stress–strain model with satisfactory accuracy was proposed based on the interpretation of test results.


ABSTRACT: A total of 67 web crippling tests were conducted on carbon fibre–reinforced polymer strengthened cold-formed stainless steel square and rectangular hollow sections in this article. Several carbon fibre–reinforced polymer strengthening schemes were adopted, such as strengthened with carbon fibre–reinforced polymer sheets, strengthened with carbon fibre–reinforced polymer plates and strengthened with anchored carbon fibre–reinforced polymer plates. Two loading conditions of end-two-flange and interior-two-flange have been considered. The tests were performed on five different tubular section sizes which covered a slightly wide range of measured web slenderness ratios from 18.70 to 68.41. The effects of carbon fibre–reinforced polymer length, number of carbon fibre–reinforced polymer layers and carbon fibre–reinforced polymer strengthening schemes on the strength enhancement have been discussed based on the test results obtained from this study. It was found that the web crippling capacity of stainless steel tubular sections can be obviously increased by carbon fibre–reinforced polymer strengthening, especially for those sections with large values of web slenderness under end-two-flange loading condition. However, the strengthening enhancement of carbon fibre–reinforced polymer sheets and carbon fibre–reinforced polymer plates is quite limited due to the debonding between stainless steel tube and carbon fibre–reinforced polymer. The anchored carbon fibre–reinforced polymer plates can effectively delay or totally prevent the debonding failure. The web crippling
behaviour of cold-formed stainless steel square and rectangular hollow sections strengthened with anchored carbon fibre–reinforced polymer plates has been significantly improved. Finally, the web crippling test results obtained from this study are compared with the current design strengths.


ABSTRACT: An important segment of the Romanian urban population, similar to other Eastern European countries, lives in collective residential apartment buildings made using large prefabricated concrete panels. Most of these structures were built between 1960 and 1989 and present major issues concerning aesthetical aspects, lack of internal space, problems related to thermal comfort and, last but not least, weak energy efficiency. The presence of flat roofing system, generally with hydrothermal faults, represents an additional problem which leads to deficient living conditions of the last-storey inhabitants in many cases. Besides other ways of improving the conditions of such apartment houses, the over-roofing is welcome in order to both increase the habitable area and provide adequate roofing for the building. This article presents three types of over-roofing structural solutions, in two solutions, based on intensive use of steel, using (1) hot-rolled steel profiles, (2) rectangular hollow sections and (3) cold-formed steel profiles, respectively. In order to determine the optimum over-roofing system, the study analyses the structural design possibilities and particularly the connection between the new and old structural elements.

End of many papers published in the journal, Advances in Structural Engineering (2012-2016)

Many papers published in the journal, Archive of Applied Mechanics (2012-2016)
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ABSTRACT: Yeast cells can be regarded as micron-sized and liquid-filled cylindrical shells. Owing to the rigid cell walls, yeast cells can bear compressive forces produced during the biotechnological process chain. However, when the compressive forces applied on the yeast go beyond a critical value, mechanical buckling will occur. Since the buckling of the yeast can change the networks in its cellular control, the experimental research of the buckling of the yeast has received considerable attention recently. In this paper, we apply a viscoelastic shell model to study the buckling of the yeast. Meanwhile, the turgor pressure in the yeast due to the internal liquid is taken into account as well. The governing equations are based on the first-order shear deformation theory. The critical axial compressive force in the phase space is obtained by the Laplace transformation, and the Bellman numerical inversion method is then applied to the analytical result to obtain the corresponding numerical results in the physical phase. The concepts of instantaneous critical buckling force, durable critical buckling force, and delay buckling are set up in this paper. And the effects of the transverse shear deformation and the turgor pressure on the buckling phenomena are also given. The numerical results show that the transverse shearing effect will decrease the instantaneous critical buckling force and the durable critical buckling force, while the turgor pressure will increase both of them.

References listed at the end of the paper:


ABSTRACT: The free vibration of annular thick plates with linearly varying thickness along the radial direction is studied, based on the linear, small strain, three-dimensional (3-D) elasticity theory. Various boundary conditions, symmetrically and asymmetrically linear variations of upper and lower surfaces are considered in the analysis. The well-known Ritz method is used to derive the eigen-value equation. The trigonometric functions in the circumferential direction, the Chebyshev polynomials in the thickness direction, and the Chebyshev polynomials multiplied by the boundary functions in the radial direction are chosen as the trial functions. The present analysis includes full vibration modes, e.g., flexural, thickness-shear, extensive, and torsional. The first eight frequency parameters accurate to at least four significant figures for five vibration categories are obtained. Comparisons of present results for plates having symmetrically linearly varying thickness are made with others based on 2-D classical thin plate theory, 2-D moderate thickness plate theory, and 3-D elasticity theory. The first 35 natural frequencies for plates with asymmetrically linearly varying thickness are compared to the finite element solutions; excellent agreement has been achieved. The asymmetry effect of upper and lower surface variations on the frequency parameters of annular plates is discussed in detail. The first four modes of axisymmetric vibration for completely free circular plates with symmetrically and asymmetrically linearly varying thickness are plotted. The present results for 3-D vibration of annular plates with linearly varying thickness can be taken as benchmark data for validating results from various plate theories and numerical methods.

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ABSTRACT: In this paper, the vibration and stability properties of fluid-conveying pipes with two symmetric elbows fitted at downstream end are investigated. The fluid, after entering from the upstream end, is pushed downwards and eventually exits from the downstream end fitted with two symmetric elbows. The equation of motion is solved by means of Galerkin’s method with a four-mode approximation. Calculations are conducted for cantilevered and also for pinned–pinned slender pipes. It is found that the stability of the pipe system can be greatly enhanced with such downstream elbows. The vibration frequency of the fluid-conveying pipes can be comfortably controlled due to the downstream elbows with a selection of angle of inclination. The proposed geometry configuration of fluid-conveying pipes may be useful for the design and improvement of engineering pipeline systems and fluidic devices.

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results show that the present model can produce the more accurate deformations and stresses compared with the zigzag theory by comparing the present results with the three-dimensional dynamics in the presence of an end-induced instability of an elastic tube. ASME Paper No. 71–Vibr.-9 (1971)


ABSTRACT: In order to conveniently develop C0 continuous element for the accurate analysis of laminated composite and sandwich plates with general configurations, this paper develops a C0-type zig–zag theory in which the interlaminar continuity of transverse shear stresses is a priori satisfied and the number of unknowns is independent of the number of layers. The present theory is applicable not only to the cross-ply but also to the angle-ply laminated composite and sandwich plates. On the premise of retaining the merit of previous zig–zag theories, the derivatives of transverse displacement have been taken out from the displacement fields. Therefore, based on the proposed zig–zag theory, it is very easy to construct the C0 continuous element. To assess the performance of the proposed model, the classical quadratic six-node triangular element with seven degrees of freedom at each node is presented for the static analysis of laminated composite and sandwich plates. The typical examples are taken into account to assess the performance of finite element based on the proposed zig–zag theory by comparing the present results with the three-dimensional elasticity solutions. Numerical results show that the present model can produce the more accurate deformations and stresses compared with the
previous zig–zag theories.

References listed at the end of the paper:
ABSTRACT: The dynamic analysis of laminated plates with various loading and boundary conditions is presented employing generalized differential quadrature (GDQ) method. The first-order shear deformation theory is considered to model the transient response of the plate. The GDQ technique together with Newmark integration scheme is employed to solve the system of transient equations governing dynamics of the plate. Different symmetric and asymmetric lamination sequences together with various combinations of clamped, simply supported, and free boundary conditions are considered. Particular interest of this study regards asymmetric orthotropic plates having free edge and mixed boundary conditions. It is shown that the method provides reasonably accurate results with relatively small number of grid points. Comparison of the results with those of other methods demonstrates a very good agreement. It is also revealed that the present method offers similar order of accuracy for all variables including displacements and stress resultants.

References listed at the end of the paper:
In this article, the governing equations of motion of thick laminated transversely isotropic plates are based on Reddy’s third-order shear deformation theory. These equations are exactly converted to four uncoupled equations to study the in-plane and out-of-plane free vibrations of thick laminated plates without any usage of approximate methods. Based on the present analytical approach, exact Levy-type solutions are
obtained for thick laminated transversely isotropic plates and, for some boundary conditions, the exact characteristic equations hitherto not reported in the literature are given. Also, the in-plane and out-of-plane deformed mode shapes are plotted for different boundary conditions. The present solutions can accurately predict both the in-plane and out-of-plane natural frequencies and mode shapes of thick laminated transversely isotropic plates.

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E. Asadi and S.J. Fariborz, “Free vibration of composite plates with mixed boundary conditions based on higher-order shear deformation theory”, Archive of Applied Mechanics, Vol. 82, No. 6, pp 755-766, June 2012

ABSTRACT: A global higher-order shear deformation theory is devised to obtain the governing equations of composite plates under dynamic excitation. The time-harmonic solution leads to an eigenvalue problem for the natural frequencies of plates. The eigenvalue problem for rectangular plates is converted to a set of homogenous algebraic equations using differential quadrature method. The formulation of the problem allows direct application of various boundary conditions. Therefore, rectangular plates with mixed boundary conditions are also considered. To show the validity of results, the fundamental natural frequencies of composite plates with different boundary conditions and those of isotropic plates with mixed boundary conditions are compared against the results available in the literature.

References listed at the end of the paper:


ABSTRACT: Self-collapse of carbon nanotubes may prominently affect their electrical properties and holds promise for important applications in the emerging nano-mechanical or electronic systems. Based upon the potential energy functional, we derived the governing equation and transversality boundary condition for a collapsed single-walled carbon nanotube (SWCNT). Considering the inextensible condition of the elastica, some closed-form solutions for the collapsed configuration were obtained in terms of elliptical integrals. These analytical solutions include the critical length of the flat contact segment, critical radii for collapsed and circular shapes of the cross-section, deflections and potential energies of the SWCNTs. Finally, the energy states and the collapsed morphologies of the SWCNTs were presented. These explicit solutions are beneficial for the design of nano-structured materials, and cast a light on enhancing their mechanical, chemical, optical and electronic properties.

References listed at the end of the paper:

ABSTRACT: The improved zigzag theory recently developed by the authors for smart, piezoelectric, and laminated cylindrical shells is assessed for the response of finite-length cross-ply shells and shell panels under mechanical, potential, and thermal loading, in direct comparison with the exact three-dimensional (3D)
piezothermoelasticity solution. This theory has the unique features of including the transverse normal strain due to thermoelastic loading without introducing additional deflection variables, capturing the nonlinear potential field and actual temperature profile across laminate thickness, accounting for the layerwise (zigzag) variation of inplane displacements, and satisfying the conditions on transverse shear stresses at the layer interfaces and at the inner and outer surfaces. For the assessment, new results are obtained for the 3D exact solution for smart cylindrical shells having a test laminate with widely different material properties across layers, a piezocomposite laminate and a piezo-sandwich laminate. To ascertain the contribution of the layerwise terms in the inplane displacements, the theory is compared with its smeared counterpart with the same number of primary variables. The effect of inclusion of transverse normal extensibility in these theories is established by comparing with their conventional counterparts that assume constant deflection across the thickness. The effect of span angle (for shell panels), length, and thickness parameters on the error of the 2D theories is illustrated.

References listed at the end of the paper:


ABSTRACT: Post-buckling behaviour of sandwich plates with functionally graded material (FGM) face sheets under uniform temperature rise loading is considered. It is assumed that the plate is in contact with a Pasternak-type elastic foundation during deformation, which acts in both compression and tension. The derivation of equations is based on the first-order shear deformation plate theory. Thermomechanical non-homogeneous properties of FGM layers vary smoothly by the distribution of power law across the thickness, and temperature dependency of material constituents is taken into account. Using the non-linear von-Karman strain-displacement relations, the equilibrium and compatibility equations of imperfect sandwich plates with FGM face sheets are derived. The boundary conditions for the plate are assumed to be simply supported in all edges.
The governing equations are reduced to two coupled equation in terms of stress function and lateral deflection. Employing the single mode approach combined with Galerkin technique, an approximate closed-form solution is presented to calculate the critical buckling temperature and post-buckling equilibrium path of the plate. Presented numerical examples contain the influences of power law index, sandwich plate geometry, geometrical imperfection, temperature dependency, and the elastic foundation coefficients.

References listed at the end of the paper:


ABSTRACT: In this paper, the nonlinear vibration of a thin circular functionally graded material plates is studied. The plate thickness is constant, and the material properties of the plate are assumed to vary continuously through the thickness. The governing equations and boundary conditions are extracted. The assumed-time-mode method is used to analyze these equations. The time variable is eliminated by assuming a harmonic response for nonlinear vibration and using Kantorovich time averaging technique. Utilizing shooting and Runge–Kutta methods, the set of first-order nonlinear differential equations are solved. The effect of volume fraction index in free and forced vibration response and jump phenomenon is studied. The results show that jump phenomenon occur according to volume fraction index and uniform temperature in the special frequencies of forced vibration response.

References listed at the end of the paper:

ABSTRACT: The subject of this consideration is a thin skeletal elastic shallow shell with an orthogonal beam–grid microstructures. The important feature of the considered shells is that a dimension of the microstructure is of an order of the shell thickness. The formulation of 2D-macroscopic mathematical model of these shells, based on a tolerance averaging approximation (Woźniak et al., 2008), is the aim of the paper. During the modeling procedure, the shell under consideration is treated as a structure with a nonuniform microstructure. The general results of the contribution will be illustrated by the analysis of natural vibrations of a cylindrical thin skeletal shallow shell.

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Peng Li, Yiren Yang, Wei Xu and Guo Chen, “On the aeroelastic stability and bifurcation structure of subsonic nonlinear thin panels subjected to external excitation”, Archive of Applied Mechanics, Vol. 82, No. 9, pp 1251-1267, September 2012

ABSTRACT: Dynamic behavior of panels exposed to subsonic flow subjected to external excitation is investigated in this paper. The von Karman’s large deflection equations of motion for a flexible panel and Kelvin’s model of structural damping is considered to derive the governing equation. The panel under study is two-dimensional and simply supported. A Galerkin-type solution is introduced to derive the unsteady aerodynamic pressure from the linearized potential equation of uniform incompressible flow. The governing partial differential equation is transformed to a series of ordinary differential equations by using Galerkin method. The aeroelastic stability of the linear panel system is presented in a qualitative analysis and numerical study. The fourth-order Runge-Kutta numerical algorithm is used to conduct the numerical simulations to investigate the bifurcation structure of the nonlinear panel system and the distributions of chaotic regions are shown in the different parameter spaces. The results shows that the panel loses its stability by divergence not flutter in subsonic flow; the number of the fixed points and their stabilities change after the dynamic pressure exceeds the critical value; the chaotic regions and periodic regions appear alternately in parameter spaces; the single period motion trajectories change rhythmically in different periodic regions; the route from periodic motion to chaos is via doubling-period bifurcation.

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ABSTRACT: Developers of new finite elements or nonlinear solution techniques rely on discriminative benchmark tests drawn from the literature to assess the advantages and drawbacks of new formulations. Buckling benchmark tests provide a rigorous evaluation of finite elements applied to thin structures, and a complete and detailed set of reference results would therefore prove very useful in carrying out such evaluations. Results are usually presented in the form of load-deflection curves that developers must reconstruct by extracting the points, a procedure which is often tedious and inaccurate. Moreover the curves are usually given without accompanying information such as the calculation time or number of iterations it took for the model to converge, even though this type of data is equally important in practice. This paper presents ten different limit-point buckling benchmark tests, and provides for each one the reference load-deflection curve, all the points necessary to recreate the curve in tabulated form, analysis data such as calculation time, number of iterations and increments, and all of the inputs used to obtain these results.

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ABSTRACT: This paper proposes an extension of the SHB8PS solid–shell finite element to large strain anisotropic elasto-plasticity, with application to several non-linear benchmark tests including sheet metal forming simulations. This hexahedral linear element has an arbitrary number of integration points distributed along a single line, defining the “thickness” direction; and to control the hourglass modes inherent to this reduced integration, a physical stabilization technique is used. In addition, the assumed strain method is adopted for the elimination of locking. The implementation of the element in Abaqus/Standard via the UEL user subroutine has been assessed through a variety of benchmark problems involving geometric non-linearities, anisotropic plasticity, large deformation and contact. Initially designed for the efficient simulation of elastic–plastic thin structures, the SHB8PS exhibits interesting potentialities for sheet metal forming applications—both in terms of efficiency and accuracy. The element shows good performance on the selected tests, including springback and earing predictions for Numisheet benchmark problems.

References listed at the end of the paper:


ABSTRACT: A family of prismatic and hexahedral solid–shell (SHB) elements, with their linear and quadratic versions, is proposed in this work to model thin structures. The formulation of these SHB elements is extended to explicit dynamic analysis and large-strain anisotropic plasticity on the basis of a fully three-dimensional approach using an arbitrary number of integration points along the thickness direction. Several special treatments are applied to the SHB elements in order to avoid all locking phenomena and to guarantee the accuracy and efficiency of the simulations. These solid-shell elements have been implemented into ABAQUS standard/quasi-static and explicit/dynamic software packages. A number of static and dynamic benchmark problems, as well as a simulation of the deep drawing of a cylindrical cup, have been conducted to assess the performance of these SHB elements.

References listed at the end of the paper:


fully nonlinear theory in the updated Lagrangian co-

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Further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitudinal stiffeners in the zone of load introduction, but with horizontal (longitudinal) stiffeners, are considered. An approximate solution for obtaining ultimate load is developed using failure (collapse) mechanism and following the upper bound theorem of plastic collapse. Procedure is based on the solution introduced by Roberts and Rocky and further elaborated by Roberts for the determination of the ultimate patch load for girders without longitud
stiffeners. Procedure presented in this paper is adapted for the girders with longitudinal stiffeners. Proposed collapse mechanism is based on the experimental evidence. When the longitudinal stiffeners have enough rigidity, deformation at collapse, buckling of the web, is limited to the part of the web between loaded flange and longitudinal stiffener. Values of the ultimate loads obtained through developed procedure as well as the values from other, earlier authors’ proposal that was accepted and applied in the British standard BS 5400 are compared with the values from authors’ experiments and available database with the test results from other investigators.

References listed at the end of the paper:

ABSTRACT: In this paper, the effect of a centrally applied external axial tensile load on the lateral-torsional buckling resistance of simply supported I-beams under uniform bending acting in the plane of maximum rigidity is studied. A linear and a nonlinear analysis are performed. Following the linear analysis, an expression for the critical moment of lateral-torsional buckling is presented in which the influence of the axial tensile force is included. There is an upper limit of this force over which the equilibrium in the deformed state is not possible. In the nonlinear analysis, the nature of the critical state is studied, considering the initial part of the post-buckling path. It is concluded that this critical state is associated with a stable symmetrical bifurcation point. Nevertheless, the post-buckling path is very shallow; therefore, the beam cannot exhibit practically post-buckling strength. The paper is supplemented by a representative example.

References listed at the end of the paper:

ABSTRACT: The thickness optimization is used to maximize the stiffness or the buckling load of a Kirchhoff plate having constant volume. The shape of the plate is arbitrary and it is subjected to any type of admissible boundary conditions. The optimization consists in establishing the thickness variation law, for which either the stiffness of the plate or the buckling load is maximized. Beside the equality constraint of constant volume, the thickness variation is subjected also to inequality constraints resulting from serviceability requirements (upper and lower thickness bounds) as well as from the condition that the Kirchhoff plate theory remains valid. The latter constraint is new and it is derived herein by approximating the plate with a three-dimensional prismatic elastic body having curved upper and lower surface. The optimization problem is solved using the sequential quadratic programming algorithm. The bending and the plane stress problem of a plate with variable thickness, required for the evaluation of the objective function, are solved using the analog equation method. The thickness is approximated using integrated radial basis functions that approximate accurately not only the thickness function but also its first and second derivatives involved in the plate equation and in the constraints. Several plate optimization problems have been studied giving realistic and meaningful optimum designs without violating the validity of the thin plate theory.

References listed at the end of the paper:
ABSTRACT: In the present study, a coupled refined high-order global-local theory is developed for predicting fully coupled behavior of smart multilayered/sandwich beams under electromechanical conditions. The proposed theory considers effects of transverse normal stress and transverse flexibility which is important for beams including soft cores or beams with drastic material properties changes through depth. Effects of induced transverse normal strains through the piezoelectric layers are also included in this study. In the presence of non-zero in-plane electric field component, all the kinematic and stress continuity conditions are satisfied at layer interfaces. In addition, for the first time, conditions of non-zero shear and normal tractions are satisfied even while the bottom or the top layer of the beam is piezoelectric. A combination of polynomial and exponential expressions with a layerwise term containing first order differentiation of electrical unknowns is used to introduce the in-plane displacement field. Also, the transverse displacement field is formulated utilizing a combination of continuous piecewise fourth-order polynomial with a layerwise representation of electrical unknowns. Finally, a quadratic electric potential is used across the thickness of each piezoelectric layer. It is worthy to note that in the proposed shear locking-free finite element formulation, the number of mechanical unknowns is independent of the number of layers. Excellent correlation has been found between the results obtained from the proposed formulation for thin and thick piezoelectric beams with those resulted from the three-dimensional theory of piezoelectricity. Moreover, the proposed finite element model is computationally economic.

References listed at the end of the paper:
ABSTRACT: The thermo-mechanical nonlinear dynamics of a buckled axially moving beam is numerically investigated, with special consideration to the case with a three-to-one internal resonance between the first two modes. The equation of motion of the system traveling at a constant axial speed is obtained using Hamilton’s principle. A closed form solution is developed for the post-buckling configuration for the system with an axial speed beyond the first instability. The equation of motion over the buckled state is obtained for the forced system. The equation is reduced into a set of nonlinear ordinary differential equations via the Galerkin method. This set is solved using the pseudo-arclength continuation technique to examine the frequency response curves and direct-time integration to construct bifurcation diagrams of Poincaré maps. The vibration characteristics of the system at points of interest in the parameter space are presented in the form of time histories, phase-plane portraits, and Poincaré sections.

ABSTRACT: This paper presents an efficient shear deformation theory for vibration of functionally graded plates. The theory accounts for parabolic distribution of the transverse shear strains and satisfies the zero traction boundary conditions on the surfaces of the plate without using shear correction factors. The mechanical properties of functionally graded plate are assumed to vary according to a power law distribution of the volume fraction of the constituents. Equations of motion are derived from the Hamilton’s principle. Analytical solutions of natural frequency are obtained for simply supported plates. The accuracy of the present solutions is verified by comparing the obtained results with those predicted by classical theory, first-order shear deformation theory, and higher-order shear deformation theory. It can be concluded that the present theory is not only accurate but also simple in predicting the natural frequencies of functionally graded plates.

ABSTRACT: A high-order theory for functionally graded axially symmetric cylindrical shell based on expansion of the axially symmetric equations of elasticity for functionally graded materials into Legendre polynomials series has been developed. The axially symmetric equations of elasticity have been expanded into Legendre polynomials series in terms of a thickness coordinate. In the same way, functions that describe functionally graded relations have been also expanded. Thereby, all equations of elasticity including Hook’s law have been transformed to corresponding equations for coefficients of Legendre polynomials expansion. Then system of differential equations in terms of displacements and boundary conditions for the coefficients of Legendre polynomials expansion coefficients has been obtained. Cases of the first and second approximations have been considered in more details. For obtained boundary-value problems’ solution, a finite element has been used and numerical calculations have been done with COMSOL MULTIPHYSICS and MATLAB.


ABSTRACT: Progressive deformation of honeycomb structures subjected to in-plane loading was approximately analyzed by using the collapse modes of hexagonal unit cells. The collapse modes were categorized as freely compressive, restricted compressive, and shear. Moreover, there were five characteristic deformation patterns, namely deformation bands. Average stresses of the collapsing honeycomb models were evaluated in terms of the plastic collapse stress per hinge and total number of hinges of progressively arising deformation bands. The displacements of the models were obtained by multiplying the displacement per cell with the number of collapsed cells. The present method was used to analyze progressive deformation of typical honeycomb structures. The validity of the stress–displacement relations derived for some structures was confirmed by comparing them with finite element method (FEM) results. Our method is much simpler than FEM but just as effective.

References listed at the end of the paper:

ABSTRACT: The effects of a piezoelectric layer on the stability of viscoelastic plates subjected to the follower forces are evaluated. The differential equation of motion of the viscoelastic plate with the piezoelectric layer is formulated using the two-dimensional viscoelastic differential constitutive relation and the thin plate theory. The weak integral form of the differential equations and the force boundary conditions are obtained. Using the element-free Galerkin method, the governing equation of the viscoelastic rectangular plate with elastic dilatation and Kelvin–Voigt distortion is derived, subjected to the follower forces coupled with the piezoelectric effect. A generalized complex eigenvalue problem is solved, and the force excited by the piezoelectric layer due to external voltage is modeled as the follower tensile force; this force is used to improve the stability of the non-conservative viscoelastic plate. For the viscoelastic plate with various boundary conditions, the results for the instability type and the critical loads are presented to show the variations in these factors with respect to the location of the piezoelectric layers and the applied voltages. The stability of the viscoelastic plates can be effectively improved by the determination of the optimal location for the piezoelectric layers and the most favorable voltage assignment.

References listed at the end of the paper:

References listed at the end of this paper:


ABSTRACT: A finite element model based on sinusoidal shear deformation theory is developed to study vibration and buckling analysis of composite beams with arbitrary lay-ups. This theory satisfies the zero traction boundary conditions on the top and bottom surfaces of beam without using shear correction factors. Besides, it has strong similarity with Euler–Bernoulli beam theory in some aspects such as governing equations, boundary conditions, and stress resultant expressions. By using Hamilton’s principle, governing equations of motion are derived. A displacement-based one-dimensional finite element model is developed to solve the problem. Numerical results for cross-ply and angle-ply composite beams are obtained as special cases and are compared with other solutions available in the literature. A variety of parametric studies are conducted to demonstrate the effect of fiber orientation and modulus ratio on the natural frequencies, critical buckling loads, and load-frequency curves as well as corresponding mode shapes of composite beams.


ABSTRACT: This paper focuses on the free vibration analysis of thick, rotating laminated composite conical shells with different boundary conditions based on the three-dimensional theory, using the layerwise differential quadrature method (LW-DQM). The equations of motion are derived applying the Hamilton’s principle. In order to accurately account for the thickness effects, the layerwise theory is used to discretize the equations of motion and the related boundary conditions through the thickness of the shells. Then, the equations of motion as well as the boundary condition equations are transformed into a set of algebraic equation applying the DQM in the meridional direction. This study demonstrates the applicability, accuracy, stability and the fast rate of convergence of the present method, for free vibration analyses of rotating thick laminated conical shells. The presented results are compared with those of other shell theories obtained using conventional methods and a special case where the angle of the conical shell approaches zero, that is, a cylindrical shell and excellent agreements are achieved.

References listed at the end of the paper:
Mario M. Attard, Jianbei Zhu and David Kellermann, “In-plane buckling of circular arches and rings with shear deformations”, Archive of Applied Mechanics, Vol. 83, No. 8, pp 1145-1169, August 2013

ABSTRACT: A finite strain formulation is developed for elastic circular arches and rings in which the effects of shear deformations are included. Timoshenko beam hypothesis is adopted for incorporating shear. Finite strains are defined in terms of the normal and shear component of the longitudinal stretch. The constitutive relations for stress and finite strain are based on a hyperelastic constitutive model. Virtual work and equilibrium equations are derived. Closed-form in-plane buckling solutions are developed for circular rings and high arches under hydrostatic pressure. The effects of axial deformation prior to buckling as well as shear deformations are included in the buckling analysis. The formulation developed is compared with solutions in the literature and to the predictions of the finite element package ANSYS. The importance of including the effects of shear deformations for deep arches is investigated.


ABSTRACT: In this paper, we propose a modified Monte Carlo method for analysis of buckling of an
imperfect beams on softening nonlinear elastic foundation. Such structures exhibit considerable imperfection sensitivity, i.e. reduction in the maximum load that the structure is able to support in contrast to classical buckling load of the perfect structure. The initial imperfections are treated as random functions of axial coordinate. In order to reduce the needed number of simulations, the Monte Carlo method is coupled with maximum likelihood methodology and the Kolmogorov–Smirnov test.

References listed at the end of the paper:


ABSTRACT: Thermomechanical instability of shallow spherical shells made of functionally graded material (FGM) and surface-bonded piezoelectric actuators is studied in this paper. The governing equations are based on the classical shell theory of shells and the Sanders nonlinear kinematics equations. It is assumed that the property of the FGMs varies continuously through the thickness of the shell according to a power law distribution of the volume fraction of the constituent materials. The constituent materials of the functionally graded shell are assumed to be mixture of ceramic and metal. The analytical solutions are obtained for uniform external pressure, thermal loading, and constant applied actuator voltage.

References listed at the end of the paper:

Huu-Tai Thai and Dong-Ho Choi, “Efficient higher-order shear deformation theories for bending and free vibration analyses of functionally graded plates”, Archive of Applied Mechanics, Vol. 83, No. 12, pp 1755-1771, December 2013

ABSTRACT: In this paper, various efficient higher-order shear deformation theories are presented for bending and free vibration analyses of functionally graded plates. The displacement fields of the present theories are chosen based on cubic, sinusoidal, hyperbolic, and exponential variations in the in-plane displacements through the thickness of the plate. By dividing the transverse displacement into the bending and shear parts and making further assumptions, the number of unknowns and equations of motion of the present theories is reduced and hence makes them simple to use. Equations of motion are derived from Hamilton’s principle. Analytical solutions for deflections, stresses, and frequencies are obtained for simply supported rectangular plates. The accuracy of the present theories is verified by comparing the obtained results with the exact three-dimensional (3D) and quasi-3D solutions and those predicted by higher-order shear deformation theories. Numerical results show that all present theories can archive accuracy comparable to the existing higher-order shear deformation theories that contain more number of unknowns.

References listed at the end of the paper:
33. Thai H.T., Kim S.E.: A simple higher-order shear deformation theory for bending and free vibration analysis of functionally graded plates. Compos. Struct. 95, 188–196 (2013)
In the current dynamic model of rotating truncated conical shells, the expressions of centrifugal and coriolis accelerations and initial hoop tension were incomplete and some terms were missing. This might cause the frequency characteristics of rotating conical shells to be overestimated (or underestimated). Therefore, the effects of rotation upon frequency characteristics of rotating truncated conical shell are studied in the paper. Accurate expressions of centrifugal and coriolis accelerations and initial hoop tension are derived, and then a modified dynamic model for the rotating truncated conical shell is presented. The generalized differential quadrature method is utilized to obtain the natural frequencies. The influences of various boundary conditions and rotating speed on the free vibration of the conical shell are discussed in detail. Through comparison analysis, the errors in current model are also pointed out.

References listed at the end of the paper:


Da-Guang Zhang, “Nonlinear bending analysis of FGM rectangular plates with various supported boundaries resting on two-parameter elastic foundations”, Archive of Applied Mechanics, Vol. 84, No. 1, pp 1-20, January 2014

ABSTRACT: In this paper, model of the FGM plates resting on two-parameter elastic foundations is put forward by using on physical neutral surface and high-order shear deformation theory. Material properties are assumed to be temperature dependent and vary along the thickness, while Poisson’s ratio depends weakly on temperature change and position and is assumed to be a constant. It is worth noting that physical neutral surface will be changed with temperature. The character of physical neutral surface higher-order shear deformation plate theory is that the displacements have special forms, stretching-bending couplings are eliminated in constitutive equations, and governing equations have the simple and similar forms as homogeneous isotropic plates. The validity of physical neutral surface higher-order shear deformation plate theory can be confirmed by comparing with related researchers’ results. Nonlinear bending approximate solutions of FGM rectangular plates with six cases of boundary conditions are given out using Ritz method, and influences played by different supported boundaries, foundation stiffnesses, thermal environmental conditions, and volume fraction index are discussed in detail.

References listed at the end of the paper:


ABSTRACT: In this paper, the nonlinear free vibration of a stringer shell is studied. The mathematical model of the string shell, which is the most convenient for frequency analysis, is considered. Due to the geometrical properties of the vibrating shell, strong nonlinearities are evident. Approximate analytical expressions for the nonlinear vibration are provided by introducing the extended version of the Hamiltonian approach. The method suggested in the paper gives the approximate solution for the differential equation with dissipative term for which the Lagrangian exists. The aim of this study is to provide engineers and designers with an easy method for determining the shell nonlinear vibration frequency and nonlinear behavior. The effects of different parameters on the ratio of nonlinear to linear natural frequency of shells are studied. This analytical representation gives excellent approximations to the numerical solutions for the whole range of the oscillation parameters. This study shows that a first-order approximation of the Hamiltonian approach leads to highly accurate solutions that are valid for a wide range of vibration amplitudes. (I think “string shell” means “stringer-stiffened shell”)

References listed at the end of the paper:

ABSTRACT: This paper is concerned with effect of mismatched pressure on buckling of stressed thin films on substrates, Archive of Applied Mechanics, Vol. 84, No. 2, pp 149-157, February 2014


ABSTRACT: This paper is concerned with effect of mismatched pressure on buckling of stressed thin films on a semi-infinite rigid substrate. Analytical approximate solutions are established in explicit form by using total potential energy of the system and the Rayleigh–Ritz’s method, and their stabilities have also been determined. The dependences of the critical stress and film-center deflection on the mismatched pressure have been
formulated. Results are compared with exact or numerical shooting solutions, and excellent agreements are observed for a large range of film-center deflection. These expressions are brief and can easily be used to derive the effects of various parameters on mechanical behavior of films.

References listed at the end of the paper:


ABSTRACT: A numerical solution methodology is proposed herein to investigate the nonlinear forced vibrations of Euler–Bernoulli beams with different boundary conditions around the buckled configurations. By introducing a set of differential and integral matrix operators, the nonlinear integro-differential equation that governs the buckling of beams is discretized and then solved using the pseudo-arc-length method. The discretized governing equation of free vibration around the buckled configurations is also solved as an eigenvalue problem after imposing the boundary conditions and some complicated matrix manipulations. To study forced and nonlinear vibrations that take place around a buckled configuration, a Galerkin-based numerical method is applied to reduce the partial integro-differential equation into a time-varying ordinary differential equation of Duffing type. The Duffing equation is then discretized using time differential matrix operators, which are defined based on the derivatives of a periodic base function. Finally, for any given magnitude of axial load, the pseudo-arc-length method is used to obtain the nonlinear frequencies of buckled beams. The effects of axial load on the free vibration, nonlinear, and forced vibrations of beams in both prebuckling and postbuckling domains for the lowest three vibration modes are analyzed. This study shows that
the nonlinear response of beams subjected to periodic excitation is complex in the postbuckling domain. For example, the type of boundary conditions significantly affects the nonlinear response of the postbuckled beams. References listed at the end of the paper:

ABSTRACT: In this paper, a unified Chebyshev–Ritz formulation is presented to investigate the vibrations of composite laminated deep open shells with various shell curvatures and arbitrary restraints, including cylindrical, conical and spherical ones. The general first-order shear deformation shell theory is employed to include the effects of rotary inertias and shear deformation. Under the current framework, regardless of boundary conditions, each of displacements and rotations of the open shells is invariantly expressed as Chebyshev orthogonal polynomials of first kind in both directions. Then, the accurate solutions are obtained by using the Rayleigh–Ritz procedure based on the energy functional of the open shells. The convergence and accuracy of the present formulation are verified by a considerable number of convergence tests and comparisons. A variety of numerical examples are presented for the vibrations of the composite laminated deep shells with various geometric dimensions and lamination schemes. Different sets of classical constraints, elastic supports as well as their combinations are considered. These results may serve as reference data for future researches. Parametric studies are also undertaken, giving insight into the effects of elastic restraint parameters, fiber orientation, layer number, subtended angle as well as conical angle on the vibration frequencies of the composite open shells.

References listed at the end of the paper:
ABSTRACT: A finite element (FE) approach is presented for the dynamic analysis of the Mindlin plates considering both shear deformation and rotary inertia effects. The model is based on the consistent version of the Mindlin plate equation.

References listed at the end of the paper:


ABSTRACT: A finite element (FE) approach is presented for the dynamic analysis of the Mindlin plates considering both shear deformation and rotary inertia effects. The model is based on the consistent version of
the Mindlin equations, which neglects the higher-order time derivative contribution. The approach provides a new class of interdependent Hermite shape polynomials by the definition of a fictitious deflection that takes into account the effective interdependence between the generalized displacements in both the continuous and FE discretized schemes. This implies that the proposed approach is free-shear-locking and is characterized by a good accuracy even for low-order FEs. Several examples are considered whose results are compared with analogous ones proposed in the literature with other approaches.

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23. Timoshenko S.P.: On the correction for shear of the differential equation for transverse vibration of prismatic bars. Philos. Mag. Ser. 6(41), 744–746 (1921)
Xiongtao Cao, Hongxing Hua and Xin Wa, “Vibroacoustic comparisons of composite laminated cylindrical shells according to three shear deformation shell theories”, Archive of Applied Mechanics, Vol. 84, No. 7 pp 1015-1036, July 2014

ABSTRACT: Whether the first-order and Reddy third-order shear deformation shell theories are able to evaluate the vibroacoustic responses of laminated cylindrical shells with normal deformation in the high frequency range or not is examined by comparison with a 3D higher-order shear deformation shell theory. The implicit governing equations of arbitrary angle-ply laminated cylindrical shells are derived from the 3D higher-order and Reddy third-order shell theories, and solved on the basis of the Fourier transform. The Reddy third-order shell theory can be obtained as a special case from the 3D higher-order shell theory. The first-order and Reddy third-order shell theories almost give rise to the same vibrational and acoustic results. These two simple shear deformation shell theories can be used to study far-field acoustic radiation from laminated cylindrical shells from the low to high frequency range, but they show some differences from the 3D higher-order shell theory in high frequency vibration of shells. Nevertheless, the differences of vibrational responses seem not to be distinct. The helical wave spectra of the higher-order radial displacements are nearly separate from those of the low-order radial displacement and play a minor role in far-field acoustic radiation, which makes the two simple shell theories applicable in prediction of acoustic power of the cylindrical shells in the much higher frequency range. Moreover, it also results in the fact that far-field sound is least sensitive in comparison with near-field sound and vibration of shells.

References listed at the end of the paper:


ABSTRACT: In this study, we investigate random vibration of vehicle model exhibiting repeated natural frequencies. It is shown that the cross-correlations have crucial effect, and their neglect may lead to considerable error in the evaluation of mean-square values of the response. In addition, we revisit some discrete systems with coinciding natural frequencies.

References listed at the end of the paper:
4. Dahlberg T.: Modal cross-spectral terms may be important and an alternative method of analysis be preferable. J. Sound Vib. 84, 503–508 (1982)

ABSTRACT: In this paper, the transient temperature distribution and the thermomechanical response of sandwich tubes with prismatic cores are analyzed considering active cooling. The effective thermal conductivities of prismatic cores with active cooling are derived. By using the effective thermal conductivities, the transient temperature fields of the tubes are predicted and are found to be very close to the results of finite element simulations, which confirms the correctness of the effective thermal conductivity. Based on the high-order sandwich shell theory, the thermal structural responses of sandwich structures are studied and compared with the results of finite element simulations. The reduction of the thermal structural response as a result of active cooling is studied to demonstrate the advantages of prismatic cellular materials. The design of replacing the solid metal with cellular materials which has the capability of active cooling can reduce the temperature and the thermal structural response of the structure.

References listed at the end of the paper:

Ren Ziachui and Wu Zhen, “Buckling of soft-core sandwich plates with angle-ply face sheets by means of a C0 finite element formulation”, Archive of Applied Mechanics, Vol. 84, No. 8, pp 1173-1188, August 2014

ABSTRACT: In order to avoid using C1 interpolation functions in finite element implementation of the previous zig–zag theories, artificial constraints, in which the first derivatives of transverse displacement will be replaced by the assumed variables, are usually employed. However, such assumption will violate continuity conditions of transverse shear stresses at interfaces. Differing from previous work, this paper will propose a C0-type zig–zag theory for buckling analysis of laminated composite and sandwich plates with general configurations. The first derivatives of transverse displacement have been taken out from a displacement field of the proposed zig–zag theory. Thus, the C0 interpolation functions are only required in finite element implementations of the proposed model. Without use of any artificial constraints, an eight-node quadrilateral element based on the proposed model is presented by incorporating the terms associated with the geometric stiffness matrix. In order to verify performance of the proposed model, several buckling problems of sandwich plates with soft core have been analyzed. Numerical results show that the proposed model is able to predict accurately buckling loads of the soft-core sandwich plates with varying fiber orientations of face sheets.

References listed at the end of the paper:

22. Matsunaga H.: Thermal buckling of cross-ply laminated composite shallow shells according to a global higher-order deformation theory. Compos. Struct. 81, 210–221 (2007)


ABSTRACT: This study presents a method of investigating the forced vibrations of pipe conveying fluid using Green function. The proposed method provides exact solutions in closed form. Green’s functions for pipes with different homogenous and elastic boundary conditions are also presented in this study. The natural frequencies of the fluid-conveying pipes can be obtained using the method of Green’s function. The results demonstrate that Green’s function is an efficient means of analyzing the forced vibration of pipes that conveying fluid.

References listed at the end of the paper:


ABSTRACT: A numerical strategy is presented to trace the pre-buckling as well as the post-buckling nonlinear equilibrium paths for elastic circular arches in which the effects of shear deformations and the geometric
nonlinearity due to large deformations are taken into account. Timoshenko beam hypothesis is adopted for incorporating shear. The constitutive relations including shear effects for stress and finite strain are based on a hyperelastic constitutive model. The finite strain equilibrium equations are developed for the circular arches. Based on the derived transformed equilibrium equations and the boundary conditions, the nonlinear buckling behaviour of circular arches is investigated using the trapezoid method with Richardson extrapolation enhancement. The results are validated using available experimental results in the literature, the finite element package ANSYS and other solutions in the literature. Parametric studies are performed on examples to identify the factors that influence the nonlinear buckling of circular arches. The shear deformation effects on the nonlinear buckling behaviour and the buckling mode are investigated for circular arches under many different loading conditions and various boundary conditions.

References listed at the end of the paper:


ABSTRACT: Helical structures are among the most universal building blocks in nature and engineering. In this work, I performed three-dimensional finite element simulations to study the transitions of shapes and multi-stability in the mechanically self-assembled helical structures driven by anisotropic misfit strains. The shape transition between a purely twisted ribbon, or a helicoid, and a general helical ribbon can be achieved by tuning a few relevant geometric and mechanical parameters, including the misfit strains, the geometric misorientation angle, the dimensions, and the mechanical properties of the composite layers. The results of our work show good agreement with the recent theoretical works and will serve as a powerful tool to facilitate on-demand designs of spontaneously curved structures at both macroscopic and microscopic scales, for a number of engineering applications including nanoelectromechanical systems, drug delivery, sensors, drug delivery, active materials, optoelectronics, and microrobotics.

References listed at the end of the paper:
In this paper, formulation of the thin cylindrical shell via the modified couple stress theory by taking account of shear deformation and rotary inertia is obtained. To do this, the study developed the first shear deformable cylindrical shell theory by considering the size effects via the couple stress theory and the equations of motion of shell with classical and non-classical boundary conditions were extracted through Hamilton’s principle. In the end, as an example, free vibrations of the single-walled carbon nanotube (SWCNT) were investigated. Here, the SWCNT was modeled as a simply supported shell, and the Navier procedure was used to solve the vibration problem. The results of the new model were compared with those of the classical theory, pointing to the conclusion that the classical model is a special case of the modified couple stress theory. The findings also demonstrate that the rigidity of the nano-shell in the modified couple stress theory compared with that in the classical theory is greater, resulting in the increase in natural frequencies. In addition, the effect of the material length scale parameter on the vibrations of the nano-shell in different lengths and thickness was investigated.

References listed at the end of the paper:

The presented approximation method is validated by comparing the results with the previous works done in similar accurate results. The present method has an advantage of being adapted by software with great ease and provides much accurate results, which makes it reasonably useful for analysis of more complex piezoceramic structures. The presented approximation method is validated by comparing the results with the previous works done in similar accurate results.
problem and by the finite element analysis.

References listed at the end of the paper:


ABSTRACT: This paper presents an exact analytical solution for the stress distributions within an elastic hollow sphere subjected to diametrical point loads. The solution is suitable for both thin and thick hollow spheres. New variables are introduced in order to uncouple the system of governing equations so that explicit differential equations are obtained for displacement components and stress components. Moreover, Fourier–
Legendre expansion technique is employed in order to determine the unknown coefficients in the analytical solutions for hollow spheres. The present solution can be considered as an extension of the classical solution by Hiramatsu and Oka (Int J Rock Mech Min Sci 3:89–99, 1966) for solid spheres under the point loads, which provided the theoretical basis for the point load strength test. Unlike in solid spheres, the stress concentrations within the hollow spheres under the point loads are usually developed at the joint point of the inner surface and the loading axis, and the thinner the hollow sphere, the larger the tensile stress concentrations developed at the inner surface. This numerical result indicates that the failure of the hollow spheres usually starts at the inner surface, and the normalized tensile stress at the inner surface increases with the increase in Poisson’s ratio and internal pressure, but decreases with the increase in the size of the loading area. Moreover, significant shear stress zone is usually developed in the areas immediately inside the outer surface, and the maximum shear stress is often developed at the point immediately inside the outer surface joining the edge of the loading area and the center of the hollow sphere. The present solution can be used to analyze the failure mechanism of bulk foams made up of hollow spheres in engineering.

References listed at the end of the paper:


ABSTRACT: Based on Mindlin’s strain gradient elasticity theory capturing microscale effects, a new extended Timoshenko beam element is proposed to study the postbuckling behavior of microbeams. So as to develop the size-dependent finite element formulation, the higher-order tensors of energy pairs in the energy functional are vectorized and represented in the quadratic form. In comparison with the standard Timoshenko beam element, the present one needs two further nodal degrees of freedom including derivatives of lateral translation and rotation. The Hermite polynomials are also implemented as shape functions. The developed model is general so that its formulation can be used for modified couple stress, modified strain gradient and classical elasticity theories. In the numerical results, the influences of the small-scale factor, geometrical parameters and boundary conditions on the bifurcation diagrams of microbeams are examined.

References listed at the end of the paper:

ABSTRACT: The thickness optimization is used to regulate the dynamic response of a thin plate of arbitrary geometry subjected to any type of admissible boundary conditions. The optimization problem consists in establishing the thickness variation law for which the fundamental frequency is maximized, minimized or forced to reach a prescribed value. Beside the equality constraint of constant volume, the thickness variation is subjected also to inequality constraints resulting from serviceability requirements (upper and lower thickness bounds) as well as to a nonlinear inequality constraint which ensures that the optimum solution remains within the limits of Kirchhoff plate theory. The evaluation of the objective function requires the solution of the dynamic bending problem of a plate with variable thickness which is solved using the analog equation method in conjunction with the boundary element method. A nonlinear optimization problem is formulated, and the optimum solution is obtained through the sequential quadratic programming algorithm. The thickness is approximated using integrated radial basis functions which approximate accurately not only the thickness function but also its first and second derivatives involved in the plate equation and in the constraints. Several plate optimization problems have been studied giving realistic and meaningful optimum designs without violating the validity of the thin plate theory.

References listed at the end of the paper:


ABSTRACT: The nonlinear dynamic response and damage evolution of functionally graded shallow spherical shell under low-velocity impact are investigated in this work. Basing on continuum damage theory, a damage constitutive relation is established for functionally graded material and the Kachanov damage evolution law is adopted to predict the damage propagation in the structure. A modified contact model suitable for non-homogenous material (functionally graded material) is applied to model the contact force in impacting process. The laminated modeling method is adopted to model the functionally graded shell with varying material constants along the thickness by dividing the shell to N plies with the constant material properties for each ply. With the established damage constitutive relations and nonlinear geometric relations of FGM shallow spherical shell with elastic modulus varying as a power-law function, the nonlinear motion equations of FGM shallow spherical under low-velocity impact have been obtained in the term of displacement functions. The problems are solved by using the orthogonal collocation point method, the Newmark method and the iterative method synthetically. Some numerical examples are carried out to validate present impacting model and the calculating methods, and parametrical analysis are presented to discuss the effects of the material properties, the geometrical size and impacting velocity on damage state and dynamic response of the structure when under low-velocity impact.

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ABSTRACT: In the present work, an innovative approach is developed and employed to investigate the buckling load of composite laminated plates using polar representation of the fourth-order flexural stiffness tensor. Based on the Rayleigh–Ritz method for calculating the buckling load of orthotropic uncoupled laminates, a new approach is proposed for calculating the critical buckling load as a function of fiber orientation and the number of layers. A new formula is also represented for measuring the possible numbers of buckling modes based on the length-to-width ratio of the plate. Moreover, the new methods make it easy to handle buckling problems, optimization and design of laminated plates subjected to in-plane loads. The efficiency and precision of this method are proved by numerical examples. The anisotropic parts of the buckling load are calculated, and their polar variations are investigated.

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structures have a simple cross section (beams, rods, etc.), and if the frequency or wavelength is with a range


ABSTRACT: Wave behavior of line-shaped structures can be analyzed with the help of beam theories if the structures have a simple cross section (beams, rods, etc.), and if the frequency or wavelength is within a range
where the theories are still applicable. If the frequencies and wavelengths exceed these limits, the modeling of line- or beam-shaped structures requires volume elements, which results in considerably higher computation time and modeling effort. The goal of this work is to keep the beam-like modeling of structures, but enhance the solution space such that arbitrary deflection shapes of the cross section can be covered. New degrees of freedom are introduced which correspond to the contribution of a unit deflection shape at each node. The unit deflection shapes are defined and computed on the basis of a 2D finite element mesh of the cross section: warp shapes for primary and secondary torsion and shear forces, eigenmodes for the problem of a plate in membrane and a plate in bending action, derived warp shapes for in-plane shapes, shapes which cover the lateral strains and—most importantly—eigenmodes of the infinite waveguide structure. By this transformation of unknowns, the number of system degrees of freedom can be reduced considerably. Different sets of unit deflection shapes are compared according to their efficiency.

References listed at the end of the paper:
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ABSTRACT: Considering thermal loads, dynamics and stability of an outer cylindrical shell conveying swirling fluid in the annulus between the inner shell-type body and the outer shell are investigated by the travelling wave approach. Shell motions are considered based on Donnell-type shell theory. The fluid forces are described by means of the potential flow theory, and thermal loads are determined by the thermo-elastic theory. The numerical analyses are conducted by a zero-level contour method. The study shows the effects of annular gaps and boundary conditions on stability of shells. The influences of angular flow on the critical axial velocity and axial flow on the critical annular velocity are discussed. Moreover, the thermal loads decrease the critical flow velocity markedly and the critical temperature rise is found.

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ABSTRACT: The main purpose of this paper is to apply the modified Vlasov foundation model to free vibration analyses of hyperbolic cooling towers resting on elastic foundations. Moreover, the influence of some characteristic parameters such as thickness, height, curvature and throat level on the frequency response of cooling towers on elastic foundations is investigated. For this purpose, a computing tool coded in MATLAB employing open application programming interface feature of SAP2000 to provide two-way data flow during execution is used to perform the analyses of hyperbolic cooling towers with supporting columns over hollow annular rafts founded on elastic subsoil. The circumferential, lateral and extensional natural frequency parameters of cooling towers are presented in tabular and graphical forms to evaluate the effects of the geometric parameters and soil-structure interaction. As far as numerical examples are considered, it can be concluded that the soil-structure interactive behavior of the tower leads to a remarkable decrease in the frequency parameter of the system compared to the fixed based condition. Moreover, the frequency parameters are considerably affected by altering geometrical parameters.

References listed at the end of the paper:
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ABSTRACT: In this paper, static and dynamic behavior of bi-stable composite laminates with [0–90]T stacking sequence and piezoelectric layers is studied. The governing equations of system were obtained using Rayleigh–Ritz method and Hamilton’s principle. In order to improve the accuracy of results, a set of higher-order shape functions were employed. The dynamic response of the system under various electrical fields applied to the piezoelectric actuators was studied, and the effects of the presented shape functions on short-circuit natural frequency and the lowest electrical field required for snap-through were analyzed. The results obtained from the developed analysis have been compared with the conventional and FEM models. Good correlation was observed between the proposed model and the finite element method.
theory agree with finite element simulation results, while the Haringx theory overestimates the buckling load. The effects of transverse shear and various different end constraint conditions on static buckling and initial post-buckling of sandwich beams are systematically explored.

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ABSTRACT: This paper presents the free vibration analysis of moderately thick and deep doubly curved laminated shell with C0 finite element model based on higher-order shear deformation theory. The strain-displacement relationships are developed using the accurate equations of elastic deformation of shell structure. An eight-noded isoparametric shell element with nine degrees of freedom per node is used to formulate the present model. The effect of incorporating the ratio of thickness coordinate to radius of curvature ($z / R$) in the strain components has been taken into account in the present study. The numerical results in terms of natural frequencies obtained by the present formulations are compared with those available in the published literature to validate the proposed model.

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ABSTRACT: The dynamic response of foam-core composite sandwich plates subjected to low-velocity impact is thoroughly investigated by means of drop-weight impact tests and numerical simulations in this paper. The influences of impact energy, foam-core thickness, and punch-head shape and size on the impact mechanical behavior including the impact force time history, the dynamic displacement time history, the residual plastic deformation, the energy absorption capacity, and the back plate deflection are contrastively studied through the control-variant approaches. Several conclusions drawn are useful and helpful to the related product design. The top faceplates of specimens with large foam-core thickness are demonstrated to be vulnerable to the low-velocity impact under stepped levels of impact energy, while large foam-core thickness can reduce deformation of the interior plates effectively. Moreover, among the three representative types of punch heads, the sharper hemispherical one is checked to be the most destructive with the lowest impact force peak. Besides, a finite element model was built to investigate the damage of faceplates and foam cores. The numerical method was proved to be accurate and efficient. A series of results were obtained revealing the damage mode of faceplates and cores under different impact energies.

References listed at the end of the paper:

Nowadays, there are no techniques or software making it possible to simulate the high strains of shells under the combined complex loadings of internal pressure and torsion. These problems are inherent for the experimental investigations of elastoplastic properties of metals and alloys on tubular samples. In this paper, we present the variation–difference method for solving similar problems with taking into consideration high strains and the conditions of an inhomogeneous stress–strain state. We conduct the numerical and experimental studies of the process of elastoplastic deformation and plastic strain localization under the combined loadings of internal pressure and torsion. The mutual influence of torsion on the shell forming under high strains is estimated. The loss of stability with axisymmetric and non-axisymmetric forms is analyzed by 2D and 3D modeling. The simulations results are finally validated by experiments.

References listed at the end of the paper:

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ABSTRACT: Many materials that have been developed recently such as titanium alloys and polymeric composites exhibit nonlinear elasticity in the “small” strain regime, and the linearized theory cannot be used to describe the response. Recently, Rajagopal (Appl Math 48(4):279–319, 2003) introduced a new implicit constitutive theory which can be used to develop models to characterize the response of these newly fashioned materials. Here, we study the response of these new classes of elastic bodies within the context of two boundary value problems: the pressurization of a cylindrical annulus and a spherical shell. In the case of the cylindrical annulus, a stress function is introduced that automatically satisfies the equilibrium equation, and the compatibility equation for strain and the nonlinear constitutive equation is used to obtain the nonlinear compatibility equation in terms of the stress function. For the spherical shell, a displacement formulation is used to arrive at a nonlinear equation for the radial stress. The governing equations in both cases cannot be solved exactly, and we use an approximate technique, the variational iteration technique, to solve the problem. We show that this approximate solution agrees very well with the numerical solution of the governing equations, and the solution is different from that obtained in the classical linearized elasticity. In the case of spherical annulus with an internal pressure of 250 MPa, the hoop stress associated with the linearized solution overpredicts the numerical solution by about 10% at the inner radius and underpredicts by about 7% at the outer radius.

Many materials that have been developed recently such as titanium alloys and polymeric composites exhibit nonlinear elasticity in the “small” strain regime, and the linearized theory cannot be used to describe the response. Recently, Rajagopal (Appl Math 48(4):279–319, 2003) introduced a new implicit constitutive theory which can be used to develop models to characterize the response of these newly fashioned materials. Here, we study the response of these new classes of elastic bodies within the context of two boundary value problems: the pressurization of a cylindrical annulus and a spherical shell. In the case of the cylindrical annulus, a stress function is introduced that automatically satisfies the equilibrium equation, and the compatibility equation for strain and the nonlinear constitutive equation is used to obtain the nonlinear compatibility equation in terms of the stress function. For the spherical shell, a displacement formulation is used to arrive at a nonlinear equation for the radial stress. The governing equations in both cases cannot be solved exactly, and we use an approximate technique, the variational iteration technique, to solve the problem. We show that this approximate solution agrees very well with the numerical solution of the governing equations, and the solution is different from that obtained in the classical linearized elasticity. In the case of spherical annulus with an internal pressure of 250 MPa, the hoop stress associated with the linearized solution overpredicts the numerical solution by about 10% at the inner radius and underpredicts by about 7% at the outer radius.

ABSTRACT: The positive gradient (PG) metallic cellular core and its initial plateau stress linearly increase from the upper face of the metallic cellular material to its bottom face. In the current study, the discussions are carried out into the influence of PG metallic cellular core on the energy dissipation of sandwich panels under indentation. An analytical model to investigate the plastic indentation response for the sandwich panel with PG metallic cellular core is developed. Finite element simulation is carried out in order to verify the analytical results. Then, the effect of the PG metallic cellular core on the energy dissipation of sandwich panels is further investigated by considering three gradient cases. And the results show that the energy dissipation of PG metallic cellular core is lower than that of the homogeneous core with equivalent mass.

References listed at the end of the paper:
ABSTRACT: In this study, the dynamic instability analysis of rotating delaminated thickness tapered composite plates with different taper configurations subjected to periodic in-plane loads is performed. The governing differential equations of motion of the various configurations of a rotating thickness mid-plane delaminated tapered laminated composite plate are presented in the finite element formulation based on classical laminated plate theory including various rotational effects. The finite element formulation developed for the dynamic instability analysis of rotating delaminated tapered composite plate is validated by comparing the parametric exciting frequencies evaluated using the present finite element method (FEM) with those presented in available literature and comparing the natural frequencies of rotating delaminated tapered composite plate evaluated using the present FEM with experimentally measured results. Various parametric studies are also performed to study the effect of taper configurations, rotational speed, delamination length, delamination location and in-plane periodic loads on stability of the structure. It was seen that the influences of rotating speed on the principal DIR spectra among taper configurations and uniform plate are significant and the normalized width of principal and second instability regions of parametric resonance frequencies increase in the order of uniform, TC3, TC2 and TC1 for all the rotating speeds.

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More papers published in the journal, Thin-Walled Structures (2017 and on):

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ABSTRACT: The design of lightweight structures is often driven by buckling phenomena. Increasing demands for fuel-efficient aircraft structures makes post-buckled designs attractive from a structural weight perspective. However, the need for reliable and efficient design tools that accurately model the emerging nonlinear post-buckled landscape, potentially one containing multiple branches, remains. With this aim, a previously derived flat shell element, MISS-4, is extended to the geometrically nonlinear analysis of variable-angle tow (VAT) composite plates using Koiter's asymptotic approach. The curvilinear fiber paths in VAT lamina open the design space for tailoring the buckling and post-buckling capability of plates and shells. A finite element implementation of Koiter's asymptotic approach allows the pre-critical and post-critical behavior of slender elastic structures to be evaluated in a computationally efficient manner. Its implementation uses a fourth-order expansion of the strain energy, failure within each layer while a mesh-independent energy-based failure
criterion for the tiebreaks was implemented in the model to effectively simulate the delamination between layers during the crushing and requires both the structural modeling and finite element discretization procedures to be, at least, of fourth order. The corotational approach adopted in the MISS-4 element readily fulfills this requirement by starting from a linear finite element discretization. VAT plates with prismatic fiber variations and different loading conditions are analyzed using the MISS-4 element and numerical results of the post-buckling paths are presented. The computed equilibrium paths are compared to benchmark results using the commercial finite element package ABAQUS, and strong asymptotic solutions of the differential equations. The results document the good accuracy and reliability of the proposed modeling approach, and also highlight the importance of multi-modal analysis when multiple buckling modes coincide as is the case in long plates, shells and other optimized thin-walled structures.


ABSTRACT: This paper presents an experimental study into the axial compressive behaviour of self-compacting concrete filled elliptical steel tube columns. In total, ten specimens, including two empty columns, with various lengths, section sizes and concrete strengths were tested to failure. The experimental results indicated that the failure modes of the self-compacting concrete filled elliptical steel tube columns with large slenderness ratio were dominated by global buckling. Furthermore, the composite columns possessed higher critical axial compressive capacities compared with their hollow section companions due to the composite interaction. However, due to the large slenderness ratio of the test specimens, the change of compressive strength of concrete core did not show significant effect on the critical axial compressive capacity of concrete filled columns although the axial compressive capacity increased with the concrete grade increase. The comparison between the axial compressive load capacities obtained from experimental study and prediction using simple methods provided in Eurocode 4 for concrete-filled steel circular tube columns showed a reasonable agreement. The experimental results, analysis and comparison presented in this paper clearly support the application of self-compacting concrete filled elliptical steel tube columns in construction engineering practice.

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ABSTRACT: This paper presents the experimental and numerical studies of concrete-filled cold-formed elliptical hollow sections with varying aspect ratios subjected to axial compression load. Twenty one stub columns were tested to investigate the fundamental behaviours of these elliptical concrete-filled steel tubular (CFST) columns. The axial load versus displacement curves, longitudinal and transverse strains in steel tube and failure modes were obtained and discussed. A constitutive model for concrete in the elliptical CFST columns was proposed. Finite element (FE) models were developed and validated against the test results. Parametric studies were carried out to identify the influence of key parameters on the load-bearing capacity.
Key parameters included aspect ratio, steel tube to concrete area ratio, yield strength of steel and compressive strength of concrete. Finally, the applicability of relevant design methods to elliptical CFST columns was assessed on the basis of the test and the FE results of this research and other related studies. Results indicated that the design method recommended in the Chinese Standard (GB50936-2014), and the design method for circular CFST columns in EC4 were found to generate accurate predictions.

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“Buckling of piecewise member composed of steel and high-strength materials in axial compression”, Thin-

ABSTRACT: The elastic buckling load of an axially compressed piecewise member was derived under various
ideal boundary conditions based on the differential element method; then, the result was simplified for a
symmetrical member. The theoretical results were found to be consistent with existing formulas for the elastic
buckling load of uniform members. Then, the elasto-plastic buckling of an axially compressed piecewise
member composed of steel and elastic materials was investigated and found to be quite different from that of a
pure steel member, and a theoretical analysis approach was developed. In elasto-plastic buckling analysis, the
load-bearing capacity of the steel section in the ultimate state is determined considering initial imperfections
and steel hardening. Furthermore, the symmetric method for obtaining the load-bearing capacity of this member
was obtained based on the ultimate state of the critical section, which is simple and reparative for design. The
theoretical results of the elasto-plastic buckling analysis were consistent with experimental results, therein
obtaining an average error of 4%.

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ABSTRACT: This paper aims to present the flexural, torsional and flexural-torsional buckling of axially loaded thin-walled functionally graded (FG) open-section beams with various types of material distributions. Properties of metal-ceramic materials are described by a monotonic function of volume fraction of particles that varying across blade thickness according to a power law. The problem is formulated by using a two-noded 14-degree-of-freedom beam element. Governing buckling equations has been developed. Warping of cross-section and all the structural coupling coming from anisotropy of material are taken into account in this study. The critical load is obtained for thin-walled FG mono-symmetric I- and channel-sections with arbitrary distributions of material. As a special case, a numerical comparison is carried out to show the validity of the proposed theory with available results in the literature. In addition, effects of gradual law, ceramic core and skin, span-to-height on the buckling parameters of an axially loaded thin-walled FG open-section beam are also investigated.

References listed at the end of the paper:

In this work, the energy absorption and collapse mode of circumferentially grooved thick-walled tubular structures are scrutinized analytically and experimentally under dynamic loading condition. Circumferential grooves are machined around thick-walled tubes and thin-walled portions are acquired within the groove spaces. Low velocity impact tests of the specimens are conducted using the drop hammer rig. An analytical formulation based on the energy dissipation through the plastic hinges is presented and the interaction at the interface of foam and tube is taken into account. Comparison of the analytical results with experimental ones shows reasonable accuracy for the analytical model. According to the experiments, circumferentially grooved tubes show favorable energy absorption behaviour and concertina mode of deformation is dominant under dynamic loading condition. Foam filled tubes show an approximately 26% increase in the energy absorption compared to empty tubes which is much lower than in the case of quasi-static loading condition. This shows that foam filling in dynamic loading, though effective from the energy absorption perspective, is not as effective as in the case of quasi-static loading.
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DOI: 10.1016/j.tws.2016.10.019

ABSTRACT: Twenty-four specimens are tested to study the static performance of axially compressed square concrete filled CFRP-steel tubular (S-CF-CRP-ST) columns. The tested results indicate that, for columns with relatively small slenderness, failure is dominated by the strength lose of the cross-section. However, for columns with relatively large slenderness, failure is controlled by instability. The load versus deflection curves at the mid-height of the composite columns can be divided into three stages, i.e., elastic, elasto-plastic and softening stages. The tested results also show that the longitudinal strain distribution along the depth on the cross-section is approximately linear, and the steel tube and its outer CFRP material can cooperate well both longitudinally and transversely. The longitudinal strain and the transverse strain at a point have opposite actions, and the steel tube under longitudinal tension has no transverse confinement effect on its concrete. Subsequently, axial load verses deflection curves at the mid-height and the deformed modes of the columns are simulated by using finite element (FE) method. The calculated results agree well with the experimental data to indicate that the accuracy of the FE model used is guaranteed. Then, stresses in the concrete, the steel tube and the CFRPs are then investigated by using FE method. The numerical results show that the transverse CFRP in tension provides effective confinement on the specimens and the longitudinal CFRP in tension provides effective enhancement on the flexural stiffness. The interaction force between the steel tube and the concrete reaches its maximum value on the mid-height cross-section, and it decreases when the distance to the end plates becomes smaller. On the cross-section, the interaction force has its maximum value at the corner and it decreases when the position moves to the mid-point of the tube side. The adhesive strength between the concrete and the steel tube has little effect on the critical buckling load and on the elastic stiffness of the columns. Equation for calculating the critical buckling load of the composite columns is proposed, and the estimated results agree well with the experimental data.
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ABSTRACT: The objective of this paper is to investigate the response of fusion welded AA5083-H116 rectangular plates and orthogonally stiffened panels, typically found in high-speed vessels and topsides of offshore platforms, under impulsive pressure loading, such as air blast and explosions. Rigorous nonlinear finite element analyses are performed by using ABAQUS/Explicit to determine the deformation of these plated-structures under different impulses. Particular emphasis is given on the effect of the heat affected zone (HAZ), which is due to fusion welding. Based on the extensive numerical results, simple yet accurate formulae to predict the permanent set of the plates are derived as function of a non-dimensional impulse parameter. The derived equations are also compared with the existing analytical and empirical formulae in the literature.

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DOI: 10.1016/j.tws.2016.11.001

ABSTRACT: This paper provides a study on a novel octagonal multi-cell tube with functionally graded thickness (FGT) under multiple loading angles. First, comparative analysis on the FGT tube and the counterpart tube with uniform thickness (UT) under multiple loading angles reveal that the energy absorption is more superior for the FGT tube when the loading angle exceeds the lower bound of the transition range of the UT tube. Second, parametric study on the FGT tube indicates that thickness gradient exponent and thickness range have significant effect on its crashworthiness. Third, multiobjective optimizations of the FGT tube are conducted, aiming to maximize specific energy absorption (SEA) and minimize initial force (IPF) under multiple

loading angles, based upon the Non-dominated sorting genetic algorithm (NAGA-II) and RBF technique. The optimized FGT tube demonstrates better crashworthiness than the UT tube in all design cases. These findings can provide valuable guidelines for the design of multi-cell tube with functionally graded thickness under multiple loading angles.

References listed at the end of the paper:
ABSTRACT: Experimental investigations were conducted to study the axial crushing behaviour of square aluminium tubes with different configurations. Quasi-static compressive loads were applied to square hollow aluminium tubes, aluminium honeycomb-filled tubes, polyurethane foam-filled tubes and aluminium tubes filled with both polyurethane foam and aluminium honeycomb at constant velocities of 0.15 mm/s, 1.5 mm/s and 15 mm/s, respectively. The effects of honeycomb core, polyurethane foam, combined polyurethane foam and honeycomb on the axial crushing behaviour of square aluminium tubes were discussed. The influence of crushing velocity on these different tubular structures was also studied. Experimental results showed that the deformation mode was a progressive folding mode for square hollow aluminium tubes, while it was a splitting mode for square tubes filled with both polyurethane foam and aluminium honeycomb. The fold wavelengths of some typical cases were measured. The most crashworthy combination was found to be square aluminium tubes filled with both polyurethane foam and aluminium honeycomb, where the maximum increases of mean crushing force, energy absorption and specific energy absorption were up to 349%, 334% and 109% respectively, compared with those of hollow tubes.

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ABSTRACT: Selective laser melting (SLM) is a mature method in the fabrication of structures bearing static loading and small strains; however, structures experiencing large deformation under impact loading remains an issue. In this paper, the author fabricates a 316L stainless steel thin-walled circular tube with preset internal circumferential rectangular groove defects using the SLM method. MTS compression and Split Hopkinson Pressure Bar tests are performed to judge the material behavior of SLM printed 316L stainless steel, and Johnson-Cook constitutive model parameters are fitted from the results. The crushing behavior of the SLM printed tube is studied experimentally and numerically via the drop hammer test and the finite element analysis. There are two stages of the crushing process of the tube as the results show: the buckling stage and the splitting
stage. The internal grooves have effects on controlling the initial buckling position and fracture position during the buckling stage. The double buckling-splitting crushing mode in one simple structure, provides a new energy absorption approach for engineering application.

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ABSTRACT: This study is concerned with the numerical prediction of energy absorption behaviour of different grades of steel sheet. Typical square crush tube is studied owing to its similarity with various automotive structural components useful in crash events. An attempt has been made to characterize the materials for high strain rate behaviour (0.001–800/s) and use a strain rate dependent constitutive model. This constitutive model is validated for multi-axial experiments and further used for predicting the energy absorption and crush efficiency of square tube at different velocities (9.7 m/s, 12.5 m/s, 15.5 m/s). Energy absorption and crush efficiency depends on peak force and steady state crush force. Results show that energy absorption and crush efficiency of DP800 is superior at lower velocity than at higher velocity whereas DP600 is found to have superior crush performance with velocity. CMn440 and IFHS has superior crush efficiency but lower energy absorption compared to DP grades.

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ABSTRACT: In the present work, the nonlinear thermoelectrical stability of perfect/imperfect circular size-dependent functionally graded piezoelectric plates is studied according to modified couple stress theory. The second, concurrent aim is to address snap-through phenomenon in the thermally preloaded plates due to concentrated/uniform lateral loads. Ritz finite element method is implemented into virtual displacement principle to construct the matrix representation of nonlinear governing equations. Under certain circumstances, bifurcational instability may occur in which case a direct displacement control scheme is utilized. In other cases, the response is unique and stable to which any standard load control strategy seems appropriate and thus Newton-Raphson method is selected. Standard load control strategies, however, fail to trace nonlinear equilibrium paths through limit points and path following methods must be employed in snap-through problems. Being more popular among the existing path following solution methods, cylindrical arc-length method is adopted. Two types of thermal loading as well as two cases of boundary conditions are considered. Moreover, various parametric studies are conducted to assess the influence of involved parameters.

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ABSTRACT: Currently, one challenge of deployable composite thin-walled lenticular tube (CTLT) is to identify its large deformation behaviors in flattening and wrapping process. In this paper, experiments and numerical simulation of flattening and wrapping of composite thin-walled lenticular tube were carried out. Firstly, elastic modulus of CFRP laminate with four-ply (45°/−45°/45°/−45°) was obtained from the uniaxial tensile test and theoretical solutions, results of which achieve a good agreement. Subsequently, the flattening experiments of composite thin-walled lenticular tube segments were performed, their corresponding tip displacements and strains on the surface were also measured in flattening process. Lastly, wrapping experiments of three CTLTs at the length of 700 mm were conducted, in the meantime, strains, deformations and wrapping moments were also measured. By using ABAQUS package, three-dimensional models were employed to numerically simulate the process of flattening and wrapping, effects of geometrical nonlinearity and contact interaction are also taken into account in the process. The results show that the numerical simulation method is available to predict mechanical characteristics of CTLT in its process of flattening and wrapping.

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ABSTRACT: This paper focuses on spherical shells under uniform external pressure. Ten laboratory scale models, each with a nominal diameter of 150 mm, were tested. Half of them were manufactured from a 0.4-mm stainless steel sheet, whereas the remaining five shells were manufactured from a 0.7-mm sheet. The geometry, wall thickness, buckling load, and final collapsed mode of each spherical shell were measured, as well as the material properties of the corresponding sheet. The buckling behaviors of these shells were demonstrated analytically and numerically according to experimental data. Analyses involved considering the average geometry, average wall thicknesses, and average elastic material properties. Numerical calculations entailed considering the true geometry, average wall thicknesses, and elastic-plastic modeling of true stress–strain curves. Moreover, the effects of purely elastic and elastic-perfectly plastic models on the buckling loads of spherical shells were examined numerically. The results of the experimental, analytical, and numerical investigations were compared in tables and figures.

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ABSTRACT: Experimental and theoretical studies are carried out to investigate the behavior and strength of cold-formed single lipped sigma columns. The local, distortional and overall geometric imperfections of sixteen
specimens are measured in the laboratory. In addition, the residual stress pattern of the sections is concluded. Only eight specimens of cold-formed sigma columns with different variables are chosen. The tested specimens are subjected to an axial compressive load. A finite element model is developed using a software program (ANSYS). The developed model includes both geometric and material nonlinearities. Numerous models of slender sigma column sections with different variables such as flange width–thickness ratios, web return ratios, and overall slenderness ratios are chosen. The behavior of sigma columns along with different failure modes illustrated local, distortional, and global buckling is investigated. Complete ultimate strength curves are drawn as well as different failure modes are discussed for different cross-sections and member lengths. Finite element axial capacities are compared with the predicted capacities using AISI and DSM methods. Both AISI and DSM results are comparable with the finite element results. Eventually, A reliability analysis is carried out.

Young Bong Kwon and Sung Woong Park (Department of Civil Engineering, Yeungnam University, Gyongsan 712-749, Republic of Korea), “Resistance of circular concrete-filled tubular sections to combined axial compression and bending”, Thin-Walled Structures, Vol. 111, pp 93-102, February 2017
DOI: [10.1016/j.tws.2016.11.014](http://dx.doi.org/10.1016/j.tws.2016.11.014)

ABSTRACT: This paper describes strength formulae and simplified strength interaction curves for the direct strength method (DSM) for circular concrete-filled tubular (CFT) sections. A simple axial strength formula and a flexural strength formula for circular CFT sections are proposed to account for the post-local buckling strength of the circular steel skin and the increase in concrete compressive strength caused by confinement of the steel skin. The squash load predicted by the proposed strength formula is compared with test results in the literature, and those predicted by AISC specifications and Eurocode4. A simplified strength interaction curve for circular CFT members under combined axial compression and bending is proposed and compared with test results. The comparison confirms that the proposed axial and flexural strength formulae and simplified strength interaction curves can be used to conservatively predict the resistance of circular CFT columns to an axial load, and combined axial compression and bending.

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ABSTRACT: Web openings are increasingly used in cold-formed steel beam members of buildings to facilitate ease of services. In this paper, a combination of tests and non-linear finite element analyses is used to investigate the effect of such holes on web crippling under the interior-one-flange (IOF) loading condition; the cases of both flange fastened and flange unfastened to the bearing plate are considered. The results of 61 web crippling tests are presented, with 18 tests conducted on channel sections without web openings and 43 tests conducted on channel sections with web openings. In the case of the tests with web openings, the hole was
either located centred beneath the bearing plate or having a horizontal clear distance to the near edge of the bearing plate. A good agreement between the tests and finite element analyses was obtained in term of both strength and failure modes.

Kun Xie, Meixia Chen and Zuhui Li (School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China), “An analytic method for free and forced vibration analysis of stepped conical shells with arbitrary boundary conditions”, Thin-Walled Structures, Vol. 111, pp 126-137, February 2017, DOI: 10.1016/j.tws.2016.11.017

ABSTRACT: An analytic method is presented for free and forced vibration analysis of stepped conical shells with general boundary conditions. The method is involved in dividing the stepped shells into segments according to the locations of discontinuities, such as thickness and semi-vertex angle. Combining Flügge shell theory with power series method, displacements and forces at cross-section of conical segments are expressed in terms of eight unknown coefficients. Meanwhile, by employing artificial springs to restrain edge displacements, arbitrary boundary conditions, including classic and elastic ones, can be analyzed. All separate segments are assembled together through displacement continuity conditions and equilibriums of forces at junctions of discontinuities. To test the validity of present method, comparisons of some stepped conical shells subjected to classic and elastic boundary conditions are firstly presented. The results of present method agree fairly well with those in literature and calculated by finite element method. Furthermore, influences of semi-vertex angle, elastic boundary conditions, discontinuity, excitation and damping are investigated. Parametric studies reveal that meridional and circumferential displacements have significant effects on fundamental and beam mode frequency parameters, and effects of the location of discontinuity and semi-vertex angle depend on boundary conditions and thickness ratios.

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ABSTRACT: The buckling of steel-polyurethane sandwich bridge deck is studied via experiment and nonlinear numerical calculations, the authors first analyzed the stress distribution of key points of a three-span continuous bridge deck with sandwich structure in the state of buckling. and then analyzed the influence of the changes of several size parameters on the buckling modes and the critical loads. The results show that when the sandwich bridge deck is compressed, the closer to the middle section in mid-span, the greater the longitudinal compressive stress on the steel faceplate, but the smaller the longitudinal compressive stress on the bottom of the stiffening ribs. The longitudinal stresses on the steel faceplate and the bottom of the longitudinal stiffeners are unevenly transversely distributed near the ends of the applied force, but the stresses are gradually uniform near the midspan section. When this kind of sandwich bridge deck is designed, its thickness should be selected first, and then adjust the spacing of the longitudinal stiffening ribs in order to reduce workload and save material.

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ABSTRACT: A novel energy absorption connector with curved plate and aluminum foam as energy absorber was developed to be inserted between a blast resistant façade and building to absorb blast energy and reduce blast load transferred to the building. Quasi-static compression loading tests were conducted to study the energy absorption performance of the proposed connectors. The crushing deformation mechanisms of the connectors were observed from the experiments and three different deformation processes were identified. The effects of aluminum foam, curved plate thickness and radius on the energy absorption performance of the connector were experimentally investigated, which showed that the energy absorption capacity of the connector could be improved by filling the connector with aluminum foam and increasing the curved plate thickness. Moreover, an analytical model was developed to predict the load–displacement curve of the energy absorption connector and the predictions from the analytical model were shown to be conservative by comparing with the experimental results.

ABSTRACT: This paper focuses on computational efficiency aspects related to Generalised Beam Theory (GBT) displacement-based finite elements. In particular, a cross-section node-based DOF approach is proposed, which makes it possible to (i) deal, straightforwardly, with discrete variations of the thickness of the walls (including holes) in the longitudinal direction and (ii) achieve significant computational savings in non-linear problems, with respect to the conventional GBT approach (based on cross-section deformation modes). The proposed approach leads to a beam-like finite element that is equivalent to an assembly of flat quadrilateral shell elements and, therefore, (i) much smaller matrices are handled and (ii) the resulting element stiffness matrix is significantly sparse. The deformation mode participations, which are the trademark of GBT, are recovered through post-processing. Several numerical examples are provided, involving both linear and non-linear (static) problems, to highlight the capabilities and efficiency of the proposed approach.

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ABSTRACT: Absorbing energy by crash tubes has been extensively employed in many applications to improve the crashworthiness of the structure. This paper proposes Piecemeal Energy Absorption (PEA) as a novel proposed strategy to perform crashworthiness in a gradual way. PEA is implemented by crash tubes adaptor, whilst this adaptor is composed of nested pieces. Based on geometrical dimensions of the nested tubes, PEA strategy generates lower damage under lower impact velocity and higher energy absorption under high impact velocity to improves the crashworthiness of the protected structure. The novel strategy is validated by numerical and experimental methods. Furthermore, PEA flexibility and capability are illustrated by implementing the strategy in two popular applications (subway buffer and UAV landing gear). Due to the generality and applicability of the proposed PEA strategy, it is recommended to replace existing vehicles absorbers in order to manipulate the damage levels, along with considering PEA roles in new crashworthy designs leads to redistribute and reduce the whole internal protected structure masses.

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ABSTRACT: The experimental natural frequencies and buckling loads of aluminium slightly non-symmetric thin-walled beams under axial force are compared with numerical results. A universal machine compressed the specimens by providing their ends with a relative axial displacement; suitable end constraints for warping were manufactured; PZT pickups, which revealed to be reliable in this field, helped extracting the natural frequencies under various compressive forces. An in-house code provided the corresponding numerical results, accounting for the effects of non-symmetric cross-sections and warping. The comparison provides a good agreement between the two sets of results, showing that the predictions of the code are verified by experiments, thus opening the way to possible applications in inverse problems.

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ABSTRACT: The structures of the vehicles during the crushing processes or accidents not only experience direct or axial collisions but sometime these structures are crushed off-axially. Therefore, it is very crucial to study whether or not a foam-filled tube is capable of supporting the oblique compression forces efficiently and effectively. In this paper, investigation of the axial and oblique loading collapse behavior of thin-walled conical tube clamped at both ends is presented. Several numerical simulations using ABAQUS finite element explicit code are carried out to study crashworthiness characteristics of empty and foam-filled thin-walled conical tubes clamped at both ends. In order to verify these numerical results, a series of quasi-static axial and oblique compression tests are performed. The validated finite element model was then used for the parametric studies, in order to determine the effect of the empty and filler tube geometry parameters (i.e. semi-apical angle) and loading parameters (i.e. load angle) on the energy absorption and mean crushing load. The primary outcome of
this study is to provide information for the use of foam-filled conical tubes as energy absorbers where oblique loading is expected.

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ABSTRACT: This paper investigates the structural behaviour and design of cold-formed lean duplex stainless steel (LDSS) hollow columns that primarily fail due to interaction of local and flexural buckling modes. Individual buckling modes observed in thin-walled metallic columns are relatively easy to deal with using available design rules, but interactions between buckling modes make it difficult to predict their structural response, especially with new material types such as LDSS. In the current study, geometric dimensions of the hollow column sections were chosen in such a way that they have almost equal local and flexural buckling stress. Finite element (FE) models for columns with pin-ended conditions were developed using ABAQUS [1], and numerically obtained results were validated using relevant test results available in literature. A total of 16 sections was used to produce 64 models offering various combination of geometry and material strength. Column resistances obtained from the parametric study were compared with those predicted using relevant American, Australian, European and DSM design techniques. Overall, it was observed that the current code guidelines fail to accurately capture the interaction of local and flexural buckling producing unconservative and unreliable predictions. Suitable modifications are proposed herein for AS/NZS standard [2], Eurocode 3 [3] and Direct Strength Method (DSM) [4] to account for the interaction of local and flexural buckling. Reliability analysis was also carried out to assess the performance of the existing as well as the proposed design rules for LDSS hollow columns.

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ABSTRACT: In this study a novel type of tubular structure was proposed, in which predesigned ellipsoidal dimples were introduced into conventional circular tubes. The influence of various design parameters of the dimples on the mechanical properties was extensively investigated by finite element modelling and was experimentally validated by quasi-static tests on 3D printed brass tubes. The results showed that properly designed dimpled tubes had substantially lower initial peak force and remarkably less fluctuation in the crushing force than circular tubes, without significantly sacrificing the mean crushing force.

J.M. Spritzer and S. Guzey (Lyles School of Civil Engineering, Purdue University, 550 West Stadium Avenue, West Lafayette, IN, USA), “Review of API650 Annex E: Design of large steel welded aboveground storage tanks excited by seismic loads”, Thin-Walled Structures, Vol. 112, pp 41-65, March 2017
DOI: 10.1016/j.tws.2016.11.013
ABSTRACT: API 650's Annex E, which is an American Standard for designing aboveground steel storage tanks subjected to seismic loads, is reviewed by comparing the design provisions in Annex E with other well-known design documents around the world, including that of New Zealand and Japan. Several limit states such as hydrodynamic hoop stress, uplift, base plate stress, buckling, freeboard, and two stability mechanisms, shear and overturning are investigated. The design provisions for each of the documents were compared for identical tank geometries and seismic parameters for several different tank aspect ratios. The results show that API 650 is slightly under conservative in each of the material failure mechanisms compared to the New Zealand and Japanese design philosophies. The small disparity in results could be due to the fact that the approach in Annex E of API 650 is for tanks of rigid walls and a rigid foundation, whereas the New Zealand and Japanese documents consider tank and foundation flexibility. Despite some marginal differences, API 650 Annex E can be considered to adequately account for all the major failure states when compared to New Zealand and Japanese design documents for design purposes.

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ABSTRACT: In this paper, the estimation of maximum torsional moment for multicorner tubes under torsional loading was investigated using nonlinear FE analysis. The effects of tube geometries and strain-hardening coefficient on the torsional behaviour were discussed. The maximum torsional moment was due to the occurrence of sectional collapse of the tubes, and the mechanism of sectional collapse could be classified into three physical phenomena, elastic buckling, plastic yielding and plastic flattening of the cross section. Moreover, based on our numerical results, analytical solution for estimating the maximum torsional moment for each phenomenon was proposed.

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“Buckling and vibrations of metal sandwich beams with trapezoidal corrugated cores – the lengthwise corrugated main core”, Thin-Walled Structures, Vol. 112, pp 78-82, March 2017
DOI: 10.1016/j.tws.2016.12.013

ABSTRACT: The paper is devoted to the stability of an orthotropic multi-layered beam. This beam is an untypical sandwich structure the faces of which consist of three layers. The original mathematical model of the beam is formulated taking into account different properties of each layer. From the Hamilton's principle the system of equations of motion is derived which is the base for the analysis of buckling and vibration problems. As a result of the analysis the buckling load and natural frequencies of exemplary plates have been obtained. The results are compared with these given by the numerical solution realised with the use of the finite element method in the ANSYS and ABAQUS systems.

Ce Liang (1), Chang Jiang Wang (1), Van Bac Nguyen (2), Martin English (3) and Diane Mynors (1)

ABSTRACT: The UltraSTEEL® forming process forms plain steel sheets into dimpled steel sheets and this process increases the sheet material’s strengths by generating plastic deformation on the material during the process. This paper presented experimental testing and developed a finite element (FE) model to predict the energy absorption characteristics of dimpled thin-walled structures under axial impact loads, and compared the energy absorption efficiencies (specific energy absorption) of plain and dimpled columns. Dynamic experimental tests were conducted using the drop tower at two different impact velocities. Explicit FE analysis were then carried out to simulate the experiments. The FE method was validated by comparing the numerical and experimental failure modes, crushing force response and specific energy absorptions. The validated FE method was then applied in an optimization study on the parameter of forming depth. The effects of forming depth on both geometry and material properties have been taken into account in the optimization study. It has been found that the specific energy absorption of dimpled columns is up to 16.3% higher than the comparable plain columns.


ABSTRACT: Blast resistance and design of sandwich cylinder with graded foam cores are investigated using numerical simulations. The finite element (FE) model is constructed based on the random Voronoi algorithm, and validated by experimental results. The deformation process of sandwich cylinder subjected to blast loading is simulated using the ABAQUS/Explicit software. Subsequently, parametric studies are carried out to analyze the effects of explosive charge, thicknesses of face-sheet and core, and core gradient on deformation pattern, plastic dissipation of the core, and maximum radial deflection (MRD) of the outer face-sheet. The cylinder structure with high plastic dissipation and low MRD is a good choice for protecting persons and objects located on the outside of the cylinder from the internal blast. The results show that the blast resistance increases with the foam core thickness increasing. However, the plastic dissipation of core and the MRD of outer face-sheet are two conflicting objectives to evaluate blast resistance for other parameters.


ABSTRACT: This paper aims at investigating the structural response and predicting the ultimate strength of the cold-formed built-up I-section columns affected by local, distortional, global and in particular by the local-distortional (LD) interactive and local-distortional-global (LDG) interactive buckling modes. For this purpose, a total of 18 single C-section columns and 18 built-up I-section columns were tested under uniaxial compression load, respectively. The cross-sectional dimension, the thickness and the length of the tested members were
varied in the test so as to cover a wide range of local, distortional and overall slenderness. It was shown in the
test that noticeable LD interaction was observed for a built-up column with short length as well as LDG
interaction for a built-up column with intermediate length. Due to the clear evidence obtained in the test that LD
and LDG interactions cause substantial ultimate strength erosion in cold-formed built-up I-section column, a
novel direct strength based method was proposed in this paper to quantify such an erosion effect. The validity of
the proposed method was then verified by comparing the results obtained from the proposed method with the
test results in this paper as well as several other test results in the literature. The comparison results proved that
the proposed method can be used successfully in estimating the ultimate strength of cold-formed built-up I-
section column affected by pure buckling mode as well as interactive buckling mode.

M.R. Feyzi and A.R. Khorshidvand (Department of Mechanical Engineering, Islamic Azad University, South
Tehran Branch, 11365/4435 Tehran, Iran), “Axisymmetric post-buckling behavior of saturated porous circular
ABSTRACT: This study aimed to investigate axisymmetric post-buckling behavior of a circular plate made of
porous material under uniformly distributed radial compression with simply supported and clamped boundary
conditions. Pores are saturated with fluid and plate properties vary continuously in the thickness direction.
Governing equations are obtained based on classical plate theory and applying Sanders nonlinear strain-
displacement relation. Shooting numerical method is used to solve the governing equations of problem. Effects
of porosity coefficient, pore distribution, pore fluid compressibility, thickness change and boundary conditions
on the post-buckling behavior of the plate are investigated. The results obtained for post-buckling of
homogeneous/isotropic plates and critical buckling load of porous plates are compared with the results of other
researchers.

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“An experimental investigation into perforated and non-perforated steel storage rack uprights”, Thin-Walled
ABSTRACT: This paper presents an experimental investigation into the behaviour of steel storage rack uprights
subjected to axial compression. Material tensile tests were carried out to determine the material properties of
cold-formed steel uprights. Geometrical imperfection measurements were recorded for the specimens prior to
testing. A total of 67 specimens were tested under axial compression, including four different cross-sections,
various lengths and specimens with and without perforations. The focus of the study is to investigate the
influence of perforations on the performance and failure mode of steel storage rack uprights, and comparisons
of performance and failure modes between perforated and non-perforated members are provided. The
interaction of distortional-global buckling is also discussed, and the results of this study explicitly show that the
strengths obtained from the tests highlight the underestimation of the existing distortional strength curve of the
Direct Strength Method (DSM) on perforated steel storage rack uprights. Hence, based on the test results, a
modified DSM for perforated uprights is proposed.

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ABSTRACT: This paper investigates the static and dynamic buckling of an anchored cylindrical steel tank subjected to horizontal and vertical ground acceleration. The buckling capacity of the tank is estimated using static pushover (SPO) and incremental dynamic analyses (IDA). Appropriate load patterns due to the horizontal and vertical components of ground excitations are utilized for SPO analyses. The buckling capacity curves and critical buckling loads computed using SPO analyses are compared to those obtained from IDA. A proper vertical to horizontal acceleration ratio \( \frac{a_v}{a_h} \) for SPO analysis is proposed that leads to good agreement between SPO and IDA results.


ABSTRACT: This article aims to present the crashworthiness performance of double section bi-tubular thin-walled structures. Double section bi-tubes were made from stainless steel sheet and consist of an outer circular cylinder and an inner tube with any one of polygonal section such as triangle, square or hexagon. By keeping the outer cylinder dimensions constant, the effect of changes in the inscribed diameter of polygonal section and the various polygonal section of the inner tube on quasi-static axial compression is studied. Bi-tubular structures with hexagonal inner tube have more energy absorption capability than the other bi-tube combinations and the single cylinder.


ABSTRACT: Majority of the available research on buckling analysis of the plates, has been devoted to plates with well-behaved configurations, e.g., rectangular or circular geometries. In the present research, thermal buckling of general quadrilateral plates fabricated from heterogeneous, orthotropic, and auxetic (with negative Poisson ratio) materials resting on elastic Winkler-Pasternak elastic media is investigated. Edges of the plate may be either simply supported or clamped. Thus, the problem is a quite general one, from the material, boundary conditions, and to some extent, geometry points of view and may cover wide ranges of the practical applications, as special cases. The stability equations are derived through transformation of the governing equations of the plate from the geometric rectangular Cartesian coordinates to the computational natural coordinates and discretization of the resulting equations by means of the differential quadratic method. Buckling analysis has been accomplished through investigation of the pre-buckling and buckling onset situations. Finally, effects of the skew angles of the general quadrilateral plate, heterogeneity index, orthotropy angle, edge condition, foundation stiffness, and auxeticity of the material on the buckling temperature rises are investigated comprehensively.
ABSTRACT: Due to their lightweight and superior load carrying capacity, corrugated web steel beams (CWSBs) have gained popularity in the last few decades. CWSBs are known to fail at much higher loads compared to stiffened flat web beams. To understand their shear response, a series of three-point load tests were performed on five shear-critical trapezoidal corrugated web beams. The test results confirmed the existence of the three shear buckling modes of failure: local, global, and interactive. In addition, all tested beams were observed to have a residual strength that is about half of their ultimate load carrying capacity regardless of the shear buckling mode. Results of the nonlinear finite element analysis showed that the shear stress is at its maximum and uniformly distributed throughout the web until buckling, afterwards, it decreases and its distribution is uneven while the entire resistance is provided by the increased tensile stress. Furthermore, stocky corrugated webs were shown to reach shear yield strength. Comparison between existing analytical models for the estimation of shear strength against test data showed that EN-1993-1-5 is accurate and conservative enough for an economic design.

ABSTRACT: Cracking damage in a stiffened plate affects its ultimate strength and collapse behavior. To examine this problem, this paper presents a nonlinear finite element study on the ultimate strength of cracked stiffened plates subjected to uniaxial compression. The cracks in transverse direction are presumed to be through-thickness, and crack propagation is not considered. The crack damage is assumed to exist on plate only or on both plate and stiffener and the relevant four types of cracked models are accounted for in this paper. The effects of crack length and crack location as well as plate thickness on the ultimate strength characteristics of cracked stiffened plates are analyzed. A series of nonlinear finite element analyses is carried out for the analyses where the crack damage effect is treated as a main parameter. It is concluded that the presence of crack may change the collapse mode and stress distributions of stiffened plate, and will decrease its ultimate strength. The reduction of ultimate strength increases as the crack length increases, while the longitudinal location of crack has little influence on the ultimate strength reduction of cracked stiffened plate.

ABSTRACT: This work investigates the compressive load carrying capability of experimentally tested reinforced steel panels with a large lightening opening. A series of experiments have been carried out on reinforced panels with circular and elongated circular opening of different sizes. The effect of different opening
shapes, different opening sizes as well as different initial imperfection shapes and amplitudes, on the loading carrying capacity are studied. The resultant collapse modes are presented and both initial and post-collapse shapes are analysed and the sequential occurrence of the post-collapse deformation shapes have been analysed. The experimental results of force-vertical/lateral displacements relationships, strain energy density and stress-strain relationships are presented and analysed. Finally, the experimental results have been compared with other experimental ones for unstiffened plates with elongated circular opening subjected to uniaxial compressive load.

S.S. Ajeesh and S. Arul Jayachandran (Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600036, India), “A constrained spline finite strip method for the mode decomposition of cold-formed steel sections using GBT principles”, Thin-Walled Structures, Vol. 113, pp 83-93, April 2017
https://doi.org/10.1016/j.tws.2017.01.004
ABSTRACT: In this paper, an analysis procedure has been presented for cold-formed steel sections, for decomposing the buckling modes obtained using spline finite strip method (SFSM) into their primary and independent buckling modes such as local, distortional and global buckling. This procedure utilizes principles of generalized beam theory (GBT) to evaluate the restraint matrices corresponding to different modes. The restraint matrices are integrated in to spline stiffness matrices using transformation technique to extract pure modes corresponding to local, distortional and global modes. The proposed analysis technique termed as constrained spline finite strip method (cSFSM) has been validated for cold-formed steel open cross-sections subjected to axial compression and bending under various boundary conditions. The results are in agreement with buckling stresses evaluated using constrained finite strip method (cFSM) and GBT.

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ABSTRACT: The bottom head in the residential electric water heater tank is an externally-pressurized, thin-walled, torispherical structure. In this paper, the buckling behavior of the bottom head was studied by experimental and finite element analysis (FEA) methods. The shapes of four randomly selected water heater tanks were measured by Computer Aided Inspection (CAI), and hydrostatic tests and strain measurements were performed. The buckling simulations of the tested tanks were carried out by finite element method, and the obtained results were in good agreement with the experimental data. Two parameters, contact imperfection ratio, $R_{imc}$, and geometry imperfection ratio, $R_{img}$, were used to quantitatively characterize the magnitudes of the main imperfections in the water heater tank manufacturing process. FEA models, including both contact and geometry imperfections, were used to investigate the buckling pressure of the bottom head. The results show that the geometry imperfection, within the range of ASME Code VIII-2 requirements, has a greater effect on the buckling pressure than the contact imperfection. The obtained curves of buckling pressure versus imperfections can provide guidance for water heater tank design and manufacture.

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ABSTRACT: The elastic stability of axially compressed column related to the cross-section distortion is investigated. Two kinds of closed quadratic cross-sections are taken into consideration with internal walls and without it. The governing differential equation is derived with aid of the principle of stationary total potential energy. The critical loads for the simply supported columns are found in an analytical form and compared with the FEM solution. Sufficient accuracy of the results is worth of noticing.

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ABSTRACT: The subject of the present paper is a family of egg-shaped shells. The meridian of these shells resembles that of a goose egg. The capacity and mass of the shell were maintained constant. The ratio of the minor $B$ to the major $L$ axis of the shell was determined according to the experimental results of the analysis of 333 goose eggs. Fourteen $B/L$ ratios were determined as follows: 0.4, 0.5, 0.6, 0.65, 0.66, 0.67, 0.68, 0.69, 0.70, 0.71, 0.72, 0.8, 0.9 and 1.0. The effect of the ratio on the buckling behavior of the egg-shaped shell was numerically and analytically analyzed.

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ABSTRACT: In cold rolling of thin sheet metal, the interstand tension has a role to mitigate the wrinkling of the plate due to residual stress. When this mechanical loading is reduced up to full unloading, it can induce or increase elastic wave buckling, leading to latent flatness defects. An experimental work is proposed to study the relation between residual stresses, global tensile stresses and buckling for wavy edge flatness defects during the mechanical unloading. Residual stresses are generated by thermal loading. The wrinkling shape and thermal field are measured by optical full-field measurements. Finite Element simulation using a combination of a non-linear algorithm and a bifurcation analysis that take into account mid-surface imperfections can follow the wrinkling behavior.

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“Stability and free vibrations of the three layer beam with two binding layers”, Thin-Walled Structures, Vol. 113, pp 144-150, April 2017, 
https://doi.org/10.1016/j.tws.2016.11.024

ABSTRACT: The paper is devoted to the stability analysis of a simply supported three layer beam. The sandwich beam consists of two metal facings, a metal foam core and two binding layers between the faces and the core. In consequence, the beam is a five layer beam. The main goal of the study is to elaborate a mathematical model of the beam, analytical description and solution of the stability problem. The beam is subjected to an axial compression and, in particular, a pulsating compression. The nonlinear hypothesis of deformation of the cross section of the beam is formulated. Based on the Hamilton's principle the system of four stability equations is derived. The system is reduced to one equation of motion (Mathieu's equation) serving as a basis for determining the critical loads, free vibrations and unstable regions. The influence of the binding layers is considered. The results of solutions of the vibration problem analysis are shown in tables and figures. The analytical model is verified numerically with the use of Finite Element Analysis.

Mohamad Eydani Asl, Christopher Niezrecki, James Sherwood and Peter Avitabile (Department of Mechanical Engineering, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, United States), “Vibration prediction of thin-walled composite I-beams using scaled models”, Thin-Walled Structures, Vol. 113, pp 151-161, April 2017, 
https://doi.org/10.1016/j.tws.2017.01.020

ABSTRACT: Scaled models of large and expensive structures facilitate in understanding the physical behavior of the large structure during operation but on a smaller scale in both size and cost. These reduced-sized models also expedite in tuning designs and material properties, but also could be used for certification of the full-scale structure (referred to as the prototype). Within this study, the applicability of structural similitude theory in design of partially similar composite structures is demonstrated. Particular emphasis is placed on the design of scaled-down composite I-beams that can predict the fundamental frequency of their corresponding prototype. Composite I-beams are frequently used in the aerospace industry and are referred to as the back bone of large wind turbine blades. In this study, the governing equations of motion for free vibration of a shear deformable composite I-beam are analyzed using similarity transformation to derive scaling laws. Derived scaling laws are used as design criteria to develop scaled-down models. Both complete and partial similarity is discussed. A systematic approach is proposed to design partially similar scaled-down models with totally different layup from those of the full-scale I-beam. Based on the results, the designed scaled-down I-beams using the proposed technique show very good accuracy in predicting the fundamental frequency of their prototype.

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ABSTRACT: Present analysis, deals with dynamic buckling of sandwich nano plate (SNP) subjected to harmonic compressive load based on nonlocal elasticity theory. The material properties of each layer of SNP are supposed to be viscoelastic based on Kelvin-Voigt model. In order to mathematical modeling of SNP, a novel formulation, refined Zigzag theory (RZT) is developed. Furthermore, the surrounding elastic medium is simulated by visco-orthotropic Pasternak foundation model in which damping, normal and transverse shear
loads are taken into account. Using energy method and D’Alembert's principle, the size dependent governing motion equations are derived. In this study, the governing motion equations are solved numerically using new procedure namely differential cubature (DC) method in conjunction with Bolotin method. The effects of some remarkable parameters such as viscoelastic foundation, damping coefficient of viscoelastic plates, aspect ratio, amount of small scale effect, various boundary conditions, different values of fiber orientation of the face sheets, number of grid points and thickness-length ratio on the dynamic instability region (DIR) are investigated. The results show that considering viscoelastic property of system is essential to obtain real mechanical behavior and instability of systems. In addition, the surrounding elastic medium is an effective parameter on the DIR of SNP.

Amit Kumar, M.K. Singha and Vikrant Tiwari (Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi 110016, India), “Nonlinear bending and vibration analyses of quadrilateral composite plates”, Thin-Walled Structures, Vol. 113, pp 170-180, April 2017

https://doi.org/10.1016/j.tws.2017.01.011

ABSTRACT: Linear and nonlinear analyses of shear deformable thin and thick arbitrary straight-sided quadrilateral plates are reported here using smoothed finite element technique. The Reissner-Mindlin plates are discretized with quadrilateral background cells. Then membrane and bending stiffness matrices of background quadrilateral cells are evaluated using edge-based smoothed finite element method(ES-FEM). The shear stiffness matrix is calculated based on "smoothed shear strain approach" and the performance is compared with "edge-consistent four-node quadrilateral finite element". The convergence, accuracy and sensitivity to mesh distortion of the present quadrilateral element is examined. Thereafter, the nonlinear bending and vibration analyses of trapezoidal and arbitrary straight-sided quadrilateral composite plates are presented for which only limited analytical results are available in the literature.

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ABSTRACT: This paper presents experimental and numerical studies on the lateral-torsional buckling behaviour of singly symmetric I-beams fabricated of Q460GJ structural steel. A total of six singly symmetric I-shaped beams, with various slenderness and height-width ratios, were designed with lateral restraints at the mid-span and tested under concentrated point loads. Experimental results demonstrated that steel beams developed lateral-torsional buckling when subject to bending moment. Comparisons between experimental and calculated values according to relevant design codes indicate that most design methods underestimate the buckling moment of Q460GJ steel I-beams to a certain extent. Finite element models were established for steel beams and validated against experimental results. Parametric studies were carried out on the effects of slenderness and height-width ratio on the buckling moment of steel beams. Comparisons were also made between numerical results with design provisions in different codes of practice. Finally, recommendations were proposed for the design of singly symmetric Q460GJ steel beams against lateral-torsional buckling in accordance with experimental and numerical results.
In this paper, the harmonic quadrature element method is presented for free vibration analysis of soft-core sandwich panels with general boundary conditions. To remove limitations existing in various beam theories, the thin faces are modeled by Euler-Bernoulli beam theory but the soft-core is directly modeled by two-dimensional elasticity theory. A novel harmonic quadrature sandwich panel element with arbitrary number of nodes is developed and the equation of motion is established utilizing Hamilton principle. Explicit formulations are worked out to ease the implementation of the element. To show the applicability of the method, several examples, including two types of core material and five combinations of boundary conditions, are investigated. Results are compared to existing data as well as finite element data of ABAQUS. Comparisons show that the proposed method exhibits a high convergence rate and can yield accurate results in all cases.

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ABSTRACT: Recently, requirements for data regarding crushing force have motivated researchers to investigate the crushing behaviour of tubes. The present work aims to study the crushing of multi-cell triangular tubes made of aluminium alloy AA6060T4 using theoretical and numerical analyses under multiple impact loadings. By dividing the profile into several basic angular elements and using the Improved Simplified Super Folding Element (ISSFE) theory, theoretical equations of the mean crushing/horizontal force, and the mean bending moment are proposed to calculate the mean crushing strength of these sections. It is found that the number of “cells” in a tube's structure and to a certain extent the load angle have a considerable effect on the Specific Energy Absorption (SEA), and Mean Crushing Force (MCF). Numerical analyses were conducted, and the simulation results show a strong correlation between the crush response and the cross-section of the tubes. The analytical predictions for the MCF are compared with the FE results.


ABSTRACT: Over the years a large number of works have shown that for many buckling problems of plates and shells in the plastic range the flow theory of plasticity seems to lead to a significant overestimation of the critical stress while the deformation theory seems to provide much more accurate predictions and therefore the latter has been generally recommended for use in practical applications. This fact is generally known in literature as the “plastic buckling paradox”. Possibly the simplest examples of such a circumstance is given by the torsional instability of a cruciform column. The present study examines the problem from its roots and shows that in order to overcome this apparent conundrum it is not only necessary to consider an imperfect column, as generally suggested in the past, but principally to account correctly for the effects of the imperfection up to the point where the limit load is attained. In such manner a very good agreement between the
results from the flow theory of plasticity and other analytical and experimental results can be obtained on the basis of classic formulae only.

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ABSTRACT: This paper is an attempt for introduction of new theoretical relations in order to predict energy absorption behavior of empty and polyurethane foam-filled composite tubes, which are made of woven fiber fabrics, during lateral compression between two rigid plates. Such theoretical relations can be used to specify portion of different deformations that are happened during crushing process in total energy absorption of the structures. Knowing these data may help the designers to reinforce the energy absorbers more effectively. Also, several experiments are conducted on empty and polyurethane foam-filled circular E-glass/Vinylester composite tubes in order to validate the theoretical relations. The specimens are laterally compressed between two rigid plates during a quasi-static process. According to experimental studies, the composite tubes collapse with different modes of deformation during lateral flattening. Different relations are introduced for prediction of the absorbed energy of tubes with different deformation modes. The theoretical and experimental energy-displacement diagrams and total absorbed energy by the composite tubes are compared and good agreements are found. Finally, theoretical relations are compared with each other and effects of different energy absorption mechanisms on total energy absorption are discussed based on the presented relations.

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ABSTRACT: In the paper the post-buckling behaviour of thin-walled channel cross-section columns made of Fiber Metal Laminate subjected to an axial compressions is considered. The main interest is focused on the initial imperfection influence on the post-buckling response and thus the sensitivity analysis with application of Monte Carlo simulations is performed. A different shapes and amplitudes of geometrical imperfections – all corresponding to a particular buckling mode or to a few superimposed, have been applied in numerical models. The numerical simulations have been performed using developed FEM software based on Koiter’s asymptotic theory for hundreds of buckling mode cases. The obtained results of numerical calculation have been compared with results of experimental investigations. Both - the numerical computations and laboratory experiments were performed on short FML channel section columns with four different layer arrangements. The strain-gauge technique, laser measurement and digital image correlation system were employed to determine deformation modes in laboratory tests. A comparison of the results shows that geometrical imperfections have substantial impact on the post-buckling response of considered columns.

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ABSTRACT: The collapse mechanics and ultimate strength of crack damaged stiffened plates are investigated by testing stiffened plates with an initial crack. A series of stiffened plates with initial distortions and with a crack are subjected to in-plane compression until achieving their ultimate strength. The crack position, length and the angle between the crack and longitudinal stiffener are changed for determining the influence of the crack on the plate ultimate strength. The ultimate strength and the strain response of the plates are reported. Finally, the ultimate strength reduction related with the presence of the crack and the failure mode are discussed for establishing a damage tolerant procedure for the design of ship structures.


ABSTRACT: This study presents the first vibration analysis of thermally post-buckled hybrid laminates with non-uniformly distributed graphite and E-glass fibers in a single lamina. A 54 degree-of-freedom high order triangular plate element is developed based on the Von Karman large deflection assumption. The formulation of the location dependent linear, nonlinear stiffness and mass matrices due to non-homogeneous material properties, geometrical stiffness matrix due to thermal effects and thermal moment vector due to temperature gradient is derived. The effects of hybrid-fiber distribution on the natural frequencies and mode shapes of thermally post-buckled laminates are discussed. The numerical results reveal that the redistribution of two fibers can considerably decrease the postbuckling deflections of the hybrid laminates and significantly modify the natural frequencies. The stiffening effect of fiber redistribution is more obvious for the laminate with a higher volume fraction index and clamped edges. Special buckling and vibration mode shapes are observed, along with multiple vibration mode shifting.


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ABSTRACT: Recently, concrete-filled steel tubular (CFST) members are becoming highly recommended by engineers for use in composite structures. Lately, carbon fiber-reinforced polymer (CFRP) composite materials have been used for strengthening steel and CFST flexural members. Both experimental and numerical studies are adopted in this research to further investigate the behavior of various sections of rectangular CFST beams strengthened and/or repaired with unidirectional CFRP sheets. The effects of the U-shaped wrapping scheme using multiple CFRP layers applied at various beam lengths was studied. In general, the results demonstrated that the moment capacity of strengthened CFST beams increased significantly with increasing CFRP layers; for example, it increased by approximately 40% and 55% for beams with compact and slender sections, respectively, when wrapped with 4 CFRP layers. The capacity of damaged CFST beams has improved over 65% when repaired with 2 CFRP layers. Moreover, the effects of wrapping the beam along 75% of its length...
achieved a similar enhancement ratio and behavior as that of the beam with wrapping along 100% of its length for the same CFRP layers.

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ABSTRACT: A parametric study of cold-formed steel sections with web openings subjected to web crippling under interior-one-flange (IOF) loading condition is undertaken, using finite element analysis, to investigate the effects of web holes and cross-sections sizes. The holes are located either centred beneath the bearing plate or with a horizontal clear distance to the near edge of the bearing plate. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the depth of the web, the ratio of the length of bearing plate to the flat depth of the web and the location of the holes as defined by the distance of the hole from the edge of the bearing plate divided by the flat depth of the web. In this study, design recommendations in the form of web crippling strength reduction factor equations are proposed, which are conservative when compared with both the experimental and finite element results.

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ABSTRACT: In this paper, an efficient Fourier-series finite element solution framework is proposed to simulate the wrinkling phenomena in two-dimensional film/substrate system. In the method, the displacement field is transformed into the slowly variable Fourier coefficient, i.e., the macroscopic displacement field, which permits to capture the wrinkling evolution in the system with much less degrees of freedom than the full finite element model. The derived macroscopic non-linear system is solved by the Asymptotic Numerical Method that is very efficient and reliable to capture the bifurcation point and the post-buckling path in wrinkling analyses. In particular, the importance of using the first harmonic of Fourier series in approximating the axial displacement in substrate is discussed and a spurious phenomenon related to the hypothesis of the used approximation functions within the Fourier-series approach, i.e., oscillation locking, is pointed out. To overcome this
phenomenon, modifications on either the Fourier series or the constitutive equations of the substrate are proposed. The efficiency and accuracy of the proposed macroscopic model are demonstrated by the wrinkling simulations for several kinds of film/substrate systems.

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ABSTRACT: The paper is devoted to mathematical modelling of multi-layered structures. The case of a metal seven-layer rectangular plate is considered. The plate is composed of a trapezoidal corrugated main core, two inner flat sheets, two trapezoidal corrugated cores of the faces and two outer flat sheets. The direction of the corrugation of the main core is orthogonal to the one of the face cores corrugations. The hypothesis of deformation of normal to middle surface of the plate after bending and the field of displacements and stresses is formulated. The plate is simply supported and subjected to a uniformly distributed compressive loads applied to the edges. Equations of motion are derived based on the Hamilton’s principle. These equations are analytically solved for static or pulsating loads. The influence of the trapezoidal corrugation pitch of the cores on the critical loads and natural frequency of the plates is analysed. The results obtained form the analytical solution are compared with the results given by the proposed finite element model.

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“Requirements for intermediate ring stiffeners placed below the ideal location on discretely supported shells”, Thin-Walled Structures, Vol. 115, pp 21-33, June 2017, https://doi.org/10.1016/j.tws.2017.02.003
ABSTRACT: Silos in the form of a cylindrical metal shell are commonly supported by a few discrete columns to permit the contained materials to be directly discharged. The discrete supports produce a circumferential non-uniformity in the axial membrane stresses in the silo shell. A combination of a ring beam and an intermediate ring stiffener can be used for large silos to redistribute the stresses from the local support into uniform stresses in the shell. Previous work done by the authors has identified the ideal location and the stiffness and strength requirements for the intermediate ring stiffener placed at this location. In cases where a shell with a large radius rests on a few supports, the ideal location can be quite high and the option of placing the intermediate ring stiffener below the ideal location may provide a viable solution. This paper explores strength and stiffness requirements for intermediate ring stiffeners placed below the ideal location. Pursuant to this goal, the cylindrical shell below the intermediate ring stiffener is analyzed using the membrane theory of shells. The reactions produced by the stiffener on the shell are identified. Furthermore, the displacements imposed by the shell on the intermediate ring stiffener are obtained. These force and displacement boundary conditions are then applied to the intermediate ring stiffener to derive closed form expressions for the variation of the stress resultants around the circumference to obtain a strength design criterion for the stiffener. A stiffness criterion in the form of a simple algebraic expression is then developed by considering the ratio of the circumferential stiffness of the cylindrical shell to that of the intermediate ring stiffener. These analytical studies are then compared with complementary finite element analyses that are used to identify a suitable value for the stiffness ratio for ring stiffeners placed at different locations.
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ABSTRACT: The interactive buckling behavior of welded steel box-section columns was studied experimentally and numerically. A total of 12 steel medium-length columns, 2 with a welded square hollow section (SHS) and 10 with a welded rectangular hollow section (RHS), were axially compressed. All specimens were designed to cover a wide range of width-to-thickness ratios and slenderness. Material properties, geometric imperfections, buckling resistance, and load-displacement/strain curves were obtained. All test data were compared with current design codes Eurocode3 and ANSI/AISC 360-10, revealing overestimated design predictions. Further, the experimental results were supplemented by finite element simulation. Reliability of the modeling methodology was verified by comparisons with previous test data. The design proposal was eventually carried out on both plain carbon steel and high-strength steel columns.

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ABSTRACT: This paper investigates, for the first time, the behaviour and design of railway double track open timber floor plate girder deck steel bridges under combined buckling modes including web distortional buckling. A 3-D finite element model has been developed for the railway bridges, which accounted for the
bridge geometries, initial geometric imperfections, material nonlinearities of the bridge components, bridge boundary conditions, interactions among bridge components and bridge bracing systems. Most of the aforementioned parameters are not incorporated in current design codes of railway bridges, which are credited to this study. The simply supported bridges investigated had a span of 30 m, a width of 7.2 m and a depth of 3.12 m. The bridge components comprising main plate girders, stringers, cross girders, connections, bracing members, stiffeners, bearings, and field splices were designed following the design rules specified in the European Code for steel bridges. The live load acting on the bridge was Load Model 71, which represents the static effect of vertical loading due to normal rail traffic as specified in the European Code. The finite element model of the double track bridge was developed depending on additional finite element models, developed by the author, for small and full-scale plate girder steel bridge tests previously reported in the literature. Ultimate loads, load-mid-span deflection relationships, failure modes, stress contours of the double track bridge as well as of the small and full-scale tests were predicted from the finite element analysis and compared well against test results. Parametric studies were performed on the railway bridges highlighting the effects on the structural behaviour and ultimate loads carried by the bridges owing to the change in the bridge geometries, slenderness and steel strength. The paper presents a complete piece of work regarding the finite element analysis and design of railway steel bridges, which can be used for further parametric studies, finite element analyses and investigations of the bridges under different loading and boundary conditions. The parametric study has shown that the presence of web distortional buckling causes a considerable decrease in the ultimate load of the steel bridges. It is also shown that the use of high strength steel offers a considerable increase in the ultimate loads of less slender steel bridges. The study has also shown that the design rules, loading and recommendations specified in the European Code provide accurate and conservative estimations for the design of railway steel bridges, except for the bridges failing mainly by web distortional buckling.


ABSTRACT: The paper deals with estimating load capacity of thin-walled composite beams with C-shaped cross-section subjected to pure bending. The discussed beams were made of eight-layer GFRP laminate. The analysis have been performed on six ply systems. To designate load capacity of analyzed structures the ANSYS program based on finite element method were employed. The experimental tests were conducted. Estimations of load capacity were based on the following failure criteria: Inverse of Tsai-Wu, Hoffman and criterion of maximum stress reduced to fiber direction. Based on the performed experimental and numerical studies it has been concluded that the largest convergence of numerical and experimental results was obtained with the implementation of the criterion of maximum stress reduced to the fiber direction. After exceeding the compressive strength or tension strength in the direction of the fibers the composite beams were characterized by a high stiffness degradation, leading to rapid destruction of the structures.

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ABSTRACT: An effective way for improving the global load-carrying capacity of a steel arch with a welded hollow section is to increase the height of its webs. However, the high and thin web may buckle locally, which will affect the global load-carrying capacity and should be taken into account in predicting the global strength of the arch. This paper presents a numerical investigation for the in-plane strength and design for pin-ended circular steel arches with a welded hollow section, focusing on the effects of web local buckling by the large deformation inelastic analysis in association with a finite shell element model. The circular steel arches subjected to a radial load uniformly distributed along the arch length, a load uniformly distributed over the full span of the arch, or/and over the half span of the arch and their various combinations are considered in the investigation of their failure modes and strengths. The initial global and local geometric imperfections as well as residual stresses are included in the finite element model. It is found that web local buckling influences the global strength of the steel arches significantly and needs to be accounted in formulating their strength design formulas. The parameters related to the web local buckling and global buckling of the arch are thoroughly explored. It is found that the stability coefficients of arches under the nominal uniform axial compression are related to the equivalent normalized web height-to-thickness ratio of the cross-section and the normalized slenderness of the arch, and accordingly the design formula of the stability coefficients is proposed by including their effects. In addition, a design formula for predicting the strengths of the arches under a load uniformly distributed over the full span is developed by introducing a corrective coefficient into the stability coefficient, and it is found that the corrective coefficient is related to the arch rise-to-span ratio and slenderness of the arch. Furthermore, a general interaction design formula is developed for predicting in-plane strength of the arches under general in-plane loading such as a load uniformly distributed over the half span of the arch and various combinations of a full span uniform load and a half span uniform load. Comparisons with the finite element results demonstrate the proposed design formulas can provide good predictions and/or lower bound predictions for the strengths of the steel arches with a welded hollow section.

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ABSTRACT: This paper studies steel circular hollow section (CHS) X-joints by conducting experiments on the axial compressive strength of unreinforced and reinforced X-joints with external stiffening rings. Three pairs of unreinforced and reinforced X-joints were tested to compare their compressive load capacity. The diameter ratios (β) between the brace and the chord β were 0.25, 0.51 and 0.73 respectively. The experimental setup, parameters and results are presented. The failure modes and load-displacement curves of the unreinforced and reinforced X-joints were compared. It was shown that external stiffening rings greatly increased the axial compressive load capacity of the X-joints, by 86%, 75%, and 58% respectively. Finite element modelling accurately predicted the structural responses of the X-joints with and without external stiffening rings.

ABSTRACT: Circular thin-walled tubes have been adopted in vehicular structures to protect occupants and cargo in the events of crash. However, crack initiation on the tubes may pose a great threat to limiting their crashworthiness performance such as the mean crushing force, energy absorption capacity, crush force efficiency and specific energy absorption. This study investigates numerically the dynamic axial crushing of a strain rate sensitive circular thin-walled tube material made from A36 steel hot rolled carbon and modeled with a crack. Six different modeled tube geometries with non-propagating crack are studied and compared with the tube geometry without crack. Results of the crashworthiness parameters, deformation modes, damage morphologies and force-displacement history were obtained. The finite element study shows and establishes the undesirable effect of crack on the overall crashworthiness performance of circular thin-walled tubes.

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ABSTRACT: The aim of this work is the numerical assessment of the ultimate behaviour of temper T6 aluminium alloy beams subjected to non-uniform bending. An extensive numerical analysis has been performed by means of FE code ABAQUS with reference to RHS sections considering the typical range of variation of the geometrical parameters governing the ultimate behaviour of RHS beams under non-uniform bending. In particular, a wide parametric analysis has been carried out by varying the flange slenderness, the flange-to-web slenderness ratio and the non-dimensional shear length accounting for the moment gradient. The ultimate behaviour of such beams has been investigated with reference to the material constitutive law proposed by Eurocode 9, based on the Ramberg-Osgood model. Particular attention has been devoted to the interaction between the different non-dimensional parameters governing the ultimate behaviour. The importance of the investigated parameters on the non-dimensional ultimate flexural strength and on the rotation capacity of aluminium alloy beams is clearly pointed out. Successively, by means of multivariate non linear regression analyses, empirical relationships are provided in order to predict both the non-dimensional ultimate flexural resistance and the rotation capacity of RHS temper T6 aluminium alloy beams, starting from their geometrical and mechanical properties.

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ABSTRACT: The paper deals with the load carrying capacity probabilistic variance-based sensitivity analysis of thin-walled box-section girders subjected to pure bending. The lower- and upper-bound load capacity estimation is performed using two different analytical methods. The sensitivity analysis performed is based on
the methodology of the Monte-Carlo method. The analysis is carried out using the polynomial decomposition and multi-dimensional linear regression. The sample results obtained are presented in diagrams and pie charts showing the sensitivity of load capacity to different random input variables (material properties and geometrical parameters). The variance-based analysis (Anova) of lower-bound and upper-bound load capacity estimation is carried out, from which some conclusions are derived, if (and how) assumed changes in standard deviations of input variables influence the magnitude of the load capacity and differences in upper-bound and lower-bound load capacity estimations. The results of Anova tests are shown in sample histograms. Some final conclusions concerning the efficiency of the applied models and the statistically significant influence of input random variables (yield stress, wall thickness, height and length of the beam) upon the upper-bound and lower bound estimation of the load capacity as well as the difference of these two estimations, are presented.


ABSTRACT: A currently used guideline for cylinder structures under axial compression is the NASA SP-8007 which is based on empirical data from the 1960s. This guideline provides knock-down factors (KDF) for the lower bound of the buckling load which depend on the cylinder radius-to-thickness ratio but neglect the influence of the cylinder length L. Experimental results indicated an influence of the cylinder length on the buckling load but a clear dependency could not be established because of the insufficient amount of available data. A comprehensive numerical investigation was performed in order to study the influence of length effect on the lower bound of the buckling load. The numerical analysis is based on the single boundary perturbation approach (SBPA) for cylindrical shells. The results verify that there is a significant influence of the cylinder length L on the lower bound of the buckling load. Semi-analytic knock-down factors for the stability failure of axially loaded cylindrical shells were determined which can be used for a simple and fast approximation of the lower bound of the buckling load. The corresponding SBPA thresholds were validated with a number of high fidelity buckling experiments and deliver much higher KDFs than currently used empirical guidelines.

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ABSTRACT: The single-layer reticulated shell with aluminium alloy gusset (AAG) joints is an innovative space structure system, and has been widely used in the building engineering. According to the bending behaviour of AAG joints obtained from the theoretical formulae, the finite element (FE) models of K6 AAG joint shells were established in the ANSYS program. The buckling performance of K6 shells with semi-rigid and rigid joints was discussed. It is indicated that the semi-rigid behaviour of AAG joints had a significant effect on the buckling performance of K6 shells. To develop a further understanding, parametric studies were performed, varying the span-to-thickness ratio, height-to-span ratio, ring, member section, joint bending behaviour, joint stiffness model, material property, load distribution, support condition and initial geometric imperfection. It is found that the effects of these parameters on the elasto-plastic stability of K6 shells with rigid
and AAG joints were different obviously. At last, to predict the elasto-plastic buckling load of AAG joint shells, theoretical formulae were proposed on the basis of the FE results of more than 8000 shell models.

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ABSTRACT: Terrorist activities, especially bomb attacks, have become more and more frequent in the past decades which put thousands of innocent lives in danger. The most common failure mode of structures subjected to blast loading is progressive collapse which is mainly resulted from the failure of load bearing columns. In this paper, finite element analysis tool, LS-DYNA is utilized to study the behaviours of ultra-high performance concrete filled double-skin steel tube (UHPCFDST) columns under blast loading. The numerical model is firstly validated against a series of laboratory and field tests and then used to derive pressure-impulse diagrams for UHPCFDST columns in terms of their residual axial load-carrying capacity after being subjected to blast loading. Different parameters are studied to investigate the effects of axial load ratio, steel tube thickness, column dimension and concrete strength on the pressure-impulse diagrams.

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ABSTRACT: Compressive tests of the CFST stub columns with artificial notches in the steel tubes were conducted in this paper to investigate the effects of the material imperfections of steel tubes on column performances. The load-strain responses, column strength and confining effects were discussed in detail. A parametric study, including the notch length, notch orientation, notch location and ductility, was also conducted. The results indicate that the notched CFST specimens have quite different failure modes from the intact CFST specimens. A notched CFST specimen may fail by bulging or closing of the notch, which was determined by the notch orientation. The results also show that the notched CFST specimens had lower mechanical performances than the intact CFST specimens because the notch steel tube could not offer sufficient confining effect on the concrete core inside it. Based on the experimental results, a practical calculation formula for the bearing capacity of notched CFST columns was proposed, which gave well agreement with the experimental results.

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ABSTRACT: This paper investigates the lateral crushing behavior of multi-cell thin-walled triangular tubes using experiments. More crushing modes are found in the lateral compression experiments of the multi-cell triangular tubes. The average crushing force, $P_a$, is governed by the plastic hinge lines. Based on experiments and the improved simplified super folding element (ISSFE) theory, theoretical models are proposed to predict average crushing force ($P_a$) in each stage. The formula of $P_a$ is a function of flow stress of material, wall thickness, and length of tube. The results show that the theoretical solutions agree well with the experiment data.

ABSTRACT: To explore diversified energy absorption methods, a new energy absorption structure was proposed based on the plastic forming mechanisms of stamping in this paper. Through three repeated quasi-static tests, this new energy absorption structure was proven to be feasible. Moreover, the effects of thickness, friction coefficients and the fillet radius of the plates on the energy absorption of this structure were studied using a verified numerical simulation model. The results show that the structure has good test reproducibility and the deformation mode of the U-shaped plates is both stable and reliable. Stamping forces rise to an initial peak value with increasing stroke and then rapidly decrease to a steady-state force and consequently stabilize. The efficiencies of stamping forces in the three tests were greater than 80%. With increasing plate thickness and friction coefficient, the total energy absorption increased, whilst plastic energy was rarely affected by friction coefficient. The initial peak value of stamping force was sensitive to fillet radius changes of the U-shaped plates; when the fillet radius was larger than 8 mm, stamping forces show an unobvious initial peak value. Steady-state force and energy distribution percentages were little impacted by the fillet radius of the plates. Furthermore, the steady-state force stabilized at around 100 kN and the energy dissipation proportions of the plastic and friction energies were basically in equilibrium.

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ABSTRACT: The parametric instability of heterogeneous orthotropic truncated conical shells under time dependent axial compressive load on the basis of Donnell shell theory is investigated. The dynamic basic equations are reduced into a Mathieu-Hill type differential equation describing the instability of heterogeneous orthotropic truncated conical shells using Galerkin's method. The backward and forward excitation frequencies are determined by using Bolotin's method. A comparison with the previous studies has been developed in order to validate the present results. The effects of axial load factors, heterogeneity, orthotropy, as well as the
variation of the characteristics of the conical shell on the backward and forward excitation frequencies are studied in detail.

ABSTRACT: This paper addresses the energy absorption response and crashworthiness optimization of a gradual energy-absorbing structure which is composed of nested thin-walled square tubes under axial quasi-static loading. The experimental and numerical results indicated that the deformation model of the structure is regularly and stable and the collapse process is clearly divided into two stages. The energy distribution of two stages are 43.83% and 56.17%, respectively. To explore the effects of thickness parameters of each part of the structure on energy absorption characteristics such as the specific energy absorption (SEA) and the dimensionless parameter $\phi_1$, which indicates that energy distribution of the collapse process, the response surface (RS) models for the design of experiments (DOE) were employed along with the finite element model (FEM) which is experimentally calibrated. In addition, based on the developed RS models, multi-objective optimization design (MOD) was carried out by using Multi-Objective Genetic Algorithm (MOGA). It was found that the uniformity of energy distribution of two stages and the SEA cannot reach the optimal value at the same time. Lastly, the optimization results can present a good design matrix to get energy-absorbing structures with excellent performance regarding the crash-worthiness of subway vehicles.

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ABSTRACT: In this paper the buckling behaviour of thin-walled members with cross-sections with curved parts is investigated. Due to the curved parts, shell-like buckling is a potential mode of failure. The objective of the research is to understand whether shell-like buckling behaviour might be governing in practical cold-formed steel members. For this aim, numerical studies have been carried out, involving linear buckling analysis as well as nonlinear shell finite element analysis with imperfections, by considering a large number of various cross-sections. Standardized capacity prediction has also been completed, based on elastic critical loads by using the direct strength method, and the results have been compared to that of shell finite element analyses. Based on the results it is concluded that shell-like behaviour might be critical in certain cases, but only in case of unusual cross-section geometries. It was also found that the simple direct strength capacity prediction can reasonably be used in most of the cases.

ABSTRACT: This paper presents a comparative study between Hashin damage criterion and the eXtended Finite Element Method (XFEM) applied to the failure of fiber reinforced polymers (FRP). A brief literature
review on failure criteria to predict the failure of FRP is firstly presented. Then, finite element models of square plates with different layer configurations, containing a circular hole with distinct radii and subjected to monotonic uniaxial tension are described within the framework of ABAQUS package. The models are validated by comparison between the numerical results and those of a benchmark model. Finally, the influence of (i) stacking sequence, (ii) hole radii and (iii) failure criteria (Hashin and XFEM) on the load vs. elongation paths, stresses distributions and collapse configurations of the plates is shown and discussed and some conclusions are drawn.

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ABSTRACT: The thermal and mechanical stability of a functionally graded composite truncated conical shell reinforced by carbon nanotube fibers and surrounded by the elastic foundations are studied in this paper. Distribution of reinforcements across the shell thickness is assumed to be uniform or functionally graded. The equilibrium and linearized stability equations for the shells are derived based on the classical shell theory. Using Galerkin method, the closed – form expression for determining the linear thermal and mechanical buckling load is obtained. The paper also analyzed and discussed the effects of semi-vertex angle, shell length, volume fraction of fibers, distribution pattern of fibers, temperature, elastic foundations on the linear thermal and mechanical buckling loads of the functionally graded carbon nanotube fibers-reinforced composite (FG CNTRC) truncated conical shell in thermal environment.


ABSTRACT: The response of elastic-plastic Miura-ori core sandwich plates to high-intensity dynamic loads is numerically studied using the commercial finite element software ABAQUS/ Explicit. Crushing simulations conducted on the Miura-ori core over a range of loading rates clearly illustrate the dynamic strengthening of the core by inertial effects, particularly at loading rates relevant to blast experiments. Exploratory design studies have been conducted to determine the influence of the unit cell parameters of the Miura-ori pattern on the energy dissipated by the core through plastic deformations, and to compare its performance with that of square honeycomb cores of equal areal density. Material strain rate effects, a material failure criterion and debonding between the core and the facesheets have not been considered. It is found that for low to moderate load intensities, the Miura-ori core consistently outperforms the corresponding honeycomb core in terms of plastic dissipation (by as much as 68%) and facesheet centroidal deflections, and offers a rich design space to tailor its mechanical performance. However, the plastic energy dissipated in the core as a fraction of the total plastic
energy dissipated in the structure is nearly the same for the Miura-ori and the honeycomb core sandwich plates of equal core areal density.

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ABSTRACT: This paper deals with sandwich structures whose core layer is made of a homogeneous foam periodically strengthened by orthogonal reinforcements. Beside traditional sandwiches which generally display satisfactory specific flexural properties but fatally insubstantial stiffnesses in the through-thickness direction, 3D reinforced sandwich materials provide optimal out-of-plane mechanical properties. Despite this, buckling remains one of the major failure modes of such structures and, compared to the case of traditional sandwiches, both global and local buckling phenomena are more complicated in presence of transverse reinforcements. Indeed, in most cases, the modal deformed shapes involve simultaneously the skins and the reinforcements in an intricate way. The main feature of these buckling modes is periodicity, but the typical wave length appears to be generally different from the characteristic length between reinforcements. However, it is possible to investigate such periodic modes on a simple unit cell by using the so-called Bloch wave theory. In this work, an efficient procedure is defined so as to deal with the buckling behavior of a sandwich column with periodic orthogonal reinforcements. First, a numerical method is implemented in the framework of the commercial software Abaqus. The evaluation of the critical strains is performed on a unit cell: an initial average compressive strain is enforced, then natural frequencies are computed and the critical strains are deduced by extrapolation of the previous eigenvalues. A Python program is developed so as to automate these successive calculation steps and a Fortran program is also needed (within Abaqus) in order to cope with the two real and imaginary problems to be solved due to the Bloch-periodic conditions. Furthermore, an exact analytical solution of this problem is obtained in the particular case of a reinforced sandwich with no foam core (for simplicity purposes). The analytical and numerical solutions obtained with a unit cell model are finally compared to the results of numerical computations performed on a complete beam with an arbitrary number of cells, for validation purposes. The critical strains/displacements are found to be in very good agreement and the buckling modes rebuilt from the real and imaginary components of the unit cell modal solutions perfectly coincide with the buckling modes of the complete beam obtained through a linearized buckling analysis.

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ABSTRACT: Recently, a short composite column consisting of dual steel tubes (external and internal stainless and carbon steel tubes, respectively) with concrete filled in the entire tubular section has been introduced. This
A column, called as the concrete-filled dual steel tubular (CFDST) column, proved that a lower cost as well as weight can be achieved compared with the concrete-filled stainless steel tubular column (CFSST). This is mainly attributed to the increased strength of the concrete fill, inside the internal tube, that is surrounded by both the external and internal steel tubes. Based on the fact that the columns are generally slender in practice, this paper investigates numerically, by means of finite element (FE) analyses, the axial compressive behaviour of the CFDST slender columns, which has been rarely investigated in literature. The external tubes are currently made of the lean duplex stainless steel material recently attracted the structural community because of its relatively lower cost. The FE models carefully consider the compressive and tensile nonlinear behaviour of the concrete. The FE models are verified for their different material models. This is followed by examining the accurate overall buckling behaviour of the slender columns. This has been made through FE comparisons with tested columns of different cross-section types existing in literature. The fundamental behaviour of the CFDST slender columns under the effect of the slenderness ratio, the concrete confinement effect and the concrete compressive strength is then investigated. The study additionally addresses the differences in behaviour between the intermediate length and long CFDST columns. Moreover, the comparison between the design strengths calculated by Eurocode 4 from one side and the FE and experimental ultimate strengths from the other side shows generally that Eurocode 4 gives unsafe predictions. Accordingly, a modified European design model is suggested at the end to predict accurately the resistance of the CFDST slender columns under axial compression.

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ABSTRACT: The performance of expanded metal tubes was studied under axial impact loading. Despite their low weight, expanded metal sheets have high energy absorption capacity. In order to evaluate the crashworthiness of the tube and to achieve maximum energy absorption, the collapse mechanism of the tube was experimentally examined considering the direction of the cells. The effect of the cell size of the expanded metal sheet, the thickness of the tube and making the absorber a multilayer on the energy absorption and the behavior of the absorbers was numerically investigated. Results demonstrated that the tubes with zero degree angle cells had a symmetric collapse mechanism. Increase in the size of the cells decreased the peak crushing force and the energy absorption capacity. It was observed that increasing the thickness of the tube and making the absorber a multilayer, will have significant effect on the initial maximum crushing force and energy absorption capacity and making the absorber a multilayer improves the crushing efficiency.

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ABSTRACT: This paper addresses the nonlinear static behavior of an elastic semi-toroidal shell of circular cross section subjected to external hydrostatic loading by using membrane theory. In this study, semi-toroidal
shell geometry can be computed by differential geometry. Energy functional of the semi-toroidal shell can be obtained by principle of virtual work, and written in the appropriate form. The static response of the semi-toroidal shell can be computed by nonlinear finite element method. The nonlinear numerical solutions can be obtained by the iterative method. The effects of sea water depth, cross-sectional radius to thickness, and cross-sectional to bend radii ratios on the displacement responses of the semi-toroidal shell are investigated in this paper. Interestingly, it is found that the maximum value of the displacement responses on the semi-toroidal shell under hydrostatic loading occurred to the toroid internal crest.


ABSTRACT: Axial length parameters of ovality are observed to have effects on the buckling capacity of a pipeline through a parameter analysis. The collapse pressure measured was considerably higher than that calculated by offshore standard DNV-OS-F101 (DNV) when the axial length of ovality was shorter. Effects of composite defects in the form of corrosion ovality on collapse pressure were examined through combined experimental and numerical efforts. We find that the final collapsed configuration and buckling capacity of a pipe are not only affected by the amplitude of maximum ovality and geometric parameters of corrosion but also by their positions. Finally, an improved formula and procedure for estimating the collapse pressure of a pipe with composite defects is established.

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ABSTRACT: This paper presents one and multi-objective crashworthiness optimization of the tapered thin-walled square tube with indentations. In this study, effects of cross section, thickness, taper angle, number and radius of indentations (as design variables) on the beam's energy absorption capability during crashes are investigated. The crashworthiness of models is evaluated using two metrics: The specific energy absorption per unit mass (SEA) and the ratio between the average and maximum crushing forces \(CFE=F_{\text{avg}}/F_{\text{max}}\). The optimum values of the number and radius of the indentations, the taper angle, the tube thickness and the cross section using a combination of response surface (RS) model, genetic algorithm and desirability function optimization are obtained. Multi-objective optimization of the tubes is performed by maximizing a composite objective including CFE and SEA. Analyses involved in this paper are undertaken using finite element models and solver (Abaqus). Also the computer program MATLAB is used to perform all the analyses and the optimization. Multi-objective optimization of the tubes showed that the tapered thin-walled square tubes with indentations have significantly, better crush performance in comparison to those without indentations. It is found that maximum CFE requires large number and radius of indentations, thickness, and cross section with small taper angle, while maximum SEA requires medium number of indentations and radius, large thickness and small taper angle and cross section. Also, the sensitivity of the design variables on the tapered square
beam's crash behavior performance is analyzed. The objective functions, including SEA and CFE, were formulated using the Response Surface Method.

ABSTRACT: This paper is dedicated to providing a detailed plastic collapse load analysis for un-cracked and circumferential through-wall cracked pipe bends under torsion moment by three dimensional FE methods considering geometric nonlinearity. For un-cracked pipe bends results show that radius-to-thickness is the main factors affecting the plastic collapse load. For cracked pipe bends the weakening factor decreases with increasing crack length, and the decreasing rate exhibits three typical stages which performs a similar trend with that in bending case. Although the weakening factor in plastic collapse load shows the similar variation based on geometric nonlinearity with that based on geometric linearity change, the limit load solutions based on geometric linearity fail to be used in prediction for torsion load based on geometric nonlinearity. So estimating limit load solutions by FE method are proposed, which shows a better choice compared with the past solutions. Furthermore the effect of yield strain is considered with the normalized parameter proposed to represent this weakening effect of yield strain on torsion moment. Results show that pipe parameters bend radius-to-radius and crack length have little impact on the weakening parameter, however radius-to-thickness have an obvious impact on the weakening parameter, which increases with decreasing weakening parameter. Results also show that radius-to-thickness has a great impact on the ovality deformation, while bend radius-to-radius hasn't. Therefore geometry effect is significant for a high yield strain value and a high radius-to-thickness value.

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ABSTRACT: An analysis of delaminated composite plates with integrated active fibre composite (AFC) actuators and sensor under hygrothermal environment has been undertaken in the present work. The top and bottom plies of the laminate constitute AFC actuators and sensors. In the present investigation, hygrothermal loading is taken into consideration, and the effect of moisture and temperature on the delaminated plate structures is analysed. The minimum total potential energy approach is used for arriving at the governing equation. A finite element model for centrally located delamination is developed on the basis of first order shear deformation theory. An eight noded serendipity element with five degrees of freedom per node is considered for the finite element formulation. A parametric study on the effect of stacking sequence, boundary conditions and environmental conditions in the presence of delamination on the laminated plate is studied. The key observations from the parametric study are: there will be reduction in natural frequencies in the presence of delamination and/or hygrothermal loading, and reduction in structural stiffness due to the presence of delamination can be negated by applying voltage to the active fibre actuator layer.

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ABSTRACT: This paper presents a method to generate design charts and preliminary design rules for the buckling behaviour of stiffened panel plate elements with buckling containment features. Two modelling approaches are used one with an analytical basis using classical plate theory and one with a numerical basis using the FEM to generate the design charts. The individual modelling approaches are used for cross verification. A novel design chart, based on key geometric ratios is introduced and its use demonstrated. Finally design chart data is explored to demonstrate the formulation of simple design rules which are appropriate for preliminary structural design.

T.A. Sebaey and E. Mahdi (Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, 2713 Doha, Qatar), “Crushing behavior of a unit cell of CFRP lattice core for sandwich structures’ application”, Thin-Walled Structures, Vol. 116, pp 91-95, July 2017, https://doi.org/10.1016/j.tws.2017.03.016

ABSTRACT: Sandwich structures made of composites are designed mainly for higher and efficient load capacity. Mostly, the use of composite materials in lattice core sandwich structures is limited to the face sheet; whereas, the core is usually made of metals due to the difficulty in producing the FRP lattice shape. A sandwich with a core made of FRP is believed to be lighter and better in terms of specific strength and absorbed energy. In order to manufacture the sandwich core, several methods and techniques were developed based on the designed core profile. In this paper, the core was extracted (using laser cutting) from the standard flame retardant carbon fiber hat stiffener. Four values of the strut angle $\alpha$ were considered ($\alpha=45, 60, 75$, and $90^\circ$). Crushing tests were performed using Instron Compression machine and a load cell of 5 kN capacity. Similar post crushing profiles were obtained for all the specimens. However, the peak load is being shifted upward. Improvements of 75% and 54% were recorded for the peak and the average crushing loads respectively. It is worth remarking that the crush load efficiency was kept constant during the tests. The energy and the specific energy absorption showed that the unit cells with $90^\circ$ are at advantage since it is almost 53% higher than that of the $45^\circ$. For the effect of filler, the tests results show how important it is to fill such thin skeletal structures.

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ABSTRACT: The behaviour of Carbon Fibre Reinforced Polymers (CFRP) reinforced mild steel isolated plate (strut) under uniform axial compression is not well understood because there is a lack of experimental research. This paper presents experimental results for a series of struts reinforced with CFRP sheets subjected to uniform axial compression. The main parameters examined were the thickness of the steel plates, and the location and the number of the CFRP sheets. Three different thicknesses of steel plates were examined, namely, 2, 3 and...
4 mm. The testing program included 21 struts with three different width-to-thickness ratios of 50, 66.7, and 100. The CFRP sheets were adhesively bonded where the fibres were aligned in the longitudinal direction parallel to the direction of the applied force. The results showed that the debonding failure strain in the compression face occurred in the range of 0.3–0.6% for all the composite specimens. It was found that the amount of permanent damage in the composite strut identified by the residual displacement is significantly less than that of the bare strut. Experimental results showed a global increase in strength, energy absorption and ductility for all test specimens where the greatest percentage increases were 452%, 259% and 107%, respectively. The 2 and 3 mm composite specimens showed greater percentage increases than the 4 mm composite specimens due to the relative thickness of the carbon fibre sheets verses steel. All experimental specimens failed by overall buckling, achieving maximum capacity at the end of their elastic range showing that the specimens were successfully bonded and acting as composites within such range. An existing rigid plastic theory considers initial imperfections (defects) was modified and used to predict the response of the struts. Experimental and theoretical curves showed consistency where initial defects controlled the elastic-inelastic behaviour and the load bearing capacity of the strut. In general, specimens with initial defects produced a smooth elastic-plastic curve, while specimens with little to no initial defects showed a sharp peak at the buckling load. The rigid plastic theory well predicted the response of the bare specimens whereas it reasonably predicted the plastic collapse curve of the composite struts.

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ABSTRACT: Natural extreme events such as earthquake and fire are destructive for building structures. Earthquake is not only a destructive extreme event but also can trigger other extreme events such as fire. The possible post-earthquake fire (PEF) can be a more destructive scenario for building structures. For safety reasons, it is necessary to capture the behaviour of structural components under PEF scenario. This study aims to investigate the behaviour of flange-welded/web-bolted steel I-beam to box column connections subjected to PEF scenario. Experimental tests were carried out on two groups of steel connections under ISO fire. In each group, four connections were fabricated with the same specifications in which one connection was tested under fire only while the other three connections were tested under cyclic loading and subsequent fire. During the fire stage, the connections were subjected to constant static load equivalent to 30% of their ultimate monotonic loading strength. The furnace temperature, temperature distribution of connection and the beam deflection of connection were measured during the fire tests. It was found that the load-carrying capacity of the flange-welded/web-bolted connections decreases significantly with the increase of pre-damage level induced by cyclic loading. Additionally, in order to study the temperature distribution of the connections under fire, preliminary finite element modelling was carried out for a heat transfer analysis on the basis of uniform fire exposure.

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ABSTRACT: The isogeometric analysis (IGA) proposed by Hughes is a new approach in which Non-Uniform Rational B-Splines (NURBS) are used as a geometric representation of an object. It has superiorities of capturing exact geometry, simplifying refinement strategy, easily achieving degree elevation with an arbitrary continuity of basic functions and getting higher calculation accuracy. In this paper, the IGA approach is extended to solve the free vibration problem of curvilinearly stiffened cylindrical and shallow shells. The first-order shear deformation theory (FSDT) and the Reissner-Mindlin shell theory are used to model the shells, and the three-dimensional curved beam theory is employed to model the stiffener which can be placed anywhere within the shell. Some numerical examples are solved to study the vibration behavior of the curvilinearly stiffened shells. The effects of shell and stiffener element numbers, boundary conditions, stiffener ply modes and shell thicknesses on the natural frequency are investigated. Results have shown the correctness and superiorities of the present method by comparing the results with those from commercial finite element software and some numerical methods in existing literatures. One of the advantages is that the element number is much less than commercial finite element software, whereas another is that the mesh refinement process is much more convenient compared with traditional finite element method (FEM).


ABSTRACT: This manuscript employed experimental and numerical procedures to investigate the effects of initial geometric imperfection on the buckling behavior of the perfect and perforated composite cylinders. In the numerical part, linear eigenvalue analysis of the perfect cylinder showed a large discrepancy in comparison to the NASA SP-8007 guideline from 1968. However, results were considerably enhanced by performing a nonlinear analysis where initial geometric imperfection was simulated using Single Perturbation Load Imperfections (SPLI) and Linear Buckling Mode-shaped Imperfections (LBMI) techniques. Numerical analyses were performed for three different groups of the perforated cylinders to evaluate the effect of the growing cutout size on the buckling behavior. In addition, the mutual effect of the cutout and the initial geometric imperfection on the buckling analysis were investigated. Results confirmed that cutout effect is dominant, for the cylinder under consideration, so considering initial geometric imperfection has a negligible effect on the predicted buckling load. In the experimental part, perfect and perforated glass/epoxy composite cylinders with a stacking sequence of [90/+23/-23/90] were manufactured using filament winding technique and tested under compressive axial loading. Buckling test data of the perfect and perforated cylinders showed an acceptable correlation with the numerical results obtained using the nonlinear analyses methods.

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ABSTRACT: A semi-analytical procedure for free and forced vibration analysis of multi-stepped circular cylindrical shell with arbitrary boundary conditions is developed with the employment of the method of
reverberation-ray matrix. Based on the Flügge thin shell theory, the equations of motion of the circular cylindrical shell are introduced and exact solutions of the traveling wave form along the axial direction and the standing wave form along the circumferential direction are obtained for each segment of uniform shell. With such a unidirectional traveling wave form solution, the method of reverberation-ray matrix is adopted to calculate natural frequencies and steady-state responses of the multi-stepped circular cylindrical shell. Comparisons of the present results with those previously published in literature and those obtained by the finite element method prove that the method of reverberation-ray matrix is applicable and of high precision for free and forced vibration analysis of the multi-stepped circular cylindrical shell. Effects of elastic support stiffness and the number of steps on natural frequencies are investigated.


ABSTRACT: Cold-formed steel hollow flange sections are structurally efficient compared to the conventional open channel sections. They can be of different forms including hollow flange I- and channel sections, which are generally fabricated by first cold-forming a single sheet to form the desired shape and then connecting their flange and web elements by continuous welding. Instead of welding, intermittently screw/rivet fastened or spot welded connection can also be used. A detailed investigation is currently under way on the structural performance characteristics of such intermittently screw/rivet fastened steel hollow flange sections. This paper presents the details of an experimental study performed to investigate the behaviour of built-up cold-formed steel hollow flange sections in compression, where more than 45 stub columns were tested. Both hollow flange I- and channel sections built-up using either single steel sheet or three steel elements were tested. Tests also included built-up hollow flange channel sections with stiffened web elements. Test results including the failure loads, load versus axial deformation plots and failure characteristics are presented in this paper. Test failure loads are compared with the predictions based on both effective width and direct strength methods to verify their adequacy in predicting the section compression capacity of built-up hollow flange sections. This paper has shown that although hollow flange I-sections made of three elements with a 100 mm fastener spacing can perform similar to continuously welded sections, hollow flange channel sections undergo premature failures even with a 50 mm fastener spacing, and the reasons are discussed.

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“Refined nonlinear finite element modeling towards ultimate bending moment calculation for concrete composite beams under negative moment”, Thin-Walled Structures, Vol. 116, pp 201-211, July 2017

ABSTRACT: In this study, a refined nonlinear finite-element (FE) model of steel-concrete composite beam (SCCB) capable of accommodating various effects such as the initial geometric imperfection, residual stress, interface slip, geometric nonlinearity, and material nonlinearity is developed to study the distortional instability of SCCBs under negative bending moment. The accuracy of the model is validated by publicly available results previously observed by experiments. On the basis of the refined nonlinear FE model, the ultimate bending moment of 54 groups of SCCBs with varying cross-section parameters is calculated. Also, the effects of the force ratio of the SCCB, width–thickness ratio of the compression flange, shear connection degree, and height–thickness ratio of the web on the ultimate bending moment stability coefficient of SCCB in negative bending
moment area are investigated in detail. Results show that the effect of the degree of shear connection on the stability coefficient of the SCCB is insignificant, while the stability coefficient decreases with the increase of the remaining parameters, among which the effect of the height–thickness ratio of the web is proven to be the most significant. Finally, considering various effects aforementioned properly, practical formulas are proposed to compute slenderness ratio and ultimate bending moment stability coefficient of SCCB in a concise form, which are shown to be consistent with the FE modelling and experimental results, and thus are suitable for engineering design.


ABSTRACT: Two type novel aluminum foam filled energy absorption connectors were proposed to be inserted between the blast resistant façade and building to absorb blast energy and reduce blast load transferred to the building. In this paper, the nonlinear finite element (FE) method was adopted to study the energy absorption performances of the two type connectors. The FE models of the connectors under quasi-static compression loading were first established and the accuracies of the FE models were verified by comparing the force–displacement curves obtained from tests and FE analyses. Then, the FE models were used to investigate the effects of filled aluminum foam, plate thickness and geometry as well as aluminum foam width on the energy absorption performances of the two type connectors. It was found that the two type connectors showed comparable energy absorption performances and the specific energy absorption could be significantly improved by filling the connector with aluminum foam.


ABSTRACT: It is well accepted that, for a long column, the effect of end conditions on the local buckling load can be ignored due to its less impact. However, such an assumption may be inappropriate for a stub column. According to the available literature, the research dealt with such a problem was found to be quite rare. In this scenario, this paper aims to derive novel local buckling formulae for cold-formed C-section column, which takes both the effects of cross-section plate element interactions and end conditions into account. Initially, an equivalent simplified web local buckling model was proposed, in which the cross-section plate element interaction of the flanges and the lips on the web were modeled by rotational springs and the loaded edges were assumed to be uniformly compressed and to be simply supported or fixed. Subsequently, based on the energy method and the theory of Bleich, explicit expressions for the local buckling load of the column were derived. Further, simplifications to the rigorous formulae were made to allow them to be easily used by the engineers. Finally, in order to verify the accuracy of the derived formulae, the results obtained from the derived formulae were compared with the numerical results obtained from the computer software CUFSM. The comparison results show that the formulae proposed in this paper can be used successfully in estimating the local buckling loads for pin-ended or fix-ended C-section columns with a practical length.

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ABSTRACT: The grout is often used to fill the gap between two tubes as binding material in some specific structures, which may actually form a grout-filled double skin steel tube. However, little literature has been found regarding the behaviour of the grout-filled double skin steel tubular (GFDST) member, while the influence of the in-filled grout could be underestimated in the steel-grout composite structure. This paper thus presents an experimental investigation of the compressive and flexural behaviour of GFDST members. A total of 14 specimens are tested, including 8 stub columns, 4 beam-columns and 2 beams. For the axially compressed stub columns, the main test parameter is the hollow ratio of the cross section, and 2 corresponding hollow steel counterparts are designed to study the effect of the grout filling. For the beam-columns, the influences of load eccentricity are analyzed through test results. The failure modes, the strain distribution and the ductility of the GFDST members are studied in order to sufficiently evaluate the performance of the steel-grout composite member. The ultimate strengths of the GFDST members are estimated by the equations of concrete-filled double skin steel tubular members tentatively. It is found that all tested specimens failed in a ductile way, and the stiffness, the ultimate strength and the ductility of GFDST member is improved attributing to the in-filled grout. In addition, the predicted stiffness and strength results generally match well with the measured ones.

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ABSTRACT: The study presents the post-buckling behaviour of thin-walled beam of open section supported by Winkler-Pasternak foundation and it is subjected to an axial compressive load. Here, the assumptions are the strains to be small and elastic, in-plan cross-sectional deformations and the shear deformations to be negligible. The post-buckling paths are determined for clamped beam of I-cross-section which is constant. The point of bifurcation for clamped beam is calculated. It is found to be symmetric and stable for various values of Winkler-Pasternak foundation parameters and Warping parameter.

ABSTRACT: The paper is devoted to a thin-walled rectangular frame. The frame is simply supported in the planes of symmetry and in-plane compression forces are applied in the corners. The longitudinal and transverse thin-walled beams of the frame are rigidly joint at the corners. Two buckling forms of the frame are studied. The analytical and numerical-FEM (SolidWorks) models are formulated. The results of the studies are presented in Tables and Figures.
ABSTRACT: Web openings are commonly used in beams of buildings to facilitate services. In this paper, a combination of tests and non-linear finite element analyses is used to investigate the effect of such web openings on the web crippling strength of cold-formed ferritic stainless steel unlipped channel-sections under the interior-two-flange (ITF) loading condition; the cases of both flanges fastened and flanges unfastened to the bearing plates are considered. The results of 54 web crippling tests are presented, with 18 tests conducted on unlipped channel-sections without web openings and 36 tests conducted on sections with circular web openings. In the case of tests with web openings, the circular web openings are located either centred or offset to the bearing plates. A quasi-static finite element model is then presented. Good agreement between the tests and finite element analyses is obtained in terms of failure load, failure modes and post-buckling behaviour.

ABSTRACT: A parametric study of unlipped cold-formed ferritic stainless steel sections with circular web openings subjected to web crippling under interior-two-flange (ITF) loading condition is undertaken, using quasi-static finite element analysis, to investigate the effects of web openings and cross-section sizes. The circular web openings are located either centred or offset to the bearing plates. The strengths obtained from reduction factor equations are first compared to strengths calculated from equations recently proposed for cold-formed stainless steel lipped channel-sections. It is demonstrated that the strength reduction factor equations previously proposed for cold-formed stainless steel lipped channel-sections can be unconservative for cold-formed ferritic stainless steel unlipped channel-sections by up to 10%. Design recommendations in the form of web crippling strength reduction factor equations are proposed, which are conservative when compared to the both experimental and finite element results.

ABSTRACT: This two-part contribution presents a novel theory of bending of thin-walled beams with influence of shear (TBTS). The theory is based on the Vlasov’s general beam theory as well as on the Timoshenko’s beam bending theory. The theory is valid for general thin-walled open beam cross-sections. Part I is devoted to the theoretical developments and part II discusses analytical and obtained numerical results. The theory is based on a kinematics assuming that the cross-section maintains its shape and including three independent warping parameters due to shear. Poisson’s effect is ignored, as well as warping constrains due to shear (as it known, those effect have small and for engineering praxis neglected influence on the stresses and
displacements). Closed-form analytical results are obtained for three-dimensional expressions of the normal and shear stresses. Under general transverse loads, reduced to the cross-section principal pole, the beam will be subjected to bending with influence of shear and in addition to torsion due to shear with respect to the cross-section principal pole and to tension/compression due to shear, in the case of non-symmetrical cross-sections. The beam will be subjected to bending with influence of shear (i) in the plane of symmetry under the loads in that plane and in addition to tension/compression due to shear, (ii) in the plane through the principal pole orthogonal to the plane of symmetry under the loads in that plane and in addition to torsion with respect to the principal pole, in the case of the mono-symmetrical cross-sections. The beam will be subjected to bending with influence of shear in the principal planes, in the case of the bi-symmetrical cross-sections. The principal cross-section axes as well as the principal pole are defined by the classical Vlasov’s theory of thin-walled beams of open section. The analytical and numerical analyses presented in part II include comparisons with the classical beam theory, Euler-Bernoulli’ theory (EBBT) as well as comparisons with the finite element method (FEM).

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ABSTRACT: This two-part contribution presents a novel theory of bending of thin-walled beams with influence of shear (TBTS). The theory is valid for general open thin-walled cross-sections. The loads are reduced to the cross-section principal pole, i.e. the cross-section shear center. In part I, the TBTS is established, in this part II, the theory is used to analyze various beam cross-section shapes, loads and boundary conditions. Beams with the extreme low ratios of beam length to beam cross-section contour dimensions are analyzed. The stress predictions of the TBTS, stresses as functions of the longitudinal coordinate as well as the cross-section curvilinear coordinate, are compared to those obtained by finite elements computations (FEM) as well as to exact solutions of the theory of elasticity. The results of the TBTS are given in closed analytic forms, i.e. parametric forms, suitable for general studies of thin-walled beam behavior under transvers bending loads, as well in the early design stage of thin-walled structures.

ABSTRACT: In the present study, the crashworthiness and the numerical simulation of circular hybrid aluminium-CFRP tubes are investigated. It can be shown that hybrids provide significant lightweight potential. The specific energy absorption is 37% higher compared to a pure aluminium structure. The post-crash analysis is done by computed tomography methods. The failure of the hybrid component shows a mixture of energy absorption mechanisms of its pure materials. Hybrid-specific energy absorption mechanisms compensate the limited primary energy absorption mechanisms of the CFRP and metal components. The simulation of axial-loaded composite structures is challenging the currently available simulation methods. In the present work, a multi shell model is used for the simulation of the hybrid structure. This approach enables an efficient design of CFRP-aluminium hybrid components. First approaches towards the simulation of hybrid specific failure modes are given.
ABSTRACT: Tailor rolled square tubes with continuous thickness variation along axial direction are successfully obtained by subsequent forming of tailor rolled blanks manufactured by variable gauge rolling technology. The crashworthiness of tailor rolled tubes and traditional equal thickness tubes under axial crashing tests are compared and analyzed. From the test results it can be known that the initial peak load of given tailor rolled tubes are ranged from 45 kN to 58 kN, which are 52–63% lower than that of traditional tubes. For the combined action of axial variable thickness and variable strength, the energy absorption value and energy absorbed efficiency of tailor rolled tubes respectively 11% and 10.7% larger than traditional tubes. The primary cause of increasing energy absorption is that more metal of tailor rolled tube be entered into plastic deformation stage. In addition, the folding of tailor rolled tubes is always stated to occur at the thin zone near the tube end. Then, it is gradually progressed to the thick zone with graded increased wavelengths. It is should be pointed out that the fold number of tailor rolled tubes after crashing is more than corresponding traditional tubes. According to the crashworthiness criteria, this novel tube structures produced by rolling technology are more suitable for energy absorbing structure. The finite element models are also established considering variation both in thickness and in material strength, and it was verified by experiments. Afterwards, these validated models are carried out to study the crashworthiness of tailor rolled tubes under different geometric parameters. It is concluded that the shorter tailor rolled tubes and proper length of thickness transition zone is of more benefit to improve energy absorption efficiency. It can be concluded that the optimization thickness distribution and material strength of tailor rolled tubes can be designed according to the actual multi-requirements, and can be large-lot manufactured by variable gauge rolling technology to maximize the energy absorption and material saving.

displacement interpolation functions. The results of the presented study were obtained using an open-source software and multi-purpose software Abaqus. Moreover, the accuracy of the applied computational approach has been verified by comparison with results from the literature. An excellent agreement of displacement fields is achieved for large deflection analyses of plates with a hole and stiffeners as well as for shells with a stepped thickness in the longitudinal direction. Additionally, results from post-buckling analyses of thin-walled structures, a snap-through and snap-back behavior of shallow shells, are matched. The work presented here has profound implications for future studies of the finite strip deployment.

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“A modified Kirchhoff plate theory for analyzing thermo-mechanical static and buckling responses of functionally graded material plates”, Thin-Walled Structures, Vol. 117, pp 113-126, August 2017
https://doi.org/10.1016/j.tws.2017.04.005
ABSTRACT: In this paper, we present a modified Kirchhoff theory for analyzing thermo-mechanical static and buckling responses of functionally graded material (FGM) isotropic and sandwich plates. In comparison to the classical Kirchhoff theory, the proposed method is taken account into the shear deformation effects, then it can be applied for both moderately thick and thin plates. On the other hand, comparing to the first order shear deformation theory (FSDT) or Reissner-Mindlin plate theory, the number of independent unknowns reduces one variable and retains four degrees of freedom (Dofs) per node. The shear locking phenomenon is also negligible due to extending from the classical Kirchhoff theory. Furthermore, a new normalization of a quartic form is used to build the shape functions in the radial point interpolation method (RPIM). The novel imposing essential boundary conditions related to slopes of deflections has been proposed, then the enforcement of these gradient deflections becomes easily and directly as the same in finite element analysis. The obtained numerical results for the thermo-mechanical static and buckling problems from the proposed method are stable and well accurate prediction as comparing to the exact solutions and other published analyses.

ABSTRACT: This paper deals with developing advanced, yet design-oriented expressions for ultimate strength of the newly developed hollow corrugated stub columns with or without ultra-high strength corner tubes under uniaxial compressive loading. This is achieved by individually analysing comprising self-strengthened corrugated plates using the effective width concept whilst the effect of corner enhancement is taken into calculation. For stiffened panels such as corrugated plates, the ultimate limit state design is equated to the lowest value among all collapse provisions. However, the finite element analyses show that Euler buckling state may govern the ultimate load capacity of corrugated plates used in the proposed columns. This is verified by comparing the results obtained from the proposed analytical formulations with those demonstrated by the finite element moulding and experiments. The results are also compared with the guidelines for design of corrugated panels available in the literature. Finally, several cases with different corrugation geometrical parameters are defined and the capacity of corresponding columns is evaluated and compared to each other.
ABSTRACT: Tensairity dome is a lightweight spatial structure composed of struts stabilized by cables and airbags inflated by low pressurized air. Two forms of Tensairity domes with annular airbags, stiffened with central cables or webs placed between the upper and lower chords, were proposed based on the Tensairity concept. The zero-stress state, the initial state and the loaded state were successively simulated to investigate the static behavior of the structures, respectively. The results indicate that both two forms of structure have good static performance and the internal pressure in the airbag at about 1000–4000 Pa can ensure the stabilizing role of the inflated airbag. The investigation reveals the subtle interplay between the internal pressure and external loads in the load state, and the tremendous effect of temperature change on overall structure is predicted. The comparisons also show the benefits of webs in the structure for all load cases. Finally, the results show the attractive advantages of Tensairity dome in comparison with conventional structures in terms of structure weight and overall stiffness.

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“Multiobjective crashworthiness optimization of thin-walled structures with functionally graded strength under oblique impact loading”, Thin-Walled Structures, Vol. 117, pp 165-177, August 2017
https://doi.org/10.1016/j.tws.2017.04.007
ABSTRACT: In this paper, the crashworthiness of a new introduced thin-walled structure made of hot stamping high strength steel with functionally graded strength (FGS), i.e. wall strength varying along the axial direction with a specific gradient, is investigated. The FGS columns are comprehensively studied under both axial crushing and oblique impact loading in the nonlinear FE mode LS_DYNA. The numerical simulation result shows that parameters of gradient exponent $m$ and top strength $S$ of FGS columns have a remarkable effect on the crashing behavior indicators such as critical load angle, energy absorption (EA) and peak crash force (PCF). To optimize the crashworthiness of the FGS columns, multi-objective optimization based on surrogate model of Radial Basis Function (RBF) and algorithm of Non-dominated Sorting Genetic Algorithm II (NSGA-II) are performed. To effectively consider the load angle uncertainty effect and obtain a more robust design, four schemes are employed to evaluate the comprehensive crashworthiness with different weight coefficient distributions. The result shows that all the Pareto fronts of FGS columns indicate considerably better crashworthiness compared to that of the counterpart uniform strength (US) columns. The consistent optimization result under different evaluation schemes not only provide guidance for the FGS column design, but also declare a good robustness for Pareto designs obtained by multi-objective optimization design (MOD) optimization. Finally, the obtained Pareto fronts of FGS columns are obviously found to consist of two parts. The first part contains the columns that possess gradient exponent ranging from 0 to 3 with top strength keeping a constant value near 480 MPa. The second part consists of the columns that possess gradient exponent keeping constants close to 0 with the top strength ranging from 700 to 950 MPa. This optimum results is different from that only obtained from pure axial crushing analyze in the previous researches and shows a better reference for engineering practice.

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ABSTRACT: Elliptical cylindrical shell is one of shells with special shape. Up to date, there is no publication on vibration and dynamic of functionally graded elliptical cylindrical shells. Therefore, the purpose of the present study is to investigate the nonlinear dynamic response and vibration of imperfect eccentrically stiffness functionally graded elliptical cylindrical shells on elastic foundations using both the classical shell theory (CST) and Airy stress functions method with motion equations using Volmir's assumption. The material properties are assumed to be temperature dependent and graded in the thickness direction according to a Sigmoid power law distribution (S-FGM). The S-FGM elliptical cylindrical shell with metal-ceramic-metal layers are reinforced by outside metal stiffeners. Both the S-FGM elliptical shell and metal stiffeners are assumed to be in thermal environment and both of them are deformed under temperature simultaneously. Two cases of thermal loading (uniform temperature rise and temperature variation through thickness) are considered. The nonlinear motion equations are solved by Galerkin method and Runge-Kutta method (nonlinear dynamic response, natural frequencies). The effects of geometrical parameters, material properties, elastic foundations Winkler and Pasternak, the nonlinear dynamic analysis and nonlinear vibration of the elliptical cylindrical shells are studied. The some obtained results are validated by comparing with those in the literature.

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"Crushing analysis and multiobjective optimization design for rectangular unequal triple-cell tubes subjected to axial loading”, Thin-Walled Structures, Vol. 117, pp 190-198, August 2017
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ABSTRACT: Multi-cell thin-walled tubes have proven to be better in energy absorption than plain square tubes subjected to axial compression. Therefore, square multi-cell structures have been extensively utilized as energy absorbers in automobiles. This paper provides an investigation on the crashworthiness of rectangular single-, double- and triple-cell columns under axial loading and an optimization design of rectangular unequal triple-cell tubes. First, a theoretical solution is derived for the mean crushing force (MCF) of tubes with unequal triple-cell configuration. Second, quasi-static crushing experiments and finite element analyses (FEA) are conducted on single-, double- and unequal triple-cell columns. Theoretical predictions compare well with experimental and numerical data, and all results show that the triple-cell tubes exhibit the best crashworthiness among all the samples. Third, in order to study effects of wall thickness distribution and the layout of internal ribs on crashing behavior, multiobjective optimization design is implemented combining Radial Basis Function (RBF) model with Non-dominated sorting Genetic Algorithm II (NSGA-II). The optimal solution obtained from Pareto frontier indicates that unequal triple-cell tube with appropriate thickness distribution and arrangement of internal ribs is superior in energy absorption to initial design.
ABSTRACT: Ultimate load behaviour of perforated steel plate girders with inclined stiffeners is presented in this paper. A series of experimental tests on ten simply supported girders were tested to failure under shear load applied at the centre of gravity of the section. Centrally located circular web openings of various diameters were introduced at the middle panels of the girders. Effects of different inclination angles of intermediate stiffeners on the post-buckling behaviour are the main focus of the present study. Five different angles, viz., 90°, 75°, 60°, 45° and 30°, measured from the bottom flange, were accounted for in the tests. Considerable variations of strength, failure characteristic, and load-deflection response may be observed due to effects of such inclinations. Test results show significant increases in the ultimate strength to the extent of 92% as the angle of inclined stiffeners reduced. Non-linear finite element analyses were also carried out to provide additional support for the test results. A reasonably close agreement between the two sets of results establishes the accuracy of the numerical analysis.

ABSTRACT: A thin-walled tube referred to as trapezoid origami crash box is recognized as an energy absorption device. The surface of this tube is prefolded in the light of a developable origami pattern that is delicately designed to introduce a special structure on the surface of a square tube. This special structure, known as trapezoid folded lobe, is employed as a type of geometric imperfection to lower the peak force and as a mode inducer to trigger the complete diamond mode. The quasi-static numerical simulations reveal that the complete diamond mode is successfully triggered. Moreover, geometric and compliance analysis suggest that three key parameters, the number of module $M$, dihedral angle $\theta$ and area ratio $\omega$, could greatly affect the collapse behavior. Based on those analysis, an optimal trapezoid origami crash box is designed to compare with the conventional square and octagonal tubes of identical weight. Furthermore, a series of diamond origami crash boxes are analyzed to compare with the trapezoid origami crash boxes. The comparative results show that the trapezoid origami crash box is the most desirable in terms of energy absorption.

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ABSTRACT: Cold formed steel members are widely applied in light roofing systems, mainly with trussed structural solutions. Developed from thin steel sheets (usually of around one millimeter thickness) stiffened trapezoidal CFS can be considered as an alternative for large span roofing, allowing the assembling of an
orthotropic roofing system. In order to improve its flexural buckling behavior, these thin-walled sections must be designed with intermediate stiffeners and quite large possibilities can be achieved in order to (i) improve the cross-section strength under bending moment, (ii) simplify and improve the stiffeners arrangement, (iii) maximize the roof covering width, (iv) develop the roofing system for long span bridging and (v) design with as thin as possible steel sheets. Considering all these conditions, the general cross-section shape can be infinitively modified adopting different stiffener geometries, dimensions, distribution, as well as combining distinct stiffeners along the cross-section. Rational systematic choices and buckling results allowed identifying the “best” solutions, taking advantage of the shape grammar contribution combined with finite strip method buckling analysis. The obtained results revealed the key geometric parameters that must be considered to perform effective improvement of roofing trapezoidal CFS.

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ABSTRACT: An efficient Galerkin meshfree flat shell formulation is presented for the analysis of buckling behaviors of stiffened plate structures. Both plate bending and membrane deformations are approximated by the reproducing kernel particle method (RKPM). The governing equation is transformed into a weak form, and it is discretized by the scattered nodes. The stiffness matrix is numerically integrated with the nodal integration technique, i.e., the stabilized conforming nodal integration (SCNI). The RKPM and SCNI based flat shell modeling approach can address the shear locking problem. Additionally, the present discretization is further improved by involving a drilling rotation component, which is to effectively model the stiffeners. There are six degrees of freedom per node. A singular kernel is also introduced into a set of the interpolants to model the web/flange connection, as well as the imposition of the essential boundary conditions. A generalized eigenvalue problem is analyzed for evaluating buckling loads/modes of the stiffened plate structures. The accuracy of the numerical results and the effectiveness of the proposed method are examined through several numerical examples.

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ABSTRACT: In this study, the effect of hole reinforcement on the buckling behaviour of thin-walled structures mostly used in aircrafts is investigated under combined loads. A fuselage floor beam with real dimensions is used for the buckling analysis, and a parametric study based on several loading scenarios is considered. Investigated structures include different ratios of hole diameter to reinforcement width (d/w), ratios of
reinforcement height to web plate thickness (h/t), and the aspect ratio of the web plate (a/b). The material of the thin walled structure is Al 7075 series. The commercial finite element analysis program, ABAQUS, is used for buckling analysis. The loading scenarios such as compression, shear, and bending, as well as combined loading are considered using a validated finite element model. For the selected range of geometrical parameters, buckling loads and allowable buckling stresses are computed. Furthermore, compression, shear and bending rates are calculated, and the interaction curves are plotted with the help of data obtained from the finite element studies. The effect of loading scenario on the buckling strength is compared for beam without a hole, with a hole and with a hole plus reinforcement cases. The main goal of this study is to provide engineers graphical data that can be used to check whether or not a structure will fail under several defined load cases including combined loading.


ABSTRACT: The purpose of this research was to experimentally investigate the effect of lateral impact on the residual axial strength of circular hollow section (CHS) columns. In this study, forty-eight specimens including three specimens left untreated for comparison were studied to investigate the effect of the impact energy, impact location and diameter-thickness ratio on the residual axial strength of CHS columns. The failure modes, residual axial strength, initial stiffness and ductility of impacted specimens were reported. The test results indicated that lateral impact has an evident effect on axial compression behaviour of CHS columns. With the increase of impact energy, the lateral plastic deformation increased and the residual axial strength reduced. In addition, the reduction of axial strength of specimens reached 40.98%, compared with that of specimens untreated. The results also show that the impact location has an evident effect on the axial bearing capacity of CHS columns, and through the analysis of the effect of diameter-thickness ratio on the residual strength of CHS columns, it could be observed that specimens with large thicknesses, have a better performance of impact resistance. Based on the extensive experimental analysis, calculation equations were proposed to predict the residual axial strength of CHS columns tested, providing reasonably good correlation with the experimental results. The research results can still provide the basis for further theoretical and relevant finite element researches.

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ABSTRACT: Aiming at the optimization of aircraft panels, a modified version of harmony search (HS) algorithm is proposed based on the information of the harmony memory (a memory location where all the solution vectors are stored) for improvisation procedure, named as adaptive dynamic harmony search (ADHS) algorithm. In order to reduce the amount of calculation, response surface method is employed, and second-order polynomial with cross terms is used to construct the model. To demonstrate the advantage of the proposed algorithm, typical aircraft panels under buckling constraint are established, and several existing HS algorithms are compared. The effects of the number of improvisation (NI) and harmony memory size (HMS) are investigated and discussed in detail. Results indicate that the proposed ADHS can provide an optimum design in a robust manner, and local optimum solutions may be reduced based on the ADHS for optimization problems.
with multiple local minima. Finally, several useful information is obtained for the design of stiffened panels with cutouts.

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ABSTRACT: When a thin-walled section arch is subjected to an in-plane central concentrated load, the load produces combined nonuniform axial compressive and bending actions, which increase with an increase of the central load and may reach the values, at which the arch suddenly deflects laterally and twists out of the plane of loading, and fails in a lateral-torsional buckling mode. The elastic lateral-torsional buckling of fixed circular arches under a central concentrated load has been a difficult problem to be solved, which is investigated in this paper. Accurate prebuckling analyses for axial compressive and bending actions produced by the central load are carried out. The analytical solution for the elastic lateral-torsional buckling load is derived using the principle of stationary potential energy in conjunction with the Rayleigh-Ritz method. The analytical solutions for the prebuckling axial compressive and bending actions and for the elastic lateral-torsional buckling load are compared with independent finite element results. It is found that they agree with each other very well, which validate the analytical solutions. In addition, the effects of load height, slenderness and in-plane boundary condition on the lateral-torsional buckling load are investigated. It is found that changes of the slenderness ratio, load height and in-plane boundary conditions have significant effects on the lateral-torsional buckling resistance of arches. This paper provides structural researchers and designers with a deep insight and useful analytical solutions for the lateral-torsional buckling of circular arches, and establishes a sound basis for investigations on the lateral-torsional strengths of fixed circular arches in the future.


ABSTRACT: In this work, we present an approach to analyze the nonlinear dynamics of shell structures, which combines a mixed finite element formulation and a robust integration scheme. The structure is spatially discretized with extensible-director-based solid-degenerate shells. The semi-discrete equations are temporally discretized with a momentum-preserving, energy-preserving/decaying method, which allows to mitigate the effects due to unresolved high-frequency content. Additionally, kinematic constraints are employed to render structural junctions. Finally, the method, which can be used to analyze blades of wind turbines or wings of airplanes effectively, is tested and its capabilities are illustrated by means of examples.

ABSTRACT: The paper introduces a generalisation of the Ayrton-Perry formula for thin-walled members, covering uncoupled and coupled instabilities of global, distortional and local type. This semi-analytical solution is based on the Generalised Beam Theory (GBT) and it provides the maximum carrying capacity in elastic domain for simply-supported thin-walled members with initial geometric imperfections, under various loading conditions. Direct generalised Ayrton-Perry formulae are developed for the buckling described by one or a combination of two pure imperfection/deformation modes; for more than two coupled modes, a simple incremental procedure is provided.

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ABSTRACT: The large amplitude free vibration behavior of pre-twisted functionally graded (FG) microbeams in thermal environment is investigated based on the modified strain gradient theory (MSGT) in conjunction with the first-order shear deformation theory (FSDT). The geometrical nonlinearity effects are taken into account in the sense of von Kármán nonlinear kinematic assumptions. The Chebyshev–Ritz method combined with harmonic balance method is employed to derive the nonlinear algebraic eigenfrequency equations of the microbeams subjected to different boundary conditions. The material properties are assumed to be temperature-dependent and graded in the thickness direction. After numerically demonstrating the fast rate of convergence and accuracy of the method, the effects of different geometrical and material parameters on the nonlinear free vibration behavior of pre-twisted FG microbeams are investigated. It is found that the effect of twist angle on the hardening or softening of the microbeams depend on the boundary conditions, and the largest and smallest values of nonlinear to linear frequency ratios belong to simply supported and fully clamped microbeams, respectively.

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ABSTRACT: New cold roll formed channel and zed sections for purlins, namely UltraBEAM™2 and UltraZED™2, have been developed by Hadley Industries plc using a combined approach of experimental testing, finite element modelling and optimisation techniques. The new sections have improved strength to weight ratio by increasing the section's strength through the use of stiffeners in the section webs. The European standard, Eurocode 3 [1], uses the traditional Effective Width Method to determine the strength of a cold formed steel member. However, the design of the new sections UltraBEAM™2 and UltraZED™2 using this method is very complicated in calculating the effective section properties as these sections contain complex folded-in stiffeners. In addition, the incorporation of competing buckling modes such as distortional buckling of these sections can be difficult to analyse. To overcome difficulties of using Eurocode 3 or such a standard with the Effective Width Method for determining the strength of these sections, the Direct Strength Method is
Four-point beam bending tests were carried out to determine the buckling and ultimate bending capacities of the UltraBEAM™ 2 and UltraZED™ 2 sections. Results from both experimental testing and Finite Element analysis were initially used as validation for the design using the Direct Strength Method. The Direct Strength Method's results were then compared with the experimental test results for a broader data in which the UltraBEAM™ 2 and UltraZED™ 2 sections had a range of different width-to-thickness ratios. It showed an excellent agreement between test and Direct Strength design values suggesting that the Direct Strength Method is a powerful tool for the design and optimisation of the new cold roll formed channel and zed purlins.

Zhe Xiong, Xiaonong Guo, Yongfeng Luo, Shaojun Zhu and Yipeng Liu (Department of Building Engineering, Tongji University, Shanghai 200092, China), “Experimental and numerical studies on single-layer reticulated shells with aluminium alloy gusset joints”, Thin-Walled Structures, Vol. 118, pp 124-136, September 2017
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ABSTRACT: Single-layer reticulated shells with aluminium alloy gusset (AAG) joints have a significant application prospect in spatial structures. To investigate their buckling behaviour, a single-layer reticulated shell with AAG joints subjected to a concentrated load at central joint was tested. The tested shell was a K6 shell with 5 rings, 8 m span and 0.5 m height. Its failure mode, buckling behaviour, internal force distribution of members, stress distribution of plates and joint stiffness were discussed. Finite element (FE) method implemented in the non-linear code ANSYS was adopted for the further investigation of single-layer reticulated shells with AAG joints. The FE procedure was accurately calibrated on the basis of the available experimental results. To develop a deep understanding, parameter studies considering the influence of joint bending behaviour on the buckling behaviour of single-layer reticulated shells were conducted.

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ABSTRACT: Over the past several decades, a noticeable amount of research efforts has been directed to minimising injuries and death to people inside a structure that is subjected to an impact loading. Comprehensive knowledge of the material properties and the structural behaviour of various TW components under various loading conditions is essential for designing an effective energy absorbing system. In this paper, based on a broad survey of the literature, a comprehensive overview of the recent developments in the area of crashworthiness performance of TW tubes is given with a special focus on the topics that emerged in the last ten years such as crashworthiness optimisation design and energy absorbing responses of unconventional TW components including multi-cells tubes, functionally graded thickness tubes and functionally graded foam filled tubes. Due to the huge number of studies that analysed and assessed the energy absorption behaviour of various TW components, this paper presents only a review of the crashworthiness behaviour of the components that can be used in vehicles structures including hollow and foam-filled TW tubes under lateral, axial, oblique and bending loading.

ABSTRACT: Application of the corrugated web girders has been widely spread due to their numerous advantages in the field of bridges and buildings in the civil engineering praxis. This girder type has a special stress distribution and buckling behavior compared to conventional steel I-girders. Despite, there are a relative small number of previous investigations dealing with the bending moment and the flange buckling resistance of the trapezoidally corrugated web girders. Previous experimental and numerical investigations confirmed that the bending moment resistance according to the EN1993-1-5 often results in unsafe resistances if the compressed flange belongs to cross-section class 4. Therefore, improved design models are developed by different researchers in the past, but there are contradictions in the previous design models regarding the consideration of the flange width and the clamping effect of the web. The current paper collects all the previous research results on the flange buckling resistance and introduces an additional experimental research program investigating the flange buckling behavior and the bending moment capacity. The companion paper (Part II) [1] introduces the executed numerical research program and the design method development for the flange buckling resistance.


ABSTRACT: Girders with trapezoidally corrugated web are widely used structural elements in the civil engineering praxis due to their numerous advantages. Despite, there are a relatively small number of previous investigations focusing on the determination of the bending moment resistance and the flange buckling behavior. Previous experimental and numerical investigations confirmed that the flange buckling resistance model provided by the EN1993-1-5 predicts often unsafe resistances. The summary of the previous investigations on the flange buckling behavior is presented in the companion paper (Part I) Jäger et al. [1] coupled with the introduction of an executed experimental research program investigating the flange buckling resistance of girders with corrugated web. Based on the test results an advanced FE model is developed, validated and presented in the current paper. In the first part of the study an imperfection sensitivity analysis is performed to develop proposals for applicable equivalent geometric imperfections for FEM based design method. In the second part of this paper an intensive parametric study is performed to investigate the buckling coefficient and the relationship between the relative slenderness and the reduction factor for corrugated web girders. The current paper also focuses on a new design method development for the determination of the flange buckling resistance.

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ABSTRACT: This work reports numerical results concerning cold-formed steel simply supported beams buckling and failing in distortional modes under uniform bending and exhibiting three cross-section shapes, namely (i) lipped channels bent about the major-axis, (ii) zed-sections under skew bending causing uniform flange compression (worst case), and (iii) hat-sections subjected to either major-axis or minor-axis bending (compressed lips in the latter case). Two end support conditions are considered, differing in the warping and local displacement/rotation restraints, which are either completely free or fully prevented. The beams analysed have several cross-section dimension ratios and lengths, in order to assess their influence on the distortional post-buckling behaviour and ultimate strength – particular attention is paid to the influence of (i) the flange-web and lip-flange width ratios, and (ii) the critical (distortional) half-wave number. In addition, the beams exhibit different yield stresses, making it possible to cover wide distortional slenderness ranges. After presenting and discussing the numerical elastic and elastic-plastic post-buckling results obtained, consisting of equilibrium paths, deformed configurations, plastic strain distributions, failure moments and collapse mechanisms, the paper shows that the currently codified Direct Strength Method (DSM) design curve fails to predict adequately the failure moments of some of the beams analysed and addresses the development/proposal of novel DSM strength curves, providing better quality predictions of all the numerical failure moments available.

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ABSTRACT: This paper introduces axial functionally graded thickness (AFGT) and lateral functionally graded thickness (LFGT) to thin-walled square structures separately, and then investigates their crashworthiness theoretically, numerically, experimentally under axial crushing load. The quasi-static axial crush experiments and the corresponding finite element models are first conducted to analysis the deformation mode and crushing force for uniform thickness (UT), AFGT and LFGT square tube under the same mass. Then, theoretical models predicting the mean crushing forces of AFGT and LFGT square tubes are established. The results show that both theoretical solutions and numerical results for FGT tubes agree well with the experimental results. Energy absorption characteristics between FGT and UT square tubes with same mass are compared based on the validated numerical models, which shows that AFGT square tube can effectively reduce the initial peak force compared to UT square tube while LFGT square tube remarkably surpasses the UT square tube in specific energy absorption (SEA) under axial crushing. Furthermore, parametric studies are performed to investigate the effects of gradient thickness variation on the energy absorption characteristics of AFGT and LFGT square tubes. The results again demonstrate that both AFGT and LFGT square tubes can improve the crashworthiness of thin-walled square tubes.

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ABSTRACT: This paper presents the modeling and analysis for the thermal postbuckling of graphene-reinforced composite laminated plates resting on an elastic foundation and subjected to in-plane temperature variation. A micromechanical model is used to estimate the temperature-dependent material properties of the graphene-reinforced composites (GRCs). Piece-wise functionally graded (FG) GRC layers along the thickness direction of a plate is considered in this study. Employing the higher order shear deformation plate theory, the governing equations for FG-GRC plates are derived and the effects of plate-foundation interaction and temperature variation are included in the modeling. A two-step perturbation technique is applied to obtain the buckling temperature and the thermal postbuckling load-deflection curves for perfect and imperfect FG-GRC laminated plates. The results show that the buckling temperature as well as thermal postbuckling strength of the plates can be increased as a result of the functionally graded graphene reinforcement for the plates.

ABSTRACT: Beams with large thin-walled cross sections are not generally following the classical beam theories such as Euler-Bernoulli and Timoshenko theories. In free vibration, the cross section is deformed by the inertia induced body loads. These deformations may have significant effect on the beam modal frequencies, especially in applications involving non-structural masses. This paper presents a method to include the effect into vibration modal results obtained by the classical beam theories. Generalized mass and stiffness of the classical results are modified according to kinetic-, and strain energies of the cross section deformation. The method is validated in typical engineering case studies against fine mesh Finite Element Method and excellent agreement is found.

ABSTRACT: The paper concerns thin-walled corrugated steel profiles used as arched roofing in architectural structures. Corrugation formed on the profile surface when the profiles are shaped affects their rigidity and load capacity. The complicated geometry of a profile surface prevents the creation of an analytical description based on the thin film theory. A loss of stability in this kind of profile is related to the formation of local instabilities in the early stage of local plastic mechanisms development. To that end, it is more relevant to identify the lower limit of load capacity to estimate the overall load capacity of the profile. The results obtained by the numerical calculations demand a thorough analysis of the map of strain, which is difficult because there are no clear
quantitative criteria describing the beginning of plasticisation formation. The paper presents a method of analysing the results of numerical calculations based on the identification of a perturbation component of displacement in selected points of the profile. The method is based on a discrete Fourier transform and allows the establishment of an estimation criterion for the lower limit of a profile's load capacity.

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ABSTRACT: This paper presents results of a numerical parametric study on elastic shear buckling of cold-formed steel channels with flat slotted webs. The study was performed on finite element models developed in ANSYS and validated against test data. The effects of perforation pattern, channel flange width, flange lip length, and aspect ratio on the elastic shear buckling load were investigated on the models with realistic and test setup boundary conditions. Equations for predicting the elastic shear buckling load of slotted channels were developed. The equations account for the effects of the studied parameters on the elastic shear buckling load of cold-formed steel channels with flat slotted webs and showed a good agreement with the finite element analysis results.

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“Numerical simulations on cold-formed steel channels with flat slotted webs in shear. Part II: Ultimate shear strength”, Thin-Walled Structures, Vol. 119, pp 211-223, October 2017
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ABSTRACT: This paper presents results of a numerical parametric study on the ultimate shear strength of cold-formed steel channels with flat slotted webs. The study was performed on nonlinear finite element models developed in ANSYS and validated against test data. The effects of perforation pattern, channel flange width, flange lip length, steel yield stress, and aspect ratio on the ultimate shear strength of the channels were numerically investigated on the models with realistic and test setup boundary conditions. Equations for predicting the shear strength of channels with flat slotted webs were developed. The equations account for the effects of the studied parameters on the shear strength of the channels and showed a good agreement with the finite element analysis results when post-buckling shear strength due to tension field action was taken into account.


ABSTRACT: This paper proposes a four-variable shear deformation refined plate theory for free vibration analysis of embedded smart plates made of porous magneto-electro-elastic functionally graded (MEE-FG)
materials. Magneto-electro-elastic properties of FG plate are supposed to vary through the thickness direction and are estimated through the modified power-law rule in which the porosities with even and uneven type are approximated. The governing differential equations and boundary conditions of embedded porous FG plate under magneto-electrical field are derived through Hamilton's principle based on a four-variable tangential-exponential refined theory which avoids the use of shear correction factors. An analytical solution procedure is used to achieve the natural frequencies of embedded porous FG plate supposed to magneto-electrical field with various boundary condition. Influences of several important parameters such as material graduation exponent, porosity volume fraction, magnetic potential, electric voltage, various boundary conditions, elastic foundation parameters and plate side-to-thickness ratio on natural frequencies of embedded porous MEE-FG plate are investigated and discussed in detail. It is concluded that these parameters play significant roles on the dynamic behavior of porous MEE-FG plates resting on elastic foundation. Presented numerical results can serve as benchmarks for future analyses of MEE-FG plates with porosity phases.

ABSTRACT: Forced vibration response of a conical panel subjected to the action of a moving load is investigated in the current research. Panel is made from a carbon nanotube (CNT) reinforced composite where the CNTs as reinforcements are distributed either uniformly or functionally graded across the panel thickness. Panel is formulated using the first order shear deformation shell theory and the Donnell kinematic assumptions. It is subjected to a moving load whose path and velocity are both arbitrary. The properties of the composite media are estimated according to a refined rule of mixtures approach. The governing equations of motion of the shell are obtained according to the Ritz method where the shape functions are obtained according to the Gram-Schmidt process. The developed equations with the aid of Ritz method are transformed into time-dependent ordinary differential equations whose solution is traced in time by means of the Newmark time marching scheme. Numerical results are provided to explore the influences of semi-vertex and opening angles of the cone, geometrical parameters and also CNT characteristics of the shell. It is shown that, dynamic deflection of the shell decreases significantly with the introduction of FG-X pattern of CNTs. Furthermore, enrichment of the matrix with more CNTs alleviates the dynamic deflection of the conical shell.

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ABSTRACT: Buckling instability refers to a significant limit on the structures with I-section members, which causes severe decreasing of critical buckling load. Many mechanisms and techniques have been developed to increase the loading capacity of I-section structures, e.g., using composite materials or changing web geometry. This study aims at theoretically investigating the effect of geometry on the buckling capacity of wood composite I-beams with sinusoidal corrugated web. Experiments and numerical simulations are carried out to validate the theoretical predictions. The presented model is also reduced to flat web to validate with an existing study. Good agreements are observed from the validations. Parametric study is conducted to indicate the effects
of web geometry on the critical buckling load. A significant increasing of buckling load (minimum 17.7%) is obtained between flat and sinusoidal web I-beams. Sensitivity study is carried out to evaluate the influences of web thickness, beam length and beam height on the loading capacity of sinusoidal I-beams. Optimal design is conducted to investigate the impact of the ratios of wavelength-to-beam length (a/L) and wave amplitude-to-flange width (A/T) on the critical buckling load and volume of wood corrugated I-beams. The findings in this study can be further used as guidance for the design of composite I-beams with sinusoidal corrugated web.

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ABSTRACT: Cold-formed steel Lipped Channel Beams (LCB) with web openings are commonly used as floor joists and bearers in building structures. Their shear behaviour is influenced by the presence of web openings and the shear capacities are considerably reduced. However, the shear behaviour and capacity of LCBs with non-circular web openings (square, rectangular and elliptical web openings) has not been investigated adequately. Hence a detailed numerical study was conducted to investigate the shear behaviour and capacity of LCBs with non-circular web openings. Finite element models of simply supported LCBs under a mid-span load with aspect ratios of 1.0 and 1.5 were developed and validated by using the available shear test results. They were then used in a detailed parametric study to investigate the effects of various influential parameters. Numerical results showed that the current shear design equations in cold-formed steel structures design standards are conservative or unsafe. New shear design equations were therefore proposed for the accurate prediction of the shear capacity of LCBs with non-circular web openings. This paper presents the details of finite element modelling of LCBs with unreinforced non-circular web openings and the development of new shear design rules. The proposed shear design equations in this paper can be considered for inclusion in the future versions of cold-formed steel design standards. Suitable design equations were also developed under the direct strength method.

ABSTRACT: Natural fibres such as flax, jute and hemp have been utilised for thousands of years, however have only recently been considered for fibre-resin composites. A major motivation for such an application is their superior sustainability attributes compared with traditional building materials. Population rise continues to place increasing demands for new infrastructure. Meanwhile, public concerns about the environment, climate change, energy consumption and greenhouse gas emissions, place increasing demands for the use of sustainable materials in infrastructure. While there is a wealth of knowledge in the materials aspects of natural fibre composites, relatively few studies have investigated their potential for structural applications. This paper presents an experimental and analytical study of natural fibre composite plates and channel sections consisting of flax, jute and hemp fibres and subjected to pure compression. The intrinsic mechanical properties are shown to be relatively modest. However, the buckling and post-buckling responses are shown to be stable, the ultimate condition is reached in a stable and predictable manner, and failure ensues in a gradual and ductile process. These characteristics show promise for the use of natural fibre composite sections in light structural applications.
such as in the residential and light commercial markets. Additionally, the analytical effective width mechanics model shows promise for use as a design technique for estimating their compression strength.


ABSTRACT: A comprehensive non-linear finite element (FE) study carried out on elliptical hollow section (EHS) steel cantilever beams of 1740 mm² cross-sectional area and 1500 mm long under extremely low cycle fatigue (ELCF) uni-directional flexural load along major and minor axes separately is presented using the general FE package, Abaqus. The aspect ratio (major to minor axis diameter ratio), $a/b$ and shell thickness, $t$ of EHS beam models are varied between 1–2.33 and 4–6 mm respectively. The effect of $a/b$ ratio and section slenderness on cyclic rotation capacity and flexural over-strength of the EHS FE beam models is investigated in this study. It is observed that the effect of $a/b$ on rotation capacity under major axis bending is significant. Also, the cyclic flexural over-strength is not significantly affected by $a/b$ ratio. New slenderness limits for circular hollow sections under bending are proposed. Modified slenderness parameters for EHSs under bending based on equivalent circular hollow section approach are derived. Empirical expressions for predicting cyclic rotation capacity and flexural over-strength of EHS beams are derived based on the FE study.

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ABSTRACT: The results of an extensive experimental campaign on centric and eccentric compressive behavior of thin-walled steel uprights of pallet-rack systems are presented. The analyzed cold-formed profiles are perforated through their whole length and have open, mono-symmetric cross-sections. Experimental results are extended through finite-element simulations, including geometrical and material nonlinearities, to obtain detailed three-dimensional compression-bending-bending strength-domains, which are compared to building-code prescriptions. Regulations are safety preserving, with an average difference of about 10%, and maximum difference for bending about the weak axis. Unlike in regulatory prescriptions, the experimental-numerical results show unsymmetrical behavior about the weak axis and nonlinear, convex bending-bending interaction.

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“Buckling of axially compressed CFRP cylinders with and without additional lateral load: Experimental and numerical investigation”, Thin-Walled Structures, Vol. 119, pp 178-189, October 2017
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ABSTRACT: Thin-walled structures are widely used in aerospace, offshore, civil, marine and other engineering industries. Buckling of such thin-walled imperfection sensitive structures is a very important phenomenon to be considered during their design phase. Existing design guidelines, being the most known the NASA SP-8007 for cylinders dated from the late 1960's are currently used in the aerospace industry and employ conservative lower-bound knock-down factors. These empirically based lower-bound methods do not include important mechanical properties of laminated composite materials, such as the stacking sequence. New design approaches that allow taking full advantage of composite materials are therefore required. This study deals with buckling experiments of axially compressed, unstiffened carbon fiber–reinforced polymer (CFRP) cylinders with and without an additional lateral load. Two geometrically identical cylinders with the same layup were designed, manufactured and tested. Before testing, the thickness of the cylinders was measured with ultrasonic inspection and the geometry was measured utilizing a 3D scanning system based on photogrammetry. During testing, a digital image correlation system was employed to monitor deformations, strain gage readings and load-shortening data was taken. Modelling of shape mid-surface and thickness imperfections as well as fiber volume fraction correction are included into the Finite Element Analysis (FEA) of the test structures, and the experimental results are compared against FEA results.

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ABSTRACT: A set of linear elastic homogeneous isotropic axisymmetric thin shells of revolution with plane projection of radius $R$ varying with the height $c$ of the pole, to keep constant mass, is introduced. Their curvature and dynamical properties depend on the ratio $c/Rc/R$, and their linear dynamics is investigated by standard modal analysis, adopting a commercial code, and accounting for curvature. Natural frequencies for a given mode are linear with $c/Rc/R$, decrease for membrane modes, and increase for transverse modes. Thus, membrane and transverse modes may shift as curvature grows; graphical and numerical results are reported.

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ABSTRACT: Orthotropic membrane structure is widely applied in construction buildings, mechanical engineering, electronic meters, space and aeronautics, etc. During their serving period, membrane structure is prone to vibrate stochastically and seriously under stochastic dynamic loads, which may lead to structural failure. For this purpose, this paper investigates the stochastic dynamic response and reliability analysis of membrane structure under impact load obeying Gaussian distribution. The equation of stochastic motion of
membrane structure is established by Von Karman's large deformation theory. The results of stochastic dynamic response are obtained with perturbation method solving the equation. Then, reliability parameters of extreme value of dynamic response are calculated by Moment method based on first-passage probabilities of level crossing. Furthermore, the theoretical model proposed is validated by experimental study using Monte Carlo method. The effects of parameters including impact velocity, pretension force and radius on structural reliability are discussed in addition. The model proposed herein provides some theoretical basis for the stochastic vibration control and dynamic design of orthotropic membrane structure based on reliability theory.

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ABSTRACT: In the present paper, the effect of the collar plate on the static capacity of circular hollow section (CHS) X-joints under brace compression is experimentally and numerically investigated. For this aim, three X-joints reinforced with collar plate, with different values of $\beta$, and three corresponding unreinforced X-joints were tested. All of the details and results of the experimental tests are presented. The static behavior of the collar plate reinforced and un-reinforced X-joints is then evaluated from the load-displacement curves and deformed shapes. The compression between the results of reinforced and unreinforced X-joints shows that the collar plate can increase both of the initial stiffness and ultimate strength. Also, these beneficial effects of the collar plate are significant in all of the joints with small, intermediate, and big values of the brace-to-chord diameter ratio ($\beta = 0.25, 0.54, 0.73$). Moreover, the compression between deformed configurations shows that deformed shape of the reinforced specimens in the near joint intersection is more uniform than the deformed shape of the corresponding unreinforced specimens. Finally, finite element (FE) model is proposed. Results show that the present FE model can accurately predict the load-displacement curves and failure modes of the unreinforced and collar plate reinforced X-joints.

B. Somodi and B. Koevesdi (Budapest University of Technology and Economics, Department of Structural Engineering, Műegyetem rkp. 3., 1111 Budapest, Hungary), “Flexural buckling resistance of welded HSS box section members”, Thin-Walled Structures, Vol. 119, pp 266-281, October 2017
https://doi.org/10.1016/j.tws.2017.06.015

ABSTRACT: The exact consideration of the global buckling behaviour of HSS steel structures is very important in the design because due to the higher yield strength smaller cross sections can be used, which might be more sensitive to stability failure. According to the previous research results, the flexural buckling behaviour of HSS and NSS columns can be significantly different, however, these differences are not considered in the current design methods. The application range of the current EN 1993-1-1 [1] is limited for steel grades up to S460. The EN 1993-1-12 [2] gives design rules for materials up to steel grades of S700, however, for the determination of the flexural buckling resistance of welded box section members there are no improved design guidelines for HSS structures. Therefore, the purpose of the current study is to investigate the column buckling behaviour of HSS welded box section columns based on previous and current experimental investigations and on numerical simulations. This paper focuses on the effect of the different material properties, imperfections
and residual stresses on the global buckling behaviour of HSS members and gives design proposal for the applicable column buckling curves for steel grades between S420 and S960.

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ABSTRACT: The various assessment methods of ultimate strength for hull girder of ships or offshore structures might lead to different results and computation time. The nonlinear finite element (FE) analyses include the implicit static analysis and explicit dynamic analysis, which both can consider the large deflection and material nonlinearity during the process of progressive collapse. Comparing with the implicit static analysis, the explicit dynamic analysis can consider the transient influence of time and avoid the convergence issue in iterative procedure. The object of the present paper is to figure out a reliable and suitable FE modelling in the explicit dynamic method, which could keep the balance of the acceptable accurate results and computation resources. Several influential factors on the collapse behaviours of hull girder are discussed including boundary conditions, geometric ranges of finite element model, element types, loading methods and loading time. The results of a Suezmax oil tanker and Reckling models assessed by the explicit dynamic method are compared with that by the other analytical methods or in the experiment.

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ABSTRACT: This study investigated the buckling of nontypical prolate domes subject to hydrostatic external pressure. The domes were shells of revolution with an egg-shaped configuration, with a base diameter and height of approximately 160 and 121 mm, respectively. Four laboratory-scale egg-shaped domes, cold-pressed from a 1-mm 304 steel sheet, were measured for geometry, tested to collapse, and analysed numerically. The experimental results and numerical evaluations were well consistent. Furthermore, the buckling behaviours of a perfect egg-shaped dome, a capacity-equivalent hemisphere, and a mass-equivalent hemisphere were numerically studied. The results indicate that the prolate egg-shaped dome has a relatively large load-carrying capacity that is not highly sensitive to material plasticity and geometrical imperfections.


ABSTRACT: An analytical study to investigate the local buckling capacity of steel I-section beams under elevated temperatures is presented. The study is based on an inelastic local buckling stability model that was
developed by the author. The study is focused on I-section beams loaded in pure bending and subjected to either uniform or linear temperature gradient through the section depth. A parametric study is presented to investigate the effect of section geometry, steel type, and temperature gradient on local buckling capacity. The parametric study results are used to propose a new method to estimate the local buckling capacity of I-section beams under elevated temperatures. A numerical example is presented to illustrate the use of the proposed method.

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“Optimal design of hierarchical grid-stiffened cylindrical shell structures based on linear buckling and nonlinear collapse analyses”, Thin-Walled Structures, Vol. 119, pp 315-323, October 2017,
https://doi.org/10.1016/j.tws.2017.06.019

ABSTRACT: This paper considers the optimization of a grid-stiffened cylindrical shell with weld and transition lands. A surrogate-based optimization framework incorporating the multi-island genetic algorithm (MIGA) is adopted based on linear eigenvalue buckling analysis (LEBA) and nonlinear implicit analysis (NIA). A novel hierarchical grid design is proposed to avoid undesired local buckling. In addition, the results indicate that the optimization based on LEBA is intended primarily to avoid local failure rather than structure collapse, and thereby deviates from the optimal design. In contrast, the optimization based on NIA yields designs that are closer to the optimal design for engineering application.

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“Innovative solution for strength enhancement of metallic-like composite tubular structures axially crushed used as energy dissipating devices”, Thin-Walled Structures, Vol. 119, pp 332-344, October 2017,
https://doi.org/10.1016/j.tws.2017.06.024

ABSTRACT: This work presents the milestones of the underlying of a patented work [1] (Abdul-Latif, 2014) which aims to enhance the plastic buckling resistance of thin-walled right-circular cylindrical mild steel tubes deformed axially under the quasi-static compressive load. The proposed concept can be described by producing a metal like-composite where a hard phase incorporates in these tubes made by case-hardening of 15% of tubes outer surface with different geometrical shapes and a constant depth along the tubes thickness. To study the effect of case-hardening configurations, several forms were designed, made and tested. They were four ring forms (with 2, 3, 4 and 5 rings), two vertical strip forms (2 and 3 strips) and, six helical strip forms with three tilt angles of 30°, 45° and 60° (2H30, 3H30, 2H45, 3H45, 2H60 and 3H60). The total energy absorption of conventional tubes could be increased up to 46%. The effects of the case-hardened zone, quasi-static strain rate and the crush force efficiency were investigated. Moreover, the deformation modes of these case-hardened tubes were analyzed. The effect of the case-hardened forms could be classified into three categories by the gain percentage (low, intermediate and high gains). Especially in the high gain category, the material behavior seems to be directed by complicated local strain induced by the metal like-composite tube, where a triaxial strain state
was encouraged particularly within the tube wall of 3H30. For this reason, the collapse load became the function of case-hardened forms.


ABSTRACT: In practical engineering, the measured differential settlement can be gained by monitoring the points beneath the tank wall and it can induce the buckling of the tank even with a small amplitude. In general, Fourier series is adopted to decompose the measured differential settlement into harmonic components with various wave numbers. However, the question that which harmonic components should be considered is a main challenge for buckling investigations of the tank under measured differential settlement. In this work, a recommendation for harmonic components needed for consideration was proposed when decomposing measured differential settlement into harmonic components in terms of Fourier series. Moreover, the effects of the harmonic components considered on buckling behavior of floating roof tanks and conical roof tanks were discussed. The results presented that three monitoring points can make a first estimate of ovaling and the harmonic components considered should be smaller than and equal to \([N/3]\) \([\text{[]}\) is the rounding function and \(N\) is the number of the monitoring points). The introduction of the harmonic component with a high wave number can cause the change of the buckling modes of the tanks under differential settlement, including floating roof tanks and conical roof tanks. Meanwhile, it can decrease the buckling strength of the floating roof tank more significantly than that of the conical roof tank.

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ABSTRACT: To systematically study and determine the failure mechanism of reticulated domes when subjected to impact, ANSYS/LSDYNA was utilized to establish a functional and effective finite-element analysis method for the impact responses of reticulated domes. The impact load characteristics imposed on reticulated domes under three types of failure modes were analyzed, and the peak value and duration time were compared. Based on structural deformation and the node velocity at critical moments during impact, the collapse of reticulated domes is classified into three stages in light of energy transfer and conversion: impulse application, energy transfer, and conversion and dissipation. On this basis, and using the single-layer Kiewitt-8 reticulated dome as an example, the characteristics of energy transfer and conversion of the impact-induced failure processes were quantitatively analyzed. Consequently, the energy-based failure mechanism of reticulated domes subjected to impact is revealed.

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ABSTRACT: For energy-absorbing systems constructed by round tubes, boundary constraints and/or inter-tube fasteners are required to prevent splashing of tubes from lateral loadings, which results in extra labor and time costs. To overcome this shortcoming, the self-locked system comprised of dumbbell-shaped tubes was recently proposed, which can prevent the lateral splashing of tubes under impact loadings without any constraints. To improve the energy-absorbing capacity of the self-locked system, the internally nested self-locked system is proposed, of which the basic unit is a dumbbell-shaped tube nested by round tubes inside. The proposed nested self-locked system not only inherits the self-locking effect of dumbbell-shaped tubes, but also significantly improves the energy absorption properties. In order to estimate the energy absorption of the proposed tube, a plastic hinge model is developed based on the analysis of the four-phase deformation process of the tube. Besides, experimental study and FEM simulations are also carried out, and the results agree well with the theoretical prediction. Furthermore, the geometric parameters of inserted round tubes and the stacking arrangement of the proposed nested self-locked systems are investigated, and suggestions on designing an internally nested self-locked energy-absorbing system are provided for practical applications.

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ABSTRACT: The compressive buckling strength of extruded aluminium alloy I-section columns with fixed-pinned end conditions has been experimentally and numerically investigated in this study. A total of 11 column tests, involving two heat-treated aluminium alloys – 6061-T6 and 6063-T5, were carried out to acquire the compressive buckling strengths. Prior to the column tests, material properties of the two aluminium alloys were determined from tensile coupon tests, while the initial local and global geometric imperfections were separately measured by means of experimental techniques. By using the ABAQUS software package, finite element (FE) models that could account for material non-linearity and initial geometric imperfections were developed. The FE models were further validated against the test results, enabling reliable simulation of the compressive buckling behaviour of the tested columns with fixed-pinned end conditions. Based on the obtained test and numerical results, the calculation methods in the current design standards, including the European, Chinese, American and Australian/New Zealand specifications, were all assessed. It was shown that the design provisions in all the four standards provided relatively conservative strength predictions, especially for the aluminium alloys with more pronounced strain hardening capacity.

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ABSTRACT: Sandwich panels having metallic corrugated cores extremely utilized in various engineering fields such as aerospace, automotive, civil, and naval engineering. Although significant efforts have been dedicated in research into corrugated sandwich panels, analytical solutions are still very few. In this paper, analysis of corrugated sandwich panels with trapezoidal shape is carried out analytically. In the present study, a new analytical approach is developed for bending analysis of corrugated sandwich panels which have not been considered yet. The out-of-plane properties of corrugated core are obtained based on three dimensional theory of elasticity. The state-space method is implemented in conjunction with double Fourier series to solve the coupled partial differential equations. To validate the present approach, numerical results are compared with the results reported in the literature. The sensitivity analysis of the stress and displacement components to the geometrical parameters of corrugated core and its orthotropy is presented by introducing dimensionless ratios.

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ABSTRACT: In this paper, the crushing responses of tubes with different shapes of windows as well as the simple tube are investigated under axial and oblique loading conditions. Numerical model was constructed with FE code LS-DYNA and was validated by experiment. The model was then employed for the dynamic crush simulation of each tube at different load angles. The initial peak, crush force efficiency, energy absorption and specific energy absorption of windowed and simple tubes were compared and their overall crushing performances were evaluated by TOPSIS method. The results have proven the effectiveness of introducing windows to improve the tube's crushing performance and have showed that square and rectangle are the best window shapes.

Lavan Sundararajah, Mahen Mahendran and Poologanathan Keerthan (Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000, Australia), “New design rules for lipped channel beams subject to web crippling under two-flange load cases”, Thin-Walled Structures, Vol. 119, pp 421-437, October 2017, https://doi.org/10.1016/j.tws.2017.06.003

ABSTRACT: Lipped channel beams (LCBs) are commonly used as floor joists and bearers in the construction industry. These thin-walled LCBs are subjected to specific local and global failures, one of them being web crippling. Several experimental and numerical studies have been conducted in the past to study the web crippling behaviour and capacities of different cold-formed steel sections under different concentrated load cases. However, due to the nature of the web crippling phenomenon and many factors influencing the web crippling capacities, capacity predictions given by most of the cold-formed steel design standards are either unconservative or conservative. Therefore a detailed experimental study was conducted to study the web crippling under End Two-Flange (ETF) and Interior Two-Flange (ITF) load cases based on the new AISI S909 standard web crippling test method. Finite element models were developed and validated using the test results.
These models were then used in a detailed parametric study to investigate the web crippling capacities of a wide range of LCB sections including different sectional geometric parameters such as section depth, inside bent radius, thickness and bearing length. This paper presents the details of the numerical study of LCBs subject to web crippling under ETF and ITF load cases. Using the extensive web crippling capacity data obtained from both numerical and experimental studies, improved unified web crippling design equations were developed. Suitable web crippling design rules were also developed under the direct strength method format.

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ABSTRACT: In order to solve the inconsistency problem of the theoretical solutions of critical buckling temperature rise for thin cylindrical shells reported in the existing literatures, a first attempt was made in the present study to perform a derivation process on the critical internal force, thermal stress and critical buckling temperature rise for the rectangular thin plate and thin cylindrical shell based on small deformation theory and the Donnell form of the nonlinear equilibrium equations, respectively. Thereafter, the theoretical solutions of the thermal stresses under different boundary conditions and temperature rise variations were determined. The results show that the theoretical solutions of the internal force, thermal stress and critical buckling temperature rise are in good agreement with the numerical results. Finally, the reason leading to the inconsistency of the theoretical solution of the critical buckling temperature rise was elucidated in detail.

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ABSTRACT: Local geometric imperfections in a cold-formed steel (CFS) member can significantly alter the force-carrying capacity of the member. These are the dents and undulations which occur during cold-rolling, handling, transportation and erection of CFS members. The buckling strength of a lipped channel section with Type I local imperfection is obtained and characterised statistically using finite element analyses and Monte Carlo simulations. The reduction in strength due to these imperfections are found to be significant. The quantification of reduction in strength due to these imperfections is found for different values of non-dimensional slenderness ratio. Based on the statistical analysis, design equations and strength curves are recommended for the buckling strength of geometrically imperfect members. Legitimacy of using a generalised statistics of imperfection, in the case of unavailability of specific data for a particular section, is also verified.

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An analytical and numerical study on the buckling of cracked cylindrical shells”, Thin-Walled Structures, Vol. 119, pp 457-469, October 2017, [https://doi.org/10.1016/j.tws.2017.06.023](https://doi.org/10.1016/j.tws.2017.06.023)

**ABSTRACT:** Presence of flaws or cracks may cause substantial decrease in the strength of a component or structure. This kind of structural damage will accumulate over time, leading to significant decrease in ultimate load carrying capacity of structural members and premature brittle failure. In this paper, a coupled analytical and numerical study is implemented in order to evaluate buckling load of cracked cylindrical shells which is often encountered in the fields of civil engineering, offshore engineering and mechanic engineering. In the first phase of the study, buckling load of cylindrical shells with circumferential crack is investigated by treating the symmetric model as a cracked rectangular beam-column on an elastic foundation. The cracked beam-column is modelled as two beam elements on elastic foundation connected by an equivalent rotational spring and governing characteristic equation is obtained. Finite element models are used to verify analytical results and assess their accuracy, based on which good agreement is observed between analytical and numerical results. Effect of different parameters such as the length of cylinder, radial stiffness of cylinder, crack location and crack severity is studied on the axial load carrying capacity of such members. A simplified equation is proposed in order to calculate buckling load of tall cylindrical shells with a circumferential crack. In the second phase, the buckling load of cylindrical shells with a partial crack is studied using the results of finite element analysis on models with varying crack length. Based on the results of numerical analysis, an empirical equation is proposed to interpolate buckling load of these members between two limiting values, namely the buckling loads of same uncracked cylinder and the cylinder with circumferential crack.

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“Experimental study of the section moment capacity of cold-formed and screw-fastened rectangular hollow flange beams”, Thin-Walled Structures, Vol. 119, pp 499-509, October 2017, [https://doi.org/10.1016/j.tws.2017.05.033](https://doi.org/10.1016/j.tws.2017.05.033)

**ABSTRACT:** This paper presents the results of an experimental study on the section moment capacity of cold-formed steel beams with rectangular hollow flanges. The new Rectangular Hollow Flange Beam (RHFB) is fabricated using a unique manufacturing process in which two cold-formed rectangular hollow flanges are screw fastened to a web plate. It possesses unique stress-strain characteristics and initial imperfections that are different from conventional open cold-formed steel sections and welded hollow flange beam sections. In this study, the section moment capacity of RHFBs was investigated using a series of full scale bending tests. Twenty two section moment capacity tests of RHFBs were conducted on short span flexural members with simply supported end conditions for three steel grades G300, G500 and G550 and varying thicknesses. Test capacity results were compared with the capacities predicted by the current design rules in the Australian and North American steel design standards, AS 4100, AS/NZS 4600 and AISI S100, to verify their applicability to RHFBs. The results show that although the current design rules based on effective width principles predicted the section moment capacities of RHFBs slightly unconservatively in comparison to test results, they can be used for RHFBs provided a suitable screw spacing is used. However, the Direct Strength Method (DSM) based design rules are found to predict the section moment capacity of this new screw-fastened hollow flange beam section conservatively in most cases. This research shows that the DSM based design rules including the new inelastic reserve bending capacity provisions in AISI S100 can be used to predict the section moment capacities of both screw-fastened and welded hollow flange beam sections conservatively.
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ABSTRACT: A recent paper by the authors showed that the innovative technique of CFRP repair of severely corroded steel circular pipes is promising. This paper presents further experimental results for two series of CFRP strengthened and rehabilitated pipes under quasi-static large deformation 3-point bending and direct indentation. The main parameters examined in this paper were the corrosion penetration in the wall thickness, its extent along the pipe, the type and number of the CFRP sheets. The corrosion in the wall thickness was artificially induced 360° around the circumference and in the wall thickness by machining where four different severity of corrosion were examined of 20% (mild), 40% (moderate), 60% (severe), and 80% (very severe). The first series was for rehabilitation of 12 artificially degraded pipes with limited corrosion repaired using externally wrapped sheets where the extent of corrosion along the pipeline was in the range of \( L_c/D_n = 1.0-3.0 \), where \( L_c \) = length of corrosion and \( D_n \) is the nominal diameter of the pipe. The second series represents strengthening of 4 degraded pipes with corrosion that extended along the full length of the pipe. The extent of corrosion along the pipeline in this series was \( L_c/D_n = 8.0 \). The external diameter-to-thickness ratios examined in this paper was in the range of \( D_0/t = 20.32-93.6 \). The results show that the combined flexural and bearing strength of the pipe can be significantly increased by adhesively bonding CFRP. The maximum gain in strength was 434% which was obtained for the most severe 80% corrosion which extended along the full length of the pipe where \( L_c/D_n = 8.0 \). The average increase in the load carrying capacity was 97% and 169% for the rehabilitation and strengthening series, respectively.

ABSTRACT: Suitable and fast calculation methods with sufficient accuracy are required to optimise large composite structures. The present paper introduces a progressive stiffness degradation analysis (PSDA), which computes skin buckling onset and strength failure initiation of skin fields separated by stiffeners, as well as the subsequent damage propagation using closed form solutions. This constitutes a simplified, but much faster approach compared to state of the art progressive failure analyses, which incorporate finite element simulations. Therefore, the computational effort can be reduced. This paper illustrates the process of the PSDA and then verifies this simplified approach by means of one example.

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ABSTRACT: Most of the existing studies on reticulated shells with a semi-rigid joint system have been focused on the mechanical properties under static loads. Taking material and geometric nonlinearities into account, the finite element analysis (FEA) model of a single-layer reticulated shell with semi-rigid joints was established using the software ABAQUS and then validated through comparison with the experimental result. Based on the bending stiffness of a bolt-column (BC) joint obtained through experiments, the dynamic behaviour and a seismic design method for single-layer reticulated shells with semi-rigid joints were investigated in this paper. First, analysis of the free vibration frequency of the single-layer latticed domes with semi-rigid bolt-column (BC) joints was conducted based on several different parameters, including joint stiffness, ratio of rise to span, initial geometric imperfection. Second, the seismic internal force coefficient of the members of the semi-rigidly jointed spherical single-layer reticulated shells of different parameters was studied in detail. Finally, the seismic internal force coefficients for spherical single-layer reticulated shells with semi-rigid joints under a common earthquake were derived.


ABSTRACT: The design of unbraced cold-formed steel beams must consider lateral-torsional buckling due to the low torsional stiffness associated with open cross-sections. The American Iron and Steel Institute incorporated design equations for the critical elastic lateral-torsional buckling stress in the North American Specification for the Design of Cold-Formed Steel Structural Members. These equations are based on elastic theory for singly-symmetric and doubly-symmetric sections. However, the equation for point-symmetric sections is only a rough approximation. Furthermore, there are no provisions for lateral-torsional buckling of non-symmetric sections, or sections oriented to non-principal axes. This paper investigates and develops a general formulation of the lateral-torsional buckling equation to broadly cover all cold-formed steel cross-sections.


ABSTRACT: In this paper, a mode identification technique in the context of spline finite strip method (SFSM) is presented to compute the contribution of primary (global, distortional and local) and secondary (shear/transverse extension) buckling modes. The base vectors corresponding to individual buckling modes are developed based on the principles of generalized beam theory. The buckling mode shape in SFSM is approximated as a linear combination of these orthonormal base vectors to evaluate the participation of individual buckling mode. The proposed mode identification technique is able to successfully quantify the participation of different buckling modes and the mode participation is comparable with mode identification using finite strip method (FSM) and generalized beam theory (GBT). Illustrative examples are presented to calculate the participation of individual modes in cold-formed steel sections under different loading and boundary conditions. Also the specific application of mode identification in SFSM is demonstrated.

Abbas Niknejad, Pourya Heidari Orojloo and Mojtaba Johari (Mechanical Engineering Department, Yasouj University, P.O. Box: 75914-353, Yasouj, Iran), “Flattening process on folded quadrangular columns under the

ABSTRACT: This article introduces a novel method to improve energy absorption performance of thin-walled columns with square and rectangular cross-sections subjected to distributed quasi-static lateral compression loading during different lateral flattening processes. Firstly, some square and rectangular columns made of aluminum and brass alloys are compressed in the axial direction to transform them into folded columns. Then, the folded specimens are used in four different lateral energy absorption processes as initial samples. All the lateral flattening tests are carried out between rigid platens. All the used specimens in the four flattening processes are prepared by initial simple square and rectangular columns. In one flattening process, the simple quadrangular specimens are used. In the second process as a novel flattening process, the folded samples are tested. Furthermore, in two other processes, the initial specimens of the novel flattening processes are prepared by folding and cutting the simple quadrangular specimens. Effects of different parameters consist of material type, wall thickness, cross-sectional aspect ratio, and length of the specimens and also, flattening process type and lateral loading direction are discussed on energy absorption performance of the quadrangular specimens. Totally, the performed experiments show that the new lateral energy absorption processes increase specific absorbed energy by the quadrangular specimens up to 7 times; and enhance their total absorbed energy more than 13 times of the corresponding simple specimens.


ABSTRACT: Test study on simply supported built-up beams (plate on top of a channel section) with two different strengthening approaches using carbon fiber reinforced polymer (CFRP) fabrics by external bonding namely flange strengthened and modified cross section strengthened has been conducted. The study specimens simulated the flange restrained C-channel sections in lateral bracing of steel bridge superstructure and steel storage structures. A total of seven different strengthening configurations were made based on the two strengthening approaches. The results indicate that the flange strengthening approach is not an efficient method of retrofitting open cross section specimens with longer length compared to the modified cross section strengthening method with infilled core which significantly improved the flexural strength. In addition, the results indicate that with an increase in a number of confinement wrap using bidirectional CFRP fabrics the wrinkling can be prevented. The results also indicate that depending on the magnitude of camber imperfection (initial bent about major axis) different failure modes of CFRP can be observed.


ABSTRACT: An experimental study was conducted to evaluate the compressive behavior of damaged circular hollow section (CHS) steel columns repaired by carbon fiber-reinforced polymer (CFRP) or high-strength grout. A total of 22 specimens, including bare steel specimens, CFRP repaired specimens and grout repaired specimens were tested under axial compression loading. The design parameters are the amount of loss in wall thickness, extent of damage along tube height, and the damage angle around the circumference. Two promising retrofit techniques, external wrapping of CFRP and grouted jacket, were adopted here. The repairing efficiency
was assessed in terms of the above-mentioned retrofit techniques and design parameters. A finite element (FE) analysis was also performed and analyzed with test results. The failure modes are presented together with load-shortening and load-strain behavior of specimens. The results indicate that the behavior of damaged CHS steel columns can be effectively rehabilitated by either CFRP or grout jacketing. The local buckling of the internal steel tube was either delayed by fibers or suppressed by the surrounding grout, leading to an improvement both in compressive strength and deformation capacity. It was also found that grouted jacket repair generally shows an overwhelming strength enhancement over the CFRP wrapping method except for specimens with 90° damage around circumference, which shows a delay of the restraining effect. A parametric study was eventually undertaken to fully understand the influences of design parameters on columns' compressive characteristics.

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ABSTRACT: Finite element analyses of the transverse impact behavior of pressurized pipelines were previously performed for a variety of outside pipeline diameters and internal pressures at two spanwise locations. In this study, quadratic response surface models (RSMs) based on a full factorial statistical design were developed to predict the maximum permanent deflection, absorbed energy, and maximum force calculated for a given impact event. The RSMs were characterized in terms of two independent variables: outside diameter and internal pressure. An analysis of variance was then conducted for each response and used to determine an appropriate statistical model. The parametric study results showed that RSMs can efficiently and accurately reveal the influences of the design variables on the lateral impact response of the pressurized pipelines.

ABSTRACT: A numerical study is conducted using finite element models of large, circular, cylindrical, aboveground, steel, open-top, liquid storage tanks subjected to horizontal seismic forces. Nonlinearities of both material properties and geometry deformations are included. Soil-structure interactions are implemented into the finite element models by using a series of elastic springs representing a stiff soil foundation. Hydrodynamic hoop stresses, elephant’s foot buckling, and uplift are measured for tanks with height to radius ratios, or aspect ratios, between 0.4 and 2.0. The finite element models are compared to the provisions of API 650 Annex E, with special attention to the anchorage ratio, J. The results show that, while the finite element models are much more complex than the theoretical and empirical equations provided in API 650, the total hoop and axial compressive stresses are comparable. Furthermore, the anchorage ratio limits set by API 650 seem to be in good agreement with the finite element models in terms of uplifting behavior.

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ABSTRACT: Natural frequencies and mode shapes of a composite shell of revolution consisting of a circular cylindrical shell and a deep or shallow hemi-ellipsoidal shell with variable thickness having a circular cylindrical hole or not are determined by the Ritz method using a mathematically three-dimensional analysis instead of two-dimensional thin shell theories or higher order thick shell theories. The present analysis is based upon the circular cylindrical coordinates while in the traditional shell analyses three-dimensional shell coordinates have been commonly used. Using the Ritz method, the Legendre polynomials, which are mathematically orthonormal, are used as admissible functions instead of ordinary simple algebraic polynomials. Natural frequencies are presented for different boundary conditions. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the composite shells. The frequencies from the present three-dimensional method are compared with those from three types of two-dimensional thin shell theories (finite element method, finite difference method, and numerical integration) by previous researchers. The present analysis is applicable to very thick shells as well as thin shells; and to shallow shells as well as deep shells.


ABSTRACT: Free vibration analysis of functionally graded (FG) open cylindrical shells is presented here using various refined higher order theories. Present study undertakes the displacement based approach including higher order shear and normal deformation theory (HOSNT) along with first order shear deformation theory (FOST) and higher order shear deformation theory (HSDT) models. Difficulty of obtaining three dimensional (3D) solutions and errors associated with classical shell theory (CST) necessitates the requirement of higher order models. Present study takes into account moderately thick shells unlike CST, by considering square of ratio of thickness to radius of shell less than unity, instead of the classical assumption of considering ratio of thickness to radius less than unity. Here Navier method of solution with double trigonometric functions for displacement terms is used to analytically reduce the given set of partial differential equations (PDEs) to an eigenvalue problem. Results are computed using MATLAB and comparison between various higher order models is discussed based on the consideration of middle surface displacement parameters. Present results should establish benchmark solutions for free vibration analysis of isotropic/orthotropic FG cylindrical panels. Functionally graded material properties are graded according to power law variation in thickness direction. Various shell solutions, based on other theories and 3D solutions available in the literature are compiled along with present solutions.

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ABSTRACT: The objectives of this paper is to investigate the mechanical behavior of steel reinforced concrete-filled square steel tubular (SRCFT) stub columns under axial loading through combined experimental and numerical studies. In total of six specimens are tested to investigate the effect of the concrete strength and steel ratio on the mechanical behavior of SRCFT stub columns. The ultimate bearing capacity, ductility, and confinement effects are discussed and clarified based on the experimental results. The inserted steel section can effectively prevent shear cracks in the core concrete from propagating quickly. The strength-weight-ratio of SRCFT stub column is larger than SCFT stub column. In addition, ABAQUS is used to establish the 3D finite element (FE) model and analyze the composite action of SRCFT stub columns under axial loading. Based on the experimental and numerical results, a simplified formula is proposed to estimate the ultimate bearing capacity of SRCFT stub columns using superposition method. The predicted results show satisfactory agreement with both experimental and FE results.

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ABSTRACT: Concrete-filled-steel-tube (CFST) columns have been increasingly adopted in many modern structures due to the beneficial composite action between steel tube and core concrete. Previous experimental and theoretical studies have proved this composite action can be further improved by providing external confinement in the form of steel rings, tie bars, spirals or jackets. A theoretical model developed by the authors previously based on (1) an accurate hoop strain equation; (2) an actively confined concrete model; (3) a three-dimensional steel model; (4) Interaction of core concrete, steel tube and external confinement was adopted in this paper to conduct a parametric study, which aims at investigating the effects of steel tube yield strength, concrete compressive strength, steel ratio and external confinement on the uni-axial behaviour of CFST columns. From the results in parametric study, two sets of critical steel ratios based on two different levels of ductility at different steel yield and concrete compressive strengths have been obtained. In addition, the maximum column strength obtained from the model and previous experimental studies was compared with the design strength calculated using different design codes. New design equations that can predict the axial strength more satisfactorily have also been proposed.


ABSTRACT: The thermal buckling of the shells is among the popular topics in solid mechanics. To date, most studies adopt the linear constitutive equation method. However, the non-linear temperature is important when studying thermal buckling. In this study, the non-linear constitutive equation of isotropic materials is derived using the tensor method to obtain the stability equation of axisymmetric spherical shells. Moreover, quadratic non-linear constitutive equations are applied to study the thermal buckling of spherical shells, and the heat stability equations of spherical shells expressed by displacements are obtained. Considering the common function of external pressure and temperature, the potential energy function of the spherical shell expressed in
displacement is obtained using the principle of least potential energy. Moreover, the Ritz method is used to study the thermal buckling of simple, supported shells. The changing trend of the critical pressure caused by the temperature change of the thin spherical shells is analyzed, as well as the influence of the temperature nonlinearity on the critical pressure.

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ABSTRACT: Concrete-filled bimetallic tubes (CFBT) could be recognized as a type of steel-concrete composite members, and have the potential to be applied in engineering structures. A three-dimensional finite element analysis (FEA) model is established to further study the axial compressive behaviour of circular CFBT stub columns in this paper. The preciseness of the FEA predictions is evaluated by comparison with experimental results collected from ten CFBT column specimens tested in a companion paper (Ye et al., 2016) [15]. Good agreement is obtained between the FEA predictions and the test results in terms of failure pattern, load versus deformation response, ultimate strength, and strain development of the two steel tube layers. In light of the FEA results, the stresses of concrete and steel, as well as the interactions and load distribution between different components of the composite section are investigated. Finally, parametric study is performed and a simplified model is proposed to be used to calculate the ultimate strength of circular CFBT stub columns.

ABSTRACT: In this work, the effect of single circular perforation in the shear behaviour of LDSS rectangular hollow beams has been presented using finite element analyses, in a systematic manner, considering a key cross sectional parameters viz., flange thickness, flange width, web thickness, shear span etc. Predominantly, the effects of single perforation size / diameter and location (along longitudinal, transverse, and diagonals) are determined with an attention on the shear load capacity ($V_s/V_y$), deformed shapes (or failure modes) etc. The effects of the perforation are presented parametrically in relation to web slenderness ($h_w/t_w$) and flange to web thickness ratio ($t_f/t_w$). The FE results are then compared with the newly amended stainless steel European design code (EN 1993-1-4, 2006/A1:2015) [8]. Additionally, based on the current FE understanding, new design expressions for shear buckling factor are proposed.

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ABSTRACT: This paper examines the load bearing capacity of medium-length steel cylindrical shells with a circular cutout under the action of axial compression. Numerical simulations were performed for a radius-to-
thickness ratio $()$ ranging from 100 to 500, and an imperfection parameter $()$ of between 1 and 4. Structural steel and the behavior of perfect plastic material were considered within the scope of the study. The investigation includes the influence of the cutout size and number, radius-to-thickness ratio. The paper also contains a comparison between theoretical predictions, FE results and experimental data for axially compressed cylinders. A reasonable correlation was obtained between numerical predictions and experimental tests. Details relating to the experimental procedure and FE model are provided. A parametric study was conducted to propose empirical equations, estimating the limit load of cylindrical shells as a function of geometry ($R/t$, alpha and cutout number) and material properties ($E, \nu$ and $\sigma_{sub-y}$). Empirical formulas were produced, fitting a surface plot using the Least Square method, for both the perfect shell structure (reference shell load) and the limit load reduction factor ($\phi$). All variables in the empirical formula were normalized. A stochastic error analysis was used as a tool to measure how the results of proposed equations approach the FE predictions. Finally, based on experimental and numerical results, formulas are presented to calculate the limit load of medium-length shells with and without circular cutouts having a discrepancy not exceeding $\pm10\%$ regarding error analysis.


ABSTRACT: This work presents and discusses numerical results concerning cold-formed steel simply supported beams subjected to uniform bending and exhibiting (i) three cross-section shapes (lipped channels, zed-sections and hat-sections), and (ii) two end support conditions (differing in the warping and local displacement/rotation restraints, which are either free or fully prevented). A systematic numerical investigation is carried out, in order to characterise the post-buckling behaviour and ultimate strength of beams experiencing more or less severe L-D interaction effects. 43 geometries and 11 yield stresses are considered for each combination of cross-section shape and support conditions, thus ensuring distinct (i) ratios between the local ($M_{crL}$) and distortional ($M_{crD}$) critical buckling moments ($0.50 \leq M_{crD}/M_{crL} \leq 2.00$), and (ii) local or distortional slenderness values, ranging from 0.50 to 3.50. The numerical results are obtained through Abaqus shell finite element analyses and concern the (i) post-buckling behaviour (elastic and elastic-plastic), ultimate strength and failure mechanisms of beams previously selected to undergo considerable L-D interaction. Based on the acquired information, a first contribution towards the Direct Strength Method (DSM) design of cold-formed steel beams undergoing different “levels” of L-D interaction is presented and discussed.

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ABSTRACT: In this work, the development of rational explicit equations for distortional buckling critical stress of lipped channel columns subject to uniform compression is presented. An energy-based approach is adopted along with two different assumed buckled shapes (models) to obtain the analytical expressions. In Model 1, stiffened flange is assumed rigid, i.e., transverse wall bending is neglected, whereas in Model 2 the flange plate flexibility is taken into account. An analytical procedure to determine warping stresses based on cross-section
displacements and considering that flange-stiffener assembly rotation center does not coincide with web-flange fold-line is described. To validate proposed equations, a parametric analysis is carried out for lipped channels with flange-to-web width ratio, $b_f/b_w$, ranging from 0.2 to 1.0 and lip-to-web width ratio, $b_s/b_w$, from 0.1 to 0.4. Results are compared to those obtained with a generalized beam theory (GBT) software for ‘pure’ distortional mode and it is shown that, within the range of typical geometries used in industry, average differences are approximately $1.062 \pm 0.073$ and $0.998 \pm 0.001$ for Models 1 and 2, respectively. The linear (natural) coupling of pure distortion and local/global deformation modes is also briefly described and its influence on the critical loads is discussed. Finally, comparison is made to benchmark methodologies currently used in design standard and specifications. The obtained results indicate that proposed equations are reliable and valuable for practical design applications.


ABSTRACT: The design of cold-formed steel columns must consider flexural buckling, torsional buckling, and flexural-torsional buckling. The American Iron and Steel Institute incorporated equations for the critical elastic buckling loads corresponding to these failure modes in the North American Specification for the Design of Cold-Formed Steel Members. These equations were originally developed for columns with consistent boundary conditions for all three modes. However it is common in practice to have different unbraced lengths for major axis flexure, minor axis flexure, and torsion. Furthermore, it is common for certain members to be oriented such that intermediate bracing restraint directions do not align with the principal axes. This paper investigates and develops a general formulation of the column buckling equation to incorporate unequal unbraced lengths and non-principal axes.


ABSTRACT: The Finite Strip Method (FSM) for pre-buckling analysis of thin-walled sections under localised loading has been developed for general end boundary conditions. For different boundary conditions at supports and locations of applied loads, different displacement functions are required for both flexural and membrane displacements. As the stresses are not uniform along the member due to localised loading, the pre-buckling analysis also requires multiple series terms with orthogonal functions. This paper briefly summaries the displacement functions used for different boundary conditions. In addition, the theory of the FSM for pre-buckling analysis of thin-walled sections under localised loading with general end boundary conditions is developed. The analysis is subsequently benchmarked against the Finite Element Method (FEM) using software package ABAQUS/Standard. The results from this pre-buckling analysis are deflections (pre-buckling modes) and membrane stresses which are used for the buckling analysis described in Part 2 - Buckling in the companion paper.

Van Vinh Nguyen, Gregory J. Hancock and Cao Hung Pham (School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia), “Analyses of thin-walled sections under localized loading for general

ABSTRACT: Thin-walled sections under localised loading may lead to buckling of the sections. This paper briefly introduces the development of the Finite Strip Method (FSM) for buckling analyses of thin-walled sections under localised loading for general end boundary conditions. This method is benchmarked against the Finite Element Method (FEM). For different support and applied loading conditions, different functions are required for flexural and membrane displacements. In Part 1: Pre-buckling described in the companion paper, the analysis provides the computation of the stresses for use in the buckling analyses in this paper. Numerical examples of buckling analyses of thin-walled sections under localised loading with different end boundary conditions are also given in the paper in comparison with the FEM.

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ABSTRACT: This paper focuses on bi-segment spherical shells under uniform external pressure. The numerical and experimental results of buckling of bi-segment spherical shells with rib-ring of different sizes were discussed. A total of six laboratory scale models with rib-ring of three different sizes were tested. The bi-segment pressure hull was assembly with two individual spherical shells and the rib-ring using the tungsten inert gas butt welding. Each segment was 150 mm diameter and about 0.8 mm wall thickness. Numerical collapse modes agreed well with those obtained from experiments. The predicted collapsed load is about 92–99% of the experimental one except the shell with no rib-ring.

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ABSTRACT: Experimental and numerical studies were conducted to investigate the behaviours of the concrete-filled cold-formed elliptical hollow section beam-columns. A total of 11 specimens were tested to evaluate the failure modes, load-deformation histories and strains development in the steel tube. Complementary finite element (FE) models were developed and validated against experimental results. Validated FE methodology was then used to study the influence of key parameters, including aspect ratio, slenderness ratio, load eccentricity ratio, yield strength of steel, compressive strength of concrete and steel tube to concrete area ratio, on the load carrying capacity. As a result, the design method for elliptical concrete-filled steel tubular (CFST)
columns in Chinese code - GB50936-2014 and the design method for circular CFST columns in EC4 were assessed to confirm their applicability for cold-formed elliptical CFST columns with aspect ratio ranging from 1.0 to 2.5.

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ABSTRACT: The dynamic deformation behaviors of the internally nested hemispherical shell system (INHSS), were explored experimentally and computationally. Two specimens with different ratios of inner shell thickness, delta, to outer shell thickness, DELTA, were tested in a drop weight machine. For the specimen with smaller delta/DELTA, non-axisymmetric deformation mode occurred with a stable force platform and longer loading history, while for the specimen with larger delta/DELTA, axisymmetric deformation was exhibited. Meanwhile, experimentally validated finite element model was employed to study the deformation mechanism after the critical point when the outer shell contacts with the inner shell based on the ratio of square of shell thickness to radius. Subsequently, parametric studies are conducted by varying governing factors, including thickness, radius and offset distance of the inner shell. Results show that the dynamic deformation process and energy absorption capability of the INHSS depends on the thickness and radius of the inner shell.

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ABSTRACT: A series of tests were performed on S30408 stainless steel, including material mechanical property tests at elevated temperatures and fire experiments on rectangular sections of stainless steel columns. Steady tests at elevated temperatures were performed to obtain the stress-strain curves of stainless steel and reduction coefficient of mechanical properties at different temperatures. The test values of the mechanical properties of the stainless steel material are close to those from European specification at temperatures between 100 °C and 700 °C, and their changed trends are basically consistent with temperature. Six axially compressed rectangular columns of stainless steel with constraints were used to investigate the effects of the load ratio, section size and restraining stiffness on the fire-resistance performance of stainless steel columns. The test phenomenon, heating curve, deformation curve and buckling temperature of specimens were determined. The
test results show that load ratio and axial restraining stiffness ratio are the key factors for buckling temperature and fire-resistance performance of axially compressed stainless steel columns with constraints. The larger the load ratio and axial restraining stiffness ratio is, the lower the buckling temperature and the worse the fire resistance of stainless steel columns. There are two main types of buckling failure modes of axially compressed stainless steel columns with constraints in fire: the first is flexural buckling and the second is coupling mode between flexural buckling and local buckling. The types of buckling failure modes depend on the cross-section size and the section type of the specimen.

ABSTRACT: This paper presents the results of an experimental study on the behavior of fiber reinforced polymer (FRP)–recycled aggregate concrete (RAC)–steel double-skin tubular columns (DSTCs) under concentric compression. Influences of the concrete strength, DSTC cross-sectional shape, and aggregate replacement ratio were experimentally investigated through the test of 24 hollow-core circular and square DSTCs. Results indicate that the overall behavior and performance of RAC DSTCs closely resemble that of DSTCs manufactured with conventional concrete, which is highly promising for structural use of RAC in the construction industry. The aggregate replacement ratio has limited influence on the ultimate condition of DSTCs. On the other hand, the replacement ratio has some influence on the trend of the stress-strain curve of concrete in DSTCs, and this is more pronounced in square specimens than in circular specimens.

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ABSTRACT: Concrete-filled double-tube (CFDT) columns, which are a new type of composite columns, have high fire resistance and the potential to be widely used in high-rise buildings. It is expected that the amount of steel used in a regular CFDT column will be relatively high due to the use of double tubes. To reduce the steel consumption, a thin-walled steel tube with longitudinal stiffeners may be adopted for the outer tube in a CFDT column. This paper studies the behaviour of concrete-filled stiffened double-tube (CFSDT) stub columns under axial compression. Tests on 12 CFSDT stub columns and two reference columns were carried out accordingly, and the test results confirm that the stiffened columns have high strength and good deformation capacity. A finite element model was developed to analyse the interaction between the steel tubes and concrete. Based on further parametric studies, a superposition model was proposed to predict the axial compressive strength of CFSDT stub columns.

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ABSTRACT: Reliability of free spanning subsea pipeline has been estimated using theory of Probability of Failure (POF) and has been analyzed in accordance with a target safety level. The POF has been calculated using First-Order Reliability Method (FORM) and Monte-Carlo Sampling (MCS). The changes in POF with regard to six different ratios of span length to pipeline diameter and six clay types and also three sand classes are calculated. Finally, sensitivity analysis is carried out to determine the contribution of each parameter on POF. It is concluded that FORM analysis can be applied for large ratios of span length to pipeline diameter.

Xuanding Wang and Jiepeng Liu (School of Civil Engineering, Chongqing University, Chongqing 400044, China), Behavior and design of slender square tubed-reinforced-concrete columns subjected to eccentric compression, Thin-Walled Structures, Vol. 120, pp 153-160, November 2017, https://doi.org/10.1016/j.tws.2017.08.023

ABSTRACT: This paper reports the studies on the behaviors of slender square tubed-reinforced-concrete (TRC) columns under eccentric loading. Eight specimens with the key parameters of length to width ratio (6, 10), load eccentricity (25 mm, 50 mm), and width to thickness ratio of the steel tube (133, 160) were tested. The test results indicate that the slender square TRC columns exhibit good ductile behavior during the eccentric loading with a global bending failure mode. A finite element (FE) analysis model was developed and the predicted results are in fine agreement with the test results. Parametric analyses were carried out to investigate the influence of the key parameters on the moment magnification factor of square TRC columns. Based on the test and parametric analyses, a regression formula of moment magnification factor is proposed to estimate the second order effect on the slender square TRC columns subjected to eccentric compression.

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ABSTRACT: A review of the literature brings out the fact that research reports on the maximization of natural frequencies of laminated composite stiffened panels are rare. The present paper combines analytical solution based on smeared stiffener technique with a novel social group optimization (SGO) algorithm to develop a procedure for the solution of such optimization problems. Cross-ply laminated circular-cylindrical panels with simply supported boundary condition, stiffened by stringers and rings are considered. Then, stiffener quantity and size are optimized for maximizing the fundamental frequency of various panel geometries considering practical constraints. Optimization shows that fundamental frequency of the structures can be increased significantly by the tailored rings, and for the numerical examples considered, stringer has no benefit with respect to maximization of the fundamental frequency. It is also confirmed that the SGO algorithm is a useful tool for this kind of mixed integer constrained optimization problems.
ABSTRACT: In this paper, a nonlinear static thermoelastic analysis of a spherical shell made of functionally graded material is performed. The material properties are assumed to be functions of both radial coordinate of the sphere and temperature. The dependence on temperature makes the governing equations nonlinear. The so-obtained nonlinear heat conduction equation is analytically solved using the perturbation technique. The approximate temperature field is then supplied to elasticity equations which are solved exactly for the case of incompressible elastic material to get displacement and stress distributions. Finally, the temperature field, material properties and radial stress versus the radial direction are shown and discussed.

ABSTRACT: This paper presents an experimental investigation on I steel reinforced concrete-filled glass fiber reinforced plastic (GFRP) tubular short columns under axial load. The study aimed to explore the effect of three parameters of steel ratio, thickness of GFRP tube and concrete strength on the mechanical behavior of I steel reinforced concrete-filled GFRP tubular short columns under axial load. A total of twenty-seven I steel reinforced concrete-filled GFRP tubular short column specimens were tested with steel ratio of 4.6%, 6.8% and 8.3%, thicknesses of GFRP tube of 5, 8 and 10 mm and concrete strengths from 20 to 40 MPa. What's more, three reference tests including the pure I-section, pure GFRP tube and fully filled GFRP tube without I-sections were conducted in this paper to compare with the proposed composite sections. The failure modes, axial load-strain relationships, axial load-axial displacement relationships and ultimate loads are presented in this paper. The strength index is proposed to better evaluate the section behavior of the composite columns. Experimental results show that the failure modes of all the specimens are basically the same. The transverse strain of GFRP tube is smaller than the axial strain under the same axial load in the linear stage. Specimens with higher concrete strength obtain higher load-bearing capacity but lower deformation capacity and strength index. Increasing steel ratio fails to improve the load-bearing capacity and stiffness, but can lighten the weight of the columns. The results also indicate that thicker GFRP tube can both improve the load-bearing capacity and obtain better deformation capacity but generate a problem of low cost-efficient. Design formulas for the load-bearing capacity of I steel reinforced concrete-filled GFRP tubular short columns under axial load are proposed.

ABSTRACT: Manufacturing-induced effects significantly affect in-service behaviour of welded structures, such as integrally stiffened panels for aeronautic applications. Being a complex phenomenon with several
variables involved, the assessment of the effects coming from welding usually relies on numerical simulations. Here, a novel shell-based finite element model is proposed to accurately simulate the transient thermal fields and stress-strain distributions resulting from friction stir welding (FSW) processes. The capability of the model to predict (i) residual stresses, (ii) material softening and (iii) geometric distortion of the welded parts is assessed by the modelling and simulation of FSW applied on aluminium integrally stiffened panels.


ABSTRACT: In this paper, a new form of energy absorbing structures has been introduced which energy absorbing is occurred during a combined process. The structure consists of a thin-walled aluminum matrix and a thin-walled steel punch. Energy is absorbed as the matrix gets expanded followed by simultaneous matrix and punch folding. In order to demonstrate the effectiveness of absorbent introduced, many samples of each type were fabricated and tested. In one case, it was found that, the new structure tends to absorb up to 32% more energy than sum of the energy absorbed by its individual parts. Also, the energy absorption properties and the parametric study were simulated using finite element code LS-Dyna. The results showed that among different section geometries, structures with rectangular section have the lowest energy absorption and the highest crush force efficiency; by increasing the number of sides of the cross section the absorbed energy increased and crush force efficiency is decreased. In addition, increasing the thickness of the punch leads to increased energy absorption. Also, it was found that, selecting an appropriate thickness for the punch, one can predict overall shape of load-displacement curve and maximum force location for the combined structure.

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ABSTRACT: In recent years, aluminum alloy single-layer latticed shell has been extensively used in civil and industrial infrastructure. The elasticity modulus of aluminum alloy is low, the rigidity of aluminum joints are weak and the roof load transmission path is different. Therefore, the stability performance of this dome is unique. To clarify the stability performance of aluminum alloy single-layer latticed shell, over 500 aluminum alloy single-layer spherical latticed shells were analyzed with nonlinear finite method. The suggested values of rise/span ratio and initial imperfection were presented. The influencing coefficients of initial imperfection, material nonlinearity and stressed skin effect on stability bearing capacity were obtained. And the structural stability safety coefficient and the approximate calculation formula for stability bearing capacity of aluminum alloy single-layer spherical latticed shell were derived. The influences of joint semi-rigidity were investigated. All the aforementioned results provide a scientific basis for future stability design of aluminum alloy single-layer spherical latticed shell structure.
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ABSTRACT: In this paper, a ductile damage constitutive model was used to describe the damage evolution of material while a structure is subjected to earthquake loading. And embedding this constitutive model into UMAT subroutine using software ABAQUS to introduce damage constitutive equations. A damage index which includes both maximum and cumulative deformations was then used to estimate the different degrees of damage of structural members caused by cyclic loading. The collapse mechanism of single-layer reticulated shell was investigated through incremental dynamic analysis (IDA). Two types of collapse, dynamic instability and dynamic strength failure, were obtained. It was found that material damage accumulation had little effect on plastic development and collapse pattern when the structure was in dynamic instability; but the effect of material damage accumulation was obvious and could not be ignored when the structure was in dynamic strength failure due to large plastic development. Last, two different structural damage models—one including multiple structural responses and the other including deformation and energy—are defined based on limit state criteria. It was found through comparison of results that these two structural damage models can be used to accurately define and quantify different damage degrees of single-layer reticulated shells during earthquake. The vulnerability at different damage degrees of structure using the structural damage model was conducted through IDA analysis, which could be used for seismic performance evaluation and risk assessment.

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ABSTRACT: In this paper, thirty-six short columns with different diameters (150 mm ≤ d ≤ 460 mm) and steel ratios (4.0% ≤ α ≤ 10.0%) were tested to failure to investigate the size effect of circular concrete-filled steel tubular short columns subjected to axial compression. Size effects on the peak axial stress, peak axial strain, composite elastic modulus, and ductility coefficient were studied. The experimental results showed that the peak axial stress, peak axial strain and ductility coefficient of the specimens tended to decrease with the increase in the column diameter. The values of the composite elastic modulus remained almost constant when the diameter of the specimens increased, indicating that size effect on the composite elastic modulus was not obvious. Meanwhile, size effect on the peak axial stress was influenced by the steel ratio in the range of 4–10%. Furthermore, the size effect tended to decrease as the steel ratio increased. By comparing with the current codes, a reduction coefficient was introduced to consider the size effect of concrete core. Based on the reduction coefficient, the size effect of the concrete core inside the steel tube is found to be weaker compared with that of the unconfined concrete columns because of the confinement effect.
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ABSTRACT: Unburied partially embedded subsea pipelines under high temperature conditions tend to relieve their axial compressive force by forming localised lateral buckles. This phenomenon is traditionally studied as a kind of imperfect column buckling problem. We study lateral buckling as a genuinely localised buckling phenomenon governed by a different static instability, with a different critical load. No ad hoc assumptions need to be made. We combine this buckling analysis with a detailed state-of-the-art nonlinear pipe-soil interaction model that accounts for the effect of lateral breakout resistance. This allows us to investigate the effect of initial embedment of subsea pipelines on their load-deflection behaviour. Parameter studies reveal a limit to the temperature difference for safe operation of the pipeline, in the sense that for higher temperature differences a localised buckling mode has lower total energy than the straight unbuckled pipe. Localised lateral buckling may then occur if the pipe is sufficiently imperfect or sufficiently dynamically perturbed.

ABSTRACT: This paper presents and discusses proposals for the codification of efficient design approaches for cold-formed steel columns affected by local-distortional (L-D) interaction. These proposals, based on the Direct Strength Method (DSM), were developed, calibrated and validated on the basis of experimental and numerical (shell finite element) failure load data concerning columns with several cross-section shapes (plain, web-stiffened and web-flange-stiffened lipped channels, hat-sections, zed-sections and rack-sections) and obtained from investigations carried out by various researchers. Three types of L-D interaction are taken into account, namely “true L-D interaction”, “secondary-local bifurcation L-D interaction” and “secondary-distortional bifurcation L-D interaction”. Moreover, previously available DSM-based design approaches developed to handle column L-D interactive failures are reviewed and their merits are assessed and compared with those exhibited by the present proposals. The paper also presents reliability assessments of the failure load predictions provided by the available and proposed DSM-based design approaches, following the procedure prescribed by the current version of the North American Specification for the Design of Cold-Formed Steel Structural Members.

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ABSTRACT: Free vibration analysis of a joined shell system composed of two conical shells is analysed in this research. It is assumed that the system of joined shell is made from a linearly elastic isotropic homogeneous
material. Both shells are unified in thickness. To capture the through-the-thickness shear deformations and rotary inertias, first order theory of shells is accompanied with the Donnell type of kinematic assumptions to establish the general motion equations and the associated boundary and continuity conditions with the aid of Hamilton's principle. The resulted system of equations are discreted using the semi-analytical generalised differential quadrature (GDQ) method. Considering various types of boundary conditions for the shell ends and intersection continuity conditions, an eigenvalue problem is established to examine the vibration frequencies as well as the associated mode shapes. After proving the efficiency and validity of the present method for the case of thin isotropic homogeneous joined shells, some parametric studies are carried out for the system of combined moderately thick conical-conical.

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ABSTRACT: The flexural behaviour including the moment capacities and failure modes of cold-formed steel built-up sections with circular web holes was investigated. Finite element analysis was performed on a wide range of cold-formed steel built-up section beams with different sizes of perforations under four-point bending. The built-up sections included both I-shaped open sections assembled from two lipped channels back-to-back and box-shaped closed sections assembled from two plain channels face-to-face. Finite element (FE) models have been developed to simulate the simply-supported cold-formed steel built-up section beams. The FE models for the built-up open sections and built-up closed sections were verified against the test results that have been conducted by the authors. The validated models were employed to carry out extensive parametric studies on cold-formed steel built-up section beams with various section slenderness and hole sizes. The beam strengths obtained from the numerical analysis together with the available test data were compared with the design strengths calculated from the current direct strength method (DSM). The critical elastic local and distortional buckling moments including the influence of holes that are required in DSM calculation were determined by rational finite strip analysis. It is shown that the DSM formulae in the North American Specification AISI S100-16 are capable for predicting the design strengths of the built-up open section beams with holes, while are quite conservative for the closed section beams with holes. Modifications are proposed for the DSM formulae for built-up closed section beams with holes. In this study, the current DSM was extended to cover the cold-formed steel built-up open and closed section beams with holes.

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ABSTRACT: Aircraft wing and fuselage panels are often built in multibay configurations. Aeroelastic studies on multibay panels in supersonic flight were addressed by many authors in the past century under the assumption of linear structural behavior, therefore unable to assess the amplitude of the limit cycle oscillations. This work contributes to the study of multibay panel flutter by extending the model to account for geometrical non-linearities, and also by using direct time integration without any sort of linearization or eigenvalue assessment procedure. Results generated for two- and three-bay panels reveal that the single-panel model can
drastically underestimate the maximum displacements at the structure, which is critical for structural design and fatigue-life estimation. Also, for the first time, the existence of discontinuous bifurcations has been observed in the limit cycle amplitude diagrams for different multibay arrangements. Such bifurcations have been proven to be directly related to the nonlinear coupling between adjacent bays and the coexistence of different stable limit cycles sensitive to initial disturbance.

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ABSTRACT: This paper reports a full-scale fire testing of concrete filled thin-walled steel tubular (CFST) column-wall structure. All together eight specimens were designed and tested under axial compression load and subjected to ISO-834 standard fire. Load ratio, fire-exposure time and insulation scenarios were varied in the testing program. Cement mortar, aerated concrete block, and mineral wool were used as the insulation layer materials. Test results including temperature to time relations, axial deformation, and fire resistance as well as failure modes were described. A finite element analysis (FEA) model was established in order to simulate the thermal and structural behavior of CFST column-wall under fire. The FEA model was verified against test data and turned out to be reasonably accurate in predicting the temperature distribution, axial displacement, fire resistance and failure modes of CFST column-walls. Sensitivity studies were carried out to determine some major parameters in the FEA model. Discussion was made on the influence of thermal resistance, spalling of the insulation layer and confinement of inner concrete on the modelling of CFST column-wall structures.

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ABSTRACT: A complete stress-strain model for cold-formed circular hollow section (CHS) stub columns under compression is proposed with emphasis placed on the modeling of post-local-buckling behavior. The proposed model comprises two mathematical expressions. One of the two equations is to define the ascending portion of the proposed stress-strain curve and depict the nonlinearity caused by residual stress induced during manufacturing process of cold-formed CHS, while the other is to define the descending portion and trace the post-local-buckling behavior. The proposed stress-strain model is a single parameter model. Only if the generalized outer diameter-to-thickness ratio is given, the compressive stress-strain relationship of a CHS can be completely determined. To calibrate the proposed model and verify its accuracy, test results of forty-eight CHS stub columns under compression are collected. The previous tests cover a wide range of structural factors such as outer diameter-to-thickness ratio and yield strength, particularly including CHS stub columns with yield strength of up to 1180 MPa. Comparisons between the measured results and the calculated ones indicate that the
proposed model can not only predict the local buckling strength as well as corresponding strain, but also trace the post-local-buckling behavior up to large strain with high accuracy.


ABSTRACT: Emerging flexible electronics industries, such as solar cells and RFID tags manufacturers, adopt the roll-to-roll (R2R) technology to improve their production efficiency. However, the flexible webs used in these fields wrinkle easily due to their tiny thickness and complex structure. Moreover, the webs are easily buckled if the rollers are misaligned. Therefore, it is desired to introduce an efficient method which can help to determine the critical buckling conditions of the webs when there is misalignment of rolls during their production. The current research presents a model based on the Kirchhoff plates buckling theory to determine the critical buckling misalignment and tension for webs transported through misaligned rollers. Webs are modeled as tensioned Timoshenko beams to obtain their stress distributions. The critical buckling conditions are calculated using the Galerkin method in the current research. Results indicate that the calculated critical conditions are close to the practical ones considering the parabolic variation of shear stress and the linear variation of bending stress. The results also indicate that the critical misalignment increases with the increase of the span ratio and tension, and critical misalignment decreases with the increase of the elastic modulus and web width. Moreover, the critical tension increases as the thickness and elastic modulus increases. The presented model provides a useful method to design and maintain R2R equipment.


ABSTRACT: This paper describes experimental and numerical investigations conducted to characterize the basic material properties and design of YSt–310 cold–formed structural steel sections at Indian Institute of Technology, Guwahati. Square (SHS) and rectangular (RHS) hollow sections with minimum yield strength of 310 MPa manufactured by Tata Steel India, were considered in the study. Initially, results from elemental analysis via optical emission spectrometer (OES) investigation and metallographic examination using optical microscope are presented. Key stress–strain parameters viz., Young's modulus, proof stress, ultimate strength, percentage elongation, strain hardening exponent etc. were generated based on flat, corner and weld coupon tests data. Extent of corner strength enhancement due to cold – forming determined using Vickers's microhardness test are reported. Additionally, cross – section capacity of the stub columns were also investigated experimentally and numerically. The column capacities generated from test and finite element study are compared with the existing design code – EN 1993–1–1 (EN 1993-1-1, 2005) [1] and design rules – continuous strength method (CSM) (Zhao et al., 2017) [2] and direct strength method (DSM) (North American Specifcation for the Design of Cold-Formed Steel Structural Members, 2016; Arrayago et al., 2017) [3,4]. Based on the comparison, modifications on the existing design code and rules are suggested to provide a more accurate and reliable compressive design prediction.

Sandor Adany (Budapest University of Technology and Economics, Department of Structural Mechanics, Műegyetem rkp. 3, 1111 Budapest, Hungary), “Constrained shell finite element method for thin-walled...
ABSTRACT: In this paper the constrained finite element method is applied for the buckling analysis of thin-walled members with holes. The method is basically a shell finite element method, but constraints are applied which enforce the member to deform in accordance with specific mechanical criteria, e.g., to force the member to buckle in flexural, or flexural-torsional or distortional mode. The method is essentially similar to the constrained finite strip method, but the trigonometric longitudinal shape functions of the finite strip method are replaced by polynomial longitudinal shape functions, and longitudinal discretization is used, which transform the finite strip into multiple finite elements. As the method has already been presented in earlier papers, here it is just briefly summarized. More detailed discussion of the secondary cross-section modes is provided, since the presence of holes might have important consequences on these secondary modes. Two basic approaches for handling the holes are discussed. Numerical examples are also presented. Comparison of linear buckling results to available results from the literature fully validates the proposed constrained finite element method. Further numerical examples illustrate the difficulties and uncertainties involved in regular unconstrained buckling analysis of members with holes, and also show that the proposed constrained finite element method eliminates the uncertainties in assessing the effect of holes on the critical loads, as well as, in general, helps to understand the effect of holes on the buckling behavior.

ABSTRACT: Along with proposing any innovative structural element for design purposes it is necessary to understand its behaviour under combined structural actions. This paper includes experimental, numerical and analytical investigations on an innovative type of hybrid fabricated section consisting of high strength tubes and mild steel plates under the effect of axial compression and bending moment interaction. As a special case of interactive condition, pure bending performance of the hybrid fabricated member is examined with focus on the local failure mechanisms and analytical expressions are proposed to predict the moment resisting capacities. Furthermore, compression-bending interaction curves are obtained from plastic analysis of hybrid hollow sections and compared to relevant standard formulations. The compression-bending curves obtained for various ratios of tube cross-section and strength to that of plate show that a linear interaction formula is applicable to predicting the plastic interaction behaviour of sections with high ratios while sections with lower ratios are closely predicted by a bilinear interaction formula. This paper also includes beam-column tests accommodating combined effects of compression, bending and also shear. Employing the developed and validated finite element model, a parametric study is conducted on the effect of section geometry and material on the axial-lateral interaction of beam-columns. Referring to the member interaction results, reaching an optimum interactive performance stands on the design of both geometry and material of plate and tube elements.

ABSTRACT: Unburied subsea pipelines operating under high-temperature and high-pressure conditions tend to relieve their axial compressive force by forming lateral buckles. Uncontrolled lateral buckling may lead to
pipeline failure. In order to control lateral buckling, a sleeper is often employed as a buckle-initiation technique. In this study, analytical solutions of lateral buckling for unburied subsea pipelines with sleeper are derived. An energy analysis is employed to investigate the stability of the buckled pipeline. The influence of sleeper height and sleeper friction on pipeline buckled configurations and typical lateral buckling behaviour is illustrated and analysed. The results are shown to be in very good agreement with experimental data in the literature. We also discuss the effect of imperfections and conduct an error analysis of one of the main assumptions of the proposed analytical method. Our results show that increasing the height of the sleeper or decreasing the friction between pipeline and sleeper can all be used to decrease the minimum critical temperature difference. However, only the sleeper height is effective in substantially reducing the maximum compressive stress.

References listed at the end of the paper:
ABSTRACT: Multi-cell tubes have been widely used in vehicle engineering for their excellent energy absorption capacity. In this paper, a group of bionic multi-cell tubes (BMCTs) with quadrilateral, hexagonal and octagonal sections were proposed. The BMCTs were constructed by filling the cylindrical tubes into different position of multi-cell tubes (MCTs), which was inspired by the microstructure of beetle forewings. The finite element (FE) models under axial impact loading were established and then validated by the Simplified Super Folding Element (SSFE) theory. The crashworthiness of different BMCTs and MCTs was compared, and the results showed that the sixth type of bionic multi-cell tube with octagonal section (O-BMCT-6) has the best crashing performance. Then, the multiobjective optimization design of O-BMCT-6 was conducted by using non-dominated sorting genetic algorithm II (NSGA-II) and radial basis function (RBF) metamodels. The optimal O-BMCT-6 showed superior crashworthiness and could be used as an energy absorber.

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ABSTRACT: The subject of the paper is the progressive failure analysis (PFA) of thin-walled Z-shape cross section members subjected to axial compression. This study concerns angle-ply multi-layered Fibre Metal Laminates (FMLs) which consist of alternating thin layers of aluminium and glass fibre-reinforced unidirectional prepreg. Laboratory damage tests were performed by the static testing unit that provided displacement control loading. Experimental results were compared with FEA wherein based on the profile's nonlinear stability investigations the failure analysis was performed. Nonlinear FE simulation combined with available progressive failure mechanics allowed to predict the initiation and propagation of the multi-failure modes within composite material. Hashin failure criterion was used to monitor the initiation of damage, whereas material degradation method (MPDG) was applied in FRP layer to define the damage evolution law. Damage variables were specified according to FEM modelling procedures in order to control material stiffness reduction after damage initiation. For aluminium layers the J2 plasticity model was employed. Progressive failure assessment by FEM allowed to estimate the post-buckling equilibrium paths and damage modes with particular regions of laminate's fracture that were found to be in a good agreement with experimental evidences. References listed at the end of the paper:

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ABSTRACT: State-of-the-art studies of the energy absorption systems reveal various techniques for enhancing the crashworthiness of a structure, and each technique has its benefits and drawbacks. For crashworthy designers, it is a challenge to design an efficient energy absorbing system which fulfills its requirements in terms of crashworthiness. Therefore, this paper proposes tailor-made technique for crashworthiness design by performing a combination of two or more energy absorption techniques to fulfill the crashworthy designer requirements. The tailor-made technique is adapted to have the ability of implementation by different structural configurations; thus, tubular square tubes configuration has been utilized as an example. Tailor-made technique implementation is validated experimentally and numerically under quasi-static and axial impact loading, afterwards, its merits are discussed through conducting a comparative study. Results show that the novel tailor-made technique provides the designers the flexibility in designing of the protected structure. Furthermore, tailor-made technique improves the crashworthiness of the energy absorbing system in terms of crushing performance and energy absorption capacity. Moreover, it leads to energy absorbing systems applicable to a wide range of impact velocities through generating low reaction force under low impact velocity and logical crushing force under high impact velocity.

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ABSTRACT: This study examines the effect of shape index on the elastic buckling of Cassini oval shells under uniform external pressure. Shells are evaluated under a uniform wall thickness (2 mm) and capacity (3.63x10^6 mm^3), with the shape index, k-sub-c = c/a, ranging from 0 to 0.99. Several numerical computations, involving linear elastic bifurcation analysis and geometrically nonlinear elastic analysis including eigenmode imperfections, are conducted for these shells. Some of them are investigated experimentally. The results show that a Cassini oval shell with a stable character seems to be an unfavorable shape due to its low load-carrying capacity, which is at variance with previous findings regarding this problem. Notably, the k-sub-c = 0.1 Cassini oval geometry, exhibiting a high load-carrying capacity, appears to be a favorable shape in various fields such as underwater tanks, pressure hulls, and artificial capsules.

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“Lateral-torsional buckling strength and behaviour of high-strength steel corrugated web girders for bridge construction”, Thin-Walled Structures, Vol. 122, pp 112-123, January 2018,
https://doi.org/10.1016/j.tws.2017.10.021

ABSTRACT: Corrugated web plates have been used in recent years as the webs of steel girders in bridge constructions thanks for their advantages, especially their superior shear capacities relative to stiffened flat webs. Therefore, they have been extensively investigated under shear compared with their limited investigations on the bending behaviour which was exclusively concentrated on the girders formed from the conventional normal strength steels. On the other hand, the use of high-strength steels (HSSs) in bridges has been increased when large and column-free spaces are key design issues. This paper focuses on the lateral-torsional buckling (LTB) of bridge girders with corrugated webs (BGCWs) built up from HSSs. This is done by using the commercially available finite element (FE) analysis package ABAQUS which has been used to generate parametric studies addressing the different affecting parameters on the behaviour of these girders. Simply-supported girders subjected to uniform bending, representing the worst case in LTB which is used in developing the member capacity design rules in different standards, are used in developing the current nonlinear FE models. The recently suggested warping constants in literature are used to compare the critical buckling moments with the elastic FE predictions. Then, the design model included in the Eurocode 3 is compared with the nonlinear strengths of the girders. The comparisons show that it provides conservative outcomes; therefore a modified version of the design model is suggested by using another buckling curve.

References listed at the end of the paper:


ABSTRACT: In this study, the behavior of multi-frusta configurations under axial loading was analyzed, the effect of column spacing, number of tubes, shells, and cone combinations investigated, and multi-objective optimization applied to obtain optimal multi-frusta configurations. The results obtained indicate that the interaction between multi-frusta configurations without shell improves the system's specific energy absorption (SEA), the SEA of multi-frusta tubes can be improved by the rigid outer shell, and the overall energy absorption of restricted size structures benefit from having an appropriate number of multi-frusta configurations. They also show that cross-arranged tapers offer better energy absorption characteristics than other arrangements.

References listed at the end of the paper:


ABSTRACT: In this article, a two-node finite strip with eight degrees of freedom for the free vibration analysis of pre-stressed rotating cylindrical shells is formulated. The circumferential mode shape profiles are described exactly using trigonometric functions. The axial mode shape profiles are approximated by bar and beam shape functions for membrane and bending displacements, respectively. In this way, a semi-analytical formulation is facilitated so that discretisation is required only in the axial direction. The accuracy and convergence of the developed finite strip are confirmed by comparisons with the analytical results. Excellent agreement is observed both for stationary and rotating shells.

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It was found that material grading can save a very significant amount of the reinforcement up to 200% relative to homogenous panels. The saving of the reinforcement depends on four factors; (1) the problem nature, (2) the boundary conditions, (3) the applied loads, (4) the direction of the material gradings.

References listed at the end of the paper:

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ABSTRACT: Foam-filled thin-walled structures signify a class of a promising energy absorber for improving the crashworthiness and safety of vehicles. Although the conventional deterministic optimization has been extensively applied to crashworthiness design of foam-filled thin-walled structures, the optimal solution could become infeasible when uncertainties of design variables and noise factors present in real world. To address this issue, a reliability based design optimization (RBDO) is adopted to consider the uncertainties of design variables and noise factors in crashworthiness optimization for the foam-filled bitubal tapered structure in this paper. Moreover, to comprehensively investigate the differences between deterministic and reliability based design optimization, single objective and multiple objective RBDO are established by integrating Kriging approximation with Monte Carlo Simulation (MCS). Since the optimal results of deterministic design usually converge at the constraint boundary, the solutions of RBDO often need to compromise some objective performance to satisfy the predetermined reliability levels. Furthermore, a comparative study on different Pareto fronts yielded from the deterministic optimization and RBDO under different reliability levels is conducted here. Besides, a grey relational analysis is carried out to determine the most satisfactory solution from the Pareto-set. The results demonstrate that the optimized foam-filled bitubal tapered columns are capable to considerably improve capacity of energy absorption with an increased reliability, potentially being a structural configuration for energy absorber.

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ABSTRACT: Intermediate diaphragms are used in box girders not only to prevent premature distortion under eccentric loading conditions but also to improve the distribution of live loads. This paper reports an investigation into the effect of intermediate diaphragms on the load-carrying capacity of a Steel—Concrete Composite Box (SCCB) girder bridge with open steel box section. In the current study, a three-dimensional finite element (FE) model of the SCCB girder is developed and analyzed using ABAQUS software. The nonlinear inelastic analysis is invoked in order to accurately capture the actual behavior of the girder. The numerical model is verified with experimental results to ensure the accuracy of the FE modeling method. A parametric analysis is implemented to study the effect of intermediate diaphragms on the load—carrying capacity of an SCCB girder with a 30–60 m span length. Based on parametric studies, the number of intermediate diaphragms (N) is recommended for practical design of the girder, which satisfies the requirement stated in the provisions of the AASHTO LRFD standard.

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Suggestions are provided for the design of folded single or multi-cell sections, on the crushing force and deformation of the folded tubes are investigated numerically. In addition, folded tubes with multi-cell sections are also analyzed and compared with traditional tubes. Some suggestions are provided for the design of folded single or multi-cell tubes. Since the folded tubes are easily fabricated by bending of metal sheets, the crushing force and deformation of these folded tubes are analyzed and compared with traditional square tubes. Nonlinear finite element code LS-DYNA is employed to simulate the crushing tests and the numerical results are compared with the experiment. The influences of various factors, including the boundary condition, loading speed, fillet radius and sectional shape, on the crushing force and deformation of the folded tubes are investigated numerically. In addition, folded tubes with multi-cell sections are also analyzed and compared with traditional tubes. Some suggestions are provided for the design of folded single or multi-cell tubes. Since the folded tubes are easily
prepared, cost-effective for small-scale production and flexible in both sectional shape and geometric parameters, they are quite promising to be applied widely in various engineering fields.

References listed at the end of the paper:

ABSTRACT: Multi-cell structures have proven to own excellent energy absorbing capability and lightweight effect in the automotive and aerospace industries. The cross-sectional configuration of the multi-cell structure has a significant effect on crashworthiness. Unlike existing multi-cell tubes, a new type of five-cell profile with four circular elements at the corners (C5C) was proposed in this study. To investigate the crashworthiness of the new C5C tube, finite element (FE) models were first established by using the nonlinear finite element code LS-DYNA and validated with experimental results. Following that, the comparison of the C5C tube and other multi-cell tubes with the same mass was conducted to quantify the relative merits of the C5C tube. Then, a detailed study was performed to analyze the effect of the corner-cell size and wall thickness. Finally, the optimization design was carried out to seek the optimal structure. The results showed that the new multi-cell structure can absorb much more crash energy than other four types of tubes. Moreover, the energy absorption of this new multi-cell tube C5C was affected by the corner-cell size and wall thickness significantly. A proper corner-cell size and slightly thicker internal ribs were recommended. In addition, the multi-objective particle swarm optimization (MOPSO) algorithm and radial basis function (RBF) surrogate model can optimize the structure effectively. The outcomes of the present study will facilitate the design of multi-cell structures with better crashworthiness.

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24 T. Tran, “Crushing analysis under multiple impact loading cases for multi-cell triangular tubes”, Thin-Walled Struct., 113 (2017), pp. 262-272
ABSTRACT: The Hencky bar-net model (HBM) has been shown to be a physical structural representation of the finite difference plate model (FDM). This paper extends the HBM to tackle buckling problems of rectangular plates under in-plane non-uniform loads. This class of problems requires a pre-buckling stress analysis involving plane-stress elasticity equations in order to establish the non-uniform stress distributions in the plate domain for input loads to the HBM. The converged results given by HBM compare well with existing reference solutions; thereby verifying the model. The HBM is also used to generate some new buckling solutions for rectangular plates under various point loads and partially distributed loads.

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In the hypothesis that the composite shell is elastic, which leads to unexpected calculation and prediction errors. In this paper, the fiber reinforcements are assumed to be elastic while the matrix is treated as a viscoelastic material. The resulting viscoelastic bistable behavior of those composite shells with viscoelastic material properties. Subsequently, the influences of applied temperature and relaxation time on the second stable configuration of bistable composite shells are analytically investigated. The results are then compared with those obtained from the experiments and numerical modeling. Comprehensive results show that the principal curvature of the shell's second stable state increases as the applied temperature and relaxation time increase. In contrast, the twisting curvature of the
second stable shape generally decreases with the relaxation time increasing but increases with the applied temperature rising.

References listed at the end of the paper:
ABSTRACT: The nonlinear bending and snap-through instability phenomenon of isotropic and composite conical shell panels are investigated here using the element free Galerkin (EFG) method with moving kriging (MK) shape function. Sanders’ shell theory along with von Kármán strain-displacement assumptions are employed to derive the nonlinear equations of equilibrium, which are solved by modified Riks technique in conjunction with Newton-Raphson method. The convergence and accuracy of the EFG method are examined for the linear and nonlinear bending behavior of conical shell panels. Thereafter, the effect of geometrical parameters on the nonlinear stability characteristics of conical panels is investigated under different loading conditions. New results for linear as well as nonlinear bending behavior of isotropic and laminated conical shell panels, hitherto not found in the literature, are presented for future reference.

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ABSTRACT: Until now, there are no analytical solutions published of the lateralexternal lateral-torsional buckling (LTB) of the prestressed steel I-beams. In this paper, the symmetric and antisymmetric elastic LTB buckling performance of prestressed steel I-beams, with rectilinear tendons, under equal end moments has been examined. Firstly, a simplified mechanical model is put forward. Secondly, based upon the Euler-Beam model & the Kirchhoff-Plate model, the strain energy equation as well as the potential energy of the prestressed steel I-beam are obtained, for the first time, and the correctness of the analytical solution of the critical moment of the symmetric buckling of the prestressed I-beam is verified by those simulated by using ANSYS. Finally, parameter analysis is carried out. It is found that: (1) the critical moment of the prestressed steel I-beam, with rectilinear tendons, under equal end moments can be determined by that of the symmetric buckling; (2) the critical prestressing force can be determined by that of the symmetric buckling or antisymmetric buckling depending on the relations of the critical moment of the symmetric buckling of the prestressed steel I-beam and the eccentricity.
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32 W.F. Zhang, Plate-beam Theory for Thin-Walled Structures, Research Report, Northeast Petroleum University, Daqing, China (2015)
ABSTRACT: A shear deformation shell theory including thickness stretching effects is used to formulate the minimization problem of the vibrational response of functionally graded truncated conical shells in different cases of boundary conditions. Mechanical control energy is introduced into the formulation as a functional containing a closed-loop control force. The optimization objective is taken as the sum of the control energy and the total energy of the shell. Based on Lyapunov–Bellman theory, optimum values for the control forces and deflections are obtained for shells with simply supported or clamped edges. A design procedure is applied to complete the minimization process for the control objective using material and geometric parameters. Numerical and graphical results are presented to show the importance of the inclusion of the thickness stretching effects into the formulation. An assessment for the current design and control approach in minimizing the optimization objective is performed.

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ABSTRACT: The paper compares the energy absorption of the AZ31 magnesium alloy with the DC04 and HC380LA steel on the example of the thin-walled model profiles made by the process of bending. Additionally, the studies involved the application of aluminium foam filling the sections in order to increase their energy absorption. The first stage of the research included the elaboration of a technology of producing the thin-walled model profiles from a magnesium alloy by way of bending, with the use of tools heated to 270 °C and 300 °C.
Next, the prepared sections halves were joined with the use of the FSW method. The static tensile tests showed that the FSW joints underwent damage in the native material or at the boundary with the heat-affected zone, which confirmed their high strength. The main aim of the use of the magnesium alloy was to lower the mass of the bodywork. And so, in order to compare the energy absorption of the profiles made of steel with those made of magnesium alloys, the mass of the samples should be taken into consideration. To that end, in the study, the parameter of specific energy absorption was introduced, which is the absorbed energy divided by the mass of the sample. The dynamic deformation tests performed on the profiles made of the AZ31 magnesium alloy and the DC04 and HC380LA steel demonstrated that the profiles made of only the AZ31 magnesium, due to their low deformability, do not exhibit sufficient energy absorption. In order to increase it, hybrid samples should be applied. The study proposed filling the profiles made of the AZ31 alloy with aluminium foam. This caused their specific energy absorption to be higher than that of the steel profiles.

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ABSTRACT: Thin-walled structures are used in safety applications such as automotive vehicles and locomotives because of their efficient energy absorption, lightweight, and reduced manufacturing cost. The performance of these structures is inhibited under oblique loading conditions. This paper numerically studies the crushing behavior and performance of corrugated tapered tubes (CTTs) as potential efficient thin-walled structures under oblique loading conditions. The proposed CTT design is impacted under 7 different loading angles with a striker mass of 275 kg and 15 m/s velocity. The material assigned to the proposed design structure is AA6060 aluminum alloy. The effect of loading angles on various performance indicators, such as the initial peak force (PF), mean crushing force (MF), energy absorption (EA) and specific energy absorption (SEA) was studied. It was found that increasing the impact angles lead to a reduction in performance, and a reduction of around 54% in EA and SEA was observed when the impact angle increased from 0° to 40°. Moreover, the effect of the geometric parameters on the performance indicators was also investigated. In addition, global bending was found to develop at higher impact angles for CTTs of 80° tapered angles. Finally, it was found that some CTTs can achieve higher SEA relative to their tapered conventional counterparts.

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38 Y. Zhang, G. Sun, X. Xu, G. Li, Q. Li, “Multiobjective crashworthiness optimization of hollow and conical tubes for multiple load cases”, Thin-Walled Struct., 82 (2014), pp. 331-342
ABSTRACT: The shear buckling behaviour of welded stainless steel plate girders with transverse stiffeners has been experimentally and numerically investigated in this paper. A total of seven plate girders with rigid/non-rigid end posts were fabricated from hot-rolled stainless steel plates, and each of the plate girders was subjected to a concentrated load at mid-span. The shear buckling characteristics and postbuckling behaviour were observed. Prior to testing, the initial local geometric imperfections and the material properties were accurately measured. The critical shear buckling strengths of the web plates were determined from the recorded surface strains and out-of-plane deflections, which were further compared with theoretically predicted values from elastic and inelastic assumptions. By using the general finite element (FE) software package ABAQUS, elaborated FE models were developed and validated against the obtained test results and other available existing test data. Upon validation of the FE models, parametric studies were subsequently carried out to explore the influences of initial local geometric imperfections, web aspect ratios, end post conditions, and material properties over a wide range of web slendernesses. The obtained test/FE results, together with other existing test
data, were summarised to evaluate the current codified provisions in GB 50017, EN 1993-1-5, EN 1993-1-4, EN 1993-1-4+A1 and the design proposals from Estrada et al. Based on the test and numerical results, an alternative design approach that could account for the material non-linearity and rigid and non-rigid end posts has been proposed, which provides accurate and reasonable strength predictions for stainless steel plate girder with transverse stiffeners.

References listed at the end of the paper:

ABSTRACT: To include ovality in the analysis of pipe bends, elliptic and semi-oval cross sections are generally assumed. This study determines collapse load equations for semi-oval cross section using finite element analysis under in-plane bending and internal pressure and compares them with the existing collapse loads for elliptic cross sections. The comparison reveals that elliptic or semi-oval cross section may be used when the pipe bend is subjected to only in-plane bending moment. With internal pressure, though elliptic cross section is suitable for low pressures, semi-oval cross section may be preferred as it is suitable for high pressures. References listed at the end of the paper:

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ABSTRACT: Experimental investigation was conducted on large-section extruded aluminum alloy columns of I-section and rectangular hollow section (RHS). Altogether seven columns with different slenderness ratios were comprised. The failure modes and stability resistance as well as load-displacement responses were identified. It was found that all tested specimens failed in flexural buckling. An extensive parametric analysis on 180 specimens was carried out with general FEA software ANSYS to evaluate the reliability level of the current design specifications including American aluminum design manual, Eurocode 9 and Chinese code GB 50429. The design stability resistance advised by Eurocode 9 and Chinese code GB 50429 is conservative, while that of American aluminum design manual slightly overestimates the practical stability resistance. Based on the parametric analysis results, a new design method was proposed to improve the design accuracy.

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ABSTRACT: An experimental study into the axial compressive behaviour of concrete-filled circular hollow section (CHS) steel columns with internal fibre reinforced polymer (FRP) tubes is presented in this paper. A total of 17 concrete-filled steel tubular (CFST) columns were tested, 15 with an inner FRP tube and 2 with no inner tube. Complementary material tests and tests on 15 FRP-confined concrete (FCC) columns were also carried out. The varied test parameters included the concrete strength, the ratio of the diameter of the steel tube to that of the FRP tube, the diameter to wall thickness ratio of the inner FRP tube and the type (influencing principally the rupture strain) of the FRP. It was found that the presence of the inner FRP tube led to considerably improved axial compressive behaviour due to the greater levels of confinement afforded to the ‘doubly-confined’ inner concrete core; the load-bearing capacity was increased by between about 10% and 50% and the ductility was also enhanced. Greater benefits arose with (1) increasing diameter of the inner FRP tube due to the increased portion of the cross-section that is doubly-confined and (2) increasing wall thickness of the inner FRP tube due to the increased level of confinement afforded to the inner concrete core. The load-deflection responses of all tested specimens were reported, revealing that failure was generally gradual with no sharp loss in load-bearing capacity, implying that the embedment of the inner FRP tube within the concrete enables it to continue to provide a reasonable degree of confinement even after the initiation of fibre rupture; this is different to the sudden loss of confinement typically observed in FRP externally jacketed concrete columns.

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ABSTRACT: The effectiveness of a simplified method for estimating an envelope curve of wrinkled membrane-surface distortion, which was recently proposed by the author, was experimentally assessed. The equation is formulated using three physical quantities regarding wrinkles: the length of the wrinkle line, the major principal strain in wrinkled regions, and the in-plane shrinkage strain appearing in the orthogonal direction of the wrinkle line. Since these three physical quantities are attributed to two-dimensional problems, the formula makes it possible to simply estimate wrinkle amplitude without a cumbersome bifurcation analysis. Applying a wrinkle strain in tension-field theory instead of the in-plane shrinkage strain in the formula, a simplified method to estimate an envelope curve of a wrinkled membrane with a low computational cost was developed using the wrinkling analysis with tension-field theory. Wrinkling phenomena appearing on two membrane models subjected to an in-plane shear and a corner-tension load were experimentally measured by photogrammetry using the direct linear-transformation method and a laser-displacement sensor. The experiment model was then subjected to a finite element analysis using tension-field theory, and an envelope curve of the wrinkled membrane was estimated using the method. The estimated envelope curves appropriately captured the actual wrinkle amplitude appearing on the membrane surface regardless of the formation process of wrinkles. From the result, the validity of the proposed estimation method was confirmed. This paper offers an effective method to predict the magnitude of the wrinkled-membrane-surface distortion with a low computational cost, and will assist the development of future gossamer space structures incorporating membranes.

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ABSTRACT: This paper deals with extending the domain of applicability of a recently developed Generalised Beam Theory (GBT) formulation intended to perform elastic linear buckling analyses of thin-walled members (i) exhibiting arbitrary flat-walled cross-sections (including those combining closed cells and open branches), and (ii) acted by general loadings. These loadings, which include transverse forces acting away from the member shear centre axis, are termed “general” in the sense that they may involve the presence of pre-buckling stress distributions associated with any possible combination of all the stress tensor membrane components (sigma(xx), sigma (ss), and tau(xs), for a plane stress state), including cell shear flows – therefore, all the relevant geometrically non-linear effects need to be taken into consideration. After briefly presenting the main concepts and procedures involved in the development and implementation of the above GBT formulation, this same formulation is employed to analyse the buckling behaviour of beams with different types of cross-section geometry (containing closed cells) and exhibiting different loading and support conditions. In particular, they consist of (i) a RHS cantilever acted by two tip point loads, (ii) a closed-flange I-section simply supported beam subjected to a uniformly distributed load and (iii) a two-cell RHS section cantilever acted by tip transverse forces and couples. In all cases, the loads are applied both along the shear centre axis and also along axes parallel to it and located at the beam top and bottom surfaces. The results presented and discussed, which consist of pre-buckling stress fields, buckling curves and buckling mode shapes, are obtained by means of the newly released code GBTul 2.0 and validated by means of the comparison with shell finite element values obtained with the code Ansys.

ABSTRACT: This paper focuses on the parametric instability of a functionally graded (FG) cylindrical thin shell under both axial disturbance and thermal environment. Based on Love's thin shell theory, and considering the temperature-dependent properties of FG cylindrical shell, the dynamic equations of the FG cylindrical shell are derived by Hamilton's principle. The multiple scales method is performed to obtain the instability boundaries of the shell with axial disturbance. The primary and combination instabilities of the shell are studied.
systematically. Moreover, numerical simulations are utilized to discuss the influences of axial disturbed amplitude, material heterogeneity and thermal effects on instability regions, frequency characteristics of the shell. Specially, some numerical results are given to illustrate the combined influence of axial disturbed amplitude and temperature variation on instability regions.


ABSTRACT: Three novel types of multi-cell tubular structures with pre-folded origami patterns were proposed in this paper, aimed at reducing the initial peak force and the crushing force fluctuation while maintaining or increasing the specific energy absorption during uniaxial crush. Experimentally validated finite element modelling was conducted to study the influence of geometric parameters on the mechanical properties. Optimal designs were obtained through multi-objective optimization. The results showed that predesigned origami patterns governed the buckling process of the tubes and quintuple-cell origami tubes could absorb the highest energy in crush with significantly reduced initial peak force and the crushing force fluctuation.


ABSTRACT: This work reports the results of a numerical investigation concerning the elastic post-buckling behaviour of fixed-ended thin-walled lipped channel and zed-section columns affected by distortional-global (D-G) interaction – “unexpected” features associated with the global buckling nature are unveiled in both cases. The columns analysed (i) exhibit cross-section dimensions and lengths ensuring the simultaneous occurrence of distortional and global critical buckling, and (ii) contain critical-mode initial geometrical imperfections (linear combinations of the critical distortional and global buckling mode shapes). For comparison and clarification purposes, the post-buckling behaviour of lipped channel columns buckling in an “isolated” distortional mode and containing “pure” distortional and global (flexural-torsional) initial geometrical imperfections are also analysed. The results presented and discussed are obtained through geometrically non-linear Generalised Beam Theory (GBT) analyses and provide the evolution, along given equilibrium paths, of the column deformed configuration (expressed in GBT modal form), relevant displacement profiles and modal participation diagrams, making it possible to acquire in-depth insight on the mechanics underlying D-G interaction in columns. Finally, particular attention is paid to interpreting the differences exhibited by the various column post-buckling behaviours investigated.


ABSTRACT: Vibrations of thin-walled systems compound of coaxial conjugate shells of revolution of different shapes with torus-elliptical members are analyzed. The shells can be composed of one or several layers, of isotropic and orthotropic materials with variable geometric and stiffness characteristics along a generatrix-
meridian. Small undamped vibrations of such systems are studied using the classical Kirchhoff-Love theory. To solve the appropriate eigen-value two-dimensional problems, the numerical-analytical technique, which includes the Fourier variable-separation method, incremental search method (delta(lambda)-method), and the orthogonal sweep method with solving Cauchy's problems by the fifth-order Runge-Kutta scheme, is developed. It is shown by a number of examples that vibrations of the shell system as a single whole have qualitative features in comparison with vibrations of its separate members.


ABSTRACT: Previous studies proved that the patch loading resistance model of the EN1993-1-5 can lead to significant underestimation of the patch loading resistance in case of longitudinally stiffened girders. Recently there are several research activities to improve the design method. In the current study experimental research program is executed on 8 large scale test specimens having different longitudinal stiffener configurations and loading lengths to extend the available background and to verify advanced numerical model. In parallel to the experiments a finite element model is developed considering the geometrical and material nonlineairities and geometric imperfections. The current paper presents the experimental tests and focuses on the modelling technique of the geometric imperfections, which can have large importance in case of coupled instabilities. Based on the experiments and numerical investigations design recommendations are given for equivalent geometric imperfection shapes and magnitudes for girders with longitudinally stiffened web. The measured resistances are compared to different resistance models found in the international literature and their accuracies are evaluated.


ABSTRACT: Following the bifurcation approach, a generalized closed form buckling solution for clamped-pinned anisotropic laminated composite columns under axial compression is developed using the energy method. The effective axial, coupling, and flexural rigidity coefficients of the anisotropic layups are determined following the generalized constitutive relationship using dimensional reduction by static condensation of $6 \times 6$ rigidity matrix. The presented analytical explicit formula reproduces Euler buckling expression in the case of isotropic or specially-orthotropic materials once the effective coupling term vanishes. On the other hand, the analytical formula furnishes two extra terms which are functions of the effective coupling, flexural and axial rigidity. The analytical buckling formula is confirmed against finite element Eigen value solutions for different anisotropic laminated layups yielding high accuracy for a wide range of stacking sequences. A parametric study is then conducted to examine the effect of ply orientations, material properties including hybrid carbon/glass fiber composites, FE element type, and column size. Relevance of the numerical and analytical results is discussed in comparison to previous results in literature for cross ply laminates.

Zhaochao Li, Yan Tang, Fujian Tang, Yizheng Chen and Genda Chen (Primarily from: Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO
ABSTRACT: In this study, a thin-walled polyhedral polymer pipe liner is proposed for the internal rehabilitation of a deteriorated/cracked underground circular metal pipe. The pipe liner is externally confined and subjected to the hydrostatic pressure of water seeped through the cracked pipe. The critical buckling pressure of the pipe liner is derived analytically based on the principle of minimum potential energy and compared with that of a cylindrical pipe liner. A finite element model of the pipe liner is established and analyzed to understand pressure-deformation equilibrium paths and the stability of post-buckling behavior. The analytical buckling pressure is in excellent agreement with the numerical results. The buckling pressure of a polyhedral liner increases with the increase of thickness-to-radius ratio and the decrease of the number of sides in polygon base shape. In comparison with the cylindrical liner, the polyhedral liner can increase buckling pressure up to 10 times but result in a less stable post-buckling behavior.


ABSTRACT: The purpose of this study was to investigate the effect of geometry on the energy absorption of aluminum tubes with different cross-section and the effect of combined bitubular tubes to absorb more energy under axial crushing. In the experimental part, aluminum tubes with circular and square cross-section were prepared and then the quasi-static tests with static loading rate were performed and the load-deflection diagrams in each test were obtained. A numerical model is proposed based on finite element analysis to simulate the collapse process considering the non-linear responses due to material behavior, contact and large deformation. The comparison of numerical and experimental results showed that the present model provides an appropriate procedure to determine the collapse mechanism, crushing load and the amount of energy absorption. The validated finite element model was then used for the parametric studies, in order to determine the effect of the geometry factors such as combined substitution of bitubular tubes, multi-cell reinforced and flat end-capped on the energy absorption. The primary outcome of the study is new research information which will facilitate the design of thin-walled tubes as energy absorbers in crushing applications.


ABSTRACT: In practical engineering, cutouts in thin-walled cylindrical shells are usually welded with ringed stiffeners for the purpose of connect and seal. In this paper, experimental and numerical studies have been conducted to investigate the effects of ringed stiffener on the buckling behavior of perforated cylindrical shells under axial compression. Three test specimens with ringed stiffener and three specimens without ringed stiffener are manufactured and tested. The mid-surface imperfections of all specimens are measured and introduced into the finite element model. The finite element method using static analysis with artificial damping is used to simulate the displacement controlled compression tests. Good agreement is found between the numerical and experimental results. It is found that the global buckling loads of perforated shells are improved by ringed stiffener. The larger the cutout size is, the more obvious improvement shows. In addition, effects of
ringed stiffener on axial stiffness and imperfection sensitivity of perforated shells are studied in details. The relationship between ringed stiffener thickness and global buckling load of perforated shell is also discussed. Meanwhile, a critical thickness parameter $k$ of approximately 15% is proposed.


ABSTRACT: The objective of this paper is to advance the design of slender steel tubes by developing a practical approach for utilizing high-resolution measurements of geometric imperfections to estimate the buckling location and strength of such tubes in bending. This approach includes a novel measure of imperfection severity that is designed to be insensitive to noise. The ability of this measure to predict buckling behavior of slender tubes in bending is assessed through comparison with eight large-scale tests, and, for this set of data, the predictions are promising. This study is intended to be a starting point in the development of a simple, but accurate, design method to quantify the impact of imperfections on the buckling behavior of slender tubes.

Songzhao Qu, Xiaohong Wu and Qing Sun (Primarily from: School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi 710049, China), “Experimental study and theoretical analysis on the ultimate strength of high-strength-steel tubular K-Joints”, Thin-Walled Structures, Vol. 123, pp 244-254, February 2018, https://doi.org/10.1016/j.tws.2017.11.014

ABSTRACT: In order to investigate the failure mode and mechanism of K-joints fabricated using high-strength steel and to develop a formula that can predict their ultimate strength, full-scale tubular K-joints with tube-gusset plate connections of Q690 high-strength steel are fabricated and tested under static loads. Based on the tubular energy theory and virtual work principle and using the ring-generator separation model, a formula for predicting the ultimate strength of high-strength steel K-joints is developed. In order to verify the correctness of the formula, using the finite element model, a sensitivity analysis is performed on the factors that affect the ultimate strength of the joints. The results indicate that the stress in the main post and the thickness and diameter of the main post significantly affect the ultimate strength of the K-joints. Moreover, the results predicted by the proposed formula correlate well with the experimental and numerical results. Hence, the proposed formula can be used for practical engineering design.


ABSTRACT: This paper presents a comparative study of circular concrete-filled steel tubular stub columns with three different stirrup confinement types: bidirectional stirrups, loop stirrups and orthogonal stirrups. Axial compression tests have been carried out aiming at investigating the effects of the stirrup form and volume-stirrup ratio on the mechanical behavior of the stirrup-confined circular CFT stub columns, and ABAQUS was used to carry out the 3D numerical modelling. Radial stress of the core concrete and the composite action among the steel tube, stirrups and the core concrete have been investigated. It is found that the confinement
provided by stirrups on core concrete strongly outperforms that provided by steel tube, steel sections or steel reinforcement. Furthermore, a simplified approach was developed to predict the ultimate bearing capacity of stirrup-confined circular CFT stub columns, which agreed well with the experimental and numerical results.

ABSTRACT: Under coupled bending-shear-torsion (B-S-T) loading combinations, the ultimate bearing capacity of concrete filled steel tube (CFST) short columns has not been studied. In this paper, the test on eight CFST short columns was carried out. The load-deformation relations and failure modes of CFST short columns were obtained and analyzed. Based on experimental results, the failure mechanism of CFST short columns were obviously affected by the ratio of bending moment to torque, and CFST short columns under coupled B-S-T loading combinations had good ductility. The ultimate bending-shear bearing capacity of CFST short columns was significantly decreased by increasing torsion moment. Moreover, nonlinear finite element analysis was performed, which generated an accurate prediction of the ultimate capacity of concrete filled steel tube short columns under coupled B-S-T. As a conclusion, a simplified design equation for calculating the coupled B-S-T bearing capacity of CFST short columns was proposed according the regression results of the finite element parametric analysis.

ABSTRACT: The continuous strength method (CSM) is a recently developed deformation-based design method for metallic structures. In this method, cross-section classification is replaced by a normalized deformation capacity, which defines the maximum strain that a cross-section can endure prior to failure. This limiting strain is used in conjunction with an elastic, linear-hardening material stress-strain model to determine cross-section capacity allowing for the influence of strain hardening. To date, the CSM has been developed for the determination of cross-section capacity under normal stresses (i.e. compression, bending and combined loading), where it has been shown to offer more accurate predictions than current codified methods. In this paper, extension of the CSM to the determination of shear resistance is described. The relationship between the normalized shear deformation capacity, referred to as the shear strain ratio, and the web slenderness is first established on the basis of experimental and numerical data. The material model and proposed resistance functions are then described. Comparisons of the developed method with the ultimate shear capacity of a series of tested stainless steel plate girders show that improved resistance predictions of test capacity over current design methods are achieved.

ABSTRACT: The paper deals with buckling of cylindrical metal silos with corrugated sheets and columns. Attention was paid to local buckling of cold-formed open-sectional thin-walled columns in metal cylindrical silos with corrugated sheets. The effect of the column profile dimensions, silo height, silo diameter, corrugated wall thickness, column number/column distance, corrugation height and bulk solid's type was comprehensively
investigated. Three-dimensional linear bifurcation analyses were performed for silos using the finite element method and compared with analytical formulae of Eurocode 3. Based on calculation outcomes some recommendations for silo dimensioning were elaborated.


ABSTRACT: Buckling behavior of cylindrical shells with measured settlement under axial compression has been researched and analyzed in this paper. Using the method of Fourier series expansion, the measured settlement data is transformed into differential settlement. Applying the finite element simulation method, the differential settlement is applied to bottom of the cylindrical shell in order to simulate behavior of the cylindrical shell under differential settlement. Based on the deformed cylindrical shell caused by settlement, the finite element simulation method is applied to research buckling behavior of the cylindrical shell under axial compression considering the geometric nonlinearity and large deformation. The meridional membrane stress distribution in the circumferential direction of the cylindrical shell under differential settlement is obtained and compared with the differential settlement distribution. Effects of liquid storage on buckling behavior of the cylindrical shell are researched by applying hydrostatic pressure to the inner surface. Parametric analysis is carried out to research the effects of diameter-thickness ratio and height-diameter ratio of the cylindrical shell on the axial buckling capability. Results show that the cylindrical shell will be subjected to deformation and meridional membrane stress because of the differential settlement and the critical axial buckling load will be decreased then. Liquid storage is helpful for the cylindrical shell to remain stable. The cylindrical shell with larger height-diameter ratio and smaller diameter-thickness ratio is more capable to resist buckling under axial compression following differential settlement.


ABSTRACT: When a train collision occurs, it is impossible for the vehicle to produce a completely axial collision. To improve the energy absorption performance of the energy-absorbing structure under an eccentric collision, in this paper, a FE model of the energy absorption structure for subway vehicles was created and validated by experimental data. Based on the validated FE model, the collision performances under a vertical offset of 0–80 mm and a horizontal offset of 0–40 mm are studied via simulation. The results show that the original structure is prone to instability when the horizontal offset is greater than 30 mm, so it is necessary to perform an optimization. Based on the bending strength, the cross-sectional shape of the guide was changed. The results show that there is no instability phenomenon in the improved structure I1 under all horizontal offsets. Under the horizontal offset of 40 mm, compared with the original structure, the energy absorption increased by 175.89%, and the peak force also increased by 14.46%. Based on the concept of gradient material, the honeycomb strength in the structure is changed into a gradient distribution, and the results show that the improved structure I2 also did not show any instability phenomenon under all horizontal offsets. Under the
horizontal offset of 40 mm, compared with the original structure, the energy absorption increased by 171.88% and the peak force decreased by 1.92% at the same time.

ABSTRACT: Liquid storage tanks are among vital infrastructures, and their seismic vulnerability assessment plays a pivotal role in uninterrupted operation of an industrial plant. Technically, vulnerability notion relates capacity of each tank component's resistance to failure subjected to different seismic hazard levels. The predominant source of damage to liquid-containing tanks is steel shell buckling which can be intensified by base flexibility of fully anchored tanks. This flexibility is mainly resulted from anchor bolt failure and base concrete damage. In other words, the presence of anchors does not necessarily preclude anchorage failure or loss of concrete support, especially during large earthquake events. A case study on a liquid storage tank is introduced in this paper to highlight the influence of base flexibility on the seismic performance of fully anchored tanks. The tank is initially designed in accordance with the requirements of American Petroleum Institute, API-650. Fluid-structure interaction (FSI) is simulated by means of so-called added-mass approach. Two sets of finite element models are constructed, namely; fixed base (FB) and flexible base (FLB) tank. Nonlinear time history analysis based on a suite of twenty-two multi-directional spectrally matched acceleration time histories are conducted. Simultaneous input motions of two horizontal components are of particular importance as they shift the position of failure mechanism to directions being more affected by combined accelerations. Critical intensity measures (IMs) according to incremental dynamic analysis are then determined. Fragility curves are obtained by introducing conditional probability of failure as a function of critical IM. Results reveal that modelling base flexibility may contribute to lower value of critical IMs compared to that obtained from restrained support model. More specifically, FLB model demonstrates lower value of endurable peak ground acceleration (PGA) compared to the initial value selected for the tank design as per API requirements.

ABSTRACT: Structural improvements for curved-surface thin-walled structures were examined. In such structures, installations of ribs—support structures for out-of-plane deformations—are often effective. These out-of-plane deformations are attributed to internal loadings induced from plane stresses. Shapes of solid curved I-sectional beams models were optimized using a structural optimization algorithm—the traction method. Ribbed structures were created semi-automatically by the structural optimization when adequate rib-triggers—striped shape constraints or humps in the initial shapes—were applied to the models. This result validates the effectiveness of rib installations on curved surface structures. It is notable that the rib formation created substantial topology changes.

ABSTRACT: This paper presents an analytical research on the in-plane stability of members in single-layer reticulated latticed shells with aluminum alloy gusset (AAG) joints. The influence of two kinds of actual boundary conditions are considered, namely, the stiffness of the AAG joint ($k_i$) and restraint of adjacent
members \(k_2\). In order to explore the influence of \(k_1\), an experimental program including 5 member specimens with AAG joints is introduced, and finite element (FE) models are established and verified. Based on the test and FE results, the effective length of the specimens are obtained. Subsequently, theoretical analysis is conducted to investigate the effect of \(k_2\), with accounting for the stiffness reduction caused by axial compressive force. Finally, the effective length factors of members in reticulated shell with AAG joints are derived and tabulated. Numerical examples are presented to illustrate the necessity of considering the influence of \(k_1\) and \(k_2\), and verify the good accuracy of the given effective length factors.


ABSTRACT: We analytically investigate infinitesimal cylindrical bending deformations of two-layered triangular corrugated and webcore linearly elastic sandwich panels by using the mechanics of materials approach and the classical plate theory. The model is validated by comparing its predictions with the solution by the finite element method of the linear elasticity equations for plane strain deformations. The model can accurately capture the secondary bending of the facesheets, manifested as changes in their curvature between the webs and the resulting changes in the axial stresses, from being tensile to possibly compressive, that the commonly-employed homogenization schemes fail to capture. Subsequently, the model is used to analyze several problems with the sandwich panel having a pinned support at the left edge and a roller support at the right edge, and a uniformly distributed load applied on the top facesheet of the panel. It is found that the core plates mostly deform in compression and bending, respectively, for corrugated and web core panels. Furthermore, a significant fraction of the work done by the external load on the structure is absorbed as strain energy of deformations of the core plates near the supports. For four hybrid combinations of corrugated and webcore configurations in two-layered panels, the combination with the upper corrugated core set-up has the least maximum face sheet deflection and axial stress. The analytical technique can be easily extended to multi-layered hybrid configurations and provides quick means of finding efficient strain-energy absorbing hybrid designs.


ABSTRACT: The paper focuses on thermal torsional post buckling of functionally graded carbon nanotube reinforced composite cylindrical shells with sur-bonding piezoelectric layers and embedded in an elastic medium. The distribution of reinforcements through the thickness of the shells is considered to be uniform and functionally graded. The basic equations using geometrically nonlinearity in von Karman-Donnell sense within the classical thin shell theory are established. The torsional post-buckling behavior of the piezoelectric functionally graded carbon nanotubes reinforced composite (FG-CNTRC) shells is analyzed with using the Airy's stress function and the Galerkin's method, in which a three-term approximate solution of the deflection of the shell is assumed. Effects of thermal environment, CNT volume fraction, piezoelectric layers (the thickness and the constant voltage), distribution type of the reinforcement, dimensional parameters and Winkler and Pasternak foundation are investigated in this paper. Numerical and graphical results show that the carbon nanotube volume fraction and the piezoelectric layers as well as the elastic foundation and the thermal loads have significantly influenced on the torsional postbuckling behavior of nanocomposite shells.

Yasushi Uematsu, Takayuki Yamaguchi and Jumpei Yasunaga, “Effects of wind girders on the buckling of open-topped storage tanks under quasi-static wind loading”, Thin-Walled Structures, Vol. 124, pp 1-12, March 2018
ABSTRACT: The present paper investigates the wind resistant design of ring-stiffened open-topped storage tanks based on finite element analyses, in which we use the distributions of wind pressure on isolated and grouped tank models measured in a wind tunnel experiment. The effects of top/intermediate wind girders on the buckling load and mode of tank shells are investigated based on the results of buckling analysis for quasi-static wind loadings. The design recommendations for the wind girders are proposed, which may provide more reasonable design criteria for the wind girders than the current design guidelines.

Bin He, Yu Zhang, Wei-Yan Ge, Yi An and Dongmei Liu, “Buckling analysis of thin-walled members with open-branched cross section via semi-analytical finite strip transfer matrix method”, Thin-Walled Structures, Vol. 124, pp 20-31, March 2018

ABSTRACT: Thin-walled members with open-branched cross section have been used in many modern engineering structures, and their buckling performance has been widely studied. In this paper, two transfer methods are developed to tackle the transfer problems at the junction of the open-branched cross-section of thin-walled members by using semi-analytical finite strip transfer matrix method (FS-TMM) which is a combined use of semi-analytical finite strip method (SA-FSM) and transfer matrix method (TMM) for the buckling analysis. Compared to traditional SA-FSM, this method has a smaller matrix and higher computational efficiency due to no global stiffness matrix generated. An asymmetric E-section member, a symmetric I-section member and a X-section member with loaded edges simply supported are analyzed by the derived formulation. All the results are compared with SA-FSM's or finite element method's results to prove the reliability and efficiency of this method.


ABSTRACT: This work aims at presenting and discussing Generalised Beam Theory (GBT) numerical results concerning the elastic geometrically non-linear behaviour of simply supported lipped channel (LC) beams under uniform major-axis bending and experiencing distortional-global (D-G) interaction, making it possible to shed fresh light on the mechanics underlying this coupling phenomenon. Two LC beam geometries are considered, each exhibiting a different type of D-G interaction, namely (i) “true D-G interaction”, associated with close distortional ($M_{crD}$) and global ($M_{crG}$) critical buckling moments, and (ii) “secondary global-bifurcation interaction – SGI”, corresponding to $M_{crD} < M_{crG}$. While the latter beam geometry contains a critical-mode distortional initial imperfection, the former one is analysed with initial geometrical imperfections exhibiting three critical-mode shapes (one distortional and two global, due to the lack of symmetry). Moreover, an investigation conducted to assess the possible occurrence of “secondary distortional-bifurcation D-G interaction – SDI” ($M_{crG} < M_{crD}$) is also presented and discussed. In order to clarify the surprising behaviour of the beam undergoing a SGI, an additional beam is analysed, exhibiting a “pure” distortional post-buckling behaviour (i.e., involving no coupling phenomenon). The GBT-based results provide the evolution, along given equilibrium paths, of the beam deformed configuration (expressed in modal terms), relevant displacement profiles and modal participation diagrams. The knowledge acquired has visible impact on the development of rational design rules for CFS beams affected by D-G interaction.

Hui-Wei Yang, Wen-Bo Guan and Guo-Yun Lu, “Experimental and numerical investigations into collapse behavior of hemispherical shells under drop hammer impact”, Thin-Walled Structures, Vol. 124, pp 48-57, March 2018

ABSTRACT: Dynamic response for a series of cylindrical shells filled with water were discussed previously, which indicated that the limit buckling load of the cylindrical shells was greatly improved by the presence of
water. To obtain a good protective structure, a double layered liquid-filled hemispherical shell structure is designed. Three kinds of structures (single layered empty hemispherical shell, double layered empty hemispherical shells, and single layered liquid-filled hemispherical shell) are compared with the double layered liquid-filled hemispherical shells. The collapse behavior of four kinds of hemispherical shell structures and their deformation modes under drop hammer impact are presented to investigate the effects of inner water on the response of the liquid-filled hemispherical shells. Test results show that the effects of inner water mainly include "distributing loadings" and "ironing effect". Double layered liquid-filled hemispherical shells have the highest bearing capacity among all four kinds of structures. Three-dimensional numerical simulations of all the tested specimens were carried out using ANSYS and LS-DYNA. Under same impact condition, the effective protection space of empty hemispherical shells is very small due to its larger vertex displacement. In terms of generalized specific energy absorption ($\eta$) of structures with same vertex displacement, liquid-filled hemispherical shells are better than empty shells. For liquid-filled shells, $\eta$ of double layered shells is smaller than single layered shell, but single layered shell has no inner space. Parameter analysis indicates that only the outer thickness has a significant effect on the impact force. Increasing the outer thickness and ensuring a reasonable distance between the inner and outer shell can improve the crashworthiness of double layered liquid-filled shells and protect the internal objects.

ABSTRACT: In this paper, the compound strip method is applied to the stability analysis of cold-formed steel built-up sections. A beam element with adjustable stiffness properties is adopted to represent the utilised fastener and the associated stiffnesses of the connection elements are incorporated in the global stiffness matrix of the built-up sections. The presented method allows for modelling arbitrarily-located discrete fasteners in the context of the semi-analytical finite strip method. The proposed numerical technique is verified against finite element solutions through various numerical examples and shown to be both accurate and versatile. Some typical and also complex built-up sections with various fastener configuration and end boundary conditions are analysed to evaluate the influence of fastener spacing. The extent of composite behaviour in built-up sections is determined by investigating the enhancement of buckling capacity and changes in the corresponding buckling modes. The simplicity of the proposed technique expedites extensive parametric studies of cold-formed built-up sections and facilitates the search for optimal placement of fasteners and choice of section geometry.

ABSTRACT: Pipe beams are considered under the action of bending. In case of elastic material, an analytical model of a one-dimensional beam is introduced, where the internal constraint between ovalization and bending curvature is deduced from mechanical considerations. Then, the softening moment-curvature relationship, able to describe the Brazier effect, is evaluated applying equilibrium equations in the nonlinear field. The same model is extended to the case where a structural foam is present as core of the pipe. The contribution of the core is analyzed in terms of its action in preventing instability phenomena. Finally, a model of lumped ovalization is discussed.

Soheil Salahshour and Famida Fallah, “Elastic collapse of thin long cylindrical shells under external pressure”, Thin-Walled Structures, Vol. 124, pp 81-87, March 2018
ABSTRACT: This paper investigates local elastic buckling of thin long cylindrical shells under external pressure. Based on Donnell's and Sanders' theories of thin shells and von Karman nonlinearity assumptions, the
potential energy is derived. The buckling load and curves of the static equilibrium path are obtained using the Ritz method. The results are validated with the existing ones in the literature. Furthermore, the case where the pressure is perpendicular to the deformed state is compared with a dead loading. It is demonstrated that the former yields a lower critical pressure in both shell theories.


ABSTRACT: Thin-walled tubes (TWTs) have been widely applied as energy absorbers in engineering. The energy absorbing property of rectangular TWTs can be substantially enhanced by changing the ultra-thin solid walls into sandwich walls. Sandwich wall has great bending rigidity and it improves the energy absorption through two aspects: shortening the wave length or improving the plastic bending moment. Competition of these two mechanisms endows the rectangular sandwich-walled tube (SWT) with excellent energy absorbing ability and the best performance is achieved when the two mechanisms appear simultaneously. Mean crushing force (MCF) of the rectangular SWT could be 2.5 times of that of the TWT. The MCF of optimally designed rectangular SWT is even greater than the yield load of the tubular structure.


ABSTRACT: This paper mainly presents a combined experimental, numerical and theoretical study on the mechanical behaviors of both conventional concrete-filled rectangular steel tubular stub columns (RST) and stirrup-confined concrete-filled rectangular steel tubular stub columns (SST) under compressive load. 16 RST stub columns and 16 SST stub columns were tested, with consideration of parameters including internal stirrup, concrete strength, and cross-sectional aspect ratio $B/D$. The failure patterns, bearing capacity, stiffness and ductility of specimens were analyzed based on the experimental results. A 3D finite element (FE) model was established for numerical simulation and parametric study to investigate the composite action among the steel tube, stirrups and the core concrete. The improvement of energy dissipation capability due to the stirrups confinement on the core concrete is also discussed. In addition, a unified theoretical formula to predicted ultimate bearing capacity for SST stub columns and RST stub columns subjected to compressive load was developed according to the superposition principle with rational simplification. It is shown that the proposed formula for these columns has a higher accuracy compared with the existing formulas in current literatures and codes.


ABSTRACT: The current investigation deals with the buckling and postbuckling behaviors of graphene-reinforced composite (GRC) laminated cylindrical shells subjected to lateral or hydrostatic pressure under thermal environmental conditions. The piece-wise GRC layers are arranged in a functionally graded (FG) pattern along the thickness direction of the shell. The temperature dependent material properties of GRCs are estimated by the extended Halpin–Tsai micromechanical model with graphene efficiency parameters being calibrated against the GRC material properties from a molecular dynamics simulation study. We employ the Reddy’s higher order shear deformable shell theory in association with the von Kármán geometric nonlinearity to model the shell buckling problem under different thermal environmental conditions. The buckling pressure and the postbuckling equilibrium path for the perfect and geometrically imperfect GRC laminated cylindrical shells are obtained by applying a singular perturbation technique along with a two-step perturbation approach.
We observe that the piece-wise functionally graded distribution of graphene reinforcement can increase the buckling pressure and the postbuckling strength of the GRC laminated cylindrical shells subjected to external pressure.


ABSTRACT: This paper presents the fundamentals and illustrates the application and potential of the recent 2.0 release of the software GBTul – a computer program developed by the authors and made available as freeware on the website of the Department of Civil Engineering of the University of Lisbon. The program is based on Generalised Beam Theory (GBT), a bar theory accounting for cross-section in-plane and out-of-plane (warping) deformation, and performs linear buckling and undamped free vibration analyses of prismatic thin-walled members. Its domain of application is much wider than that of the previous release (1.0β), making it possible to analyse single or multi-span members (i) with various support conditions, namely those due to discrete bracing systems, (ii) exhibiting arbitrary (open, closed or “mixed”) flat-walled cross-sections and (iii) acted by fairly general loadings, including concentrated and/or distributed transverse forces applied away from the member shear centre axis. After providing a brief overview on the GBT fundamentals, the program capabilities and innovative aspects are addressed, and its application is illustrated by means of a few relevant numerical examples. Moreover, the program Graphical User Interface is described and the procedures and/or options associated with its main commands are mentioned.


ABSTRACT: Two key reference loads: (i) the plastic collapse load and (ii) the elastic buckling load are commonly used to determine the slenderness and hence the resistance of structural steel elements in international design standards. Utilising numerical methods, the plastic collapse loads are typically obtained through a Materially Nonlinear Analysis (MNA) based on small displacement theory (i.e. a first order plastic analysis). However, such analyses can often yield ambiguous or even spurious results due to, for example, the load-deformation paths not reaching a peak value or reaching a peak value but only after unrealistically large deformations, resulting in misleading predictions of plastic collapse loads and mechanisms. In this paper, a standardised means of determining plastic collapse loads from numerical MNA based on attaining a tangent stiffness of 1% of the initial slope of the load-deformation curve is presented. Furthermore, for analyses that terminate prematurely, an extrapolation technique to predict the full load-deformation paths and hence estimate the plastic collapse load is proposed. The accuracy and practicality of the proposed approach over existing methods is illustrated for a wide range of structural scenarios, with an emphasis on structural elements under concentrated transverse forces.

Hongyong Jiang, Yiru Ren and Jinwu Xiang, “A numerical study on the energy-absorption of fibre metal laminate conical frusta under quasi-static compression loading”, Thin-Walled Structures, Vol. 124, pp 278-290, March 2018

ABSTRACT: The energy-absorption (EA) of fibre metal laminate (FML) conical frusta under quasi-static compression loading is studied by performing virtual test. A progressive deterioration model combined with the conventional shell model is initially employed to simulate collapse behaviors of composite wrapped aluminium conical (CWAC) frusta. To sufficiently understand collapse behaviors, the stacked shell model is used to reproduce intralaminar damage and delamination. The numerical models are validated with available experimental results and the collapse behaviors of aluminium wrapped composite conical (AWCC) frusta are
detailedly discussed. The effects of conical frusta with single and hybrid materials towards EA are investigated. The triggering mechanisms including inward and outward chamfer triggers, and convex and concave plug-type triggers are studied to better induce collapse modes of FML conical frusta. Results show that the stacked shell model has better predictive ability of collapse behaviors. The only difference between experiment and simulation is that the initial load is not perfectly captured due to specific conical profile, complex failure modes and hybrid fibre metal materials. The FML conical frusta with appropriate hybrid materials, such as AWCC frusta, present a higher EA capacity with an increase of 28.7% in SEA. The outward chamfer trigger and convex plug-type trigger can effectively improve EA of FML conical frusta.


ABSTRACT: The behaviour of dune sand concrete-filled steel tubular (CFST) stub columns under axial compression was experimentally investigated in this paper, where the nominal cube strength of concrete was 60 MPa. A total of 24 specimens including 20 dune sand CFST stub columns and 4 reference hollow steel tubular stub columns were tested. The effects of tube thickness, cross-sectional dimension and concrete infill on the behaviour of the composite stub columns were investigated. The results showed that, similar to conventional CFST stub columns, the tested dune sand CFST stub columns behaved in a ductile manner and displayed an outward buckling failure model with high compressive strength. It indicates that it is feasible to use dune sand to replace normal sand to fabricate CFST columns in regions close to deserts. Comparisons were made between the test results and the predicted ultimate strength using the existing codes AIJ (2008), AISC360-10 (2010), BS5400 (2005), DBJ/T13-51-2010 (2010) and EC4 (2004). Generally, these codes are conservative but acceptable for predicting the ultimate strength of dune sand CFST stub columns.

Najmeh Rezaee, Seyed Mohammad Hossein Sharifi, Gholam Reza Rashed and Abbas Niknejad, “Denting the oil pipelines by a rigid cylindrical indenter with conical nose by the numerical and experimental analyses”, Thin-Walled Structures, Vol. 124, pp 312-322, March 2018

ABSTRACT: The present research discusses indentation process on the oil pipelines using a rigid indenter in the quasi-static condition by the experimental and numerical analyses. This article investigates influences of internal pressure, diameter and wall thickness of pipes and geometrical characteristics of rigid cylindrical indenters with conical nose such as cone angle, conical nose diameter and cylindrical part diameter on mechanical behavior of the circular steel pipes under concentrated lateral loading (denting). In the experimental part, some specimens made from the steel API5L L245 were prepared and they laterally compressed by a rigid cylindrical indenter with the conical nose to perform the indentation process on them. In the numerical part, some finite element models were prepared and indentation process was simulated on different models with various tube and indenter geometries in different conditions of internal pressure. By comparing the numerical and experimental results, precision and accuracy of the simulations were affirmed. The discussed results show that when tube diameter increases, bending moment arm of the concentrated applied load around the formed plastic hinge lines enhances; therefore, lower lateral load can create a certain plastic deformations in the tube wall; and also, total absorbed energy by the tube enhances. Results demonstrate that when a conical projectile with a certain mass and initial velocity laterally compresses a circular tube, increment of tube diameter causes reduction of probability of the tube failure. The results show that when cone angle of conical indenter decreases and reaches to a certain value that called critical angle, the penetration occurs during the indentation process. Furthermore, it is found that by increasing the diameter of cylindrical part of the indenter, lateral indentation load increases; and when applied internal pressure on the tube increases, ultimate lateral displacement of the indenter decreases; but, the maximum load for the tube wall fracture enhances.
Zhibin Li, Rong Chen and Fangyun Lu, “Comparative analysis of crashworthiness of empty and foam-filled thin-walled tubes”, Thin-Walled Structures, Vol. 124, pp 343-349, March 2018

ABSTRACT: Quasi-static axial compression tests were conducted on two types of empty aluminum alloy tubes (circular and square) and five types of aluminum ex-situ foam filled tube structures (foam-filled single circular and square tubes, foam-filled double circular and square tubes, and corner-foam-filled square tube). The load-deformation characteristics, deformation mode and energy absorption ability of these structures were investigated. Several parameters related to their crashworthiness were compared, including the specific energy absorption, the energy-absorbing effectiveness factor, etc. The influence of physical dimension on the crushworthiness of these structures was explored. Dimensions of the inner tube were found to have significant influence on the structural crushworthiness of foam-filled double tubes. The averaged crush force, specific energy absorption, energy absorption per stroke and energy-absorbing effectiveness factor of thin-walled circular structures are higher than those of thin-walled square structures, respectively. Foam-filled single and double circular tube structures are recommended as crashworthy structures due to their high crush force efficiency and energy-absorbing efficiency.


ABSTRACT: The problem to identify pre-buckling states for thin-walled shell corresponds to the problem to identify pre-bifurcation solutions (the inverse bifurcation problem) for von Karman equations that govern the structure. Typical solution sequences similar to those of post-bifurcation solutions observed along the bifurcation paths of the nonlinear boundary problem for von Karman equations are extracted to serve as precursors of bifurcation (tools to solve the problem). The method allows one to divide all operations required to solve the problem under study into two non-equal parts. The most time-consuming part (to trace bifurcation paths and cluster the respective solution) is performed off-line, while the part of the algorithm that is carried out on-line (the identification algorithm) requires a relatively small number of arithmetic operations. This allows development of the efficient system of rapid identification of pre-buckling states.

Dabin Yang, Chaoguang Yun, Jinzhi Wu and Yunlong Yao, “Seismic response and failure mechanism of single-layer latticed domes with steel columns and braces as substructures”, Thin-Walled Structures, Vol. 124, pp 458-467, March 2018

ABSTRACT: Seismic response and failure mechanism of single-layer latticed domes with steel columns and braces as substructures are studied using incremental dynamic analysis in the paper. The member models considering cyclic buckling and low cycle fatigue of steel are used in the analyses. The results show that the seismic responses will be greatly influenced by the material low cycle fatigue under strong earthquakes in different ways for the domes with different parameters. Two typical failure modes are found for the structures: one is the failure of domes and the other is the failure of both the dome and the substructure. Influence of rise-span ratio of domes, brace sections and column sections in substructures on the ultimate PGA and yielding PGA are studied, and the optimized values of the parameters are suggested for structural designing.


ABSTRACT: Thin-walled cylindrical tubes are usually employed as impact energy absorbing members in automotive vehicles due to their high energy absorption capacity through progressive plastic deformation. Despite their superior impact performance, high initial peak force is the crucial problem which has potential to
cause serious injury to the occupants. Hence in this study, end-capped cylindrical tubes with reduced initial peak force are proposed as energy absorbing members when subjected to axial static and impact loading conditions. The proposed tubes were fabricated by a multi-stage deep drawing process, that induces forming effects such as thickness variation, and residual stress/strain. Subsequently, numerical simulations were carried out using HyperForm 14.0® and LS-DYNA R-971® with particular attention for the transfer of forming history from deep-drawing simulations to the subsequent crash models. The axial crash performance of the end-capped tubes was also compared with open cylindrical tubes and it was found that the initial peak force of the end-capped tube is significantly reduced by 15–30% than the open cylindrical tube without compromising the energy absorption capacity. The results revealed that end-capped tubes can stabilize the deformation behavior and could be used as a good alternative to the conventional energy absorbing structures in aerospace and automotive applications respectively.

J. Zheng, K. Li, S. Liu, H. Ge, . . . Z. Hua, “Effect of shape imperfections on the buckling of large-scale thin-walled ellipsoidal head in steel nuclear containment”, Thin-Walled Structures, Vol. 124, pp 514-522, March 2018

ABSTRACT: Buckling is a failure mode of a large-scale thin-walled ellipsoidal head for a cylindrical steel containment vessel, which is widely used in nuclear power plants such as AP1000 and CAP1400. Manufacturing processes always induce shape imperfections in large-scale thin-walled ellipsoidal heads. However, the study on the effect of shape imperfections on the buckling of a large-scale thin-walled ellipsoidal head subjected to internal pressure is still lacking. In this work, we first used a 3D laser scanner to measure the overall shape of the ellipsoidal head which has a diameter of 5000 mm, a radius-to-height ratio of 2.0 and a thickness of 5.5 mm. On the basis of the measured overall shape, shape imperfections were determined, and an equation was proposed to quantitatively characterize bulging of weld in the knuckle. Secondly, the measured overall shape and the equation were used to develop FEA models with shape imperfections. Buckling pressures were predicted by using nonlinear FEA. Good agreement between the predictions of the FEA models with shape imperfections were predicted by using nonlinear FEA. Good agreement between the predictions of the FEA models with shape imperfections indicates that bulging of weld has a considerable effect on buckling pressure. Thirdly, a buckling experiment was performed on the ellipsoidal head and buckling behavior was obtained. The experimental results show that all the buckles occurred at the bulgings of welds. The agreement between the experimental results and the predictions based on the models with shape imperfections is good. At last, FEA models, including different bulging heights of welds characterized by the equation, were established to perform an imperfection sensitivity analysis. Thin-walled ellipsoidal heads subjected to internal pressure demonstrate a significant sensitivity to the bulging height of weld in the knuckle.

Shouchao Jiang, Zhe Xiong, Xiaonong Guo and Zhili He, “Buckling behaviour of aluminium alloy columns under fire conditions”, Thin-Walled Structures, Vol. 124, pp 523-537, March 2018

ABSTRACT: This paper presents a systematic investigation on the buckling behaviour of aluminium alloy columns under fire conditions. One hundred and eight aluminium alloy columns, including sixty rectangular tubes and forty eight circular tubes, were tested under axial load at elevated temperature and at ambient temperature as reference. All the column specimens failed by flexural buckling. Finite element (FE) models implemented in the non-linear code ANSYS were established and verified against the experimental results. To develop a further understanding, 8829 FE models considering geometrical and material nonlinearity were conducted with four kinds of material properties, thirty four kinds of sections and five elevated temperature points. According to the FE results and statistical regression method, formulae to estimate the stability coefficients of aluminium alloy columns under fire conditions were proposed. Finally, the proposed formulae were compared with the experimental results and the stability coefficients from existing codes. It is found that
the proposed formulae can provide accurate stability coefficients of aluminium alloy columns under fire conditions.


ABSTRACT: We investigate the bistable behaviour of folded thin strips bent along their central crease. Making use of a simple Gauss mapping, we describe the kinematics of a hinge and facet model, which forms a discrete version of the bistable creased strip. The Gauss mapping technique is then generalised for an arbitrary number of hinge lines, which becomes the generators of a developable surface as the number becomes large. Predictions made for both the discrete model and the creased strip match experimental results well. This study will contribute to the understanding of shell damage mechanisms; bistable creased strips may also be used in novel multistable systems.

Chu Chang Huang, Shih Chung Peng, Wen Li Lin, Fumio Fujii and Kuo Mo Hsiao, “A buckling and postbuckling analysis of axially loaded thin-walled beams with point-symmetric open section using corotational finite element formulation”, Thin-Walled Structures, Vol. 124, pp 558-573, March 2018

ABSTRACT: The axially loaded thin-walled beams with point symmetric open section are studied using a corotational finite element formulation. The kinematics of the beam element is described in the current element coordinate system. The element nodal forces are derived using the virtual work principle, and consistent second order linearization of the fully geometrically non-linear beam theory. Different axial load systems with the same centric resultant axial force but different resultant bimoments are considered. Numerical examples studied show that the effects of bimoments on the buckling and postbuckling behavior of point symmetric open section beams are remarked.


ABSTRACT: A recent computational study identified four distinct domains of stability behaviour at different lengths in thin elastic cylindrical shells under global bending. Cylinders of sufficient length suffer from fully-developed cross-sectional ovalisation and fail by local buckling at a moment very close to the Brazier prediction. Progressively shorter cylinders experience less ovalisation owing to the increasingly strong restraint provided by the boundary at the edges. Very short thin cylinders, however, restrain the formation of even a local buckle and fail through a limit point instability at moments and curvatures significantly in excess of the classical elastic prediction. This limit point behaviour is not caused by ovalisation but by the growth of a destabilising fold on the compressed meridian. The nonlinear behaviour of very short cylinders under global bending is investigated in detail herein, covering a wide range of lengths, radius to thickness ratios and boundary conditions with both restrained and unrestrained meridional rotations corresponding to ‘clamped’ and ‘simply-supported’ conditions respectively. Two types of imperfections are investigated, the critical buckling eigenmode and a realistic manufacturing-related ‘weld depression’. A complex insensitivity to these imperfections is revealed owing to a pre-buckling stress state dominated by local compatibility bending, and the cylinder length is confirmed as playing a crucial role in governing this behaviour. The study contributes to the characterisation of multi-segment shells with very short individual cylindrical segments, often found in the aerospace and marine industries as well as in specialised civil engineering applications such as LIPP silos.

References listed at the end of the paper:
[3] R. Greiner, Cylindrical shells under uniform external pressure, in: J.G. Teng, J.M. Rotter (Eds.), Buckling of Thin Metal Shells,
ABSTRACT: Web crippling of aluminium alloy tubular structural members may occur due to the highly concentrated loadings. A nonlinear finite element analysis was performed based on a series of laboratory tests on carbon fibre–reinforced polymer (CFRP) strengthened aluminium alloy tubular structural members subjected to web crippling. The finite element models were then used for an extensive parametric study of different tube dimensions. The finite element results explained the behaviour of the CFRP-strengthened aluminium alloy specimens subjected to web crippling. The finite element results demonstrated that the ultimate load-carrying capacity (web crippling strength), web crippling failure modes, and web-deformation curves agreed well with the tests. The verified finite element models were then used for an extensive parametric study of different tubular dimensions. This paper presents numerical data from the finite element analysis for a total of 151 simulations. It was found that the verified finite element models provided an effective and time-efficient means of predicting the web crippling strengths of CFRP-strengthened aluminium alloy members. Design equations are proposed to predict the web crippling strengths of CFRP-strengthened aluminium alloy tubular sections against web crippling loading.
Xianfeng Yang, Yuxin Sun, Jialing Yang and Qifan Pan, “Out-of-plane crashworthiness analysis of bio-inspired aluminum honeycomb patterned with horseshoe mesostructure”, Thin-Walled Structures, Vol. 125, pp 1-11, April 2018

ABSTRACT: Numerous composite structures with excellent integrative performance that can replicate the mechanical properties of biological materials have been created to fill gaps in material-property charts, and these bio-inspired structures have crucial implications in a wide range of engineering communities. In this paper, a series of novel bio-inspired aluminum honeycombs consisting of horseshoe mesostructure have been proposed on the basis of triangular honeycomb, square honeycomb, hexagonal honeycomb and kagome honeycomb to improve the energy absorption capacity. The three-dimensional finite element models of the bio-inspired horseshoe-shaped aluminum honeycombs are developed in order to explore the mechanical behaviors under the out-of-plane uniform compression. The simulation results are validated based on the compression experiments of regular hexagonal honeycombs. Besides, parametric investigations are carried out to understand the influences of the wave amplitude, wave number and cell-wall thickness on the out-of-plane crashworthiness. The numerical results demonstrate that adding the horseshoe mesostructure to the regular honeycombs can increase the plateau force greatly compared with the traditional honeycomb structure, leading to the higher specific energy absorption although increasing the initial peak force as well. Finally, a multi-objective optimization is carried out to seek for the optimal honeycombs with the maximum specific energy absorption together with the minimum initial peak force simultaneously.

Xuhong Zhou and Ming Chen, “Experimental investigation and finite element analysis of web-stiffened cold-formed lipped channel columns with batten sheets”, Thin-Walled Structures, Vol. 125, pp 38-50, April 2018

ABSTRACT: This paper presents an experimental investigation and a finite element analysis on web-stiffened cold-formed lipped channel columns with batten sheets connected between the column's two lips at reasonable space. Initially, the paper presents the static compressive test results on 18 specimens under pinned-end restraint conditions with different column length and load eccentricities considered. It is shown that the batten sheets exert significant influence on both the buckling modes and the ultimate strength of the specimens under positive eccentric loading and/or axial loading conditions, while they just have few impacts on that of the specimens under negative eccentric compression. Strengthened by the batten sheets, the columns performed obviously higher ultimate strength under axial and positive eccentric compression compared with the ones without batten sheets and the strengthening effect increase with the increase of column length. Furthermore, the tested specimens were also numerically investigated by finite element program of ANSYS. Geometric and material nonlinearities were both included in the finite element models and it is demonstrated that the numerical analysis can closely predict the ultimate strength and the buckling behavior of the tested columns. Finally, a parametric study was conducted by using program of ANSYS, in which effect of the increasing lip stiffener width and varying batten sheet space were all investigated and it is concluded that the contribution of the batten sheets to the columns’ strength decreased notably with the increasing lip width or batten sheets’ space for axial and/or positive compressed columns. The best choice of the distance between batten sheets (d≤l/3) for axial compressed lipped channel columns must also be a reasonable choice for positive compressed columns.


ABSTRACT: A new analytical approach for the determination of natural frequencies of a long cylindrical shell containing a variably oriented semi-elliptical surface crack is presented in this paper. Equations of motion for the cracked shell are obtained based on classical shell theories and are simplified using the Donell–Mushtari–Vlasov (DMV) theory. It has been assumed that the crack length is far smaller than the radius of curvature of
the shell and line-spring model (LSM) is used in order to calculate crack compliance coefficients which are subsequently to be added into the equations of motion to include crack effects in the problem. An analytical solution has been developed using Hamilton's principle and the results are obtained for the shells considering clamped-clamped (C–C) and simply supported (S–S) boundary conditions at both ends. Results obtained from the proposed model are verified using a finite element model created with ABAQUS and there is an acceptable agreement between analytical and FEM results. Effects of the shell properties such as length, radius and thickness as well as the effects of the crack characteristics such as its length and orientation on the natural frequencies of the cracked shell are analyzed in this study.

Yonghao Luo and Hualin Fan, “Investigation of lateral crushing behaviors of hierarchical quadrangular thin-walled tubular structures”, Thin-Walled Structures, Vol. 125, pp 100-106, April 2018

ABSTRACT: Energy absorbing efficiency of thin-walled tubular structures is restricted by the folding of the ultra-thin walls, depressing the mean crushing force (MCF) of the tubular structure. Hierarchical topology increases the energy absorbing ability of tubular structure notably without increasing the weight. In an effort to reveal this advantage, hierarchical quadrangular tubes (HQTs) are proposed in this paper. These proposed structures have multi-cellular structure and sandwich cellular walls. During the crushing, two deformation stages, including crushing of the side walls and compression of the short vertical ribs in the horizontal sandwich walls, were observed in the experiments. The latter greatly increases the MCF of thin-walled quadrangular tubes (TQTs). Based on three typical folding elements and two energy absorbing mechanisms, the MCF can be consistently predicted. According to the research, extraordinary energy absorption can be achieved through hierarchical topology design.


ABSTRACT: This paper presents an experimental and theoretical study of CFRP-confined concrete-filled circular steel tube (CFT) stub columns, which aims at investigating the effects of different numbers of CFRP layers and concrete strengths on the mechanical performance of CFRP-confined CFT stub columns. Based on continuum mechanics, a mechanical model of concentric cylinder consisting of CFRP, circular steel tube and concrete core under concentric loading was established and the corresponding elasto-plastic methods were obtained through a FORTRAN program. The influence of the number of CFRP layers on the ultimate capacity, ductility and confinement effect of the steel tube on the core concrete was discussed and identified. Finally, based on the limit equilibrium and elasto-plastic methods, a simplified formula for the ultimate capacity of CFRP-confined CFT stub columns was proposed. Good agreement of the ultimate capacity was found between the elasto-plastic methods and the proposed formula, with the maximum discrepancy less than 12%.


ABSTRACT: Propagation buckling mechanisms in pipe-in-pipe (PIP) systems with thin and moderately thin carrier pipes with a diameter-to-thickness (D_o/t_o) ratio in the range 26–40 are investigated using 2D analytical and 3D nonlinear (material and geometry) finite element (FE) models. The FE models are validated against hyperbaric chamber tests of a PIP system with D_o/t_o of 30. Using the validated FE model a parametric study is conducted and two distinct buckle propagation modes in PIPs are observed. Empirical expressions for each mode are proposed and are found to be different from previous expressions suggested for PIPs with (D_o/t_o) ratio in the range 15–25.
Ming-Xiang Xiong and J.Y. Richard Liew, “Discussion on the applicability of the M-N interaction curve for the fire resistance design of CFT members”, Thin-Walled Structures, Vol. 125, pp 172-186, April 2018

ABSTRACT: When subjected to combined axial force and bending moments at ambient temperature, concrete filled tubes (CFTs) show a marginal increase in bending resistance at low level of axial compression, but the bending resistance reduces when the compression force is high. To evaluate the buckling resistance of CFT member subject to axial compression (N) and moment (M), a second order analysis approach is proposed by EC 4: EN 1994-1-1 in which the cross section check can be carried out using the N-M interaction curve which is derived based on the plastic design principle. When the CFTs are further subjected to high temperature due to fire, the design method is however not available in EC 4: EN 1994-1-2. This paper proposes a modified M-N interaction curve based on plastic stress distribution as in EC 4: 1994-1-1 for fire resistance design of CFT members. The superiority of the M-N interaction curve is the universality to both axially loaded members and members subjected to combined axial force and bending moments, regardless of the moments being induced by load eccentricities or initial bow imperfections. Backgrounds of the existing simple calculation model in EC 4 using buckling curves and the proposed M-N interaction curve were first discussed. Then the validity of the said M-N interaction curve was established by comparisons with test results. The proposed M-N interaction curve was found to provide better predictions of the fire resistance than the simple calculation model. Hence, it could be safely extended to EC 4: 1994-1-2 for the design of CFT members under fire.


ABSTRACT: The objective of this paper is to present and discuss numerical results concerning the geometrically non-linear behaviour of thin-walled lipped channel columns experiencing local-distortional (L-D) interaction that will shed fresh light on the mechanics underlying this coupling phenomenon. These results, obtained through Generalised Beam Theory (GBT) elastic post-buckling analyses, provide the evolution, along given equilibrium paths, of the column (i) deformed configuration, expressed in modal form, (ii) relevant displacement profiles, and (iii) modal participation diagrams. Taking full advantage of the GBT modal features, it becomes possible to unveil the most relevant behavioural/mechanical aspects associated with the occurrence of L-D interaction. Particular attention is devoted to the structural interpretation and explanation of the quantitative and qualitative differences exhibited by the column post-buckling behaviours associated with (i) “pure”/individual local and distortional behaviours and (ii) the occurrence of L-D interaction stemming from either the closeness between the local and distortional critical buckling loads (“true L-D interaction”) or from a secondary bifurcation phenomenon (“secondary distortional or local bifurcation L-D interaction”). The columns analysed exhibit (i) the aforementioned different types of L-D interaction, (ii) two support conditions, namely fixed (mostly) or pinned end cross-sections, and (iii) several critical-mode initial geometrical imperfection shapes.

Zbigniew Kolakowski and Jacek Jankowski, “Interactive buckling of steel C-beams with different lengths – from short to long beams”, Thin-Walled Structures, Vol. 125, pp 203-210, April 2018

ABSTRACT: The present paper deals with the interactive buckling of thin-walled C-beams with imperfections, subjected to the bending moment in the web plane when the shear lag phenomenon and distortional deformations are taken into account. A plate model (2D) was adopted for the C-beams. The structures were assumed to be simply supported at the ends. Two kinds of cross-sections in the C-beams were considered: channels and lip channels. A method of the modal solution to the coupled buckling problem within Koiter's asymptotic theory, using the semi-analytical method (SAM) and the transition matrix method, was applied. The calculations were carried out for C-beams of different lengths – from short through medium-long to long beams.

ABSTRACT: A thermal postbuckling analysis for composite laminated plates reinforced with graphene sheets is performed in this research. All of the thermomechanical properties of the composite media are assumed to be temperature dependent. Volume fraction of the graphene in each layer is assumed to be different which results in a piecewise functionally graded plate. Based on the third order shear deformation plate theory of Reddy, the total strain energy of the plate is obtained. Composite laminated plate is assumed to be under uniform temperature rise. Properties of the graphene reinforced composite media are estimated by means of a refined Haptin-Tsai approach which contains efficiency parameters to capture the size dependency of the constituents. Afterwards, a non-uniform rational B-spline (NURBS) based isogeometric finite element method is implemented to study the thermal postbuckling response of the graphene reinforced composite laminated plates. Thermally induced postbuckling curves of the composite plate reinforced by graphene are provided for different functionally graded patterns, aspect ratios, side to thickness ratios and boundary conditions. It is shown that, FG-X pattern of graphene reinforcement results in the highest critical buckling temperature and the lowest postbuckling deflection.

Gong-Wen Li and Yuan-Qi Li, “Overall stability behavior of axially compressed cold-formed thick-walled steel tubes”, Thin-Walled Structures, Vol. 125, pp 234-244, April 2018

ABSTRACT: This research is focused on the overall stability of axially compressed cold-formed thick-walled square and rectangular steel tubes, which is generally represented by the column curve. An experimental study on axially compressed pin-ended columns was conducted to investigate the failure mode and overall stability. Then, further parametric finite element analysis was conducted to get more data. Also, a comparison between the test and FEA data and the column curves in different codes, including the Chinese codes and North American specifications, was presented in this paper. It was found that the column curves in Technical code of cold-formed thin-walled steel structures (GB50018-2002) and AISI S100-2016 were not suitable for thick-walled steel members. Subsequently, a fitted curve and corresponding calculation formula for stability coefficient was proposed separately for Q235 and Q345 cold-formed thick-walled square and rectangular steel tubes. Finally, the tangent modulus curves were compared with the test and FEA results and the fitted curves. It was found that the fitted curves were in better agreement with the corresponding test and FEA results while the tangent modulus curves were unconservative.

Jun Ye, Iman Hajirasouliha and Jurgen Becque, “Experimental investigation of local-flexural interactive buckling of cold-formed steel channel columns”, Thin-Walled Structures, Vol. 125, pp 245-258, April 2018

ABSTRACT: This paper presents the results of a comprehensive experimental programme aimed at studying the interaction of local and overall flexural buckling in cold-formed steel (CFS) plain and lipped channels under axial compression. The results were further used to verify the accuracy of the current design procedures in Eurocode 3, as well as to evaluate the effectiveness of a previously proposed optimisation methodology. A total of 36 axial compression tests on CFS channels with three different lengths (1 m, 1.5 m and 2 m) and four different cross-sections were conducted under a concentrically applied load and pin-ended boundary conditions. The initial geometric imperfections of the specimens were measured using a specially designed set-up with laser displacement transducers. Material tests were also carried out to determine the tensile properties of the flat parts of the cross-sections, as well as the cold-worked corner regions. A comparison between the experimental results and the Eurocode 3 predictions showed that the effective width approach combined with the P–M interaction equation proposed in Eurocode 3 to take into account the shift of the effective centroid consistently provided safe results. However, the Eurocode 3 procedures were also quite conservative in predicting the capacity.
pertaining to local-global interaction buckling, especially for plain channels. Furthermore, the experimental data confirmed the results of an optimisation study and demonstrated that the optimised CFS columns exhibited a capacity which was up to 26% higher than the standard channel with the same amount of material taken as a starting point.

Seyed Morteza Hosseini and Mahmoud Shariati, “Experimental analysis of energy absorption capability of thin-walled composite cylindrical shells by quasi-static axial crushing test”, Thin-Walled Structures, Vol. 125, pp 259-268, April 2018

ABSTRACT: The energy absorption capability of thin-walled composite cylindrical shells is experimentally investigated. Effects of six parameters on absorption energy of composite shells are studied. These parameters including three geometric parameters of inner diameter, length and shell thickness and the other three parameters are layer orientation, reinforcing fibers and manufacturing process. The design of experiment was accomplished by applying Taguchi method and the axial crushing test was conducted on shells. The resulting data was statistically analyzed which led to the ranking of the six parameters and an optimized structure based on the selected parameters was proposed. Finally, different kinds of complicated failure modes controlling absorption capacity were studied. In addition, effects of the six mentioned parameters on both stable and unstable crushing modes of shells were investigated. It is found that a good correspondence exists between statistical analysis results and crushing collapse mechanisms in experimental analysis results, which both of the analysis are accorded to specific energy absorption.

Daniel C.T. Cardoso and Barbara S. Togashi, “Experimental investigation on the flexural-torsional buckling behavior of pultruded GFRP angle columns”, Thin-Walled Structures, Vol. 125, pp 269-280, April 2018

ABSTRACT: In this paper, the findings from an experimental investigation on the flexural-torsional buckling behavior of pultruded glass-fiber reinforced polymer (GFRP) angle columns are reported and discussed. The program included the study of two sizes of equal-leg angles made with different resins (polyester and vinylester). Prior to testing, a detailed material characterization was carried out and signature curves (critical load x length) were obtained using a generalized beam theory (GBT) software for predicting critical loads. Lengths were selected in order to ensure ‘pure’ flexural-torsional buckling, in a range of slenderness not studied in previous works. Twenty-two members with fixed ends and clamped walls were tested in concentric compression and had their motions measured during loading. Load-deflection curves are presented and the influences of post-buckling reserve of strength, damage and differential rotation of legs are discussed. Experimental critical loads obtained using Koiter's method are reported and shown to be in good agreement with GBT predictions. Finally, a design recommendation through the use of a Winter-type equation accounting for the plate-like behavior is made.

Kang Gao, Wei Gao, Binhua Wu, Di Wu and Chongmin Song, “Nonlinear primary resonance of functionally graded porous cylindrical shells using the method of multiple scales”, Thin-Walled Structures, Vol. 125, pp 281-293, April 2018

ABSTRACT: An analytical method is proposed for the nonlinear primary resonance analysis of cylindrical shells made of functionally graded (FG) porous materials subjected to a uniformly distributed harmonic load including the damping effect. The Young's modulus, shear modulus and density of porous materials are assumed to vary through the thickness direction based on the assumption of a common mechanical feature of the open-cell foam. Three types of FG porous distributions, namely symmetric porosity distribution, non-symmetric porosity stiff or soft distribution and uniform porosity distribution are considered in this paper. Theoretical formulations are derived based on Donnell shell theory (DST) and accounting for von-Kármán strain-displacement relation and damping effect. The first mode of deflection function that satisfies the
boundary conditions is introduced into this nonlinear governing partial differential equation and then a Galerkin-based procedure is utilized to obtain a Duffing-type nonlinear ordinary differential equation with a cubic nonlinear term. Finally, the governing equation is solved analytically by conducting the method of multiple scales (MMS) which results in frequency-response curves of FG porous cylindrical shells in the presence of damping effect. The detailed parametric studies on porosity distribution, porosity coefficient, damping ratio, amplitude and frequency of the external harmonic excitation, aspect ratio and thickness ratio, shown that the distribution type of FG porous cylindrical shells significantly affects primary resonance behavior and the response presents a hardening-type nonlinearity, which provides a useful help for the design and optimize of FG porous shell-type devices working under external harmonic excitation.

ABSTRACT: Ships and offshore structures operate in harsh and corrosive environments and they are subject to high hydrodynamic and inertial loads. Thus it is important to accurately predict the mechanical response of thin-walled marine structures subject to corrosion damage in loaded conditions. This paper present a transition study to investigate in depth the usage of shell and solid elements in nonlinear finite element structural analysis with localised corrosion features. An experimental, stereo full field imaging technique, 3D digital image correlation is used to verify both the shell and solid modelling results. The solid-to-shell coupling techniques were subsequently assessed based on a deck plate model. Models containing a localised section using either the second-order hexahedral element C3D20 or tetrahedral element C3D10I show a similar performance that is compatible with the model using only shell element. The proposed coupling method works well for localised electrochemical or mechanical-electrochemical analysis with subsequent geometrical updates.

ABSTRACT: Aircraft structures must meet several design requirements such as, minimum weight, high stiffness and fail safe design; these competing criteria must all be met by the final design. A new stringer design concept for conventional aircraft fuselage proposed in [1] showed some encouraging results; this paper is a continuation of the work there in where supporting frame elements are added to the fuselage structure. The proposed design is simulated using a finite element model that has been validated through experimental data available from the literature. Results show improved performance of the structure in terms of eigenfrequencies and virtually unchanged performance in terms of stresses and displacements.

Yongwook Kim and Teoman Pekoez, “Numerical slenderness approach for design of complex aluminum extrusions subjected to flexural loading”, Thin-Walled Structures, Vol. 127, pp 62-75, June 2018
ABSTRACT: Aluminum structural members can be extruded to various cross-sectional shapes, including additional elements projecting out of flat flanges or webs. The additional elements contribute to flexural strength increase due to local buckling strength increase. In this study, a general design approach is developed for complex extrusions, accounting for the local buckling strength increase. This approach uses numerical buckling analyses, while the overall framework of the existing specification provisions is maintained. The approach is evaluated through parametric studies of seven different kinds of cross-sections, using finite element analysis. The FEA models and the parametric study results are validated through physical tests.
ABSTRACT: In recent years, the steel corrugated shear walls (SCSWs) are widely used in building structures to serve as lateral force resistant members. For some practical engineering applications that the width of the infilled SCSWs in frame structure is much greater than its height, it is common to add vertical stiffening systems to the SCSWs, thus forming the stiffened SCSWs (SSCSWs), and the stiffening system is composed of a pair of vertical stiffeners installed on both sides of the corrugated plate and the connecting high-strength bolts. In this paper, the shear resistant behavior of the SSCSWs is investigated via FE analyses considering both the geometrical and material nonlinearities, and over 300 models are analyzed through elastoplastic numerical process. The comparison of the shear resistant behavior of SSCSWs with different stiffening rigidities is performed, which indicates that the stiffening system can effectively restrain the out-of-plane displacements of the corrugated wall, and can improve both shear resistance and ductility of the SSCSWs. Then a transition rigidity ratio of the stiffening system is proposed to reflect the critical value of the stiffening rigidity that the out-of-plane displacements of the corrugated plate are fully restrained at the bolted locations. Correspondingly, curve fitted formula of the transition rigidity ratio is provided to enable a conservative prediction. Finally, shear buckling formulas are fitted to reveal the relationship between the reduction factor and the normalized aspect ratio, and they are validated to be able to conservatively predict the ultimate shear stress of SSCSWs. Accordingly, some design recommendations are presented, which could provide valuable references for practical design of SSCSWs.

Zhejian Li, Wensu Chen and Hong Hao, “Numerical study of sandwich panel with a new bi-directional load-self-cancelling (LSC) core under blast loading”, Thin-Walled Structures, Vol. 127, pp 90-101, June 2018
ABSTRACT: A new form of bi-directional Load-Self-Cancelling (LSC) sandwich panel is proposed in this paper. An array of square dome shaped steel sheet as core of the proposed sandwich panel is designed to cancel a certain amount of load during blast event owing to its arching geometry. The blast resistance and energy absorption capabilities of the sandwich panel are investigated numerically by using finite element analysis software LS-DYNA. The peak deflection of centre point on back face sheet, internal energy and peak boundary reaction forces are compared among monolithic plate, multi-arch uni-directional LSC structure, sphere dome structure and the proposed bi-directional LSC square dome sandwich panel. It is found that using the proposed bi-directional LSC square dome leads to 69%, 48% and 56% reduction in the out-of-plane boundary reaction force as compared to the flat plate, multi-arch panel and grid sphere panel, respectively. In addition, parametric studies of the influences of dome number, height, and layer material on the performances of the proposed bi-directional LSC sandwich panel subjected blast loads of different intensities are carried out to investigate the panel configuration on the effectiveness of its blast resistance and load-self-cancelling capability. The results demonstrate the superiority of the sandwich panel with the proposed bi-directional LSC core.

ABSTRACT: Carbon fiber reinforced polymer (CFRP) strengthened concrete-filled thin-walled steel tubular (CFST) column can improve its load carrying capacity and resolve local bugles or corrosion of thin-walled steel tube. However, little attention to CFRP strengthened CFST columns has been paid. This paper reported an experimental and numerical analysis on eccentric compressive behavior of circular CFST stub columns partially-wrapped by CFRP strips. A series of circular composite columns, including nine CFRP strengthened CFST stub columns and one bare CFST stub column, were tested subjected to eccentric compression. Moreover, a nonlinear finite element (FE) modeling in considering contact interactions of the composite
columns was developed and verified by the test results in terms of eccentric load (N) - longitudinal shortening (δ) curves and failure patterns. Then, the influence of extensive parameters on the eccentric compressive behavior of CFRP strengthened circular CFST columns was also evaluated. Meanwhile, a simplified empirical method on the eccentrically-loaded stub composite columns was proposed on the basis of unified theory. The experimental and analytical data indicated that the eccentric compressive strength of CFRP strengthened circular CFST stub column was obviously influenced by load eccentricity, CFRP confinement factor, steel strength, core concrete strength and CFRP strength. The proposed simplified empirical formulas may provide a considerable approach for designing this type of composite structures in engineering practice.

ABSTRACT: This study introduces a comprehensive set of designed and tested glass/epoxy composites, AE monitoring and signal processing techniques; (i) to investigate the effect of multiple delaminations on buckling and post-buckling behaviors of laminated composites and (ii) to evaluate Acoustic Emission (AE) technique ability to monitor the buckling delamination growth and to classify the occurred damage mechanisms. The pre-delaminations were made by inserting a Teflon film at the plies interfaces during fabrication. Three different types of specimens were fabricated and subjected to compression loading to study the effects of the location, the number of delaminations, and the thickness of the Teflon film on buckling and post-buckling behaviors of the specimens. The mechanical results showed that the number of delaminations has a major effect on the critical and maximum loads and the location of delamination and the thickness of the Teflon film have minor effects on the critical and maximum loads. The AE signals of the specimens were then classified using Gaussian Mixture Model (GMM) and the evolution of different damage mechanisms was investigated. The AE results showed that AE is a robust technique to classify damage mechanisms in buckling of laminated composites and could identify delamination propagation earlier and with a lower standard deviation, compared with the conventional methods.

ABSTRACT: In the present research, an analytical solution based on a new idea of superposition of two kinematic descriptions is presented for dynamic response analysis of a multi-layer/sandwich composite plate with point supports subjected to an eccentric low-velocity impact. Direct and virtual-work-based novel energy formulations are proposed for the problem that take into account the potential energy of the indentation region. The nonlinear governing equations of motions are found based on minimization of the total potential energy of the whole mass-plate system, including work of the inertia forces, employing Ritz technique and transformation of the time-dependent nonlinear system of governing equations to a non-linear algebraic one through a novel concept. In contrast to the available researches, influence of the lower layers on the stiffness of the contact region is incorporated. Time-dependent responses of a sandwich composite plate with simply supported edges are compared with those of a plate resting on point supports. Verification of the results has been accomplished based on results of ABAQUS computer code. In the results section, the significant effects of the point supports (in comparison to the complete edge supports), initial velocity of the indenter, aspect ratio of the plate, and material properties of the layers on time histories of the contact force and lateral deflection of the plate are investigated.
Chenfeng Li, Huilong Ren, Zhiyao Zhu and C. Guedes Soares, “Numerical investigation on the ultimate strength of aluminium integrally stiffened panels subjected to uniaxial compressive load”, Thin-Walled Structures, Vol. 127, pp 221-234, June 2018

ABSTRACT: The objective of this study is to analyse numerically the ultimate strength of stiffened aluminium panels built with extruded aluminium profiles. A finite element code is used to reproduce the mechanical response of the stiffened panels subjected to axial compression. The fabrication related imperfections, such as initial deformations, material softening in Heat-Affected Zone (HAZ) and residual stresses are simulated. The numerical simulations are compared with the experimental response curves, and sensitivity to geometric parameters, initial imperfections and material properties are analysed. The results show that for the considered panel: 1) The ultimate strength is more sensitive to the cross-section dimensions than to the length; 2) The initial deformation has a strong effect not only on the level of ultimate strength but also on the failure mode as well; 3) Both the width of the HAZ and the yield strength in the HAZ has little effect on the ultimate strength of the considered aluminium integrally stiffened panels; 4) The residual stresses will improve the ultimate strength for the considered panels.

Cilmar Basaglia, Dinar Camotim and Humberto Breves Coda, “Generalised beam theory (GBT) formulation to analyse the vibration behaviour of thin-walled steel frames”, Thin-Walled Structures, Vol. 127, pp 259-274, June 2018

ABSTRACT: This paper reports the results of an investigation on the use of Generalised Beam Theory (GBT) to analyse the vibration behaviour of thin-walled steel frames. After an overview of the main concepts and procedures involved in performing a GBT vibration analysis, the formulation and implementation of a GBT-based beam finite element are presented, namely the determination of the finite element and frame linear stiffness and mass matrices (incorporating the influence frame joint configurations). Finally, in order to illustrate the application and capabilities of the proposed GBT-based finite element formulation, numerical results concerning the local, distortional and global vibration behaviour of (i) a symmetric portal frame and (ii) an “L-shaped” frame exhibiting four commonly used joint configurations are presented and discussed. For validation purposes, some GBT results (frequency values and vibration mode shapes) are compared with values yielded by Ansys shell finite element analyses.

David C. Fratamico, Shahabeddin Torabian, Xi Zhao, Kim J.R. Rasmussen and Benjamin W. Schafer, “Experimental study on the composite action in sheathed and bare built-up cold-formed steel columns”, Thin-Walled Structures, Vol. 127, pp 290-305, June 2018

ABSTRACT: This paper reports on experiments addressing the buckling and collapse behavior of common built-up cold-formed steel (CFS) columns. The built-up column consists of two individual CFS lipped channels placed back-to-back and connected at the web using two self-drilling screw fasteners at specified spacing along the column length. The experiments aim to quantify ultimate strength, composite action, member end fixity, and buckling interactions and collapse behavior for common built-up CFS members. The testing also explicitly explores the effect of sheathing, as typically employed in cold-formed steel framing, on the response. The experiments provide benchmarks for design that include specific considerations for both thin-walled buckling and fastener behavior. A total of 17 monotonic, concentric compression tests with a column length of 1.83 m (6 ft) are completed with an array of position transducers monitoring displacements at key locations. Tests are conducted with the built-up member seated in CFS tracks. Results indicate a large range of deformation behavior, with local-global interaction and flexural-torsional modes common in many of the unsheathed specimens. Columns sheathed with oriented strand behave as braced against global buckling in the plane of the wall, and local buckling induced failures prevail. The end condition for the tested built-up members seated in track is determined to be semi-rigid, but generally closer to fixed than pinned.
Qiang Cao and Jingyu Huang, “Experimental study and numerical simulation of corrugated steel plate shear walls subjected to cyclic loads”, Thin-Walled Structures, Vol. 127, pp 306-317, June 2018
ABSTRACT: This paper describes experimental and numerical investigations of the hysteretic behaviour of the corrugated steel plate shear wall (CSPSW). Two single-bay, two-storey CSPSWs without elastic buckling were cyclically tested. A numerical model was developed to simulate the experimental results. The inelastic buckling capacity and failure mode of the corrugated steel plate shear wall were examined. The results revealed that through the proper design of the corrugation parameters, the corrugated steel plate shear wall could avoid elastic buckling, and this shear wall had high initial stiffness buckling, strength, energy dissipation and ductility. In addition, the feasibility of the simultaneous construction of corrugated steel plates and frames was discussed. Finally, the serviceability of the existing design methods for corrugated steel plate shear walls was examined, which proved that the plate-frame interaction model could predict the shear strength and initial stiffness of the corrugated steel plate shear walls with good accuracy.

ABSTRACT: This paper was aimed to evaluate crashworthiness capability of new designed multi-cell structures with different cross-sectional shapes (i.e. square, hexagonal, octagonal, decagonal and circular) to dissipate collision energy. The multi-cell structures included outer and inner tubes connected together by four stiffening plates. Two dimensional parameters (i.e. $S_1$ and $S_2$) were defined to describe cross sectional configuration of the structures. Indeed, $S_1$ and $S_2$ were ratios of the inner tube side length to the outer tube side length at the ends of the structures. Values of both $S_1$ and $S_2$ were assumed as 0, 0.25, 0.5, 0.75 and 1. Longitudinal geometry of the outer tube was straight; while, both the straight or tapered geometry could be generated for the inner tube depending on the values of $S_1$ and $S_2$. An experimentally validated model generated in finite element code LS-DYNA was utilized to study crushing behavior of these structures under axial impact. Geometrical dimensions of these structures were optimized using ANNs (artificial neural networks) and GA (genetic algorithm) by considering three different scenarios. The optimal structures were compared together from the crashworthiness point of view by considering two conflicting crashworthiness indicators namely SEA (specific energy absorption) and PCF (peak crush force) using a decision making method called TOPSIS (technique for ordering preferences by similarity to ideal solution). Ranking of the studied cross sections was obtained as Octagonal-Circular-Decagonal-Hexagonal-Square for all the mentioned scenarios. Consequently, octagonal multi-cell structure was selected as the best cross sectional configuration among the studied cross sections. In addition, the proposed octagonal multi-cell structure was found to have higher crashworthiness capacity than conventional single-cell and simple multi-cell ones.

Liming Chen, Jian Zhang, Bing Du, Hao Zhou, ... Daining Fang, “Dynamic crushing behavior and energy absorption of graded lattice cylindrical structure under axial impact load”, Thin-Walled Structures, Vol. 127, pp 333-343, June 2018
ABSTRACT: Dynamic behavior of lattice cylindrical structures with triangular and hexagonal configurations subjected to constant velocity impact was studied theoretically and numerically. The dynamic plateau stress of lattice cylindrical shell was well predicted by analytical predictions based on the one-dimension shock theory. The uniform and density gradient lattice cylindrical structures were investigated using finite element models. It was found normalized plastic energy absorption was significantly affected by relative density for two kinds of lattice cylindrical shells. And the ratio of cell wall to skin thickness was found the vital factor determining the specific energy absorption and deformation modes of lattice sandwich cylindrical shell. By introducing density gradient along crushing direction, the results showed that, for lattice cylindrical shell, introducing positive
density gradient can enhance energy absorption at the early stage in high velocity. For lattice sandwich cylindrical shell, introducing density gradient can efficiently reduce the peak crushing force but have little effect on the energy absorption.

Reaz A. Chaudhuri, “A nonlinear resonance (eigenvalue) approach for computation of elastic collapse pressures of harmonically imperfect relatively thin rings”, Thin-Walled Structures, Vol. 127, pp 344-353, June 2018
ABSTRACT: A nonlinear resonance (eigenvalue) based semi-analytical approach is employed here for computation of the elastic mode 2 collapse pressures of moderately-thick to thin isotropic rings, weakened by harmonic or modal type imperfections. The mode 2 collapse pressure is, by definition, associated with the buckled mode shape of cos(2\theta) type, and is the harmonically imperfect ring counterpart to the Euler type buckling pressure of a hydrostatically pressurized thin perfect ring. A von Karman type iterative nonlinear analysis, which is based on the assumptions of transverse inextensibility and first-order shear deformation theory (FSDT), is utilized for computation of hydrostatic collapse pressure of a harmonically imperfect ring. Interesting and hitherto unavailable numerical results pertaining to the effects of harmonic imperfections on the hydrostatic collapse pressures of imperfect metallic rings are also presented.

ABSTRACT: Presented in this paper is a size-dependent analysis of the surface stress and nonlocal influences on the free vibration characteristics of rectangular and circular nanoplates. Nanoplates are assumed to be made of functionally graded materials (FGMs) with two distinct surface and bulk phases. The nonlocal and surface effects are captured by the Eringen and the Gurtin-Murdoch surface elasticity theories, respectively. The Mori-Tanaka distribution scheme is also used for obtaining material properties of nanoplate. In addition to the conventional procedure of deriving the formulation, a novel matrix-vector form of the governing differential equations of motion is presented. This form has the capability of being used directly in the finite element method or isogeometric analysis. To show the effects of surface parameters and small scale influences on the vibrational behavior of rectangular and circular FGM nanoplates with various boundary conditions, several case studies are presented.

Jingwei Zhou, Shurui Wen, Fengming Li and Yu Zhu, “Coupled bending and torsional vibrations of non-uniform thin-walled beams by the transfer differential transform method and experiments”, Thin-Walled Structures, Vol. 127, pp 373-388, June 2018
ABSTRACT: This paper describes a new methodology capable of analyzing coupled bending and torsional vibrations in non-uniform thin-walled beams. The transfer matrix method (TMM) and the differential transform method (DTM) are combined to create the proposed transfer differential transform method (TDTM) for solving equations coupling bending and torsional vibrations in non-uniform beams. Compared with the finite element method (FEM), the TDTM utilizes a type of changeable mode shape functions so that the number of meshed elements can be reduced greatly when the beam's geometric size is uniform. The equations of motion of the non-uniform thin-walled beams are established using Hamilton's principle. The method considers both the warping and rotary effects of the beam section. The natural frequencies and mode shapes of the bending and torsional components are obtained using the TDTM. The accuracy of solutions can be controlled by the mesh density and the series expansion order of the mode shape whose ranges are also discussed. For illustrative purposes, the natural frequencies and the frequency response curves of a uniform beam and a non-uniform beam are studied respectively and are validated by experiments. The effects of warping and the distance between the centroid of a given section and the corresponding shear center on the vibration properties of the beam are also investigated.

**ABSTRACT:** To investigate the structural dynamic response of long span reticulated shell under external blast loading considering explosion-protection wall, explicit finite element (FE) programme LS-DYNA is used to set up the analytical model of explosion-protection wall corresponding to an experiment to grasp the propagation law of blast shock waves around the wall. The results of simulation and experiment are compared and the results verify the creditability and applicability of numerical simulation by using ALE (Arbitrary-Lagrange-Euler) algorithm. A Kiewitt8 single-layer reticulated shell of refinement with span of 40 m is established to simulate the responses of structure considering explosion-protection wall, which contains reticulated shell member, purlin hanger, purlin, rivet and roof boarding. According to simulation results from the maximum nodal displacement, average plastic strain and yielding degree of cross section of reticulated shell member, the dynamic response laws are proposed based on varying parameters, including height, position, length, material of the explosion-protection wall, rise-span ratio of reticulated shell and TNT explosive weights. Meanwhile, the influence rules of explosion-protection wall and structure on diffraction and reflection action of blast shock wave are obtained. In addition, the adverse height of the explosion-protection wall for reticulated shell with span of 40 m under external blast loading is proposed. Four damage types of reticulated shell with the explosion-protection wall subject to external blast loading are defined by summarizing all the structural response of FE numerical models, which could provide reference for reasonable explosion-proof design for reticulated shell structure.


**ABSTRACT:** In this study, the dynamic stiffness method (DSM) is applied to study the free and forced vibration behaviors of thin, three-dimensionally coupled plate structures. Both the flexural and in-plane vibrations are taken into consideration. In the formulation, the coupled plate structures are divided into several sub-plates, then the dynamic stiffness matrices of the sub-plates are derived separately by combining the superposition method with the projection method. According to the geometrical coupled condition between the sub-plates, the dynamic stiffness matrix of the whole coupled structure is assembled. To validate the present method, three numerical examples of coupled plate structures subjected to external excitations are performed and analyzed. The accuracy and reliability of the present method are demonstrated by comparing the present results with those obtained by the FEM. Then, the effects of the directions of external harmonic excitations and the coupled angle between the coupled plates on the dynamic responses are investigated. Furthermore, a computational efficiency study is given to illustrate the convergence and accuracy of the DSM.

Mahdi Omidali and Mohammad Reza Khedmati, “Reliability-based design of stiffened plates in ship structures subject to wheel patch loading”, Thin-Walled Structures, Vol. 127, pp 416-424, June 2018

**ABSTRACT:** Reliability-based design methods are among the engineering tools for design of structures considering uncertainties in the design variables such as loads, material properties, manufacturing tolerances, etc. In design of stiffened plates of ship structures, there are some sources for uncertainties regarding the loads due to the highly nonlinear environment of the ocean. In addition to the environmental uncertainties, internal forces decrease the reliability of design due to the vagueness of items, which are included in the deadweight. Cargos with patch loading pattern like wheel and steel coil are common type of loading in some ships. These cargos are usually transferred by ferries, general cargo ships and bulk carriers. The application of reliability method in design of such structures against this local loading pattern has not been studied so far. Therefore, in this paper, the stochastic method and plastic formulas have been explained in designing steel panels subject to
the patch loading. As a case study, stiffened plate structure of the ships subject to the truck wheel was investigated considering all design parameters as random variables. Bound theorem model for the patch loads is used to calculate the plastic load carrying capacity of the plate. First Order Second Moment (FOSM), First Order Reliability Method (FORM) and Importance Sampling method have been employed in the analyses. Both probability of failure and reliability index are calculated for different axel load distribution functions. The total failure probability was determined based on the rule of total probability. Sensitivity analyses for all parameters were carried out and the effects of coefficient of the variation of dominant variables were studied.

Zheyi Zhang, Shujuan Hou, Qiming Liu and Xu Han, “Winding orientation optimization design of composite tubes based on quasi-static and dynamic experiments”, Thin-Walled Structures, Vol. 127, pp 425-433, June 2018
ABSTRACT: Compared with traditional metal materials, composite materials can be better designed by changing layup condition or ply orientation to meet performance requirements. In this study, influences of stacking sequence and fiber orientation of glass fiber reinforced polymer (GFRP) circular tube on energy absorption performance were evaluated by axial quasi-static compression, drop weight tests and numerical simulation. Optimal ply angle and layup condition of composite tubes were obtained based on the finite element modeling and regression analysis. The optimization design result was validated by experiments. Drop weight tests results were analyzed and compared with quasi-static experimental results. Experimental and numerical results illustrate that proper increase of axial layups can improve the specific energy absorption of composite tubes.

ABSTRACT: The axial compressive behavior of carbon fiber reinforced polymer (CFRP)-confined post heated square concrete-filled steel tube (CFST) stub columns is experimentally investigated in this paper. Twenty CFRP-confined post heated square CFST stub columns and one CFST stub column left untreated at ambient temperature were axially tested. Subsequently, the failure mode, ultimate strength, load versus displacement curves, load versus strain distribution curves, initial stiffness, and ductility of the specimens were obtained and analyzed. The maximum temperature (600 °C, 800 °C,1000 °C, 1100 °C) CFST stub columns exposed to and the number of the layer of CFRP sheets (zero, one, two, three and four) were considered as main parameters. The test results showed that, in general, the CFST stub columns wrapped with CFRP sheets shown a better mechanical behavior than those without CFRP sheets wrapping. Furthermore, the more the layers of CFRP sheets are, the higher the ultimate strength and initial stiffness of the CFST stub columns are. Based on the regression of the test data, the simplified formulae for ultimate strength of CFRP-confined post heated square CFST stub columns was proposed. Accuracy of the formulae was evaluated by comparison between the calculated and experimental results.

ABSTRACT: Metal cylindrical shells with different wall thicknesses were subjected to double explosion detonated at varying stand-off distances. For comparison, single-explosion tests were conducted under the same conditions as those in the second explosion of the double-explosion tests. Five different types of failure modes were observed. Here, the energy distribution of the different failure modes is discussed. The effects of the double-explosion impact, the stand-off distance, and the wall thickness of the cylindrical shell on the deformation and damage of the metal cylindrical shells were investigated. The results indicated that the
deformed cylindrical shells which were impacted by the first blast absorbed more energy under a given explosion load than the undamaged shells under the same explosion load according to the energy absorption theory. Vickers hardness tests presented a noticeable increase in the hardness of the cylindrical shell at the plastic hinge region and the central region with the number of witnessed blast loads increased. The stand-off distance and the wall thickness significantly influenced the failure mode and the energy absorption and distribution of the cylindrical shells under double-explosion loadings. The severity of the damage observed in the cylindrical shell increased with a decreasing stand-off distance. Moreover, when the cylindrical shell further deformed from local plastic deformation to crack, the local plastic deformation zone was decreased abruptly. The ability of the cylindrical shell to resist double explosions was enhanced by increasing the wall thickness because thicker shells have more energy absorption capacity and higher threshold for damage than thinner shells. Under the same explosive load, of which the energy has not reached the damage threshold of the cylindrical shell, the energy absorption of the cylindrical shell and the magnitude of the energy reduction both decreased when the wall thickness of the cylindrical shell increased in equal increments. Under the presented experimental conditions, the cylindrical shell first cracked along the radial direction.

Guochang Li, Bowen Chen, Zhijian Yang and Yihe Feng, “Experimental and numerical behaviour of eccentrically loaded high strength concrete filled high strength square steel tube stub columns”, Thin-Walled Structures, Vol. 127, pp 483-499, June 2018

ABSTRACT: Using high strength materials in concrete filled steel tube (CFST) columns is expected to achieve better structural performance and fulfil the requirements of sustainable construction. To study the mechanical behaviour of eccentrically loaded high strength concrete filled high strength square steel tube (HCFHSST) stub columns, this paper describes 12 tests with different eccentricity ratios and steel ratios. The cubic strength of high strength concrete under investigation was 110.5 MPa, and the yield strength of the high strength steel was about 434 MPa. Curves of load-lateral deformation were presented, along with values of ductility index, and the minimum ductility index based on the steel ratio of columns was suggested. Finite element analysis (FEA) software ABAQUS was applied to simulate HCFHSSTs. The analytical results were in good agreement with the experimental ones. The load-lateral deformation curve was divided into four stages: elastic, elastic-plastic, plastic hardening and descending. The confinement effect of steel tube at various stages was analysed. The parametric studies were carried out to evaluate the influences of the eccentricity ratio, concrete compressive strength, steel yield strength and steel ratio on the strength reduction factor (SRF), concrete contribution ratio (CCR), P-M and P/P_u-M/M_u interaction curves of the HCFHSST members. The bending moments at balanced points of P/P_u-M/M_u curves calculated by the plastic stress distribution models (PSDM) and FEA models were compared. The ultimate bearing capacities obtained from the tests and the values calculated from the AISC 360, GB 50936 and CECS 28: 90 design codes were compared. Finally, the formulas were proposed to predict the P/P_u-M/M_u curves for the HCFHSST stub columns subjected to eccentric load. The proposed formulas’ predictions agreed well with the test results.


ABSTRACT: This study explored the elastic buckling of egg-shaped shells made of stereolithography resin. The shells had identical nominal geometry parameters with the thickness of 2 mm, the major axis of 232 mm, and the minor axis of 160 mm, respectively. Five near-perfect laboratory-scale models were fabricated using stereolithography appearance (SLA), a rapid prototyping technique. Each model was scanned by a three-dimensional optical scanner, measured using a micrometer, and tested in a pressure chamber. The buckling behaviours of egg-shaped shells with deterministic geometric imperfections were experimentally, analytically,
and numerically analysed. The perfect egg-shaped shell was also compared with the fabricated egg-shaped models. A good agreement among them was obtained. The remarkable experimental results of egg-shaped shells were presented in this paper by using 3D printing technologies, which shows the high machining accuracy of 3D printing technologies and provides a new solution for the limitation of experimental study into non-typical shells of revolution. Also, the study could provide a new non-typical shell structure and its stability evaluation approach for space vehicles, pressure tanks, and pressure hulls.


ABSTRACT: This paper investigates the elevated-temperature flexural-torsional buckling behavior of aluminum alloy members under eccentric compression by means of experimental and numerical study. Firstly, fourteen I-shaped aluminum alloy members were tested under eccentric compression at elevated temperatures. All the members failed by flexural-torsional buckling. The test results indicated that the bearing capacity of the specimens decreases with the rise of the temperature and the increase of the eccentricity. Subsequently, finite element (FE) models were established using the non-linear code ANSYS, and were verified against the experimental results. In order to develop a further understanding, numerical analysis was carried out using numerous FE models considering two kinds of aluminum alloy brands, two kinds of section types, nine types of section dimensions and three types of temperatures. Finally, 432 correlation curves were obtained and all of them were above the linear correlation curve. Due to its simplicity, the linear correlation curve was proposed to calculate the bearing capacity of aluminum alloy members under eccentric compression at temperatures under 300 °C. The test data were used to validate the reliability of the proposed curve. The results revealed that the proposed correlation curve is safe and economical, while the design method suggested in EC9 is more conservative, which can be used as re-checking for important structures.

Mohamed Rusthi, Anthony Deloge Ariyanayagam and Mahen Mahendran, “Fire design of LSF wall systems made of web-stiffened lipped channel stud”, Thin-Walled Structures, Vol. 127, pp 588-603, June 2018

ABSTRACT: Cold-formed steel stud sections are commonly used as compression members in fire rated load-bearing light gauge steel frame (LSF) wall systems. Although conventional lipped channel section (LCS) studs are commonly used in LSF wall systems, there is a growing interest in developing innovative stud sections to increase the load carrying capacities when used in fire rated LSF wall systems. One such section is the web-stiffened section (WSS), which has increased load carrying capacities as well as enhanced acoustic properties. However, the applicability of the existing structural fire design rules has not been investigated for the WSS stud sections while the advantages of using such sections have not been demonstrated. Therefore, the structural behaviour of WSS stud sections was investigated under ambient and fire conditions using finite element analyses and their capacities were compared with those of conventional LCS studs. Three different LSF wall configurations and three stud thicknesses were considered for both stud sections. The applicability of existing structural fire design rules for LCS and WSS studs used in fire rated LSF wall systems was then investigated based on finite element analyses, effective width method and direct strength method. The results show that WSS studs have much higher load carrying capacities than LCS studs under ambient and fire conditions and that direct strength method based design rules are simpler to use than the effective width based design rules for the structural fire design of LSF wall systems made of both LCS and WSS studs. This paper presents the details of this investigation and the results.

ABSTRACT: For the design of thin-walled cylindrical shells under axial compression empirical knockdown factors are applied. These knockdown factors are based on experimental results from the beginning of the 20th century and have been shown to be very conservative for modern shell structures. In order to determine less conservative and physically based knockdown factors for the design of axially loaded shells, different analytical and numerical design approaches have been developed. In this paper common as well as new shell design approaches are presented in detail and evaluated regarding the lower-bound buckling load. Among these design approaches are the EN 1993 1–6, the reduced energy method, linear buckling eigenmode imperfections, perturbation approaches and the new threshold knockdown factors. Important analysis and modeling details of each design approach are described and test examples are given and validated. Advantages and disadvantages of each approach are listed and design recommendations are given. A comparison of deterministic design approaches with modern probabilistic design methods is shown and the range of application of both design philosophies is discussed. Orthogrid stiffened cylinders with weld lands from NASAs Shell Buckling Knockdown Factor Project (SBKF) are modeled, analyzed and lower-bound buckling load calculations for improved knockdown factors are shown.


ABSTRACT: Experimental investigations were carried out on Q235 steel cylindrical shell-water-cylindrical shell (CWC) structures subjected to near field or contact underwater explosion loading. All the tests were conducted in an artificial water pool detonating 50 g charge weight of trinitoluene (TNT) explosive. Corresponding plastic deformation of the CWC structures were measured for different structural parameters and standoff distances. Three major deformation modes including seven typical subdivided deformation characteristics were classified and analyzed considering the effect of standoff distance, shell thickness and water interlayer thickness. Microscopic analysis was performed using the SEM method to further compare two typical subdivided fracture modes with the combination of the macroscopic deformation features.


ABSTRACT: This paper presents a new advanced analysis method, specifically a new improved fiber plastic hinge method, for analyzing the nonlinear inelastic behavior of 3D steel frames accounting for lateral-torsional buckling. The second-order effects are considered by the use of the geometric stiffness matrix and stability functions obtained from the exact solution of beam-columns under axial force and bending moments at two ends. The spread of plasticity along the member length due to both residual stresses and the impact of axial force is considered by utilizing the Column Research Council (CRC) tangent modulus concept, while the gradual yielding due to flexure is represented by two fiber plastic hinges at the ends of the element. The lateral-torsional buckling stiffness matrix is established by the virtual work principle using the updated Lagrangian formulation. The generalized displacement control method is applied to solve the nonlinear equilibrium equations in an incremental-iterative scheme. The nonlinear load-displacement behavior and ultimate load results compare well with those of previous studies. It is concluded that accurately using only one element per member likely predicts the second-order inelastic behavior of 3D steel frames including the effect of lateral-torsional buckling.
ABSTRACT: Single-layer reticulated shells are a type of spatial lattice structures with closely spaced natural frequencies and significant higher mode effects. An accurate calculation of the seismic responses of these structures necessitates the modal combination of dozens or even hundreds of modes when using mode superposition method. To precisely identify the modes that are significantly contributory to the seismic responses, the time-averaged modal strain energy ratio, denoted as TAMSER for brevity, is derived and then selected as the only evaluation metric, taking into account both the modal characteristics of a given structure and the spectral characteristics of an input ground motion. In terms of this metric, a methodology for identifying dominant modes is developed for structure systems under unidirectional or multi-directional seismic excitation. Based on this methodology, the dominant modes of two typical single-layer reticulated shells are identified and investigated, and then the responses resulting from the modal combination of these identified dominant modes are compared to that of the first 30 and 250 modes, as well as the time history analysis results. It is finally concluded that this proposed methodology is capable of accurately identifying the dominant modes of single-layer reticulated shells subjected to seismic excitations, and the incorporation of the identified dominant modes only into the modal combination is appropriate and sufficient to consider the higher modes effects and to get a satisfactory engineering accuracy in the mode superposition analysis.

Fei-Hao Li, Bin Han, Qian-Cheng Zhang, Feng Jin and Tian Jian Lu, “Buckling of a standing corrugated sandwich plate subjected to body force and terminal load”, Thin-Walled Structures, Vol. 127, pp 688-699, June 2018
ABSTRACT: The global buckling behavior of a vertically standing corrugated sandwich plate subjected to body force and terminal load is analyzed through an improved first order zig-zag shear deformation theory, with the transverse shear effect of face sheets taken into account. When the face sheets are relatively thick and/or the sandwich plate has relatively large thickness to height ratios, the transverse shear effect of the face sheets affects significantly the critical buckling load. The effect becomes more obvious when body force rather than terminal load is applied on the clamped plates. The influence of geometric parameters on critical buckling parameters is also explored.

Priyankar Datta and M.C. Ray, “Smart damping of large amplitude vibrations of variable thickness laminated composite shells”, Thin-Walled Structures, Vol. 127, pp 710-727, June 2018
ABSTRACT: This paper is concerned with the smart constrained layer damping (SCLD) treatment of laminated composite shells with variable thickness undergoing geometrically nonlinear vibrations. Three dimensional fractional derivative model (FDM) has been implemented for modelling the constrained viscoelastic layer of the SCLD treatment. The constraining layer of the SCLD treatment is made of vertically/obliquely reinforced 1–3 piezoelectric composites (PZCs) and acts as the distributed actuator. The strain-displacement relations are based on the simplified Novozhilov nonlinear shell theory to introduce the geometric nonlinearity in the large amplitude vibrations of the variable thickness shells. A three dimensional smart nonlinear finite element (FE) model has been developed for carrying out this analysis. Several numerical results are presented to check the accuracy of the present three-dimensional FDM for analyzing the passive and active control authority of the SCLD patch. Also the efficacy of the activated SCLD patch in controlling geometrically nonlinear vibration is computed for variable thickness shells and compared with shells of constant thickness.

ABSTRACT: Traditional multi-cell tubes exhibit much higher energy absorption capacity and efficiency than single-cell tubes when subjected to axial or transverse loads. This work investigates the bending resistance of a type of composite multi-cell tubes, which is easily obtained by embedding a group of small single tubes into an enveloping tube. This type of embedded multi-cell tubes is flexible in sectional dimensions and shape, easily prepared and highly cost-effective. Three-point bending tests are first performed to investigate the bending behavior and response of embedded multi-cell tubes with different cell configurations. The influences of friction condition, end treatment and partially filling are also studied experimentally. Numerical simulation of the experiment is then carried out by employing the explicit finite element code LS-DYNA. The simulation results generally compare well with experiment. The quasi-static and dynamic bending responses of both embedded and traditional multi-cell tubes with almost the same sectional shape and dimensions are investigated numerically. The bending resistance of embedded multi-cell tubes is found to account for about 65–72% of corresponding traditional multi-cell tubes.


ABSTRACT: This study proposes a new composite structure to promote energy absorption capability of railway vehicles by integrating characteristics of a thin-walled steel structure and aluminum honeycomb fillers. Non-linear explicit code LS_DYNA3D(971) was utilized in building detailed finite element models, which were also validated by previous test data. Considering the expensive selling price, complicated fabricating technology and low production rate of high strength honeycomb, honeycombs with appropriate strength should be selected to fill in the steel structure. Therefore, scientific sampling points were chosen from the design space using Box-Behnken design method. Analysis of variance was performed in order to explore the effects of distributed honeycomb strength in four levels on crashworthiness indicators. Response surface methodology (RSM) was well applied to perform both parametric analysis and multiobjective optimization for searching the optimal configurations. Here, two different criterion were conducted in optimization process by adopting desirability approach. It was find that the composite structure with high strength honeycombs in level-1 and level-2 and relatively low strength honeycombs in level-3 and level-4 are preferable for use. Comparing with the empty steel structure, the optimal EA capacity is promoted by 35.32% in criterion 1 and 34.35% in criterion 2, being able to bear the condition with crashing speed of 36 km/h and impacting mass of 55.3 t. It illustrates that the new composite structures can be recommended as excellent crashworthy devices.

Fa-cheng Wang, Lin-hai Han and Wei Li, “Analytical behavior of CFDST stub columns with external stainless steel tubes under axial compression”, Thin-Walled Structures, Vol. 127, pp 756-768, June 2018

ABSTRACT: Concrete-filled double skin steel tubular (CFDST) stub columns with external stainless steel and internal carbon steel tubes can be considered as new types of composite members and expected to combine the advantages of all three kinds of materials. This paper presents non-linear finite element (FE) analysis and design of circular and square CFDST stub columns with external stainless steel under axial compression. FE models are developed, where non-linear material property of stainless steel is considered, and verified through comparisons with experiments in terms of failure modes, load-deformation histories and ultimate strength. Behaviors of stainless steel composite columns are compared with that of columns with both carbon steel tubes. Parametric studies are conducted to investigate the influence of the outer stainless steel tube strength, concrete strength, inner carbon steel tube strength and hollow ratio on structural behavior of axially loaded columns in terms of loading and interaction performance.
Nuno Peres, Rodrigo Goncalves and Dinar Camotim, “GBT-based cross-section deformation modes for curved thin-walled members with circular axis”, Thin-Walled Structures, Vol. 127, pp 769-780, June 2018

ABSTRACT: This paper presents an improvement of the first-order Generalised Beam Theory (GBT) formulation proposed in [1], which was developed for naturally curved thin-walled members with deformable cross-section and whose undeformed axis is a circular arc with no pre-twist. In this paper, the restrictions on the cross-section shape are removed (in the previous paper only rather simple cross-sections were dealt with) by proposing and discussing a novel and systematic procedure to obtain the cross-section deformation modes for arbitrary flat-walled cross-sections (open, closed or “mixed”). The proposed procedure retains the nomenclature of the deformation mode subsets defined in [2,3], even though the kinematic constraints employed to subdivide the modes are much more complex than for prismatic members. A set of representative illustrative examples is presented, involving complex local-distortional-global deformation, to show the efficiency of the proposed procedure when used together with a standard displacement-based GBT finite element. It is demonstrated that extremely accurate results are obtained with rather few DOFs and that the GBT modal solution provides in-depth insight into the structural behaviour of naturally curved members.

Ropalin Siahaan, Poologanathan Keerthan and Mahen Mahendran, “Section moment capacity design rules for rivet fastened rectangular hollow flange channel beams”, Thin-Walled Structures, Vol. 127, pp 781-797, June 2018

ABSTRACT: The rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new type of cold-formed steel section, made of two torsionally rigid rectangular hollow flanges, connected to a web via intermittent rivet fastening. The hollow flanges and the absence of free edges in the RHFCB contribute to improved structural performance. The structural behaviour of the RHFCB is unique compared to other conventional cold-formed steel sections and its moment capacity reduces with increasing rivet spacing. The current cold-formed steel design standards do not provide a calculation method to include the effects of intermittent fastening. In this research an extensive parametric study was conducted using validated finite element models to investigate the section moment capacity of RHFCBs. This paper presents the findings from the parametric study and proposes new design equations for the section moment capacity of RHFCBs in the Direct Strength Method format. The parametric study considers various slenderness regions, section dimensions and rivet spacing. In the new design equations, a reduction factor parameter is included to calculate the section moment capacity of RHFCBs at any rivet spacing up to 200 mm. Optimum rivet spacing was also recommended for RHFCBs.


ABSTRACT: It is important to increase energy absorption of a tube under axial loading without using any reinforcement material. Also, such a process results directly in an increase of specific energy absorbing (SEA) capability of the tube. Based on this consideration, applicability of annular rolling process to thin-walled aluminium 6063-T5 tubes (D/t = 58/1.5) has been investigated experimentally and numerically. The study was conducted with two groups of tubular specimens. After determining the appropriate restricted fold length (RFL) value from short length tubes, the data were applied to long tubes. From the experimental studies of long-length annular-rolled tube, folding initiates within the RFL, and it enhances not only maximum folding, but also upper and lower force peaks in force-displacement curve. Thus, 23% improvement in SEA was obtained. Moreover, annular rolled tubes exhibited more outward folding with respect to that of the base tube, and this folding behaviour was used to explain results of the finite element (FE) analyses. It is concluded that annular rolling process is promising for thin-walled circular tubes for enhancing their energy absorption capabilities.
Shitang Ke, Lu Xu and Yaojun Ge, “Sensitivity analysis and estimation method of natural frequency for large cooling tower based on field measurements”, Thin-Walled Structures, Vol. 127, pp 809-821, June 2018

ABSTRACT: The natural frequency is a key factor for estimation of dynamic deformation and mechanical performance. As simple and effective estimation equation for natural frequency of cooling tower is absent, current investigations of natural frequency of cooling towers are basically based on finite element analyses. In this study, 38 models of a 179 m cooling tower were established by tuning key structural parameters (e.g., tower height, throat height, throat diameter, inlet height, and pillar sectional area) and dynamic characteristics of these models were analyzed. Also, effects of structural parameters on fundamental frequency and overturning frequency were investigated. The sensitivity analysis of structural natural frequency for cooling towers was executed using the perturbation method and the Latin hypercube sampling method and sensitivity factors of different parameters corresponding to different orders were obtained. Based on that, multi-parameter empirical estimation equations for fundamental frequency and overturning frequency considering weighted sensitivity factor were proposed. Then, the estimation equation of natural frequency is verified by field tests of eight cooling towers with typical tower heights and configurations. Specifically, the measured acceleration signals were pre-treated using random decrement method (RDT) and natural excitation technique (NExT) and the first 10 order natural frequencies of the cooling tower using three time-domain modal identification methods (ARMA, ITD, and STD). Finally, structural parameters of cooling tower obtained by field tests were fitted. The results indicated that the fundamental frequency of cooling towers decreases as tower height and throat height increase and increases as throat diameter, inlet height, and pillar sectional area increase. Although sensitivity factors obtained by the two methods are similar, the LHS method shows higher accuracy. The effect of tower height on natural frequency is most significant among all parameters, which means the sensitivity factor of tower height is higher than those of other parameters. The measured fundamental frequencies of cooling towers were between 0.6 Hz and 1.9 Hz and heights and configurations of cooling towers have significant effects on their dynamic characteristics. The field test results of eight cooling towers demonstrated reasonable effectiveness of the proposed empirical estimation equations for the fundamental frequency and overturning frequency of cooling towers (the maximum goodness of fit of fundamental frequency and overturning frequency were 0.996 and 0.975, respectively). Error analysis indicated that the proposed estimation equation for natural frequency is highly accurate and reliable. This study provides references for determination of structural natural frequency of large cooling towers and future studies on structural natural vibration characteristics.


ABSTRACT: Six conferences in the CIMS series have been held quadrennially starting in Timisoara in 1992 and subsequently in Liege (1996), Lisbon (2000), Rome (2004), Sydney (2008) and Glasgow (2012). The current conference in Baltimore (2016) is therefore following a long tradition in the area of advanced research on structural stability and more specifically, the coupling of buckling modes in metal structures. In the beginning, the focus was very strongly on coupling of simultaneous or near simultaneous buckling modes of thin-walled metal structures including members, plates and shells. Secondary bifurcation may occur in this case with unstable post-buckling for shells and some thin-walled columns. The resultant behavior is sensitive to structural imperfections which may cause substantially reduced failure loads.

For the early conferences, it was already recognized that the buckling modes to be investigated were not simply the local and overall modes, but newly discovered modes such as distortional. Continued development of Generalized Beam Theory (GBT) and the constrained Finite Strip Method (cFSM) has allowed better identification of the modes. Research into modal identification and coupling of the wider range of modes now identified has grown substantially and is reported in the conference series.
The preface to the second conference in Liege states that there is a need to improve the incorporation of the theoretical methods into design standards and specifications. Therefore, there has been an ongoing thread in the CIMS series on how this research has and could be implemented in design. Related areas such as buckling of structural members under elevated temperatures and dynamic buckling have been expanded. The paper reviews the research from the six previous conferences with a view to finding “what have we learned”. It then moves on to investigating the future research needs and steps required for further implementation of the research in design standards and specifications.


ABSTRACT: The aim of this work is to provide an overview of the current status of an extensive ongoing investigation on cold-formed steel columns and beams affected by mode coupling phenomena involving distortional buckling, namely local-distortional (L-D), local-distortional-global (L-D-G) and distortional-global (D-G) interaction. The investigation comprises experimental tests, numerical simulations and design proposals, intended to (i) acquire in-depth knowledge on the post-buckling behaviour (elastic and elastic-plastic), ultimate strength and failure mode nature of the members under consideration, and (ii) take advantage of the above knowledge to develop, calibrate and validate efficient Direct Strength Method (DSM)-based design approaches to predict their ultimate strength. Initially, column results are used to illustrate and help grasp some fundamental concepts, namely the characterisation of the (i) three above mode coupling phenomena, (ii) different sources of mode interaction that may cause ultimate strength erosion, (iii) global post-buckling behaviour and (iv) the most detrimental initial geometrical imperfections. Then, the paper addresses separately each mode coupling phenomenon, for columns, and only L-D interaction for beams. For columns undergoing L-D and L-D-G interaction, the research activity reported concerns experimental investigations, numerical (shell finite element) simulations and the development and/or assessment of DSM-based design approaches and/or guidelines. The picture is different for columns experiencing D-G interaction and beams affected by L-D interaction, due to the lack of available experimental results – nevertheless, even if only numerical results are reported, they enable unveiling rather interesting (and unexpected) behavioural features concerning the real nature of these mode coupling phenomena.


ABSTRACT: In this paper a novel method for the analysis of thin-walled members is presented: the constrained finite element method. The method is basically a shell finite element analysis, but carefully defined constraints are applied which enforce the thin-walled member to deform in accordance with specific mechanical criteria, e.g., to force local, global or distortional deformations. The constrained finite element method is essentially similar to the constrained finite strip method, but the trigonometric longitudinal shape functions of the finite strip method are replaced by polynomial longitudinal shape functions, which – together with longitudinal discretization – transforms a finite strip into multiple finite elements. This change in longitudinal interpolation makes the method applicable for a wide range of practical problems not yet handled by other modal decomposition methods. The new shell finite element is briefly presented here, but the main focus of this paper is on how the constraining criteria can be applied for a thin-walled member. More specifically, in this paper a band of finite elements is discussed in detail, where ‘band’ is a segment of the member with multiple elements along the cross-section, but with one single finite element longitudinally. The possible base systems for the
ABSTRACT: In this paper a novel method is employed for the buckling analysis of thin-walled members. The method is basically a shell finite element method, but constraints are applied which enforce the thin-walled member to deform in accordance with specific mechanical criteria, e.g., to force the member to buckle in flexural, or lateral-torsional or distortional mode. The method is essentially similar to the constrained finite strip method, but the trigonometric longitudinal shape functions of the finite strip method are replaced by polynomial longitudinal shape functions, and longitudinal discretization is used, which transform the finite strip into multiple finite elements, that is why the new method can readily be termed as constrained (shell) finite element method. In the companion to this paper a band of finite elements is discussed in detail, where ‘band’ is a segment of the member with one single finite element longitudinally. In this paper the constraining procedure is applied on thin-walled members discretized both in the transverse and longitudinal direction. The possible base systems for the various deformation spaces are demonstrated here, as well as numerous buckling examples are provided to illustrate the potential of the proposed method.


ABSTRACT: This paper presents a study on the influence of the deformation mode nature (global, local, distortional) on the load carrying capacity of beams beyond the yield load. Following recent investigations on the decomposition of elastic buckling modes into combinations of structurally meaningful deformation modes, this work applies the same concept to the 1st order failure modes (elastic-plastic collapse mechanisms). To achieve this goal, a GBT-based code that performs first-order elastic-plastic analyses of thin-walled members is employed. In order to study the influence of the mode nature on the post-yielding strength, five beams with different cross-sections, lengths, supports and loadings are analysed, and the results displayed by means of load-deflection curves, failure mode configurations and modal participation diagrams. On the basis of the limited study performed, it is concluded that larger contributions of local and distortional modes to the beam failure mode lead to a higher post-yielding strength reserve, which implies a higher beam load carrying capacity beyond the yield load. The opposite occurs for the contributions of global modes. Therefore, the member strength reserve obtained in geometrically non-linear analysis should not be credited only to the elastic post-buckling effects, but also to the plastic post-yielding effects.

References listed at the end of the paper:
[6] S. Ádány, A.L. Joó, B.W. Schafer, Buckling mode identification of thin-walled members by using cFSM base functions, Thin-
extensive experimental data collected from the literature that comprised various load cases, fabrication
Finally, beam
also determined experimentally, and the sectioning technique was classically used to record the deformations of the released material; these results have been compared to measurements taken with electrical strain gauges.

ABSTRACT: This paper presents a series of twelve buckling tests on rectangular and circular hollow section tubular beam columns of nominal steel grade S355. The columns were fabricated by either the hot-rolling or the cold-forming process, and were subjected to different load cases through the application of eccentric compression: mono-axial bending ($M_y$) or bi-axial bending ($M_y + M_x$) combined with axial compression ($N$). Preliminary measurements of cross-section geometry, material properties, geometrical imperfections, residual stresses as well as stub column tests are also reported in this paper. The (imperfect) initial geometry was measured along the whole column by means of two different procedures; the first method relied on the use of a set of equally spaced Linear Variable Displacement Transducers (LVDTs) displaced on each specimen’s plates. The second method consisted in scanning the specimen's plates by means of a laser Tracker AT401. Residual stresses were also determined experimentally, and the sectioning technique was classically used to record the deformations of the released material; these results have been compared to measurements taken with electrical strain gauges. Finally, beam-column buckling strengths were plotted in an O.I.C.-type format, and complemented with an extensive experimental data collected from the literature that comprised various load cases, fabrication
processes, yield strengths, cross-sections shapes, and elements’ lengths. The O.I.C. approach was shown to adequately capture the behavior of hollow section beam-columns in a straightforward and simple manner, and its potential for efficiently and rationally predicting carrying capacities was evidenced.


ABSTRACT: This paper investigates the elastic post-buckling behaviour of simply supported thin-walled lipped channel beams undergoing local-distortional (L-D) interaction. The beams are uniformly bent about the major-axis and experience flange-triggered local buckling (most common situation in practice). Three beam geometries are considered, each exhibiting a different type of L-D interaction, namely (i) “true L-D interaction” (close local and distortional critical buckling moments – two critical-mode initial geometrical imperfections are used, akin to the competing critical buckling modes), (ii) “secondary local-bifurcation L-D interaction” or (iii) “secondary distortional-bifurcation L-D interaction” (critical distortional-to-local buckling moment ratio well below or above 1.0, respectively, with “high enough” yield stresses). The results presented and discussed are obtained through elastic geometrically non-linear Generalised Beam Theory (GBT) analyses and provide the evolution, along given equilibrium paths, of the beam deformed configuration (expressed in GBT modal form), relevant displacement profiles and modal participation diagrams, making it possible to acquire in-depth knowledge on the beam L-D interaction mechanics. Particular attention is devoted to interpreting the quantitative and qualitative differences exhibited by the beam post-buckling behaviours associated with the three aforementioned L-D interaction types.


ABSTRACT: While there are precise analytical model available to assess the calculation of critical and ultimate load for global and local buckling separately, the interaction of both modes prove to be difficult as membrane effects and imperfections are of major impact. In an experimental programme, thirteen tests on columns with high b/t-ratio were carried out on square welded box sections made of S500 and S960 steel material, varying the global slenderness. The experiments were re-calculated with the Finite-Element-programme Ansys. The calibrated numerical model was subsequently used for parametric studies. The study at hand provides additionally an analytic approach to determine a slenderness depending reduction factor to design box sections prone to coupled instability. This approach, subsequently denoted as “generalised slenderness approach (gs)” is still orientated on the Ayrton-Perry format, which is also the basis of the Eurocode design procedure. Local effects are not included by omitting parts of the cross-section in the gs-approach, but by adding an additional equivalent global imperfection. The amplitude of this imperfection is based on the effective width method, but design charts for box sections are developed to ease the application.


ABSTRACT: The buckling behaviour of thin-walled tubes with regular convex polygonal sections (hereafter the “convex” will be implied) has been analysed a number of times over the last half a century, yet literature on such members in torsion has traditionally been lacking. Despite recent advances, there is still significant scope to further expand understanding of the behaviour of these members in torsion. Using the generalised constrained finite strip method (cFSM) and a semi-analytical finite strip method (FSM) that utilises an augmented
longitudinal displacement field of sines and cosines, the elastic buckling behaviour of long regular polygonal tubes in uniform torsion is assessed. The analysed polygons all have the same centreline perimeter and uniform thickness of constituent plate elements. It is found that the signature curves of critical stress vs. buckling half-wavelength converge as the number of sides in the tube is increased and that notable differences between the signature curves of tubes with consecutive numbers of sides occur at shorter and shorter half-wavelengths as the number of sides is increased, due to the decreasing width of the individual flats and also the occurrence of an increasing number of distortional modes. At very long half-wavelengths flexural buckling occurs in a helical-like manner, similar to the twisting of a hosepipe. The mechanics of this buckling mode are briefly investigated and it is noted that it is necessary to include all of the non-linear components of the in-plane shear strain, as opposed to only the flexural components, in order to obtain accurate solutions for this mode. Results for pure local and pure distortional buckling are also compared to those obtained via Generalised Beam Theory (GBT).


ABSTRACT: A variational model formulated using analytical techniques describing the nonlinear coupling between local and global buckling modes within an elastic thin-walled rectangular hollow section strut is presented. A system of nonlinear differential and integral equations subject to boundary conditions is derived and solved using numerical continuation techniques. The nonlinear behaviour of four representative lengths is investigated, which are characterized by the post-buckling equilibrium paths. The numerical results from the variational model are validated using a nonlinear finite element model and largely show excellent comparisons, particularly for the practically important ultimate load and the initial post-buckling behaviour. Boundaries for the four distinct length-dependent zones are identified and the most unstable zone is demonstrated to have a considerably narrower length range than previously determined for practical corner boundary conditions within the cross-section.


ABSTRACT: The purpose of this paper is to investigate the impact of the geometric imperfection on the interaction of buckling modes for thin-walled cold-formed steel members with a quantitative modal identification approach. Previous studies showed that the interaction of buckling modes varies during the loading process and how buckling interacts depends not only on the section itself but also on the geometric imperfections in the member. This interaction could change the failure modes of the member and its strength accordingly. This paper integrates a modal identification approach based on constrained finite strip method to track this interaction out of the shell finite element model for nonlinear collapse analyses. The geometric imperfections are included in the computational shell finite element model using the traditional modal approach with stochastically simulated magnitudes. The simulations are performed on five specially selected cold-formed steel sections that are deemed to be local-dominant, distortional-dominant, local-distortional interacted, Pcr-equal interacted, and Pn-equal interacted. The deformations of the analyses are categorized into the fundamental deformation modes commonly available to cold-formed members: local, distortional, and global. Sensitivity of imperfection is studied by tracing the variation of mode interaction, in particular, for the failure mode. Peak load and associated mode participations are investigated. In addition, a statistical study of the impact of imperfections on the potential failure mode at peak is provided. The potential correlation of the member strength with mode participation is explored, which will shed light on the coupled instability of cold-formed steel member, in particular on investigating the impact of mode participations to member strength.

ABSTRACT: The paper investigates the possibility to use the local plastic mechanisms to characterise the ultimate strength of short thin-walled cold-formed steel members subjected to eccentric compression about the minor axis. The research is based on previous studies and some new investigations of the authors. The plastic mechanisms for lipped channel members in eccentric compression about minor axis and the evolution of those mechanisms are analysed. Five different types of mechanisms for members in compression with different eccentricities are examined.


ABSTRACT: Accurate thermal buckling analysis of functionally graded orthotropic cylindrical shells is presented based on the Reissner’s shell theory under the symplectic framework. By introducing a full-state vector, the high-order governing differential equation is reduced into a set of low-order ordinary differential equations. The fundamental unknowns are expanded in terms of the symplectic eigensolutions without any trial function. The buckling equations and buckling mode shapes are analytically obtained. The present study demonstrates that the expressions of displacements have different forms and strongly depend on the end conditions and thickness. Some new results are presented in numerical examples.


ABSTRACT: This paper presents the results of a large parametric study concerning the evaluation of the critical local buckling coefficient for thin-walled rectangular hollow section (RHS) members subjected to combined axial load and biaxial bending, accounting for web-flange interaction. The calculation of the half-wavelength leading to the minimum critical local bifurcation load is performed by means of a Generalized Beam Theory specialization, which makes it possible to quickly solve a large set of cases. In particular, taking advantage of the small half-wavelength of local buckling, it is assumed that the stresses are uniformly distributed along the member length, making it possible to resort to semi-analytical solutions using sinusoidal half-wave amplitude functions for the GBT cross-section deformation modes. On the basis of the results obtained, the key parameters governing local buckling are identified, leading to easy-to-use charts and closed-form formulae to determine the local buckling coefficient.


ABSTRACT: The structural performance of cold-formed lean duplex stainless steel beams at elevated temperatures ranging from 24 to 900 °C was investigated in this study. A finite element model was developed. The numerical analysis covered the specimens of square and rectangular hollow sections. The material properties obtained from tensile coupon tests on lean duplex stainless steel at elevated temperatures were used in the finite element model. A total of 125 numerical flexural strengths were obtained from the finite element analysis. The numerical results were compared with the design values calculated by the existing design rules, including the American Specification, Australian/New Zealand Standard, European Code, direct strength
method and continuous strength method. The suitability of these design rules for lean duplex stainless steel beams at elevated temperatures was assessed using reliability analysis. It was shown that the existing design rules are generally quite conservative in predicting the flexural strengths at elevated temperatures, except that the modified direct strength method provides accurate and reliable predictions. Therefore, it is recommended that the modified direct strength method be used for cold-formed lean duplex stainless steel beams at elevated temperatures.

ABSTRACT: Composite thin-walled structures are of much interest in different applications as well as energy absorption devices for their great crashworthiness and light weight. In this paper, a new corrugated composite cylindrical tube has been introduced in order to improve crashworthiness along with a stable crushing. In cylindrical composite tubes, the effects of corrugations regarding characteristics of energy absorption have undergone quasi-static axial and oblique loading investigations. For this reason, composite cylindrical tubes with different corrugation geometries were analyzed using finite element explicit code and the effects of corrugations on crush force efficiency and specific energy absorption were comprehensively studied. The finite element model has been validated by experimental quasi-static compression tests. An efficient analytical solution for SEA during axial loading has been also derived and compared with FEM solution. Furthermore, a comparison of empty and foam-filled corrugated composite tubes has been done. Based on the obtained results, generating corrugated surfaces on tubes improved the crush force efficiency significantly in both axial and oblique crushings. Performing a parametric study on geometrical corrugation parameters of tubes has been indicated that the energy absorption of these structures depends strongly on the corrugation parameters. Furthermore the absorbed energy has been increased by using foams in both axial and oblique crushing. SEA increases by increasing the foam density while the CFE decreases.

ABSTRACT: In the over-bend straightening process of longitudinally submerged arc welding (LSAW) pipes, the cross section tends to be distorted due to the axial curvature variation in the reverse elastic-plastic bending. Based on the minimum work principle, a analytical model of the cross-sectional distortion of the curved pipe with initial curvature in the reverse axial elastoplastic bending is established, and the prediction error is not more than 10% compared with the experimental value of the maximum distortion coefficient. Especially for smaller deformations and thinner pipes, the prediction accuracy is higher. Compared to ovality, the maximum distortion coefficient with a smaller error can be used as an effective prediction parameter. In addition, the application of this prediction model is analyzed by an example of a straightness-offgrade LSAW pipe. The results show that the maximum value and position of cross section with most serious distortion can be determined once the initial curvature of a curved pipe is measured, which can be compared with the standard to adjust the shape of the straightening tools and process parameters.

ABSTRACT: The paper proposes a comparative study between different analytical and numerical three-dimensional (3D) and two-dimensional (2D) shell models for the bending analysis of composite and sandwich
plates, spherical and doubly-curved shells subjected to a transverse normal load applied at the top surface. 3D shell models, based on the equilibrium equations written in mixed orthogonal curvilinear coordinates, are proposed in closed form considering harmonic forms for displacements, stresses and loads and simply supported boundary conditions. The partial differential equations in the normal direction are solved in analytical form using the Exponential Matrix (EM) method and in numerical form by means of the Generalized Differential Quadrature (GDQ) method. The first 3D model is here defined as 3D EM model and the second one is here defined as 3D GDQ model. Two-dimensional shell solutions are based on the unified formulation which allows to obtain several refined and classical 2D shell theories in both Equivalent Single Layer (ESL) and Layer Wise (LW) form. Classical theories such as the First order Shear Deformation Theory (FSDT), the Third order Shear Deformation Theory (TSDT) and the Kirchhoff-Love (KL) theory are obtained as particular cases of refined 2D ESL models. 2D shell solutions are proposed by means of a complete generic numerical method such as the GDQ method which allows the investigation of complicated geometries, lamination schemes, materials, loading conditions and boundary conditions. The analyses and comparisons are proposed in terms of displacements, stresses and strains. In 2D GDQ models the transverse shear and transverse normal stresses are recovered from the 3D equilibrium equations allowing results in accordance with the 3D shell solutions. After these validations, the refined 2D GDQ shell models are used for the investigations of new cases which cannot be analyzed by means of closed form solutions. In the present work, the static analysis of an elliptic pseudosphere is proposed. Considerations about the typical zigzag form of displacements for multilayered structures are given. The interlaminar continuity in terms of compatibility and equilibrium conditions are also discussed for all the proposed assessments and benchmarks.


ABSTRACT: In this paper, the free vibration of the stepped doubly-curved shells of revolution is investigated by using a semi-analytical method with arbitrary boundary conditions. The stepped doubly-curved shells of revolution are divided into their segments in the meridional direction according to the steps of the structures, and the analysis of the theoretical model is formulated by using Flügge’s thin shell theory. The Jacobi polynomials along the revolution axis direction and the standard Fourier series along the circumferential direction consist of the displacement functions of shell segments. The boundary conditions at the ends of the stepped doubly-curved shells of revolution and the continuity conditions at two adjacent segments were enforced by penalty method. Then, the accurate solutions about the vibration characteristic of the stepped doubly-curved shells of revolution were solved by the method of Rayleigh–Ritz. For arbitrary boundary conditions, the present method does not need any changes to the mathematical model or the displacement functions, and it is very effective in the analysis of free vibration for the stepped doubly-curved shells of revolution. The accuracy and reliability of the proposed method are verified with the results of finite element method (FEM), and some numerical results are reported for free vibration of the stepped doubly-curved shells of revolution under arbitrary boundary conditions. Results of this paper can provide reference data for future studies in related field.


ABSTRACT: This study focuses on the investigation of the stability in a rectangular FGM plate with central crack. The plate thickness is changed linearly following the length of the plate. Using the Reissner-Mindlin first order shear deformation theory (FSDT), phase field theory and finite element method (FEM), the stability of
fracture of the plate is determined. In order to ensure the reliability of the study, the obtained numerical results in this paper are compared with results reported in other publications. The work also presents the analysis of critical buckling computation for plate that have variation in thickness, the length of the crack on plate as well as the inclined angle of the crack. The numerical results show that the crack length impacts significantly to the critical buckling values of the plate, whereas the impact of inclined angle is less.

ABSTRACT: Round-ended elliptical concrete-filled steel tube (RECFST) column is a novel type of composite member which is gradually used in engineering practices (i.e. piers and arches) because of its low flow resistance coefficient and reasonable distribution of major-minor axis. However, little attentions to the structural behavior of RECFST columns have been paid. This paper makes an attempt to conduct a numerical analysis on the axial compressive performance of RECFST stub columns. Firstly, an equivalent constitutive model for the confined round-ended concrete of the RECFST column was proposed. Following this, a nonlinear finite element (FE) modeling considering contact interactions of the type of thin-walled CFST column was developed and verified by the test results in terms of axial load (N) - longitudinal shortening (δ) curves and failure modes. The influence of extensive parameters, including diameter-to-thickness ratio, aspect ratio and cross-section area etc., on the performance of thin-walled RECFST stub columns under axial compression was estimated as well. The analytical results demonstrated that the axial compressive strength of thin-walled RECFST stub columns was substantially improved with the increase of the steel strength, the concrete strength and the cross-section area, and the trend of the N-δ curves was obviously affected by the confinement factor. Finally, two simplified design methods to predict the axial compressive strength of thin-walled RECFST stub columns were established on the basis of the simple superposition approach and the unified theory. The studies may provide a considerable reference for designing this type of structures in engineering practice.

ABSTRACT: This paper investigates the axial compressive behaviour of T-shaped concrete-filled steel tube (CFST) stub columns with blinding bars. In this column system, binding bars are applied cross-through the section and produce confinement effects. Eleven specimens with binding bars and five ones without binding bars were tested under axial compressive loading. The experimental results demonstrate that, by setting binding bars, the local buckling failure modes are changed and the occurrence of local buckling is delayed, and the global outward bulge of the steel tube at the concave corners can be effectively restrained. The ultimate strength and ductility of the columns with binding bars can achieve up to 1.53 and 7.5 times higher than those of the columns without binding bars, respectively. Taking into consideration the contribution of binding bars, the confinement effects of steel tube and the other sectional characteristics, a method for predicting the ultimate axial compressive strength of the columns with or without blinding bars is established. The accuracy of the method is validated through comparisons of the experimental results reported in this paper and in other available open literatures.

ABSTRACT: Modern transportation systems require light materials with an increased level of protection thus thin walled structures are in the focus of structural engineers. The latest developments in the field of manufacturing processes allow the use of Rapid Prototyping technologies for custom safety devices and Additive Manufacturing is a candidate that already captured some attention. In this work Fused Deposition Modelling method was used to manufacture samples for material characterization and multi-cell insert designed as safety devices and the material is ABS. Traction tests were performed and some SEM images complete the specimens’ analysis. From this analysis, in order to define a simple material model for numerical analysis, a stacking configuration -45°/0°/45°/90° was selected. A model for material damage is also presented in this paper. Circular structures with rectangular multi-cell were manufactured and tested in compression. In order to improve the performances a hybrid structure was investigated. Aluminium tubes were added in order to enhance the performances of the printed structures. For each step of the experimental work a numerical companion is presented. Modelling techniques and parameters are presented and discussed in this paper. By adding the aluminium tube there is an increase in the performances of the structure. A progressive profile for the crushing force is obtained. By adjusting the support (outer aluminium tube) and designing multi-cell insert, structures for safety enhancement can be developed.


ABSTRACT: This paper presents an investigation on the structural performance of welded S460 steel columns under axial compression at elevated temperatures using finite element analysis. Stub and long columns with box and H-sections were considered. A new stress-strain curve model for S460 steel at elevated temperatures was proposed and adopted to obtain the stress-strain curves for the finite element analysis. A finite element model was developed and verified against the available test data for welded S460 steel columns subject to axial compression at room and elevated temperatures. A parametric study was carried out to generate additional data of the axial compressive strength of box and H-section columns with various cross-section slenderness and column slenderness ratios at elevated temperatures. The obtained numerical results of the column strength were compared with the design predictions using the European and American specifications and the direct strength method by substituting the material properties at elevated temperatures. It was found that the provisions in European and American standards for elevated temperature conditions provide relatively conservative predictions. The direct strength method overestimates the strength of stub columns while accurately predicts the strength of long columns at elevated temperatures. Modifications are proposed for the European and American standards and direct strength method and these modified design rules are recommended to be used to more accurately estimate the design strength for welded S460 steel columns at elevated temperatures.


ABSTRACT: As a large span structure that might serve many occupants, the deflation behavior of an air-supported membrane structure under emergency deflation is of critical importance for safety assessment on occupants' evacuation but has received few studies. This paper presents experimental field tests and numerical simulations on deflation behaviors of a real-life air-supported membrane structure. A numerical model is employed in deflation simulation which considers tension-only membrane based on the vector form intrinsic finite element method for membrane motion analysis and pressure change due to air loss in deflation according to the classic thermodynamics. The correctness and the applicability of the model are verified by good correlation of prediction in response of pressure, displacement, and wrinkling formation and development of the
structure with those measured and observed in deflation tests. The study shows that the structure in emergency deflation will lose its high pressure quickly first, and then sustain deflating under low residual pressure for a long time. The model is further used in parametrical analysis on factors that affect deflation progress and a complete deflation simulation to predict the whole collapse process, which is accordingly characterized by two typical phases, the tender deflation stage and the severe deflation stage. In tender stage the structure holds a relatively plump form, while in the severe stage the structure bears low decreasing residual pressure, membrane losses most tension stress so that many elements wrinkle and the structure experiences instability. Due to wrinkling, the residual pressure is found to approximately balance with its vertical loads. As a result, the feasible method proposed based on the residual pressure in deflation is very simple and reliable to predict the deflation duration and evaluate maximum escape area for deflation assessment of the studied structure.


ABSTRACT: In this paper, a variational approach for the wave dispersion in anisotropic doubly-curved nanoshells is presented. To study the doubly-curved nanoshell as a continuum model, a new size-dependent higher-order shear deformation theory is introduced. In order to capture the small scale effects, nonlocal strain gradient elasticity theory has been implemented. The present model incorporates two scale coefficients to examine the wave characteristics much accurately. Based on Hamilton’s principle, the governing equations of the doubly-curved nanoshells are obtained. These equations are solved via analytical approach. From the best knowledge of authors, it is the first time that present formulation is used to investigate the wave dispersion in anisotropic doubly-curved nanoshells. Also, it is the first time that small scale effects are considered in doubly-curved nanoshells made of anisotropic materials. Unlike the classical (scaling-free) model, the presented nonlocal strain gradient higher-order model shows a good calibration with the experimental frequencies and phase velocities. It is demonstrated that the material properties, nonlocal-strain gradient parameters and wave number have remarkable influences on wave frequencies and phase velocities. Presented results for wave dispersion can serve as benchmarks for future analysis of doubly-curved nanoshells.


ABSTRACT: This work aims at presenting and discussing numerical results concerning the post-buckling behaviour, strength and design of cold-formed steel simply supported lipped channel and zed-section beams under uniform bending and undergoing distortional-global (D-G) interaction – two different support conditions are considered in the lipped channel beams. The relevance of the interaction effects is assessed by identifying the beams whose ultimate strength and/or failure mode are visibly affected by them. Distinct (i) global-to-distortional critical buckling moment ratios ($R_{GD}$) and (ii) yield-to-non-critical buckling (distortional or global) moment ratios ($R_g$) are considered, which are expected to lead to different failure mode natures (global, distortional or interactive). For each beam type, combinations of 41 geometries and 11 yield stresses are considered, in order (i) to characterise the beams experiencing “true D-G interaction” ($R_{GD} \approx 1.0$) and “secondary global-bifurcation D-G interaction” ($R_{GD} > 1.0$ and high $R_g$) and (ii) to investigate the possible occurrence of “secondary distortional-bifurcation D-G interaction” ($R_{GD} < 1.0$ and high $R_g$). Moreover, an in-depth investigation on the elastic post-buckling behaviour is carried out, to assess how the initial geometrical imperfection shape/configuration influences the behaviour and strength of beams prone to D-G interaction. The results presented consist of (i) relevant non-linear equilibrium paths, (ii) deformed configuration evolutions along those paths and (iii) figures providing the failure mode characterisation. Then, the numerical failure
moments obtained are compared with their predictions by means of (i) the currently available Direct Strength Method (DSM) beam distortional and global strength curves, and also (if necessary) (ii) proposed DSM-based design approaches, specifically developed to handle beam D-G interactive failures.


ABSTRACT: This study examined the buckling of unstiffened cylindrical shells under external pressure. Six stainless steel cylindrical shell specimens were tested, with a length-to-radius ratio, L/R, ranging from 1 to 7. The wall thickness, diameter, axial length, and geometry of each specimen and the material properties of the corresponding sheets were measured. All cylindrical specimens were subjected to external pressure in a pressure chamber; the buckling load and final collapsed mode were recorded. This paper presents a comparison among theoretical calculations, finite element (FE) results, and experimental data for externally pressurized cylindrical shells. In the numerical calculations, true geometry, average wall thicknesses, and elastic–perfectly plastic modeling were considered. Deviation between theoretical and FE results was 0% to −22%, and it increased with the length-to-radius ratio. Experimental results are consistent with FE results, with deviation of 2–9%, and final collapsed modes of all shells are consistent.


ABSTRACT: Confusion as to the way in which the bending of Z-section beams has been described has led to misleading descriptions of the limiting moments of beams which undergo non-linear biaxial bending and twisting as being elastic buckling moments. Further difficulties arise from the use of the same symbols to describe both the principal and the rectangular axes of Z-sections. A constrained beam with restraints which prevent lateral displacement of the compression region does not buckle laterally, and only needs to be designed against in-plane failure. A beam with restraints which prevent lateral displacement of the tension region should be designed against lateral-distortional buckling, which may be approximated by lateral buckling with an enforced centre of rotation. An unconstrained beam bent about its minor principal axis does not buckle laterally, and should be designed against in-plane failure. An unconstrained beam bent about its major principal axis may buckle laterally. An unconstrained beam under biaxial bending deflects and twists as soon as loading commences and reaches very large deformations as a limiting moment is approached. The large deformations cause premature yielding before the limiting moment is reached. Pre-buckling effects reduce these large deformations somewhat, but not sufficiently that the limiting moment can be safely used in first yield design. Instead, interaction equations may be used. The linear interaction equation is unnecessarily conservative, and may be replaced by a parabolic interaction equation.


ABSTRACT: In previous research, an innovative hybrid material double-hat thin-walled beam has been proposed for vehicle bumper system, which has demonstrated great potentials for improved pedestrian safety and reduced weight. In this work, we have used aluminum foam to fill the hybrid double-hat beam to further its application in vehicle bodies with increased bending resistance and energy absorption efficiency. Bending behaviors of both empty and foam-filled hybrid beams were numerically investigated using the validated LS-DYNA models. Three representative loading positions including the mid-span, 50 mm and 100 mm offsets from
the mid-span were simulated to reveal the effect of load position uncertainty. It was found that the foam filler could increase the specific energy absorption (SEA) by more than 30% and double the bending moment (\(M_b\)) of the empty hybrid beam by changing its deformation pattern. Moreover, the foam-filled beam shows more robust crashworthiness performance against load position variation. Using radial basis function (RBF) metamodels, the multi-objective design optimization (MDO) problems were formulated for both empty and filled hybrid beams to maximize SEA and \(M_b\) and minimize the initial peak force (\(F_{ip}\)). The multi-objective particle swarm optimization (MOPSO) was used to seek the Pareto fronts of the MDO problems. The MDO results show that the foam-filled beam has much broader performance space in terms of \(F_{ip}\), SEA and \(M_b\) and has great potentials for high-energy crash applications. It was also found that the Pareto front varies for different loading positions for either empty or filled hybrid beam. Including multiple loading positions could achieve a more robust design against load uncertainty. Appropriate weighting factors should be chosen for different loading positions to yield realistic and more robust designs of the proposed hybrid beams.

ABSTRACT: Availability of newly developed rapid manufacturing processes may in the near future enable the integration of continuous fiber composites into vehicles while maintaining the volume production rates typical for the automotive industry. In particular, polymer matrix composites reinforced with continuous carbon fibers are considered as substitutes for metals in the design of front rail components, owing to their exceptional impact energy dissipation capabilities. To support development of such structures, it is important to revise capabilities of available composite material models for prediction of axial crushing – a major loading mode experienced by front rails. In this study, predictive capabilities of three widely used LS-DYNA composite material models – MAT054, MAT058 and MAT262 – were investigated and compared with respect to modeling of axial crushing of CFRP energy absorbers. Results of crush simulations with non-calibrated material models were compared with available experimental data, and then parameter tuning was conducted to improve correlation with experiments. Furthermore, calibrated material models were used to conduct independent crash simulations with distinct composite layups. As a result, advantages and shortcomings of the considered material models, as well as directions for future developments, were identified.

ABSTRACT: This paper presents results on the crushing behavior of aluminum foam–filled columns with square cross section. Here, the effect of inserting an aluminum foam to single–walled and double–walled columns were studied. Parametric study for both types of columns compared with single–walled and double–walled columns were also carried out. In this work, the effect of strain rate of the aluminum foam was considered in the material model. The numerical results were compared with the available experimental data and shown to be in a very good agreement. The models that considered the strain rate effect of foam core gave better predictions compared to the ones without considering the strain rate effect. It will result in higher energy absorption and bigger local deformation on corners resulting a slightly increase of the overall crushing force. It can be said that the strain rate of the foam core plays a quite significant role in crushing behavior of the foam–filled columns, and should be taken into account. The results also showed that the interaction between the foam core and the column wall will change the deformation mode from one localized fold to multiple propagating folds and lead to the increase of total mean crushing force of the column. Similar effect of foam filling was also found in double–walled foam–filled columns. Further investigation has been conducted on the effect of core
thickness to the mean crushing force response of the columns. It is also found that increasing the core thickness in double–walled foam–filled column will improve the crushing behavior up to a point where there is still interaction between the walls. After that, the further increase of the core thickness will make the column response approaching the crushing force of single–walled foam–filled.

ABSTRACT: This paper provides means for obtaining the first three significant vibration modes for rectangular plates based on mass participation ratios. A non-dimensional frequency parameter is presented which results into the vibration frequency of rectangular plates at each of these three significant modes. Various aspect ratios and four combinations of boundary conditions at the plate edges are studied. A correlation between the nonlinear load-deformation behavior of the plate and its vibrational behavior is also presented accordingly. It is demonstrated that the vibration frequency of the studied rectangular plates increases significantly upon increasing the applied lateral pressure if the large deformation effects are considered in the analysis. The easy-to-follow method of frequency calculation presented in this paper is useful for assessing the dynamic characteristics of rectangular plates with or without lateral pressure that are subject to vibration.

ABSTRACT: This study investigates the non-linear load-deflection behavior of a composite plate reinforced with Shape Memory Alloy (SMA) fibers. The plate is subjected to the uniform lateral pressure and thermo-mechanical loading while resting on a Winkler-Pasternak type elastic foundation. In SMA fibers, simple one-dimensional Brinson’s model is implemented to determine tensile recovery stresses due to the phase transformation. The non-linear semi-analytical solution is formulated for the examination of the large deflections including the preliminary geometrical imperfection. The governing equations of equilibrium are derived in terms of displacement and stress function. The Galerkin technique is chosen to solve the nonlinear partial differential equations of motions. A detailed parametric study including different SMA material properties, SMA fiber pre-strain values, SMA fiber volume fraction, foundation stiffness, and activation temperature are examined.

ABSTRACT: Special-shaped CFST columns are becoming increasingly attractive as alternative solutions to engineering design. Three-dimensional FE models are developed and verified against experimental results in terms of failure modes, load-deformation curves and ultimate loads, where circular, triangular, Fan-shaped, D-shaped, 1/4 circular and semi-circular sections are considered. In light of the FE simulations, the composite actions between the special-shaped steel tubes and concrete cores have been investigated through load-deformation and interaction stress-deformation histories. Possible parameters affecting specimens loading behaviors have been studied. The studies generally show that the failure modes, composite behaviors and load-deformation histories of the axially loaded special-shaped CFST stub columns are similar to those of SHS/RHS specimens.
ABSTRACT: The paper studies on experimental and theoretical investigations into the crushing response of the nested rectangular-square tube structures under lateral loading. Lateral crushing behavior of these nested tube structures is described in this work. The effect of peak crushing load on mean crushing load is pointed out for each nested tube structure. The theoretical formula is proposed based on the simple superposition principle and the modification of the simplified super folding element theory. The mean crushing load depends on the length of the plastic hinge line, wall thickness, and flow stress of material. The value of the mean crushing load obtained from calculation is compared with the results of the tests, resulting in good agreement with acceptable errors.

ABSTRACT: This paper presents results of a numerical finite element parametric study on elastic shear buckling and ultimate shear strength of cold-formed steel channels with longitudinally stiffened slotted webs. The following parameters were varied: channel height, thickness, flange width, flange lip length, longitudinal stiffener size, perforation pattern, aspect ratio, steel yield stress and boundary conditions. Channels with longitudinally stiffened solid webs subjected to shear load were also studied to provide reference data for comparison with the slotted channels. The parametric study described in this paper allowed us to develop equations for predicting the shear buckling coefficient of longitudinally web stiffened solid channels, as well as equations for predicting the elastic shear buckling load and the ultimate shear strength of channels with longitudinally stiffened slotted webs. The developed shear strength equations without and with tension field action are presented in the paper in the traditional and direct strength method formulations. The developed equations account for the studied parameters and showed good agreements with the finite element simulation results.

ABSTRACT: Due to the expensive cost of full-scale tests, more and more designs rely on simulation. For highly nonlinear crash simulation, numerical uncertainty is an inherent by-product, which refers to the oscillation of results when the simulation is repeated at the same design or the design variables are slightly changed. This oscillation directly influences the quality and reliability of the optimal design. This paper shows how these issues can be addressed by proposing a simple uncertainty quantification method for numerical uncertainty (noise) and surrogate model uncertainty (error) in the optimization process. Three engineering problems, a tube crush example, an automotive front-rail crush example and a multi-cell structure crush example, are used to illustrate this method. Firstly, the level of numerical uncertainty is quantified in terms of noise frequency and amplitude, and the convergence study of these two criteria is employed to determine an appropriate data size to describe numerical noise. Secondly, an estimation method considering both numerical noise and surrogate model error is proposed based on the prediction variance of the polynomial response surface. Finally, the tube and front rail structures are optimized according to the proposed uncertainty quantification method. It was found that by considering the two sources of uncertainty, the optimal designs are more reliable than the deterministic solutions.
ABSTRACT: There are three kinds of fundamental deformation of thin-walled members, namely global, distortional and local modes. A set of identification criteria based mainly on the characteristics of forces rather than conventional deformation shapes are proposed. The three newly defined deformation modes based on these criteria cover the entire deformation field of a thin-walled member, including those parts triggered by shear strains and transverse membrane strains. Moreover, it is proved that the three deformation modes are orthogonal to each other with respect to the elastic stiffness, which indicates the accuracy of the corresponding separation of the total strain energy, the portion of which is then designated as the participation factor of the individual mode, which is widely considered to be more physically appealing. Theoretically, the proposed criteria impose no restriction on cross-sectional types or geometric/loading boundary conditions. The proposed criteria are utilised to decompose the buckling results of several examples calculated by Finite Element Method. The resulting participation factors of each buckling mode are compared with those from the base functions of the constrained Finite Stripe Method (cFSM). The comparisons between the results of the two methods indicate the validity of the proposed criteria.

ABSTRACT: Cold-formed steel haunched portal frames are popular structures in industrial and housing applications. They are mostly used as sheds, garages, and shelters, and are common in rural areas. Cold-formed steel portal frames with spans of up to 30 m are now being constructed in Australia. As they are relatively new to the market, current design recommendations are fairly limited. In the specific frame system analyzed herein, the column is partially restrained against twist rotation at an intermediate point where the knee brace joining the column and rafter is connected. An experimental program was carried out on a series of portal frame systems composed of back-to-back channels for the columns and rafters. It was found that changing the knee brace and knee brace-to-column connection bracket significantly affected the buckling capacity of the column, however this was not captured in design calculations. In order to correctly predict frame behavior and ultimate loads for design purposes, the column buckling capacity must be accurately calculated. This paper presents an energy method approach to calculate the buckling load of a column with an intermediate elastic torsional restraint. Various end conditions of the column are considered including column base semi-rigidity, as well as multiple loading conditions. Displacement functions are determined based on measured experimental data. The Southwell and Meck plot methods to determine column buckling loads are discussed. The column buckling loads determined from the plot methods and calculated by the energy analysis are compared to the experimental column buckling loads. It is shown that the energy method outlined herein predicts the buckling load within 6% for columns with an intermediate elastic torsional restraint.

ABSTRACT: This paper is aimed at assessing the effects of local random external pitting defects on the collapse pressure of pipe under external pressure. In this two-part paper series, the buckling performance of locally random corroded pipe was experimentally and numerically studied. The experimental program described in Part I involves seamless carbon steel tubes with $D/t = 17$ and with different size of pitting defects. The random pitting defects were introduced into the outside surface of pipe using 6% FeCl$_3$ solution and then the collapse pressure of such locally random corroded pipe was obtained experimentally. The profile of pipe was
examined in details using Hexagon's new RA7320 Portable Arm Coordinate Measuring Machine (PACMM) and the measured data were analyzed meticulously. It indicated that either the out-of-roundness imperfection shape \( n = 2 \) or \( n = 3 \) fits best with the measure data. The characteristics of random pitting corrosion were statistically analyzed and the mass loss of pipe due to pitting corrosion was also determined after buckling test, the analysis results indicate that both lognormal and generalized extreme value (GEV) distribution are adequate to depict the distribution of pitting depth and pitting diameter-to-depth ratio (DDR). The corrosion morphology was observed using scanning electron microscope (SEM), which indicates that the shape of pitting defect is cylindrical or semi-ellipsoid. Finally, the relationship between collapse pressure and geometry defects was analyzed based on the experiment results.


ABSTRACT: In the second part of this investigation, a 3D nonlinear (Finite Element) FE models was established to systematically study the collapse pressure of random corroded pipe. The models are developed within the framework of the nonlinear finite element ABAQUS in combination with a user defined Python program. Two constraints technique including surface-based tie constrain (SBTC) and shell-to-solid coupling (SSC) were implemented to take the complex geometry into account without the sacrifice of model accuracy while minimizing the computational cost. It was found that SBTC is more robust to simulate the locally random corroded pipe (external corrosion) than SSC. After validation models, a parametric investigation is performed to study the influence of wave number and amplitude of out-of-roundness, random pitting factors (pitting shape, pitting density and the length of pitting affect zone \( L_c \)). It was revealed that the amplitude \( w_{\text{max}} \) and wave number \( n \) of out-of-roundness, pitting density and mass loss are the main factors that govern the collapse pressure \( P_{CO} \) of 3D random corroded pipe whereas pitting shape has minor impact on \( P_{CO} \). Finally, a simplified pitting model was proposed, it was found that the circumferential and axial bending rigidity are key parameters that govern the \( P_{CO} \) of pipe, which is mainly determined by the minimum remaining area in circumferential and axial direction.


ABSTRACT: This paper presents the experimental and numerical studies on the full torsional behavior of single-box multi-cell box-girders with corrugated steel webs (BGCSWs) under pure torsion. Two specimens of BGCSWs with double cells and triple cells are tested under pure torsion using a new apparatus. Then the accuracy and efficiency of finite element analysis (FEA) models are validated by comparing with the experimental results, including the overall torque-twist curves, crack patterns of concrete slabs and shear strains in concrete slabs and corrugated steel webs (CSWs). Next, a parametric study is carried out, which shows that the torsional capacity is in linear proportion to the compressive strength of concrete, the thickness, yield strength and transverse position of CSWs and the number of cells in the given ranges. Besides, this study demonstrates that the CSW located at the torsional center of multi-cell BGCSWs has little effect on the torsional responses and the other inner CSWs in the multi-cell BGCSWs have little contribution to the cracking torques but have significant effects on the yield and ultimate torques. At last, a new fitted formula for the relations of smeared shear strains between the inner CSWs and the outermost CSWs is obtained from a series of case studies.
ABSTRACT: A theoretical model called unified softened truss model for torsion (USTMT) is presented in this study to analyze the full torsional behavior of single-box multi-cell box-girders with corrugated steel webs (BGCSWs) under pure torsion. The predicted results have good agreement with the experimental and FEA results from the companion paper and the newly built shear strain relations between the corrugated steel webs (CSWs) of multi-cell BGCSWs in the companion paper is proved to be reasonable and can be employed in the proposed model. The comparisons of various shear strain relations between concrete slabs and CSWs show the correctness of new assumption in the proposed model. The results also indicate that the tension stiffening effect of concrete cannot be ignored and it is necessary to correct the thickness of shear flow zone in concrete slabs. In addition, the parametric study shows that the torsional capacity is in linear proportion to compressive strength of concrete, the thickness and yield strength of CSWs in the properly designed range of parameters. The proposed model is capable to predict the full torsional behavior of multi-cell BGCSWs with no more than 10 cells.

ABSTRACT: This paper evaluates the performance of the material point method for the simulation of thin-walled tubes under lateral compression. Validation is carried out against actual experimental results for three different scenarios, namely: quasi-static loading, impact on rigid target, and wave propagation. A systematic approach is taken to gain insight on the trade-off between accuracy and computational cost at different levels of refinement of the model. Accuracy is assessed by comparing simulation results against experimental data. Computational cost is measured by the simulation runtime, or more specifically, in terms of the ratio between simulation time and execution time. Results indicate that, from highest influence to lowest, the factors affecting accuracy are: grid resolution, particle count along the thickness of the tube, and particle count along the circumference of the tube. Overall, it is demonstrated that the MPM is a reliable and accurate method to model circular thin-walled tubes under various excitation conditions.

ABSTRACT: Recently, the combined mechanism of energy absorption has been considered for increasing energy absorption efficiency. The combined deformation of circumferential expansion and folding in the cylindrical aluminum thin-walled tubes is one of these mechanisms that can be effective in improving energy absorption. In this paper, the effect of parameters of diameter, height and thickness of the tube, friction, and interference of the tube and punch, as well as the half-angle of the tip of the conical punch on the energy absorption have been investigated using LS_Dyna software. Taguchi method was used to design the experiments and response surface method was used for optimization. In the Taguchi method, the design limit has been significantly reduced and the effect of different parameters on energy absorption has been demonstrated. In optimization with response surface method, optimal states have been proposed that increased energy absorption compared to reference test. Finally, by providing a mathematical model for single-objective optimization, the specific energy absorption increased by 127%, but the maximum force in this case was increased by 130%. In multi-objective optimization, specific energy absorption and maximum force were considered as design parameters that optimized specific energy absorption increased by 77%, while the
maximum force was only 37% higher. Thus, by combining suitable types of energy absorption mechanisms and optimizing them, absorbents with a higher specific energy absorption capacity and lower maximum force were designed.

ABSTRACT: Large steel silos are typical kinds of thin-walled structures that are widely used to store large quantities of granular solids in the industrial and agricultural sectors. In the present analyses, the buckling design of large steel silos subjected to wind pressure is demonstrated in accordance with Eurocode (EN1990, 1991, 1993) and proposed combinational Load Cases WE (wind and empty silo) and WF (wind and full silo). Six steel silos with capacities of 30,000–60,000 m³ with slenderness from 4.77 to 0.35 and thus representing very slender, slender, intermediate slender, squat and retaining silos are examined as examples. The finite element model is established using the commercial general purpose computer package ANSYS. Five types of buckling analyses are conducted on geometrically perfect and imperfect models with and without consideration of material plasticity. These models are designated as LBA, GNA, GMNA, GNIA, and GMNIA in EN 1993 Part 1–6. The concept of critical wind velocity $v_{bc,cr}$ is put forward and defined for the first time in reference to our wind induced buckling analysis, according to which the silo structure obtains the equivalent buckling strength for Load Case WE and WF. The dominant loading conditions of Load Cases WE and WF can be determined by drawing comparisons between the critical wind velocity and designed wind velocity proposed by meteorological conditions. Nonlinear buckling deformations corresponding to the critical point in Load Case WE are governed by circumferential compression generated in the windward region of shells localized at the top of the silo wall. Nonlinear buckling modes of Load Case WF take the form of well-known elephant-foot deformations found at the base of the shell wall, which are induced by meridional compressive stress. Effects of geometrical and material nonlinearities and weld imperfection on the buckling behaviour of steel silos are very complex and are closely correlated with the slenderness of silo structures.

ABSTRACT: In this paper, the enhanced resistance of Steel Hollow Section, SHS, braces, strengthened using Fiber Reinforced Plastics, FRP, was investigated. In this direction, a number of braces with two different slenderness ratios was reinforced with externally over-wrapped CFRP sheets and tested under cyclic loading. It is shown that the adopted strengthening method can preclude the local buckling which yields to improve ductility and energy dissipation capabilities of braces. The proposed technique also minimizes brace strength reduction during the load cycles. Furthermore, in the current work, a numerical simulation was generated in conjunction with damage criteria of materials. The validity of numerical analysis was accurately verified by the experimental results.

ABSTRACT: Stainless steel is now widely used in construction as structural members in recognition to its unique beneficial properties such as corrosion resistance, higher strength, ductility, and negligible maintenance cost. Recent research on stainless steel has led to the evolution of a deformation based design rule, the Continuous Strength Method (CSM), which has been shown to perform well in predicting cross-sectional
resistances but still requires considerable research to be used in predicting member resistances. The current paper proposes a new design method for lateral-torsional buckling (LTB) behaviour of welded stainless steel I-sections combining CSM design philosophy and traditional Perry-type concept used for column buckling. As part of the numerical study presented herein, nonlinear finite element (FE) models were developed and validated using available test results. Once the FE modelling technique was validated, a large number of reliable numerical results were generated to investigate effects of various factors on the resistance of members subjected to LTB. Obtained results showed that the cross-section slenderness and the non-dimensional proof stress $e$ have significant influences on LTB resistance. Effects of $e$ was appropriately incorporated by introducing a correction factor to modify $(math)$. As LTB curves were mostly affected by $(math)$, it was included in the equation for calculating imperfection parameter $\eta_{\text{CSM, LTB}}$, which is a key parameter to include member imperfections in Perry-type design equations. This new approach ensures appropriate utilization of strain hardening for stocky cross-sections and allows to avoid the complex process of calculating effective geometric properties for slender sections. All available test and generated numerical results were used to assess the performance the current European, the Australian and the proposed CSM based design rules for LTB. Comparisons clearly showed that the proposed approach performed significantly well in predicting the LTB response of stainless steel I-sections.


ABSTRACT: This paper presents an experimental investigation on a wide range of aluminium alloy stub, intermediate and slender columns containing multiple circular openings. Three series of compression tests including six different cross-section dimensions of columns with different lengths were conducted by applying uniform axial load to the pin-ended specimens, which were fabricated by extrusion of square and rectangular hollow sections (SHS and RHS) using 6061-T6 and 6063-T5 heat-treated aluminium alloys. In test series I, the specimens were fabricated by welding aluminium alloy plates at both ends of the columns for pin-ended compression tests. In test series II, the specimens were further reinforced by carbon fiber-reinforced polymer (CFRP) at the heat-affected zone resulted from the welding. In test series III, the special aluminium alloy sleeves were designed instead of welding at both ends of the columns to preclude the form of the heat-affected zone. The column strengths, failure modes, load versus axial shortening curves, and strain distributions along the circular openings of test specimens were all obtained from the experimental investigation. In addition, the test strengths of aluminium alloy SHS and RHS columns with or without openings were compared with the design strengths calculated using the design rules given in the current design guidelines. It is shown from the comparison that the first design method proposed by Zhu and Young for aluminium alloy SHS and RHS welded columns is comparatively appropriate for the design of aluminium alloy SHSs and RHSs under axial compression. Whereas, the current design rules for cold-formed steel structural members with openings may be inapplicable to the design of perforated aluminium alloy SHSs and RHSs under axial compression.


ABSTRACT: An efficient multiscale finite element method is developed for large deflection analysis of thin-walled composite structures with complicated microstructure characteristics. The multiscale base functions are reconstructed to consider the coupling effects of thin-walled composite structures by introducing some additional coupling terms among translations and rotations. For the construction of multiscale base functions, two kinds of displacement boundary conditions are proposed for in-plane and out-plane degrees of freedom.
Moreover, two kinds of relaxed decoupled displacement boundary conditions are constructed by adopting the oversampling technique to further improve the accuracy of the method. Then, the equivalent incremental/iterative equilibrium equations for each load step can be constructed and solved directly on the macro scale which will improve the computing efficiency significantly. The microscopic results can be obtained by downscale computation in which the incremental/iterative equilibrium equations on the micro scale are solved under the incremental boundary conditions updated by incremental macroscopic displacements. Several numerical examples demonstrate that the developed method possesses high computing accuracy and efficiency compared with the conventional finite element method.


ABSTRACT: Stainless steel tubular members are employed in a range of load-bearing applications due to their strength, durability and aesthetic appeal. From the limited existing test data on stainless steel circular hollow sections (CHS) columns it has been observed that the current Eurocode 3 provisions can be unconservative in their capacity predictions. A comprehensive experimental programme has therefore been undertaken to provide benchmark data to validate numerical models and underpin the development of revised buckling curves; in total 17 austenitic, 9 duplex and 11 ferritic stainless steel CHS column buckling tests and 10 stub column tests have been carried out. Five different cross-section sizes (covering class 1 to class 4 sections) and a wide range of member slendernesses have been examined. The experiments were initially replicated using finite element (FE) simulations; the validated FE models were then used to generate 450 additional column buckling data points. On the basis of the experimental and numerical results, new design recommendations have been made for cold-formed stainless steel CHS columns and statistically validated according to EN 1990.


ABSTRACT: Thin-walled tubes play a very important role in energy absorbing for car crash. Current studies mainly focus on the design theory and performance improvement by proposing different structures. However, the practical performances might be influenced by manufacturing process, but few studies on this aspect could be found. In this paper, the crashworthiness of several star-shaped tubes, i.e., the hexagonal, octagonal and twelve corners, which were made with different material and fabrication methods, are compared through the experimental analysis. It is found that the energy absorption of octagonal star-shaped tubes is the best and that of the twelve corners star-shaped tubes is the lowest. Under quasi-static compression, the $P_m$ of the octagonal star-shaped tubes increases by 7.94% with respect to the hexagonal star-shaped tubes, while the $P_m$ of star-shaped tubes with twelve corners decreases by 15.75% with respect to the octagonal star-shaped tubes. The star-shaped tubes manufactured by different processing methods have some influence on the deformation mode, but the effect on overall crashworthiness is limited. Finally, the axial mean crushing force of the star-shaped tubes was analyzed theoretically based on the simplified Super Folding Element theory. A theoretical solution for the mean crushing force of the star-shaped tubes was derived, and the theoretical solutions show an excellent agreement with the experimental results.

ABSTRACT: This paper proposes a new type of composite walls, namely concrete-infilled double steel corrugated-plate walls (CDSCWs). The CDSCW consists of a wall element that is formed by two steel corrugated-plates, where they are interconnected through high-strength bolts, and the spacing between the two steel corrugated-plates is filled with concrete. Additionally, two concrete-infilled steel tubes (CFSTs) are assigned as vertical boundary elements at both sides of the wall element. Not only the corrugated configuration of steel sheets themselves would significantly improve the load-bearing efficiency of CDSCWs, but also the interactions and combined actions among steel corrugated-plates, high-strength bolts and concrete could provide much better load-bearing capacity and seismic performance for CDSCWs. In addition, industrial mass production of the CDSCWs can be achieved by adopting integrated cold-formed steel rolling techniques. Therefore, the CDSCWs are much more suitable for applications in high-rise building structures as shear wall structural systems that carry axial loads and bending moments as well as shear loads. This paper mainly investigates the overall instability performance of I-section CDSCWs under uniform compressions and corresponding design formulae are recommended. Firstly, Finite Element (FE) eigenvalue buckling analyses are carried out to investigate the overall elastic buckling behavior of CDSCWs subjected to vertical compressive loads. The formulae for estimating the elastic buckling loads of CDSCWs and corresponding normalized slenderness ratios $\lambda_n$ are obtained based upon the form of Euler's formula. The overall instability performance of CDSCWs under compressions is then studied by FE nonlinear analyses, leading to the overall stability coefficient $\phi$ as well as $\phi-\lambda_n$ curve for their strength design. Moreover, an I-section CDSCW specimen has been designed and tested under uniform compressive load, and its overall instability performance is investigated experimentally. The results obtained from the experiment show an agreement with those obtained from FE numerical analyses, which also verifies the safety and validity of $\phi-\lambda_n$ curves for the strength design of CDSCWs.


ABSTRACT: This study employed experiments and numerical simulations to investigate the impact of pressure hulls’ degree of out-of-roundness on their buckling strength and buckling modes. In addition, post-buckling simulations were conducted to analyze the post-buckling behavior of the said pressure hull. Regarding numerical simulations for analyzing pressure hull buckling, the common analysis method is to first calculate the eigenvalue and the eigenmodes of buckling and then introduce an appropriate number of eigenmodes based on the initial defect of the structure before conducting a nonlinear buckling simulation. In addition to employing this common nonlinear analysis method (in which ABAQUS was used), this study adopted the PD-5500/33 specification to measure the circularity of the pressure hull for experimentation to confirm that the circularity satisfied the PD-5500/33 specification. Finally, this study compared the differences in nonlinear buckling strength between two numerical models and compared the numerical simulation results with the experimental results. This study verified that by employing the analysis method of eigenmode superpositioning, the buckling and post-buckling behavior of an out-of-roundness pressure hull could be more accurately simulated.


ABSTRACT: Buckling of steel jacking pipes subjected to axial compression and surrounded by soil is investigated. The jacking pipes are simplified as simply-supported circular cylinders embedded in tensionless Winkler-Pasternak foundation that reacts to soil compression only. The governing equation for tensionless buckling analysis is established based on the spline finite strip method (SFSM), and the critical buckling load is obtained by solving the governing equation through an iterative procedure. Numerical examples are analyzed,
and the comparison of buckling loads with available solutions and finite element results shows good accuracy of the SFSM. Based on a parametric study, the variation of tensionless buckling loads with slenderness ratio of jacking pipes is first studied. Moreover, the effects of diameter-thickness ratio and foundation stiffness are also investigated. The present SFSM-based tensionless buckling analysis is applicable to cylinders of any length and on tensionless foundation, and it is capable of efficiently and effectively predicting buckling of steel jacking pipes subjected to axial compression and surrounded by soil.

Shuguang Yao, Kaibo Yan, Sisi Lu and Ping Xu, “Prediction and application of energy absorption characteristics of thin-walled circular tubes based on dimensional analysis”, Thin-Walled Structures, Vol. 130, pp 505-519, September 2018, https://doi.org/10.1016/j.tws.2018.06.015

ABSTRACT: In this paper, the energy absorption characteristics of a circular tube are studied using the dimensional analysis method. First, circular tubes composed of different materials, namely, mild steel and aluminium alloy, are used in this study, and the material parameters are obtained from tensile tests. A finite element simulation model of an energy-absorbing circular tube is established and validated through experiments. Second, the Hammersley sampling method was used to design an experiment for the energy-absorbing circular tube under three deformation modes (i.e., concertina mode, mixed mode and diamond mode). Dimensional analysis of the deformation displacement, energy absorption and mean crushing force of the energy-absorbing circular tube under the three deformation modes was carried out. Relationships between the deformation displacement, energy absorption and mean crushing force of the energy-absorbing circular tube and the parameters of the impact mass, impact velocity, etc. are obtained by fitting the results of the dimensional analysis. The fitting accuracy is greater than 0.95. Next, the energy-absorbing circular tube impact experiments were performed, and the experimental results were compared with the fitting results. The error between the predictions and the experimental results is within 10%, so the prediction results are accurate. Finally, the equivalent substitution method between the aluminium alloy and mild steel energy-absorbing circular tube is discussed. The results show that the equivalence of energy absorption is the best equivalent substitution method for the lightweight design of an energy-absorbing circular tube and the length and diameter of the energy-absorbing circular tube should be held constant to obtain the equivalent thickness.


ABSTRACT: Multi-strake cylindrical and conical shells of revolution are complex but commonplace industrial structures which are composed of multiple segments of varying wall thickness. They find application as tanks, silos, circular hollow sections, aerospace structures and wind turbine support towers, amongst others. The modelling of such structures with classical finite elements interpolated using low order polynomial shape functions presents a particular challenge, because many elements must be sacrificed solely in order to accurately represent the regions of local compatibility bending, so-called ‘boundary layers’, near shell boundaries, changes of wall thickness and at other discontinuities. Partitioning schemes must be applied to localise mesh refinement within the boundary layers and avoid excessive model runtimes, a particular concern in incremental nonlinear analyses of large models where matrix systems are handled repeatedly. In a previous paper, the authors introduced a novel axisymmetric cylindrical shell finite element that was enriched with transcendental shape functions to capture the bending boundary layer exactly, permitting significant economies in the element and degrees of freedom count, mesh design and model generation effort. One element is sufficient per wall strake. This paper extends this work to conical geometries, where axisymmetric elements enriched with Bessel functions accurately capture the bending boundary layer for both ‘shallow’ and ‘steep’ conical strakes, which are characterised by interacting and independent boundary layers, respectively. The bending shape functions are
integrated numerically, with several integration schemes investigated for accuracy and efficiency. The potential of the element is illustrated through a stress analysis of a real 22-strake metal wind turbine support tower under self-weight. The work is part of a wider project to design a general three-dimensional ‘boundary layer’ element. References listed at the end of the paper:


ABSTRACT: Steel tube filled with ultra-high performance concrete (UHPCFST) is an innovative and efficient structural form. To promote its application, a comprehensive experimental program was conducted to investigate the structural behavior of UHPCFST columns subjected to axial compression. The key issue is to clarify the differences in mechanical behavior between UHPCFSTs and CFSTs, and to evaluate whether the current design guidelines related to CFSTs are applicable to UHPCFSTs. To address this, the compression characteristics of UHPCFSTs were analyzed, including failure mode, load versus deformation relationship, axial compressive strength and strain development. The test results showed that the steel tube and UHPC worked well together, but the enhancement effect of the steel tube on the core UHPC strength was not as significant as that of ordinary concrete. Moreover, an experimental database of UHPCFSTs including this study was established, and the experimental results were compared with the predictions by various design codes. Based on the regression analysis of the database results, a simplified model for predicting the ultimate strength of UHPCFSTs was developed. It was concluded that the proposed model could accurately predict the axial compressive strength of UHPCFSTs with circular and square cross-sections, and was also applicable to UHPCFSTs with high-strength steel (HSS).


ABSTRACT: In this paper, a double-corrugated-plate shear wall (DCPSW) is proposed. It consists of two trapezoidally corrugated plates connected with high-strength bolts. It could be utilized in high-rise buildings as an alternative of the ordinary corrugated plate shear wall (CPSW) to resist lateral shear loads resulting from horizontal seismic or wind effects. In this paper, the elastic buckling behavior of DCPSWs subjected to pure in-plane shear loads is of major concern and is firstly investigated. The DCPSWs are equivalent into orthotropic plates, and accordingly, the rigidity constants, including flexural rigidity constants in the orthotropic directions ( and ) and the torsional rigidity constant (), are defined and theoretically derived. By comparing the theoretical formulas of the rigidity constants with the results obtained from finite element (FE) eigenvalue buckling analyses, these theoretical formulas are validated to be accurate enough for practical engineering applications. Then, the shear elastic buckling formulas of the DCPSWs are provided by means of FE analyses and numerical fitting technique, and these formulas are validated to be able to conservatively predict the shear elastic buckling loads of DCPSWs with good accuracy. Finally, the shear-resistant behavior of the DCPSWs is investigated via a parametric study of FE models subjected to monotonic shear loads. It is concluded that the normalized aspect ratio could be regarded as a comprehensive design parameter which reflects the ultimate shear resistance of the DCPSW.


ABSTRACT: Studies on buckling of steel tubular truss arches are lacking in contrast to steel arches with solid web sections, although they have been widely applied in long-span structures. This paper deals with the in-plane elasto-plastic buckling and strength design of circular steel tubular truss arches with triangular sections by using finite element analyses (FEA). Firstly, the in-plane buckling failure modes are explored to reveal the buckling mechanics of truss arches. By introducing the normalized slenderness of the entire arch and the chord tube, as well as the interactive coefficient that accounts for the effect of chord tube buckling, the unified buckling curve for truss arches in uniform compression are obtained. Lastly, an interactive equation is proposed for in-plane buckling resistance of steel tubular truss arches under combined compressive and bending actions. It is found that, the buckling of diagonal web tubes greatly reduces the load-carrying capacity and deformation ability of
truss arches hence should be prevented in design. The chord tube deformation always exists during the buckling failure of the truss arch and its effect on the buckling resistance is inevitable. The buckling curve $b$ in the codes can used for truss arches in uniform compression, and the interactive equation can provide satisfactory lower bound predictions for truss arches under general loading.

ABSTRACT: This paper studies static and free vibration of multilayered plates based on isogeometric analysis (IGA) and higher-order shear and normal deformation theory. In which, the plate model with higher-order terms in the displacement fields can capture both shear deformation and thickness stretching effects. Consequently, it passes shear locking and achieves more accurate results in deflection, shear stress distributions, which are satisfied with traction free and interlaminate continuity conditions, and natural frequencies especially for sandwich plates. Utilizing non-uniform rational B-splines (NURBS) basis function fulfills $C^1$-continuity required by the plate model without additional variables.

ABSTRACT: To improve energy absorption performance of thin-walled sections, the present research work investigates energy absorption capability of a type of thin-walled profiles with H-shaped cross-section during quasi-static flattening process and optimizes its geometry, using the Taguchi method; and also derives some theoretical formulas to predict total absorbed energy by the H-shaped section. Two theoretical analyses are performed based on two different material models consist of Power hardening and Rigid-Linear work hardening. In each theoretical analysis, general formulations are derived to estimate absorbed energy by a plastic hinge line and an unbending process. In the optimization trend, design of experiment (DoE) is carried out by the Taguchi method. Due to experimental limitations in providing the various samples with different geometrical dimensions, ABAQUS/Explicit software is used. As control factors, influences of geometrical parameters and lateral loading angle are studies on specific energy absorption (SEA); and design of optimum geometry of the H-shaped profile is discussed. Contribution percentage of each control factor is determined on the SEA of the profile, which provides important reference for designing the H-shaped profile in practical energy absorption applications. Results show that wall thickness of the profile cross-section has the highest effect on the SEA of the H-shaped section with contribution ratio of 47.02%. Furthermore, loading angle has the smallest influence on the specific energy absorption capacity. Finally, optimum geometry of the profile is introduced. Also, comparison of the obtained results by theoretical predictions and numerical simulations illustrates precision and acceptable accuracy of the derived theories.

ABSTRACT: The present study investigates the lateral-torsional buckling of wide flange steel members strengthened by a Glass Fiber Reinforced Polymer (GFRP) plate bonded to one of the flanges through an adhesive layer. A variational formulation and two finite elements are developed for the problem. The formulation captures global and local warping effects, shear deformation due to bending and twist, and partial interaction between the steel and GFRP provided by the flexible layer of adhesive. The destabilizing effects due to strong axis bending, axial force and load height effect are incorporated into the formulation. The first element
involves two nodes and 16 buckling degrees of freedom (DOFs) while the second element involves three nodes and 14 DOFs. Comparisons of present model results against those based on 3D finite element analysis based on solid elements demonstrate the ability of the present models to accurately predict the buckling loads and mode shapes at a fraction of the modelling and computational efforts. Practical examples quantify the gain in elastic buckling strength achieved by GFRP strengthening, and characterize the moment gradient factors and load height effects. Elastic buckling interaction diagrams are developed for beam-columns and comparisons are provided to interaction diagrams of un-strengthened beams.


ABSTRACT: Thin-walled single and multi-cell structures are an ongoing topic of interest in the field of crashworthiness, due to their wide range of applications in automotive and aerospace industry as lightweight energy-absorbing structures in crash environments. This work presents a new five-cell cross-section that merges high performance multi-cell and twelve-edge cross-sections from previous research, and compares its performance to four- and nine-cell square cross-sections. Super Folding Element (SFE) theory and Finite Element Analysis (FEA) in LS-DYNA are used to analyze cross-sections and found to have good agreement. The LS-DYNA environment is validated with physical testing. The geometry of the cross-sections is varied in order to find maximal values of the performance parameters specific energy absorption (SEA) and crush force efficiency (CFE) under stable progressive buckling mode and constraints for manufacturability. The nine- and five-cell cross-sections ultimately out-perform the four-cell cross-section, with the nine-cell having the highest SEA and CFE, though the five-cell design has a significantly lower (47%) mean crush force (Pm) for only an 11% and 14% loss in SEA and CFE respectively. As a final refinement, the geometry was varied across these two high-performing cross-sections to create equivalent mean crush forces to the four-cell cross-section, which showed the five-cell cross-section to have an improved SEA and better mass efficiency over the nine-cell under a mean crush force constraint.


ABSTRACT: The effect of hygrothermal conditions such as temperature and moisture on free vibration frequency and buckling load of composite laminated plates was investigated in present article. For this purpose, the effect of changing in material characteristics with changing in temperature and moisture on buckling capacity and natural frequency of plates with different end conditions and biaxial loading was evaluated. In addition, the effect of delamination of layers on buckling load and natural frequency of plate was studied in different situations. The finite strip method was used in present paper to calculate the critical load of plate considering first-order shear deformation theory. In finite strip formulation for evaluating the displacement field of each strip, the trigonometric shape functions were used in longitudinal direction and the Hermitian and linear shape functions were used for out–of–plane and in–plane transverse direction, respectively. The place and dimension of delaminating layers was modelled by separating the adjacent elements and reconstructing the standard, geometric, force and mass matrices, so, the critical load and natural frequency of laminated plates was calculated in different configurations.

ABSTRACT: This paper describes an experimental study to estimate the stub columns capacity of cold–formed square (SHS) and rectangular hollow sections (RHS) containing two opposite central circular perforations at column mid–height. The stub columns were extracted from commercially available Tata Structura–YSt 310 tubular sections, with minimum yield strength of 310 MPa, conforming to Indian Standard 4923. The influence of two opposite central circular perforations on the structural performance of tubular steel stub columns under concentric loading was investigated for perforation size to flat width ratios up to 0.9. The local geometric imperfections, load–end shortening curves, strain distributions at mid height of column and typical failure modes observed from the present test programme are documented in this paper. Further, the ultimate column capacities recorded from the test programme are compared with codified design predictions as well as design equations proposed by various researchers. Based on the comparison, it is observed that the predictions made by most of the currently available design equations are conservative and reliable but generally scattered for design of cold–formed tubular structural steel stub columns having central circular perforations.


ABSTRACT: The local indentation of thin-walled beams is a key mechanism for the collapse of beams under lateral loads. The indentation behavior of multi-cell tubes is investigated in this work. Quasi-static experimental tests are conducted first for multi-cell tubes with three different sections. The deformed shapes and force responses are obtained by indenting the tubes resting on a rigid surface. Numerical simulations are then performed to analyze the static and dynamic responses of the tubes, and the accuracy of the numerical model is validated by the experimental results. The crushing force responses and deformation characteristics of the multi-cell sections are analyzed in detail and the energy absorption performances of them are evaluated. Results reveal that the cross-sectional shapes of the tubes have great influence on their deformation process and crushing force responses. Moreover, to further increase the energy absorption efficiency, sequential response surface method (SRSM) is employed to achieve the optimal designs of the multi-cell sections. Results show that the energy absorption performances of the sections are greatly improved by the SRSM optimization.


ABSTRACT: Concrete filled steel tubular (CFST) columns used in multi-storey buildings are generally designed as continuous members. The fire behaviour is predicted based on the results of experimental standard fire testing of CFST members where the same temperature is applied to the column over the full column height. Over the past 36 years, 238 experimental tests have been reported in the literature on CFST columns; different types of concrete infill have been considered: plain, steel fibre and bar reinforced concrete. In these tests, the columns were loaded axially under either concentric or eccentric load, and subjected to the standard ISO 834 fire or its equivalent in a furnace. This paper has focused on the in-depth analysis of behaviour of a continuous CFST columns in fire and provided a simple design procedure to calculate the axial capacity of the CFST columns at elevated temperature. The examples given in the later section gives a step by step design procedure for practicing engineers to calculate the axial capacity of both concentrically and eccentrically loaded CFST columns in fire.

Jia-Hui Zhang and Ben Young, “Finite element analysis and design of cold-formed steel built-up closed section columns with web stiffeners”, Thin-Walled Structures, Vol. 131, pp 223-237, October 2018, https://doi.org/10.1016/j.tws.2018.06.008
ABSTRACT: This paper presents a numerical investigation and design of cold-formed steel built-up closed section columns with web stiffeners. A finite element model (FEM), considering the initial geometric imperfections and nonlinear material properties, was developed to simulate the structural behaviour of fixed-ended built-up closed section compression members. The comparison between the numerical results and the available test results show that this FEM can provide good predictions for both the ultimate strength and the failure modes of the test specimens. The verified FEM was used to conduct an extensive parametric study for the investigation on the structural behaviour of cold-formed steel built-up closed sections with web stiffeners. The parametric study was designed to investigate the effect of web stiffeners as well as to evaluate the current design method. The column strengths obtained from the finite element analysis and the test results were compared with the design strengths calculated using the direct strength method in the North American Specification and the Australian/New Zealand Standard for cold-formed steel structures. Design curves modified from the current direct strength method are proposed for flexural, local and distortional buckling. The reliability analysis was used to assess the current design rules and the modified design curves. It is shown that the modified direct strength method is generally conservative and reliable for the design of cold-formed steel built-up closed section compression members.


ABSTRACT: Carbon fibre reinforced polymer (CFRP) has become popular and used in various engineering applications. Strengthening of hollow steel sections using CFRP has proven improved structural characteristics under static loading conditions. However, there are very few studies available related to the axial dynamic impact behaviour of CFRP strengthened steel hollow sections. This paper evaluates the behaviour of CFRP wrapped hollow square steel tube sections under axial impact loading through validated numerical models. A comprehensive parametric study has been conducted to evaluate the effects of impact mass, impact velocity, adhesive strength and fibre modulus on the impact performance of these tubes. Crash behaviour is studied by comparing the peak impact force, axial deflection, absorbed internal energy and failure modes between CFRP wrapped and bare steel models. The results show that the variations in impact velocity and fibre modulus can have significant effect on the impact response of CFRP wrapped tubes.


ABSTRACT: To explore an energy-absorbing device satisfying the crashworthy requirements of railway vehicles, a new type energy-absorbing structure (EAS) was developed according to the energy-absorbing mechanism of a thin-walled metal plate subjected to plastic upheaval deformation. Quasi-static tests were performed on rectangular and U-shaped thin-walled plates to validate the feasibility of the proposed EAS. Additionally, the numerical simulation test was conducted to investigate the influences of the spacing between pressure plates, punching parameters and the thickness of thin-walled plates on the energy-absorbing properties of the proposed structure. The results showed that the structure had favourable repeatability in compression and the deformation of thin-walled plates was shown to be regular and controllable. In the whole compression stage, the force effects exceeded 70% with no peak being found. In the first stage, the force rapidly increased with the growth of height of the upheavals on the thin-walled plates; in the second stage, the force slowly rose when the increase in the height of the upheavals was ceased in which the mean forces in two groups of tests were both about 12 kN. The energy-dissipation forms of the structure appeared as two types: energy dissipation induced by
plastic deformation of thin-walled plates and that caused by friction between the thin-walled plates and the punch. Increasing the height of the punch and the thickness of the plates cannot significantly improve the energy absorption of the structures. Additionally, decreasing the spacing between pressure plates and enlarging the width of the punch also can increase the amount of energy absorbed. After decreasing the inclination angle of the punch, there was a lag in the change of force.


ABSTRACT: Welded hollow spherical joints (WHSJs) are widely used in space lattice structures. Corrosion is inevitable for WHSJs during service, and this phenomenon will significantly reduce loading capacity and seriously threaten the structural safety. Pit corrosion is a typical corrosion type for steel structures. In this study, nonlinear numerical analyses were conducted to investigate the influence of several parameters on the bending capacity of a WHSJ. A numerical model of the WHSJ with random pit corrosion was proposed to investigate the mechanical behavior of the corroded WHSJ. Results indicated that the moment capacity of the WHSJ with random corrosion pits was normally distributed. A probabilistic distribution model of the corroded WHSJ was proposed. The failure probability could be deduced based on the formulae of the upper and lower bounds of the moment capacity.


ABSTRACT: The influence of the Poisson's ratio of the foam on the energy absorption of the foam-filled tube is investigated in this paper. Firstly, the relationship between the mechanical properties and the structural parameters of the 3D lattice structure is calculated by using the theory of material mechanics. The finite element analysis software ABAQUS is used to simulate the axial dynamic response of cylindrical tubes filled with conventional and negative Poisson's ratio foams. Based on this, the interaction between the tube wall and foam is analyzed in detail. Combining the structural properties of both the positive and negative Poisson's ratio foams, a new foam model with mixed Poisson's ratio (MPR) is proposed, and the crashworthiness of three different types of tubes, namely the sandwich double tubes filled with positive, negative and mixed Poisson's ratio foams, is analyzed. The results show that the interaction between the foam and the tube wall has a significant effect on the energy absorption performance. The sandwich double tube filled with MPR foam has better specific energy absorption (SEA) and stronger interaction than those filled with pure positive or negative Poisson's ratio foam. This study provides a new insight into crashworthiness design of foam-filled structures.


ABSTRACT: There is an increasing trend in using aluminum foam-filled columns in crash management systems due to their light weight in automotive industry. The main goal of this study is to optimize the crashworthiness of aluminum foam-filled thin-walled multi-tubular circular columns under quasi-static loading. The existing studies in the literature considered only lateral foam filling (the foam lateral dimension is variable and the foam height is equal to the column height). In the present study, we considered both lateral and axial foam filling and compared the performances of these two options. In optimization, the column thicknesses, taper angle, foam density, and foam height/diameter are considered as design variables. The quasi-static responses of the columns are determined through explicit dynamic Finite Element Analysis (FEA) using LS-
DYNA software, and validated with quasi-static tests conducted in our facilities. Response surface based crashworthiness optimization of the columns for maximum Crush Force Efficiency (CFE) and maximum Specific Energy Absorption (SEA) is performed. It is found that lateral foam filling is superior to axial foam filling in terms of both CFE and SEA maximization. The maximum CFE obtained through lateral foam filling is 19% larger than the maximum CFE obtained through axial foam filling. Similarly, the maximum SEA obtained through lateral foam filling is 6% larger than the maximum SEA obtained through axial foam filling. For both CFE and SEA maximization, the columns should be tri-tubular type and have a large thickness and a taper angle. To attain the maximum CFE, foam should be designed with large density and medium foam diameter. However, foam plays an adverse role in maximization of SEA because of its weight. The increase in energy absorption obtained by using foam does not compensate the additional weight introduced by the foam.


ABSTRACT: A Pseudo Curved Beam (PCB) model is proposed to analyze the buckling behaviors of inflated arch. The wrinkling (local buckling) effect is considered in the PCB model by modifying the cross-sectional area and sectional moment of inertia in the stiffness matrix. The wrinkling angle, wrinkling and failure load are then predicted based on the proposed PCB model. The bending experiment and numerical simulation of a quarter-circle inflated arch are performed to verify the validation of the PCB model. The effects of load conditions, constraint conditions, structural geometric parameters, inflation pressure and material properties on the buckling characteristics of inflated arch are parametrically studied in the end. The method and results provide good references for the load-carrying design of inflated structures.


ABSTRACT: The main objective of this research is to investigate the damage progression and the failure mechanism of Glass-Fiber Reinforced-Plastic (GFRP) pipes subjected to compressive transverse loading. An experimental study is performed to observe the level of diametric deflection where failure takes place under transverse loading and also to monitor experienced failure mode. Then, conducted experimental study is simulated in commercial finite element software taking into account both interlaminar and intralaminar failure modes, simultaneously. The degree to which the pipe can withstand diametric deflection without experiencing any failure mode is extracted. Then, appropriate in-plane failure criteria are chosen for identifying the onset of in-plane failure mode while cohesive approach is employed for identifying the initiation of delamination as the out-of-plane failure mode. Results of numerical simulation reveal that the liner is debonded from its adjacent hoop layer at 27% diametric deflection which is in a reasonable agreement with experimentally observed 31%. Moreover, the magnitude of the reaction force at 5% diametric deflection is obtained as 1242 N which is in a good agreement with experimentally measured 1225 N. Therefore, a satisfactory level of accuracy is achieved in constructed model implying on the appropriate modeling of damage progression. Finally, a parametric study is conducted to investigate the influence of various effective parameters on the pipe resistance level against transverse loading wherein neither in-plane nor out-of-plane failure is experienced.

ABSTRACT: In order to comprehensively understand the dynamic response of auxetic honeycombs, theoretical analysis are conducted to predict the NPR effect and the crushing stress of the re-entrant hexagonal honeycomb. The honeycomb’s crushing stress is a function of the cell’s geometric parameters, crushing velocity and the mechanical property of the cell-wall material. Results show that the crushing stress enhances with the increasing crushing velocity. A dynamic sensitivity index is employed to quantitatively evaluate this enhancement. It is shown that small cell-wall angle, low relative density or high cell-wall length ratio of the honeycomb attribute high velocity-sensitivity to the crushing stress. The Poisson’s ratio of the re-entrant honeycomb is also expressed as a function of the cell’s geometric parameters. It is revealed that the NPR effect enhances with the increasing cell-wall angle and the decreasing cell-wall length ratio. All the theoretical predictions are verified by numerical simulations. Besides, an interesting phenomenon is noticed that the crushing velocity has significant influence on the honeycomb’s NPR effect at the early stage of crushing. However, this influence almost vanishes when the overall strain is larger than about 0.2. This present work is supposed to shed light on the design of the auxetic honeycomb.


ABSTRACT: In this study, the thermal buckling behavior of plain woven C/SiC composite plate is investigated by a noncontact measurement based on the three-dimensional digital image correlation (DIC) technique and finite element analysis. The plain woven C/SiC composite plate is fixed by a water-cooling steel frame and one-side heated by quartz lamp array heating apparatus. The buckling temperature and the first buckling mode shape of the C/SiC composite plate are determined from the temperature-displacement curves and full-field deformation that are obtained from the DIC-based experiment. A nonlinear finite element buckling analysis with initial imperfection is performed using the ANSYS software. In order to improve the accuracy of the numerical simulation, a clamping frame model is further proposed for simulating the real clamping boundary in experiment. The results of the finite element simulation and DIC-based measurement coincide well regarding the temperature-displacement curve tendency and critical buckling temperature. Finally, a parametric study is performed using the presented numerical model to investigate the thermal buckling behavior of plain woven C/SiC composite plates with various dimension sizes.


ABSTRACT: Experimental investigation on deflection behaviour of fly ash cenosphere/epoxy syntactic foam at room temperature and under thermal environment (three different heating conditions) is investigated. Influence of fly ash cenosphere volume fraction and nature of temperature variation on deflection behaviour of syntactic foam beam is discussed elaborately. Results reveal that the syntactic foam beam experience snap-through buckling under thermal environment and is reflected by two bifurcation points in temperature-deflection plot. It is observed that the time duration for which the foam beam stays in the first buckled position increases with increase in cenosphere content. Thermal environment induces compressive stresses in the samples causing such snap-through buckling. However, such phenomenon is not observed when mechanical compressive loads are applied under room temperature conditions. Temperature variation across the beam strongly influences snap-through buckling in syntactic foams in addition to volume fraction of filler content.

ABSTRACT: A comprehensive numerical investigation of cold-formed stainless steel cross-sections subjected to combined compression and bending is presented in this paper. A non-linear finite element model (FEM) including geometric and material non-linearities was developed using the finite element package ABAQUS. Upon validation of the FEM, the model was then used for an extensive parametric study to investigate the interaction effects of constituent plate elements of cold-formed stainless steel square and rectangular hollow section beam-columns. The investigation indicates that the interaction effects of constituent plate elements on cross-section response are obvious particularly for slender sections. Current design provisions on Class 3 and Class 2 slenderness limits and effective width equations specified in American Specification, EC3 code and proposed by Gardner are not suitable for square and rectangular stainless steel hollow section beam-columns since the interaction effects of constituent plate elements are ignored. The new Class 3 and Class 2 slenderness limits and the section capacity design equations based on the whole cross-section response enable more accurate prediction of local buckling, thus allowing better utilization of material and more economic design.


ABSTRACT: Offshore steel tubular structures may be subjected to damage perforations by long-term operation in a corrosive environment, which reduces their structural strength. There is a lack of standards and procedures to quantify the loss of structural capacity in view of the damage dimension and geometrical and material characteristics of the tubular member. The present paper proposes the use of symbolic regression for assessing the remaining capacity of perforated steel tubular members from aged offshore units subjected to axial compressive forces. A Finite Element Analysis campaign was generated in combination with a full factorial design of experiments. Length-to-diameter, diameter-to-thickness and damage extension ratios have been addressed as potential preponderant factors for the experimental design. Results from numerical simulations were statistically evaluated and then symbolic regression was handled to generate an optimized expression by minimizing the worst error case between predicted and numerical results. Capacity responses from the generated expression lie close to the Finite Element Analysis and experimental results, suggesting that the proposed methodology can be alternatively employed to assess the remaining capacity of perforated steel tubular members subjected to axial compressive loads.


ABSTRACT: Quasi-static axial compression tests were undertaken using a hydraulic testing machine to study the collapse mode and energy absorption capacity of magnesium alloy AZ31B circular tubes. The effects of the tube wall thickness, length, inner diameter and fillings of aluminium foam and honeycomb were investigated. The results showed that the AZ31B tubes tended to fracture rather than deform. Besides the deformation modes of Euler buckling, concertina mode, diamond mode, mixed concertina and diamond mode and the consequent fracture, large segment fracture, sharding and axial splitting were all observed in the tests. These collapse modes of the tubes depended on their material properties and the geometry of the cross-section. The global buckling fracture showed a poor energy absorption capacity. The sharding mode of thicker tubes and the axial splitting mode of thinner tubes outperformed the other collapse modes on the energy absorbing characteristic.
The fillings of the aluminium foam and honeycomb could improve the collapse modes and energy absorption capabilities significantly.

ABSTRACT: Cold-stretching is an important lightweight technology for reducing cost of cryogenic vessels, which are widely used for storing liquefied gas. This paper studied the influence of cold-stretching on the buckling behavior of cylindrical vessels with different initial out-of-roundness under external pressure. Buckling pressures, strains, and buckling modes of cylindrical vessels were obtained from experiments. A 3D laser scanner was used to obtain the complicated geometry of the vessels before and after cold-stretching. Based on the 3D scanned geometry, we performed FEA to evaluate the buckling pressures, which resulted in a good agreement with the experimental values. The effects of cold-stretching on buckling are discussed based on four factors: out-of-roundness, thickness, diameter and yield strength. Firstly, buckling of cylindrical vessels is elastic buckling in our case, so yield strength has no influence on buckling pressure. Secondly, the negative effect of diameter-thickness ratio increasing was proved to be slight (within 3.3%) in our case. Finally, buckling pressure increased after cold-stretching because out-of-roundness decreased. Experiments showed that buckling pressures were enhanced by 10.8% and 13.6% after cold-stretching for long and short cylindrical vessels with 1.9% and 1.6% in out-of-roundness.

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ABSTRACT: In the context of Gurtin-Murdoch (GM) surface elasticity theory, a size-dependent third-order shear deformable plate model is developed herein in order to study the nonlinear forced vibration behavior of rectangular nanoplates with considering surface stress effect. Nanoplates are assumed to be made of functionally graded materials (FGMs) whose properties are graded in the thickness direction based on a power-law distribution. First, the constitutive relations of GM model are matricized. Then, Hamilton’s principle is used to derive the governing equations. The variational differential quadrature, a numerical Galerkin, time periodic discretization, and pseudo arc-length methods are also employed for numerical solution of the geometrically nonlinear forced vibration problem. The frequency-response curves of rectangular nanoplates with different boundary conditions are investigated for different values of thickness, power-law index, surface constants and side length-to-thickness ratio. The results reveal that the surface stress has an important influence on the frequency-response curve of nanoplates at very small scales.

ABSTRACT: A thin-walled structure inspired from a biologic creature known as balanus was investigated experimentally and numerically under quasi-static and dynamic loads for load-carrying and energy absorption properties. The structure was composed of an inner conical core with a hemispherical cap and an outer shell in frusto-conical shape and formed by deep drawing. The applied deep drawing process was modelled using nonlinear finite element code LS-DYNA to determine the residual stress/strain and the non-linear thickness distribution after the forming process. It was also shown that the load carried by the balanus structure was greater than the arithmetic sum of the load carried by the inner core and by the outer shell separately. Although the mean force increase due to interaction effect at quasi-static strain rate was approximately 5%, while it increased to roughly 26% at dynamic strain rates in drop weight experiments. The numerical models also showed that the outer shell absorbed more energy than the inner core while the difference between the energy absorbing performance of the core and shell decreased with increasing deformation rate. The effect of strain rate and inertia on the increase in crush load increased with increasing impact velocity, while the strain rate effect had greater influence than the inertia on the crush load. The increased load carrying capacity of the balanus at quasi-static and dynamic strain rates was ascribed to the interaction between the core and shell and the confinement effect of the outer shell particularly at dynamic strain rate.

ABSTRACT: The ultimate buckling strength of axially loaded cold-formed lipped channel columns is studied. Variations of boundary conditions and eccentricities of the applied load are considered. The strength is
calculated by a geometrically and materially nonlinear FEM analysis. Numerical study is carried out for two columns previously analysed under fixed boundary conditions and centroidal load. Geometrical imperfections in the shapes of eigenmodes of the corresponding linearized buckling problem are assumed. For comparing the imperfections their sizes are set to a uniform level of an energy measure. Particularly the worst eigenmode imperfection is determined for each studied design case. By the corresponding lowest collapse loads the effects of varying boundary conditions and load eccentricities on the ultimate buckling strength of the columns are shown.

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ABSTRACT: Fire incidents at fuel storage tank farms are high risk incidents due to the fact that can result in severe socio-economic losses, injuries, deaths and have a serious environmental impact. In the case of a tank fire, there is a serious possibility that the fire will spread to adjacent tanks. The research activity in this area is mainly focused on the prediction of the heat transfer characteristics of pool fires, the thermal response of neighbouring tanks (or target tanks) and the potential of fire spreading. On the contrary, the research for the structural integrity of tanks involved in pool fire scenarios is limited. This paper aims to study the thermal buckling behaviour of fixed-roof tanks in the case of pool fire scenarios, considering one or more burning tanks. To this end, different scenarios are examined, aiming to study the key factors (the burning fuel, the wind, the separation distance between tanks and the size of the burning tanks) that may affect the thermal buckling response of the target tanks. Semi-empirical models, available in the literature, are used for the calculation of the characteristics of flames that arise from burning tanks. Then, the problem is solved numerically, through the Finite Element Method. The heat transfer from the burning tanks to the target tank is treated through the open cavity option, and the response of the target tank is predicted in the same thermo-mechanical analysis. The basic objective is the investigation of the inherent fire resistance of thin-walled tanks and to predict their failure.

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ABSTRACT: The dynamic responses of the liquid-filled hemispherical shell structures under axial impact loading were studied through impact experiments and numerical simulations. At first, the deformation mode and impact forces were obtained by the experimental research. The ironing areas and fluted areas were observed on the edge zone of the liquid-filled single-layer shell. Next the dynamic behaviors of liquid-filled sandwich shell under axial impact loading were investigated numerically. The simulation results were found to match well with those obtained from experiments. It was found that since the filled liquid transfers and disperses the impact load, the stress of shells and the water pressure is going to be distributed uniformly as the impact processes and due to the low compressibility, the filled liquid absorbs small energy. Then effect of liquid radial thickness, wall thickness and impact velocity on dynamic responses of the liquid-filled sandwich shell was discussed.

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ABSTRACT: Relevance of finite strain shell piezoelectric analysis is significant due to the general use of polyvinylidene fluoride (PVDF). A finite-strain geometrically exact shell model for the analysis of piezoelectric laminated structures is introduced. An assumed-strain formulation is employed, with least-squares fitting of contravariant linear stress fields. This allows the condensation of internal degrees-of-freedom corresponding to
the assumed strains. The resulting piezoelectric shell has 8 degrees-of-freedom in each node, with 3 position/displacement degrees-of-freedom, 3 rotation parameters and the upper and lower electrostatic potential at the nodes. This contrasts with available formulations where only one electric degree-of-freedom is considered. A total of 32 degrees-of-freedom in each 4-node element are used. In term of implementation, we use a generalized strain and generalized stress formulation to reproduce the conventional finite element organization. Six examples are presented, with transversely isotropic and orthotropic cases, including finite strains and asymmetric plies. Results show a remarkably good agreement with the sources and we achieve higher values of actuation.


ABSTRACT: In the present study, the crushing mechanism of two types of thin walled structure, holed tube and grooved tube, were analyzed by analytical, numerical and experiments. Plastic deformation was occurring on thin walled tubes by introducing grooves and holes predetermined intervals along the tube. For this purpose, crushing performance of grooved model and holed model were analyzed through finite element simulation and then verified with experiment. Firstly, the comparison of crushing performance, load-displacement curve, energy absorption, mean crushing load and Mass specific energy (SEA) was performed for grooved and holed thin walled tube of mild steel analytically, numerically and experimentally. Secondly, crushing mechanics of holed tube with grooved tube were investigated. At last, the load-displacement curve of holed steel tube and grooved steel were investigated and then the load displacement curve of holed thin walled tube which were made by mild steel and aluminum were investigated. The results indicate that the holed thin walled tube which was made from aluminum has the maximum crushing performance, SEE and energy absorption.


ABSTRACT: This paper investigates the dynamic buckling behavior of steel silos subjected to horizontal base excitations. The elastic-plastic buckling resistance of three silos with different aspect ratios is estimated using Incremental Dynamic Analyses (IDA). Accordingly, the critical base shear, base moment and the peak ground acceleration (PGA) at the buckling instant are calculated. Moreover, the additional normal pressures induced from bulk solids on silo walls are evaluated and compared with those of Eurocode 8. The results obtained suggest that slender silos are more vulnerable to buckling failure, while squatter silos represent a considerably higher resistance under same seismic conditions.


ABSTRACT: X-Frame core sandwich structures are fabricated with carbon fiber reinforced polymer (CFRP) face sheets and aluminum alloy cores. The hybrid combination enables composite face sheets to maximize specific flexural stiffness and X-Frame metal core to improve the impact resistance. The effects of impact energy, impact site and face sheet material type on the impact response and resulting damage state have are investigated experimentally and numerically. The low-velocity impact tests are carried out to study the impact response in terms of the impact load, absorbed energy and failure modes. Meanwhile, finite element analysis is implemented to simulate the impact behaviors and failure mechanisms by the VUMAT subroutine in ABAQUS/Explicit, using a progressive damage model based on the Hashin and Yeh delamination failure
For comparison, all-metallic sandwich structures are also studied to better understand the influence of face sheet materials. These studies reveal that impact response and resulting damage state are strongly dependent on the impact energy and impact site. Composite sandwich structure absorbs more impact energy than aluminum sandwich structure for the perforation case, indicating that the former has better impact resistance. The predicted results of the low-velocity impact response are fairly consistent with the experimental measurements, which suggests that the numerical procedure could be a helpful tool in developing novel lightweight multifunctional structures.


ABSTRACT: In this paper the nonlinear finite element approach is used to solve the problems of first ply failure of laminated composite skewed hypar thin shell roofs. The geometrically nonlinear strains terms are incorporated in the present finite element code which is validated through solution of the problems solved and published by earlier researchers. The first ply failure loads of the industrially popular, aesthetically appealing hypar shells are studied meticulously for varying aspect ratios and thicknesses for clamped boundary condition. The paper gives specific recommendations regarding choice of linear and nonlinear approaches for obtaining failure loads in different specific cases.


ABSTRACT: The paper is devoted to diminishing of the edge effect in three nonstandard dished heads of a cylindrical pressure vessel subjected to internal uniform pressure. The problem of the edge effect diminishing in the joint of the dished head with the cylindrical shell is analytically and numerically studied. The meridians of the analysed dished heads as the shells of revolution are plane curves in the Cassini oval, Booth lemniscate and clothoid forms. Geometrical relationships of the middle surfaces of the dished heads are formulated. The stress state of these dished heads are analytically and numerically studied using finite element method in Ansys system. The results of the studies are compared and presented in Tables and Figures.


ABSTRACT: Gridshells are form-resistant structures, which are suitable for covering large spans, especially when lightness and transparency are respectively relevant architectural and functional requirements. The majority of built gridshells are characterised by one or more free-edges, which derive from trimming the gridshell reference surface in order to provide building access or to integrate the gridshell within existing structures. Up to now, only few scientific systematic studies have been devoted to the effects of elastic boundary structures on the stability of gridshells. This study aims at filling some gaps about this issue. To do so, an ideal free-edge bending-inactive hybrid single-layer gridshell is analysed. The gridshell sensitivity to the flexural stiffness of the boundary arch and to the shear stiffness of the gridshell are investigated through an extensive parametric analysis, which was performed by means of numerical experiments. Results are first discussed in terms of the well-established load factor and buckling shape. Then a complementary mechanical reading is provided by introducing ad-hoc conceived local metrics of the in-plane and out-of-plane deformations at collapse. Three different mechanical regimes at collapse are outlined. In conclusion, a range-finding chart
within the design parameter space is proposed to orient the structural analyst in the choice of the preferred regime.

ABSTRACT: In this study, a nanostructure model is used to predict the stress-strain curves of the aluminium alloys AA6063, AA6061 and AA6110 in T6, T7 and O tempers based on the chemical composition and the thermo-mechanical history. The predicted stress-strain curves are then employed in finite element analyses of rectangular hollow section (RHS) profiles of the same materials subjected to axial quasi-static crushing. Thus, the simulations are performed without any calibration of the plasticity model based on material tests. In addition, simulations with the material model calibrated from tensile tests on the same materials are performed for comparison. An experimental programme of the RHS profiles is conducted for validation purposes and compared to the numerical results in terms of the force-displacement curves and the peak and mean forces. To put emphasis on the performance of the nanostructure model, a refined solid element model is used to capture accurately the deformed geometry during axial crushing. A separate study is conducted to investigate the effect of friction on the simulated behaviour of the profiles. The numerical and experimental force-displacement curves display good agreement with deviations in the mean absolute percentage error (MAPE) of the peak and mean force less than 10% and 8%, respectively. By visual inspection of the deformed profiles, excellent agreement is found between the numerical simulations and the experimental tests. The results suggest that the nanostructure model can be used with confidence in design of energy absorbing structural components made of 6xxx aluminium alloys.

ABSTRACT: This paper presents an evaluation method of residual stresses in large welded thin-walled structures based on eigenstrain analysis and small sample residual stress measurement. In this method, small samples containing weld and heat-affected zones are firstly cut from large thin-walled structures, then residual stress in the small samples are measured to determine the welding-induced eigenstrains using a finite element-aided inverse solution. Finally, residual stress in large thin-walled structures are evaluated based on the obtained eigenstrain distribution. The feasibility of the proposed method was validated by evaluating residual stresses in welded plates with different lengths or widths. The method was then applied to evaluating residual stress in a welded skin-stiffener panel. Good agreement between the evaluated residual stress and measurement by diffraction technique has demonstrated the practicability of the method.

ABSTRACT: A finite element model for static response and free vibration analysis of delaminated composite laminates with active layers is developed based on a coupled layerwise laminate theory. The proposed model assumes full layerwise variations for both mechanical displacements and the electric field, and more importantly, both strong and weak discontinuous functions are introduced into the displacement fields to model the displacement discontinuity induced by the delamination and strain discontinuity induced by the interface between the layers, respectively. This refined layerwise mechanics can give a more accurate description of displacement discontinuity. The formulation naturally includes the coupling and interactions between the
composite laminates and piezoelectric layers. Various examples are investigated by the developed model and the results are compared with previously obtained alternative solutions or experimental results to verify the justification and accuracy of the present formulation. Finally, the effect of delamination on static response and vibration mode are studied in detail to provide beneficial information for the promising damage identification techniques.


ABSTRACT: In this study, thin-walled sandwich composites made of glass fiber-reinforced polymer (GFRP) facesheets and a three-dimensional (3D) woven fabric core were studied. A total of 30 small-scale sandwich beam specimens were manufactured across six unique beam varieties with dimensions of 50 mm in width, and 200 or 350 mm in length to be tested under four-point bending up to failure. The load-deflection behavior, load-strain behavior, moment-curvature behavior, and neutral axis location were analyzed. Based on the test results, the flexural stiffness, shear stiffness, core shear modulus of the sandwich beams were calculated. Also, an analytical model is presented to consider the effect of core shear modulus on deformation and composite action of the test specimens. The model is capable to quantify the degree of composite action based on the geometry and material properties of sandwich beams. Overall, the sandwich beams displayed a partial-composite behavior raging from 15% to 91% of full-composite behavior, which was a function of the relative stiffness of the facesheets and the core plus the length of the shear span. It was shown that compatibility between the mechanical properties of the facesheet and core is a key factor in optimizing sandwich panels made of the core. The results will be used for the design of thin-walled sandwich liners for the rehabilitation of underground infrastructure including existing highway culverts and large diameter drainage systems.


ABSTRACT: Steel corrugated shear wall (SCSW) is an alternative to traditional shear walls with flat plates. However, shear resistance behavior and design of the infilled corrugated panels in SCSWs has not been well studies. This paper focuses on the shear resistance of sinusoidally corrugated panels in SCSWs under monotonic lateral shear force, via finite element analyses (FEA) considering both geometric nonlinearity and material elasto-plasticity. Firstly the effects of initial imperfections and geometric dimensions on shear resistance of corrugated panels are explored. Then based on extensive FEA, the maximum and the post-buckling strengths are investigated, and fitting equations to predict the shear resistant behavior of corrugated panels are proposed by introducing the normalized height-to-thickness ratio. It is found that, the maximum shear resistance of corrugated panels has a consistent relationship to the normalized height-to-thickness ratio, however variation of the post-buckling resistance is complex and geometric parameters have to be properly chosen to avoid significant strength drop after buckling. The equations proposed agree with the FEA results, and can be utilized in design of corrugated panels in SCSWs.


ABSTRACT: This paper presents the results of experiments and numerical simulations carried out to characterise and assess the effects of orientation of blast loading onto a quadrangular plate. The study was carried out in two distinct arrangements. In one configuration, the explosive was tilted at different angles (0°
(use as baseline for comparison), 15°, 30° and 45°) with respect to the target plate to provide different impact angles of the shock wave front with respect to the plate. In the other configuration, the target plate was tilted at two different angles (15° and 45°) with respect to the explosive. The blast load was achieved by detonating a 38 mm cylindrical disc of explosive. The stand-off distance, defined as the distance between the plate and the centre of the nearest face of the explosive cylinder, was kept constant at 40 mm. The mass of explosive was varied between 8 and 28 g of PE4 to achieve different responses of the plate ranging from large inelastic deformation to tearing of the structure. For all the different loading scenarios, the target plate consisted of a 2 mm thick DOMEX steel quadrangular plates with an exposed area of 300 × 300 mm. Each loading scenario was quantified in terms of impulse imparted onto the target in the axial direction of a horizontal ballistic pendulum. The damage was evaluated in terms of maximum deflection/tearing of the target plate. Numerical simulations was carried out in ANSYS AUTODYN using a coupled Eulerian and Lagrangian solver approach to provide insights in the mechanism of the blast load in terms of load distribution on the target plate.

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ABSTRACT: Mullions are the vertical members used in the frames of curtain wall systems. Although they are commonly used in building construction, their structural performance under wind actions has not been adequately investigated in the past. This is because these extruded sections are available in a vast array of complex and asymmetric profiles. This paper presents an experimental investigation into the section moment capacity of aluminium mullions used in unitised curtain walls of high-rise buildings under wind pressure (positive) and suction (negative) load cases. In this experimental investigation, 30 tests were conducted where 15 complex-shaped mullion sections were tested under both positive and negative wind actions. The tested mullions included those used in the captive and structural glazing systems. This paper presents the details of the mullion tests and the test results including the failure loads and the load versus displacement curves. Furthermore, it compares the section moment capacity predictions using three different design approaches in the currently available aluminium design standards and previous research studies, namely, direct strength method, limiting stress method and total moment capacity approach, with the test results. The commonly used limiting stress method is found to be giving conservative results. Based on the comparisons, this paper recommends the use of direct strength method to determine the section moment capacities of aluminium mullion sections.

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ABSTRACT: Present research aims to analyze the nonlinear bending response of the functionally graded material curved tube subjected to the uniform lateral pressure. The effect of thermal environment is also included. Properties of the arch are distributed through the radial direction using a power law function. Thermomechanical properties of the media are assumed to be temperature dependent. The governing nonlinear equilibrium equations of the arch are obtained by means of the von Kármán assumption and a higher order shear deformation tube theory which satisfies the traction free boundary conditions on the inner and outer surfaces of the tube. The three coupled nonlinear equations of the tube are reduced to new two ones in a dimensionless presentation. These two equations are solved using the two step perturbation technique for pin ended and clamped ended boundary conditions. Closed form and accurate expressions are provided to estimate the deflection of the arch as a function of the thermal and mechanical load parameters. Numerical results are provided to explore the effect of different parameters such as the power law index of the FGM tube, boundary conditions of the tube, thermal environment, and three geometrical parameters.

ABSTRACT: Prestressed tube stayed columns with one and two crossarms are investigated. The analyses are performed using SCIA Engineer software and ANSYS package and validated by tests of four stayed columns. First, the investigations concern the ideal (perfect) columns and cover linear buckling analyses (LBA) and geometrically nonlinear analyses (GNIA) to obtain critical loads and buckling modes under various prestressing levels. Second, the collapse loadings of the imperfect columns with initial deflections required by Eurocode EN 1993-1-1 are analysed with respect to relevant initial deflection modes and material behaviour (elastic for mild steel, nonlinear for stainless steel). All the analyses are performed for geometrical characteristics of the tested columns and the results concerning both the column with one or two crossarms are set against each other to assess the respective effectivity. In addition, the geometrical analysis of the prestressed ideal column with two crossarms and respective formulas concerning optimal prestressing and maximal critical loading are presented. Finally some recommendations for practical use are suggested.


ABSTRACT: Although guidelines exist for evaluation of the buckling strength of curved plates on ships and offshore structures, they do not reflect the effects of curvature or detail their geometric characteristics. From estimations made using cylinder models, it is known that curvature is expected to increase the buckling strength and the ultimate strength of a curved plate. Therefore, it may be designed accordingly. This study aims to clarify and examine the fundamental behaviour of cylindrically curved plates under axial compression and lateral pressure via a series of elasto-plastic large deflection analyses. On the basis of these results, the effects of curvature, initial deflection, slenderness and aspect ratio, boundary conditions and secondary buckling behaviour are discussed and developed with a modified Faulkner's formula to obtain a double beta formula to predict the ultimate strength of the curved plate.


ABSTRACT: This study focused on the nonlinear elastic buckling of mass equivalent egg-shaped shells with variable and constant wall thicknesses under uniform external pressure. The shells were made of photosensitive resin and had a nominal mass of 570 g, a nominal major axis of 260.36 mm, and a nominal minor axis of 181.32 mm. Four egg-shaped shells were fabricated using the aforementioned parameters and using the rapid prototype technique—stereo lithography appearance. Two shells had a constant wall thickness, whereas the remaining shells had a variable wall thickness along the meridian. The geometry of all shells was accurately measured, and the shells were slowly pressurised to destruction, thus yielding good repeatability. On the basis of the measured results, the buckling performance of the tested shells was further studied numerically. The experimental data were found to be in agreement with the numerical predictions. The results revealed that the average collapse pressure for the egg-shaped shells with variable wall thickness was approximately 24% higher than that for the egg-shaped shells with constant wall thickness, thus indicating that the load-carrying capacity of the egg-shaped shells was significantly improved when variable thickness was used.

ABSTRACT: Purlins are usually connected to roof sheeting by sliding-clips, while wall sheeting is often screw-fastened to girts. This paper investigates the buckling of such two types of parallel purlin/girt systems interconnected by multiple lines of sag rods. One single purlin braced by one sag rod at any place along the span is first analyzed, and its buckling deformation at any cross-section is seen as a flexibility coefficient which is then used to study the buckling of the purlin braced by multiple sag rods along span. A flexibility matrix is constructed, whose eigenvalues are the base of critical equations. In the case where the sag rods are placed with equal spaces along span, the eigenvalues are expressed in explicit forms, of which each represents one buckling mode. Threshold stiffness of the sag rods are presented for multiple sag rod bracings for these two types of sheet-to-purlin connection. Based on the findings of this paper, the differences of buckling behaviors between these two types of purlin systems have been revealed. The effect of local deformation of the web at the sag rod connecting points on the sag rod stiffness is also included. Parallel purlin systems are then investigated in a compact matrix form. After carrying out matrix operations and slight approximations, a key parameter is found to be used to reflect the effect of the number of purlins and zig-zag layout of sag rods in adjacent bays on the effective sag rod stiffness.


ABSTRACT: This paper presents a cyclic loading investigation on double-tube concrete-filled stainless steel tubular (CFSST) columns with circular outer stainless steel tube and circular inner carbon steel tube. A total of eight specimens were tested under constant axial compressive load and lateral cyclic loading. The main variables explored in the test are: (a) axial load level (0.046–0.56); (b) diameter ratio of inner tube to outer tube (0.36, 0.57); and (c) presence of inner concrete or not. A finite element (FE) model was then developed and the prediction of lateral load (P)–lateral displacement (Δ) curves agree well with the test results. Furthermore, effects of various parameters on the P–Δ curves of the double-tube CFSST columns were analyzed in comparison to the double-tube concrete-filled steel tubular (CFST) columns.


ABSTRACT: Vertical circular rings and a system of three nested rings are tested and analyzed. The rings are clamped to a flat rigid base and are loaded vertically at the top by either a concentrated load or a rigid plate. The tests involve rings made by 3D printing. In the analysis, each ring is modeled as an inextensible elastica. For downward quasi-static loading, point contact at the base becomes line contact under sufficiently high loads. Deformations are determined, and small vibrations about equilibrium are examined. Good agreement is found between experiments and theory. The topic is motivated by the application of short nested tubes for energy absorption.


ABSTRACT: Single-layer reticulated domes are very common spatial structures. As landmarks, these types of structures can more easily be the targets of terrorist attacks than other buildings. However, blast resistance is not
taken into consideration in the design of most civil structures. Therefore, it is important to know the damage level that may be imparted to single-layer reticulated domes after a blast attack. In this study, the dynamic response of reticulated domes subjected to an interior blast was investigated with numerical simulations, and five typical failure modes were identified from the results. In addition, the effects of some important parameters were investigated with a case study. Relationships between failure modes and interior blast impulses were summarised. Finally, the failure mechanisms were analysed, which could provide some design suggestions to decrease the probability of severe damage in spatial structures subjected to extreme dynamic loads.


ABSTRACT: Non-symmetric thin-walled open-sections are used extensively in metal structures. The behaviour of such sections is usually complex because their shear centre and centroid do not coincide, and as a result, they are often susceptible to lateral-torsional and/or flexural-torsional buckling. This paper develops an efficient and robust computational framework for practical application, including a refined beam-column element for non-symmetric sections, a cross-section analysis algorithm for determining pertinent properties of open-sections, and an Updated-Lagrangian (UL) solution method for large deflection analysis. Details of the derivation of element stiffness matrices and the related numerical procedures are provided. Several examples are given that demonstrate accurate results from its implementation within the educational structural analysis software MASTAN2.


ABSTRACT: The present paper aims at introducing the constrained spline Finite Strip Method (csFSM). The proposed approach is basically a spline Finite Strip Method (spline FSM) that allows the modal decomposition. Similarly to the constrained Finite Strip Method (cFSM), some mechanical assumptions are made in order to constrain the general spline FSM model to buckle in specific modes, for example to enforce the member to buckle in the local-plate mode, or distortional mode. Derivation of matrices that define the distortional (D) and global (G) modes for thin-walled members with unbranched open and closed cross-sections is the main objective of this paper. To define these subspaces, a standard practice is followed which consists in forming R-sub-GD, the constraint matrix of the combined GD space, then, R-sub-G and R-sub-D the constraint matrices of pure global and distortional buckling modes, respectively. Mechanical criteria are used to derive R-sub-GD and R-sub-G matrices, while orthogonality conditions are used to derive R-sub-D matrix. The implementation of the mechanical criteria is done by using FEM procedure rather than the cFSM one. Moreover, some practical aspects on how to constrain a spline FSM model are also discussed, including how to force the torsional mode of closed cross-sections. Numerical examples of modal decomposition are provided for a column - beam problem, with standard boundary conditions. The distortional and global buckling loads obtained are found to be in good agreement with those calculated via the cFSM and the Generalized Beam Theory (GBT). The paper concludes with a discussion on the applicability of csFSM in cold-formed steel member design.


ABSTRACT: A variational model based on total potential energy principles that describes the nonlinear mode interaction in thin-walled unequal-leg angle struts under pure axial compression is presented. The formulation,
which combines continuous displacement functions and generalized coordinates, leads to the derivation of a system of differential and integral equations that describe the static equilibrium response of the strut. Solving the system of equations using numerical continuation techniques reveals, for the first time, progressive cellular buckling (or *snaking*) represented by a sequence of snap-back instabilities arising from the nonlinear interaction of the weak-axis flexural, strong-axis flexural and torsional buckling modes—the resulting behaviour being highly unstable. For verification purposes, a finite element (FE) model is also devised and the sequential snap-back instabilities are also captured within its framework. Moreover, once an initial geometric perturbation is incorporated within the variational model it compares very well with the FE model.


**ABSTRACT:** The crushing behavior of a multilayer 1050 H14 aluminum corrugated core was investigated both experimentally and numerically (LS-Dyna) using the perfect and imperfect models between 0.0048 and 90 m s\(^{-1}\). The dynamic compression and direct impact tests were performed in a compression type and a modified Split Hopkinson Pressure Bar set-up, respectively. The investigated fully imperfect model of the corrugated core sample represented the homogenous distribution of imperfection, while the two-layer imperfect model the localized imperfection. The corrugated core experimentally deformed by a quasi-static homogenous mode between 0.0048 and 22 m s\(^{-1}\), a transition mode between 22 and 60 m s\(^{-1}\) and a shock mode at 90 m s\(^{-1}\). Numerical results have shown that the stress-time profile and the layer crushing mode of the homogeneous and transition mode were well predicted by the two-layer imperfect model, while the stress-time profile and the layer crushing mode were well approximated by the fully imperfect model. The fully imperfect model resulted in complete sequential layer crushing at 75 and 90 m s\(^{-1}\), respectively. The imperfect layers in the shock mode only affected the distal end stresses, while all models implemented resulted in similar impact end stresses. The distal end initial crushing stress increased with increasing velocity until about 22 m s\(^{-1}\); thereafter, it saturated at \(\sim 2\) MPa, which was ascribed to the micro inertial effect. Both the stress-time and velocity-time history of the rigid-perfectly-plastic-locking model and the critical velocity for the shock deformation were well predicted when a dynamic plateau stress determined from the distal end stresses in the shock mode was used in the calculations.


**ABSTRACT:** The glass fiber-reinforced polymer (GFRP)-recycled aggregate concrete (RAC)-steel double-skin tubular column (DSTC) combines and optimizes the benefits of the fiber-reinforced polymer (FRP)-concrete-steel DSTC, and RAC. To study the axial compressive behavior of the GFRP-RAC-steel DSTC, tests on ten column specimens which consider the difference of the replacement percentage of the recycled coarse aggregate (RCA), the concrete strength and the thickness of the GFRP tube were conducted. The failure mode, ultimate load, confinement factor, load-longitudinal curve, ductility, and stress-strain curve were analyzed and discussed. In addition, the theoretical formulae to estimate the ultimate load of the GFRP-RAC-steel DSTC were derived. The results showed that (1) the development of the lateral expansion of the concrete led to the hoop rupture of the GFRP tubes and the inward buckling of the inner steel tube; (2) the natural aggregate concrete (NAC) in the traditional DSTC can be replaced with RAC and the strength can be guaranteed, and a GFRP-RAC-steel DSTC specimen with a 50% replacement percentage of the RCA was recommended; (3) the theoretical results agreed well with the experimental results. The application of RAC to the DSTC can utilize these materials effectively and make a contribution to the economic development and environmental protection.

ABSTRACT: A novel approach to detect and locate buckling from distributed optical sensors is proposed in this paper by means of a second derivative analysis of the strain measurements. This methodology demonstrates that non-linear events are prone to significant changes in the full-field strain shape obtained using a dense distributed optical network, whose measurements were processed earlier using a Savitzky-Golay filter. Moreover, these non-linear events can be identified without needing to know the load step value. A buckling test was conducted in a stiffened composite panel representative of a cockpit fuselage skin stiffened by two omega stiffeners plus two fastened metallic frames. A distributed fibre optic network was bonded to the flat panel side in a crooked configuration. The panel was also instrumented using conventional back-to-back strain gauge rosettes and a high-speed-camera to establish a qualitative comparison with the distributed strain contour map. Through the proposed methodology, the detection and location of the global and local buckling were successfully conducted.


ABSTRACT: The compressive stress is remarkable in design of steel plate walls (SPWs) for high-rise buildings. Stiffeners are required to avoid the compressive buckling in service limit state. This paper first studies the elastic stability of horizontally stiffened steel plate walls (S-SPWs) in compression. The effect of stiffener torsional stiffness on elastic buckling stress is presented. Then the study extends to the elastic-plastic stability of imperfect S-SPWs. Comparing the elastic and elastic-plastic behaviour, the increased ultimate compressive strength is smaller than the increased elastic buckling stress due to the column type buckling behaviour of wide plate. Stiffener torsional stiffness can also increase the ultimate capacity. Formulas to predict the stiffness requirement on horizontal stiffeners are proposed based on the philosophy similar to the stiffness requirement on brace for columns in compression. With some minor modifications, the proposed formulas show good accuracy compared with numerical results.


ABSTRACT: This study is focussed on the performance evaluation of built-up cold-formed steel (CFS) columns under monotonically increasing axial compression loading. Five test specimens of built-up columns were fabricated using four CFS angle sections connected by single lacing systems. Width-to-thickness ratios and slenderness ratios of chord and lacing elements, and height of columns were varied in the test specimens. Column strengths, axial load vs. displacement response, mode of failure, and deformed configurations were the main parameters evaluated in the experimental investigation. In addition, a numerical study was conducted to predict the behaviour of laced built-up CFS columns using a finite element software ABAQUS. The developed numerical models were validated using the test results. Test results were used to develop the column strength curves for built-up laced CFS columns. Finally, the results of this study were compared with the design strength predictions by North American Standards and European Standards for CFS sections.

ABSTRACT: The objective of this study is to analyze the formation behavior of welding residual stresses during the circumferential TIG butt welding of pipes. A three-dimensional thermo-elastic-plastic numerical model has been developed by using MSC-Marc software to predict welding residual stress distributions during single-pass welding of pipes. Using a numerical computational approach, the mechanisms of the changes in stress and strain throughout the pipe welding process is described. Compared with the features of butt welded plate joints, the distribution of welding residual stress in butt welded pipe structures is obviously different. Considering the deformation effect on the plastic strain distribution, the calculation results indicate that the axial and hoop compressive plastic strain at the inner surface of welded pipes is much larger than that at the outer surface. As a result, the tensile axial and hoop residual stress is generated at the inner surface due to the thermal contracting deformation. Consequently, compressive axial residual stress occurs at the outer surface because of the inward contracting deformation and internal stress self-balance. Moreover, it is investigated and explained the phenomenon in which both axial and hoop residual stresses have sharp gradients near the weld stop location at the overlapped weld line of pipe. Because of redistribution of axial residual stresses and hoop plastic flow behaviors, residual stresses near the weld stop location could be changed.


ABSTRACT: This paper presents a refined model for local buckling of rectangular concrete-filled steel tubular (CFST) columns with binding bars under axial compression due to a deficiency in the previous model i.e. the influences of horizontal spacing and diameter of binding bars were not considered. The influences of longitudinal spacing, horizontal spacing and diameter of binding bars on the critical local buckling stress can be reasonably considered in the proposed model, which is applicable to both elasto-plastic phase and elastic phase. The refined model is verified against the experimental results, showing better agreement than the previous model. Then, the proposed model is employed to investigate the influences of longitudinal spacing, horizontal spacing, diameter of binding bars and cross-sectional aspect ratios on the critical local buckling stress. It is found that the critical local buckling stress increases considerably with the decrease of the spacing of binding bars. Furthermore, the influence of longitudinal spacing of binding bars on the critical local buckling stress is more significant than that of horizontal spacing. It is also found that the critical local buckling stress increase modestly with the increase of diameter of binding bars in the case of small spacing of binding bars. In addition, the cross-sectional aspect ratio have little influence on the critical local buckling stress, which can be ignored. Aiming at delaying the occurrence of local buckling of steel plates in rectangular CFST columns with binding bars, it is suggested that decreasing longitudinal spacing as an efficient measure has priority over other measures.


ABSTRACT: The aim of the study is to examine the effect of damages on the load carrying capacity of stringer-stiffened cylinders under external hydrostatic pressure. Experiments were conducted on three small-scale steel stringer-stiffened cylinder models that were fabricated by cold bending and arc welding. Drop tests with a knife-edge indenter were conducted on two test models to induce damage on the cylinders. Hydrostatic pressure tests of all models including an intact model were performed to characterize the ultimate strength
behaviour of the stringer-stiffened cylinders in damaged and intact conditions. The results indicated that the effects of damage on the ultimate strength of stringer-stiffened cylinders were extremely low. Interestingly, during the collapse tests, it was also discovered that the shell failed several times after an initial failure, as evidenced by a sudden decrease in pressure. Subsequently, the shell recovered as “hardened-up” to reach a higher pressure level prior to the final collapse. Furthermore, the drop tests and hydrostatic pressure tests were simulated by using the finite element software package ABAQUS. The agreements between the tests and numerical predictions were satisfactory.


ABSTRACT: Concrete-filled steel tubular (CFST) structures have been widely applied in modern construction industry owing to the composite action between the concrete and the steel tube. The benefits of CFST structures can be further achieved if high-strength materials are used. However, when high-strength steel is applied to CFST structures, the thin-walled steel section may not develop its yield strength owing to the early crushing of the cover concrete. Therefore, this paper presents an experimental study on concrete-filled circular high-strength steel stub tube (CFHST) focusing on the effect of the diameter-to-thickness (D/t) ratio. Fifteen specimens were tested under axial compression, with D/t ratios ranging from 50 to 130. The effects of the D/t ratio on the failure mode, load-versus-deformation relationship, and axial compression strength were investigated. Test results showed that the CFHST with a large D/t ratio can still reach the plastic section design. The fibre element method proposed by Liang et al. was revised to predict the load-axial deformation curves and then validated by using the ultimate bearing strength of CFST columns from 215 collected data. Finally, the bearing capacity of CFHST columns was compared with the present design codes, namely, Eurocode 4, American Institute of Steel Construction standard (AISC 360-10), Architectural Institute of Japan (AIJ) standard, and the proposed model, to evaluate the feasibility of the current codes for predicting the axial compressive strength of CFHST under axial compression.


ABSTRACT: Fire accidents occur occasionally when grid structures are extensively applied, although many grid structures do not suffer general failure after fire disasters and can be used again after reasonable evaluation and reinforcement. To reasonably evaluate the residual load bearing capacity of grid structures, this paper investigated stability bearing capacity of steel tube members in grid structures after fire disasters through axial compression experiment and numerical simulation. Axial compression experiments performed on 32 steel tubes after exposure to the ISO-834 standard fire, and three highest fire temperatures were considered, including 600 °C, 800 °C and 1000 °C. The temperature distributions in the specimens during the heating and related mechanical properties such as load-displacement curves, ultimate loads and strain distributions of the specimens, were obtained and analyzed. Finite element analysis was also conducted by using ABAQUS software. Then, the main factors influencing the residual stability bearing capacities of the steel tube members exposed to high temperatures were obtained through a lot of numerical analysis. Based on the results of experiments and numerical analysis, the formula for the computation of the residual stability bearing capacities of the steel tube members after fire disasters was presented. And calculated results using the formulas accorded well with experimental results.
ABSTRACT: Aluminum honeycomb-filled Carbon Fibre Reinforced Plastic (CFRP) thin-walled square beams is a new outstanding energy absorption component. In this paper, dynamic impact tests for bending of aluminum honeycomb-filled CFRP beams with different configurations are carried out, and the failure mode and force responses are investigated. For the failure mode, modified Chang-Chang failure criteria are used to predict tensile and compressive fibre failure, as well as tensile and compressive matrix failure. Numerical simulation of the tests is also performed, and the accuracy is validated by the experimental results. The influences of some factors, including the wall thickness, fibre direction, stacking sequence, and impact velocity, on the bending resistance, are analyzed. The effect of aluminum honeycomb filler on the crashworthiness characteristics is also discussed. The results show that the energy absorption and specific energy absorption of filled composite tubes can significantly increase by 104.3% and 26.8% respectively compared with those of CFRP hollow beams. This study demonstrates the potential of CFRP beams filled with aluminum honeycomb to be used as energy absorbers.

ABSTRACT: In this study, new types of folded structures with different base shapes (i.e. triangle, square and pentagon) are proposed. Each structure is folded from a thin sheet of aluminium, with the geometry of open-top truncated pyramid and connected inclination sidewalls. The purpose of this unique geometry is to increase the crushing resistance of the folded structure while maintaining a uniform collapsing behaviour under different crushing rates as compared with other existing folded kirigami structures. Three base shapes, i.e. triangle, square and pentagon, are considered in this study. Geometric parameters are derived for these structures based on three governing parameters: top and bottom edge length and cell height. Numerical models of these structures are firstly calibrated with quasi-static crushing test data followed by dynamic crushing simulations. To evaluate the crushing performances, structural responses including peak and average crushing stress, uniformity ratio and densification strain are compared among these three structures and also with the widely studied Miura-origami structure of the same density. Superior performances of crushing are observed for the proposed open-top truncated pyramid structure with higher average stress and more uniform collapsing under various loading rates, indicating potential application as energy absorber.

ABSTRACT: (Only a graphical abstract is given. Keywords: similarity criteria; Thin-walled cylinder; Thermomechanical loads; Thermal elastoplastic; Buckling; Dynamic rupture)

ABSTRACT: The structural behaviour and design of hot-rolled and cold-formed steel continuous beams with square and rectangular hollow sections are studied in the present paper, with a focus on the beneficial effects of material strain hardening and moment redistribution. Finite element (FE) models were first developed and validated against existing test results on hot-rolled and cold-formed steel square and rectangular hollow section
continuous beams. Upon validation against the experimental results, parametric studies were carried out to expand the available structural performance data over a range of cross-section geometries, cross-section slendernesses, steel grades and loading conditions. Representative material properties and residual stress patterns were incorporated into the FE models to reflect the two studied production routes – hot-rolling and cold-forming. The experimental results, together with the parametric numerical results generated herein, were then used to evaluate the accuracy of the design provisions of EN 1993-1-1 (2005) as well as the continuous strength method (CSM) for indeterminate structures, the latter of which is extended in scope in the present study. It was shown that the current provisions of EN 1993-1-1 (2005) for the design of hot-rolled and cold-formed steel continuous beams are rather conservative, while the proposed CSM yields a higher level of accuracy and consistency, due to its rational consideration of both strain hardening at the cross-sectional level and moment redistribution at the global system level. Finally, statistical analyses were carried out to assess the reliability level of the two design methods according to EN 1990 (2002).

ABSTRACT: Inflated membrane cones have attracted extensive research efforts in various fields owing to features such as ultra-light weight, high packaging efficiency. The pressure effect was considered in the vibration analysis of these structures because pressure was the main contributor to structural stiffness. Based on the virtual work principle and Timoshenko beam theory, an improved beam model considering the pressure effect, which includes the prestress stiffness and follower force effects, was proposed for the vibration of an inflated cone. The results calculated from the proposed model agreed strongly with the experimental results. Moreover, the pressure follower force effect was investigated using different pressures and taper angles. The study proved that the follower force effect decreased the natural frequencies in lower modes, and increased them in higher modes.

ABSTRACT: In the current study, the stability analysis of functionally graded (FG) thin-walled porous beams reinforced by nanocomposite graphene platelets (GPLs) under compressive axial load is investigated. It is assumed that the thin-walled porous beam is spinning along its longitudinal axis and both symmetric and asymmetric distributions of porosity are considered. Furthermore, the GPLs are distributed thorough the thickness direction both uniformly and non-uniformly. The effective material properties such as Young's modulus, mass density and Poisson's ratio of the porous beams are computed based on the Halpin-Tsai micromechanics model and the rule of mixture. The extended Hamilton's principle is utilized to establish the governing equations and they are discretized by the extended Galerkin method (EGM). The effects of various parameters such as GPL porous distribution patterns, GPL weight fraction, geometry of GPL nanofillers and porosity coefficient on the frequencies as well as flutter and divergence instabilities of the thin-walled porous beams have been studied. Numerical results demonstrate that the best efficient way to increase the stability region is considering GPL pattern A, with dispersing more GPL fillers near the top and bottom surfaces of the thin-walled porous beam along with symmetric porosity distribution.

ABSTRACT: As the design methodology of the corrugated steel shear wall (CSSW) has not yet been included in the design standards, this paper presents a step-by-step design procedure based on the corrugated panel-frame interaction (CPFI). To ensure that the plastic hinges occur at the beam ends and not within the beam span or in the columns, a reduced beam section (RBS) connection was used in steel plate shear walls (SPSWs). In this paper, the corrugated steel shear wall with a reduced boundary beam section (RBS-CSSW) is presented as a promising type of lateral-load-resisting system. Analytical equations were proposed to estimate the strength of RBS-CSSW based on the frame plastic hinge development considering the interactive shear buckling stress in the corrugated panel. The equations of strength estimation for RBS-CSSW were also evaluated by comparing their results with the numerical results of the two models. The comparison showed that the strength based on the proposed analytical equations were accurate (with more than 95% accuracy) compared to the strength from the FE pushover analyses for the two models.


ABSTRACT: Experimental and numerical evaluation is performed on a square hollow aluminium column, an aluminium honeycomb filled column, an aluminium column filled with combined carbon fibre and an aluminium honeycomb at constant velocity of 3.06 mm/s to analyze the axial crushing phenomenon at low speed axial loads. To validate experimental outputs, numerical simulation is performed using PAMCRASH explicit finite element code. The effects of honeycomb core and carbon fibre reinforced aluminium honeycomb were analysed experimentally and numerically. A decent agreement between experimental and numerical results is observed. The effects of deformation modes and force-displacement curves on these different structural columns were studied. Experimental and numerical results showed the square aluminium column filled with carbon fibre reinforced aluminium honeycomb was the most crashworthy combination, where the maximum increase of energy absorption, specific energy absorption and crush force efficiency were up to 60.6%, 27.8% and 17.4% respectively, compared with bare aluminium hollow column.


ABSTRACT: Shell buckling process is studied by implicit structural dynamics time-stepping schemes with numerical dissipation (in the high-frequency range), which fall into the class of Generalized energy-momentum method. In particular, modified Generalized-alpha, Bossak, HHT, and Newmark’s schemes are considered, as well as Energy-momentum conserving scheme, and Energy-decaying scheme with controllable numerical dissipation. We are interested in the assessment of the ability of these schemes to handle complex buckling and post-buckling processes of thin shells (even for cases when path-following methods fail). The schemes are specialized for geometrically exact shell formulation (with only displacement-like degrees of freedom). Computed numerical examples include classical shell buckling problems: snap-through, shell collapse, and buckling of perfect and imperfect cylinder under axial load. The examples illustrate that (high-frequency) numerical dissipation is absolutely necessary for an efficient implicit dynamic simulation of complex shell buckling and post-buckling processes. Since the Energy-momentum conserving scheme does not damp high-frequency oscillations that accompany shell buckling (and thus accumulates large error in the high-frequency range), it is not suitable for the simulation of shell instabilities (the scheme fails to converge for several computed examples). The dynamic results are compared with the static ones that were computed by the path-following method. It turns out that implicit dynamic analysis with (high-frequency) numerical dissipation is
considerably more robust and efficient than static analysis for several computed examples, including snap trough problems and buckling of cylinder under axial load.


ABSTRACT: The main objective of the present paper is to draw the attention of researchers towards the analyses of composite structures in non-deterministic environment. The various distinguishing features of the stochastic finite element methodologies for the analysis of composite structures have been discussed. A thorough literature review has been carried out while emphasizing on the bending, buckling, vibration analysis and failure analysis of composite structures by considering the uncertain behavior of material properties, mechanical loadings and others. This paper also presents an overview of various micromechanical models in the deterministic and stochastic domains, plate theories and impact of uncertainties on the processing techniques of various composite structures. The future research directions have been discussed which will be prolific to the material, design, civil, mechanical and aerospace engineers.


ABSTRACT: Thin-walled cylindrical shells subjected to axial load are prone to buckling and very sensitive to the geometric imperfections. In order to determine a rational design load for axially loaded cylindrical shells, different analytical and numerical design methods have been developed. As an extension of single perturbation load approach (SPLA), multiple perturbation load approach (MPLA) is a promising method but has not been thoroughly studied. In this paper, the buckling tests of three steel cylindrical shell specimens are conducted. Combined with experimental and numerical results, the advantages and limitations of several commonly used design methods are discussed in detail, including NASA SP-8007, the measured imperfection approach, SPLA and MPLA. The results validate that SPLA is indeed risky to be adopted as a design method for isotropic metallic cylindrical shells. Meanwhile, it indicates that MPLA can not only improve the knock-down factor but also give a more safe design load than SPLA. The comprehensive numerical investigations are performed to study the effects of each perturbation load parameter on MPLA, including the number of perturbation loads, their relative position and magnitude. It is found that the symmetry of perturbation loads plays an important role in the global buckling load of cylindrical shell. Moreover, some guidance for the future application of MPLA is provided and the four perturbation load approach (4PLA) is proposed as an improved method for the preliminary design of isotropic metallic cylindrical shells.


ABSTRACT: This paper presents the results of numerical and analytical studies to obtain ultimate strength enhancement coefficient \( \left( C_{\text{ue}} \right) \) equations for external-ring-stiffened circular hollow section (CHS) X-joints under axial compression. The FE modeling approach is validated by the results of axial compressive experiments conducted in the authors’ previous research on six X-joints with and without stiffeners. In all, 160 unstiffened and ring-stiffened FE models of CHS X-joints subjected to brace axial compression were investigated. The effects of the brace-to-chord diameter ratio \( \beta \), the ratio of chord diameter to twice the chord wall thickness \( \gamma \), the stiffening ring width factor (i.e. where is the ring width and is the chord diameter), and the stiffening ring thickness factor (i.e. where is the stiffening ring thickness and is the chord wall thickness) on the structural
behavior of external-ring-stiffened CHS X-joints were evaluated. Parametric analysis showed that the ultimate strength enhancement coefficient decreased with the increase in the diameter ratio between the brace and the chord $\beta$, but once $\beta$ exceeded 0.4, the effect on was slight. Furthermore, the ratios of chord diameter to twice the chord wall thickness $\gamma$, the stiffening ring width factor, and the stiffening ring thickness factor were all positively correlated with improvement in the ultimate strength of the external-ring-stiffened CHS X-joints. An analytical formula based on the yield volume model was derived to predict the ultimate strength enhancement of external-ring-stiffened X-joints. (This abstract contains math expressions that are not reproduced here.)


ABSTRACT: Buckling of slender structures constitutes a hazardous failure mechanism that can yield partial or total collapses. Nonetheless, given that buckling failure is characterized by a highly non-linear and sudden loss of stability, most off-the-shelf monitoring systems fail to detect buckling and very few research works in the literature can be found in this regard. Recent advances in the field of Nanotechnology have fostered the development of innovative composite materials with multifunctional properties, offering vast possibilities in the field of Structural Health Monitoring. Along these lines, the present work proposes a novel concept of smart beams for buckling detection applications. This consists of the deployment of carbon nanotube-reinforced epoxy strip-like sensors on the upper and bottom faces of a beam-like structure. Carbon nanotube-reinforced composites exhibit strain self-sensing capabilities, that is to say, these composites provide measurable variations in their electrical properties under the action of mechanical strains. In this way, the proposed sensing strips not only act as mechanical reinforcements, but also confer self-diagnostic properties to the system. The failure detection principle of the proposed smart beams consists of the assessment of the bending-induced variations of the normal strains during buckling. To do so, the electrical resistance of the sensing strips is continuously monitored through a two-probe resistivity measurement scheme. The present research furnishes detailed numerical parametric analyses to investigate the effectiveness of the proposed smart beams to detect buckling under uniaxially compression, as well as to evaluate the influence of design parameters such as filler volume fraction, boundary conditions and electrodes layouts. The macroscopic behaviour of the smart beams is simulated by a micromechanics-based piezoresistivity model and a multiphysics finite element code. The numerical results demonstrate that the buckling failure can be tracked through sudden disturbances in the electrical output of the smart strips.


ABSTRACT: In this study, the energy absorption characteristic of two-layered corrugated core sandwich panels with different arrangements under quasi-static compression loading were firstly investigated experimentally. Then compared the experimental results of these two different arrangements two-layered sandwich panels, it was found that the symmetric-arranged corrugated sandwich panel has better energy absorption characteristic, which is more than 17.17% at 6 mm displacement before densification stage compare to regularly-arranged. Numerical calculations were carried out and good agreement is achieved between the experimentally results and numerical results. Finally, parameter analysis and optimization study of the symmetric-arranged two-layered corrugated sandwich panel under planar impact was carried out with crashworthiness criteria by using finite element model and response surface method. The selection of parameters in optimization study were determined by parameter analysis. The size of sandwich panel was firstly optimized for maximizing specific energy absorption (SEA). Then the multi-objective optimization of core cell shape with optimal sandwich panel
size was optimized by maximizing SEA and minimizing the peak force, a Non-dominated Sorting Genetic Algorithms (NSGA-II) code was used to perform the optimization process in a gradual evolution trend, which led to obtain the Pareto front that consisted of a set of optimal objective function vectors.


ABSTRACT: The ultimate strength of stiffened panels under compressive loads is assessed by numerical simulations, in order to compare with tests made to investigate the influence on the ultimate strength of varying pit location, pit diameter and pit depth. The validated model is them used for a numerical study on the influence of pitting on the residual ultimate strength of stiffened panels by a series of non-linear finite element analysis. The parameters of pit position, diameter, number, depth, and corroded volume loss will be investigated for the stiffened panels subjected to axial compressive load with initial deformations. It is found that the pits will induce the buckling failure of stiffened panels. All parameters discussed in this paper have significant influence on the residual ultimate strength of the pitting corroded stiffened panel. A formula was derived by introducing the reduction of plate slenderness and column slenderness.


ABSTRACT: This paper deals with the derivation of the exact solutions for the static electro-mechanical response of a simply-supported doubly curved (DC) smart shell, composed of a piezoelectric fiber reinforced composite (PFRC) placed over a laminated substrate. These responses are evaluated when the system is subjected to distributed electrical and mechanical loads. The electro-mechanical governing equations and the associated boundary conditions have been derived here for the curvilinear coordinate system using the variational principle. Closed-form expressions for the mechanical displacement and the electrical potential have been obtained by solving these governing differential equations and simultaneously satisfying the derived boundary conditions. Numerical results have been presented for different shell geometries. The effect of the curvature and the geometric parameters of the PFRC layer over its performance as an actuator are studied and compared for these shells. Also, the effect of varying geometric parameters of the PFRC over its performance as a sensor is studied. Optimal dimensions of the PFRC for use as an actuator and sensor/harvester have been proposed. This study may be considered as a benchmark for use in the numerical and experimental studies involving smart shells.


ABSTRACT: For the first time, the parametric instability regions of variable stiffness laminated composite quadrilateral plates subjected to uniform in-plane loadings are studied. The static as well as time-varying inplane loadings are assumed distributed throughout the whole geometry. The isogeometric analysis finite element formulation based on non-uniform rational B-splines is developed in order to address the dynamic instability of quadrilateral panels. The problem has been formulated by utilizing the principle of virtual work based on first order shear deformation plate theory. In terms of tow-steered reinforcements, the fiber orientations in every lamina is assumed to change linearly in the panel longitudinal direction. In order to demonstrate the capabilities of the developed formulation in predicting the structural parametric dynamic behavior, some representative results are obtained and compared with those available in the literature.
effects of geometry layout, loading frequency and amplitude, changes in curvilinear fiber orientations, and material orthogonality on the parametric instability regions are studied by applying Bolotin's first order approximation.


ABSTRACT: Cross-sectional ovalization (ovalisation) usually occurs when thin-walled tube is subjected to large plastic bending. This paper is concerned with residual deformation of tube’s cross-section in radial direction when external bending moment is removed. A combination of experiments and theoretical modeling is used to study this issue. Firstly the four-point pure bending experiments involving fifteen stainless steel specimens with a range of diameter-to-thickness ratios are carried out to observe the shape of the ovalized cross-section and to obtain the cross-sectional flattening (value of ovalization) along the circumferential direction. Secondly the theoretical modeling procedure is performed to derive a rational model for predicting the maximal residual cross-sectional flattening of the thin-walled tube subjected to pure bending after unloading process, employing the thin-shell kinematics, the principle of virtual work and the classic unloading rule. Finally the model is validated by comparing the theoretical results with the experimental ones with less than 10% error. And the relationships between the residual flattening and the bending radius as well as the wall thickness are also revealed by the numerical results. The application of this investigation will play a positive role in thin-walled steel tube bending operation.


ABSTRACT: This paper presents experimental and numerical investigations and design of concrete-filled double-skin aluminum stub columns with circular hollow sections (CHS) as both outer and inner skins. A series of tests was carried out to investigate the effects of the geometric dimension of the aluminum CHS and concrete strength on the behaviour and strength of the composite columns. The CHS tubes were fabricated by extrusion using 6061-T6 heat-treated aluminum alloy having nominal 0.2% proof stress of 240 MPa. The structural performance of the composite columns was investigated using different nominal concrete cylinder strengths of 40, 70 and 100 MPa. A non-linear finite element model is developed and verified against the experimental results. The test results and the composite column strengths predicted from the finite element analysis (FEA) were compared with the design strengths to evaluate the reliability of the design rules in the current American specifications for aluminum and concrete structures. Furthermore, design equations were proposed to consider the benefits of the composite columns due to the composite action between the aluminum tubes and concrete. The proposed design equations accurately predicted the ultimate strengths of the concrete-filled double-skin aluminum CHS stub columns.


ABSTRACT: A higher-order isoparametric superelement is developed to study the vibration of functionally graded shells of revolution. The effective material properties of functionally graded materials (FGMs) vary continuously along the thickness direction of the shell in accordance with the power law distribution. The governing equations are presented based on the three-dimensional elasticity theory using Hamilton’s principle. Since the isoparametric formulation is considered, a unified formulation is presented for all types of shells of revolution. The properties of the FG shells are graded through the thickness direction, and consequently, the
analysis of such structures is quite difficult using conventional three-dimensional finite elements. The proposed superelement facilitates the analysis of FG shell structures. Different types of circular shell structures including cylindrical, conical, spherical and circular toroid are considered in this study. To show the accuracy and efficiency of the proposed superelement, different comparative studies are presented.

ABSTRACT: The new hierarchical circular-joint quadrangular honeycomb is proposed by iteratively replacing the edge-junctions of regular honeycomb with a circular joint. Firstly, the nonlinear finite element analysis is performed through LS-DYNA and the results are validated by experimental data. Then, analytical solutions to crushing resistance of the hierarchical honeycomb are obtained based on the Simplified Super Folding Element (SSFE) theory. The results between the numerical and analytical method are in good agreement, which indicates that the analytical solutions are reliable. Furthermore, parametric studies of the first and second hierarchical order structures are conducted numerically. The results show that the specific energy absorption of the first and second-order hierarchical honeycomb is improved by up to 81.8%, 115.3% respectively compared with the regular honeycomb. It is also found that the out-of-plane crashworthiness performance of the second-order hierarchical honeycomb can be enhanced by increasing relative density. However, the peak crushing force would also increase with the increase in relative density. The findings of this study show that the proposed hierarchical honeycomb is a structural configuration with high energy absorption capacity.

ABSTRACT: Design of cold-formed high strength steel (HSS) tubular sections undergoing web crippling is examined in this study. Finite element (FE) models were developed and validated against available test results, showing the capability of replicating the experimental web crippling strengths, failure modes and load-web deformation histories. On validation of the FE models, an extensive parametric study comprised of 224 FE analyses was performed. The web crippling provisions in the current North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel structures were assessed. The web crippling strengths obtained from the numerical investigation together with available experimental data from the literature were compared with the nominal strengths derived from the aforementioned specifications. Overall, the comparisons showed that the nominal strengths predicted by the existing codified provisions are either unconservative or overly conservative. Hence, improved design rules are proposed for cold-formed HSS tubular sections undergoing web crippling by means of modified unified equation and Direct Strength Method. The reliability of the modified design rules has been proven through reliability analysis.

ABSTRACT: The hierarchical stiffened shell is a promising aerospace structure configuration with high load-carrying capacity, however, it is challenging to fully explore its optimal load-carrying efficiency. Therefore, a bi-level optimization framework is proposed for hierarchical stiffened shells. In the first level of the optimization framework, a parallel computing numerical-based smeared stiffener method (NSSM) is first introduced for the fast prediction of critical buckling load and mode, by combining the numerical implementation of asymptotic homogenization (NIAH) method with the Rayleigh-Ritz method. Then, a large-
scale Latin hypercube sampling (LHS) is performed in the entire design space based on NSSM, and a set of competitive sampling points is collected from the Pareto front of LHS results according to a screening criterion of load-carrying efficiency. In the second level, a surrogate-based optimization using radial basis function (RBF) technique is performed based on generated competitive sampling points with high load-carrying efficiency. Finally, detailed comparisons between optimal results of the proposed optimization method based on the competitive sampling method and the traditional surrogate-based optimization method based on the RBF technique and the LHS sampling method are made from the viewpoint of computational efficiency and global optimizing ability. Spending an approximate computational time, the optimal buckling result of the proposed method increases by 23.7% than that of the traditional method. In order to achieve an approximate global optimization result, the proposed method is able to reduce the computational time by 74.4% than the traditional method. By evaluating competitive sampling results, it can also be concluded that the partial global buckling mode and global buckling mode are most dominant buckling modes for hierarchical stiffened shells with the thick skin and closely-spaced stiffeners, which are prone to obtain a higher load-carrying efficiency.


ABSTRACT: Existing parameterization of origami structures is based on angles, which is an inconvenience for the fabrication and calculation of the geometrical properties of an origami-engineering project. In this paper, a unified parameterization based on the dimensional parameters, including the length and height instead of the angles, is proposed. Various origami-based tubes reconstructed through the proposed parameterization process and compiled into a program are then described. Three types of tubes including non-flat foldable, locally flat-foldable, and entirely flat-foldable are systematically divided when forming a closed-loop tube, and a criterion is proposed for estimating the flat foldability of the tube. Finally, the proposed theory is validated based on physical prototypes folded using paperboard and fabricated using polymer through a blow molding process. The constructed origami-based tubes provide extensive guidance for the design of energy absorbing structures.

End of more papers published in the journal, Thin-Walled Structures (2017 and on).


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ABSTRACT: Tapered concrete filled steel tubular (CFST) columns have been used in some spatial structures, however, research on the structural performance of such tapered composite columns under combined compression and bending is relatively seldom, and this paper thus intends to fill this knowledge gap through experimental investigations. A total of twenty-four tapered CFST specimens were tested under combined compression and bending, including twelve square columns and twelve circular ones. The test parameters
included sectional type, tapered angle, slenderness ratio and load eccentricity. Typical failure modes, the load versus deformation relations, the strain development of tapered composite members and the influence of significant parameters were evaluated based on the testing results. Finally, simplified design method for predicting the load carrying capacity of tapered CFST column under combined compression and bending was discussed.

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Emad M. Hassan, Mohammed H. Serror and Sherif A. Mourad (Department of structural engineering, Faculty of Engineering, Cairo University, Egypt), “Numerical prediction of available rotation capacity of cold-formed steel beams”, Journal of Constructional Steel Research, Vol. 128, pp 84-98, January 2017
DOI: 10.1016/j.jcsr.2016.08.010

ABSTRACT: The rotation capacity of cold-formed steel (CFS) beams has been evaluated through numerical investigation. Studies on different structural levels have been performed. At the beam level, different values of profile thickness have been considered in the range from 1 mm up to 4 mm. In addition, different section shapes have been investigated by increasing the number of flange bends: C-section, broken-section and curved-section, which represents an infinite number of flange bends. At the connection level, a web bolted moment resistant type of connection using through plate has been adopted with different configurations of the through plate dimensions. In web bolted connections without out-of-plane stiffeners, premature web buckling results in early loss of strength. Hence, different configurations of out-of-plane stiffeners have been examined to delay web and flange buckling and to produce relatively high moment strength and rotation capacity. The finite element method results revealed that increasing the number of flange bends will not in all cases enhance the behavior. Meanwhile, the use of out-of-plane stiffeners can increase seismic energy dissipation, strength, initial stiffness, and rotation capacity, when compared with the case without stiffeners.

References listed at the end of the paper:


ABSTRACT: The paper reports the results of a numerical (Abaqus shell finite element analysis) investigation on the influence of local-distortional (L-D) interaction on the ultimate strength and design of fixed-ended cold-formed steel lipped channel columns with web and flange intermediate stiffeners. The columns analysed exhibit various geometries and yield stresses, ensuring several combinations of ratios between the (i) local and distortional critical buckling stresses, and (ii) yield stress and the highest of the above two critical buckling stresses (local or distortional). The objectives of this work are (i) to acquire in-depth understanding on the mechanics underlying the L-D interaction in the columns under consideration, and also (ii) to provide a contribution towards the development of an efficient Direct Strength Method (DSM) approach to design these structural elements. The results presented and discussed concern the post-buckling behaviour, ultimate strength and failure mode of fixed-ended web-flange-stiffened lipped channel columns previously selected to undergo more or less severe L-D interaction. Special attention is paid to the comparison between the ultimate strength erosion, due to L-D interaction, occurring in the columns analysed in this work and the (i) “plain” cross-section (i.e., without intermediate stiffeners) and (ii) web-stiffened lipped columns investigated earlier by the authors. Then, available experimental ultimate strengths of web-flange-stiffened lipped channel columns failing in L-D interactive modes are employed, together with the numerical failure loads obtained in this work, to assess the quality of the estimates provided by the existing DSM design approaches. The paper closes with (i) the reliability assessment of the DSM-based L-D approaches to predict the numerical and experimental failure loads, and (ii) some considerations about the impact of the findings reported on the design of cold-formed steel columns undergoing L-D interaction.
References listed at the end of the paper:


ABSTRACT: Eurocode allows for finite element modelling of plated steel structures, however the information in the code on how to perform the analysis or what assumptions to make is quite sparse. The present paper investigates the deterministic modelling of flexural column buckling using plane shell elements in advanced non-linear finite element analysis (GMNIA) with the goal of being able to reestablish the European buckling curves. A short comprehensive historical review is given on the development of the European buckling curves and the related assumptions made with respect to deterministic modelling of column buckling. The European buckling curves allowing deterministic analytical engineering analysis of members are based on large experimental and parametric measurement programs as well as analytical, numerical and probabilistic investigations. It is of enormous practical value that modern numerical deterministic analysis can be performed based on given magnitudes of characteristic yield stress, material stress–strain relationship, and given characteristic values for imperfections and residual stresses. The magnitude of imperfections and residual stresses are discussed as well as how the use of equivalent imperfections may be very conservative if considered by finite element analysis as described in the current Eurocode code. A suggestion is given for a slightly modified imperfection formula within the Ayrton-Perry formulation leading to adequate inclusion of modern high grade steels within the original four buckling curves. It is also suggested that finite element or frame analysis may be performed with equivalent column bow imperfections extracted directly from the Ayrton-Perry formulation.

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ABSTRACT: The structural resistance of high-strength steel seamless tubular beam-columns of circular cross-section subjected to axial compression and bending loading is investigated, using experimental testing and numerical finite element simulations. Experiments on short and slender seamless tubular specimens are conducted, and simulated with rigorous finite element models. Prior to experimental testing, initial imperfections and residual stresses are measured, and the measurements are taken into account in the numerical models as initial conditions. A good comparison is achieved between numerical simulations and experimental results in terms of ultimate strength capacity. Using the finite element tools, parametric numerical analyses are conducted under combined axial-bending loading conditions. First, the influence of initial imperfections (wrinkling) on the structural behavior of high-strength steel tubular members is examined, in terms of their cross-sectional strength. Subsequently, stability curves for axial compression, and thrust-bending interaction diagrams for the high-strength steel tubular members are obtained. The cross-sectional strength, the stability curves and the interaction diagrams obtained numerically are compared with existing relevant provisions of European and American specifications (EN 1993, API RP 2A and AISC) for the design of beam-column tubular members. The comparison shows that the provisions of those specifications, originally developed for mild steel CHS members, result in reasonable, yet conservative, predictions for the structural resistance of high-strength steel seamless CHS members. It is also suggested that significant improvement of EN 1993 predictions can be achieved revising the classification of high-strength steel CHS sections.

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ABSTRACT: This paper presents a comprehensive study on local web buckling behaviour of double-coped steel beam connections, cases which are common when beams of similar heights are joined. The study commenced with a series of full-scale tests on 11 specimens, covering a spectrum of cope lengths and cope depths. Local web buckling was observed as the main failure mode for most specimens. The ultimate load was found to decrease with increasing cope length and cope depth, and in addition, an increase of the rotational stiffness of the beam end connection could benefit the local web buckling capacity. A numerical study was subsequently performed enabling further interpretation of the test results. Good agreements were observed between the test results and finite element analysis predictions, and the stress conditions within the cope web panel at different loading stages were fully revealed. The numerical study also showed that the ultimate loads of some models were not sensitive to initial imperfection amplitudes, especially when the cope length was large (i.e. 450 mm or longer). It was believed that the imperfection insensitivity characteristic was due to the presence of post-buckling mechanism. Summarising the available test data, including the current test results and those previously reported by other researchers, design comments were made through comparisons against the existing design method. Conservative test-to-predicted ratios were generally shown, but unsafe predictions were
obtained for some cases. A modification to the existing design approach was finally proposed for safer design of such connections.


ABSTRACT: The application range of the current EN 1993-1-1 [1] for column buckling resistance determination is limited for steel materials up to the steel grade of S460. The EN 1993-1-12 [2] gives design rules for materials up to steel grade of S700. The stability failure of HSS steel structures is very important in the design, because due to the higher yield strength smaller cross sections can be used, which might be more sensitive for stability failure. According to the previous research results, the global buckling behavior of HSS and NSS columns can be significantly different, however these differences are not considered in the Eurocode based design process. The purpose of the current research is to study the column buckling behavior of HSS cold-formed hollow section columns based on previous and current experimental investigations and based on numerical simulations. This paper focuses on the effect of the different material properties, imperfections and residual stresses on the global buckling behavior of HSS members and to give design proposals for the applicable column buckling curves for steel grades between (S420) S500 and S960.

References listed at the end of the paper:
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ABSTRACT: Spiral welded tube (SWT) structures have found worldwide application in pipeline construction, wind turbine towers, foundation piles, and columns in tall buildings. However, the understanding of their fundamental behaviour is still insufficient and efficient analysis and design methods have not been precisely developed owing to the lack of experimental and numerical research on these types of structures. A distinct advantage of SWT is their streamlined manufacturing process, so that today large diameter SWT can be economically produced. Due to the application of SWT as structural members being relatively new, this paper presents an investigation into the behaviour of hollow and concrete-filled steel SWT columns when subjected to axial compressive loading. Parameters of particular interest affecting the strength and failure modes include the weld's spiral geometry and initial imperfections from the production process. To evaluate the behaviour of SWT columns, an accurately developed finite element model (FEM) which incorporates the effects of initial local imperfections and residual stresses using the commercial finite element program ABAQUS has been prepared. The FEM buckling behaviour of SWT is compared with that of longitudinally welded tubes (LWTs). Experimental laboratory testing is carried out on twenty columns under displacement-controlled loading conditions in order to calibrate and verify the accuracy of the model results. Furthermore, a design model is proposed for circular concrete-filled steel tube columns. In addition, comparisons with the prediction of axial load capacity using the proposed design model, Australian Standards, Eurocode, and American Institute of Steel Construction code provisions for hollow and concrete-filled SWT and LWT columns is also carried out.

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common nominal residual stresses and geometric imperfections in test simulations. In addition, these members subjected to uniform moment. These studies justify the use of as low as one

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aims to resolve this disconnect

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Lakshmi Subramanian and Donald W. White (Georgia Institute of Technology, United States), “Resolving the disconnects between lateral torsional buckling experimental tests, test simulations and design strength equations”, Journal of Constructional Steel Research, Vol. 128, pp 321-334, January 2017

DOI: 10.1016/j.jcsr.2016.08.009

ABSTRACT: The lateral torsional buckling (LTB) resistance equations of the current AISC and AASHTO Specifications are based on unified design provisions. These provisions are a fit to a large body of experimental test data for light to medium weight rolled and welded I-section members. The resulting nominal LTB resistances differ considerably from those of the Eurocode provisions, which tend to provide a lower-bound fit to experimental and simulation data. It is observed that finite element test simulations conducted with defacto standard practices commonly predict lower capacities than indicated by experimental tests. This disconnect is shown to be partly due to the use of simple deterministic residual stress patterns and geometric imperfections in test simulations that are conservative approximations of the true values occurring in physical tests. This paper aims to resolve this disconnect by employing an “inverse solution” approach, wherein appropriate simplified residual stresses and geometric imperfections to model in test simulations are determined based on correlation with experimental data. In addition, the paper presents the results of extensive sensitivity studies on I-section members subjected to uniform moment. These studies justify the use of as low as one-half the magnitudes of common nominal residual stresses and geometric imperfections in test simulations. In addition, these
comparisons justify reductions in the “plateau length,” $L_p$, used in the AISC and AASHTO flexural resistance calculations, as well as in the stress limit $F_{ly}$ in AISC and $F_{y}$ in AASHTO corresponding to the applicability of the theoretical elastic LTB equations.

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Three different section forms were conducted in this paper. The results of finite element analysis are close to the capacity tests and finite element analysis of nine multi-columns [1].


DOI: 10.1016/j.jcsr.2016.09.005

Multi-columns built-up cold-formed steel stub column is a main structural member consisting of a single C-shaped and U-shaped basic component connected by self-drilling screws. Axial compression bearing tests and finite element analysis of nine multi-columns built-up cold-formed steel stub columns with three different section forms were conducted in this paper. The results of finite element analysis are close to the


Fangfang Liao, Hanheng Wu, Ruizhi Wang and Tianhua Zhou (School of Civil Engineering, Chang’an University, Xi’an 710061, China), “Compression test and analysis of multi-limbs built-up cold-formed steel stub columns”, Journal of Constructional Steel Research, Vol. 128, pp 405-415, January 2017

DOI: 10.1016/j.jcsr.2016.09.005

ABSTRACT: Multi-limbs built-up cold-formed steel stub column is a main structural member consisting of a single C-shaped and U-shaped basic component connected by self-drilling screws. Axial compression bearing tests and finite element analysis of nine multi-limbs built-up cold-formed steel stub columns with three different section forms were conducted in this paper. The results of finite element analysis are close to the
test results, which verify the accuracy of the finite element analysis. In order to study the influence of width–thickness ratio and screw spacing on the bearing capacity of the build-up column, the parametric analysis was carried out on the maximum width–thickness ratio of the plates and the screw spacing. The results show that the failure modes of all specimens are local buckling and distortional buckling. Multi-limbs built-up cold-formed steel stub columns consisting of a few basic components can work in harmony, the integral behavior is desirable. The axial load bearing capacity of the multi-limbs built-up section stub column increases when the maximum width–thickness ratio of the plates decreases; the screw spacing has a little impact on the ultimate axial compressive capacity and the buckling capacity of the multi-limbs built-up cold-formed steel stub columns.

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ABSTRACT: A novel partially connected buckling-restrained steel plate shear wall as a robust and effective lateral load-resisting system is proposed in this paper. The influence of the superposition of the tension field and the high-order buckling deformation of the inner steel plate which is called “panel action” on the behavior of the new system is investigated. A modified method considering the effect of the panel action is developed to determine the minimum stiffness requirements of the vertical boundary elements so that the tension field will fairly uniformly form in the diagonal area. In addition, the nonlinear finite element method is adopted to carry out the push-over analysis to evaluate the effect of the initial imperfection on the behavior of the proposed shear wall. Meanwhile, based on the FE models validated using the available test data, an extensive parametric study is also performed to examine the effect of a change in the second moment of area of VBEs on the behavior of the novel shear wall. Finally, the FE results are compared with that predicted by the proposed method and a reasonable agreement is generally achieved between them.
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[1] A. Astaneh-Asl, Seismic behavior and design of steel shear walls SEOANC Seminar, Structural Engineers Associate of Northern California, San Francisco (2001)
ABSTRACT: This paper examines the behaviour of steel beams with web openings under combined axial compression, bending moment and shear force through numerical simulation modelling. The numerical simulation results show that under either pure compression or pure bending, the plastic axial or bending capacities of beams are limited by buckling of the compressive tee-section with the reduction being much more significant in the case of axial compression. The numerical study results also show that when dealing with the general situation of a beam under combined axial compression, bending moment and shear force, the effect of compressive force and consequent tee-section buckling should be included to reduce both the bending moment and shear resistances of the perforated section. Based on the numerical simulation results, an analytical method has been derived. The method was developed by modifying existing shear-moment interaction equations for the Vierendeel mechanism to incorporate the influences of tee-section buckling and additional compressive force in reducing the bending moment and shear capacities. To account for the effects of additional compression force on bending resistance, the plastic moment-axial compression interaction equation may be used, however, the plastic bending moment capacity (without axial compression) and the plastic compression resistance (without bending) should be replaced by those under the influence of T-section buckling. To allow for T-section buckling, an effective T-section buckling length of 0.5L or L (where L is the T-section length) should be used when calculating the bending moment or compression resistance of the perforated section. The shear resistance of the perforated section is obtained by calculating a critical shear stress in the T-section. This critical shear stress -direct stress interaction is according to the von Mises equation, but the square power in the von Mises equation is replaced by a function that reflects the influence of T-section buckling. A comparison between the numerical simulation results and the analytical results using the proposed method indicates very good agreement, with the inaccuracy mainly attributed to inaccurate calculation of the bending – shear interaction of the existing methods which do not consider the effects of additional compression and T-section buckling.

References listed at the end of the paper:
With the help of this model, the interaction between individual member buckling and structural global complete loading period by using one element, especially the inelastic post-buckling behaviors of members of single layer reticulated domes under severe earthquake. The model was established based on finite element (FE) method and it can well reflect the performance of individual member during the complete loading period by using one element, especially the inelastic post-buckling behaviors. By using the model, the failure behavior of single-layer reticulated domes under severe earthquake can be well captured. With the help of this model, the interaction between individual member buckling and structural global

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ABSTRACT: This paper focuses on proposing an efficient theoretical strut model to predict the post-buckling behaviors of members of single-layer reticulated domes under severe earthquake. The model was established based on finite element (FE) method and it can well reflect the performance of individual member during the complete loading period by using one element, especially the inelastic post-buckling behaviors. By using the model, the failure behavior of single-layer reticulated domes under severe earthquake can be well captured. With the help of this model, the interaction between individual member buckling and structural global
instability can be accounted, and then the influence on plastic internal forces redistribution due to the degradation of bearing capacity of members under large displacement can be well depicted. The model is suitable for severe seismic analysis as it involves a wider range of strain than the existing phenomenological models. At last, the efficient model is verified by several experiments and good agreement is found between the simulated and experimental results.

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ABSTRACT: The conventional discrete element method (DEM) is usually applied to solve the elastic problems of granular materials. The DEM fibre constitutive model, which can consider the plasticity development of a cross-section, is derived, and then the fracture simulation algorithm for members is established based on the elastic–plastic analysis using this fibre model. Thus, the DEM is extended to study the continuum structures. Next, the proposed method is applied to the collapse simulation process of two single-layer reticulated dome test models. The simulation results, including the collapse process and the fracture location of joints, agree well with the shaking table test measured response. In addition, the displacement responses of representative nodes and axial force responses of representative members also are consistent with the experimental measured response, which demonstrates the accuracy and validity of this method. This study provides a new numerical analysis method for further investigation of the complicated mechanical behaviour—including large deformation, material nonlinearity and fractures—of large or super-large member structures.

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ABSTRACT: The paper addresses the ultimate buckling strength of thin-gauge axially loaded lipped channel columns with initial geometrical imperfections related to execution tolerances. For computational modelling of the column strength respecting the tolerance limits a deterministic method employing geometrical and material nonlinear FEM analysis with imperfections (GMNIA) is suggested. The imperfections are assumed in the shapes of eigenmodes of the corresponding linearized buckling problem and their combinations. For comparing their influence on the column strength, the imperfections are normalized by the energy measure. The comparison is carried out on the top energy measure level limited by execution tolerances. Referring to published experimental work three cross-sections and several column lengths are considered in a numerical study. Summarizing the numerical results and abilities of the energy measure to facilitate the treatment, guidance for the use of FEM GMNIA in the estimation of the column least strength is suggested. References listed at the end of the paper:

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ABSTRACT: The paper addresses the ultimate buckling strength of thin-gauge axially loaded lipped channel columns with initial geometrical imperfections related to execution tolerances. For computational modelling of the column strength respecting the tolerance limits a deterministic method employing geometrical and material nonlinear FEM analysis with imperfections (GMNIA) is suggested. The imperfections are assumed in the shapes of eigenmodes of the corresponding linearized buckling problem and their combinations. For comparing their influence on the column strength, the imperfections are normalized by the energy measure. The comparison is carried out on the top energy measure level limited by execution tolerances. Referring to published experimental work three cross-sections and several column lengths are considered in a numerical study. Summarizing the numerical results and abilities of the energy measure to facilitate the treatment, guidance for the use of FEM GMNIA in the estimation of the column least strength is suggested. References listed at the end of the paper:
Thin-walled structural channel members are commonly manufactured with cut-outs to allow access for building services such as plumbing, electrical and heating systems in the walls and ceilings. The presence of holes in the members will cause changes in the stress distribution and there will be consequently changes in the buckling characteristic and ultimate strength capacity. Recent work by Pham and Hancock has provided solutions to determine the shear buckling load using the Spline Finite Strip Method (SFSM) for whole thin-walled channel sections without holes. In this paper, the same methodology is utilised to study and provide solutions to the elastic shear buckling firstly for the perforated square plates and subsequently for the whole thin-walled lipped channel sections with centrally located holes. Both circular and square holes with the same sizes and diameters were chosen for investigation. The main variables are the diameters of the circular holes and the sizes of the square holes. While there is only uniform pure shear applied throughout in square plates, three different cases for shear loading in the channel are considered to maintain longitudinal equilibrium. The method is also benchmarked against the Finite Element Method (FEM) using software package ABAQUS/Standard in.
all cases. Comparisons between hole shapes, loading cases and buckling modes of both square plates and channels are included. For design purposes, approximate equations for shear buckling coefficients of square plate and channel section containing central circular and square holes are also proposed in this paper. Design example is also provided for design purposes.

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ABSTRACT: A new approach to estimate the web crippling failure load of cold-formed steel beams under Internal Two Flange (ITF) loading using the Direct Strength Method (DSM) is proposed in this paper. After the description of the existing test data to calibrate the DSM based formula, the accuracy of the analytical expressions given in Eurocode 3 [1] and the North-American Specification [2] is briefly assessed. In order to obtain additional information on the web crippling behaviour of each test specimen, several types of analyses are performed: (i) quasi-static non-linear analyses (using finite elements), (ii) elastic buckling analyses (using finite elements and the GBTWEB software), and (ii) rigid-plastic analyses (using yield-line theory). The coefficients of a DSM-based formula are determined on the basis of the set of 85 experimental results available in the literature and the corresponding buckling and plastic load values. In spite of the different cross-sections, fastening conditions and test set-ups considered in the calibration procedure, it is possible to establish a clear
relationship between the web crippling slenderness and the nominal-to-plastic load ratio. Finally, it is shown that the proposed DSM-based formula for ITF loading yields reasonable predictions of web crippling loads and provides safe estimates of flange crushing loads.

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ABSTRACT: This paper presents a design proposal for the out-of-plane buckling resistance of prismatic beam-columns subject to axial compression and uniaxial major-axis bending that was developed based on the well-known Ayrton-Perry formula. Firstly, the relevant theoretical background is summarized, closely following the theoretical derivation performed by Szalai and Papp (2010). Secondly, the required transformations for the engineering application of the design procedure are detailed and extended to arbitrary bending moment distributions. Appropriate generalized initial imperfection factors for the out-of-plane buckling of beam-columns are defined so as to achieving complete consistency across the stability verifications for columns, beams and beam-columns. The proposed procedure is subsequently validated against a large set of advanced numerical simulations. A good agreement was found between the numerical results and the estimates provided by the proposed design procedure, both in terms of the overall trend and the specific quantitative results. Based on a statistical assessment, the comparison with the interaction expression of Eurocode 3 (2005) (method 2) showed that this proposal slightly outperforms the Eurocode procedure, both in terms of average values and dispersion of results.

References listed at the end of the paper:


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Abstraction: The recently incorporated Direct Strength Method (DSM) rules for shear in the North American Specification for Cold-Formed Steel Structural Members (NAS S100:2012) consist of design equations for unperforated sections with and without Tension Field Action (TFA). The TFA is mobilised as a result of the strain hardening of the steel strips in the vicinity of the slots, which is induced by the lateral-torsional buckling of tapered beams. The slotting of the steel strips enhances the energy dissipation capacity of the restrained steel plate shear wall (SPSW) and reduces the shear force and energy dissipation ratio. The slotted SPSW can sustain a roughly 2.8% lateral drift ratio without a reduction of the shear force and energy dissipation ratio.

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Abstraction: This paper presents a novel buckling-restrained steel plate shear wall with inclined slots (simply referred as “slotted SPSW”) that can be used as an energy dissipation device of structures. The slotted SPSW consists of boundary members and an inner steel plate with inclined slots sandwiched between two external concrete panels which provide lateral restraints. The steel strips between the inclined slots behave like a series of struts to dissipate the energy through inelastic axial deformation during reversal loading. Theoretical analyses and finite element monotonic pushover analyses are conducted to investigate the general behavior of slotted SPSWs. Calculations for shear resistance is determined to consider the reduction coefficient of inclined slots. Some key parameters, such as the width of steel strips, and steel panel slenderness, are investigated through numerical analyses. A half-scale slotted SPSW quasi-static cyclic test was carried out to provide the data about the general behavior of the slotted SPSWs. When a slotted SPSW is properly detailed and fabricated, buckling failure of the steel strips can be avoided and the slotted SPSW can sustain a roughly 2.8% lateral drift ratio without a reduction of the shear force and energy dissipation ratio.


Abstraction: The recently incorporated Direct Strength Method (DSM) rules for shear in the North American Specification for Cold-Formed Steel Structural Members (NAS S100:2012) consist of design equations for unperforated sections with and without Tension Field Action (TFA). The TFA is mobilised as a result of the...
development of diagonal tension due to the full depth bolt restraints. The design shear equations based on a reduction factor $\alpha$ to account for reduced TFA were proposed by Pham and Hancock in cases of partly bolted connections with lateral flange restraints. This paper presents an experimental program to further investigate the TFA of cold-formed C-sections in shear. A total of twelve tests were carried out at the University of Sydney. Three different bolted connection configurations were chosen with and without lateral restraints of the top flanges at the supports. Numerical simulations using the Finite Element Method (FEM) were also performed to validate test results and extend data range. For tests without lateral flange restraints, combined twisting and shear failure modes were observed. The lack of lateral flange restraint leads to a significant reduction of the ultimate load especially when more bolts were removed. Based on these experimental and FEM modelling data, a further reduction factor $\beta$ dependent upon the slenderness of the sections is introduced in this paper to account for the lack of lateral flange restraint along with the previously proposed reduction factor $\alpha$ which accounts for bolt reduction.

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ABSTRACT: A new type of large-section high strength steel Y-shaped (HSSY) column was presented. 24 specimens in total were designed and subject to experiment in order to investigate the overall buckling behavior. The columns including two commonly-used slenderness ratios of 35 and 40 were divided into two groups for axial and eccentric compression, respectively. Prior to the buckling test, the material properties, initial geometric imperfections and longitudinal residual stresses were measured. The buckling deformations and ultimate strengths were obtained by test and compared with numerical results, which were based on validated finite element models taking the real initial imperfections and boundary conditions into account. A good agreement was reached between the test and numerical approaches. Buckling factors and column curves of axial compression specimens were obtained and compared with existing code design curves. To accurately predict the overall buckling strengths of HSSY columns, recommended column curves and their formulae corresponding to different codes were proposed through nonlinear regression method. In addition, the influence of loading eccentricity on ultimate buckling capacity was analyzed. Furthermore, the cross section efficiency was formulated and criteria for section optimal selection were concluded for making the best use of the column. Finally, a variety of large-section and medium-section columns with potentially high utilization ratios were recommended for engineering application.

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ABSTRACT: For compression members with primarily axial forces, steel angles with bolted connections are often used. Due to the eccentric connection on only one leg additional bending moments are acting on the member, leading to a complex load carrying behaviour with flexural and/or lateral torsional buckling phenomena. The paper mainly focuses on the presentation of the influence of realistic end support conditions at
the gusset plates on the member capacity in compression. In the first part of the paper, about 300 existing test results for steel angles in compression with bolted connections are prepared in such a way that they can be compared with different design rules. This was achieved through the common representation of all test results as a function of the normalized slenderness $\bar{\lambda} v$ about the weak axis. In the second part, systematic numerical calculations are conducted for limit cases of the stiffness of the boundary condition of the load-introducing gusset plates (rigid/hinged). The results are also presented in dependency of the relative slenderness $\bar{\lambda} v$. The consolidation of all tests and numerical results shows (besides the well-known difference between one-bolt and two-bolt connections) a very high influence of the end support of the gusset plate.

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ABSTRACT: Extensional and in-extensional folding elements are two conventional plastic collapse mechanisms for thin-walled tubes to predict their anti-crushing behaviors. In the compression experiments of triangular tubes, a new folding element, named as inward-contracted folding element, was observed. Accompanying with this folding mechanism, double zigzags and half-shortened wavelength were observed in the corresponding deformation curve compared with the deformation curves of tubes collapsing at conventional modes. This inward-contracted folding element always follows behind the extensional folding to form a hybrid folding element. A plastic model was proposed, through which the mean crushing force (MCF) and the folding wavelength are predictable.

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ABSTRACT: Multi spine composite concrete-deck steel-box girder bridges became a very popular choice in highway bridges due to their high torsional and wrapping stiffness as well as for economic and aesthetic reasons. This study presents an experimental investigation on both elastic and ultimate behavior of composite box girder bridges in order to study the effect of internal cross bracing between box girders along with the curvature effect at different loading stages. Three composite concrete deck-steel simply-supported twin-box bridge models, two curved and one straight, were fabricated, and tested. First, the response of each model was monitored under free-vibration excitation, then an eccentric loading was applied and the corresponding deflections were recorded in the elastic range. Finally, the bridge models were tested up to collapse. The structural behavior of the three bridge models was compared at the three loading stages. It was noticed that the presence of an external cross bracing system between the steel boxes had an insignificant effect on the developed deflection and the fundamental natural frequency in the elastic range of loading. On the other hand, these external bracings assisted in decreasing the developed deflection approaching failure and in increasing the load carrying capacity by about 8.9%. In addition, the external bracing ensured a better distribution of the stresses under ultimate
loading conditions. Moreover, the experimental findings were verified numerically using finite element modeling. A good agreement was noticed to exist between the experimental findings and the numerical results.

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ABSTRACT: Steel-concrete-steel (SCS) sandwich structures consisting of two steel face plates infilled with lightweight cement composite material has been developed. This paper reviews the recent innovations of SCS sandwich structures subject to blast, impact, fatigue, and static loads. Novel J-hook connectors, high strength steel plates and new lightweight cement composite materials have been considered for the development of the SCS sandwich products to improve their strength-to-weight performance. Extensive tests have been conducted to investigate the effectiveness of J-hook connectors to achieve better composite action to resist flexural, shear, impact, blast and fatigue loads. Flat and curved SCS sandwich plates under patch loading are also investigated. The experimental results are essential to understand the structural behaviour of the SCS sandwich structures and to provide data for the development of analytical models for design implementation. Design equations have been proposed to predict the shear and tensile resistances of J-hook connectors and to determine the flexural, shear, impact, blast and fatigue resistances of SCS sandwich beam. The punching shear resistance of sandwich shells and compression resistance of sandwich walls are also investigated. The accuracy of the design equations are validated by the test data and finite element analysis results.

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ABSTRACT: Concrete-filled steel tubular (CFT) columns and high-strength steel have been increasingly used in construction. However, the application of high-strength steel in CFT columns has not been permitted in many design codes. This paper reports an experimental investigation on the behavior of rectangular CFT beam-columns using high-strength steel. The influences of the in-fill concrete, eccentricity ratio and the width-to-thickess ratio on the resistance of the test columns are discussed. The contact behavior is studied using the finite element analysis. Chinese code DB 29-57 adopts the assumption that the concrete bears the axial load only, and the steel tube withstands the bending moment and part of the axial load. A new N-M interaction approach is developed based on the foresaid assumption to account for the plastic behavior of high-strength steel. The approach is verified by the experimental results and the available current design codes to be reasonably conservative, and it can be employed to design rectangular CFT beam-columns using high-strength steel.
ABSTRACT: The development of all-steel tube-in-tube buckling controlled brace (TinT-BCB) is presented. The efficiency of the TinT-BCBs is evaluated experimentally and numerically. The cyclic behavior and fracture life of TinT-BCBs was first investigated through physical testing, followed by FE-based simulations revealing the inherent correlation between fracture and peak cyclic strain in load-bearing braces. The cyclic strain in plastic zones was recorded up to 0.02 strain range during the cyclic tests, enabling the study to use the recorded strain in verifying the FE simulation models. The strain response of plastic zones was captured by the FE simulation up to fracture in conventional large-size braces. The paper concludes that (1) the TinT-BCB, developed based on the buckling-controlling concept, has demonstrated stable and symmetrical cyclic response, with global and local buckling controlled up to 0.035–0.04 story drift ratio; (2) the TinT-BCB is proven to be effective in elongating cyclic fracture life of conventional CBF from 2% SDR to 3.5–4% SDR by adding simple buckling controller. The cost for adding the buckling controller is low in comparison with the substantially increased lateral strength and energy dissipation capacity; and (3) the efficiency of the TinT-BCB in improving overall cyclic behavior in general and elongating fracture life of braces in particular is attributed to its ability in controlling highly concentrated strain in plastic zones of conventional braces. By spreading the concentrated strain demand throughout the entire length, the buckling controller is shown to reduce excessive peak strains in conventional braces by 7–8 times.

ABSTRACT: Reinforced concrete (RC) shear wall is one of the predominant structural components used extensively in high-rise buildings to resist lateral loads induced by earthquakes around the world. However, the past earthquake experience and previous research indicated that RC shear walls at the bottom of high-rise buildings may display the undesirable performance when subjected to severe earthquakes. For this reason, the steel plate reinforced concrete (SPRC) composite shear walls have been developed, and especially popularly used in super-tall buildings in China Mainland in recent years. At first, the application of SPRC shear walls in China Mainland is briefly introduced. Then the modelling techniques with the aid of software OpenSees to simulate the hysteretic behavior of SPRC shear walls are presented and validated by typical experimental results. The verified numerical model is further used in the parametric study focusing on a number of important parameters, including the steel plate ratio, the axial compressive load ratio, the concrete strength, and the web reinforcement ratio. The results of this parametric study provide useful information for the engineering application of SPRC shear walls.

ABSTRACT: A new assembled buckling-restrained brace (ABRB) wrapped with carbon or basalt fiber cloth is proposed. It has the following advantages: 1) it can be disassembled by cutting the fiber cloth; 2) it is easy to inspect and repair the core plates after destructive earthquakes; 3) the outer fiber material also serves as a corrosion resistance to the outer steel tube. A total of eight ABRB specimens were tested under quasi-static axial loads. The test results indicate that the ABRB is capable to undergo fully-reverse yielding cycles without loss of stiffness and strength with sufficient ductility and energy absorption capacity. Multi-wave buckling occurred on the core plates of ABRBs resulting in “jumped” hysteretic curves in compression stage. ABRB specimens fractured in the middle of the core plate elements when a loading protocol included increasing deformation amplitudes with additional fatigue cyclic loading; while when the loading protocol consisted of increasing deformation amplitude cyclic loading without maximum amplitude limit, rupture of the ABRB specimens occurred at the junctions of yielding segments and non-yielding segments of core plate. When a pair of restraining members of an ABRB are connected and restrained with fiber cloth, the assembled constraint mechanics can resist the lateral thrust exerted by core plate. The nonlinear finite element analysis results show good agreement with the experimental data. Both the results from the experiment and numerical simulation show that the proposed ABRBs can satisfy the performance requirements for the BRB components and provide a beneficial alternative for BRB fabrication and application.


ABSTRACT: Longitudinally unstiffened steel I-girders are commonly used structural elements in the engineering practice. Previous research results proved that the current design method of the EN1993-1-5 EN 1993-1-5 (2005) for M-V interaction check is not always on the safe side for longitudinally stiffened girders, however a systematic review of the M-V interaction behaviour for unstiffened girders was missing from the international literature. The aim of the current paper is to analyze the M-V interaction behaviour of longitudinally unstiffened I-girders with slender webs and to determine the applicability interval of the M-V interaction resistance model of the current EN1993-1-5 EN 1993-1-5 (2005) . Based on the executed numerical investigation a refined M-V interaction equation is proposed to ensure safe design in the whole analyzed parameter range.

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ABSTRACT: Experimental study on thin-walled welded steel beam-to-column connections under cyclic large plastic strain loading was conducted. Severe shear buckling in panel zones was observed during the testing. The connections have stable and excellent seismic performance, and finally failed due to the post-buckling ductile fracture. This paper aims to numerically simulate the post-buckling ductile cracking process using a proposed micro-mechanism based ductile fracture model, and further investigate critical factors, such as equivalent panel
zone width-to-thickness ratio, axial load ratio and initial geometrical imperfection, that affect cracking behaviors of the connections. The cyclic ductile fracture model is verified with the experimental data, and employed to conduct the parametric analyses. Deterioration of stress-carrying capacity is also considered, so the fracture model can successfully simulate the load decrease in the load-displacement curves of the experimental results.


ABSTRACT: Thin-walled cold-formed steel beams are investigated with existing experimental data and shell finite element simulations to characterize their in-plane moment-rotation behavior, up to and past peak strength, in local or distortional failure modes. Although ultimate strength prediction of cold-formed steel members is generally well addressed in design codes, pre- and post-peak member stiffness is only partially addressed; while member ductility and post-peak moment-rotation response suffers from a lack of any clear guidance. Without fundamental information on cold-formed steel moment-rotation/curvature response, i.e. the backbone curve, system modeling for cold-formed steel structures to collapse remains severely hampered. Existing data on cold-formed steel beams are used as the basis for the study conducted herein. Simplified moment-rotation models, motivated from ASCE 41 characterizations, defined with pre-peak flexural rigidity degradation, post-peak plateau and strength drop are explored by equating the area under the backbone moment-rotation response (energy) between the available data and simplified models. In-plane response of cold-formed steel beams is parametrized with new design expressions depending on local and distortional cross-section slenderness. This research provides work for potential incorporation into design standards such as ASCE 41 and AISI S100. Out-of-plane response of cold-formed steel beams, including lateral-torsional buckling, remains as needed future work.


ABSTRACT: Cruciform diaphragm welded joints (CDWJ) has been adopted in large-span single-layer latticed shell as a new type of joint. The behavior of such kind of joint has not been well studied and understood. In this paper, the in-plane bending hysteretic behavior with axial force of CDWJ was investigated by performing both experimental tests in full scale prototypes and nonlinear numerical analyses. The results in terms of behavior, ultimate load and collapse mode were analyzed and compared. Experimental and numerical analysis results had good agreement for the CDWJ. Parametric analysis was performed on 14 CDWJ considering the influence of geometric size of components, angle between tubes and the axial compressive ratio. Moreover, Menegotto-Pinto mathematical model was established to describe the nonlinear rotation stiffness of CDWJ.

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ABSTRACT: The use of high strength materials in steel-concrete composite members is expected to provide greater resistance meanwhile fulfilling the requirements of sustainable construction. Many of the modern design codes place some limits on the strength of steel and concrete in designing steel-concrete composite members due to limited test data and design experience on their applications in construction. The use of high strength materials was found to have noticeable benefits in high-rise building construction. To extend their applications, a comprehensive experimental program has been carried out to investigate the behaviour of concrete filled steel tubes (CFSTs) with high tensile steel and ultra-high strength concrete at ambient temperature. This paper presented new test results on the structural performance of CFST members subject to flexural loads. High tensile steel with yield strength up to 780 MPa and ultra-high strength concrete with compressive cylinder strength up to 180 MPa were used. The test results seek to clarify if the cross-section plastic moment resistance can be achieved if high tensile steel and ultra-high strength concrete are used in CFST members. The maximum moment resistance from tests were compared with the analytical results predicted by Eurocode 4 method. Then design recommendations were provided so that Eurocode 4 method could be safely extended to determine the flexural resistance of CFST members with high tensile steel and ultra-high strength concrete.


ABSTRACT: According to European building code provisions, compression diagonals should be neglected during the analysis stage of concentrically braced frames (CBFs) with X and N type bracings, and the inelastic capacity of the tension bracings only should be considered in the design. This provides simplifications at analysis and design stages for practising engineers. Such an assumption can be rational in the high-seismicity context, where the compression bracings undergo buckling at the early stages of the seismic event, and the shear demand is very high. On the other hand, in moderate seismicity areas (that is estimated as the 90% of the seismic regions of the world), where the shear deformation demand for braced frames and the number of high-amplitude cycles are very limited, it may be reasonable to consider both tension and compression diagonals in the analysis. Accounting for compression diagonals at the analysis stage, and exploiting their post-buckling resistance and dissipative contribution in design, may allow using a higher behaviour factor, and increase the economic efficiency of CBF structures in moderate seismic regions. To understand the real seismic performance of braced frames in moderate seismicity areas, a sound characterization is needed, focusing on behaviour of compression diagonals. In the literature, many tests have been performed to analyse the behaviour of bracing elements, but they were mostly designed to meet high seismicity criteria with significant connection over-strengths. The European research project RFSR-CT-2013-00022 MEAKADO investigated the influence of compression diagonals on the global performance of CBF structures, by means of experimental and numerical studies. This paper presents the results of full scale tests performed within this research project, focusing on the stiffness and post-buckling performances of double-angle bracings with bolted connections, which are the most common bracing configurations in the European construction market characterized by low-to-moderate seismicity. Experiments have shown that extra stiffness and strength provided by the contribution of the compression diagonals to the structural response are significant for moderate seismicity drift and shear demands, and may be worth considering in the analysis and design phases.
ABSTRACT: The coupled steel plate shear wall (CSPSW) is an efficient lateral load resisting system consisting of two or several steel plate shear walls connected to each other in story levels in order to increase the lateral strength. In this paper, 4-story capacity designed CSPSWs are considered with different cross section size and lengths for coupling beams to capture shear, flexural and shear-flexural failure modes in these members. The specimens are modeled using nonlinear finite element method and analyzed under cyclic loading. A comparison of performance characteristics including shear strength, plasticity factor, energy dissipation, stiffness variation and Von-Mises stress distribution of models are presented. According to the results, the shear resistance and energy dissipation of models increases with the increase of capacity and length of coupling beams. The difference between FE shear resistance and the predictions from theoretical calculations decreased as the capacity and length of coupling beams increased. With an increase in the coupling beam capacity and/or decrease of its length the wall deformations was changed from shear into flexural mode. The hysteretic behavior of coupling beams leads to the suggestion of these beams rotation as design criteria of CSPSWs.


ABSTRACT: This paper presented seismic behavior of a novel Self-Buckling-Restrained (SBR) Steel Plate Shear Wall (SPSW) that was made by two Incline-Slotted Infill Plates (ISIPs) which were tied together by one rubber plate. The directions of the incline slots on the two ISIPs were opposite. Stable cycling responses of the SBR-SPSW could be achieved since at least incline strips on one plate were in tension under the cycle load. At the same time, the strips in tension could provide lateral support to those in compression on the other plate. Behaviors of the SPSW with two ISIPs and with one Solid Infill Plate (SIP) were compared to show advantages of the proposed SBR-SPSW. The stress state changed from the tension-compression bi-direction stress state in a SIP to uniaxial tension or compression in an ISIP. The cracks that usually encountered in a solid steel infill plate under repeated shear buckling could be avoided. And the incline steel strips yielded sequentially that could provide energy dissipation capacity at small drift ratio. At the same time, the ISIP could always ensure the plate yield prior to the frame yield. Parameters of ISIP, including the infill plate thickness, the strips width and the slot width, were investigated through finite element analyses. Shear strengths of the SPSW with two ISIPs decreased with the increase in slot width and increased with the increase in strip width. Design recommendation for the SBR-SPSW was provided as results of theoretical and numerical analysis. The shear strength of the SBR-SPSW made by two ISIPs could be calculated by simplified theoretical equations on the safe side.


ABSTRACT: Most of the previous studies on composite columns made of concrete-filled hollow sections in case of fire have addressed the effect of the depth-to-thickness ratio, column slenderness, initial applied load level, load eccentricity and local buckling in the steel tube on the fire resistance of these columns. However these studies have not analysed the influence of the axial and rotational restraint on the buckling behaviour of
these columns in case of fire. So, a series of fire resistance tests on this type of columns are presented and discussed in this paper. The primary test parameters taken into account were the column slenderness, type of cross-section, and axial and rotational restraining of the surrounding structure to the testing columns. The specimens were uniformly exposed to a fire curve and the critical times (fire resistance), failure temperatures and respective failure modes were assessed. The experimental results were still compared with the predictions from available analytical models in order to check if these are safe and consistent for fire design. Finally, results of this research study showed that the fire resistance of the columns may be not significantly affected by the stiffness of the surrounding structure and that the simplified calculation method for fire design of concrete filled hollow sections exposed to fire all around the column presented in Annex H of EN 1994-1-2:2005 is unsafe, except for the elliptical columns.


ABSTRACT: The paper describes the experimental and numerical investigation of the stabilization of cold formed thin-walled Z-beams by sandwich panels. The scope of the laboratory tests included sandwich panels freely placed on Z-beams and sandwich panels mechanically fastened to Z-beams by a diverse number of fasteners. It has been shown in laboratory experiments that the sandwich panels provide lateral stabilization of the thin-walled Z-beams. Moreover, the capacity of the thin-walled beam is determined by the number of fasteners along its length. The static and low cyclic loads were investigated. The FE model defined and presented in the paper allows for the accurate determination of the kinematical and mechanical elastic response of the thin-walled Z-beam stabilized by the sandwich panels, provided the specific bow imperfection of both the beams and the specific material parameters of the beams and the sandwich panel layers.


ABSTRACT: In this study, low cyclic loading tests were performed on nine seamless steel tube columns filled with recycled aggregate concrete (RAC) and two steel tube columns filled with normal concrete to analyse their seismic performance and damage mechanism. The hysteresis behaviour, skeleton curve, ductility coefficient, stiffness degradation, and energy dissipation capacity of the steel tube columns were studied. The influence of the axial compressive ratio, steel strength, and steel thickness on the seismic performance of the steel tube columns was discussed. In addition, the failure mode and damage mechanism of the specimens were investigated; a skeleton curve–fitting formulation based on the Boltzmann mathematical model was proposed. A damage degree–based model was built for representing the damage degree quantitatively. The results indicate that the RAC-filled steel tube columns exhibit a full hysteresis loop, the equivalent coefficient of viscosity ranges from 0.402 to 0.572, and the coefficient of energy dissipation ranges from 2.617 to 3.595. The comparisons between the two types of steel tube columns indicate that the seismic performances of the RAC-filled steel tube columns are similar to those of the corresponding normal concrete–filled steel tube columns and that the RAC-filled steel tube columns even have appreciably better lateral bearing capacity, better ductility, and slightly lower energy dissipation ability at the same displacement level. These results consistently indicate
that desirable seismic performance is achieved, and they serve as a potential reference for the structural design and application of RAC components in seismic areas.

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ABSTRACT: To promote special-shaped concrete-filled rectangular steel tubular (SCFRT) columns in high-rise buildings, this study proposes the innovative SCFRT column chevron concentrically braced frame. To study the seismic performance of the braced frame, this paper experimentally investigated the behavior of SCFRT column chevron concentrically braced frames subjected to constant axial load and cyclically flexural load. The braced frames exhibited rational failure mechanism, favorable ductility, and high deformation capacity. The hysteretic curves of the specimens were smooth and spindle indicating the good energy dissipation capacity of the braced frames. Stiffness and strength degradation were not obvious. Hence, the SCFRT column braced frame has good anti-seismic performance. The load carrying capacity and the stiffness increased with the increase of axial compression ratio, whereas, the energy dissipation ability and ductility decreased. The lateral stiffness, horizontal bearing capacity, energy dissipation capacity, and ductility could be improved significantly when the columns were strengthened from L-shape to combined T-shape and cross-shape.

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ABSTRACT: This paper studies the cross-sectional behaviour of austenitic, ferritic and duplex stainless steel hollow sections subjected to several loading conditions and presents a full slenderness range DSM approach for the prediction of cross-sectional strengths. Pure compression, pure bending moment and combined uniaxial bending and compression loading resistances are predicted using the same strength curve, which is based on experimental data gathered from the literature and ultimate strengths generated through parametric studies. The proposed approach is applicable to slender and stocky cross-sections leading to an accurate full slenderness range DSM design approach since the resistance reduction due to local buckling and the effect of strain hardening are taken into account, as is the effect of partial yielding of the cross-section in bending. A new method based on the actual stress distribution of the cross-section is also presented for combined loading conditions, where the cross-sectional behaviour is directly tackled through the same strength curve, providing more accurate results than the methods considering the uncoupled problem. Finally, a statistical analysis is presented to demonstrate the reliability of the proposed DSM approach.

ABSTRACT: Because of the booming of the winery industry in some seismic countries such as, the U.S, Italy, Chile and Argentina, the seismic protection of wine storage tanks may be of a practical importance. Previous numerical and theoretical investigations have shown that seismic isolation can reduce the seismic demand on liquid storage tanks compared to the fixed base case. However, there are not experimental works about the seismic performance and protection of legged wine storage tanks, nor practical applications, reported in the technical literature. Therefore, in this paper, the effectiveness of a novel seismic isolation system has been investigated by shaking table tests on a full-scale legged tank, typically used in the wine industry. A comparison of the seismic behaviour of fixed base and isolated base configurations is presented. Two alternative base isolation systems have been studied: flat sliding bearings with a central leg acting as restoring element, and flat sliding bearings without any restoring element. The restoring force of the central leg was performed by means of five compression springs. The experiments were carried out using 3 natural and 3 artificial records. Measurements were made of the shear and axial forces in one leg of the tank, and the horizontal displacement of the tank. The experiments showed the beneficial effects of using the proposed isolation system in legged wine storage tanks, reducing the shear and axial forces in comparison with the fixed base configuration and reducing the horizontal displacement compared to the flat sliding bearing configuration without any restoring element.


ABSTRACT: Thin-walled cold-formed hollow flange channel (HFC) sections are increasingly becoming popular due to their potential benefits such as increase in buckling capacities provided by the presence of two torsionally rigid hollow flanges and the elimination of free edges. Past research studies of HFC sections were limited to their shear and bending capacities. This paper investigates their section compression capacities through a series of stub column tests, followed by finite element modelling of welded HFC columns. The developed finite element models were validated using experimental results, and then used to investigate the section compression capacity of HFCs made by welding rectangular sections to a steel plate or cold-forming and rivet/screw fastening to hollow flanges, where steel plates with different strengths and thicknesses were used as web and flange elements. Extensive structural performance data of HFC stub columns subject to local buckling was thus obtained covering the effects of varying slenderness of plate elements and the use of different strength steels for web and flange elements. Furthermore, the applicability of the available design rules such as effective width and direct strength methods to predict the compression capacity of such HFC sections was also evaluated. Suitable recommendations are then proposed to improve their accuracy. This study facilitates and advances the use of HFC sections as compression members.


ABSTRACT: This study proposes a fiber-based hinge damage accumulation model that is able to replicate the nonlinear response of I-shaped beams of steel moment resisting frames. The model is developed in OpenSees
and consists of a beam with hinges element with fiber cross-section discretization within the plastic hinge zone. Among various plastic hinge integration methods, the modified Gauss-Radau integration scheme was selected. The proposed model incorporates strength and stiffness deterioration caused by flange local buckling of I-shaped beams which is simulated by assigning a calibrated low-cycle fatigue material model to flange fibers. In this formulation, fatigue material uses a modified rainflow cycle counting algorithm to accumulate damage based on Miner's rule. The values of fatigue material coefficients were calibrated against 16 experimental test results selected from the literature. An equation able to predict the fatigue ductility coefficient that follows a linear variation along the flange width is proposed based on regression analysis. In addition, a global damage index, DI, defined as the ratio between the number of fibers that reach fatigue and the number of fibers within the top and bottom flanges of I-shaped cross-section, is developed and a global damage index value associated with the onset of beam failure, labelled DI_{\text{prop}}(80\%) is proposed. An application comprising a single-storey, one-bay steel MRF is carried out in OpenSees, which validates the proposed beam model as computationally effective under cyclic quasi-static and dynamic loading.

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ABSTRACT: The stability of prismatic columns subjected to internal axial loads is a common issue during engineering analysis and design. Because of the big difference between the effects of internal loads and end loads, the traditional effective length method is not applicable. Current codes do not provide design method for this issue and engineers require the ability to analysis and design this kind of columns efficiently. Using the concept of negative stiffness, a relationship between end loads and internal axial loads applied on sway-permitted prismatic columns is established so that the internal loads can be considered equivalent to end loads and the critical value can be obtained easily by Euler formula. A practical method to determine the second-order effect is also developed. Eigenvalue buckling and elastic nonlinear analyses are performed to examine the proposed method and the comparison results indicate it has high accuracy.

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ABSTRACT: This paper addresses the characterization of the behaviour of the column web panel components in bolted end-plate steel joints subject to cyclic loading. Based on experimental test results, a calibrated parametric FE model of a double extended beam-to-column end-plate steel joint is implemented, that allows characterizing the behaviour of the joints both globally and in terms of the dissipative components. The numerical models have been developed using the ABAQUS FE package considering a detailed representation of the various joints components and taking into account the different sources of geometrical and material nonlinearities. Finally, based on the integration of the stress and displacement fields in predefined paths along
the column web, a detailed extraction procedure for the cyclic force-deformation behaviour of the column web panel components is proposed, however extensible to other components. These relationships are needed for implementation in a components based approach that accounts for cyclic loading conditions.

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ABSTRACT: Seven pinned double-rectangular tube assembled buckling-restrained brace (DRT-ABRB) specimens are investigated by axial cyclic loading tests in this study. The core member of the specimen is a single flat-plate, with two rectangular tubes assembled to form the external restraining member by high-strength bolts. Each rectangular tube is composed of external channel steel and an external cover plate. The influence of end detailing of DRT-ABRBs on the energy dissipation is explored in the tests, which demonstrates that, compared with the end strengthening measure using an external hoop, the counterpart with a bench ribbed stiffener provides better energy dissipation capacity. In addition, the gap between the bench ribbed stiffener and the external channel steel should be controlled in design. All DRT-ABRBs studied exhibit excellent energy dissipation capacity, which proves the effectiveness of the DRT-ABRB end detailing proposed.


ABSTRACT: The paper presents the results of an experimental program which consists of 15 T and X truss joints fabricated from grade C450 cold-formed rectangular hollow sections (RHS). The aim is to study the effect of the increased yield stress and the somewhat reduced ductility resulting from the cold-working process on the static capacity of these joints. The experimental program was designed to include the full range of possible failure modes and covers a comprehensive spectrum of geometries, including commercially available sections which fall outside the CIDECT limits in terms of wall slenderness ratios. In a next step, the results are compared to the current CIDECT design rules where applicable. In particular, the need for a reduction factor of 0.9 on the capacity of grade C450 connections, imposed by both the CIDECT rules and the Eurocode, is evaluated.

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ABSTRACT: The present study proposes a new-type all-bolted connection that can be used to connect trusses to columns and columns to columns on site in modularized prefabricated multi-rise and high-rise steel structures. The proposed connection connects columns through flanges, connects trusses to columns through cover plates that extend from the flanges and through vertical connecting plates and joint flitches. The stiffness of the connection can be controlled by adjusting the number or size of the bolts and undergoes step-like change as the load changes. Therefore, the connection can be rigid during weak earthquake, while the cover plates can slip relative to the chord members during strong earthquake, thereby dissipating energy. The FEA results was compared with experimental results and showed good agreement at all stages of loading, then the static performance of six connections with different friction coefficient or size of components were studied by FEA. The FEA results were used to determine mechanical properties of the connections that were difficult to obtain from the tests, such as the changing rule of the bolt tension, the stress distribution of bolt, the contact force on various contact surface, and the pressure on the wall of bolt hole, as well as the effects of friction coefficient on the performance of the connections. The mechanical model of the connection was established and the mechanical mechanism of the connection was got. Furthermore, simplified calculating formulas for the connection under slip state, yield state and ultimate state were proposed respectively.

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ABSTRACT: Steel concentrically braced frames (CBFs) are frequently used as efficient lateral load resisting systems to resist earthquake and wind loads. This paper focuses on high seismic applications where the brace members in CBFs dissipate energy through repeated cycles of buckling and yielding. Widely-used seismic provisions have somewhat different approaches for the seismic design of CBFs. The present study evaluates in detail the similarities and differences between the design philosophies and provisions used in the United States and Europe for these systems. The requirements of both provisions applied during a full design procedure are summarized and compared. Furthermore, X-braced, split X-Braced, and V-braced archetypes are designed accordingly and the differences in the design outcomes are investigated regarding section sizes and the weight of steel used in each design. Finally, inelastic structural models of the designed archetypes are developed and subjected to a large set of ground motions to study their seismic behaviors. The results of a total of 880 nonlinear time history analyses are then synthesized to investigate the way in which the requirements of these provisions affect the seismic behavior of the designed CBF. Notable differences are observed between the performances of the CBFs designed using American and European provisions. The similarities and differences as well as drawbacks of the provisions are thoroughly discussed. Recommendations and future research needs are suggested to enhance the seismic performance of steel CBFs designed according to these provisions.

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ABSTRACT: High-strength steel is permitted in steel structures, whereas, further studies are needed to allow the use of high-strength steel in concrete-filled tubular (CFT) structures. In this study, twelve rectangular CFT columns using Q460-grade steel were tested under eccentric load and the test results were discussed. A nonlinear finite element model (FEM) was developed to predict the load-displacement and ultimate resistance behaviors of the test columns. Parametric studies were conducted using the verified FEM to investigate the influence of aspect ratios, steel strength, and width-to-thickness (h/t) ratio of steel plate. The ultimate resistance calculated by European Code (EC4), American Code (AISC 360) and Chinese Code (CECS 159) is compared with the FEM predictions to evaluate their feasibility in the use of higher aspect ratios, high-strength steel, and various h/t ratios. The results indicate that the three design codes are safe in the design of columns with higher aspect ratios. EC4 is conservative in the design of rectangular CFT columns with high-strength steel up to 690 MPa under its h/t ratio limitation. AISC 360 method can accurately predict the maximum resistance of rectangular CFT columns with steel strength 550 MPa. CECS 159 method is highly conservative and can be safely extended to the use of steel strength up to 690 MPa and plate slenderness ratio.

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ABSTRACT: An experimental programme was conducted to investigate the compressive behaviour of concrete-filled cold-formed steel tubular (CFCFST) stub columns with thicker tubes. A total of 30 CFCFST stub columns were tested. The cold-formed square hollow section (SHS) tubes included unstiffened sections and longitudinally inner-stiffened sections using different stiffening methods. Two tubular thicknesses of 6 mm and 10 mm were considered. The overall nominal dimension of the steel section was 200 × 200 mm, and the length of the stub columns was 600 mm. Normal concrete and self-consolidating concrete with a nominal compressive strength of 30 MPa were used to fill the cold-formed SHS steel tubes. The effects of the stiffeners on the rigidity, ductility, failure mode and average sectional strength of the CFCFST specimens were examined. The measured strengths of the CFCFST specimens were also compared with the predicted capacities using methods in various codes including AISC, BS5400, EC4, and DBJ and from a finite element (FE) analysis. Results demonstrate that the inner stiffeners affect the deformability, failure mode and overall strength of the stub columns with the 6 mm-thick tubes more significantly. The DBJ code method is comparatively the best in predicting the strength capacity. Using the validated FE model, an extended analysis has been conducted and this has provided further insight into the mechanical behaviour of the CFCFST specimens.

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ABSTRACT: In this study, a total of 18 cold-formed built-up T-section (CFIBUT) columns with two sectional dimensions and three length types were tested under uniaxial compression. The failure mode, ultimate strength and load-uniaxial displacement curve of the specimens were investigated. The test result shows that the main failure modes of long columns (LC), short columns (SC) and intermediate long column (MC) were flexural-torsional buckling mode, distortional buckling mode as well as flexure-torsional buckling mode, respectively. Subsequently, parametric analyses were conducted on the investigated specimens using the finite element analysis. The influences of the slenderness ratio and the web depth to plate thickness ratio on the mechanical behavior of the CFIBUT columns were studied. Finally, the validation and accuracy of the effective width method in both Chinese design code GB50018-2002 and American code AISI-2007 and the direct strength method in AISI-2007 were evaluated for the CFIBUT columns by using both the test and numerical results. The comparison results show that the prediction results obtained by adopting the two methods in both Chinese and American specification for LC, MC and SC-90 type specimen were rather conservative. However, for the SC-140 type specimen, the prediction difference between the experimental and calculation results obtained by adopting the two methods in both Chinese and American specifications can be controlled within 15%.

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ABSTRACT: Buckling behaviors of steel silos subjected to locally distributed axial load (LDAL) were studied by a Finite Element Model (FEM), which was verified by available test and analytical results. Studied
parameters included the internal pressure, the Local edge load Center Angle (LCA) and the radius-to-thickness ratio \((R/t)\) of a silo. Buckling modes, distributions of reaction forces along the silo bottom edge and buckling stresses were presented. FEM simulations showed that a compression arch was formed on the silo wall to transfer the LDAL to boundaries; and between the feet of compression arch the reaction was in tension. The span and the height of the compression arch almost did not change with the varying of LCA for silos having the same internal pressure and \(R/t\). However, the height of the compression arch decreased with the increase in internal pressure. A silo under LDAL was more likely failed by elastic buckling when the internal pressure was at low level; and at this circumstance the buckling stress increased with the increase in internal pressure. At high level of internal pressure, buckling failure modes of a silo under LDAL changed from elastic buckling to elastic-plastic buckling; and the buckling stress decreased with the increase in internal pressure. For silos with same internal pressure and \(R/t\), the buckling stress decreased with the increase in LCA. Design equations in EC3-4-1 could overestimate the buckling stress of steel silos under combination of internal pressure and LDAL. Based on parameter study results, a practical design equation was proposed for calculating the buckling stress of a steel silo under combined internal pressure and LDAL. Buckling stresses predicted by the proposed equation agreed well with those obtained by FEM.

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ABSTRACT: Coupon tests confirmed that Q345GJ steel had good ductility and rarely cyclic hardening. Therefore, 12 shear links using such steel were designed and tested. The explored parameters included web aspect ratio, flange width-thickness ratio, the equivalent link length coefficient \(eV_p/M_p\), stiffener spacing and thickness, hysteretic loadcase, and welding details. Discussions and analysis on the failure mode, the hysteretic behavior of shear load and displacement angle, the strain distribution, the bearing capacity and stiffness, the plastic overstrength, the deformation and energy dissipation capacity, were also conducted. The shear links had satisfactory energy dissipation capacity under multiple hysteretic loading with almost no cyclic hardening. Web aspect ratio and stiffener spacing had determinate influence on cyclic web buckling, as well as the ultimate deformation capacity. Yet, more intensive stiffener spacing was prone to result in more serious stress concentration in the web, and caused web fracture. Also, smaller coefficient \(eV_p/M_p\) was harmful to the ultimate deformation capacity. The ultimate plastic overstrength \(V_u/V_p\) of the shear links was about 1.35 to 1.5, influenced by web aspect ratio, the coefficient \(eV_p/M_p\), and stiffener spacing. To avoid cyclic flange fracture, the coefficient \(eV_p/M_p\) was also suggested be within 1.7.

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ABSTRACT: In this paper, an explicit dynamic analysis method is proposed to calculate the progressive collapse of a high-rise power transmission tower structure subjected to earthquake; the failure rule for member
elements and the effect of different ground motion inputs and tower heights on the tower's collapse pattern in an earthquake are investigated. The study results show that explicit dynamic analysis can be easily applied to member fractures and that this method is suitable for calculating the seismic collapse of a power transmission tower. The selection of the member element failure rule has a significant impact on the forecast collapse pattern of a power transmission tower in an earthquake. The compression member buckling and softening failure rule, coupling the material nonlinearity with elastic buckling phenomenon, can stave off the effort in modeling the constructional eccentricities, which result in Euler buckling. For different earthquake waves, the high-rise power transmission tower demonstrates different collapse failure modes. The static collapse pattern from a pushover analysis and the dynamic collapse pattern are very different. The actual collapse pattern of a power transmission tower during the Wenchuan earthquake and the computer simulated collapse pattern are compared to validate the algorithm proposed in this paper. Finally, the seismic collapse vulnerability of a high-rise power transmission tower is evaluated based on probability estimate method.

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ABSTRACT: One issue of major importance regarding the application of seismic assessment guidelines is that of the deformation capacity limits prescribed for the various limit states. In the case of existing steel structures, Part 3 of Eurocode 8 (EC8-3) defines the limits in terms of plastic rotations, which are only applicable to cases where normalized axial load levels are lower than 0.3 and to cross-section classes of type 1 and 2. These limits resemble the ones defined in ASCE 41, suggesting a direct reproduction from the latter document despite their derivation on the basis of typical American profiles. Hence, this paper aims at evaluating the deformation capacity of European steel members and to answer the question of how adequate are the current EC8-3 limits. Based on detailed FE models, the influence of member imperfections, axial load and real ground motion records is assessed. Fracture due to ultra-low cycle fatigue is taken into account and general expressions for predicting the rotation capacity of a wide number of European cross-section profiles are proposed.

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ABSTRACT: There is complex interaction between the infill steel plate and frame edges in the steel plate shear wall structure. The bearing capacity and stiffness of SPSW structure not only depends on the section sizes of frame and wall, but also relates to the stiffness of joint connection. The beam-to-column connection is easy to construct using semi-rigid joints which enhances the deformation and energy dissipation capacities of SPSW structure and effectively avoids the brittle failure of traditional welded joint. Based on the pseudo static test of cross stiffened SPSW structure with semi-rigid connected frame, this paper analyzes the failure mode and energy dissipation mechanism of the structure, discusses the influence of joint connecting forms and
arrangement of stiffeners on the seismic performance of the structure. According to the results, the effect of the beam-to-column connection stiffness on the bearing capacity of SPSW structure is small and the differences among the ultimate bearing capacities are less than 5%. When the inter-story displacement angle is 1/50, the ductility factor is between 3.69 and 4.4, which indicates that SPSW structure is good in plastic deformation capacity. The cross stiffeners divide the thin steel plate into small cell plates. By setting the cross stiffeners, the thin steel plate is divide into small cell plates, and mainly pattern of local buckling.

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ABSTRACT: Concrete filled double-skin steel tubular (CFDST) members have a large potential to be used in trusses, bridges and lattice structures. Previous research work has focused on the structural performance of individual CFDST components whilst there is a lack of understanding on the behaviour of typical connections formed by such composite members. This paper intends to fill the knowledge gap in this area. A total of 20 K-joints with circular CFDST chords and circular hollow section (CHS) braces were tested under two typical sets of boundary conditions. Effects of important parameters were investigated based on the test results, including brace to chord diameter ratio (β), chord hollow ratio (χ) and preloads on the chord. Typical failure modes and load-deformation relations were investigated, in-depth study on the interactions between materials and the load-transfer mechanism were conducted, simplified strength-prediction method for this new type of composite joints was also proposed.

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ABSTRACT: Buckling behavior and hysteretic performance of a new type of buckling-restrained brace (BRB), namely core-separated buckling-restrained brace (CSBRB), are theoretically and experimentally investigated. The material utilization efficiency of the CSBRB is significantly improved compared with common BRB, since its cross-section spreads outwards by spacing two cores, thus improving the flexural rigidity of the restraining system. On the basis of the elastic buckling loads of pin-ended CSBRBs, a design procedure involving two design parameters, namely normalized slenderness and buckling factor, is firstly established. Then, hysteretic behavior of CSBRBs is investigated by FE nonlinear analysis to obtain the critical normalized slenderness. Finally, test results of four specimens with different normalized slenderness values are presented to reveal the hysteretic characteristics and the energy-dissipation abilities, concluding that a CSBRB with adequate restraining rigidity can provide stable hysteretic performance. The test results coincide well with the results obtained from refined FE numerical analyses.
ABSTRACT: A total of eleven loading tests were conducted to study the influence of local corrosion on the behavior of steel I-beams subjected to end patch loading. The test parameters included: corrosion pattern (web corrosion, and flange corrosion), corroded length (100 mm, 200 mm, and 300 mm), corroded thickness (4 mm, and 6 mm), and length of the bearing plate (80 mm, and 160 mm). Comparisons have been made between the test results and the predicted strengths using current design codes: AISC, AASHTO, and EN1993-1-5. The test results indicate that the web corrosion has a more detrimental effect than the flange corrosion. The behavior of the steel I-beams (e.g., ultimate load, web deformation, and flange and web's strains) is significantly affected by the corroded thickness of the web. However, this is mainly related to the web corrosion within the flange diffusion range. In general, the web local yielding provisions in AISC and AASHTO give the best prediction.

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ABSTRACT: Based on the test results of two composite frame specimens with concrete-encased CFST columns under lateral cyclic loading, the numerical models of the specimens are established by fiber beam-column elements, and the whole hysteretic process are investigated. The parameter analysis of the hysteretic behavior of the frame specimens are conducted, and the influence are observed. The main studied parameters include column slenderness ratio, axial compressive ratio, sectional modules of steel and reinforcement ratio, the ratio of steel tube in column, steel tube confinement coefficient, radius-thickness ratio, concrete strength and prestressing level. The hysteretic models of one-storey and one-bay composite frame are proposed on the basis of a large number of parameter analyses. The results indicated that the hysteretic curves calculated show plump shape, and the frame behaves favorable energy-dissipating capacity and when the axial compression level is bigger than 0.6, the displacement ductile of frames decrease; the proposed hysteretic models by parameter analysis could give reliable prediction of the composite structure under horizontal loading.

ABSTRACT: The paper presents a set of newly developed exact analytical solutions for triple- equal-span arrangements of panels with fully profiled faces in flexure. Their derivation was based on a set of general fundamental equations retrieved from the governing differential equations for sandwich beams. Specifically designed tests of single- and triple-span fully profiled panels with steel faces (outer fully profiled and inner lightly profiled) and polyisocyanurate cores were conducted to investigate the response with regards to stiffness and initial failure, which are critical for serviceability limit states. Good agreement between test and theory was demonstrated, with safe results in all cases. The new design method permits the elimination of a significant amount of conservatism compared to current methods.
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ABSTRACT: The present paper focuses on a new, alternative design philosophy: the Overall Interaction Concept (O.I.C.). This concept, based on the well-established resistance-instability interaction and the definition of a generalised relative slenderness, was thought and built to i) improve actual design practice, ii) increase accuracy, iii) advance simplicity and consistency, and iv) provide a sound framework for computer-assisted resistance predictions. This paper first details the bases and features of the O.I.C. approach, and provides mechanical interpretations of its application steps. Comprehensive sets of results at the cross-sectional level are then presented, for both H-shaped and hollow sections. Ayrton-Perry-based \( \chi \cdot \lambda \) design relationships for hollow structural shapes are proposed and shown to lead to more accurate, consistent and safe resistances when compared to Eurocode 3 rules, in addition to being significantly simpler in application. As for the behaviour and response of members, numerous F.E. results are reported, demonstrating the potential of a \( \chi \cdot \lambda \) approach to successfully apply to members under combined load cases. Also, the challenging case of coupled instabilities is investigated, and the O.I.C. approach is showed to be very efficient and appropriate. Further developments towards the derivation of full O.I.C. procedures to steel members are currently under way.

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ABSTRACT: The present paper describes a theoretical study on the effect of pre-buckling displacements on the elastic instability of U-shaped members. Expressions for the elastic critical bending moments under mono-axial bending and the elastic critical load amplification factor for the case of bi-axial bending are derived and validated through elastic geometrically non-linear analysis including a geometric imperfection. It will be shown that pre-buckling displacements have a non-negligible influence on the behaviour of U-shaped members, especially when subjected to minor-axis and bi-axial bending. It will be shown that, contrariwise to the natural feeling, U-shaped members under minor-axis bending may, in some cases, be sensitive to elastic instability (lateral-torsional buckling). Moreover, the validated analytical expressions show that shorter members are more sensitive to elastic instability under minor-axis bending than their longer counterparts!

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ABSTRACT: Detailed finite element modelling of key elements is necessary to improve the robustness assessment of structures subjected to a coupled effect of fire and blast loads. This paper presents a method for a realistic multi-hazard approach by studying the residual load bearing capacity of steel columns under fire conditions and followed by an explosion. The approach adopts the use of a material constitutive law able to take into account both the strain rate sensitivity and the thermal softening. Explicit nonlinear dynamic analyses are performed using the explicit commercial code LS-DYNA. Results show that the residual load bearing capacity is influenced by the stand-off distance. The time of fire loading at which an explosion is triggered is a critical parameter as well. High strain rates in the typical blast range ($10^2$ ÷ $10^3$ s$^{-1}$) are numerically obtained as a consequence of explosions in the close proximity. A comparison with the Eurocode approach is also reported. The results can be of great interest to establish the initial conditions that could potentially lead to the onset of progressive collapse in steel framed structures subjected to a combined effect of fire and blast loadings.

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ABSTRACT: Additive manufacturing, a common example of which is 3D printing, has become more prevalent in recent years with it now being possible to form metallic structural elements in this way. There are, however, limited available experimental data on the material behaviour of powder bed fusion (PBF) additive manufactured metallic structural elements and no existing data at the cross-section level; this is addressed in the present paper through a series of tests on additive manufactured stainless steel material and cross-sections. Tensile and compressive coupon tests were used to assess anisotropy, symmetry of stress-strain behaviour and the influence of building direction on the material properties. The yield and ultimate tensile strengths were seen to generally decrease in magnitude with increasing build angle, while a reduction in ductility was observed in some building orientations, and the Young's moduli were typically insensitive to the build angle. The structural behaviour of PBF additive manufactured cross-sections was investigated through a series of square hollow section (SHS) stub column tests, and the results compared with conventionally produced stainless steel SHS. The generated test results have been used to evaluate the applicability of existing design guidance for conventionally produced sections to additive manufactured sections.

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ABSTRACT: In the present paper, results of comprehensive finite element (FE) analyses performed on 210 generated models of T/Y-joints strengthened with doubler plate are presented. The results of FE models were validated against the data available from 12 experimental tests. These FE models investigate the effect of the doubler plate size and joint geometry on the static strength of doubler plate strengthened tubular T/Y subjected
to in-plane bending (IPB) load. Afterwards, the ultimate capacity and deformed shapes of doubler plate and collar plate reinforced T- and Y-joints are compared. Results indicated that the doubler plate can significantly enhance the initial stiffness, ultimate capacity, and considerably improve failure patterns of T- and Y-joints under IPB load. In spite of the remarkable difference between the static capacity of un-strengthened and doubler plate strengthened T- and Y-joints subjected to IPB, the static strength of doubler plate strengthened T/Y-joints under IPB load has not been investigated so far and no design equation is available to calculate the ultimate strength of doubler plate reinforced T/Y-joints. For this reason, geometrically parametric study was followed by a set of nonlinear regression analyses to propose an ultimate capacity parametric formula for the static analyses of doubler plate strengthened tubular T/Y-joints subjected to IPB load


ABSTRACT: Steel corrugated webs are vertical and lightweight plates responsible for carrying large in-plane loads before buckling. Three modes of shear failure are typical for these elements: local, global, and interactive shear buckling. In this paper, previously published analytical models for the estimation of the shear strength of trapezoidal corrugated webs are summarized, and a new model is developed. The proposed model takes into account the interaction between the modes of shear buckling. Twelve shear-critical corrugated web steel beams (CWSBs) were manufactured and tested to failure. The results were added to update the existing database, resulting in 125 test results, which were then used to compare the performance of developed and existing models. The new model is shown to be more accurate than previously published models for estimating the shear strength of corrugated steel webs, allowing for more economic designs.

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ABSTRACT: Design recommendations for concrete filled steel tubular (CFST) columns in fire are based on the results of experimental standard fire testing of CFST members where the same temperature is applied to the column over the full column height. However, this is not representative of a CFST column in a typical building, which is continuous between floors and which, in fire, is subjected to severe fire conditions on one floor at a time while the floors above and below remain cooler. In the experimental tests described in this paper, the columns are of 3.2 m height with the fire applied only to the central 2 m. Significant differences are observed between these tests and those previously conducted due to the partial length heating. In total, ten tests are conducted; the tests cover three different types of infill: plain concrete; bar reinforced concrete; and steel fibre reinforced concrete. End restraint conditions of fixed-fixed (F-F) and pinned-fixed (P-F) are considered; the axial load levels are between 0.33 to 0.38 of the squash load. The longitudinal elongation of the steel tube was
less than 3 mm. Using the experimentally measured structural fire resistance (R), the axial capacity in fire was calculated in accordance with the codes of practice and are Compared with the experimentally tested structural fire resistance, showing that in some instances current design practice can be un-conservative.


ABSTRACT: To investigate the behaviour of square hollow steel tubular (SHST) stub columns after elevated temperatures under axial compression, a total of 51 specimens were tested, including 48 SHST stub columns after elevated temperatures and 3 SHST stub columns at ambient temperature, of which 12 SHST stub columns were carried out load-strain tests. The main parameters explored in the test include temperature ranging from 400 °C to 1000 °C, thickness (2.0 mm, 3.0 mm, 4.0 mm) and high temperature duration (1.0 h, 1.5 h, 2.0 h, 2.5 h). This paper presents the failure modes, load-bearing capacity, load-strain curves, load versus displacement curves, initial stiffness at elastic stage and ductility of the specimens. Results show that failure modes of SHST columns at ambient temperature and elevated temperature follow similar pattern. It was found, in general, that temperature and thickness have significant influence on the behaviour of SHST columns; however, high temperature duration has negligible influence on the behaviour of SHST columns. Based on the experimental results, a formula is proposed to calculate the load-bearing capacity of SHST stub columns after elevated temperatures. It is evident from the comparisons between the results calculated from the formulas and the experimental results that the calculation gives results with reasonable accuracy. Finite element models having the same dimensions of test specimens were simulated to compare the finite element analysis results with experimental results. It can be seen from the comparison that finite element analysis results were in good agreement with experimental results.


ABSTRACT: Structural stainless steel requires appropriate recognition of its beneficial properties such as material nonlinearity and significant strain hardening. The Continuous Strength Method (CSM) exploits those benefits through a strain based approach for both stocky and slender cross-sections. In this paper, a new design method is proposed that combines the CSM design principles with Perry type buckling curves for stainless steel square and rectangular hollow sections (SHS and RHS) subjected to compression. Numerical models were developed to investigate effects of various parameters on column strength and to develop complete column curves for hollow members. It was observed that cross-section slenderness λp and material properties such as non-dimensional proof stress e and strain hardening exponent n significantly influence column resistances. Effects of e and n were appropriately incorporated through introduction of correction factors to modify non-dimensional member slenderness. It was observed that the shapes of column curves were mostly affected by λp, and hence imperfection parameter η, as used in Perry formulations, was expressed as a function of λp, this technique yielded separate column curves for different λp values. The proposed method includes the strain hardening benefits for stocky sections, and abolished the necessity of calculating effective cross-sectional properties for slender sections. Performance of the proposed technique is compared against those obtained by using the European guidelines.
ABSTRACT: In this paper, a new finite element (FE) model using ATENA-3D software was developed to investigate the compressive behavior of circular steel tube confined concrete (STCC) stub columns with taking into account various concrete strengths. The “CC3DNonLinCementitious2User” material type for concrete in ATENA-3D with some modifications of material laws was adopted to simulate the behavior of concrete core with consideration of the confinement effect induced by steel tube. Both ultimate load and axial load versus strain obtained from FE model were compared with those from previous test results. This comparison indicates that the new FE model in ATENA-3D is capable of predicting the compressive behavior of circular STCC stub columns. An extensive parametric analysis using this established FE model was then conducted to examine the influence of concrete compressive strength, steel yield strength and steel tube thickness on the strength and the ductility of circular STCC stub columns. Furthermore, based on previous test database, some analytical model for concrete confined by steel tube was evaluated and a simplified formula for predicting the ultimate load of circular STCC stub columns was also proposed. There was a good agreement between the predictions of the ultimate load using this proposed formula and FE model.

ABSTRACT: Beams with corrugated webs and flat plate flanges have been used in buildings around the world for many years. In the design of these beams, the longitudinal stiffness of the corrugated web is assumed to be negligible and so the moment capacity is derived entirely from the flanges while the shear capacity of the beam is based on the shear strength of the web alone. The advantage of beams with corrugated webs is the increased resistance to shear buckling without the need to weld stiffeners to the web. Despite the extensive use of beams with corrugated webs, there are no formal Australian or American design rules for the shear capacity of the corrugated web. In this paper, design equations based on the direct strength method are derived for the shear capacity of beams with trapezoidal corrugated webs. Finite element analysis results from previous research are analysed to determine the local shear buckling coefficient which is used to calculate the local shear buckling force in the design equations. The proposed design equations are then compared with previous shear test results on beams with corrugated webs and a reliability analysis is performed to calculate the capacity factor.

ABSTRACT: Cylindrical shell structures such as silos and wind turbine towers often feature openings for internal access, and these may have a significant detrimental effect on the buckling load. This paper numerically investigates the buckling of cylindrical shells with cutouts near the cylinder end using nonlinear finite element analysis. The finite element (FE) model was validated against published experiments on the axial compression of moderately thin-walled cylinders with cutouts of various sizes and shapes. The results indicate excellent qualitative and quantitative agreements for loads, deflections, and buckled mode shapes. Using the validated FE model, it was found that the opening width is the most critical geometric parameter in terms of loss of carrying capacity. The model was then extended to explore a variety of stiffener configurations aimed at recovering the capacity lost due to the opening. These configurations included a frame ring, as well as the simpler option of straight ribs on either side of and above the hole. Thickness and protrusion were also considered in the analysis. It was found that the frame ring achieved full recovery of the lost capacity, while the straight stiffeners were effective where only up to 67% recovery was required. The results also indicated that the optimum placement of stiffeners was immediately adjacent to the cutout. This study demonstrates that the optimum stiffener is a fully enclosed ring immediately adjacent to the cutout edge, and that full load recovery can be achieved with an appropriate design.


ABSTRACT: A comparison was made of the static behavior of a double-layer reticulated shell, a local triple-layered reticulated shell, a ribbed type mega-latticed structure and a Kiewitt type mega-latticed structure with the same geometrical parameters and loads. The results show that the Kiewitt type mega-latticed structure has the best structural performance. Then a complex structural configuration was analyzed in detail, using CAD 3D modeling, and a command-flow was developed to create the new structure automatically by ANSYS Parameter Design Language as an innovative structural-programming method. The static analysis and comprehensive stability analysis were conducted. The reasonable values of parameters for the overall buckling mode were summarized and the ultimate bearing capacity was accurately obtained by considering geometrical nonlinear, material nonlinear and initial curvature of the members. The nonlinear equilibrium paths were traced using the Arc-length method. Results indicate that the 800 m Kiewitt type mega-latticed structure has a very low sensitivity to geometrical nonlinear and a low sensitivity to initial curvature of members, but a high sensitivity to material nonlinear. Therefore, the Kiewitt type mega-latticed structure could be regarded as a reasonable super-large span structure with several advantages, including reasonable stresses, clear force transmission lines, economic steel consumption, high stiffness and good bearing capacity.

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ABSTRACT: This paper presents a numerical investigation on the compressive behaviour of thin-walled concrete-filled steel tube (CFST) columns with encased built-up latticed angles. The additional confinement provided by encased angles was considered in the finite element (FE) model, in addition to the contact between tube wall and inner concrete and the effect of tube-wall confinement on concrete model. The established FE model is verified against the existing test results that it can well predict the behaviour of reinforced composite columns under axial compression. The composite action between encased angles and concrete and the efficiency of built-up angle configurations on performance improvement are extensively analyzed through the validated FE models. The influence of three parameters, namely confinement factor ($\xi$), reinforcement ratio ($\rho_{sr}$) and slenderness ratio ($\lambda$), to the angle-contributions on lateral confining pressure and the ultimate strength are evaluated and quantified. It is found the relationship between the strengths of CFST columns and built-up member can be defined as an exponential equation. Finally the design equation based on AISC 360-10 design provisions with consideration of angle-contributions is proposed, and the comparison results show it has a desirable accuracy and satisfactory correlation with both experimental and numerical results.


ABSTRACT: A shaking table test of a 1:3 scale semi-rigid steel frame with buckling-restrained steel plate shear wall was conducted herein to study the seismic performance of this type of structure. The model was designed as ordinary steel plate shear walls, but with buckling-restrained. Its members consisted of non-simplified sections. The descriptions of the test specimen, instruments, set-up procedures were also presented. The dynamic characteristics, acceleration, displacement, and shear force were analysed. The maximum inter-storey drift angle in elastic-plastic was 1/68. The lateral stiffness drop was only 12% when completely loaded. The test model did not collapse under rare earthquakes. The results showed that the seismic behaviour was adequate for survival in large seismic excitations, and the design methods of the members and the semi-rigid connections were reasonable.


ABSTRACT: The purpose of this research was to experimentally investigate the effect of lateral impact energy, impact location and width-thickness ratio on the residual axial bearing capacity of square steel tubes. In this study, the investigation on residual axial bearing capacity under different lateral impact energy, impact location and width-thickness ratios was carried out. Forty-eight specimens including three specimens untreated for comparison were studied to investigate the influence of the impact energy, loading position and width-thickness ratios on the residual axial bearing capacity of square steel tubes. In this study, the investigation on residual axial bearing capacity under different lateral impact energy, impact location and width-thickness ratios was carried out. Forty-eight specimens including three specimens untreated for comparison were studied to investigate the influence of the impact energy, loading position and width-thickness ratios on the residual axial bearing capacity of square steel tubes. The failure mode, residual axial bearing capacity, initial stiffness and ductility of specimens were presented. The typical failure modes observed from the tests include that with the increase of load, the deformation of impact location or bottom of the specimens increased and then local buckling occurred. The results indicated that with the increase of impact energy, lateral plastic deformation increased while the remaining axial capacity reduced and the maximum decreasing of bearing capacity reached 21%. The results also show that the impact location and width-thickness ratio exert no evident effects on residual axial bearing capacity of square steel tubes, in other words, impact location and width-thickness ratio possess a limited influence on the bearing capacity of square steel tubes. According to the
experimental results, calculation equations were proposed to predict the residual axial bearing capacity for all square steel tubes tested, providing reasonably good correlation with the experimental results. The research results can provide reference for the further research.

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ABSTRACT: Double-coped beams are usually employed to avoid spatial interference when similar elevations of both the top and bottom flanges of the connected beams are required. Due to the removal of the flange parts, the load resistance can be significantly compromised. This paper discusses the effectiveness of various reinforcing strategies aiming to increase the load resistance of newly designed double-coped beams or to upgrade the existing ones. A series of full-scale tests are conducted first, covering a set of reinforcement types and varying coping dimensions. Local web buckling is found to be the governing failure mode for the unreinforced specimens, and the presence of the considered stiffeners can effectively increase the load resistance. In particular, a pair of longitudinal stiffeners for the top cope edge is shown to completely mitigate the risk of local web buckling, and the final failure mode is tensile cracking at the bottom cope corner. The doubler plates, either full-depth or partial-depth, can delay the initiation of local web buckling, and as a result the load resistance is remarkably increased. The effects of the varying reinforcement types and coping dimensions on the utilisation efficiency of section capacities are discussed in detail. A finite element study is subsequently conducted to enable further understanding of key structural characteristics and to help explain some test phenomena. Preliminary design comments and recommendations are finally proposed based on the exiting test and numerical data.


ABSTRACT: The paper deals with buckling of metal cylindrical silos composed of corrugated sheets and vertical stiffeners (columns). Comprehensive finite element analyses were carried out for three real perfect silos with a different geometry (two slender silos and one intermediate slender silo) by means of a linear buckling approach. Corrugated walls were simulated as an equivalent orthotropic shell and thin-walled columns as beam elements. Numerical calculations for perfect silos with different numbers of columns made it possible to establish three different ranges of the silo buckling performance. Based on results of three dimensional calculations, an original simplified segment silo wall model was proposed for calculations of silo global buckling for sparsely distributed columns. In addition, a single column resting on the elastic foundation with the improved stiffness was suggested. Both models are shown to produce predictions that are much closer to rigorous FE calculations than the hand calculation procedures of EN 1993-4-1.
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ABSTRACT: This study is motivated by increasingly prevalent use of high strength steel and concrete materials in high-rise buildings to achieve better structural performance with less material usage. Previous studies and many modern design codes place some limits on the strength of steel and concrete for designing steel-concrete composite members, attributed to insufficient test data and design experience on their applications in construction. With this research gap being identified, an experimental program has been carried out to investigate the composite behaviour of concrete filled steel tubes (CFST) employing high tensile strength steel (HTS) and ultra-high strength concrete (UHSC). Both concentric and eccentric compression loads were applied to evaluate the overall buckling resistances and moment-axial force interaction with second-order effect considered. The yield strength of HTS under the investigation was about 800 N/mm² and the concrete compressive cylinder strength was up to 200 N/mm². To examine the test results, the rotational stiffness of semi-rigid end supports was analytically derived and the stress-strain models of HTS and UHSC were properly calibrated to predict the composite behaviour through finite element analysis. The Eurocode 4 approach was then checked regarding its applicability to the said high- and ultra-high strength construction materials for composite design. A new database including 1160 test data was established to further study the reliability of the use of HTS and UHSC, and suggestions were made to extend the Eurocode 4 design approach.

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ABSTRACT: The probabilistic distribution of ultimate buckling strength for stiffened steel plates subjected to a distributed axial stress was obtained using Monte Carlo simulations in association with the response surface method. The plates of both normal and high-performance steel (SBHS) were taken into account, and their thickness was varied from 10 to 90 mm. The ultimate buckling strength was determined by nonlinear elasto-plastic finite element (FE) analysis, considering geometric and material nonlinearity. The initial out-of-plane deflection and residual stress were considered as two independent random variables upon which the ultimate buckling strength depends. The response surface, showing the variation of ultimate strength due to the initial deflection and residual stress, was estimated using the nonlinear FE results. Based on the obtained statistical distribution, partial safety factors for the ultimate buckling strength were proposed.

Quan Shi, Xiaqiang Shi, Joseph M. Gattas and Sritawat Kitipornchai (School of Civil Engineering, University of Queensland, Australia), “Folded assembly methods for thin-walled steel structures”, Journal of
ABSTRACT: There has been significant recent interest in origami-inspired foldable structures for applications in which transportability and rapid construction are primary design drivers, for example, emergency shelters and staging structures. However, widespread application is not yet seen due to complexities in folded geometry and modelling the structural behaviour of folded sheet material. This paper proposes a fundamentally new approach whereby folded assembly methods are developed for conventional thin-walled steel construction and benchmarked in terms of their assembly effort, manufacturing accuracy, and structural performance. Manufacturing accuracy was benchmarked with 3D digital image correlation and 3D scanning and showed a folded assembly method to be accurate to within ±50% of plate thickness with assembly by unskilled persons. Structural performance under uniaxial compressive load was assessed with experimental and numerical analyses, with consistent predictions showing that conventional thin-walled steel analysis techniques are sufficient to model folded structure behaviours. Modelling of the novel folded steel structures is therefore also shown to avoid much of the complexity normally encountered in folded structure analysis, such as characterisation of fold-line rotational stiffness or folding plasticity behaviours.

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ABSTRACT: The behaviour of austenitic, ferritic and duplex stainless steel Rectangular and Square Hollow Section members subjected to compression and combined loading is investigated in this paper. A full slenderness range Direct Strength Method (DSM) approach is proposed based on experimental results and numerical strengths obtained from FE parametric studies. The method accounts for local buckling effects and enhanced material properties are also incorporated for those members stable enough to allow partial yielding of the cross-sections. The proposed method is based on strength curves previously provided for cross-sections although additional limitations have been adopted. The DSM approach for columns is based on existing buckling curves and provides accurate resistance predictions for slender and stocky cross-sections. The proposed DSM approach for beam-columns also improves capacity predictions for stocky and slender cross-sections obtained from the traditional methods for different bending moment distributions. This is attributed to the fact that the beam-column behaviour is directly calculated with a unique strength curve, considering the member and section slendernesses based on the elastic instabilities of the section subjected to the actual stress distribution instead of calculating the compressive and flexural strengths independently and combining these through an interaction equation, as is the traditional uncoupled approach. Finally, a reliability study of the full slenderness range DSM approach is presented to determine resistance factors for the different stainless steel grades columns and beam-columns.

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ABSTRACT: This paper presents an investigation on the static strength of high strength steel circular hollow section (CHS) X-joints subjected to axial compression in the braces which failed by chord face plastification. Using validated finite element models, extensive numerical simulations were conducted considering a wide range of geometric parameters and chord preload ratios. The material properties of high strength steel with nominal yield stresses of 700, 900 and 1100 MPa were carefully incorporated in finite element models. The static strengths obtained from numerical analysis in this study and experimental tests in the literature were compared with those calculated from mean strength equations on which the design equations in Eurocode EN 1993-1-8 and the CIDECT design guide are based. The comparison results show that the mean strength equation adopted by the CIDECT design guide is generally more accurate than that of EN 1993-1-8. The mean strength prediction of the CIDECT design guide without using reduction factors of joint strength is relatively accurate for CHS X-joints with nominal steel yield stresses ranging from 650 to 700 MPa. However, the mean strength predictions of EN 1993-1-8 and the CIDECT design guide generally become more unconservative with increasing steel yield stress. The mean strength equations are unconservative for CHS X-joints with nominal steel yield stresses exceeding 700 MPa.

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ABSTRACT: This paper presents a systematic experimental investigation into high strength Q690 steel welded H-sections under combined compression and bending. A total of 8 slender columns with four sections of different cross-sectional dimensions were tested successfully under eccentric loads. All columns failed in overall buckling about the minor axes of their cross-sections with significant material yielding. In some cases, plastic local plate buckling in the flange outstands became apparent at failure. After tests, all the columns were inspected closely, and no fracture in welding was found. As expected, these high strength Q690 steel welded H-sections were demonstrated to behave in various ways similar to those of conventional strength steel welded H-sections. Hence, these tests may be regarded to be confirmatory tests to structural behavior of Q690 steel welded H-sections under combined compression and bending. It should be noted that the measured failure loads were compared with the predicted resistances of these H-sections based on their measured geometrical and material properties according to various design rules given in EN1993-1-1, ANSI/AISC 360-16 and GB 50017-2003 respectively. Among all these three sets of design rules, EN1993-1-1 is shown to be effective and efficient in predicting resistances for high strength Q690 steel welded H-sections under combined compression and bending with properly selected parameters. Hence, EN1993-1-1 should be readily adopted by design and construction engineers in designing these Q690 steel welded H-sections under combined compression and bending.
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ABSTRACT: Design formulae of buckling-restrained braces, considering the stiffening part of the core and the effect of friction, are proposed, based on theoretical analyses of the buckling mechanism of the steel core in the presence of a gap between the core and the restraining member. The theoretical analyses are validated by finite element analyses. Compared to existing methods, the results of the proposed analyses are generally better and show the closest correlation with the results of the finite element analysis.


ABSTRACT: Hot rolled beams can show insufficient strength or inertia and result in the utilization of steel plate girders in the design. For cost-effective design, tapered plate girders are employed, where the depth of the end web panel is linearly varied with the panel length. In most of design codes, the shear capacity is well estimated for prismatic web panels, with reasonable accuracy. The tapered web panels, however, are lacking investigation. The objective of this numerical study is to examine the effect of different geometric parameters of tapered end web panel on the elastic shear buckling and the nominal shear strength. The geometric parameters in question are, namely: tapering angle; tapering direction; panel aspect ratio; web slenderness ratio; flange to web thickness ratio; and attachment of transversal vertical stiffeners to panel ends. The finite element method has been employed, where linear elastic buckling and nonlinear inelastic post-buckling analyses have been performed. The numerical results have been verified against classical web buckling theory, design codes, and experimental results published in the literature. Furthermore, regression analysis has been performed for the obtained results, where new design rules have been proposed for both elastic and nominal shear strength. It has been reported that tapered end web panels possess post-buckling strength that is highly dependent on the geometric parameters.


ABSTRACT: Steel structures may need rehabilitation and restoration due to different reasons including design and calculation errors, lack of proper implementation, change in application, damage as a result of random loads, exhaustion and corrosion, and natural disasters such as earthquakes, fires, and environmental conditions. Carbon Fiber Reinforced Polymer (CFRP) is one of the advanced materials for strengthening structures. This study aims to examine the structural behaviors and impact of CFRP on strengthening steel Circular Hollow Section (CHS) short columns with initial horizontal or vertical deficiency. A total of six steel CHS columns
were studied in laboratory, and the same plus two more specimens were modeled using ABAQUS software. Static gradual compression force was applied in laboratory, and the Riks Non-Linear Analysis Method was utilized in simulation to observe the plastic zone buckling after post buckling. The results showed that deficiency led to reduce bearing capacity of steel columns and the impact of horizontal deficiency was higher than the vertical one. Using CFRP for strengthening deficient columns showed that CFRP yielded appropriate impact on rising bearing capacity rise, reducing stress in the damage location, and preventing local deformation (local buckling) around the deficiency appropriately.

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ABSTRACT: Concrete-encased concrete filled steel tube (concrete-encased CFST) columns have been increasingly used in high-rise buildings and bridges in China in recent years. In practice, these composite columns may be subjected to combined compression and torsion under earthquake loads when they are adopted as columns in high-rise buildings or piers of viaducts. The corresponding behaviour of such composite columns thus needs to be thoroughly investigated to fill this knowledge gap. Results of a series of tests on concrete-encased CFST columns under combined compression and torsion are presented in this paper. A total of 26 tests were conducted on three types of specimens, i.e., concrete-encased CFST columns, hollow reinforced concrete (RC) columns without inner CFST components and conventional CFST columns. Based on the test results, effects of cross-sectional shape, axial load level and cross-sectional area of the inner CFST on the failure mode and the torque-rotation angle relation are investigated. Design formulae are then proposed which can reasonably predict the torsional strength of concrete-encased CFST columns.

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ABSTRACT: The introduction of web openings in existing steel floor beams is a common occurrence in practice. Such modifications are often necessary to accommodate additional services driven by a change of building use, thus extending the service life of the structure. Depending on their size and location, openings in the web can present a major challenge to the strength and stiffness of the beam. Strengthening around an opening is often necessary to maintain the required performance of the floor beam, traditionally this is affected via application of additional steel plate, either bolted or welded. This paper focusses on the novel application of carbon fibre reinforced polymer (CFRP) to the problem of strengthening web openings, taking advantage of the material’s ease of handling, superior strength-to-weight ratio and corrosion resistance. An experimental study involving 4 full scale universal beams was conducted in order to investigate the ability of CFRP to recover the strength and stiffness of beams following the introduction of web openings. All the specimens were tested under
6-point bending in the experiments. For further comparison, the equivalent test series without the addition of strengthening was modelled numerically via finite element analysis. The effectiveness of the strengthening technique was demonstrated with increases in the load carrying capacity over the un-altered beam of between 5 and 20% being achieved.


ABSTRACT: Web crippling is often a critical design problem in cold-formed steel flexural members. Lipped channel beams (LCBs) are commonly used as floor joists and bearers in the construction industry and are often subjected to concentrated loads. Design capacity predictions from most of the cold-formed steel design standards such as AISI S100 [1], AS/NZS 4600 [2] and Eurocode 3 Part 1-3 [3] are empirical, developed based on past experimental studies. They were found to be either unconservative or conservative in most cases. Inconsistencies in design capacity predictions are considered to be due to the fact that the specimen length and support conditions pertaining to the test set-up varied among past experimental studies. In 2008, American Iron and Steel Institute introduced a standard test method for conducting web crippling studies [4]. However, limited web crippling studies have been conducted to date for LCB sections under EOF and IOF load cases. Therefore a detailed experimental study consisting of 36 tests was conducted to investigate the web crippling behaviour of high strength cold-formed steel LCB sections under EOF and IOF load cases based on the AISI web crippling standard test method. This paper presents the details of this experimental study of LCBs unfastened to supports, using which it proposes suitable modifications to the current unified web crippling design equation. It also presents suitable direct strength method based design equations and associated predictive equations for elastic buckling and yield loads of LCBs under EOF and IOF load cases.


ABSTRACT: An all-steel buckling-controlled brace (BCB) with two different configurations is studied and its behavior is compared with the conventional braces in terms of energy dissipation and ductility capacities. A parametric study was first conducted on an ensemble of all-steel BCBs in a general purpose finite-element (FE) software in order to study the influential parameters of these braces. The select types of BCBs were then experimentally investigated. Finally, seismic performance of buckling-controlled braced frames (BCBFs) was compared with that of special concentrically braced frames (SCBFs) as well as that of buckling-restrained braced frames (BRBFs). The study concludes that (1) the BCB with round-in-square tube section has stable hysteretic behavior either when thickness ratio of the outer tube to inner tube is greater than one or when an enhanced gusset plate is employed. Furthermore, due to much increased compressive strength in square in round BCBs, it is necessary to utilize an enhanced gusset plate in order to achieve ductile behavior; (2) BCBs have a stable and symmetrical hysteretic behavior in tension and compression with little post-yielding strength decrease or increase, avoiding the significant unbalanced force on the brace-intersected beams in SCBFs and BRBFs; (3) BCBFs are capable of sustaining larger story drift ratio response without considerable strength loss in comparison with SCBFs; (4) Inelastic deformation demand distributes throughout the height of BCBF floors, preventing the occurrence of weak story often observed in SCBFs.
ABSTRACT: (none)
Highlights:
Geometrically and materially non-linear finite element model using solid finite elements
Introduction of initial random imperfections of a steel beam subjected to lateral-torsional buckling
Polynomial approximation of the load-carrying capacity (LCC) of a steel beam with imperfections subjected to bending
Simulation computational analysis of the LCC of steel beams with initial random imperfections
Statistical and sensitivity analysis of the random LCC with emphasis on design percentiles and reliability.

ABSTRACT: This paper studied buckling of parallel Z- and C-purlin systems inter-braced by sag-rods at mid-span under pure hogging moment. The purlins are connected to metal sheeting by self-drilled screws and the lateral movement of the top flange is prevented. The paper studied first in detail the buckling of a single purlin, and then buckling of parallel purlin systems. The alternate offset of the sag-rods in adjacent bays and the local deformation of the purlin web have been taken into consideration in parallel purlin systems. For one-purlin system, the buckling moments are given, valid for different combinations of sag-rod and distributed rotational stiffness. The threshold stiffness of the sag-rod, at which the buckling mode changes from symmetrical buckling to anti-symmetrical buckling, is also given. For parallel purlin systems, the buckling moments are calculated by the formulas of one-purlin system, but with a reduced equivalent sag-rod stiffness used in the calculation. Numerical examples for the reduced sag-rod stiffness reveal that an astonishingly large reduction of the sag-rod effective stiffness occurs when the purlin number and the sag-rod offset increase, and the sag-rod stiffness is maximum if the sag-rod is set as close to the bottom flange as possible. And finally some strengthening practices and details are recommended.

ABSTRACT: Stability is a decisive factor in the design of domes. The relative gradient of joint well-formedness (gra_r) is defined in the present paper to represent the stability of domes from the perspective of joint well-formedness. The lowest value of gra_r (gra_rmin) functions as an indicator of the buckling capacity. The gra_r and gra_rmin, numerical representations of dome stability, lay the mathematical groundwork for optimization against instability. Characterized by clarity in physical meaning and simplicity of calculation, gra_r is suitable for a high-performance optimum algorithm. To improve the buckling capacity of space domes, an optimization model against instability, which takes the maximization of gra_rmin as the objective and the member sections as discrete variables, is formulated subject to the constraints on design specifications and steel
consumption. Subsequently, a guided genetic algorithm (GGA) is proposed for the stability optimization of large-scale space domes. Information on joint well-formedness that is calculated for a fitness function is re-used to identify stability-vulnerable elements and stiffness-redundant members. Mutation then operates on these members under the guidance of an instability mechanism. The GGA works on guided mutation rather than stochastic mutation of the canonical genetic algorithm, to realize oriented evolution for rapid search. The performance of the proposed method is validated on two large-scale domes. For real-life space domes, the GGA presented shows advantages in computational efficiency, robustness and engineering application, particularly for real-life large-scale domes.


ABSTRACT: Introducing the concept of Tube-in-Tube buckling restrained brace (TiTBRB) members, a comprehensive parametric investigation has been carried out involving the influential parameters affecting the behaviour and modes of failure of the TiTBRBs during cyclic loading through detailed finite element analysis procedures accounting for material and geometric nonlinearities as well as the effects of gaps and contacts. Several BRB related parameters have been considered here for parametric analysis that had not been investigated previously: the strength and stiffness of external restraining tube, the core strength, the core diameter to thickness ratio, the friction coefficient between the core and the restraining tube, the gap size between the core and the external tube, the gap size between rings and the external tube, the magnitude of initial imperfection, the number of intermediate rings along the length of the member and the particulars of the end collars. On the basis of the finite element analysis results, it has been demonstrated that the proposed TiTBRB - if well designed - would be quite competent in accomplishing the intended tasks as a buckling restrained bracing member. Properly designed TiTBRBs can exhibit stable cyclic behaviour and satisfactory cumulative plastic ductility capacity, so that they can serve as effective hysteretic dampers. At the same time, in such all-steel TiTBRBs concreting has been eliminated and hence much lighter members are obtained. This is also associated with ease and speed of fabrication, erection, inspection, replacement and hence a more economical and environmentally friendly design.


ABSTRACT: This paper describes an experimental and numerical investigation of stainless steel material response and behaviour of press-braked channel sections under pure axial compression. A material test programme that covers austenitic stainless steel EN 1.4301 was carried out to study the nonlinear stress–strain relationship and changes of basic mechanical properties due to the press-braking processes. The key experimental results were used to estimate the appropriateness of existing analytical material models and to determinate strain-hardening exponents. The validation of recently proposed models for predicting the strength enhancements in cold-formed sections was also performed. Additionally, corresponding Finite Element (FE) models were built for flat and corner coupons to match the tensile test results and to establish the parameters of a ductile damage model in Abaqus. The susceptibility to local buckling of the channel section was determined by stub column tests. The FE model, calibrated and validated against the experiments, was used to perform a parametric study over a wide range of section slenderness. This allowed the quantitative assessments of design
procedures stated in Eurocode 3 and American Specifications, and the Continuous Strength Method (CSM). The comparisons between generated data and predicted strengths reveal the conservatism of the Eurocode 3 design method for both non-slim and slender channels. In contrast, the CSM reflects significantly better the nonlinear buckling behaviour of non-slim channels. Although this method gives more accurate results comparing to effective method employed in Eurocode 3, the slight unsafe predictions were found for slender channels in the intermediate cross-section slenderness.


ABSTRACT: This paper conducts a numerical investigation on the behaviour of tapered concrete-filled double skin steel tubular (CFDST) stub columns subjected to axially partial compression. A finite element analysis (FEA) model is developed to investigate the partial compressive behaviour of the CFDST column. The full-range load versus deformation relations of tapered CFDST columns under partial and overall compression are both analyzed using the verified FEA model. A parametric study is then conducted to investigate the ultimate strength of the column with various geometric and material parameters. Finally, a simplified model is proposed based on the parametric analysis, which could predict the ultimate strength under partial compression with generally good accuracy.


ABSTRACT: This paper focuses on the assessment of the behaviour of Concrete Filled Steel Tube (CFST) columns with square/rectangular cross-section, made with Rubberized Concrete (RuC), under flexural loading. The study aims to evaluate the differences between this type of composite members and typical CFST members made with standard concrete (StdC), namely in terms of the influence of the rubber aggregate replacement ratio on member strength, ductility, and energy dissipation capacity. The experimental campaign comprised the testing of 16 square members, 12 RuCFST and 4 StdCFST, and 4 rectangular RuCFSTs. A number of parameters were investigated, namely the cross-section slenderness (i.e., the width-to-thickness ratio of the steel tube), the aggregate replacement ratio (i.e., the percentage of sand aggregate of the concrete mixture that is substituted by rubber particles), axial load level and lateral loading type. The test results are compared with the member capacities obtained with the application of Eurocode 4. The results show a minimal influence of the type of concrete infill on the monotonic and cyclic behaviour of the members and also allow concluding that the European code is conservative in predicting the capacity of the specimens. Furthermore, the results obtained demonstrate that the cross-section slenderness has an important role on the behaviour of these members. Nonetheless, the requirements pertaining this parameter that are currently defined in Eurocodes 4 and 8 can be relaxed.

B. Koevesdi and B. Somodi (Budapest University of Technology and Economics, Department of Structural Engineering, Műegyetem rkp. 3, 1111 Budapest, Hungary), “Buckling resistance of HSS box section columns
ABSTRACT: The accurate consideration of the flexural buckling resistance of high strength steel (HSS) structures is highly important in the design. Higher yield strength indicates the applicability of smaller cross-sections, which might be more sensitive for stability problems. The purpose of the current study is (1) to investigate the flexural buckling behaviour of HSS welded box section columns and (2) to determine a reliable column buckling curve. The characteristic and design values of the buckling resistances for HSS welded box section column are determined by using Monte Carlo simulation technique for a wide range of relative slenderness and steel grades. Based on the simulation results buckling curves are proposed for all the analysed steel grades. Required value for the partial safety factor is also determined considering the design resistance level of the Eurocode. The proposed buckling curves are applicable for HSS welded box section columns made from steel grades between S420–S960.

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16 High Strength Long Span Structures (HILONG), Final report, RFCS Research Project, RFSR-CT-2012-00028 (2017)
17 SSAB steel manufacturer, Stockholm, Sweden.

ABSTRACT: The accurate and economical consideration of the flexural buckling resistance of high strength steel (HSS) structures is highly important in the design. According to the previous research results the flexural buckling behaviour of HSS and NSS columns can be significantly different, which differences are not considered in the current design rules. The aim of the current study is to obtain a reliable design method for the flexural buckling resistance of HSS welded box section columns. The buckling resistance is previously determined by the authors based on an experimental research program and based on stochastic numerical simulations. The current paper focuses on the investigation of the theoretical background of the flexural buckling phenomena and on the implementation of the specialties regarding HSS materials into the buckling curve formulation. The analytically derived Ayrton-Perry type formulation is studied and modified based on the theoretical and numerical investigations implementing the effect of residual stresses and geometrical imperfections into the design method. Using the revised buckling curve, the flexural buckling resistance of welded box columns can be predicted with larger accuracy for steel grades between S420 – S960.


ABSTRACT: The concrete-filled-steel-tube (CFST) column has been widely used in construction due to the benefit of composite action between inner concrete and exterior steel tube. Under axial compression, the steel tube is subjected to biaxial stress state in the hoop and axial direction, and the hoop stress component provides confinement for the inner concrete. However, the existence of axial stress component accelerates the buckling of steel tube, which hinders its confinement effect to inner concrete and accordingly column's axial compressive strength and ductility. This paper aims to enhance the axial compressive strength and ductility of CFST stub columns by improving its confinement effect provided by the steel tube. CFST stub columns axially loaded/unloaded were experimentally studied for different cases: a) varying concrete strength, b) lubrication on the contact between steel tube and concrete and c) corrugations in the steel tube that are introduced to intentionally weaken the tube vertically. It was found that axial compressive strength of CFST stub columns was effectively enhanced by reducing the axial stress in the steel tube. The introduction of corrugations in the steel tube led to largely concentrated axial deformation which reduced axial stress in other portions of the steel tube and consequently resulted in “tighter” hoop confinement to the inner concrete; both axial compressive strength and ductility were enhanced.

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ABSTRACT: Carbon fiber is considered as a newly alternative technique used in enhancing the strength and behavior of different members in many steel structures applications. In this research, an experimental study for strengthening of cold-formed lipped channel columns using carbon fiber reinforced polymers (CFRP) is conducted. Twelve cold-formed columns specimens with different parametric variables are chosen. Different variables such flange width-thickness, web depth-thickness ratios for un-strengthened, partially, and fully
strengthened short columns, as well as overall slenderness ratios for partially strengthened short and medium columns are selected. The cold-formed column specimens were tested under axial compression load. A finite element model is developed using ANSYS program to simulate and verify the laboratory tested specimen's results. The developed FE model includes both geometric and material nonlinearities. The strengthened columns behavior along with local, distortion and rupture failure modes are investigated. A comparison between experimental and finite elements as well as the direct strength method (DSM) axial capacities, is carried out. Finite element and direct strength method results are comparable with the experimental results.

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ABSTRACT: Cylindrically curved plates are increasingly used in steel construction. In particular, there is a clear trend for their use in box-girder steel bridges with curved bottom flanges. However, there is a gap in standards dealing accurately with these types of structural elements under several arrangements of loadings and boundary conditions. This paper provides a state-of-the-art on the stability behaviour and design of cylindrically curved panels under generalised in-plane loading. A detailed review of the behaviour of curved panels subject to uniaxial compressive stresses, circumferential stresses, shear stresses and combined in-plane compressive stresses is presented, followed by a comparison of the design provisions of DNV and DNVGL standards with FEM numerical results obtained by the authors.

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ABSTRACT: Concrete-filled steel tubular (CFST) columns with round-ends own the same advantages of typical CFST columns, besides their aesthetical appearance. The smoothness of the cross-section gives the effectiveness to resist running water impact when they are used as piers. Despite these advantages, there are limited researches on the behaviour of round-ended CFST columns. The paper investigates the behaviour of round-ended rectangular CFST (RRCFST) columns. Three-dimensional finite element (FE) models for RRCFST columns are developed using the ABAQUS software. The novelty of this FE model is the consideration of the confinement in the round-ended concrete. The existing experimental behaviour has been captured properly, compared with other previously suggested FE models. After the validation of FE models, a parametric study is generated taking into account wider parameters than those previously considered by other researchers. The results show two different axial load-strain responses based on the B/t ratios of the cross-sections. RRCFST columns with small B/t ratios are found to fail in a ductile manner with large axial strains. The failure of the columns with relatively high B/t ratios has been found to occur suddenly with a rapid reduction in the strength after reaching the ultimate load. The numerical results indicate that the brittle failure is associated with the columns formed from outer slender steel cross-sections. The FE strengths are compared with the available design model which was formulated based on limited research results. This design model is found to predict the strengths unconservatively. A new design model, providing better estimates, has been suggested at the end.

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ABSTRACT: In parallel with an experimental investigation of the flexural buckling behaviour of built-up stainless steel columns presented in the accompanying paper (Dobrić et al., submitted for publication), a detailed Finite Element Analysis (FEA) has been performed to simulate the experiment and identify the key factors affecting the buckling response. The FEA entailed realistic geometry, measured geometric imperfections and material properties of the specimens. Very good agreement was obtained between the experiment and FEA, which proved the capability of the computational approach to replicate experimental results and predict ultimate buckling loads. In the absence of explicit design rules for flexural buckling resistance of stainless steel closely spaced built-up members, the experimental results were compared with design predictions according to the existing European Standard and American Specification for carbon steel structures. The findings indicate that the mentioned design standards may be very conservative regarding the buckling resistance of stainless steel built-up members; this under-prediction may be associated with the impact assessment of chord slenderness and interconnection stiffness on the buckling response. The main purpose of this research is to establish a qualitative data base reliable for the further quantitative numerical parameter analysis and for the development of new design rules for compressed stainless steel cold-formed built-up members.

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16 J. Dobrić, “Behaviour of Built-up Stainless Steel Members Subjected to Axial Compression”, University of Belgrade, Faculty of Civil Engineering, PhD thesis (2014)

ABSTRACT: This paper discusses the behaviour of stainless steel rectangular and square hollow sections (RHSs and SHSs) under combined constant compression and uniaxial cyclic bending. A total of 10 specimens were tested, covering a variety of section slenderness, axial load ratio, and bending direction. These test parameters were found to have evident influences on the local buckling resistance of the specimens. It was also observed that the current codified classification limits underestimate the ability of the stainless steel sections to develop plastic stresses. Moreover, the specimens exhibited low to moderate levels of ductility and energy dissipation capacity due to a relatively early occurrence of local buckling. A numerical study was subsequently conducted, shedding further light on the strength, stress pattern, ductility, and local failure behaviour of the specimens. A more extensive parametric study was then carried out, which provides basis for the proposal of a ductility-oriented design approach that aims to offer a quick yet reliable evaluation tool for predicting the available ductility supply of stainless steel RHSs/SHSs under different loading conditions. The rationality of the current major design codes for predicting the strength of stainless steel members was also evaluated, and it was found that the design codes tend to be conservative.


ABSTRACT: A stiffness reduction method for the design of laterally restrained web-tapered steel structures fabricated through the welding of individual steel plates is presented in this paper. Stiffness reduction functions for welded members, accounting fully for the deleterious influence of the spread of plasticity and imperfections on the structural resistance, are developed. The method is implemented through (i) dividing tapered members into prismatic segments along their lengths, (ii) reducing the flexural stiffness of each segment by means of the developed stiffness reduction functions considering the first-order forces and cross-section properties of each segment, (iii) performing Geometrically Nonlinear Analysis and (iv) making cross-section strength checks. Essentially, it is proposed to replace the current typical approach to structural design of conducting a simple elastic (with nominal stiffness) structural analysis followed by elaborate member checks with an integrated process utilising more sophisticated second-order analysis (with stiffness reduction) but very simple design checks. The distribution of internal forces within the structure is captured more accurately due to the allowance for imperfections, residual stresses and plasticity through stiffness reduction and the allowance for frame and member instability effects through the use of second-order analysis. The need for determining effective lengths and for conducting member buckling checks is also eliminated. Verification of the proposed approach against the results obtained from nonlinear shell finite element modelling is presented for various tapering geometries, slenderness values and loading conditions. Assessment of the proposed method against the European and North American steel design codes for tapered steel structures is also provided.

V.K.R. Kodur and M.Z. Naser (Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, USA), “Approach for shear capacity evaluation of fire exposed steel and
ABSTRACT: A simplified approach for evaluating degradation of shear capacity in fire exposed steel and composite beams is presented. This approach takes into account temperature-induced strength degradation, and sectional instability effects, as well as level of composite action developed at the beam-slab interface. The validity of the approach in evaluating shear capacity of fire exposed steel and composite beams is established by comparing predictions from the proposed approach with results obtained from finite element analysis and fire tests. Results generated from numerical studies and illustrative examples infer that the proposed approach can evaluate degradation in shear capacity of fire exposed steel and composite beams under wide range of loading scenarios.


ABSTRACT: Global and local imperfections are required to capture accurate buckling loads and overall structural behaviour of axially loaded structural steel hollow sections in finite element (FE) models. In this paper, three methods of geometrical imperfections are considered for square and rectangular structural steel hollow sections: (i) creating the profile of the brace using a half sine wave, (ii) applying an equivalent notional lateral load at mid-length, and (iii) combining sinusoidal local imperfections with an equivalent notional lateral load for global imperfections. When modelling the initial shape of brace members with global imperfection at mid-length of the magnitude used to establish the European buckling curves (L/1000, where L is the length of the brace member), it was found that the equivalent notional lateral load methodology could best predict the buckling capacity of brace members when compared to physical test data and European buckling curves. However, both methodologies neglect the effect of local imperfection on the initial buckling loads. When it was included by generating a continuous sinusoidal wave along the member length, it did not affect the initial buckling loads, but gave a more overall representative behaviour of the brace members.

The FE model is then validated using sixteen cyclic tests for brace members. The FE results are found to match the physical tests values relatively well. In other words, when comparing the ratio of yield force, buckling resistance, and total energy dissipated estimated from the FE model to the measured values in physical tests, the mean values are found to be 1.04, 0.99 and 1.24, respectively, with a coefficient of variation of 0.07, 0.07 and 0.17, respectively.


ABSTRACT: Bending is one of the most common forms of deformation that may cause failure of a structural member, such as a column, especially when the member is exposed to fire. Fire resistance design is therefore an important factor that must be considered in the design process of modern building structures. Based on the authors' previous work on the unified formulation of axially loaded CFST hollow and solid columns with circular and polygonal sections, a unified formula for calculating the ultimate bending moment of solid and hollow CFST columns at room temperature is proposed first in this paper. The formula is then extended to include elevated temperature using the average temperature method. Finally, a unified formula for both room and elevated temperature are presented. Validations are carried out through comparisons with the results from experimental tests and finite element simulations.

ABSTRACT: The global stability of a spatial structure is usually analysed via a nodal load-displacement curve (NLDC). However, the global mechanical properties of a structure can hardly be reflected comprehensively by specific NLDCs, and no criterion is available to select the representative node for getting the most reasonable NLDC. In this paper, a scalar parameter derived from the incremental equilibrium equation of nonlinear stability analysis, named Eigen-stiffness, is defined to characterize the global structural stiffness. The Structural Eigen-curve (SEC), based on Eigen-stiffness, is proposed to depict the equilibrium path. Two types of extreme points on SEC are defined to determine the critical state of the structure, including the structural limit state and the structural snap-back. Firstly, the stability of a hinge-supported planar arch is analysed to introduce the SEC concept. Then a K6 reticulated shell is designed to give further understanding. Subsequently, practical application of the SEC is illustrated in the stability analysis of a roof structure, namely, Shanghai International Conference Centre. In addition, a parametric study on a K6 reticulated shell is carried out, based on the Eigen-stiffness and the SEC, to investigate the effects of the rise to span ratio and the geometric imperfection amplitude on the structural stiffness and the structural load-carrying capacity. The results demonstrate that the ultimate load-carrying capacity obtained from the SEC is equal to that from NLDC. More importantly, unlike NLDC, the SEC — free from node selection — can efficiently capture the features of global structural behaviour and the evolution of structural stiffness.


ABSTRACT: In the current Eurocode 3-1-5 [1] for local buckling, the resistance curve used to represent the reduction factor of plated elements due to local failure is based on the so-called Winter-curve, derived on a semi-empirical approach by George Winter in 1947. This design curve represents the mean reduction values achieved in the experiments conducted by Winter and other researchers. However, when applying the safety concept of EN 1990 [2], an additional safety factor $\gamma_M$ is necessary to ascertain a defined level of failure probability. Currently, this factor is set to 1.0 for applications in building structures. In this paper 34 stub column tests on welded, squared box sections of steel grade S500 up to S960 are described. In combination with an experimental database on stub column tests summarised in Ref. [3], a new, optimised resistance curve is derived which could act as an alternative to the Winter curve. Additionally, both functions are evaluated in regard to the safety standard EN 1990 [2] with focus on the resulting $\gamma_M$. As $\gamma_M$ represents the safety factor for the actual material and geometric properties, which are not known by the designer, the more decisive safety factor is $\gamma_M^*$. This factor is used throughout Eurocode and refers to the nominal material and geometric properties. Its derivation and the influencing parameters are discussed and evaluated in the study at hand.

Hui Ma, Jing Dong, Yunhe Liu and Tingting Guo, “Compressive behaviour of composite columns composed of RAC-filled circular steel tube and profile steel under axial loading”, Journal of Constructional Steel Research, Vol. 143, pp 72-82, April 2018

ABSTRACT: Axial loading tests are conducted on composite columns composed of recycled aggregate concrete (RAC) filled circular steel tube and profile steel. This research primarily aims to investigate the compressive behaviour of composite columns on the basis of the axial compression tests of 11 specimens under uniaxial loading. The design parameters of these columns in the tests are recycled coarse aggregates (RCA) replacement percentage, diameter-thickness ratio of circular steel tube, profile steel ratio and slenderness ratio. The failure process and modes, load-displacement curves, Poisson's ratio of circular steel tube, characteristic
loads and ductility of composite columns are presented and analysed. The influence of design parameters on the compressive behaviour of columns is also investigated in detail. Results show that the composite columns present good mechanical performance under axial loading. The profile steel yields ahead of the steel tube and the core RAC exhibits shear failure or crush failure. The axial bearing capacity of composite columns decreases as the magnitude of RCA replacement percentage increases, but the deformability still performs well. The decrease in diameter-thickness ratio and the increase in profile steel ratio are beneficial to the axial bearing capacity and column ductility. In addition, the axial compression behaviour of composite columns decreases significantly as slenderness ratio increases. On the basis of the test and analysis results, a modified AISC design method is proposed to calculate the nominal axial bearing capacity of composite columns composed of RAC-filled circular steel tube and profile steel.

ABSTRACT: Requirements of industrial piping and pipelines to withstand extreme cyclic loading conditions have been motivating increasing interest on a particular extreme fatigue regime: the ultra-low cycle fatigue (ULCF). This damage domain corresponds to a transition between low-cycle fatigue and monotonic ductile damage. Albeit better understanding of this damage regime is required, very few studies are available covering full-scale testing. This study aims at investigating the performance of X60 and X65 piping steels, subjected to extreme cyclic loading conditions resulting in a reduced number of fatigue cycles ($N < 100$). Experimental tests were carried out on full-scale straight pipes subjected to cyclic pure bending, which were performed under the framework of the ULCF RFCS/EU project. Additionally to the large-scale tests, plain material was also tested under monotonic and ULCF conditions, supported by small-scale smooth and notched specimens. Large-scale tests were simulated by means of elastoplastic finite element models in order to reproduce the local plastic instability (buckling) where fatigue cracking was verified. Classical Coffin-Mason relation and a modified Xue relation were calibrated using small-scale testing data, the latter relation accounting for triaxiality and Lode angle stress tensor dependencies. The referred models were applied in the damage prediction of the full-scale pipes and results compared with code based procedures such as the ones proposed in the ASME VIII, Div.2. In general, the incorporation of the stress state parameters in the computation of ULCF damage produced improved predictions with respect to the pure strain range based models as the Coffin-Manson or ASME VIII, Div.2 code.

ABSTRACT: The inelastic outward local buckling of steel tubes is common in concrete-filled steel tube (CFST) columns. The use of fiber-reinforced polymer (FRP) to suppress outward local buckling has been proposed and proven to have potential in both strengthening and new construction. This paper presents the results of an experimental program performed to study the effect of slenderness ratio on the behavior of CFRP-confined CFST columns. Eight specimens with heights ranging between 588 and 2688 mm were tested under axial compression. The effect of the number of CFRP layers was also studied. The results showed that the CFRP hoop wraps provided confinement to the concrete and the steel tube, and thus effectively improved the behavior of the CFST columns. The strengthening effect of the CFRP hoop wraps decreased when the slenderness ratio increased. The existing AISC expression of stability coefficient for CFST columns was extended to propose a formula for the stability coefficient of CFRP-confined CFST columns, and the predictions showed good agreement with the experimental results.

ABSTRACT: Built-up tapered I-beams, which are mostly loaded so as to be under bending about their strong axis for the economical use of the structural material, are commonly used in wide span steel structures. Lateral-torsional buckling, excessive deflection and partial or complete yielding of the material are the important failure modes, which should be considered in design of these members. However, today's “modern design” concept not only requires the satisfaction of certain constraints but also a lightweight structure. This study presents the shape optimization of flange and/or web tapered doubly-symmetric I-beams and discusses the contribution of flange and/or web tapering and inflection point location to the economical design. The optimization procedure is constructed by slightly modifying the Big Bang - Big Crunch algorithm, which is a simple and effective population-based metaheuristic, and installing the Deb's constraint handling method. Four beam configurations with various loading and restraint conditions are optimized and final designs are validated by finite element analysis software. It is shown that tapering, and therefore the inflection point location may not have a significant effect on the material economy in certain conditions.


ABSTRACT: To improve the seismic behavior of cold-formed steel (CFS) shear walls, cold-formed steel high-strength lightweight foamed concrete (CSHLFC) shear walls with straw boards are proposed. This study conducted tests of six full-scale shear wall specimens to investigate the failure mode, load-bearing capacity, ductility, stiffness characteristic and energy dissipation capacity. The test parameters included HLFC density grade, stud section area, wall thickness and vertical load. Test results indicated that HLFC has greater effect on seismic performance and failure mode of the shear walls. The failure modes were cracking and crushing of HLFC, cracking of straw boards, local buckling of studs, and relative slippage between HLFC and studs, which made the wall exhibit good ductility and energy dissipation capacity. Compressive bearing capacity of HLFC and restrictive effect of HLFC on steel frame increased the shear strength and stiffness. The most effective way of improving seismic performance was to increase wall thickness, followed by increasing HLFC density grade and stud section area, but increasing vertical load had an adverse effect on seismic performance. Based on experimental results and mechanism analysis of shear walls, a simplified design formula for predicting the shear strength was proposed base on strut-and-tie model. The calculated results obtained by the proposed formula showed better agreement with the experiment results compared with the results from ACI 318-14, EC8 and CNS 383-16 standards.


ABSTRACT: The problem addressed in this paper is the thermal buckling behaviour of thin-walled steel cylindrical fixed-roof tanks under non-uniform loading, induced by an adjacent tank. This specific type of thermal loading can be triggered by a neighboring tank fire where heat is transferred mainly through radiation. Since the calculation of the temperature field of the heated tank lies in other scientific fields (e.g. Computational Fluid Dynamics), a thermal pattern, proposed in literature, is used for the simulation of the fire-induced load and the investigation of the structural response of the tank due to heating. The study is conducted numerically through the Finite Element method, using coupled thermo-mechanical analysis. The general purpose Finite Element code MSC Marc, is used for the simulation. Three-dimensional models are developed using shell elements. Firstly, a detailed study of the failure mechanisms that take place in case of non-uniform loading is
carried out. Furthermore, tanks with different geometries are studied. The main objective is the calculation of the critical temperature i.e. the temperature where the failure appears and the determination of the failure modes. Finally, a parametric study is conducted for the evaluation of the effectiveness of stiffening methods that are commonly used at ambient temperature design (stiffeners and stepwise wall thickness), in the case of the non-uniform heating load. In this study, the heated tanks are considered to be empty, which is the most severe scenario, for their structural integrity.


ABSTRACT: The ultimate strength and behavior of steel H-sections are investigated experimentally and theoretically in this paper. The main considered parameters include different combinations of flange and web width-to-thickness ratios and varying axial force ratios, with both major and minor axis bending responses being examined. It is found that the section behavior, including occurrence of local buckling, stress distribution form after buckling and ultimate strength, is strongly dependent on the interaction between flange and web. The "plastic effective width" method (PEM) for the ultimate moment resistance of H-sections bent about strong or weak axis is refined and improved using an adjustment factor, namely cross-section slenderness, which accounts for the interactive effect of the plates under different loading conditions. Finally, PEM is proved to provide satisfactory predictions for H-sections over a spectrum of web and flange width-to-thickness ratios and axial force ratios for both the strong and weak axis bending.


ABSTRACT: Pitting corrosion poses a threat to plated steel structures serving in aggressive corrosion environments. This paper involves numerical studies on the structural behaviour and ultimate strength reduction of plated steel structures due to random pitting damage. Stochastic simulations were used to model the random nature of the pitting corrosion varying pitting shape, depth and distribution. A series of nonlinear analyses were performed on unstiffened plates and stiffened panels to understand the mechanisms of structural collapse due to random pitting damage. Empirical formulae were derived respectively for the prediction of ultimate strength reductions of unstiffened plates and stiffened panels in terms of regression analysis from the numerical results. Random pitting corrosion induces a variation and reduction in ultimate strength, and can lead to a transition in failure mode. The collapse of pitted structures under uniaxial compression has a feature that the onset of plasticity initiates in the areas close to the unloaded edge of the structure, and propagates into a continuous plasticity region linking the pits with highly concentrated stress. The pitted area with intensively stress-concentrated pits undergoes a locally amplified deformation that determines the failure mode, leading to structural failure.


ABSTRACT: This paper presents a numerical investigation of the dynamic performance of steel plate shear walls (SPSWs) stiffened by non-welded multi-rib stiffeners. Multi-rib stiffeners are installed on both sides of the steel plate and connected by threaded bolts through the plate, rather than direct welding as conventionally being done. The influence of constraints between multi-rib stiffeners and steel plate on the performance of SPSWs is first examined by finite element analysis. Afterwards, a numerical model for SPSW structure is developed and validated by the test results. The dynamic performance of SPSW structures with and without non-welded stiffeners is compared in terms of inter-story drift, acceleration response and out-of-plane deformation. Test results indicate that constraints between multi-rib stiffeners and steel plate slightly affect the
loading capacity of SPSWs. The loading capacity of the SPSWs with non-welded multi-rib stiffeners is 5.8% lower than that with welded stiffeners. However, buckling of stiffeners can be avoided in the non-welded multi-rib stiffened SPSWs. For the dynamic performance of SPSW structures, use of non-welded multi-rib stiffeners is effective in reducing the inter-story drift, acceleration and out-of-plane deformation of SPSW structures under earthquake attacks, particularly for those subjected to main shocks followed with aftershocks. The use of non-welded stiffeners decreases the maximum inter-story drift and the maximum out-of-plane deformation of SPSW structures by 14.7% and 57.0%, respectively. In addition, non-welded multi-rib stiffeners can uniformly distribute the stiffness of SPSWs along the floors. In general, the proposed non-welded multi-rib stiffeners are effective in enhancing the dynamic performance of SPSWs.


ABSTRACT: This paper presents a numerical investigation on elastic buckling and hysteretic behavior of a steel angles assembled buckling-restrained brace (SAA-BRB). The SAA-BRB is composed of a cruciform-sectional steel core encased by an external restraining system, which consists of four steel angles connected together by high-strength bolts and spacers. It is found that the SAA-BRB may fail in a global buckling mode or in a local buckling mode. In order to predict the global and local buckling behavior of SAA-BRBs, two design parameters: the restraining ratio and segment restraining ratio are proposed. To determine these two design parameters, a simplified theoretical model of SAA-BRBs and an accurate finite element (FE) model are used to investigate the global and local elastic buckling behaviors of SAA-BRBs. Based on more than 500 FE results, explicit expressions of the restraining ratio and segment restraining ratio are obtained and validated to be sufficiently accurate for practical design applications. In addition, 20 refined FE models considering material and geometrical nonlinearities are used to carry out parametric studies for comprehensively investigating the hysteretic behavior of SAA-BRBs. Finally, the following design recommendations for fix-ended SAA-BRBs are proposed: (1) the restraining ratio should be >2.2 to prevent a SAA-BRB from the global buckling failure, and (2) the segment restraining ratio should be >6.0 to prevent a SAA-BRB from the local buckling failure.


ABSTRACT: The lateral-torsional buckling behavior of hot-rolled steel beams has been studied extensively. Much of the research carried out has been limited to doubly symmetric beams and a few other common geometries. The study of monosymmetric and non-symmetric geometries has not been as extensive. This paper presents a study of the lateral-torsional buckling behavior of monosymmetric beams having the monosymmetry introduced by flange end upstands. The study is carried out using finite element modelling. The behavior is investigated for various spans and with various heights of upstands. It is observed that the upstands increase the critical buckling moment of the section but that this increase diminishes with increase in upstand height. It is further observed that this unique behavior could be influenced by a movement in the relative position of the shear center to the geometric centroid as the flange upstands are adjusted. In addition there exists for these geometries unique points where the monosymmetric sections have properties typically associated with doubly symmetric sections. It is shown that the relative position of the shear center and centroid have some influence on the strength gain pattern observed.

ABSTRACT: This paper reports on experiments addressing the buckling and collapse behavior of back-to-back lipped channel built-up cold-formed steel (CFS) columns assembled using 16 different CFS lipped channel sizes. The lipped channel sections are connected at the web using a pair of self-drilling screw fasteners at a specified spacing along the column length of 1.83 m (6 ft). These experiments aim to quantify the effect of two web fastener layouts on composite action for each section size, study member end fixity, observe buckling and collapse behavior, and provide benchmarks for design that includes specific considerations for thin-walled member buckling. A total of 32 monotonic, displacement-controlled, concentric compression tests are completed with up to 17 position transducers monitoring displacements at key locations. All tests are conducted with the built-up member seated in CFS tracks, as would be found in practice. Local–global interaction is shown to be a prevalent failure mode, and the stud-to-track end condition is determined to be semi-rigid, but generally closer to a fixed condition. End rigidities are estimated using a Southwell approach. Rational design approaches extending the application of the Direct Strength Method (DSM) and employing current state-of-the-art numerical modeling techniques are proposed and validated with test data. In addition, the development of definitive design recommendations that help reduce the complexity of fastener designs and incorporates the DSM framework when predicting built-up member strength is underway.


ABSTRACT: This paper aims to study the interaction of local and overall flexural buckling in cold-formed steel (CFS) channels under axial compression. Detailed nonlinear FE models were developed and validated against a total of 36 axial compression tests on CFS plain and lipped channel columns with pin-ended boundary conditions. The numerical models incorporated the non-linear stress-strain behaviour of CFS material and enhanced properties of cold-worked corner regions obtained from coupon tests. The effects of initial geometric imperfections of the specimens measured by a specially designed set-up with laser displacement transducers were also taken into account. The developed FE models produced excellent predictions of the ultimate strength of the specimens obtained from experimental tests. The validated FE models and experimental results were then used to assess the adequacy of the effective width method in Eurocode 3 (EC3) and Direct Strength Method (DSM) in estimating the design capacity of a wide range of conventional and optimised design CFS channel column sections. The results indicate that Eurocode 3 provides conservative predictions (on average 21% deviation) for the compressive capacity of plain and lipped channel sections, while in general DSM predictions are more accurate for lipped channels. A comparison between FE predictions and tested results show that geometric imperfections can change the FE predictions by up to 20% and 40%, respectively, for lipped and plain channel columns, while the strain hardening effect at the rounded corner regions of the cross-sections is negligible. The results also confirmed that the proposed numerical model is able to provide a consistent and reliable prediction on the efficiency of a previously proposed optimisation methodology.


ABSTRACT: In conjunction with the experimental investigation described in the paper [1], a numerical modeling programme has been carried out to investigate further the structural behaviour of high strength Q690 steel columns of welded H-sections under combined compression and bending. Finite element (FE) models were developed by using the FE package ABAQUS. Geometrical and material non-linearities were incorporated in the FE models. Through the validation against the experimental results, these FE models showed excellent capability of replicating the key test results, including failure modes, failure loads and full load-axial
deformation and load-lateral deflection histories. Upon validation of the FE models, parametric studies were conducted focusing on the effect of member residual stresses and material yield to tensile strength ratios. Then a large number of FE models were established to generate additional structural performance data over a wide range of cross-section dimensions, member slenderness and initial loading eccentricity ratios. The FE model results were then compared with the design buckling resistances of columns under combined compression and bending according to the current European Standard EN 1993-1-1, American Specification ANSI/AISC 360-16 and Chinese Standard GB 50017-2003. The comparisons revealed that by properly selecting design parameters, the design rules in EN 1993-1-1 and GB 50017-2003 could provide close and safe predictions to the buckling resistances of Q690 steel columns of welded H-sections while the design rules in ANSI/AISC 360-16 was readily applicable to the design of Q690 steel columns of welded H-sections.

ABSTRACT: This paper mainly presents a pseudo-static test program on 12 terminal stirrup-confined square concrete-filled steel tube (SCFT) columns and 14 rectangular SCFT columns under constant axial pressure. The effects of various factors on the hysteretic behavior of specimens are investigated. These factors include with or without stirrups, height of terminal stirrup region, equivalent stirrup ratio, stirrup form, loading direction, height-length ratio (L/B), length-width ratio (B/D), axial compression ratio (n) and sliding support. The failure mode, strain ratio, hysteretic curve, skeleton curve, ultimate bearing capacity, ductility, stiffness degradation, energy dissipation, as well as the residual deformation of the specimens are analyzed. The results indicate that: (1) When n is relatively larger, the bidirectional stirrups can effectively delay the local buckling of steel tube and greatly increase the ultimate bearing capacity, stiffness, equivalent damping viscosity index, residual deformation rate and ductility index, and further significantly improve the seismic behavior of the rectangular SCFT columns; (2) Axial pressure can improve the confinement effect from the steel tube to the core concrete, also bidirectional stirrups can directly confine the core concrete to decrease strain ratio of the steel tube; (3) With the same value of n, increasing the height of terminal stirrup region or increasing the equivalent stirrup ratio can effectively improve the seismic behavior of the rectangular SCFT columns; (4) The influence of loading direction, L/B and B/D on the ductility of rectangular SCFT columns are not obvious.

ABSTRACT: High strength low alloy (HSLA) steel pipes such as API-X80 and beyond, have found increasing applications in deep offshore hydrocarbon development projects. The current paper reports the results of inelastic uniaxial cyclic creep and incremental collapse experiments on API X80 steel pipes at different accelerated corrosion exposure. Effects of parameters such as the exposure duration, corrosion morphology and loading conditions on the monotonic response, cyclic response, local deformation mode, number of cycles to failure and modes of failure were examined. The corrosion morphology as well as the deformations in the pipe specimens were recorded and monitored using non-contact 3D optical measurement techniques. In relative terms, the corrosion effects were much more pronounced under cyclic loading than monotonic loading. The rate of the cyclic creep and the number of cycles to failure were radically affected by the corrosion exposure. The corrosion morphology had, comparatively, smaller effects. Uncorroded specimens showed axisymmetric ductile modes of failure. The failure mode in corroded specimens was non-axisymmetric and also included a brittle low-cycle fatigue failure mode.

ABSTRACT: Cold-formed steel hollow flange beams have been commonly used as flexural members in buildings due to their structural efficiency. The rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new type of cold-formed steel section, characterized by two torsionally rigid hollow flanges connected to a web element. The RHFCB takes advantage of an intermittent fastening method using self-pierce riveting. Buckling analyses have shown that the moment capacity of short-span RHFCB is governed by local buckling while intermediate span RHFCB is governed by the unique lateral distortional buckling. An experimental investigation of RHFCB flexural members was carried out based on a quarter point loading method to investigate their lateral distortional buckling behaviour and moment capacities. It considered the effects of intermittent rivet spacing on the member moment capacity of RHFCBs. The results from the experiments were compared with the member moment capacities predicted using the Australian cold-formed steel structures standard. Following the experimental study, finite element models of tested RHFCBs were developed to simulate the experiments. The developed finite element models were validated by comparison of ultimate moment capacities, applied moment versus deflection curves and failure modes. This paper presents the details of the experimental investigation, the development of finite element models of RHFCBs subject to lateral distortional buckling effects, and the results.


ABSTRACT: Shell structures are built using a number of welded curved panel parts. Hence, some geometrical imperfections emerge. These imperfections have a direct impact on structural behavior of shells during the external compressive loading. In this research, a field study was accomplished on the implementation of the storage tanks in a refinery site and then, the resulted imperfections were identified and categorized. The survey of imperfections revealed that the imperfection in form of concavity of vertical weld line is the most prevalent type of imperfection seen in the steel tanks. This imperfection experimentally modeled and the buckling behavior of these tanks was evaluated under uniform external pressure. Comparing obtained results of estimation, ASME code and experimental research represented a considerable difference in the amount of buckling load. Results show that the imperfections due to concavity of vertical weld line are very important in buckling of the tanks under uniform external pressure. This imperfection decreases initial, full and post buckling capacity of the tanks under uniform external pressure, significantly. Findings of this research show that for design of steel tanks under uniform external pressure load, 65% of the buckling load obtained from the ASME Code should be used.

Xianzhong Zhao, Jintai Liu, Xiangbin Xu, Ken Siva Sivakumaran and Yiyi Chen, “Hysteretic behaviour of overlapped tubular k-jo8nts under cyclic loading”, Journal of Constructional Steel Research, Vol. 145, pp 397-413, June 2018

ABSTRACT: Overlapped K-joints arise in truss type structures when one diagonal (overlap brace) intersects the other diagonal (through brace). In such joints, part of the through brace is hidden within the overlap brace, and the hidden toe of the through brace may or may not be welded to the chord. This study investigates the hysteretic behaviour of partially overlapped circular hollow section K-joints, with and without hidden welds, under cyclic loading. This study involved nine full-scale specimens, out of which four specimens had hidden welds. One joint was statically loaded and the remaining eight joints were cyclically loaded until failure. Chord plastification, brace local buckling, and cracking of the brace adjacent to welds were observed in these tests. The hysteretic performance indicators, such as ultimate capacity, joint ductility, energy dissipation, ultimate
stiffness, etc., were established, which were then used to understand the hysteretic behaviour of overlapped K-joints. Results show that, compared with static loading, brace cracking occurred more easily under cyclic loading with a reduced joint capacity of up to 7% and a severely decreased ductility. Joints with hidden welds may exhibit a higher strength by approximately 10% and an increased hysteretic energy dissipation capacity, but with a reduction in joint ductility. The analysis of strain distributions around the joint zone indicates that, even though the joints with hidden welds experience lower strains, the hidden weld creates an asymmetric strain profile in the joints, which may be a weakness as some locations may become stress raisers leading to crack initiation.


ABSTRACT: This work reports the available results of an ongoing numerical (shell finite element) investigation on the post-buckling behaviour, strength and design of fixed-ended cold-formed steel columns undergoing distortional-global (D-G) interaction. Columns with different cross-section shapes are analysed, namely plain lipped channel (LC), web-stiffened lipped channel (WSLC) and zed-section (Z) columns, in order to investigate distinct D-G interaction natures: involving either distortional and (global) flexural-torsional buckling (LC and WSLC columns) or distortional and (global) minor-axis flexural buckling (Z columns). In particular, the relevance of these D-G interaction types is discussed, by assessing when they affect visibly the column ultimate strength and/or failure mode. The results presented and discussed concern columns with various geometries and yield stresses, thus ensuring a wide variety of range combinations involving (i) global-to-distortional critical buckling load ratios ($R_{GD}$) and (ii) squash-to-non critical buckling (distortional or global) load ratios ($R_s$) and leading to non-negligible failure load erosion. The possible occurrence and failure load impact of “secondary (distortional or global)-bifurcation D-G interaction” ($R_{GD} < 1.0$ or $R_{GD} > 1.0$ and high $R_s$) are investigated - it is well known that such impact may be significant in columns experiencing “true D-G interaction” ($R_{GD} \approx 1.0$). The above results consist of (i) relevant non-linear (elastic and elastic-plastic) equilibrium paths, (ii) deformed configuration evolutions along those paths, evidencing D-G interactive effects, and (iii) figures providing the failure mode characterisation. Then, the numerical failure load data obtained are compared with their predictions by (i) the currently codified DSM (Direct Strength Method) column global and distortional strength curves, and (when necessary) (ii) proposed DSM-based design approaches, specifically developed to handle D-G interactive failures - a few design considerations are drawn from these comparisons.


ABSTRACT: Steel I-girders with longitudinally stiffened webs are commonly used in the civil engineering field, especially in bridges. Therefore, the load-carrying capacity of these types of girders under a combined loading scenario (interaction of bending and shear) is an important feature of the design. Previous research results proved that the current design method of EN1993-1-5 [1] does not always provide safe resistances for the M-V interaction in scenarios where longitudinally stiffened and unstiffened girders are utilised. Because there has only been a small number investigations on this topic, a systematic review of the M-V interaction behaviour for unstiffened girders was executed by Jáger et al. [2] in 2016. This type of review is still missing in international literature for longitudinally stiffened girders; therefore, the current study focuses on the M-V interaction behaviour of longitudinally stiffened I-girders with slender webs, and investigates the applicability of the M-V interaction resistance model developed for unstiffened girders [2].

ABSTRACT: Nowadays, the codified procedure for design of centrically compressed cold-formed stainless steel (CFSS) built-up members is absent in Europe. Besides, there are no published research information and experimental data in this structural area. This paper focuses on a comprehensive experimental investigation of closely spaced CFSS built-up columns and addresses their flexural buckling capacity about the minor principal axis. Two series with a total of 36 built-up members were assembled, each formed by two discontinuously and directly connected channel chords oriented back-to-back to form an I-section. The chords were press-braked from flat strips of austenitic stainless steel EN 1.4301 as non-slender channel sections. The chords were uniformly interconnected by bolts or by welds. To identify the effects of interconnection spacing on chords' composite action, the overall and chord slenderness ratios were varied. Material properties, cross-section response and initial imperfections were quantified before testing. As a result, the overall flexural buckling without any local-overall interactions was observed as the dominant failure mode. All findings were used in the accompanying paper [1] to establish qualitative data base through numerical simulations of flexural buckling tests. Additionally, a quantitative accuracy assessment of the design methods for carbon steel built-up columns provided in Eurocode and American Specification was reported on the basis of their ability to predict flexural buckling resistances of the tested columns. This enabled numerical parametric studies and proposing design rules for CFSS built-up columns with non-slender sections that capture interconnection shear stiffness, overall and chord slenderness ratio and strain hardening effects.


ABSTRACT: This study examines the performance of a new type of composite column: L-shaped columns comprising concrete-filled steel tubes connected by double-vertical steel plates (LCFST-D). The fundamental structural behaviour of the LCFST-D columns is discussed. Seven LCFST-D columns were tested under axial compression. In the experiments, the variables were the height and the width of the vertical steel plates. The experimental results were used to assess the load-deformation relationship, strain distribution, and strength index. The tests demonstrated that the axial-compressive performance of the LCFST-D columns was favourable and showed that the mono-columns worked more cooperatively in the LCFST-D column structural form. Next, 3D nonlinear element models were used to analyse the mechanical properties and axial compressive behaviour of the LCFST-D columns. The results of the finite-element analysis were in good agreement with the experimental results. Based on the finite-element model, parametric studies were conducted to investigate the effects of the thickness and width of the vertical steel plates; the slenderness ratio, size and thickness of the steel tube; and the steel and concrete strengths. A method is proposed to calculate the slenderness ratio. This method considers the material properties of the steel and concrete and the sectional shape. Based on the confined effects of the concrete-filled steel tube, a method is proposed to calculate the axial-compressive bearing capacity of an LCFST-D column. The calculation results are in good agreement with the finite-element and experimental results, and the error is <10%.


ABSTRACT: This paper is an attempt to study the mechanical behavior of square concrete-filled bimetallic tubular (CFBT) stub columns subjected to axial compression. The bimetallic tubes in the CFBT columns in this
research comprised an outer layer made of stainless steel and an inner layer made of carbon steel. 200-mm square carbon steel tubes (wall thickness \( t_{sc} = 3.30 \, \text{mm} \)) were manufactured first, then the bimetallic tubes were fabricated by cladding the carbon steel tubes with stainless steel sheets. In the experimental program, fourteen CFBT columns and two conventional concrete-filled steel tubular (CFST) counterparts were tested to failure under axial compressive loading. The test parameters included the stainless steel grade (Grade 316, 304, and 202), wall thickness of the stainless steel tube layer (\( t_{ss} = 0.84, 1.32, \) and 1.88 mm), and cube compressive strength of concrete (\( f_{cu} = 54.5, 68.4, \) and 80.5 MPa). A finite element analysis (FEA) model was established and validated against the experimental measurements. The failure mode and mechanical behavior of the square CFBT stub columns were then investigated and compared with those of the conventional CFST columns. Finally, the ultimate loads obtained from the experiments were compared to those predicted by the available design codes.


ABSTRACT: Cable-stiffened steel columns can significantly enhance the stability behaviour of ordinary compression columns because of the additional stiffness offered by the pre-tensioned cables and crossarms. Most of the previous studies aimed to investigate the behaviour of stiffened steel columns with four branch crossarm systems; however, the current work focuses on investigating the interactive buckling of cable-stiffened steel columns with pin-connected three branch crossarm system via buckling analysis. The analysis shows that the crossarms remain straight in the antisymmetric buckling mode, which distinguishes them from stiffened columns with rigidly connected crossarms. In addition, the interactive buckling must be considered in nonlinear buckling analyses in some cases to obtain the actual capacities of the stiffened columns. The method to consider the interactive buckling is to introduce asymmetric initial geometric imperfections during buckling analysis; the principle to form the asymmetric initial imperfections is suggested.


ABSTRACT: This paper reports an investigation into the impact resistance of concrete-encased concrete-filled steel tube (CFST) members with circular sections. A finite element analysis (FEA) model was established to simulate the impact behaviour of concrete-encased CFST under laterally low velocity impact, in which the strain rate effects of steel and concrete, the element erosion criteria of concrete, the interactions between concrete and steel, as well as the combined effects of axial load and lateral impact, were considered. Experimental data on reinforced concrete (RC), CFST and concrete-encased CFST members under drop hammer impact were used to verify the accuracy of the FEA model and a generally reasonable agreement was achieved for all three types of structures. A full-range analysis of the behaviour of concrete-encased CFST members with circular sections was then carried out with the FEA model to investigate the impact behaviour and impact resistance of the composite structure. The failure modes, sectional moment development, stress and strain development, as well as the contact behaviour between different parts were analyzed to highlight the reasons behind the good impact resistance of the composite structure. A parametric study was finally conducted with the FEA model to investigate the major parameters that may influence the impact resistance of the concrete-encased CFST members.

Lifeng Li, Cong Zhou and Lianhua Wang, “Distortion analysis of non-prismatic composite box girders with corrugated steel webs”, Journal of Constructional Steel Research, Vol. 147, pp 74-86, August 2018,

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ABSTRACT: In this study, the distortion effect of non-prismatic composite box girders with corrugated steel webs (CBGCSWs) is theoretically analyzed under eccentric loads during the elastic stage. Considering the mechanical properties of corrugated steel web, a governing differential equation for distortion is derived for non-prismatic CBGCSWs. The differential equation is solved using the Newmark method to obtain the distortional warping normal stresses of angular points. The feasibility of the proposed theoretical method is validated by the finite element (FE) method. The proposed method is then applied to examine the effects of the number of diaphragms ($N$), girder length ($L$), girder width ($b$), shortest girder height ($h_{\text{min}}$) and girder height ratio ($\xi$) on the maximum ratio of distortional warping normal stress to longitudinal bending normal stress (distortion-to-bending stress ratio, $\zeta$) of non-prismatic CBGCSWs. Based on the results of the parametric study, a diaphragm spacing equation is developed for determining the diaphragm spacing of non-prismatic CBGCSW bridges to reach the desired distortion-to-bending stress ratio. The presented equation can be further used as a reference to design the diaphragm spacing of this type of bridge.


ABSTRACT: In order to predict the ultimate resistance of members by means of numerical simulations (GMNIA – geometric and material non-linear analysis with imperfection), it is indispensable to realistically assume geometric and material imperfections. For I-shaped profiles, it is possible to find several studies concerning the influence of geometric (for example member out-of-straightness) and material imperfections (residual stresses) on the ultimate resistance of the member. However, the sensitivity of hot-rolled U-shaped members to geometric and material imperfections has not been addressed in detail before. Moreover, the research projects concerning hot-rolled U-shaped members performed in the past often assumed different forms of geometric imperfections and residual stresses. Sometimes one may even find contradictory recommendations concerning the form of the geometric imperfection to be applied to the member. Therefore, it seemed interesting and necessary to conduct a comprehensive study explicitly addressing the sensitivity of the ultimate resistance of U-shaped members on the assumption of the geometric imperfections and residual stresses. The results of this study are presented hereafter and recommendations on the form and amplitude of geometrical imperfections and residual stresses to be included into numerical simulations are derived.


ABSTRACT: To search for an accurate calculation method for the bearing capacity of stainless steel lipped C-section columns, a series of tests was performed on columns under axial compression and eccentric load, respectively. Comparison of test results with code predictions indicates that the design strengths are not safe. The numerical models, which were developed using the finite element (FE) package ANSYS, were verified by experimental results, and thus they can exactly simulate the mechanical properties of stainless steel lipped C-section columns. The models were used to conduct parametric studies. Finally, based on the numerical analysis of 129 and 128 columns under axial and eccentric compression, respectively, direct strength equations for axially and eccentrically loaded stainless steel lipped C-section columns are proposed. Comparison of test results with equation predictions indicates that the formulas have high accuracy and reliability and can accurately calculate the bearing capacity of stainless steel lipped C-section columns.

ABSTRACT: Six L-shaped and twelve T-shaped concrete-filled steel tubular (CFST) stub columns subjected to axial compression were experimented in this paper. The L-shaped CFST stub columns were welded vertical stiffener at the concave corner. The T-shaped CFST stub columns were stiffened by steel plate stiffeners. During the test, the experimental phenomenon and failure mode of special-shaped CFST stub columns were observed. According to axial load-displacement curves, mechanical properties such as stiffness, bearing capacity and ductility were compared and analyzed. According to the load-strain curves and load-stress curves, strain and stress development of steel tubes and constraint effect for concrete provided by steel tubes were studied. The test results show that the stiffeners can effectively delay the local buckling of steel tubes, increase the buckling capacity, and increase the constraint effect for concrete. The cross-sectional dimension of specimens has no obvious effect on the ductility and the failure modes of T-shaped CFST stub column due to the restriction of steel plate stiffener, while obviously affects the stiffness and the bearing capacity. Finite element (FE) software ABAQUS was used to analyze special-shaped CFST columns subjected to axial compression and the simulated results were in good agreement with the experimental results. Further parameter analysis with ABAQUS was carried out to study the influences of the steel ratio α, steel yield strength fy, concrete strength fck and slenderness ratio λ. Based on the experimental results and FE analysis, design formulae for calculating sectional bearing capacity and stability bearing capacity of special-shaped CFST columns are proposed.


ABSTRACT: In this paper, the results of an experimental investigation of 12 concrete-filled steel tubular (CFST) stub columns subjected to concentric loads are presented. In this program, different cross-sectional shapes are considered: circular, square and rectangular. In order to study the effect of the concrete infill strength in the ultimate capacity of the columns, two types of concrete infill are employed: normal and high strength concrete of grades C30 and C90 respectively. The specimens are classified into three different series so all the columns of a series have equivalent cross-sectional area to perform a proper comparison and draw consistent conclusions. During the tests, the response in terms of load versus column shortening is registered. In view of the experimental results, the dependency of the type of response and failure mode on the cross-sectional shape and type of infill of the columns is analysed. Besides, the influence of the concrete infill, the result of the composite action and the level of ductility are also studied. Finally, the experimental ultimate loads of the specimens are compared with the corresponding failure loads given by the codes. In this case, comparison showed that Eurocode 4 and the Chinese and Australian standards overestimate the failure load of the specimens, particularly for square and rectangular CFST columns. The American code tends to be more conservative in its predictions for circular columns, although it is still unsafe for those with square and rectangular steel tubes.


ABSTRACT: In cold-formed steel structures, such as trusses and portal frames, the use of back-to-back gapped built-up cold-formed steel channel-sections for column members are becoming increasingly popular. In such an arrangement, the lowest flexural buckling mode may not necessarily be overall buckling of the whole column.
In the literature, only three test results have been previously reported for such cold-formed steel columns, and limited to values of non-dimensional slenderness ranging from 1.08 to 1.16. This issue is considered herein. The results of 40 experimental tests are reported, conducted on back-to-back gapped built-up cold-formed steel channel-sections covering the range of non-dimensional slenderness from stub to slender columns. A nonlinear finite element model is then described that shows good agreement with the experimental results. The finite element model is then used for the purposes of a study comprising 84 models. Using the experimental and finite element results, it is shown that design in accordance with the American Iron and Steel Institute (AISI) and Australian and New Zealand Standards (AS/NZS) can be conservative by as much as 53%. However, use of a modification to the non-dimensional slenderness, that considers the gap, results in the design standards being within 5% conservative with respect to the experimental and finite element results.


ABSTRACT: Tapered steel members offer a better cross-section utilization along the member, which makes them an interesting and more economical alternative to prismatic ones. Yet, the design methodologies available do not provide a clear and sufficient guidance for the stability verification of such members. Alternatively, nowadays, the existing computer capacity and software programs provide an accessible and rapid means of reproducing the structural performance of members and systems, although they require beforehand validation to assure the plausibility of their predictions. For that, a full-scale experimental programme on non-uniform members was carried out, covering column, beam and beam-column tests. The test results are used to validate a numerical model commonly used for the assessment of stability design rules. In this paper, firstly, a global overview of the experimental tests is presented, which covers the test layout, member dimensions and the supplementary tests, essentially characterization of material properties, geometrical dimensions and imperfections, and residual stresses. The key results from each experiment are presented and discussed, they are further compared with numerical and analytical estimations of the member resistance. Finally, the experimental results provide physical validation of the design method proposed in Marques et al. (2012) for web-tapered columns.


ABSTRACT: Concrete-filled Rectangular Hollow Sections have been tested under large-scale, far-field, air-blast loading for the first time. The concrete-filled, cold-formed steel tubes performed well under the blast loads, with a significant reduction in the global and local displacements compared to unfilled RHS members. The heavily instrumented tests provided a large quantity of response data that was used for the validation of numerical models. Numerical models of the concrete-filled steel tubes were first developed using explicit finite element methodologies. A parametric study was conducted with the validated finite element model to further characterize the response of the concrete-filled steel tubes under air-blast loading. The influence of several key variables on the response of the tubular members was determined and preliminary design guidance is provided. Finally, the test and finite element results were used to develop an idealized single-degree-of-freedom numerical model that is well-suited to future use in design problems.

ABSTRACT: Energy dissipaters constructed in structures play an important fuse-type role in concentrating damage and protecting the primary structure. A stable hysteretic behavior, easy fabrication and a low cost are expected characteristics of high-performance energy dissipaters. Previously studied energy dissipaters have disadvantages such as difficult grouting, insufficiently hysteretic capacity and low material utilization. In this paper, a new partially restrained energy dissipater consisting of an inner core bar and an outer partially restraining tube was developed. The inner core bar is milled along the longitudinal direction of the core bar, avoiding the adverse effects of grouting and welding and improving the utilization of the material. Parametric studies on geometrical variables were performed to investigate the low-cycle fatigue behaviors and deformation patterns of the proposed partially restrained energy dissipaters. Test results showed that the partially restrained energy dissipaters demonstrated stable hysteretic performance, and no local or overall buckling was observed. Design guidelines concerning the prevention of torsion buckling, control of section expansion and avoidance of local failure of the transitional segment were developed. The buckling responses, contact conditions and plastic deformations were analyzed via validated numerical models.


ABSTRACT: This paper presents an experimental investigation conducted on cold-formed steel built-up closed section columns with web stiffeners. To fabricate a built-up closed section, the single open sections were formed by brake press operation with high strength steel plate of thickness of 0.48 and 1.0 mm, then two identical sections were connected together face-to-face by self-tapping screws. After the measurements of material properties and the initial geometric imperfections were made, the built-up closed section specimens with inward or outward stiffeners at the web were tested between fixed-end boundary conditions with various column lengths ranging from 300 to 3200 mm. The tested specimens were failed by local buckling and interaction between local and flexural buckling. The ultimate strengths of the specimens were used to compare with the column strengths predicted using direct strength method, which is adopted in the North American Specification and Australian/New Zealand Standard for cold-formed steel structures. In addition, a reliability analysis was performed for this design method to access its reliability with cold-formed steel built-up closed section compression members. The results show that the direct strength method is applicable for the design calculation of cold-formed steel built-up closed section compression members with web stiffeners.


ABSTRACT: An experimental and numerical study of hot-rolled steel I-sections under combined compression and bending moment is presented herein. A total of two stub column tests and 12 mono-axial or bi-axial eccentric compression tests on HEB 160 cross-sections with two different material grades (S235 and S355) were carried out. The tested cross-sections were of stocky proportions to enable the influence of material strain hardening on the strength and behaviour of hot-rolled steel I-sections to be investigated. The loading eccentricities for the eccentric compression tests were varied in order to achieve different axial compression-to-bending moment ratios. Measured geometric and material properties, together with the full load-deformation histories from the test specimens, were reported. Finite element (FE) models were developed and validated against the experimentally obtained load-deformation curves, as well as the failure modes. The FE results successfully captured the experimental structural performance of hot-rolled steel I-sections and the validated FE models were then used for parametric studies in the companion paper to generate additional numerical results, considering different cross-section slendernesses, material grades and combinations of loading. The
experimental and numerical results are employed in the companion paper for the assessment of the design rules given in EN 1993-1-1 (2005) and AISC-360-16 (2016) and for the extension of the deformation-based continuous strength method to the case of hot-rolled steel I-sections under combined loading.

ABSTRACT: The seismic design of light steel frames (LSF) can not only rely on the application of cold-formed steel (CFS). Some mixed systems and integrated solutions such as hybrid systems can offer new possibilities, in particular with regard to applications in mid-rise construction. A hybrid solution is to replace some CFS chord studs with hot-rolled square hollow section SHS, in order to achieve higher capacity. This paper provides the results of experimental studies on the lateral behaviour of a hybrid light-weight steel panel and investigates the implication of any further system improvements for mid-rise construction. Each hybrid wall panel (HWP) consists of a hot-rolled SHS frame, laterally incorporated in a cold-formed panel. The study includes investigating the lateral performance of HWP, while a CFS top chord acting as a load collector, and a hot-rolled steel frame acting as a lateral load resisting system. The behaviour of specimens is investigated under monotonic and cyclic loads, and the step-by-step enhancement is implemented according to the results. The outcomes revealed that although the hysteretic behaviour of the HWP represents pinching effect, mainly due to poor performance of the cold-formed steel collector, by strengthening the top chord design the behaviour is improved. Relying on the cold-formed part to resist the major portion of gravity loads, while the hot-rolled collector transfers the entire lateral load to the hot-rolled frame, results in significantly improved hysteretic behaviour.

ABSTRACT: Concrete filled steel tubes (CFST) have been widely used in modern constructions. The cross-section shapes of circular and rectangular are mostly used. This paper presents an investigation on CFST with a new cross-section shape - octagonal shape which combines both advantages from circular and square cross-sections. In this study, 21 CFST stub columns were tested accompanying with 9 plain concrete columns under uniaxial compression. Three cross-section shapes, octagonal, circular and square sections were considered. In parallel, 10 associated CFST stub columns with octagonal cross-sections from literature were also complied. The measured steel yield strength was between 383 MPa to 485 MPa. Both normal and high strength concrete were used with measured cylinder compressive strengths ranging from 38 MPa to 112 MPa. The key investigation focuses on the relationship between the cross-section shapes and confinement effectiveness which can provide an understanding on the difference in load bearing capacity of CFST with those three section shapes. Design formulae for the cross-section capacity in the current code of practice were assessed by the experimental results and modification was proposed to the existing formula for circular cross-section which could be adopted for the CFST with octagonal cross-section.

ABSTRACT: A steel plate shear wall with slits (SPSWS) is an effective anti-seismic component element, which owns good ductility and energy dissipation capacity. The infill steel plate is divided into flexural links by slits, which changes the path of conducting force. As a result, the SPSWSs obtain higher energy dissipation
capacity and better ductility compared with conventional steel plate shear walls. However, both tests and finite element method (FEM) analysis have shown that the slits lower the ultimate bearing capacity and the lateral stiffness of the steel plate shear wall. In this case, two steel plate shear walls with unequal length slits (SPSWUS), i.e. papilionaceous SPSWUS and fusiform SPSWUS, are proposed and analyzed in this paper. Four 1/3-scaled test specimens are designed for the experimental study. Two of the specimens are SPSWUSs, and the other two are traditional SPSWSs. Testing of the systems were performed under cyclic lateral loading. Results show that SPSWUS has rather high energy dissipation capacity and good ductility as well as relatively high lateral stiffness and ultimate bearing capacity when compared with the traditional SPSWS. Experimental results correlate well with those from the finite element analysis, which validates the finite element model.


ABSTRACT: This study evaluates the performance of the design equations given in the Australian/New Zealand bridge and steel structures design standards AS 5100.6, AS 4100 and NZS 3404.1 based on reliability analysis. For this evaluation, the following two methods were utilised: (i) a capacity factor calibration method to meet the target reliability level when there are a limited number of steel yield strength tests; and (ii) an inverse reliability analysis method to calculate the required minimum number of steel yield strength tests to achieve the target reliability level when using capacity factors provided in the design standards. The methods were applied to steel and composite members including I-beams, hollow section columns, CFST columns, and composite beams. To ensure the adoptability of imported steel for these members, structural steel that conforms to European, Korean, Japanese, American, Chinese and Australasian manufacturing standards were considered in the analyses. The results showed that, for an infinite range of manufacturing data, the capacity factors were insensitive to the different manufacturing tolerances. Furthermore, when a limited number of mechanical tests were available, a much larger number of results were needed to achieve the target capacity factor for composite members in comparison with non-composite members. Finally, when considering hollow sections used as columns, the current design equations were unable to deliver the target reliability levels for any of the manufacturing standards used internationally.


ABSTRACT: A performance based seismic design method for eccentrically braced frames (EBFs) and buckling restrained braced frames (BRBFs) is developed herein. The method is a force-based seismic design one where the design base shear is obtained by using different modal strength reduction factors for each one of the first four modes of the frame, instead of using a constant behavior factor for all modes as in all current design codes. These modal strength reduction factors incorporate the dynamic characteristics of the structure, different soil types and different performance targets. Thus, the proposed method can automatically satisfy deformation demands at all performance levels without requiring deformation checks, as it is the case with code-based design methods. The basic concept of the method is associated with the determination of an equivalent elastic structure that retains the mass and initial stiffness of the original nonlinear one, and is characterized by high amounts of viscous damping in order to equilibrate the nonlinear energy of dissipation by the viscous one. The above mentioned factors are obtained through the use of extensive parametric studies on 98 steel plane frames subjected to 100 far-field ground motions. Empirical expressions for those modal strength reduction factors as functions of period, deformation/damage and soil types, which can be used directly in conjunction with the conventional elastic pseudo-acceleration design spectra with 5% damping for seismic design of steel EBFs and
BRBFs, are provided. The proposed method is illustrated with representative numerical examples that demonstrate its advantage over code-based seismic design methods.


ABSTRACT: Design guidance for stainless steel structures has become more comprehensive and widely available in recent years. This, coupled with a growing range of structural products and increasing emphasis being placed on sustainable and durable infrastructure, has resulted in greater use of stainless steel in construction. A recent addition to the range of structural stainless steel products is that of laser-welded sections. Owing to the high precision and low heat input of the fabrication process, the resulting sections have smaller heat affected zones, lower thermal distortions and lower residual stresses than would typically arise from traditional welding processes. There currently exists very limited experimental data on laser-welded stainless steel members and their design is not covered by current design standards. The focus of this study is therefore to investigate the cross-sectional behaviour of laser-welded stainless steel I-sections in bending. The present paper describes a series of laboratory tests performed on laser-welded stainless steel I-sections, including tensile coupon tests, initial geometric imperfection measurements and in-plane bending tests. Results of the bending tests are used to validate finite element (FE) models, which are subsequently employed for parametric investigations. The obtained experimental and FE results are used to assess the applicability of the existing design provisions of EN 1993-1-4, AISC Design Guide 27 and the continuous strength method (CSM) to laser-welded stainless steel sections. It was found that the scope of application of these existing design provisions may be safely extended to laser-welded sections.


ABSTRACT: Hollow flange steel plate girder (HFSPG) is a new hollow flange I-section made using cold-formed rectangular hollow sections (RHS) as flanges and a steel plate as web. Due to the increased torsional rigidity and unique geometry, it can provide enhanced flexural capacities and thus are effective flexural members in long span applications. The production of proposed HFSPGs contains welding currently available RHS sections to a web plate, which allows engineers to form girders by varying dimensions, thicknesses and grades to suit their design requirements. As the first step of this study, the section moment capacities of fully laterally restrained HFSPGs were investigated. Despite earlier researches on the flexural capacities of hollow flange sections, HFSPGs have not been tested previously. Therefore, twelve section moment capacity tests were conducted to study the flexural performance and capacities of HFSPGs. The ratios of ultimate moment capacity per unit area of tested beams were compared with conventionally used hot-rolled I-sections with similar cross-sectional area, which proved the structural efficiency of HFSPGs over commonly used hot-rolled I-sections. The ultimate capacities of tested HFSPGs were then compared with capacity predictions provided by the Australian, American and European design standards (both hot-rolled and cold-formed). It was found that the current design standards under-estimate the section moment capacities of HFSPGs in general and the level of under-estimation varied depending on the section slenderness. Suitable recommendations are made regarding the appropriate use of these design standards for HFSPGs. This paper presents the details of this research and its findings.

This paper studies the minimum **stiffness** required to ensure elastic buckling and elastic-plastic post-buckling strength of subpanels of vertically stiffened **steel** plate walls (S-SPWs) under compression. In the linear elastic analysis, the threshold stiffness at which the buckling mode of S-SPWs changes from overall to subpanel **local buckling** is determined. Based on the understanding that the increased elastic critical buckling strength of the S-SPW is provided by the elastic buckling resistant capacity of the stiffeners, a formula is proposed to predict the elastic threshold stiffness. The elastic-plastic threshold stiffness of vertical stiffeners, which makes the subpanels develop their full elastic-plastic post-buckling capacity, is obtained through nonlinear analysis. This paper investigated the effects of subpanel aspect ratio, subpanel width-to-thickness ratio, number of stiffeners on the elastic-plastic threshold stiffness. The effect of initial imperfection is also included. Based on the understanding that the increased capacity of the S-SPW from overall to subpanel post-buckling is provided by the elastic-plastic strength and stiffness of the stiffeners, a formula to predict the elastic-plastic threshold stiffness is proposed. The proposed formulas for both threshold stiffness are found to possess good accuracy after some minor modifications. The comparison between elastic and elastic-plastic threshold stiffness is also presented.


**ABSTRACT:** To improve the strength and ductility of the core walls in high-rise buildings which would be subjected to combined high axial compressive force and bending moment during the earthquake, an innovative concrete filled double-skin steel-plate composite (CFDSC) wall is proposed. The CFDSC wall is composed of the concrete filled double-skin steel-plate wall body with transverse stiffeners, vertical diaphragms and distributed batten plates welding on the internal surface of the double steel plates, and the concrete filled steel tube (CFST) columns including a pair of CFST columns positioned at the end of the cross section as boundary elements and an additional one located in the central section of the wall. Five CFDSC wall specimens were tested under constant axial compressive force and lateral reversed cyclic loading to investigate the seismic behaviour of the wall considering the effect of axial force ratio and shear span ratio. The favourable seismic performance of the CFDSC walls was demonstrated in the test. No serious pinching effect was observed on the hysteresis curves of all the specimens. The drift ratios corresponding to the ultimate stage were recorded as being in the range from 1/67 to 1/30 and the ductility coefficients were varied from 4.50 to 8.22. The experimental results manifest that the CFDSC walls have great energy dissipation capacity. Formulae for calculating the lateral load-carrying capacity of the CFDSC wall, taking the confinement effects from steel plates into account, were proposed. The results calculated by the proposed method show good agreement with the experimental results.


**ABSTRACT:** The second part of the study on the ultimate capacity of hot-rolled steel I-sections under combined compression and bending moment, focussing on parametric studies and design, is presented herein. An extensive numerical parametric study was carried out, using the verified finite element (FE) models from the companion paper, to generate further structural performance data for specimens with different steel grades, cross-section slendernesses and loading cases. The numerical results together with the experimental results were then used to assess the accuracy of two codified design methods: the European Standard EN 1993-1-1 (2005) and the American Specification AISC-360-16 (2016). The design strengths predicted by the current design standards were found to be generally rather conservative and scattered when applied to non-slender cross-
sections, owing principally to the neglect of material strain hardening and reserve capacities between the classification limits. To improve the accuracy and efficiency of the design rules, the continuous strength method (CSM) – a deformation-based design approach which relates the resistance of a cross-section to its deformation capacity – was extended to cover the design of hot-rolled steel I-sections under combined loading, underpinned by both the experimentally and numerically derived ultimate capacities. Overall, the CSM was shown to offer more accurate and consistent predictions than the current design provisions. Finally, reliability analysis was performed to evaluate the reliability level of the design rules.

ABSTRACT: Recent research has proven that cold-formed steel shear wall with corrugated steel sheathing is a promising lateral force resisting system in high wind and seismic zones. Extensive experimental investigations, including monotonic and cyclic tests on cold-formed steel shear walls with corrugated steel sheathing, were recently completed at University of North Texas. This paper summarizes previous and newly conducted tests and presents finite element analyses in order to establish a set of nominal shear strengths for the corrugated steel sheathed shear walls. In addition, a design method for determining the deflection of the corrugated steel sheathed shear walls under in-plane lateral loading was proposed based on the experimental results and nonlinear regression analyses. The deflections obtained from the proposed design equation were compared with the test deflections and good agreement was obtained.

ABSTRACT: This research presents a study about the structural behavior of steel cellular beams, focused on the web-post buckling. The main objective of this study is to propose a new formulation to calculate the shear resistance of cellular beams for this phenomenon, based on laboratory tests and numerical analysis. Series of tests were performed in this work, with full-scale steel cellular beams. In these experiments, vertical and lateral displacements were measured, as well as web-post deformations. The steel mechanical properties of these beams were determined by tensile testing. A numerical model was proposed, developed in ABAQUS software, to perform parametric analysis. From these numerical models, processing 597 cases, a new formulation to determine the shear resistance in cellular beams for the web-post buckling was proposed, based on resistance curves. The proposed formulation was verified in several situations of geometry and material properties, presenting compatible results with those obtained numerically, and showing better accuracy than those available in the literature.

ABSTRACT: When structural steel members are in contact with horizontal members, such as concrete slabs, dust and moisture easily accumulate at their junction. This can induce local corrosion at their ends, and consequently, reduce their compressive strengths. In this study, compressive tests were conducted on circular tubular short columns to examine the change in compressive strength with local corrosion at the ends of the columns. The columns were fabricated to have corrosion levels of various depths, heights, and circumferences. As a result, local buckling occurred near the column ends. Moreover, residual compressive strengths linearly decreased as the corroded depth, height, and circumference increased. An evaluation method using the effective
volume was proposed to assess the residual critical compressive strengths of circular tubular short columns with locally corroded ends.


ABSTRACT: Welding is extensively used in industries for the assembly of different products including ships, automobiles, trains, bridges etc. Welding distortion is usually a source of dimensional imprecision in assembly and higher manufacturing costs. So, it is of crucial importance to predict and minimize welding-induced distortion by improving the quality of the welded structure. The purpose of this research is to reduce the distortion in large ship panels. The study uses two methods. First, distortion prediction by thermal elastic plastic FE analysis is employed to estimate the inherent deformations of different SM490A steel welded joints. Then, the welding process of a large ship panel is elastically analyzed on the basis of the theory of inherent strains. The elastic analysis reveals some distortions on the edge and inside of the panel. The distortions can be minimized by changing welding sequence of panel stiffeners to symmetrical welding of type B and changing shape to L-stiffener as well as changing stiffener material to the SM570.


ABSTRACT: Shear behaviour of cold-formed steel beams with an aspect ratio (shear span/web depth) of 1.0 has been studied thoroughly, mainly using central point load tests. However, for beams with longer aspect ratios, the effect of bending causes reduction of shear capacity and alters the failure modes. This paper summarises experiments recently performed at the University of Sydney on channel section members using a new test configuration to minimize bending moments. Shear strength close to pure shear capacity can be therefore reached even at an aspect ratio of 2.0. The test results were compared with the strength predictions using the current direct strength method (DSM) of design for shear specified in the North American specification for the design of cold-formed steel structural members, AISI S100:2016 and the Australian/New Zealand Standard for cold-formed steel structures, AS/NZS 4600:2018. A good agreement between the experimental results and the predicted values has confirmed the viability of the DSM design rules for structures with aspect ratios up to 2.0. Numerical models were developed to foresee potential issues prior to the experimental work, and were subsequently calibrated against the tests to produce reliable results.


ABSTRACT: In Eurocode 3 (2005) the buckling curve approach is adopted for verification of prismatic columns and beams. It has the flexibility of adjusting imperfection factors according to their sections, steel grade and other relevant parameters. However, for generic single members, built-up or not, uniform or not, with complex support conditions or not, the available possibilities for such cases are the General Method given in clause 6.3.4 of Eurocode 3 (2005) or advanced numerical simulations. The applicability of the general method, however, is limited and in some aspects inconsistent (Simões da Silva et al., (2010)). As an alternative, the stability of non-uniform members can be analysed using numerical GMNIA which is a time-consuming procedure and the output is highly dependent on the experience of the user. In this paper, a novel general formulation for stability design of steel columns, beams and beam-columns with variable geometry, loads and complex support conditions is presented. The verification is based on the buckling mode as shape of the initial
imperfection with an amplitude previously calibrated for the standard prismatic simply-supported columns and beams in Eurocode 3. The verification is performed as an interaction equation where the first and second order contributions to the longitudinal stress utilization are added for each cross-section along the member length. Several aspects regarding the member behaviour in the context of a specific buckling mode are discussed and finally, validation of the approach is carried out to show its consistency and accuracy.


ABSTRACT: During the construction process of the ship's hull, the ultimate strength of the stiffened panels is reduced due to both initial imperfections and residual stresses. In service, these stiffened panels are exposed to damage that causes permanent deformations and localized residual strength, reducing additionally the ultimate strength of damaged panels, which must be considered in the design process to preserve the structural integrity. The paper provides analyses of the effect of damaged stiffened panels on the ultimate strength considering the residual stresses caused by indenting depth and different locations. Experiments were performed using small-scale models representative of a full-scale bottom panels from a cargo compartment at the midship of a typical Suezmax tanker. Experimental tests of the indentation were conducted on the intersection plate-stiffeners, where the force-displacement responses were analyzed. After the indentations, the panels were submitted to uniaxial compression experimental tests, in order to evaluate the loss of ultimate strength compared with the equivalent intact panel. Finite element models were developed by ABAQUS software in three steps sequentially: panel indentation, indenter taking off, and uniaxial compressive loading. Plastic strains and residual stresses caused by the indentation are incorporated in the ultimate strength analysis of the panels. Initial imperfections and maximum denting depth of the panels were measured in the small-scale models for the numerical-experimental correlation. Both indentations and ultimate strength presented a good agreement. A parametric study was performed using the numerical model to determine the residual strength due to the damage and its relationship with both dent depth and location.


ABSTRACT: Concrete-filled round-ended elliptical hollow section (CFREHS) columns are gradually coming into use as piers and arches in engineering practice, owing to their unique properties concerning aesthetic perception and low flow resistance coefficients. However, there has been a paucity of studies focusing on the structural behaviour and design methods for CFREHS columns. The present study has involved investigating the behaviour of eccentrically-loaded CFREHS stub columns. A nonlinear numerical model that adopts an equivalent stress-strain model for the novel type of confined core concrete was established, and verified via experimental data. Subsequently, the effects of various parameters on the eccentric compressive response of CFREHS stub columns were analysed, including the diameter-to-thickness ratio, load eccentricity ratio, and the cross-section slenderness. Eccentric compressive capacities, failure patterns, strength indexes, stress-strain responses, contact stress, typical force-displacement curves, and M–N curves of eccentrically pressed CFREHS stub columns were also evaluated. The findings of the numerical analysis indicated that the eccentric load bearing capacity of CFREHS stub columns evidently increased for increases in the cross-section area, steel strength, and concrete strength, while the opposite was observed for increases in the load eccentricity ratio and diameter-to-thickness ratio. Finally, simplified empirical formulae were presented to predict the eccentric load bearing capacities of CFREHS stub columns. The results of the study are expected to provide a reliable reference for application to the proposed CFREHS columns in concrete-filled steel tube (CFST) structures.
ABSTRACT: In this study, a nonlinear three-dimensional finite element (FE) model was developed and validated to investigate the response of concrete filled tube (CFT) columns subjected to post-earthquake fires. Three steps were considered successively in the modelling, namely, cyclic, thermal and structural analyses. Outputs from the cyclic loading including residual deformations were imposed as an initial condition to the thermal-stress model, imitating the seismic response of the column. Subsequently, a nonlinear sequentially thermal-stress analysis was conducted to simulate the fire response of column after the earthquake. The proposed FE model was validated by comparing the simulation results with the observations of full-scale fire and cyclic tests available in the literature. The validated numerical model was then used to study the behavior of CFT columns under the combined action of earthquake and fire as a multi-hazard event. Three probable seismic damage scenarios were considered in the column, namely, middle length, bottom and top end region damages. The level of damage was assumed as a high damage level, presuming that the column reached 50% of its lateral resistance while still maintaining its overall stability after the earthquake. The results showed that the top and bottom end region damages have not significantly influence the fire response of the damaged column. Besides, the column with the middle span damage performed a lesser fire resistance time owing to the coincidence of damage location to that of onset of global buckling.

ABSTRACT: The current codified treatment of local buckling in stainless steel cross-sections is based on the traditional cross-section classification framework and a simplified elastic, perfectly-plastic material model, providing consistency with the corresponding carbon steel design rules. However, the cross-section classification framework treats the cross-section as an assemblage of isolated plate elements without considering the beneficial element interaction effect, and the elastic, perfect-plastic material model neglects the pronounced strain hardening exhibited by stainless steels. These limitations have been generally found to result in unduly conservative and scattered resistance predictions through comparisons against previous test data. To address these shortcomings, a deformation-based continuous strength method (CSM) has been developed, which relates the strength of a cross-section to its deformation capacity and employs a bi-linear (elastic, linear hardening) material model to account for strain hardening. The CSM has been established for the design of doubly symmetric plated sections and circular hollow sections, and shown to yield a high level of design accuracy and consistency. In this paper, the scope of application of the CSM is extended to cover the design of non-doubly symmetric cross-sections in bending. Global member buckling is not investigated. The developed design methodology and comparisons with existing test data and numerical results generated herein are described. Finally, reliability analysis is performed, which demonstrates the suitability of the proposals for inclusion in structural design codes.

ABSTRACT: There has been considerable interest over the past decade in the transverse impact response of steel columns and composite steel-concrete columns. While several researchers have developed analytical procedures for specific types of steel sections, a unified design approach has yet to be established. The present
paper develops a generalised rigid-plastic procedure to calculate the design transverse impact capacity for a wide range of steel and composite column sections. The design procedure is specifically developed to align with current international hot-rolled steel design specifications, including those in Australia, North America, the European Union and China. A database of 320 impact experiments is collated from the literature, and used to validate the general design procedure. It is demonstrated that the procedure provides robust transverse impact capacity predictions for solid rectangular steel sections, steel I-sections, circular and rectangular steel hollow sections, concrete filled circular and rectangular steel hollow sections and concrete filled double skin steel hollow sections. In some cases stainless steel members were additionally included.


ABSTRACT: This paper presents a combined experimental and analytical study on the compressive behavior of FRP-steel composite tubed steel-reinforced columns (FSCSCs) through a total of 14 specimens. The key parameters examined included the cross-sectional shape, the width of grooves on the steel tube, and the number of CFRP sheet layers. The ultimate load-carrying capacity and axial deformation capacity of all circular specimens were strengthened by CFRP layers substantially, whereas the improvement was not observable for square hybrid columns. Meanwhile, the experimental results indicate that the confinement provided by CFRP-steel composite tube is more efficient when no direct axial load was applied on the steel tube, especially in circular specimens. ABAQUS was adopted for establishing an accurate FE model and the excellent agreement had been achieved between the numerical results and experimental results. Parametric studies were performed to investigate the influence of several important parameters using the validated FE model. Based on the results of the parametric analyses and previous studies, a proposed equation shows a great performance in predicting the load carrying capacity of experimental ones with high strength concrete in this study and other literature.


ABSTRACT: Postbuckling capacity of plate girders still occurs after the occurrence of local buckling in the web panel. The postbuckling capacity of mild steel plate girders gradually develops because mild steel exhibits a clear yielding point and a yielding plateau. However, there are no clear yielding points nor distinct yielding plateaus for the high-strength steel (HSS) Q550 and Q690. Even though the postbuckling shear resistance is considered for the mild steel plate girder design in many international design codes, the design formula suggested for mild steel plate girders might not be suitable for HSS plate girders. The objective of this research is to quantify the shear resistance for HSS plate girders. The buckling strength and postbuckling capacity of HSS plate girders are investigated in this study by performing the nonlinear finite element analyses (FEA) that includes the tested material properties. The tested stress–strain curves of HSS Q550 and Q690 are idealized by bilinear and multilinear models. This shows that the strain hardening do have an effect on the postbuckling capacities of HSS plate girders. Therefore, a more accurate multilinear material model is selected for further FEA on the shear resistance of plate girders. The differences between the FEA and EC3 formulae outcomes are notably identified. Based on the numerical studies, a new buckling coefficient formula and a new ultimate shear resistance formula for HSS plate girders are proposed in the study.

ABSTRACT: The flexural strength of the concrete-filled steel tube (CFST) composite girder was investigated in this study. Firstly, simple equations to evaluate the flexural strength of the CFST composite girder under both positive and negative bending moment were derived based on the plastic stress distribution method (PSDM). A series of tests was then conducted to verify the accuracy of the proposed equation, and to investigate the effect of internal shear connectors between the steel tube and concrete infill. Further, non-linear finite element analysis for each test specimen was performed to demonstrate the failure mechanism, and to set up the verified finite element analysis model. From the results, it was found that the proposed equations provided a reasonably conservative prediction of the flexural strength of the CFST composite girder under both positive and negative bending moment, and the effect of internal shear connectors between the steel tube and concrete infill on the flexural strength was negligible. A series of parametric studies was performed to investigate the effect of the $D/t$ ratio, compressive strength of the concrete infill, and local buckling of the steel tube on the flexural strength of the CFST composite girder. Finally, some design considerations are noted based on the results of the parametric study.


ABSTRACT: Concrete-encased concrete-filled steel tube (CFST) column consists of a CFST component and an outer reinforced concrete (RC) encasement. This paper numerically investigates the behaviour of concrete-encased CFST columns subjected to long-term sustained loading. A finite element analysis (FEA) model is established which incorporates the time-dependent behaviour of concrete under sustained loading using the viscoelastic model. The FEA model is validated against the experimental results from long-term loading tests. By using the FEA model, the behaviour of concrete-encased CFST columns subjected to long-term loading is thoroughly analysed, such as the full-range strain development, the internal force distribution among different components, the confinement effects between the steel tube and surrounding concrete, and the comparisons of three types of columns, i.e. concrete-encased CFST column, RC column and traditional CFST column. The creep deformation of the concrete-encased CFST column is also evaluated by the FEA model and existing design standards. The parametric analysis is conducted to investigate the influence of various parameters on the strength degradation of concrete-encased CFST columns, including the material strength, the steel ratio of CFST component, the sectional configuration, longitudinal rebar ratio, stirrup characteristic value, and the long-term axial load level. Finally, the ultimate strength of the concrete-encased CFST columns after long-term loading is evaluated, with calculation tables provided for the referencing of practical design.


ABSTRACT: Steel beams and girders with corrugated webs have found many applications, especially in industrial structures and bridges. This choice is backed by the many features, this class of structural members can offer, such as the high load carrying capacity before failure due to the web geometry. The failure of a corrugated web may occur due to material yielding or due to geometrical buckling. Three modes of shear buckling are typical for corrugated webs: local, global, and interactive shear buckling. In this paper, the shear failure mechanisms of trapezoidal corrugated webs are investigated. Nine, shear-critical, corrugated web panels were tested until failure. The new test results confirmed a previous observation that all panels achieved a residual strength of about half of the buckling shear strength, regardless of their geometry and most of them reached yielding before buckling takes place. Since the shear strength of corrugated webs is a function of several material and geometric parameters, a comprehensive global, density-based, sensitivity analysis was
performed to estimate the relative contribution of each parameter to the behavior of shear strength through a previously developed mathematical model. The analysis revealed that the length of the flat folds is the most influential parameter on the shear strength of corrugated webs, while the modulus of elasticity is the least influential. The study was extended to determine ranges on which each parameter is non-influential.

ABSTRACT: Spiral-welded steel tubes (SWTs) are fabricated by helically bending a steel plate and welding the resulting abutting edges. These tubes enable larger diameters, longer joint-less lengths, smaller dimensional tolerances, and more cost-effective construction compared to other types of steel tubes. Notwithstanding this, the use of SWTs for concrete-filled steel tubes (CFSTs) has been rather limited. Many international design standards contain guidelines on strength assessment of CFST columns. Even so, unlike for other tube types, there is a lack of experimental verification of the applicability of those guidelines for concrete-filled spiral welded steel tube (CF-SWST) columns. This has inhibited their widespread use, especially since the residual stresses in SWTs are generally larger than for other tubes. Given this context, twelve self-compacting CF-SWST short columns with nominal diameters (D) equal to 102, 152, 203 and 229 mm were tested under axial compression, considering load eccentricities of 0, 0.15D and 0.4D. The tube walls were nominally 2 mm thick while the effective length to diameter ratios were in the range 4.5–6.0. A ductile failure mode was observed for all the tests consisting of flexural local buckling in the maximum compression region, which was observed during post-peak deformation. The spiral weld seam was observed to neither provide a preferential location for failure nor be detrimental to the strength capacity. On average, the predicted capacities as per six commonly used international standards agreed well with the experimentally obtained values. The predicted capacities were observed to be more conservative for eccentric loading compared to concentric loading. For eccentric loading, fibre-element analyses using material models proposed for confined concrete provided better predictions of the actual capacity. This suggested that greater confinement benefit than considered in the codes is effective for eccentrically loaded CF-SWST short columns. The study provided evidence of equivalent behaviour of CF-SWST columns to other tested CFSTs and the applicability of existing guidelines for assessing their strength.

ABSTRACT: A comprehensive experimental and numerical investigation on cold-formed steel semi-oval hollow section pin-ended columns was performed and is presented herein. The semi-oval hollow sections investigated in this study are composed of one semi-circular flange, one flat flange and two flat web plates. Four cross-section sizes were included and a total of 19 tests was conducted under concentric loading with different specimen lengths in the test program. A finite element model was developed and validated against the test results. The numerical model is capable to replicate the test results. Upon the validation of finite element model, an extensive parametric study was performed consisting of 200 numerical data cases, which cover a wide range of cross-section geometries and column slenderness. The results obtained from experimental program and numerical study were compared with the predicted strengths by the existing and modified Direct Strength Method. Reliability analysis was conducted to assess the reliability of the design methods. The comparison results show that the existing Direct Strength Method generally provides conservative predictions, but the predictions are scattered for slender sections. Modification was proposed to address this issue. The modified Direct Strength Method provides accurate and less scattered predictions in a reliable manner. The modified
Direct Strength Method is suitable for cold-formed steel semi-oval hollow section columns, especially for short column members and columns with slender sections.


ABSTRACT: In this paper, the behaviour of concrete filled tubular flange girders (CFTFGs) is investigated through both numerical and analytical modelling. These are new and complex members and their behaviour is governed by a number of inter-related parameters. This work aims to study the relative influence of a number of these variables on the flexural behaviour, particularly for CFTFGs with stiffened webs. A nonlinear three-dimensional finite element (FE) model is developed in the ABAQUS software and is validated using available experimental data. The validated model is then employed to conduct parametric studies and investigate the influence of the most salient parameters. For comparison purposes, and to observe the effect of the concrete infill, steel tubular flange girders (STFGs) with a hollow flange are also studied. The finite element models consider the effects of initial geometric imperfections, as well as other geometrical and material nonlinearities, on the response. In addition, simplified analytical expressions for the flexural capacity are proposed, and the results are compared to those from the FE analyses. It is found that CFTFGs and STFGs with the same dimensions have similar buckling shapes but different buckling loads, with the CFTFG offering greater buckling resistance. This highlights the influence of the concrete infill which increases the stiffness of the upper flange, and hence allows the member to carry additional bending moments compared to STFGs. The proposed analytical expressions, which are suitable for design, are also shown to be capable of providing an accurate depiction of the behaviour and bending moment capacity.


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ABSTRACT: A superconvergent alpha finite element method (SaFEM) based on triangular mesh is presented for static and free vibration analysis of shell structures. In the SaFEM model, a linear strain field is reconstructed from the standard FEM piecewise constant strain field by devising a unique procedure with a tunable parameter α. The discretized system equations are then established based on the re-constructed strain
field and the Hellinger-Reissner variational principle. By changing the value of the parameter $\alpha$, our $S\alpha$FEM can provide a proper softer stiffness leading to a “nearly exact” solution in strain energy norm. To avoid the transverse shear locking (caused by the Hellinger-Reissner theory), the discrete shear gap technique for triangular element (DSG3) is employed. From several typical numerical examples, it is demonstrated that the proposed $S\alpha$-FEM-DSG3 (or $S\alpha$-DSG3) possesses superconvergence property and can provide very accurate solutions for shell structures.

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ABSTRACT: A thin-walled beam finite element with a varying quadrilateral cross section is formulated based on a higher order beam theory. For the calculation of distortions, the beam frame approach, which models the cross section by using two-dimensional Euler beams, is used. Distortions induced by the Poisson’s effect and warping are analytically derived. Three-dimensional displacements at an arbitrary point of a present beam element can be described by interpolating three-dimensional displacements at the end sections. Straight and curved thin-walled beams with varying cross sections are solved to show the validity of the proposed approach.

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ABSTRACT: A higher order beam model for the buckling analysis of thin-walled structures is presented in this paper. The model considers an enrichment of the displacement field so as to accurately represent the three-dimensional behaviour of thin-walled structures. The definition of an uncoupled set of deformation modes allows a meaningful definition of hierarchical higher order solutions, which are useful for the linear buckling analysis of thin-walled structures. A criterion for the definition of local and global buckling modes, as well as possible interaction between modes is put forward. A comparison between the results obtained with the higher order beam model and results obtained from a shell finite element model implemented in Abaqus allows to conclude not only the efficiency of the beam model but also its simplicity of use.

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https://doi.org/10.1016/j.compstruc.2016.11.004
ABSTRACT: We presented in Ko et al. (2016) an MITC4+ shell element that shows a much improved convergence behavior when compared to the widely used MITC4 (Dvorkin and Bathe, 1984) shell element. However, the element does still not show optimal convergence behavior when used in distorted meshes in the analysis of some shell problems. In the present paper, we establish a new MITC4+ shell element which shows significantly improved and indeed an almost optimal convergence behavior. In this new continuum mechanics-based shell element, the shear locking is alleviated using the well-known assumed transverse shear strain field of the original MITC4 shell element and the membrane locking is alleviated using a new assumed membrane strain field. The new MITC4+ shell element passes all basic tests: the isotropy, zero energy mode and patch tests. The excellent performance of the shell element is demonstrated through convergence studies in the solution of well-selected behavior-encompassing shell benchmark problems.

Adraen Boyez, Adam J. Sadowski and Bassam A. Izzuddin (Department of Civil & Environmental Engineering, Imperial College London, United Kingdom), “A novel ‘boundary layer’ finite element for the efficient analysis of thin cylindrical shells”, Computers & Structures, Col. 182, pp 573-587, April 2017
https://doi.org/10.1016/j.compstruc.2016.10.016

ABSTRACT: Classical shell finite elements usually employ low-order polynomial shape functions to interpolate between nodal displacement and rotational degrees of freedom. Consequently, carefully-designed fine meshes are often required to accurately capture regions of high local curvature, such as at the ‘boundary layer’ of bending that occurs in cylindrical shells near a boundary or discontinuity. This significantly increases the computational cost of any analysis. This paper is a ‘proof of concept’ illustration of a novel cylindrical axisymmetric shell element that is enriched with rigorously-derived transcendental shape functions to exactly capture the bending boundary layer. When complemented with simple polynomials to express the membrane displacements, a single boundary layer shell element is able to support very complex displacement and stress fields that are exact for distributed element loads of up to second order. A single element is usually sufficient per shell segment in a multi-strake shell. The predictions of the novel element are compared against analytical solutions, a classical axisymmetric shell element with polynomial shape functions and the ABAQUS S4R shell element in three problems of increasing complexity and practical relevance. The element displays excellent numerical results with only a fraction of the total degrees of freedom and involves virtually no mesh design. The shell theory employed at present is kept deliberately simple for illustration purposes, though the formulation will be extended in future work.

References listed at the end of the paper:

ABSTRACT: In this paper, The Isogeometric approach (IGA) and Carrera's Unified Formulation (CUF) are employed for free vibration and linearized buckling analysis of laminated composite plates. The non-uniform rational B-spline (NURBS) basis functions utilized in IGA, are employed as higher order smooth functions to approximate field solution leading to enhance precision of analysis. CUF presents an effective formulation to employ any order of Taylor expansion to analyze two-dimensional plate models. Higher order NURBS basis functions attenuate the shear locking properly and higher order theories supposed by CUF are free from Poisson locking phenomenon and they do not need the use of any shear correction factor. Therefore, combining IGA and CUF ends in a suitable methodology to analyze laminated plates.

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ABSTRACT: A series of aeroelastic optimization problems are solved on a high aspect ratio wingbox of the Common Research Model, in an effort to minimize structural mass under coupled stress, buckling, and flutter constraints. Two technologies are of particular interest: tow steered composite laminate skins and curvilinear stiffeners. Both methods are found to afford feasible reductions in mass over their non-curvilinear structural counterparts, through both distinct and shared mechanisms for passively controlling aeroelastic performance. Some degree of diminishing returns are seen when curvilinear stiffeners and curvilinear fiber tow paths are used simultaneously.

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ABSTRACT: In this paper, modification of an existing equivalent model of the corrugated panel is investigated. The axial and bending coupling of the corrugated panel supplements the previous equivalent properties when the corrugated panel has a fixed boundary condition. The analytical expressions of the coupling vertical deflections are obtained and verified by the finite element method. A method to eliminate the vertical deflection is proposed, and the importance of the coupling effect is demonstrated by the application of the modified model in a compliant structure.

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ABSTRACT: The presence of a hole, cut-out or void in a structure makes it difficult to be modelled for calculating natural frequencies. A theoretical basis for simplifying the modelling of cut-outs in a structure by attaching a negative structure is presented. The Dynamic Stiffness Method has been used to prove that this method yields the required natural frequencies. The derivations also show the presence of additional natural frequencies which correspond to the vibration of the positive and negative parts vibrating together while the actual structure with the hole or cut-out usually remains stationary.

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ABSTRACT: We present the large displacement and rotation formulation of the new MITC4+ shell finite element recently proposed by Ko, Lee and Bathe for linear analysis (Ko et al., 2017) and demonstrate the
performance in geometric nonlinear analysis. The element shows in linear analysis an almost ideal convergence behavior since shear and membrane locking is alleviated using the MITC approach. We show now that using the total Lagrangian formulation for large displacements and large rotations, the element is also robust and efficient in nonlinear analysis. We demonstrate the element performance through the solutions of various benchmark problems and reach the important conclusion that the MITC4+ shell element performs reliably and well even when the mesh undergoes large displacements and significant distortions during the response.

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ABSTRACT: In the numerical simulation of structural problems, a crucial aspect concern the solution of the linear system arising from the discretization of the governing equations. In fact, ill-conditioned system, related to an unfavorable eigenspectrum, are quite common in several engineering applications. In these cases the Preconditioned Conjugate Gradient enhanced with the deflation technique seems to be a very promising approach in particular because an effective deflation space is already at hand. In fact, it is possible to utilize rigid body motions of the system, that can be calculated easily and cheaply, and only the knowledge of the geometry of problem is required. This paper investigates the advantages of using a Rigid Body Modes Deflated Conjugate Gradient in the solution of challenging systems arising from structural problems. Two different situations are analyzed: the ill-conditioning caused by low constraining is addressed deflating the total rigid body modes, while the one concerning the heterogeneity of the problem by using the rigid body modes of separate components. Moreover, the implemented method is highly parallel and therefore suitable for High Performance Computing. Numerical results show how both approaches performed successfully in reducing the overall system solution time cost and iterations required for convergence.


ABSTRACT: We present a novel extension of the Bathe subspace iteration method for the solution of the generalized eigenvalue problem in structural dynamics. The key idea is to enrich the subspace by using some turning vectors to replace current iteration vectors. The turning vectors are evaluated from the subspace of the current iteration. The scheme is simple and a considerable improvement in computational efficiency is achieved. A simplified convergence analysis is given and the results of some example solutions show the effectiveness of the method.

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ABSTRACT: This article presents an energy-momentum integration scheme for the nonlinear dynamic analysis of planar Euler-Bernoulli beams. The co-rotational approach is adopted to describe the kinematics of the beam and Hermitian functions are used to interpolate the local transverse displacements. In this paper, the same kinematic description is used to derive both the elastic and the inertia terms. The classical midpoint rule is used to integrate the dynamic equations. The central idea, to ensure energy and momenta conservation, is to apply the classical midpoint rule to both the kinematic and the strain quantities. This idea, developed by one of the authors in previous work, is applied here in the context of the co-rotational formulation to the first time. By doing so, we circumvent the nonlinear geometric equations relating the displacement to the strain which is the origin of many numerical difficulties. It is rigorously shown that the proposed method conserves the total energy of the system and, in absence of external loads, the linear and angular momenta remain constant. The accuracy and stability of the proposed algorithm, especially in long term dynamics with a very large number of time steps, is assessed through four numerical examples.


ABSTRACT: We present novel overlapping finite elements for a new paradigm of solution proposed in our previous papers, see Bathe (2016) and Bathe and Zhang (2017). We give the formulation of the new overlapping elements and the solutions of basic numerical examples to investigate the robustness and efficiency of the new finite elements. The results show that the new overlapping elements are quite distortion insensitive and the numerical integration of the element matrices is efficient. The computational effort to integrate the matrices is much less than in meshfree methods. Finally, we illustrate the complete solution scheme of the new paradigm using the overlapping finite elements in the analysis of the bracket problem already considered in Bathe and Zhang (2017). While the paper proposes and studies new overlapping elements, we conclude that further research is needed to fully harvest the potential of the new analysis approach.


ABSTRACT: In the extended layerwise method (XLWM) established in the previous studies (Li et al., 2015; Li, 2016), the delamination front has to be consistent with the element edges. However, the general delamination damage region detected by the nondestructive evaluation (NDE) has extremely complex front, it should be very difficult to exactly model and analysis general delamination damage region in the XLWM. A full extended layerwise method (Full-XLWM) is developed in this study to avoid the dependence of the delamination region on the finite elements. In the Full-XLWM, the delamination is simulated by the Heaviside function and branch function of the displacement field in the thickness direction, whilst transverse cracks are modeled by the extended finite element method (XFEM). The weak discontinuous function along the thickness direction is adopted to consider the interlaminar interfaces. The delamination front is independent on the meshing as the level set function is employed, so the analysis model of delamination can be established from a uniform finite element meshing. In the numerical examples, the static analysis of the composite plates and spherical shells are investigated for the straight and circular delamination front.
ABSTRACT: This paper describes the use of a quadratic manifold for the model order reduction of structural dynamics problems featuring geometric nonlinearities. The manifold is tangent to a subspace spanned by the most relevant vibration modes, and its curvature is provided by modal derivatives obtained by sensitivity analysis of the eigenvalue problem, or its static approximation, along the vibration modes. The construction of the quadratic manifold requires minimal computational effort once the vibration modes are known. The reduced-order model is then obtained by Galerkin projection, where the configuration-dependent tangent space of the manifold is used to project the discretized equations of motion.

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ABSTRACT: This article deals with advanced, coupled numerical approaches for simulating the transient fluid structure-interaction as occurring during aircraft emergency landing on water, i.e. ditching. The structure is discretized using the Finite Element method, while for the fluid domain the Arbitrary Lagrangian-Eulerian and the hybrid Smoothed Particle Hydrodynamics-Finite Element method are employed. First, the structural models are thoroughly validated ensuring differences arising from the use of two software packages to be as small as possible. Secondly, selected benchmark cases of guided ditching experiments are simulated with both numerical approaches and numerical results are compared with experimental data. A good agreement is found for pressure, normal force, and strain time histories. Finally, modeling aspects affecting the results such as the effects of the plasticity computation algorithm, air, and model simplifications are discussed.

ABSTRACT: A higher-order beam theory is proposed for the analysis of a thin-walled beam with a generally shaped cross section, which consists of straight cross-section edges and is non-uniform along the axial direction. To derive cross-sectional shape functions for the higher-order deformation modes, a new approach is introduced using a set of beam frame models. The distortions with inextensional cross-sectional walls are determined by solving an eigenvalue problem of a beam frame model under inextensional wall constraints. Subsequently, the distortions with extensional cross-sectional walls are evaluated by considering orthogonality with respect to the inextensional distortions. Moreover, the extensional distortions due to the Poisson effect, which is generated due to the uniform axial strain of the rigid-body cross-sectional deformations, are considered. Warps induced by the inextensional and extensional distortions are consistently defined based on the orders of the tangential
displacements of their corresponding distortions. To deal with the varying cross section, three-dimensional
displacements at an arbitrary point are interpolated using those at the cross sections of the nodes, where the
beam frame analyses are performed. The proposed method is validated by performing static and vibration
analyses of beams with varying single- and multi-cell cross sections.

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“Size-dependant behaviour of functionally graded microplates based on the modified strain gradient elasticity
https://doi.org/10.1016/j.compstruc.2017.05.014
ABSTRACT: This paper presents a robust numerical model, which takes into account both size-dependent and
shear deformation effects, for the bending, buckling and free vibration analyses of functionally graded
microplates. The size-dependent effect is captured by using the modified strain gradient elasticity theory with
three length scale parameters, whilst the shear deformation effect is accounted by using the third-order shear
deformation theory. The rule of mixture is employed to describe the distributions of material phrases through
the plate thickness. By using Hamilton’s principle, the governing equations are derived and then discretized by
employing an Isogeometric Analysis (IGA) approach, where the Non-Uniform Rational B-Splines (NURBS)
basis functions are adopted to meet the C^2-continuity requirement. Physical mesh convergence and verification
studies are performed to prove the accuracy and reliability of the present model. In addition, parametric studies
are also carried out to investigate the size effect in conjunction with the influences of gradient index, shear
defor-
mation effect and boundary conditions on the responses of microplates.

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avenue Antonine-Maillet, Université de Moncton, Moncton E1A 3E9, Canada), “Improved algorithm for the
detection of bifurcation points in nonlinear finite element problems”, Computers & Structures, Vol. 191, pp 1-11,
ABSTRACT: Dealing with bifurcation points when solving large deformation finite element problems is not an
easy task. Near such points, the Jacobian matrix becomes singular and the problem becomes difficult to solve
numerically. In these situations, increasing heuristically the loading parameter during the simulation in order to
follow the solution branch is not an option as this approach usually results in the divergence of the process.
Efficient numerical techniques capable of handling the presence of bifurcation points are therefore necessary
and continuation methods have proved to be powerful tools when dealing with these kind of issues. In Léger et
al. (2015), a new implementation technique based on a Schur complement approach for the Moore-Penrose
continuation method, which facilitates the detection of bifurcation points and enables branch following, was
presented. This method has proved to perform well in most situations; however, in others (i.e. when mesh
adaptation is added to the algorithm), some difficulties appear. In this paper, we therefore present an improved
approach, which is much more robust, for the detection of bifurcation points in nonlinear finite element
problems. Numerical examples will be presented to show the efficiency of the new approach.
ABSTRACT: A theoretical study is conducted to predict the progressive buckling and energy absorption of the sinusoidal corrugated tube subjected to axial crushing. Based on the super folding element theory, the stationary plastic hinge mechanism is proposed. The theoretical prediction of the progressive buckling and energy absorption is proposed by taking the eccentricity factor and amplitude factor into account. In the theoretical analysis, the idealized elastic-plastic material model is adopted and strain hardening effect is employed. Also, the new lower bound and upper bound of the solutions for the mean crushing force are obtained. The theoretical result can predict the crushing behavior of the circular tube which produces the axisymmetric ring mode under axial crushing. The mean crushing force is related to the eccentricity factor and the amplitude factor, but the total energy is independent of the eccentricity factor. The theoretical results are compared well with the numerical and experimental results of previous studies. The theoretical predicts of corrugated tube produce excellent characteristics in term of force-consistent and low crushing force and provide a reference to the research of the progressive buckling and energy absorption of corrugated tube subjected to axial crushing.
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ABSTRACT: We present in this paper a new reliable and efficient 4-node quadrilateral element, which we call the 2D-MITC4 element, for two-dimensional plane stress and plane strain solutions of solids using the MITC method. We also present an extension of the element assuming a constant element pressure, which we call the 2D-MITC4/1 element. The elements show a much better predictive capability than the displacement-based element and perform in linear analyses almost as well as the 4-node element with incompatible modes, an enhanced assumed strain (EAS) element. However, unlike when using EAS elements, we do not observe spurious instabilities in geometrically nonlinear solutions. Embedding the new MITC formulation into the previously presented MITC4+ shell element, we improve the membrane behavior of the shell element. The new 2D solid elements and the improved MITC4+ shell element pass all basic tests (the isotropy, zero energy mode and patch tests). We present the finite element solutions of various benchmark problems to illustrate the solution accuracy of the new elements.


ABSTRACT: The present paper presents a refined one-dimensional finite element model with node-dependent kinematics. When this model is adopted, the beam theory can be different at each node of the same element. For instance, in the case of a 2-node beam element the Euler-Bernoulli theory could be used for node 1 and the Timoshenko beam theory could be used for node 2. Classical and higher-order refined models have been established with the Carrera Unified Formulation. Such a capability would allow the kinematic assumptions to be continuously varied along the beam axis, that is, no ad hoc mixing techniques such as the Arlequin method
would be required. Different combinations of structural models have been proposed to account for different
kinematic approximations of beams, and, beam models based on the Taylor and the Lagrange expansions have
in particular been used. The numerical model has been assessed, and a number of applications to thin-walled
structures have been proposed. The results have been compared with those obtained from uniform kinematic
models and convergence analyses have been performed. The results show the efficiency of the proposed model.
The high accuracy of refined one-dimensional models has been preserved while the computational costs have
been reduced by using refined models only in those zones of the beam that require them.

Hazem Madah and Oded Amir (Faculty of Civil and Environmental Engineering, Technion – Israel Institute of
Technology, Israel), “Truss optimization with buckling considerations using geometrically nonlinear beam
https://doi.org/10.1016/j.compstruc.2017.07.023
ABSTRACT: A unified approach that accounts for various buckling phenomena in truss design optimization is
presented. Euler buckling of slender members, global buckling and stability of sequences of bars are all
considered by optimizing the geometric nonlinear response instead of by imposing a large number of
constraints. In the proposed approach, each truss member is modeled as a sequence of co-rotational beam
elements with appropriate end-releases. By applying various imperfections, buckling of single truss members,
unstable configurations and global buckling can be taken into account implicitly. A detailed discussion on key
aspects of the proposed approach is presented, showing how the choice of imperfections highlights certain
buckling types and leads to respectively stable designs. A comparison to other approaches and to results from
the literature shows that the proposed approach can ensure local and global stability without actually imposing
any buckling constraints. Finally, truss optimization for various levels of global deflections is presented,
exposing the potential of the formulation for optimizing highly nonlinear responses.

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“Geometrically nonlinear isogeometric analysis of functionally graded microplates with the modified couple
https://doi.org/10.1016/j.compstruc.2017.07.017
ABSTRACT: In this study, a new and efficient computational approach based on isogeometric analysis (IGA)
and refined plate theory (RPT) is proposed for the geometrically nonlinear analysis of functionally graded (FG)
microplates. While the microplates’ size-dependent effects are efficiently captured by a simple modified couple
stress theory (MCST) with only one length scale parameter, the four-unknown RPT is employed to establish the
displacement fields which are eventually used to derive the nonlinear von Kármán strains. The NURBS-based
isogeometric analysis is used to construct high-continuity elements, which is essentially required in the
modified couple stress and refined plate theories, before the iterative Newton-Raphson algorithm is employed to
solve the nonlinear problems. The successful convergence and comparison studies as well as benchmark results
of the nonlinear analysis of FG microplates ascertain the validity and reliability of the proposed approach. In addition, a number of studies have been carried out to investigate the effects of material length scale, material and geometrical parameters on the nonlinear bending behaviours of microplates.

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ABSTRACT: Recently, new 3-node and 4-node MITC shell elements, the MITC3+ and MITC4+ elements, have been proposed. The two shell elements were tested through theoretically well-established convergence studies. In this paper we continue to investigate the performance of the MITC3+ and MITC4+ shell elements in relatively simple but widely adopted benchmark problems. To perform these tests as usually done, the predictive capability of the elements is assessed through point-wise convergence of displacements at specific locations of shell structures. The results obtained using the MITC3+ and MITC4+ shell elements are compared with those found for some other shell elements.

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ABSTRACT: This paper proposes a probabilistic approach for the solution of elastic buckling of columns, involving uncertainties, using stochastic element free Galerkin method. In the present work, modulus of elasticity is modeled as a homogeneous random field. Karhunen-Loeve expansion and shape function method are used to represent random field and their effectiveness is compared in modeling the same in a computationally viable manner. Both Gaussian and non-Gaussian field are considered for the present study. The stochastic eigenvalue problem is solved for first and second moment characteristics of buckling load, using perturbation analysis. Numerical examples of columns with different boundary conditions are solved. Monte Carlo simulation is used as a validation tool. The obtained results are found in good agreement with those obtained by Monte Carlo simulation.


ABSTRACT: In this paper an efficient numerical tool is proposed to investigate delamination type failure in multi-layered composite shells. In the current contribution the extended finite element method (XFEM), the mixed-mode cohesive zone model, the contact formulation, and the damage criterion are incorporated into a
new algorithm to study the interfacial delamination initiation and growth with less computational effort. A flat-shell formulation is developed in the geometrically non-linear regime to study the response of shells in small strains and moderate rotations. In addition, the equivalent single layer theory (ESLT) is applied to simulate the multi-layered laminates. This formulation is enhanced through the XFEM topology to be able to model discontinuous domains and a mixed-mode bilinear cohesive formulation to track the delamination growth. In the current study, the simulation can be initiated in an intact laminate. Thus, unlike formulations in existing finite element models, incorporating cohesive zone model at all available interfaces is not necessary. The interlaminar stresses are calculated during post-processing and they are being used in the delamination onset criterion. As soon as the criterion is satisfied at a specific layer and location, the formulation of that corresponding element is locally changed to XFEM and the cohesive behaviour. Consequently, the possibility to track delamination growth is locally provided; and hence, the computational cost is reduced.


ABSTRACT: Many engineering structures consist of thin-walled beams and shells. Especially for fast design in an early design stage, a simplified analysis using beams for load-carrying members and shells for panels is very useful, but there appears no accurate beam-shell combined finite element model. The main reason is that the Timoshenko or Euler beam elements are incapable of representing significant sectional deformations near beam joints or near beam-panel interfaces. Although some progress has been made in developing higher-order beam elements that can accurately capture the sectional deformations, there is no investigation to develop higher-order beam and shell combined models useful to analyze various engineering structures. The main contribution of this work is to present the first attempt to model structures made of thin-walled closed beams and shells in terms of higher-order beam elements and shell elements and to establish the matching conditions between the dissimilar field variables of higher-order beam and shell elements along their interfaces. For the finite element analysis of a whole structure, the interface matching conditions are imposed through Lagrange multipliers. High accuracy of the proposed higher-order beam-shell method is demonstrated through static and modal analyses of various structures including a simplified model of a vehicle body-in-white (BIW).


ABSTRACT: Nonlinear normal modes offer a solid theoretical framework for interpreting a wide class of nonlinear dynamic phenomena. However, their computation for large-scale models can be time consuming, particularly when nonlinearities are distributed across the degrees of freedom. In this paper, the nonlinear normal modes of systems featuring distributed geometric nonlinearities are computed from reduced-order models comprising linear normal modes and modal derivatives. Modal derivatives stem from the differentiation of the eigenvalue problem associated with the underlying linearised vibrations and can therefore account for some of the distortions introduced by nonlinearity. The cases of the Roorda’s frame model, a doubly-clamped beam, and a shallow arch discretised with planar beam finite elements are investigated. A comparison between
the nonlinear normal modes computed from the full and reduced-order models highlights the capability of the reduction method to capture the essential nonlinear phenomena, including low-order modal interactions.

ABSTRACT: The efficient multiscale membrane locking free shell elements are developed to study the dynamic and postbuckling characteristics of carbon nanotubes incorporating material and geometric nonlinearities. The constitutive relation at continuum level is derived through the Cauchy–Born rule incorporating the effect of curvature tensor on bond lengths and using the Tersoff–Brenner atomic interaction potential per unit area of a unit cell. The membrane locking is eliminated by using the smoothed shape functions derived through the least square strain smoothing technique for the interpolation of the transverse displacement in the circumferential strain. The performance of the four/eight noded inconsistent/consistent Kirchhoff rectangular and improved discrete Kirchhoff quadrilateral (IDKQ) shell elements is investigated. It is found that the four noded elements with smoothed interpolation of transverse displacement in the circumferential strain yield accurate results and are computationally efficient. The multiscale modelling results are found to be in close agreement with the molecular mechanics simulations. The significant effect of material nonlinearity on the nonlinear dynamic and postbuckling responses is predicted.

ABSTRACT: A Rayleigh–Ritz solution approach for generally restrained multilayered variable angle tow stiffened plates in postbuckling regime is presented. The plate model is based on the first order shear deformation theory and accounts for geometrical nonlinearity through the von Kármán’s assumptions. Stiffened plates are modelled as assembly of plate-like elements and penalty techniques are used to join the elements in the assembled structure and to apply the kinematical boundary conditions. General symmetric and unsymmetric stacking sequences are considered and Legendre orthogonal polynomials are employed to build the trial functions. A computer code was developed to implement the proposed approach and to establish its applicability and its features for investigating variable angle tow structures. The proposed solution is validated by comparison with literature and finite elements results. Original results are presented for postbuckling of variable angle tow stiffened plates showing the potentialities of the method.

David P. Thambiratnam, “Shell structures in civil and mechanical engineering by Professor Alphose Zingoni, University of Cape Town, South Africa”, Computers & Structures, Vol. 197, pp 70-70, February 2018

ABSTRACT: The objective in this paper is to present some new insights into an implicit direct time integration scheme, the Bathe method, for the solution of the finite element equations of structural dynamics. The insights pertain to the use of the parameters in the method, and in particular the value of the time step splitting ratio. We show that with appropriate values of this ratio large amplitude decays can be obtained as may be desirable in some solutions. We give the theoretical analysis of the method for the parameters used, including for very large time steps, and illustrate numerically the new insights gained.

ABSTRACT: The present paper addresses a weak form quadrature element formulation for the geometrically exact thin shell model in which the Kirchhoff-Love hypothesis is adopted. The displacement derivative continuity conditions are enforced by the reconstruction of rotation variables at the edges of elements. By the utilization of rotation quaternions, a total Lagrange updating scheme is implemented for edge constraint director rotations. Several numerical examples are presented to illustrate the effectiveness of the proposed formulation and the significant reduction in the number of degrees of freedom in geometrically nonlinear thin shell analysis with large displacements and rotations.


ABSTRACT: This article proposes a method for solving generalized eigenvalue problems on medium-power computers with a moderate memory in the particular context of studying fluid-structure systems with sloshing and capillarity. This research was performed following many RAM problems encountered when computing the modal characterization of the system studied. The methodology proposed is one solution to reduce RAM and time required for the computation, by using methods such as double projection or subspace iterations.


ABSTRACT: A computationally efficient framework has been developed for the elastoplastic analysis of compact and thin-walled structures using a combination of global-local techniques and refined beam models. The theory of the Carrera Unified Formulation (CUF) and its application to physically nonlinear problems are discussed. Higher-order models derived using Taylor and Lagrange expansions have been used to model the structure, and the elastoplastic behavior is described by a von Mises constitutive model with isotropic work hardening. Comparisons are made between classical and higher-order models regarding the deformations in the nonlinear regime, which highlight the capabilities of the latter in accurately predicting the elastoplastic behavior. The concept of global-local analysis is introduced, and two versions are presented - the first where physical nonlinearity is considered for both the global and local analyses, and the second where nonlinearity is considered only for the local analysis. The second version results in reasonably accurate results compared to a full 3D finite element analysis, with a twofold reduction in the number of degrees of freedom.


ABSTRACT: An efficient semi-analytical simulation framework is presented, that allows a highly systematic analysis of the mechanical behaviour of laminated prismatic thin-walled beams. It is excellently suitable for extensive case studies and can serve as a key ingredient for the optimization of shape, geometry and stacking sequences of laminated beams. The proposed method can be coded as a stand-alone solution and easily and directly be embedded in existing numerical optimization tools, without the overhead of common simulation tools (like FE-codes). Thus, long-winded and time consuming data transfers are avoided. Additionally, as a consequence of the structural clearness of the proposed method, the simulation framework can also be used as an environment for the development and testing of new beam models. By analogy with existing models for thin-walled beams, the kinematic of the cross-section is described by a proper set of deformation modes. There are
no restrictions regarding these modes, i.e. rigid body modes (axial extension, mayor- and minor-axis flexure, and torsion) as well as higher-order modes (involving warping, distortion and transverse bending of the cross-section walls) can be considered. It is shown that for each given set of modes, the resulting system of equations can be derived - both analytically and systematically - in a straight-forward manner. In contrast to common beam formulations, the introduction of both stress resultants and cross-section values is not required.

ABSTRACT: The Multi-point methods are efficient and accurate techniques for solving nonlinear equations. In this article, these methods are used to develop incremental/iterative techniques for nonlinear analysis of structures. The numerical results show that these methods only have the ability to converge to the equilibrium path before the first limit-point. To improve the performance of Multi-point methods, modified techniques which have the ability to fully trace the geometrically nonlinear response of structures are proposed in this paper. Four novel algorithms are presented which follow the defined constraint while solving the equilibrium equations using modified Multi-point methods. The Multi-point methods and the modified ones are comparatively investigated for the geometrically nonlinear analysis of structures in both continuum and discrete problems (dome and cylindrical shell). Selected examples represent a host of nonlinearities, including large fluctuations in stiffness, snap-back, and snap-through behaviors. The numerical results show that the modified methods have the ability to fully capture the geometrically nonlinear response of structures, including snap-back and snap-through behaviors.

ABSTRACT: In this study, a novel interface shell element (ISE) is developed based on a variable-node element formulation to couple non-matching quadrilateral shell meshes. Shape functions for ISEs are explicitly presented in a polynomial form with the use of appropriate supports of weight functions in moving least square (MLS) approximation. Assumed natural strains in the form of the mixed interpolation of tensorial components (MITC) approach are employed to avoid the transverse shear locking when the thickness of shell tends to zero. Moreover, an assumed membrane strain field defined over quadrilateral subdomains subdividing an ISE is used to alleviate the membrane locking in curved ISEs. Numerical experiments show the effectiveness and efficiency of ISE for connecting dissimilar quadrilateral shell meshes at a common interface.

ABSTRACT: The present study develops a unified distortional lateral torsional buckling finite element formulation for the elastic analysis of beam-columns with wide flange doubly symmetric cross-sections. The solution captures several non-conventional features including the softening effect due to web distortion, the stiffening effect induced by pre-buckling deformations, the pre-buckling nonlinear interaction between strong-axis moments and axial forces, the contribution of pre-buckling shear deformation effects, the destabilizing effects due to loads being offset from the shear centre, and the presence of transverse stiffeners on web distortion. In the present theory, it is possible to evoke/suppress any combination of features and thus isolate the individual contribution of each effect or quantify the combined contributions of multiple effects. The effects of beam span-to-depth, flange width-to-thickness, web height-to-thickness, and flange width-to-web height ratios
on the critical moments are investigated. Comparisons with conventional lateral torsional buckling solutions that omit distortional and pre-buckling effects quantify the influence of distortional and/or pre-buckling deformation effects. The theory is also used to investigate the influence of P-delta effects of beam-columns subjected to transverse and axial forces on their lateral torsional buckling. The solution is adopted to quantify the beneficial effects of transverse stiffeners in controlling/suppressing web distortion in beams.


ABSTRACT: A large number of advanced finite element shell formulations have been developed, but their adoption is hindered by complexities of transforming mathematical formulations into computer code. Furthermore, it is often not straightforward to adapt existing implementations to emerging frontier problems in thin structural mechanics including nonlinear material behaviour, complex microstructures, multi-physical couplings, or active materials. We show that by using a high-level mathematical modelling strategy and automatic code generation tools, a wide range of advanced plate and shell finite element models can be generated easily and efficiently, including: the linear and non-linear geometrically exact Naghdi shell models, the Marguerre-von Kármán shallow shell model, and the Reissner-Mindlin plate model. To solve shear and membrane-locking issues, we use: a novel re-interpretation of the Mixed Interpolation of Tensorial Component (MITC) procedure as a mixed-hybridisable finite element method, and a high polynomial order Partial Selective Reduced Integration (PSRI) method. The effectiveness of these approaches and the ease of writing solvers is illustrated through a large set of verification tests and demo codes, collected in an open-source library, FEniCS- Shells, that extends the FEniCS Project finite element problem solving environment.

(No articles in November 2018)

End of more papers published in the journal, Computers & Structures (2017 and on).


Chao Gao and Yaning Li (Department of Mechanical Engineering, University of New Hampshire, 33 College Road, Durham, NH, 03824, USA), “Tuning the wrinkling patterns of an interfacial/coating layer via a regulation interphase”, International Journal of Solids and Structures, Vols. 104-105, pp 92-102, January 2017 https://doi.org/10.1016/j.ijsolstr.2016.08.003

ABSTRACT: In this investigation, the mechanical response of a tri-phase system subjected to far-field compression is explored. The system includes a stiffer interfacial/coating layer surrounded by an interphase/regulation layer, and both layers are embedded in an infinite softer matrix. Both theoretical and finite element (FE) mechanical models of the system are developed. From the results of these models, three wrinkling patterns are proved to exist: (I) single-layer wrinkling mode, (II) bi-layer wrinkling mode, and (III) the simultaneous nested-wrinkling mode. The wrinkling patterns are reported to be attributed to the instability of the system. The results of FE simulations show that the theoretical model can accurately predict the instability of the system. The influences of the geometry and material properties of all three phases on the transition between the three instability modes are quantified. It reveals that the regulation layer/interphase around the
interfacial/coating layer is the key to tune the wrinkling patterns. The critical physical parameters to determine the characteristics of the three instability modes are the effective thickness ratio between the regulation layer and interfacial/coating layer, the effective stiffness ratio between the interfacial/coating layer and the regulation layer and that between the interfacial/coating layer and the matrix. As an example of the application of the theoretical model, a graded interfacial wrinkling pattern is designed and verified via FE simulations.

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ABSTRACT: A numerical approach for the study of the elastic buckling of slender columns with unilateral supports is proposed. This new approach is based on the numerical solution of a special type of eigenvalue problems that takes into account the complementarity character of the pair (displacement, obstacle reaction) at each unilateral support. The implementation of the proposed approach is illustrated by the determination of bifurcation loads and corresponding modes for several finite element models of columns.

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ABSTRACT: This paper is focused on the effect of imperfect bonding and partial composite interaction between the sub-elements of a box-type column on the critical buckling loads. The box column is modelled as a symmetric three-layer composite structure with interlayer slips at the interfaces, based on the Engesser–Timoshenko theory with uniform shear deformation assumptions. Linear shear springs or slip modulus is considered at the interfaces to model the partial interaction between the sub-elements of the structure. The minimum total potential energy principle is utilized to obtain governing equations and boundary conditions. A direct analytical solution of the original governing equations is presented for obtaining exact buckling characteristic equation of the three-layer partial composite column with different end conditions including clamped-pinned end conditions. Also, the coupled equations are recast into an efficient uncoupled form and shown that there is a strong similarity with those for the two layer element. It is shown that the obtained formulae are converted to the known Euler column formulae when the slip modulus approaches infinity (i.e. perfect bonding) and no shear deformations in the sub-elements are considered. A differential shear Engesser–Timoshenko partial composite model is also employed and critical buckling loads, obtained from an inverse solution method, are compared to examine the validity and accuracy level of the uniform shear model. Comprehensive dimensionless numerical results are presented and discussed.

ABSTRACT: Numerous papers deal with the Equivalent Plate Model (EPM) for corrugated panels. Comparison of published formulas for the four relevant equivalent bending stiffnesses $D_{11eq}$, $D_{22eq}$, $D_{66eq}$, and $D_{12eq}$ revealed ambiguities: Three different formulas were found for $D_{22eq}$, which describes the bending of the ridges and troughs; for $D_{66eq}$ two ‘competing’ formulas emerged. Expressions not converging to the flat-plate values in the limit of vanishing corrugation height were discarded. All discussed formulas are written in a uniform notation for general one-dimensionally periodic shapes. Formulas derived for isotropic panel materials were generalized to the orthotropic case. In order to resolve the ambiguities and assess the EPM with regard to its range of applicability, vibration modes of six rectangular corrugated panels were measured. While agreement with numerical results obtained with COMSOL was fair, the EPM predictions of natural frequencies were satisfactory only for low-order modes. Finally, equivalent bending stiffnesses were determined numerically from COMSOL results for a few low-order modes by inverse methods. Thus the ambiguities with regard to $D_{22eq}$ and $D_{66eq}$ could be resolved. However, the $D_{12eq}$ values determined numerically came out significantly larger than the EPM prediction, in particular for stronger corrugations. Even though this discrepancy had little effect on the natural frequencies tested in the present paper, it remains a theoretical challenge.


ABSTRACT: This paper presents a novel scheme to biaxially package and deploy flat membranes, in which the thickness of the membrane is accounted for through the novel concept of slipping folds. The membrane is divided into parallel strips connected by slipping folds, and specially chosen wrapping profiles that require zero slip along the edges of the membrane are identified. This packaging scheme avoids the kinematic incompatibilities that in other schemes result in local buckles and wrinkles that increase the deployment force and permanently deform the membrane. The paper also presents a scheme to apply uniform uniaxial prestress to the deployed membrane, as well as a two-stage deployment scheme. Packaging efficiencies of up to 83% have been demonstrated for meter-scale models, although for large membranes the packaging efficiency approaches 100%.

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ABSTRACT: This paper experimentally investigates multilayers corrugated core sandwiches under out-of-plane compressive impact loading. The manufacturing method of corrugated core sandwiches in our laboratory is presented at first and its mechanical behavior under quasi-static loading shows a good repeatability. A testing configuration on the basis of a 97 mm diameter and 8 m long Nylon Hopkinson pressure bar is proposed to host
this large sandwich sample and to impose a nominal strain of 70% to multilayer sandwich samples of 45.5 mm long. High-speed imaging system provides their deforming modes and reveals the interactions between adjacent layers. Finally, testing results on 1060 aluminum corrugated core sandwiches are obtained under quasi-static and impact loadings. Significant rate sensitivity is observed and it can be reproduced by the numerical simulation. The bending of the interlayer plate is also observed, which contributes to reduce the force oscillation during successive folding.

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ABSTRACT: Buckling of centrosymmetric anisotropic beams is studied within strain gradient theory. First, the three dimensional anisotropic gradient elasticity theory is outlined. Then the dimension of the three dimensional theory is reduced, resulting in Timoshenko beam as well as Euler–Bernoulli beam theories. The governing differential equations together with the consistent (classical and non-classical) boundary conditions are derived for centrosymmetric anisotropic beams through a variational approach. By considering von Kármán nonlinear strains, the geometric nonlinearity is taken into account. The obtained nonlinear formulation can be used to study the postbuckling configuration. The analysis of size effect on anisotropic beam structures is missing in the literature so far, while the present model allows one to characterize the size effect on the buckling of the centrosymmetric anisotropic micro- and nano-scale beam structures such as micropillars. As a specific case, the governing buckling equation is obtained for the more practical case of orthotropic beams. Finally, the buckling loads for orthotropic simply supported Timoshenko and Euler–Bernoulli beams as well as a clamped Euler–Bernoulli beam are obtained analytically and the effect of the internal length scale parameters on the buckling load is depicted.

Hossein Ghayoor, Mohammad Rouhi, Suong V. Hoa and Mehdi Hojjati (Concordia Center for Composites (CONCOM), Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec, Canada H3G 1M8, Canada), “Use of curvilinear fibers for improved bending-induced buckling capacity of elliptical composite cylinders”, International Journal of Solids and Structures, Vol. 109, pp 112-122, March 2017, https://doi.org/10.1016/j.ijsolstr.2017.01.012
ABSTRACT: In this work, the bending-induced buckling of elliptical composite cylinders is significantly improved by using curvilinear fiber paths. The orientation angle in the composite plies are designed to circumferentially vary in elliptical multi-layered composite cylinders for the best bending-buckling performance. To this end, a metamodeling based design optimization approach is successfully employed. The resulting elliptical cylinders with so-called variable stiffness (VS) laminates are shown to have bending buckling capacities up to 70% higher than their constant stiffness (CS) counterparts made with traditional straight-fiber laminates. Unlike the circular cylinders, the non-uniform curvature of the elliptical cylinders adds more complexity to the buckling behavior when the direction of the bending moment is changed. The effect of loading direction on the buckling performance of VS and CS elliptical cylinders is then investigated. Finally, a VS elliptical composite cylinder is designed for having maximum bending buckling capacity in two opposite directions simultaneously, and its buckling performance in different directions is compared with its CS counterpart.

ABSTRACT: Although geometric imperfections have a detrimental effect on buckling, imperfection sensitivity has not been well studied in the past during design of sinusoidal micro and nano-scale structures via wrinkling of supported thin films. This is likely because one is more interested in predicting the shape/size of the resultant patterns than the buckling bifurcation onset strain during fabrication of such wrinkled structures. Herein, I have demonstrated that even modest geometric imperfections alter the final wrinkled mode shapes via the mode locking phenomenon wherein the imperfection mode grows in exclusion to the natural mode of the system. To study the effect of imperfections on mode locking, I have (i) developed a finite element mesh perturbation scheme to generate arbitrary geometric imperfections in the system and (ii) performed a parametric study via finite element methods to link the amplitude and period of the sinusoidal imperfections to the observed wrinkle mode shape and size. Based on this, a non-dimensional geometric parameter has been identified that characterizes the effect of imperfection on the mode locking phenomenon – the equivalent imperfection size. An upper limit for this equivalent imperfection size has been identified via a combination of analytical and finite element modeling. During compression of supported thin films, the system gets “locked” into the imperfection mode if its equivalent imperfection size is above this critical limit. For the polydimethylsiloxane/glass bilayer with a wrinkle period of 2 µm, this mode lock-in limit corresponds to an imperfection amplitude of 32 nm for an imperfection period of 5 µm and 8 nm for an imperfection period of 0.8 µm. Interestingly, when the non-dimensional critical imperfection size is scaled by the bifurcation onset strain, the scaled critical size depends solely on the ratio of the imperfection to natural periods. Thus, the computational data generated here can be generalized beyond the specific natural periods and bilayer systems studied to enable deterministic design of a variety of wrinkled micro and nano-scale structures.


ABSTRACT: This work presents an analytical study of the electromechanical buckling of a micro spherical thin film bonded to a compliant elastic substrate. The spherical film is subjected to electrostatic attraction forces that are induced by applying a voltage difference between an outer spherical elastic film electrode and inner rigid, fixed and grounded spherical electrode. When the applied voltage is small, the film contracts while maintaining its complete spherical shape. However, when the applied voltage reaches a critical value, the film buckles into high-ordered periodic patterns (i.e. elastic surface wrinklings). Motivated by experimental results of other studies, this work examines the critical buckling state of one-dimensional, square checkerboard and hexagonal patterns. As will be shown, the above considered patterns are associated with the same critical state, and therefore, all patterns have equal buckling voltage and critical wavelength. Furthermore, with increasing radius of the film/substrate system the electromechanical buckling response converges to the electromechanical pull-in instability of the well-known two parallel plate electrodes, as will be revealed by the asymptotic analytical solution. Finally, the elastic ripples of the electromechanically buckled film can be generated or removed by a simple On/Off switching of the applied voltage. The ability to generate and remove elastic ripples tremendously increases the potential of such microsystem to be utilized in different applications in the field of Micro and Nano electromechanical systems.
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ABSTRACT: It is well known that the macroscopic behaviour of many engineering materials is strongly affected by the role of underlying microstructure. Currently though, mathematical expressions linking behaviour of large scale structures to the geometry of their microscopic structure are largely lacking. In this respect, establishing quantitative links across different material lengthscales may offer new pathways for engineering design. In the present work an analogy between cross sectional geometrical properties, representing macrostructure, and a material length parameter, representing microstructure, is presented. The analogy is established through the study of a thin plate subject to axial loading undergoing finite displacements from two alternative perspectives. First, we consider a thin elastic plate with a pretwist about the loading axis where a warping term is introduced accounting for the out-of-plane deformation of the cross section. The coupled governing differential equations and the corresponding coupled boundary conditions are explicitly derived employing a classical structural mechanics approach utilising an energy variational statement. Secondly, an axially loaded thin flat plate (i.e. with no pretwist) is studied with strain gradient elasticity theory incorporating only one material length parameter representing the microstructure, in addition to the two classical Lamé stiffness constants. The ensuing analogy emerges by comparison of the governing equations of the two formulations which shows a mathematical expression can be identified, which incorporates both geometric and material length variables, that formalises the link between microscale and macroscale. This mathematical expression, which constitutes the kernel of the proposed multiscale approach, admits a twofold interpretation depending on the assumed independent variable. On the one hand, the proposed multiscale modelling approach suggests that a plate with complex global geometry can be substituted by a structurally - equivalent, flat plate with constitutive relations given by a non - local, strain gradient theory. On the other hand, the material length parameter can be interpreted on a physical basis because for the first time it has been identified as a known function of geometrical features of the structure through simple algebraic relationships for various cross sectional profiles.

ABSTRACT: This work presents an analytical study of the electromechanical postbuckling of a spherical elastic thin film electrode that is bonded to a spherical dielectric compliant substrate. The compliant substrate is bonded to an inner rigid, fixed and electrically grounded spherical electrode. As will be shown, when the applied voltage reaches a critical value, the film buckles into a well ordered periodic surface patterns. The electromechanical postbuckling problem will analytically be solved for the one-dimensional, square checkerboard, hexagonal and herringbone periodic patterns. This work studies the effect of different geometry and material parameters on the selection and wavelength of the preferred/stable surface pattern of the buckled film. As will be deduced, the preferred buckling pattern can be determined to be either hexagonal or herringbone pattern depending on the geometry and material parameters of the film/substrate system.
Furthermore, we study the effect of nonlinear stiffness of the compliant substrate on the electromechanical behavior of the film. The simplicity of generating and removing elastic surface wrinklings by On/Off voltage switching sufficiently increases the potential of the electromechanical buckling response to be employed in different MEMS application, such as, micro sensors, micro optical switches and deformable micro mirrors.

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ABSTRACT: In this paper a semi-analytic solution for the post-critical behavior of compressed thin walled members with generic cross sections is presented. It is based on the Koiter approach and the method of separation of variables. The buckling solution is exactly evaluated using a single sinusoidal function and the initial post-critical behavior is obtained as a decoupled sinusoidal series solution along the beam axis. A specialized integration scheme allows obtaining the solution with only a few terms and a very low cost, with respect to standard finite element analyses. This tool is then used to highlight the reason of the poor behavior of beam models enriched with cross section deformation modes in reconstructing the post-critical solution. Successful strategies are proposed in order to overcome these limitations. A series of numerical tests are reported.


ABSTRACT: Stress-strain relationships for rubbery materials are highly non-linear. In this work, a particular configuration of electroactive material is considered: an isotropic, incompressible electroelastic squared plate is subjected to equal biaxial homogeneous deformation and a scalar electrical potential is applied on the sides of compliant electrodes. This case is analysed according to two methodologies: the Hessian approach and the use of incremental deformation together with increment in the electric displacement. First, an extended Mooney–Rivlin model is considered for the material and then an Ogden model is also analysed. Results, show, that despite of available experimental results, some predictions can be made and the pertinent analysis show complex bifurcation maps. This can help in the future progress in the knowledge of the instabilities and bifurcation phenomena which should appear in these materials. The present paper has been mainly motivated by the work of Ogden and Dorfmann.

ABSTRACT: This paper presents an experimental study of imperfection insensitive composite wavy cylindrical shells subject to axial compression. A fabrication technique for making cylindrical shells with intricate shape of cross-sections has been developed. A photogrammetry technique to measure the geometric imperfections has also been developed. The behavior of the wavy shells under axial compression was predicted through simulations and measured through compression tests. Both the analyses and experiments have confirmed that the wavy shells are imperfection insensitive. Comparisons between the wavy shells and circular shells have also confirmed that introducing optimal symmetry-breaking wavy cross-sections can significantly reduce the imperfection sensitivity and improve the load-bearing capability of cylindrical shells.

References listed at the end of the paper: (Cannot cut and paste them)
of wrinkled paperboard. The constitutive model enables the explicit finite element simulation of the deep drawing of a non-creased paperboard blank, including spring-back after the forming process. The results of the simulated deep-drawing process were validated against experimental deep-drawn paperboard cups, and parametric studies were conducted to investigate the effects of process and material parameters on three different quality measures (spring-back magnitude, asymmetry, and punch force). In addition to aiding the development of the simulation of paperboard deep drawing, the hinge yield strength was also found to be the only studied material property which could simultaneously improve all three quality measures.

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ABSTRACT: Micro- and nanoelectromechanical systems (MEMS/NEMS) incorporating two-dimensional structural elements such as plates and shells attracted significant interest in recent years. These structures demonstrate rich electromechanical behavior and could be advantageous in applications. In this work, we explore implementation of two models describing axisymmetric behavior of initially curved circular micro plates, subjected to a distributed nonlinear electrostatic force. While both models are based on the Kirchoff hypothesis and on the nonlinear Föppl von Kármán (FvK) strain-displacements relations, the second model employs the Berger approximation, which significantly simplifies the formulation and describes the plate by a single governing equation. In both cases, the solution is based on the Galerkin decomposition with buckling modes of an initially flat plate used as the base functions. To track the unstable branches of the equilibrium curve, continuation methods in conjunction with the Riks algorithm are implemented. The validation of the models is conducted for two loading cases, namely “mechanical” deflection-independent load, and electrostatic displacement-dependent load. Results of a finite elements (FE) analysis, as well as of a finite differences (FD) solution of the differential equations, were used as a reference. We estimate the accuracy of the RO models and provide recommendations concerning the number of degrees of freedom (DOF) required to reach a desired accuracy. We show that a simple RO model based on Berger plate theory, can be conveniently used for analysis of electrostatically actuated plates with low initial curvature and small thickness to electrostatic gap ratio.

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ABSTRACT: Energy perturbation is applied as a measure in the stability analysis of a spherical shell subjected to uniform external pressure. The energy barrier (buckling energy) is calculated using asymptotic method, which allows to estimate sensitivity of the structure to the perturbation. It is possible to define the level of external pressure separating areas of small and extensive sensitivity of the structure to the perturbations. This pressure level can be recommended as a design buckling load for spherical caps. The obtained result corrects NASA SP-8032 recommendations which are over-conservative. The asymptotic approach is validated using
ANSYS software package. In addition, the influence of boundary conditions on buckling load is estimated using the software.

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ABSTRACT: We examine the mechanical response of an incompressible thin-wall composite sphere (TWCS) within the framework of finite deformation elasticity. Specifically, we consider TWCSs with a neo-Hookean core phase and a stiffer or a softer shell subjected to simple shear displacement and traction boundary conditions. We derive the general forms of the displacement and the pressure fields in both phases in terms of a power series about the shear magnitude. The predictions of the analytical solutions are analyzed and compared with corresponding results of finite element simulations. In order to examine the range of the validity of the thin shell assumption we model TWCSs with shell volume fractions of 5 and 10%. We find that a relatively small number of terms in the series is required for a good agreement with the numerical simulations in the cases of TWCSs with a stiffer shell under displacement boundary condition and TWCSs with a softer shell under traction boundary conditions. For the dual pair of TWCSs with a softer or stiffer shell under displacement or traction boundary conditions, respectively, the analytical solution is applicable only when the contrast between the phases shear moduli is considerably smaller than the shell volume fraction. Moreover, for each of the above pairs the spatial distributions of the stresses in the core are rather similar. In the shell, however, the stress distributions depend primarily on the contrast between the shear moduli of the two phases. At the macro-level we find that while the stored strain energy is identical in TWCSs subjected to identical magnitudes of shear strain or shear stress under both types of boundary conditions, a Poynting effect is observed in the finitely deforming TWCSs.


ABSTRACT: The strong SaS formulation for the three-dimensional (3D) stress analysis of layered shells is based on a new concept of SaS located at Chebyshev polynomial nodes throughout the layers and integration of the equilibrium equations of elasticity. The idea of the SaS method consists in choosing the arbitrary number of SaS parallel to the middle surface in order to introduce the displacements of these surfaces as basic shell unknowns. Such choice of unknowns with the use of the Lagrange polynomials in assumed approximations of displacements and strains through the layer thicknesses leads to a compact form of the layered shell formulation. The feature of the proposed approach is that all SaS are located inside the layers at Chebyshev polynomial nodes. The use of interfaces is avoided that makes possible to minimize uniformly the error due to the Lagrange interpolation. Therefore, the strong SaS formulation can be applied efficiently to the 3D analysis of layered composite shells.

Takashi Iwasa (Department of Mechanical and Aerospace Engineering, Tottori University, 4-101, Koyama-cho Minami, Tottori, 680-8551, Japan), “Approximate estimation of wrinkle wavelength and maximum amplitude
ABSTRACT: Membrane-based space structures such as solar sails, inflatable antennas and sunshields have attracted attention for use on future advanced space science and engineering missions. Since these membrane-based space structures are easily deformed by small disturbances, a practical calculation method for the surface configuration of the deformed membranes is required to realize the membrane structures without failure. This study formulates an equation to estimate the wrinkle wavelength and maximum amplitude appearing on thin membranes based on a tension-field solution. The equation calculates the wrinkle wavelength and maximum amplitude using three wrinkling parameters, which are the major principal stress in the wrinkled region, the length of the wrinkle line, and the wrinkle strain. Because these wrinkling parameters are given by a traditional wrinkling analysis using tension-field theory, the formulated equation reveals an approximate wrinkle wavelength and a maximum amplitude appearing on the thin membranes without cumbersome bifurcation analysis and has characteristics applicable to various types of structures. By conducting a wrinkling analysis using tension-field theory for the two classical membrane models, which have wrinkling phenomena appearing across the entire membrane and in part of the membrane, a wrinkle wavelength and maximum amplitude are estimated from the formula. Comparing the estimated results with those given by wrinkling analysis using shell theory, it is observed that the estimate appropriately captures the wrinkle wavelength and maximum amplitude in the wrinkled region where tension-field theory is applicable. The equation presented in this study offers a new, practical approach to estimate the wrinkled membrane surface configuration.

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ABSTRACT: Anisotropic generalized shear deformation plate theory is formulated and the results in the framework of zigzag analyses are discussed. The anisotropic nonlinear model is recovered reusing the model available in the linear context. The anisotropic nonlinear model is obtained by modifying the description of the continuum in terms of nonlocal Biot stress/strain tensors and using convenient assumptions for the linear stress/strain tensors. The results of zigzag analyses for different and complex plate cross-section geometries, emphasizing distortional and local buckling behaviors, are presented and comparisons with other methods made.

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ABSTRACT: We investigate the stability of the deformation modeled by the opening angle method, often used to give a measure of residual stresses in arteries and other biological soft tubular structures. Specifically, we study the influence of stiffness contrast, dimensions and inner pressure on the onset of wrinkles when an open sector of a soft tube, coated with a stiffer film, is bent into a full cylinder. The tube and its coating are made of isotropic, incompressible, hyperelastic materials. We provide a full analytical exposition of the governing equations and the associated boundary value problem for the large deformation and for the superimposed small-amplitude wrinkles. For illustration, we solve them numerically with a robust algorithm in the case of Mooney–Rivlin materials. We confront the results to experimental data that we collected for soft silicone sectors. We study the influence of axial stretch and inner pressure on the stability of closed-up coated tubes with material parameters comparable with those of soft biological tubes such as arteries and veins, although we do not account for anisotropy. We find that the large deformation described in the opening angle method does not always exist, as it can become unstable for certain combinations of dimensions and material parameters.

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ABSTRACT: In this paper we describe experiments and a continuum phase transition model for the compression of carbon nanotube (CNT) forests. Our model is inspired by the observation of one or more moving interfaces across which densified and rarefied phases of the CNT forests co-exist. We use a quasi-static version of the Abeyaratne-Knowles theory of phase transitions for continua with a stick-slip type kinetic law and a nucleation criterion based on the critical stress for buckling of CNT forests to describe the formation and motion of these interfaces in uniaxial compression experiments. We investigate micropillars made from bare CNTs, as well as those coated with different thicknesses of alumina using atomic layer deposition (ALD). The coating thickness affects the moduli of individual CNTs as well as the adhesion energy per contact between CNTs. In order to test the applicability of our model to more complex stress states, we carry out nanoindentation experiments on the CNT pillars and interpret the load-indentation data by incorporating a constitutive law allowing for phase transitions into solutions for the indentation of a linearly elastic half-space. Even though the state of stress in a nanoindentation experiment is more complex than that in a uniaxial compression test, we find that the parameters extracted from the nanoindentation experiments are close to those from uniaxial compression. Our models could therefore aid the design of CNT forests to have engineered mechanical properties, and guide further understanding of their behavior under large deformations.

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ABSTRACT: This paper is dedicated to creep buckling predictions. Thin walled cylinders having an aspect ratio of one are subjected to an uniform external pressure. The material is a special type of nickel which “creeps” at ambient temperature. The material parameters for the creep law are identified from experimental results. The creep failure experiments are described and corresponding failure times are given. The paper then compares three alternatives of finite element modeling of the experiments (3D Shell with integration through the thickness with a periodic or non periodic initial imperfection are compared with COMU quasi axisymmetric imperfect shell element). These 3 modeling show consistent predictions. The simulation time is a hundred times faster with the COMU model. It is shown that the prediction of failure time of these experiments is extremely sensitive to the initial imperfection amplitude. The effect of creep law modeling is also important. Finally a parametric analysis on different types of cylinders is given: some general trends are proposed for this type of delicate predictions.

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ABSTRACT: Stability is an important problem in applications of plate and shell structures as well as newly arisen nano-structures, such as nanotubes and graphene sheets. Most classical methods for stability analysis require buckling modes, which are difficult to be accurately predicted, especially for the structures with complex boundary boundaries and load conditions. In this paper, we propose a half-analytical method to predict the critical buckling of structures, named mode-independent energy-based buckling analysis method (MIEM), in which the buckling mode is not needed to be presupposed. The proposed MIEM shows great superiority in dealing with structure buckling under complicated loads and constraints. Besides, it is more suitable for large-scale nanostructures due to its extremely small amount of calculations, and the calculation amount can be further reduced for periodic structures. With the MIEM, the critical buckling of substrate-supported graphene sheets under complex strain states is investigated comprehensively. Furthermore, a unified criterion to predict the critical buckling of substrate-supported graphene is given by a simple expression, which could be of great help in design and manufacture of graphene-based electronics and devices. The MIEM developed in this paper can be used in buckling analysis of structures such as beams and plates as well.

Vahid Zamani and Thomas J. Pence (Department of Mechanical Engineering, Michigan State University, East Lansing, MI, USA). “Swelling, inflation, and a swelling-burst instability in hyperelastic spherical shells”,
ABSTRACT: The incompressible hyperelastic Mooney-Rivlin constitutive model allows for pressure-inflation response of spherical shells that could either be globally stable (a monotonic pressure-radius graph) or could instead involve instability jumps of various kinds as pressurization proceeds. The latter occurs when the pressure-radius graph is not monotonic, allowing for a snap-through bifurcation that gives a sudden burst of inflation. For a given structure (shell thickness) composed of a specific material (a parameter choice in the M–R constitutive model), the form of the pressure-radius graph becomes fixed, enabling the determination of whether and when such a burst will be triggered. Internal swelling of the material that makes up the shell wall will generally change the response. Not only does it alter the quantitative pressure-inflation relation but it can also change the qualitative stability response, allowing burst phenomena for certain ranges of swelling and preventing burst phenomena for other ranges of swelling. This paper provides a systematic framework for predicting how such swelling ranges depend on structural geometry and material parameters.


ABSTRACT: A state space solution is developed to analyze surface instability of cylindrical structures with Young's modulus varying arbitrarily in the radial direction. By using the incremental theory for surface instability of elastic materials, the equilibrium equations for the incremental stress field from a fundamental state are derived for radially graded elastic cylinders subjected to an axial compression, which together with the boundary conditions constitute an eigenvalue problem. In the present work, a state space method is established to solve the eigenvalue problem and predict the critical condition for onset of surface instability. The state space solutions for three typical examples are presented and shown to be in good agreement with the numerical results by the finite element method, including the analytical solution for a thin cylindrical shell. In particular, a transition of the critical buckling mode for a soft cylinder covered by a bilayer is illustrated clearly by the present method. In contrast to the finite element method, the state space method is a semi-analytical approach with higher computational efficiency for arbitrarily graded elastic cylinders, including layered structures.

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ABSTRACT: There has been a strong and recent research activity to obtain tunable wrinkling patterns in film/substrate systems, which proposes to use geometric curvature as a control parameter. This paper studies core-shell cylindrical systems under thermal loads, with the aim to describe possible wrinkling modes, bifurcation diagrams and dimensionless parameters influencing the response of the system. In the companion case of axially compressed core-shell cylinders, it was established that instability modes can be axisymmetric or
diamond-like, the post-buckling response of the system is governed by a single dimensionless parameter \( C_1 \), and the bifurcation becomes supercritical for a sufficiently stiff core. In the present case of cylindrical core-shells subjected to thermal loading, one finds quite different buckling patterns, named churro-like modes that are characterized by a fast undulation in the circumferential direction. There exists another curvature-related influencing parameter \( C_3 \), and a subcritical to supercritical bifurcation transition is observed when the core stiffness increases. The problem is analyzed both theoretically and numerically based on finite element calculations. Lastly, the obtained instability modes remain about the same as in pure shell structures, the main difference being the stabilization of the post-bifurcation behavior.

References listed at the end of the paper:


ABSTRACT: The quasi-static compressive behavior of novel aluminum hexagonal honeycombs with perforations on the cell wall is investigated experimentally and numerically. Compressive experiments on the perforated honeycombs with different cell numbers are conducted to study the effect of specimen sizes. The measured collapse stress is almost insensitive to the specimen sizes, while the crushing stress increases with the cell numbers and finally converges to a stable plateau for the specimens beyond $15 \times 15$ cells. Finite element simulations are performed to study the effects of perforation size, spacing and shape on the mechanical properties of honeycombs. The results reveal that perforation size is a key parameter that affects the compressive mechanical properties and deformation patterns of honeycombs. The perforation number along the height direction of a cell has nearly no influence on the collapse stress, and only affect the crushing stress when the perforation size is large. The perforation shape impacts the collapse of honeycombs but has minor effect on the subsequent crushing stage.

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ABSTRACT: This paper develops a static and dynamic large deformation model to investigate the post-buckling response of slender beams constrained by movable and flexible bilateral confinements. A novel discretization algorithm is proposed to convert the irregular constraints into gap vectors. Governing equations are formulated based on the Euler-Bernoulli beam theory. An energy method is presented to solve the equations using a modified Nelder–Mead algorithm. A constrained minimization of the total energy is carried out with respect to the gap vectors. The theoretical results of the proposed model, i.e., the deformed beam shape configuration and force-displacement relationship, are compared with existing studies and experiments. The regularly and movably constrained, static model is compared with the existing small and large deformation models, respectively. The regularly and flexibly confined, dynamic model is compared with experiments. Satisfactory agreements are observed. Parametric studies are conducted to investigate the post-buckling response in terms of loading and constraints conditions. In particular, the loading condition is first examined by changing the loading frequency. The highest achievable buckling mode is then studied with respect to the Young’s moduli ratios of movable constraints-to-beam and flexible constraints-to-beam, respectively, and the ratio of walls gap-to-beam length. The proposed theoretical models are effective in understanding and predicting the static and dynamic post-buckling response of beams constrained by movable and flexible confinements.

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ABSTRACT: Understanding the effects of water absorption on the geometry of a paper sheet is important for inkjet printing applications, since internal moisture content differences may cause unacceptable out-of-plane deformations. The present work focuses on moisture-induced deformations due to a moisture content that is uniform over the thickness of the sheet. Large enough in-plane differences will cause the sheet to buckle, leading to a wavy pattern at the edges of the sheet. Two approaches are utilized to study this for levels of moisture content up to and including the threshold for buckling. An analytical approach, based on geometrically nonlinear plate theory (von Kármán theory), and a numerical one, using commercially available finite element software, are presented. As a first reference problem an isotropic circular plate, wetted uniformly at its center, is solved both analytically and numerically for the in-plane stress distribution, the buckling threshold, and the resulting buckling mode. Secondly, the same is done for an orthotropic rectangular plate, wetted at its edges. Here, in the analytical approach a Rayleigh–Ritz analysis is employed to approximate the buckling threshold. The latter is also calculated by numerical means. The results show that the methods provide results consistent with each other.

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ABSTRACT: Imperfections from manufacturing process can cause a scattered reduction of the load-carrying capacity or buckling load of axially compressed cylindrical shell structures. To isolate the influence of
geometric imperfections from other imperfections such as welding, a sub-scaled, integrally manufactured cylindrical shell with small-amplitude geometric imperfection was manufactured, analyzed and tested in this study. A test facility and measurement system (including imperfection measurement and buckling test) were constructed. Finite element (FA) numerical procedure for predicting the buckling load was developed. Results indicate that the buckling load predicted by the FE analysis is very close to that from the test. Knockdown factor (KDF) is discussed with reference to the NASA design document. Furthermore, the influence of pure geometric imperfections including imperfection component and amplitude on the buckling behavior is discussed based on Fourier series method. Some guidance for the dimensional tolerance in manufacturing process relating to the load-carrying capacity of thin-walled structures is provided.

ABSTRACT: The characteristic surface morphology of the mammalian brain is closely correlated with brain function and dysfunction. During development, the initially smooth surface evolves into an elaborately convoluted pattern. Growing evidence suggests that mechanical instabilities emerging from differential growth between a faster growing outer gray matter and a slower growing inner white matter play a major role in brain morphogenesis. Previous studies assume uniform growth and stiffness; yet, recent experiments indicate that the properties of brain tissue are highly inhomogeneous. Here, we hypothesize that regionally varying developmental pathways across the brain result in nonuniform material properties at the onset of cortical folding. We establish a computational model of brain growth to explore the effects of stiffness and growth variations in gray and white matter tissue to mimic cellular processes and evolving tissue microstructure. We present an effective approach to determine critical growth values from geometrical data and systematically study the effect of inhomogeneous material properties on growth-induced primary and secondary instabilities. Our results reveal that critical growth and wavelength strongly depend on the stiffness distribution in the developing brain. Regional variations in cortical growth affect secondary instabilities and evoke highly irregular folding patterns, but characteristic wavelength and critical growth remain relatively stable. The interplay of different influential factors including cortical thickness, brain geometry, stiffness, and growth explains how primary folds are highly preserved across individuals, whereas secondary and tertiary folds vary significantly. Our findings are directly applicable to imaging data of fetal brains and ultimately enable early diagnostics of cortical malformations to improve treatment of neurodevelopmental disorders including epilepsy, autism, spectrum disorders, and schizophrenia.

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ABSTRACT: Variable angle tow (VAT) laminates that generally exhibit variable stiffness properties not only provide extended design freedom, but also offer beneficial stress distributions. In this paper, the prospect of VAT composite panels with significantly reduced loss of in-plane compressive stiffness in the postbuckled state in comparison with conventional structures, is studied. Specifically, we identify that both thickness and local
fiber angle variation are required to effectively define “Buckle-Free” panels under compression loading. In this work, the postbuckling behaviour of variable thickness VAT composite panels is analysed using an efficient and robust semi-analytical approach. Most previous works on the postbuckling of VAT panels assume constant thickness. The additional benefits of tailoring thickness variation in the design of VAT composite panels are seldom studied. However, in the process of manufacturing VAT laminates, either by using the conventional Advanced fiber Placement (AFP) machine (tow overlap) or the newly developed Continuous Tow Shearing (CTS) process (tow shrink) thickness build-up is inevitable. The postbuckling optimization for the design of VAT layups is conducted by a two-level framework using lamination parameters as intermediate design variables. The objective is to determine optimal lamination parameters and thickness distributions for maximizing the axial compressive stiffness of VAT laminates that are loaded in the postbuckling regime. The thickness variation due to both manufacturing of VAT laminates and for where it is independent of manufacturing process are considered. In accordance with the first-level optimal postbuckling solutions in terms of lamination parameters, we investigate a practical “Buckle-Free” VAT panel using a blended layup configuration. This blended VAT panel consists of a piecewise combination of segmental CTS layers and constant-thickness VAT layers. The prospect of taking advantage of a benign combination of stiffness and thickness to improve the overall compressive strength of VAT panels is studied. Finally, the optimal results are analysed to provide insight into the manufacturing of VAT laminates using either the AFP or the CTS process for improved postbuckling stiffness under compression loading.

References listed at the end of the paper:


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characteristics of the periodic solutions. This suggests that unstable periodic solutions act as separatrix between extremely close initial conditions are revealed. The characteristics of these solutions match with the resulting boundary value problem requires special numerical methods due to the stiffness of the governing differential equations. Algorithm is applied to find the solutions of problems for three different size pipelines; an 8.625 inch, a 16 inch, and a 32 inch diameter. Multiple stable chaotic solutions corresponding to distinct but extremely close initial conditions are revealed. The characteristics of these solutions match with the characteristics of the periodic solutions. This suggests that unstable periodic solutions act as separatrix between
narrow zones containing stable chaotic solutions. It is seen that chaotic solutions can relieve a significant portion of the thermal and pressure loads without inducing excessive pipeline displacements. The results show that the pipeline end expansion is significantly less than the value given by common engineering methods. It is also shown that pipeline operating conditions and soil-pipe interaction parameters influence the stability and bifurcations of solutions.


ABSTRACT: Mechanical properties and failure mechanisms of sandwich panels with “corrugated-pyramidal” hierarchical lattice cores were investigated through analytical modeling and detailed numerical simulations. This included studying the behavior of hierarchical lattice core material under compression and shearing, as well as investigating the mechanical performance of sandwich panels subjected to in-plane compression and three-point bending. Failure maps were constructed for the hierarchical lattice cores, as well as sandwich panels with hierarchical lattice cores by deriving analytical closed-form expressions for strength for all possible failure modes under each loading. 3D printed samples were manufactured and tested under out-of-plane compression in order to provide limited experimental validation of the study. Our study provides insights into the role of structural hierarchy in tuning the mechanical behavior of sandwich structures, and new opportunities for designing ultra-lightweight lattice cores with optimal performance.


ABSTRACT: Photo-chromic liquid crystalline polymer (LCP) is a type of smart materials which are sensitive to light. Here we harness its photo-mechanical response to flexibly control surface patterning, through modeling a film involving homeotropic nematic liquid crystals with director perpendicular to the polymer film attached on a compliant substrate. Theoretical and numerical analyses were conducted to explore the surface instability of such film/substrate systems under both uniform and non-uniform illuminations by ultraviolet (UV) light, respectively. By minimizing energy, the film can buckle into checkerboard patterns at the critical photo load. Fourier spectral method is applied to study the post-buckling evolution of various 3D wrinkling patterns including wavy shaped, ring-like, checkerboard, stripe and herringbone patterns. Besides, non-uniform illumination is investigated through square and circular patterned lights, respectively, where the wrinkles can be ordered and controlled remotely and flexibly. Furthermore, the geometric and size effects of local illumination are discussed and characterized by some critical dimensionless parameters. Phase diagrams are provided and agree with experimental observations, which could be used to guide the photo design of wrinkling morphogenesis that is particularly attractive for remote control applications.


ABSTRACT: Hierarchy has been introduced to honeycomb structures in pursuing ultralight materials with outstanding mechanical properties. Nevertheless, the hierarchical honeycombs under the out-of-plane loads have not been well studied experimentally and analytically for energy absorption to date. This study aimed to apply a special structural hierarchy to the honeycomb by replacing the sides of hexagons with smaller hexagons. The quasi-static test of the hierarchical honeycomb specimen was first conducted experimentally to investigate the crushing behaviours; and then the corresponding finite element (FE) analyses were performed. Finally, the analytical solutions to the mean crushing force and plateau stress were derived based on the simplified super
folding element (SSFE) method. It was shown that the experimental data and numerical results agreed well in terms of crushing force versus displacement relation and energy absorption characteristics; and the analytical results were validated by the experimental test. Importantly, the hierarchy could improve the energy absorption; and the increase in the order and number of replacement hexagons could excavate the advantage even further. Specifically, the second order honeycomb characterized by five smaller replacement hexagons at each order can yield a plateau stress 2.63 and 4.16 times higher than the regular honeycomb and the aluminium foam, respectively. While it might lead to global bending, structural hierarchy provides new architectural configurations for developing novel ultralight materials with exceptional energy absorption capacity under out-of-plane loads.

Takashi Iwasa, “Experimental verification on wrinkling behavior given by wrinkling analysis using the tension field theory”, International Journal of Solids and Structures, Vols. 136-137, pp 1-12, April 2018

ABSTRACT: This study investigates the physical meaning of membrane surface features given by a wrinkling analysis based on tension field theory and wrinkle strain, which releases the compressive stress in membranes in tension field theory. A rectangular membrane was subjected to shear loading, and the wrinkle geometry and strain field were measured by photogrammetry using a direct linear transformation method. The experimental model was then subjected to a wrinkling analysis based on tension field theory, and the calculated wrinkled membrane behavior was quantitatively compared to the measured results. The analyzed membrane surface features approximately represented the neutral curved surface bisecting the actual wrinkle geometry (the difference was approximately 10% of the maximum wrinkle amplitude), even when the membrane surface feature was not initially flat. The wrinkle strain, defining an in-plane shrinkage strain that releases compressive stress on the membrane in tension field theory, agreed with the experimentally observed in-plane shrinkage strain regardless of the formation process of the wrinkles. The relation between the in-plane shrinkage strain and ratio of the wrinkle amplitude to the half-wavelength of the wrinkles was then derived from inextensional theory. This relation appropriately described the relation measured in the experiment, confirming that inextensional theory describes the wrinkle formation. The results of this study will assist the evaluation of the simulation results using tension field theory for the development of future lightweight, membrane-based space structures such as sunshields and solar sails.


ABSTRACT: We study the inflation of a weakly magnetizable isotropic incompressible cylindrical membrane and the effects of an external magnetic field generated by a current carrying wire placed along the axis of cylinder. A variational formulation based on magnetization is used and the computational results obtained by using four elastic constitutive models (neo-Hookean, Mooney–Rivlin, Ogden, and Arruda–Boyce) are studied and compared. Cylinders of various aspect ratios are studied in each case. Our study shows that the external magnetic field alters the elastic limit point, does not lead to equilibrium solutions below certain value of internal pressure, and can give rise to multiple equilibrium states for a given value of pressure. Presence of magnetic limit point, a phenomenon recently reported in the literature is reconfirmed. Magnetic limit point is a state where a further strengthening of the applied magnetic field at a given pressure does not yield any static equilibrium state. In this case it is detected when the cylindrical membrane deflates into the volume enclosed by itself. We also observe a quadratic relation between the defined magnetic energy parameter and the internal pressure at the magnetic limit point. Relaxed form of the strain energy density is used to account for wrinkling in this case of inward inflation. A finite difference method coupled with an arc-length technique is used for the computations and the stability of the solution is determined from the second variation.
Xiaodong Chen, Zhangming Wu, Guojun Nie and Paul Weaver, “Buckling analysis of variable angle tow composite plates with a through-the-width or an embedded rectangular delamination”, International Journal of Solids and Structures, Vols. 138, pp 166-180, May 2018

ABSTRACT: Variable angle tow (VAT) composite laminates, in which fibre orientation varies spatially in-plane in a continuous fashion yet is piecewise constant through-thickness, have been made possible by advanced automated fibre placement technology. Such designs have shown considerable potential to improve the performance of lightweight composite structures. In the present study, an analytical model is developed to study the buckling behaviour of VAT composite plates with a through-the-width or an embedded rectangular delamination under compression loadings. The proposed model can accurately capture the global, local and mixed buckling response of delaminated VAT composite plates. Both free and constrained modes are assumed in the delamination buckling analysis. A constrained point approach is employed to analyse the buckling response when contact occurs between delaminated layers. The accuracy and reliability of this proposed delamination buckling model is validated by finite element analysis and with prior results. The influence of delamination size, position and varying fibre orientation angles on the buckling response of delaminated VAT composite plates is studied by numerical examples. It is shown that the buckling loads decrease with an increase of the delamination size. The VAT laminates with an off-midplane delamination may lead to the delamination opening up, which further reduces the buckling loads. Finally, the mechanism of taking advantages of VAT laminates to improve the buckling performance of delaminated composite plates is thoroughly investigated in a parametric study. This study also shows that the residual buckling resistance of the delaminated composite plates can be significantly improved through using the VAT design concept.


ABSTRACT: Spinning membrane structures provide a mass-efficient solution for large space apertures. This paper presents a detailed study of the wrinkling of spinning circular membranes loaded by transverse, uniform loads. Experimental measurements of the angular velocities at which different membranes become wrinkled, and of the wrinkling mode transitions that occur upon spin down of the membrane, are presented. A theoretical formulation of the problem is presented, from which pairs of critical angular velocities and critical transverse loads are determined. A general stability chart is presented, which identifies the stability limits in terms of only two dimensionless parameters, for any membrane. The transition between bending dominated behavior and in-plane dominated behavior is identified, and it is shown that in the bending-dominated case the critical non-dimensional transverse load is independent from the non-dimensional angular velocity.


ABSTRACT: A data-driven computational framework combining Bayesian regression for imperfection-sensitive quantities of interest, uncertainty quantification and multi-objective optimization is developed for the design of complex structures. The framework is used to design ultra-thin carbon fiber deployable shells subjected to two bending conditions. Significant increases in the ultimate buckling loads are shown to be possible, with potential gains on the order of 100% as compared to a previously proposed design. The key to this result is the existence of a large load reserve capability after the initial bifurcation point and well into the post-buckling range that can be effectively explored by the data-driven approach. The computational strategy
here presented is general and can be applied to different problems in structural and materials design, with the potential of finding relevant designs within high-dimensional spaces.

ABSTRACT: Wrinkling is commonly observed when a rectangular plate is stretched with fully-clamped boundaries. Experimental results of a highly orthotropic polypropylene thin film show a counterintuitive phenomenon – wrinkles occur when stretched in the low-stiffness direction, while no wrinkles are observed when stretched in the high-stiffness direction. A comprehensive analysis of this problem is carried out using energy approach by decomposing the total energy into several components with different physical meanings. The mechanism of stretch-induced wrinkling is clarified and it is found that for the formation of wrinkles, the energy release in the transverse direction must exceed the energy barriers for bending, shearing, out-of-plane expanding, and stretching in the loading direction. Based on the energy analysis, a semi-analytical model is established and the Puntel–Deseri–Fried solution of critical stretch strain for isotropic materials is extended by introducing the coefficient of orthotropy $r$, which is the ratio of stiffness in the transverse direction to the loading direction. The criterion of the lower limit of $r$ for wrinkling to occur is derived based on several simplifications. Both the extended solution of the critical stretch strain and the criterion of $r$ are shown to be of satisfactory accuracy, as compared to experimental results.

ABSTRACT: Main concern of the paper is to illustrate the generic application of the optimal control method in the analysis of a constrained buckling problem and its simple and elegant formulation when compared to other techniques. Thus, an optimal control methodology is adopted to investigate the buckling behavior of thin elastic structures under the presence of unilateral constraints. We particularly explore the post-buckling response of a constant or variable length elastica constrained by rigid walls. The equivalence between the calculus of variations and the optimal control is first demonstrated, with a main focus on the post-buckling behavior of a constant length elastica which is constrained by horizontal walls. The gradual construction of the constrained buckling problem as an optimal control problem from its equivalent Lagrangian form clearly shows its advantage when compared to the calculus of variations. The necessary optimality conditions, which constitute the Pontryagin’s minimum or maximum principle, are also derived by considering a direct adjoining approach. The solution of the optimal control problem is then performed by applying a direct method. Validation of the methodology is first achieved by reproducing examples available in the literature. Then the effects of factors, such as the geometry of the walls and the variability in the bending stiffness of the elastica, on its buckling response are analyzed. These constrained buckling problems are investigated for the first time, while through them it is also readily shown that the presence of geometric or material nonlinearity does not introduce any essential complexity in the buckling analysis when the optimal control methodology is adopted.

Si-Fan Yin, Bo Li, Yan-Ping Cao and Xi-Qiao Feng, “Surface wrinkling of anisotropic films bonded on a compliant substrate”, International Journal of Solids and Structures, Vols. 141-142, pp 219-231, June 2018
ABSTRACT: Material anisotropy regulates the instabilities of film–substrate systems at different length scale. In this paper, we investigate the surface wrinkling and morphological evolution of an orthotropic thin film resting on a compliant substrate. Under different loading conditions, the system may buckle into various surface patterns, e.g., stripe, checkerboard, and herringbone, which are analyzed by using the Föppl–von Kármán plate theory. The Fourier spectral method is employed to simulate the morphological evolutions of surface patterns
under different loading biaxialities. We find that both loading biaxiality and material anisotropy affect the characteristics of surface wrinkling patterns and their evolutions. Stripe and checkerboard modes often emerge at the critical buckling and they tend to transform into herringbone and labyrinth patterns during postbuckling. Phase diagrams are established to reveal the dependence of surface patterns on material anisotropy, Poisson's effect, and loading biaxiality. This study may help design diverse functional surfaces and deepen our understanding of the morphogenesis of some soft biological tissues and organs.


ABSTRACT: Magneto-responsive slender bodies are used in a range of promising applications, such as artificial cilia, magnetic fiber networks and cellular actuators. To accurately describe the magneto-elastic deformations, both the demagnetization field as well as the resulting magnetic loads on the body should be properly accounted for. The calculation of the demagnetization field for a general sample shape is very challenging, which has hampered the experimental characterization of the intrinsic magnetic and magnetoelastic properties. Here, a methodology is developed to accurately calculate the demagnetization field for slender bodies, i.e., for long beams having a rectangular or circular cross-section. We propose two different expressions for the magnetic load on slender bodies. To validate the two expressions, we solve the magnetic buckling problem for cantilever beams using an analytical approach for small deflections. We compare the critical buckling fields with an energy approach and with experimental results from three different studies. The load and energy methods were found to be similar and to correspond very well with the experimental data. To also validate our slender body approach (i.e., demagnetization field calculation and magnetic load expression) for large deflections, we analytically solve for the large (postbuckling) rotational deformation of slender beams. To do so, we formulated a weak form of the governing equations using a variational approach, which can be readily solved using finite elements and does not require a discretization of the space surrounding the magnetic material. We use this generic 3D continuum formulation as a starting point to derive the governing equations for slender bodies, which can be solved in a weak sense to find an approximate analytical formulation for large deflections and non-linear ferromagnetic materials. We compared the analytical results with experimental data on the post-buckling deformation of long cantilever beams and found excellent agreement. We anticipate that our results will be valuable for magneto-elastic (soft) robotics, homogenization approaches of magneto-elastic constitutive relations and other applications where strong magneto-elastic coupling is important.


ABSTRACT: A membrane is flexible and tends to wrinkle under small compression. The wrinkling deformation adversely affects its surface profile and mechanical behavior and it should be controlled. Identifying the wrinkle-influencing factors and analyzing their effects on the performance of a membrane may help to devise a better way to reduce or eliminate the wrinkling deformation. In this paper, the authors discuss the wrinkle-influencing factors such as pre-stress, Poisson ratio, Young's modulus, thickness and boundary conditions, and numerically analyze their effects on the dynamic properties of a rectangular membrane under shear and a square membrane under corner loads with the membrane element previously proposed by the authors. Some interesting phenomena are noted in the analysis and they are discussed.

ABSTRACT: Simulating polymer-based composite structures under low-velocity impact and sequencing compression after impact loading, is a complex problem that requires using well-suited constitutive models and defining advanced finite element capabilities. Therefore, developing simplified and efficient, but sufficiently accurate finite element models to solve such problems, is of interest. Here, a finite element modelling strategy is presented for simulating low-velocity impact and compression after impact tests on composite laminates using Abaqus/Explicit software. The strategy is based on using conventional shell elements and cohesive surfaces. The proper out-of-plane structural response is solved by considering surface elements located on the bottom and top faces of the layers. The key parameters requested for defining the models are concisely described and the values selected are well justified. The accuracy of the modelling strategy is proved by simulating monolithic and rectangular laboratory coupons. The results of the simulations reveal good agreement with most of the experimental data reported.


Abstract: Membrane fixtures provide external tensile forces and boundary conditions for thin membranes; thus, they play an important role in the minor principal stress distribution and wrinkling patterns. Here, we propose a global optimization approach for designing the shape of membrane fixtures to suppress stress-related wrinkles under large membrane deformations. The objective of the optimization model is to maximize the minimal value of the in-plane minor principal stress over the entire membrane. This model incorporates the Kriging surrogate method, which is a robust optimization technique, to make the membrane in a taut state and to find out the global optimal solution. Several examples with different stretching displacements are presented to demonstrate the effectiveness of this proposed optimization method. Moreover, the method provides an efficient way to obtain wrinkle-free membrane structures without reducing the membrane area.


Abstract: Many existing shape memory alloy (SMA) devices consist of slender beams and frames. To better understand SMA beam behavior, we experimentally examined the isothermal, room temperature response of superelastic NiTi rods and tubes, of similar outer diameters, subjected to four different modes of loading. Pure tension, pure compression, and pure bending experiments were first performed to establish and compare the baseline uniaxial and bending behaviors of rods and tubes. Column buckling experiments were then performed on rod and tube columns of several slenderness ratios to investigate their mechanical responses, phase transformation kinetics under combined uniaxial and bending deformation, and the interaction between material and structural instabilities. In all experiments, stereo digital image correlation measured local displacement fields in order to capture phenomena such as strain localization and propagating phase boundaries. Superelastic mechanical behavior and the nature of stress-induced phase transformation were found to be strongly affected by specimen geometry and the deformation mode. Under uniaxial tension, both the rod and tube had well-defined loading and unloading plateaus in their superelastic responses, during which stress-induced phase transformation propagated along the length of the specimen in the form of a high/low strain front. Due to the dependence of strain localization on kinematic compatibility, the high/low strain front morphologies differed between the rod and tube: for the rod, the high/low strain front consisted of a diffuse “neck”, while the high/low strain front in the tube consisted of distinct, criss-crossing “fingers.” During uniaxial compression, both cross-sectional forms exhibited higher transformation stresses and smaller transformation strains than uniaxial tension, highlighting the now well-known tension-compression asymmetry of SMAs. Additionally,
Phase transformation localization and propagation were absent under compressive loading. During pure bending, the moment-curvature response of both forms exhibited plateaus and strain localization during forward and reverse transformations. Rod specimens developed localized, high-curvature regions that propagated along the specimen axis and caused shear strain near the high/low curvature interface; whereas, the tube specimens exhibited finger/wedge-like high strain regions over the tensile side of the tube which caused nonlinear strain profiles through the thickness of the specimen that did not propagate. It was therefore found that classical beam theory assumptions did not hold in the presence of phase transformation localization (although, the assumptions did hold on average for the tube). During column buckling, the structures were loaded into the post-buckling regime yet recovered nearly-straight forms upon unloading. Strain localization was observed only for high aspect ratio (slender) tubes, but the mechanical responses were similar to that of rods of the same slenderness ratio. Also, an interesting “unbuckling” phenomenon was discovered in certain low aspect ratio (stout) columns, where late post-buckling straightening was observed despite continuous monotonic loading. Thus, these behaviors are some of the challenging phenomena which must be captured when developing SMA constitutive models and executing structural simulations.


ABSTRACT: The aim of this article is to model and analyze the buckling behaviors of NiTi-based moderately thick shape memory alloy (SMA) tubes with short, intermediate and long lengths. A robust three-dimensional constitutive model is implemented so that it is capable of realistic simulations of anisotropic martensitic transformation, reorientation of martensite variants and asymmetry in tension and compression in the finite-strain regime. The governing equations of equilibrium are derived based on the total Lagrangian description and discretized in a finite element framework. They are then solved using an elastic-predictor inelastic-corrector return mapping algorithm along with iterative Newton–Raphson and Riks techniques to trace the non-linear equilibrium path. Experimental result of a uniaxial tension–compression test performed on an NiTi tube is first simulated in a Gauss point level. It is shown that the present constitutive model replicates well the main features such as martensitic phase transformation in a smooth and gradual manner, strain hysteresis width, pseudo-elasticity and asymmetry in tension and compression. Afterwards, computational assessment of mechanical response of NiTi tubes under axial edge load is carried out and comparisons with available experimental data are made. Effects of radial geometric imperfection and length as well as finite-strain modeling are investigated, and their implications on the buckling behaviors of NiTi moderately thick tubes are put into evidence and conclusions are drawn. It is shown that increasing the length tube reduces the structural resistance so that buckling–unbuckling behavior of short NiTi moderately thick tubes changes to kinking phenomenon in intermediate tubes and finally results in a smooth snap-type buckling in long tubes. Finally, it is concluded that the finite-strain model implementing a displacement/force-controlled method and kinking consideration is able to replicate well the main buckling features observed in the experiments.


ABSTRACT: In this paper, a new analytical approach is developed for global buckling of composite sandwich cylindrical shells with lattice cores under uniaxial compression by using the smeared stiffener method. The stiffness contribution of stiffeners is evaluated through the new force and moment effect analysis of the stiffener network on a general unit cell. In these analyses, outer skin-stiffener and inner skin-stiffener interactions are considered, appropriately. The equivalent stiffness of the composite sandwich cylindrical shells with lattice cores is then computed by superimposing the stiffness contribution of stiffeners, outer and inner skins. The
critical buckling load is calculated by Rayleigh–Ritz method. Finally, various test examples with different scales of the structure, outer and inner skins ply stacking sequence, outer and inner skins thicknesses were analyzed and the results were compared with results obtained by finite element methods and other works. The results show that the proposed approach has high prediction accuracy and low computational cost for the global buckling analysis of composite sandwich shells with lattice cores. Also, another advantage of the developed approach is able to prediction of the global buckling load of stiffened composite cylindrical shells with better accuracy. Therefore, the proposed approach is highly attractive for the preliminary design of composite sandwich structures in the aerospace industry.


ABSTRACT: The work considers shells of a stepped variable thickness when a thickness variation is set by means of unit bar graph functions equal to a difference of two unit functions. It enables for considering ribs, reinforcement plates and cutouts in one structure; a rib and shell contact is arranged along a strip. It is shown on the basis of the variational procedure for derivation of equilibrium equations that the boundary conditions (free boundary) are fulfilled automatically at the lateral surface of ribs and boundary of the cutouts when solving boundary-value problems.


ABSTRACT: Origami, the art of paper folding, is a technologically transformative art with applications at many length scales from material microstructure design to space deployable structures. The transformation of a two-dimensional fold pattern to a three-dimensional structure makes origami a practical basis for deployability, light-weight materials, and self-actuation. In order to predict the complex motions of origami structures including path traversal of instabilities, accurate and efficient modeling techniques are required. While many approaches consider rigid facets and/or linear approximations to rotations, a truss and hinge finite element method is presented here within a global coordinate system framework to accurately capture the geometric nonlinearities while allowing for small to moderate facet deformation. Accurately capturing these modes of deformation is critical toward understanding the elastic energetic states required for design and analysis of multistable origami structures and mechanical metamaterials. Particular formulation developments that we address to solve origami mechanics problems include formulation of a continuous and differentiable fold angle, strategy for selecting fold path off the flat state, and integration of common numerical approaches important for origami (large rotation formulation, enforcement of periodic boundary conditions for tessellations, arc-length continuation method for solving highly nonlinear loading paths, and a perturbation strategy for handling bifurcations). After formulating this truss finite element method, we verify our modified finite element method on well-studied structures. The waterbomb fold pattern is studied, and the interplay of the stretching and folding energies are considered toward design of a bistable structure that exhibits a fold based snap-through instability. This study is followed by analysis of a cylindrical network of waterbombs (axial periodicity) that exhibits a stretch driven instability. Lastly, a tessellated square twist pattern, exhibiting multiple bifurcations off the flat state is presented that employs all aspects of our numerical method.

ABSTRACT: Mechanically-guided three-dimensional (3D) assembly of mesostructures through controlled compressive buckling represents a promising approach, because of the versatile applicability to a broad set of advanced materials, over length scales from sub-micrometers to centimeters. Based on this approach, a spatial variation of thickness in the initial 2D structures was demonstrated as an effective strategy to produce engineered folding deformations at regions with lower bending stiffness, thereby with an ability to enable autonomous origami assembly. The reliability of this strategy requires the development of a theoretical model as a design reference, such that targeted folding deformations can be achieved without inducing any structural failure. This work presents a finite-deformation model of controlled buckling in straight ribbons with engineered thickness reductions at two or three sites. A comparison of predicted maximum strains and deformed configurations to the finite element analyses (FEA) and experimental results elucidates the validity of the developed model. The results uncover the coupled effect of different geometric parameters on the maximum strain. For relative flexible creases that lead to evident folding deformations, the theoretical model gives approximate analytic solutions to the deformed configurations and maximum strain. Furthermore, the theoretical model was exploited in a design optimization to achieve highly sensitive rotatable micro-mirrors with a desired mechanical tunability of the optical transmittance. This study can be useful in the future designs of 2D precursor structures for the origami-inspired assembly of different 3D mesostructures and micro-devices.


ABSTRACT: The Worst Multiple Perturbation Load Approach (WMPLA) has been validated by full-scale tests to be an effective and credible determination method for the lower-bound buckling load of stiffened shells. In spite of its high prediction accuracy and robustness, the large computational time is a burden because this method is based on the large-scale optimization of detailed finite element (FE) models. Therefore, a high-fidelity approximate modeling strategy is proposed in this paper, to improve the efficiency of WMPLA and then promote its application for the preliminary design stage of stiffened shells. In the first step, an initial approximate model is established by means of the Representative Volume Element (RVE) equivalent method. In the second step, a modified equivalent model is generated after optimizing the effective stiffness coefficients of the initial equivalent model. In the optimization process, the objective is minimizing the relative error in buckling load between a detailed FE model and the modified approximate model. The constraint condition is controlled by the Modal Assurance Criterion (MAC) coefficients for buckling mode. In particular, the global and local deformation features are simultaneously considered in the MAC coefficients. After the establishment of the high-fidelity approximate model, it is then integrated into WMPLA. By optimization of the positions and amplitudes of the multiple perturbation loads, the minimum buckling load is obtained as the lower-bound value. By comparison against known methods, the lower-bound buckling load predicted by the proposed strategy is quite close to the test result, succeeding in providing a safe design load prediction. The proposed strategy reduces the computational time sharply by 94% compared to the WMPLA based on detailed FE models, indicating high efficiency. Additionally, an illustrative example is shown to highlight the importance of the prediction accuracy of buckling mode on the fidelity of approximate models for WMPLA. Finally, it is concluded that the proposed strategy is a potential and efficient approach to predict lower-bound buckling loads of stiffened shells.

ABSTRACT: Snap-through instability of shallow reticulated (lattice) domes subjected to a quasi-static downward displacement or force at a joint is analyzed. For the case of unilateral displacement control, the joint is pushed downward by an indentor until it snaps (jumps) to another equilibrium configuration, and then pushed further until another snap occurs, and so on. Under force control, the magnitude of the force is increased, and a different sequence of snaps (local and then global) is exhibited. Green–Lagrange strain is assumed, as well as engineering strain for the smaller dome. The equilibrium equations are solved numerically using Mathematica. For force control, snaps may occur on the equilibrium path (force versus displacement at the force) at limit (maximum) points and at bifurcation points. For unilateral displacement control, snaps may occur at points where the associated downward force decreases to zero, at turning points (which have a vertical tangent), and at bifurcation points (if the bifurcating path moves downward at the loaded joint).


ABSTRACT: In order to ensure integrity of thermal protection system (TPS) subjected to a combination of thermal and acoustic loadings, a thin composite plate resting on a two-parameter elastic foundation is used to characterize the behavior of the thin top facesheet of TPS. The nonlinear dynamic response of a thermal loaded, acoustic excited plate is investigated. A theoretical model is developed based on Kirchhoff thin plate assumptions and von Kármán-type equation. General static condensation and Galerkin's method are used to derive a set of ordinary differential equations with cubic nonlinearity related to nonlinear coupling between mid-plane stretching and transverse deflection. The reduced-order model has been validated by comparison of postbuckled displacements with those obtained from full-order FEM analysis. Variations of transverse displacement and in-plane strain statistics with acoustic loading level and temperature rising are presented. It is proposed that the in-plane strain located on the plate surface is dominated by the competition of the linear and quadratic nonlinear modal amplitude terms, thus the characteristic of the strain histogram can be used to identify oscillation transition from no snap-through to persistent dynamic snap-through for the thermally buckled plate. The skewness of the strain histogram can be used to evaluate the degree of dynamic geometrical nonlinearity quantitatively for the postbuckled plate with symmetric snap-through motion.


ABSTRACT: This work focuses on the general nonlinear dynamic formulation of sandwich panels based on the Extended High-order Sandwich Panel Theory. The faces and the core are both considered undergoing large deformation with moderate rotation. In the literature, when it comes to nonlinear dynamic response, various simplifying assumptions are adopted in the nonlinear kinematic relations. A critical assessment of these simplifications, as well as a comprehensive investigation of the geometric nonlinearity effects on the dynamic response of sandwich beams/wide panels is presented. The Extended High-order Sandwich Panel Theory (EHSAPT)-based finite element is used to formulate the equations of motion, and the time response is obtained by the central difference method. The transient response of a sandwich panel subjected to a distributed blast loading is studied as a numerical example. By neglecting the nonlinear terms, the nonlinear dynamic analysis is reduced to the linear dynamic small deformation analysis, for which a closed-form elasticity solution exists. This, the linear response is first compared with the closed-form linear dynamic elasticity solution. It is shown that the linear EHSAPT yields an identical response to the dynamic elasticity analysis. Subsequently, the dynamic response is evaluated by considering the geometric nonlinearities. Several simplified nonlinear models with partial nonlinear terms included are considered. These models reflect the assumptions commonly adopted
in the literature. Numerical results are presented to investigate the effects of geometric nonlinearities on the displacements and stresses. It is shown that the geometric nonlinearities have a significant effect on the dynamic response of sandwich panels and, in particular, the nonlinear terms in the core kinematic equations are especially important.


ABSTRACT: The non-linear response of a sandwich panel with the core that consists of a functionally graded material (FGM) undergoing in-plane loading is investigated. The panel consists of two face sheets, metallic or composite laminated, and an FGM core that is a medium whose mechanical properties change through the depth facilitating a desirable response of the structure. The effect of the FGM core is introduced through the constitutive relations that affect conventional and high-order stress resultants and stress couples in the panel. The formulation employs the Extended High-Order Sandwich Panel Theory (EHSAPT) to assess the effect of the FGM material of the core. A variational approach is adopted to derive the linear and non-linear governing equations with a prescribed FGM distribution through the depth of the core. The wrinkling study of FGM panels includes two loading scenarios where in-plane loads are applied through a rigid edge beam connected to the core only and where the loads are applied through a rigid edge structure attached to both the face sheets and core causing uniform end shortening. The post-wrinkling behavior is also considered to prove that the initial pattern of wrinkles is not affected.


ABSTRACT: The elastic buckling of shell structures such as spherical shells subject to external pressure and cylindrical shells loaded in axial compression is highly sensitive to imperfections and often catastrophic. Recent studies of spherical shells have provided accurate quantitative results for the relation between the buckling pressure and the amplitude and shape of geometric imperfections and, additionally, quantitative results for the energy barrier that must be overcome to buckle the shell by extraneous loadings or disturbances when it is loaded to pressures below the buckling pressure. Results for the simultaneous interaction of imperfections and energy barriers for spherical shells under external pressure will be presented. Numerical studies for probing forces illustrate their use in determining the buckling energy barrier, and new experimental results on energy barriers obtained by others by probing spherical shells will be discussed and compared with predictions. It will be argued that while imperfections determine the buckling load of a shell, the energy barrier at loads below the buckling pressure supplies important additional information about the relative safety or precariousness of the shell to additional disturbances. Results for the energy barrier for perfect and imperfect spherical shells under external pressure provide important insights into the shell's robustness, or lack thereof, at pressures below the buckling pressure. In particular, the energy barrier trends provide critical insights into the low knockdown factor usually employed in establishing the design load of unstiffened spherical and cylindrical shells. These design loads are shown to correlate with conventional predictions provided that imperfection amplitudes scale as the shell radius.

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ABSTRACT: This paper addresses the buckling behaviour of a long thin orthotropic plate on a tensionless rigid foundation under combined in-plane shear and bending, where the sheet can only buckle away from the foundation due to the tensionless foundation support. Two boundary conditions at the longitudinal edges (y=0 and b) are investigated, i.e. clamped and simply supported. The energy method is used to derive the explicit expression for the lateral buckling mode function. The buckling response is then obtained by solving the governing differential equation after substituting the lateral buckling mode function. Based on the analytical solutions developed in the paper, fitted formulae are given for buckling coefficients and the interaction curve. Finally, a numerical example of a corrugated sheet is given to verify the presented model through comparing the results with finite element (FE) analysis.

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(No papers for November 2018)
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ABSTRACT: A fast and efficient reduced order formulation is presented for the first time to study dynamics and stability of conical/cylindrical shells with internal fluid flows. The structural and fluid formulations are developed based on general assumptions to avoid any deficiency due to modeling. Their respective solutions and the final solution to the coupled field problem are also developed in a way to be capable of capturing any desirable set of boundary conditions. In addition to the flexibility provided by the solution methodology and generalization provided by the formulation, current solution proposes an additional advantage over others which
is the minimal computational cost due to the special reduced order model proposed. Therefore, stability margins of the problem at hand can be obtained both efficiently and accurately. Proposed formulation is verified by comparing the results of the present study with the results available in literature for cylindrical/conical shells at different boundary conditions. Comprehensive parameter studies are performed in order to draw general insights over the effects of boundary conditions, semi-vertex angle and compressibility on the dynamics and stability margins of conical shells with internal fluid flows.

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“Analysis of wrinkling during sheet hydroforming of curved surface shell considering reverse bulging effect”,
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ABSTRACT: Wrinkling in unsupported region is a worthy problem to be solved in sheet metal forming process. Sheet hydroforming is advantageous in the prevention of unsupported wrinkles. However, the simply increasing of liquid pressure is not enough to suppress the wrinkling even though with the occurrence of “reverse bulging effect”. In order to predict and control the wrinkling quantitatively in unsupported region for thin-walled shells with curved surface, a theoretical model on critical wrinkling stress was proposed by considering proper “reverse bulging effect” based on energy method. The influence of liquid pressure and other parameters on the critical wrinkling stress was analyzed. The critical loading path of the liquid pressure to control wrinkling was obtained by combining critical wrinkling stresses and circumferential stresses. An experimental setup for an extremely thin-walled shell with semi-ellipsoidal geometry was designed and manufactured to verify the theoretical model. It is found that at a certain punch stroke, the magnitude of the critical wrinkling stress increases and that of circumferential compressive stress decreases with the improvement of the liquid pressure. The critical loading path can be utilized to get well formed shells with a ratio of thickness to diameter equals 0.27% in the experiments. The proposed method can be applied to predict and control wrinkling in unsupported region for hydroforming of thin-walled shell with high accuracy and considerably reduced simulation time.

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ABSTRACT: In this paper, analysis of the wrinkling and kink characteristics of the inflated beam under local uniform loadings is presented. Firstly the thin-walled beam modal, which is filled with uniform internal pressure, is established. Next the local uniform loads are applied on the beam. This introduces the load geometric parameters to the equations to predict the wrinkling characteristics. Then the kink, which is similar to a plastic hinge, is assumed to describe the invalid state of the inflated beam for the first time. In order to verify the assumptions of the kink and the theoretical predictions of the wrinkling and kink characteristics, the non-contact experimental tests are performed. Moreover, the theoretical and experimental results, which include the initial wrinkling and kink positions, the critical wrinkling and kink loads, the wrinkling strain, the length of the wrinkled region and the kink angle, are compared. The differences according to these comparisons are less than 10%, which means that the predicted results are reliable. In addition, the local uniform load position and its
length as well as the edge shape and the middle cylinder length of the inflated beam can make great effects on the wrinkling and kink characteristics. These obtained results provide a new insight into the wrinkling and kink behaviors of the inflated beam and give good guidance for designing the inflated structures.

Li Li and Yujin Hu (State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China), “Post-buckling analysis of functionally graded nanobeams incorporating nonlocal stress and microstructure-dependent strain gradient effects”, International Journal of Mechanical Sciences, Vol. 120, pp 159-170, January 2017, https://doi.org/10.1016/j.ijmecsci.2016.11.025

ABSTRACT: On the basis of the nonlocal strain gradient theory, a size-dependent Euler–Bernoulli beam model is formulated and devoted to investigating the scaling effect on the post-buckling behaviors of functionally graded (FG) nanobeams with the von Kármán geometric nonlinearity. The developed beam model can incorporate the scaling effect of both nonlocal long-range force and microstructure-dependent strain mechanism. To simplify the redundancy of the governing equation and derive the closed-form solutions, a physical neutral surface is applied for removing the bending-stretching coupling due to geometric nonlinearity and the coupling rigidity between the extensional and bending rigidities of the though-thickness FG material. The closed-form solutions for the post-buckled configuration and the critical buckling force (CBF) are deduced in the case of hinged-hinged boundary conditions. The effects of scaling parameters and material property variation on the post-buckled configuration and the CBF are investigated in detail. It is found that the stiffness-hardening or stiffness-softening effect is dependent of the values of scaling parameters.


ABSTRACT: This paper discusses classical and refined beam and plate theories based on the Carrera Unified Formulation (CUF). Attention is focussed on (but not limited to) a new refined beam element with enhanced kinematics based on Legendre polynomial expansions of the primary mechanical variables. By employing CUF, the governing equations and the related finite element arrays are written in a hierarchical, compact and general manner. Readily, these characteristics are used to arbitrarily tune the finite element model at the cross-sectional level, by locally enriching the theory kinematics up to the desired accuracy. The uncompromising accuracy of the present beam model is demonstrated by considering various numerical examples, including solid and thin-walled beams with open and close cross-sections as well as plate structures. The results are compared with those from classical and already established refined CUF models. Eventually, three-dimensional elasticity solutions by the commercial tool MSC Nastran are also given to underline the high accuracy of the present methodology. The numerical efficiency and the capabilities of the Legendre-based CUF beam models to deal with complex structures with no geometrical approximations result clear from the analyses conducted.

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ABSTRACT: The objective of this paper is to propose a general algorithm to obtain approximate analytical solutions for the study of the free vibrations of a rectangular anisotropic thin plate with an internal curved line hinge and general restraints. In this system, there exists an intermediate condition that requires the continuity of the transverse displacements. It is well known that the difficulty in choosing admissible functions has been the most significant drawback of the Ritz method. To relax the admissibility requirement the Ritz method, with polynomials as coordinate functions, in conjunction with the Penalty Function method is proposed. This study is focused on different problems related the curved hinge and a natural parametrization is used to treat the mentioned curves. The accuracy of the formulation is ensured by comparing some numerical examples with those available in the literature. Cases not previously treated are particularly analyzed. Frequencies parameters and several sets of vibration mode shapes are included, to provide a better understanding of the dynamical behavior of these plates.

ABSTRACT: A strong form finite element technique, termed SFEM, has been presented recently. This approach resulted to be accurate and reliable for different engineering problems. The SFEM merges the high convergence rates of strong form pseudo-spectral methods and the versatility of domain decomposition
techniques proper of the Finite Element Method (FEM). The governing differential equations and the compatibility conditions between two adjoining elements are transformed through the mapping technique. Due to its higher order nature given by the collocation of several points in each single element, classic 8 node elements are not often sufficient to map a geometry with the smallest amount of elements. Therefore, a new mapping approach based on blending functions is introduced in this paper for investigating membrane structures. In particular, isogeometric mapping based on Non-Uniform Rational Basis Spline (NURBS) will be considered. This kind of nonlinear mapping is generally associated with Isogeometric Analysis (IGA). Therefore, the present new approach is termed Strong Formulation Isogeometric Analysis (SFIGA). In order to prove the accuracy and stability of this technique several analytical and other results from the literature will be presented together with new applications.

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ABSTRACT: In this investigation, an improved Fourier series method is presented for the free vibration analysis of the moderately thick laminated composite rectangular plate with non-uniform boundary conditions, a class of problems which are rarely attempted in the literatures. Under the current framework, the displacement and rotation functions are generally sought, regardless of boundary conditions, in spectral form, as a double Fourier cosine series and three supplementary functions. These supplementary functions are introduced to remove the potential discontinuities associated with the original displacement functions along the edges when they are viewed as periodic functions defined within the entire coordinates of laminate plate. The boundary conditions can be readily realized by setting the stiffness of the five types restraining springs. All the series expansion coefficients are treated as the generalized coordinates and determined using the Rayleigh-Ritz technique. Unlike most of the existing studies, the presented method can be readily and universally applied to a wide spectrum of plate vibration problems involving different boundary conditions, varying material, and geometric properties with no need of modifying the basic functions or adapting solution procedures. The excellent accuracy of the current result is validated by comparing the present results with those Finite Element Method (FEM) data. Numerous new results for free vibration of moderately thick rectangular plates with various multi-points supported and non-uniform partially supported boundary conditions are presented, which may serve as benchmark solution for future researches in the field.

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ABSTRACT: Suppressed vibration of shear deformable plates with hybrid viscoelastic damping of material and foundation is investigated. Viscoelasticity of foundation is established by adopting Kelvin-Voigt model while viscoelasticity of materials is expressed by Boltzmann superposition integral, which uses dynamic mechanical
analysis (DMA) results in terms of Prony series. Application of Laplace transformation and Mindlin plate theory with Hamilton principle led to a system of coupled integro-PDE of motions. Weighted residual method, numerical iterative algorithm and Fourier transform are implemented to achieve complex frequencies and transient responses of plates. Assessment of accuracy is carried out in both elastic and viscoelastic domains. In the earlier, the frequencies are compared with counterparts obtained by p-version Ritz method, and in the latter, dynamic characteristics of Mindlin and classic plates are examined that represent acceptable correlation. The influences of hybrid material-foundation damping, edge conditions, foundation characteristics and geometrical parameters on dynamic characteristics of plates are studied via a set of parametric study.


ABSTRACT: A novel thin-walled tube, named as origami crash box, is recognized as a promising energy absorption device. Experimental results reveal that unintentional imperfection could trigger the symmetric mode with low mean crushing force rather than a high-performance mode, known as complete diamond mode. Therefore, the imperfection-sensitivity of origami crash boxes is investigated in this paper. Appropriate geometric imperfection which is regarded as a substitution of the real defect is introduced into finite element models to trigger the symmetric mode. Numerical simulation shows that the specific energy absorption SEA declines with the increase in imperfection amplitude $A_t$. And a critical value of ratio $A_t/t$ that is just able to trigger the symmetric mode is obtained. A detailed parametric analysis indicates that a suitable geometry is beneficial to improve the compliance of origami crash box, leading to stable collapse behavior with higher performance in terms of energy absorption. Moreover, a bulkhead reinforced origami crash box is proposed as a low imperfection-sensitivity energy absorption device. And an optimal wall thickness ratio $t_1/t$ is obtained through numerical analysis.

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ABSTRACT: In this paper, starting with the thin shell theory, the governing partial differential equation of motion for the transverse deflection of a rotating pre-twisted airfoil is derived. Strain-displacement relationships include the effect of warping of the cross-section due to twist-bend coupling effect introduced as a result of varying stagger angle and camber radius of the blade. The equation of motion, thus derived, is used to formulate the free vibration of a typical turbo-machinery cantilevered airfoil by considering it as an anisotropic shell in full curvilinear coordinates subjected to a centrifugal force field. The analytical derivation considers both the stress-stiffening as well as stress-softening effects of the centrifugal forces on the spinning airfoil. The fourth-order partial differential equation characterizing the flexural motion of the airfoil is transformed into a matrix-eigenvalue form using a Rayleigh-Ritz technique. The blade deformations are represented by a set of “admissible” sinusoidal trial functions, which fully satisfy all the clamped-end constraints as well as the free-edge boundary conditions. The numerical results presented in a non-dimensional parametric form are directly
applicable in determining the static and running frequencies of typical composite blades used in the fan module of an aeroengine.

Suchao Xie, Weilin Yang, Ning Wang and Haihong Li (Key Laboratory of Traffic Safety on Track, Ministry of Education and School of Traffic & Transportation Engineering, Central South University, Changsha, Hunan 410075, PR China), “Crashworthiness analysis of multi-cell square tubes under axial loads”, International Journal of Mechanical Sciences, Vol. 121, pp 106-118, February 2017
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ABSTRACT: In this paper, a theoretical expression for the mean crushing force $F_{av}$ and the analysis of specific energy absorption (SEA) ratios of five different multi-cell square tubes were derived by applying the Simplified Super Folding Element (SSFE) theory. Then, the response surface models of the tubes were established separately based on the polynomial response surface method (PRSM). The models describe the response surfaces of SEA, peak crushing force $F_{ma}$ and mean crushing force $F_{av}$ under the variation of the side-length $l_1$ of the exterior tube, the side-length $l_2$ of the interior tube, and section form of the structure. Crashworthiness rules for tubes with different geometrical configurations including $l_1, l_2$ and different cross-sections were analysed. The numerical results matched the theoretical predictions. $l_1$ exerted a slight influence. Compared to $l_1$ and $l_2$, the sectional form exerted a greater influence on the crushing force and energy absorption.

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ABSTRACT: The present work is inspired by the fact that tension enforced by external force applied directly to the outermost layers of a (usually incommensurate) multilayer graphene sheet cannot be effectively transferred to all inner layers due to interlayer sliding, and therefore tension force in inner layers can be much lower than the tension force in the outermost layers. In this paper, a three-beam model is presented to study vibration of a multilayer graphene sheet under layerwise tension forces. In contrast to the commonly used single-beam model which assumes that tension in all layers of a multilayer graphene sheet are identical, the present model treats the top and bottom layers as two beams, and all other inner layers together as another beam which has different tension force than the top and bottom beams. Our results indicate that actual tensile stress/strain in the outmost single layers of a multilayer graphene sheet can be much (for instance, almost ten times, for specific examples discussed here) higher than that estimated by the widely used single-beam model, and the latter can badly underestimate actual tensile stress/strain of multilayer graphene resonators. In addition, at least for typical examples discussed here, the present model shows that vibrational frequencies of a multilayer graphene sheet are largely determined by the total tension, and the distribution of the total tension over different layers does not make a huge impact to vibrational frequencies of multilayer graphene resonators. Based on this conclusion, an explicit formula is given for resonant frequencies of multilayer graphene sheets under layerwise tension forces although the actual maximum tension depends on how total tension is distributed over all layers.

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ABSTRACT: Hydrodynamic deep drawing (HDD) is an effective method for the fabrication of the sheet metal parts with deep cavity and complex surface configuration. Despite the remarkable progress that has been made on the development of one-stroke HDD process, a number of fundamental challenges are still unsolved in the multi-stage HDD technology due to the unique process allocation and continuous deformation behavior. In this study, the effect of pre-forming parameters and loading locus of cavity pressure on the sequential deformation of aluminum alloy is explored to determine the suitable working conditions to form a conical part with deep cavity using multi-pass HDD process. Based on the equal allowance function method, the material deformation amount for the multi-pass process is allocated and optimized. In addition, the defect patterns including wrinkling and tearing during the multi-step process are discussed. The effect of pre-forming depth and loading loci of cavity pressure on the dimensional accuracy and thickness variation of the workpiece is analyzed, the appropriate pre-forming depth and loading loci of cavity pressure are achieved by using numerical models implementing diverse yield criteria. The results mirror that yld2000-2d and BBC2005 yield functions predict the pre-forming depth more accurately with respect to Von Mises isotropic formulation and Hill’48 yield criterion. However, the prediction accuracy of the pre-forming stage is superior to that of the final forming period using yld2000-2d yield formula due to the error accumulation and the effect of prestrain on the sequential process. Moreover, the reasonable loading path of cavity pressure for the intermediate cylindrical part is characterized by three feature points, whereas the suitable pressure locus for the final conical part is featured with four unique points and three distinct segments containing low-pressure stage, pressure-raising stage and full pressure period. By using the suitable working conditions, the well-formed conical part with homogenous thickness distribution, desirable surface finish, and high dimensional precision is fabricated, which highlights that the proposed multi-step HDD technology is valid for the integration and precision forming of the workpiece with complex feature and high drawing ratio.
(i.e. geometrical parameters and initial conditions), we perform a thorough study to reveal how the oscillatory frequency will change by moving the tip of the semi-infinite tube.

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ABSTRACT: The paper proposes the first 18 vibration modes for plates, and the first 14 vibration modes for cylinders and cylindrical shells. All the edges of these structures are simply supported and the free frequencies are calculated using an exact three-dimensional shell model. A comparison is proposed using two different numerical models such as a classical two-dimensional finite element model and a refined two-dimensional generalized differential quadrature model. The 3D exact model gives all types of vibration modes, when the four edges are simply supported, changing the imposed half-wave numbers m and n in the two in-plane directions $\alpha$ and $\beta$. Some of these modes have one of the two half-wave numbers equals zero. When this condition is simultaneously combined with the condition of transverse displacement different from zero, the resulting vibration mode is defined as cylindrical bending mode. The cylindrical bending case has all the derivatives made in the direction where $m=0$ or $n=0$ equal zero. This feature means that the vibrational behavior does not change along this particular direction. The numerical models with the simply supported boundary conditions for all the edges do not achieve these results. These cylindrical bending numerical results are obtained modifying the boundary conditions. Proposed results will demonstrate the validity of this idea and how to modify the mathematical models in order to obtain and improve the cylindrical bending solutions.

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ABSTRACT: In this paper, we study the variation of natural frequencies for thin walled circular cylindrical shells subject to external radial load (uniform and hydrostatic pressure). The study has been performed for four different types of boundary conditions viz. pinned-pinned, pinned-free, clamped-free and one end is pinned and other end axially constrained. Towards this, we have used approximate shape functions and Galerkin projections of the PDEs governing the shell motion, linearized about a steady state solution due to the applied mean radial pressure. Our results have very good agreement with the experimental and theoretical results available in literature. They have also been verified against finite element analysis (FEA) using ABAQUS. We have found that with increasing magnitude of inward radial load, the natural frequency decreases, however, the circumferential wavenumber corresponding to the lowest natural frequency increases. For outward radial load the opposite happens. Furthermore, the circumferential wavenumbers corresponding to lowest natural frequency and first buckling mode are different for short cylinders with the difference decreasing with increasing length of the cylinder. We have also found an interesting result for the beam mode vibration of cylindrical shells. For short cylinders, the natural frequency of the beam mode increases (decreases) with internal (external) pressure, which is consistent with other circumferential modes. Subsequently, we obtain a critical length at which the applied radial pressure has no effect on the natural frequency. For cylinders longer than the critical length, the
effect of the radial load is opposite of that observed for the short cylinders, and this is contrary to the behavior of the other circumferential modes. As a result, buckling of the beam mode happens for an outward radial (internal) pressure.

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ABSTRACT: A free vibration analysis of joined spherical-cylindrical shell structures is presented. The effects of transverse shear and rotary inertia are taken into account. The deflections and the rotations of spherical and cylindrical shells are represented by the expansions of Chebyshev polynomials in the colatitudinal and axial directions and Fourier functions in the circumferential direction. When the open ends of two hemispheres face each other the opposed circumferential directions should be taken into account in the governing equations and in the continuity conditions. The equations of motion are collocated to yield the system of equations that correspond to the circumferential wave number. To satisfy the continuity conditions the expansions are matched at the junctions of the substructures. The number of collocation points is chosen to be less than the number of expansion terms, and the set of algebraic equations is condensed so that the number of expansions matches the number of degrees of freedom of the problem. Numerical examples are provided for full sphere, bell structure and hermetic capsule.

ABSTRACT: Cellular materials are characterized by a complex interconnected structure of struts or plates and shells, which make up the cells edges and faces. Their structure can be advantageously engineered in order to tailor their properties according to the specific application. This aspect makes them particularly attractive for the manufacturing of bone prosthetics, where the elastic modulus of the implant should match that of the bone in order to avoid loosening due to the stress shielding phenomenon. In this regard, the ability to design a component with the desired mechanical response is crucial. For this reason, the present paper evaluates the stiffness of 2D cellular structures with variously arranged square cells. Specifically, two spatial arrangements are considered: the former one is a regular square cell honeycomb, while in the latter the square cells are staggered by a prescribed offset of half of the cell wall length. An analytical model based on classical beam theory is proposed to identify the effect of stretching and bending actions on the stiffness of a single cell by applying the periodic boundary conditions. The theoretical beam model is fitted on the results from a 2D Finite Elements model based on plane elements via an extensive parametric analysis. In this way, semi-analytical formulas are proposed to calculate the stiffness in large domains of the geometric parameters: wall thickness to edge length ratio in the interval [0.04,0.20] and fillet radius to edge length ratio in the interval [0,0.15].

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ABSTRACT: This study investigated crashworthiness characteristics of a circular aluminum tube internally reinforced with a composite skeleton and aluminum foams subjected to quasi-static axial crushing load. For a comparative purpose, an empty tube and tubes with single reinforcement (aluminum foams or composite skeleton) were tested as well. The deformation patterns and several key parameters related to the crashworthiness of these structures were investigated and compared. The experimental results showed that the proposed design offered the best energy absorption characteristics, and the specific energy absorption increased by 32% compared to the empty tube. In order to explore the mechanisms of enhancement in energy absorption, the composite skeleton and the tube filled with separated foams were tested, and the strong interaction between foams and the skeleton has been found to have a very remarkable contribution to total energy absorption. Additionally, numerical models were built based on different material constitutive relationships and validated by experimental results. Further parametric studies were performed to investigate the effects of tube thickness, skeleton thickness and foam density on crashworthiness. It is found that tube thickness is more important to affecting crashworthiness, which provides a basis for structural optimization.


ABSTRACT: Herein, by using a refined exponential shear deformation shell theory in conjunction with non-classical Eringen's nonlocal elasticity theory, the size-dependent buckling and postbuckling responses of hybrid functionally graded nanoshells integrated with surface-bonded piezoelectric nanolayers are studied in the presence of initial geometric imperfection. In order to eliminate the stretching-bending coupling terms coming from the inhomogeneous properties of the substrate made of functionally graded material (FGM), the physical neutral plane is considered as the reference surface. The hybrid FGM nanoshells are assumed to be subjected to combination of axial compressive load, lateral electric field and through-thickness temperature variation. With the aid of polynomial series, the distribution of temperature along thickness of hybrid FGM nanoshells is determined. A perturbation-based boundary layer-type solution methodology is employed to achieve explicit expressions for nonlocal equilibrium paths of hybrid FGM exponential shear deformable nanoshells. It is depicted that in comparison with the local shell model, the influences of heat conduction and lateral electric field on the axial instability characteristics of nonlocal nanoshell are more significant.


ABSTRACT: The vibrational behaviours of single-walled carbon nanotubes (SWCNTs) bridged on a silicon channel are investigated using a three-segment Timoshenko beam model and a one-segment Timoshenko beam model with elastic boundaries together with molecular dynamics (MD) simulation. A modified Fourier series method (MFSM) is proposed to analyse the free vibration of the Timoshenko beam models with elastic boundary conditions. Explicit formulas are derived for the van der Waals (vdW) interaction coefficients between the SWCNTs and silicon substrates. The boundary elastic constants of the SWCNTs bridged on the
silicon channel are obtained by fitting the bending curve of SWCNTs subjected to a static uniformly distributed lateral load simulated via the MD method. The MD simulations show that both the three-segment Timoshenko beam model and the one-segment Timoshenko beam model with elastic boundaries have a relatively good ability to predict the vibrational behaviours of SWCNTs bridged on a silicon channel.

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“Influence of boundary conditions on the prediction of springback and wrinkling in sheet metal forming”, International Journal of Mechanical Sciences, Vol. 122, pp 244-254, March 2017
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ABSTRACT: The high-strength steel sheets currently used in the automotive industry are prone to non-traditional behaviour during forming, being wrinkling and springback two of the most challenging geometrical predictions for numerical simulation. Thus, the finite element method requires accurate and reliable numerical models. This study presents the experimental and numerical analysis of a rail component with high tendency to develop wrinkling and 2D springback. Two different materials are used for the sheet blank, namely a mild steel (DC06) and a dual phase steel (DP600). The frictional behaviour between each metallic sheet and the forming tools is evaluated through the flat-die test, allowing the determination of a friction coefficient as a function of the normal pressure. The influence of the applied boundary conditions on the numerical results is evaluated by means of two distinct numerical models (full blank geometry and 1/4 of the blank with symmetry conditions). The results show that the wrinkling behaviour is strongly affected by the blank’s material, as well as by the symmetry conditions defined in the numerical model. In fact, considering the full model of the blank, the numerical results are in better agreement with the experimental ones. However, the computational cost of the numerical simulation considering the full blank is substantially higher than using 1/4 of the blank.

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ABSTRACT: An efficient nonlinear finite element model based on a higher-order beam theory is developed for accurately predicting the response of two layered composite beams with partial shear interaction. This is achieved by taking a third order variation of the longitudinal displacement over the beam depth for the two layers separately. The deformable shear connectors joining the two different material layers are modelled as distributed shear springs along the beam length at their interface. In order to capture the geometric nonlinear effects of the beam, the Green-Lagrange strain vector is used to develop the one dimensional finite element model. The nonlinear governing equations are solved by an incremental-iterative technique following the Newton-Raphson method. To assess the performance of the proposed model, the results predicted by the model
are compared with published results as well as numerical results produced by using a detailed two dimensional finite element modelling of the composite beams.

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ABSTRACT: Stability issue has a significant role in the design of structures; especially it becomes even much more substantial when the design deals with the thin-walled structures under complex loading condition, which is a combination of two or more loading types at the same time. The present research paper aims to analyse the stability region of the thin-walled beams with doubly symmetric cross-sections under combined loads simultaneously: axial force, uniformly distributed transverse loads and bending moments at the ends. A novel approach was proposed by the authors and the energy method was used to solve the problem. The final results are able to be represented by mean of not only generalized algebraic equations among the critical loads, but also by three-dimensional graphs. Based on a particular thin-walled beam as an example, the analytical results obtained by using a novel approach were in agreement with the numerical results of analysis by finite element method in the feasible computational software.

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ABSTRACT: The vibration behaviour of a geometrically imperfect three-layered shear-deformable microbeam is analysed via model development and numerical simulations. Taking into account all the translational and rotational motions, considering continuous variations through the thickness for the displacement field, employing the modified couple stress theory for including small-size effects, and using constitutive relations for both stress and the deviatoric part of the couple stress tensors, the size-dependent elastic energy stored in the three-layered shear-deformable microbeam is obtained. The kinetic energy, work of an internal damping mechanism, and the work due to an external harmonic excitation force of the three-layered microsystem are also obtained and dynamically balanced by the size-dependent elastic energy by means of Hamilton’s principle. The continuous expressions obtained for the axial, transverse, and rotational motions of the three-layered microsystem are truncated to high-dimensional reduced-order models with the help of a weighted-residual method. Numerical simulations are conducted by means of the backward differentiation formula (BDF) in conjunction with a continuation method. The nonlinear vibration behaviour of the microsystem is then analysed by plotting the coupled frequency-responses. The effect of the length-scale parameters as well as the material fraction and thickness of each layer on the vibration behaviour of the microsystem is highlighted.
ABSTRACT: Thin-walled round tube systems are widely used in impact protection. However, in these systems, additional installation time and cost is required to constrain the tubes and prevent their splashing under impact loadings. To address this problem, a self-locked system comprised of thin-walled dumbbell-shaped tubes was recently proposed, which can prevent lateral splash from impact loadings without the presence of any constraints on the boundary or between the tubes. This paper provides a theoretical analysis on the deformation and collapse of dumbbell-shaped tubes under quasi-static lateral loads. A plastic hinge model is developed to estimate the force-displacement relationship, deformation efficiency and specific energy absorption of the dumbbell-shaped tube, and besides, an elastic solution is derived to describe the mechanical response of the dumbbell-shaped tube at small deformation. The theoretical models are validated by both finite element method (FEM) simulation and experiments. Based on the theoretical analysis, the effects of the geometry of the dumbbell-shaped tube on energy absorption are studied, and the optimal geometry design of the tube is discussed. The relation between each geometry parameter and energy absorption properties is summarized in a table, which provides important reference for designing dumbbell-shaped tubes in practical applications.


ABSTRACT: This study investigated the nonlinear dynamic and vibration of the S-FGM shallow spherical shells with ceramic-metal-ceramic layers (in two cases: non-axisymmetric and axisymmetric shells) on an elastic foundations (EF) with different types of boundary conditions in thermal environment. Material compositions of the shell are graded in the thickness direction according to a sigmoid law distribution in terms of the volume fractions of the constituents. The governing equations are derived by using the classical shell theory and Pasternak's two parameters EF. The motion equations of dynamic analysis are determined due to Galerkin method and the obtained equation is numerically solved by using Runge–Kutta method. The approximate solutions are assumed to satisfy the different types of boundary conditions. The criterion suggested by Budiansky–Roth is applied to determine the dynamic critical buckling load and the nonlinear dynamic response is found by numerical form. In numerical results, the effects of geometrical parameters, material properties, the EF, boundary conditions, mechanical loads and temperature on the nonlinear dynamic and vibration stability of the shells are investigated.
ABSTRACT: A semi-analytical approach to understand the manifestation of plate modeshapes associated with twin frequencies has been presented. Square Mindlin’s plate, clamped on all sides, has been considered here. It highlights the importance of efficacy of the beam-wise trial functions in an energy-based plate vibration analysis method, in terms of (a) accuracy, (b) orthogonality, (c) sense (plus/minus) and (d) interference. The inconsistency in the modeshapes of repeated frequencies, seen extensively in literature, has been attempted to be removed, through superior closed-form orthogonal set of Timoshenko admissible functions into the Rayleigh-Ritz method. The constructive/destructive interferences of the admissible functions, which are the products of the beam-wise modeshapes, give the final nodal patterns and the prominence of the anti-nodes. Also, the pairs of ‘very close’ but distinct frequencies, which were often considered as ‘numerical errors’, have been counter-intuitively justified through their Eigenvectors, which are either symmetric or skew-symmetric in the matrix form. Nodal patterns for CCCC plate modeshapes are accurately investigated; i.e. chess-board and diagonal nodal patterns.

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ABSTRACT: This article investigates the axisymmetric buckling of annular plates under in-plane loading applied at the inner and outer boundaries. The first order shear deformation theory is used to represent the displacement field and the governing equations are derived from the principle of virtual work. Unlike the circular plate in which the prebuckling stress components are constant, for an annulus, these stress components are functions of the radial distance from the plate center. As a consequence, the resulting eigenproblem, which is in the form of coupled differential equations with variable coefficients, does not have a closed form solution. In this article, an asymptotic approximation based on the perturbation technique is introduced to solve this problem. A parametric analysis is performed and the effects of different combinations of boundary conditions at the inner and outer edges, load ratios, inner to outer radius ratios and thicknesses are investigated. The obtained results are in a good agreement with the numerical data and also with the other references.

ABSTRACT: A rigorous analytical symplectic method is introduced into the free vibration of a rectangular double-layered orthotropic nanoplate system. Eringen's nonlocal elasticity theory is taken to capture the small size effect. Meanwhile, it leads to a high-order differential governing equation in the Lagrangian system, which can only be analytically solved by the semi-inverse method with pre-determined trail functions in previous studies. To overcome this drawback, a Hamiltonian system is established by introducing a new total unknown vector consisting of the displacement amplitude, rotation angle, shear force and bending moment. The
governing equation is reduced to a set of one-order ordinary differential equations so that they can be systematically solved by the method of separation of variables and the expansion of eigenfunctions. Analytical frequency equations are derived for the Levy-type edges and vibration modes are expressed in terms of the total unknown vectors. Comparison is presented to verify the accuracy of the symplectic method and comprehensive numerical examples are given also.

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ABSTRACT: This paper deals with geometrically nonlinear transient analysis of sandwich beams with viscoelastic cores and laminated composite skins. The formulation is based on the Full Layerwise theory (FLWT) and the Boltzmann's superposition principle and using weakly singular Koltunov-Rzhanitsyn kernel for modelling the viscoelastic core. The nonlinear governing integro-partial differential equations (IPDEs) of the sandwich beams are derived using Hamilton's principle. The Galerkin method in combination with the Newmark-Beta procedure, which is coupled to the Newton-Raphson algorithm, are employed to solve the obtained nonlinear IPDEs. The effects of using integral model and considering the history of strain for viscoelastic core on the dynamic response of sandwich beams are investigated. The results indicate that, employing the integral model with Koltunov-Rzhanitsyn kernel in the constitutive equation affects the amplitude and the frequency of the dynamic response of sandwich beam. For comparison purpose, the finite element analysis is carried out within ANSYS software environment and the user-material subroutine is developed to model the Koltunov-Rzhanitsyn kernel. The results of the used semi-analytical model agree well with those obtained from finite element method (FEM) of analysis. It should be noted that, because of employing a large number of degrees of freedom in the FEM analysis for accurate modelling of the viscoelastic sandwich beams, the FEM analysis is rather computationally inefficient in comparison to the presented method. Moreover, the Koltunov-Rzhanitsyn kernel is capable of modelling the viscoelastic behaviour accurately with lower number of rheological parameters in comparison to the Prony series.

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ABSTRACT: In this paper, a method has been presented to study the free vibration of a rotating shell consisting of p coupled conical shells. This method considers the Coriolis and centrifugal forces as well as the initial hoop tension resulting from rotation of the shell. Matrix transform and power series methods were employed to solve the equations. The advantage of using the matrix transform approach is that the dimension of the coefficient matrix, which is finally constructed to obtain the natural frequencies of a shell made of p cones, remains 8×8. The obtained results were validated with the help of existing special cases of the studied problem reported in the literature, and by means of FEM software programs. By verifying the presented equations and their solution method, the fundamental natural frequencies of a rotating shell made of two conical shells were obtained for
different conditions. Every thin-walled axisymmetric shell can be represented by a number of joined conical shells. So, as a practical example, the presented method was employed to analyze the vibrations of an automobile tire ring as a rotating thin-walled shell with a relatively complex geometry.

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ABSTRACT: Post-buckling phenomenon has been performing advantages in many applications. In particular, buckling snap-through of slender beams under lateral constraints is of great research interest since low-rate and low-frequency excitations can be transformed into high-rate motions. Electrical energy can be generated from ambient energies through the process. Efficient conversion of the energy phases requires sufficient control over post-buckling response. However, inadequate studies have been conducted to investigate the influence of different lateral constraints on buckling mode transitions. This study aims at developing static and dynamic theoretical models to capture buckling snap-through of slender beams subjected to irregularly bilateral constraints. The models are created based on small and large deformations assumptions, respectively. An algorithm is introduced to discretize the irregular constraints into a gap vector. The equilibrium equations in the presented models are solved using an energy method that minimizes the total energy in the gap vector with respect to the weight coefficient \( C_m \) of different buckling modes. Experiments were carried out to validate the theoretical results. Good agreements were observed. The proposed models are then used to investigate the effects of the linearly and sinusoidally varied constraints on the beams' post-buckling response. It is found that the deformed shapes of the beams meet the patterns of the constraints. Both the static and dynamic large deformation models are able to measure the end-shortenings that result in severe rotation of the beams' neutral axes. Significant shifting is observed between the deflected beam shapes solved by the static and dynamic models. The presented models are effective in understanding and predicting the static and dynamic post-buckling responses of irregularly constrained beams under small and large deformation assumptions.

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ABSTRACT: This paper investigates the small- and large-amplitude vibrations of thermally postbuckled sandwich plates with carbon nanotube-reinforced composite (CNTRC) face sheets resting on elastic foundations. Two types of CNTRC face sheets, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The material properties of FG-CNTRCs are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The material properties of both CNTRC face sheets and homogeneous core layer are assumed to be temperature-dependent. The motion equations are derived based on a higher order shear deformation plate theory. The nonlinearity effect is taken into account in the sense of von Kármán nonlinear kinematic assumption. The plate-foundation interaction and
the initial deflection caused by thermal postbuckling are also included. The numerical illustrations concern small- and large-amplitude vibration characteristics of thermally postbuckled sandwich plates with CNTRC face sheets under uniform temperature field. The effects of CNT volume fraction and distribution pattern of face sheets, the core-to-face sheet thickness ratio as well as foundation stiffness on the vibration characteristics of sandwich plates are examined in detail.


ABSTRACT: In this paper theoretical wrinkling analysis of the inflated beam was conducted and an experiment was then completed. The bending stiffness and load-deflection relationship in wrinkling condition were derived and then validated by experimental results. A comparative analysis of full shell, multi-scale and pseudo-beam on bending wrinkling of the inflated beam was performed. It was found that multi-scale method offered a considerable interest in computation efficiency while ensuring reliability in numerical simulation. Parametric analysis was done and showed that mesh coarseness, interface connection and the ration of full shell component have a strong influence on wrinkling analysis accuracy.

W.D. Yang, F.P. Yang and X. Wang (School of Naval Architecture, Ocean and Civil Engineering (State Key Laboratory of Ocean Engineering), Shanghai Jiao Tong University, Shanghai 200240, PR China), “Dynamic instability and bifurcation of electrically actuated circular nanoplate considering surface behavior and small scale effect”, International Journal of Mechanical Sciences, Vol. 126, pp 12-23, June 2017 https://doi.org/10.1016/j.ijmecsci.2017.03.018

ABSTRACT: In this paper, the dynamic pull-in instability and bifurcation characteristics of circular nanoplate subjected to electrostatic and Casimir forces are studied. Surface effect originates from high surface/volume ratio of nanostructures, where atoms at a free surface experience distinct local environments with respect to those in the bulk material. Thus, the surface free energy being negligible in classical elastic theory, becomes significant in dynamic behaviors of nanostructures. Based on Eringen’s nonlocal elasticity and Gurtin-Murdoch surface model, the nonlinear governing equation of electrically actuated circular nanoplate is derived in polar coordinate. The closed-form solution of dynamic frequency and electrostatic voltage is obtained by utilizing the homotopy perturbation method (HPM). Furthermore, the coupling effects of nonlocal parameter and surface characteristics on the dynamic pull-in instability of circular nanoplate are investigated, and the nonlinear dynamics behaviors, time histories and phase diagrams of electrically actuated circular nanoplate are discussed. Some new results obtained in this work could be helpful in design of 2-D circular nanoplate-type actuator considering size-dependency and quantum vacuum fluctuation effects.

Wenqian Hao (1), JiaMiao Xie (1), Fenghui Wang (1), Zhifang Liu (2) and Zhihua Wang (2) (1) Department of Engineering Mechanics, Northwestern Polytechnical University, Xi’an 710129, China (2) Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, Taiyuan 030024, China “Analytical model of thin-walled corrugated tubes with sinusoidal patterns under axial impacting”, International Journal of Mechanical Sciences, Vols. 128-129, pp 1-16, August 2017, https://doi.org/10.1016/j.ijmecsci.2017.03.033

ABSTRACT: In this paper, the dynamic pull-in instability and bifurcation characteristics of circular nanoplate subjected to electrostatic and Casimir forces are studied. Surface effect originates from high surface/volume ratio of nanostructures, where atoms at a free surface experience distinct local environments with respect to those in the bulk material. Thus, the surface free energy being negligible in classical elastic theory, becomes significant in dynamic behaviors of nanostructures. Based on Eringen’s nonlocal elasticity and Gurtin-Murdoch surface model, the nonlinear governing equation of electrically actuated circular nanoplate is derived in polar coordinate. The closed-form solution of dynamic frequency and electrostatic voltage is obtained by utilizing the homotopy perturbation method (HPM). Furthermore, the coupling effects of nonlocal parameter and surface characteristics on the dynamic pull-in instability of circular nanoplate are investigated, and the nonlinear dynamics behaviors, time histories and phase diagrams of electrically actuated circular nanoplate are discussed. Some new results obtained in this work could be helpful in design of 2-D circular nanoplate-type actuator considering size-dependency and quantum vacuum fluctuation effects.
ABSTRACT: Corrugated tube with a special corrugated surface has wide engineering applications because it can decrease the impacting force. The dynamic response of corrugated tube under axial impacting belongs to the "Type II structures" response. The main inertia effect in corrugated tube is lateral inertia and the axial inertia effect is negligible. By taking the eccentricity factor and amplitude factor into account, three plastic hinge mechanisms and a theoretical model of dynamic progressive buckling are proposed. The results conclude that displacement and impacting force are related to the eccentricity factor and the amplitude factor, but total absorption energy is independent of the eccentricity factor. There is a critical folding angle during the formation process of plastic hinges. The theoretical results are compared well with the numerical and experimental results of previous studies. The theoretical predict of corrugated tube produces excellent characteristics in term of force-consistent and low initial impacting force. And it also provides a reference to the research of the dynamic response of corrugated tube under axial impacting.

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ABSTRACT: An analytical model is proposed for global buckling circular tubes of low diameter-to-thickness ratio (25<D/t<4025<D/t<40) and moderate length (7<L/D<87<L/D<8), based on experimental observations and numerical simulations. Compared with FEM simulations, the current model gives accurate predictions on the whole load-displacement curve, energy dissipation and peak force. Employing this model, the energy absorption properties of circular metal tubes are analyzed. For global buckling tubes of same geometry, fixed boundary can absorb more energy than free boundary due to the bending plastic mechanism at ends. For oblique compression (compression angle \( \leq 30^\circ \)), the load-displacement curve of global buckling is similar to that of uniaxial compression. For tubes of different geometries under uniaxial compression, the total response and energy absorption ability are compared between global buckling and progressive buckling. If the effective stoke is small, the specific energy absorbing (SEA) of global buckling tube could be higher than progressive buckling tube.


ABSTRACT: This paper presents the nonlinear flexural-torsional vibration and instability analysis of thin-walled column with different mono-symmetric open sections subjected to periodic axial load. Non-linear partial differential equations (PDEs) governing the dynamic instability behavior of the considered sections are derived. Galerkin's method is employed to reduce the coupled partial differential equations to a set of coupled Mathieu equations. The amplitudes of steady state vibrations are determined from the non-trivial solution of Mathieu equations in terms of excitation frequency. Following Bolotin's method, principal instability regions are determined for different mono-symmetric section columns having various boundary conditions. Numerical results for the natural frequencies, instability regions and frequency-amplitude responses for thin-walled columns are presented. Influence of eccentricity, shape of the cross-section and boundary conditions on frequency-amplitude responses and instability regions are investigated.
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“Distortional buckling of perforated cold-formed steel channel-section beams with circular holes in web”,
International Journal of Mechanial Sciences, Vol. 126, pp 255-260, June 2017
https://doi.org/10.1016/j.ijmecsci.2017.04.001
ABSTRACT: This paper presents the numerical and analytical investigations on the distortional buckling of perforated cold-formed steel channel-section beams with circular holes in web. The numerical investigation involves the use of finite element methods. In the analytical analysis the distortional buckling model recommended in EN1993-1-3 is employed. The influence of the web holes on the distortional buckling behaviour and corresponding critical stress and moment of perforated cold-formed steel channel-section beams are discussed. Finally, a simple analytical formulation is proposed for evaluating the effect of hole size on the reduction of critical stress and critical moment of the channel-section beams with circular holes in web.

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ABSTRACT: This paper investigates a new design model for energy absorption of empty and polyurethane foam-filled circular bitubal tubes. In this study, an experimental technique is used to evaluate crashworthiness parameters and crushing behavior of the bitubal energy absorbers under compressive quasi-static loading. One of the aims of this new and innovative design is to increase the energy dissipation maximally through the tube inversion and the axial collapse, simultaneously. To do so, the inner tube with inversion and the outer tube with the collapse leads to a dissipation of energy in the deformation process. However, the stable collapse in the outer tube is required for a complete inversion of the inner tube. Therefore, by creating outer grooves at some determined areas along tube length, a long tube is divided into small parts to prevent asymmetric folding. In the present work, the effects of shrink-fitting and polyurethane foam are studied to control the sudden force applied to the main part of the structure when the accident occurs. The results of experimental tests show that the energy absorption capacity of bitubal specimens are greater than that of monotubal ones. Also, the foam-filled in the bitubal structures and the shrink-fitting of tube leads to increase the energy absorption and the specific energy absorption in comparison with the simple ones. The proposed method would help to reach the improved crashworthiness structure in the hope of reducing the occupant injury in a collision.

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ABSTRACT: The nonlinear responses and stability of double-layered nanoplate embedded in the elastic medium are investigated in the presence of 3:1 internal resonance. By the nonlocal theory, the method of multiple scales is employed to obtain the analytical nonlinear frequency-response relations. Two different external primary resonance conditions, i.e. the first and the second modes being directly excited, are considered. The influences of the small scale effect and viscous damping on the nonlinear vibration are explored in details. From the results, the frequency-response curves for the two primary resonance cases present complete different characteristics. It should be noted that the response curves are closed loops for the resonance of the second mode, which implies the steady-state response just exists in a finite frequency range. The regions of multi-values appear for both cases and the stability of the response is determined. When the first mode is directly excited, the impact of the viscosity of nanoplate and small scale effect on the frequency range of unstable response is rather significant. Furthermore, when the second mode is directly excited, a novel phenomenon, i.e. the frequency range for the closed loops of response diminished enormously as the increase of the viscosity of nanoplate, can be observed.

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ABSTRACT: In this paper, the vibration of the isotropic single-walled piezoelectric conic nanotube was investigated using Love's thin shell model and couple stress theory. In this formulation, to model the size effects in the nanoscale, the size-dependent couple stress theory was employed. This theory has recently been developed for piezoelectric materials. Besides, to model the nanotube in a more precise fashion, the shell model was used instead of the beam model. By measuring strain energy, kinetic energy and the work of external forces, Hamilton's principle was used to develop the couple equations between the mechanical and electoral effects in the piezoelectric nanotube along with the related boundary conditions. To evaluate the equations in a special case, the shell equations together with the related boundary conditions were solved using the two Galerkin and Kantorovich Methods. Finally, size effects, flexoelectric effects, and the effects of geometric dimensions on the vibrations of the piezoelectric nanotube were investigated. The findings demonstrated that this model is capable of eliminating the difference between the results of MD simulation and classical theoretical models.

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ABSTRACT: Nonlinear forced vibration analysis on axially functionally graded (AFG) non-uniform plates has been carried out in the present study. Nonlinear strain displacement relations are used to incorporate geometric nonlinearity in the system. The problem is formulated using energy method and governing equations are derived on the basis of Hamilton's principle. An indirect approach is adopted for solving the problem where, the problem is reduced to a static case by assuming that the dynamic system fulfils the force equilibrium conditions
at maximum amplitude of excitation. One of the multidimensional Secant methods, known as Broyden method, is utilised for solving the set of nonlinear equations. Different combinations of clamped and simply supported boundary conditions are considered in the analysis and generated results are furnished in non-dimensional frequency-amplitude plane. Taper parameter and excitation amplitude are observed to significantly affect the forced vibration response of the plates. The deflection shapes for various boundary conditions are presented and the forced vibration response in the proximity of second mode is also investigated. The results of the present analysis are validated with the studies available in the literature.

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ABSTRACT: This article focuses on evaluating the large deflection of the thin strip under practical condition of residual stress after cold rolling. In order to describe the problem mathematically, the incompatible von Kármán equations were introduced as the governing equations. Given the deflection of the strip along the rolling direction presenting the periodic form, the incompatible von Kármán equations along with the free boundary conditions were simplified to be a nonlinear boundary value problem in dimensionless form and turned out to be a boundary layer problem. Then composite expansion-Ritz method (CERM) was proposed to solve the problem. The composite expansion method was used to determine the form of deflection, while the geometry parameters, such as wave length, positions of boundary layers, were obtained by Ritz method. Finally, the accuracy of CERM is verified by actual measured data.

Kun Xie, Meixia Chen, Lei Zhang and De Xie (School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China), “Free and forced vibration analysis of non-uniformly supported cylindrical shells through wave based method”, International Journal of Mechanical Sciences, Vols. 128-129, pp 512-526, August 2017
https://doi.org/10.1016/j.ijmecsci.2017.05.014

ABSTRACT: This paper presents a unified analytic method, wave based method (WBM), to investigate free and forced vibrations of non-uniformly supported cylindrical shells. WBM is involved in decomposing the cylindrical shell to several shell segments according to locations of interior supports and excitations. Flügge shell theory is adopted to describe motions of segments. Displacement functions are expanded as wave functions, rather than general trigonometric functions or polynomials, and they can accurately satisfy both motion equations and boundary conditions. Two kinds of non-uniform supports, point and line ones, are consistently considered through discrete artificial springs. Boundary and continuity conditions modified by supports and excitations are assembled to the governing equation. To examine accuracy of WBM, vibration results of cylindrical shells subjected to different supports are firstly compared with the ones in literature and calculated by finite element method, which demonstrates high accuracy and wide application of WBM. Some mode shapes are also presented to visually illustrate coupling effects of different modes. Furthermore, influences of stiffness constants of springs, point supports and structural damping are discussed. They reveal that fundamental frequencies can be maximally increased as point supports equally spaced in circumferential direction.
https://doi.org/10.1016/j.ijmecsci.2017.05.022

ABSTRACT: Cylindrical metal shells with elliptical cross-sections are gaining increasing popularity as hollow sections due to their unique aesthetic appearance and different geometric properties about their two principal axes, with one axis exhibiting properties that are significantly more favourable than the other under flexure. However, in comparison with other hollow geometries, elliptical cross-sections have only recently begun receiving significant research attention. This is partly because even simple analytical treatments inevitably encounter cumbersome elliptical integrals that have no closed-form solutions, a problem now attenuated by powerful modern computing capabilities. A recent computational study investigated the nonlinear buckling resistance of perfect elastic circular cylindrical shells under uniform bending, establishing four distinct length-dependent domains of behaviour and characterising these in compact form using specially chosen dimensionless parameters. The present study extends this work to cylinders with elliptical cross-sections under bending about both principal axes. The same qualitative domains of length-dependent nonlinear elastic behaviour are found as for circular cylinders, but requiring a different algebraic characterisation that takes account of the varying elliptical radii. On the basis of computational results, a reference equation for the moment governing the ‘Brazier’ ovalisation cross-sectional failure mode for long elliptical thin-walled cylinders is deduced and presented for publication for the first time.

References listed at the end of the paper:

ABSTRACT: Analytical studies on the dynamic instability analysis of a functionally graded (FG) skew plate subjected to uniform and linearly varying in-plane periodic loadings with four different types of boundary conditions are presented. The total energy functional of the FG skew plate is formulated based on Reddy's third order shear deformation theory (TSDT) and this functional is mapped from the physical domain to computational domain using transformation rule. The boundary characteristics orthonormal polynomials (BCOPs) are generated for different boundary conditions using Gram–Schmidt process, which satisfy the essential boundary conditions of skew plates in the computational domain. The energy functional is converted into a set of ordinary differential equations (Mathieu–Hill equations) using Rayleigh–Ritz method in conjunction with BCOPs. The solution of Mathieu–Hill equations describes the dynamic instability behavior of skew plate. The instability regions are traced using Bolotin method. The effect of skew angles, power-law distributions, span-to-thickness ratios, aspect ratios, boundary conditions and static load factors on the instability region of FG skew plates are presented. The result indicates that the width of instability region become narrow with the increase in skew angle. Moreover, the time history response and corresponding phase plot in the unstable and stable region is studied to identify the instability behavior such as existence of beats, bounded and unbounded response, and effect of forcing amplitude and its frequency on the response.

Arash Kazemi, Ramin Vatankhah and Mehrdad Farid (School of Mechanical Engineering, Shiraz University, Shiraz, Iran), “Nonlinear pull-in instability of microplates with piezoelectric layers using modified couple stress theory”, International Journal of Mechanical Sciences, Vol. 130, pp 90-98, September 2017
ABSTRACT: In this study, the effects of piezoelectric layers, residual stresses and von Karman nonlinearity on the pull-in instability of a microplate are studied by taking into account the size effect of the system. The strain energy is obtained using the modified couple stress theory and the set of nonlinear equations of motion are derived using Hamilton's principle and finite element method (FEM) based on classical plate theory. Newton–Raphson's procedure is used to solve the nonlinear equations. The proposed model is used to study the pull-in voltage, pull-in displacement, and small amplitude vibration about the equilibrium position of microplates with piezoelectric layers. The results are validated by available experimental and theoretical data. They show that the pull-in voltage is affected by the material length scale parameter, but this effect is quite negligible when the ratio of plate thickness to material length scale parameter is larger than 10. It is found that the results obtained by the nonlinear theory are larger than those by the linear theory and their differences are increased by increasing the ratio of initial gap to the plate thickness. Moreover, it is found that applying a small positive voltage to the piezoelectric layers can decrease the maximum pull-in voltage.

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ABSTRACT: This study investigates the static and free vibration behavior of rotating functionally graded (FG) truncated conical shells reinforced by carbon nanotubes (CNTs) with a gradual distribution of the volume fraction through the thickness. CNTs are here selected as reinforcement, because of their noteworthy physical and chemical properties, together with their ability to enhance the mechanical properties of the whole composite structure. A two-parameter agglomeration model is considered to describe the micromechanics of such particles, which tend to agglomerate into spherical regions when scattered in a polymer matrix. From the macro-mechanical point of view, the conical structures are characterized by a gradual variation of their mechanical properties along the thickness direction, since different distributions are explored to describe the volume fraction of the reinforcing phase. The governing equations of motion for the rotating truncated composite conical shells are derived and solved numerically by means of the Generalized Differential Quadrature (GDQ) method combined with the third-order shear deformation theory (TSDT) in small deformations. The GDQ approach has recently emerged as a very promising numerical tool to solve complex problems without passing through any variational formulation, but solving directly the equations of motion in a strong form. In this paper, a parametric study based on the GDQ is systematically performed to exploit the effect of some geometry parameters, i.e. the length, the radius, the thickness and the semi-vertex angle of the cone, as well as the different distribution of CNTs along the thickness, on the frequency at different circumferential wave numbers and rotating speeds. A convergence study of the numerical results is also made in terms of deflection and stress distributions of the structure, which proves the efficiency of the GDQ approach, also for coarse mesh discretizations in the meridional direction.

A. Almasi, M. Baghani and A. Moallemi (School of Mechanical Engineering, College of Engineering, University of Tehran, PO Box 11155-4563 Tehran, Iran), “Thermomechanical analysis of hyperelastic thick-

ABSTRACT: In this investigation, employing the multiplicative decomposition of the deformation gradient, both analytically and numerically thermomechanical analysis of a hyperelastic thick-walled cylindrical pressure vessel are presented. The exp − exp energy density function due to its excellent agreement with experiments and including exponential terms for compressible and particularly incompressible materials is used to predict the hyperelastic response of elastomers. It is found that the radial and axial stresses are more sensitive to variation of the angular velocity than the hoop stress. Also, the variation of the axial stretch has the most significant effect on the axial and hoop stresses. Moreover, the behavior of the axial stress, for a constant axial stretch \( \lambda \), depends on the value of \( \lambda \) whether it is larger than 1 or not, while in the inner radius of the vessel, the hoop stress has the same behavior for various values of the axial stretch. It is concluded that the positive temperature gradient leads to tensile radial stress and compressive hoop and axial stresses in the rotating cylinder, and the increase in the temperature gradient leads to increase in all stress components. The radial and hoop stresses through the wall-thickness are more sensitive to the temperature change than the thermal axial stress. Moreover, increasing the angular velocity makes the cylinder more unstable, while the stability increases with \( \lambda > 1 \). It is deduced that the more axial stretch in the inner radius of the pressure vessel, the more stable it is. It was shown that the comparison of the results of Finite Element and analytical method shows a good fit as a verification of the analytical solution. This analytical solution can be used either for parametric study (material or geometrical parameters) of the pressure vessels or for design and optimization that involve a large number of simulations where computational cost is a crucial parameter.

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ABSTRACT: The present research deals with general wave propagation in a piezoelectric sandwich plate. The core is consisted of several viscoelastic nanocomposite layers subjected to magnetic field and is integrated with viscoelastic piezoelectric layers subjected to electric field. The piezoelectric layers play the role of actuator and sensor at the top and bottom of the core, respectively. The core layers are composed of temperature-dependent polymeric layers which reinforced by functionally graded carbon nanotubes (FG-CNTs). The material properties of the nanocomposite layers are estimated based on the extended mixture rule and also the Kelvin-Voigt model is employed to consider the viscoelastic properties of the structure. It is assumed that the structure is embedded in a viscoelastic foundation which is simulated according to orthotropic visco-Pasternak model. The governing equations of the structure are developed on the basis of refined piezoelectricity zig-zag theory and Hamilton's principle. An analytical solution is applied to obtain the phase velocity, cut-off and escape frequencies. Furthermore, a proportional-derivative (PD) controller is employed to control the phase velocity in the structure. The effect of various parameters such as geometric constants, viscoelastic foundation, structural damping coefficient, applied voltage, volume fraction and distribution types of CNTs, temperature changes and magnetic field on the analysis and control of the wave propagation in the smart nanocomposite structure is examined. The results show that the applied voltage to the actuator and the exerted magnetic field to the core can be considered as effective parameters to control the wave propagation in the system.
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ABSTRACT: A new analytical (non-linear) model for the impact of a solid sphere on a fluid-filled spherical shell is developed by including the stress wave propagation effect in addition to the Hertzian contact deformations and the shell membrane and bending actions. The expressions for determining the maximum mutual approach and impact duration are analytically derived using the principle of energy conservation. A simplified (linearized) model incorporating the elastic energy loss due to the stress wave propagation is then formulated by using a linear force-deflection relation, which leads to a closed-form expression for the impact duration. It is shown that the new non-linear model reduces to that of Young (2003) and the linearized model recovers that of Mansoor–Baghaei and Sadegh (2011) when the stress wave propagation effect is not considered. By directly applying the newly obtained non-linear and linearized models, three representative problems simulating blunt head impacts are analyzed. The first problem characterizes the blunt impact of a human head on the ground or on an automobile, the second one simulates the blunt impact of a non-lethal projectile on a human head, and the third one represents two football players’ head collision. Numerical results for the maximum deflection, maximum impact force and impact duration are provided to quantitatively show their variations with the impact velocity and shell thickness. The values predicted by the current new models are also compared with those given by the two existing models and with available finite element simulation results, and a good agreement is observed.


ABSTRACT: With the aid of a more comprehensive size-dependent continuum elasticity theory, the nonlinear instability of functionally graded multilayer graphene platelet-reinforced composites (GPLRC) nanoshells under axial compressive load is examined. To accomplish this end, the newly proposed theory of elasticity namely as nonlocal strain deflection elasticity theory is implemented into a refined hyperbolic shear deformation shell theory to establish a more accurate size-dependent shell model. The graphene platelets (GPLs) are supposed to be randomly oriented with uniform and three different functionally graded dispersions relevant to each layer as the weight fraction of GPL varies layerwise through the shell thickness direction. In accordance with the Halpin–Tsai micromechanical scheme, the effective material properties are achieved corresponding to uniform (U-GPLRC) and X-GPLRC, O-GPLRC, A-GPLRC functionally graded patterns of dispersion. The boundary layer theory of shell buckling and a two-stepped perturbation solving process are employed jointly to capture explicit analytical expressions for nonlocal strain gradient stability curves of axially loaded functionally graded GPLRC nanoshells. Among different patterns of GPL distribution, it is observed that for both nonlocality and strain gradient size dependencies, the maximum and minimum size effects on the critical buckling loads are corresponding to X-GPLRC and O-GPLRC nanoshells, respectively.
ABSTRACT: This paper proposes an analytical model for analysing the interaction between web distortion and lateral-torsional buckling of partially restrained I-section beams under transverse distribution loading. The analysis is performed by using Rayleigh-Ritz method, in which the web is modelled as a plate and the two flanges are treated as two independent beams. The total potential energy functional of the system is derived using three-dimensional strain-displacement relationships in solid mechanics. The critical buckling stress and critical buckling moment of the I-section beam are calculated by solving a $3 \times 3$ eigen-matrix equation. For the validation of the present model the finite element analysis using three-dimensional shell elements is also carried out. The comparison between the analytical and numerical results demonstrates the correctness and rigorous of the proposed analytical model despite its simplicity.

ABSTRACT: To improve their energy-absorption capacity and induce failure mechanisms, the plug-type triggers of composite square tubes are designed and compared. A progressive failure model verified by the axial quasi-static loading test is proposed. Six different plug initiators including circle convex plug initiator, two types of square convex plug initiators, two types of groove-like plug initiators, and ditch-like plug initiator are given. To understand the triggering mechanism, the crashworthiness of chamfered square tubes is compared. Further, the influence of width of ditch plug-initiator towards energy-absorption characteristics and failure modes is investigated. Results show that well agreements in the failure and energy-absorption mechanisms between the simulation and experiment are identified. Three types of convex plug initiators can reduce the initial peak load and induce the out-ward petaling and splaying mode. The progressive inward-folding mode is similarly triggered by both two groove plug initiators. The ditch plug initiators are recommended as the best plug design with reasonably induced failure modes and an increase of 31.9% in total energy absorption. Comparing with non-plug initiator, square tubes crushed by narrower ditch plug initiator possess higher energy-absorption capacity, with an increase of 51.9% in SEA.
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ABSTRACT: A non classical analytical model is presented for free vibration of the cracked rectangular isotropic and functionally graded micro plates in the presence of thermal environment. The new approach is based on the combination of classical plate theory and the modified couple stress theory. The crack terms are based on the Line Spring Model whereas the thermal environment is accommodated in the form of thermal moment and in-plane forces. The solution for fundamental frequencies of the cracked plate is obtained by discounting geometric nonlinearity. A non classical relation for geometrically linear thermal buckling phenomenon of a cracked micro-plate is also proposed. The variation of critical buckling temperature and fundamental frequency with uniform rise in temperature of the cracked plate is studied for various crack length ratios, gradient index and internal material length scale parameter. Furthermore the variation of the buckling coefficient with plate aspect ratio and thickness of the cracked micro-plate is established. A comparison is presented between the classical results and present results as affected by thermal environment and microstructure of the plate. It is concluded that the presence of cracks affects the critical buckling temperature and fundamental frequencies of micro plates. The consideration of size effect increases the buckling temperature which shows the significance of the internal material length scale parameter in the presence of thermal environment.

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ABSTRACT: This investigation focuses on the multiobjective optimization of a crash box subjected to static loading by using a validated numerical model and an analytical approach. The crash box is made with a unique combination of three materials: an aluminium tube filled with polyethylene terephthalate (PET) foam and a glass-fibre reinforced polymer (GFRP) skeleton. A finite element model was calibrated based on the results obtained in a material testing campaign using appropriate constitutive equations. A J2–plasticity model was used for the material behaviour of the aluminium alloy, and the PET foam was modelled using Deshpande and Fleck’s model. Regarding the short-fibres GFRP, a Voce plasticity model was fitted to the experimental data. After a successful validation of the finite element model, the filled aluminium tube was subjected to a structural optimization to achieve the best crash performance. Three relevant design variables were selected: the thickness of the outer aluminium cylinder, the thickness of the GFRP and the density of the PET foam, the last being related to the crushing strength of the foam. Given the high computational cost of each finite element model, a multi-adaptive regression splines metamodel was fitted to a large-scale sampling. Optimum pairs were obtained
for the absorbed energy, the specific energy absorption, the peak load and the mass of the component; stating
the relative contribution of each design variable to the crashworthiness of the crash box and enabling the choice
of a balanced optimum design. A semi-empirical model based on Hanssen’s interaction formula was calibrated
with the data from a validated finite element model. This analytical model was able to reproduce the behaviour
of the component over the design region selected for the optimization, and was also used for its optimization
with satisfactory results.

Durgesh Bahadur Sing and B.N. Singh (Department of Aerospace Engineering, Indian Institute of Technology
Kharagpur, Kharagpur 721302, India), “New higher order shear deformation theories for free vibration and
buckling analysis of laminated and braided composite plates”, International Journal of Mechanical Sciences,
ABSTRACT: In this work, two new shear deformation theories namely Trigonometric Deformation Theory
(TDT) and Trigonometric-Hyperbolic Deformation Theory (THDT) are developed and implemented for the
analysis of laminated and three dimensional braided composite plate. Both models are based upon shear strain
shape function which yields non-linear distribution of transverse shear stresses and these models also satisfy the
traction free boundary conditions on top and bottom surfaces of the plate. Virtual work principle is used to
obtain the governing differential equations and boundary conditions. Both the proposed theories are formulated
and validated for the free vibration and buckling of laminated and Three Dimensional (3D) braided composite
plate. From the obtained results, the proposed theories are more accurate in predicting the response for free
vibration and buckling analysis of laminated and 3D braided composite plates. Intensive numerical studies of
3D braided composite are performed in detail. It is further observed that the geometric parameter (aspect ratio),
boundary conditions, fiber volume fraction and braiding angle have significant effect on the free vibration and
buckling response of the 3D braided composite plates. In the framework of finite element analysis, both
proposed theories anticipate exemplary results for the laminated and braided composite plates compared to
existing theories.

Yang Zhou, Arne Nordmark and Anders Eriksson (KTH Mechanics, Royal Institute of Technology, Osquars
backe 18, SE-100 44 Stockholm, Sweden), “Multi-parametric stability investigation for thin spherical
membranes with contacts”, International Journal of Mechanical Sciences, Vols. 131-132, pp 334-344, October
ABSTRACT: The instability behavior for a thin truncated spherical membrane completely filled with fluid or
containing both gas and fluid, fixed on a circular platform and in contact with two vertical planes was
investigated. Different penalty functions for contacts, and symmetry aspects of the discretized model were
studied, and gave effects on instability behavior. Stability conclusions for the multi-parametric problems were
made using generalized eigenvalue analyses, showing limit points, bifurcation points and turning point. Contact
conditions were shown to introduce bifurcations and secondary paths, dependent on the contact
implementations and discretizations. Their effects on stability behaviors in connection with various controlling
equations are discussed.

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ABSTRACT: The present paper investigates the biaxially compressed buckling and postbuckling behaviors of functionally graded multilayer composite plates reinforced with a low content of graphene nanoplatelets (GPLs) that are randomly oriented and uniformly dispersed in the polymer matrix within each individual layer. The material properties of the GPL-reinforced composite (GPLRC), which are graded along the thickness direction due to a layer-wise change in GPL weight fraction, are evaluated through a micromechanics model. Theoretical formulations are based on the first-order shear deformation plate theory and von Kármán-type nonlinear kinematics and include the effect of an initial geometric imperfection. A two step perturbation technique is employed to determine the asymptotic postbuckling solutions and the biaxial compressive postbuckling equilibrium paths of both perfect and imperfect plates simply supported on all edges. The effects of GPL weight fraction, distribution pattern, geometry and size as well as total number of layers on the buckling and postbuckling behaviors of functionally graded GPLRC plates are examined in detail.

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ABSTRACT: In this study, the effect of foam fill ratio on the energy absorption capacity of axially compressed thin-walled multi-cell square and circular tubes is investigated. In the experimental study, Aluminum tubes having circular cross-sections with four different foam fill ratio (11.4%, 22.8%, 34.2%, 100%) were subjected to compression tests under quasi-static test conditions. The finite element (FE) models of these tests were prepared and FE analysis were conducted using LS-DYNA program for validation study. After validating the FE models with real experiments, a total of 24 different multi-cell geometries (6 square empty, 6 square with various foam fill ratio, 6 circular empty and 6 circular with various foam fill ratio) were created. A total of three different wall thicknesses were used for each geometry in the explicit dynamic analyses. It is found out that specific energy absorption (SEA) of foam-filled square design is 5 times larger compared to the empty square design which has minimum SEA. By varying the wall thickness, the SEA and crush force efficiency (CFE) performances of the foam-filled square design can be increased by 87% and 42% respectively. The main goal of this study is to find the best multi-cell design having maximum SEA and CFE.

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ABSTRACT: In the present study, a simple analytical method is introduced for determination of natural frequencies of generally laminated conical and cylindrical shells with arbitrary boundary conditions. The governing equations of motion employed are those of thin-walled shell theory of Donnell. The free-vibration equations are solved using state space method and series solution in meridional direction. The results are compared and validated with the available especial results in the literature. The effects of bending-stretching coupling, semi-vertex angle, meridional length, shell thickness, fiber directions of composite plies, and lamination sequences on the natural frequency of conical and cylindrical shells are further investigated and presented.

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ABSTRACT: The axial crushing resistance of a new type of embedded multi-cell (EMC) tubes is investigated in this paper. Quasi-static tests are carried out first to investigate the deformation and force response of both empty square tubes and EMC tubes. The components of the crush force of EMC tubes are analyzed quantitatively. Nonlinear explicit finite element method is then employed to simulate the crushing process and the numerical results compare well with experiment. By using the FE model validated by experiment, parametric study is then performed to investigate the energy absorption performance of embedded tubes with various configurations. Finally, theoretical analysis is conducted to analyze the components of crush resistance of the whole structure and an expression is derived to predict the mean crushing force of EMC tubes. Theoretical predictions are in good agreement with experimental and numerical results.

ABSTRACT: The effect of bend angle on plastic limit loads of pipe bends under different load conditions is presented using three-dimensional non-linear finite element analyses. Based on finite element analysis, the characteristics of deformation, stress and strain were studied and effect of bend angle on the limit load was discussed. The results show that the effect of bend angle on limit load is great both at 0°~120° range under internal pressure, torsion moment and in-plane bending moment and at 0°~90° under out-of-plane moment. Then existing expressions of limit load and the finite element results were compared, and the solutions of limit load under single load condition were made. The proposed unified load solutions were obtained by fitting the finite element data under internal pressure, in-plane bending moment, out-of-plane bending moment and torsion moment. The results show that the proposed unified load solutions are consistent and in good agreement with the current finite element results.
ABSTRACT: In many industrial applications, thick-walled cylindrical components are subjected to high pressure and/or temperature. During the operation the cylinder wall may undergo elastic–plastic deformation. This paper presents plane-stress and plane-strain thermo-elastic–plastic stress analyses of thick-walled cylinders subjected to a radial thermal gradient. A three-dimensional finite element method (3D FEM) analysis of the thermo-elastic–plastic stresses in thick-walled cylinder is also carried out. The 3D FEM results are compared with the analytical plane stress and the generalized plane strain analyses in order to study the validity of these models on the basis of length to wall-thickness ratio of cylinders. The plane stress and generalized plane strain analyses are based on the Tresca yield criterion and associated flow rule. The strain hardening behavior of the material of the cylinder is taken into account. It is observed that for the length to wall thickness ratio of more than 6, the generalized plane strain analysis can provide sufficiently accurate results. Similarly, for the length to wall thickness ratio of less than 0.5, plane stress analysis can be used. When the length to wall thickness ratio is more than 0.5 but less than 6, a three-dimensional analysis is needed.

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2. XL. Gao, “An exact elasto-plastic solution for an open-ended thick-walled cylinder of a strain-hardening material”. Int J Press Vessel Pip, 52 (1992), pp. 129-144

ABSTRACT: In this paper the commercial finite element software Abaqus was employed to analyze the effect of mechanical discontinuities on the crashworthiness performance of aluminum profiles. Special emphasis was placed on material damage and its evolution during a crash event. The discontinuities were located at different heights on two opposite walls of aluminum profiles. During the crash simulations, the profiles were subjected to axial impact loads using a 500 kg rigid body striker with an initial velocity of 10 m/s. The ductile material properties of aluminum alloys were considered using the shear, ductile and Müschenborn–Sonne Forming Limit Diagram (MSFLD) damage initiation criteria in the discrete models. In order to model the progressive failure and removal of finite elements, damage evolution option was applied. In all cases, the implementation of discontinuities showed a reduction of peak load \(P_{\text{max}}\) of up to 4.74% with respect to a profile without discontinuities. In the same way, an increase in energy absorption \(E_{\text{a}}\) and crush force efficiency (CFE) of 7% and 12.69% respectively, was observed. It was found that the implementation of discontinuities increases the crashworthiness performance of the aluminum profiles. Moreover, the best location for the discontinuities was at the top of the walls of the structure. Following this finding, a typical application in automotive crashworthiness design was demonstrated successfully.

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ABSTRACT: In this paper, the free vibration characteristics of cylindrical shells with arbitrary boundary conditions are investigated. The Sanders shell theory is used to calculate the elastic strain energy. Artificial springs are implemented at the ends of the shells to represent the arbitrary boundary conditions. The shell displacements are expanded by three different sets of formulations, namely, the modified Fourier series, the Orthogonal polynomials, and the Chebyshev polynomials. A unified solution for the three different types of expansion functions is developed using the Rayleigh-Ritz method. The unified solution is validated by comparing with the available results in the literature. The accuracy, convergence rate, and computational efficiency of the three expansion functions are compared. Based on the comparison studies, the Chebyshev polynomials of high computational efficiency are selected to investigate the influence of boundary conditions on the free vibration characteristics of cylindrical shells.

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ABSTRACT: Origami is an ancient art of the paper folding that has been the source of inspiration in many engineering designs due to its intrinsic ability of changing shape and volume. Self-expandable devices have been created based on origami concept together with smart materials. Shape memory alloys belong to this class of materials and provide high forces and large displacements by varying their temperature. This work deals with the nonlinear dynamics of an origami-stent, a cylindrical shaped origami structure, which has the capacity of changing its radius. The actuation is provided by antagonistic torsional shape memory alloy wires placed in the origami creases. The mathematical model assumes a polynomial constitutive model to describe the shape memory alloy thermomechanical behavior. Geometric assumptions establish a one-degree of freedom model with constitutive and geometric nonlinearities. Numerical simulations are carried out considering different thermomechanical loadings that represent operational conditions. The system presents complex responses including chaos.

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ABSTRACT: In this paper, free vibration of open noncircular cylinders with spiral cross section are studied under arbitrary boundary conditions. For deriving the strain energy function, Kirchoff-Love hypotheses are employed. To obtain the solutions, Rayleigh-Ritz technique is implemented by selecting Chebyshev orthogonal polynomials of first kind as admissible displacement functions in three directions. Convergence of the proposed formulation is verified for spiral cylindrical panel and the results are compared with those of ABAQUS. Parametric study is undertaken to highlight the effect of inner radius, separation distance, subtended angle, thickness, and length of the spiral cylinders on the free vibration characteristics. Results obtained in this research are the first step toward modeling spiral cylinders and can be used for comparison in future studies. Finally, the design strategy for the spiral cylinders with specific vibration characteristics is presented. The results imply that spiral cylinder with specific vibration characteristics can be designed using equivalent open circular cylinder.

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ABSTRACT: The purpose of the present study is to investigate dynamic response and vibration of composite double curved shallow shells with negative Poisson's ratios in auxetic honeycombs core layer on elastic foundations subjected to blast and damping loads using analytical solution. This study considers composite double curved shallow shells with auxetic core which have three layers in which the top and bottom outer skins are isotropic aluminum materials; the central layer has honeycomb structure using the same aluminum material. Based on the first order shear deformation theory (FSDT) with the geometrical nonlinear in von Karman and using Airy stress functions method, Galerkin method and the fourth-order Runge–Kutta method, the resulting equations are solved to obtain expressions for nonlinear motion equations. The effects of geometrical parameters, material properties, elastic foundations Winkler and Pasternak, the nonlinear dynamic analysis and vibration of double curved shallow shells with negative Poisson's ratios in auxetic honeycombs core layer are studied.

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ABSTRACT: In this work, we experimentally evaluate the rendering of topology optimisation through the design of hollow structures manufactured using a 3D printing technique. The moving asymptote method is used as a mathematical optimisation strategy to virtually minimise the volume of 2D designs subject to hydrostatic pressure by half. Designs are converted to 3D models by extrusion in the building direction and printed using the Fused Deposition Modelling technique. Compression testing up to densification is performed and designs are evaluated. The results show that extrusion of the design in the building direction provides the best option to avoid mechanical anisotropy induced by processing. Depending on the type and extent of excluded regions, mechanical performance proves to be adapted to a wide range of designs and different types of mechanical anisotropies can be derived. Comparison with finite element results shows differences in behaviour related to mechanical instabilities that occur as a result of the lack of inter-filament cohesion and external frame unsoldering.


ABSTRACT: Considering the fluid viscosity, the dynamic behavior of a functionally graded materials (FGMs) cylindrical shell conveying a swirling annular fluid in the annulus between the inner shell and the outer shell are investigated, where material properties are graded across the thickness of the S-FGM thin shell with metal-ceramic-metal layers according to a Sigmoid power law. The shell-vibration-induced inviscid fluid-dynamic forces are described in the frame of the potential flow theory; the steady viscous forces are established based on the time-averaged Navier-Stokes and continuity equations. The shell is modeled by Flügge's shell theory. The zero-level contour method, the Galerkin's method and the traveling-wave type solutions are used for dynamic analysis of the S-FGM shell. The results show effects of the fluid rotation, viscosity and material properties on the dynamic behavior of the S-FGM shell. The coupling influences of the fluid rotation and viscosity on the stability of the shell are evaluated. The critical annular flow velocity, at which the form of the stability loss begins to change, is found.


ABSTRACT: Thin-walled beams are always subjected to both indentation and bending collapse during the transverse crush under accidental events. However, the mechanisms for indentation are not clear, and few studies are concerned with this problem because of the complex deformation features. In this paper, the local indentation behavior of thin-walled aluminum rectangular tubes by a cylindrical indenter with a rigid flat base as a support is investigated experimentally, numerically and theoretically. Quasi-static crushing tests of square tubes are carried out first and numerical simulations of the tests are then performed by nonlinear finite element code LS-DYNA. On the basis of the experimental observations, an analytical model is established to analyze typical characteristics of the structural response and deformation mechanisms of the specimens. By assuming rigid-perfectly plastic material, the crushing force response with respect to the crushing distance can be predicted by the proposed model. Comparisons show that the theoretical predictions are in good agreement with experimental and simulation results.

ABSTRACT: Due to excellent energy absorption efficiency under bending collapse, multi-cell beams are extensively used as the components of protection structures. However, the theoretical prediction of their responses is still an unsolved problem. In this paper, two methods: dimensionless analysis method and energy analysis method are employed to derive the bending moment response of multi-cell tubes. Numerical simulations of double-cell tubes with different section dimensions are conducted first. The dimensionless analysis method is then employed to correlate the bending moment of double-cell tubes with the ratio of width to thickness $b/t$, the flow stress and the bending rotation angle. Based on Kecman's model, a theoretical model of double-cell tubes is presented and the bending moment response is derived according to the energy equilibrium of the system. Finally, the expression of a rolling radius of plastic hinge lines in the energy analysis method is determined to bridge the two methods. A comparison shows that the predictions provided by the present two methods agree well with the numerical results. Quadruple-cell tubes are also employed to validate the present methods and results show that the present methods are applicable for multi-cell tubes with other cross-sections.


ABSTRACT: In this paper, a semi-analytical method is described and applied to investigate the free vibration of the functionally graded (FG) sandwich doubly-curved panels and shells of revolution with arbitrary boundary conditions, in which the first-order shear deformation theory is considered. Two types of sandwich models and four kinds of common functionally graded distribution, which determine the mechanical properties, are considered in the theory model process. In despite of the external factors which consist of boundary conditions, geometric model, material constants and so on, each of the unknown displacement functions of the FG sandwich doubly-curved panels is expanded as a novel Fourier series expression. Since the auxiliary function is introduced in the Fourier series expression, it can remove any potential discontinuities of the original displacement and its derivatives at the edges and it also has excellent convergence, accuracy, stability and a wide range of the boundary conditions including the simple classical boundary conditions, general elastic restraints and their combining cases. The linear vibration information including the natural frequency together with the mode shapes of the FG sandwich doubly-curved panels is obtained by means of the Ritz-variational energy method. A number of examples of the FG sandwich doubly-curved panels and shells are examined to assess the convergence, accuracy and stability of the current solutions, and then the first known results with various boundary conditions, geometric and material constants are presented. Additionally, the parameter studies of the FG sandwich doubly-curved panels and shells are also reported.

S. Chahardoli and A. Alavi Nia (Department of Mechanical Engineering, Bu-Ali Sina University, Hamedan, Iran), “Experimental and numerical investigations on collapse properties of capped-end frusta tubes with
ABSTRACT: In this paper, collapse properties of the capped-end cone tubes made from steel alloy 430 with circular holes under quasi-static axial loading have been studied experimentally and numerically. Simulations were performed using finite element LS-Dyna software and 11 types of cone with various number of holes (3, 4 and 5) and heights (20, 40 and 60 mm relative to bottom base of cone) in four different thicknesses (0.2, 0.4, 0.6 and 1 mm), so, 44 different states were totally simulated and the collapse properties of them were extracted. The samples with the thickness of 0.2 mm were tested on an experimental basis in order to ensure the accuracy of the simulation results. Comparing the obtained results indicates good agreement between the experimental and numerical data. According to the obtained results, it was found that open end absorbers are more efficient compared to similar capped-end structures. Also, it was revealed that creating holes in the capped-end cone decreases the maximum force and increases crush force efficiency. In addition, it was found that creating hole farther away from the underlying base is more effective for improving the collapse properties. In the final section, the effects of thickness on the collapse properties were evaluated. The obtained results in this study can be a good guidance for investigation on the effect of discontinuity on collapse properties.

Hui-Shen Shen, Y. Xiang and Yin Fan (Primarily from: School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China), “Postbuckling of functionally graded graphene-reinforced composite laminated cylindrical panels under axial compression in thermal environments”, International Journal of Mechanical Sciences, Vol. 135, pp 398-409, January 2018. This paper investigates the buckling and postbuckling behaviors of graphene-reinforced composite (GRC) laminated cylindrical panels. The GRC layer is made of polymer matrix reinforced with graphene fillers. The GRC layers may contain different volume fractions of graphene fillers to achieve a piece-wise functionally graded distribution of graphene reinforcement along the thickness direction of the panels. The material properties of GRC layers are temperature dependent and are estimated by a micromechanical model based on the results from MD simulations. The governing equations for the postbuckling of the panels are based on the Reddy's higher order shear deformation shell theory and the von Kármán strain-displacement relationships. The panel-foundation interaction and the effects of thermal conditions are both considered. A singular perturbation technique along with a two-step perturbation approach is employed to determine the buckling loads and the postbuckling equilibrium paths. It is observed that the piece-wise functionally graded distribution of graphene reinforcement can increase the buckling loads and the postbuckling strengths of the panels. The postbuckling path of a GRC laminated cylindrical panel with immovable unloaded straight edges is no longer the bifurcation type.

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ABSTRACT: This paper overviews the efforts that led to new improved knockdown factors for the design of cylindrical shells under axial compression. The corresponding design methods were derived by means of three step procedure involving deterministic methods for the buckling load prediction, modern experimental results and an extensive probabilistic analysis. The new design procedure is demonstrated by means of a full-scale primary launch-vehicle shell and the results show an estimated weight reduction of about 20%. The potentials of the new knockdown factors are shown and open questions regarding the influence of manufacturing specific imperfection signatures on the buckling load are addressed and design implications are derived and discussed. Dynamic load-controlled simulations with imperfection signatures for different manufacturing qualities and processes are performed and the influence of load introduction and mechanical boundary conditions on the buckling load is studied. From the results it is concluded that the commonly used practice of displacement-controlled shell buckling experiments and numerical simulations is sufficient for conservative design of real shell applications.
Rihuan Lu, Weizhao Gao, Xianlei Hu, Weihai Liu, ... Xianghua Liu, “Crushing analysis and crashworthiness optimization of tailor rolled tubes with variation of thickness and material properties”, International Journal of Mechanical Sciences, Vol. 136, pp 67-84, February 2018

ABSTRACT: Novel method-VGR technology is adopted to successfully produce tailor rolled tubes with axially varied thickness. Through microstructure observation and mechanical tests, there are obvious differences of grain size and properties in different thickness locations. After quasi-static axial-crushing tests for these tailor rolled tubes, it shows that the first fold always starts at the end of thin zone and gradually extends to the thick zone. Meanwhile, the loading and energy absorption trends show obvious increases, which are closer to the ideal case for energy absorbing parts. The corresponding FE models considering both thickness and performance distributions are also established, which have been verified by experimental test. Moreover, dynamic tensile tests are performed at varied strain rates. The effect of strain rate on crashworthiness is quantitatively analyzed and it is taken into account in the FE model. Combined with the practical part, a typical vehicle front assembly is used in frontal collision. Among these, the car crash boxes with conventional uniform thickness and novel varied thickness are selected to compare their crashworthiness. In order to determine the optimized geometric distribution of this novel structure, a multi-objective optimization technique is applied to the crashworthiness problems. Based on the Response Surface Methodology (RSM) and Genetic Algorithm (NSGA-II), the energy absorption of the optimized design has increased by 16.2% and 6.71% in two frontal collision conditions, while the weight reduced by 12.9%. From the failure modes, the deformation stability of novel design under shearing action is even higher.


ABSTRACT: Elastic memory composites (EMCs) consisting of carbon fibers embedded in a shape memory polymer (SMP) matrix are receiving substantial interests in deployable space structures. Their favourable ability to be packaged to a much high folding curvature is due to that the soft SMP matrix allows the fibers to micro-buckle without breaking. This paper studies the buckling mechanics of fibers embedded in a thin EMC plate at finite strain under pure bending. The analytical expressions of three key parameters, namely the locations of neutral strain surface and critical buckling surface, the half-wavelength of buckling fibers, are determined by energy method. The fiber is modeled as 3D linear elastic solid, and its size effect on the shear strain of matrix is considered. Detailed discussions and comparisons are provided between the results obtained from this work and the ones without considering the fiber size effect. It is shown that considering the size effect of fibers has an influence on the half-wavelength and could reasonably predict the scope of the model, but it produces little differences on the variation trend of locations of neutral strain surface and critical buckling surface.

Rihuan Lu, Xianghua, Shutao Fu, Zigan Xu, ... Lizhong Liu, “Experiment and simulation for the crushing of tailor rolled tubes with various geometric parameters”, International Journal of Mechanical Sciences, Vol. 136, pp 371-395, February 2018

ABSTRACT: By properly controlling the parameters of the rolling mill, multiple types of tailor rolled blanks (TRBs) are obtained, which in turn are used to form the tailor rolled tubes (TRTs) with axially varied thickness. Axial-crushing tests have been performed, and the results show that the reaction forces of TRTs show a rising trend with the integrative effect of crushing and repetitive load fluctuations after reaching the relatively low initial loads. Furthermore, investigations of different thickness and lengths are introduced into the TRT structures. It can be concluded that more energy can be absorbed for TRTs when choosing more edge numbers of the polygonal cross-sections. By contrast, the biggest difference in energy absorption is between the triangle and circular section shape, which is about 43.4%. In addition, the energy absorption capacities of TRTs with
longer tube or side lengths are improved, but the energy absorption efficiencies are decreased by 21.76% and 8.7%, respectively. Meanwhile, the various distributions of transition zone and layout mode not only alter the characteristics of load curves but also affect the energy absorption capacity and initial resistance. Furthermore, multi-tube structures including TRTs, tailor welded tubes (TWTs) and traditional uniform tubes (UTs) are introduced to carry out the contrast crushing experiments. The initial peak loads of TRTs are the lowest, which are in the range of 43.05–58.28 kN. For the energy absorption, the UT structures can absorb more energy before the moving head reaches about 2/3 of the overall collapse stroke. However, the ability of TRTs to absorb energy is improved significantly in the later stage, making the overall energy absorption greater than in UTs. The reasons for the improved energy absorption efficiency of TRTs are discussed in detail. The corresponding FE models considering the variation of thickness and material properties of TRTs are established and verified with the experiment results. In order to conveniently predict the energy absorption performance of crushing TRTs, mathematical models are adopted.

ABSTRACT: This paper presents a simplified analytical model for determining the critical stress of distortional buckling of lipped channel-sections with stiffened web made from cold-form steel (CFS). Lipped channel-section with stiffened web have been shown to have a distinct advantage in resisting local buckling and are associated with the higher distortional buckling stress, when compared to the channel-section without stiffeners. It is widely used as a substitution for standard channel-section in cold form steel construction applications. In the current work, CFS channel-sections with stiffened web are investigated based on the flange–lip model. In order to determine the stiffness of rotational springs representing the restraining effect of the web to the flange–lip system, the web with different type of stiffeners is modeled as an orthopedic plate. Using the total potential energy principle, the formula for calculating the local buckling stress of the stiffened web considering loading scenarios including a pure compression and a pure bending moment are derived. The stiffness of rotational spring can be obtained. Finally, the prediction of distortional buckling critical stress of lipped channel-section with different type of stiffened webs is carried out, which is shown to be in good agreement with those calculated by the finite strip method (FSM).

ABSTRACT: Composite lattice cylindrical shells widely utilized in aerospace engineering are susceptible to experience large temperature excursions, and generate undesirable thermal deformation. Here, we devise novel composite lattice cylindrical shells which can exclusively present a wide range of negative, positive and especially zero coefficient of thermal expansion (CTE) through structural design and rational arrangement of commonly available positive CTE composites. Theoretical analysis figures out the thermal deformation mechanism, and clearly establishes the important relationship that with adequate circumferential triangle units, the CTEs of the lattice cylindrical shells closely approach to the CTEs of the corresponding triangle and planar lattice composites. Finite element analysis firmly confirms the tailorable thermal expansion characteristics. Furthermore, in practical design of lattice cylindrical shells with commonly available composites, a wide range of tailorable thermal expansion up to −2200 to 2200, which is substantially larger than those of available engineering materials, can be easily achieved. Such wide range of CTEs and lightweight feature enable these composite lattice cylindrical shells to be potentially used in aerospace engineering.

ABSTRACT: Thin elastic circular rings can be subject to various loading profiles when used to stiffen long pipes or aboveground cylindrical storage tanks. Specific nonuniform loading profiles have been used by many researchers in theoretical analyses. However, real loading patterns may deviate slightly from the theoretical approximation. The sensitivity of rings to initial imperfections is highlighted in this work. This study investigates the effect of small imperfections in nonuniform loading of the cosine form. A Duffing-type nonlinear differential equation was solved using a perturbation technique to describe the effects of a “follower” loading normal to a ring with large deformations. It is found that the lower buckling mode will govern with the existence of any magnitude of imperfection corresponding to the shape of the fundamental mode.

Feng Liang, Xiao-Dong Yang, Ying-Jing Qian and Wei Zhang, “Transverse free vibration and stability analysis of spinning pipes conveying fluid”, International Journal of Mechanical Sciences, Vol. 137, pp 195-204, March 2018

ABSTRACT: In this paper, the transverse free vibration and stability are analyzed for spinning pipes conveying fluid as a typical example of doubly gyroscopic systems. The partial differential equations of motion are derived by the extended Hamilton principle, and are then truncated by the 4-term Galerkin technique. The natural frequencies, complex modal motions and responses to initial conditions are comprehensively investigated to display the essential dynamical properties of such spinning structures conveying fluid. It is indicated that the qualitative stability of the present system mainly depends on the effects of fluid-structure interaction (FSI) and mass ratio, while the spinning speed plays a significant role in determining the quantitative values of the frequency. The critical flow velocities are independent of the spinning speed and mass ratio. Forward and backward whirling motions are found to take place alternatively for the first four modes, and a ‘traveling wave’ with spatial configuration is observed during vibrations. The gyroscopic couplings caused by spin and FSI will yield great impacts on the energy transfers between different general coordinates.


ABSTRACT: Dynamic buckling of viscoelastic sandwich truncated nanocomposite conical shell subjected to moisture, temperature and magnetic field is presented in this paper. This class of structures is of great interest due to its extensive use in aerospace applications. The layers of the structure are made from a multiphase nanocomposite consist of polymer-carbon nanotubes (CNT)-carbon fibers. The micromechanics and Halpin-Tsai equations in hierarchy are applied for calculating the effective material properties of the multiphase nanocomposite layers. The structural damping effects are considered based on Kelvin–Voigt theory. The surrounding medium is simulated using visco-Pasternak model. Utilizing the first order shear deformation theory (FSDT), energy method and Hamilton's principle, the motion equations are derived. Differential quadrature method (DQM) and Bolotin's method are applied for solution of the motion equations to obtain the dynamic instability region (DIR) of the structure. The effects of various parameters such as structural damping, viscoelastic medium, magnetic field, number of layers, volume fraction of CNTs, temperature and moisture changes as well as boundary conditions on the DIR of the structure are studied. The results reveal that by increasing the moisture and temperature changes, the DIR will be happened at lower excitation frequencies.

ABSTRACT: This paper presents an investigation on the energy absorption behavior of shrink circular tube under quasi-static loading by experimental and numerical methods. The circular tube is shrunken in radial direction under axial compression by a cone bush. Energy is absorbed by the plastic bending/compression of tube and the friction between tube and cone bush. Quasi-static crushing tests on aluminum alloy circular tubes demonstrate the feasibility of this type of energy absorber. Numerical simulations are performed to investigate tube deformations and driving force – stroke responses, which agree well with experimental results. On the basis of validated numerical model, effects of friction coefficient, cone angle, and tube dimension on driving force response and energy absorption efficiency are investigated by numerical simulations. It is observed that the shape of driving force – stroke curve is significantly affected by cone angle and tube dimension, whereas it is almost not affected by friction coefficient. Friction energy is almost linearly dependent on friction coefficient, and plastic energy almost linearly increases with an increase in cone angle. In addition, the compact tube has a higher energy absorption efficiency. A comparison on the maximum specific energy absorptions of shrink circular tube and expansion circular tube, reveals that shrink circular tube has a higher energy absorption efficiency.


ABSTRACT: In this article, a three-dimensional nonlinear dynamic model, which takes into account both the geometric and hydrodynamic nonlinearities, is presented to characterize the behavior of a flexible fluid-conveying pipe under vortex-induced vibration by extended Hamilton's principle. It should be noted that the pipe conveying fluids is placed in a uniform cross flow. Two distributed and coupled van der Pol wake oscillators are utilized to model the fluctuating lift and drag coefficients, respectively. The finite element method is adopted to directly solve the highly coupled nonlinear fluid-structure interaction equations. Model validations are firstly performed through comparisons with published experimental data and numerical simulation results. The results show that the natural frequency will rapidly decrease with the increase of internal flow velocity. Parametric studies highlight that the maximum displacements and stresses of the riser can be increased or decreased depending on the internal flow velocity, and the critical internal flow velocities result in the increase of mode order for different cross-flow velocities. The opposite variation between axial and in-line or cross-flow displacement amplitude and maximum stress within the modal transition region is revealed. Moreover, the discontinuous jumping phenomenon of in-line response modal is discovered.


ABSTRACT: The purpose of this paper is to study dynamic analysis of composite laminated doubly-curved shells with various boundary conditions by a domain decomposition method. Multi-segment partitioning technique is used to establish the formulation based on the first-order shear deformation theory. Meanwhile, the interfacial potential energy is introduced to maintain the continuous condition on the contact surface of the adjacent segments. The displacement admissible functions for each doubly-curved shell segment are uniformly expanded to the double mixed series which is with the Fourier series along the circumferential direction and the orthogonal polynomials (i.e. Chebyshev orthogonal polynomial, Legendre orthogonal polynomials and Ordinary power polynomials) along the meridional direction. A series of numerical examples are given for the free vibration, steady-state vibration and transient vibration of laminated doubly-curved shells subject to different geometric and material constants. By comparing with the literature results and the results conducted by the general finite element program ABAQUS, the numerical results show that the present formulation has good
computational accuracy and efficiency. Based on the verification, the effect of external forces, geometric and material parameters on dynamic analysis (free, steady-state and transient vibration) of laminated doubly-curved shells are also studied.

Kang Gao, Wei Gao, Di Wu and Chongmin Song, “Nonlinear dynamic buckling of the imperfect orthotropic EFGM circular cylindrical shells subjected to the longitudinal constant velocity”, International Journal of Mechanical Sciences, Vols. 138-139, pp 199-209, April 2018
ABSTRACT: In this study, an analytical approach on the nonlinear dynamic buckling of the orthotropic circular cylindrical shells made of exponential law functionally graded material (E-FGM) subjected to the longitudinal constant velocity is investigated with the incorporation of mercurial damping effect. The material properties are assumed to vary gradually in the thickness direction according to an exponential distribution function of the volume fraction of constituent materials. Theoretical formulations are derived based on improved Donnell shell theory (DST) and accounting for von-Kármán strain-displacement relation, initial imperfection and damping effect. By applying Galerkin method and Airy’s stress function, the obtained nonlinear differential equations are solved numerically by the fourth-order Runge–Kutta method. The nonlinear dynamic stability of the orthotropic FG cylindrical shell is assessed based on Budiansky–Roth criterion. Additionally, a parametric study is conducted to demonstrate the effects of various velocities, initial imperfections, damping ratios, inhomogeneous parameters on nonlinear dynamic buckling behavior of an imperfect orthotropic FG cylindrical shell. Comparing results with those in other publications validates the proposed method.

ABSTRACT: Electrostatic instability is one of the main features of many electrostatic MEMS and NEMS devices. In this paper, we investigate how the electrostatic instability of a plate-like electrode can be affected by a differential pressure. The results of this study indicate that the presence of differential pressure can have a significant influence on the equilibrium path, the number and location of unstable points, and the post-instability behavior. As a result, while the system is loaded and unloaded electrically, the electrostatic instability might lead to a snapping behavior. The noticed snapping behavior of a flat plate makes it very appealing for sensing and actuating applications. This study is based on both a semi-analytical framework and finite element simulations. The proposed analytical solution is shown to be accurate enough to be used as an effective tool for design.

Xianqian Wu, Kailu Xiao, Qiuyun Yin, Fachun Zhong and Chenguang Huang, “Experimental study on dynamic compressive behaviour of sandwich panel with shear thickening fluid filled pyramidal lattice truss core”, International Journal of Mechanical Sciences, Vols. 138-139, pp 467-475, April 2018
ABSTRACT: The dynamic compressive behaviour of sandwich panels with shear thickening fluid (STF) filled pyramidal lattice truss cores at high strain rates is studied and compared with that of pure STF as well as the sandwich panels with empty and water filled pyramidal lattice truss cores by modified split Hopkinson pressure bar (SHPB) apparatus. The dynamic compressive strengths of the sandwich panels while filled with STF increase significantly when compared to the strengths of the sandwich panels with empty pyramidal lattice truss cores. It is interesting to note that the sandwich panel with the STF filled pyramidal lattice truss core shows “1 + 1 >> 2” dynamic energy absorption behaviour. The excellent energy absorption behaviour of the sandwich panel with STF filled truss core is interpreted by the transformation of deformation modes of core beams from non-symmetry to symmetry after filled with the STF through strong interaction between the buckling behaviour of pyramidal lattice truss core and the shear thickening behaviour of the filled STF material.

ABSTRACT: In order to improve the crashworthiness and energy absorption performance, this paper introduces the structural bionics to the structural design of crash box and proposes a novel structure. Taking the human tibia as a bionic object, the novel crash box is composed of a concave structure shell and an inner core filled with negative Poisson's ratio (NPR) structure material. In view of the gradient characteristics of the cancellous bone structure of the tibia, the NPR inner core is designed as a functional gradient distribution structure along the longitudinal direction of the crash box. Based on this, by combining the optimal Latin hypercube design and response surface methodology, a multi-objective optimization design is conducted for the novel crash box based on archive-based micro genetic algorithm (AMGA) and improved non-dominated sorting genetic algorithm (NSGA-II). Simulation results show that the novel crash box optimized by NSGA-II algorithm can improve the energy absorption characteristics and comprehensive crashworthiness more effectively, and make the collision process controllable and stable. The results of this paper can provide some reference for the design and optimization of the crash box.


ABSTRACT: In this paper, we proposed a strategy to improve the energy absorption efficiency of a square multi-cell tube by designing the lateral wall thickness distribution. We uniformly arranged the walls so that we could vary the thickness of the walls while forming a square multi-cell tube. Explicit formulations for predicting the mean crushing force of the multi-cell tube under axial compression were derived based upon the Super Folding Element method. The energy absorption capacities of a variety of typical square multi-cell tubes with different lateral thickness distribution were obtained by theoretical and numerical analysis. The predicting results of the formulations have good agreement with the numerical simulation performed by explicit non-linear finite element method. The theoretical and numerical results showed that the energy absorption capacities could be improved by modifying the lateral thicknesses of the multi-cell tube. The optimization based on a surrogate model and the explicit prediction formulations was carried out to find the optimal lateral thickness distribution of $3 \times 3$ square multi-cell tube. We found that the tube has better energy absorption properties when the material is concentrated in the center of the cross-section. Based on the optimization results, a non-convex multi-corner multi-cell square tube with lateral variable thickness was proposed that resulted in a 48.3% improvement in energy absorption capacity compared with traditional uniform thickness multi-cell tube.


ABSTRACT: This paper presents a new spectral element based on the dynamic stiffness matrix of a prestressed cylindrical shell. The dynamic stiffness matrix is built using first-order shear deformation theory, and natural frequencies are processed easily. Vibration analyses are performed with numerical examples to determine the performance of this approach and the effect of prestressing on frequency response functions. This element has many advantages over the finite element method in terms of accuracy, model size and computing time.
M. Sahebnasagh, M. Nikkhah-Bahrami and R.D. Firouz-Abadi, “Effect of multiphase fluid and functionally 
graded density fluid on the stability of spinning partially-filled shells”, International Journal of Mechanical 
ABSTRACT: The effect of a multiphase fluid, including an arbitrary number of liquid phases, and a 
functionally graded density fluid on the stability of rotating partially-filled cylindrical shells is investigated. The 
first-order shear shell theory is used for modeling the structural dynamics of the shell and a 2D model is 
introduced based on the Navier–Stokes equations, for fluid motion. The multiphase and the functionally graded 
density fluids are arranged according to the mass density in a steady state condition due to centrifugal forces. 
Using the boundary conditions between liquid phases and the boundary conditions of the fluid on the cylinder 
wall, the coupled fluid-structure system model is obtained. This coupled fluid-structure model is then used to 
specify the critical velocity of the system. Due to the extreme complexity of the characteristic equation of a 
rotating shell partially filled with a functionally graded density fluid, a numerical technique is devised to 
alalyze the stability of the coupled system by using a multiphase fluid.

Jie Wang and Adam J. Sadowski, “Elastic imperfect tip-loaded cantilever cylinders of varying length”, 
ABSTRACT: A number of recent publications have explored the crucial relationship between the length of a 
thin cylindrical shell and the influence of pre-buckling cross-sectional ovalisation on its nonlinear elastic 
buckling capacity under bending. However, the research thus far appears to have focused almost exclusively on 
uniform bending, with ovalisation under moment gradients largely neglected. This paper presents a comprehensive computational investigation into the nonlinear elastic buckling response of perfect and imperfect thin cantilever cylinders under global transverse shear. A complete range of practical lengths was investigated, from short cylinders which fail by shear buckling to very long ones which exhibit 
local meridional compression buckling with significant prior cross-section ovalisation. Two imperfection forms 
were applied depending on the length of the cylinder: the linear buckling eigenmode for short cylinders and a 
realistic weld depression imperfection for long cylinders. The weld depression imperfection was placed at the 
location where the cross-section of the perfect cylinder was found to undergo peak ovalisation under transverse 
shear, a location that approaches the base support with increasing length. Compact closed-form algebraic 
expressions are proposed to characterise the elastic buckling and ovalisation behaviour conservatively, suitable 
for direct application as design equations. This study contributes to complete the understanding of cylindrical structures of varying length where the 
dominant load case is global transverse shear, including multi-strake aerospace shells with short individual 
segments between stiffeners and long near-cylindrical wind-turbine support towers and chimneys under wind or 
seismic action.

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[5] Lundquist EE. Strength tests of thin-walled duralumin cylinders in combined transverse shear and bending. National Advisory 
Committee for Aeronautics; 1935. Tech- nical Note 523.
Weiwei Li, Yonghao Luo, Ming Li, Fangfang Sun and Hualin Fan, “A more weight-efficient hierarchical hexagonal multi-cell tubular absorber”, International Journal of Mechanical Sciences, Vol. 140, pp 241-249, May 2018
ABSTRACT: Hierarchical metallic thin-walled tubes are more weight-efficient than single-cell tubes (STs) in energy absorption. Tubes with regular hexagonal single-cell section and hierarchical section are designed, tested and analyzed. Crushing mechanisms of these structures are revealed through finite element analyses (FEAs) and axial compression experiments. It is found that for hierarchical tubes (HTs) there are three folding styles, including sub-cell folding, mixed folding and global folding. Sub-cell folding greatly increases the mean crushing force (MCF) of the tube and the MCF reaches to the apex when appears the mixed folding, which is the transition from sub-cell folding to global bending. Plastic models for these three folding styles are built and consistently predict the MCF. The research indicates that the HT is a more weight-efficient energy absorber.

ABSTRACT: Hierarchical anisogrid stiffened panel (HASP) is applied to construct a protective door structure, for its advantages in rigidity improving and weight saving. In this research, sheet molding compound (SMC) material is selected to make a new all-composite blast-resistant door structure through hot-pressing molding method. Facesheet of the blast-resistant door is stiffened by two-scale stiffeners to improve the global bending rigidity and restrain the local deformation of the facesheet simultaneously. Explosion experiment has been carried out to reveal the blast response of the composite door. Equivalent theory and dynamic structural model are built to analyze the blast response and predict the potential failure of the protective HASP. In the analysis, damping effect to the dynamic deformation and permitted blast wave of the SMC door is analyzed through introducing damping coefficient and damping force into the dynamic motion equation. An engineering method is introduced to calculate the damping coefficient based on the strain variation. Damping of the composite material greatly reduces the magnitude of the dynamic deformation and attenuates the vibration rapidly.

ABSTRACT: Hierarchical structures are widely observed in nature, and used in engineering due to superior mechanical properties. In this paper, a novel hierarchical circular tube (HCT) by iteratively adding self-similar sub-circle at the junctions of the primary ribs is proposed to enhance structural crashworthiness performance. The finite element model of HCT is firstly established through LS-DYNA and validated via experiment testing. The energy absorption performance of different hierarchical HCTs is investigated under dynamic load. The hierarchical organization has remarkable potential to improve the crashworthiness behavior of thin-walled structure, especially, the 2nd order HCT exhibits significant advantages for energy absorption efficiency. Then, parametric designs are performed to explore the crashworthiness effect on main geometrical parameters of 2nd order HCT. Furthermore, theoretical model of 2nd order HCT is derived based on super folding element method, and obtain the good prediction accuracy for energy absorption and mean crushing force. To further obtain the optimal design of the 2nd order HCT, multi-objective optimization is performed by employing radial basis function (RBF) neural networks and multi-objective particle swarm optimization (MOPSO) algorithm. The several optimal structures are obtained under different peak crushing force (PCF). The findings of this research offer a new route of designing novel crashworthiness structure with high energy absorption capacity.
ABSTRACT: The mechanical properties of anti-trichial honeycombs under quasi-static compression with large deformation are studied by both experiments and theoretical analysis. It is shown that the cells’ collapse of the anti-trichiral honeycombs dominated by both the ligaments’ rotation around the plastic hinges and the rotation of cylinders. The theoretical analytical models are established to predict both the NPR and the crushing stress of the anti-trichiral honeycombs. The analytical predictions show good agreement with the experimental results. It is shown that the crushing stress of the honeycomb decreases with the ligament's length ratio \( L/r \), but increases with the wall thickness. As for the honeycomb’s Poisson's ratio, it increases with the ligaments’ length ratio and decreases with the honeycomb's deformation, while the wall thickness has no influence on it. The anti-trichiral honeycomb exhibits NPR effect only when the ligament's length ratio less than 5.5. However, when the ligaments’ length ratio is more than 10, the anti-trichiral honeycomb shows positive Poisson's ratio during the whole compression. When the ligaments’ length ratio is in the range of 5.5 through 10, the anti-trichiral honeycomb appears NPR under small deformation, but positive Poisson's ratio under large deformation. These light up a refer to the design of the anti-trichiral honeycombs.

ABSTRACT: Considering surface effects on nanoscale structures, an isogeometric shape optimization method is developed for curved structures using Naghdi’s shell formulation. Since the curved structures are very sensitive to geometrical changes, the geometric exactness of isogeometric approach successfully prevents the loss of higher-order geometric information in design sensitivity analysis (DSA). A direct differentiation method is employed for the DSA, where the control points are selected as the design variables and describe the flexible modeling of free-form shell surfaces. Through numerical examples, we verified the accuracy of isogeometric analysis whose framework shows better convergence rate than finite element analysis due to the exact geometry and the higher order geometric information in the DSA formulation. The surface Lamé constants turns out to alter the ratio between the portion of membrane and bending energies. Also, the optimal shape is dependent on the residual surface stress that affects its stress state.

ABSTRACT: In this paper a physically based and deterministic design procedure for spherical shells under external pressure is introduced. Within the new design concept the membrane energy of a sphere is incrementally reduced by means of perturbation cutouts, until a bending energy dominate state is identified. The threshold between membrane energy state and bending energy state represents a robust plateau for the buckling pressure.
A comprehensive numerical investigation was performed in order to study the influence of radius-to-thickness ratio (R/t) as well as the dome height-to-base radius ratio (H/r). The results verify that both geometric properties ratios significantly influence the lower-bound buckling pressure, especially if plastic buckling occurs. Improved shell buckling design factors are given in the form of an simple analytic equation. The corresponding threshold KDFs were validated with a large number of buckling experiments and deliver much higher KDFs than currently used empirical guidelines.
Based on the new design criterion lower-bound estimation for the buckling pressure of a tori-spherical bulkhead and the inner dome of the cryogenic upper stage ESC-A from the European space launch-vehicle Ariane 5 are determined.

ABSTRACT: In this study, we investigate buckling and postbuckling of etching-induced wiggling in a bilayer structure consisting of mask and masked layers. To show effects of explicit modeling of etching process, two mask–masked ridge models with and without etching (Models w/E and w/oE) are analyzed using finite element analysis. The etching process is explicitly introduced via step-by-step eigenvalue buckling analysis. Although Model w/oE predicts a constant value of the critical wavelength of wiggling regardless of the change in ridge width, Model w/E predicts a shorter wavelength depending on the decrease in ridge width and the increase in intrinsic compressive stress in the mask layer. In postbuckling analysis, Model w/oE predicts a monotonic increase in the wiggling amplitude with the constant wavelength, whereas Model w/E predicts saturation of the wiggling amplitude owing to the decreasing wavelength. In the explicit modeling of etching process, the wiggling behavior shows completely opposite tendencies. Dimensional analysis is performed to obtain empirical equations, which are compared with an experiment.

ABSTRACT: In this paper, rectangular and slotted windows were introduced to thin-walled square tubes to improve the crashworthiness of tubular structures. Four one-windowed tubes, twelve three-windowed tubes and two conventional tubes were studied by quasi-static axial crushing tests and numerical simulations. Optical measurement system MatchID was employed to achieve full-field strain measurement. The results showed that the collapse modes of conventional tubes belonged to symmetric mode, while the others were irregular mode. In addition, the introduction of windows could effectively reduce the initial peak load and increase the crush force efficiency (CFE) over conventional tube. However, the SEAs of windowed tubes did not necessarily improve even though large mass reduction for windowed tubes. The initial peak load is inclined to decrease with the increase in area ratio (η, defined as the ratio between the windowed area and the surface area of conventional tube). Furthermore, it was found that cracks appeared in numerous specimens in the tests due to welding. And with the increase in length ratio (λ, defined as the ratio between the length of all cracks in one tube and the tube height), CFE and SEA had a decreasing trend, while length ratio had little effect on initial peak load.

ABSTRACT: The natural frequencies of pipes conveying gas-liquid two-phase slug flow are explored, considering the significance of the intermittent characteristic of gas-liquid two-phase slug flow particularly. The widely used finite element method is employed to establish the theoretical model. The local flow parameters including local gas and liquid velocities and local liquid holdup varying with time and position along the pipe are calculated to obtain the global matrix equation of motion for the system. An experiment is conducted to verify the theoretical model. The results show that the time domain values of the natural frequency would keep periodicity during the process of slug flow. Root-mean-square of the natural frequency is employed to represent the characteristic of the piping system natural frequency. If the superficial gas velocity is given, root-mean-square of the natural frequency will decrease with the increase of the superficial liquid velocity. Yet if the
superficial liquid velocity is given, root-mean-square of the natural frequency will increase firstly and then decrease with the increase of superficial gas velocity when the superficial liquid velocity is relatively large. Thus a critical superficial gas velocity exists for these conditions. The range of superficial gas velocity that could make the system become unstable may be predicted preliminarily by analyzing this critical value. Sufficient analysis of slug parameters and geometrical parameters of the pipes is necessary to obtain the critical superficial gas velocity. Finally, the divergent instability of the piping system is predicted based on the above analysis.

ABSTRACT: This paper presents the extensive non-linear finite element (FE) analysis of the dynamic ultimate strength of the ship plate structures under uniaxial compressive load. An empirical formula for predicting the dynamic ultimate compressive strength of ship plates, expressed in terms of the geometric dimensions of plates and impact speeds, was developed by curve fitting of FE results of 561 ship plates. The dynamic ultimate strength of a tested specimen is calculated based on the nonlinear finite element method, and the comparison with test results show the applicability of the present numerical method. The comparison between the proposed empirical formulation and the FEM results of 561 ship plates show the accuracy of curve fitting. The formula implicitly includes the effect of initial imperfections with an average level. The proposed formula was also applied to the outer bottom plates of container ships and oil tanker and a satisfactory agreement between the proposed formula and FE results was obtained.

ABSTRACT: This article presents theoretical analysis of the bifurcation behavior of metallic thick-walled cylindrical structures, extremely loaded by combined pressure and axial force. The analysis, which is based on the continuum theory, takes into account large elastic–plastic deformations and non-linear isotropic hardening. Bifurcation analysis investigates the uniqueness of the velocity field in the fundamental state, which adopts a constitutive law is based on the von Mises yield criterion. The solution successfully predicts load and deformation limits associated with the onset of bulging and buckling bifurcation of thick-walled cylindrical structures. The theoretical solution is validated by comparing the theoretically obtained results with those obtained independently using nonlinear finite element simulations utilizing the commercial FEA software Abaqus. As an example, the numerical solution is presented for a thick, relatively long cylinder. The results show that, for axially compressed long cylinders, axial deformations at column buckling increase with additional internal or external pressure. The results also explain and quantify the transition from axisymmetric bulging to column buckling bifurcation modes. It also explains the occurrence of non-symmetric (localized) bulging, which follows the axisymmetric bulging. The findings provide valuable information in the safety design of extremely loaded hollow cylindrical columns, thick-walled pressure vessels, piping and other cylindrical structures.

ABSTRACT: Thin-walled structures have been widely used as energy absorbers due to their light weight, high energy absorption efficiency and good machinability. However, the existing researches mainly focus on different sizes of tubes with the same shape, but the topological relationship of cross-sectional shape also has an
important effect on the energy absorption of structure. In view of the fact that the existing corrugated tubes are mainly studied about the corrugation in the axial direction, we put forward a new type of lateral corrugated tube (LCTs) with a sinusoidal cross-section. The evolution of its cross-section could be controlled through the amplitude (A), the basic nominal diameter (R₀) and the number of corrugations (N). In the meantime, a systematic crashworthiness study is carried out with multi-objective optimization design. The results show that A, N and the wall thickness (t) are the important parameters that affect the deformation mode and crashworthiness. Numerical simulation of axial compression of 16 different LCTs with different A and N shows that when N = 6 and N = 8, the SEA of the LCTs are increased by 27.91% and 27.24% respectively compared with that of the ordinary circular tube (CTs). Subsequently, the optimal Latin hypercube design method is used to determine the sample points and Kriging method is used to construct the surrogate models of specific energy absorption (SEA) and initial peak force. Finally, the multi-objective optimization of LCTs and CTs are carried out by using the non-dominated sorting genetic algorithm-II. The optimization results show that the LCTs has better crashworthiness than CTs, and the SEA is increased by 53.65% compared with the optimized design of the CTs. Compared with CTs, the SEA of the LCTs can be extended to a wider area, indicating that the LCTs has a wider range of application and design space than CTs.

ABSTRACT: The creep failure lives of a pyramidal lattice truss panel structure at compressive and tensile loads have been investigated by theoretical and finite element methods. Two analytical models are derived to calculate the life of creep-rupture and creep-buckling. The results reveal that the creep-rupture life is highly sensitive to the geometry dimensions. With the decreases of the stamping angle, cutting angle, truss length and the increases of the truss width and thickness, the creep-rupture life decreases significantly. The creep-buckling model presents that the creep-buckling life can be improved by increasing the width and thickness of truss and decreasing the length of truss. A synthetically analytical model combines the creep-rupture and creep-buckling is proposed to predict the creep failure time accurately. The transition mechanism from creep-buckling to creep-rupture is also extensively studied. Creep-buckling is the dominant failure mechanism as the applied stress approaches the critical stress. The solid truss is inclined to creep-rupture when the compressive stress is smaller than the critical stress.

Zhaoye Qin, Zhengbao Yang, Jean Zu and Fulei Chu, “Free vibration analysis of rotating cylindrical shells coupled with moderately thick annular plates”, International Journal of Mechanical Sciences, Vols. 142-143, pp 127-139, July 2018
ABSTRACT: Thin cylindrical shells are commonly employed to connect adjacent disks in large rotating machinery. The vibration characteristics of coupled cylindrical shell and annular plate components have a significant influence on the rotor dynamics. This paper provides a general approach for the vibration analysis of a rotating cylindrical shell coupled with an annular plate. The Sanders shell theory and Mindlin plate theory are employed to calculate the strain energy of the shell and plate, respectively. The Coriolis and centrifugal effects due to the rotation are taken into account. The artificial spring technique is adopted to simulate the coupling and boundary conditions. By taking Chebyshev polynomials as the admissible functions, the Rayleigh–Ritz method is employed to derive the motion equations for the rotating shell-plate combination. The approach proposed is validated by comparing with the available results in literature and finite element analysis results. The traveling wave motion of the coupled shell and plate structure is investigated. The effects of the geometric parameters and the boundary and coupling conditions on the vibration behavior of the coupled structure are evaluated. The
present approach can not only evaluate free vibrations of coupled shell and plate structures, but also be extended to vibration analysis of disk–drum rotors involving cylindrical shells.

Yuanlong Wang, Wanzhong Zhao, Guan Zhou and Chunyan Wang, “Analysis and parametric optimization of a novel sandwich panel with double-V auxetic structure core under air blast loading”, International Journal of Mechanical Sciences, Vols. 142-143, pp 245-254, July 2018
ABSTRACT: Blast shock wave is a big threat to the military vehicle and may cause vehicle damages and passenger casualties. It is a big issue to balance the protective performance and lightweight property of military vehicle. In these days, many types of sandwich panels with different cores were applied as protective plates in military vehicles. In view of the excellent energy absorption capability of auxetic structure, applying auxetic structure as sandwich panel core for blast protection purpose is a promising field. However, existing in-plane configuration of two-dimensional auxetic honeycomb core always represent anisotropic behaviour. In this paper, a novel sandwich panel with three-dimensional double- V Auxetic (DVA) structure core, which can produce isotropic mechanical behavior, was proposed for air blast protection purpose. Its primary structural parameters and their relations were discussed, and a parametric numerical model was established. In order to reduce both the dynamic response under air blast loading and mass, the design variables and objective function of the DVA core optimization problem were confirmed, then parametric optimization was conducted based on Latin Hypercube Sampling (LHD) method, Gaussian process metamodel (GPM) and multi-objective particle swarm optimization algorithm (MOPSO). Finally, it is proved that the applied optimization process is efficient and can obtain accurate optimum points. The proposed DAV core sandwich panel performed much better both in lightweight and protection than solid plate and has an apparent merit in lightweight aspect compared with square honeycomb core sandwich panel.

ABSTRACT: We present a non-classical model for bending, free vibration and buckling analyses of functionally graded (FG) isotropic and sandwich microplates based on the modified couple stress theory (MCST) and the refined higher order shear deformation theory. Unlike the classical higher order shear deformation theory, the present model retains four variables and contains a single material length scale parameter which can be considered as the size-dependent effect. Effective material properties of FG isotropic and sandwich microplates are calculated by a rule of mixture. The discrete system equations are derived from the Galerkin weak form and are then solved using the moving Kriging meshfree method. Due to satisfying the Kronecker delta function property of moving Kriging integration (MKI) shape function, essential boundary conditions are directly enforced by the same way as the standard finite element method. In addition, a simple rotation-free technique originated from isogeometric analysis is used to eliminate the slopes in clamped plates. The effects of material length scale parameter, volume fraction, geometrical parameters and boundary conditions are investigated to conduct the effectiveness of the present approach.

ABSTRACT: This paper investigates free vibration of graphene nanoplatelet (GPL) reinforced laminated composite quadrilateral plates using the element-free IMLS-Ritz method. The effective material properties including Young's modulus, mass density and Poisson's ratio are determined by the modified Halpin–Tsai
model and rule of mixture. The first-order shear deformation theory (FSDT) is employed for formulation of the energy functional. Based on the IMLS-Ritz approximation, the discrete vibration equation of the laminated composite quadrilateral plates is derived. The accuracy of the IMLS-Ritz results is examined by comparing with the published values. A comprehensive parametric study is carried out, with a particular focus on the effects of weight fraction, distribution pattern, geometry and size of GPL reinforcements, total number of layers and geometric parameters of quadrilateral plates on the natural frequencies of GPL reinforced laminated composite quadrilateral plate.


ABSTRACT: Well-designed honeycomb sandwich panels are known to have superior blast performance compared to their corresponding solid panel of the same mass. However, the residual structural capacity of honeycomb sandwich panels and their blast resilience has not been systematically studied. Here, we investigate the structural behavior of all-metal honeycomb sandwich panels after shock loading using detailed numerical simulations. The initial shock is varied from relatively small intensities to moderate intensities sufficient to create material failure and significant plastic deformation in the panel. The structural response of the shock-loaded panels is investigated under quasi-static punch indentation and in-plane compression. The maximum load carrying and energy absorption capacities of shock-loaded panels are quantified for a wide range of initial shock intensities and different panel core densities. Failure maps for the honeycomb panels were constructed for each quasi-static loading condition by considering three failure modes: core failure, face sheet failure, and total panel detachment from its support. This study provides new insights into the behavior and structural resilience of the shock-loaded sandwich panels, while further highlighting their potential in the development of resilient structural systems.


ABSTRACT: A thin-walled circular tube is known to be able to invert externally under axial compression when it is placed upon a profiled rigid die. Such a structure has become a promising candidate for energy absorbing applications due to its high reaction force and good load uniformity. However, the inversion process could become rather unstable when imperfections are present and the friction between the tube and die is high, which largely limits its application. In this paper, we propose the use of corrugated thin-walled tubes. Both simulation and experimental results show that thin-walled corrugated tubes can have a much more stable inversion in comparison with their circular counterparts. They are less sensitive to the surface imperfections, and no stringent requirement of lubrication on the die is necessary. Our research has paved the way for such devices to be used as an effective energy absorption device in many practical applications.


ABSTRACT: This paper deals with the representative challenging buckling problem of a fully free plate under biaxial compression by a distinctive symplectic superposition method, which yields the benchmark analytic solutions by converting the problem to be solved into the superposition of two elaborated subproblems that are solved by the symplectic elasticity approach. The solution is advanced in the symplectic space-based Hamiltonian system rather than in the classic Euclidean space-based Lagrangian system, which shapes the main advantage of the method that a direct rigorous derivation is qualified for obtaining the analytic solutions,
without any assumptions or predetermination of the solution forms. Comprehensive new analytic results for both the buckling loads and mode shapes are presented and validated by the finite element method. The fast convergence and accuracy of the method make it applicable to analytic modeling of more plate problems.


ABSTRACT: The thermal post-buckling responses of Functionally Graded Material shell structures are reported in this paper. Geometrically nonlinear analysis based on a modified First order Shear Deformation Theory are proposed. The modified theory takes into account the shear strains with a parabolic shape function and it verifies a zero shear stresses condition at the top and bottom surfaces. For the numerical computation, four nodes shell elements are implemented. The large displacement is described by Green–Lagrange nonlinear strains. Moreover, it is assumed that the shell structures are exposed to uniform, linear and nonlinear temperature distributions through the thickness direction. The thermal and the mechanical properties are described according to a power law distribution and either temperature-independent or temperature-dependent material properties are considered. Two numerical examples of functionally graded plates and cylindrical shells are presented to highlight the effectiveness and the accuracy of the present finite element procedure. The effect the geometrical parameters, the volume fraction index and boundary conditions on nonlinear responses are performed.


ABSTRACT: Using nonlocal elasticity theory of Eringen, free transverse thermo-elastic vibrations of vertically aligned double-walled carbon nanotubes (DWCNTs) with a membrane configuration is going to be explored methodically. Accounting for nonlocal heat conduction along the side walls of DWCNTs with allowance of heat dissipation from the outer surfaces, the nonlocal temperature fields within the constitutive tubes are assessed for a steady-state regime. The van der Waals interactional forces between atoms of each pair of DWCNTs as well as the innermost and outermost tubes are displayed by laterally continuous springs whose constants are appropriately evaluated. By establishing suitable discrete and continuous models on the basis of the Rayleigh and higher-order beam theories, nonlocal in-plane and out-of-plane vibrations of thermally affected nanosystems of monolayers of DWCNTs are examined and discussed. The critical values of the temperature change are stated explicitly and the role of influential factors on this crucial factor as well as the free vibration behavior are investigated in some detail. Through conducting a fairly comprehensive numerical study, the influences of the slenderness ratio, temperature change in the low and high temperatures, number of nanotubes, small-scale parameter, intertube distance, and stiffness of the surrounding environment on the nonlocal-fundamental frequency are explained. The obtained results from this work could provide crucial guidelines for the design of membranes or even jungles of vertically aligned DWCNTs as thermal interface nanostructures.


ABSTRACT: Due to the mid-frequency problem, the Hybrid Statistical Energy Analysis (SEA) / Traditional Finite Element Methods (TFEMs) methods still cannot provide the dynamic responses of the stiffened-plate composite structures in a wide frequency domain. The main reason is that all of the SEA and TFEMs cannot
provide the reliable numerical solutions in the middle frequency domain when simulating the thin plate substructures. In order to solve the problem, this paper proposes the Composite B-spline Wavelet Elements Method (CBWEM) based on the $c_1$ type wavelet plate and beam elements for modeling the stiffened-plate composite structures and predicting its dynamic responses in a wide frequency domain. Unfortunately, due to the complex interpolation functions and transformation matrices of these $c_1$ type wavelet elements, the existing numerical scheme to construct the constraint matrix will be invalid when modeling the coupling relationship between the $c_1$ type wavelet plate and beam elements. To solve the problem, this study deduces and gives the formulas of the new numerical scheme for constructing the constraint matrix and modeling the stiffened-plate composite structures based on the CBWEM. Besides, the numerical and experimental studies are carried out to verify the CBWEM, respectively. On the one hand, the numerical study displays that the proposed method can solve the mid-frequency problem and provide reliable dynamic responses in a wide frequency domain within an acceptable computational cost. On the other hand, the experimental study shows that the Central Processing Unit (CPU) time to predict the dynamic response in a wide frequency domain is less than 3.5 s only based on the proposed method and the personal computers, and the corresponding numerical solutions are in good agreement with the experimental results. Thus, we can easily conclude that the proposed method can be taken as one useful numerical technique to solve the mid-frequency problem and predict the dynamic responses of the stiffened-plate composite structures in a wide frequency domain.


ABSTRACT: This paper deals with the dynamic buckling analysis of sandwich plates with magnetorheological (MR) fluid core and piezoelectric nanocomposite facesheets. The core is subjected to magnetic field and the facesheets are exposed to 3D electric field. Due to the piezoelectric properties of the facesheets, the top and bottom layers can be used as actuator and sensor, respectively. Hence, a proportional-derivative (PD) controller is employed to control the dynamic buckling and vibration responses of the structure. In addition, the facesheets are reinforced by with non-uniform graphene platelets (GPLs) which their equivalent material properties are obtained using Halpin-Tsai micromechanics model. The structural damping of the piezoelectric layers is considered according to Kelvin-Voigt theory. The sandwich structure is rested on orthotropic viscoelastic model with normal, shear and damping forces. Based on the sinusoidal shear deformation theory (SSDT) and piezoelasticity theory, the motion equations are derived utilizing Hamilton's principle. Applying differential cubature method (DCM), the motion equations are solved for calculating the dynamic instability region (DIR) of the structure. The influences of various parameters such as magnetic field, applied voltage, structural damping, viscoelastic medium, volume fraction and distribution of GPLs, boundary conditions and geometric parameters of the structure are shown on the dynamic buckling behavior of the system. The results are validated with other published work for indication the accuracy of the obtained results. The results reveal that by applying the magnetic field to the MR fluid core, the DIR with be happened at higher excitation frequencies.


ABSTRACT: In this paper, field equations and general solution for axisymmetric thick shell composed of functionally graded incompressible hyperelastic materials are presented. The solution is applied to find stress components in general form for these shells. Both curvilinear and Cartesian coordinates are used to find field equations and general solution. As a special case of the general axisymmetric problem, field equations and stress components of thick-walled hollow cylindrical shell composed of functionally graded material in a
generalized plane strain condition are developed. For modeling hyperelastic behavior, power law strain energy function with variable material parameters is used. Material inhomogeneity is assumed to vary by a power law function in the radial direction and inhomogeneity parameter \( (m) \) is power in the mentioned power law function. Nonlinear regression method is used to find material constants of strain energy function from experimental data. As a result circumferential stretch, radial stress, circumferential stress and longitudinal stress through the radial direction is presented for different values of \( m \). The achieved outcomes display that the material inhomogeneity parameter \( (m) \) and structure parameter \( (\beta) \) of outer radius to inner radius influence considerably on the mechanical behavior of thick-walled hollow cylindrical shell made of functionally graded materials. Accordingly with opting for a proper \( m \) and structure parameter \( (\beta) \), particular FGM hollow cylinder that can meet some special requirements will be designed by engineers.


ABSTRACT: A semi analytical approach is employed to analyze the free vibration characteristics of uniform and stepped combined paraboloidal, cylindrical and spherical shells subject to arbitrary boundary conditions. The analytical model is established on the basis of multi-segment partitioning strategy and Flügge thin shell theory. The admissible displacement functions are handled by unified Jacobi polynomials and Fourier series. In order to obtain continuous conditions and satisfy arbitrary boundary conditions, the penalty method about the spring technique is adopted. The solutions about free vibration behavior of uniform and stepped combined paraboloidal, cylindrical and spherical shells were obtained by approach of Rayleigh–Ritz. To confirm the reliability and accuracy of proposed method, convergence study and numerical verifications for combined paraboloidal, cylindrical and spherical shell with different boundary conditions, Jacobi parameters, spring parameters and maximum degree of permissible displacement function are carried out. Through comparative analyses, it is obvious that the present method has a good stable and rapid convergence property and the results of this paper agree closely with FEM. In addition, some interesting results about the geometric dimensions are investigated.


ABSTRACT: The mechanical behaviour of membranous liquid-filled cylinders is important in many industrial and biomedical applications, such as in modelling the incudostapedial joint in the middle ear. Although membranous liquid-filled containers with various geometries have been investigated under different loading conditions, no study on the mechanical behaviour of membranous circular tubes under tension-compression testing has been published. In this work, we use the theory of large deformations of elastic membranes to develop an analytical model for a liquid-filled circular tube under an axial load, neglecting the effect of gravity. We use the Mooney–Rivlin strain-energy function and numerically calculate solutions for short to moderate tube lengths. A finite-element model of the tube is also developed and the simulation results are compared with the solution from the analytical model. The finite-element model is then used for the case of a tube with an elliptical cross-section. We observe a nonlinear behaviour in the force-displacement curve of the tubes when close to the zero-force configuration. Furthermore, the tube can go through instabilities when the force changes sign. The unstable region grows if some liquid is removed from the membranous container, causing the straight walls to become convex, and also if the tube length is increased. The tube becomes stiffer and the nonlinear
behaviour becomes less significant when the tube cross-section is changed from circular to elliptical. The results may provide insight into experimental observations of the mechanical behaviour of the incudostapedial joint.

ABSTRACT: Wave propagation is studied and analyzed in a piezoelectric cylindrical composite shell reinforced with carbon nanotubes (CNTs) by using the Mori-Tanaka micromechanical model and considering the transverse shear effects and rotary inertia via the first-order shear deformation shell theory for the first time. The novelty of this study is to provide a mathematical model and solution to investigate the wave behavior in a CNT-reinforced piezoelectric cylindrical composite shell by considering the transverse shear effects and rotary inertia. Dispersion solutions are obtained by solving an eigenvalue problem. The effects of axial and circumferential wave numbers on dispersion curves are explained. The effects of carbon nanotubes and shell geometry parameters on dispersion solutions are examined as well. In addition, a comparison of dispersion solutions from different shell theories within different axial and circumferential wave numbers and CNT volume fractions is provided to illustrate the transverse shear and rotary inertia effects on wave propagation characteristics. The results of this paper can be used for studies on wave propagation in piezoelectric composite shell structures and in design of smart composite shell structures with piezoelectric materials for dynamic stability analysis and structural health monitoring.

ABSTRACT: The present study investigates the exact buckling behavior of a new lattice plate theory, called microstructured thick plate model, that accounts for the shear effect. Three different kinds of continuous nonlocal elasticity plate theories for capturing the small length scale effect of this bending-shear lattice plate have been compared: a fourth and a sixth order continualized models based on the derivation of continuous equations from discrete ones and a phenomenological nonlocal Uflyand–Mindlin plate model. The phenomenological nonlocal model is the stress gradient model of Eringen (1983) applied at the plate scale for the bending part and eventually the shear part of the constitutive law. Each nonlocal plate model is calibrated with respect to the lattice plate model. By definition, the length scale coefficients are constant for the two proposed continualized models. For the phenomenological model, these coefficients are structural dependent and vary with different parameters, such as the aspect ratio or the buckling mode. More especially, it is shown that the calibrated small length scale coefficient is influenced by the shear effect. The comparison of the nondimensional buckling loads calculated with the optimal value of the small length scale coefficient, which differ for each nonlocal model, shows that the continualized models constitute a much better, more consistent and more accurate approximation than the phenomenological nonlocal approach.

ABSTRACT: This research aims to elucidate the effects of foam filling on the dynamic response of metallic corrugated core sandwich panels by conducting air blast testing. The panels were designed to investigate the influences of specific parameters, like the foam filler density, the core configuration and the filling material, on the blast performance from the aspects of permanent deformation, failure modes and associated mechanisms.
Experimental results demonstrate that foam filling is an effective way to improve blast resistance of sandwich panels. The benefits from foam filler for the reduction of the levels of the failure damage and plastic deformation of panels would be improved with the increase of foam density. Comparisons of panels with different core configurations verify that the foam-filled sandwich panel performed the best under low intensity blast loading. The superiority of foam-filled sandwich panel over the foam core sandwich panel would be swallowed up with the increase of blast loading intensity. The panels filled with PVC foams displayed a superior blast resistance over the ones filled with aluminum foams of almost same density. Moreover, the difference in blast resistance would increase with the decrease of blast intensity.

ABSTRACT: With the development of the additive manufacturing technique, periodic lattice structures have received increased attention due to their excellent stiffness-to-weight ratio. In this study, the effects of layer and cell numbers on the quasi-static compressive responses of a lattice sandwich panel are systematically investigated through theoretical modeling, experimental testing, and finite element method. A theoretical model is proposed to predict the compressive modulus and initial crushing strength of the multi-layer lattice panels with body-centered cubic with vertical strut (BCCZ) cells. A series of BCCZ panels with various layers is fabricated by selective laser melting (SLM) using AlSi10Mg. The deformation mode and failure mechanism of the structures are analyzed based on the compressive results. Finite element analysis (FEA) is conducted, and its results are compared with the experimental and theoretical results. Modulus and strength decrease remarkably with the increase in layer number ascribing to the weak boundary of cells close to the edge. Layer-by-layer progressive damage is the main failure mode in the multi-layer panel, and multiple peak stresses are observed. The theoretical prediction results are in line with the experimental and FEA results. This work can provide guidance in the design of lightweight lattice structures.

ABSTRACT: In this paper, the parametric stability of rotating cylindrical shells under static and time dependent periodic axial loads is analyzed. The present work is on the basis of the dynamic version of linear Donnell type equations for thin cylindrical shells under simply-supported boundary conditions. The assumed mode method is employed to reduce the partial differential equations into a system of coupled Mathieu–Hill type equations describing the dynamic instability behaviors of the shell. Using Floquet exponent method, parametric instability regions of rotating cylindrical shells are determined. The correctness of present analysis is examined by comparing the results with those in the literature and very good agreement is observed. The results reveal that for rotating cylindrical shells under periodic axial loads there are only combination instability regions. It is also found that the instability of rotating cylindrical shells may be enhanced under some cases due to the existence of viscous damping. In addition, the influences of circumferential wave number, static loading and shell geometrical characteristics on the location and width of instability regions for rotating cylindrical shells are discussed in detail.

ABSTRACT: Thin-walled conical shells are used as adapters between cylindrical shells of different diameters in launch-vehicle systems. Conical shells carry heavy payloads and are consequently subjected to axial compression. The buckling load of these shells is very sensitive to imperfections (geometry, loading conditions) which results in a critical disagreement between theoretical and experimental results for axially loaded conical shells. The design of these stability critical shells is based on classical buckling loads obtained by a linear analysis which are corrected by a single knockdown factor (0.33 - NASA SP-8019) for all cone geometries. This practice is well established among designers and hasn't changed for the past 50 years because the buckling behavior is till today not very well understood. Within this paper an analytical and numerical lower-bound procedure for conical shells under axial compression is proposed. Data of previous experimental testing campaigns are used to validate the new design criteria for different conical shell geometry configurations. The whole design concept is demonstrated by means of the Interstage 1/2 of the Vega launcher and it is concluded that a revision of the current design recommendation for conical shell structures may results in a significant weight reduction potential.


ABSTRACT: An axially moving sandwich beam with two nanotube-reinforced metallic facings and thick viscoelastic core in thermal environment is analyzed. Using the frequency-temperature equivalence principle, both the covers and the core are modeled using four-parameter fractional rheological model in the frequency domain. The tuning of the two characteristics in the frequency domain made it possible to determine the partial equation of motion of the axially moving beam. The Galerkin method is used to solve the governing partial differential equation. Beryllium copper and 2024-T4 aluminum alloy, are taken into numerical investigations as the matrix materials in facings. The effect of the transport speed and the cover parameters on the dynamic behavior of the moving system is investigated in under-critical range of transport speed.


ABSTRACT: Vertically aligned carbon nanotubes (VACNTs) have been explored widely in various applications due to their unique anisotropic properties. However, its application is limited due to large aspect ratio of nanotubes which lead to buckling phenomena. In this paper, we perform a finite element analysis to predict the variation of elastic modulus and critical buckling load of VACNTs. While elastic modulus is obtained from the slope of stress–strain variation of tubes when one end is fixed and another end is subjected to longitudinal loading, critical buckling load is found using eigenvalue analysis corresponding to first buckling mode. We also perform study to show size dependence of elastic modulus and buckling load of single walled carbon nanotubes (SWCNTs) using FEM approach and compare the results with MD results found in the literature. After validating FEM approach with available results of single-walled and double-walled carbon nanotubes, we apply the same method to arrays of VACNTs. It is found that elastic modulus of VACNTs increases from 1.18 TPa to 2.02 TPa when the size increases from 4 to 36 tubes and then it becomes nearly size independent. The variations of critical buckling load versus other parameters such as tube diameter, intertube spacing, etc., are also obtained. It is found that with the increase in diameter, there is a steep rise in the buckling load for the case of VACNTs arrays. In order to show the influence of non-linear van der Waals force in VACNTs, we compare the above results with and without the presence of van der Waals force and discuss its significance. The modelling and analysis presented in the paper can be used to optimise the number density of VACNTs for different applications.

ABSTRACT: The performances of graphene sheets in nano-devices strongly depend on their morphology, which can be changed enormously by the nanoscale asperities of the substrate. Therefore, it is of great importance to predict morphologies of graphene supported by substrates with different rough surfaces and non-developable curved surfaces. To study the morphology of substrate-supported graphene, a novel methodology is proposed based on the mode-independent energy method (MIEM) and the theoretical analysis on the strain field of graphene. In the method, the morphology of the supported graphene is predicted by judging the stability of graphene in its hypothetical conforming state. Thus, there is no need to concern the complex morphology of graphene sheets, and accordingly, this method is applicable to the substrates with non-developable surfaces, of which the graphene morphologies are difficult to predict by conventional methods. Using this method, the critical condition for the morphology of graphene sheets supported by substrates with convex asperities is established, which agrees well with the results of molecular dynamics (MD) simulations. It is revealed that the shape of the convex asperity is the most important factor that affects the morphology. As long as the half-cone angle of the asperity is small enough, for example, below about 0.4 for silicon substrates, the graphene sheet that covers the convex can conform completely to the substrate. Otherwise, if the half-cone angle is larger, the sizes of the graphene and the asperity also affect the morphology. The shape and size effects on the graphene morphology is summarized in a phase diagram, which provides guidance for the design of graphene-based systems in advanced nano-devices. The methodology developed in this paper is applicable to other two-dimensional materials as well.


ABSTRACT: Bifurcation behavior of cylindrical pressure vessels simultaneously loaded by internal pressure and axial tension is investigated theoretically and numerically with emphasis on the transition between diffuse bulging and necking modes of bifurcation. It is illustrated that in very long cylinders, bifurcation occurs always instantly once instability is reached, resulting in catastrophic failure under all loading conditions. For short cylinders, both axisymmetric necking and bulging occur after the peak load, as steady deformation continues under falling loads before the occurrence of bifurcation. The delay is more obvious in shorter cylinders as axisymmetric bifurcation is delayed under some loading conditions so much that it does not occur, even after extremely large steady deformation under decreasing loads. A transition line, defined for any specified cylinder diameter ratio, separates bulging and necking modes of bifurcation for all associated slenderness ratios. The delay of bifurcation after instability decreases significantly when a cylinder is loaded along the transition line, diminishes for thin walled cylinders, as localized necking occurs almost instantly, once the instability condition has been reached, leading to catastrophic failure. The style of bifurcation limit curves of thick-walled cylinders is generally similar to that of thin-walled cylinders. However, bifurcation of short thick cylinders is delayed noticeably, even when loaded along the transition line. Transition lines are defined and presented for cylinders with different diameter ratios. Axisymmetric bulging and necking bifurcation limits are displayed in correlation with the corresponding transition lines. The theoretical analysis is based on the continuum theory, takes into account large elastic–plastic deformation and non-linear material hardening. The theoretical solution is validated by comparing the theoretical results with FEA simulation results using independent commercial software. The findings provide a clear mapping of the loading conditions, which should be avoided in order to delay or prevent catastrophic failure when pressurized cylinders are accidentally overloaded.

ABSTRACT: In this paper, a hierarchical RVE-based continuum-atomistic multi-scale procedure is developed to model the nonlinear behavior of nano-materials. The atomistic RVE is accomplished in consonance with the underlying atomistic structure, and the inter-scale consistency principals, i.e. kinematic and energetic consistency principals, are exploited. To ensure the kinematic compatibility between the fine- and coarse-scales, the implementation of periodic boundary conditions is elucidated for the fully atomistic method. The material properties of coarse-scale are modeled with the nonlinear finite element method, in which the stress tensor and tangent modulus are computed using the Hill-Mandel principal through the atomistic RVE. In order to clearly represent the mechanical behavior of the fine-scale, the stress-strain curves of the atomistic RVE undergoing distinct type of deformation modes are delineated. These results are then assessed to obtain the proper fine-scale parameters for the multi-scale analysis. Finally, several numerical examples are solved to illustrate the capability of the proposed computational algorithm.


ABSTRACT: Experiments, upper bound models, and finite element simulations are used to determine forming loads needed to microcoin surface ripples in thin metal foils. Coining is traditionally performed in a closed die, however enclosing all non-patterned surfaces is difficult to directly scale down to sub-millimeter foils. We find different forming regimes can exist at this small scale in an open pressing configuration. We explore the effects of the metal foil thickness and its work hardening behavior, two primary factors controlling the microcoining ripple forming load. For very thin foils, the load needed to coin a ripple pattern is lower than the load needed to compress the foil so that the open pressing configuration behavior is effectively closed with pattern formation without thickness change. For moderate thickness foils, the load needed to coin significantly drops as the entire foil compresses. For thick foils approaching bulk materials, the pattern will not completely form as the die macroscopically indents into the metal. Work hardening is found to raise the forming load for the thin, effectively closed die scenario, however it is a secondary effect at moderate thickness. This insight is used to microcoin patterns in extremely hard, thin metal foils.


ABSTRACT: In this study, a new tubular corrugated configuration mimicking the coconut tree profile, here named “conical corrugation tube” (CCT), was proposed, in an attempt to enhance the energy absorption, minimize the initial peak crushing force, and stabilize the crushing process. The effects of geometrical features, especially tapered angle and wavelength of CCTs on the deformation mode and energy absorption characteristics, were investigated through a series of numerical simulations. The results showed that the deformation modes of CCTs could be mainly classified into four modes, which were clearly influenced by the tapered angle and the wavelength of the CCTs. Moreover, the initial peak force of the CCTs was reduced significantly compared with that of the circular straight tube and the tapered tube. In addition, the undulation of the load-carrying capacity parameter, which is used to evaluate the stability of the crushing force, is minimized, and the CCTs produced smoother force-displacement curves compared with the circular straight tube and the
tapered tube. Finally, a theoretical model was proposed to predict the mean crushing force of CCTs under dynamic impact loading. The theoretical results showed a good agreement with the numerical results.


ABSTRACT: Thin walled structures have been applied in engineering field to improve the passive safety of automobiles. This paper studies the crashworthiness of thin-walled tube with elliptical cross section. The influence of aspect ratio \( f \), perimeter of section \( C_0 \) and thickness \( h_0 \) on energy absorption characteristics were investigated based on the theory of plastic deformation. First, the plastic deformation mode of the elliptical thin-walled tube (ETT) is expounded under axial impact. Second, the theoretical model to predict the mean crushing force of the ETT under axial impact is developed based on the principle of the folding deformation mechanism; finally, the comparison of the theoretical and numerical predictions of ETT are conducted to verify theoretical model. The results also show that the mean crushing force \( P_m \) is positively correlated with \( C_0 \) and \( h_0 \), and negatively related to \( f \).


ABSTRACT: The nonlinear vibration and the dynamic buckling of a graphene platelet reinforced sandwich functionally graded porous (GPL-SFGP) plate are thoroughly investigated in this paper. The investigated GPL-SFGP plate consists of two metal face layers and a functionally graded porous core with graphene platelet reinforcement. The effects of the Winkler–Pasternak elastic foundation, thermal environment and damping are incorporated. The open-cell metal foam model is implemented to model the mechanical properties of the porous core. Axial compressive stress is applied on the GPL-SFGP plate by exerting various compressive loading speeds at one edge of the plate. Grounded on the classical plate theory, both motion and geometric compatibility equations of the plate are deduced by introducing the Von Kármán strain-displacement relationship and stress function. Both the Galerkin and the fourth-order Runge–Kutta methods are implemented to solve the governing equation of the dynamic system. Meticulously designed numerical experiments are conducted to identify the critical influential factors of the dynamic stability of the GPL-SFGP plate. The influences of loading speed, damping ratio, temperature variation, initial imperfection, elastic foundation parameters, porosity, GPL weight fraction and the dimensions of the GPL on the overall dynamic stability of the GPL-SFGP plate are evidently demonstrated.


ABSTRACT: In the present work, a new dynamic homogenization model is developed to investigate the long-wavelength wave propagation in a corrugated sandwich plate. With the harmonic motion assumption and using a shifting operator, the governing equations of the plate are firstly represented in a state-space form. Then, a dynamic homogenization model is developed via the two-scale homogenization method. Based on this model and considering the propagation of sinusoidal waves, the dispersion relations and corresponding wave modes can be easily obtained. In order to validate the developed homogenization model, the obtained dispersion relations are compared with those predicted by the spectral element method. It is found that the present method gives accurate results in low frequency range. Furthermore, the effects of some geometric and material
parameters on the dispersion relations for the corrugated sandwich plate are also discussed. The developed homogenization model is expected to be helpful in the prediction and control of dynamic responses of corrugated or even lattice sandwich structures.

ABSTRACT: Thermoplastic composite sandwich structures are being widely investigated due to their excellent properties such as recycling feasibility and high damage tolerance to meet the increasing demand for lightweight engineering components. Three-point-bending (TPB) behavior of glass fiber reinforced polypropylene curved corrugated sandwich beams taking account of the effects of core configuration and interface property were analytically and experimentally investigated. Analytical models were developed to predict the failure loads considering face sheet buckling/crushing, core buckling/crushing and core debonding. The curved axial corrugated sandwich beams (CACSB) and curved circular corrugated sandwich beams (CCCSB) were fabricated by hot-pressing and adhesive bonding. Interface enhancement was implemented by polypropylene glue stick insertion. Compared with unenhanced ones, the peak load of polypropylene glue stick reinforced (PPRGs) CACSB is 1.6 times and the maximum displacement before failure extends to 5.9 times. Failure maps were constructed to insight the failure modes of three configurations and also provide useful instruction for designing lightweight sandwich structures.

ABSTRACT: This study investigated the effect of transverse pre-impact damage on the load bearing capacity and failure behavior of square carbon fiber reinforced plastic (CFRP) tubes for axial crushing. The CFRP tubes were impacted transversely in different levels of impact energies to generate initial damage, and then the specimens were further crushed axially to evaluate the relation between transverse impact energies/positions and the residual axial crashworthiness. A finite element (FE) model was also developed to simulate the complex damage behavior of the CFRP tubes under these two different loading processes, based upon the continuum damage model (CDM) with user-defined material subroutine in Abaqus. A combined failure mode was observed in the transverse pre-impact tests, in which delamination was combined with partial or complete fiber breakage when increasing the impact energy from 10 J to 30 J. In the axial compression tests, two typical failure modes with circumferential fracture near the pre-impact position were identified for the damaged tubes, exhibiting significant difference from the progressive folding failure seen in undamaged tubes. Further, the damaged tubes yielded up to 38%, 58.5% and 58.3% reduction in terms of the peak load, mean load and energy absorption respectively in comparison with the specimens without pre-impact damages. It is also found that the residual crushing capacity decreased with increase in the transverse pre-impact energy; nevertheless the residual axial crushing properties were insensitive to single or double impacts on different circumferential positions. The failure modes of fiber breakage, delamination and matrix crack were investigated in detail by using the FE analysis.

ABSTRACT: Based on the Kirchhoff-Love's assumptions, shell equations with non-ideal boundary conditions are established to describe the deformation of thin-walled aircraft panel resulting from positioning variation and clamping force in the assembly process. The shell equations are simplified by the theory of functions of a complex variable, and the analytical solutions are presented by the Fourier series approach and Galerkin method. Meanwhile, the potential functions are introduced to calculate the particular solution, which successfully avoids employing specialized displacement functions with different types of loads. A coordinate transformation model is also developed to transform the actual displacement and rotation boundary constraint in a Cartesian coordinate system into the non-ideal boundary in the curvilinear coordinate system. To verify the general applicability of the proposed method, analytical calculation, the finite element (FE) simulation and experiment in real application have been performed taking into account simply supported, ideal boundary and non-ideal boundary conditions, respectively. The results have shown the good performance of the accuracy of presented solution.


ABSTRACT: Microlattice is the most advanced version of truss cellular materials with ultralow density and high mass productivity, thanks to the mask-based lithography. However, its structure lacks in-plane truss elements, which results in low structural stability. This paper investigates the effect of the structural incompleteness on its mechanical behavior of Microlattice by comparison with that of another Microlattice with in-plane truss elements added on its outer faces. The mechanical properties of the Microlattices with and without in-plane elements were evaluated through compression tests of the single-layered specimens in two different directions. Under out-of-plane compression, the in-plane elements added to the conventional Microlattice specimens did not show any effect and failed to enhance the strength and stiffness. Finite element analysis revealed that high friction at contacts caused the unexpected results. In contrast, under in-plane compression, the in-plane elements showed significant enhancement. Simple analytic solution of the compressive strength of the enhanced Microlattices under in-plane compression agreed fairly well with the experimental results, and explained well the failure mode transition.

(The rest of the December 2018 issue is included in Part 2)


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ABSTRACT: Flow of Bingham plastics through straight, long tubes is studied by means of a versatile analytical method that allows extending the study to a large range of tube geometries. The equation of motion is solved for general non-circular cross-sections obtained via a continuous and one-to-one mapping called the shape factor method. In particular the velocity field and associated plug and stagnant zones in tubes with equilateral triangular and square cross-section are explored. Shear stress normal to equal velocity lines, energy dissipation distribution and rate of flow are determined. Shear-thinning and shear-thickening effects on the flow, which cannot be accounted for with the Bingham model, are investigated using the Hershey-Bulkley constitutive formulation an extension of the Bingham model. The existence and the extent of undeformed regions in the flow field in a tube with equilateral triangular cross-section are predicted in the presence of shear-thinning and shear-thickening as a specific example. The mathematical flexibility of the analytical method allows the formulation of general results related to viscoplastic fluid flow with implications related to the design and optimization of physical systems for viscoplastic material transport and processing.

ABSTRACT: The multifold nature of structural instability problems necessitates a number of different kinds of analytical and numerical approaches. Furthermore, instability collapses of large-span roof sensitized the global community to reduce the effects of geometrical imperfections, then some limiting recommendations have been recently proposed. This study provides new insights into the interaction between the two different categories of structural instability and, for the first time, a unified theoretical evaluation of the critical load due to interaction is proposed. The snap-through phenomenon of 2D Von Mises arches was investigated by an incremental-displacement nonlinear analysis. At the same time, the equilibrium paths were considered in relation to the Eulerian buckling loads for the same structural systems. For each structural scheme the effect of the two governing parameters was investigated: slenderness and shallowness ratios. For these purposes, several original theoretical and numerical snap-through versus buckling interaction curves were obtained. These curves provide indications about the prevailing collapse mechanism with regards to the geometric configuration of the structure. Consequently, this innovative method is able to predict the actual instability of a wide range of mechanical systems. With this approach, it is possible also to establish the connection between the magnitude of structural imperfections (defects) and instability behavior. The proposed procedure is able to provide the effective critical load given by the interaction effect and to correlate the instability behavior to the maximum tolerable imperfection sizes.

References listed at the end of the paper:
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ABSTRACT: We study networks of coupled oscillators governed by ODEs and yielded by physically validated sets of a few PDEs governing dynamics of structural members (plate and beams), chaos and phase synchronization and contact/no-contact non-linear dynamics of structural members coupled via boundary conditions. We have detected, illustrated and discussed a few novel kinds of hybrid states of the studied plate-beam(s) contact/no-contact interactions as well as novel scenarios of transition into chaos exhibited by the interplay of continuous objects. Classical (time histories, phase portraits, Poincaré maps, FFT, Lyapunov exponents) and non-classical (2D Morlet wavelets) approaches are used while monitoring non-linear dynamics of the interacting spatial structural members. Our results include examples from structural mechanics and the studied objects are modelled by validated mechanical hypotheses and assumptions. Novel non-linear phenomena including switching to different vibration regimes and phase chaotic synchronization are illustrated and discussed.

Y. Kiani (Faculty of Engineering, Shahrekord University, Shahrekord, Iran), “Axisymmetric static and dynamics snap-through phenomena in a thermally post-buckled temperature-dependent FGM circular plate”, International Journal of Non-Linear Mechanics, Vol. 89, pp 1-13, March 2017
ABSTRACT: Thermal postbuckling analysis and the axisymmetric static and dynamic snap-through phenomena due to static/sudden uniform lateral pressure in a thermally postbuckled functionally graded material circular plate are performed in this research. Plate is formulated using the first order shear deformation plate theory. Thermo-mechanical properties of the plate are assumed to be temperature dependent where dependency is described according to the higher order Touloukian representation. Two types of temperature loading are considered. Uniform temperature rise and heat conduction across the thickness direction. The obtained system of equations is nonlinear since the thermal conductivity itself is a function of the unknown nodal temperatures. Using the von-Kármán assumptions, the governing equations of the plate are obtained in a matrix representation with the aid of the conventional Ritz method whose shape functions are developed using the Gram-Schmidt process. At first thermal postbuckling analysis is performed which is a nonlinear problem with respect to both temperature and displacements. Afterwards, response of the bulged thermally postbuckled plate is obtained under the static and dynamic uniform pressure. Snap-through phenomenon may be observed in both static and dynamic loading cases, due to the immovability of the edge of the plate and the initial deflection caused by postbuckling deflection. To capture the snapping phenomenon and trace the path beyond the limit loads, cylindrical arch-length technique is used. In dynamic snap-through analysis, the effect of structural damping is also included. Numerical results of this study reveal that the structure is sensitive to the initial deflection caused by thermal postbuckling load. Increasing the temperature prior to mechanical loads enhances the snap-through intensity and also increases both the upper and lower limit loads. As shown, dynamic snap-through loads are lower than the static ones, however dynamic snap-through intensity is more than the static snap-through intensity. Furthermore, structural damping enhances the dynamic buckling loads of the plate and decreases the dynamic postbuckling deflection of the plate.


ABSTRACT: An analytical model describing the nonlinear interaction between global and local buckling modes in long thin-walled rectangular hollow section struts under pure compression founded on variational principles is presented. A system of nonlinear differential and integral equations subject to boundary conditions is formulated and solved using numerical continuation techniques. For the first time, the equilibrium behaviour of such struts with different cross-section joint rigidities is highlighted with characteristically unstable interactive buckling paths and a progressive change in the local buckling wavelength. With increasing joint rigidity within the cross-section, the severity of the unstable post-buckling behaviour is shown to be mollified. The results from the analytical model are validated using a nonlinear finite element model developed within the commercial package Abaqus and show excellent comparisons. A simplified method to calculate the local buckling load of the more compressed web undergoing global buckling and the corresponding global mode amplitude at the secondary bifurcation is also developed. Parametric studies on the effect of varying the length and cross-section aspect ratio are also presented that demonstrate the effectiveness of the currently developed models.

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ABSTRACT: In this paper a Hybrid Domain Boundary Element Method is developed for the geometrically nonlinear dynamic analysis of inelastic Euler-Bernoulli beams of arbitrary doubly symmetric simply or multiply connected constant cross-section, resting on viscous inelastic Winkler foundation. The beam is subjected to the combined action of arbitrarily distributed or concentrated transverse dynamic loading and bending moments in both directions as well as to axial loading, while its edges are subjected to the most general boundary conditions. A displacement based formulation is developed and inelastic redistribution is modelled through a distributed plasticity (fibre) approach. A uniaxial hysteretic law is considered for the evolution of the plastic part of the normal stress following the phenomenological hysteresis model, while hysteretic force-displacement model is also employed in order to describe the inelastic behaviour of the Winkler springs. Numerical integration over the beam cross sections is performed in order to resolve the hysteretic parts of the stress resultants. Application of the boundary element technique yields a system of nonlinear Differential-Algebraic Equations, which are written in state-space form and solved by an incremental–iterative solution strategy. Numerical examples are worked out confirming the accuracy and the computational efficiency of the proposed beam formulation, as well as the significant influence of material and geometrical nonlinearities in the response of beam-soil interaction systems.

ABSTRACT: We are concerned with the deformation of thin, flat annular plates under a force applied orthogonally to the plane of the plate. This mechanical process can be described via a radial formulation of the Föppl–von Kármán equations, a set of nonlinear partial differential equations describing the deflections of thin flat plates. We are able to obtain analytical solutions for the radial Föppl–von Kármán equations with boundary conditions relevant for clamped, loosely clamped, and free inner and outer. This permits us to study the qualitative behavior of the out-of-plane deflections as well as the Airy stress function for a number of cases. Provided that an appropriate non-dimensionalization is taken, we find that the perturbation solutions are surprisingly valid for a wide variety of parameters, and compare favorably with numerical simulations in all cases (rather than just for small parameters). The results demonstrate that the ratio of the inner to outer radius of the annular plate will strongly influence the properties of the solutions, as will the specific boundary data considered. For instance, one may choose to fix the plate in place with a specific set of boundary conditions, in order to minimize the out-of-plane deflections. Other boundary conditions may result in undesirable behaviors.

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https://doi.org/10.1016/j.ijnonlinmec.2017.02.003
ABSTRACT: Nonlinear dynamics of an extensible cantilevered pipe conveying pulsating flow is considered in this paper. The fluid flow fluctuates harmonically and exhausts via a nozzle attached to the end of the pipe.
Taking into account the extensibility assumption, the coupled nonlinear lateral–longitudinal equations of motion are derived using Hamilton's principle and discretized via Galerkin's method. The adaptive time step Adams algorithm is applied to extract the time response, and then the bifurcation, power spectral density and phase plane maps are plotted for some case studies. Effects of some geometrical parameters such as flow mass, pulsating flow frequency, gravity, nozzle mass and nozzle aspect ratio parameters are studied on the dynamics of such system and the validity of extensibility assumption is investigated and some conclusions are drawn.

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ABSTRACT: This paper investigates the small- and large-amplitude vibrations of thermally postbuckled carbon nanotube-reinforced composite (CNTRC) beams resting on elastic foundations. For the CNTRC beams, uniformly distributed (UD) and functionally graded (FG) reinforcements are considered where the temperature-dependent material properties of CNRTC beams are assumed to be graded in the thickness direction and estimated through a micromechanical model. The motion equations are derived based on a higher order shear deformation beam theory with including the beam-foundation interaction. The initial deflection caused by thermal postbuckling is also included. The numerical illustrations concern small- and large-amplitude vibration characteristics of thermally postbuckled CNTRC beams under uniform temperature field. The effects of carbon nanotube (CNT) volume fraction and distribution patterns as well as foundation stiffness on the vibration characteristics of CNTRC beams are examined in detail.

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ABSTRACT: Curved structures, such as beams, arches, and panels are capable of exhibiting snap-through buckling behavior when loaded laterally, that is they can exhibit multiple stable equilibria, sometimes after any external loading is removed. This is a consequence of highly nonlinear force-deflection relations with perhaps multiple crossings of the zero-force axis for typical equilibrium paths. However, the propensity to maintain a stable snapped-through equilibrium position (in addition to the nominally unloaded equilibrium configuration) after the load is removed depends on certain geometric properties. A number of clamped arches are used to illustrate the relation between geometry (essentially the shape) and corresponding equilibrium configuration(s), and especially those conditions for which the initial equilibrium configuration is the only stable shape possible. Furthermore, related results are obtained when a change in the thermal environment may cause a system to exhibit a stable snapped-through equilibrium even when the system at ambient thermal conditions does not. Some representative examples are produced using a 3D printer for verification purposes.
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ABSTRACT: Thin-walled structures are widely used as energy absorption devices for their proven advantages on lightweight and crashworthiness. However, a majority of studies have been focus on exploring separately the crashworthiness of the thin-walled structure with a specific geometric section, such as circular, square, hexagon, octagon etc., and little research has investigated the relationship of crashworthiness among thin-walled structures with different sections systematically. This paper utilizes Fourier series expansion to generate a series of novel sectional configurations, namely Fourier varying sectional tubes (FVSTs), to look into their advantages of crashworthiness, thereby developing some FVSTs with highest possible energy absorption capacity. Based on the validated finite element (FE) models, parametric analysis is conducted to investigate the effects of cross-sectional configuration, perimeter and thickness of FVSTs on collapse mode and energy absorption. The results showed that the collapse modes of FVSTs are fairly sensitive to cross-sectional configuration, perimeter and wall thickness. Of these FVSTs generated, the highest specific energy absorption (SEA) increases 77.54% by increasing perimeter and 69.73% by decreasing wall thickness. Finally, a discrete optimization based on the orthogonal arrays is conducted to obtain the optimal FVST for maximizing SEA under the constraint of the initial peak crushing force (IPCF). The optimized FVSTs are of superior crashworthiness and great potential as an energy absorber.

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ABSTRACT: In this paper an integral equation solution to the linear and geometrically nonlinear problem of non-uniform in-plane shallow arches under a central concentrated force is presented. Arches exhibit advantageous behavior over straight beams due to their curvature which increases the overall stiffness of the structure. They can span large areas by resolving forces into mainly compressive stresses and, in turn confining tensile stresses to acceptable limits. Most arches are designed to operate linearly under service loads. However, their slenderness nature makes them susceptible to large deformations especially when the external loads increase beyond the service point. Loss of stability may occur, known also as snap-through buckling, with catastrophic consequences for the structure. Linear analysis cannot predict this type of instability and a geometrically nonlinear analysis is needed to describe efficiently the response of the arch. The aim of this work is to cope with the linear and geometrically nonlinear problem of non-uniform shallow arches under a central concentrated force. The governing equations of the problem are comprised of two nonlinear coupled partial differential equations in terms of the axial (tangential) and transverse (normal) displacements. Moreover, as the cross-sectional properties of the arch vary along its axis, the resulting coupled differential equations have variable coefficients and are solved using a robust integral equation numerical method in conjunction with the arc-length method. The latter method allows following the nonlinear equilibrium path and overcoming
bifurcation and limit (turning) points, which usually appear in the nonlinear response of curved structures like shallow arches and shells. Several arches are analyzed not only to validate our proposed model, but also to investigate the nonlinear response of in-plane thin shallow arches.


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ABSTRACT: Delaminated regions figure prominently among potential threats to the structural integrity of layered plate configurations. Under a certain thermal loading threshold, geometrically nonlinear local instabilities in the form of buckling or wrinkling across the delaminated region crop up, giving rise to markedly amplified distributions of contour peeling stresses. The present paper aims to shed light on and quantify the manifold aspects and implications of the delamination-thermal-wrinkling trio. The paper faces the challenges of handling the nature of the layered configuration, the inherent geometrical irregularity of delaminated regions, the discontinuous interfacial conditions, the 3D stress state along the delamination contour, and the nonlinear evolution of local instabilities across an orthotropic delamination. For that purpose, a specially tailored 2D multi-layered plate model and a corresponding triangular finite element are derived. The original contribution of the proposed model is in its ability to capture the thermally-driven, nonlinear small scale phenomena related to geometrically nonlinear response of the layered structure, using a 2D multi-layered plate theory solved with efficient 2D multi-layered triangular finite elements, as opposed to computationally expensive 3D finite element analysis. This is accomplished via the integration and synergy of methodologies that include: multi-layered high order plate theory to account for the layered layout, geometrically nonlinear strain-displacement relations to account for geometrical nonlinearities, orthotropic and thermo-elastic constitutive laws to account for thermal loads, and interlayer interface modelling which, combined with a the shear-locking free triangular FE, allows accounting for arbitrarily shaped delaminations. The model is validated against a 1D closed form solution and a 3D continuum based finite element analysis and is then used for a numerical study. In the study, the onset and the evolution of local instabilities in an adhesively bonded orthotropic layer across an irregular delamination are looked into. Special attention is given to the significant influence of material orthotropy and the relative directionality of the delamination on the threshold thermal load, the nonlinear wrinkling patterns, and the peeling traction distribution.


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ABSTRACT: Linear and non-linear vibrations of a U-shaped hollow microcantilever beam filled with fluid and interacting with a small particle are investigated. The microfluidic device is assumed to be subjected to internal flowing fluid carrying a buoyant mass. The equations of motion are derived via extended Hamilton's principle and by using Euler-Bernoulli beam theory retaining geometric and inertial non-linearities. A reduced-order model is obtained applying Galerkin's method and solved by using a pseudo arc-length continuation and collocation scheme to perform bifurcation analysis and obtain frequency response curves. Direct time integration of the equations of motion has also been performed by using Adams-Moulton method to obtain time histories and analyze transient cantilever-particle interactions in depth. It is shown that exploiting near resonant non-linear behavior of the microcantilever could potentially yield enhanced sensor metrics. This is found to be
due to the transitions that occur as a matter of particle movement near the saddle-node bifurcation points of the coupled system that lead to jumps between coexisting stable attractors.

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ABSTRACT: The paper is devoted to the effect of some geometrical imperfections on the critical buckling load of axially compressed thin-walled I-columns. The analytical formulas for the critical torsional and flexural buckling loads accounting for the initial curvature of the column axis or the twist angle respectively are derived. The classical assumptions of theory of thin-walled beams with non-deformable cross-sections are adopted. The non-linear differential equations are derived and the critical buckling loads are approximated by means of the Galerkin’s method. Comparison of analytical results to numerical analysis of simply supported I-columns by means of finite element method (FEM) is provided. Moreover the analytical formulas is adapted to I-columns with lipped flanges and satisfactory agreement of analytical and numerical results of stability analysis is observed.

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ABSTRACT: The nonlinear dynamics of a fluid-conveying cantilevered pipe with loose constraints placed somewhere along its length is investigated. The main objective of this study is to determine the effects of several geometrical and physical parameters of the loose constraints on the characteristics and behavior of pipes conveying fluid. Based on the full nonlinear equation of motion, the dynamical behavior of the pipe system is investigated. Phase portraits and bifurcation diagrams are constructed for a selected set of system parameters. Typical results are firstly compared to numerical ones reported previously and excellent agreement is obtained. Then, the threshold flow velocities for several key bifurcations including pitchfork, period doubling, chaos, and sticking behaviors are predicted, showing that in many cases, the gap size, stiffness, and asymmetry of the loose constraints have remarkable effects on the nonlinear responses of the cantilevered pipe conveying fluid. For a pipe system with small/large constraint gap sizes, small constraint stiffness, or large constraint offset, some of the complex dynamical behaviors including chaos and period-doubling bifurcations would disappear, at least in the flow velocity range of interest.

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ABSTRACT: Rubber-like materials are very applicable in almost all fields of industries, but due to their large deformation characteristic, they can exhibit a variety of instabilities. Accordingly, many researchers have been motivated to investigate the effects of different parameters on the stability of hyperelastic cylindrical tubes under finite deformation, while the effects of temperature gradient have not been considered. In this paper, the effects of temperature variation on the stability and thermo-mechanical behavior of the cylindrical tubes made of the entropic materials such as rubber-like materials and elastomers are investigated via an effective strain energy density function. To this purpose, an Ogden-type strain energy density with only integer powers is applied in order to determine an analytical solution, not involving the integral form, for the stress distribution through the wall thickness of cylindrical tubes at finite deformation thermoelasticity. This problem is examined in two cases including (i) a thick-walled cylindrical tube under internal pressure and uniform variation of temperature and (ii) a thick-walled cylindrical tube under internal pressure and temperature gradient, simultaneously. It was observed that the positive temperature gradients in comparison with environment temperatures improve the stability of the circular tubes made of the entropic materials.

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ABSTRACT: We model a perivascular supported arterial tube as a uniform cylindrical membrane tube enclosed by a soft substrate, and derive the solution bifurcation criterion. We assume the surrounding soft substrate as an elastic foundation with distributed stiffness. We consider the tube to be a neo-Hookean material with isotropic and anisotropic (orthotropic) properties, and study solution bifurcation at a constant axial stretch. In the isotropic case, the surrounding soft substrate can substantially delay the onset of bifurcation through a subcritical jump in circular distension at bifurcation with increasing substrate stiffness. Introduction of anisotropy can significantly change the jump behavior from subcritical to supercritical.


ABSTRACT: One common phenomenon native to inflation of membranes is the elastic limit-point instability—a bifurcation point at which the membrane begins to deform enormously at the slightest increase of pressure. In the case of magnetoelastic materials, there is another possible phenomenon which we call magnetic limit-point instability, a state referring to the non-existence of an equilibrium state – either stable or unstable. In this work, we are concerned with such instabilities in an incompressible isotropic magnetoelastic toroidal membrane with an initial circular cross-section. A non-uniform magnetic field is generated using a circular current carrying loop placed inside the membrane in addition to inflation by a uniform hydrostatic pressure. An energy formulation based on magnetization is used to model the magneto-mechanical coupling along with a Mooney–Rivlin
constitutive model for the elastic strain energy density. Computations show that the magnetic field strongly influences the location of elastic limit points and in some cases can cause them to vanish. Multiple equilibrium states are obtained as solutions of the governing equations and a criterion based on second variation is employed to determine their stability. Existence and dependence of magnetic limit point on the magnetic field is demonstrated. While the quantitative results obtained here are specific to the toroidal geometry, the deformation behaviour can be generalized to any magnetoelastic membrane.

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ABSTRACT: We investigate the mechanical stability of L-section and T-section composite struts with single edge delamination. We propose a solution procedure based on a layerwise theory and the first order shear deformation theory by taking into consideration of the von Karman geometrical nonlinearity. We derive the nonlinear equilibrium equations according to the minimum total potential energy principle, and solve them using Rayleigh–Ritz method and Newton–Raphson method. In modeling the delaminated L-section and T-section struts, we divide the structures into regions, and exert continuity conditions between different regions. The proposed model is capable of analyzing both local buckling of the base laminate and sublaminate as well as the global buckling of the whole structure. We present numerical results to provide an insight into effects of size of delamination on buckling mode and post-buckling behaviors of the struts. We perform the three-dimensional finite element analysis using the ABAQUS commercial software. The results show a very good agreement with those obtained by the analytical method. The results indicate that the presence of delaminations not only reduces the load-carrying capacity of open section struts remarkably, but also plays a pivotal role in the critical buckling load and buckling mode shape of the struts.

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ABSTRACT: This paper investigates quantitatively the post-buckling response of irregular wrinkles in a trapezoidal film/substrate bilayer. The geometric gradient can change the wrinkling profile to create ribbed and graded structural patterns with variations of wave direction, amplitude and wavelength. The tapered angle and edge dimension are examined numerically using a nonlinear shell/solid coupled finite element model that incorporates a path-following continuation technique, which explores their influences on secondary bifurcations, localization and surface mode transition. For instance, the competition between plate-like and
beam-like post-buckling behavior is discussed. An analysis of graded amplitude is also provided based on Fourier envelope equations of beam/foundation models, which gives an insightful understanding of these fading wrinkles that differ from the ones usually observed in rectangular geometric cases. The results of this work can be used to guide the design of geometrically gradient film/substrate systems to achieve desired wavy instability patterns.

ABSTRACT: A fluid-filled truncated spherical membrane fixed along its truncated edge to a horizontal, rigid and frictionless plane and spinning around a center axis was investigated. A two-parameter Mooney–Rivlin model was used to describe the material of the membrane. The truncated sphere was modeled in 3D using finite element meshes with different symmetry properties. A quadratic function was used for interpolating hydrostatic pressure, giving a symmetric tangent stiffness matrix, thereby reproducing the conservative problem. Various problem settings were considered, related to the spinning, and different instability behaviors were observed. Multi-parametric problems were defined, generalized paths including primary and secondary paths were followed. Stability of the multi-parametric problem was evaluated using generalized eigenvalue analysis based on the total differential matrix for the constrained problem. Numerical results showed that mesh symmetry affected the simulated stability behavior. Fold line evaluations showed the parametric effects on critical solutions.

ABSTRACT: In this work, a thorough investigation is presented into the nonlinear resonant dynamics of geometrically imperfect shear deformable nanobeams subjected to harmonic external excitation force in the transverse direction. To this end, the Gurtin–Murdoch surface elasticity theory together with Reddy’s third-order shear deformation beam theory is utilized to take into account the size-dependent behavior of nanobeams and the effects of transverse shear deformation and rotary inertia, respectively. The kinematic nonlinearity is considered using the von Kármán kinematic hypothesis. The geometric imperfection as a slight curvature is assumed as the mode shape associated with the first vibration mode. The weak form of geometrically nonlinear governing equations of motion is derived using the variational differential quadrature (VDQ) technique and Lagrange equations. Then, a multistep numerical scheme is employed to solve the obtained governing equations in order to study the nonlinear frequency–response and force–response curves of nanobeams. Comprehensive studies into the effects of initial imperfection and boundary condition as well as geometric parameters on the nonlinear dynamic characteristics of imperfect shear deformable nanobeams are carried out through numerical results. Finally, the importance of incorporating the surface stress effects via the Gurtin–Murdoch elasticity theory, is emphasized by comparing the nonlinear dynamic responses of the nanobeams with different thicknesses.

ABSTRACT: The nonlinear dynamic response of elliptical cylindrical shell under transverse harmonic excitation is experimentally investigated. The elliptical cylindrical shell depicts softening nonlinearity for the excitation range considered. The circumferential variation of acceleration at different time instants of a cycle depicts standing, travelling waves over part of the circumference and travelling waves along the full circumference with/without variable amplitude depending upon the forcing frequency. For symmetric excitation, the travelling wave response is observed for the forcing frequency, 85–89, 97.5–99.6, 112, 123.2, 149–155, 178–200 Hz. The participation of different modes involving 1:1, 1:2, 1:3 external, 1:1, 1:2, 2:3 internal resonances and the presence of harmonics including multiples of 1/2, 1/3 are reported.

ABSTRACT: This paper investigates numerically the post-bifurcation evolution of ellipsoidal or spherical balloons subject to internal pressure, where the primary -shaped curves of pressure vs. principal stretch and the corresponding bifurcated branch, i.e. pear-shaped deformation, are captured quantitatively. We quantify and discuss the range of pear-shaped bifurcation intervals of ellipsoids and the associated critical points. For rugby-shaped ellipsoidal balloons, we find that there exists a threshold for the aspect ratio of the major and minor axes that leads to pear-shaped bifurcation, which is detected by the finite element method. When the rugby shape becomes sufficiently slender, the nonlinear response of the ellipsoidal balloons is well approximated by the deformation of a tube with localized bulging instead of pear-shaped configuration. We obtain the nonlinear evolution of the localized bulging of rugby-like ellipsoids numerically. Furthermore, we examine the influence of various aspect ratios for rugby-shaped balloons on the localized bulging response. We find that pumpkin-shaped ellipsoids can always bifurcate into pear shape. Lastly, we provide a unified phase diagram on instability mode selection of various aspect ratios of ellipsoidal balloons, with diverse representative deformed configurations.

ABSTRACT: Axial compression of a rubber tube where the movement of the outer surface is restricted is an important procedure used to seal a packer. Instabilities may cause the seal to fail. In this paper, we study the bifurcations of a hyperelastic tube under restricted compression and consider both axial and circumferential modes. Bifurcation condition is numerically determined and it is found that the critical stretch is a decreasing function of the ratio of inner and outer radii . Furthermore, the critical mode number is always finite for both modes. In particular, a transition between axial and circumferential modes occurs when passes through a critical value of 0.6716. A WKB analysis is carried out to provide an asymptotic expression for the axial stretch when the mode number is large. Finally an application of our results in sealing devices is discussed.

ABSTRACT: A variational model describing the interactive buckling of thin-walled rectangular hollow section struts with geometric imperfections is developed based on analytical techniques. A system of nonlinear differential and integral equilibrium equations is derived and solved using numerical continuation. Imperfection sensitivity studies focus on the cases where the global and local buckling loads are close. The equilibrium behaviour of struts with varying imperfection sizes, characterized by the equilibrium paths and the progressive change in local buckling wavelength, is highlighted and compared. The numerical results reveal that struts
exhibiting mode interaction are very sensitive to both local and global imperfections. The results from the variational model are verified using the finite element method in conjunction with the static Riks method and show good comparisons. A simplified method to calculate the pitchfork bifurcation load where mode interaction is triggered for struts with a global imperfection is developed for the first time. The simplified method is calibrated to predict the ultimate load for struts with tolerance level global imperfections and combined imperfections based on the parametric study, which also reveals that local and global imperfections are relatively more significant where global and local buckling are critical respectively. Finally, the ultimate load for struts with tolerance level geometric imperfections is compared with the existing Direct Strength Method (DSM). Potential dangers of making unsafe load-carrying capacity predictions by the DSM are highlighted and an improved strength equation is proposed.


ABSTRACT: In this paper we investigate the large-amplitude axisymmetric free vibrations of an incompressible nonlinear elastic cylindrical structure. The material behavior is described as orthotropic and hyperelastic using the physically-based invariants proposed by Rubin and Jabareen (2007, 2010). The cylinder is modeled using the theory of a generalized Cosserat membrane, which allows for finite deformations that include displacements along the longitudinal axis of the structure. The bi-dimensional approach represents a significant contribution with respect to most works published in this field, which approach the problem at hand assuming plane strain conditions along the axis of the cylinder. We have carried out a systematic analysis of the parameters that govern the dynamic behavior of the structure, paying specific attention to those describing the orthotropy of the material and the dimensions of the cylinder. Using Poincaré maps, we have shown that the motion of the structure can turn from periodic to quasi-periodic and chaotic as a function of the initial conditions, the elastic and kinetic energy supplied to the specimen, the dimensions of the cylinder and the degree of mechanical orthotropy of the material.


ABSTRACT: Experimental investigation performed to evaluate buckling strength of a cylindrical panel exposed to non-uniform temperature field is presented. A novel experimental set-up developed in-house is used to evaluate buckling strength of a cylindrical panel made of Aluminum. Influence of nature of non-uniform temperature variation, structural boundary conditions and panel aspect ratio on buckling strength is investigated experimentally. Experimental results reveals that effect of nature of temperature field, resulting from the location of heat source, on buckling strength is significant. It is also observed that buckling strength is less when the least stiffness area of the panel is exposed to peak temperature of a particular temperature field. Similarly, CCCC boundary constraints results in high thermal stress which lowers the buckling strength of the panel as compared to CCFC boundary constraints. Temperature-deflection plot and corresponding buckling strength evaluated experimentally are compared with those obtained using non-linear finite element analysis, taking into account the initial geometric imperfection.

Anandamoy Mukhopadhyay and souradip Chattopadhyay, “Long wave instability of thin film flowing down an inclined plane with linear variation of thermophysical properties for very small Bio number”, International Journal of Non-Linear Mechanics, Vol. 100, pp 20-29, April 2018
ABSTRACT: We investigated interfacial instability of a thin liquid film flowing down an inclined plane, considering the linear variation of fluid properties such as density, dynamical viscosity, surface tension and thermal diffusivity, for the small variation of temperature. Using long wave expansion method and considering order analysis specially for very small Biot number we obtained a single surface equation in terms of the free surface. Considering sinusoidal perturbation method we carried out linear stability analysis and obtained the critical Reynolds number and linear phase speed, both of which depend on but independent of . Using the method of multiple scales, weakly nonlinear stability analysis is carried out. We demarcated subcritical, supercritical, unconditional and explosive zones and their variations for the variation of and . Also we discussed the variations of threshold amplitude in the subcritical as well as in the supercritical zones for the variation of and . Finally we discussed the variation of nonlinear wave speed for the variation of and . (There is a lot of math in this abstract.)


ABSTRACT: In this paper, crushing behaviors of tube with shallow and deep corrugation are experimentally and theoretically examined under axial loading condition. Three types of specimens were tested under quasi static axial loading. Their failure mechanism and failure history are presented and discussed. The experimental result showed that corrugated metal tubes demonstrate perfect energy absorption characteristics in terms of uniformity of load–displacement diagram, reduction of initial peak load and controlling failure mechanism. The theoretical solution based on experiment and modified simplified super folding element (MSSFE) theory is proposed that depends on the number of plastic hinge line, wall thickness, length of structure and flow stress of material. The comparison between theoretical solution and experiment shows a good agreement with acceptable errors.


ABSTRACT: This paper presents a novel numerical procedure to predict nonlinear free and steady state forced vibrations of clamped–clamped curved beam in the vicinity of postbuckling configuration. Nonlinear Euler–Bernoulli kinematics assumptions including mid-plane stretching are proposed to exhibit a large deformation but a small strain of von Kármán. To simulate the interaction of beam with the surrounding elastic medium, nonlinear elastic foundation with cubic nonlinearity and shearing layer are employed. The nonlinear integro-differential equation that governs the buckling of beam is discretized using the differential-integral quadrature method (DIQM) and then is solved using Newton’s method. The problem of linear vibration is discretized using DIQM and then is solved as a linear eigenvalue problem. Afterwards, a single-mode Galerkin discretization is used to reduce the nonlinear governing equation into a time-varying Duffing equation. The Spectral differentiation matrix operators are exploited to discretize the Duffing equation. The discretized Duffing equation is a nonlinear eigenvalue problem which is directly solved using pseudo arc length continuation method. Results obtained by the proposed numerical solution are compared with analytical solutions available in the literature and good agreement is obtained. Parametric studies are carried out to show the effects of applied axial load, imperfection and nonlinear elastic foundations on the natural frequency as well as forced damped vibration behavior of the beam. The above mention effects play very important role on the dynamic behavior of buckled curved beam.
ABSTRACT: Surface influences on the nonlinear vibrations of micro- and nano-shells are investigated by an efficient numerical approach. The seven-parameter geometrically nonlinear first-order shear deformation shell theory in Lagrangian description is formulated for the bulk part of structure. To consider surface stress effects, the Gurtin–Murdoch surface elasticity theory with considerations proposed by Ru (2016) and Shaat et al. (2013) is employed. In this regard, two thin inner and outer surface layers are considered, and the corresponding constitutive relations are incorporated into the shell formulations. The stress–strain and strain–displacement relations are represented in a novel matrix–vector form by which the governing equations of motion are derived based on Hamilton’s principle. The isogeometric analysis (IGA) is then utilized due to having the capability to construct exact geometries of shells and the associated powerful features. The obtained ordinary differential equations from IGA are finally solved by the periodic grid approach which can be considered as a suitable solution strategy for the analysis of free and harmonically forced vibrations of different structures. The present work contributes to the literature with developing the isogeometric model of size-dependent geometrically nonlinear shells subjected to large-amplitude vibrations.

ABSTRACT: The influence of the internal debonding on the structural stiffness and the nonlinear modal characteristics of the layered structure are examined extensively in the current research article. For the investigation purpose, the shell frequency responses are obtained numerically for both the linear and the nonlinear cases via a generic type of mathematical formulation using the Equivalent Single Layer (ESL) theory in the framework of two kinematic models. The current formulation not only includes the influence of the transverse shear deformations but also satisfies the parabolic variation of transverse shear stress through the thickness. Additionally, the geometrical nonlinear distortion modeled via Green–Lagrange strain–displacement relations. Further, the internal debonding between the adjacent layers are modeled using sub-laminate approach and the displacement continuity between segments (laminate and delaminate) have been established through the intermittent continuity conditions. The nonlinear system governing equation of the vibrated structure is obtained via Hamilton’s principle and converted to set of nonlinear algebraic equations through the isoparametric finite element (FE) steps. The desired responses are solved numerically with the help of robust (direct iterative method) technique and compared with available results to demonstrate the solution accuracy. Subsequently, an adequate number of examples are solved for the delaminated structure using the current higher-order nonlinear models and the influential parameters discussed in detail.

ABSTRACT: This paper investigates the global bifurcations and multi-pulse jumping chaotic dynamics of circular mesh antenna. An equivalent continuum circular cylindrical shell is employed to represent the circular mesh antenna. Based on the four-dimension non-autonomous nonlinear governing equations of motion for the equivalent continuum circular cylindrical shell derived by Zhang et al. (2016, 2017), the improved extended Melnikov theory of the non-autonomous nonlinear system is utilized to conduct a theoretical analysis of the multi-pulse jumping chaotic motions for the equivalent continuum circular cylindrical shell. The thermal excitation and damping coefficient are considered as the controlling parameters to analyze their effect on the
nonlinear vibrations and bifurcations of the equivalent continuum circular cylindrical shell. Numerical simulations are also introduced to further verify the existence of the multi-pulse jumping chaotic motions for the equivalent continuum circular cylindrical shell. The results obtained from the numerical simulations are compared to those obtained from the Melnikov theoretical prediction.

ABSTRACT: A new theoretical model is developed for the three-dimensional (3D) nonlinear vibration analysis of fluid-conveying cantilevered micropipes. Particular attention is given on the derivation and analysis of the reduced equations, and the small-scale effect on the periodic motions. Based on the modified couple stress theory (MCST), the governing equations are derived by using Hamilton’s principle. The material length scale parameter and large-deflection-induced geometric nonlinearities given by the Lagrangian strain tensor are incorporated into the governing equations. Utilizing the center manifold theory, normal form method and O(2) symmetry, the original governing equations can be rigorously reduced to a two-degree-of-freedom (2DOF) dynamical system. Then two possible types of periodic motions, i.e. planar periodic and spatial periodic motions, together with their stabilities are investigated by means of averaging methods and numerical simulations. Results show that the larger the dimensionless material length scale parameter is, the wider the region of mass ratio for stable planar periodic motion is. Particularly, the presence of small length scale parameter makes micropipes be more likely to oscillate in a plane. It is also shown that for mass ratio corresponding to the hysteresis of the curves of critical flow velocity versus mass ratio, the stabilities for bifurcating periodic motions at lower, moderate and higher critical flow velocities may be different.

ABSTRACT: In this paper, a modular methodology, in which constraints associated to compatibility conditions can be included a posteriori, is applied for the derivation of a non-linear reduced order model of a cantilevered pipe conveying fluid, a classical problem in the area of Fluid–Structure Interaction (FSI). The dynamic response of this model is detailed in the neighborhood of the equilibrium state, by describing the dependency of the eigenvalues of its linearized form with respect to its parameters. For two scenarios, these responses are compared to benchmark results available in the literature. Also, two numerical simulations are proposed to compare how accurately the reduced order model can reproduce the results computed by a non-linear FEM model, previously proposed by the authors for this problem. The assessment of the numerical analyses indicates good agreement in the performed comparisons, which illustrates the good quality of the non-linear reduced order model proposed and suggests that the adopted modeling approach might be successfully applied for other problems in FSI.

ABSTRACT: In this paper, a mathematical model was developed to predict the effective material properties of graphene nanoplatelets/fiber/polymer multiscale composites (GFPMC). The large deflection, post-buckling and free nonlinear vibration of graphene nanoplatelets-reinforced multiscale composite beams were studied through a theoretical study. The governing equations of laminated nanocomposite beams were derived from the Euler–Bernoulli beam theory with von Kármán geometric nonlinearity. Halpin–Tsai equations and fiber
micromechanics were used in hierarchy to predict the bulk material properties of the multiscale composite. Graphene nanoplatelets (GNPs) were assumed to be uniformly distributed and randomly oriented through the epoxy resin matrix. A semi-analytical approach was used to calculate the large static deflection and critical buckling temperature of multiscale multifunctional nanocomposite beams. A perturbation scheme was also employed to determine the nonlinear dynamic response and the nonlinear natural frequencies of the beams with clamped–clamped, and hinged–hinged boundary conditions. The effects of weight percentage of graphene nanoplatelets, volume fraction of fibers, and boundary conditions on the static deflection, thermal buckling and post-buckling and linear and nonlinear natural frequencies of the GFPMC beams were investigated in detail. The numerical results showed that the central deflection and natural frequency were significantly improved by a small percentage of GNPs. However, addition of GNPs led to a lower critical buckling temperature.

References listed at the end of the paper:


ABSTRACT: An accurate and efficient gradient weighted finite element method (GW-FEM) is developed for linear elastic, free vibration and material nonlinear analyses. The new approach is based on the triangular and tetrahedral elements that can be generated automatically for any complicated geometries in 2D and 3D spaces. Shepard interpolation technique (SIT) is used to formulate the weighted gradient field considering the effect of the element itself and its adjacent elements sharing common edges (2D) or faces (3D). Due to the simple formulations, the SIT is easily implemented and coded in constructing the weighted gradient field. Both of the...
linear elastic and work-hardening-based elastic–plastic material models are incorporated in the GW-FEM for the linear and nonlinear analyses. The GW-FEM is then coupled with the total strain theory and projection method to solve the nonlinear elastic–plastic problem. Our numerical examples, including both of benchmark and practical engineering cases, reveal that GW-FEM provides superior performance in accuracy and efficiency, compared to the standard finite element method.


ABSTRACT: In this study, geometrically nonlinear dynamic behavior of laminated composite super-elliptic shells is investigated using generalized differential quadrature method. Super-elliptic shell can represent cylindrical, elliptical or quasi-rectangular shell by adjusting parameters in super-ellipse formulation (also known as Lamé curve formulation). Geometric nonlinearity is taken into account using Green–Lagrange nonlinear strain–displacement relations that are derived using differential geometry and theory of surfaces. Transverse shear effect is considered through the first-order shear deformation theory. Equation of motion is obtained using virtual work principle. Spatial derivatives in equation of motion is expressed with generalized differential quadrature method and time integration is carried out using Newmark average acceleration method. Several super-elliptic shell problems under uniform distributed load are solved with the proposed method. Effects of layer orientations, boundary conditions, ovality and ellipticity on dynamic behavior are investigated. Transient responses are compared with finite element solutions.


ABSTRACT: Trusses with geometric and loading symmetries have been used in many structures to reduce the complexity of the design. Slight asymmetries in geometry and in loading could lead to bifurcation in the structural response. Failure of such structures still occur occasionally causing major damage to the property and to the human lives. A fully nonlinear structural analysis is expected to detect such symmetry breaking bifurcations. In this paper, we conducted the bifurcation analysis of a two-bar truss and a shallow arch structure with seven bars. Two program packages Gesa and Ansys based on finite elements method have been used to detect the symmetry breaking bifurcation points. However, unlike typical bifurcation analysis packages they cannot detect the bifurcation point without inserting a small perturbation in the initial geometry or the loading of the structure. Such a bifurcation can be easily missed in finite element-based analysis. The theoretical analysis reveals that the bifurcation leads to a much lower critical load in the presence of small asymmetry compared to the symmetric case. The results are verified by using Gesa program in Matlab for fully nonlinear analysis and with results by using Ansys commercial program. The two structural examples serve to illustrate the limitations of widely used finite element analysis packages for nonlinear bifurcation analysis.


ABSTRACT: The present work is concerned with the application of the variational differential quadrature (VDQ) method (Faghih Shojaei and Ansari, 2017), in the area of computational mechanics, to the nonlinear large deformation analysis of shell-type structures. To this end, based on the six-parameter shell model, the functional of energy in quadratic form is derived based on Hamilton’s principle which is then directly
discretized by the VDQ technique. The formulation of article is presented in a general form so that it can be readily used for different structures such as beams, annular plates, cylindrical shells and hemispherical shells under various loading conditions. In order to reveal the accuracy of developed solution strategy, it is tested in several popular benchmark problems for the geometric nonlinear analysis of shells. The results show that the present numerical method is capable of yielding highly accurate solution in the nonlinear large deformation analysis of shells. It is also easy to implement due to its compact and explicit matrix formulation.


ABSTRACT: Tensegrity systems occur when self-equilibrated states are achieved through the interplay of pretensed (cables) and precompressed (struts) elements. The principles that govern these types of structures have been widely observed in many living systems across the scales and recently recognized, with soft or buckling bars, in the cytoskeleton as well as within single protein architectures as associated with key cellular and subcellular processes. To properly model these mechanical phenomena, some limitations dictated by the mostly linear approaches – used in literature when dealing with tensegrity structures – need to be overcome. To this aim, the present work provides a novel 2-element soft-tensegrity paradigm that includes, for the first time, (neo-Hookean) finite hyperelasticity for cable and strut, the latter potentially undergoing both contraction and buckling at each prestressed equilibrium stage. It is finally shown that constitutive properties, instability and bar deformability cooperate to determine unusual form-finding results, providing peculiar overall mechanical responses as external forces are applied.

(December 2018 papers are included in Part 2)

**End of more papers published in the journal, International Journal of Non-Linear Mechanics (2017 and on).**


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ABSTRACT: A fatigue reliability analysis of dented pipeline subjected to internal pressure load is presented based on limited experimental data. Different failure criteria considering the dent size and applied load are analysed and reliability as a function of number of load cycles is defined. The analysed pipeline is modelled as a series of segments, where any of them is characterized by the fatigue strength properties and reliability descriptors derived from the Weibull model analysis. The pipeline is assumed as a series system in which the segments, are modelled as random correlated elements. The developed approach may be used to identify
practical scenarios for inspections and repair, accounting for the damage tolerance and load subjected to the pipeline.


ABSTRACT: The paper discusses load carrying capacity of steel cones subjected to combined loading by simultaneously acting uniform pressure and axial load. The following combinations of loads are considered: external/internal pressure plus axial tension. Depending on the load combination various modes of failure are studied. These includes bifurcation buckling, plastic load and plastic instability load. For the case of internal pressure/axial tension: envelopes of the first-yield, plastic load and plastic instability load are computed. All of these domains are convex and closed. This is not true for the case of external pressure and axial tension where bifurcation buckling becomes an active mode of failure. Due to substantial plastic straining, numerical results are based on true stress-strain modelling of material beyond necking and for up to fracture.


ABSTRACT: This paper focuses on spherical shells with openings and reinforcement under uniform external pressure. To reduce the local weakening and buckling effects of the openings on these spherical pressure shells, the opening reinforcement parameters were optimized to minimize the buckling instability. According to the result of the optimization, two laboratory-scale models were manufactured and tested. The geometry, spherical shell thickness, wall thickness, buckling load, and final collapsed mode were measured for each spherical shell with an opening; the material properties of the corresponding sheets were also measured. The buckling behavior of a simulated spherical shell with an opening was demonstrated numerically according to experimental data. Numerical calculations involved considering the real geometrical shape, average values of parameters, and elastic-plastic modeling of true stress-strain curves. Moreover, the effects of initial geometrical imperfections on the critical load of the simulated spherical shell were analyzed numerically. The scanning model was calculated according to deterministic imperfections obtained from measured geometrical shapes. The theoretical model was calculated according to the equivalent geometrical imperfection valued as the first buckling mode of linear buckling. The results of the experimental and numerical investigations were compared in tables and figures.


ABSTRACT: This article presents a theoretical and numerical investigation of the instability and bifurcation of metallic thick-walled cylindrical pressure vessels loaded by combinations of large pressure and axial force. A general bifurcation theory is developed considering elastic-plastic material behavior with non-linear isotropic hardening. The constitutive law is based on applying the von Mises yield criterion in association with the normality rule. Instability limit loads and deformations are obtained and compared with those associated with axisymmetric bifurcation. The developed theory is validated by comparing the theoretically obtained results
with those obtained numerically using nonlinear finite element simulations. It is shown that axisymmetric bifurcation occurs at descending loads after the instability limit has been reached. The unstable regular deformation, which continues under descending loads prior to bifurcation, is more evident in shorter cylinders where the delay of bifurcation after instability depends on the loading combination. While in some cases, bifurcation immediately follows instability, leading to catastrophic failure, in some other cases axisymmetric bifurcation is delayed so much that it does not occur at all, even after extremely large unstable regular deformations have developed under descending loads, which provides the opportunity for further energy absorption through unstable, albeit regular plastic deformations. This investigation addresses and provides a solution for a long-standing unresolved problem. The findings provide valuable information in the safety design of extremely loaded pressure vessels.

References listed at the end of the paper:

ABSTRACT: This paper focuses on the buckling and post-buckling of horizontal steel tanks with conical end-caps, supported on discrete saddles, under pressure caused by internal vacuum and liquid pressure. Linear bifurcation, as well as geometrically nonlinear analyses with imperfections, was performed on a single geometric configuration in order to highlight modeling differences, imperfection sensitivity, and post-buckling behavior. Results are presented for (a) increasing uniform external pressure; (b) increasing pressure under fixed fluid level; (c) coupled increasing pressure and decreasing fluid. For perfect shells, the lowest maximum loads are reached at the conical end-caps; however, imperfection-sensitivity is more stringent for the cylindrical shell.
than for the conical caps, with the consequence that the buckling mode has displacements in the cylinder and in the conical caps. The influence of radius to thickness ratio and fluid level are investigated by means of parametric studies.


ABSTRACT: Pipelines, and more generally long tubular structures, are major oil and gas industry tools used in exploration, drilling, production, and transmission. Technical challenges of the field have spawned significant research and development efforts in the mechanical behavior and the modes of failure of long tubes and pipes under various loads. Nonlinear bending analysis of anisotropic laminated composite tubular beams with different kinds of distributed loads resting on a two-parameter elastic foundation is investigated. Based on Hamilton's principle and the displacement field by Laurent series expansion form with a von Kármán-type of kinematic nonlinearity, the governing differential equations are obtained. Composite tubular beams with clamped-clamped, clamped-hinged, and hinged-hinged boundary conditions including two kinds of end conditions, namely movable and immovable are considered. A numerical solution of the transverse deflection of tubular beams by using Galerkin's method is employed to determine the relations between distributed loads and deflections of a composite beam with or without initial axial loads. The results of the present formulation concern the large-deflection bending behavior of laminated beams with different geometric and material parameters, distributed loads, end conditions and effect on elastic foundation, the obtained numerical results are also compared with the results of nonlinear finite element method. Some new results for anisotropic laminated tubular beams, such as effects of the end conditions, load characteristics and foundation stiffness are obtained for future references in the design of the civil, mechanical, aeronautical and aerospace industries.


ABSTRACT: This paper focuses on two opening reinforcement methods of spherical shells under uniform external pressure. To reduce the local weakening and buckling effects of openings in spherical shells, designs comprising the wall reinforcement and the combination of a wall and thick plate reinforcement were employed to minimize buckling instability. In addition, the equal-proportion models of two kinds of reinforcement methods were manufactured and tested. The geometry, thickness, buckling load, and final collapsed mode were measured for each spherical shell with opening reinforcement. The paper contains a comparison between theoretical predictions, numerical analysis results and experimental data for two reinforced spherical shells. The theoretical and numerical results were in good agreement. The numerical solution result, obtained by considering the real defect, was consistent with the experimental result, and the failure mode was consistent with the location of the defect.


ABSTRACT: The mechanical behavior of spiral-welded large-diameter steel pipes is simulated, with the purpose of defining their bending deformation capacity against local buckling. The steel pipes are candidates for hydrocarbon onshore pipeline applications with diameter-to-thickness ratio D/t equal to 53 and 69, and are subjected to longitudinal bending under internal pressure levels ranging from zero to 75% of the nominal yield pressure. Initial geometric imperfections are considered in the form of short-wave axial wrinkles and girth weld
misalignment, whereas residual stresses are taken into account as computed from a special-purpose finite element simulation of the spiral bending process, which also accounts for both de-coiling process and hydrotesting. The sensitivity of critical bending curvature on the level of internal pressure is examined, the value of buckling wave length is discussed and the effects of hydrotesting after spiral forming on structural performance are also investigated. Finally, the value of critical bending curvature is compared with analytical and empirical equations, widely used in pipeline design applications. The results of the present study determine the main parameters affecting the buckling deformation capacity of large-diameter spiral welded pipes in a strain-based design framework, and indicate that these pipes can be used in demanding pipeline applications, such as in geohazard areas.

ABSTRACT: Blast loads and designing blast load-resistant pipelines have attracted attention because of the multiple terrorist attacks against buried pipelines during recent years. The present investigation is carried out numerically for reducing the deformation of buried pipelines without internal pressure exposed to subsurface explosion. This study presents a novel approach, using Glass Fiber Reinforced Polymer (GFRP) blanket for reducing the deformation of buried pipelines against blast loads. For this purpose, a 3D finite element model (3DFEM) was developed using nonlinear finite element code and combined Eulerian-Lagrangian (CEL) method. JWL equation of state, the ideal gas equation of state, Johnson-Cook plastic model and anisotropic material model were used to simulate the behavior of explosive substances, air, pipe and GFRP Blanket, respectively. In addition, the behavioral model of soil was considered to be Drucker-Prager. The results of this study for the size of crater, the shape of detonation products cloud, maximum longitudinal strain of pipelines and attenuation of blast wave in soil were compared with field results as well as empirical relations and a good concordance was obtained between them. According to our results, a GFRP blanket can significantly reduce pipelines deformation induced by explosion so that the length of damaged zone, cross sectional deformation and the maximum longitudinal strain of pipeline decrease by 59%, 48% and 73%, respectively. Moreover, a GFRP blanket with appropriate thickness is more economic and shows better performance compared with increasing the thickness of pipelines. The results of this study can be used to effectively reinforce constructing or operating buried pipelines against blast load effects.

ABSTRACT: In this paper, a new set of six-variable linear partial differential equations of motion of fluid-conveying pipes with general boundary conditions are derived using the Hamilton principle and these equations are solved by the receptance method. The frequencies of the straight pipes conveying fluid with or without elastic supports are determined and the results are compared with experimental ones. Then a fluid-conveying, semi-circular pipe and complex piping system with different kinds of boundary conditions are studied. These pipes are divided into some straight pipe units and are assembled using the receptance method. The numerical results show that the receptance method is efficient for pipes with arbitrary geometrical layouts and support types, and once the dynamic receptance of the elastic support of a piping system is obtained via experiment, its dynamic stability at different fluid velocities can be analysed by the receptance method.

(November and December 2018 papers included in Part 2.)


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ABSTRACT: The inelastic response of thin aluminium and steel plates subjected to airblast loading is studied numerically and validated against experimental data. Special focus is placed on the influence of elastic effects and negative phase on the structural response. The blast loading was varied by detonating spherical charges of plastic explosives at various stand-off distances relative to the centre point of the plates. The numerical results obtained with the finite element code EUROPLEXUS were in good agreement with the experiments and predicted the entire range of structural response from complete tearing at the supports to a more counter-intuitive behaviour (CIB) where the final configuration of the plate was in the opposite direction to the incident blast wave due to reversed snap buckling (RSB). RSB attracted special attention since this is an unstable configuration sensitive to small changes in the loading and in structural characteristics. The negative phase of the blast pressure is usually neglected in blast-resistant design. However, the numerical simulations showed that the negative overpressure dominated the structural response and led to RSB at some loading and structural conditions. Two distinctive types of CIB were identified and both were found to depend on the timing and magnitude of the peak negative overpressure relative to the dynamic response of the plates. The study also revealed that CIB may occur in thin plates when the negative impulse is of the same order of magnitude as the positive impulse. The partial and complete failure along the boundaries observed in some of the tests was also successfully recreated in the simulations by using an energy-based failure criterion and element erosion.

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ABSTRACT: The split Hopkinson pressure bar was used to investigate the dynamic behavior of high density aluminum alloy (Al 6061-T6) – tungsten (W) fibers composite tubes with periodic arrangements of W fibers in
axial and hoop directions processed by using the combination of Cold Isostatic Pressing (CIPing) and Hot Isostatic Pressing (HIPing). Additional heat treatment of some samples allowed them to regain the original strength of Al 6061-T6, which was annealed during HIPing. The high-strain-rate deformation resulted in the strength increase for both types of samples (with and without the heat treatment) compared to quasi-static deformation. Samples after additional heat treatment exhibited higher dynamic strength. We consider that the strain rate sensitivity of the composite samples is caused by W fibers, which are responsible for the high strength of the samples and mechanism of their fracture. After dynamic tests, the Al matrix was chemically removed from the heavily deformed samples to reveal the mode of deformation of the W fibers: microbuckling and kinking in the axial direction. These mechanisms initiated the fracture of the composite samples followed by sample bulging due to plastic flow of the Al matrix and the subsequent fracture of W fibers in the hoop direction.

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ABSTRACT: This paper presents the results of an experimental work on the response of multi-layered protective structures subjected to underwater contact explosions. Multi-layered structures are used in anti-explosive design to resist underwater explosions and protect the equipment in some important ship compartments. The target experiment model is designed as a three-compartment box, an air, a fluid and another air compartment, which is made of four plates with thickness 4 mm that resist the propagation of damage. A series of experiments with increasing dynamite charge weight were conducted on this multi-layered structure. The damages and pressures of the test specimens were obtained. In general, it is shown that large damages and plastic deformations happened in the test structures, especially for the plate in contact with the dynamite. With the increase of the charge a trend of increasing damages in the outer and intermediate plates was observed, but the increase was small for the inner plate. Some important factors in plate damage are analyzed and the role of the compartments with different medium in the damage and energy dissipation is discussed. It is found that the multi-layered structure can resist the explosive loading very effectively.

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“Effect of fibre orientation on the low velocity impact response of thin Dyneema composite laminates”,
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ABSTRACT: Ultra-high molecular weight polyethylene (UHMWPE) fibre reinforced composite materials are widely used in ballistic impact and collision scenarios due to their extremely high specific strength and
stiffness. Exceptional levels of protection are provided by controlling the damage and deformation mechanisms over several length scales. In this study, the role of UHMWPE fibre architecture (cross-ply, quasi-isotropic and rotational “helicoidal” layups) is considered on the damage and deformation mechanisms arising from low velocity impacts with 150 J impact energy and clamped boundary conditions. Dyneema® panels approximately 2.2 mm thick were impacted with a fully instrumented hemi-spherical impactor at velocities of 3.38 m/s. Full field deformation of the panels was captured through digital image correlation (DIC). The results indicate that the cross-ply laminate [0°/90°] had the largest back face deflection, whilst quasi-isotropic architectures restricted and reduced the central deflection by an average of 43%. In the case of the [0°/90°] panel, the deformation mechanisms were dominated by large amounts of in-plane shear with limited load transfer from primary fibres. Conversely, the failure of the quasi-isotropic panels were dominated by large amounts of panel buckling over various length scales. The observed mechanisms of deformation with increasing length scale were; through thickness fibre compression, fibre micro-buckling, fibre re-orientation with large matrix deformation, lamina kink band formation, and laminate buckling. The helicoidal panels showed that bend-twist and extension-twist coupling were important factors in controlling clamped boundary conditions and the laminate buckling/wrinkling shape. Further examination of the impact zone indicated that the damage mechanisms appear to be fibre orientation dependent, with quasi-isotropic laminates having up to 37.5% smaller impact damage zones compared with [0°/90°]. The experimental observations highlight the importance of fibre orientation in controlling the deformation mechanisms under dynamic impact, in particular limiting the shear deformation of Dyneema® panels.

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ABSTRACT: With the increasing trend towards using concrete-filled steel tubes (CFST) in civil structures, understanding their mechanical properties under impact loads has attracted the interest of researchers. The dynamic properties of concrete confined by steel tubes are size-dependent. An experimental program was carried out to investigate the relation between the size and impact response of CFST sub-samples. High-strain-rate tests were conducted on specimens made from self-consolidating normal concrete confined by mild steel tubes. To take into account the stress uniformity and confinement effects in the specimens, various height-to-diameter ratios (H/D) and diameter-to-tube-wall thickness ratios (D/t) were considered. Dynamic increase factors (DIFs) were derived as the ratio of the material strength at high strain rate to those of the same size under quasi-static loading conditions. The results were compared to two sets of reference tests, namely unconfined concrete and hollow steel tube specimens of the same size and with the same boundary conditions. The results indicate the influence of H/D ratio, D/t ratio, and end-friction coefficient on the stress–strain distribution, dynamic compressive properties and failure modes of sub-scale concrete-filled steel tubes under impact load. The size-dependent behaviour of the CFST is found to be a function of the level of confinement the circumferential steel tube imposes on the concrete filling. Two expressions are proposed for predicting the DIF of yield stress for CFSTs: one considering the concrete–steel interaction relationship presented in Eurocode 4, and an empirical expression based on the Cowper–Symonds model for steel. The proposed rate- and size-dependent expressions show close correlations with experimental results.
ABSTRACT: In this paper, high velocity impact responses of newly designed sandwich panels with aluminium (AL) foam core and metal fibre laminate (FML) skins, which are comprised of aluminium sheets and plain woven E glass fibre composite plies are investigated. Gas gun impact tests were conducted to investigate the high velocity impact response of the panels subjected to the impact from a steel ball bearing at an impact velocity of around 210 m/s. The effect of the thickness of the foam core and FML skin on the impact resistance of the panels is also investigated via experimental study. A finite element model is developed for effective numerical modelling of the impact behaviour of the sandwich panels using the commercially finite element software ANSYS LS-DYNA for more extensive study of the impact response of the sandwich panels. The simplified Johnson Cook material model, the composite damage material model based on the Chang-Chang criteria, and the crushable foam material model are used to model the aluminium sheets, composite plies and the AL foam respectively. Three types of contact algorithms, i.e. the erosion contact type, the tie-break contact type and the general 3D contact type are employed to define the various contacts during the impact and to model the delamination between the FML layers and debonding between the FML skin and the AL foam. The finite element model is validated by comparing the simulated impact behaviour to that from experimental for a sandwich panel subjected to high speed impact and demonstrated to be effective and accurate. The effect of the shape of projectile and impact angle on the impact behaviour of the sandwich panels is studied using the developed finite element model. The research findings are summarized and concluded finally.
in good agreement with those by the analytical model. Sensitivity analyses were carried out that offer new insights on the influence of the beam’s aspect ratio and inertial mass.

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https://doi.org/10.1016/j.ijimpeng.2016.11.006  
ABSTRACT: Due to the influence of strain-rate effect of rate dependent materials, the relations of responses between scale-down model and prototype plates under blast loads cannot assure the satisfaction of the scaling laws, which is known as non-scalability of structure under impact loads. In this paper, by employing the dimensional analytical method, the strain-rate effect involved in blast loaded plates with different scaled values was firstly analyzed, then a corrected equation was established by taking a correction factor of impulse per unit area into consideration. Besides, a set of empirical formulae used to calculate the impulse per unit area is given, in which the relations between the mass of TNT, the stand-off distance and the impulse per unit area is determined. Furthermore, this paper adopted the method presented by Oshiro and Alves [14] to establish the corrected similarity relation between incomplete scale-down models and prototype. On the basis of this, a rapid solution to predict the value of exponent $n$ is proposed, guaranteeing this method could be used more smoothly in practical engineering.

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ABSTRACT: Detonations of nitromethane spherical charges have been carried out to study close-in blast loading of steel plates and the effectiveness of several protective solutions. Three types of bare steel plates, namely mild steel, high-strength steel, and stainless steel were subjected to explosive blast loading. Steel plates of the same type with polyurea coating and composite covers were also subjected to localized blast loading. During an explosive field trial, the blast pressures and displacements of steel plates were measured. Additionally, loading of steel plates by the impinging detonation products was captured by high-speed video recordings. This experimental program has produced results which can be used to calibrate numerical models and to refine the simplified models for predicting blast loads and response of structural elements due to close-in detonations. The effectiveness of polyurea coating for enhancing blast protection of steel plated structures is discussed. The engineering-level model for predicting the blast impact impulse of the detonation gases from the
charges in close proximity from the target is introduced and validated using the experimental results obtained during the course of the explosive trials.

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ABSTRACT: This paper deals with the investigation of a numerical simulation method to appropriately represent relevant failure mechanisms of carbon fiber reinforced plastic (CFRP) components subjected to dynamic crash loads. The presented work considers the stacked shell approach, using a stack of continuum shell elements and cohesive elements, and focuses on the calibration of simulation input parameters. Furthermore, modeling aspects are discussed to reduce mesh-dependencies for the simulation of progressive crushing. The validation of the numerical approach is performed on the basis of an extensive test program of CFRP crush absorbers on the structural level. The capability of current state-of-the-art technologies for the simulation of progressive crushing is identified. The simulations capture general failure effects and force-displacement characteristics for different designs and loading conditions. Drawbacks are identified in the definition of cohesive input parameters to obtain numerical stability for complex loading conditions. The numerical simulations were performed using the commercial finite element software Abaqus/Explicit.

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ABSTRACT: An experimental study of the stress–strain behaviour of titanium alloy (Ti6Al4V) lattice structures across a range of loading rates has been reported in a previous paper [1]. The present work develops simple numerical models of re-entrant and diamond lattice structures, for the first time, to accurately reproduce quasi-static and Hopkinson Pressure Bar (HPB) test results presented in the previous paper. Following the development of lattice models using implicit and explicit non-linear finite element (FE) codes, the numerical models are first validated against the experimental results and then utilised to explore further the phenomena associated with impact, the failure modes and strain-rate sensitivity of these materials. We have found that experimental results can be captured with good accuracy by using relatively simple numerical models with beam elements. Numerical HPB simulations demonstrate that intrinsic strain rate dependence of Ti6Al4V is not sufficient to explain the emergent rate dependence of the re-entrant cube samples. There is also evidence that, whilst re-entrant cube specimens made up of multiple layers of unit cells are load rate sensitive, the mechanical properties of individual lattice structure cell layers are relatively insensitive to load rate. These results imply that a rate-independent load-deflection model of the unit cell layers could be used in a simple multi degree of freedom (MDoF) model to represent the impact behaviour of a multi-layer specimen and capture the microscopic rate dependence.

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“A combined experimental and numerical investigation on the scaling laws for steel box structures subjected to internal blast loading”, International Journal of Impact Engineering, Vol. 102, pp 36-46, April 2017
https://doi.org/10.1016/j.ijimpeng.2016.12.003
ABSTRACT: The present work aims at the problem of scaling the deformation of steel box structures subjected to internal blast loading through experimental and numerical investigations. Three sets of steel box model with different scale-down factors were designed according to the geometrical similarity law (“Replica”), with three different explosive masses considered in each set based on Hopkinson's scaling law. The numerical results show good agreement with the experiments, and the results present that outward bulging produced in all sides and inplane buckling in the central area of boundary plate. And imperfect similarity was observed through comparing the plate center deflections though the deformation shapes present good similarity. The observed scale values are larger than those of geometry scale, and the difference increases with the increasing of geometry scale. In addition, the reasons for the deviation of the traditional scaling law were discussed. And then, based on the experimental results, correction of the scaling law for steel box structure was conducted which considered both the scale-down factor (size effect) and the scale distance (strain-rate effect).

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ABSTRACT: Analytical predictions and finite element (FE) calculations are performed to predict the 1D response to underwater blast loading of sandwich plates with elastic cores, in contact with water on both sides and loaded by an exponentially decaying shock wave on one side. The theoretical models explicitly account for cavitation processes and effects of deep water, and their formulation helps identifying the governing parameters of the problem. Three characteristic regimes of behaviour are identified and regime maps are constructed. The analytical models are validated by FE simulations and used to explore the sensitivity of the predictions to the governing non-dimensional parameters. It is shown that, in the absence of plastic core deformation, sandwich plates with stiff cores are imparted higher blast impulses compared to those with softer cores and equivalent areal mass.

Z.L. Yu, P. Xue and Z. Chen (School of Aeronautics, Northwestern Polytechnical University 127 West Youyi Road, Xi'an, Shanxi 710072, PR China), “Nested tube system applicable to protective structures against blast shock”, International Journal of Impact Engineering, Vol. 102, pp 129-139, April 2017
https://doi.org/10.1016/j.ijimpeng.2016.11.018
ABSTRACT: Aiming at developing an efficient energy absorption component for protecting structures against blast shock, this paper proposes a triple-tube system (TT) consisting of three tubes. Its performance is studied experimentally and numerically, and compared with that of a double-tube system (DT) and a single-tube system (ST). The results show that the TT system can provide the highest energy absorption efficiency and the most stable deformation mode, so as to enhance energy absorption capacity for protecting structures. Then a parametric study is conducted to investigate the effect of the geometric parameters on the performance of the TT system and theoretical prediction of stage load is proposed to provide guidance for designing an effective TT system. Finally, the TT system is applied to a blast-resistance
door used in civil air defense headquarters. The results demonstrate that the TT system can provide the most efficient impact force reduction and the lightest weight in protecting the structures from damage under blast shock wave.

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ABSTRACT: The effect of tailoring the properties of a hot stamped axial crush rail on its axial crush response is investigated. Four configurations of rails of thickness 1.2 and 1.8 mm were formed: a non-tailored (fully martensitic) configuration and three tailored configurations in which one-half of the rail was quenched while the other half was formed in tooling that was heated at different temperatures (in the range 400–700°C). Impact experiments showed that the non-tailored, fully hardened components did absorb the highest energy (15.4–24.1 kJ at 165 mm displacement), but exhibited extensive tearing and fracture. The tailored configurations with a single soft zone were less susceptible to fracture, but the thinner rails were more likely to buckle and absorbed less energy (9.7–20.5 kJ at 165 mm) as a result. Graded tailored configurations with two soft zones and one hard zone did not buckle and absorbed slightly higher energy. The results show that tailoring can introduce graded properties to promote a progressive folding deformation mode, thereby improving energy absorption without fracture. Numerical models of the forming and impact response were developed in which strain rate-sensitive constitutive properties and fracture limit strain versus triaxiality loci were prescribed to be a function of the as-formed hardness and microstructural phase fractions. The models were able to predict the energy absorption of the various axial crush rails to within 10% accuracy, as well as the large difference in extent of tearing occurring in the fully martensitic versus tailored configurations.


ABSTRACT: An aluminum (1050 H14) multi-layer corrugated structure composed of brazed 16 trapezoidal zig-zig fin layers was direct impact tested above the critical velocities for shock formation using a modified Split Hopkinson Pressure Bar. The experimentally measured stress-time histories of the cylindrical test samples in the direct impact tests were verified with the simulations implemented in the explicit finite element code of LS–DYNA. The quasi-static experimental and simulation deformation of the corrugated samples proceeded with the discrete, non-contiguous bands of crushed fin layers, while the dynamic crushing started from the proximal impact end and proceeded with a sequential and in-planar manner, showing shock type deformation characteristic. The experimental and numerical crushing stresses and the numerically determined densification strains of the fin layers increased with increasing impact velocity above the critical velocities. When the numerically determined densification strain at a specific velocity above the critical velocities was incorporated, the rigid-perfectly-plastic-locking idealized model resulted in peak stresses similar to the experimental and simulation mean crushing stresses. However, the model underestimated the experimental and simulation peak stresses below 200 m s⁻¹. It was proposed, while the micro inertial effects were responsible for the increase of
the crushing stresses at and below subcritical velocities, the shock deformation became dominant above the critical velocities.


ABSTRACT: Scaled models are important in marine engineering since it is prohibitive testing of actual ship size. However, the crashworthiness analysis on marine structures in reduced scale is not an ordinary research topic given the scientific and technical limitations surrounding this type of practice. It is reported here a series of collision tests of marine structures in reduced scale. These experiments are used to validate the subsequent finite element analysis. The scaled shiplike specimens were built from metallic thin-walled structures in a reduced scale of 1:100 taken into account shipbuilding processes analogous to that used in real scale marine structures. The experiments include scaled collision tests of a T cross-section beam, head-on collision of an oil tanker against a rigid wall, ship grounding and collision between two oil tankers. It is discussed the influence of different numerical and experimental aspects inherent to experimental impact tests of marine structures. This includes the mechanical properties of the materials, slight misalignments in test arrangements, failure criteria, weld joints and sloshing effect of ship cargo. These aspects are thoroughly analyzed and discussed here so bringing new insights in the modeling of marine structures subjected to collision events using reduced scale experiments.

Yayun Zhao, Yuxin Sun, Ruiyu Li, Qiran Sun and Jiangtuo Feng (National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China), “Response of aramid honeycomb sandwich panels subjected to intense impulse loading by Mylar flyer”, International Journal of Impact Engineering, Vol. 104, pp 75-84, June 2017, https://doi.org/10.1016/j.ijimpeng.2017.02.008

ABSTRACT: The deformation/failure modes and impact resistance of composite sandwich panels with titanium alloy plates and aramid honeycomb cores subjected to intense impulse loading were investigated experimentally using electric gun technique. A velocity measuring instrument, known as the velocity interferometer system for any reflector (VISAR), measured the velocity history at the mid-point of the back plates. Typical deformation/failure modes were analyzed and classified systematically, and then a comparison of structural deformation resistance between sandwich panels and plates of equivalent mass was studied. It was found that both the deformation/failure modes and the dynamic response of the plates were sensitive to the impact velocity. The impact resistance of sandwich panels could be improved by core crushing and deformation of the front plate. Finally, effects of impact velocity and boundary conditions on the dynamic response of sandwich panels were identified. It was worth noting that the fully clamped boundary reduced the damage extent of the front plate, but increased the local plastic deformation of the back plate.

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ABSTRACT: The blast resistance of glass-fibre reinforced polymer (GFRP) sandwich structures has been investigated for increasing shock intensity and for multiple blast exposures. In this study, sandwich panels of 1.6 m x 1.3 m were subjected to 30 kg charges of C4 explosive at stand-off distances from 8 m to 16 m. These targets formed part of two studies presented here: one, to observe the loading of the same geometry of target to an increasing shock intensity; and the second, to observe the response of one target to multiple blast impacts. Experimental data provides detailed data for sandwich panel response, which are often used in civil and military structures, where air-blast loading represents a serious threat. High-speed photography, with digital image correlation (DIC), and laser gauge systems were employed to monitor the deformation of these structures during the blasts. The experimental data provides for the development of analytical and computational models. Initial analysis of the blast experiments are presented alongside a finite element model to establish trends in deformation behaviour. Details of failure mechanisms and the conditions for the onset of failure are also discussed.

ABSTRACT: A novel technique for efficient modelling of progressive delamination in large-scale laminated composite structures is presented and applied to the simulation of two dynamic events involving axial crushing of tubes and transverse impact loading of plates. During the transient analysis, continuum elements that are prone to delaminate are adaptively split through their thickness into two shell elements with cohesive elements planted between them. The numerical results using this adaptive placement of inter-laminar cohesive zones combined with a continuum modelling approach for capturing the intra-laminar damage modes in the composite are compared to the available experimental data as well as to the results obtained using the conventional application of the cohesive zone method, where the discrete cohesive interfaces/elements are introduced prior to the analysis.

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ABSTRACT: Additive manufacturing (AM) enables the design of new cellular materials for blast and impact mitigation by allowing novel material-geometry combinations to be realised and examined at a laboratory scale. However, design of these materials requires an understanding of the relationship between the AM process and material properties at different length scales: from the microstructure to geometric feature rendition to overall dynamic performance. To date, there remain significant uncertainties about both the potential benefits and pitfalls of using AM to design and optimise cellular materials for dynamic energy absorbing applications. This experimental investigation focuses on the out-of-plane compression of stainless steel cellular materials fabricated using selective laser melting (SLM), and makes two specific contributions. First, we demonstrate how the AM process itself influences the characteristics of these cellular materials across a range of length
scales, and, crucially, how this influences the dynamic deformation. Secondly, we demonstrate how an AM route can be used to add geometric complexity to the cell structure, creating a versatile basis for future geometry optimisation. Starting with an AM square honeycomb (the reference case), we add porosity to the walls by replacing them with a lattice truss, while maintaining the same relative density. This geometry hybridisation is an approach uniquely suited to this manufacturing route. It is found that the hybrid lattice-walled honeycomb geometry significantly outperforms previously reported AM lattices in terms of specific strength, specific energy absorption, and energy absorption efficiency. It is also found that the hybrid geometry outperforms the benchmark metallic square honeycomb in terms of energy absorption efficiency in the intermediate impact velocity regime (i.e. between quasi-static loading and loading rates at which wave propagation effects begin to become pronounced), a regime in which the collapse is dominated by dynamic buckling effects.

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ABSTRACT: Dynamic response of geometrically asymmetric sandwich plates with aluminum hexagonal honeycomb core subjected to blast loading is investigated experimentally and theoretically. Specimens of various face sheet thicknesses are tested for three blast intensities which are varied by changing the weights of cyclotrimethylene trinitramine (RDX) explosive charges at a constant standoff distance. Four edges of sandwich plates are fully clamped. The deformation and damage modes of sandwich plates are obtained. The influences of the blast loading and the core density on the dynamic response of sandwich plates are analyzed. The analytical model is developed to predict the blast response of the geometrically asymmetric sandwich plate subjected to blast loading. It is shown that the theoretical predictions of the deflection of the center point at the rear face sheet is in good agreement with the experimental results. The geometrical asymmetry due to the thicknesses of the face sheets has a significant effect on the deformation and damage of sandwich plates.

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ABSTRACT: This paper presents the work performed to design a novel tail leading edge structure by employing the finite element method coupled with the SPH method to simulate the bird strike process. The bird is simulated by the SPH model while the structure is modeled with the traditional Lagrangian elements. Bird strike experiments are conducted to validate the numerical model. Good agreements between simulation and experimental results showed that the coupled SPH-FE method provides a valid and effective means to predict the deformation and damage behavior of aircraft structures subjected to bird strike. Thus, it can be used as a tool
to design bird strike-resistant structures. It is found that the novel design, which introduces a triangular reinforcement component to the leading edge structure, greatly enhances the anti-bird strike performance. Finally bird strike simulations and experiments are conducted for the Horizontal tail leading edge of a commercial aircraft with the above mentioned novel design. No penetration on the frontal beam is observed, suggesting that the novel design meet the certification requirement of CCAR part 25.

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ABSTRACT: We modeled the formation and development of shear bands in metals on the mesoscale at a micrometer-scale resolution. We used the overstress approach to dynamic elasto-viscoplasticity rather than the flow stress (radial return) approach, which helped us to avoid noise upon partial unloading. To verify our model, we focused on the torsion of a thin-walled tube and assumed axial symmetry, so that our simulations were of simple shear in one dimension. We applied our modeling approach to four types of steel and compared the results to torsional Hopkinson testing data reported in the literature. We obtained good agreement with the experimental data in terms of the localization threshold strain, perturbation influence, shear band width, temperature and plastic strain evolution in the shear band. We were also able to relate the localization onset to the elastic unloading.

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ABSTRACT: This paper presents an experimental study on dynamic response of clamped sandwich plates with PVC foam core subjected to lab-scale impulsive loading. DIC-3D method and post-test are presented to investigate the permanent deformation, dynamic response and failure modes of the plates. Failure modes of PVC foam layers with three densities as well as front and rear metallic sheets are identified and discussed. Comparison methodologies concerning the blast resistance and energy absorption performance of four configurations in same mass with three densities and thicknesses are carried out. It is indicated that configuration 3 performs well in reducing permanent deformation of structure, and configuration 1 performs well in protecting the structure from destruction and have advantage in blast resistance under high impulsive intensity. The descending order of core densities have advantage in blast resistance than the core with ascending order of densities. Choosing the most efficient density, thickness and sequence of core layers is very helpful in structural optimization design, and especially in blast resistance for a prescribed load.

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ABSTRACT: In this study, cylindrical absorbers made of expanded metal structures subjected to impact loading were investigated. Experimental, numerical, and analytical approaches were employed for the analysis. Studied absorbers were made of unit cells with different angles. Experiments were performed using a drop hammer. Numerical analysis was accomplished using Abacus finite element software. Energy Method was applied for analytical study. Based on the results obtained in this study, the absorber with cell angle of $\alpha = 0^\circ$ had symmetric collapse. For $\alpha = 30^\circ$ and $45^\circ$, the point buckling had occurred. In addition, full buckling had occurred in the structure with $\alpha = 90^\circ$. The amount of crush resulting from different drop heights were also compared. Increase in the drop height of the hammer would increase the crush length, average force, and amount of energy absorption. In the analytical phase, using the energy method, a system of equations was achieved; which led to a force-displacement graph which can determine the behavior of the expanded metal cylindrical absorber with changes in the geometrical parameters and mechanical properties.

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ABSTRACT: Investigations of the large commercial aircraft impact effect have been drawing extensive attention, and the detached massive engine during aircraft collision would cause severer local damage to structures than the aircraft fuselage. Ultra high performance steel fiber reinforced concrete (UHP-SFRC) is an excellent material for the construction of valuable infrastructures to resist the intensive loadings. This paper aims to study the impact resistance of UHP-SFRC panels subjected to the aircraft engine. Firstly, a series of reduce-scaled engine model perforation test was conducted, in which the residual velocities of the engine missiles as well as the damage of both engine missile and target slab were derived and assessed. Then, a mesoscopic model of UHP-SFRC considering the random distribution, volumetric ratio, as well as the bonding and slipping effects of the fibers was established. By using the finite element program LS-DYNA and comparing with the macroscopic homogenous approach, the present test was better reproduced by the mesoscopic approach. Furthermore, based on the parametric analyses of panel thickness and engine missile impact velocity, a modified empirical formula for predicting the engine missile residual velocity was presented to guide the design of protective structures.

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ABSTRACT: Quasi-static perforation and low-velocity impact tests at different temperatures were carried out for sandwich panels with aluminum face sheets and a closed-cell aluminum foam core. The deformation and failure behaviors, load carrying capacity and energy absorption capability of sandwich panels were explored and compared at different temperatures. In the experiments, effects of several key parameters, i.e. soaking time, boundary condition, and geometrical size of the indenter, on the load carrying capacity and energy absorption of the sandwich panels during perforation were discussed. The differences of the perforation behavior of sandwich panels at elevated temperatures under quasi-static and low velocity impact tests were also studied.


ABSTRACT: The behaviour and failure of stiffened panels made of the aluminium alloy AA6082-T6 is investigated under quasi-static and low-velocity impact loading conditions. The strain rate and inertia effects are found to be negligible suggesting that quasi-static tests might be representative for low-velocity impacts where a large mass is placed on the impactor. A simplified approach to the finite element modelling of aluminium panels under impact loading, including a regularised failure criterion, is proposed and validated against the experimental data. The effect of mesh size is investigated with shell elements of various sizes in the range from 1 to 5 times the thickness. A good correlation is obtained between experiments and simulations for fine meshes, while large shell elements have difficulties to initiate and propagate properly the observed cracks.


ABSTRACT: The structural engineering problem associated with a ship colliding with an ice-ridge involves highly nonlinear mechanisms including buckling, collapse, crushing, plasticity and fracture together with environmental and operational factors, such as the loading speed (strain rate), temperature and salinity. The objective of this paper is to develop an advanced technology for numerical computations of structural crashworthiness in the event of a ship colliding with an ice-ridge. The nonlinear finite element method is used for modelling the problem, in which the ship structures are modelled by plate-shell finite elements and the ice-ridge structures are modelled by solid elements together with the KOSORI ice material models. Two sets of experiments are performed to validate the numerical computations. In the first set of experiments, ice is dropped on a steel plate from a height of 2 m, and in the second, a steel solid (rigid) body is dropped on a steel plate under the same conditions. The results of the two experiments are compared to determine the differences between the ice responses and solid (rigid) body responses on the steel plate. It is concluded that the developed technology is very useful for computing the structural crashworthiness of a ship when colliding with an ice-ridge. Details of the test results are documented.

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ABSTRACT: This paper presents a detailed investigation of short tubes under combined lateral compression and shearing by applying two parallel rigid platens in an oblique manner. The tubes were placed between the two parallel platens. The relative directions of the two platens were 0°, 15°, 30°, 45°, 60° and 75°, respectively; a value of 0° corresponds to pure compression while a 90° would be for pure shearing. Quasi-static tests were conducted by an INSTRON machine and the force-displacement curves were obtained. A finite element (FE) analysis was performed, which revealed more detailed deformation mechanisms. Subsequently, an analytical model is established for rigid, perfectly plastic material, which invokes stationary and travelling plastic hinges. The analytical results are in agreement with those obtained from the experiments and the FE analysis. The dynamic effect was also considered in the FE analysis.

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12 Burton RH, Craig JM. An investigation into the energy absorbing properties of metal tubes loaded in the transverse direction. UK: University of Bristol BSc (Eng) Report; 1963.
ABSTRACT: Experimental tests of the collision of reduced scale naval structures is here detailed described. First, a web girder section constructed in two different scales, 1/1 and 1/4, is subjected to the impact of a rigid indenter at mid span. The second experiment employs a more complex structure: a head-on collision of a 1/100 scaled tanker against a rigid obstacle. Special attention is given to some similarity complications that are frequent in real tests: model yielding stress different from the prototype and material strain rate. Since the standard similarity laws are unable to deal with those issues, it is shown how to modify the scaling factors to generate a replica similar to the corresponding prototype. Results are shown that support the approach with the modified scaling factors producing a behavior closer to the full-size structure. In the study of the ship head-on collision, only a 1/100 scaled specimen could be tested. In this case, the equivalent prototype was calculated with the assistance of the scaling factors and compared with empirical formulations found in the literature. The methodology depicted in this manuscript can be used as a guidance for scaled impact tests of vessels and other types of large structures.


ABSTRACT: The effect of strain rate on dynamic external inversion loading of Functionally Graded Thickness (FGT) tubes are studied analytically and their results are compared with Finite Element (FE) results. Based on the deformation theory and using rigid-perfectly plastic (R-PP) material idealization, a theoretical solution for dynamic inversion crushing load is derived by dividing the contact region of circular sections into three different sections. Comparing analytical and FE results indicates that prediction of crashworthiness loading for different thickness distribution of FGT tubes are satisfactory. Also, it is found that the concave distribution of thickness for FGT tubes improves the energy absorption more efficient than other geometries.


ABSTRACT: This paper reports on the response of cladding sandwich panels with tubular cores to uniform blast load. The core of the cladding sandwich panels consisted of empty or foam-filled thin-walled circular tubes (38 mm in diameter) made from either aluminium 6063-T6 or mild steel riveted laterally between the skin plates at varying spacing arrangements. The tubular cores were arranged to provide four different types of panels. The front plate skin of the panel, exposed to the blast load, was made from DOMEX 700 Steel while the back plate skin was made from mild steel. Three types of polymeric cellular foams, namely self-raising polyurethane, expanded polystyrene and cross-linked polyethylene, were used to fill the circular tubes. The “uniform” blast load was achieved by detonating varying charge masses of explosive (ranging from 6 g to 50 g) with a prescribed load diameter of 40 mm at a stand-off distance of 200 mm down a square tube. Energy was dissipated mostly through the plastic deformation of the tubular cores. The foam added extra energy absorbing capacity. The results showed an increase in average deflection with an increase in charge mass/impulse for the different types of panels. The cladding panels with the least interaction between the tubular cores were observed to have the highest energy absorption capabilities for a given charge mass.

ABSTRACT: The objective of this paper is to establish a yielding criterion for a sandwich beam by considering the time inhomogeneity of foam core deformation, which results in the time-varied neutral surface and cross-sectional area. Taking into account of the bending and axial stretching, a unified dynamic yielding criterion for metallic sandwich beams considering the mass redistribution along with the core compression is established. A membrane factor is proposed and an analytical solution for the large deflection of the beam under high velocity impact is given. Different from the traditional yielding surface, when the core is partially densified, the yielding surface is asymmetric. Comparison of analytical solutions with numerical ones reveals that the present model improves the prediction accuracy of high-velocity impact responses of fully clamped sandwich beams.

The present method can also be degenerated to predict the low velocity/energy impact responses of sandwich beams.


ABSTRACT: Braided composites tubes have been reported to have a great potential in crash energy absorption applications. In this study, an innovative chamfer external trigger was introduced which is different from the traditional chamfer-flat crush-cap to guide the 2D braided tube. To make the material fully destroyed in the impact process, the innovative trigger restricts the space of tube under compression by a semi-circle cavity. A 3D-FE model for impacting processes of thin-walled braided tubes was built to study the effects of geometrical parameters on external trigger guiding tubes. Simulation and analysis of the influence laws of geometrical parameters on the cavity were then carried out. The results show that braided tubes worked with cavity effect can increase the energy absorption efficiency by 53% than traditional crush-cap, and the result and failure mechanism is significantly affected by the ratio of cavity radius of tube thickness(R/t). It is found that as the R/t ratio increases, the amount specimen energy absorption increases sharply then decreases and tend to be stable, while the ratio of peak load to mean load decreases and then increases. These two trends are very instructive for designing effective energy absorption structures using braided tubes with this innovative external trigger.

References listed at the end of the paper:

The characteristics of the permanent upper and lower surface deformations of acceleration and deformation of pipes are measured, and a method to determine global and local deformations is according to the outside diameters of 25-70 pipes are tested using a drop hammer rig under various impact energies and are categorized into five groups. Lateral impact loadings should be investigated in order to ensure safe operations. An experimental programme is studied on the deformation of fully clamped pipes under lateral impact, International Journal of Impact Engineering, Vol. 111, pp 94-105, January 2018, https://doi.org/10.1016/j.ijimpeng.2017.09.008

ABSTRACT: Accidental loads often cause failure to tubular structures on offshore platforms and subsea pipelines due to, for instance, dropped objects and collisions. Thus, the dynamic behavior of pipes subjected to lateral impact loadings should be investigated in order to ensure safe operations. An experimental programme is used in this paper to study the deformation mode since it is an important characteristic of the behavior. About 70 pipes are tested using a drop hammer rig under various impact energies and are categorized into five groups according to the outside diameters of 25 mm, 42 mm, 60 mm, 89 mm and 114 mm, respectively. The impact acceleration and deformation of pipes are measured, and a method to determine global and local deformations is proposed. The characteristics of the permanent upper and lower surface deformations of a pipe are investigated.
as well as the relative magnitude of those two values. With upper and lower surface information, the deformation process of the impacted section and deformation modes along the axial direction can be precisely portrayed which are helpful for establishing an integrated system to evaluate the dynamic response of pipes under impact loads. Other parameters, such as the dent length, are also measured in this paper for a better understanding of denting changes and can be a basis for further theoretical study. Overall, a method to describe the deformation profile is proposed in this paper according to the impact experiments which gives a clear explanation of the phenomenon observed in the tests. The mechanism of dynamic behavior of pipes under lateral impact can be established in an integrated way based on the deformation mode in this paper.

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ABSTRACT: An analytical model is developed to predict the dynamic response of fully clamped square sandwich plate with metal foam core struck transversely by a heavy mass with low-velocity. Large deflection effect is incorporated in analysis by considering the interaction between the plastic bending and stretching. The analytical expressions are obtained for the structural deflection, the structural response time and the impact force. The finite element results validate the accuracy of the analytical model and good agreement is achieved.

References listed at the end of the paper:
ABSTRACT: Dynamic compressive behaviour of cellular materials is crucial to their applications in energy absorption, ballistic mitigation and blast/impact protection. The recent research progress in this subject has led to an improved understanding of the experimental, analytical and numerical observations. This review focuses on the aspects of phenomena, mechanisms and modelling on the concerned subject. Attention is paid to linking macroscopic dynamic compressive behaviour with the subscale influential factors. The characteristics of cellular materials at different spatial scales and their compressive behaviours at different loading rates are introduced, based on experimental observations in the quasi-static, transitional dynamic and shock regimes of compression. Then a comprehensive discussion about the roles of the micro- and meso-scale mechanisms in the dynamic compressive behaviour is presented. Finally, important modelling approaches and results are reviewed and commented. The main conclusions are: (1) the strain-rate sensitivity of cellular materials is closely associated with base material properties (both quasi-static and dynamic ones) and cell structure; (2) the
Compaction shock in cellular materials has mesoscopic structural causes and its formation leads to unique deformation mode, load transmission and stress–strain states; (3) shock initiation requires sufficient loading rate or intensity, and its critical condition can be described based on impact velocity; (4) cell-based modelling is useful for the identification and examination of the underpinning mechanisms, while continuum-based modelling is necessary for the analysis of structures made of cellular materials. Outstanding issues on the subject of the dynamic compressive behaviour of cellular materials are also addressed.


ABSTRACT: Filling structures with foam filler is a typical method to increase the bending resistance of thin-walled beams. In this paper, a new type of tube filler is suggested with good cost-effectiveness and easy availability. Quasi-static and dynamic impact tests for bending of tube-filled beams with different configurations are carried out, and the deformation mode and force responses are investigated. Numerical simulation of the tests is also performed, and the accuracy is validated by the experimental results. The influences of some factors, including the perturbation in the position of the filler, the wall thickness of it, the number of them, and the punch diameter, on the bending resistance, are analyzed. A preliminary comparison between tube filler and foam filler is also conducted. Results show that tube fillers considerably improve the performance of thin-walled beams and outperform the aluminum foam filler in the present analysis.


ABSTRACT: Graded lightweight structure is a new trend to improve energy absorption capacity of such structural materials. This study aims at the influence of property gradients on the overall behavior of graded multilayer sandwiches with corrugated cores under impact loading. The design of the property gradient of graded multilayer sandwiches as well as the manufacturing of different corrugated cores is presented at first. The graded multilayer sandwich is tested under various experimental configurations at rather low (9 m/s) and high (38 m/s) impact velocities. It turned out that no influence of gradient is found for low impact velocity because a quasi-static equilibrium state is reached. However, at high impact velocity, the test revealed a significant difference between different property gradient profiles. Numerical models are also built to simulate those tests. It allows for the further numerical analysis on a larger range of gradient profiles and higher impact velocities. A general trend for the design of the graded multilayer sandwiches with corrugated cores to improve energy absorption efficiency is proposed, which consists of placing the weakest layer near the protected structure and the hardest layer near the impacted end of the graded sandwich.


ABSTRACT: This paper presents experimental studies on the plastic behavior of circular steel tubes subjected to transverse low-velocity mass impact. A total of 73 impact tests and 7 quasi-static tests were conducted on the circular steel tubes, which have span lengths of 900, 1200 and 1500 mm. Three representative indenters, i.e., wedge-shaped, hemispherical and cylindrical indenters, were used to impact the specimens, which were fully clamped at both ends by a specially designed clamping system. The impact energy was sufficient to ensure the
structural collapse of the tube due to tensile tearing. Both the impact and quasi-static test results showed that the fully clamped steel tube under transverse impact loads involved the three-hinge mechanism to deform. Based on experimental observations, four deflection modes and four failure modes were proposed. Moreover, the plastic dent zones were described in detail. The influences of the geometrical parameters, indenter types and local denting on the magnitudes of the dent zone length and the transverse load were investigated and discussed. Based on the test results, empirical formulae for calculating the length of the plastic dent zone and the transverse load were proposed. These formulae are useful for engineers to evaluate these two values in practice. Good agreement was achieved between the experimental and the predicted results.

ABSTRACT: There has recently been a growing trend of replacing conventional structural elements by innovative components so as to achieve more resilient infrastructures. Owing to the recent benchmark study conducted at Monash University, it has been demonstrated that the ultimate compressive capacity of hollow box members consisting of self-strengthened corrugated plates is significantly more than those made of flat plates. However, the behaviour of hollow corrugated members subjected to lateral impact loading has never been investigated. This paper fundamentally reports the behaviour of members built up from four corrugated plates, which are butt-welded at the apexes of the section, under lateral impact loading. Three different types of corrugation profiles as well as two levels of impact energy are considered to investigate the influence of geometric parameters and impact energy level on the member behaviour. The samples are transversely hit by an indenter with defined weight dropping from desired height. It will be demonstrated that the corrugation shape may influence the peak impact force, stabilised post-peak forces, and contact duration. A numerical model is also developed and verified against the experimental results using ABAQUS. Good agreement between experimental and numerical results including recorded data histories and damage patterns is achieved.

ABSTRACT: In this paper, the dynamic behaviour of aluminium foam sandwich plates (AFSPs) under impact loadings at low temperature was experimentally investigated. The impact force and the deformation as well as the energy absorption performances of AFSPs at room temperature and low temperature were obtained by using the drop tower INSTRON 9350 with thermostatic test chamber. The effects of impact energies and repeated impact loadings on the dynamic behaviour of AFSPs at room temperature (20 °C) and low temperature (−60 °C) were further examined. Experimental results showed that with the increase of the impact energy, the effect of low temperature on the dynamic behaviour of AFSPs under single impact loadings was enhanced gradually, the deflections of AFSPs at low temperature were smaller compared to that at room temperature, as a result of the increase in the yield stress of aluminum foam and mild steel at low temperature. Under repeated impact loadings, the deflections and absorbed energies of AFSPs at low temperature were smaller than those at room temperature. With the increase of impact number, the effect of low temperature on dynamic behaviour of AFSPs became much more significant.

ABSTRACT: Composite structures due to their low strain to failure are regarded as a brittle material and are susceptible to possible impact damage during manufacture, maintenance and in use. This paper describes the
influence of tension, compression and hybrid preload on E-glass/polyester composite plates under high velocity impact loading in a velocity range of 185 to 235 m/s. Six layered, E-glass plain weave woven roving \([0/90]_6\) composite panels were made by hand layup method. An innovative preloading apparatus, which is patented with number IRI-83450 was developed to apply the preloading in uniaxial and biaxial directions. This device was used simultaneously with a gas gun to conduct high velocity impact tests. A spherical hard body projectile was used in the impact tests. Uniaxial tension, uniaxial compression and biaxial tension and compression preload were applied to each specimen. To assess the strain rate sensitivity of the material concern under different preloading, three different impact velocities were used. Result showed, the ballistic resistance of the samples with the different preloading condition decreased compared to no preload case. Less variation was observed in exit velocities in the upper impact velocity range test (235 m/s) conducted for all boundary conditions used. A significant increase in the rate of change of residual velocity was observed for the impact velocity of 185.3 m/s compared with that of higher impact velocities tested. Delamination and fiber fracture constituted the major fracture modes followed by matrix fracture.


ABSTRACT: This study examined the large inelastic deformation of FH32 grade steel stiffened plates subjected to a low-velocity mass impact. The impact scenario considered is relevant to the operation of marine structures in Arctic environments. Drop-weight impact tests were conducted on specimens with three different geometries at room temperature and \(-60^\circ\text{C}\). This paper provides details of the tests for obtaining the quasi-static and rate-dependent mechanical properties of FH32 at room and low temperature, as well as the experimental setup and the testing procedure of the drop-weight impact tests. The experimental results showed that for the tested structures, the crashworthiness was improved significantly at low temperatures, and ductile or brittle fracture was not observed under the testing conditions considered. Numerical simulations of the tests were also performed using several different approaches. In particular, the numerical predictions were more accurate when the rate-dependent plasticity was considered.


ABSTRACT: We report an experimental study on three new types of tubes inspired by the cross-section and nodes of bamboo with the aim of improving the crashworthiness of three types of cylindrical metal tubes: Bionic Tubes of Variable Thickness (BTVTs), Bionic Tubes with Rib (BTRs), and Bionic Tubes with Bamboo Cross-section (BTBCs), respectively. The EA capacity and deformation modes of the bionic tubes and a cylindrical tube were experimentally investigated in this study by drop-weight test. The drop test results revealed that 8 of the 14 bionic specimens exhibited greater SEA than the CT. And these results indicate that the bionic method can improve crashworthiness and affect the deformation mode under certain conditions. Different bionic feature have different effects on the deformation of thin-walled tube. Further research is required to optimize the bionic cross-section, rib, and thickness for the new types of tubes.


ABSTRACT: In this study, a new type of aluminium sandwich structure with folded square dome as core is proposed. The square dome tessellated core is folded using a single piece of aluminium sheet. Four types of folded dome structures with different base sizes and top face configurations, i.e. 10 mm closed top dome, 20 mm
closed top dome, 10 mm open top dome, 20 mm open top dome are studied. A single cube strip model is numerically simulated and calibrated with the experimental results from the previous studies. Good agreement on the peak and average stress between numerical results and test data is achieved. The calibrated model is then used to simulate structural response of the proposed folded dome shape structures. The damage modes and the structural responses including average and peak stress, energy absorption, uniformity ratio and densification strain are compared among these folded structures. The proposed square dome kirigami foldcore shows good energy absorption characteristics under quasi-static loading and dynamic loading by yielding a large densification strain, a low initial peak stress and a small ratio of average stress to peak stress. In addition, unlike the existing cube strip structures, the proposed folded square dome structure shows insensitivity to the crushing speed in terms of initial peak stress and uniformity ratio. Compared with the existing tessellated kirigami foldcore of cube strip, the proposed folded square dome demonstrates a superior performance than most of Miura folded structures.


ABSTRACT: This paper focuses on the impact responses of large-diameter, thin-walled steel stringer-stiffened cylinders subjected to low-velocity mass impact. The impact scenarios employed in this study represent load actions as a result of supply vessel collisions with the main legs of floating offshore platforms and wind turbine structures. Two steel stringer-stiffened cylinders were fabricated and drop tests were performed at mid-span, using a rigid knife-edged indenter. The details of the experimental setup, test procedure and test results are reported in this paper. The experimental data appear to be useful for future benchmark studies. Numerical predictions of the impact response of the test models were simulated by means of the explicit solver of the finite element software package ABAQUS. The numerical predictions show a good agreement with the test results. The effect of the strain-rate hardening definition on the results is highlighted. Furthermore, parametric studies were conducted on stringer-stiffened cylinder models in order to clarify the progressive impact responses.


ABSTRACT: The deformation of square honeycomb core, stainless steel sandwich panels by the impact of explosively accelerated granular matter has been investigated and compared to results from a previous study using equivalent (same material and mass per unit area) solid plates subjected to similar impulsive loadings. Spherical explosive charges surrounded by 25–150 kg mass annular shells of water-saturated granular media (either fused silica or zirconia particles) were suspended above the center of the edge clamped test panels. The radially expanding granular particle front velocities were measured from high-speed video images, and revealed that the granular matter had been accelerated to velocities of 500–1200 m/s after detonation. A Kolsky bar was used to measure the time-dependent pressure and impulse at a position equivalent to the panel center, while the permanent deflections of the sandwich panels were determined by profilometry after the experiments. Even though fracture of electron beam welds used to attach the back face sheet to the sandwich panel core occurred in all the tests, the permanent deflections of the sandwich panel back faces were significantly less than those of equivalent solid plates, and were accompanied by minimal core compression. Discrete particle simulations of the granular matter acceleration and impact loading of the sandwich panels indicated that their superior deflection benefit arose from their high bending resistance rather than particle-structure interactions. This benefit was offset when the rear face of the sandwich was kept the same distance from the impulsive source as that of the solid plate since the impact face of the sandwich panel was closer to the impulsive source, subjecting
it to a higher impulse than the solid plate. However, a substantial deflection reduction was still achieved by use of a strong core sandwich design.

ABSTRACT: This paper proposes some simple formulae based on the rigid-perfectly plastic method to examine the dynamic response of stiffened rectangular plates repeatedly impacted by a rigid knife-edged striker at any location. To validate the proposed theoretical method, experiments and numerical simulations are also conducted. The permanent deflection of the tested specimens and rebound velocity of the striker obtained from experiments show good agreement with the numerical simulations performed using the commercial software package ABAQUS. The influences of the material properties including the strain rate, strain hardening and material elasticity, on the accuracy of the theoretical predictions, are assessed by comparison with the numerical simulations. It shows that when accounting for these effects of the material properties in the rigid plastic analysis, the theoretical solutions could provide a good prediction of the structural dynamic behavior for repeated impacts.

ABSTRACT: Explosion-resistant containers and chambers show promise for the safe storage and disposal of explosive materials and munitions. Light-weight explosion proof vessels, that are made of fiber-reinforced composite materials, are of specific interest, as their decreased mass allows for an ease in transportation. When developing fiber-reinforced composite structures for dynamic loading, efficient and reliable computational analysis techniques are required. The objectives of this study deal with developing a computational methodology that can be implemented when designing blast loaded composite structures. Specifically, efficient analysis procedures to predict large scale deformation and composite failure in dynamically loaded composite structures are developed for use with LSTC's LS-DYNA. In the process of developing the modeling methodology, a survey of the blast modeling methods available within LS-DYNA is completed and a recommendation is made considering both accuracy and computational cost. The developed methods are then used to simulate the blast loading and response of small, hollow composite cylinders, and the measured results of instrumented explosive tests are used for model validation.

ABSTRACT: This paper presents a series of experimental and numerical studies on the behaviour of scaled tubular components and T-joints subjected to transverse impact loads. These scaled specimens are made to represent tubular joints on a jack-up or jacket offshore platform. They are struck transversely by a falling wedge indenter. Measurements are taken of the impact force, the permanent deformation and the displacement of the falling wedge. The force-displacement responses show distinctly three stages, which are the initial vibratory stage, the steady deflection stage and the rebounding stages. The tests demonstrate that the brace increases the energy absorption of the chord members, and that the T-joints carries more impact loads when subject to impacts of higher impact velocities. Numerical simulations are also carried out for these scaled tests while the steel is modelled based on the measured strain-stress curves. Good agreements between tests and simulation were achieved. These numerical simulations provide additional information about the structural behaviours. It is
also demonstrated that properly modelling the support structures in the lab tests is also important for accurately capturing the structural behaviours.


ABSTRACT: Honeycomb sandwich structures have excellent energy absorption capabilities, combined with good mechanical properties and low density. These characteristics make them ideal for the transportation industry, which has a growing interest in reaching higher safety standards. The purpose of the present paper is the introduction of lightweight and more efficient crashworthy structures. Double-layer honeycomb sandwich structures were analysed and their energy absorption capabilities were evaluated by means of low-velocity impact tests. The specific energy absorption of double-layer panels was compared to single-layer honeycomb and other lightweight panels, in order to assess the effectiveness and the convenience of the introduced solution for lightweight and crashworthy devices. The impact absorption mechanism was evaluated through Computed Tomography images and visual inspection. A theoretical evaluation was applied to investigate the mono-layer impact response. The results were compared to those obtained with different boundary conditions and with a full-scale test. Contact parameters were influenced by boundary conditions since they depend on the specimens stiffness. Double-layer panels displayed a progressive collapse sequence, depending on the core arrangement and on the cell size. Honeycomb with larger cell size showed a better distribution of the impact loading which generated an almost uniform compression of the core. Such observations suggested the possibility to obtain energy absorber devices with a controlled deformation. Preliminary considerations on the existence of a size effect were drawn, since it was observed a relation among the contact parameters and the geometrical characteristics of the honeycomb and the indenter.


ABSTRACT: In this paper, the drop-weight impact loading tests were conducted to study the dynamic crushing behaviors of the proposed energy absorption connectors with curved plate and aluminum foam as energy absorber. The dynamic collapse modes of the connectors were obtained from the tests and three deformation processes were identified. The effects of loading rate, filled aluminum foam, curved plate thickness and radius on the energy absorption performances of the connectors were quantitatively evaluated, which showed that filling the connector with aluminum foam as well as increasing loading rate, curved plate thickness and radius generally led to increase of energy absorption capacity of the connector. Besides the experimental works, the numerical and analytical models were also developed to predict the force–displacement responses of the connectors and the accuracies of the two models were validated against the test results. The developed analytical model could be utilized as a convenient tool to quickly evaluate the energy absorption performances of such connectors under impact loading.


ABSTRACT: The performance of glass fiber-reinforced epoxy resin (GFRP) reinforced thin-walled circular steel tubes under axial impact loads was studied using both numerical and experimental methods. The specimens’ failure modes and the effects of steel diameter, winding angle (the angle between the axis of the tube and the tangential direction of winding fiber) and impact velocity were studied through tests. Explicit
solver of ABAQUS was chosen and a VUMAT subroutine considering Hashin criterion, Puck criterion and modified Hashin criterion was written to simulate the failure and damage evolution of GFRP. Simulation results matched experiment results well. The influence of steel tube thickness and outer diameter, GFRP thickness and winding angle, specimen length and impact velocity was analyzed using finite element analysis. Predictive formulas were introduced to estimate the peak and mean impact force on specimens experiencing strength failure.

ABSTRACT: It is very important to ensure that the results of a scale model experiment of the large-span space steel structure under internal explosion could accurately show the characteristics of its original model. For this purpose, a one-way inclined bar type of single layer cylindrical lattice shell was taken as an example in this paper, and the similarity law between the scale models and the original model under the internal explosion was deduced by the dimension analysis principle. Then, the original model and the scale models under internal explosions were simulated by ANSYS/LS-DYNA, and the correctness and the feasibility of the similarity law were compared and confirmed. The research results showed that: if the scale models conform to the similarity law, the propagation law and the overpressure distribution of shock waves to the scale models subjected to internal explosions were consistent with the original model; the phenomena of critical destruction of the scale models were similar to the experimental results. But the accuracy of the loading effects of blast (such as the overpressure peak of shock waves, the positive pressure time and the impulse etc.) and the structural dynamic responses obtained by the scale models was affected by the geometric incomplete similarity of the scale models and the strain rate effect of steel respectively, which would reduce with the decrease of the scaling coefficient. Especially, the research results also indicated that if the scaling coefficient was not less than 0.1, the maximum deviations of the overpressure peak of shock waves, the positive pressure time after conversion and the specific impulse after conversion would be 10%, 4.78% and 29.8%, respectively, and if the scaling coefficient was less than 0.25, the stress responses and displacement responses of the scale model under internal explosion would not be reliable. Based on the research results, the reasonable scaling coefficients to the scale model experiment of cylindrical lattice shell under internal explosion are proposed.

ABSTRACT: This paper presents a combined experimental and numerical study on the dynamic response and failure mechanisms of honeycomb sandwich panels subjected to high-velocity impact by a spherical steel projectile. Impact tests were performed in a velocity range from about 70 to 170 m/s to investigate the effects of facesheet thickness, core height, cell wall thickness and cell size of honeycomb on the impact behaviour of sandwich panels. These geometric parameters were found to influence the impact performance mainly by changing the deformation and failure mechanisms of both sandwich facesheets. Moreover, the ballistic limit velocity and critical perforation energy of each sandwich configuration were obtained by numerical simulation. It was found that increasing facesheet thickness and reducing honeycomb cell size were two weight-efficient ways to enhance the perforation resistance of sandwich panels when the areal density exceeded a certain value. The projectile's penetration process into the sandwich panel and the associated energy absorbing mechanisms were analysed, the results of which showed that facesheets contributed most to energy absorption. Further numerical simulation was conducted to explore the influences of core stiffness and the thickness ratio of front to back facesheet. It was found that core stiffness had a significant effect on the deformation and failure initiation
of front facesheet; more specifically, the front facesheet failed more easily due to stress concentration with the increase of core stiffness. When the total thickness of front and back facesheets remained constant, increasing the front-to-back thickness ratio led to higher damage resistance but greater deformation area on the front facesheet. Finally, a discrete optimisation was conducted to generate an optimal design of sandwich structure for achieving the highest specific energy absorption without perforation under a certain impact energy. The optimised sandwich panel exhibited an increase of 23.7% in specific energy absorption compared with the initial design.


ABSTRACT: In this paper, the analytical and numerical analyses are conducted to predict the dynamic response of fully clamped double-layer rectangular sandwich plates with metal foam cores subjected to blast loading. The so-called ‘bounds’ of analytical solutions for dynamic response of double-layer sandwich plates are obtained by using the inscribing and circumscribing squares of the exact yield locus. Also, the membrane mode solution for large deflection of the double-layer sandwich plates is presented. The effect of the double-layer factor on the dynamic response of double-layer sandwich plates is also discussed. The finite element calculation is carried out to study the dynamic response of the double-layer sandwich plates subjected to blast loading. Good agreement is achieved between the analytical predictions and numerical results. It is demonstrated that the impact resistance of the double-layer sandwich plate is better than that of the monolayer one with the same mass subjected to the higher impulse.


ABSTRACT: Motivated by the biaxial plastic dynamic buckling behavior of tubular structures, the particular interest of this work was to develop a non-conventional energy-dissipating system. This system is based on the studying of the experimental behavior of square metallic tubular structures under dynamic complex loading paths. This non-conventional solution aims to enhance the strength properties of the used structures. Accordingly, the well-developed device (the ACTP: Absorption par Compression-Torsion Plastique) has been employed where biaxial loading paths (combined compression-torsion) with different complexities were generated from a uniaxial compressive load. Thus, five inclination angles (30°, 37°, 45°, 53° and 60°) were used to study their effect on the biaxial plastic buckling of square aluminum tubes. This new comprehensive experimental study aimed to investigate the effect of three loading boundary conditions (i.e., simple, intermediate and severe) on the tubes’ behavior. The dynamic deformation, mean collapse load ($P_m$) and energy absorbed are key parameters that require investigation. They are largely affected by the loading path complexity, applied strain rate and their interaction. The results showed that the higher the biaxial loading complexity provided by the ACTP, the greater the interaction between the loading complexity and the strain rate, and the greater the energy absorbed by the structures. Changes in local deformation mechanisms induced by the loading complexity thus lead to the energy absorbed enhancement. The latter was higher than 100%, in favor of the most complicated loading path (i.e., Biaxial-60°) compared to the classical uniaxial case for an axial deflection of 20 mm. Simple mathematical equations were proposed predicting the $P_m$ of buckled tubes. These equations can describe the tubes’ behavior fairly well.
ABSTRACT: The collapse of circular cylinders, having circular perforations distributed in a single or multiple rows, when subjected to axial impact was investigated. Extensive numerical simulations were carried out to first identify the effect of the wall thickness, the perforation size and their arrangement on the peak load, the deformation pattern and the energy absorption characteristics of cylinders undergoing progressive collapse. The results indicated that, while the presence of holes considerably reduced the initial peak, they localized the deformation to such an extent that the load at the formation of subsequent buckles increased, which affected the energy efficiency adversely. Experiments were conducted by impacting the cylinders with a moving mass. Destabilization of the progressive mode of collapse due to cracking was observed in some cases. For the cases in which the cylinders did not crack, the experimental and numerical observations were in agreement. Through numerical analysis, a design in which subsequent rows of holes having a lesser number of holes was identified such that, the load peaks at the formation of all buckles were equalized. The energy efficiency in this case improved and was higher than that of a cylinder without holes. The experiments conducted for selected cases confirmed the numerical findings. Therefore, this study presents a methodology to reduce and equalize the peak loads at formation of buckles and simultaneously improve the energy efficiency without destabilizing the progressive mode of collapse.

ABSTRACT: Latest development in material and manufacturing technologies make it possible to increase the yield strength of steel to more than 1200 MPa. These steel grades, suitable for structures prone to extreme loadings, give potentials for considerable weight reduction and a cost-effective way to produce energy-efficient members. Having analysed the impact behaviour of corrugated members recently, this paper now investigates the performance of hybrid corrugated (HC) sections consisting of mild-steel corrugated plates and ultra-high strength (UHS) steel tubes. Three different types of trapezoidal corrugated plates are considered so as to examine the effect of geometrical corrugation parameters on the performance of entire member. Along with this, in order to study the contribution of UHS tubes in the performance of HC members under impact loading, their performance is also examined separately. In combined lateral impact and axial loading scenario, the tube is initially compressed axially; thus an indenter perpendicularly impacts the specimen at mid-span. An advanced numerical model in which nonlinear strain-rate dependent material behaviour of steel is taken into account is also developed by using ABAQUS/Explicit. Thus, the residual deformations, time histories, global lateral deflection, and energy absorptions are discussed and compared with those of experimental results.

ABSTRACT: Large scale aircraft composite panels can be damaged by hail ice in high speed ductile impacts (without penetration by sharp shape) and predicting the damage modes and failure mechanisms under these complex boundaries and loading conditions poses a unique challenge. Thus, the dynamic behavior and failure of stringer-stiffened curved carbon/epoxy composite panels impacted by hail ice at two classic locations (mid-bay of impact type I and mid-flange of impact type II) with different velocities have been investigated in this research via experimental and numerical methods. The results show that panel damage from ice sphere impacts is a stress wave dominated dynamic response and the initial delamination of the panel always occurs at the skin-
stringer interface when the ice sphere reaches a minimum threshold impact velocity irrespective of the loading site. The finite element methodology employing rate sensitive ice models and composite laminates with failure is capable of accurately predicting, the delamination site, the total delamination area versus impact velocity, and the separation of the skin-stringer bonded joints which may be located away from the impact site at areas not typically examined. The numerical simulation has been validated at two different impact sites and provides insight into stress wave propagation despite non-uniform thickness and stiffness variations of the stringer flange bonded to the composite skin. These experimental and finite element methodologies can be applied to improve the design of new airframes, composite joints, and improve the accuracy of residual strength evaluation of existing aircraft panels under hail ice impacts.


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ABSTRACT: The size-dependent oscillations of a third-order shear-deformable functionally graded microbeam are investigated taking into account all the longitudinal and transverse displacements and inertia as well as the rotation and rotary inertia. The modified couple stress theory along with the Mori–Tanaka homogenisation technique is employed to develop formulations for the elastic potential energy as well as the kinetic energy of the system. The energy of the system is balanced by the work of a harmonic excitation force via an energy method based on Hamilton's principle, yielding the size-dependent coupled nonlinear continuous models of the functionally graded system for the longitudinal and transverse displacements as well as the rotational motion. A model reduction procedure, on the basis of a weighted-residual method, is applied without any simplifications on the displacement/inertia/rotation. This operation yields three sets of second-order reduced-order coupled model of the functionally graded system for the longitudinal, transverse, and rotational motions. These reduced-order models are solved via use of a continuation method in order to construct the nonlinear frequency-response and force-response curves of the functionally graded system. A linear analysis is also performed by means of an eigenvalue extraction method in order to determine the linear natural frequencies of the system. It is shown that the material gradient index as well as the length-scale parameter of the functionally graded system affects the system dynamics substantially.

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ABSTRACT: Several computational models are available for studying cardiac mechanics. These models incorporate tissue passive/active response in conjunction with hyperelasticity and anisotropy. For capturing the active response they involve complicated non-conventional strain energy functions which account for tissue active contraction. They are either implemented as custom-developed non-linear finite element (FE) codes or require user-defined subroutines compiled within commercial FE software packages. Difficulty of computational implementation of such models remains an issue for the research community. Furthermore, myocardial tissue has sophisticated microstructure while pathologies may alter its constituents and their organization. Hence, cardiac mechanics models adaptable to various pathological conditions are advantageous. This paper aims at developing a cardiac mechanics model using a novel approach which does not require strain energy functions developed specifically for simulating myocardial tissue active response, lending itself for effective implementation in off-the-shelf FE solvers. This model considers myocardial hyperelasticity, anisotropy, and active contraction. It was developed using a tissue composite material model which includes two major parts: background part and myofibers. The model was applied to an in silico geometry of a canine left ventricle (LV). Resulting diastolic pressure-volume curve shows very good agreement with corresponding experimental observations. Also, calculated mid-ventricular end-diastolic strain components are within one standard deviation of measurements performed through the LV equatorial area. Furthermore, computed end-systolic strain components and ejection fraction are close to or within one standard deviation of in-vivo measurements of a beating canine LV. These results demonstrate that the proposed model can be employed as an effective alternative for studying cardiac mechanics.

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ABSTRACT: The nonlinear motion characteristics of a bilayered Timoshenko microbeam is analysed taking into account all the translational (i.e. longitudinal and transverse) and rotational motions; the effect of size is included through use of the modified couple stress theory. Considering a continuous variation through the thickness for the displacement field, the geometrically nonlinear strain terms are developed. Relating these strain terms to stress terms, via use of constitutive relations, leads to a stress tensor in terms of the displacement
field; the same is applied to the symmetric curvature tensor and the deviatoric part of the symmetric couple stress tensor by means of a constitutive relation incorporating size effects. The potential energy of the bilayered microbeam is formulated via the modified couple stress theory. The kinetic energy along with the work of an external dynamic force is formulated in terms of the displacement field of the bilayered microbeam. A dynamic equilibrium state is obtained via balancing the energy and work. Three-dimensional reduced-order models for the transverse, longitudinal, and rotational motions are obtained via Galerkin's method. These coupled models are solved via a continuation method coupled with direct time-integration. The resonant responses are constructed with special consideration to the effects of the length-scale parameter and the material percentage and thickness of each layer; a comparison is also made between the motion characteristics of the bilayered and monolayered microbeam.


ABSTRACT: An asymptotically exact two-dimensional theory of functionally graded piezoelectric shells is derived by the variational-asymptotic method. The error estimation of the constructed theory is given in the energetic norm. As an application, analytical solution to the problem of forced vibration of a functionally graded piezoceramic cylindrical shell with thickness polarization fully covered by electrodes and excited by a harmonic voltage is found.

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ABSTRACT: In this paper, dynamic behavior of double layered nanoplate systems (DLNPS) with respect to a moving nanoparticle is investigated. Both layers of DLNPS are assumed to be orthotropic and each layer is bearing a biaxial load while internal damping effects are also taken into account. Furthermore, coupling between layers are modeled using Kelvin-Voigt viscoelastic theory and moving nanoparticles path are assumed to be linear and circular with constant velocities. Governing equations of motion are derived by using D'Alembert's principle, Kirchhoff-Love plate and Eringen's nonlocal theory. Galerkin's and Laplace transform methods is used to solve the governing equations and analytical solution is presented for linear moving nanoparticle while close-form solution is obtained for circular moving nanoparticle. In order to clarify the influence of different parameters such as small scale effect, stiffness and damping in coupling, biaxial compression and tension of layers, path of the moving mass, etc. on dynamic behavior of each layer, parametric study is presented. Accordingly, with the brand new discussions in moving atoms, molecules, nanocars, nanotrims, point loads on different nanosctructures using scanning tunneling microscopes (STM) and atomic force microscopes (AFM), this study could be a step forward in understanding such kind of behaviors.

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ABSTRACT: This paper, for the first time, analyses the size-dependent global dynamics of imperfect axially forced microbeams and shows that how a small initial imperfection (due to improper manufacturing of microbeams) can substantially change the size-dependent global dynamical behaviour of the microsystem; moreover, it investigates the effect of small size of the microbeam on the appearance and vanishing of different chaotic and quasiperiodic motions. More specifically, the continuous expressions for the size-dependent potential energy as well as kinetic energy of the microsystem are constructed and dynamically balanced via an energy method. A transformation to a reduced-order model is performed via a weighted-residual method. The bifurcation diagrams of Poincaré maps are constructed by means of direct time-integrating the reduced-order model for the imperfect microsystem. Poincaré sections, phase-plane diagrams, time histories, and fast Fourier transforms are also plotted for some cases in order to shed light on the microsystem size-dependent global dynamics.

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ABSTRACT: In this paper, we provide alternative Uflyand–Mindlin's plate equations taking into account rotary inertia and shear deformation, based on both asymptotic expansion and variational arguments. The aim is to
derive truncated versions of Uflyand–Mindlin's equations, specifically without the fourth order derivative term with respect to time. The truncated version of Uflyand–Mindlin's plate model may be derived starting from three-dimensional elasticity equations, by using asymptotic arguments based on expansion of displacements with respect to a small geometrical parameter. This expansion method also leads to a proper identification of the shear correction factor. It is shown that suitably modified variational derivation leads to an additional term which is shown to be negligible for determination of the fundamental natural frequency of the all-round simply supported plates, but may contribute significantly in estimation of higher natural frequencies. It is argued that the proposed version of Uflyand–Mindlin's plate equations is simpler and more consistent than the original Uflyand–Mindlin equations. Likewise, it is advantageous over the equation that stems from neglecting the fourth order time derivative in original Uflyand–Mindlin equations. The two alternative truncated models serve as intermediate theories between the classical plate theory and the original Uflyand–Mindlin theory their usefulness depending on the problem at hand.

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ABSTRACT: The inconsistency of Eringen’s nonlocal differential model, as applied to investigate nanostructures, has recently triggered the study of nonlocal integral models. In this paper we adopt Eringen’s two-phase nonlocal integral model to carry out an analytical study on the buckling problem of Euler–Bernoulli beams. By using a reduction method rigorously proved in the previous work, the resulting integro-differential equation for the problem is firstly reduced to a fourth order differential equation with mixed boundary conditions. Exact characteristic equations are then obtained for four types of boundary conditions. Further, after some detailed asymptotic analysis, asymptotic solutions for the critical buckling loads are obtained, which are shown to have a good agreement with the numerical solutions. The analytical solutions show clearly that the nonlocal effect reduces the buckling loads. It is also found that the effect could be first-order or second order depending on the boundary conditions.

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ABSTRACT: This work investigates nonlinear size-dependent resonant characteristics of fluid-conveying extensible micropipes subjected to a harmonic load. The nonlinear governing equation and corresponding boundary conditions of system are developed on the basis of modified couple stress continuum theory in conjunction with Euler–Bernoulli beam theory and von Kármán's geometric nonlinearity. Galerkin technique is employed to discretize the integro-partial-differential governing equation into a set of second-order nonlinear ordinary differential equations with coupled terms. After that, an embedded Runge–Kutta method is utilized to
solve numerically the resultant equations. The nonlinear size-dependent primary resonant characteristics of a simply supported micropipe conveying fluid in subcritical domain are examined via depicting frequency-response and force-response curves. The influences of different parameters i.e., flexural rigidity ratio which represent the effect of size-dependency, slenderness ratio, and dimensionless mean flow velocity on the nonlinear size-dependent forced vibration characteristics of system are examined.

Hamed Farokhi (1), Mergen H. Ghayesh (2), Alireza Gholipour (2) and Mohammad Tavallaieجاد (2) (1) Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada H3A 0C3 (2) School of Mechanical Engineering, University of Adelaide, South Australia 5005, Australia “Nonlinear oscillations of viscoelastic microplates”, International Journal of Engineering Science, Vol. 118, pp 56-69, September 2017, https://doi.org/10.1016/j.ijengsci.2017.05.006

ABSTRACT: The nonlinear oscillations of viscoelastic microplates is addressed in this paper based on the modified couple stress theory (MCST). Employing the Kirchhoff plate theory, both out-of-plane and in-plane motions as well as the corresponding inertia are taken into account; an internal damping mechanism, based on Kelvin–Voigt model, is employed to model the behaviour of the material. The strain energy, the kinetic energy, the work done by the viscous parts of the classical and non-classical stresses, and the work of the external time-dependent force are obtained and implemented into Hamilton's framework so as to derive a set of fully coupled nonlinear partial differential equations (PDEs) for motions in the out-of-plane and in-plane directions. The Galerkin scheme is utilized to reduce the set of viscoelastically coupled nonlinear PDEs into a set of nonlinear ordinary differential equations (ODEs). Thereupon, this set of equations is transformed into a new set of size-dependent viscoelastically coupled nonlinear first-order ODEs and then is solved with the aid of a continuation scheme. The nonlinear oscillations is thoroughly investigated through conducting extensive numerical simulations and plotting force-response and frequency-response diagrams of the viscoelastic microsystem. The results reveal that the contributions of the nonlinear damping terms, arising due to employing a viscoelastic model, in the response of the viscoelastic microsystem increase substantially when the forcing amplitude is increased. Moreover, the concurrent presence of the nonlinear amplitude-dependent damping mechanism and the length-scale parameter affects the resonant response of the microplate significantly in both linear and nonlinear senses.


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Nanocrystalline nanoplates are composed from three phases which are nano-grains, nano-voids and interface. This paper develops a higher order refined plate model with a sinusoidal shear strain function for vibration analysis of porous nanocrystalline nanoplates based on modified couple stress theory. Nano-voids or porosities inside the material have a stiffness-softening impact on the nanoplate. Modified couple stress theory is employed to capture grains rigid rotations. The governing equations obtained from Hamilton's principle are solved applying Galerkin's method which satisfies various boundary conditions. The reliability of present approach is verified by comparing obtained results with those provided in literature. Finally the influences of couple stress parameter, grain size, porosities and shear deformation on the vibration characteristics of nanocrystalline nanoplates have been explored.

ABSTRACT: This work revisits the finite pure bending problem for circular cylindrical shells within the elastic range. The interest here is primarily directed towards the bifurcation instabilities of such configurations when the progressive flattening of the cylindrical cross-section is explicitly taken into account (the so-called Brazier effect). By coupling Reissner’s axisymmetric solution to the buckling equations for a quasi-shallow toroidal shell we formulate a novel boundary-value problem able to capture such bifurcations. Numerical simulations of this problem confirm that buckling occurs before the usual limit-point instability is reached, while singular perturbation methods allow us to obtain simple asymptotic approximations for the critical curvature and bending moment associated with the bifurcations.

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ABSTRACT: This paper performs a thorough investigation on the nonlinear size-dependent bending characteristics and natural frequencies of doubly curved shallow microshells. A nonlinear continuous model for a general doubly curved microshell is developed on the basis of Donnell's nonlinear shell theory and in the framework of the modified couple-stress strain gradient theory. In particular, the doubly curved microshell equations of motion of partial differential type are derived while accounting for geometric nonlinearities and small-scale effects. The continuous model is transformed into a discretised set of equations via application of the two-dimensional Galerkin technique. A large number of modes are retained in both linear and nonlinear investigations of microshells to ensure converged and reliable results. The linear natural frequencies are reported for various microshells of rectangular and square bases. The nonlinear static deflection curves for both in-plane and out-of-plane displacements are constructed and the effects of different parameters, such as the radius of curvature, sign of the radius of curvature, and the length-scale parameter are examined.


ABSTRACT: In this paper, a general nonlocal strain-gradient (NSG) elasticity model is developed for vibration analysis of porous nano-scale plates on an elastic substrate. The present model incorporates two scale coefficients to examine the vibration characteristics much accurately. The application of present nanoplate model as nano-mechanical mass sensors is also investigated. Porosity-dependent material properties of the nanoplate are defined via a modified power-law function and Mori–Tanaka model. Based on Hamilton's principle, the governing equations of the nanoplate on the elastic substrate under hygro-thermal loading are obtained. These equations are solved for hinged nanoplates via Galerkin's method. It is demonstrated that nanopores, temperature change, humidity change, nonlocal-strain gradient parameters, gradient index and attached nanoparticle have a remarkable influence on vibration frequencies of nanoscale plates.
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ABSTRACT: In this paper, a comprehensive study on mechanical behavior of non-uniform small scale beams in the framework of nonlocal strain gradient theory is presented. The governing equations and boundary conditions have been developed using Hamilton's principle and solved with the aid of finite element method for introducing the bending, buckling and free vibration response of nano-beams. The current formulation could be used for all types of non-uniformities by varying the width and thickness of nano-beams along the length. The accuracy of the current model and formulation is verified by comparing the results with previous literature and those obtained by analytically solving simplified problems. In order to understand the influence of having non-uniform cross section on static and dynamic behavior of small scale beams, parametric study is presented and the effects of different parameters such as non-uniformity, non-local and strain gradient terms on natural frequency, buckling load and deformation are observed and discussed. It is seen that having non-uniform cross section in nonlocal strain gradient beams could lead to significant changes in mechanical behavior of such structures.

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ABSTRACT: In this work, the effects of cell size and cell wall thickness variations on the compressive and shear strengths of closed-cell foams were investigated using Laguerre tessellation models. It is found that the compressive and shear strengths of closed-cell foams decrease as cell size and cell wall thickness variations increase, and the compressive strength reduces more significantly. At a given level of variation, the effect of cell size variation on strength reduction is comparable to that of cell wall thickness variation on them. In the foam studied (M130 foam), cell wall thickness has a larger dispersion than cell size, and therefore is the main contributor to the strength reduction of the foam. In comparison to compressive and shear stiffnesses, cell size and cell wall thickness variations reduce compressive and shear strengths more significantly. Cell size variation results in strain concentration at the end of foam samples, thereby reducing the compressive strength of closed-cell foams. Cell wall thickness variation leads to cell wall buckling and thus reduction in compressive and shear strengths of closed-cell foams. As cell size and cell wall thickness in foams become less uniform, the relationships of compressive and shear strengths to relative density become less linear.

ABSTRACT: Micropipe conveying fluid as a core element can be found in many microfluidic devices. In such scale, size effect phenomenon in micropipe may play a significant role in the mechanical behavior of system. In addition, due to the improper production process, the micropipe may be fabricated with a geometric imperfection. Hence, this study objects to investigation of the size-dependent and -independent stability behavior of geometrically perfect and imperfect extensible micropipe conveying fluid under different boundary conditions. In the framework of modified couple stress theory, the nonlinear equations of system are established based on Euler-Bernoulli beam theory. Statics-based analytical solutions are developed to study the nonlinear stability characteristics of system. The statics-based results are verified by aid of a dynamics-based numerical solution. It is indicated that for a perfect case the system becomes unstable at a critical velocity via a pitchfork bifurcation. But, for an imperfect case the system may lose its stability at a primary critical velocity by a perturbed pitchfork bifurcation also it becomes unstable at a secondary critical velocity by a transcritical bifurcation. It is found that the primary and secondary critical velocities of the imperfect case are, respectively, smaller and greater than the critical velocity of the perfect case. A parametric study is conducted to highlight the influence of different dimensionless parameter as well as boundary conditions on the nonlinear stability behavior of system. Finally, it should be pointed out that the analytical solution and the presented results not only for the size-dependent pipe conveying fluid in micro scale but also for the size-independent pipe conveying fluid from macro to micro scale can be utilized.

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ABSTRACT: For the first time, the size-dependent thermal buckling and post-buckling behavior of nanotubes made of functionally graded materials (FGMs) with porosities is investigated by using a refined beam theory. This non-classical nanotube model is based on Eringen nonlocal elasticity model which incorporates the small scale effect. Two types of porosity distribution, including even and uneven distribution, are taken into account. The material properties of the nanotubes are temperature-dependent and vary in the radial direction. The size-dependent governing differential equations are derived by employing the generalized variation principle and solved by using a two-step perturbation method. The effects of small scale parameter, porosity volume fraction, the volume fraction index and boundary conditions on thermal buckling and post-buckling of FGM nanotubes are studied by several numerical examples. It can be concluded that the porosity volume fraction and small scale parameter change the buckling and post-buckling behavior of the nanotubes.

Mohammad Reza Barati (Aerospace Engineering Department & Center of Excellence in Computational Aerospace, Amirkabir University of Technology, Tehran, Iran), “On non-linear vibrations of flexoelectric

ABSTRACT: In this article, non-linear vibration problem of flexoelectric nanobeams with surface and thermal effects is investigated. Flexoelectricity in piezoelectric nanobeams can be interpreted as the strain gradient-electrical polarization coupling. There are two flexoelectric mechanisms which are direct and converse flexoelectricity. An electric voltage is applied to the top surface of the nanobeam which introduces a closed-circuit electric field condition. Employing He's variational method, the nonlinear governing equation of flexoelectric nanobeam is solved and nonlinear frequencies are obtained. The flexoelectricity effect is less important for large scale beams, therefore it has a great influence on vibration behavior of piezoelectric nanobeams. Also, the effects of several parameters including temperature change, elastic foundation, surface coefficients and nanobeam thickness on nonlinear frequency are investigated.

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ABSTRACT: By using the variational-asymptotic method, a two-dimensional mechanical model for laminated composite shells is established from a mathematical perspective, having the energy functional asymptotically correct up to the desired order in the small parameters. However, it is not in a practical form from an engineering perspective because of the appearance of partial derivative terms, which bring unnecessary mathematical complexity and obscure physical interpretation of mechanical boundary conditions in the shell modeling. Therefore, one more procedure is inevitably required – a so-called energy transformation procedure, which constructs a mathematical link between the energy functional derived herein and a simpler engineering model, such as a generalized Reissner–Mindlin model. In a different manner from previous works, this article introduces a hybrid energy transformation procedure composed of two successive steps: an equilibrium transformation via a linear algebraic approach, and an energy transformation via a perturbation approach. During this procedure, the first step is to transform the two-dimensional equilibrium equations from a hyperstatic system into an isostatic system by augmenting them with the two-dimensional compatibility equations. Then, for obtaining a generalized Reissner–Mindlin model, the second step is to introduce initial curvature/twist as small parameters (in the sense of perturbations) into the constitutive law. The coupling stiffness terms between the transverse shear generalized strain measures and the remaining generalized Reissner–Mindlin strain measures are shown to be identically zero for laminated composite plates/shells (in contrast to the analogous terms of a similarly constructed generalized Timoshenko model for composite beams). Several examples are presented to demonstrate the capability and accuracy of this new approach.

References listed at the end of the paper:
1 O.A. Bauchau, J.I. Craig, Structural analysis with applications to aerospace structures, Springer (2009)

ABSTRACT: The size-dependent nonlinear oscillation characteristics of a functionally graded microplate is investigated numerically, in which all the displacements, i.e. in-plane as well as out-of-plane, and their inertia are accounted for. The potential energy of the functionally graded microsystem is obtained based on a modified version of the couple stress theory, so as to account for size effects, together with the Mori-Tanaka homogenisation mixture model for the graded material property. The kinetic and size-dependent potential energies of the microsystem are dynamically balanced by the work of an external force via the Lagrange equations and truncated employing an assumed-mode discretization scheme. Extensive numerical simulations are conducted upon the discretised model of the microsystem through use of a continuation technique as well as an eigenvalue extraction method (for the nonlinear and linear studies, respectively). The effect of several functionally graded microsystem parameters, namely the material gradient index, the material length-scale parameter, and the frequency and amplitude of an exciting external force on the response is investigated.

References listed at the end of the paper:
44 M.R. Nami, M. Janghorban, “Resonance behavior of FG rectangular micro/nano plate based on nonlocal elasticity theory and strain gradient theory with one gradient constant”, Composite Structures, 111 (2014), pp. 349-353
ABSTRACT: In this study, a size-dependent Timoshenko beam model is used for free vibration and instability analysis of a nanotube conveying nanoflow. To capture the size effects, nonlocal strain gradient theory and Knudsen number are applied. The extended Hamilton's principle is employed to obtain the size-dependent governing equations of motion and associated boundary conditions. The Galerkin approach is utilized to convert the partial differential equation into a set of ordinary differential equations. The resulting eigenvalue problem is solved for cantilever Timoshenko nanotubes. Some numerical instances are presented to study the effects of various parameters such as strain gradient length scale, small length scale, length-diameter ratio, nanotube's thickness, Knudsen number and gravity on the eigenfrequencies, critical flutter velocities and instability of the system. The results reveal that the natural frequencies and critical flutter velocities are closer to the ones from Euler-Bernoulli beam model just for long nanotubes and low mode numbers. Furthermore, it is shown that by increasing the strain gradient length scale, the critical flutter velocity and stability region increase.

ABSTRACT: The three-dimensional nonlinear mechanics and pull-in characteristics of a microplate-based microelectromechanical system (MEMS) are investigated via a multi-degree freedom energy-based technique where the in-plane and out-of-plane motions are retained in the modelling and simulations; the deformable microplate is modelled using the Kirchhoff's plate theory in conjunction with von Kármán nonlinear strains, and it is assumed to be fully clamped at all the edges; an electrical field in the form of a combination of DC and AC voltages is applied to the deformable electrode of microplate-type. The modified couple stress theory is
employed to model the small-size effects. The potential energy with size-dependent characteristics, together with the deformable microplate's kinetic energy, is formulated as functions of the displacements and mechanical and geometric parameters of the system. These energy terms, along with the Rayleigh energy dissipation and the electrical potential energy, are inserted into Lagrange's equations to derive the discretised model of the microplate-based MEMS consisting of three sets of second-order coupled reduced-order models for the in-plane and out-of-plane motions. Numerical simulations are conducted for both static and dynamic responses of the MEMS device. The numerical simulations have been performed via use of the pseudo-arc-length continuation technique in conjunction with backward-differentiation-formula (BDF) (for the nonlinear analysis); the Floquet theory is used for stability analysis. An eigenvalue extraction is employed for the linear analysis. Results are shown through DC voltage-deformation and AC frequency-motion diagrams in order to highlight the motion characteristics as well as pull-in instability of the microplate-based MEMS device.

ABSTRACT: Dielectric elastomer tubes are employed as actuators by radial electric stimulus. Their functionality is affected by electromechanical instabilities, whose study was mainly limited to the analysis of the free energy Hessian. In this paper, we identify a different class of instabilities—prismatic diffuse modes—by employing the linearized theory of superposed deformations on finitely strained deformable dielectrics. We develop the equations that determine the onset of such modes, and show through numerical examples that the tube may enter diffuse states before the Hessian criterion fails. Moreover, we find that loading paths that are stable according to the Hessian method, can bifurcate into diffuse modes.

ABSTRACT: In this work, nonlocal nonlinear analysis of functionally graded plates subjected to static loads is studied. The nonlocal nonlinear formulation is developed based on the third-order shear deformation theory (TSDT) of Reddy (1984, 2004). The von Kármán nonlinear strains are used and the governing equations of the TSDT are derived accounting for Eringen’s nonlocal stress-gradient model (Eringen, 1998). The nonlinear displacement finite element model of the resulting governing equations is developed, and Newton’s iterative procedure is used for the solution of nonlinear algebraic equations. The mechanical properties of functionally graded plate are assumed to vary continuously through the thickness and obey a power-law distribution of the volume fraction of the constituents. The variation of the volume fractions through the thickness have been computed using two different homogenization techniques, namely, the rule of mixtures and the Mori–Tanaka scheme. A detailed parametric study to show the effect of side-to-thickness ratio, power-law index, and nonlocal parameter on the load-deflection characteristics of plates have been presented. The stress results are compared with the first-order shear deformation theory (FSDT) to show the accuracy of nonlocal nonlinear TSDT formulation.

ABSTRACT: In this study, the vibration behaviors of porous nanotubes are investigated for the first time. The nonlocal strain gradient theory in conjunction with a refined beam model are employed to formulate the size-dependent model. It is presumed that the porous nanotubes are made from functionally graded materials, and the material parameters of nanotubes relate to temperature variation and vary continuously in the radial direction. Employing a refined beam theory which includes the effects of transverse shear deformation, the equations of
motion are derived based on Hamilton's variation principle and solved by the Navier solution method. Some comparisons are presented to validate the correctness of the present solution method. The effects of the nonlocal parameter, strain gradient parameter, temperature variations, porosity volume fraction and material variation on the vibration characteristics of the nanotubes are discussed in detail.


ABSTRACT: The present work is devoted to the modelling of strongly size-dependent bending, buckling and vibration phenomena of 2D triangular lattices with the aid of a simplified first strain gradient elasticity continuum theory. As a start, the corresponding generalized Bernoulli–Euler and Timoshenko sandwich beam models are derived. The effective elastic moduli corresponding to the classical theory of elasticity are defined by means of a computational homogenization technique. The two additional length scale parameters involved in the models, in turn, are validated by matching the lattice response in benchmark problems for static bending and free vibrations calibrating the strain energy and inertia gradient parameters, respectively. It is demonstrated as well that the higher-order material parameters do not depend on the problem type, boundary conditions or the specific beam formulation. From the application point of view, it is first shown that the bending rigidity, critical buckling load and eigenfrequencies strongly depend on the lattice microstructure and these dependencies are captured by the generalized Bernoulli–Euler beam model. The relevance of the Timoshenko beam model is then addressed in the context of thick beams and sandwich beams. Applications to auxetic strut lattices demonstrate a significant increase in the stiffness of the metamaterial combined with a clear decrease in mass. Furthermore, with the introduced generalized beam finite elements, essential savings in the computational costs in computational structural analysis can be achieved. For engineering applications of architectured materials or structures with a microstructure utilizing triangular lattices, generalized mechanical properties are finally provided in a form of a design table for a wide range of mass densities.


ABSTRACT: This study examines the nonlinear large-amplitude static and dynamic responses of a doubly curved shallow microshell in the framework of the modified couple stress (MCS) theory. To this end, the expressions for the classical and higher-order stresses and strains are consistently derived in an orthogonal curvilinear coordinate system employing the Novozhilov shell theory. The strain energy of the system is then consistently derived utilising the Novozhilov shell formulations in the framework of the MCS theory. The kinetic energy of the microshell is obtained while accounting for all out-of-plane and in-plane displacements. Furthermore, the work of the distributed out-of-plane load is accounted for and the energy dissipation is taken into account via the Rayleigh energy dissipation function. An assumed-mode technique is utilised to expand the out-of-plane and in-plane displacements via series expansions. The Lagrange equations are then utilised to derive the discretised equations of motion in the form of a set of nonlinearly coupled ordinary differential equations (ODEs). This set of nonlinear ODEs is solved making use of a continuation technique (for the nonlinear static and dynamic analyses) as well as an eigenvalue extraction method (for the linear natural frequency analysis). Extensive numerical simulations are carried out for both static and dynamic cases and the effects of different parameters, such as the radius of curvature, the magnitude and direction of the applied distributed load, and the small-scale parameter are investigated. The numerical results are constructed in the form of nonlinear static deflection curves, nonlinear dynamic frequency-amplitude diagrams, time traces, and phase-plane portraits.

ABSTRACT: This paper is the first to analyse the coupled fluid-structure viscoelastic dynamical characteristics of a fluid-conveying viscoelastic microtube resting on a nonlinear elastic bed subject to large rotations. None of the axial and transverse motions/accelerations is neglected in the modelling and simulations. The dissipation is modelled using the Kelvin–Voigt scheme for the deviatoric segment of the symmetric couple stress tensor and the stress tensor. Based on the Euler–Bernoulli theory, in which the microtube cross-section remains perpendicular to the centreline, and the modified couple stress theory (MCST), the energies and the work of external load and damping are formulated. Through use of Hamilton's principle, the coupled transverse-longitudinal equations governing the motion of the fluid-conveying viscoelastic microtube are developed. A weighted-residual-based discretisation method is applied to the continuous vibration model and the resultant reduced model is simulated via a continuation technique. The coupled fluid-structure dynamical characteristics of the fluid-conveying viscoelastic microtube are analysed by constructing the frequency-amplitude diagrams. It is shown that slight changes in the flow speed significantly affects the resonant response and modal interactions.


ABSTRACT: It is well-known that a growing tubular tissue with geometric constraint will buckle and the threshold value can be determined by solving a variable coefficient eigenvalue problem. In this paper, we study the growth induced wrinkling for both single- and bi-layer tubes and aim to deduce some asymptotic expressions for the critical growth factor and critical mode number. Explicit bifurcation conditions are derived by use of the WKB approach when the mode number $n$ is large. For the single layer case, an iterative method is utilized to deduce an asymptotic solution for the critical growth factor $g_c$ and critical mode number $n_c$ under the thin layer limit. It is found that the critical mode number $(\ln H/H)^{1}$ and the leading-order term of $g_c$ is a constant 1.839. For a bilayer tube with each layer having its own shear modulus, we further assume that a scaled thickness $\eta$ for the inner layer is small and the modulus ratio $\xi$ between the inner and outer layers is large. An order analysis shows that the critical growth factor for the inner layer and . Besides, we also provide some necessary higher-order corrections. All asymptotic results are validated by the corresponding numerical solutions. (Lots of math in this abstract.)


ABSTRACT: This study provides an exact solution for the size dependent buckling and post-buckling behavior of functionally graded (FG) micro-beams with arbitrary boundary conditions which are subjected to combined thermo-mechanical loading. To this end, a theoretical formulation including the effects of size dependency, elastic foundation and uniform temperature distribution is first derived using the modified couple stress theory and through the principle of minimum total potential energy. Next, the nonlinear equations governing bending and stretching behavior of FG micro-beams are uncoupled to a fourth-order ordinary differential equation. Finally, the differential operator method is utilized to exactly solve the decoupled equation. Also, a Fourier series solution is presented for doubly-simply supported FG micro-beams to show the importance of exact solution. In the numerical results section, the effects of the geometric ratios, material distribution, temperature variation, and material length scale parameter on the post-buckling behavior are discussed in detail. Findings show that the Fourier series solution is not able to correctly predict the post-buckling behavior of FG micro-beams, since the effect of flexural-extensional coupling stiffness term appearing in the natural boundary condition is ignored. Also, it is seen that critical values of axial traction obtained from the post-buckling analysis are significantly varied with the transverse force per unit length and temperature variation, while the
buckling analysis predicts that buckling values of beam remain constant. Therefore, it can be concluded that the buckling analysis is inadequate for analyzing FG micro-beams under thermo-mechanical loadings.

ABSTRACT: A size-dependent nonlinear nonlocal strain gradient model for nanoscale tubes is proposed in this investigation and the forced mechanical behaviour is examined. This continuum model is better capable of incorporating size effects as it includes two independent length-scale parameters. The scale-dependent elastic energy and motion energy as well as the work carried out by the excitation load are formulated. The nonclassical nonlinear differential equation of motion of the nanoscale tube is obtained using Hamilton's work/energy principle together with the nonlocal strain gradient elasticity. A precise numerical solution is presented for the nonlinear dynamic characteristics within the framework of Galerkin's scheme in conjunction with a continuation approach. The influences of nanosystem parameters such as the scale parameters, the length-to-gyration-radius ratio as well as the amplitude of the excitation force on the frequency/force responses are explored and discussed in details.

ABSTRACT: The criterion defining the geometric parameters guaranteeing bistable behavior of electrostatically actuated curved axisymmetric circular plate is established. The usage of Berger’s approximation for von-Kármán nonlinear plates, combined with single degree of freedom (DOF) reduced order (RO) modeling, allowed derivation of a simple semi-analytical bistability criterion, obtained in the form of an implicit algebraic equation in terms of critical deflection and plate geometric parameters. The criterion is verified by direct numerical solutions, combined with the arc-length method. Case studies are presented, illustrating the implementation of the suggested criterion as a useful tool for the early design stage for MEMS/NEMS devices.

ABSTRACT: The global buckling and wrinkling behavior of sandwich plates with anisotropic facesheets is investigated by means of a linearized stability analysis. High-order plate models are formulated referring to a sublaminate variable-kinematic approach: an axiomatic through-thickness description of the displacement field is introduced, wherein the selected model is employed for an arbitrarily defined group of plies, i.e., the sublaminate. The two-dimensional governing equations of the plate model are solved in weak form by means of the Ritz method. The modeling approach is applied to sandwich plates with anisotropic laminated facesheets and orthotropic cores. A wide set of configurations is analyzed: critical loads and wrinkling patterns are determined for panels with foam and honeycomb cores, subjected to uniaxial as well as multiaxial loads. The proposed approach is shown to provide accurate, quasi-3D predictions for both long and short wavelength buckling with a reduced computational effort.

ABSTRACT: Mechanical metamaterial beams (MMB) have been extensively studied given their potential functional applications in various areas, e.g. micro-electro-mechanical systems (MEMS), energy harvesting,
actuation. This study presents a novel class of graphene-reinforced MMB (GR-MMB) with arbitrarily periodic webbing. A size-dependent theoretical model is developed to predict and control the buckling response of the GR-MMB. The modified couple stress theory is expanded to include the effective material properties of microstructures. Clamped-clamped and simply supported GR-MMB with oval, hexagonal and cylindrical webbing patterns are showcased. Numerical simulations are conducted to validate the theoretical model and satisfactory agreements are obtained. Parametric studies are presented to unveil the effects of the graphene reinforcements and periodic design patterns on the buckling response of GR-MMB. The enhancement factor of the axial force between the GR-MMB and MMB, $\psi$, is studied with respect to the material ratio and geometric ratio. Density plots of the presented microstructures are provided to demonstrate the desired geometries that lead to the highest axial load and largest webbing diameter, i.e., lowest self-weight. The theoretical model presented in this study can be deployed to predict and tune the buckling response of GR-MMB with arbitrarily periodic webbing for different purposes.


ABSTRACT: The present paper investigates the small size effect on a localized transition zone in the merging of two wrinkles in constrained suspended graphene under in-plane shear. It is found the classical elasticity theory overestimates the wrinkle amplitude and wavelength in contrast with the results of atomistic simulation. The analytic formulations for the wrinkling hierarchy are obtained by using nonlocal plate theory. Here, this small size effect can be estimated by correct value of nonlocal parameter $e_0a = 1.9$ nm. Besides, the orientation of graphene slightly influences the wrinkling hierarchy of graphene. The temperature effect is significant under small shear strain, while this effect is significant in the constrained edges and insignificant in the middle region under large strain. The occurrence of cracking is always in constrained edges, where the stress concentration releases in the wrinkling hierarchy. This work is expected to provide a better understanding of the mechanism of nanometer scale wrinkles.


ABSTRACT: Due to their extraordinary and unique properties, graphene sheets have been attracted tremendous attention in recent years. This paper is concerned with the dynamic stability of an embedded orthotropic single layer graphene sheet (SLGS) subjected to periodic excitation compressive load with various boundary conditions. In order to obtain more accurate results, the material properties of graphene sheet are assumed to be viscoelastic using Kelvin-Voigt model. The surrounding medium is described by visco-Pasternak foundation model, which accounts for normal, transverse shear and damping loads. Adopting the first order shear deformation theory (FSDT) in the framework of Eringen's differential constitutive model, the governing equations of motion are obtained via energy method and Hamilton's principle which are then solved numerically via Ritz method in conjunction with Bolotin method. The parametric studies are carried out to explore the effects of the static load factor, structural damping, nonlocal parameter, stiffness and damping coefficients of the foundation and aspect ratio on the dynamic instability region (DIR) of SLGS for each of the boundary conditions separately. Results indicate that with increasing the structural damping coefficient, the dimensionless pulsation frequency decreases and DIR moves to left, consequently. Moreover, it is observed that when one edge of the nanoplate changes from free to simply supported or from simply supported to clamped, the dimensionless pulsation frequency enhances.

ABSTRACT: An analysis of forced vibration of a porous functionally graded (FG) nanoshell is conducted employing a two-parameter non-classical elasticity theory called nonlocal strain gradient theory. A transverse partial dynamic load with specific frequency of excitation is applied to the nanoshell. Even and uneven dispersion of pores due to material imperfections have been considered. The modified power-law modeling of FG materials is introduced to incorporate the pore content effects. The problem of forced vibration is solved by using a hybrid analytical-numerical method in order to derive deflection-frequency curves. According to the provided graphical results, it can be concluded that pore amount, type of pore distribution, two scale parameters, material gradation and geometrical parameters of applied dynamic load have important influences on deflection-frequency curves of nanoshells.


ABSTRACT: One of the most high-risk locations of plaque growth and rupture initiation (and hence occurrence of heart attack) is the first main bifurcation of the left main coronary artery; the aim of this investigation is to analyse the nonlinear three-dimensional biomechanics of bifurcated atherosclerotic left coronary artery. In order to examine the influence of different system parameters, a biomechanical model of a bifurcated coronary artery is developed. Three plaques of varying geometry and material properties inside the three branches of the left main (LM), the left anterior descending (LAD), and the left circumflex (LCx) are modelled incorporating three-dimensionality, nonlinear geometric and material properties, asymmetry, viscosity, and hyperelasticity, and fluid-solid interaction. A finite element method (FEM) is employed to incorporate all of the above-mentioned important features in addition to physiological blood pulsation, heart motion, active media layer contraction, lipid plaque, calcium deposition, three different artery layers, micro-calcification, and non-Newtonian model for blood. Moreover, the effects of different system features such as stenosis, curved shape of the artery, plaque location, and fibrous cap thickness on the stress field (shear and structural) are examined. The developed biomechanical model could be utilised to estimate the risk of the initiation of plaque rupture inside the human coronary artery and the occurrence of heart attack.


ABSTRACT: In this paper, attention is paid to the prediction of vibration characteristics of two-dimensional functionally graded (2D-FG) tubes based on higher order theory. The tubes are formed of two different materials, and the material properties of the nano-scaled tubes vary both in the length and radial direction. To incorporate the size effect, the nonlocal strain gradient theory is employed. The thermal force is considered to be uniform temperature across the radial of the nonlocal tube, on the basis of the Hamilton's principle, the size-dependent governing equations are derived. After solving these equations using the generalized differential quadrature method (GDQM), the impact of the nonlocal parameter, strain gradient parameter, temperature variations, material variation on the vibration characteristic of the tubes with various boundary conditions are discussed in details.

ABSTRACT: A nonlocal strain gradient elasticity approach is proposed for the mechanical behaviour of fluid-conveying nanotubes; a nonlinear analysis, incorporating stretching, is conducted for a model based on both a nonlocal theory along with a strain gradient one. A clamped–clamped nanotube conveying fluid, as a conservative gyroscopic nanosystem, is considered and the motion energy and size-dependent potential energy are developed via use of constitutive and strain–displacement relations. An energy minimisation is conducted via Hamilton's method for an oscillating nanotube subject to external forces. This gives the nonlinear equation of the motion which is reduced to a high DOF system via Galerkin's technique. As many nanodevices operate near resonance, the resonant motions are obtained using a frequency-continuation method. The effect of different nanosystem/fluid parameters, including fluid/solid interface and the flow speed, on the nonlinear resonance is analysed.


ABSTRACT: This paper investigates the nonlinear forced dynamical behaviour of a geometrically imperfect viscoelastic shear-deformable microplate. The third-order shear deformation plate theory and the Kelvin–Voigt viscoelastic model are utilised in the framework of the modified version of the couple-stress theory to develop a model for the microsystem. The developed model is in the form of partial differential equations (PDEs) and accounts for geometric nonlinearities, damping nonlinearities, micro-scale size effects, and initial imperfection. Five coupled PDEs are derived for the five independent displacements and rotations. These PDEs are truncated to a set of nonlinearly coupled ordinary differential equations via application of a two-dimensional modal decomposition based on the Galerkin technique. The final set of equations consists of quadratic and cubic nonlinear terms for both damping and stiffness. An efficient numerical algorithm based on a continuation scheme is utilised to analyse the nonlinear forced vibration characteristics of such complicated system. The effects imperfection amplitude, damping nonlinearities, and micro-scale size on forced resonant vibration response are highlighted.


ABSTRACT: Converging and diverging nozzles and skyscrapers are examples of hollow structures with curved bounding surfaces. We study torsional deformations of such structures, namely, truncated conical cylinders with curved inner and outer bounding surfaces and made of linearly elastic and orthotropic functionally graded materials (FGMs). Simplifying assumptions include a plane section remains plane, deformations are axisymmetric about the cylinder axis, and a power-law relation between the radial and the axial coordinates describes the curved mantle. For four spatial variations of the two shear moduli, we analytically solve governing equations for the two non-zero shear stresses and the tangential displacement. For a general variation of the shear moduli we employ the weighted residuals approach to find an approximate solution and establish its convergence and accuracy. We also analyze the material tailoring problem to attain a desired shear stress distribution on a cross-section. We include numerical examples to illustrate spatial distributions of shear stresses for prescribed shear moduli variations, and of the shear moduli for achieving desired shear stress distributions. The analytical solutions provided herein should serve as benchmarks to verify numerical solutions of similar problems.

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ABSTRACT: Concrete-filled stainless steel tubular (CFSST) slender columns are increasingly used in composite structures owing to their distinguished features, such as aesthetic appearance, high corrosion resistance, high durability and ease of maintenance. Currently, however, there is a lack of an accurate and efficient numerical model that can be utilized to determine the performance of circular CFSST slender columns. This paper describes a nonlinear fiber-based model proposed for computing the deflection and axial load-moment strength interaction responses of eccentrically loaded circular high-strength CFSST slender columns. The fiber-based model incorporates the accurate three-stage stress-strain relations of stainless steels, accounting for different strain hardening characteristics in tension and compression. The material and geometric nonlinearities as well as concrete confinement are included in the computational procedures. Existing experimental results on axially loaded CFSST slender columns are utilized to verify the proposed fiber-based model. A parametric study is conducted to examine the performance of high-strength slender CFSST beam-columns with various geometric and material parameters. It is shown that the fiber-based analysis technique developed can accurately capture the experimentally observed performance of circular high-strength CFSST slender columns. The results obtained indicate that increasing the eccentricity ratio, column slenderness ratio and diameter-to-thickness ratio remarkably decreases the initial flexural stiffness and ultimate axial strength of CFSST columns, but considerably increases their displacement ductility. Moreover, an increase in concrete compressive strength increases the flexural stiffness and ultimate axial strength of CFSST columns; however, it decreases their ductility. Furthermore, the ultimate axial strength of CFST slender columns is found to increase by using stainless steel tubes with higher proof stresses.

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ABSTRACT: The search for passive control systems has increased in some high seismicity areas of the world, especially in terms of the strengthening of existing RC or steel building structures designed without earthquake-resistance considerations (pre-code structures) or with outdated structural codes. One of the most promising
techniques consists of adding steel Buckling Restrained Braces (BRBs) to the existing structure. This paper presents an applicability study of these devices in the retrofit of a typical existing RC pre-code school building structure. The effectiveness of the retrofit solution, initially designed according to Kasai et al. (1998) formulation, was assessed through non-linear static and dynamic numerical analyses. The results of these analyses, led to the design method being developed with the purpose of optimising the dimensions of the steel dampers at different storeys and therefore improving the structural performance. This development is based on a simplified method of predicting the response of a passive system, by devising a single degree of freedom system. The effectiveness of the seismic retrofit solution designed through the improved design procedure was confirmed, showing that the studied strengthening solution results in a significant increase in strength, deformation and energy dissipation capacity, thereby limiting damage in the original structure to admissible levels.

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ABSTRACT: The use of recycled aggregate concrete (RAC) for the fill in concrete filled steel tube (CFST) members (RACFST members) is proposed as a practical structural application. An experimental study of RACFST members with normal-strength concrete under combined loading is summarized. Forty-eight columns and three beams in groups of 3 identical specimens were tested to failure. Study parameters included recycled coarse aggregate (RCA) replacement percentage, source of RCA, eccentricity, slenderness, and the steel to concrete area ratio. Experimental results are consistent with less than 3% scatter within each group. The maximum compressive load of the columns decreased modestly with increasing substitution level of RCA (up to 11.2%), and the structural effects of the recycled aggregate replacement on load capacity and initial stiffness are smaller than the corresponding changes in material properties. The source of RCA had little effect on the behavior of RACFST under combined loading for this test program, and the similar size grading and index of crushing obtained in the aggregates may have provided this benefit. These observations support the use of RACFST in structural engineering. Current CFST design provisions are compared to the RACFST test results, and the design recommendations for RACFSTs are presented.

Nian-Zhong Chen (School of Marine Science and Technology, Newcastle University, United Kingdom), “Panel reliability assessment for FPSOs”, Engineering Structures, Vol. 130, pp 41-51, January 2017 https://doi.org/10.1016/j.engstruct.2016.10.014

An assessment method is developed for the panel reliability of ship-shaped Floating, Production, Storage and Offloading units (FPSO). Not only axial compressive loads but also internal and external lateral pressures are taken into account in the reliability assessment. Beam-column buckling and flexural-torsional buckling are regarded as two primary failure modes of stiffened panels. Variability of corrosion wastage and material properties are accounted for in modelling the panel’s time-dependent ultimate strength. Uncertainty of axial compressive loads induced by hull girder bending is evaluated based on probabilistic characteristics of still-
water bending moment (SWBM) and vertical wave-induced bending moment (VWBM). A case study is performed to demonstrate this method and the effects of the lateral pressure, the return period of the extreme value of VWBM, the environmental severity factor, and the corrosion wastage on the panel reliability are investigated. Sensitivity measures for random variables are also carried out.

References listed at the end of the paper:
References listed at the end of the paper:

ABSTRACT: This paper presented a new type of I-girder which consists of a rectangular concrete-filled tubular flange and corrugated web. In the new I-girder, the concrete-filled tubular flange has much stronger torsional and flexural stiffness, which is advantageous for improving the resistance to global buckling. Corrugated web, which is much lighter in weight due to its very small thickness compared to flat web with transverse or longitudinal stiffeners, has much better out-of-plane bending stiffness and shear stiffness, and thus it can enhance the capacity of resisting local buckling of the web more efficiently. To investigate the behavior of the presented new I-girder, experimental test is carried out to study the static failure process of a new I-girder specimen together with a corresponding conventional I-girder with flat-plate flanges and web. The two specimens are subjected to a concentrated load at the mid-span. Experimental results indicate that the failure of the traditional I-girder is global buckling while the presented new I-girder deforms gradually until a maximum deflection surpass the serviceability limit. It fails due to flexural yielding. The static performances of the two different I-girders, including strain development, lateral displacement development and load-deflection relationship, are compared and discussed in details based on the experimental results. Finally, theoretical equations for predicting the flexural strength of the new I-girder are presented, and the accuracy of these equations is also verified through comparison with experimental results.

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“Experimental study on static behavior of I-girder with concrete-filled rectangular flange and corrugated web under concentrated load at mid-span”, Engineering Structures, Vo. 130, pp 124-141, January 2017
In total six S460NH and five S690QH hot (HSS) square and rectangular hollow sections is described in this paper. Both hot-rolled and cold-formed HSS sections were examined. In total six S460NH and five S690QH hot-rolled section sizes and three S500MC, two...
S700MC and four S960QC cold-formed section sizes were tested. The experimental programme comprised tensile coupon tests on flat and corner material, measurements of geometric imperfections, full cross-section tensile tests and stub column tests. The results of the experiments presented in this paper have been combined with other available test data on high strength steel sections, and used to assess the existing design guidelines for high strength steels given in Eurocode 3. The focus has been on the material ductility requirements, the Class 3 slenderness limit for internal elements in compression and the effective width formula for Class 4 internal elements in compression. Reliability assessments of the Class 3 slenderness limit (both the current value of 42 and a proposed value of 38) and the effective width formula for Class 4 internal elements in compression were carried out. The analysis indicated that, based on the assembled test data considered in this study, and the assumptions made regarding the statistical distributions of material and geometric properties, a partial safety factor greater than unity is required for HSS. Similar findings have also recently been presented for ordinary strength steels.

References listed at the end of the paper:
[37] G. Sedlacek, C. Müller, A. Nussbanumer, Chapter 5.1 – Toughness requirements in structural applications, Use and application of high-performance steels for steel structures, International Association for Bridge and Structural Engineering (IABSE) (2005)
ABSTRACT: Research work carried out on steel special truss moment frames (STMFs) with double-angle sections as chord members during the 1990s led to the formulation of design code provisions. Further research results using double-channel specimens resulted in a modified equation for the expected vertical shear strength of the central special segments, $V_{cr}$, and has been incorporated into the current AISC Seismic Provisions for Structural Steel Buildings. Double hollow structural sections (double-HSS) have the advantages of minimizing lateral torsional buckling and maximizing compactness in the flanges as compared to single HSS with the same flexural capacity. In this research, double-HSS members were proposed for the chord and web members of STMFs instead of double-angle, double-channel, or single-HSS. Double-HSS can effectively delay flange local buckling and enhance rotational ductility due to reduced width-to-thickness ratio $b/t$ without increasing the wall thickness of the members. A full-scale STMF subassembly with double-HSS as truss members was tested under large displacement reversals to simulate a severe earthquake ground motion. Testing results indicate that using double-HSS truss members is a viable alternative for STMFs in high seismic regions. Plastic hinge models are also suggested for computer analysis and design of non-yielding members outside of the special segments.
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“Concentrically loaded slender square hollow and composite columns incorporating high strength properties”,  
ABSTRACT: This paper presents an experimental investigation of longitudinally slender box sections (HS)  
having compact and non-compact cross-sections as well as slender composite sections (CB) fabricated from  
high strength steel (HSS) and high strength concrete (HSC). Fifteen test specimens (HS) and thirty nine test  
specimens (CB) having width to thickness ratios (b/t) ranging from 15 to 40 and slenderness ratios ranging  
from 18 to 124 were tested to failure. Finite element modelling (FEM) of the test specimens (HS and CB) was  
verified with the experimental results for further analysis. The FEM was used to investigate the effects of  
residual stresses induced from lightly and heavily welded box sections on the member capacity of slender box  
sections. The column curves of various design specifications pertaining to slender welded box sections were  
reviewed by the experimental and FEM peak strengths for the purpose of selecting the most appropriate curves  
for non-compact box sections. Likewise, the column curves pertaining to the slender composite sections were  
reviewed by the experimental and FEM peak strengths for the purpose of selecting the most appropriate curves  
for high strength composite columns fabricated from HSS (690 MPa) and HSC (80–130 MPa).  

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“Numerical analysis and design of slender concrete-filled elliptical hollow section columns and beam-columns”,  
ABSTRACT: A numerical model simulating the behaviour of elliptical concrete-filled columns under either  
concentric or eccentric compressive load has been developed in ABAQUS. The numerical results have been  
compared against a range of experimental results for ultimate load, load–deflection behaviour and failure  
modes, with good agreement observed. An extensive parametric study has been undertaken whereby the  
slenderness, load eccentricity, cross-sectional geometry and reinforcement ratio of the concrete-filled columns  
were varied, creating a data set upon which to formulate design guidance since currently there are no specific  
columns or beam-columns. It is shown that the current provisions of EN 1994-1-1 [1] for the design of  
concrete-filled steel columns of circular or rectangular cross-section are also appropriate for the design of  
members of elliptical cross-section, employing either buckling curve b or c, depending on the level of steel  
reinforcement. Finally, an assessment is made of the reliability of the design proposals for concrete-filled  
elliptical hollow section columns and beam-columns.  

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ABSTRACT: A novel energy absorption connector with pleated plate and aluminum foam as energy absorber was proposed to be inserted between the blast resistant façade and building to absorb blast energy and reduce blast load transferred to the building. The energy absorption performance of the connector under quasi-static compression loading was first studied by using experimental method. The deformation mechanisms were observed from the experiment and three different deformation processes were also identified. The effects of aluminum foam, pleated plate thickness and angle \( \theta_0 \) (the angle between flat plate and pleated plate) as well as pleat number on the energy absorption performance of the connector were experimentally investigated, which showed that the energy absorption capacity could be improved by filling the connector with aluminum foam and increasing the pleated plate thickness, angle \( \theta_0 \) and pleat number. Moreover, an analytical model for determining the load–displacement curve of the energy absorption connector was also developed and the predictions by the analytical model were proven to be reasonable by comparing with the experimental data.

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ABSTRACT: A stress-strain model is proposed to define the relationship between axial compressive stress and strain for square steel tube stub columns, which have been widely used as predominant gravity-sustaining structural components in high-rise buildings and skyscrapers. The proposed model consists of two equations, defining the ascending branch and descending branch of the stress-strain curve, respectively, and has a significant advantage over previous models in that it can trace effects of both the residual stress induced during manufacturing process and the local buckling of steel plate on the compressive stress-strain behavior of square steel tube stub columns. Another feature of the proposed model is that it can be used to the stub columns made of very thin steel plates. In order to calibrate the new stress-strain model and verify its reliability and accuracy, sixty-eight hollow square steel tube stub columns under monotonic axial compression are collected. The previous tests cover a wide range of structural factors such as yield strength and width-to-thickness ratio of steel plates. In particular, the previous tests include stub columns made of steel plate with high yield strength of up to 835 MPa. Comparisons between the experimental results and the calculated ones indicate that the proposed model cannot only predict the local buckling strength and the corresponding strain very well, but also trace the compressive stress-strain behavior of square steel tube stub columns up to large strain with high accuracy.

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ABSTRACT: A number of structural collapses are initiated from losing stability locally. The monitoring and detection of instability is rarely studied in both research communities of structural health monitoring and structural stability. In order to capture member buckling at an early stage to prevent a local instability from propagating into an overall structural failure, in this study, an approach to detect one type of instability (member overall buckling) is proposed for civil large-scale space grid structures. The foundation of this approach lies in: once a member buckles, a large bending stress due to buckling is developed and dominates the total normal stress of the member. Since the bending stress varies along a member, the total normal stress varies along the member, so does the total normal strain on the surface of the member. Therefore, by identifying the deviation in normal strain at two different cross sections of a member, overall buckling of the member can be detected. This study will justify that strain gauges can pick up all the bending stress induced by buckling as long as they are deployed before buckling. Numerical simulations have been conducted on large-scale space grid structures with different types of connections between members and loading situations. The obtained results have shown that once a member buckles, the strains measured at two different cross sections on the member deviate from each other significantly, verifying the efficacy of the proposed approach.

Qing Quan Liang (College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia), “Nonlinear analysis of circular double-skin concrete-filled steel tubular columns under axial compression”, Engineering Structures, Vol. 131, pp 639-650, January 2017
https://doi.org/10.1016/j.engstruct.2016.10.019
ABSTRACT: The use of the circular hollow steel tube in a circular concrete-filled steel tubular (CFST) column significantly alters the confinement mechanism in the conventional CFST column. The confinement models proposed for conventional circular CFST columns are therefore not applicable to circular double-skin CFST (DCFST) columns. This paper presents a new numerical model for predicting the structural performance of circular DCFST short columns under axial compression. The numerical model incorporates new material constitutive relationships of sandwiched concrete in circular DCFST columns. The confinement effects provided by the outer and inner steel tubes on the sandwiched concrete in circular DCFST columns are taken into account in the numerical formulations. Comparisons with existing experimental results on circular DCFST short columns are made to verify the numerical model developed. The numerical model is used to undertake parametric studies to examine the effects of important geometric and material parameters on the strength and ductility of axially loaded DCFST short columns. It is demonstrated that the numerical model can accurately capture the complete axial load-strain characteristics of circular DCFST short columns under axial compression. A design formula is proposed and found to predict well the ultimate axial loads of circular DCFST short columns.

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ABSTRACT: In practice, the steel pipe-jacking can be regarded as a thin-walled cylindrical shell mainly subjected to jacking force in the axial direction and surrounded by the soil which is usually simplified and modeled as an elastic foundation. In this paper, the elastic buckling behavior of steel jacking pipes primarily under axial compression and with the Pasternak foundation is analyzed by the finite strip method (FSM). The elastic foundation is considered in the stiffness matrix through the strain energy, and the deformation in the longitudinal direction is simulated by the series functions in FSM. A parametric study is conducted to analyze buckling of cylindrical shells embedded in different elastic foundations. It indicates that the Pasternak foundation is more conducive to prevent buckling of cylindrical shells under axial compression. The critical length and the lower bound of buckling loads are obtained, and they offer the basis for optimal design of steel pipe-jacking. Finally, the case study combined with the buckling accident in the steel pipe-jacking event is presented. The present buckling analysis of soil-embedded cylindrical shells under axial compression provides design guidance for steel pipe-jacking construction.

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ABSTRACT: In this paper free vibrations of rotating cylindrical shells with both ends free are studied. The model used also allows for considering a flexible foundation supporting the shell in the sense of a radial and circumferential distributed stiffness. Furthermore, a circumferential tension (hoop stress) which may be due to pressurisation or centrifugal forces is taken into account. Natural frequencies and mode shapes are determined exactly for both stationary shells and for shells rotating with a constant angular speed around the cylinder axis. Trigonometric functions are assumed for the circumferential mode shape profiles, and a sum of eight weighted exponential functions is assumed for the axial mode shape profiles. The functional form of the axial profiles is shown to greatly vary with the roots of a characteristic bi-quartic polynomial that occurs in the process of satisfying the equations of motion. In the previously published work it has been very often assumed that the roots are two real, two imaginary, and two pairs of complex conjugates. In the present study, a total of eight types of roots are shown to determine the whole set of mode shapes, either for stationary or for rotating shells. The results using the developed analytical model are compared with results of experimental studies and very good agreement is obtained. Also, a parametric study is carried out where effects of the elastic foundation stiffnesses and the rotation speed are examined.

ABSTRACT: Insulated concrete sandwich panels are comprised of two outer concrete wythes and an inner layer of foam insulation. They have been increasingly used because of their advantages of light weight and energy efficiency. Various shear connectors can be used to connect the two outer concrete wythes. More recently, Fiber-Reinforced Polymer (FRP) shear connectors have been used, which can eliminate thermal bridging and improve the thermal performance. Typical approaches to Finite Element (FE) analysis treat static and dynamic analyses separately. However, due to the flexibility of the FRP shear connectors and the cracking of the concrete in insulated concrete sandwich panels, a nonlinear static analysis model would often diverge early based on a preliminary FE study conducted by the authors. To address this issue, a nonlinear explicit dynamic FE model using ABAQUS was developed, which can study both the panels’ static behavior under typical flexural loading and dynamic behavior under blast loading. Nonlinear material properties were incorporated and damaged plasticity model was used to model concrete in both compression and tension. In order to simulate the static behavior, the time loading control was applied to the FE model to slow down the rate of loading to smoothly capture the response. For dynamic analysis under blast loading, a verification study was conducted first using the developed FE model, where good correlations can be obtained between the FE and test results on a panel tested in a previous study. The FE model was further used to study the dynamic behavior of two panels under blast loading: one is a solid concrete panel and the other is an insulated concrete sandwich panel. It can be concluded that, although the insulated concrete sandwich panel is lighter, it still performs relatively well compared to the solid panel under blast loading. Therefore, it is promising to use insulated concrete sandwich panels for both conventional and blast-resistant structures.


ABSTRACT: The design of gridshells is subject to strong mechanical and fabrication constraints, which remain largely unexplored for non-regular patterns. The aim of this article is to compare the structural performance of two kind of gridshells. The first one is the kagome gridshell and it is derived from a non-regular pattern constituted of triangles and hexagons. The second one results from a regular pattern of quadrangles unbraced by diagonal elements. A method is proposed to cover kagome gridshells with planar facets, which reduces considerably the cost of fabrication of the cladding. The sensitivity of kagome gridshells to geometrical imperfections is discussed. The linearised buckling load of kagome gridshells is then compared to the one of quadrilateral gridshells. The most relevant design variables are considered in the parametric study. Two building typologies are studied for symmetrical and non-symmetrical load cases: dome and barrel vault. It reveals that the kagome gridshell outperforms quadrilateral gridshell for a very similar construction cost.
ABSTRACT: Angles exhibit a complex structural behaviour, responsible for the fact that, in the current North American Specification for Cold-Formed Steel Structures, short-to-intermediate equal-leg angle columns are (i) not yet pre-qualified for the Direct Strength Method (DSM) design and (ii) excluded from the application of the LFRD resistance factor $\varphi = 0.85$, valid for all other cold-formed steel compression members. Recently, the specific behavioural features exhibited by the above angle columns were incorporated into the proposal of a novel DSM-based design approach, for both fixed-ended and pin-ended columns, and it was shown that this added rationality goes along with quite accurate and reliable failure load predictions. However, the investigation leading to this design proposal also unveiled that there are no available experimental failure loads of slender pin-ended columns with intermediate-to-high slenderness values, which implied that the design procedure was validated for such columns exclusively on the basis of numerical failure loads. The research work reported in this paper provides a contribution towards filling this gap, since it mainly consists of an experimental study, carried out at the Federal University of Rio de Janeiro, on the behaviour and collapse of short-to-intermediate slender pin-ended cold-formed steel equal-leg angle columns. After addressing the selection of the columns to be tested, the experimental set-up and test procedure are described in detail and the results obtained are presented and discussed. Such results involve (i) initial imperfection measurements, (ii) equilibrium paths relating the applied load to key column displacements, (iii) deformed configurations (including the collapse mode) and (iv) failure loads. Next, those same experimental results are used to validate a shell finite model previously developed by the authors, which is subsequently employed to obtain additional numerical failure load data concerning the pin-ended angle columns under scrutiny. Then, attention is turned to assessing the merits of the novel design approach. The comparison between the experimental and numerical values obtained in this work and their estimates provided by the design equations shows a very good correlation, perfectly in line with that observed in the recent studies available in the literature – this means that the validation and calibration of the above design approach may be deemed (successfully) completed. Finally, the paper closes with the presentation and assessment of small alterations to the existing design expressions, aimed at improving their accuracy and rationality, thus paving the way towards codification in the near future.
buckling” behavior of long hybrid members. In addition, a good agreement between FEA and bucking test results is achieved. Finally, based on FEA and the traditional Perry-Robertson formula, the column curves for long CFRP-Al hybrid tubes are given for design.

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ABSTRACT: Reinforced concrete shell structures have been widely used in a variety of modern engineering applications. It is found from earthquake reconnaissance that reinforced concrete (RC) shell structures, such as nuclear containments, cooling towers, roof domes, shear walls, etc., are the key elements in resisting earthquake disturbances. This paper presents the development of a finite element analysis (FEA) program, SCS-3D, to predict the inelastic behavior of RC shell structures. In the program, a Cyclic Softened Membrane Model (CSMM)-based shell element is developed based on the degenerated shell theory with a layered approach and taking into account the CSMM developed at the University of Houston. To form the FEA program, the constitutive relation modules and the analysis procedure were implemented into a finite element program development framework, OpenSees developed at UC Berkeley. Several large-scale structural tests were employed to validate the developed FEA program, including RC panels subjected to a combination of shear and bending, three-dimensional RC shear wall and cylindrical RC tanks subjected to reversed cyclic loading.

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ABSTRACT: The external restraining members in an Assembled Buckling-Restrained Brace (ABRB) are mainly connected by high-strength bolts. Because of the bolts’ longitudinal discrete layout, the stiffness reduction of the external restraining members should be considered, and a significant increase in the local stress of the external member between two bolts must be considered as well. Thus, this study first uses theoretical derivation and numerical verification to investigate the stress state of BRB subjected to core single-wave overall deformation and core multi-wave buckling deformation, respectively. Based on the unique mechanical characteristics of the pinned ABRBs, a design method applicable for the pinned ABRB with a flat core is put forward, considering the external restraining stiffness reduction coefficient and the additional local influence of contact force when the core deforms in a multi-wave form. Finally, six ABRB FE models are presented to verify the rationality of the design method being safe and reliable to predict the ABRB’s overall buckling failure and bending failure in the ECSR of BRBs. This design method also considers the influence of a series of design parameters, including the gap between the core and external members, pinned connector length, extended core length, length, strength, stiffness and imperfection of the external restraining members, bolt dimensions and layout, etc.
ABSTRACT: Due to its relatively good safety performance and aesthetic benefits, laminated glass (LG) is increasingly being used as load-carrying members in modern buildings. This paper presents a study into one application scenario of structural LG subjected to axial compression. The aim of the study is to reveal the flexural buckling behavior of the LG columns made up of multi-layered annealed glass plies. The LG specimens respectively consisted of two, three and four plies of annealed glass, bonded together by two prominent types of adhesives. To reach the research aim, both full-scale tests and nonlinear numerical simulations were carried out. Based on the test and numerical results, the influences of interlayer type, laminate number, load duration and ambient temperature on the buckling resistance of the LG columns were studied in detail. In addition, the applicability of the so-called Southwell plot method for LG columns was examined and discussed. Subsequently a characteristic initial geometrical imperfection for LG columns made of annealed glass was suggested. Finally design buckling curves were proposed for LG columns carrying axial loads with the various durations in various ambient temperatures. The results obtained are expected to provide supplementary information that is currently lacking in existing literature.


ABSTRACT: Steel corrugated webs are likely used in the field of bridges in the last few decades due to their numerous advantages. The most favorable layout is the hybrid girder with upper and lower reinforced concrete slabs and with steel corrugated webs. During incremental launching – without concrete flanges – the steel girder can be subjected by the combination of bending (M), shear (V) and transverse forces (F) which result in a complex stress field and a coupled instability phenomenon may occur. In the international literature there are just a limited number of previous investigations focusing on the M-V-F interaction behavior of girders with corrugated webs. The authors previously developed a proposal for the consideration of the M-V-F interaction behavior of trapezoidally corrugated web girders based on FE simulations, which interaction equation was verified only based on test results found in the international literature. Those test results were mainly related to the investigation of pure bending moment, shear buckling and patch loading capacities and laboratory tests were missing to investigate the M-V-F interaction behavior and to determine the load carrying capacities under coupled instabilities. In the current research the authors designed and executed a complex experimental research program focusing on the M-V-F interaction behavior of girders with trapezoidally corrugated web. The current paper introduces the executed experimental research program, presents the results of the laboratory tests and gives final conclusions to the M-V-F interaction behavior based on test results and numerical simulations.

Zdenek Kala and Jan Vales (Brno University of Technology, Faculty of Civil Engineering, Department of Structural Mechanics, Veveri Street 95, 602 00 Brno, Czech Republic), “Global sensitivity analysis of lateral-

ABSTRACT: The article examines a hot-rolled steel I-beam subjected to lateral-torsional buckling (LTB) due to bending moment. The paper describes a non-linear finite element (FE) model and numerical approximation and simulation methods used for the global sensitivity analysis of the static resistance of a beam under major axis bending. The presented geometrically and materially non-linear FE model based on solid elements models in detail the LTB and the effects of initial imperfections on the ultimate limit state of a steel beam. Simulation runs of random imperfections are generated using the Latin Hypercube Sampling (LHS) method. Polynomial approximation of the model output helped minimise the number of runs of the non-linear finite element model. The approximation polynomial then facilitated the evaluation of sensitivity indices using a high number of simulation runs. The relationships between the slenderness and the first and second-order sensitivity indices are plotted in graphs. The graphs show the results of global sensitivity analyses of stochastic effects of initial imperfections and residual stress on the resistance of the investigated steel beam.

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ABSTRACT: This paper proposes a new type of buckling-restrained brace (BRB), the so-called corrugated-web connected buckling-restrained brace (CWC-BRB), which is a core-separated BRB. The external restraining system of the CWC-BRB is composed of two all-steel external tubes connected by either single or double sinusoidal corrugated webs. Each of the two cores of the CWC-BRB has a single steel plate section and an extended projection at each end of the CWC-BRB, and the two core projections at each end are connected by a core stiffener. The external restraining systems, corrugated webs, two cores and core stiffeners form a firm and robust I-section CWC-BRB, and the flexural stiffness and load-carrying capacity of the proposed steel CWC-BRB are much larger than those of ordinary single-cored steel BRBs. The elastic buckling load of the CWC-BRB is derived by considering the shear deformation of the corrugated webs in the external restraining system. The ultimate load-carrying capacity under monotonic axial compression of CWC-BRBs and their hysteretic and low-cycle fatigue performance under repeated compressive-tensile cyclic loads are investigated using a shell element FE model. In addition, the effect of the restraining ratio or normalized slenderness ratio on the load resistance and failure mode of a CWC-BRB is explored. To further investigate the hysteretic performance and corresponding failure modes of CWC-BRBs and to validate the FE model, experimental studies are reported on four CWC-BRB specimens: two having a single sinusoidal corrugated web and other two having double sinusoidal corrugated webs. It is shown that the FE model provides excellent correlations with experimental results.

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ABSTRACT: An analytical method to predict the thermal buckling of simply supported and clamped-clamped FGM box beams is presented in this paper. By means of Galerkin’s method, a new expression of the critical moment inducing lateral buckling for simply supported beams under thermo-mechanical loads is established. The beam thermo-mechanical properties are graded along the wall thickness according to a power law of the porous volume fraction. The critical temperature gradients given by the present method are compared to those provided by the commercial FEM code Abaqus, and the difference among the results is quite small. To investigate the effects of temperature and porosity on the instabilities of beams, some numerical examples are presented.


ABSTRACT: Conical vessels are used around the globe for liquid storage in water tanks. These vessels can be made of steel, reinforced concrete, or composite; i.e. concrete and steel. Composite vessels consist of an external steel shell attached to an internal reinforced concrete wall through steel studs. Previous studies available in the literature focused on studying steel or reinforced concrete vessels. To the best of the author’s knowledge, this paper presents the first comprehensive study conducted on liquid-filled composite tanks. A Finite Element Model for Composite tanks (CFEM), which accounts for both the geometric and material nonlinearities, is developed. The material nonlinearity is considered by including nonlinear models for both steel and concrete. The developed CFEM also considers nonlinear behaviour of studs by including the nonlinear load-slip and load-peel curves obtained from test results reported in the literature. In the CFEM, both the concrete and steel walls are modelled using 13-node subparametric shell elements, while the connecting studs between the two walls are modelled using 26-node contact elements using a smearing approach. Validation of the CFEM is conducted by modelling two composite slabs from the literature and comparing the results with their counterparts obtained from the conducted experiments. The CFEM is used to evaluate the deflections, stresses, and internal forces in the concrete and steel walls as well as steel studs. An Equivalent Section Method (ESM) for the analysis of composite tanks, which is based on using an equivalent single wall, is introduced. Deflections, stresses, and internal forces in the steel and concrete walls predicted using this simplified approach are compared to those predicted by the detailed finite element model.

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ABSTRACT: During the 2011 Great East Japan earthquake occurring at the north-east pacific region, serious secondary disasters caused by collision of drifting containers or ships occurred in various structures when tsunami came. Disaster deterioration caused by earthquake and drifting object impact during earthquake and tsunami has become another problem. This study presents an effective method to evaluate the accumulative response of steel bridge under earthquake and large drifting object impact due to tsunami flow, and the earthquake and tsunami come from the same fault motion. The main innovation has to do with the quantification of the earthquake effect and the ship-impact effect due to earthquake-induced tsunami directly into ductility demands, a phenomenon which has not been studied in the past. A series of seismic response analysis and impact analysis are carried out, and damage to the main tower of bridge is evaluated by means of elastic-plastic finite element analysis. This study shows that piers of main tower of bridge can be severely damaged due to the earthquake and ship impact effect compared to only impact effect. An effective evaluated method that could be useful for evaluating damage of lifeline engineering under such mega earthquake and tsunami is proposed.

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ABSTRACT: In this study, various retrofit methods for concrete columns with non-seismic reinforcement details were developed and investigated: steel jacketing, carbon fiber reinforced polymer (CFRP) wrapping, concrete jacketing with non-shrinkage mortar, and new concrete jacketing with amorphous metallic fiber (AMF) reinforced concrete. Eleven half-scale reinforced concrete columns including two different control specimens, which were designed to fail in shear or flexure-shear, and nine retrofitted specimens were fabricated and tested under cyclic loading, simulating earthquake loading combined with axial loading. Two different retrofit strategies were applied to the control specimens: partial retrofit in the plastic hinge zone, mainly aiming at increasing deformability, and full retrofit in the entire range of columns, aiming at increasing both shear strength and deformability. The seismic capacity of the test specimens was analyzed in terms of various factors: load–drift relationship, dissipated energy, damping ratio, effective stiffness, and ductility. The test results showed that the retrofitted specimens presented ductile failure mode and enhancement in the dissipated energy and the damping ratio, but the effect differed for each retrofit method. Furthermore, based on the test results, the variables (or conditions) used to define the modeling parameters of the nonlinear analysis specified in ASCE 41-13 were modified in order to use the parameters of nonlinear analysis after retrofitting the columns. In addition, the nonlinear load-deformation curves established based on the modified conditions were compared with the test results.


ABSTRACT: Traditional civil structures with yielding systems can be subjected to damage and permanent deformation through major earthquakes, which may induce substantial post-earthquake repair costs and is a critical issue for performance-based seismic design. A novel capped column with an elastic buckling mode jump (BMJ) mechanism is introduced as an economical passive alternative for obtaining flag-shaped hysteretic damping, self-centering and reusability in seismic design. A simple analytical model for the BMJ mechanism is
derived and verified with finite element model simulation results for a variety of capped column geometric configurations. Using the validated analytical model, a parametric study is conducted on the geometric properties to provide design guidance. A practical passive self-centering hysteretic damping brace design is also provided in this paper, based on a combination of multiple BMJ mechanisms. The seismic performance of a 3-story frame building under a suite of 20 earthquake ground motions with BMJ brace is compared with a buckling-restrained brace (BRB) frame system as well as a conventional brace (CB) frame system. The results demonstrate the potential of a brace system utilizing BMJ mechanisms to outperform BRB and CB by achieving acceptable inter-story drift response without sustaining residual drift.

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ABSTRACT: Due to the booming of the winery industry in some seismic countries such as, the U.S, Italy, New Zealand, Chile and Argentina, the seismic protection of wine storage tanks may be of a practical importance. Wine storage tanks are classified in two major groups: continuously supported tanks and legged tanks. Previous research has described the seismic reliability of continuously-supported tanks, with and without seismic protection devices. Conversely, the seismic reliability of legged wine tanks has not been reported. Therefore, in this study, the seismic reliabilities of two typical stainless steel legged wine storage tanks (one of 3000 L capacity and one of 17,100 L capacity), used for fermentation and wine storage, in original and updated states are assessed by means of simulation. For the updated state, a non-linear isolation system for seismic isolation of legged wine tanks is used. The effect of the isolation system was numerically estimated by performing a group of non-linear time history analyses for each tank. Each non-linear time history analysis was obtained by means of a mathematical model. A set of different seismic ground motions was used for the purpose of obtaining robust results in the reliability analysis. Finally, the seismic reliability analysis shows that, for steel legged wine storage tanks, the effect of the isolation system would reduce the limit state probability in the order of 90%.

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ABSTRACT: Recently, there have been many attempts all over the world to reduce the own weight of the superstructure of the bridges, as well as reducing the work and cost involved in construction. One attempt is to utilise the tapered (i.e. non-prismatic with varying depth) steel plate girders with corrugated webs (TPGCWs). The corrugated steel plates are widely used as structural elements in many structural applications because of their numerous favourable properties compared with traditional flat plates. Moreover, they have been used due to their aesthetical appearance, especially in the case of TPGCWs. On the other hand, the use of high strength steels (HSSs) has gained greater commercial interest over the last decades. The capabilities of these HSSs allow obtaining smaller structural parts and slender sections and less weight without compromising security. Hence, the present paper combines the advantages of the tapered corrugated webs and the HSSs by investigating the strength and behaviour of the TPGCWs built with HSSs. The corrugated webs considered in this finite element (FE) analyses have practical dimensions similar to those used in available bridges with corrugated webs.
Accordingly, a nonlinear modelling, using the ABAQUS programme, was conducted on TPGCWs after validating the FE models through comparisons with the experimental results available in literature. Parametric study was, then, performed on TPGCWs to study their behaviour under shear loading using HSSs. Finally a new equation was proposed for calculating the ultimate shear strength of TPGCWs. Overall, this investigation expands the available engineering knowledge and assists in utilising the HSS, currently used in a wide range of applications, with the TPGCWs with their favourable aesthetical and structural characteristics.

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ABSTRACT: Concrete filled steel tube (CFST) columns are deployed as the main load carrying members in high performance structures as they integrate the beneficial properties of constituent materials. In recent years, there has been an increased interest in the literature to further improve the performance of the CFST columns. The work presented in this paper, for the first time, investigates through experimental and statistical analyses the potential of concrete filled double circular steel tube (CFDCST) columns to improve the efficiency of the composite members. Experimental results validated the capability of CFDCST columns in performing high strength, stiffness and ductility properties which can be utilized in challenging design scenarios. Employed statistical analysis characterized the impact of parameters on the collapse performance of the CFDCST column. To establish whether the configuration of CFDCST members could be used in repairing process of highly stressed and deformed CFST columns, a further set of experimental work was undertaken. Deformed CFST stub columns were centred in a larger diameter steel tube and the region between the existing CFST column and the larger diameter tube was filled with concrete. Repaired forms of the columns were tested and the performances were compared against the performances of the CFDCST counterparts. Results show that it is possible to employ such a repairing, since the repaired CFST columns exhibit performances very close to that of CFDCST counterparts. The findings are quite revealing for design purposes and have important implications for advancing the knowledge on composite compression members.

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ABSTRACT: An experimental investigation of the behaviour of composite reinforced-concrete/steel beams with corrugated webs under flexure is presented in this paper. This study focuses on the effect of a top steel flange on the failure mechanism of a composite concrete/steel beam. Accordingly, four full-scale composite concrete/steel beams are fabricated and tested. Two beams have concrete and steel flanges that consist of shear connectors. The other beams have concrete-only flanges with shear connectors and additional steel mesh. All specimens are loaded at points dividing the beam length into thirds. Consequently, the zero shear and constant moment regions are created by this loading distribution in the middle third of the specimens. Both the local and global failure mechanisms are influenced by the top steel flange composition. Moreover, the effects of the top
steel flange on the beam stiffness, ultimate load, local buckling of the corrugated web, concrete slip, and failure mechanism of the concrete slab are discussed.

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ABSTRACT: Extensive experimental and theoretical studies have been conducted on the compressive strength of concrete-filled steel tubular (CFST) columns, but little attention has been paid to their compressive stiffness and deformation capacity. Despite this, strength prediction approaches in existing design codes still have various limitations. A finite element model, which was previously proposed by the authors and verified using a large amount of experimental data, is used in this paper to generate simulation data covering a wide range of parameters for circular and rectangular CFST stub columns under axial compression. Regression analysis is conducted to propose simplified models to predict the compressive strength, the compressive stiffness, and the compressive strain corresponding to the compressive strength (ductility) for the composite columns. Based on the new strength prediction model, the capacity reduction factors for the steel and concrete materials are recalibrated to achieve a target reliability index of 3.04 when considering resistance effect only.

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ABSTRACT: Torsion and bending/torsion buckling may occur for compressed thin-walled open profiles used in engineering and architecture applications. We report experimental results provided by PZT pickups stuck on thin-walled aluminium beams with open modified cruciform cross-section, exhibiting non-zero warping stiffness. The buckling loads and the natural frequencies corresponding to various compressive forces were detected for free and (at least partially) restrained warping of the ends of the specimens. The results are compared with those of a FEM (commercial) and an in-house numerical code that examines the stability of non-trivial equilibrium paths in a dynamic setting. The results seem new and confirm that: (a) PZT pickups can be efficient in extracting modal parameters of thin-walled beams; (b) the numerical simulations are robust and accurate in finding the buckling loads in all analyzed configurations.

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ABSTRACT: This contribution contains the results of experimental measurements and modelling of torsional warping free vibrations of beams with rectangular hollow cross-sections. The experimental results are compared with results from a semi-analytical method, proposed by the authors, and from Finite Element (FE) computations by means of a standard commercial code. In these calculations, beam, solid, and shell elements are used. The semi-analytical calculations are based on the analogy between second-order beam theory, including consideration of the shear force deformation effect, and non-uniform torsion, considering the Secondary Torsion Moment Deformation Effect (STMDE). The influence of warping and of the STMDE on the torsional eigenfrequencies and eigenforms is evaluated. The difference between the measured and calculated eigenfrequencies is investigated and quantified.


ABSTRACT: In this paper, the modified Mindlin theory is used for the construction of the dynamic stiffness matrix, the flexibility matrix, and the transfer matrix of a thick plate simply supported at two opposite edges. The modified Mindlin theory operates with bending deflection as the basic variable for the determination of the total (bending + shear) deflection and the angles of rotation. It is shown that the appropriate application of the constructed matrices to various boundary conditions leads to a determined formulation of the eigenvalue problem. As a result, the problem can be treated using ordinary algorithms for linear eigenvalue problems. Therefore the application of the relatively complex Wittrick-Williams algorithm, developed for the transcendental eigenvalue problems with the unusual forms of non-zero determinant is avoided. Using this technique, dynamic finite elements can be obtained in a simpler form than that based on the application of the conventional Mindlin theory. All phenomena related to the dynamic finite element application are investigated in the case of an axial bar vibration in a transparent analytical way. Furthermore, the application of the developed thick plate elements is illustrated through several numerical examples. Examples include using single elements as well as an assembly of elements. In the examples of single elements transcendental eigenfunctions are derived. Also a dynamic beam finite element is considered as a special case of the plate finite strip which exhibits no variation in the transverse direction.

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ABSTRACT: Concrete-filled steel tube columns with solid steel core are increasingly used in high-rise building practice due to their high load-bearing capacity and exceptional structural fire behavior. Simulating the structural fire behavior of these innovative composite columns by means of advanced numerical models is a promising tool to achieve an enhanced understanding of the basic thermo-mechanical behavior observed in costly full-scale fire tests, and eventually, to partially replace them. Moreover, the data necessary for the development of a simplified fire design method can be compiled from a parametric study with such models. This paper presents an advanced nonlinear Finite-Element-Method model that incorporates complex experimental calibration data and therefore can robustly simulate various full-scale fire tests of this type of composite columns. Furthermore, tracking in the model the load share redistribution processes between the different components, confirms the innovative design concept of the structural fire behavior of this type of composite column. Finally, a simplified model version that qualifies for partial replacement of full-scale fire tests or use in both a parametric study and advanced structural design is presented and conditionally validated.

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ABSTRACT: This paper analyzes lateral-torsional buckling (LTB) of elastic beams with rectangular cross section having constant thickness, and depth symmetric with respect to the midpoint and tapered linearly in each half with smallest depth at the midpoint. This type of butterfly-shaped beam is used as a shear link in steel plates that serve as structural fuses to reduce the seismic response of buildings. LTB has been observed in previous quasi-static tests and found to be a critical limit state. The ends of the beam are prevented from twisting and can be assumed to be pinned with respect to bending in the weak direction. Numerical results are obtained for LTB of butterfly-shaped beams with the use of a shooting method assuming uniform torsion. Pure bending, reversed moments, and end moments with unequal magnitudes are investigated first. A compressive load is included next, and interaction curves for combinations of critical moment (squared) versus axial load are determined. Finally, the effect of in-plane shear deformation on LTB is examined. Plots showing the influence of various parameters are presented, along with some analytical approximations for the critical moment in terms of geometric and material quantities.

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ABSTRACT: A new type of core-separated buckling-restrained braces, namely a core-separated battened buckling-restrained brace (B-BRB) has been proposed. Its load-carrying capacity and hysteretic response are investigated theoretically and experimentally in this paper. The B-BRB has a remarkable advantage over a common buckling-restrained brace (BRB), in which the newly formed cross-section of the B-BRB is spread outwards by spacing two cores, hence resulting in higher material utilization efficiency in its structural design. In addition, the two independent all-steel BRBs, each having a single plate core simply in-filled in a narrow hollow section, are connected by longitudinally distributed battens rather than continuous plates. Based on the elastic-plastic FE analysis of a B-BRB under monotonic compressive load, its ultimate resistance and failure
modes are investigated numerically, considering the effect of its overall initial geometric imperfection. An interaction formula between normalized slenderness ratio and buckling factor of the B-BRB is proposed for predicting its ultimate load-carrying capacity. Consequently, the hysteretic response of the B-BRB is explored through elastic-plastic FE analysis. The maximum normalized slenderness ratios of the B-BRBs required for a load-bearing type and an energy-dissipation type are proposed in their strength designs, respectively. Ultimately, hysteretic responses of five B-BRB specimens have been experimentally investigated. The experimental results are compared with the FE numerical analysis, which considers plate local buckling of all components of the B-BRBs. The comparison has verified the rationality of the proposed design method.

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ABSTRACT: The use of high strength concrete and steel have significant advantages for composite members subject to significant compression as in the cases of high-rise buildings. Current design codes place limits on the strengths of steel and concrete due to limited test data and experience on the behaviour of composite members with the high strength materials. To extend their applications, a comprehensive experimental program has been carried out to investigate the behaviour of concrete filled steel tubes (CFSTs) with high- and ultra-high-strength materials at ambient temperature. This article presented some new findings on the axial performance of 56 short CFSTs. High tensile steel with yield strength up to 780 MPa and ultra-high strength concrete with compressive cylinder strength up to 190 MPa were used to prepare the CFST test specimens. The key issue is to clarify if the plastic cross-sectional resistance could be used at ultimate limit state as for CFSTs with the normal strength materials. To address this, experimental and analytical methods were adopted where the test results were compared with the predictions by various design codes world widely, and design recommendations were therefore proposed so that the prediction methods could be safely extended to the short CFSTs with the high- and ultra-high-strength materials.


ABSTRACT: Analytical, finite element and experimental analyses of thin butt-welded plates are performed for estimating thermal field, distortions and residual stresses. The existing empirical equations for the maximum distortion amplitudes are evaluated and new relationships are developed to estimate the distortion and residual stress spatial distributions on the thin butt-welded plates. To validate the newly developed equations, experimental test results and finite element analyses are used. The validation confirms that the developed relationships are in a good agreement with the collected experimental results and finite element analyses, representing common shipyard welding conditions. In addition, different thicknesses of thin plates are numerically investigated to validate the accuracy level of the new regression equations.

ABSTRACT: The recent experimental results and proposed strut-and-tie model (STM) for deep beams reinforced entirely with glass-fiber-reinforced polymer (GFRP) bars have suggested that a comprehensive examination is required to improve the strut efficiency factor and its affecting parameters. This study uses nonlinear finite-element analysis (FEA) to perform an in-depth investigation. FEA response was compared against the experimental results in terms of crack patterns, failure modes, strains in reinforcement and concrete, and load–deflection relationships. The results show that the simulation procedures employed were stable and compliant, and that they provided reasonably accurate simulations of the behavior. FEA was used to confirm some hypotheses associated with the experimental investigations. A comprehensive parametric study was conducted to investigate the effect of web reinforcement and loading-plate size on the strut efficiency factor. It was shown that vertical web reinforcement has no clear effect on the strength, but it is required for crack control. On the other hand, horizontal web reinforcement should be accompanied with vertical reinforcement. Loading-plate size showed a clear effect on the deep-beam strength. Based on the numerical simulation results, a modification to a recently proposed STM is suggested. The modified STM was compared to available STMs in design codes and provisions, yielding better correlation with experimental results.

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ABSTRACT: This paper presents a method for the second-order elastic and stability analyses of a corroded tubular member with initial geometric imperfections, resting on a two-parameter elastic foundation. It is assumed that the member is a simply supported Euler–Bernoulli beam-column with a corroded, yet compact cross section. Corrosion is modeled as symmetric loss of wall thickness that varies in magnitude along the member length. Moreover, the member is loaded both axially, transversely and simultaneously subjected to internal and external pressures. Despite all the effects considered herein, this model neglects the effects of thermal loads and torsion, as well as shear and axial deformations along the member. The fourth-order boundary value problem that governs the second-order elastic behavior of the tubular member is solved using the Galerkin method. The proposed method and corresponding equations are used to obtain the second-order transverse deflections, as well as the bending moment and shear force diagrams. This method is also used to estimate the buckling load and compressive strength of the tubular member, which play an important role in the design of tubular structures. The accuracy and effectiveness of the aforementioned formulation are evaluated using four comprehensive examples. The results from the examples demonstrate that the proposed method can be used in the analysis and design of submerged or non-submerged tubular members at a low computational cost.

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ABSTRACT: Based on investigation of recent strong earthquakes, there is a potential that BRBs may rupture during a strong earthquake or subsequent repeated aftershocks. This study aims to propose a novel type of light-weighted all-steel dismountable BRB with fish-bone shaped core plate, which is termed FB-BRB in this paper. The FB-BRB consists of a core plate, two filling plates, two restraining plates and un-bonding material. Deformation capacity of the proposed FB-BRB is to be maximized by generating several necking locations at the core plate, and details to avoid strain concentration at stoppers are also proposed. Experimental study is carried out using four scaled specimens with different configurations. Favorable seismic performance is obtained through comparison with that of a conventional BRB. The failure mechanisms of the newly proposed FB-BRBs are also further verified through numerical study using a combination of a ductile fracture model and a cyclic plasticity model, where further improvement is required to fully achieve the expected deformation mechanism.

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ABSTRACT: This paper theoretically studies the mechanical behavior of buckling restrained steel plate shear walls (BRSPSW) with two-side connections and various height-to-width ratios. A concept of boundary restraining region at the edges of steel plates is proposed. Due to the restraining from the boundary restraining region, the middle portion of the steel plate is in pure shearing which is equivalent to the BRSPSW with four-side connections. The stress development in the BRSPSW with two-side connections is studied and a simplified formula is deduced to determine its load-bearing capacity. The results show that the steel plate with a small height-to-width ratio (<1.5) has a middle shearing region and boundary restraining regions at the left and right edges with a width of 1/3 of the height of steel plate. No middle shearing region occurs in BRSPSW with large height-to-width ratios (≥1.5). It is found that the yielding region in BRSPSW with small height-to-width ratios is in an I shape and has a flange height of 1/10 of the height of the steel plate. For BRSPSW with small height-to-width ratios, the beam connected to the steel plate is subjected to shear forces at the middle imposed by the shearing region of the steel plate, and tensile or compressive force at ends by the boundary restraining region of the steel plate. For BRSPSW with large height-to-width ratios, only vertical tensile or compressive forces are transferred from the steel plate to the beam. The accuracy of the proposed formula for calculating the load-bearing capacity of BRSPSW is verified by comparing the numerical results, since the differences are within 10%.

Guan Quan, Shan-Shan Huang and Ian Burgess (Department of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, United Kingdom), “The behaviour and effects of beam-end buckling in fire using a component-based method”, Engineering Structures, Vol. 139, pp 15-30, May 2017
https://doi.org/10.1016/j.engstruct.2017.01.076
ABSTRACT: A combination of beam-web shear buckling and flange buckling at the ends of steel beams is very commonly observed during full-scale fire tests. This can affect the behaviour of the steel beams, as well as on their adjacent connections, under fire conditions. This phenomenon has not previously been sufficiently investigated and cannot be simulated in high-temperature global frame analysis, which could potentially lead to unrealistic results being used in structural fire engineering design. In this research, a component-based beam-end buckling element has for the first time been created for Class 1 and 2 beams. The beam-end buckling element is composed of nonlinear springs, respectively representing the buckling of beam flange and web, also considering the interaction between these two buckling phenomena. Each spring is able to deal with loading-unloading-reloading force-deformation paths. A significant challenge is to enable the flange buckling spring to deal with post-buckling deformation reversal. The buckling element has been implemented into the structural fire engineering frame analysis software Vulcan, to be used adjacent to existing connection elements in frame modelling. The buckling element has been verified against ABAQUS finite element modelling on isolated beams. It is shown that the newly created component-based buckling element is able to simulate the effects of beam-end shear buckling in the web and local buckling of the bottom-flange, with satisfactory accuracy. The influence of the buckling element on the bolt-row force distribution within the adjacent connection element has been investigated. Analyses using isolated beams indicate that the implementation of the buckling element considerably improves the prediction of connection force resultants. A general observation from numerical studies with and without the buckling element is that beam-end buckling seems to reduce the connection component forces generated at elevated temperatures.

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“Effects of edge-stiffened circular holes on the web crippling strength of cold-formed steel channel sections under one-flange loading conditions”, Engineering Structures, Vol. 139, pp 96-107, May 2017
https://doi.org/10.1016/j.engstruct.2017.02.042
ABSTRACT: Cold-formed steel sections are often used as wall studs or floor joists and such sections often include web holes for ease of installation of services. The holes are normally punched or bored and are unstiffened; when the holes are near to points of concentrated load, web crippling can be the critical design consideration. Recently, a new generation of cold-formed steel channel sections with edge-stiffened circular holes has been developed, for which web crippling may not be so critical. In this paper, a combination of experimental investigation and non-linear elasto-plastic finite element analyses are used to investigate the effect of such edge-stiffened holes under the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions; for comparison, sections without holes and with unstiffened holes are also considered. A total of 90 results comprising 36 tests and 54 finite element analysis results are presented. Owing to manufacturing constraints, in the test programme, the edge-stiffener length was fixed at 13 mm. Good agreement between the experimental and finite element results was obtained. For the case of the unstiffened hole, it is shown that the web crippling strength is reduced by up to 12% and 28% for the IOF and EOF loading conditions, respectively. However, with the edge-stiffened circular hole, the web crippling strength is only reduced by 3% for the IOF loading condition and there is no reduction in strength for the EOF loading condition. The finite element model was used for the purposes of a parametric study on the effects of different hole sizes, edge-stiffener length and distances of the web holes to the near edge of the bearing plate. The results indicate that with a suitable edge-stiffener length,
the web crippling strength of cold-formed steel channel section with holes can be as high as the one without holes.

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ABSTRACT: In current structural stainless steel design codes, local buckling is accounted for through a cross-section classification framework, which is based on an elastic, perfectly-plastic material model, providing consistency with the corresponding treatment of carbon steel cross-sections. Hence, for non-slender cross-sections, the codified design stress is limited to the 0.2% proof stress without considering the pronounced strain hardening exhibited by stainless steels, while for slender cross-sections, the effective width method is employed without considering the beneficial effect of element interaction. Previous comparisons between test results and codified predictions have generally indicated over-conservatism and scatter. This has prompted the development of more efficient design rules, which can reflect better the actual local buckling behaviour and nonlinear material response of stainless steel cross-sections. A deformation-based design approach called the continuous strength method (CSM) has been proposed for the design of stocky cross-sections, which relates the strength of a cross-section to its deformation capacity and employs a bi-linear (elastic, linear hardening) material model to account for strain hardening. In this paper, the scope of the CSM is extended to cover the design of slender stainless steel cross-sections under compression, bending and combined loading, underpinned by and validated against 794 experimental and numerical results. The proposed approach allows for the beneficial effect of element interaction within the cross-section, and is shown to yield a higher level of accuracy and consistency, as well as design efficiency, in the capacity predictions of slender stainless steel cross-sections, compared to the effective width methods employed in the current international design standards. Non-doubly symmetric sections in bending, which may be slender, but still benefit from strain hardening, are also discussed. The reliability of the CSM proposal has been confirmed by means of statistical analyses according to EN 1990, demonstrating its suitability for incorporation into future revisions of international design codes for stainless steel structures.

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ABSTRACT: This paper presents an investigation on the nonlinear bending and thermal postbuckling behaviors of nanocomposite beams in thermal environments and supported by an elastic foundation. Graphene-reinforced
composite (GRC) material is used for the beams with piece-wise functionally graded (FG) graphene reinforcement along the thickness direction of the beams. A refined micromechanical model is applied to estimate the material properties of GRCs and the effect of temperature is included in the model. The governing equations of a GRC beam are based on a higher third order beam theory with the effect of temperature variation and foundation interaction and the von Kármán geometric nonlinear strain terms are also considered. Applying a two-step perturbation technique, the governing equations of the GRC beams are solved to determine the nonlinear bending load-deflection curves and the thermal postbuckling equilibrium paths of the beams. The effects of the graphene reinforcement distribution, laminate layer stacking sequence, temperature variation and foundation stiffness on the nonlinear bending and thermal postbuckling behaviors of the beams are discussed in details.

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ABSTRACT: In nonlinear structural analysis, shear walls within whole-system models are often modeled using a spring model with a single degree of freedom where the lateral stiffness of the shear wall is modeled as a nonlinear spring. The stiffness of the spring is often described by the hysteretic relationship between the lateral restoring force and shear wall lateral deformation. In this study, a new shear element is introduced, which couples the lateral and vertical stiffness of the shear wall. This new shear element is able to better describe the behavior of shear walls in mid-rise and tall buildings. An illustrative example is presented to help explain the application of the new shear element in finite element modeling. In the examples, the new shear element is used to calculate displacement and internal forces for cold-formed steel frames. The results show that without including vertical wall stiffness, the lateral displacement is significantly underestimated. The difference increases with the height of the building and for a ten-story frame the new model demonstrates an increased lateral displacement at roof level of 64.1% when compared with current typical shear element model (lateral stiffness only).

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“Nonlinear free vibration of functionally graded polymer composite beams reinforced with graphene nanoplatelets (GPLs)”, Engineering Structures, Vol. 140, pp 110-119, June 2017
https://doi.org/10.1016/j.engstruct.2017.02.052
ABSTRACT: This paper studies the nonlinear free vibration of a multi-layer polymer nanocomposite beam reinforced by graphene platelets (GPLs) non-uniformly distributed along the thickness direction. Theoretical formulations are based on Hamilton’s principle, Timoshenko beam theory, and von Kármán nonlinear strain-displacement relationship. The effective Young’s modulus of the GPL/polymer composites is estimated by Halpin-Tsai micromechanics model to account for the effects of GPL geometry and dimensions. The vibration frequencies and amplitude of the beam are obtained numerically by employing Ritz method. The influences of the distribution pattern, weight fraction, geometry and size of GPL nanofillers, the total number of layers
together with the vibration amplitude and boundary conditions on the nonlinear free vibration behavior are investigated. The results show that adding a very small amount of GPLs into polymer matrix as reinforcements significantly increases the natural frequencies of the beam. Using larger sized GPLs with fewer single graphene layers and placing more GPLs near the top and bottom surfaces of the beam are the most effective ways to strengthen the beam stiffness and increase the linear and nonlinear natural frequencies.

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ABSTRACT: Rectangular concrete-filled stainless steel tubular (CFSST) beam-columns utilized as supporting members for building frames may experience axial compression and biaxial moments. A numerical simulation considering the local buckling effects for thin-walled rectangular CFSST slender beam-columns has not been performed. This paper reports a stability modeling on the structural characteristics of rectangular CFSST slender beam-columns accounting for different strain-hardening of stainless steel under tension and compression. The influences of local buckling are considered in the simulation utilizing the existing effective width formulations. The developed numerical model simulates the strength interaction and load-deflection behavior of CFSST slender beam-columns. Comparisons of computed results with test data provided by experimental investigations are performed to validate the proposed fiber model. The influences of different geometric and material property on ultimate strengths, ultimate pure moments, concrete contribution ratio, strength interaction and load-deflection responses of CFSST slender beam-columns are examined by utilizing fiber model. A design formula considering strain hardening of stainless steel is derived for calculating the ultimate pure moment of square CFSST beam-columns.

ABSTRACT: The rotational behavior of the web-flange junctions (WFJs) of a pultruded glass fiber-reinforced polymer (GFRP) bridge deck system with trapezoidal cell cross-sectional geometry was investigated. The rotational response of three WFJ types, in two bending moment directions each, was characterized. An experimental procedure based on three-point bending and cantilever experiments conducted on the web elements and simple analytical models was used. The WFJs generally exhibited non-rigid and nonlinear behavior. The overall moment-rotation relationships, rotational stiffness, strength and failure modes differed depending on the web type, the location of the WFJ within the deck profile, the existing initial imperfections and the direction of the bending moment applied. This evidenced the relevance of separately characterizing the response of all WFJ types in the two possible bending directions. Simplified expressions to model the WFJ rotational behavior were derived. The validity of the experimental and idealized rotational responses was assessed by means of numerical simulations of full-scale experiments conducted on the GFRP deck.

ABSTRACT: The fire behaviour of composite columns made with concrete filled hollow sections under different structural boundary conditions was experimentally investigated and their results are presented and discussed in this paper. The main objectives of this research were therefore to investigate the influence of the section geometry, slenderness, section factor, boundary conditions, and stiffness of the surrounding structure to the thermal elongation of the columns on the structural performance of such columns exposed to fire. The critical time (fire resistance), the failure temperature distribution and the respective failure modes of the columns were then assessed. These experimental results were still compared with predictions from the currently European design rules (EN 1994-1-2:2005) in order to observe how unsafe they might be. Finally, results of this research study showed that circular composite tubular columns presented an enhanced fire performance, comparing to other sections (square and rectangular sections for instance). As the difference between the principal moments of inertia for the cross-section of a column increases, the effect of the boundary conditions in their fire resistance increases.

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ABSTRACT: Proposed herein is a simple but powerful method for optimization of inhomogeneous, elastically restrained columns against buckling when subjected to both compressive concentrated and distributed axial loads that include self-weight. Unlike previously published studies on the subject, we do not have to specify any prescribed geometrical variation and analysis may be readily performed on columns with any complex geometrical shape. In the proposed method, the differential equation governing the buckling of Euler columns is discretized by adopting the Hencky bar-chain model, and critical buckling loads are evaluated by seeking the lowest eigenvalue of the resulting system of algebraic equations. The discrete nature of the formulation, as well as the reduced number of parameters to be optimized, is well suited for the adopted optimization process that is based on evolutionary algorithms. We propose an optimization scheme based on a parallel genetic algorithm. A comparison study between the obtained optimal column shape and buckling loads on homogeneous and isotropic columns with circular cross section, and the numerical and analytical solutions found in the open literature shows fast convergence, high accuracy and flexibility of the proposed method.

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ABSTRACT: Wood, as a naturally-grown material, exhibits a highly anisotropic and inhomogeneous material structure, with a complex wood fibre distribution influenced by randomly occurring knots. Thus, for the prediction of effective strength properties of wood, advanced computational tools are required, which are able to predict as well as consider multidimensional strength information at different scales of observation. Within this work, three such computational methods will be presented: an extended finite element approach able to describe strong strain-softening and, thus, reproduce brittle failure modes accurately; a newly-developed limit analysis approach, exclusively describing ductile failure; and an elastic limit approach based on continuum micromechanics. All three methods are applied to earlywood and latewood unit cells and to clear wood, finally yielding effective failure surfaces for a range of multidimensional stress states. These failure surfaces are compared with each other and with experimental results from biaxial tests. Based on these comparisons, the strengths and weaknesses of the three computational methods are discussed, and their applicability to wood is evaluated. The extended finite element method is a powerful technique that allows for a very realistic description of strength-governing processes. Nevertheless, its complexity and high computational effort prevent widespread use in the engineering field. The plastic limit analysis and elastic limit approaches, however, show good predictive performance compared with the extended finite element method, coupled with excellent efficiency and stability. In this study it is found that together, the latter two approaches are able to enclose the experimentally-obtained failure regions for clear wood almost perfectly, while also delivering new insights with respect to the ductile failure potential of wood. The conclusion can be drawn that there exist promising computational methods that are capable of delivering reliable multidimensional strength information for wood and, subsequently, will enable effective strength predictions for wooden boards and wood-based products. Finally, this work is intended as a contribution to performance-based optimisation of wooden structures, a necessity for wood to become competitive with respect to other building materials.

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ABSTRACT: This paper presents an analytical study on seismic performance of special concentrically braced frames (SCBFs) with and without brace buckling. It demonstrates that the collapse prevention goal needs attention in modern buildings using SCBFs as main seismic-force-resisting systems, and an simple and low-cost solution is possible to achieve this goal. Typical 6-story buildings using two-story X-braced frames with strong and weak braced-intersected beams and inverted V braced frames with and without brace buckling were subjected to a set of 15 earthquake ground motions, and resulting seismic responses were discussed in terms of seismic strength and deformation demands on braces, beams and columns. The study finds that the braces in SCBFs often fracture prior to 2% story drift ratio response, particularly in the popular two-story X-braced frames with weak beams, mainly due to premature yielding of the beams. The buckling-controlled braced frames (BCBFs) are shown to be a cost-effective system to improve the seismic performance of SCBFs. The analysis indicates that the buckling-controlled braces may substantially reduce story drift response, eliminate weak beam yielding, and prevent braces from fracturing.
ABSTRACT: This paper examines the dynamic behaviour of collar plate reinforced tubular T-joints with precompression chord by means of experimental and numerical studies. An experimental programme involved one test on unstiffened tubular T-joint and three on stiffened configurations is carried out through a high-performance drop hammer machine. A series of disc springs is installed to apply axial compression to the chord. The dynamic response of four tubular T-joints are described and discussed with emphasis on the effect of the stiffener, especially for dimensional parameters of collar plate. Based on the experimental results, the key behavioural patterns including the development of impact force, deformation and strain, as well as deformation modes are identified. The impact mechanism is also investigated. The finite element (FE) models of the tubular T-joints subjected to impact loadings are then developed by commercial software of ABAQUS, where nonlinear material behaviour and pre-compressive loads are all considered. The numerical findings exhibit close agreement with experimental results in terms of failure pattern as well as the development of impact force and the corresponding displacements. Finally, the dynamic performance of unreinforced and collar plate reinforced tubular T-joints is revealed based on the numerical simulation. Particularly, the joint deformation and impact resistance are examined by the equivalent area method and the formula in NORSOK Standard, respectively. In general, the presence of collar plate stiffeners significantly improves the impact resistance of tubular T-joints.

Hai-Ting Li and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Tests of cold-formed high strength steel tubular sections undergoing web crippling”, Engineering Structures, Vol. 141, pp 571-583, June 2017, https://doi.org/10.1016/j.engstruct.2017.03.051
ABSTRACT: This paper presents an experimental investigation of cold-formed high strength steel tubular sections undergoing web crippling. The tests were conducted on square and rectangular hollow sections of high strength steel with nominal 0.2% proof stresses of 700 and 900 MPa. The measured web slenderness values of the tubular sections ranged from 8.3 to 35.8. Tensile and compression coupon tests were conducted to obtain the material properties of the test specimens. The web crippling tests were conducted under the four loading conditions as specified in the North American Specification and Australian/New Zealand Standard for cold-formed steel structures, namely, the End-One-Flange, Interior-One-Flange, End-Two-Flange and Interior-Two-Flange loading conditions. It should be noted that the web crippling design provisions in these two specifications were mainly developed based on sections with web slenderness value greater than 40 and 0.2% proof stress less than 500 MPa. The test strengths obtained from this study were compared with the nominal strengths calculated from the North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel structures. Furthermore, the test strengths were also compared with the nominal strengths calculated from the Australian Standard AS4100. Reliability analysis was performed to assess the reliability of the design provisions in the aforementioned specifications. Generally, it is shown that the nominal strengths predicted by the codified web crippling design provisions are either unconservative or very
conservative. Hence, the existing codified design provisions are not appropriate for the cold-formed high strength steel square and rectangular hollow sections undergoing web crippling.

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ABSTRACT: This study investigates an innovative method of avoiding brittle fracture at the beam-column connection welds of steel moment frames in earthquakes. The reduced web section (RWS) approach introduces large openings into the web to shift the location of inelasticity away from the connections. The configuration of the openings governs the mode and capacity of inelastic mechanism in the beam. In this paper, experimental results are reported for five RWS specimens that were subjected to quasi-static cyclic loading. Four specimens were designed to develop Mode-A mechanisms; three had a single unique opening at midspan, and one had two openings near the beam-column connections. The other specimen was designed to develop a Mode-B mechanism without having web post buckling (observed in the Phase 1 specimens Shin et al., 2017), which had a wide opening and two brass plates clamped to the web. The application of web openings was successful in achieving the intended inelastic mechanisms; inelastic deformation was due to yielding, buckling, and/or fracture of the webs around the opening(s) and plastic hinging of the T-sections above and below the opening(s). The three specimens with a single opening at midspan exhibited the most stable load-drift responses; the specimens displayed a loss of strength during the 3 or 4% drift cycles (due to local buckling and/or fracture of the webs) and subsequent transition from “full” to “S-shaped” hysteretic loops, but they regained full strength by the end of testing at story drifts up to 7%.

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“Analytical investigation of buckling restrained braces’ applications in bidirectional ductile end diaphragms for performance of slab-on-girder bridge”, Engineering Structures, Vol. 141, pp 634-650, June 2017
https://doi.org/10.1016/j.engstruct.2017.03.034
ABSTRACT: The AASHTO Guide Specifications for Seismic Bridge Design includes provisions for the design of ductile diaphragms as Permissible Earthquake-Resisting Elements (ERE s) to resist seismic loads applied in the transverse direction of bridges. However, two major limitations for this system are that: (1) other lateral-load resisting strategies have to be combined with the transverse ductile diaphragms to address seismic excitations acting along the bridge’s longitudinal axis; (2) the existing AASHTO provisions (reflecting the limits of existing research) only apply to straight bridges and provide no guidance on how to implement ductile diaphragms in skew bridges. This paper investigates ductile end diaphragm systems (EDSs) inserted in the slab-on-girder bridge superstructure, with Buckling Restrained Braces (BRBs) arrayed in two different bidirectional configurations so as to provide bi-directional resistance. Benchmark skew and straight bridge models were designed with both EDSs and analyzed using nonlinear time history analysis method to examine their seismic performance. Variations in skew, fundamental period of vibration, and earthquake excitation characteristics
were considered. These dynamic analyses allowed investigating the impact of these parameters on global behavior, as well as understanding the magnitude of local demands and the extent of bidirectional displacements that the BRBs must be able to accommodate while delivering their ductile response. The long-term service life of BRBs installed across expansion joints and subjected to bridge thermal expansion histories was also studied and a minimum ratio of the BRB core length over the whole bridge length was recommended. For BRBs’ design and implementation in EDSs, these analytical results can help predict a regime of relative end-displacements representative of the BRB’s demands, when the bridge is subjected to both earthquake and temperature change in the superstructure.

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ABSTRACT: This paper studies the effect of structural dynamics on the response of an offshore wind turbine (OWT) supported by a jacket and subjected to wave loads. The study includes a series of time-domain dynamic analyses based on loading from regular and irregular wave histories and three example OWT support structures. The OWT support structures are proportioned to collectively span a broad range of the first fundamental period of an OWT supported by a jacket. For each dynamic analysis, a representative static analysis is also considered, and a dynamic amplification factor (DAF) is calculated and discussed as a function of wave height, wave regularity, and structural period. The results demonstrate that dynamic effects may amplify the structural response significantly for loading caused by smaller waves, but the amplification is minimal for loading caused by large waves, which have longer periods and, for the jacket geometry considered here, cause large wave-in-deck forces. For the specific scenarios and models considered in this paper, the structural period is found to have a small influence on the DAF.

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ABSTRACT: The objective of this paper is to examine the reliability of cold-formed steel framed shear walls with a particular emphasis on walls sheathed with wood structural panels. A sheathed cold-formed steel framed shear wall is a system consisting of studs, tracks, and sheathing often with bridging and/or blocking, connected with steel-to-steel and sheathing-to-steel fasteners. The shear walls may be integrally connected to foundations, floors, or other shear walls through a variety of means including hold downs, straps, diaphragm chords and collectors. Shear wall lateral resistance in cold-formed steel framed buildings varies because of the randomness in the components and connections that comprise the wall. The interaction between fasteners and sheathing is particularly important because (1) sheathing-to-steel fastener response is the main source of shear wall
nonlinearity (2) there is high variability in this fastener response. Although the nominal strengths for different shear wall configurations are stated in current design specifications (e.g., AISI S400), variability of shear walls has not been explicitly considered. Existing resistance factors are extrapolations from steel diaphragm testing. To explore the impact of fastener response variability on shear wall reliability, Monte Carlo simulation of typical cold-formed steel framed wood sheathed shear walls with random fastener input was conducted. Variability in fasteners was determined based on existing physical fastener tests. Statistical properties of shear wall strength, demand capacity ratio of key fasteners, as well as relations between fastener strength and shear wall strength are all explored. Reliability evaluation is provided for four different design methods. The results indicate that shear wall strength benefits from a system effect whereby variability in fastener response is reduced through redistribution resulting in reduced variability in overall shear wall strength. Concomitant with this is a slight decrease, approximately 3%, in the mean system strength that also must be considered.

Shi-Dong Nie, Shao-Bo Kang, Le Shen and Bo Yang (Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing 400045, China; School of Civil Engineering, Chongqing University, Chongqing 400045, China), “Experimental and numerical study on global buckling of Q460GJ steel box columns under eccentric compression”, Engineering Structures, Vol. 142, pp 211-222, July 2017, https://doi.org/10.1016/j.engstruct.2017.03.064

ABSTRACT: This paper describes an experimental and numerical study on the global buckling behaviour of welded Q460GJ steel box columns subject to eccentric compression. Eight box columns with various cross sections, slendernesses and eccentricities were tested in the experimental programme. All columns exhibited global buckling with significant lateral deflections. Comparisons were made between test data and design values calculated from different design codes. Besides, numerical models were developed in which initial geometric imperfections and residual stresses were considered. The model was verified by experimental results and reasonably good agreement was obtained between numerical and experimental results. Parametric study was conducted on the effects of slenderness and eccentricity ratio on the load capacity of box columns. Finally, design recommendations were made based on the comparisons between numerical results and design curves in different codes. It was suggested that curve “a” in GB50017-2003 and curve “c” in Eurocode 3 are appropriate for the global buckling design of welded Q460GJ steel box columns under eccentric compression. Design curves in ANSI/AISC360-10 and AIJ 2010 also provides good predictions of the load capacity.

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ABSTRACT: A new type of cellular beams fabricated from hot rolled profiles appeared recently, whose openings have a sinusoidal shape. These beams are used either for steel or composite structures and they allow rectangular ducts, even with large sizes, to pass through their openings. They can thus lead to a substantial reduction of the floor thickness and they contribute to increase the competitiveness of steel buildings. The aesthetic shape of the openings is also an advantage to improve the architectural attractiveness of steel frames. To take benefit from these possibilities, accurate design methods are required and this research project has been undertaken to establish the static behaviour of these beams with sinusoidal openings. This paper presents the
results of 4 tests (on 3 steel beams and on a composite beam) and of 287 numerical simulations carried out to determine ultimate loads and failure modes under the simultaneous effects of bending and shear. A new analytical design method is then proposed for the resistance of cellular beams with sinusoidal openings taking into account the Vierendel effect. This new model can be used within the range of the geometrical and mechanical scope. Finally the comparison of the ultimate loads according to this new model and according to the reference database (experimental or numerical data) is provided to assess the safety and accuracy of the proposed expressions.

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“Assessing the structural behaviour of square hollow glass columns subjected to combined compressive and impact loads via full-scale experiments”, Engineering Structures, Vol. 143, pp 127-140, July 2017
https://doi.org/10.1016/j.engstruct.2017.04.016

ABSTRACT: Glass is largely used in buildings as a novel construction material. Due to the intrinsic mechanical properties of such material, however, specific design recommendations are demanded in order to offer appropriate “fail-safe” requirements. This is especially true in the case of load-bearing structural glass elements where redundancy, stability and residual resistance should be guaranteed. In this regard, based also on a past research effort, the paper experimentally investigates the structural performance of full-scale square hollow glass columns, whose resisting cross-section consists of four adhesively joined laminated glass panes. Impact tests are carried out on in-plane compressed specimens, including both a reference undamaged column and a deliberately, preliminary broken specimen. The effects of multiple impact test configurations (inclusive of various release configurations for the impact mass as well as type of impact body) are hence emphasized, with critical discussion of the observed overall results and failure mechanisms.

Aleksandar Nikolic and Slavisa Salinic (Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Dositejeva 19, 36000 Kraljevo, Serbia), “Buckling analysis of non-prismatic columns: A rigid multibody approach”, Engineering Structures, Vol. 143, pp 511-521, July 2017
https://doi.org/10.1016/j.engstruct.2017.04.033

ABSTRACT: A new approach to the buckling analysis of non-prismatic columns is proposed. The method of rigid elements is used for this purpose. The general form of the characteristic equation is given by which it is possible to perform buckling analysis of columns with continuously varying cross-section and multiple-stepped columns under different boundary conditions. It is assumed that the column cross-section is doubly symmetric. The proposed method is verified through numerical examples. The influence of different geometric parameters, self-weight of the column, and stiffness of the introduced springs on the critical buckling load is analysed.

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ABSTRACT: Practical design of bridges and other structures requires the use of quick and simple calculation methods, rather than the use of tridimensional models using shell or solid finite elements. These methods have to be used for a general loading state, taking into account the different structural mechanisms, and generating the results required to apply the verifications of the structural codes and to understand the structural behavior. In this work, a beam-type element is proposed to address these objectives for the case of thin walled sections. This element has three nodes, with five-degrees of freedom per node, more than the six degrees of a conventional 3D beam, incorporates the effects of shear lag, torsion and distortion homogeneous and non homogeneous in the distribution of normal stress. Various examples were tested to verify the validity of the beam element according different calculation methods.

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ABSTRACT: Wide-flange members with sinusoidal corrugations in webs are recently developed and gradually accepted as alternatives to wide-flange members with flat webs and trapezoidally corrugated webs. However, limited knowledge is available regarding flexural behavior of such members. This research investigates flexural behavior of the cantilever wide-flange members with sinusoidal corrugations in webs. First, four cantilever specimens were constructed. Each specimen was tested using a monotonically increased point load applied at the free end. Test results show that the specimens overall exhibited the flexural torsional buckling behavior, which is similar to that of the conventional wide-flange members with the flat webs and subjected to the same loading and boundary conditions. Next, computer models were developed for the tested specimens. Both eigenvalue analyses and nonlinear static analyses were conducted to glean the buckling strength of each specimen. It was found that the nonlinear static analyses can provide reasonable predictions of the strengths of the tested specimens. Based on the validated computer models, parametric analyses were conducted to investigate the influence of initial geometrical imperfection on strength of the cantilever wide-flange members with corrugations in webs. In addition, the flexural performances of the cantilever wide-flange members with sinusoidally corrugated webs were compared with those of the corresponding wide-flange members with the flat webs based on the computer simulations. The computer models were further analyzed to assess adequacy of some existing models for calculating strength of the wide-flange members with sinusoidal corrugations in webs.

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ABSTRACT: A weak-form quadrature element formulation is presented for the three-dimensional beam element for use in the geometrically nonlinear and postbuckling analysis of space frames. Starting from the virtual work equation of a beam in the linearized, incremental sense, the quadrature element method (QEM) is
employed to derive the elastic stiffness, geometric stiffness, and induced moment matrices of the beam with due account taken of the large rotations in three-dimensional space. All the stiffness matrices are adopted in the incremental-iterative analysis using the generalized displacement control (GDC) method, with specific considerations for the predictor and corrector phases. By comparing the results obtained for all the benchmark problems studied with existing ones, it is demonstrated that the present formulation is capable of predicting large displacements and rotations, as well as the postbuckling paths of space frames. The present formulation is featured by the fact that it is simple, straightforward, and reliable.

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“Distortional analysis of simply supported box girders with inner diaphragms considering shear deformation of diaphragms using initial parameter method”, Engineering Structures, Vol. 145, pp 44-59, August 2017
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ABSTRACT: In this paper, the distortion of simply supported girders with inner diaphragms subjected to concentrated eccentric loads is investigated using initial parameter method (IPM), in which the in-plane shear deformation of diaphragms is fully considered. A statically indeterminate structure was modeled with inner redundant forces, where the interactions between the girder and diaphragms were indicated by a distortional moment. Considering the compatibility condition between the girder and diaphragms, solutions for the distortional angle, warping displacements and stresses were derived and further simplified by establishing a matrix equation system. The validity of IPM was intensively verified by a finite element analysis and distortional experiments. Parametric studies were then performed to examine the effect of the diaphragm number on the distortional angle, warping displacements and stresses under various ratios of height to span of the girder and the diaphragm thicknesses. Besides, stabilities of the local web plate and mid-span diaphragm were analyzed based on IPM for box girders with symmetrical three inner diaphragms. Results show that the local web plate will buckle before overall yielding with the increment of the eccentric loads $P_e$, and the mid-span diaphragm is constantly stable in the whole deformation process. It shows that more attentions should be paid on the stability of the local web plate than overall yielding for girders subjected to eccentric loads.

References listed at the end of the paper:
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ABSTRACT: Several types of tubular, origami-inspired plate mechanisms have been proposed for use as metamaterials and deployable structures. However, research into mechanical properties of these mechanisms is limited to rectilinear forms. This paper investigates the structural feasibility of non-rectilinear rigid-foldable
cellular materials for application as deployable arch structures. An experimental and numerical investigation is first conducted on a new type of folded tubular arch, with failure contributions identified from hinge rotation and plate buckling failure mechanisms. A common geometric description is then developed between three different types of origami-inspired tubular arches, which are numerically investigated under three-point loading. The double-kite arch developed in this paper is seen to have the highest failure load.

Hai-Ting Li and Ben Young (Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China), “Cold-formed ferritic stainless steel tubular structural members subjected to concentrated bearing loads”, Engineering Structures, Vol. 145, pp 392-405, August 2017
https://doi.org/10.1016/j.engstruct.2017.05.022

ABSTRACT: The behaviour and design of cold-formed ferritic stainless steel tubular structural members subjected to concentrated bearing loads are presented in this paper. A total of 37 web crippling tests was conducted on cold-formed square and rectangular hollow sections of grade EN 1.4003 ferritic stainless steel. The tests were conducted under end loading and interior loading conditions, which closely simulated the support conditions of floor joist members seated on solid foundation. Finite element (FE) models were developed and validated against the experimental results. Upon validation of the FE models, a parametric study comprised 160 FE analyses was performed using the validated models. The web crippling strengths obtained from experimental and numerical investigations were compared with the nominal strengths calculated using the current American, Australian/New Zealand and European specifications for stainless steel structures. Furthermore, the North American Specification (NAS) and the Australian Standard AS4100 for carbon steel structures as well as the suggested design rules in the literature for stainless steel structures were also compared. Improved design rules are proposed for ferritic stainless steel tubular structural members subjected to concentrated bearing loads by means of modified NAS and Direct Strength Method. The reliability of the proposed design rules has been assessed through reliability analysis.

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“Numerical studies of cyclic behavior and design suggestions on triple-truss-confined buckling-restrained braces”, Engineering Structures, Vol. 146, pp 1-17, September 2017
https://doi.org/10.1016/j.engstruct.2017.05.032

ABSTRACT: The cyclic behavior and design of a triple-truss-confined buckling-restrained brace (TTC-BRB) is investigated, especially when it is used in mega-frame high-rise buildings and long-span spatial structures as a long-span BRB. The TTC-BRB is formed by introducing an additional structural system of rigid truss frames to the outside of a common double-tube BRB in order to achieve a higher external restraining flexural stiffness as well as a high overall load-carrying capacity. An analytical method is utilized to derive a formula of the elastic buckling load of a pin-ended TTC-BRB, which is verified and modified through FE analyses. The effect of restraining ratio of the TTC-BRB on its cyclic behavior and failure mechanism is explored. The findings indicate that the TTC-BRB may have two different failure modes, namely in-plane and out-of-plane instability failures of the chord subjected to compression at the mid-span of the TTC-BRB. In addition, the load-carrying capacity of the TTC-BRB under cyclic loading is found to be proportional to the restraining ratio, and there exists a lower limit of the restraining ratio which ensures the core could reach its full cross-sectional yield load before overall instability failure of the TTC-BRB. Furthermore, in order for the TTC-BRB to be an energy
dissipation type of BRBs, the lower limit requirement of the restraining ratio should be satisfied and its end constructional and strength design should be carefully carried out to avoid its premature failure. The investigation of the elastic buckling load and cyclic behavior as well as failure mechanism of the TTC-BRB provides fundamentals to the further development of a comprehensive design method of the TTC-BRB.

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“Shear analysis and design of high-strength steel corrugated web girders for bridge design”, Engineering Structures, Vol. 146, pp 18-33, September 2017, https://doi.org/10.1016/j.engstruct.2017.05.035

ABSTRACT: Steel girders with corrugated web plates (BGCWs) have already been used in many bridges around the world because they own several advantages compared with traditional plate girders with flat webs. They have considerably high shear resistances and provide weight saving by reducing the web thickness and by eliminating the use of transversal stiffeners. However, these girders practically have been designed based on half-scale experimental tests. On the other hand, it has been recently recognised that high strength steels (HSSs) provide designers with the opportunity of creating more slender and weight efficient structures than would be possible if the normal strength steels (NSSs) have been used. To gain benefit from the advantages of both the BGCWs and the HSSs in one structure, this research work is carried out to investigate the BGCWs built with HSSs which have seldom been explored in literature despite being utilised in the Pennsylvania Demonstration Bridge with corrugated web, USA, which was opened for service in 2005. Finite element models, by using ABAQUS programme, have been used to accomplish this investigation. They are firstly verified by comparing their results with the existing test results in literature. Then, extensive nonlinear parametric studies are generated considering the corrugation dimensions used in the available constructed bridges. The strengths of the girders are compared with the available design models and the best model calculating the ultimate shear strength is highlighted. Additionally, from this investigation, an understanding for the real behaviour of the BGCWs built with HSSs is established.


ABSTRACT: In this paper, a generalized analytical approach for lateral-torsional buckling of simply supported anisotropic hybrid (steel-FRP), thin-walled, rectangular cross-section beams under pure bending condition was developed using the classical laminated plate theory as a basis for the constitutive equations. Buckling of such type of hybrid members has not been addressed in the literature. The hybrid beam, in this study, consists of a number of layers of anisotropic fiber reinforced polymer (FRP) and a layer of isotropic steel sheet. The isotropic steel sheet is used in two configurations, (i) in the mid-depth of the beam sandwiched between the different FRP layers and (ii) on the side face of the beam. A closed form buckling expression is derived in terms of the lateral, torsional and coupling stiffness coefficients of the overall composite. These coefficients are obtained through dimensional reduction by static condensation of the $6 \times 6$ constitutive matrix mapped into a $2 \times 2$ coupled weak axis bending-twisting relationship. The stability of the beam under different geometric and material parameters, like length/height ratio, ply orientation, and layer thickness, was investigated. The analytical formula is verified
against finite element buckling solutions using ABAQUS for different lamination orientations showing excellent accuracy.

R.H. Plaut (Virginia Tech, Department of Civil and Environmental Engineering, Blacksburg, VA 24061, USA), “Lateral-torsional dynamic instability of uniform and double-tapered rectangular beams under harmonic shear deformation”. Engineering Structures, Vol. 146, pp 140-147, September 2017
https://doi.org/10.1016/j.engstruct.2017.05.043

ABSTRACT: This paper analyzes lateral-torsional dynamic instability of elastic beams with rectangular cross section having constant thickness, with the depth symmetric with respect to the midpoint and either uniform or tapered linearly in each half. Free vibrations are also investigated. The ends of the beam are prevented from twisting and are pinned with respect to bending in the weak direction. In the strong direction, one end of the beam is fixed and the other is subjected to transverse harmonic motion. This problem was motivated by “butterfly-shaped links” proposed for use in seismic mitigation. Uniform torsion is assumed. Frequencies of free vibration are computed, critical excitation frequencies for lateral-torsional instability are determined, and critical combinations of excitation amplitude and frequency are obtained. The effects of geometric parameters of double-tapered beams on instability are presented. Lateral-torsional instability may occur for very small amplitudes of the moving end of the beam, as is typical for such problems involving parametric resonance.

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ABSTRACT: This paper proposes a new type of buckling-restrained braces (BRBs), namely shuttle-shaped buckling-restrained braces (SS-BRBs). The proposed SS-BRB is composed of a circular steel tube as the inner core, and a shuttle-shaped thin-walled steel tube as the external restraining member. The space between them is filled by a steel-plate isolation system. The shuttle-shaped restraining member of the SS-BRB significantly improves load-carrying efficiency and saves material in its strength design. Moreover, the SS-BRB is more aesthetically appealing and can be utilized as an exposed BRB in long-span or spatial structures. In terms of the concept of restraining ratio of a BRB, no design method of an SS-BRB is available currently because it concerns the solution of the elastic buckling load of an SS-BRB. Therefore, the elastic buckling load of a pin-ended SS-BRB is initially studied by adopting the equilibrium method and is further verified through finite element (FE) method. The lateral displacement function of an SS-BRB, and the longitudinal stress at the extreme fiber of the restraining member are derived by considering an initial geometric imperfection that is consistent with the first order overall buckling shape of the SS-BRB. A correction factor considering shear deformation has been incorporated for a more accurate prediction. The lower limit of the restraining ratio for a load-bearing type of SS-BRBs is further obtained based on yielding of the extreme fiber of the restraining member. Furthermore, the proposed formula has incorporated a strain hardening factor for the SS-BRB that experiences strain hardening of the core after its initial yielding. The proposed formulas have been validated through FE numerical analysis. The findings in this paper provide fundamentals to develop the design method for an energy-dissipation type of SS-BRBs.
ABSTRACT: A new composite column named concrete-encased concrete-filled fibre reinforced polymer tube (CCFT) column has been proposed in this study. This composite column consists of an inner concrete-filled fibre reinforced polymer (FRP) tube, outer concrete confined with polymer grid, and concrete cover. In this study, a total of 16 concrete stub columns were cast and tested under axial compression. Columns were divided into eight groups, which included one group of plain concrete columns, two groups of FRP confined concrete columns, and five groups of CCFT columns. For FRP confined concrete columns, one layer and two layers of carbon FRP (CFRP) sheet were wrapped, respectively. For CCFT columns, glass FRP (GFRP) tube was used to confine the inner concrete, and polymer grid was used to confine the outer concrete. The test results show that considerable increase in strength and ductility can be obtained for CCFT columns. An analytical model has been developed to predict the axial compressive behaviour of CCFT columns. The analytical results have been found to be in good agreement with the experimental results. Based on the analytical model, the influences of different parameters on the axial compressive behaviour of CCFT columns have been investigated through parametric analyses.

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ABSTRACT: For pipelines with vertical imperfection, upheaval buckling may occur if the axial compressive force reaches the critical axial force of upheaval buckling. The critical axial force is sensitive to the pipeline imperfection and previous researchers have suggested that there is no universal analytical solutions for the critical axial force of upheaval buckling for imperfect pipelines. However with theory of dimensional analysis, it was proved that there should be a general form of the approximation formulas of the critical axial force, although the coefficients in the formulas are different for different imperfection shapes. And most recently, Zeng et al. proposed approximation formulas of the critical axial force accounting for the Out-of-Straightness (OOS) of the imperfection, while they haven’t considered the influence of the imperfection size. In this paper, effect of the imperfection size on the critical axial force was proved significant even when the OOS and shape of the imperfection are determined. To account for this size effect, a parameter named the dimensionless imperfection length is proposed based on theory of dimensional analysis. This parameter combined the effects of the imperfection length, the vertical distributed force and the pipeline bending stiffness. A formula of the critical axial force, covering the newly proposed parameter and the OOS of the imperfection, is derived, and coefficients in the formula are determined with numerical results from the Vector Form Intrinsic Finite Element (VFIFE) simulations. Notably, the coefficients in the formulas are not constants but assumed to change with the OOS and the dimensionless imperfection length to account for the geometric nonlinearity of the initially curved pipeline. The proposed formulas are proved more accurate than previous ones and applicable for pipes with...
different cross-sectional properties and different buried conditions. They are also suggested within the error range of ±5% in the dimensionless scope of the OOS from 0.001 to 0.01 and the dimensionless imperfection length from 0.89 to 4.95.

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ABSTRACT: Finite element analysis was first used to replicate the inelastic cyclic test response of previously tested concrete filled steel sandwich panel (CFSSP) walls, to determine the material and contact models best able to capture the wall’s initial stiffness, the ultimate wall strength at each cycle, the web plate and HSS local buckling, and the pinching in the hysteresis loops. Results obtained show good agreement with all those aspects of response, while providing insights, guidance, and a validated model that will be of benefit in future studies of CFSSP-Walls. In a second part of this paper, the calibrated finite element model is used to provide insights and generate knowledge on some important aspects of wall behavior that is valuable for the design of CFSSP-Walls. Designers of CFSSP-Walls are typically provided little prescriptive guidance by design specifications and must instead rely, to a large extent, on findings from the recent research literature to ascertain that designs will perform as intended. For this new structural system, such insights into structural behavior are severely lacking. The findings here provide such insights on the distribution of wall-to-footing forces, shear force demands in critical tie bars, cumulative plastic strain value at failure due to low-cycle fatigue, the effect of hoop and shear stresses on uniaxial steel plate yielding, and the effect of interface friction on the force flow within boundary elements. These allow research to verify the adequacy of many of the assumptions used to determine the wall’s plastic moment, which is typically considered to be the flexural strength of CFSSP-Walls.

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ABSTRACT: The casting of concrete in concrete-filled steel tube (CFST) can, via the confinement effect of the steel tube, significantly increase the ductility of the concrete and, in the case of high-strength concrete (HSC), alleviate the shortfall in ductility of the HSC. This kind of structure is gaining popularity but its behaviour is quite complicated. In an axially loaded circular CFST column, the confinement is uniform and equi-biaxial (isotropic within the cross-section). But, when the circular CFST column is under eccentric load, the confinement becomes non-uniform and anisotropic. Such complicated confinement effect is not easy to analyse and for such analysis, a rigorous finite element (FE) method is generally needed. In this paper, a new FE model considering the lateral strain-axial strain relation of the confined concrete covering the full range from the initial elastic stage to the inelastic stage is developed for the analysis of circular CFST columns under eccentric load. The FE model is used to analyse a total of 95 CFST specimens tested by other researchers and the numerical results are compared to the published test results for verification.
ABSTRACT: This paper numerically studies the wind effect on grooved and scallop domes. The introduction of a groove on a spherical dome causes abrupt change on its wind pressure coefficient (Cp) in the vicinity of the groove. The sharpness of indentation varies with the position angle of the axis of the groove to wind direction and obtains its highest effect at 90°. This paper develops equations for the distribution of Cp on the surface of spherical, grooved and scallop domes with rise to span ratios [0, 0.7]. The results of the equations agree reasonably well with that of CFD.

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ABSTRACT: The aim of the present study is the assessment of a residual ultimate strength of an Aframax-class double hull oil tanker damaged in collision. A contribution to the research of the problem is given in a systematic investigation of the influence of the rotation of neutral axis (NA), which is performed by imposing appropriate boundary conditions. Nonlinear finite element method (NFEM), using explicit dynamic integration method implemented in LS-Dyna, is employed. NFEM results are compared with the IACS CSR progressive collapse analysis (PCA) method. Residual strength diagrams are developed for a rapid residual ultimate longitudinal strength assessment in both sagging and hogging and accounting for correction factor because of the rotation of NA. Following this, developed diagrams are compared with previously published researches. The results of this study may be used by classification societies in a Rules development process, in the risk assessment studies of the maritime transportation and for a quick calculation of the hull girder residual strength of a damaged ship in the situation requiring emergency response action.

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ABSTRACT: To meet the requirement of larger bearing capacity and better material economization than traditional main members in latticed transmission towers, a novel Y-section column is put forward in this paper. A series of full-scale tests is carried out to investigate the buckling behavior of 420 MPa high strength steel Y-section (HSSY) columns. 57 columns including three different sectional dimensions and nine slenderness ratios ranging from 30 to 80 are designed for axial compression tests. The width-to-thickness ratios, reduction factors
accounting for the design stress or effective cross section area, material mechanical properties, initial geometric imperfections and longitudinal residual stresses are measured and discussed in detail. Based on the validated finite element results taking the initial imperfections into account, the buckling deformations and ultimate strengths are obtained and demonstrate a good agreement with the test results. The buckling factors are calculated and compared with different code results such as Eurocode 3, GB 50017-2003, ASCE 10-97, ANSI/AISC 360-10, CSA S16-09, AS4100-2012, BS 5950-1 and AIJ 2010. Related buckling curves and formulae are derived through nonlinear fittings and compared with the code design curves. It is concluded that the HSSY columns characterize very strong stability and high buckling strengths. Finally, the recommended buckling curves and design formulae are proposed to predict the buckling strengths of HSSY columns.

ABSTRACT: Compressed reinforcements on reinforced concrete (RC) and steel fibre reinforced concrete (SFRC) columns are generally submitted to cyclic and monotonic loading, which can buckle. This phenomenon can cause the reduction of both ductility and peak loads, which is why design standards propose constructive details to avoid this. Although the bibliography mentions that steel fibres in concrete can delay buckling of reinforcements, design codes do not distinguish between concrete types (with and without fibres) in these constructive details. Analytical models that determine the length and critical buckling stress of reinforcements may consider this effect. Nowadays, analytical models can be classified as discrete and distributed depending on whether they consider transverse reinforcement stiffness and the stiffness of the concrete cover that concentrates on transverse reinforcements, or if they are distributed along the element, respectively. Both discrete and distributed models are valid for small transverse reinforcement separations, while distributed models that only consider the concrete cover effect are valid for large transverse reinforcement separations.

ABSTRACT: This paper presents a general methodology for predicting the critical buckling loads of spherical shells using a nondestructive test. For this purpose, the well known graphical method of predicting buckling loads, i.e., the Southwell’s nondestructive method for columns is analytically extended to spherical shells and a new formula is derived for the critical buckling load of uniformly compressed spherical shells. Subsequently, finite element simulation and experimental work proved that the theory is also applicable to spherical shells with an arbitrary axi-symmetrical loading as well. The results show that the technique provides a useful estimate of the elastic buckling load provided care is taken in interpreting of the results. The usefulness of the method lies in its generality, simplicity and in the fact that, it is non-destructive. Moreover, it does not make any assumption regarding the number of buckling waves or the exact localization of buckling.

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ABSTRACT: An experimental investigation was conducted on empty and grouted stainless steel square hollow section (SHS) tubular X- and T-joints subjected to axial compression. A total of 24 specimens including empty tubular joints, tubular joints with grouted brace members only, tubular joints with grouted chord member only and tubular joints with both grouted brace and chord members were tested. The joint strengths, failure modes, axial load-vertical displacement curves, axial load-chord deformation curves and strain distribution curves of all specimens were reported. The corresponding finite element analysis (FEA) was also performed and calibrated against the test results. Therefore, an extensive parametric study was carried out to evaluate the effects of main influential factors (β, τ, grouting and grout strength) on the behaviour of grouted stainless steel SHS tubular X- and T-joints subjected to axial compression. It is shown from the comparison that the ultimate strengths of empty and grouted stainless steel SHS tubular X- and T-joints generally increased with the increase of the β and τ values. The enhancement of joint strengths obtained from grouting both brace and chord members is much greater than that obtained from grouting chord member only. In addition, the ultimate strengths of stainless steel SHS tubular X- and T-joints with both grouted brace and chord members generally increased with the increase of the grout strength. Whereas, the grout strength has little influence on the ultimate strengths of stainless steel SHS tubular X-joints with grouted chord member only. On the other hand, the joint strengths obtained from the tests and parametric study were compared with the design strengths calculated using the current design rules. It is shown from the comparison that the current design rules are generally conservative for the design of empty stainless steel SHS tubular X- and T-joints subjected to axial compression, but unconservative for the design of grouted stainless steel SHS tubular X- and T-joints subjected to axial compression. Therefore, the new design equations were proposed in this study, which were verified to be more accurate.
ABSTRACT: Thin-walled structures have been widely used in energy absorption and safety applications such as automotive, due to their lightweight and progressive folding modes. This work studies the collapse behavior and energy absorption of corrugated tapered tubes (CTT) under axial crushing numerically. The tested tubular structures were impacted axially with a striker’s mass that is restricted to translational motion along the structures’ axes. The effect of CTT’s geometric features on different performance indicators, namely the initial peak force (PF), mean crushing force (MF), energy absorption (EA) and specific energy absorption (SEA) was studied. The results showed that the amplitude of corrugation is the most influential factor on the force-displacement characteristics of CTTs. Moreover, three deformation modes were found for CTTs, and the development of a mode was mainly influenced by the corrugation’s amplitude and wavelength. In addition, for the tested range of geometric features, the initial peak force was found to be reduced when corrugation is adopted, especially for longer corrugation’s amplitudes and wavelengths. On the other hand, the energy absorption (EA) and specific energy absorption (SEA) were found to be reduced when corrugation is adopted. Finally, it was found that the two most influential geometric factors on the performance indicators of CTT were the corrugation’s amplitude and wall thickness.

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“Post-buckling of functionally graded microplates under mechanical and thermal loads using isogeometric analysis”, Engineering Structures, Vol. 150, pp 905-917, November 2017,  
https://doi.org/10.1016/j.engstruct.2017.07.073  
ABSTRACT: The present study uses the isogeometric analysis (IGA) to investigate the post-buckling behavior of functionally graded (FG) microplates subjected to mechanical and thermal loads. The modified a strain gradient theory with three length scale parameters is used to capture the size effect. The Reddy third-order shear deformation plate theory with the von Kármán nonlinearity (i.e., small strains and moderate rotations) is employed to describe the kinematics of the microplates. Material variations in the thickness direction of the plate are described using a rule of mixtures. In addition, material properties are assumed to be either temperature-dependent or temperature-independent. The governing equations are derived using the principle of virtual work, which are then discretized using the IGA approach, whereby a C2-continuity requirement is fulfilled naturally and efficiently. To trace the post-buckling paths, Newton’s iterative technique is utilized. Various parametric studies are conducted to examine the influences of material variations, size effects, thickness ratios, and boundary conditions on the post-buckling behavior of microplates.

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ABSTRACT: This report presents the experimental results of a comprehensive investigation on the buckling of an encased liner under external water pressure. The pre- and post-buckling behaviours of tightly and loosely fitted liners, as well as their collapse mechanism, were investigated by performing a series of experiments using novel pressurizing equipment. The experimental results clearly show that an encased liner can collapse due to inelastic single-lobe buckling or elastic buckling, depending on the liner and constraint conditions. In addition, the existing related solutions are discussed, and it is identified that none of the solutions can appropriately evaluate the critical pressure for both tightly and loosely fitted liners. Moreover, recent buckling accidents are discussed, and suggestions for safe design are presented.

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ABSTRACT: Linear and nonlinear seismic responses can be estimated using the time history analysis for given ground motion records. To reduce the computing time, design codes prescribe guidelines to select a small number of ground motion records to perform the analysis and to estimate the seismic design demand. However, the assessment of the statistics of the seismic design level by using a small number of record components and the evaluation of the failure probability of the designed structures in such a manner are unavailable. The assessment and evaluation focused on the lattice dome are presented in this study. The results indicate that the use of average response from seven ground motion record components for design can lead to over- or under-estimation of the seismic design effect, the frequency of underestimation is about 50%. The variability of the seismic design effect estimated by using seven selected record components is considerable. By carrying out simulation analysis with 1000 trials, the minimum underestimation and the maximum overestimation of the seismic design demand are 35% and 64%, respectively; the estimated failure probabilities of the dome designed by using average response from seven record components can be about half an order of magnitude greater or smaller than that of the dome designed without the effect of small sample size. This suggests that to reduce the observed relative differences in the failure probabilities, an increased number of ground motion record components needs to be used in seismic design.

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ABSTRACT: Linear and nonlinear seismic responses can be estimated using the time history analysis for given ground motion records. To reduce the computing time, design codes prescribe guidelines to select a small number of ground motion records to perform the analysis and to estimate the seismic design demand. However, the assessment of the statistics of the seismic design level by using a small number of record components and the evaluation of the failure probability of the designed structures in such a manner are unavailable. The assessment and evaluation focused on the lattice dome are presented in this study. The results indicate that the use of average response from seven ground motion record components for design can lead to over- or under-estimation of the seismic design effect, the frequency of underestimation is about 50%. The variability of the seismic design effect estimated by using seven selected record components is considerable. By carrying out simulation analysis with 1000 trials, the minimum underestimation and the maximum overestimation of the seismic design demand are 35% and 64%, respectively; the estimated failure probabilities of the dome designed by using average response from seven record components can be about half an order of magnitude greater or smaller than that of the dome designed without the effect of small sample size. This suggests that to reduce the observed relative differences in the failure probabilities, an increased number of ground motion record components needs to be used in seismic design.

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ABSTRACT: A numerical investigation on cold-formed high strength steel (HSS) tubular beams is presented in this paper. The nominal 0.2% proof stresses of the HSS sections ranged from 700 MPa to 1100 MPa. In the complementary study [1], experimental investigation on the beam specimens have been performed. In the present study, numerical modelling methodology for beams was first validated and parametric study on the cold-formed HSS tubular beams was conducted. A total of 423 numerical data was obtained to investigate the structural performance of HSS tubular beams. The experimental and numerical results were then compared with the codified design guidelines from ANSI/AISC 360-10 [2], EN 1993-1-1 [3], AS 4100 [4] and AISI S100 [5] in addition to the predictions from Direct Strength Method (DSM) for square hollow sections (SHS), rectangular hollow sections (RHS) and circular hollow sections (CHS). The codified slenderness limits for sections subjected to bending were examined. Improvements on the design guidelines are proposed in this paper.

Changzai Zhang, Yuansheng Cheng, Pan Zhang, Xinfeng Duan, Jun Liu and Yong Li (School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China), “Numerical investigation of the response of I-core sandwich panels subjected to combined blast and fragment loading”, Engineering Structures, Vol. 151, pp 459-471, November 2017, https://doi.org/10.1016/j.engstruct.2017.08.039

ABSTRACT: The LS-DYNA software was employed to investigate the dynamic response of I-core sandwich panels under combined blast and fragment loading. The combined blast loading was simulated by placing prefabricated fragments at the bottom surface of bare explosive. To facilitate evaluating the synergistic effect under combined blast loading, the resistance of sandwich panels under bare blast loading was also assessed. The results demonstrated that the damage caused by combined blast loading was more severe than that by bare blast loading. The roles of charge mass, face-sheet configuration and core configuration on the deformation/failure behavior and energy absorption characteristics of panels were analyzed and discussed in detail. Under combined blast loading, the panels exhibited a perforation and tearing failure mode accompanied by structural fragments from failed front face. The charge mass is relevant to whether the residual momentum of fragments is large enough to penetrate the back face. The face-sheet configuration that had thick front face and thin back face was favorable in mitigating the damage response. The core configuration with dense core webs provided more assistance in preventing the appearance of failure pattern with a large connected region. The face-sheet configuration and core configuration have negligible influence on the total energy absorption, but they would redistribute the energy dissipation among each panel component. Furthermore, the comparisons of blast resistance between sandwich panels and conventional monolithic counterparts were made. It turned out that the sandwich panels experienced lower level damage failure on back face but dissipated similar energy relative to equivalent solid plates.

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ABSTRACT: Vierendeel steel truss arches are often used in lighting zones of the spatial roof to obtain good permeability and lighting effects. They are different from conventional steel truss arches in terms of failure mechanism and strength design because they have only transverse tubes without diagonal tubes between chords. The chords of the Vierendeel truss arch undertake axial, bending and shear actions while the transverse tubes...
only resist the bending action. Hence, their structural design against strength is different from conventional steel truss arches. However, this aspect is not well analyzed in literature. This study analyzed the in-plane instability mechanism, failure mode and corresponding strength of the Vierendeel truss arch under a uniform radial load, a full-span uniform vertical load, a half-span uniform vertical load and their combinations. The global in-plane elastic buckling load of the arch under a uniform radial load is derived firstly and an interaction design formula for predicting the global in-plane strength of the arch under a uniform axial compression is proposed. It is found that the chords of the arch may fail in fully sectional plastic moment mode. Transverse tubes may fail because of the end moments. Slender enough arches may also undergo global failure. Strength design equations for local chord failure and for global failure of arches are developed. All of the equations proposed for predicting global in-plane elastic buckling, global in-plane ultimate strength and chord local strength of the arch agree quite well with the finite element results.

ABSTRACT: (none given)

ABSTRACT: Axial compression tests of circular concrete-filled steel tubes with different diameters (219 mm, 426 mm, and 630 mm) and ratios of tube diameter to steel thickness (55 and 88) were conducted to investigate the effect of size on the bearing capacity. The experimental results indicated that the peak nominal stress decreased as the size increased, and the decrease in the nominal stress due to the size effect increased at higher ratios of diameter to thickness. At the peak load moment, an increased specimen diameter corresponded to a decreased hoop stress in the steel tube as well as a decreased concrete strength due to the confinement effect of the steel tube. When the ratio of diameter to thickness increased, the extent of reduction of the hoop stress and the confining effect of the steel tube influenced by the increasing specimen size increased. However, the vertical stress in the steel tube was increased at increased size, and increases in the ratio of diameter to thickness improved the increase degree of the vertical stress of steel tube due to the enlargement of specimen size. Hence, the vertical bearing capacity of the steel tube was affected by both the specimen size and the ratio of diameter to thickness. Based on the size effect law (SEL) proposed by Bazant, and taken the effect of the ratio of diameter to thickness into consideration, a size-dependent formula to evaluate hoop stress in the steel tube was developed. A size-related model considering situations with different ratios of diameter to thickness was established in order to estimate the bearing capacity of large-size circular concrete-filled steel tubes. The model and experimental results showed good agreement.

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ABSTRACT: Bellows joint is a critical part of an underground pipeline system, which can undergo severe damage such as breaking, crushing, and bending under a strong earthquake. In our research work, finite element analysis (FEA) of the bellows joint was studied using LS-DYNA. Single convolution and multi-convolution bellows joints applied with different loadings were investigated. Force–displacement curve, plastic strain distribution and bending moment–angular displacement curve were obtained. Furthermore, low frequency cyclic experiment on 4-convolution bellows joints was conducted and the results from the experiment were compared with the results from FEA. The load capacity of the multi-convolution bellows joint was almost the same as the single convolution bellows joint, and the energy absorption increased with the number of the convolution linearly.

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ABSTRACT: Both three-point and four-point bending tests were conducted on aluminum square and rectangular beams with circular perforations. Test specimens consist of 9 perforated and 4 imperforated beams subjected to gradient and constant bending moment. The extrusion of 6061-T6 and 6063-T5 heat-treated aluminum alloys were used to manufacture square and rectangular hollow sections (SHS and RHS), respectively. The evaluation of the strength and behavior of aluminum square and rectangular beams focuses on the effects of the aspect ratio, the ratio of plate width, the ratio of plate slenderness, the ratio of perforation dimension and the number of perforations. Test results including the ultimate strengths, failure modes of local and flexural buckling failure, bending moment versus curvature curves and strain distributions along the circular perforations are all reported, which were employed to assess the suitability of the current design specifications. The comparison of test strengths with design strengths shows that the modified DSM for aluminum structural members is somewhat conservative with the lowest value of COV, whereas other design specifications for cold-formed steel and aluminum structural members are quite conservative with comparatively high value of COV. It is also demonstrated from the comparison that the perforated sections close to the mid-span of the beams are the critical section under gradient and constant bending moment. In addition, the comparison of test strengths with design strengths also reveals that the current design rules for perforated cold-formed steel and aluminum structural members are all conservative, in which North American Specifications (NAS) for perforated cold-formed steel structural members are generally appropriate with the lowest value of COV.

ABSTRACT: In geohazard areas, buried pipelines are subjected to permanent ground-induced deformations, which constitute major threats for their structural safety. Geohazards include seismic fault movement, liquefaction-induced lateral spreading, slope instability or soil subsidence, and are associated with the development of severe strains in the pipeline. Calculation of these strains is necessary for assessing pipeline integrity. In the present paper, an analytical methodology is presented that allows for simple and efficient pipeline strain analysis in geohazard areas. The methodology is compared with existing more elaborate analytical methodologies and finite element predictions. The analytical formulation results in closed form expressions and the model contributes to better understanding of buried pipeline behavior subjected to permanent ground-induced deformations. The proposed methodology is directly applicable to fault actions, but it can be also applicable to a wide range of geohazards. Furthermore, using this methodology, one may predict the strains developed in the pipeline wall due to ground-induced actions in a simple and efficiently manner and is suitable for the preliminary design of pipelines.

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ABSTRACT: The collapse mechanics and ultimate strength of a stiffened plate with pitting damage are investigated experimentally with specimens with circular shaped holes representing the pits in the plate. A series of compressive tests has been conducted to investigate the effect of pitting corrosion, including the initial imperfections. The pit location, pit diameter and pit depth are examined to determine the influence of the pitting on the ultimate strength. The experimental results of load-displacement relationship, the strain response and the ultimate strength under compressive loads are analysed. The ultimate strength reduction is related with the degree of pitting or volume loss.

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ABSTRACT: This paper presents an experimental study on seismic behavior of ultra-high performance steel fiber reinforced concrete (UHPSFRC) columns. Based on a series of cyclic loading tests on 14 UHPSFRC specimens subjected to combined static axial loading and cyclic lateral loading, the investigation and analysis
have been carried out on crack status, failure modes, hysteretic loops, skeleton curves, strength and stiffness 
degradation, energy dissipation capacity and ductility of UHPSFRC columns. The influence of stirrup spacing, 
type of stirrup, axial compression ratio and shear span ratio on the seismic performance of UHPSFRC columns 
was also investigated in details. The experiment results show that three typical failure modes are observed, i.e., 
flexural, flexural-shear and shear failure mode. The existence of steel fiber could prevent the cracked concrete 
from spalling efficiently and delay the bulking of longitudinal reinforcement further. It noteworthy that the limit 
plastic drift ratio of all columns changes from 0.036 to 0.061, indicating that the UHPSFRC columns represent a 
good ductility which is obviously different from the conventional high strength concrete columns that exhibit 
much more brittleness with the increase of strength.

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China). “Global buckling prevention of end collared buckling-restrained braces: Theoretical, numerical analyses 
and design recommendations”, Engineering Structures, Vol. 152, pp 289-306, December 2017, 
https://doi.org/10.1016/j.engstruct.2017.09.014

ABSTRACT: In recent years, buckling-restrained braces (BRBs) have been widely utilized in engineering 
structures. Generally, BRBs are diagonally installed in frame structures to serve as lateral-resistance and 
energy-dissipation members. To prevent the local buckling of the unrestrained portion of a pin-ended BRB, an 
end collared BRB (EC-BRB) was proposed by prior researchers by installing end collars at both ends of an 
ordinary BRB. By using this approach, the enhancement construction of the unrestrained portion could be 
remarkably simplified, and the end collars can provide lateral restraints to the restraining member, thus 
improving the global stability of the BRB member. In this paper, a design method for global buckling 
prevention of pin-ended EC-BRBs based on the restraining ratio requirements is provided via theoretical and 
numerical analyses. The equation of elastic buckling loads of EC-BRBs is firstly derived and validated by the 
eigenvalue buckling analyses via ANSYS, and the restraining ratios of EC-BRBs could be further calculated. 
Then, the restraining ratio requirements of EC-BRBs are theoretically proposed based on the magnification 
factor of the mid-span lateral deformation, and accordingly a recommended design procedure is provided. The 
design procedure is further validated by numerous finite element (FE) models subjected to hysteretic and 
monotonic loadings, indicating that this procedure can conservatively ensure the global stability of EC-BRBs 
and it is suitable for practical engineering applications.

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“FRP-confined concrete-encased cross-shaped steel columns: Concept and behaviour”, Engineering Structures, 

ABSTRACT: FRP-confined concrete-encased cross-shaped steel columns (FCCSCs) are a new form of hybrid 
columns recently developed at the University of Wollongong. An FCCSC consists of a square FRP outer tube, a 
cross-shaped steel section and concrete filled in between. This sectional configuration ensures that the concrete 
is very effectively confined despite the square shape of the column. In addition, the cross-shaped steel section 
serves as the ductile longitudinal reinforcement for loads in the two lateral directions and its possible buckling 
is constrained by the FRP outer tube and the concrete, leading to a column that is highly ductile. In this paper, 
results from a series of stub column tests are presented to demonstrate the concept of the new column form. The 
experimental program involved the testing of FCCSC specimens as well as four types of similar column forms,
namely, square FRP-confined plain concrete columns (SFCPCs), circular FRP-confined plain concrete columns (CFCPCs), concrete-encased cross-shaped steel columns and square plain concrete columns. The test results confirmed the excellent performance of FCCSCs. The test results also showed that compared with the concrete in SFCPCs and that in CFCPCs, the concrete in FCCSCs has a much larger ultimate axial strain and a larger compressive strength, when the same FRP tube is used.


ABSTRACT: Eurocode 3 (EC3) states that the shear design resistance of a plate girder is given by the sum of the web resistance and the flanges contribution, being these calculated separately. The accuracy of these provisions is normally assessed by comparison with the results of numerical simulations using numerical models duly validated with experimental tests. However, the web resistance alone cannot be directly obtained by the numerical model. The usual procedure is to calculate the numerical resistance of the web by subtracting the flange contribution, obtained using the EC3 expression, from the ultimate shear strength directly predicted by the numerical model. Consequently, the accuracy of the EC3 expression to predict the flanges contribution may influence this assessment. Hence, the accuracy of the EC3 design expressions to calculate the contribution from the flanges to shear buckling is evaluated here. An improvement on the calculation of the distance c, which defines the position of the plastic hinges that forms in the flanges, is proposed. The ultimate shear strength predicted by EC3 has been compared with numerical results at both ambient and elevated temperatures, considering the original and proposed values for the distance c.

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ABSTRACT: Prestressed concrete-filled steel tube (CFT) truss girders usually consist of CFT chords, hollow steel tube braces, and high-strength prestressing strands. This paper investigates the behavior of prestressed CFT truss girders by conducting both experimental tests and finite element analyses. Experimental tests on five prestressed CFT truss girders are first conducted. The test parameters are the prestress level and shear span-to-depth ratio. Results from the experimental tests indicate that: (i) the initial flexural stiffness and flexural strength of prestressed CFT truss girders increase as the prestress level or shear-span-to-depth ratio increases, and (ii) the failure modes of prestressed CFT truss girders are influenced by the prestress level and shear span-to-depth ratio. Finite element models, which were developed previously by the authors for CFT truss girders, are then modified to predict the behavior of prestressed CFT truss girders. Comparisons with experimental load-deformation responses indicate that the developed finite element models can reasonably predict the behavior of prestressed CFT truss girders.

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ABSTRACT: Circular reinforced concrete (RC) columns have been widely used in the bridge structures (e.g., piers) due to their economic and functional advantages. However, RC columns are usually subjected to a lateral impact load under extreme loading conditions, especially under the collision event of an aberrant vehicle or vessel. Although a number of low-velocity impact tests on RC beams have been conducted, few experiments have been performed to clarify the dynamic behaviors of axially-loaded RC columns subjected to lateral impact loading. To this end, low-velocity impact tests on the axially-loaded circular RC columns are designed and conducted in this paper. Ten circular RC column specimens are fabricated with two different reinforcement ratios. Two out of these specimens are tested under static axial loading to determine their compressive resistances and the axial load levels applied in the impact tests. The other eight specimens with different axial load levels are tested under impact loading through the drop hammer test system at Hunan University. It is found that the applied axial loads have a great effect on the impact responses (e.g., impact forces, maximum and residual deformations) of the circular RC columns. Generally, the axial loads play a positive effect when the deformations of the column specimens are relatively small. On the contrary, the presence of an axial load exhibits catastrophic effects (e.g., complete collapse) in the case of the column with a low reinforcement ratio subjected to a high-energy impact. To further interpret the experimental data, the corresponding finite element (FE) models are developed for the impact simulation of axially-loaded RC columns. The conventional modeling used for RC beams is shown to have some disadvantages in the prediction of the impact-induced responses (e.g., resilient deformations) of the axially-loaded columns. For this reason, an improved FE modeling technique is proposed to simulate the axially-loaded RC columns subjected to impact loading. In the improved FE model, the concrete material model is modified to accurately consider the confinement effect of the spiral stirrup. The influences of both the bond-slip and crack closure behaviors on the impact-induced responses are also identified and considered in the improved FE models. The numerical results obtained from the improved models are in good agreement with the experimental data, indicating the applicability of the proposed FE modeling. These findings drawn from the experimental and numerical investigations can facilitate more reliable evaluation of a bridge structure with RC columns subjected to vehicle or vessel impacts.
iteration, based on the sensitivity analysis all the free nodes are moved along certain directions to reduce the compliance. A volume adjustment scheme is applied to satisfy the volume constraint. Jagged surfaces are automatically smoothed during the volume adjustment process and therefore no extra smoothing procedure is needed. A variety of 2D and 3D examples are presented to verify the effectiveness and the validity of the proposed method. It is shown that the new node-shifting method developed in this paper can be used for finding optimal shapes of general reticulated spatial structures including those with cantilevered parts where traditional inverse hanging method would fail.

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ABSTRACT: This paper presents a comprehensive numerical study on the strength and behaviour of double-coped beams (DCBs), with the focus on reinforcing strategies against local web buckling. Four reinforcement types, namely, longitudinal web stiffener (Type A), combined longitudinal and vertical web stiffeners (Type B), vertical and double longitudinal web stiffeners (Type C), and full-depth doubler plate (Type D), are considered. Through examining a suite of validated numerical models with a spectrum of cope details, it is found that the considered reinforcement types are in general effective, especially for the models with long or deep copes. Depending on the cope details and stiffener type, a series of failure modes, including local web buckling, web shear yielding, tensile fracture of the bottom cope corner, and web crippling, are identified, and the effectiveness of the different reinforcement types on preventing or postponing these failure modes is discussed in detail. A preliminary design rule for checking the capacity of the reinforced coped section is also proposed in the paper, and additional analysis is performed to further evaluate the influences of varying reinforcement dimensions and boundary conditions on the ultimate capacity of the DCBs. Based on the numerical analysis, a set of prescriptive recommendations on reinforcement details is finally proposed, offering a simple yet safe guidance for new design or upgrade of DCB members.

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ABSTRACT: The behaviour of unusual composite column sections is difficult to examine owing to their asymmetric geometry. In this study, seven L-shaped columns fabricated using concrete-filled steel tubes connected via double-vertical steel plates (LCFST-D columns) were tested under axial compression. The failure modes, load–deformation relationship, strain distribution, ductility, and strength index of the columns were
studied. Test results demonstrated that the local buckling of the vertical steel plates was delayed by filling with concrete. The bearing capacity and ductility ratio increased by 21.1% and 8.1%, respectively, compared with the specimen without concrete in the vertical steel plates. Transverse stiffeners were used to increase the axial stiffness by restraining the deformation of the vertical steel plates. However, the effect of the transverse stiffeners on the bearing capacity was negligible. The behaviour of the LCFST-D columns with concrete filled in between the two vertical steel plates, without the transverse stiffeners, was more favorable than the LCFST-D columns with the transverse stiffeners, and thus recommended for practical engineering application. The monocolumns worked more cooperatively in this connecting pattern. 3D nonlinear finite element models were developed and verified to analyze the mechanical properties and bearing capacity of the LCFST-D columns. The approach is verified by the experimental results and the available current design codes to be reasonably conservative. EC4 showed the best agreement with the experimental values. The results of this study provide a basis for the application of LCFST-D columns in high-rise composite structures.


ABSTRACT: In this paper, laboratory and numerical evaluations on the web bearing capacity of unlipped cold-formed ferritic stainless steel channels are described. The channels considered have circular perforations in the web and are loaded under the end-two-flange (ETF) load case. A total of 387 results comprising 27 laboratory and 360 numerical results are presented. A nonlinear quasi-static finite element (FE) model was developed for the numerical investigation. An extensive parametric study is described to determine web bearing capacity reduction factors for different sizes of circular web perforations and cross-section dimensions; the circular web perforations are either centred or offset to the load and reaction plates. It is noted that no cold-formed stainless steel standard provides capacity reduction factors for any end-two-flange load case. The capacity reduction factor equations are first compared to reduction factors previously recommended for lipped cold-formed stainless steel channels. It is found that these existing equations are unreliable and unconservative for unlipped channels by as much as 11%. The laboratory investigation shows that, for the case of plain unlipped channels (i.e. without web perforations), the ASCE Specification (SEI/ASCE 8-02) is conservative by as much as 14%. From both laboratory and finite element results, web bearing capacity design equations are proposed for both sections, with and without perforations in the web.

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ABSTRACT: Thin-walled circular cylindrical shells under axial compression are prone to buckling; the reduction of buckling load from the theoretical estimation is considered primarily due to imperfection sensitivity. The buckling load from carefully conducted experiments using nominally similar shells falls below the prediction by the classical theory with substantial scatter. The current design recommendations apply highly conservative knockdown factors to the theoretical buckling loads to estimate the load carrying capacity of the shell structures. In this study, a systematic analysis of experimental data from the literature has been conducted using the artificial neural network (ANN). The networks were trained using Bayesian regularisation
backpropagation training function. Two network models with eight and ten neurons were used to train, test and validate 390 sets of experimental data. The buckling loads predicted by the ANN models were compared with the design recommendations by National Aeronautics and Space Administration (NASA), Eurocode 3 (EC3) and the experimental buckling loads. The ANN models predict buckling load within 10% of the experimental buckling load and can be reliably used within the parametric range used in training. The NASA design recommendations provide 10–50% conservative estimates compared to the experimental loads while EC3 predictions are conservative by more than 50%.


ABSTRACT: Even under gravitational loading alone, horizontally curved girders experience not only bending moment but also torsional moment. The torsional moment acting on open sections simultaneously produces shear and normal stress due to pure and warping torsion respectively. Consequently, bending moment, pure torsion and warping torsion are coupled, which results in a very complicated stress state that makes it difficult to calculate the ultimate strength of horizontally curved members. This study revealed that the initial curvature can reduce the ultimate strength of horizontally curved members by up to 50%. Although current design specifications such as the AASHTO LRFD Bridge Design Specifications, suggest some alternatives, the exact behavior of a curved member cannot be considered well with those provisions. While it is true that the one-third rule is convenient to apply and gives good results, there is no strength equation for curved members. In order to derive an adequate strength equation for curved members, this research suggests a new concept of ultimate state. Finite element analysis using ABAQUS is used to consider the effects of sectional rigidities for bending, pure torsion and non-uniform torsion separately. Finally, an ultimate strength equation is suggested for simply supported curved girders that are subjected to equal end moments.


ABSTRACT: Since an aluminum alloy structural component can be manufactured through extrusion technology, the cross section can easily comprise various longitudinal stiffeners to strengthen the thin wall and to hold the partition wall panel. In this paper, experimental and numerical investigations on distortional buckling behaviors of thin-walled irregular-shaped aluminum alloy stub columns under axial compression were carried out. Initial geometric imperfections of six extruded aluminum alloy columns were measured using LVDT. The ultimate strength, failure deformation, out-of-plane displacement and strain development of six test specimens were recorded and used to verify a Finite Element Model (FEM) developed by the finite element software ABAQUS. The open plates in the irregular-shaped section had low distortional buckling resistance, which causes the premature failure of the studied columns. 117 columns with different length and plate thickness were numerically simulated by the verified FEM to reveal the influences of plate thickness on column distortional buckling behaviors. The Direct strength method (DSM) was applied and it was essential to determine column distortional buckling stress before performing DSM to calculate column ultimate strength. A modified calculation method for distortional buckling stress of the irregular-shaped aluminum alloy columns was proposed. Distortional buckling stresses of 81 aluminum alloy columns with different plate thickness were
analyzed by the FEM to evaluate the modified calculation method. It was accurate and more efficient to use the modified calculation method to calculate distortional buckling stress of the irregular-shaped aluminum alloy columns in DSM.


ABSTRACT: Enhancing the load capacity of aged and deficient thin-walled steel structures can be accomplished by increasing member stiffness in buckling prone regions. The literature shows that composite materials have become a major player in retrofitting applications. A new strengthening concept, Strengthening-by-Stiffening (SBS), is applied to buckling prone web panels in thin walled steel beams by bonding pultruded glass fiber reinforced polymer (GFRP) sections. The first part of present study is focused on the construction of a finite element (FE) model for accurate simulation of experimentally obtained results. Initial imperfections, material non-linearity, interlaminar fracture law to simulate adhesive debonding, and GFRP rupture or delamination are accounted for in the construction of the FE model. The second part of the study was focused on parametric studies using the validated FE model to investigate different GFRP sizes, contact areas, panel aspect ratio and slenderness of the web panels on steel beam with SBS retrofitting. Results from the parametric study were used to establish some limits to assist in SBS design. Finally, possible use of SBS strengthening method in new construction was investigated by substituting all steel stiffeners with bonded composite GFRP stiffeners for the improvement of fatigue related behavior that is known to start at the weld toes of steel stiffeners.


ABSTRACT: Generally, when marine vessels encounter the water surface on entry and subsequently re-enter the water at high speed, this can subject the bottom section of the vessels to high hydrodynamic loads, especially over very short durations. This phenomenon generates high hydrodynamic loads, which can cause a catastrophic failure in the structure. In contrast, the interaction between deformable structures and free water surface can be modified the fluid flow and changed the estimated hydrodynamic loads comparing with rigid body, due to appearance of hydroelastic effects. These effects are considered active challenge areas in structural ship design. This work presents an experimental study of the water impact for composite laminate wedge at different constant entry velocities. The aim of this study is to investigate the dynamic structural response of panels and predicts the hydrodynamic loads to meet the specific requirements of marine vessels. In order to better describe hydroelastic influence, two composite panels with different thicknesses namely 8 mm and 13 mm are subjected under constant impact velocities of 4, 6 and 8 m/s with the deadrise angle of 10°. The obtained experimental results were indicated that more flexible panels had a higher peak force and significant dynamic noise compared with higher stiffness panels. In addition, the maximum deformation occurred in the centre and close to the chine edge of the panel due to changes in local velocity and local deadrise angle. For this reason, special attention requires in both design phase and operation phase.

ABSTRACT: The Ayrton-Perry (or Perry-Robertson) formula based stability resistance model (APF) is very popular in steel structural design standards. Although the original version of the model is more than 100 years old, it is still frequently used and continuously researched due to its simplicity and adaptability. The original and most widely accepted version of the APF is valid only for the flexural buckling of compression members yielding the basic formulation of the column buckling curves of several structural design codes. Recently there were more successful attempts for the extension of the APF type resistance model for other buckling modes such as torsional buckling or lateral-torsional buckling. The paper continues this research by deriving a complete closed-form universal APF type solution for steel beam-column stability problems. Rigorous mathematical solution is given for the so-called “fundamental case” which is defined by a simply supported prismatic beam-column with arbitrary cross-section subjected to uniform compression and biaxial bending. The exact interpretation and the universal form of the member slenderness, imperfection and reduction factors are presented for all possible buckling cases. The results of the paper can widen significantly the field of applicability of APF based design methods providing a theoretically consistent physical model for the beam-column stability problems.


ABSTRACT: The performance of new type Buckling-Restrained Braces (BRB) is evaluated. The new type BRB is efficient since the steel core is constructed with prismatic steel plates that are straight throughout its length. Connection plates attaching the BRB to gusset plates are welded perpendicular to the steel core plates; this configuration is different from conventional BRBs in which the core plates also serve as the connection plates. Since the steel core plates are prismatic, construction of new type BRBs saves material and reduces the cost of manufacturing. Four full-scale new type BRBs were tested under quasi-static cyclic loading with either a single core plate or dual core plates using either bolted or welded connections to gusset plates. The hysteresis curves exhibited stable behavior with positive incremental stiffness; the ratio of maximum compression to tension capacity and the cumulative inelastic deformation were satisfactory. There was no rupture or instability and at failure the core plates achieved maximum tensile strains between 3.2% and 4.2%. Failure modes included core plate buckling about the strong or the weak axis and local bulging. The strong and weak axis buckling behavior is modeled using a strut-and-tie model. The local bulging behavior about either the strong or the weak axis is modeled using plastic analysis. Recommendations are presented for preventing strong axis buckling of the steel core and local bulging of the steel casing about the strong axis.


ABSTRACT: Concrete roof shells have shown to be inherently able to sustain earthquakes, but the reasons for this apparent seismic resistance have been subject to limited research. Concrete shells exhibit a high structural efficiency and thus can be constructed very thin. Because of their relative lightweight nature, the earthquake
forces induced in a thin shell structure are relatively low. However, the shape of a shell structure is typically established so that it performs optimally under gravity loads, carrying the loads to the foundations mainly through membrane action over the shell surface. Unanticipated horizontal forces induced by earthquakes generate bending stresses in concrete shell structures, which could lead to structural damage. Through a parametric study of 8 cm thick, concrete roof shells with a square plan, the research presented in this paper demonstrates that small to mid-sized (span < 15 m) thin concrete roof shells can indeed be intrinsically earthquake resistant. They owe this resistance to their great geometric stiffness and low mass, which lead to high fundamental frequencies that are well above the driving frequencies of realistic seismic actions. Due to these characteristics the shells analyzed in this paper behave elastically under the earthquake excitation, without surpassing the maximum allowable concrete strength. For shallow shells it is observed that the vertical components of the earthquake vibrations, can induce larger stresses in the shell than the horizontal components. It is further demonstrated that by increasing the rise and curvature of larger shells (20 m by 20 m), their fundamental frequencies are increased and the damaging effect of the vertical earthquake vibration components mitigated.


ABSTRACT: An approach to reliability-based design (RBDO) of beam reinforced composite structures with non-linear geometric behavior is proposed. A unified approach following both buckling and first-ply failure (FPF) is used to verify the integrity of beam reinforced shallow shell laminated structures. A new RBDO methodology using a genetic algorithm and a hierarchical decomposition searches the global most probable failure point (MPP). For the reliability analysis, the random parameters are the mechanical properties of laminates. Simultaneously the optimal design based on weight minimization under prescribed reliability and buckling constraints is searched through this hierarchical genetic algorithm (HGA). The design variables are the ply angle, the ply thickness, the height and the width of the cross sections of the stiffeners. Numerical results show the capabilities of the proposed approach using the MPP search inner loop integrated in a HGA scheme. Based on a sensitivity methodology the uncertainty for the optimal solution obtained from HGA is analyzed. In the neighborhood of critical buckling values of the structural response the asymptotic behavior of uncertainty propagation is observed. The influence of uncertainties from random parameters and design variables are studied on critical load factor and critical displacement. The variability of these structural response functions are measured by their coefficients of variation and Sobol indices. The most important influences for uncertainty propagation are obtained from ply angle of shell laminates and from longitudinal elastic modulus group.


ABSTRACT: Cold-formed steel channel sections are generally used as flexural members in light weight steel construction. Improved channel section profiles such as SupaCee sections with longitudinal web stiffeners and curved lips are also used instead of the conventional lipped channel sections. Web crippling capacities of these innovative sections can be different from those of conventional lipped channel sections. However, the web crippling behaviour and strength of these high strength SupaCee sections has not been investigated yet. Current web crippling design methods given in cold-formed steel design standards do not include any design procedures.
for SupaCee sections. Hence an experimental study involving 36 web crippling tests was first undertaken to investigate the web crippling behaviour and strengths of SupaCee sections under two flange load cases with their flanges unfastened to the supports. Comparison of experimental results showed that the web crippling capacities of SupaCee sections are reduced in comparison to lipped channel sections. Therefore the current web crippling design equations in the American and Australian/New Zealand cold-formed steel design standards were modified by including suitable web crippling coefficients for SupaCee sections. Finite element models of tested SupaCee sections were also developed and validated using the experimental results. This paper presents the details of the experimental and numerical web crippling studies of SupaCee sections under two flange load cases and the results. It also presents the details of direct strength method based design equations developed in this research.


ABSTRACT: The objective of this study is to develop an effective numerical model within the framework of an isogeometric analysis (IGA) to investigate the geometrically nonlinear responses of functionally graded (FG) microplates subjected to static and dynamic loadings. The size effect is captured based on the modified strain gradient theory with three length scale parameters. The third-order shear deformation plate theory is adopted to represent the kinematics of plates, while the geometric nonlinearity is accounted based on the von Kármán assumption. Moreover, the variations of material phrases through the plate thickness follow the rule of mixture. By using Hamilton’s principle, the governing equation of motion is derived and then discretized based on the IGA technique, which tailors the non-uniform rational B-splines (NURBS) basis functions as interpolation functions to fulfil the C2-continuity requirement. The nonlinear equations are solved by the Newmark’s time integration scheme with Newton-Raphson iterative procedure. Various examples are also presented to study the influences of size effect, material variations, boundary conditions and shear deformation on the nonlinear behaviour of FG microplates.


ABSTRACT: This paper investigates the elastic buckling behaviour and load resistance of a double cross-arm pre-tensioned cable stayed buckling-restrained brace (DPCS-BRB) where an extra cross-arm is assigned within a longitudinal cable truss along its length. Naturally, the span and efficiency of the PCS-BRB can be increased and improved by adopting multiple cross-arms. Equilibrium method is utilised to derive the formula of elastic buckling load of a pin-ended DPCS-BRB, and the obtained results have been verified through FE analysis. It is found from theoretical derivations and FE analysis that there exists a single-wave symmetric and double-wave antisymmetric buckling modes in the DPCS-BRB, respectively. In addition, a negative linear correlation exists between the elastic buckling load and the initial pre-tensioning force of the cables in the DPCS-BRB. Furthermore, it has been explored through FE analysis that the optimal location of the cross-arms for achieving higher elastic buckling load as well as higher ultimate compressive load-carrying capacity is found to be a quarter length to each end of the DPCS-BRB. At last, the ultimate compressive load-carrying capacity of the DPCS-BRB is found to be directly proportional to its restraining ratio, and there exists a lower limit of the
restraining ratio which ensures the core could reach its full cross-sectional yield load without overall instability of the DPCS-BRB. The investigation of the elastic buckling behaviour and ultimate compressive load-carrying capacity as well as the failure mechanism of the DPCS-BRB provides fundamentals to the further development of a comprehensive design method of the DPCS-BRB subjected to axial cyclic loads.


ABSTRACT: The rhombic grid hyperboloid-latticed shells (RGHLSs) in the China Comic and Animation Museum (CCAM) are located on the ground floor, and they sustain enormous vertical and horizontal loads induced from upper building structures on top of them. Each RGHLS consists of numerous bidirectional inclined major and secondary columns that intertwine with one another to form a rhombic grid with X-shaped joints. Without both horizontal circumferential members and horizontal lateral braces in the radial direction of the RGHLS, as well as the existence of significant difference of compressive stiffness between major and secondary columns, the RGHLS would ultimately fail in a complicated form of in-plane and out-of-plane multi-column interaction instability in addition to its overall twist deformation under relatively low vertical loads. Currently, no design method for estimating its design strength and safety is available. Therefore, the load-carrying capacity of the RGHLS must be examined experimentally. This paper selects the RGHLS denoted by Y4 in the structure of the CCAM as the prototype, and presents an experimental investigation of its reduced scale (1:1/4) test model. A loading protocol consisting of six loading phases has been devised in order to predict the static vertical and horizontal load resistance, and horizontal hysteretic response of the RGHLS by keeping the amplitudes of the vertical load constantly as 1.0, 1.4 and 1.6 times the vertical design load of the reduced-scale test model, respectively. The experimental results obtained indicate that the test model remains elastic under 1.8 times its design loads, which is commonly adopted as static structural strength limit in practical design in China. In addition, horizontal cyclic load test indicated that the reduced-scale test model demonstrated sufficiently large horizontal load-carrying capacity as well as exhibited stable and ample hysteretic curves even under 1.6 times vertical load actions without any obvious stiffness reductions. This study comprehensively introduces the experimental test schemes and deeply analyzes the experimental results, thus forming an important basis for designing the load-carrying capacity of such RGHLSs. Ultimately, according to the experimental loading protocol, numerical simulations and analyses of the test model have been conducted by adopting ANSYS 12.1. The interaction strength design curve of the test model under a combination of vertical and horizontal loads is also proposed by carrying out additional numerical simulations of the model. The FE and experimental results have been compared, and they correspond well to one another, indicating that the results of the reduced-scale test model are accurate enough and reliable.


ABSTRACT: Concrete-filled steel tubular (CFST) columns have frequently been utilised in the construction of mid-rise and high-rise buildings as they offer smaller cross-sectional size to load carrying capacity ratio than ordinary reinforced concrete or steel solutions. The steel tube component of CFST columns can be shaped into different forms to further increase its strength and this article focuses on hexagonal CFST short columns in compression. Firstly, the literature is revised and it was found that the available experiments on the hexagonal
columns cover relatively limited hexagonal dimensions and material properties. Additionally, existing design models were observed to be inaccurate for certain diameter-to-thickness (D/t) ratios of the columns. Accordingly, this paper intends to widen the available pool of data and proposes a new design model to design hexagonal CFST short columns in compression. This is made herein through comprehensive finite element (FE) models by using Abaqus software, carefully validated against experimental results and subsequent parametric studies covering a wide range of hexagonal dimensions of regular cross-section (circular-like). The effect of various D/t ratios, material steel grades and concrete compressive strengths (math) on both the behaviour and strength of the hexagonal CFST short columns is investigated. Based on observations made and conclusions drawn upon analysing numerical data generated, a new design model is presented which provides better strengths compared with available design models and with accurate predictions for the full range of ratios.


ABSTRACT: Foam filled multi-cell tubes have attracted much attention recently because of their exceptional advantages in energy absorption characteristics and lightweight. The study aims to explore the effects of cross-sectional configurations, including topological distribution of empty and foam-filler in the multi-cell tube, on the crashworthiness; and further optimizing the wall thickness and foam density. First, the coupled finite element method (FEM) and element free Galerkin method (EFGM) were adopted to model the foam filled multi-cell tubes. Second, the multi-criteria decision making method, namely COPRAS (complex proportional assessment), was used to rank the energy absorption characteristics of the considered foam filled multi-cell tubes with different topological configurations. The results show that the five-cell tube with four cells in the corners filled with forms was the best choice compared with the other topological configurations for the given design domain. Finally, the discrete optimization based on successive orthogonal arrays was employed to conduct the topological design of foam filled multi-cell tubes for maximizing the specific energy absorption (SEA) under the constraint of the global peak crushing force (GPCF). The results showed that the SEA of the optimized design is about 6.15% higher than the best choice from COPRAS analysis within the GPCF constraint, which demonstrated that the proposed approaches can be an effective tool for crashworthiness topology optimization of foam filled multi-cell tubes.


ABSTRACT: An innovative composite column, named concrete-filled RPC (reactive powder concrete) tube (CFRPCT), is presented in the paper. In this hybrid system, high-strength spiral hoops are arranged in the prefabricated RPC tube and then concrete is poured in the RPC tube. Besides serving as formwork, the RPC tube can provide excellent stiffness and can directly carry considerable axial load attributed to its ultra-high compressive strength. Moreover, high-strength hoops in the RPC tube provide lateral confinement for the inner concrete. A total of 27 large-scale columns were tested under axial compression load, to investigate the composite effect between RPC tube and inner concrete. The results show that axial load carrying capacity of the CFRPCT columns is about 6.0% higher than the total capacity corresponding to the hoop-confined column and the hollow RPC tube. The CFRPCT system effectively combines the high strength of RPC and hoop
confinement. Based on experimental findings and modified existing model, a confinement model was proposed to predict the axial load carrying capacity of CFRPCT columns and it was also validated with experimental results. This CFRPCT system provides a type of cement-based composite column, which owns high compressive performance, excellent durability and corrosion resistance.


ABSTRACT: So far, the loading path effect on the compressive strength of confined concrete has been poorly investigated. To clarify the compressive strength of confined concrete in concrete-filled steel tube (CFT) columns, experimental tests with a total of 18 specimens are conducted to investigate the loading paths of confined concrete in concrete loaded CFT stub columns. The parameters that are varied in the experiment include the steel strength, the unconfined concrete strength and the $D/t$ ratio. Two evaluation indices, namely the laterally dominant index and the effect index, are proposed to characterize the loading path and its effect on the compressive strength of confined concrete, respectively. A detailed parametric study is conducted on the loading paths and the corresponding effects on compressive strength. The results suggest that the loading paths of confined concrete in CFT column are affected by the column parameters. Depending on the loading paths by which the concretes are confined, the loading path effects on the compressive strength of the confined concrete in CFT columns could be totally different. Based on the test results, a compressive strength model incorporating the loading path effect is developed and good performance was found in comparison with the experimental results.


ABSTRACT: The geometrically nonlinear harmonically excited vibration of third-order shear deformable functionally graded graphene platelet-reinforced composite (FG-GPLRC) rectangular plates with different edge conditions is examined. The considered plate with -layers is made from a mixture of an isotropic polymer matrix and graphene platelets (GPLs) in each layer. The weight fraction of GPLs changes in a layer-wise manner. The modified Halpin-Tsai model and rule of mixture are utilized to compute the effective material properties of FG-GPLRCs. To mathematically model the vibrations of FG-GPLRC plates, the displacement field, strain tensor and constitutive relations as well as the energy functional of system including strain and kinetic energies and external work are represented in matrix forms as a function of the displacement components. Then, by simultaneous use of Hamilton’s principle and an efficient numerical scheme namely, the variational differential quadrature (VDQ) technique, the weak form of discretized nonlinear equations of motion is obtained. The present model includes the influences of geometric nonlinearity, rotary inertia and transverse shear deformation. Furthermore, a multistep numerical approach based on the Galerkin method, time periodic discretization method and pseudo arc-length continuation technique in conjunction with the modified Newton-Raphson method is employed to solve the problem of nonlinear harmonically excited vibration of FG-GPLRC rectangular plates. Results are plotted in the form of frequency-response and force-response curves to indicate the effect of various parameters such as GPL distribution pattern, weight fraction, geometry of GPL nanofillers and boundary constraints of FG-GPLRC plates.
ABSTRACT: The aim of the paper is to propose a new approach for the optimization of grid shell structures based on a mixed sizing/topologic process, which specifically accounts for the global buckling behavior. The approach consists of merging a sequence of sizing and topological optimization processes where local and global buckling phenomena are opportunistically introduced. Indeed, in addition to the removal of some members and the increase/decrease of the cross section size of the remaining ones, the proposed approach accounts for the possibility to convert some of the elements composing the grid shell structure, generally trusses, into beam elements with the aim of having an optimized solution also with respect to the global buckling behavior. The selection of the truss members to convert into beams is made by considering two different strategies presented in detail in the paper. Numerical analyses referring to some case studies derived from the current literature are developed by considering the proposed approach and a traditional sizing/topologic mono objective approach. The results obtained from the numerical analyses clearly underline the reliability of the proposed approach and its efficiency in comparison to traditional approaches of structural optimization.

ABSTRACT: The confinement provided in concrete-filled steel tube (CFST) columns can significantly increase the strength and ductility of the concrete columns. However, in non-circular CSFT, the confining stresses are non-uniform and anisotropic, making their incorporation in structural analysis and design fairly difficult. Herein, a novel finite element (FE) model, which takes into account the lateral expansion and triaxial behaviour of the confined concrete, plastic behaviour of the steel tube and interaction at the concrete-steel tube interface in the evaluation of the confining stress field, is developed. It is applied to analyse a total of 92 axially loaded square CFST specimens published in the literature with concrete cylinder strength ranging from 24 to 110 MPa, steel yield strength from 262 to 835 MPa and steel tube depth-to-thickness ratio from 18 to 102. Overall, the FE analysis yielded full-range load-strain curves in good agreement with the experimental results. Using the new FE model, parametric studies on the effects of corner radius have been conducted and it is found that increasing the corner radius would produce better confinement at post-peak stage and thus would improve the post-peak behaviour of square CFST columns.

ABSTRACT: High performance cementitious materials have made possible the construction of slender thin cementitious shells. For their design, the most relevant recommendations are those provided by the International Association of Spatial Structures (IASS), which, however, are inconsistent with the modern European design framework. In the case of steel shells, Eurocode 3 provides a simplified design approach based on the well-known buckling capacity curves. The aim of this paper is the determination of the capacity curve of a radially compressed spherical cementitious shell, for different fabrication quality classes and the determination of the four buckling parameters that describe the curve.

ABSTRACT: This paper presents a comprehensive test database of concentric compression experiments on pultruded fiber-reinforced polymer (PFRP) specimens that failed in a global flexural buckling mode published in literature between 1969 and 2016. A new closed-form equation to determine the reduction factor for global
flexural buckling of PFRP structural struts under axial compression is developed on the basis of the Ayrton-Perry formula and observed initial out-of-straightness of PFRP members measured by other researchers. Recognizing that data on initial imperfections may be unavailable, a second new empirical closed-form equation is derived based upon the experimental database. Validation of the two explicit expressions is performed by both comparison to experimental data and comparison with validated numerical simulations. In addition, the accuracies of the two proposed equations are compared with those of five closed-form solutions available in the literature; both results in more accurate predictions than the extant equations. Both new proposed equations can be conveniently used by structural engineers at the preliminary engineering design stage for accurately assessing the reliability and safety of composite structures under concentric compressive loading.


ABSTRACT: The current study forms a part of a larger experimental program investigating the performance of novel, lightweight, cost-effective, cold-formed, steel sandwich panels with different core configurations under blast induced out-of-plane loading. In the body of literature on sandwich panels, no general methodology is provided to assess their post-elastic behavior under either static or dynamic loading. This study represents a first step in determining the resistance of novel sandwich panels under blast pressure: it focuses on evaluating the quasi-static resistance function of the panels, which is instrumental to the determination of their dynamic response to blast, in accordance with recent American (ASCE/SEI 59-11) and Canadian (CSA S850-12) design standards. The tests carried out by the authors involve twenty-one panels categorized in several configurations, each characterized by a different core topology and deck profile, including uni-directional corrugated, bi-directional corrugated, and X-core panels. These configurations are investigated as plausible solutions to the problem of improving the strength, ductility, and energy absorption capabilities of panels tested in a previous stage of the experimental program. The modes of failure experienced by the test panels are identified and discussed. The load and deflection measurements recorded during the tests are used for the characterization of each panel resistance function in terms of yield load, ultimate load, and the corresponding displacements. The influence of core configuration and sheet thickness on the panels’ ductility and energy absorption capacity is also examined. The results presented in this study will be instrumental in the future development of lightweight, cost-effective sandwich panels, to be used as sacrificial cladding in blast resistant buildings.


ABSTRACT: This work presents an analysis of upheaval buckling of pipelines triggered by internal pressure. It discusses the existing relationship between internal pressure and equivalent compressive axial force in the buckling context. The main focus is on the relative influence of prop imperfections and soil friction coefficients in critical load prediction and post-buckling configuration. To perform the analyses, numerical models are developed using geometrically-exact finite element of beams, undergoing large displacements and finite rotations. Contact between the pipeline and the soil is also included in the models. As a result, the work shows the equivalence of applying the internal pressure as a distributed load dependent on pipe curvature and as a follower compressive axial force, both in terms of critical load and post-buckling configuration. Varying prop imperfections and soil friction coefficients, it is concluded that the first parameter has more influence in critical load prediction than the last one. The same occurs in terms of post-buckling configuration: for the same increase of internal pressure from critical load, the imperfections have more influence in the post-buckling displacements than the friction between the pipeline and the soil.

ABSTRACT: The objective of the present paper is to develop an efficient and accurate design optimization procedure to minimize the mass of the stiffened panels subjected to uniform compression loading, while guarding against the buckling failure. A Finite Element (FE) model based on the Integrated Force Method (IFM) is developed to perform the buckling analysis of stiffened panels. It has been shown that the finite element analysis based on the force methodology is able to predict the critical buckling load accurately and efficiently. The Sequential Quadratic Programming (SQP) is then applied to the established IFM model to minimize the mass of stiffened panels while guarding against buckling failure. An efficient analytical formulation to perform the sensitivity analysis is formulated using the developed finite element force method, and then utilized in the SQP formulation as the gradient information. Illustrated examples have been presented to verify the validities of the proposed methodologies. It has been shown that comparing to the numerical sensitivity analysis, the design optimization using the developed analytical sensitivity formulation is very efficient and accurate.


ABSTRACT: Composite tanks with truncated cone vessels, consisting of an outer thin steel shell and an inner concrete wall, are becoming common. Such composite conical tanks benefit from the high buckling resistance to compressive meridional forces of the concrete walls and the efficiency of the steel shells in resisting tensile hoop stresses. Motivated by the lack of information in the literature and the codes of practice about the seismic behaviour and design of such structures, this paper represents the first comprehensive study focusing on the seismic analysis of composite conical tanks. The study is conducted numerically using an in-house developed model that accounts for the hydrodynamic pressure resulting from the vibration of the contained fluid. The model also accounts for the interaction between the fluid and the structure vibrations. In this model, both the steel and concrete walls are modelled separately using shell elements and a special interface element is included to account for the connecting shear studs. The model is capable of conducting both free vibration and seismic analyses for the composite tank-liquid system taking into account the sloshing effect. The model is used to assess the adequacy of using a simplified technique in the seismic analysis and design of such structures. In order to examine the seismic behaviour of those structures, a real composite conical tank is considered as a case study. Time histories and maximum values for stresses at the concrete and steel walls, forces at the base, and forces in the studs under different earthquake excitations are reported. Those values are compared to their counterparts resulting from the hydrostatic pressure to assess the importance of including the seismic loads in the analysis of such structures.


ABSTRACT: The Generalized Differential Quadrature (GDQ) and Newmark methods are chosen to solve time integration problems such as the dynamics of composite arches and vaults with constant and variable cross-sections, under seismic impulse loading applied at the base. A 2D Equivalent Single Layer (ESL) shell theory is used to analyze the problem numerically, where the governing equations of motion are solved in a strong form without passing through any variational formulation. The total time interval is discretized in time steps, as required by a Newmark approach, and the GDQ method is applied to solve a system of linear ordinary differential equations for each time step. The accuracy of the proposed method in predicting the dynamic
response of the arched or vaulted structures is demonstrated by comparing the GDQ-based results for different geometries and external loadings, with the ones obtained with a standard Finite Element Method (FEM).


ABSTRACT: The use of FRP with seawater and sea sand concrete (SWSSC) holds great potential for marine and coastal infrastructure, and concrete-filled FRP tubular columns are among the attractive forms of structural members for such applications. This paper presents a theoretical model for the compressive behaviour of seawater and sea sand concrete-filled circular FRP tubular stub columns. FRP tubes can be manufactured to possess considerable strength and stiffness in the longitudinal direction, so the behaviour of concrete-filled FRP tubes differed substantially from that of concrete columns with an FRP wrap (also referred to as “concrete-filled FRP wraps”) which commonly contains fibres only in the hoop direction. Many theoretical models have been proposed for concrete-filled FRP wraps, but very limited work has been conducted on the theoretical modelling of concrete-filled FRP tubes. In the present study, an existing dilation model for concrete-filled FRP wraps is combined with a biaxial stress analysis of the FRP tube so that the effect of the Poisson’s ratio of the FRP tube is properly accounted for. In order to predict the buckling of the FRP tube, a maximum strain buckling failure criterion is proposed and is shown to be in reasonable agreement with the experimental results. Moreover, the load carried by the FRP tube is studied, and a simplified model is proposed to determine the load shared by the FRP tube during the entire loading process. Finally, a theoretical model for SWSSC-filled FRP tubular columns is proposed, in which the behaviour of both the concrete and the FRP tube as well as their interactions are explicitly modelled (i.e., an analysis-oriented model). The proposed model gives reasonably close predictions of the existing experimental data.


ABSTRACT: In this study, an innovative composite shear wall, comprised of boundary Concrete Filled Steel Tubular (CFST) columns, and Reinforced Concrete (RC) walls embedded with multiple steel plates has been developed. Seven specimens were investigated by cyclic loading tests. The parameters were the type of the boundary CFST columns, the number of multiple steel plates and the axial force ratio. There were two loading stages for the tests. During stage 1, the specimens were tested until a 2.0% drift ratio was attained. After stage 1, damaged specimens were retrofitted and tested in stage 2. The failure characteristics, hysteretic behavior, strength and deformation, strains, energy dissipation capacity and stiffness were studied. The results show that the hysteretic curves of the innovative shear walls were stable. The embedded multiple steel plates had a considerable effect on the seismic behavior of the innovative shear walls, and the strength increased with increasing number of steel plates. There was no considerable difference in the effect on seismic behavior for the different types of the boundary CFST columns. The developed shear walls, after retrofitting, were shown to satisfy seismic requirements. Finally, an evaluation method for the ultimate strength of the shear walls was developed with adequate accuracy.


ABSTRACT: Steel plate reinforced concrete composite shear wall (abbreviated as SPRW) is a novel type of composite shear wall which consists of a steel plate incased in the middle of a reinforced concrete shear wall. This arrangement aims at improving the performance of the wall, as steel plate can effectively increase the
seismic behavior and concrete can protect steel plate from buckling and corrosion. In this paper, a total of 16 SPRW specimens and 3 traditional reinforced concrete (RC) walls are designed for the cyclic loading test to study the seismic performances, including failure phenomena, failure mechanism, load carrying capacity, ductility and energy dissipation characteristics, etc. Based on the extensive experimental results, the influences on the seismic behavior of SPRW are analyzed through varying parameters, e.g. aspect ratio, thickness of the wall and the steel plate, structural detailing. Finally, the hysteretic curve model and shearing capacity are generalized based on massive test data, and the design formula of shearing capacity is also proposed based on current design codes.


ABSTRACT: Compressed reinforcement buckling in concrete columns can reduce ductility in structural elements. In order to avoid this, design codes propose maximum required tie spacing. Nonetheless, they do not incorporate the positive effect of concrete fibers in their formulation, whose capability of delaying buckling has been proved. For this reason, recommendations for maximum required tie spacing for elements made with concrete, with or without steel fibers, and with normal or high strength, are proposed in this article. In order to achieve this, the mixed model proposed by Pereiro-Barceló and Bonet was extended to consider elements made of HSC with and without steel fibers thanks to the results of an experimental campaign of HSC columns with and without fibers, under monotonic loading. In these tests, the buckling critical load in compressed reinforcement was experimentally determined in all the columns. In addition, a comparison of the proposed transverse concrete separation with respect to the recommendations proposed by the main existing codes was made.


ABSTRACT: Analytical investigation of collapse of a pinned non-uniform shallow circular arch under uniform radial pressure is presented in this paper. The non-uniformity is introduced by dividing the arch into three regions of constant stiffness. The equilibrium equations are obtained by using least potential energy principle. By proper nondimensionalization, the presented solution is independent of total length of the arch. And two modified slenderness parameters are identified which enables the result to be valid for any symmetric cross-section shape. Parametric study on different geometric parameters has been carried out on the snap-through buckling load and anti-symmetric bifurcation load. The validity of the analytical result is verified by comparison with FEA results. Criteria concerning four deformation modes are identified. We show there is an equal potential energy load for some non-uniform shallow arches by a straightforward deduction, the existence of which load is a necessary condition for the buckle propagation of a corresponding long shallow panel. Finally two limiting cases (rigid center case and rigid end case) with extreme non-uniformity are analytically studied by using augmented potential energy with Lagrangian multipliers. For rigid center case, closed-form condition for the possible occurrence of symmetric snap-through is presented. For rigid end case, an asymptotical analysis leads to a somewhat surprising critical value of slenderness which makes the snap-through buckling just possible. This paper intends to improve the understanding of the effect of non-uniformity on collapse of shallow arch under radial uniform pressure.

ABSTRACT: Cold-formed steel (CFS) elements are increasingly used as load-bearing members in construction, including in seismic regions. More conventional hot-rolled steel and concrete building structures are typically allowed by the design standards to exceed their elastic limits in severe earthquakes, rendering parameters indicating ductility and energy dissipation of primordial importance. However, insufficient research has yet been conducted on the energy dissipation of CFS structures. In the majority of previous optimization research on CFS sections the ultimate capacity, as typically controlled by local, distortional and/or global buckling modes, is considered to be the sole optimization criterion. This paper aims to improve the seismic performance of CFS elements by optimising their geometric and material highly non-linear post-buckling behaviour to achieve maximum energy dissipation. A novel shape optimisation framework is presented using the Particle Swarm Optimisation (PSO) algorithm, linked to GMNIA ABAQUS finite element analyses. The relative dimensions of the cross-section, the location and number of intermediate stiffeners and the inclination of the lip stiffeners are considered to be the main design variables. All plate slenderness limit values and limits on the relative dimensions of the cross-sectional components as defined by Eurocode 3, as well as a number of practical manufacturing and construction limitations, are taken into account as constraints in the optimisation problem. It is demonstrated that a substantial improvement in energy dissipation capacity and ductility can be achieved through the proposed optimization framework. Optimized cross-sectional shapes are presented which dissipate up to 60% more energy through plastic deformations than a comparable commercially available lipped channel.


ABSTRACT: A corrugated web beam (CWB) is a variation to the universal hot rolled or welded I section. CWBs usually comprise of wide thick plate flanges and a thin corrugated web. Due to the accordion effect shear is carried primarily by the corrugated web while bending moments are resisted by the flanges. Under shear action three different modes of shear buckling may be realised in the web – local, global or interactive. This paper describes analyses performed to investigate the local shear buckling behaviour of beams with trapezoidal corrugated webs. Finite element models of cantilever beams with different web geometries were prepared and an elastic eigenvalue buckling analysis was performed using the program ABAQUS. The influence of web thickness, panel width and web height on the local shear buckling coefficient $k_L$ was investigated. Values of $k_L$ were compared against existing equations from theory and other research. The effect of these dimensions on the local shear buckling stress was also considered. In total, 90 models were analysed. Overall, it was found that the value of $k_L$ lies between 5.34 and 8.98. This corresponds to panel boundary conditions that are between simply supported and clamped. The analysis results revealed that $k_L$ increases with stockier panels (large panel width to height ratio) but decreases with thicker webs. When the panel width was decreased, local shear buckling occurred at larger stress values. Similar results were observed when the web height was decreased and the panel thickness was increased. These results are consistent with plate buckling theory. Finally, based on these findings an equation to approximate the local shear buckling coefficient in corrugated web beams is recommended.


ABSTRACT: A type of precast slender composite shear wall was proposed and experimentally studied. In this new precast structural wall system, concrete-filled steel tubes (CFSTs) were used to entirely replace the longitudinal reinforcement in the boundary elements of conventional reinforced concrete (RC) shear walls. At joints, the CFSTs and wall web reinforcement were connected by sleeves filled with high-strength mortar. To examine the seismic performance of the proposed system, seven 1/3-scale specimens were built and tested
under quasi-static and dynamic cyclic lateral loading with a top displacement rate up to 20 mm/s. Major test variables included axial force ratio ranging from 0.075 to 0.19 and loading rate. This paper reports the damage pattern, hysteretic load-deformation response, energy dissipation capacity, and connection performance of the test specimens. Under the considered axial force levels and loading rates, lateral loads were successfully resisted at the joints and the response of all specimens was dominated by flexure. The use of CFSTs increased lateral strength and deformation capacity. The highest axial force ratio caused drift capacity to be reduced from 2.5% to 2.0%. Although loading rate nearly had no influence on either lateral stiffness or strength, it reduced energy dissipation capacity. Finally, the effectiveness of proposed detailing of sleeve-mortar connections in load transfer was validated by the similar hysteretic response, joint opening, and wall sliding between monolithic and precast CFST wall specimens.

Xiaoyi Lan, Junbo Chen, Tak-Ming Chan and Ben Young, “The continuous strength method for the design of high strength steel tubular sections in compression”, Engineering Structures, Vol. 162, pp 177-187, May 2018

ABSTRACT: This paper aims to extend the deformation-based design method named continuous strength method (CSM) for the design of high strength steel tubular sections in compression. The CSM employs a base curve relating the cross-section resistance to its deformation capacity and adopts an elastic, linear hardening material model. Non-slender and slender circular hollow sections (CHS), elliptical hollow sections (EHS), square hollow sections (SHS) and rectangular hollow sections (RHS) were investigated in this study. Hot-finished, cold-formed and built-up steel tubular sections with yield stresses up to 1405 MPa were covered. An extensive numerical study was carried out to supplement the limited test results of high strength steel stub columns in the literature. The cross-section resistances obtained from the proposed CSM, the direct strength method (DSM), and design methods in EN 1993-1-5, EN 1993-1-6, ANSI/AISC 360-10 and AISI S100 were compared with the experimental and numerical capacities of 742 stub columns. It is shown that the proposed CSM can produce more accurate and less scattered strength predictions than the current DSM and design codes.


ABSTRACT: This paper is concerned with the effects of distortion on the lateral buckling of steel beams which have rectangular or square hollow flanges and folded plate webs. The hollow flanges potentially make very large contributions to the torsional stiffness, but flange distortion (in a shear mode) causes a significant reduction in the effective torsional stiffness and in the lateral buckling resistance.

In this paper, the shear distortion of the hollow flanges is analysed, and the strain energy stored in a distorted flange is compared with the strain energy stored during uniform torsion of the flange. This comparison allows the development of a suitable parameter for use in the evaluation of the effect of flange distortion on the torsional stiffness of a hollow flange beam. Uniform torsion test results are used to confirm the significance of this parameter.

Finite strip analyses of simply supported hollow flange beams in uniform bending show that there is a significant interaction between distortion and uniform torsion during lateral buckling, which may be approximated by combining their flexibilities. More accurate finite element analyses show that the finite strip predictions are conservative. An approximate method of predicting the effects of flange distortion on elastic lateral buckling is presented which shows good agreement with the finite element predictions.

ABSTRACT: In this paper, the effect of non-uniform bending on the lateral torsional buckling (LTB) of steel beams with slender cross-sections subjected to elevated temperatures is numerically investigated. Local buckling is the main failure mode for slender sections whereas the lateral torsional buckling is one of the principal failure modes for beams, thus the interaction between these two failure modes greatly affects the load-bearing capacity of the beams. In the case of fire, recent studies have shown that the design procedures of Part 1–2 of Eurocode 3 are unreliable and too conservative due to the inconsistent treatment of such interaction phenomena. On the other hand, it is known that non-uniform bending has a beneficial effect on the ultimate capacity of beams but there is limited knowledge about its influence on beams with slender cross-sections. This work aims at studying the influence of non-uniform bending on the combined local-global interaction response of beams with slender open I-sections in the case of fire. The inclusion of the factor “” in a recently proposed LTB design procedure that groups the response of the beams into different ranges of effective section factors is analysed and the accuracy of such proposal is demonstrated against around 20,000 GMNIA (Geometrically and Material Non-Linear Analyses with Imperfections) simulations. Finally, the improvements of this proposal on the current Eurocode 3 design procedure are highlighted.

Yuner Huang and Ben Young, “Design of cold-formed stainless steel circular hollow section columns using direct strength method”, Engineering Structures, Vol. 163, pp 177-183, May 2018

ABSTRACT: Cold-formed stainless steel circular hollow section (CHS) columns have been increasingly used in construction, due to its aesthetic appearance, long life-span and good ductility. It is shown that direct strength method (DSM) is capable of predicting cold-formed steel column strengths accurately. However, the DSM is developed for cold-formed steel sections with plate rather than curved elements, and thus its applicability for cold-formed stainless steel CHS is worth investigating. This paper presents a numerical investigation of cold-formed stainless steel CHS columns. A non-linear finite element model was developed and verified against column tests. Extensive parametric study of cold-formed duplex, lean duplex and ferritic stainless steel CHS columns has been performed to obtain column strengths. A total of 273 experimental and numerical cold-formed stainless steel CHS column strengths, which are obtained from previous researches and parametric study obtained from this study, are compared with the design strengths predicted by the current DSM. Reliability analysis was performed to evaluate the reliability of the design rules. It is shown that the current DSM provides unconservative and not reliable prediction for cold-formed stainless steel CHS columns. Therefore, modified DSM is proposed for cold-formed stainless steel CHS columns. It is shown that the modified design rule is more accurate than the current DSM, and the modified design rule is considered to be reliable.

Zhigang Li, Haifeng Yang, Xiongwei Hu, Jifei Wei and Zhitong Han, “Experimental study on the crush behavior and energy-absorption ability of circular magnesium thin-walled tubes and the comparison with aluminum tubes”, Engineering Structures, Vol. 164, pp 1-13, June 2018

ABSTRACT: In this study, a series of axial crush tests were performed on AZ31B magnesium and A6063 aluminum thin-walled circular tubes to investigate the influence law of the failure mode and energy absorption capacity dictated by length/diameter (L/D) ratio, compression speed, and induced features as well as their difference. In general, the magnesium tubes absorbed energy mainly by fracture while the aluminum tubes absorbed energy by plastic yielding with folding generated. With increasing L/D, the failure mode of magnesium tube generally tended to change from a splitting mode with relative good crashworthiness to a bi-tube slicing mode with inferior crashworthiness and, finally to an Euler mode that nearly lost its crashworthiness, whereas, for the aluminum tubes, the ring or diamond or ring & diamond mixed mode was observed, with crashworthiness parameters changing very slightly. The compression speed has more obvious effect on the energy-absorption increment of magnesium tube than that of the aluminum tube. The SEA (specific energy absorption, which is defined as the energy absorbed per unit mass of the crushed tubes) of the
magnesium tube was lower than that of the aluminum tubes at quasi-static condition regardless of the failure modes; however, it outperformed the aluminum tube at the compression speed equal or greater than 0.1 m/s. The induced features characterized in this study exhibited an alternating trend between the original deformation/failure mode and an inferior mode, which did not facilitate the load-carrying and energy absorption of both the magnesium and aluminum tubes.

ABSTRACT: Thermal upheaval buckling of continuously reinforced concrete pavements is widely reported around the world in conjunction with the evolution of global warming trends and increasing numbers of prolonged heatwaves, and which may lead to catastrophic scenarios. Such heatwaves may produce a large temperature gradient through the thickness of the pavement, and there is a need to examine the effects of a temperature gradient on pavement buckling. This paper proposes an analytical closed-form model for the thermal upheaval buckling of pavements, with a temperature gradient being embedded in the formulation. The principle of stationary total potential is employed to develop the non-linear equations of equilibrium for the postbuckling response of the pavement, and these equations are solved analytically by considering both the lift-off region and the adjoining region. It is found that the temperature gradient has no influence on a continuous lengthwise-symmetric pavement, so two pavement types are analysed in this investigation, one is a continuous pavement with a joint and the other is a continuous pavement adjoining a rigid structure. The paper demonstrates that a positive temperature gradient will lower the safe temperature of a concrete pavement with a joint, while it raises the safe temperature of a pavement adjoining a rigid structure. The buckling and postbuckling responses of pavements with different characteristics are analysed by considering the temperature gradient; the parameters being the pavement thickness, pavement base and effective weight.

Amine Osmani and Sid Ahmed Meftah, “Lateral buckling of tapered thin walled bi-symmetric beams under combined axial and bending loads with shear deformations allowed”, Engineering Structures, Vol. 165, pp 76-87, June 2018
ABSTRACT: In this paper, the effect of shear deformations on elastic lateral buckling of tapered thin-walled open and closed bi-symmetric section beams under combined bending and axial forces is investigated. For the purpose, a geometrical non-linear beam theory is presented according to a new kinematic model that incorporates shear flexibility components. Ritz method is applied to obtain the governing equilibrium equations, then the buckling loads are computed by solving the eigenvalue problem basing on the singularity of the tangential stiffness matrix. The elastic lateral buckling resistances given by the proposed method are generally in good agreement with the finite element simulation using Abaqus software. The numerical results for cantilevers and simply supported thin walled beams with open and box sections reveal that the classical stability solution tends to overestimate the real lateral buckling resistance of short tapered box cantilever beams.

ABSTRACT: The seismic performance of reinforced concrete-filled steel tube (RCFST) drilled shafts, also known as RCFST pile-columns, was examined based on experimental tests conducted on twelve half-scale RCFST specimens at the soil-structure interaction facility at the North Carolina State University, Constructed Facilities Laboratory (NCSU-CFL). The specimens consisted of steel tubes with diameter-to-thickness (D/t) ratios ranging from 48 to 95 that were filled with reinforced concrete. Spirally welded steel tubes with outer diameters (D) of 12” (305 mm) and 12–3/4” (324 mm) were utilized. The specimens were tested with
aboveground-to-diameter (L_a/D) ratios of 5.5 and 7.5, and they were embedded 14′ (4270 mm) into poorly graded sand (SP). Different levels of soil stiffness were induced in the sand by using a soil-sandwich approach, which allowed for modifying the soil stiffness profile by means of applying a surcharge on the soil surface. Cyclic lateral load was applied by a 100-kip (445 kN), 70-in. (1780 mm) stroke hydraulic actuator, supported on a braced steel frame, and pin-connected to the pile-column head ensuring that the plastic hinge developed below ground. The failure mechanism was controlled by the tensile strain in the steel tube and it was caused by a combination of tube local buckling and tube fracture. First, tube local buckling developed outward at the extreme compression fiber of the section. Tube fracture then occurred in the section with the largest buckle and it extended around about half of the section perimeter. The plastic hinge developed at depths of 2D to 4D. Onset of tube local buckling was observed at higher displacement ductility levels (µ = 3) for specimens using thicker tubes (D/t = 48) than for those using thinner tubes (D/t = 95). The force-displacement response, tensile strain distribution, and hysteretic equivalent viscous damping are discussed in this paper.

Wei Zhang, Zheng Fang, Xiao-Dong Yang and Feng Liang, “A series solution for free vibration of moderately thick cylindrical shell with general boundary conditions”, Engineering Structures, Vol. 165, pp 422-440, June 2018
ABSTRACT: In this paper, a modified Fourier cosine series method for beams and plates is proposed for free vibration analysis of moderately thick cylindrical shell with general boundary conditions. Displacement functions are assumed as a superposition of Fourier cosine series and two types of supplementary functions. Traditional method for elastic constraint which has been used in the classical thin shells is extended to treat the moderately thick shell involving first-order shear theory. The advantage of the approach is that the method can conveniently solve general boundary conditions including elastic constraints in practical engineering field by only varying the stiffness coefficients.

ABSTRACT: This paper presents the instability mechanism of an innovative Rhombic Grid Hyperboloid-Latticed Shell (RGHLS) under vertical load through experimental and numerical investigations. The RGHLS is only composed of bidirectional inclined primary and secondary columns without any circumferential members or lateral braces in its radial direction along its height. Therefore it would likely fail by out-of-plane multi-column interaction instability and the corresponding load-carrying capacity should be predicted. The experimental investigation of a reduced-scale test model of RGHLS was firstly performed to study its vertical load-carrying capacity and the multi-column interaction instability. A special spatial beam-string device for vertical multi-point loading of the test model has been initially designed and fabricated to precisely distribute the concentrated load to the top of the columns according to proportional distribution of loads required by designers. The experimental results revealed that the inclined columns indeed exhibited strong mutual restraining actions, and the ratio of the actual ultimate load-carrying capacity of the test model to its design load was 3.37, indicating a reasonable safety margin. In addition, FE numerical results of the test model corresponded well with the experimental results. Ultimately, additional FE numerical analyses have been conducted on the test model. Accordingly the effects of the ratio of stiffness between the secondary and primary columns, overall initial geometric imperfection, in-plane stiffness of top ring beam, and dimensions of portal columns on the load-carrying capacity and failure mode of RGHLS have been investigated extensively. As a result, the ratio of stiffness between the secondary and primary columns has been particularly recommended within a range of 0.46–0.70, so as to eliminate premature failure of X-joints prior to the instability of columns in the prototype of RGHLS.

ABSTRACT: Liquid storage tanks in the form of truncated cone steel vessels are widely used to provide water supply or to store other liquids. For the case of elevated conical tanks, the effect of the tank vessel base rotation has been assumed to be negligible in previous studies related to seismic behaviour of such tanks. In this study, this assumption is assessed by studying the effect of this rotation on the seismic behaviour and the vibration characteristics of elevated steel conical tanks using finite element models where a fluid-added mass matrix incorporating this effect is derived and then incorporated in dynamic and free-vibration analyses. It is found that the percent reduction in the natural frequency of the first impulsive mode is almost constant for the cases of conical tanks with angle of inclination of 30° and 45°, while it is lower for tanks with inclination angle of 60°. Regarding the base forces, it is found that the percent increase can reach up to 37% for the overturning moment and 34% for the base shear compared to the case of rotation-prevented tanks. In addition, a mechanical analog that simulates the forces acting on an elevated conical tank subjected to a horizontal excitation including the effect of this base rotation is developed taking into consideration the flexibility of the tank walls. Different parameters of the mechanical model are displayed in the form of charts for different tank dimensions. Finally, an example is provided to show how the developed mechanical model is applied.


ABSTRACT: The honeycomb configuration of the many Diamatic dome patterns available is particularly convenient for reciprocally supported element (RSE) transformation. This is due to there being only three lattice bar elements intersecting at any apex, irrespective of the number of the bar elements used to form the crown polygon. RSE transformation effort therefore is both reduced and simplified compared to some RSE forms. To inform the understanding of the structural behaviour of honeycomb RSE lattice domes, a study comparing structural modelling predicted behaviour with monitored behaviour in the laboratory was carried out. This investigation focused on the structural behaviour of a RSE lattice honeycomb dome structure under applied static loading. The first part of the study included configuration processing, structural modelling and analysis. The second part involved manufacture, construction and monitored behaviour of the dome in the laboratory. The creation of the selected RSE honeycomb lattice structure together with the structural modelling and experimental outputs are presented and discussed. Predicted displacements and stresses are compared under varying applied loading, boundary support conditions and connection stiffnesses. The locations of the onset of local yielding is considered and discussed. The applied loading did not exceed the tube yield stress according to the von Mises ductile material failure criterion indicating that the dome behaviour observed was elastic.


ABSTRACT: This paper numerically investigates the structural response and crashworthiness performance of a hexagonal thin-walled grooved tube subjected to axial and oblique impact loading conditions. First, an analytical formulation that estimates the mean crushing force and total energy absorption are obtained for both hexagonal and circular tubes subjected to high dynamic impact loading conditions. The solutions of the analytical model are used to verify and compare the approximate solutions of the finite element model. The inclusion of grooves to the conventional hexagonal thin-walled tubes shows the great potential for improving the crashworthiness performance such as the energy absorption capacity, crushing force efficiency and specific energy absorption. In further, parametric studies are performed, deformation modes of different models are
obtained and their crushing force-displacement characteristics are described. The improved crashworthiness performance of the hexagonal thin-walled grooved tubes make them good candidate used as energy absorbers.


ABSTRACT: Due to mainly thermal and energy potentials, Insulated Glass Units (IGUs) are largely used in modern buildings to realize curtain walls and enclosures. The typical IGU consists of two glass layers, either monolithic and/or laminated, joined together by enclosing an hermetically-sealed air (or gas) cavity between them. There, maximum stresses and deformations derive from external pressures (wind loads, etc.) or environmental/climatic loads (temperature variations, etc.). While the common IGU application involves 4-side continuous supports, novel restraint configurations are increasingly used in practice (i.e. 2-side supports, point-fixings, etc.), hence resulting in additional loading scenarios that could compromise the integrity of these systems. In this paper, following earlier research contributions, a standardized buckling approach in use for structural glass elements mainly compressed or under combined compression/bending is assessed, for the specific case of IGUs with 2-side continuous supports. Analytical and Finite Element (FE) numerical studies are reported, giving evidence of their actual performance and buckling resistance, including parametric analyses and comparisons towards simplified design formulations for both external and internal pressures.


ABSTRACT: Local buckling remarkably reduces the strength of steel plates in rectangular thin-walled concrete-filled steel tubular (CFST) columns at ambient temperature. This effect is more remarkable at elevated temperature. However, there have been very limited experimental and numerical investigations on the local and post-local buckling behavior of steel plates in CFST columns at elevated temperatures. This paper presents numerical studies on the local and post-local buckling behavior of thin steel plates under stress gradients in rectangular CFST columns at elevated temperatures. For this purpose, finite element models are developed, accounting for geometric and material nonlinearities at elevated temperatures. The initial geometric imperfections and residual stresses presented in steel plates are considered. Based on the finite element results, new formulas are proposed for determining the initial local buckling stress and post-local buckling strength of clamped steel plates under in-plane stress gradients at elevated temperatures. Moreover, new effective width formulas are developed for clamped steel plates at elevated temperatures. The proposed formulas are compared with existing ones with a good agreement. The effective width formulas developed are used in the calculations of the ultimate axial loads of rectangular CFST short columns exposed to fire and the results obtained are compared well with the finite element solutions provided by other researchers. The initial local buckling and effective width formulas can be implemented in numerical techniques to account for local buckling effects on the responses of rectangular thin-walled CFST columns at elevated temperatures.


ABSTRACT: The objective of this work is to investigate numerically (using the non-linear FEM and the approach stipulated by the Common Structural Rules) the severe nonuniform corrosion degradation effect on the ultimate strength of stiffened plates and compare the results to the already published experimental works. Different factors governing structural behavior of corroded stiffened plates are investigated, such as corrosion
degradation level, material properties, initial imperfections and boundary conditions. The numerically estimated ultimate strength demonstrated to be very close to those observed during the experimental test. A sensitivity analysis with respect to the most important governing parameters of the numerical estimation of the ultimate strength is also performed and several conclusions are derived. The applied calculation procedure avoids using of a pitted surface of the corroded plates and instead of that an equivalent thickness is applying leading to a relatively fast and practical approach for ultimate strength assessment of corroded stiffened plates.


ABSTRACT: Tapered steel members are often chosen instead of prismatic due to a better cross-section utilization along the member, which makes them an interesting and more economical alternative. Although EN1993-1-1 offers several methodologies for the stability verification of steel members and frames, it does not provide a clear guidance for the stability design of such members. Recently, the research group has provided simplified stability verification methodologies for tapered columns and beams. The developed methodologies are based on analytical derivations which were validated with advanced numerical simulations. In order to improve the accuracy of the proposed procedures, full-scale experimental tests on tapered columns, beams and beam-column were carried out. The experiments are used to calibrate a numerical model, incorporating all relevant parameters, such as: geometrical imperfections (local and global) and material imperfections (residual stresses). In this paper, firstly a global overview of the experimental programme on web-tapered steel members is given. The key results from each experiment are summarized; they are further used for the calibration of an advanced numerical model.


ABSTRACT: Unburied subsea pipelines operating under high-temperature and high-pressure conditions tend to relieve their axial compressive force by forming lateral buckles. In order to manage lateral buckling, a sleeper is often employed as a buckle-initiation technique to ensure pipeline integrity. In this study, analytical solutions of third-mode lateral buckling for unburied subsea pipelines with sleeper are derived. The analytical solution is compared with experimental data in the literature and shows good agreement. The stability of the buckled pipeline is investigated by means of an energy analysis and it is found that third-mode lateral buckling has lower energy than first-mode buckling, which means that third-mode buckling is more likely to happen in practice. The influence of sleeper height and sleeper friction on lateral post-buckling behaviour is illustrated and analysed, with particular attention paid to the minimum critical temperature difference, lateral displacement amplitude and maximum stress. Our results show that increasing the height of the sleeper or decreasing the friction between pipeline and sleeper can both be used to decrease the minimum critical temperature difference, but their influence on the maximum stress is opposite.


ABSTRACT: In the present work, local optimal solutions in shape optimization of cable-stiffened latticed shells are discussed and a modified optimization method is presented. Firstly, a shape optimization method is used to minimize the strain energy of different kinds of cable-stiffened shells. It can be confirmed that local optimal solutions exist in this shape optimization problem. Secondly, in order to get smooth solutions, this paper puts
forward a modified optimization method, in which total length of members or smoothness parameter is employed as a correction term in the optimization equation. In this approach, the modified equation can be solved by weight sum method. The results indicate that smooth optimal solutions can be obtained by solving this equation. Finally, a variable weight method is proposed to achieve the global optimal shape from any initial shape in one-step optimization. In this approach, the weight changes along with the iteration process. The results illustrate that this method is efficient and the global optimal shape is achieved successfully.

ABSTRACT: The Hencky bar-net model, developed from a finite difference plate model, is proposed for buckling and vibration analyses of rectangular plates with non-uniform thickness. The Hencky bar net comprises rigid bars joined by elastic rotational springs to allow for bending flexibility and diagonal springs in each panel to simulate the twisting effect. The non-uniform plate thickness can be readily handled by adjusting the spring stiffnesses. For generality, the edges of the plate are elastically restrained where the special cases are the classical boundary conditions of simply supported edge, clamped edge and free edge. The plate is subjected to uniaxial load or biaxial loads. In order to demonstrate the versatility and the accuracy of the Hencky bar model, some plate problems are analysed and the obtained results compared with existing results reported in the open literature.

ABSTRACT: Finite element models for elastic thin-walled rectangular hollow section (RHS) struts with predefined local and global geometric imperfections are developed within the commercial package Abaqus. A unified local imperfection measurement based on equal local bending energy is proposed. The effects of imperfect cross-section profiles, imperfection wavelength in the longitudinal direction and the degree of imperfection localization on the ultimate load and equilibrium path are investigated and the most severe imperfection profiles are determined. A parametric study on the wavelength of the most severe local imperfection profile is conducted and a semi-empirical equation to approximate the corresponding wavelength is proposed. Moreover, an equation to calculate the global buckling load of thin-walled RHS struts with tolerance level doubly-symmetric cross-section local imperfections is proposed.

ABSTRACT: The reuse of coarsely crushed demolished concrete lumps (DCLs) with fresh concrete (FC) in compound concrete (i.e. concrete composed of DCLs and FC) provides a viable option to recycled concrete aggregates for recycling concrete waste. Compound concrete-filled steel tubular (CCFST) columns further improve the efficiency with which DCLs are used due to the advantages of concrete-filled steel tubular columns, such as improved strength and ductility. This paper presents an experimental study of the compressive behavior of thin-walled circular steel tubular columns filled with compound concrete with and without internal steel stirrups. Twenty CCFST columns were tested for experimental investigation of the effects of the replacement ratio of DCLs, the strength of the FC, the thickness of the steel tubes, and the distribution of steel stirrups. The test results show that steel stirrups can considerably enhance the load-carrying capacity of CCFST columns and significantly improve their ductility regardless of the strength of the FC, and a non-uniform layout
(mainly in the middle height of the column) of steel stirrups can further enhance the performance of the CCFST columns without increasing the amount of steel. Based on the results, a simplified design method proposed for CCFST columns reinforced with internal steel stirrups compared well with the test results.

ABSTRACT: This paper presents an experimental study on the mechanical behaviors of engineered cementitious composite (ECC)-encased concrete filled steel tube (CFST) columns under axial loading. Six specimens, including four ECC-encased CFST columns and two concrete-encased CFST columns were tested. According to the test results, ECC-encased CFST columns showed both higher loading carrying capacity and more ductile behavior. The influence of longitudinal reinforcement ratio, stirrup ratio and the thickness of steel tube were discussed in this paper. Furthermore, a new method to calculate the carrying capacity of ECC-encased CFST columns was proposed and verified with experimental results.

ABSTRACT: This paper dealt with the restraint stiffness and strength requirements for axially loaded columns with lateral restraints, accounting for inelastic flexural buckling and random imperfections. Firstly, the buckling behaviour of restrained columns with classic deterministic imperfections was discussed to verify the effect of section dimensions, material properties and imperfection shapes. Then by using probabilistic distribution of imperfections along the column, extensive numerical results were gained through random imperfection finite element analyses, followed by restraint stiffness and restraint force proposed statistically corresponding to full restraining for columns. Results showed that, the full restraining stiffness of perfect columns proposed by Winter is sufficient for columns with imperfections and inelastic buckling. The traditional approach with predetermined artificial imperfections is deficient to evaluate the restraint force properly and rationally, due to ignoring the effect of random imperfections.

ABSTRACT: The standard hot-rolled sections with various shapes are used to construct the skeletal structural system of the steel civil engineering structures. The conventional design rules direct the engineer to select the smallest section from the manufacturers’ catalog that satisfies the considered constraints. However, use of these predesigned sections may result in waste of structural material. This problem can be handled by searching for optimal built-up section designs, which can be manufactured by cutting the plates to the determined dimensions and welding them to each other so as to form the optimized shape. This paper presents the optimal design of prismatic I-section beam-columns under stress, non-linear deflection and global buckling constraints with one of the recent metaheuristic algorithms and discusses the influence of variable grouping on the optimization results. Four optimization types are introduced and the contribution of using optimized shapes instead of hot-rolled sections to the structural material economy is demonstrated over numerical examples. It is shown that optimization may lead up to 23% lighter solutions than the hot-rolled sections and it is possible to obtain adequately efficient doubly-symmetric I-section designs (in terms of material amount used) from an engineering point of view.

ABSTRACT: Hierarchical anisogrid stiffened panel (HASP) consists of three parts: main stiffeners, sub-stiffeners, and panel. The basis of HASPs’ dynamic response calculation is equivalent to the orthotropic panel. There are mainly two methods to calculate the dynamic response of orthotropic panels. One is the modal superposition method, and this method is an accurate calculation; the other method is equivalent static load method, which is an approximate calculation of deflection. Equivalent static load method is equivalent to the structure as a single-degree-of-freedom (SDOF) system. Deflection and strain equivalent method were compared for structural failure analysis. On this basis, the dynamic amplification factor (Kd) was calculated and the effects of parameters on it were discussed. According to these two deflection calculation method, the pressure-impulse ($P-I$) curve was plotted and the variation of the $P-I$ curve under different conditions was analyzed. These theories were applied to the composite HASP protective door, the deflection and $P-I$ curve of the doors were obtained and verified by tests.


ABSTRACT: Waste tyres are among the largest and most problematic sources of waste in modern society due to their durability and high rate of dumping in landfills. One possible recycling alternative is to incorporate waste tyre rubber as an aggregate replacement in concrete to promote sustainability and utilise the elastic properties of rubber. Rubberised concrete has not reached its full potential because of the decrease in compressive strength and a lack of research to solve such challenge. Recent research suggests that combining rubberised concrete with confinement increases ductility and energy absorption. Specifically, confined rubberised concrete using single skin or double skin square hollow section tubular columns present higher ductility than those made of normal concrete. This study explored experimentally the use of rubberised concrete filled single skin and double skin steel tubes under concentric axial compression. The experimental investigation included changing the confinement of the outer and inner square hollow sections and explored how confinement affected normal concrete compared to rubberised concrete. Four variations of double skin steel tubes with a total of twelve 300 mm long columns of 0%, 15%, and 30% rubber replacement were created and tested concentrically. Three single skin short columns with 0%, 15%, and 30% rubber content were also tested and compared. The compressive strengths were determined theoretically and compared against those measured experimentally. An interesting spring back phenomenon occurred where the infill rubberised concrete moved upwards after testing due to the large confinement of the core and elasticity of the rubber. This study examined the use of rubberised concrete filled double skin steel tubular columns as a promising construction technique for applications such as columns in buildings located in seismic active zones, security bollards and flexible road side barriers.


ABSTRACT: Rectangular plates with different kinds of attachments (continuous or lumped) and various opening shapes are main constituitive parts of almost all engineering structures, e.g. aircrafts, bridges, buildings, ships, offshore structures, etc. Therefore, an assessment of their free and forced responses is generally very important for safe and rational structural design. In this paper, a range of different vibration problems inherent
to rectangular plate systems, that can be solved by the energy based assumed mode method is considered. The concept of assumed mode method is outlined together with application of the mode superposition method to forced response calculation for plates under concentrated harmonic forces or enforced boundary displacement. Furthermore, complete mathematical model for vibration analysis of plate structures carrying arbitrary number of spring-mass systems is developed, based on the receptance method application. The plate is modelled by the Mindlin thick plate theory and Timoshenko beam theory is applied for stiffeners. The eigenvalue problem represented with a multi-degree-of-freedom system equation is formulated by Lagrange's equation of motion, while characteristic orthogonal polynomials having the properties of Timoshenko beam functions and satisfying the specified edge constraints are used as approximation functions. The corresponding in-house software is developed and dynamic responses of rectangular plate systems having different sets of edge constraints are analysed. Comparisons of the results with existing solutions and general finite element (FE) software are included, and very good agreement is achieved.


ABSTRACT: This work analyses the natural frequencies of composite conical panels made of a polymeric matrix reinforced with uniform or functionally graded carbon nanotubes (FG-CNTs). The mechanical properties of the composite conical panels rely on a refined rule of mixtures, whereas the kinematics of the problem is here tackled with the first order shear deformation shell theory (FSDT) and the Donnell’s theory. The expressions of the virtual strain and kinetic energies of the conical panels are substituted into the Hamilton’s principle. A matrix formulation of the free vibration problem is achieved using the conventional Ritz method, with the shape functions stemming from the Gram-Schmidt process. Based on a parametric investigation, we assess the key role of the CNT volume fractions and patterns, and check for their effect on the free vibrations of the composite conical panels, as useful for practical applications.


ABSTRACT: Collapse of the inner pipe of a pipe-in-pipe (PIP) system under external pressure is studied experimentally and numerically herein. Hyperbaric chamber test results of three PIP systems with identical inner pipes and different outer pipes are presented. It is observed that the geometric and material properties of the outer pipe affect the collapse pressure of the inner pipe. Using validated finite element analyses (FEA), a parametric study is conducted and collapse mechanisms of PIPs with various combinations of outer and inner pipes with practical range of diameter-to-thickness ratios \(D/t\) between 15 and 40 are discussed. Empirical expressions are proposed for the collapse pressure of the inner pipe \(P_{ci}\), and its upper and lower bounds. The proposed empirical equation for \(P_{ci}\) is shown to agree well with the experimental results of the tested PIPs. Moreover, two distinctive modes of collapse in the inner pipe are identified and discussed.


ABSTRACT: This paper presents Best Theory Diagrams (BTDs) constructed from non-polynomial terms to identify best shell theories for the free vibration analysis of laminated and sandwich shell. The shell theories have been constructed using Axiomatic/Asymptotic Method (AAM). The refined models are implemented following the compactness of a unified formulation developed. The governing equations are derived from the
Hamilton’s Principle. Navier-Type solution technique is used for solving the eigenvalue problem of simply supported shell. The BTDs use 3D equilibrium solutions as a reference. The BTDs built from non-polynomial functions are compared with Maclaurin expansions. The results are compared with Layerwise solutions. Cylindrical and spherical shells with different layer-configurations are investigated. The results demonstrate that the shell models obtained from the BTD using non-polynomial terms can improve the accuracy obtained from Maclaurin expansion for a given order of expansion of a displacement field.

ABSTRACT: This paper mainly concentrates on obtaining the explicit solutions of the forced vibrations of oil-conveying pipes on two-parameter foundations with generalized boundary condition by means of Green’s functions. The generalized boundary condition (BC), which can be reduced to many different simple BCs, is considered in the vibration problems. Green’s function and the superposition property of linear vibrations are employed to derive the analytical solutions, and the Laplace transforms are applied with intention of gaining the Green’s functions under various BCs. In the numerical section, the present solutions are validated by comparing with the results in the other literature. In addition, the effects of some important physical parameters, for instance boundary stiffness, foundation parameters, geometric parameters, etc., on the natural frequencies and the critical flow velocities are discussed as well.

ABSTRACT: High-strength concrete (HSC) can be of great interest for the construction of lower-stories reinforced-concrete (RC) columns in high-rise buildings. This superior material can reduce the dimensions of the columns, and therefore, can be considered as a more advantageous material than normal-strength concrete (NSC). To compensate for its higher brittleness nature, the confinement reinforcement ratio required for HSC has to be larger than that required for NSC. The aim of this study is to examine the confinement transverse steel reinforcement amounts required for HSC circular columns part of high-rise buildings. The study first compares the confinement reinforcement requirements given by leading standards. Following the comparative research, an experimental study on six HSC columns subjected to axial loading was performed. The results show that in terms of axial capacity, it is recommended to further examine the concrete strength reduction factor and that it is more reasonable to consider a value lower than 0.85 for the design of HSC columns. Moreover, in terms of confinement and ductility, the recommended volumetric transverse steel reinforcement ratio for HSC circular columns not considered as part of the seismic-force-resisting system (SFRS), can be based on the ACI standard requirement and equal to half of the maximum specified volumetric transverse steel reinforcement ratio required for HSC columns considered as part of the SFRS.

ABSTRACT: Elliptical concrete-filled steel tubular (CFST) columns have recently attracted significant attention because of their increased strength and stiffness compared with empty elliptical hollow sections (EHSs). As with any new cross-section, there are still many aspects to be investigated to allow for its inclusion in different design specifications. Based on literature survey, this paper investigates the elliptical CFST columns
which are filled with high-strength concrete (HSC). Numerical investigations into the structural behaviour of the elliptical CFST columns subjected to pure axial compression and eccentric loading have been performed using the general purpose commercial finite element (FE) software, Abaqus. The validity of the current FE models is examined by comparing their outcomes with those test results in literature. Then, parametric studies are performed considering three main parameters, namely the slenderness of the EHS, the steel yield strength and the concrete compressive strength. This is followed by a discussion of the results, showing in detail the characteristics of their load-strain responses. A comparison of the ultimate strengths with the existing design models is then considered, from which it is found that improved design model could be suggested to save additional weight and reach an optimum design. Hence, a new design formula is presented at the end which considers the effective confined concrete strength. Overall, this investigation expands the available engineering knowledge and assists in utilising the HSC, currently used in a wide range of applications, with the elliptical CFST columns with their favourable aesthetical and structural characteristics.


ABSTRACT: The stiffened pipe structure is analyzed by using a pipe element with variable cross-section. The pipe element uses a much less number of DOF (degree-of-freedom) and it has exactly smooth configuration and high order solution of displacement. The Consistent Orthogonal Basis Function Space is applied to define the pipe’s displacement basis functions. The nonlinear finite element implementation details are also presented for the completeness of the method. The stiffened pipe collapse problem and the buckling propagation problem are both solved. The numerical results are compared and verified with ANSYS. It is observed that the stiffness can be largely increased by using stiffeners on pipes. The number of DOF is also compared between the proposed method and ANSYS. The post buckling profile of the stiffened pipe is obtained. The maximum and minimum buckling propagation pressure are calculated. The design based on buckling collapse and buckling propagation are discussed.


ABSTRACT: In this self-contained paper free vibrations of a pressurised toroidal shell, rotating around its axis of symmetry, are considered. Extensional and bending strain-displacement relationships are derived from general expressions for a thin shell of revolution. The strain and kinetic energies are determined in the co-rotating reference frame. The strain energy is first specified for large deformations and then split into a linear and a non-linear part. The nonlinear part, which is afterwards linearized, is necessary in order to take into account the effects of centrifugal and pressure pre-tensions. Both the Green-Lagrange nonlinear strains and the engineering strains are considered. The kinetic energy is formulated taking into account centrifugal and Coriolis terms. The variation of displacements $u$, $v$ and $w$ in the circumferential direction is described exactly. This is done by assuming appropriate trigonometric functions with a unique argument in order to allow for rotating mode shapes. The dependence of the displacements on the meridional coordinate is described through Fourier series. The Rayleigh-Ritz method is applied to determine the Fourier coefficients. As a result, an ordinary stiffness matrix, a geometric stiffness matrix due to pressurisation and centrifugal forces, and three inertia matrices incorporating squares of natural frequencies, products of rotational speed and natural frequencies and squares of the rotational speed are derived. The application of the developed procedure is illustrated in the cases of a closed toroidal shell and a thin-walled toroidal ring. With the increase of the rotation speed the natural frequencies of most natural modes are split into two (bifurcate). The corresponding stationary modes are split into two modes rotating forwards and backwards around the circumference with different speeds. The obtained
results are compared with FEM results and a very good agreement is observed. The advantage of the proposed semi-analytical method is high accuracy and low CPU time-consumption in case of small pre-stress deformation for realistic structures. The illustrated numerical examples can be used as benchmark for validation of numerical methods.


ABSTRACT: This is the third part in a trilogy of papers examining ways in which additive manufacturing can be used to facilitate the introduction of basic principles in structural analysis. Each paper uses 3D-printing and simple, but non-trivial, slender geometric forms, to provide a hands-on aspect to structural behavior in which flexure plays a dominant role. The first part dealt with linear structural analysis (Virgin, 2017), extended to dynamics and vibration in the second part (Virgin, 2017). The current paper focuses on slender structures in which compressive axial loading is the new ingredient and hence buckling becomes a central issue. This has similarities and differences with the two previous papers, but in all instances the role played by relatively high-precision 3D-printing opens the door to versatile and effective illustration, and the development of a deeper appreciation of structural phenomena.


ABSTRACT: Based on theoretical analyses, the development of buckling mode of steel core is revealed for buckling restrained braces (BRBs) with fixed ends. The formulae are derived for the bending moments of the stiffening part of the core and restraining member of BRBs. Then a global stability design method of fixed-end BRBs is proposed. The results of the contact force, flexural response and buckling half wavelength with finite-element analysis agree with the theoretical analysis. The design criteria as well as the buckling half wavelength were validated by the quasi-static tests of five BRBs. Compared to existing methods, the proposed design approach can ensure a proper safety margin of the stiffening part.


ABSTRACT: Rectangular concrete-filled double steel tubular (CFDST) columns with inner circular steel tube possess higher structural performance than conventional concrete-filled steel tubular (CFST) columns. However, the local buckling of the outer steel tube of thin-walled rectangular CFDST columns has not been accounted for in the existing fiber element models and design codes that may overestimate the column ultimate axial strengths. This paper describes a computationally efficient fiber-based modeling technique developed for determining the behavior of concentrically-loaded rectangular CFDST short columns including the local buckling effects of the external steel tube and the confinement offered by the internal circular steel tube. The effective width concept is used to simulate the post-local buckling of the outer steel tube. Comparative studies are undertaken to verify the fiber-based model with the relevant test results. The computational model is then employed to investigate the axial load–strain responses of rectangular CFDST short columns with various key design variables. A design equation is developed for computing the ultimate axial loads of short rectangular CFDST columns and compared with design methods given in several international design codes. It is shown that the fiber-based modeling technique and the proposed design model predict well the structural performance of short CFDST columns.

ABSTRACT: Sandwich pipe (SP), consisting of two comparatively thin-walled metal tubes and a thick polymer or cement-based core, is believed to be a feasible conception to transport hydrocarbons in deep sea. In this paper, the buckle propagation experiments were carried out on small-scale SP test specimens composed of two aluminium tubes and the polypropylene (PP) core. In association with experimental efforts, dedicated finite element models of SP test specimens under external pressure were established to reproduce the local collapse and consequent buckle propagating scenarios using the software ABAQUS, and good agreements were observed between the experimental and numerical results. Then, influencing mechanisms of inter-layer adhesion behaviour on the stress state, cross-section deformation and buckle propagation pressure of SPs were systematically studied, and broad parameter correlation analyses were performed to explore geometric and material properties of two steel tubes and polymer core on the buckle propagation pressure of SPs. The results show that good interface bonding conditions can markedly enhance the buckle propagation pressure of SPs and improve the energy dissipation and the deformation capacity of the structures. The core layer thickness and the ratio of the wall thickness between inner and outer tubes have extremely noticeable effect on the buckle propagation pressure of SPs. Additionally, based upon extensive numerical results, an empirical design expression was developed to conservatively estimate the buckle propagation pressure of SP systems for the no inter-layer adhesion case.


ABSTRACT: Cold-formed steels typically exhibit a rounded stress-strain response with gradual yielding merging into strain hardening. This form of stress-strain curve is at odds with the elastic, perfectly plastic material model that underpins many of the provisions set out in current structural steel design standards. In particular, the beneficial influence of strain hardening on cross-section capacity is neglected. The continuous strength method (CSM) is a deformation-based design method that enables material strain hardening properties to be exploited, thus resulting in more accurate and consistent capacity predictions. The aim of this study is to extend the CSM to the design of cold-formed steel non-sleender tubular cross-sections subjected to compression, bending and combined loading, and to verify the proposals through comparisons with existing test data from the literature and finite element results generated herein. The finite element models were first developed and validated against test results on cold-formed steel cross-sections collected from the literature. An extensive parametric study was then conducted to generate additional data over a wider range of cross-section geometries, slendernesses and loading conditions. The numerical results together with the experimental results were then compared with capacity predictions, calculated according to the current design rules in European Standard EN 1993-1-1 (2005) and American Specification AISC-360-16 (2016) as well as the CSM. The CSM is shown to provide more accurate and consistent design predictions for cold-formed steel cross-sections under different loading conditions than those obtained from existing design methods. The improvements arise from the use of the continuous deformation based design approach, as well the rational exploitation of strain hardening. Finally, the reliability levels of the different design methods were assessed by conducting reliability analyses in accordance with EN 1990 (2002).

ABSTRACT: This paper presents the details of experimental and numerical investigations on the behaviour and axial compression capacity of Carbon Fibre Reinforced Polymer (CFRP) strengthened cold-formed, short Square Hollow Section (SHS) steel columns. Initially, an experimental investigation consisting of seven test columns was conducted to investigate the influence of CFRP strengthening layout on the axial compression capacity of short SHS steel columns. In addition, the effect of CFRP wrapping end condition was also investigated. Experimental results showed that CFRPs are very effective in strengthening short SHS columns, where axial compression capacity enhancements up to 2.6 times were observed. Then a numerical simulation was implemented using ABAQUS by which CFRP and adhesive were modelled using continuum and cohesive elements deploying Hashin and cohesive law criteria. The finite element models were validated using experimental results and then used in a detailed parametric study. Using the finite element analysis results suitable improvements were proposed to the existing design equations available in the literature. Finally, a new set of design equations based on Direct Strength Method (DSM) is proposed in this paper to determine the axial compression capacity of CFRP strengthened SHS columns subjected to local buckling.


ABSTRACT: Long-span spatial structures are commonly used as landmarks in modern cities and may be potential targets of terrorist attacks; thus, it is important to study the dynamic behaviour of such structures under blast actions. In this study, experiments were conducted on two reduced-scale models which were designed and manufactured. The aims of the experiments were to (i) assess the accuracy of a numerical approach for simulating the structural dynamic responses based on the finite element software, “ANSYS/LS-DYNA”, and (ii) survey the various failure modes of single-layer reticulated domes under an external blast loading. The numerical results showed a good agreement with the experiments when the empirical load model was used to study the elastic and inelastic deformation of a multi-curved shell. Additionally, the deformation, development of plasticity, and energy absorbing behaviour of each component were examined, and the following four major response patterns were identified: elastic vibration, slight damage, local failure, and global collapse.


ABSTRACT: This study deals with the manufacturing and testing of sandwich beams with carbon/epoxy composite skins and a honeycomb core filled with magnetorheological elastomer (MRE) in different proportions of magneto/elastomer (w/w%). Free and forced vibration tests conducted under several magnetic field intensities were performed to evaluate dynamic properties of the sandwich beams. The experimental results favorable reduction of mechanical vibrations, especially on the fundamental mode of the structure in question. We can see that MRE sandwich beam shifted the natural frequencies and amplitude of vibration due to the increase of an induced magnetic field.


ABSTRACT: Bridges with box cross-sections are usually stiffened by the combination of longitudinal and transverse stiffeners. The longitudinal stiffeners are loaded by axial force, and the transverse stiffeners should give sufficient support to them. The design of transverse stiffeners without direct loading can be done by the
verification of the minimum stiffness requirements. It has been proved by several researchers in the past that the requirement of the EN1993-1-5 (2005) regarding the out-of-plane bending inertia of the transverse stiffeners is not on the safe side and needs further improvement. At the same time, designers have difficulties in fulfilling the torsional stiffness requirements for the transverse stiffeners using practical stiffener sections. Therefore, the current research program has the aim of harmonizing the minimum requirements for transverse stiffeners and giving applicable design proposals. Complex research strategy and advanced numerical model have been developed to determine the minimum stiffness requirement for transverse stiffeners based on bifurcation analysis and GMNI simulations. More than 3900 simulations have been executed on different geometries to investigate the structural behaviour of the longitudinally stiffened plate and the transverse stiffeners. On this basis a design method has been developed to determine the required minimum transverse stiffener.


ABSTRACT: Seawater and sea sand concrete (SWSSC) filled double-skin stainless steel (SS) tubes consist of two concentric circular SS tubes, sandwiching SWSSC between them. This paper presents an experimental study on SWSSC-filled double-skin SS tubes (CFDSTs) under axial compression. Unfilled circular hollow sectional (CHS) specimens, fully-filled tubes (CFSTs) and double-skin tubes without inner tube (CFHT) were also tested for comparison purpose. Load-axial strain curves, stress in concrete, post-peak behaviour and energy absorption are investigated in this study. The effects of some key parameters, including confinement factor, void ratio and tube slenderness ratio, on the structural behaviour of SWSSC-filled SS tubes are discussed. It is found that the ultimate stress in concrete is mainly affected by confinement factor and the post-peak behaviour depends on both confinement factor and inner tube slenderness. Formulas are proposed to estimate the load carrying capacity of SWSSC-filled SS circular tubes in compression.


ABSTRACT: An existing hydroelastic model is extended for a flat plate subjected to a compression force with spiral spring boundary conditions during water entry. Both vertical and oblique impacts of the plate into calm water are investigated. A longitudinal strip of the plate is analyzed by fully coupling hydrodynamic pressure with elastic responses. Hydrodynamic pressure is determined by potential flow theory and plate deflections are expressed in terms of dry normal modes. The plate deflections are validated through comparison with available asymptotic models, semi-analytical and experimental results. The effect of compression force on the plate deflection is investigated at the midpoint considering different horizontal velocities and inclination angles. Dry and wet frequencies and the minimum threshold values of the compression forces are obtained for plates with different boundary conditions during vertical and oblique impacts. The results show that the plate responses may reach the plastic region at low compression force and high horizontal velocity. It is also found that for all the cases studied yielding occurs before buckling during water impact of the plate.


ABSTRACT: To improve the compression performance and ductility of rectangular concrete-filled steel tube (CFST) columns with large dimensions, longitudinal stiffeners, horizontal tie bars, studs, internal diaphragms, and steel reinforcement cages, were set inside the columns. Six CFST column specimens with different
construction characteristics were designed and tested under repeated uniaxial compression loading. Test samples were extracted from the rectangular cavities at the two ends and along the long axis of the mega-column from China Zun Tower. The hysteretic curves, skeleton curves, energy dissipation capacity, bearing capacity, stiffness and strain of specimens, and the effect on the axial compression performance based on different construction characteristics are herein discussed and clarified. Based on the conducted tests on these columns, a bearing capacity calculation method is proposed. The test results indicate that the longitudinal stiffeners set inside the CFST columns facilitate the sharing of axial forces and strengthen the stiffness, bearing capacity, and ductility. The horizontal tie bars help the improvement of the constraint of the concrete at loads higher than the ultimate load. Welding studs on the inner surface of the steel tubes help to strengthen cooperative work between the steel tubes and the concrete upon application of the ultimate load. Setting internal diaphragms inside CFST columns can enhance the ultimate bearing capacity and energy dissipation significantly. The setting of steel reinforcement cages inside the CFST columns stabilizes the mechanical performance manifested by the significant improvements in the ultimate bearing capacity and ductility.


ABSTRACT: This paper presents experimental and numerical investigations on cold-formed ferritic stainless steel (CFFSS) square and rectangular hollow sections undergoing web crippling. A total of 44 web crippling tests was carried out under the four codified web crippling load cases as per the American cold-formed stainless steel specification. Numerical model of each load case was built and verified with the web crippling test results. After the verification, a parametric study comprised of 154 finite element analyses was undertaken thereafter to gain further insight into the behaviour of the CFFSS sections undergoing web crippling. The current design provisions in the American, Australian/New Zealand and European stainless steel codes of practice were assessed. Moreover, the North American Specification (NAS) provisions for carbon and low-alloy steel sections were evaluated. Furthermore, design recommendations in the literature for stainless steel sections were examined. Improved design rules are proposed in this study for CFFSS square and rectangular hollow sections by modifying NAS and Direct Strength Method. Reliability analysis was also undertaken to assess the reliability levels of the existing and modified provisions.


ABSTRACT: This paper presents an investigation on the material properties, residual stress distributions and cross-sectional behavior of cold-formed steel semi-oval hollow sections. Four cross-section series were included in the test program. The test specimens were cold-formed from hot-extruded seamless steel circular sections. Tensile coupon tests were conducted on coupon specimens extracted from three critical locations, namely the flat, curved and corner portions, of each cross-section as well as half of the cross-section of a representative section. Membrane and bending residual stresses distributions on the representative section were measured in both longitudinal and transverse directions. In addition, initial geometric imperfections were measured for each cross-section series and stub column tests were conducted to determine the average stress-strain relationship over the complete cross-section in the cold-worked state and to examine the cross-sectional behavior of cold-formed steel semi-oval hollow sections. Furthermore, a finite element model was developed and validated against the test results. With the verified finite element model, an extensive parametric study over a wide range of cross-section geometries was performed. The load-carrying capacities of stub columns obtained from experimental and numerical investigation were compared with the design strengths predicted by the Direct
Strength Method using the design equations originally developed for open sections and the Continuous Strength Method with the design curves originally developed for traditional tubular sections. The comparison results show that the existing design methods provide conservative design strength predictions. In this study, modification on the Continuous Strength Method is proposed, which is shown to improve the accuracy of the design strength predictions in a reliable manner.


ABSTRACT: This paper focuses on a new methodology for substitution of Liquid Hydrogen (LH2) contained in cryogenic tank in vibration analysis by using surrogate granular materials. Our analysis is limited to a 3D tank that is supposed to be fully filled with granular grains and tries to establish a modal equivalence between (tank fully filled with LH2) and (tank fully filled with granular grains) systems. For this, we determine required pre-stresses based on a homogenization technique from properties of grains. After reviewing some important mathematical formulations of vibration and homogenization model, an example of modal equivalence between these two systems is presented. Analytical results are also compared with numerical simulations in order to prove the suitability of the new method.


ABSTRACT: The present research is concerned with the vibration analysis of thin isotropic and orthotropic rectangular plates with crack defects under thermal environmental conditions. In the literature, there are only few studies reported in this direction. Based on the classical plate theory, the governing equations of the isotropic and orthotropic cracked rectangular plates can be derived, in which a surface crack located at the plate center is formulated based on a line-spring model. Since the dynamic behavior of structural elements is significantly affected by thermal effects, a thermal buckling analysis for isotropic and orthotropic plates is also conducted. A uniform heating load on the cracked rectangular plates is considered and the critical buckling temperature of the plates with or without cracks is investigated. The discrete singular convolution (DSC) method is then applied to formulate the eigenvalue equations for the cracked rectangular plates under various thermal conditions. The DSC technique is an ingenious method in stability and dynamic analysis of plates, not only it is a flexible local method to handle complex geometries and boundary conditions, but also it performs as a global approach with a high degree of accuracy. To go beyond the limitation of the DSC method, the use of Taylor’s series expansion method is incorporated for the treatment of free boundary conditions. In addition, this is the first attempt to explore its application on the analysis of cracked rectangular plates under thermal effects. In this work, the vibration of isotropic and orthotropic cracked rectangular plates with various combinations of boundary conditions is studied. A special restrained manner of simply supported conditions that are permissible for in-plane movements is also analyzed. The obtained solutions herein are compared with the existing results to verify the accuracy and reliability. Besides, accurate first-known solutions are also presented.


ABSTRACT: This paper presents a numerical investigation into the structural performance of cold-formed high strength steel tubular columns with square, rectangular and circular cross-sections. A finite element model was
developed and validated against experimental results on the cold-formed high strength steel tubular columns. Parametric studies using the validated finite element model were carried out to determine the strengths of cold-formed tubular columns with various cross-sectional dimensions, member slenderness values, geometric imperfections and steel grades of S700, S900 and S1100. It was found that increasing the steel grade of the columns led to higher normalised column strengths which were less severely affected by geometric imperfections. The effect of material tensile strength to yield strength ratio on the column strengths was found to be insignificant. Based on the experimental results in literature and the results obtained from parametric studies, the applicability of the design rules in European, Australian and American Standards to cold-formed high strength steel tubular columns was evaluated. The reliability of the design rules was also assessed by performing reliability analysis. The design rules in these standards provide conservative predictions for the strengths of cold-formed high strength steel tubular columns. Recommendations on the column buckling curve selection are discussed. An improved column buckling curve expression considering the increment in normalised column strength with increasing steel grade is also proposed.


ABSTRACT: In this paper, a higher order beam theory is employed for linear local buckling analysis of beams of homogeneous cross-section, taking into account warping and distortional phenomena due to axial, shear, flexural, and torsional behavior. The beam is subjected to arbitrary concentrated or distributed loading, while its edges are restrained by the most general linear boundary conditions. The analysis consists of two stages. In the first stage, where the Boundary Element Method is employed, a cross-sectional analysis is performed based on the so-called sequential equilibrium scheme establishing the possible in-plane (distortion) and out-of-plane (warping) deformation patterns of the cross-section. In the second stage, where the Finite Element Method is employed, the extracted deformation patterns are included in the buckling analysis multiplied by respective independent parameters expressing their contribution to the beam deformation. The four rigid body displacements of the cross-section together with the aforementioned independent parameters constitute the degrees of freedom of the beam. The finite element equations are formulated with respect to the displacements and the independent warping and distortional parameters. The buckling load is calculated and is compared with beam and 3d solid finite elements analysis results in order to validate the method and demonstrate its efficiency and accuracy.

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ABSTRACT: Sandwich composites with single type foam are very much prevalent in the applications to absorb energy under impact load. However, there is increasing awareness that graded cores in sandwich composites
can significantly affect the impact performance. In this work, the perforation energy and failure modes of curved sandwich composites with layer wise graded cores are studied experimentally. Three types of foam were used for flat and curved sandwich composites with layered cores. A series of six different core layer arrangements were studied. The contact forces, displacements and corresponding perforation energies of square panels were measured and failure modes after perforation were observed. The results indicate that the perforation energies of the sandwich panels are dependent on various geometrical and material parameters. The perforation energies of the curved panels with single type foam were increased compared to similar flat panels, whereas panels with graded foam behaved differently due to the foam layer arrangements. Furthermore, it was observed that the failure modes were not similar when the panels were perforated. Contribution of present study to current literature is the use of different core layer arrangements to increase the impact performance of curved sandwich panels which are inevitable parts of various applications.

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ABSTRACT: Present study deals with the non-linear vibration of orthotropic cylindrical shells on the nonlinear elastic foundations. To account for the large deformations of the orthotropic cylindrical shell, von-Karman type of geometrical nonlinearity is included into the formulation. The shear deformation theory (SDT) is used to obtain the basic equations of orthotropic cylindrical shells on the nonlinear elastic foundations within the Donnell’s shell theory. The superposition and Galerkin methods are adopted to convert the above equations into a nonlinear ordinary differential equation. The frequency-amplitude relationships for orthotropic cylindrical shells on the nonlinear elastic foundations in the framework of the SDT are obtained in the form of Jacobi elliptic function. The validity of the present method is demonstrated by comparing the present results with those available in the literature. Moreover, some new results are also presented for the nonlinear frequency parameters of the cylindrical shells to study effects of non-linear elastic foundations, vibration amplitude, shear stresses, orthotropy and shell characteristics.

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ABSTRACT: A solution of the buckling problem for a shear loaded composite anisogrid lattice plate with the clamped edges based on the Galerkin method is presented in this paper. The lattice plate is modelled as an equivalent continuous orthotropic plate with effective stiffness parameters. The deflection of buckled plate is presented in the form of a double series containing clamped–clamped beam functions. The critical in-plane shear load is found solving the generalised eigenvalue problem for a homogeneous system of algebraic equations in which the unknowns are the coefficients of the double series. Based on this solution, the effects of the plate dimensions and parameters of lattice structure on the value of critical load are investigated and analysed. Results of these analyses are successfully verified using the finite element method. An approximate analytical expression providing fast and reliable way of calculation of the critical buckling load is obtained for the lattice plate composed of the ribs made of the same composite material and with the same size of their cross-sections.

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ABSTRACT: The mechanical response of three different structural core sandwich panels in out-of-plane compression and shear has been analyzed. Specific core shapes examined are arc-tangent, wavy trapezoidal and hemispherical. Unit cells consisting of representative elements of the core attached to face sheets were selected for analysis. Both face sheets and core were assumed made from paper. Finite element analysis employing large deformation and rotations and orthotropic elastic–plastic behavior was used. The results show that the arc-tangent and trapezoidal cores are prone to collapse by extensive bending and buckling, whereas the hemispherical core behaved more stably in compression and shear. Core sheets with a hemispherical shape were prepared from copy paper sheets in a specially designed forming machine. Sandwich test specimens were prepared from this core and tested in out-of-plane compression, and the load-displacement response was compared to predictions from finite element simulations. The experimental and finite element results were consistent.

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https://doi.org/10.1016/j.compstruct.2016.09.058

ABSTRACT: This paper investigates buckling characteristics of a curved functionally graded (FG) nanobeam based on nonlocal strain gradient elasticity theory accounting the stress for not only the nonlocal stress field but also the strain gradients stress field. The modeling of nanobeam is carried out via a higher order refined beam theory which captures shear deformation influences needless of any shear correction factor. Power-law model is adopted to describe continuous variation of material properties of curved FG nanobeam. The governing equations of nonlocal strain gradient curved FG nanobeam in the framework of refined hyperbolic beam model are obtained using Hamilton’s principle and solved implementing an analytical solution for simply-supported and clamped boundary conditions. To validate the present model, the results are compared with those of straight FG nanobeams by extending the radius of nanobeam to infinity. The effects of nonlocal parameter, length scale parameter, power-law exponent, boundary conditions and slenderness ratio on the buckling response of curved FG nanobeams are investigated.

Marija Nefovski-Danilovic, Nevenka Kolarevic, Miroslav Marjanovic and Mira Petronijevic (Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia), “Shear deformable dynamic stiffness elements for a free vibration analysis of composite plate assemblies – Part I: Theory”, Composite Structures, Vol. 159, pp 728-744, January 2017
https://doi.org/10.1016/j.compstruct.2016.09.022

ABSTRACT: A procedure for developing the dynamic stiffness matrix of a completely free laminated composite plate based on the first-order (FSDT) and higher-order shear deformation theory (HSDT) is presented. The proposed method allows the computational analysis of free transverse vibrations of the individual rectangular laminated composite plates, as well as the composite plate assemblies, without any restrictions regarding the boundary conditions or frequency limitations. The general solution of the governing differential equations of the HSDT and FSDT is established using the superposition method. Continuous boundary conditions are discretized by using the projection method. The dynamic stiffness matrices of plate elements are then formulated from the assembly of the four dynamic stiffness matrices (four symmetry contributions). The validation of the theory and its application are provided in the Part II of this two-part paper.
Miroslav Marjanovic, Nevenka Kolarevic, Marija Nefovska-Danilovic and Mira Petronijevic (Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia), “Shear deformable dynamic stiffness elements for a free vibration analysis of composite plate assemblies – Part II: Numerical examples”, Composite Structures, Vol. 159, pp 183-196, January 2017
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ABSTRACT: The dynamic stiffness elements based on the HSDT and FSDT (and the corresponding dynamic stiffness matrices of a laminated composite plate) have been implemented into the original MATLAB code, and a variety of numerical investigations is performed in this paper. The obtained results are validated against the exact and numerical solutions or the experimental data from the literature. In the absence of the analytical solutions, the numerical solutions obtained by using the Abaqus software are used. Excellent agreement is achieved against the existing exact solutions. After the detail convergence study considering both low and high modes of vibration, the effects of the plate side-to-thickness and orthotropy ratios, as well as the influence of boundary conditions, have been discussed by comparing the proposed models with the exact Levy-type solutions from the literature. A variety of new results for non-special boundary conditions is provided. Two additional examples of a completely free laminated composite plate undergoing free vibrations are provided and the results are validated against the experiment. Finally, the analyses considering the Z- and U-shaped composite plate assemblies with various boundary conditions are provided as a benchmark for future research.

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ABSTRACT: This paper presents a novel deformation mechanism based material model for topology optimization of laminated composite plates and shells. Discussed firstly are the one-node hinges in optimum designs of plate and shell structures and the numerical issues caused by void elements in geometrical nonlinear analysis. To circumvent these two problems, we propose a new material model in which different penalties are applied to different strain energy terms related to extensional, shear, bending and extensional-bending coupling deformation mechanisms and void elements are removed in nonlinear finite element analysis. An efficient algorithm is developed by using the present material model and the moving isosurface threshold method. Numerical results are presented for isotropic and composite plates and shells and compared with those available in the literature to validate the present material model.

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Furthermore, this type of composites are eager to exhibit the secondary instability which is designated with a pattern results in higher buckling temperature and also decreases the postbuckling deflection of the plate.

Distribution of carbon nanotubes as reinforcements may be uniform or functionally graded. To account for the large deformations of the plate, geometric nonlinearity is included into the formulation. The virtual displacements principle associated with the conventional Ritz formulation whose shape functions are selected as the Chebyshev polynomials is used to be uniform or functionally graded. To account for the large deformations of the plate, geometric nonlinearity is included into the formulation. The virtual displacements principle associated with the conventional Ritz formulation whose shape functions are selected as the Chebyshev polynomials is used to

ABSTRACT: Present research deals with the postbuckling problem of carbon nanotube reinforced composite plates subjected to uniform temperature rise loading. Distribution of carbon nanotubes as reinforcements may be uniform or functionally graded. To account for the large deformations of the plate, von-Kármán type of geometrical nonlinearity is included into the formulation. The virtual displacements principle associated with the conventional Ritz formulation whose shape functions are selected as the Chebyshev polynomials is used to obtain the matrix representation of the nonlinear equilibrium equations. The solution method is general and may be used for arbitrary combination of boundary conditions. The postbuckling equilibrium path which is governed by a nonlinear eigenvalue problem is traced using a displacement control strategy. Results of this study are compared with the available data in the open literature for the cases of isotropic homogeneous plates and crossply laminated plates. Afterwards numerical results are given for FG-CNTRC plates. It is shown that, FG-X pattern results in higher buckling temperature and also decreases the postbuckling deflection of the plate. Furthermore, this type of composites are eager to exhibit the secondary instability which is designated with a snap-through phenomenon in the post-buckling equilibrium path.

https://doi.org/10.1016/j.compstruct.2016.09.084

ABSTRACT: Present research deals with the postbuckling problem of carbon nanotube reinforced composite plates subjected to uniform temperature rise loading. Distribution of carbon nanotubes as reinforcements may be uniform or functionally graded. To account for the large deformations of the plate, von-Kármán type of geometrical nonlinearity is included into the formulation. The virtual displacements principle associated with the conventional Ritz formulation whose shape functions are selected as the Chebyshev polynomials is used to obtain the matrix representation of the nonlinear equilibrium equations. The solution method is general and may be used for arbitrary combination of boundary conditions. The postbuckling equilibrium path which is governed by a nonlinear eigenvalue problem is traced using a displacement control strategy. Results of this study are compared with the available data in the open literature for the cases of isotropic homogeneous plates and crossply laminated plates. Afterwards numerical results are given for FG-CNTRC plates. It is shown that, FG-X pattern results in higher buckling temperature and also decreases the postbuckling deflection of the plate. Furthermore, this type of composites are eager to exhibit the secondary instability which is designated with a snap-through phenomenon in the post-buckling equilibrium path.
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ABSTRACT: As a first attempt, optimum stacking sequences of thick laminated composite plate is obtained to maximize its buckling load via employing the finite element (FE), genetic algorithms (GAs) and particle swarm optimization (PSO) methods. The higher-order shear deformation theory (HSDT) is used to obtain governing equations of the plate. The finite element method (FEM) is employed to solve these equations and to gain buckling load of the plate. The FEM solution is linked with a developed optimization algorithm which is a mix of genetic algorithms (GAs) and particle swarm optimization (PSO) techniques. Some examples are solved to show applicability and usefulness of the proposed hybrid method for maximizing buckling load of the plate via finding optimum stacking sequences of the plate. Also, influences of different parameters on the optimum stacking sequences of the thick plate are studied.

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ABSTRACT: Free vibration characteristics of carbon nanotube reinforced composite spherical panels are studied in the present research. First order shear deformation shell theory and the Sanders kinematics are considered as the basic assumptions. Distribution of carbon nanotubes (CNTs) across the panel thickness may be uniform or functionally graded. Equivalent properties of the media are estimated according to a modified rule of mixtures approach which consists efficiency parameters to capture the size dependency of the properties. Using Hamilton’s principle and the conventional Ritz formulation, the matrix representation of the equations of free vibration motion is obtained. Shape functions of the Ritz method are obtained according to the Gram-Schmidt process. The resulting eigenvalue problem is solved to obtain the frequencies as well as mode-shapes of the spherical panel reinforced with CNTs. Convergence and comparison studies are provided to assure the effectiveness and accuracy of the proposed method. Afterwards, parametric studies are given to explore the effects of volume fraction of CNTs, distribution pattern of CNT, boundary conditions and geometric characteristics of the panel. It is shown that, enrichment of the polymeric matrix with more CNT results in higher frequencies. Furthermore, graded pattern of CNT is an influential factor on frequencies.

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ABSTRACT: The buckling response and load carrying capacity of thin-walled open cross-section profiles made of Fibre Metal Laminates, subjected to static axial compression loading are considered. These include thin-walled Z-shape and channel cross-section profiles adopting a 3/2 FML lay-up design, made of 3 aluminium layers. The objective of the investigation is the comparison of standard thickness Fibre Reinforced Plastic layers versus thin-ply material technology. Whilst thin ply designs differ only by the layer thickness, they offer an exponential increase in stacking sequence design freedoms, allowing detrimental coupling effects to be eliminated. The benefit of different hybrid materials are also considered. The comparisons involve semi-analytical and finite element methods, which are validated against experimental investigations.
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ABSTRACT: In this paper free vibration and bending analyses of a sandwich microbeam with two integrated piezo-magnetic layers as sensor and actuator are studied. Strain gradient theory of micro-structures is used to derive the governing equations of motion. First-order shear deformation theory as well as strain gradient theory is used for this purpose. The micro-piezo-magnetic layers are subjected to applied electric and magnetic potentials. The sandwich microbeam rests on visco-Winkler-Pasternak foundation. Electric and magnetic potentials are assumed as combination of linear function along the thickness direction that reflects applied electric and magnetic potentials and a cosine function that satisfies boundary conditions. Numerical results of this problem investigates the effect of some important parameters of sandwich microplate such as three micro length scale parameters, applied electric and magnetic potentials and parameters of foundation on the magneto-electro-mechanical responses of the problem.

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ABSTRACT: This paper investigates the free and forced vibration characteristics of functionally graded multilayer graphene nanoplatelet (GPL)/polymer composite plates within the framework of the first-order shear deformation plate theory. The weight fraction of GPL nanofillers shows a layer-wise variation along the thickness direction with GLPs uniformly dispersed in the polymer matrix in each individual layer. The effective Young’s modulus is predicted by the modified Halpin-Tsai model while the effective Poisson’s ratio and mass density are determined by the rule of mixture. Governing differential equations of motion are derived and Navier solution based technique is employed to obtain the natural frequencies and dynamic response of simply supported functionally graded GPL/polymer plates under a dynamic loading. A parametric study is conducted, with a particular focus on the effects of GPL distribution pattern, weight fraction, geometry and size as well as the total number of layers on the dynamic characteristics of the plates.

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ABSTRACT: Grid-stiffened composite structures not only allow for significant structural weight reduction but also are competitive in terms of structural stability and damage tolerance compared with conventional stiffened candidates. As the development of Automated Fibre Placement (AFP) technology matures, a unitized construction of skin and stiffeners is easily manufacturable. In this paper, a curved stiffener layout is optimized to enhance the structural buckling resistance. A linear variation of stiffener angles is used, resulting in the formation of a locally rhombic lattice pattern. Due to the spatial variation of angle and spacing induced by the use of curved stiffeners, analytic solutions for the responses are not generally applicable. Thus, global and local buckling loads are calculated based on finite element models by a previously-developed global/local coupled strategy. Since the stiffeners are not explicitly modelled in the finite element calculations, a fixed mesh is used for gradient-based optimization. Both parametric design and optimization are performed in order to find the optimal curved grid pattern, whose practical performances are assessed by post-buckling analysis. A comparison between the performances of structures with curved stiffeners, with straight stiffeners, and variable-stiffness skins with curved fibres, demonstrates the potential of curved stiffener configurations in improving the structural efficiency.

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ABSTRACT: This paper presents a unified nonlinear analytical solution of bending, buckling and vibration for the temperature-dependent functionally graded (FG) rectangular plates subjected to thermal load. Geometric nonlinearity resulted from mid-plane stretching is considered. Material properties of FG plates are assumed to vary with temperatures and the volume fractions of the constituents. Newly proposed higher order shear deformation theories in present available literature are sorted out and given a unified application. Three types of mathematical models, P-FG, S-FG and E-FG models, describing effective material properties of functionally graded materials (FGMs) are discussed. Finally, based on the unified nonlinear analytical solution, influences of material heterogeneity, thermal load, and plate geometry on bending, buckling and vibration of FG plates are studied. Outcomes reveal that the nonlinear solution exhibits better accuracy in calculation of shear stress in bending responses. The thermal load plays an important role in determining the bending, buckling and vibration of the FG plate. In addition, the characteristics of these three types of mathematical models to simulate effective material properties of FGMs are numerically compared and discussed.

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arbitrary quadrilateral plates are examined. Thereafter, geometrically nonlinear analyses of trapezoidal and
applicability and accuracy of the EFG method for the linear and nonlinear bending analyses of
composite straight
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ABSTRACT: Element free Galerkin (EFG) method with moving kriging (MK) shape functions is employed here to investigate geometrically nonlinear bending behavior of shear deformable isotropic and laminated composite straight-sided quadrilateral plates. Nonlinear governing equations derived based on the first order shear deformation theory and von Karman strains are solved using Newton-Raphson iterative technique. The applicability and accuracy of the EFG method for the linear and nonlinear bending analyses of isotropic arbitrary quadrilateral plates are examined. Thereafter, geometrically nonlinear analyses of trapezoidal and
arbitrary straight-sided quadrilateral thin and moderately thick composite plates are presented for the first time, which may serve as benchmark results for future research purposes.

References listed at the end of the paper:

ABSTRACT: This paper investigates nonlinear bending and buckling behavior of composite plates characterized by a thickness variation. Layer interfaces are described as functions of inplane coordinates. Top and bottom surfaces of the plate are symmetric about the midplane and the plate could be considered as a flat surface in analysis along with thickness parameters which vary over the plate. The variable thickness at a certain position in the midplane is modeled by a set of control thickness parameters through NURBS (Non-Uniform Rational B-Spline) basic functions. The knot parameter space which is referred in modeling geometry and approximating displacement variables is employed for approximating thickness, simultaneously. The use of quadratic NURBS functions results in $C^1$ continuity of modeling variable thickness and analyzing solutions. Thin to moderately thick laminates in bound of first-order shear deformation theory (FSDT) are taken into account. Strain-displacement relations in sense of von-Karman theory are employed for large deformation. Riks method is used for geometrically nonlinear analysis. The weak form is approximated numerically by the isogeometric analysis (IGA), which was recently found to be a robust, stable and realistic numerical tool. Numerical results confirm high reliability and capacity of the present method.

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“Analytical investigation on mechanical buckling of FGM truncated conical shells reinforced by orthogonal stiffeners based on FSDT”, Composite Structures, Vol. 159, pp 827-841, January 2017
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ABSTRACT: This work presents an analytical investigation for analyzing the mechanical buckling of truncated conical shells made of functionally graded materials, subjected to axial compressive load and external uniform pressure. Shells are reinforced by closely spaced stringers and rings. The change of spacing between stringers in the meridional direction also is taken into account. Using the adjacent equilibrium criterion, the first order shear deformation theory (FSDT) and Lekhnitskii smeared stiffener technique, the linearization stability equations
have been established. The resulting equations which they are the system of five variable coefficient partial differential equations in terms of displacement components are investigated by Galerkin method. The closed-form expression for determining the critical buckling load is obtained. The effects of material properties, dimensional parameters, stiffeners and semi-vertex angle on buckling behaviors of shell are considered. Shown that for thick conical shells, the use of FSDT for determining their critical buckling load is necessary and more suitable.

References listed at the end of the paper:
[38] R. Khakimova, R. Zimmermann, D. Wilekens, K. Rohwer, R. Degenhardt, Buckling of axially compressed CFRP truncated cones with additional lateral load: experimental and numerical investigation, Compos Struct (2016)

ABSTRACT: The crashworthiness of fiber reinforced plastics (FRP) is attracting more interest as they are currently contributing to several industries. In the present study, internally strengthened foam-filled rectangular carbon fiber reinforced plastics (CFRP) composites are presented for energy absorption applications. Commercially available carbon/epoxy beams/tubes were employed. After arranging the internal strengthening, each structure was filled with foam for better structural integrity. The structures were subjected to lateral compression and their crashworthiness was assessed using the peak load, the mean crushing load, the stability during post-crushing, the energy absorption, and the specific energy absorption. Up to 100% improvement was observed in both the energy absorbed and the load carrying capacity (referring to the peak load and the mean crushing load). Moreover, the stability in the post-crushing stage did not show significant dependency on the strengthening arrangement. Since it is highly dependent on the specimen weight, which is different from one specimen to another, the specific energy absorption showed different responses compared to the scalar value of the energy. For some configurations, internal strengthening had a negative effect on the specific energy. In contrast, an improvement of up to 22.5% was achieved for the other specimen configurations.

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ABSTRACT: Open holes or cutouts have been commonly used in composite structures for various engineering purposes. This paper aims to investigate the load bearing behavior and failure characteristics of the square weave carbon fiber reinforced plastic (CFRP) tubes with open holes subjected to axial compression. Effects of hole size, hole shape and hole distribution on failure modes and mechanical behaviors were evaluated experimentally and numerically. Different with the progressive crushing mode seen in the intact CFRP tubes, mid-height collapse and unstable local buckling were observed in the axial crushing tests. The peak load and specific energy absorption (SEA) of the perforated tubes decreased by around 3–22% and 26–57%, respectively, compared to those of the intact CFRP counterparts. It was found that the effect of hole size on failure strength in tubes was less sensitive than that in perforated composite laminates, but was relatively stronger than the perforation shape and distribution. The damage mechanisms were explored in-depth using strain gauge tests and finite element analysis, which showed a significant increase in shear stress around the holes prior to final failure.


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ABSTRACT: Functionally Graded Materials (FGMs) are the advanced materials in the field of composites, which can resist high temperatures and are proficient in reducing the thermal stresses. In recent decades,
significant investigations are reported in the predicting the response of FGM plates subjected to thermal loads. This paper presents a comprehensive review of developments, applications, various mathematical idealizations of materials, temperature profiles, modeling techniques and solutions methods that are adopted for the thermal analysis of FGM plates. An attempt has been made to classify the various analytical and numerical methods used for the stress, vibration and buckling analyses of FGM plates under one-dimensional or three-dimensional variation of temperature with constant/linear/nonlinear temperatures profiles across the thickness. An effort has been made to focus the discussion on the various research studies carried out till recently for the thermal analysis of FGM plates. Finally, some important conclusions and the suggestions for future directions of research in this area are presented. It is felt that this review paper will serve the interests of all the academicians, researchers and engineers involved in the analysis and design of FGM plates.

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“Flexural performance of innovative hybrid sandwich panels with special focus on the shear connection behavior”, Composite Structures, Vol. 160, pp 100-117, January 2017
https://doi.org/10.1016/j.compstruct.2016.10.066
ABSTRACT: The present study intends to evaluate the flexural performance of hybrid sandwich panels through the execution of four point bending tests. The proposed hybrid sandwich panel uses Deflection Hardening Cementitious Composites (DHCC) on the top layer, a GFRP bottom layer and perforated shear connectors in the GFRP ribs to transfer shear stresses between top and bottom layers. The tested hybrid slabs use two types of shear connectors, which include indented and perforated shapes. The tests were performed to study the behavior of a novel shear connection between the GFRP ribs and the DHCC layer that is here proposed. A comparison on the obtained experimental results was executed to clarify the influence of the shear connectors’ geometries on the flexural performance of the developed hybrid slabs. The results show that the shear connection mechanical behavior strongly influences the peak load, the deflection at peak load, the post-peak load carrying capacity and the degree of composite action of the hybrid slabs.

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ABSTRACT: The focus of this study is the development of a computational model with damage to predict failure of carbon fiber/epoxy filament wound composite tubes under radial compressive loading. Numerical analysis is performed via Finite Element Method (FEM) with a damage model written as a UMAT (User Material Subroutine) and linked to commercial software. The experimental analysis carried out followed ASTM D2412-11, where the specimen is parallel-loaded by two steel-based plates. Three stacking sequences have been evaluated. Both numerical and experimental results show that the presence of hoop layers at inner and outer
layers plus ±75° non-geodesic layers gives maximum compressive load to the composite tube, since the reinforcement is wound closer to the loading direction. Moreover, failure modes are predominantly delaminations, which are confirmed via numerical analyses through high in-plane shear stresses levels, and via experimental analyses through stereoscopic micrographs.

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ABSTRACT: The substitution of conventional mechanical fasteners by adhesive joints has been advocated by the aircraft and aerospace industries due to the weight saving potential. Flaws such as debonding of the adhesive layer between the skin and the stiffener may greatly affect the structural behavior of composite panels. Within this context, this work presents a semi-analytical approach for the numerical investigation on the effects of skin-stiffener bonding flaw size on the vibration and linear buckling behavior of T-stiffened composite panels. Skin and stiffener have been modeled using an assembly of curved and flat panel components, with each domain approximated using a set of hierarchical polynomial functions. A penalty-based approach has been used to assemble the various domains and to model the debonded region between the stiffener flange base and the plate. This approach ensures full compatibility in terms of displacements and rotations between the stiffener’s base top face and the panel bottom face allowing to model different skin/stiffener debonding lengths. The results obtained using the proposed semi-analytical models have been compared and verified against numerical predictions based on finite element analyses.

Oemer Civalek (Akdeniz University, Faculty of Engineering, Civil Engineering Dept., Division of Mechanics, 07200 Antalya, Turkiye), “Discrete singular convolution method for the free vibration analysis of rotating shells with different material properties”, Composite Structures, Vol. 160, pp 267-279, January 2017
https://doi.org/10.1016/j.compstruct.2016.10.031

ABSTRACT: Using the discrete singular convolution (DSC) method, this paper presents the free vibration analysis of rotating truncated conical shells, circular shells and panels. Isotropic, orthotropic, functionally graded materials (FGM) and laminated material cases are considered. The influences of centrifugal and Coriolis accelerations and the effects of initial hoop tension have been taken into account. The present analysis is based on Love’s first approximation shell theory. Frequency values are obtained for different types of boundary conditions, rotating velocity, circumferential wave number, geometric and material parameters. To verify the accuracy of this method, comparisons of the present results are made with results available in the literature. Some results related to rotating annular plates are also presented via conical shell equations. It is shown that the present method is reliable and applicable for vibration analysis of rotating shells and plates.

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https://doi.org/10.1016/j.compstruct.2016.10.035

ABSTRACT: This paper presents a stochastic approach to study the natural frequencies of thin-walled laminated composite beams with spatially varying matrix cracking damage in a multi-scale framework. A novel concept of stochastic representative volume element (SRVE) is introduced for this purpose. An efficient radial basis function (RBF) based uncertainty quantification algorithm is developed to quantify the probabilistic variability in free vibration responses of the structure due to spatially random stochasticity in the micromechanical and geometric properties. The convergence of the proposed algorithm for stochastic natural frequency analysis of damaged thin-walled composite beam is verified and validated with original finite element method (FEM) along with traditional Monte Carlo simulation (MCS). Sensitivity analysis is carried out to ascertain the relative influence of different stochastic input parameters on the natural frequencies. Subsequently the influence of noise is investigated on radial basis function based uncertainty quantification algorithm to account for the inevitable variability for practical field applications. The study reveals that stochasticity/system irregularity in structural and material attributes affects the system performance significantly. To ensure robustness, safety and sustainability of the structure, it is very crucial to consider such forms of uncertainties during the analysis.

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https://doi.org/10.1016/j.compstruct.2016.10.072

ABSTRACT: In this work, an equivalent continuum multiscale formulation is presented for the geometrical nonlinear analysis of the structures with lattice truss materials. This formulation is established by combining the extended multiscale finite element method and the co-rotational approach. Firstly, the lattice truss unit cell is equivalent to a continuum coarse element by using a numerical constructed interpolation function in the local coordinate system. Then the tangent stiffness matrix of this coarse element is derived by employing the basic idea of the co-rotational approach in the global coordinate system. Thus, the global nonlinear equilibrium equations of the structure at the macroscopic level can be solved by using the general displacement control algorithm to capture the equilibrium path with multiple critical points. After performing all of the incremental steps and the iterative steps on the macroscopic scale, the microscopic information, such as the displacement, stress and strain, can be obtained easily by virtue of the afore-constructed numerical interpolation functions once again. In addition, several numerical examples are carried out to study the effects of the layout and size of unit cell, investigate the sensitivity of coarse-scale meshes and verify the validation and efficiency of the presented multiscale formulation.

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ABSTRACT: Featured by the two material length parameters in the nonlocal strain gradient theory, it is still unknown that what are the boundary conditions of nonlocal strain gradient beams, since the equations of motion and boundary conditions of these beam models appear in the same form as those of the classical ones. Based on the weighted residual approaches, this paper provides the boundary value problems of Euler–Bernoulli beams within the framework of the nonlocal strain gradient theory in conjunction with the von Kármán nonlinear geometric relation. The closed-form solutions for bending and buckling loads of nonlocal strain gradient beams are obtained. Numerical results show that the higher-order boundary conditions have no effect on the static bending deflection of beams for the cases studied. However, the higher-order boundary conditions and the material length parameters have a significant effect on the buckling loads. Finally, when the two material length parameters are the same, the buckling loads can not always reduce to the classical solutions, the findings of which violate our expectations. The results provided in this work are expected to be helpful for the applications of this theory to the analysis of engineering structures.

https://doi.org/10.1016/j.compstruct.2016.10.086
ABSTRACT: This study presents a comprehensive investigation on structural collapse of a 47 m composite blade under combined bending and torsion in a full-scale static load test. The primary focus is placed on root causes and failure mechanism of the blade collapse. The investigation consists of three parts. First, video records of the blade collapse are examined on a frame-by-frame basis. Direct evidence is presented on how the blade collapses in progressive chain events. Second, the detailed post-collapse investigation is conducted both in-situ and in laboratory. The critical failure modes and the associated stress/strain state once experienced by the blade are indentified. Third, strain measurements are analyzed to provide quantitative evidence of the process leading to the blade collapse and consequently confirm the findings of this study. It is found that longitudinal compressive crushing failure and the following delamination of the spar cap, which are driven by local buckling, are the root causes of the blade collapse. The constraint of the loading saddle and local reinforcement of the blade section also contributes to the blade collapse. Torsion loads, although exhibiting no significant effect on the blade strength, are found to affect post-collapse characteristics of the blade.

https://doi.org/10.1016/j.compstruct.2016.10.079
ABSTRACT: This paper presents a detailed investigation about the geometric non-linear stiffness behavior of corrugated laminates in six different load cases. The considered tensile, bending, and shear load cases allow the modeling with a unit-cell approach assuming a generalized plane strain state. The torsional load case is more complex. There the mechanical response depends on the number of unit-cells and the width of the samples in case of geometric non-linearities. We first identify the load cases that show a non-linear stiffness response under large deformation. Then the non-linear behavior is analyzed in detail using numerical simulation and we
aim for mechanical explanations to describe the non-linear behavior. The FE simulations of the torsional load case are validated using experiments with 3D printed samples.


ABSTRACT: Model definition accuracy dictates the reliability of a predictive analysis for 3D woven composites (3DWC). The traditional modeling approach is based on analysis of ideal geometry with user specified imperfections. In that case, co-relating the actual imperfections arising from manufacturing processes with that of the model becomes an iterative process. In this study, a digital element (DE) approach is implemented for creating the woven architecture of the composite. This technique simulates the individual fibers and their interactions allowing the user to create a reference unit cell with imperfect geometry induced during manufacturing stages of 3DWCs. Thus the response and strength analysis account for the unique weaving signature and provide better predictions without the necessity to run iterative analysis procedures required for idealized geometry models. X-ray CT images or detailed statistical data for variations in specimen geometry are not required which makes this approach more attractive in terms of cost and creation time. A representative model created using the DE approach is used for prediction of compressive failure of 3DWC without having to seed imperfections for failure initiation. The analysis also captures the formation of a kink band as observed in experimental tests. Results of this study are compared with the experimental results and simulation results of idealized geometry reported previously in literature.


ABSTRACT: In the present work, a new design of honeycomb is proposed by embedding the rhombic configuration into the normal re-entrant hexagonal honeycomb (NRHH), in order to enhance the honeycomb’s in-plane mechanical properties. Both theoretical analysis and numerical simulations are employed to calculate the in-plane mechanical properties of the new honeycomb under uniaxial compression, including Young’s modulus, Poisson’s ratio and critical buckling strength. The results show that the new honeycomb can maintain auxetic performance, while both the in-plane Young’s modulus and the critical buckling strength are significantly improved compared to the NRHH. Comparisons between the present design and other exiting enhanced periodic topologies are also carried out. With respect to them, the present design features superior performances. For these outstanding properties, this layout may provide a new concept for the optimization and design of auxetic materials.

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The behavior and characteristics of classical membrane theory of isotropic materials are different from that of anisotropic materials. Care must be taken to prevent secondary bending moments due to the unbalanced arrangement of laminates of anisotropic materials. At times, bending theory may have to be adopted and the current design codes, such as ASME, API and ACI must be reviewed for the case of anisotropic materials. The stresses and strains can be significantly different between the pure membrane and bending theories. This paper derives a membrane type shell theory of hybrid anisotropic materials, governing differential equations together with the procedures to locate the mechanical neutral axis. The theory is derived by first considering generalized stress strain relationship of a three dimensional anisotropic body which is subjected to 21 compliance matrix and then non-dimensionalizing each variable with asymptotic expansion. After applying to the equilibrium and stress-displacement equations, we are allowed to proceed asymptotic integration to reach the first approximation theory. Also possible secondary moments due to the unbalanced built up of lamination are quantifiably expressed. The theory is different from the so called pure membrane or the semi-membrane analysis.

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ABSTRACT: In this paper, a new Fourier-related double scale approach is presented to study the wrinkling of thin films on compliant substrates. By using the method of Fourier series with slowly variable coefficients, the 1D microscopic model proposed by Yang et al. (2015) is transformed into a 1D macroscopic film/substrate model whose mesh size is independent on the wrinkling wavelength. Numerical tests prove that the new model improves computational efficiency significantly with accurate results, especially when dealing with wrinkling phenomena with vast wavenumbers. Besides, we propose a strategy to efficiently trace the wrinkling pattern corresponding to the lowest critical load by accounting for several harmonics of Fourier series in this new model. The established nonlinear system is solved by the Asymptotic Numerical Method (ANM), which has advantages of efficiency and reliability for stability analyses.

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ABSTRACT: In this paper, free vibration behavior of carbon nanotube (CNT) reinforced functionally graded thick laminated composite plates utilizing Reddy’s higher-order shear deformation theory (HSDT) is studied. To the best of authors’ knowledge, this paper is the first to incorporate HSDT with one of the element-free
approaches to investigate this issue. The element-free IMLS-Ritz method is employed and four types of CNT
distributions are considered. The resulting effective material properties of the CNT-reinforced composite are
estimated by a detailed and straightforward Mori–Tanaka approach. The numerical results have been compared
with the literature showing excellent agreement. Considering various CNT orientation angles, a parametric
study showing the effects of CNT volume fraction, plate aspect ratio, plate width-to-thickness ratio and number
of plate’s layers on the non-dimensional natural frequencies is investigated. Finally, the influence of boundary
conditions on the sequence of the first six mode shapes for various lamination arrangements is presented.

TrongNhan Tran (Division of Computational Mechatronics, Institute for Computational Science, Ton Duc
Thang University, Ho Chi Minh City, Vietnam), “Crushing analysis of multi-cell thin-walled rectangular and
https://doi.org/10.1016/j.compstruct.2016.10.106
ABSTRACT: Crushing behaviors of multi-cell thin-walled rectangular and square tubes are investigated in case
of lateral loading. Considering crushing force efficiency (CFE) shows that the connecting type of web-to-corner
(W2C) is more efficient than that of web-to-web (W2W). Multi-cell square tube with connecting type of W2C
is more effective than multi-cell rectangular tube with connecting type of W2C or W2W in lateral crushing
case. The theoretical models of the crushing force are proposed based on improved simplified super folding
element (ISSFE) theory and the crushing process for all types of tubes. The plastic hinge lines control the mean
crushing force, which is a function of flow stress of material, wall thickness, and length of tube. The peak
crushing force is determined based on the mean crushing force and the crushing force efficiency. The
theoretical results compare well with the experiment data.

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“Buckling of uniaxially compressed composite anisogrid cylindrical panel with clamped edges”, Composite
ABSTRACT: An analytical solution of the buckling problem for a uniaxially compressed composite lattice
cylindrical panel with the clamped edges is presented in this paper. The compressive load applied to the two
opposite curved sides of the panel induces compression in the circumferential direction due to Poisson effect
which is taken into account in this study. The lattice panel composed of the helical and hoop ribs is modelled as
an equivalent orthotropic cylindrical panel with effective stiffness parameters. The deflection of buckled panel
is described using the equations of the engineering theory of orthotropic cylindrical shells. The buckling
equations are solved using the Galerkin method in which the displacements and deflection of the panel are
approximated by the mode shape functions of a clamped-clamped beam. An analytical formula providing fast
and reliable way of calculation of the critical buckling load is derived and applied to the analyses of the
composite anisogrid panels with various parameters of lattice structures. The results are verified using a finite-
element method. The mass efficiency of the lattice panels designed for a required critical load is analysed.

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ABSTRACT: The axial crushing response of fibre metal laminates (FML), in particular GLARE top-hat structures, has been investigated using experimental and numerical techniques, which are reported in this paper. Crushing performance (crush force, energy absorption) was evaluated for formed GLARE top-hat structures as an analogue for an energy absorbing aircraft sub-floor structure. A numerical simulation methodology was established which could accurately predict the crushing performance of GLARE top hat structures using commercial explicit finite element (FE) analysis tool LS-DYNA. Material characterisation at coupon level was conducted to measure the appropriate material properties required for the model to achieve good predictability. The successful demonstration of GLARE energy absorbing structures widens options to enhance crashworthiness; numerous applications of such GLARE structures could be envisaged, including reinforcement of aircraft sub-floors. The crushing modes of GLARE top-hat structures were found to be complex, exhibiting mixed-mode failure which was a combination of the individual constituent failure modes. The metallic layers plastically deformed by folding and tearing while the composite layer failed with a wide range of failure patterns i.e. splaying, delamination and cracking. The top hat structures, most importantly, crushed in a stable progressive manner making them suitable for energy absorbing (EA) applications. The GLARE top hat structure’s crushing response is superior to its bare metal equivalent. Given the complexity of the FML crushing process, there is tremendous scope for optimisation of the laminate parameters to maximise energy absorption. The good agreement obtained between the numerical and experimental results highlights the benefits of using simulation to predict the overall crashworthiness of FMLs.


https://doi.org/10.1016/j.compstruct.2016.10.105

ABSTRACT: To overcome the instability encountered in axial crash simulations of composite tubes with shell elements, a new modeling technique: the shell-beam (SB) element method, has been developed. This method creates an element which is capable of deforming in the through thickness direction while retaining the efficiency of the shell elements. The SB element was evaluated with virtual one-element, cantilever beam and in-plane compression tests. The results showed that the SB element is effective in terms of overcoming the instability and convergence issues of traditional 2D and 3D discretized elements under in-plane compression. The SB element was further evaluated together with an in-house material model, called the enhanced continuum damage mechanics (ECDM) model, in crash simulations of triaxial braided composite tubes with five configurations and seven test conditions. The simulations captured both the failure morphologies and force-displacement responses obtained in experiments.

L.W. Zhang (State Key Laboratory of Ocean Engineering, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China), “On the study of the effect of in-plane forces on the frequency parameters of CNT-reinforced composite skew plates”, Composite Structures, Vol. 160, pp 824-837, January 2017

https://doi.org/10.1016/j.compstruct.2016.10.116
ABSTRACT: This paper investigates the effect of in-plane forces on the vibration behavior of carbon nanotube (CNT) reinforced composite skew plates. The analysis is performed by implementing the first-order shear deformation theory (FSDT) with the element-free/mesh-free Improved Moving Least Square-Ritz (IMLS-Ritz) method for solution to the problem. Two varieties of carbon nanotube-reinforced composite skew plates, namely uniformly distributed and functionally graded reinforcement are considered. A micromechanical model is employed to estimate the material properties of CNT-reinforced composite plates. Comparison studies are implemented to validate the accuracy of the proposed method. The frequency parameters and mode shapes for the skew plates are presented. A detailed parametric study is carried out to reveal many complicated effect on the frequency parameters of the plate. These effects include in-plane stress ratio, boundary conditions, CNT-volume fraction and geometric size. The obtained results will be references of future research and corresponding engineering project.

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ABSTRACT: A finite element formulation based on a higher-order layerwise theory is presented for the first time to investigate thermally induced vibrations of functionally graded material (FGM) sandwich plates and shell panels. The properties of FGM sandwich are assumed to be position and temperature dependent. The upper and lower layers of the sandwich panel are considered to be made of pure ceramic and metal, respectively and the elastic properties of FGM core are varied according to a power-law function. The top surface is exposed to a thermal shock and the bottom surface of the panel is either kept at a reference temperature or thermally insulated. The one-dimensional transient heat conduction equation is solved using a central difference scheme in conjunction with the Crank-Nicolson method. A higher-order layerwise theory is used for FGM sandwich panels, in which a higher-order displacement field for the FGM core and a first-order displacement field for the facesheets are assumed. The governing equations are solved using Newmark average acceleration method. It is shown that the proposed layerwise finite element formulation is simple and can easily be applied to investigate FGM sandwich plates and shell panels subjected to rapid heating.


ABSTRACT: Lateral buckling of thin-walled functionally graded (FG) open-section beams is studied, regarding mono-symmetric I- and channel-sections. The approach based on assumption that the volume fraction of particles varies through the wall thickness according to a power law. Governing buckling equations and a finite element method have been developed to formulate the problem. By means of Vlasov’s assumption, the theory accounts for warping of cross-section and all the structural coupling coming from anisotropy of material. The lateral buckling parameter and mechanism are obtained for thin-walled FG beams under central point load, uniformly distributed load, and moment gradient with several types of material distributions. In order to show the validity of proposed theory, as a special case, a numerical comparison is carried out with available results in literature. Moreover, effects of load height, gradual law, end-moment ratio and ceramic skin-core-skin thickness on the buckling capacity of a thin-walled FG open-section beam are also included in the analysis.
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ABSTRACT: This paper represents the methodology of analytical design and the selection of the optimal geometry of sandwich panels made of glass fiber reinforced plastic (GFRP) with a thermal insulating core and external heat shielding coating for the rescue vehicles operating in Arctic. The proposed methodology is based on the use of analytical solutions for the problems of thermal physics and structural mechanics for a preliminary assessment of the heat shield and strength characteristics of the panel. In the design process, we solve the optimization problem with objective function of the mass per unit area. Optimization constraints are formulated based on the conditions of thermal protection in a steady-state and transient cooling and heating conditions, strength and local and global buckling under shear, compression and bending of the panel. It is shown that the optimization could be limited by the strongest conditions, which are thermal protection at low temperatures and the condition for the web plate local instability under impact loading. It is shown that the use of a thermal barrier coating inevitably entails significant and not always allowable increase in structural mass, the panel thickness and strength safety factors.

Hamidreza Yazdani Sarvestani and Mehdi Hojjati (Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada), “Failure analysis of thick composite curved tubes”, Composite Structures, Vol. 160, pp 1027-1041, January 2017
https://doi.org/10.1016/j.compstruct.2016.10.133

ABSTRACT: In the present paper, a progressive failure analysis of thick laminated composite curved tubes subjected to pure bending moment is conducted proposing a novel high-order displacement-based method. The most general displacement field of elasticity of thick laminated composite curved tubes is developed employing a displacement approach of Toroidal Elasticity and the layer-wise method. Subsequently, the accuracy of the proposed method is verified by comparing numerical results obtained by the proposed method with finite element method (FEM) and experimental data. By employing the proposed method, a progressive failure analysis is performed using Tsai-Wu criterion. Finally, effects of lay-up sequences of thick composite curved tubes on stress distributions and failure sequences are investigated.

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ABSTRACT: In this paper, a piecewise shear deformation theory for laminated composite and sandwich plates is presented by integrating the advantages of the layerwise theory and equivalent single layer theory. A \( C^0 \) continuous four-noded quadrilateral isoparametric plate element based on this theory is developed for free and forced vibration analysis of laminated composite and sandwich plates in thermal environments. The accuracy and effectiveness of piecewise shear deformation theory and finite element formulation are validated by comparing the numerical results obtained by the present finite element formulation with the analytical and exact results available in literatures as well as the numerical results computed by MSC.Nastran software. It is demonstrated that the piecewise shear deformation theory and finite element formulation are suitable for the vibration analysis of thin and thick laminated composite and sandwich plates. As compared with the layerwise theory, high-order zigzag theory and high-order equivalent single layer theory, the piecewise shear deformation theory is able to produce a sufficiently accurate result at a very low computational cost. The work reported in this paper provides an efficient modeling approach for thermal vibration analysis of laminated composite and sandwich plates in practical engineering.


ABSTRACT: The worst geometric imperfection is a mathematical concept which should deliver in theory a lower bound for the buckling load of unstiffened cylindrical shells. The corresponding knock-down factors could be used as base for improved shell design guidelines in order to reduce weight and cost of unstiffened shells. Commonly used worst geometric imperfections include eigenmode or axisymmetric imperfection pattern. However, experimental results show that buckling failure is induced by an isolated single dimple which can be classified as a realistic worst geometric imperfection. It is hypothesized that the interaction between single dimple motion and the deformation behavior in the pre-buckling range of cylindrical shells significantly influences the buckling load. A numerical model is proposed in order to study the before mentioned thesis. The results show that the proposed numerical model induces a physical meaningful and realistic buckling response in a cylindrical shell. It can be validated that the interaction between single dimple motion and the deformation behavior of a cylinder in the pre-buckling range significantly influences the buckling load. Based on experimental data it can also be shown that the lower bound of the buckling load is accompanied by a characteristic post-buckling pattern shortly after collapse.

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ABSTRACT: Lattice truss reinforced honeycombs (LTRHs), termed honeytubes, were developed based on a hybrid design of micro-lattice truss and square honeycomb topologies. Carbon fiber reinforced composite and polymer LTRHs were fabricated using different manufacturing approaches. Out-of-plane compression tests were performed on the LTRHs, and the properties were compared with the conventional square honeycombs. The stiffness and strength values of composite LTRHs didn’t surpass those of composite square honeycombs due to the manually induced defects. On the other hand, polymeric LTRHs with perfect geometries were stiffer and stronger than the corresponding polymeric square honeycombs. A parametric study of the buckling resistance was carried out via finite element analysis, and the results indicated that hollow lattice stiffens honeycombs and increases the resistance to buckling, while the specific properties of honeytubes depend on their geometrical parameters. Moreover, the crush force efficiency and specific energy absorption were greater than those of square honeycombs and hollow lattice. This work demonstrates that hybrid designs that capitalize on micro-topologies can populate vacant regions in mechanical property charts, and provide increased energy absorption as crushing protection structures.

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ABSTRACT: When subjected to uniformly compression, the film/substrate system will present buckling instability. With an appropriate size of pre-existing interfacial imperfection, there will be local buckling delamination which will result in a buckling delamination induced microchannel. This microchannel has exhibited a potential application of directing and manipulating fluid flow. In this paper, we explore the on-off, evolution and failure process of the buckling delamination induced microchannel with both analytical and finite element method and investigate the flow behavior within this microchannel. We present the analytical solution to determine the critical strain for different film/substrate systems. The linear buckling analysis has been utilized to predict the buckling modes. The characteristics and configuration of the induced microchannel for different compressive strain have been investigated using nonlinear buckling analysis. The Lattice Boltzmann method has been used to study the microflow behavior within the microchannel. The theoretical and numerical buckling delamination analysis, together with the microflow analysis within the microchannel, will lay a foundation to design a flexible microvalve to regulate fluid flow where the use of traditional rigid microvalve is improper in flexible microfluidic device.

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ABSTRACT: Fibre reinforced plastic (FRP) composite materials can provide superior specific energy absorption performance over conventional metallic structures if crush stability can be maintained during the impact event. The core in sandwich structures helps to stabilise the crush front by preventing global buckling, but delamination remains a barrier to optimal crushing performance. In this work, the in-plane crushing
response of sandwich structures was improved by adding through-thickness reinforcement in the form of aramid fibre tufts. The effect of tufting different sandwich cores and facesheet orientations was investigated in both static and dynamic crushing modes. A drop-tower test rig was used to crush panels in realistic automotive crash conditions and a high-speed camera captured the crushing mechanisms. The through-thickness reinforcement improved the facesheet to core adhesion, resulting in a more localised and stable fracture of the facesheets. Tufting improved the specific energy absorption (SEA) from 11.5 kJ/kg to 20.5 kJ/kg and the crush force efficiency (CFE) from 0.22 to 0.55.

ABSTRACT: Without adding new degrees of freedom, this paper presents a new finite element formulation that combines three important ingredients for precise analysis of displacements and transverse stresses in laminated shells and plates, namely: (i) Presence of Zig-Zag effect, (ii) regularization of transverse stresses in order to guaranty their continuity and (iii) cinematically exact description in FEM nonlinear geometric formulation. The accuracy of the proposed formulation in both displacements and stresses will be proven by comparing results with linear elastic benchmarks of literature. Furthermore, the possibilities of the formulation are shown by solving an extreme geometric nonlinear problem of orthotrophic laminated shells, considering results in displacements and stresses.

ABSTRACT: The main purpose of this study is to give a numerical solution for static buckling problem of circular cylindrical panels, conical panels, conical shells and circular cylindrical shells under axial load. Isotropic, laminated composite, functionally graded material (FGM) and carbon nanotube (CNT) reinforced functionally graded cases are taken into consideration. By using the Donnell’s shell theory and first-order shear deformation (FSDT) shell theory, the related equations have been obtained for buckling phenomena of shells. Then, the method of discrete singular convolution (DSC) based on the Shannon’s kernel is applied for the solution of these equations. Convergence and comparison studies are carried out to check the validity and accuracy of the DSC method. The effects of shell geometric quantities and material properties on buckling are examined and results are presented for isotropic, FGM, CNT reinforced FGM and laminated composite conical and cylindrical shells and panels. Performance and convergence conditions of the method of DSC have also been investigated.

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ABSTRACT: This paper investigates the buckling and postbuckling behaviours of functionally graded multilayer nanocomposite beams reinforced with a low content of graphene platelets (GPLs) resting on an elastic foundation. It is assumed that GPLs are randomly oriented and uniformly dispersed in each individual GPL-reinforced composite (GPLRC) layer with its weight fraction varying layerwise along the thickness direction. The effective material properties of each layer are estimated by the Halpin-Tsai micromechanics model. The nonlinear governing equations of the beam on an elastic foundation are derived within the framework of the first-order shear deformation beam theory then are converted into a nonlinear algebraic system by using the differential quadrature method. A detailed parametric study is carried out to examine the effects of the distribution pattern, weight fraction, geometry and size of GPL nanofillers, foundation stiffness parameters, slenderness ratio and boundary conditions on the buckling and postbuckling behaviours. The results show that GPLs have a remarkable reinforcing effect on the buckling and postbuckling of nanocomposite beams.


ABSTRACT: For the three-node triangular elements, the displacement parameters are linear variation within one element, so that the second and the third derivatives of displacement parameters are close to zero. Therefore, the three-node triangular element will encounter difficulty to accurately predict transverse shear stresses by integrating the three-dimensional equilibrium equation through the thickness direction. Thus, the few three-node triangular plate elements can accurately yield the transverse shear stresses of multilayered composite plates. A higher-order zig-zag model accounting for the zero transverse shear strain conditions at the top and the bottom surfaces is firstly presented in this work. Based on the proposed model, a refined three-node triangular plate element satisfying the requirement of C^1 weak-continuity conditions in the inter-element is developed to accurately produce the distributions of displacements and stresses through the thickness of multilayered composite plates. To obtain the improved transverse shear stresses, the simplified three-dimensional equilibrium equation has been a priori used. It is significant that the higher-order derivatives of displacement parameters have been taken out from the expression of transverse shear stresses by employing the three-field Hu-Washizu (HW) variational principle, which is convenient for the finite element implementation. Performance of the present element is tested by comparing with three-dimensional elasticity solutions as well as the reference results evaluated using other models. A detailed study is conducted to highlight the influences of boundary condition, number of layers and aspect ratio on the static response of multilayered composite plates, and numerical results can show the accuracy and range of applicability for the proposed element.

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ABSTRACT: This paper presents a novel methodology to design wind turbine blades using the Inverse Finite Element Method (IFEM). IFEM takes as domain of analysis the geometry of the blade after large elastic deformations caused by given service loads. The deformed shape of the blade is that determined to be efficient
using an aerodynamics analysis. From this analysis, the aerodynamic loads on the blade are known. Then, we choose the materials to manufacture the blade. As usual, the blade is assumed to be made of multiple layers of composite materials. After materials selection, the stationary inertial loads on the blade are known. Finally, given the desired deformed shape and all the service loads, we use IFEM to compute the manufacturing shape of the blade. This is a one-step, one-direction strategy where the aerodynamics analysis feeds the structural (IFEM) analysis, and no further interaction between both solvers is required. As an application of the proposed strategy, we consider a medium power 40-KW wind turbine blade, whose whole design is detailed along this work.


ABSTRACT: In this present study, the geometrical nonlinear static behaviour of the functionally graded carbon nanotube reinforced doubly curved shell panel is investigated under uniform thermal environment. The material properties of the carbon nanotube and matrix are assumed to be graded through the thickness of panel via four types of grading rule. The mathematical model of nanotube graded composite panel is derived using Green-Lagrange type geometrical nonlinearity in the framework of the higher-order kinematics. In addition, thermal environment dependent properties of the individual constituent (carbon nanotube and matrix material) are considered in the present investigation to achieve the generality. Further, the motion equation of equilibrium is obtained by minimizing the total energy functional and discretized with the help of suitable isoparametric finite element steps. The necessary large deflection values are worked out numerically through a generic MATLAB computer code in conjunction with developed nonlinear higher-order model and the direct iterative method. Lastly, the effects of different geometrical and material parameter (aspect ratios, support conditions, thickness ratios, volume fractions, temperature load and type of grading) on the linear and nonlinear deflection behaviour of functionally graded carbon nanotube reinforced composite doubly curved shell panel are examined and discussed in details.

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ABSTRACT: This paper presents Best Theory Diagrams (BTDs) employing combinations of Maclaurin, trigonometric and exponential terms to build two-dimensional theories for laminated cross-ply plates. The BTD is a curve in which the least number of unknown variables to meet a given accuracy requirement is read. The used refined models are Equivalent Single Layer and are obtained using the Unified Formulation developed by Carrera. The governing equations are derived from the Principle of Virtual Displacement (PVD), and Navier-type closed form solutions have been obtained in the case of simply supported plates loaded by a bisinusoidal transverse pressure. BTDs have been constructed using the Axiomatic/Asymptotic Method (AAM) and genetic algorithms (GA). The influence of trigonometric and exponential terms in the BTDs has been studied for
different layer configurations, length-to-thickness ratios and stresses. It is shown that the addition of trigonometric and exponential expansion terms to Maclaurin ones may improve the accuracy and computational cost of refined plate theories. The combined use of CUF, AAM and GA is a powerful tool to evaluate the accuracy of any structural theory.


ABSTRACT: A tolerance modelling approach for problems of periodic media and structures is adopted here to investigate free vibrations of thin functionally graded plates with a microstructure along one direction in the planes parallel to the plate midplane. The size of the microstructure is assumed to be of an order of the plate thickness. To show the effect of the microstructure on dynamic behaviour of these plates the tolerance modelling method is used, cf. Jedrysiak (2013). This method leads to model equations with smooth functional coefficients, which describe the effect of the microstructure size of these plates not only in dynamic but also in stationary problems. In order to take into account this effect two models – the asymptotic-tolerance model and the tolerance model are used. As an example of applications of these models free vibration frequencies for simply supported rectangular plate are calculated. A certain verification for some cases is also shown by using the finite element method.


ABSTRACT: The Koiter–Newton method is a novel reduced-order modeling technique to efficiently trace the geometrically nonlinear equilibrium path of the structure in the presence of buckling. In this paper, the existing method is extended for nonlinear buckling analysis of thick and thin laminated composite plates. A 4-node quadrilateral element S4AT is developed as a geometric linear element in the co-rotational formulation of the Koiter–Newton method. The developed element S4AT is a combination of the membrane part and the plate-bending part. The quadrilateral area coordinate method is applied to make the element insensitive to the mesh distortion. The Reissner–Mindlin laminated composite plate theory is used to consider the transverse shear deformation effect, and the shear-locking phenomenon is eliminated using the Timoshenko laminated composite beam theory. The performance of the method in terms of reliability, accuracy and computational effort is demonstrated with several examples.

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ABSTRACT: Practical applications such as airplane wings are usually subjected to combined thermal and mechanical loads, and they hence are prone to buckling failure. Preceding works on the buckling of advanced materials, e.g., functionally graded materials, under combined thermal and mechanical loads are rather rare in literature. In this paper, we report new numerical results of thermal-mechanical buckling of functionally graded rectangular and skew plates (FGPs) under combined thermal and mechanical loads. The numerical responses of buckling are computed using isogeometric analysis (IGA) based on the first-order shear deformation plate theory (FSDT) without shear-locking effect. We present formulations and then provide validation of numerical results computed by the proposed formulation against reference existing solutions. Parametric study is also performed to explore insight into the effects of various numerical aspect ratios such as gradient index, plate aspect ratio, loading type, skew angle, and boundary condition, etc. on mechanical response of FGPs. The stability diagrams are also presented.

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ABSTRACT: This paper is focused on a method for calculating the optimal drape origin on arbitrary surfaces considering a minimal shear-deformation of the applied fiber-reinforced material. The presented method is based on the mesh from a triangulated surface and therefore not restricted by the assumption of a mathematical differentiable surface description. It is shown how the information of the mesh can be used to calculate the point-wise Gaussian-curvature on the given surface. It is further shown how this curvature information can be used to construct a directed planar graph and how this graph can help calculating the optimal drape sequence in order to minimize the shear-deformation of the applied fabric. The paper is concluded by a demonstration of the developed method for different example surfaces.

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ABSTRACT: An analytical study to the nonlinear vibration of imperfect stiffened FGM sandwich toroidal shell segment containing fluid in external thermal environment is approached in this present. The toroidal shell segments consist of two types convex shell and concave shell which are reinforced by ring and stringer stiffeners system. Material properties of shell are assumed to be continuously graded in the thickness direction. Based on the classical thin shell theory with geometrical nonlinearity in von Karman-Donnell sense, Stein and McElman assumption, and the smeared stiffeners technique theoretical formulations are established. In addition, the dynamical pressure of fluid is taken into account. The fluid is assumed to be non-viscous and ideal.
incompressible. The nonlinear vibration analyses of full-filled fluid toroidal shell segment are solved by using numerical method fourth-order Runge-Kutta. Furthermore, effects of geometrical and material parameters, imperfection, fluid and change of temperature field on the nonlinear vibration responses of shells are shown in obtained results. It is hoped that the obtained results will be used as benchmark solutions for an analytical approach of fluid-structures vibration in further research.


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ABSTRACT: The paper presents a new numerical approach for buckling analysis of non-uniform thickness nanoplates in an elastic medium using the isogeometric analysis (IGA). By ignoring the van der Waals interaction between two adjacent plates, non-uniform thickness nanoplates are described as a single-layered graphene sheet. The governing differential equation of the nanoplates is derived by the nonlocal theory in which the nonlocal stress-strain relation is used to capture the nonlocal mechanics caused by small size effects. The governing equation is then discretized into algebraic equations and solved by using IGA procedure to determine the critical buckling load. By using the non-uniform rational B-splines, IGA easily satisfies the required continuity of the partial differential equations in buckling analysis. Several numerical examples are solved and compared with those of previous publications to illustrate the performance of IGA for buckling analysis of nanoplates.

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ABSTRACT: Low-velocity impact on the free edge of composite stiffener is considered as a critical factor on the loss of compression strength. This paper proposes a phenomenologically-based mechanical finite element model for the Compression-After-Edge-Impact (CAEI) failure prediction of the composite panel stiffened with T-shaped stiffeners, of which the web is subjected to edge impact damage. Based on the specific failure mechanisms during an edge impact, localized crushing failure, which is insignificant during a classic skin impact, however is considered as a key point of the proposed model for the simplification of impact-induced damage. With the help of a composite damage model comprising both continuum damage mechanics model and surface-based cohesive contact model, a good correlation between the experimental and numerical results is obtained, and therefore validates correctness and effectiveness of the proposed mechanical model. Furthermore, the results reveal that the propagation of fiber compressive failure plays a major role in the compressive failure of the impacted web, of which complete fracture determines the ultimate failure load of the T-stiffened composite panel.

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ABSTRACT: The nonlinear model of a single-walled carbon nanotube (SWCNT) modeled as a nanobeam embedded in a Kelvin-Voigt viscoelastic medium is developed by using the nonlocal continuum theory. It is assumed that the nanobeam vibrates under the influence of the longitudinal magnetic field and time-varying axial load. Based on the nonlocal Euler-Bernoulli beam theory, Maxwell’s equations and von Karman nonlinear strain-displacements relation, we obtain the nonlinear partial differential equations of transversal motion of the embedded nanobeam with different boundary conditions. The relationship between nonlinear amplitude and frequency of variable axial load in the presence of the longitudinal magnetic field is derived by using the perturbation method of multiple scales. An approximate analytical solution for nonlinear frequency and instability regions for the linear case of vibration is also considered in this paper. In order to analyze nonlinear dynamical stability regions of SWCNT, the incremental harmonic balance (IHB) method is introduced for obtaining iterative relationship of frequency and amplitude of time-varying axial load. It is showed that the nonlocal parameter, magnetic field effects and stiffness coefficient of the viscoelastic medium have significant effects on vibration and stability behavior of nanobeam and therefore receive substantial attention. In addition, from the presented numerical results one can see the influence of the small scale, magnetic field and foundation coefficients on the frequency-response curve, nonlinear frequency and instability regions for the linear and nonlinear cases.
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“Dynamic instability of functionally graded multilayer graphene nanocomposite beams in thermal environment”, Composite Structures, Vol. 162, pp 244-254, February 2017
https://doi.org/10.1016/j.compstruct.2016.12.001
ABSTRACT: This paper studies the dynamic instability of functionally graded multilayer nanocomposite beams reinforced with a low content of graphene nanoplatelets (GPLs) and subjected to a combined action of a periodic axial force and a temperature change. The weight fraction of GPL nanofillers is assumed to be constant in each individual GPL-reinforced composite (GPLRC) layer but follows a layerwise variation across the beam thickness. The Halpin-Tsai micromechanics model is used to estimate the effective Young’s modulus of GPLRC layers. The differential quadrature method is employed to convert the partial differential governing equations into a linear system of Mathieu-Hill equations, from which the principle unstable region of functionally graded multilayer GPLRC beams is determined by Bolotin’s method. Special attention is given to the effects of GPL distribution pattern, weight fraction, geometry and dimension on the dynamic instability behaviour. The thermal buckling and free vibration are also discussed as subset problems. Numerical results show that distributing more GPLs near the top and bottom surfaces can effectively increase the natural frequency and reduce the size of the unstable region. The influences of GPL geometry and dimension tend to be insignificant when the GPL width-to-thickness ratio is larger than 10^3.

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https://doi.org/10.1016/j.compstruct.2016.12.009
ABSTRACT: As a first endeavor, the free vibration behavior of the pre-twisted functionally graded carbon nanotube reinforced composite (FG-CNTRC) beams in thermal environment is studied. The governing equations are derived based on the higher-order shear deformation theory of beams by considering the temperature dependence of material properties and the initial thermal stresses. The free vibration eigenvalue equations are extracted by using the Chebyshev–Ritz method. In this regard, Chebyshev polynomials together with appropriate boundary functions are utilized as admissible functions of the Ritz method, which enables one to handle the problem with different sets of boundary conditions. The fast rate of convergence of the method is demonstrated numerically and its accuracy is verified by comparing the results in the limit cases with existing
solutions in the literature. The effects of pre-twist angle together with carbon nanotubes (CNTs) distribution in thickness direction, the temperature dependence of material properties, the temperature rise, the geometrical shape parameters and boundary conditions on the frequency parameters are investigated. It is shown that the effects of the pre-twist angle on the natural frequencies depend on the beam boundary conditions and also the mode number.

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ABSTRACT: The objects of consideration are thin linearly elastic Kirchhoff-Love-type open circular cylindrical shells having a functionally graded macrostructure and a tolerance-periodic microstructure in circumferential direction. The first aim of this contribution is to formulate and discuss a new non-asymptotic averaged model for the analysis of selected dynamic problems for these shells. As a tool of modelling we shall apply the tolerance averaging technique. Contrary to the starting exact shell equations with highly oscillating, non-continuous and tolerance-periodic coefficients, governing equations of the proposed tolerance model have continuous and slowly varying coefficients depending also on a cell size. Hence, an important advantage of this model is that it makes it possible to study the effect of a microstructure size on the global shell dynamics (the length-scale effect). The second aim is to derive and discuss a certain asymptotic model being independent of a microstructure size. It will be shown that in the framework of the tolerance model not only the fundamental lower, but also the new additional higher-order free vibration frequencies can be derived and analysed.

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ABSTRACT: This study deals with the thermoelectroelastic behaviors of a fluid-filled functionally graded piezoelectric material (FGPM) cylindrical thin-shell under the combination of mechanical, thermal and electrical loads. The FGPM is composed of piezo ceramic and metal components and the holistic material properties are assumed to vary continuously through the thickness of the shell with power law. Based on the classical cylindrical shell theory, the governing differential equations are derived. Applying the analytical method, exact solution of the problem is obtained. Finally, through numerical examples, the influences of various factors on the thermoelectroelastic behaviors of the fluid-filled FGPM cylindrical thin-shell have been analyzed and discussed.

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ABSTRACT: The non-linear transverse dynamic response of laminated composite simply supported circular cylindrical shell subjected to periodic radial point loading and static axial partial loading is studied in this paper considering von Kármán type of non-linearity. The applied partial edge loading is represented by Fourier series and the exact prebuckling stress distribution within the cylindrical shell is computed by solving the in-plane elasticity problem. Donnell’s shell theory incorporating first order shear deformation, in-plane and rotary inertia is used to model the cylindrical shell. Galerkin’s method is used to reduce the governing partial differential equations to a set of non-linear ordinary differential equations. These equations are solved using Incremental Harmonic Balance (IHB) method to obtain frequency-amplitude responses for free and forced vibration. The numerical results illustrate the effects of number of layers, static partial preloading, and initial geometric imperfections on the non-linear forced vibration of laminated composite cylindrical shells.


ABSTRACT: In this article, a layerwise shear deformation theory is incorporated for geometrically nonlinear vibration (GNV) analysis of multiferroic composite plates and doubly curved shells. The coupled constitutive equations involving ferroelastic, ferroelectric and ferromagnetic properties of multiferroic composite materials along with the total potential energy principle are utilized to derive the finite element formulation for the multiferroic or magneto-electro-elastic (MEE) plates/shells. The electric and the magnetic potentials are assumed to vary linearly in the transverse direction. The electric and magnetic potential distribution in the plate/shell is computed by using the Maxwell's electromagnetic relations. The significance of geometric nonlinearity has been considered using the von Kármán nonlinear strain-displacement relations. Importance of curvature aspect ratio, curvature ratio and the thickness aspect ratio on the nonlinear frequency ratios of the multiferroic/MEE doubly curved shells has been investigated. The backbone curves for multiferroic plates and shells have been studied by considering various aspect ratios. Impact of layer stacking sequence, boundary conditions and coupled fields on the central deflection and nonlinear frequency ratio of the multiferroic plates and shells have been investigated.

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ABSTRACT: Influence of axial compression load on buckling and free vibration characteristics of natural fiber fabric polymer composite beam is analyzed experimentally. Critical buckling strength, free vibration frequencies and modal loss factors are obtained and analyzed. It is found that buckling strength increases with number of layers of fabric in composite. It is also observed that weaving pattern of the fabric influences buckling strength of the composite and basket type woven fabric enhances the buckling strength compared to plain and herringbone woven fabric composites. Sandwich composites with glass fiber fabric facing layer and
natural fiber fabric as core layer having higher buckling strength. Free vibration frequency reduces with increase in axial compression load while modal damping factor increases in the pre-buckling region. However, this behavior reverses in the post-buckling region. The load-deflection obtained experimentally is compared with finite element result obtained considering the geometric non-linearity.

Shanshuai Wang, Shuhui Li and Ji He (State Key Laboratory of Mechanical System and Vibration, and Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures, Shanghai Jiao Tong University, Shanghai 200240, PR China), “Buckling behavior of sandwich hemispherical structure considering deformation modes under axial compression”, Composite Structures, Vol. 163, pp 312-324, March 2017

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ABSTRACT: Sandwich structures are often used in space and aviation industry as energy absorption elements due to their load carrying capacity and light weight features. In experiments, it has been found that sandwich hemispherical structures have two different deformation modes referred as dimpling and flat mode under axial compression load. Deformation modes exercise a great influence on load carrying capacity of sandwich hemispherical structure. In this paper, theoretical models for two deformation modes of sandwich hemispherical structures under axial compression have been proposed. The reason for two different deformation modes observed in the compression tests has been explained. A finite element model has been set up and validated by the experimental results. Based on the numerical simulation results, buckling behaviors, load carrying capacities and displacements of top points of two different deformation modes have been compared. It is found that the load carrying capacity of the sandwich hemispherical structure under dimpling mode is about half of that under flat mode with very similar configurations. The deformation mode can be changed from dimpling to flat by adjusting the thicknesses of the outer and inner metal sheets. This is a feasible and efficient way to improve the load carrying performance of the sandwich hemispherical structure. The optimal thickness ratio range of outer and inner metal sheet is proposed. The methods can help improve the design of sandwich hemispherical structures to obtain better load carrying capacity with reasonable configuration.

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ABSTRACT: This paper presents a first know study of the effect of orientation angle of carbon nanotubes (CNTs), embedded in a single-ply polymer-based CNT-reinforced composite, on buckling behavior of skew plates using an isogeometric analysis. The plate model is based on Reddy’s higher-order shear deformation theory (HSDT). Four in-plane loading conditions together with simply supported and cantilevered boundary conditions have been considered. The optimum CNT fiber orientations for CNT-reinforced composite rhombic plates with varying skew angles and boundary conditions are presented. Moreover, the effect of width-to-
thickness ratio on optimum CNT orientation is explored. The results show that the efficiency of the skew plate structures can be significantly improved by simply placing the CNTs in the correct orientation.

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ABSTRACT: Free vibration of layered truncated conical shells filled with quiescent fluid using spline method is studied. Love’s first approximation theory is used to formulate the equations of motion of truncated conical shells. Velocity potential and Bernoulli’s equations have been applied for the expression of the pressure of the fluid. The fluid is assumed to be incompressible, inviscid and quiescent. The solutions of displacement functions are assumed in a separable form to obtain a system of coupled differential equations in terms of displacement functions. The displacement functions are approximated by Bickley-type splines to obtain the generalized eigenvalue problem by combining with boundary conditions. A generalized eigenvalue problem is obtained and solved numerically for frequency parameter and an associated eigenvector of spline coefficients.

Two layered shells are considered. Parametric studies are made to investigate the effect of fluid on the frequencies with respect to the relative layer thickness, semi cone angle and length ratio.

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ABSTRACT: Effect of fatigue loading on impact damage and buckling/post-buckling behaviors of stiffened composite panels under axial compression were studied in this paper. Barely visible impact damage (BVID) was introduced to stiffened composite panels. Damage areas and crater depths data were analyzed and their distributions were determined, whose upper limits were also calculated under different reliability. Then fatigue experiments were conducted on impact specimens. Damage areas, damage site shapes and crater depths were measured at every certain fatigue cycles. Compression after impact (CAI) as well as compression after impact and fatigue (CAIF) were also studied, with a comparison of virgin specimens. The results exhibited impact damage and the following fatigue loading had no obvious influence on the bucking load and buckling modes. Additionally, failure modes of all types of specimens were similar, which included debonding and fracture of stiffeners together with splitting and cracking of skin bays. However, the average failure load of impact specimens decreased 9.9% compared to that of virgin specimens. Fatigue loading would lead a further decrease
about 6.1% in failure load compared to impact specimens, although the impact damage had no obvious changes during and after fatigue loading.

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ABSTRACT: This paper proposes a method based on efficient higher-order zig-zag theory to analyze the viscoelastic response of doubly-curved laminated shell structures. In the general curvilinear coordinates, displacement fields are obtained by imposing a varying cubic displacement field on a varying linear zig-zag field. Then, the transverse shear stress-free condition at the top and bottom surfaces and the continuity condition at the interfaces are employed to reduce the number of unknown variables. The Laplace transformation is then used to simplify the integral-formed constitutive equation for viscoelastic material in the real time domain into a linear system equation in the Laplace domain so that all computations can be carried out in the Laplace domain. Therefore, the equilibrium equation for general viscoelastic Naghdi shell model can be obtained by converting the virtual work principle into the Laplace domain. Finally, solutions for the long-term viscoelastic properties in the real-time domain are obtained by using numerical inverse Laplace techniques. To simplify the formulation and conveniently evaluate the method proposed in the present study and to compare its outcomes with those of an elastic laminated composite shell, several numerical examples for a cylindrical shallow shell model are investigated.

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ABSTRACT: Nonlinear bending, thermal buckling and post-buckling analysis for functionally graded materials (FGMs) tubes with two clamped ends by using a refined beam theory are investigated. The theory satisfies the traction-free boundary conditions on the inner and outer surfaces of the tube and also takes into account the transverse shear effects without artificially introducing shear correction factors. The material properties of FGM tubes are assumed to be temperature-dependent and vary in the radial direction. The asymptotic solutions of the FGM tubes under nonlinear bending and thermal post-buckling are solved by using a two-step perturbation method. The analytical solutions of Timoshenko beam and Euler beam are also presented. Detailed parametric studies are performed to investigate effects of inner-to-outer radius ratio, volume fraction as well as shear deformation on nonlinear bending, thermal buckling and post-buckling characteristics of the FGM tubes.

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ABSTRACT: This paper presents analytical buckling and vibration solutions for two nonlocal circular arch models. One model is based on Eringen’s stress gradient theory while the other model is based on continualization of a lattice system. Both nonlocal arch models contain the unknown small length scale coefficient $e_0$. In order to calibrate $e_0$, exact buckling and vibration solutions for Hencky bar-chain model (HBM) are first obtained. On the basis of the phenomenological similarities between the HBM and the nonlocal arch models, the matching of buckling and vibration solutions for HBMs and those for nonlocal models allows one to calibrate the $e_0$ values. It is found that $e_0$ for Eringen’s nonlocal circular arch (ENCA) varies with respect to geometrical property of the arch and boundary conditions. However, $e_0$ for a continualized nonlocal circular arch (CNCA) is found to be a constant value, regardless of geometrical properties or boundary conditions.


ABSTRACT: Variable-stiffness panel with curvilinear fibers is a promising structural concept compared to constant-stiffness designs. However, for the traditional finite element analysis (FEA), there is no guarantee that the fiber angle is continuous and smooth due to element discretization. In this study, on the basis of Mindlin plate theory, the buckling behavior of composite variable-stiffness panels is investigated based on isogeometric analysis (IGA), whose main feature is that the continuity of fiber angle on the whole panel is guaranteed. In particular, since geometric stiffness matrix has a significant influence on the buckling behavior, it is obtained by performing a static analysis prior to the buckling analysis herein, which can further improve the prediction accuracy of current methods. Different fiber path functions, ply number, geometric parameter, as well as various boundary and loading conditions are adopted to verify the proposed buckling analysis method. Finally, the prediction accuracy, total degree-of-freedom and CPU time are compared with the traditional FEA, which indicates that the isogeometric buckling analysis method can provide an adequate accuracy in a more efficient manner.

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ABSTRACT: In this work, we create a framework for linear buckling and free vibration analyses of sandwich beams using a microstructure-dependent Timoshenko beam model founded on the modified couple-stress theory. The stiffness parameters of a structural web-core sandwich panel are determined by unit cell analysis.
An extension to homogeneous cores is also carried out. By employing the exact general solution to the governing equations of the beam, an accurate approximate finite element stiffness matrix is formulated. Furthermore, the static shape functions are used to derive consistent linear geometric stiffness and mass matrices. A convergence study shows that the approximate finite element has good accuracy although the hyperbolic terms of the exact general solution have been expanded into only relatively low-order polynomial series. Results from examples show that the microstructure-dependent beam can predict critical buckling loads and natural frequencies with very good accuracy when compared to more sophisticated finite element models. Unlike the classical Timoshenko beam model, the microstructure-dependent model yields accurate results also when the sandwich assembly is transversely flexible and the bending stiffness of the faces non-negligible.

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ABSTRACT: Thermal post-buckling and limit-cycle oscillation characteristics of Functionally Graded Material (FGM) structures are investigated based on the neutral surface concept. In particular, the material properties are non-homogeneous and vary gradually from one surface to the other. Furthermore, the properties are to be considered as temperature-dependent characteristics, and the neutral surface concept is adopted instead of the mid-plane to consider the reference plane due to the asymmetric properties in the thickness direction of model. In the formulation, the First-order Shear Deformation Theory (FSDT) of plate is used, and the geometric nonlinearity is accounted for by the von Karman strain-displacement relations. Also, steady state thermal conduction effects are assumed as a one dimensional heat transfer on the surface of the structure. For the numerical analysis, the Newton-Raphson method is applied to solve the thermal post-buckling behavior, while Newmark's time integration method is employed to resolve the limit-cycle oscillation. In order to validate the analysis results, the results of this paper based on the neutral surface are compared with the data from previous papers using the conventional approach for FGMs model. Finally, effects of the neutral surface on the non-linear thermo-mechanic behavior of structure are discussed in detail.

Xiaobai Li, Li Li, Yujin Hu, Zhe Ding and Weiming Deng (State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China), “Bending, buckling and vibration of axially functionally graded beams based on nonlocal strain gradient theory”, Composite Structures, Vol. 165, pp 250-265, April 2017
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ABSTRACT: A size-dependent inhomogeneous beam model, which accounts for the through-length power-law variation of a two-constituent axially functionally graded (FG) material, is deduced in the framework of the nonlocal strain gradient theory and the Euler–Bernoulli beam theory. By employing the Hamilton principle, the equations of motion and boundary conditions for size-dependent axially FG beams are deduced. A material length scale parameter and a nonlocal parameter are introduced in the axially FG beam model to consider the significance of strain gradient stress field and nonlocal elastic stress field, respectively. The bending, buckling and vibration problems of axially FG beams are solved by a generalized differential quadrature method. The influences of power-law variation and size-dependent parameters on the bending, buckling and vibration
behaviors of axially FG beams are investigated. The mechanical behaviors can be affected by the through-length grading of the FG material and therefore may be controlled by choosing appropriate values of the power-law index. When considering concentrated and uniformly distributed loads, the maximum deflection decreases with increasing length scale parameter. The axially FG beam may exert a stiffness-softening effect or a stiffness-hardening effect on the critical buckling force and the natural frequencies depending on the values of the two size-dependent parameters.

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ABSTRACT: The collapse behavior of random, woven [0/90] and angle-ply [±60°] oriented Glass Fiber Reinforced Composite (GFRP) conical frusta under low velocity axial impact loading is reported in this work. The GFRP conical frusta having uniform wall thickness with semi-apical angle in the range of 15–24° were fabricated using chopped random, woven roving and uni-directional ply-oriented E-glass fiber mats through hand layup method. The low velocity drop weight impact test setup was utilized to study the load-deformation and energy-absorption characteristics of conical frusta at different strain rates. The finite element analysis (FEA) were also performed using ABAQUS software to predict the collapse behavior and energy-absorption characteristics of the same categories of GFRP specimen models similar to the experimental conditions. The results from both the procedures were compared and the crashworthiness characteristics of GFRP conical frusta were studied. The energy-absorption characteristics of conical frusta during impact and quasi-static loading testing were also compared and reported.

ABSTRACT: This research studies the post impact response of damaged area of variable stiffness curved composite plates. Varying thicknesses of sections is widely found in aerospace and automotive composite sub structures. In this regard, the impact response of this geometry characteristic has to be studied in thin-walled structures. In our model, a removal of ply technique is used to represent damaged region within a curved panel, thus degrading the stiffness in that area is considered in the theoretical models. A summation of spring-mass systems is used in the modelling of damaged variable stiffness plate to analysis post impact behaviour of these structures. The theoretical force-time results are also compared with the relevant finite element outcomes in LSDYNA. The comparison establishes a good prediction capability of the proposed model.

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(2) Lodz University of Technology, Department of Strength of Materials (K12), PL – 90-924 Lodz, Stefanowskiego 1/15, Poland “Influence of mechanical couplings on the buckling behaviour of thin-walled plates made of general laminates under compression”, Composite Structures, Vol. 167, pp 68-76, April 2017
ABSTRACT: The present paper deals with the buckling and post-buckling behaviour of plates made of coupling laminates (the so-called general laminates). Such laminates consist of a number of layers arranged in an arbitrarily way. Thus, the sequences of laminated layers are non-symmetric. In this case, the coupling between tension, flexure, shearing and twisting takes place. The behaviour of general laminates substantially differs from that of laminates with a symmetric layup or isotropic materials. Therefore, they undergo out-of-plane deformation (i.e., warping, bending and/or twisting) when exposed to in-plane loads. Due to a wide range of application possibilities for general laminates, it is worth focusing on their advantages. The analytical-numerical method (ANM) based on Koiter’s theory was used to determine the static buckling loads and post-buckling equilibrium behaviour. In order to obtain the equations of equilibrium for plates, the classic laminate theory was used. The plate displacements were considered within the nonlinear geometrical relations. For special laminates (i.e., regular anti-symmetric angle-ply laminates), there are closed-form solutions of the equilibrium equations of the plate when displacements are slight. Those results were the same as the results produced with the presented methods. The differences in buckling stresses are very low, amounting to less than 5%.

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“Numerical and experimental study of dynamic buckling behavior of a J-stiffened composite panel under in-plane shear”, Composite Structures, Vol. 166, pp 96-103, April 2017
https://doi.org/10.1016/j.compstruct.2017.01.022

ABSTRACT: The buckling behavior and failure mode of a composite panel stiffened by J-shaped stringers under in-plane shear is studied by experiments and numerical analysis. Digital fringe projection profilometry was applied to monitor and measure the buckling morphology changes of the stiffened composite panel during in-plane shearing, which was verified by strain gauge measurement. Numerical simulation was performed using the finite element method to predict the failure load and buckling modes of the stiffened composite panel under in-plane shear. Numerical results showed good agreement with the full-field optical buckling measurement. The combination of experimental and numerical prediction can be effective in revealing the deformation process and failure mechanism of the stiffened composite panel.

S. Sahmani and M.M. Aghdam (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “Size dependency in axial postbuckling behavior of hybrid FGM exponential shear deformable nanoshells based on the nonlocal elasticity theory”, Composite Structures, Vol. 166, pp 104-113, April 2017, https://doi.org/10.1016/j.compstruct.2017.01.051

ABSTRACT: The objective of this study is to examine the nonlocal nonlinear instability of functionally graded cylindrical shells at nanoscale integrated with piezoelectric nanolayers under combination of axial compressive load and lateral electric field. Eringen's nonlocal continuum elasticity is incorporated within the framework of the exponential shear deformation shell theory to consider the influence of transverse shear deformation in a refined form. Additionally, in order to eliminate the stretching-bending coupling terms, the change in the position of physical neutral plane corresponding to different volume fractions is taken into account. With the aid of the boundary layer theory of shell buckling and employing a perturbation-based solution methodology,
explicit expressions for the size-dependent equilibrium paths before and after buckling point are proposed for functionally graded hybrid nanoshells with various nonlocal parameters, material property gradient indexes and subjected to different values of lateral electric field. It is indicated that the both width and depth of the snap-through phenomenon related to the axial postbuckling behavior of hybrid FGM nanoshells decrease due to the nonlocality influence.

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ABSTRACT: The present work aims to provide a detailed study regarding the nonlinear dynamic response of heterogeneous (HT) orthotropic cylinders resting on the nonlinear elastic foundations. The problem is formulated on the basis of the shear deformation theory (SDT) using von Karman type geometric nonlinearity in the framework of the Donnell's shell theory. Material properties of the cylinders vary continuously in the thickness direction according to the exponential-law distribution. Nonlinear ordinary differential equation is obtained with the use of superposition and Galerkin methods and solved applying the homotopy perturbation method (HPM). The validity of the present method is demonstrated by comparing the present results with existing results in the literature in the limit cases. Numerical simulations are performed to discuss the influences of the nonlinear elastic foundations, vibration amplitude, shear stresses, heterogeneity and cylinder characteristics on the nonlinear frequency parameters.

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ABSTRACT: By considering the small-scale effect based on the nonlocal elasticity theory, the nonlinear postbuckling of thick and moderately thick rectangular piezoelectric-piezomagnetic nanoplates with various edge supports subjected to the magneto-electro-thermo-mechanical loading is investigated. For this objective, a unified nonlocal nonlinear higher-order shear deformable plate model is proposed. By adopting the nonlocal theory to capture the small-scale effect and utilizing a generalized displacement field to consider the influence of transverse shear deformation, unified size-dependent nonlinear governing equations and related boundary conditions are derived based on the virtual work principle in conjunction with von Kármán geometric nonlinearity. By choosing appropriate shape functions, the developed plate model can be reduced to the size-dependent Kirchhoff, Mindlin, Reddy, parabolic, trigonometric, hyperbolic and exponential shear deformable plate models. The nonlinear governing equations and boundary conditions are discretized using the generalized differential quadrature method first. Then, the pseudo arc-length continuation technique is used to solve the discretized equations and obtain the secondary equilibrium path of nanoplate in the postbuckling regime. In addition to providing significant guidelines for accurate prediction of the stability conditions nanoplates,
extracting various plate models on the basis of any existing shear deformable plate theory becomes readily attainable by utilizing the proposed unified plate model.

ABSTRACT: Dynamic instability of a variable angle tow (VAT) composite plate subjected to periodic in-plane compressive load is investigated using finite element analysis. First order shear deformation theory was used to model the VAT laminate and the effect of fiber angle orientation on the instability behavior of VAT laminates is studied. Unlike straight fiber composites, the pre-buckling problem of VAT laminate is solved initially to obtain the plate in-plane stress distribution due to the applied uniform compression along the edges. Subsequently, the evaluated stress distributions were used in the equations governing the dynamic instability of VAT laminates. The dynamic instability regions of VAT laminates are determined using Bolotin’s first order approximation. The dynamic instability results of VAT plates are evaluated for linear fiber angle distribution and their performances are then compared with straight fiber laminates. Effect of the fiber angle orientation, load parameters, boundary conditions, orthotropy ratio and aspect ratio on the dynamic instability regions of VAT laminate are investigated in detail.

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ABSTRACT: Aircraft skin panels stiffened with attached stiffeners are commonly used in aerospace design. Recent interest on investigations of supersonic flutter of composite panels have concentrated on developments to deal with typical nonlinear aeroelastic responses. Few research on stiffened composite panels is observed in the literature, particularly on aeroelastic tailoring of laminate composites regarding supersonic flutter. This work contributes with an investigation on the aeroelastic tailoring of stiffened laminate composite panels constrained for flutter conditions, thereby allowing design approach for passive flutter avoidance. The finite element method is used to model the panel structural dynamics admitting aerodynamic coupling through the first order piston theory model. The optimization approach is based on a conventional genetic algorithm to maximize the critical flutter dynamic pressure for different arrangements of stiffened laminate composite panels. Stiffened panels were assumed to be restrained with SS1-type boundary condition or an elastic foundation of arbitrary stiffness. Optimized panels for different supersonic flow directions have shown that flutter limits can be elevated by adequate laminate orientation and by altering the flutter mechanism.

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ABSTRACT: Current paper is the second part of Kolakowski Z, Mania RJ paper entitled: “Influence of the coupling matrix \(B\) on the interactive buckling of FML-FGM columns with closed cross-section under axial compression”, Composite Structures, in press. The problem of non-linear multi-mode buckling of thin-walled columns with open cross-sections made of Functionally Graded Materials (FGMs) and Fibre Metal Laminate (FML) was discussed. FGM layers are a thermal barrier, whereas the FML composite provides rigidity and strength. This new hybrid thin-walled structure is very interesting but there are no interactive buckling solutions. The non-linear problem of buckling was solved with the analytical-numerical method (ANM) based on Koiter’s theory. An interaction of global buckling mode with many different local buckling modes was discussed. A plate model and the classical laminate theory are used to define government relations. The differential equilibrium equations were obtained with a variational method. Each column was made of an FML sublayer, a single AL-TiC-type FGM layer and/or a TiC ceramic layer. The FML sublayer consisted of two outer aluminium layers and even carbon-epoxy prepreg interlayers. The layup configuration of the FML/FGM composite is non-symmetric, so the coupling matrix \(B\) is non-trivial. Simply supported columns are under mechanical compression only.


ABSTRACT: A formulation is presented for an enriched shell finite element capable of progressive damage simulation in composite laminates. The element enrichment uses the Floating Node Method to discretely represent delamination, and the Virtual Crack Closure Technique to predict damage growth. The damage path is not predefined by the user and it can consist of delaminations and transverse matrix cracking. The element is computationally efficient and is intended to demand less time and expertise from the user than existing laminate damage simulation tools. In this study, the enriched element is used to simulate delamination-migration in a composite laminate. Good correlation was found between the enriched shell element model results and the experimental data set.

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ABSTRACT: In this contribution, an efficient multiscale computational formulation is developed for the geometric nonlinear analysis of heterogeneous piezoelectric materials. In this formulation, the relations between the microscopic heterogeneous properties and macroscopic behaviors of the piezoelectric composite are
established by the numerically constructed displacement and electric potential base functions. The heterogeneous and complex microstructure can be equivalent to a simple macroscopic piezoelectric coarse element through those constructed multiscale base functions. Then the equivalent tangent stiffness matrix and internal force vector of the macroscopic coarse element are deduced based on the co-rotational approach, which can describe the motion of macroscopic coarse element clearly and efficiently. Thus the original electromechanical coupling geometric nonlinear problem could be solved iteratively on the macroscopic scale, which will save a tremendous amount of computing time and cost. After all the macroscopic calculations, the microscopic mechanical and electrical responses could be retrieved and calculated from the macroscopic solutions by using the above-mentioned multiscale shape functions. To verify the validation and high-efficiency of the proposed multiscale computation formulation, several typical numerical examples are carried out. All the computation results indicate that the developed multiscale formulation not only could provide high precision solutions but also has high efficiency.

ABSTRACT: This paper presents a detailed investigation about the vibration behavior of corrugated laminates. In highly anisotropic corrugated laminates different non-classical vibration modes were observed and are reported in this work. Apart from in-plane modes, we show in particular shear rotational modes which occur due to the high anisotropy, the distribution of mass, and the influence of the shear compliance. The work contains a detailed FEM study, a comparison with an equivalent plate model and an analytical model and examines the limitations of the latter two. It points out for which geometry and material parameters the well known and often used homogenized plate models are applicable. Parametric studies are conducted investigating the influence of the corrugation amplitude, the aspect ratio, the anisotropy of the material, and boundary conditions on the vibration behavior. The found results can be used for the design of highly anisotropic corrugated laminated plates and the analysis of their vibration behavior.

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ABSTRACT: Carbon fiber reinforced polymers (CFRP) laminates are extensively employed to manufacture the deployable composite thin-walled lenticular tubes (CTLTs). This paper presents a comparison of experimental and numerical and analytical results of compressive and tensile flattening types of deployable CTLTs. Firstly, a compressive flattening model created by ABAQUS was introduced to obtain its strain and stress of each ply of composite tube. Secondly, compressive flattening experiments were performed for CTLT specimens to explore compressive flattening mechanism of CTLTs. Then, the numerical simulation methods to simulate the compressive flattening of CTLTs were verified by comparing measurements and corresponding numerical results. Thirdly, analytical models are employed to predict the flattening process of CTLTs under compression.
Lastly, for the tensile flattening process of CTLTs, the numerical simulation method and corresponding experiments and theoretical results are respectively also carried out with aim of revealing mechanical properties of CTLTs under tension. The flattening process of CTLTs can be considered to be a nonlinear deformation and small strain process. For the compressive flattening, the maximum compressive force, displacement and strain are 98N, 60mm and 0.29%, respectively. For the identical tensile flattening, the maximum tensile force, displacement and strain are 550N, 42.5mm, 0.53%. respectively. It is found that the compressive flattening way is a better choice in the design of the actuated mechanism.


ABSTRACT: In this paper, we revisit the FEM solution of laminated plates and shells that nowadays are mostly done by low order solid or shell finite elements enriched by stress or strain fields, or by specific kinematics dedicated to the analysis of such structures. We introduce a triangular based prismatic finite element of any approximation order capable of solving from very thin to very thick laminated plates and shells, with the following properties: (i) locking-free behavior; (ii) good stress distribution even for complex materials; (iii) geometrically exact description of large displacements; and (iv) geometry dedicated to evaluate plates and shells (laminated or not) free of problems due to distorted meshes or ill-conditioned systems as thickness decreases. This triangular based prismatic finite element can also be employed in laminated beams, holding the same properties. The proposed element uses total Lagrangian description based on positions, and its performance regarding the claimed properties is demonstrated in several examples.

Ke Liang and Qin Sun (School of Aeronautics, Northwestern Polytechnical University, Xi’an 710072, PR China), “Buckling and post-buckling analysis of the delaminated composite plates using the Koiter-Newton method”, Composite Structures, Vol. 168, pp 266-276, May 2017
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ABSTRACT: The Koiter–Newton method has been proved to be a computationally efficient method for buckling and post-buckling analysis of structures, using a novel reduced-order modeling strategy. In this paper, the existing method is extended for laminated composite plates with delamination. We develop a 4-node quadrilateral element S4DE as a geometric linear element in the co-rotational formulation of the Koiter–Newton method. The assumed layerwise displacement model of the developed element is enriched with Heaviside unit step functions to model delamination. The displacement fields of each layer are described using the superposition of first-order shear deformation and layerwise functions. The zig–zag theory is applied to enhance the numerical accuracy and computational efficiency of the developed element. The construction of the reduced order model requires derivatives of the strain energy with respect to the degrees of freedom up to the fourth order, which is two orders more than traditionally needed for a Newton based nonlinear finite element technique. The geometrical nonlinearities are taken into account using derivatives of the local co-rotational frame with respect to global degrees of freedom. Various laminated plates with different thicknesses, delamination lengths and stacking sequences are considered to validate the good performance of the present method in terms of numerical reliability, accuracy and computational effort.
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ABSTRACT: In this study, the nonlinear thermal buckling of axially functionally graded (AFG) Euler-Bernoulli micro/nanobeams is analyzed. The Eringen’s nonlocal elasticity theory is used to develop the governing equations of nanobeam and the modified couple stress theory is used to study the microbeam. The micro- and nanobeams are made of pure metal, pure ceramic and axially functionally graded material which is the composition of metal and ceramic. Boundary conditions are considered as clamped (CC) and simply supported (SS). The generalized differential quadrature method (GDQM) is used along with the iteration technique to solve the nonlinear equations. The parametric studies are served to examine the effects of the small scale parameters, length to height ratio (L/h), nonlinear amplitude and AFG power index on the buckling temperature of the micro- and nanobeams.

ABSTRACT: Buckling is one of the main failure type of slender structures, therefore it is important to get know how delaminations affect the critical buckling loads. In this work orthotropic rectangular plates with trough-the-width delamination are modelled using special types of Mindlin plate finite elements. The simulations are verified through experiments. The verification shows that the presented progressive finite element model is able to model the effect of delamination growth on the critical buckling load of uni-axial compressed plates. Possible generalization of the results is also presented.

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ABSTRACT: Aeroelastic flutter characteristics and dynamic response of a composite laminated circular cylindrical shell under combined action of radial harmonic excitation, compressive in-plane force and aerodynamic pressure are studied in this paper. The first-order piston theory is employed to model the aerodynamics pressure. Partial differential equations governing the vibrations of the cylindrical shell are derived based on the Hamilton’s principle and the Donnell’s nonlinear shell theory. The Galerkin’s method is adopted to discretize the partial differential governing equations to a set of nonlinear ordinary differential equations. The four-dimensional averaged equation is obtained by applying the method of multiple scales under the case of 1:2 internal resonance. The critical free stream static pressure originating flutter of the shell is determined by solving the eigenvalue problem. The phase portrait and time history diagrams are presented to demonstrate the character of the limit cycle oscillation of the shell. The influence of different geometrical parameters, such as
the radius, length and thickness of the shell, on the flutter characteristics of the composite laminated circular cylindrical shell are discussed in details. The influences of the amplitudes of the in-plane and transverse excitations on the frequency–response curves and force-response curves are also investigated.


ABSTRACT: In this paper, an analytical study on thermal, mechanical, and thermomechanical buckling and post-buckling of symmetric laminated composite plates reinforced with shape memory alloy (SMA) fibers are presented. The closed-form solution used in this study is developed based on the FSDT incorporated with the Von-Karman non-linear strains. The effect of SMA fibers is captured by adding a tensile recovery, stress term that determined using 1-D simplified Brinson’s model, in the constitutive equations of the SMA composite plate. Galerkin technique is implemented for solving the nonlinear partial differential equations of motion to obtain buckling load and post-buckling path. The influence of several parameters such as SMA activation temperature, SMA fiber volume fraction, SMA pre-strain, biaxial ratio, etc., are studied in this work. Due to the generation of recovery force, significant improvement in buckling load is attained by increasing each of the SMA fiber volume fraction, activation temperature or SMA pre-strain. 

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ABSTRACT: A progressive damage model is proposed to predict buckling strengths and failure mechanisms for both symmetric and asymmetric patch repaired carbon-fibre reinforced laminates subjected to compression without lateral restraints. Solid and cohesive elements are employed to discretize composite and adhesive layers, respectively. Coupling with three dimensional strain failure criteria, an energy-based crack band model is applied to address the softening behaviour in composites with mesh dependency elimination. Both laminar and laminate scaled failure are addressed. Patch debonding is simulated by the cohesive zone model with a trapezoidal traction–separation law applied for the ductile adhesive. Geometric imperfection is introduced into the nonlinear analysis by the first-order linear buckling configuration. Regarding strengths and failure patterns, the simulation demonstrates an accurate and consistent prediction compared with experimental observations. Though shearing is the main contributor to damage initiation in adhesive, stress analysis shows that lateral deformation subsequently reverses the distribution of normal stresses which stimulates patch debonding at one of the repair sides. The influence of patch dimensions on strengths and failure mechanisms can be explained by stress distributions in adhesive and lateral deformation of repairs. Comparison between symmetric and
asymmetric regarding strength and failure modes shows that structural asymmetry can intensify lateral flexibility. This resulted in earlier patch debonding and negative effects on strengths.

ABSTRACT: An analytical computational scheme for nonlinear dynamic characteristics and stability of an eccentrically composite orthotropic plate on Winkler-Pasternak elastic foundation subjected to different axial velocities is proposed with the incorporation of mercurial damping effects under thermal environment. Incorporating the classical plate theory and Von-Kármán strain-displacement relation, the nonlinear compatibility equation is derived. The Galerkin method and Airy’s stress function are implemented to establish the nonlinear dynamic buckling equation accommodating the thermal and damping effects. Then the developed nonlinear differential equations are solved numerically by the fourth-order Runge-Kutta method. The characteristics of natural frequency, linear and nonlinear vibration, frequency-amplitude curve and nonlinear dynamic responses are investigated by the developed approach with validations by other literatures. The nonlinear dynamic buckling loads are determined by using Budiansky-Roth criterion. Additionally, various effects of velocity, damping ratio, temperature change, buckling mode, initial imperfection and foundation parameter on nonlinear dynamic buckling of the orthotropic plate are discussed.

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ABSTRACT: Indentation response and energy absorption property of honeycomb sandwich panels subjected to drop-weight impact under a spherical impactor were investigated. Experiments were conducted using a pendulum-impact system. A three-dimensional finite element model with micro-structure considered was built and validated. In conjunction with experimental and numerical methods, analytical models of indentation response and energy balance specifically aimed to solve problems of low-velocity impact of a spherical indenter on sandwich panels were deduced. Results show that a hemispherical residual dent caused by bending of top face-sheet and core crushing is left on top face-sheet after impact. It also concludes that more than 80% of impact energy is absorbed mostly by top face-sheet and honeycomb core. The main form of energy dissipation is plastic dissipation. In addition, parametric studies were carried out to explore effects of impact energy on impact behavior by altering impact velocity or impactor mass. Different effects are observed for the two approaches and some useful semi-empirical formulations based on both experimental and numerical results are overfitted to estimate the residual dent depth and energy absorbed during a drop-weight impact event on a honeycomb sandwich panel under a spherical impactor.
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ABSTRACT: A method to predict the nonlinear dynamic behavior of the fluid-conveying functionally graded (FG) cylindrical shell is presented in this paper. The thermal effects are included and the material properties of the FG cylindrical shell are assumed to be temperature-dependent and vary through the thickness according to the power-law function. By considering the in-plane and rotary inertia, the nonlinear dynamic equations of the fluid-conveying FG cylindrical shell are derived based on the von Kármán nonlinear theory, Hamilton’s principle and the fluid velocity potential. Galerkin’s method is utilized to convert the governing partial differential equations to nonlinear ordinary differential equations. A reduction model is developed to describe the nonlinear dynamics behavior of the fluid-conveying FG cylindrical shell. Emphasis is placed on investigating the effects of the variations of the flow velocity, the thermal load, the axial load and the volume fraction exponent on the nonlinear vibrations of fluid-conveying FG cylindrical shells. The results obtained by this method are compared with those of other experimental and numerical investigations and good agreement is obtained.

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ABSTRACT: The feasibility of probabilistic design methods to overcome conservatism associated with deterministic design methods for unstiffened cylindrical composite shells has been shown, but studies are frequently based on assumptions regarding relevant uncertainties due to the lack of available data. The reliability based calibration method suggested here relies on extensive measurements regarding the statistical characteristics of thickness, fibre volume fraction, fibre orientation, material stiffness and geometric imperfections of 11 previously tested cylinders. Furthermore, the stiffness of the potting of tested cylinders is estimated using Finite Element Analysis and the introduction of a pre-stress state through the potting process investigated. Following a sensitivity study, Bayesian inference is used to update the information of relevant uncertain variables. Monte Carlo simulation is employed to compute the distribution functions of the buckling load, and these are used to calibrate structural safety factors at a chosen reliability level. A multiplicative error model is established to compute safety factors covering the model uncertainty inherent to the approach. In combining these two safety factors in a Bayesian sense, a transparent, updatable safety-factor concept is developed, leading to less conservative design loads than currently considered.

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ABSTRACT: This study proposes a skin-added X-lattice composite structure consisting of corrugated ribs and a very thin skin, as an alternative form of anisogrid composites, for the efficient lightweight structural concept under compression loading. The high mechanical capability of skin-added X-lattice structures is numerically analyzed, followed by introduction of the related manufacturing method. This manufacturing process is composed of preparation of corrugation units and co-curing of the units with a thin skin. The results of compression tests of fabricated X-lattice panels agree with numerical predictions in terms of buckling loads and buckling modes, while skin-added X-lattice panels exhibited somewhat lower buckling load than the prediction. Feasibility of the proposed skin-added X-lattice is demonstrated in this work by fabrication and mechanical characterization.

ABSTRACT: Stability of laminated structural glass is one of the design requirements to be considered due to the brittle and slender nature of this kind of glass elements. Since laminated glass is mainly manufacture with viscoelastic interlayers, its mechanical properties are temperature and time dependent. This implies that, i.e., the critical load of a laminated glass beam subject to constant compressive load decreases with time as well as with temperature. In this paper, the equations of the Euler Theory for buckling of monolithic beams are extended to multi-layered laminated glass beams using an effective stiffness. This proposal is based on the idea of calculating the thickness (time and temperature dependent) of a monolithic element with bending properties equivalent to those of the laminated one, that is, the deflections provided by the equivalent monolithic beam are equal to those of the layered model with viscoelastic core. In this work, the analytical predictions are validated by compressive experimental tests carried out on a simply supported beam composed of three glass layers and two polyvinyl butyral (PVB) interlayers. Moreover, a finite element model was assembled to validate the proposed methodology for any boundary conditions. The results shown that a good accuracy can be obtained with the proposed equations being the errors less than 7% for all the experiments and simulations considered.

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ABSTRACT: A methodology of multiobjective design optimization of laminated composite plates with piezoelectric layers is presented in this paper. Constrained optimization is conducted for different behaviour objectives, like the maximization of buckling load or natural frequencies of specific vibration modes or prescribed displacements for example. Weight minimization can also be considered or the minimization of the
electric voltages applied in the piezoelectric actuators. The optimization problems are constrained by stress based failure criteria and other structural response constraints like limits imposed on certain displacements, buckling characteristics and natural frequency constraints. The design variables considered in the present work are the fiber reinforcement orientations in the composite layers, thicknesses of individual layers and the electric potentials applied to the actuators. The optimization problems are solved with two direct search derivative-free algorithms: GLODS (Global and Local Optimization using Direct Search) and DMS (Direct MultiSearch). DMS, the multiobjective optimization solver, is started from a set of local minimizers which are initially determined by the global optimizer algorithm GLODS for each one of the objective functions.

ABSTRACT: A theoretical model is obtained to predict the dynamic response of a clamped sandwich beam with thick weak core impacted centrally by a projectile. The core is weak and thick enough that only part or all of the front face sheet and the core undergo permanent plastic deformations, while the back face sheet undergoes an elastic vibration. The core is taken to be rigid-plastic and the front face sheet is treated as an individual rigid-plastic beam resting on a foundation. The back face sheet is modeled as an Euler–Bernoulli beam. Based on the rigid-perfectly theory and Galerkin method, two types of the sandwich beam response are given, i.e., intermediate strength and low strength core type responses. The critical kinetic energy of the projectile as the back face sheet reaches its elastic limit is studied. The localized indentation and response history of the sandwich beam are presented. It is found that the dynamic response of the sandwich beam is sensitive to the core strength, mass ratio, breadth and impact velocity of the projectile. The finite element (FE) simulation is also carried out to verify the analytical predictions and a good agreement is achieved.

ABSTRACT: Glass fiber reinforced polymer (GFRP) stiffened composite plates with and without rectangular cutout are analysed under axial, lateral and combined axial and lateral loading using finite element software ABAQUS®. Ultimate load, maximum displacements and failure modes of GFRP stiffened composite plates with and without cutout obtained from finite element analyses are compared with experiments carried out at Department of Civil Engineering, IIT Madras. Validation of the finite element model is carried out by analysing a blade-stiffened composite panel and compared with the experimental results of Falzon and Hitchings (2003). Parametric studies are carried out for various plate slenderness ratios, column slenderness ratios, lateral pressure intensity and material type. Analysis of stiffened composite plates with reinforced cutout is carried out to determine the type and size of reinforcement required for restoring the lost strength and stiffness.

ABSTRACT: The paper deals with estimating the load capacity of thin-walled composite columns with C-shaped cross-section subjected to uniform compression. The discussed columns were made of eight-layer GFRP
laminate. Three symmetric arrangements of layers were taken into consideration: \([0/-45/45/90]_S\), \([90/0/90/0]_S\), \([45/-45/45/-45]_S\). The experimental research was conducted with the use of the ultimate testing machine and the DIC system Aramis®. Additionally, the numerical analyses were performed employing the Ansys® software. The numerical calculations were conducted with the implementation of the progressive failure algorithm, based on the material property degradation method and implementation of the Hashin’s criterion as the damage initiation criterion. In all analyzed cases high consistency of numerical and experimental results was achieved and the failure mechanism included the initiation of the fiber failure in the corner of the columns and its propagation in the direction of the web and the flange of the columns.

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ABSTRACT: The fact that complex simulation can be carried out at present days allows to go further to answer new questions in the compressive failure of polymer composites. A thorough understanding of fiber kinking is essential for the prediction of stiffness and strength of fiber reinforced composites. The goal of this paper is to give a deep understanding of some topics which are still unclear in the micro modeling of fiber kinking. Such are the kinking mechanism and the difference in the kinking mechanics between global and local imperfections, the determination of kink band angle and consideration of statistical distributions of fiber waviness. 3D micro models are presented in Part-I in order to simulate the compressive failure in continuous fiber reinforced composites under pure compression considering the effect of fiber kinking. It is shown that the kinking mechanism is changed by changing the type of fiber waviness, the angle of the kink band is depend on the tensile strength of the fibers and the kink bands in a model with statistical distributions of fiber waviness are located at the edges of the specimen.

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ABSTRACT: The compressive failure of multidirectional laminates can be considered as an interaction of four failure mechanisms: fiber kinking, fiber splitting, matrix cracking and delamination. The interaction of these four failure mechanisms is responsible for the macroscopically observed nonlinear behavior and ultimate failure of the structure. In this paper, a numerically efficient 3D Finite Element modeling approach is presented combining the benefits of homogenizing material models and micromechanical modeling strategies. The micro model is used to resolve the regions which are prone to fiber kinking. In all other regions, a single UD ply is considered as a continuum (i.e. in a homogenized way) and the material properties are represented using a transversely-isotropic constitutive model. At both scales, fully 3D elastic–plastic material models regarding nonlinearities and failure under multiaxial loading conditions are used. With this approach, the progressive failure of multidirectional laminates under compressive loading can be simulated in detail considering the complete kinking process and the progression of kink bands. The sequence and interaction of the different
failure mechanisms is studied and discussed. In order to validate the numerical results, the nonlinear stress–strain response and ultimate failure stress of selected carbon epoxy laminate layups is predicted and compared with experimental results.


ABSTRACT: In the present paper, the dynamic response of a three-layered thin-walled spatially curved beam of open profile is investigated. As a result of the homogenization of heterogeneous rheological parameters of such a beam, its behaviour could be described by the dynamic constitutive Cosserat equations characterizing a general isotropic, linear micropolar material. Under the action of nonstationary excitations on the beam, plane transient waves (surfaces of discontinuity) are generated in the beam. By the help of the generalized Hadamard–Thomas conditions of compatibility, the velocities of four types of transient waves are found from the set of dynamic Cosserat equations, and the recurrent equations have been obtained which allow one to determine the discontinuities in the desired values and discontinuities in the arbitrary order time-derivatives of these values on each of four waves. This procedure enables one to construct the desired values in terms of the ray series behind the wave fronts up to the boundary where the waves have been generated. The superposition of the ray series for four types of waves allows one to define completely each of the values to be found within the entire disturbed domain. As an example illustrating the proposed procedure for solving boundary-value dynamics problems for beams subjected to transient loading, the problem of the normal impact of a long elastic rod with a rounded end upon a lateral surface of a three-layered thin-walled beam of open profile is considered.


ABSTRACT: The current paper is concerned with the micro-scale laminated composite Euler-Bernoulli beams under the hygrothermal environment. The aim is mainly focused on the static and dynamical responses of micro-scale beams under consideration in both prebuckling and postbuckling cases. Meanwhile, the mechanism how temperature and hygrothermal concentration affect the critical buckling load is discussed. The material properties are considered to be temperature- and hygroscopic concentration-dependent. And the hygrothermal deformation caused by both variations in temperature and hygroscopic concentration is taken into account. The modified couple stress Euler-Bernoulli beam model involving geometric nonlinearity due to the mid-plane stretching is adopted. Then, an analytical formulation of postbuckling and buckling vibration is derived as a function of the external compressive axial load. Exact solutions for the critical buckling load, the postbuckling configuration and the natural frequency of vibration around the buckling configuration of the beam with various boundary conditions are investigated.

ABSTRACT: The Carrera Unified Formulation (CUF) was recently extended to deal with the geometric nonlinear analysis of solid cross-section and thin-walled metallic beams (Pagani and Carrera, 2017). The promising results provided enough confidence for exploring the capabilities of that methodology when dealing with large displacements and post-buckling response of composite laminated beams, which is the subject of the present work. Accordingly, by employing CUF, governing nonlinear equations of low- to higher-order beam theories for laminated beams are expressed in this paper as degenerated cases of the three-dimensional elasticity equilibrium via an appropriate index notation. In detail, although the provided equations are valid for any one-dimensional structural theory in a unified sense, layer-wise kinematics are employed in this paper through the use of Lagrange polynomial expansions of the primary mechanical variables. The principle of virtual work and a finite element approximation are used to formulate the governing equations in a total Lagrangian manner, whereas a Newton–Raphson linearization scheme along with a path-following method based on the arc-length constraint is employed to solve the geometrically nonlinear problem. Several numerical assessments are proposed, including post-buckling of symmetric cross-ply beams and large displacement analysis of asymmetric laminates under flexural and compression loadings.

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“Nonlinear bending of functionally graded graphene-reinforced composite laminated plates resting on elastic foundations in thermal environments”, Composite Structures, Vol. 170, pp 80-90, June 2017
https://doi.org/10.1016/j.compstruct.2017.03.001

ABSTRACT: This paper presents an investigation on the nonlinear bending of functionally graded graphene-reinforced composite (FG-GRC) laminated plates resting on an elastic foundation and in a thermal environment. The plate is subjected to a transverse uniform or sinusoidal load combined with initial compressive edge-in-plane loads. The plate is made of graphene-reinforced composites which are functionally graded in the thickness direction with a piece-wise type. The material properties of GRCs are estimated through a refined micromechanical model. Governing differential equations for the bending of the FG-GRC plates are based on a higher order shear deformation plate theory and the general von Kármán-type equation and the effects of plate-foundation interaction and temperature variation are taken into consideration. A two-step perturbation technique is employed to determine the load-deflection and load-bending moment curves. The nonlinear bending responses of FG-GRC laminated plates under different sets of loading and thermal environmental conditions are presented and discussed in details.

Xinwei Wang (State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, No. 29 Yudao Street, Nanjing 210016, China), “Free vibration analysis of angle-ply symmetric laminated plates with free boundary conditions by the discrete singular convolution”, Composite Structures, Vol. 170, pp 91-102, June 2017, https://doi.org/10.1016/j.compstruct.2017.02.089

ABSTRACT: The discrete singular convolution (DSC) is used for free vibration analysis of three-layer angle-ply symmetric laminated plates with free boundaries, including laminated plates with two adjacent free edges. During formulating the weighting coefficients of derivatives having different orders, two Taylor series expansions with different orders are used to eliminate the degrees of freedom at fictitious points outside the
physical domain. Thus, the difficulty in handling free boundary conditions by using the DSC is overcome. Results are presented and compared with either exact solutions or the ones obtained by the differential quadrature method (DQM). It is shown that the DSC with the novel way to apply the boundary conditions yields very accurate lower mode frequencies as well as relatively accurate higher mode frequencies. The excellent performance of the DSC on high mode frequencies of beams and isotropic plates is retained and also independent of boundary conditions.

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“Research on nonlinear bending behaviors of FGM infinite cylindrical shallow shells resting on elastic foundations in thermal environments”, Composite Structures, Vol. 170, pp 111-121, June 2017
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ABSTRACT: This paper pays attention to predicting the nonlinear bending behaviors of functionally graded materials (FGM) infinite cylindrical shallow shells with a two-parameter elastic foundation by using a two-step perturbation method. The shells are subjected to uniform temperature rise and temperature dependency of the constituents is also taken into account. Two ends of the shells are assumed to be clamped or pinned and in-plane boundary conditions are immovable. The governing equations are derived based on physical neutral surface concept and high order shear deformation theory. The explicit expressions between the transverse load and the deflection are obtained by perturbation method. In numerical examples, some comparisons are shown to verify the correctness of the present research and solution method. It can be concluded that FGM cylindrical shallow shells subjected to uniform bending loadings will bring about snap-through buckling and jump changes, and the foundation can enhance the stability of the shells.

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ABSTRACT: Owing to inappropriate fabrication processing it is likely to fabricate a geometrically imperfect functionally graded (FG) microbeam. In addition, the experimental tests show that the classical continuum theory is incapable of interpreting the mechanical behavior of microstructures when the role of size-dependency is significant. Therefore, this investigation aims to examine the influences of geometric imperfection on the nonlinear stability behavior as a prominent characteristic of microstructures for a thermally loaded doubly-clamped microbeam made of temperature-dependent FGMs by taking into account the size effect phenomenon. The geometrically nonlinear size-dependent governing equation of system is derived in the framework of modified couple stress theory in conjunction with Euler-Bernoulli beam theory and the classical rule of mixture. Based on the static form of governing equation, a closed-form solution for the nonlinear critical snap-through
buckling temperature rise as well as the nonlinear thermal stability behavior of system in pre- and post-snap-through buckling domains is proposed and analytical study is then carried out by consideration of different effective parameters i.e., dimensionless imperfection amplitude, size-dependency, temperature-dependency, and power index. To verify the closed-form solution, the dynamic response of system is numerically evaluated by implementation of Galerkin scheme in conjunction with Runge-Kutta finite difference method.

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ABSTRACT: In this study, a free-form optimization method is proposed that maximizes the fundamental frequencies of the orthotropic shells to avoid vibrational resonance. The negative fundamental vibrational eigenvalue is employed as the objective function, which is minimized by subjecting to the governing equation of the natural frequency analysis and area constraint. In the free-form optimization process, the natural frequency analysis of the orthotropic shells is performed to calculate the shape gradient function. The shape gradient function is then applied to the velocity analysis for determining the optimal shape variation. The repeated eigenvalues are considered by converting the fundamental eigenvalue to a summation form of the repeated eigenvalues. The proposed optimization method is validated using three examples of the orthotropic shells. The numerical results show that the optimized shapes of the orthotropic shells are smooth, and their fundamental frequencies are significantly enhanced using the proposed free-form optimization method.

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“Static and dynamic analyses of laminated plates using a layerwise theory and a radial basis function finite element method”, Composite Structures, Vol. 170, pp 158-168, June 2017
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ABSTRACT: A layerwise shear deformation theory for composite laminated plates is discretized using a radial basis function finite element method (RBFEM). The RBFEM is the radial basis function (RBF) method in weak-form and is a partially mesh free method. Therefore, elements of complex shapes can be easily constructed. Compact-support Wendland function is used in the RBFEM. A layerwise theory based on a linear expansion of Mindlin’s first-order shear deformation theory in thickness direction is employed for static and dynamic analysis. The combination of the RBFEM with the layerwise theory allows an accurate and very flexible prediction of the field variables. Laminated composite and sandwich plates were analyzed. The RBFEM solutions were compared with various models in literatures and showed very good agreements with exact and other high accurate results in literatures based on similar layerwise theories. The analysis of composite plates based on the layerwise theory indicates that the RBFEM is an effective method for high accuracy analysis of large-scale problems.
https://doi.org/10.1016/j.compstruct.2017.01.088
ABSTRACT: An analytical framework which incorporates damage propagation/growth into the general structural stability analysis is presented. Therefore, the conventional total potential energy approach is extended by introducing an extended total potential energy-like functional capable of describing inelastic processes in which equilibrium holds between available and the required force for producing a change in structure. The work deals with systems which are described by \( I \) generalized coordinates and \( K \) damage parameters. The damage parameters are found to be functions of \( I \) generalized coordinates and \( M \) load parameters. The underlying variational principle for inelastic solids may be solved using discrete formulations or approximate methods such as a Rayleigh–Ritz formulation. This leads to a set of non-linear algebraic equations, comprising post-critical equilibrium paths and damage propagation. In order to verify the framework, it is applied to the well-known problem in which a delaminated composite strut/plate is subjected to an in-plane compressive load.

Tao Yu, Shishun Zhang, Le Huang and Chunwa Chan (School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia), “Compressive behavior of hybrid double-skin tubular columns with a large rupture strain FRP tube”, Composite Structures, Vol. 171, pp 10-18, July 2017
https://doi.org/10.1016/j.compstruct.2017.03.013
ABSTRACT: A hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular column (DSTC) consists of an outer FRP tube and an inner steel tube, with the space in between filled with concrete. This paper presents results from the first ever experimental study on hybrid DSTCs with a large rupture strain (LRS) FRP tube, namely, polyethylene terephthalate (PET) FRP tube. The experimental program involved the testing of 12 hybrid DSTC specimens with or without additional concrete inside the inner steel tube. The test results confirmed the ample ductility of hybrid DSTCs with a PET-FRP tube despite the severe local buckling of the inner steel tube at large axial deformations. The test results also suggested that the diameter-to-thickness ratio of the inner steel tube is a more critical parameter in such DSTCs than in DSTCs with a glass, carbon or aramid FRP outer tube.

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https://doi.org/10.1016/j.compstruct.2017.01.048
ABSTRACT: The objective of this research is to scrutinize large amplitude vibration response of functionally graded carbon nanotube reinforced composite (FG-CNTRC) annular sector plates with surface-bonded piezoelectric layers. A nonlinear formulation is derived based on the first-order shear deformation theory (FSDT), von Karman geometrical nonlinearity along with the Hamilton principle. The distribution of electric potential through the thickness of the piezoelectric layers is simulated by a sinusoidal function. The closed
circuit electrical boundary condition is taken into consideration for the top and bottom surfaces of the piezoelectric layers. The nonlinear dynamic equations, boundary conditions and Maxwell equation are discretized using the generalized differential quadrature method and direct iterative method is then employed to solve the nonlinear system of equations. The variation of nonlinear frequency versus the vibration amplitude is highlighted considering various influential parameters such as distribution and volume fraction of the CNTs, geometrical parameters, boundary conditions and the thickness of the piezoelectric layers. It is found that the dynamic responses of the CNTRC sector plate may be noticeably enhanced by adjusting values of the CNT volume fraction and distribution. The numerical results reveal that the increase in the nonlinear frequency descents at certain vibration amplitude owing to vibration mode redistribution.

A. Ghaznavi and M. Shariyat (Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Tehran, Iran), “Non-linear layerwise dynamic response analysis of sandwich plates with soft auxetic cores and embedded SMA wires experiencing cyclic loadings”, Composite Structures, Vol. 171, pp 185-197, July 2017
https://doi.org/10.1016/j.compstruct.2017.03.012

ABSTRACT: Non-linear dynamic behavior of sandwich plates with shape memory alloy (SMA) reinforced face sheets and soft auxetic (negative Poisson ratio) cores is investigated in the present article. Plates with stiff or traditional cores may be regarded as special cases. One of superiorities of the present work is considering the localized and instantaneous changes of martensite volume fraction of the individual particles of the SMA wires, through proposing a constitutive law and a cyclic phase-transformation tracing algorithm that are appropriate for pursuing the cyclic loading events and the relevant nested hysteretic pseudoelastic loops due to the plate vibration. Another novelty is incorporation of the core auxeticity and transverse compliance, through an efficient global-local layerwise plate theory. An updating iterative approach is employed to solve the resulting non-linear time-dependent finite element formulation. Results confirm the vibration attenuation due to the loss in the stored energy of the plate that is consumed by the SMA wires during the phase transformation. Moreover, the auxeticity of the core has led to significant stiffening in both the core and plate and consequently, reductions in the lateral deflections of the plate.


ABSTRACT: Compression After Impact (CAI) strength is critical to the safety and weight of carbon fibre aircraft. In this paper, the standard aerospace industry practice of using separate analyses and tests for panel buckling and CAI strength is challenged. Composite panels with a range of stacking sequences were artificially delaminated and subject to compression testing in a fixture that allowed local sublamine and global panel buckling modes to interact. Compared to panels without delamination, interaction of buckling modes reduced panel buckling strains by up to 29%. Similarly, compared to delaminated panels restrained against panel buckling, interaction reduced delamination propagation strains by up to 49%. These results are the first to indicate that restriction of interaction during CAI testing is unconservative and therefore potentially unsafe. A novel integration of an analytical Strip model, for sublamine buckling driven delamination propagation, and a Shanley model, for determining increased local strain due to sublamine-buckling-induced panel curvature, is used to calculate the reduction in strength due to buckling mode interaction. Assuming a typical sublamine post to pre-buckling stiffness ratio of 0.65, the difference in integrated model and experimental results is <11% – a level of accuracy that will allow the integrated model to drive initial design studies.
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ABSTRACT: A fully analytical approach on thermal and mechanical buckling and postbuckling of cylindrical shell surrounded on nonlinear elastic foundation is presented. The shell is composed of composite material, piezoelectric actuator, and eccentrically/concentrically isotropic stringers and rings. The equilibrium and compatibility equations of shell are derived based on Kirchhoff assumptions taking into account von Karman nonlinearity. Two types of simply-supported boundary conditions are considered as freely movable and immovable edges. The equations are solved by definitions of stress function and applying Galerkin method. Numerical examples are well verified with available data in the literature. Several parametric investigations are conducted to examine the effects of voltage, different stiffeners, lay-up configuration, and nonlinear elastic foundations on equilibrium paths.

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ABSTRACT: Square CFRP tubes were wrapped externally with aluminium sheets and crushed quasi-statically in the axial direction to investigate the effect of aluminium sheet-wrapping on the energy absorption of CFRP tubes. Moreover, a specially designed and manufactured platen with cutting blades was employed, as a new energy dissipating mechanism, to simultaneously cut and crush both CFRP tubes and aluminium sheet-wrapped CFRP tubes. Notches were introduced at one end of some tubes which were crushed by a platen with blades to control the location of the failure. Experimental results showed that the deformation mode of CFRP tubes and aluminium sheet-wrapped CFRP tubes that were crushed by a flat platen or by a platen with blades was a combination of splaying progressive and transverse shearing failure mode. By wrapping CFRP tubes with
aluminium sheets and using cutting blades, the mean crushing force and energy absorption increased by up to 70%. The crushing response of tubes without notches crushed by a platen with blades was similar to those tubes crushed by flat platens. Tubes with notches crushed by a platen with blades had a lower initial peak force, higher mean crushing force, larger energy absorption and higher specific energy absorption in comparison with counterpart tubes crushed by flat platens.


ABSTRACT: The main aim of the paper is to present a new numerical method to solve the weak formulation of the governing equations for the free vibrations of laminated composite shell structures with variable radii of curvature. For this purpose, the integral form of the stiffness matrix is computed numerically by means of the Generalized Integral Quadrature (GIQ) method. A two-dimensional structural model is introduced to analyze the mechanical behavior of doubly-curved shells. The displacement field is described according to the basic aspects of the general Higher-order Shear Deformation Theories (HSDTs), which allow to define several kinematic models as a function of the free parameter that stands for the order of expansion. Since an Equivalent Single Layer (ESL) approach is considered, the generalized displacements evaluated on the shell middle surface represent the unknown variables of the problem, which are approximated by using the Lagrange interpolating polynomials. The mechanical behavior of the structures is modeled through only one element that includes the double curvature in its formulation, which is transformed into a distorted domain by means of a mapping procedure based on the use of NURBS (Non-Uniform Rational B-Splines) curves, following the fundamentals of the well-known Isogeometric Analysis (IGA). For these reasons, the presented methodology is named Weak Formulation Isogeometric Analysis (WFIGA) in order to distinguish it from the corresponding approach based on the strong form of the governing equations (Strong Formulation Isogeometric Analysis or SFIGA), previously introduced by the authors. Several numerical applications are performed to test the current method. The results are validated for different boundary conditions and various lamination schemes through the comparison with the solutions available in the literature or obtained by a finite element commercial software.


ABSTRACT: Textile-reinforced concrete (TRC) as a novel composite material offers a wide range of capabilities and flexibility in the manufacturing of thin-walled, lightweight structures. The application of textile reinforcement in fine aggregate high-performance concrete has enabled the dimensioning of structural concrete in very small thicknesses. This possibility allows for the fabrication of thin-walled TRC shell structures with complex geometries. On the other hand, structural planning and construction require new modeling approaches to comprehend the structural behavior of such forms. In this paper, we present the fabrication procedure of a large-scale TRC vault shell, together with the performed experimental study. The shell structure was tested under a two-step loading scenario to study the load-bearing behavior. The particular focus of the paper is on the analysis of the structural behavior by means of an anisotropic strain-hardening material model specifically developed for the simulation of TRC shells. The prediction obtained using the nonlinear finite element simulation has been compared with the test results to validate the modeling approach. The performed studies are
used to evaluate and discuss the structural redundancy included in the applied linear ultimate limit state assessment procedure.

ABSTRACT: Sandwich plates and cylindrical shells composed of two composite laminated faces and an ideally orthotropic elastic core are considered in this paper. Since the natural frequencies of sandwich structures may not be affected by the accuracy of local behaviors, to avoid the complexity involved in the higher-order shear deformation theory and layerwise theory and to supplement the loss of the transverse shear deformation in the classical lamination theory, a modified first-order shear deformation theory was employed to obtain the closed-form solutions of natural frequencies of certain particular problems of sandwich plates and shells such as a rectangular composite sandwich plate with symmetric cross-ply laminates with all edges simply supported. Mathematical formulation extended by the classical methods used in isotropic thin plates was also established to deal with the general cases of sandwich plates and cylindrical shells. Numerical results show that the solutions obtained by the present methods are accurate enough to serve as a quick check for the other numerical solutions.

ABSTRACT: Circularizing a square column by bonding concrete segments onto the sides of the column and then wrapping with fibre reinforced polymer (FRP) is considered an effective technique in strengthening square solid columns. This paper investigates the suitability of the circularization technique for strengthening square hollow concrete specimens. Eight specimens in two groups (four solid specimens and four hollow specimens) were cast and tested under axial compression. The first specimen from each group was the reference specimen. The corners of the second specimen were rounded to 20 mm radius and wrapped with two layers of carbon fibre reinforced polymer (CFRP). The third specimen was circularized with full length concrete segments and wrapped with two layers of CFRP. The fourth specimen was circularized with concrete segments shorter than the length of the specimen and wrapped with two layers of CFRP. The test results demonstrate that circularization of hollow specimens similar to the circularization of solid specimens reduces the stress concentration at the corners and enhances the ultimate load carrying capacity and ductility. The circularization with short concrete segments is more effective for hollow specimens than the circularization with full length concrete segments when the ductility is of main concern.

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ABSTRACT: The von Karman large deformations are considered in the Mindlin plate theory described by the nonlocal and gradient elasticity for piezoelectric nanoplates. It is shown that electric intensity vector can be expressed by mechanical quantities. The governing equations for bending moments, normal and shear stresses are derived from the variational principle. The finite element method is developed for considered governing equations. Differences of both theories are presented.

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ABSTRACT: The free vibration and buckling behaviors of foam-filled composite corrugated sandwich plates under thermal loading are investigated theoretically. A refined shear deformation theory is extended incorporating two different combinations of hyperbolic and parabolic shear shape functions. Equivalent thermoelastic properties of the foam-filled corrugation are obtained using the method of homogenization based on the Gibbs free energy. Based on hyperbolic-polynomial variation of all displacements across the thickness of both face sheets and sandwich core, the shear plate theory accounts for both transverse shear and thickness stretching effects. The theoretical predictions are validated against existing results as well as finite element simulations. The effects of geometric and material parameters on natural frequency and critical temperature change for buckling are systematically investigated. The proposed theory is not only accurate but also simple in predicting the free vibration and thermal buckling responses of composite sandwich plates with foam-filled corrugated cores.

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ABSTRACT: The laminated circular cylindrical shells are complicated to analyze and more complicated when anisotropic materials are used with different thickness and different material properties. Also computing the critical stresses under various boundary and loading conditions is exceptionally sensitive and therefore reasonable simplification of the governing equation is in demand for practical design purpose. This article first formulated a shell theory for hybrid anisotropic materials by use of asymptotic integration method, the results are same as classical Donnell-Vlasov theory of single layer isotropic material, then a simplified governing equation was developed by means of adopting a different length scale. The new simplified version can be very useful when multiple materials and thicknesses are designed for practical purpose. Comparison of two different shell bending theories is discussed. Also presented are proper choices of the governing equations for different
loading conditions. The theories are extremely useful for the analysis and design of advanced space vehicles and pressure vessels featured cylindrical shells with laminated walls of various materials and thicknesses.

Li Li and Yujin Hu (State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China), “Torsional vibration of bi-directional functionally graded nanotubes based on nonlocal elasticity theory”, Composite Structures, Vol. 172, pp 242-250, July 2017, https://doi.org/10.1016/j.compstruct.2017.03.097

ABSTRACT: The equation of torsional motion is presented in this paper to investigate the free torsional vibration behaviors of tubes made of a bi-directional functionally graded (FG) material, which is composed of two different materials with continuously varying along the radius and length directions. To incorporate the size effect of long-range forces, the nonlocal elasticity theory is employed to derive the difference equation of torsional motion, which can be reduced to the classical governing equation by simply setting a zero nonlocal parameter. Suppose that the effective material properties of the nanotube vary in the length direction according to an exponential distribute function and in the radius direction according to a power-law function. The closed-form solutions of torsional frequencies and mode shapes are derived. It is shown that the torsional frequencies can be significantly affected by the through-radius and through-length gradings of the bi-directional FG nanotubes and hence can be prescribed by tailoring the bi-directional nano-structures of the FG material. The torsional frequencies can be increased with the decreasing nonlocal parameter, whereas the size-dependent behaviors on the mode shape cannot be observed.

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ABSTRACT: A simple and effective corotational triangular facet shell finite element is proposed for the geometric nonlinear analysis of thin piezoactuated structures. The structures under investigation are laminated shells composed of elastic layers and sensory/active piezoelectric layers, perfectly bonded to each other. A polar decomposition based corotational framework is adopted. By filtering out large rigid body motions from structural displacements, this framework allows (i) to account for arbitrarily large displacements/rotations, provided strains are small, and (ii) to use existing and high-performance linear elements as core-elements. Within the classical laminated plate theory, the small strain core element formulation based on superposition of OPT membrane and DKT plate element is used, along with a layer-wise constant interpolation of the transversal component of the electric field. Numerical simulations dealing with benchmark problems and applications of technological interest prove accuracy and effectiveness of the proposed formulation.

Peng Wang, Hocine Chalal and Farid Abed-Meraim (LEM3, UMR CNRS 7239 – Arts et Métiers ParisTech, 4, rue Augustin Fresnel, 57078 Metz Cedex 03, France), “Quadratic prismatic and hexahedral solid-shell elements

ABSTRACT: The current contribution proposes two quadratic, prismatic and hexahedral, solid–shell elements for the geometric nonlinear analysis of laminated composite structures. The formulation of the proposed solid–shell elements is based on a fully three-dimensional approach combining the assumed-strain method and the reduced-integration technique. In particular, only translational degrees of freedom are considered in the formulation and a preferential direction is chosen as the thickness direction, along which an arbitrary number of integration points are arranged. Making use of different physical local frames, these elements are coupled with fully three-dimensional orthotropic constitutive equations, which allows modeling multilayered composite structures with only a single element layer through the thickness. A series of popular nonlinear benchmark tests for laminated composite structures is performed to assess the performance of the proposed SHB elements. Compared to reference solutions taken from the literature, the results provided by the SHB elements show excellent agreement. Moreover, on the whole, the proposed SHB elements perform better than state-of-the-art ABAQUS elements, which have the same geometry and kinematics, using comparable mesh discretizations.


ABSTRACT: Multiscale eigenelement method (MEM), which was presented by the author and co-authors, is based on the idea of eigenvector expansion, and the shape functions in MEM bridge the information between macro and micro scales. In previous works, the shape functions in the classical MEM are solved from the self-equilibrium equation of unit cell, while in the improved MEM they are from the self-equilibrium equation as well as the eigenvalue problem of clamped unit cell. In this work, MEM is compared with substructure method for static problem, two effective correction terms are suggested to improve accuracy if necessary. Another contribution of the present work is, the dynamic governing differential equation of MEM is derived for periodical composite structures according to the generalized Hamilton variational principle, and the details about efficient and accurate use of mode superposition method and Newmark integration method are presented. The numerical comparisons with the standard FEM using fine meshes are conducted for free and forced vibration analyses of one-dimensional and two-dimensional problems. And it is concluded that the improved MEM is suitable for the analyses of both static and dynamic problems, and the classical MEM is suitable for the static problems, especially the one with correction term.


ABSTRACT: The study of the coupled instabilities of thin-walled columns with trapezoidal and square cross-sections, which are made of Functionally Graded Materials (FGMs) and Fibre Metal Laminates (FMLs) is presented in the paper. It is assumed that each column wall is made of a stack of nine FML layers and/or a single FGM (Al-TiC) and/or ceramics (TiC). The GLARE 3 type FML part was made of an alternate sequence of Al 2024-T3 and even GFR prepreg layers where aluminium was always the outer layer. In the case of the FGM layer, volume fractions of ceramics and the metal distribution throughout the layer thickness are described by a simple power law. It is assumed that the columns are subjected to axial compression and simple supported at their loaded edges. All constituent materials obey Hooke’s law. The effect of temperature influence is
neglected. To determine governing equations of considered FML-FGM structures the classical laminate plate theory (CLPT) is used. The solution to the problem of the non-linear buckling of hybrid thin-walled structure is based on the Koiter’s theory. An interaction of the global buckling mode with two local buckling modes is taken into account. In order to derive the equilibrium equations of FML-FGM profiles, the full Green’s strain tensor and the second Piola-Kirchhoff’s stress tensor have been adapted. The presented solution seems to be especially important as the authors have not found no earlier studies on the coupled buckling of thin-walled FML-FGM structures with closed cross-sections.

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ABSTRACT: An analytical solution of the buckling problem formulated for a composite cylindrical shell with its ends closed by rigid disks and subjected to hydrostatic pressure is presented in the paper. The problem is solved using Fourier decomposition and the Galerkin method. The boundary conditions are assigned in the form accounting for axial displacements of the end disks caused by an axial contraction of the deformed shell. The hoop displacement and deflection of the shell are approximated by the beam function corresponding to the first mode shape of vibration of a clamped-clamped beam. The axial displacement is approximated by the third derivative of the beam function. Based on this solution, a number of analytical formulas enabling calculations of critical hydrostatic pressure for composite orthotropic cylindrical shells are derived. Using these formulas, the critical loads are calculated for the shells with various elastic and geometric properties. The calculations are verified by comparisons with the results of finite-element analyses. The efficiency of analytical solutions in the search for fibre reinforcement arrangements providing maximum resistance to buckling is demonstrated by several examples.

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ABSTRACT: This paper seeks to investigate thermal behaviour of a thin-walled deployable composite boom (DCB) in a space environment using ground thermal-vacuum test and FEA methods. Thermal tests simulating a space environment include three key conditions, namely ultra-high level of vacuum (lower than 10^{-5} Pa), heat sink (~180 °C) that is realized using black panels with the liquid-nitrogen cooling system and thermal loading that is achieved through infrared lamps. The thermal tests of the DCB under seven typical heat fluxes were conducted to characterize heat transfer mechanisms and to obtain temperature fields. The basic heat transfer methods for the DCB in a space environment were surface radiation, cavity radiation and heat conduction. These led to significant temperature difference and gradient occurring on the irradiated and shadowed parts of the DCB at nighttime and daytime. FE models were established to predict temperature fields and thermally induced deformation. Good correlation was achieved between experimental and numerical results.
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ABSTRACT: Sandwich panels with triple layered graded honeycomb cores were tested under blast loading. The structural response was analyzed by using finite element software LS-DYNA after validation against the experiments. The structural deformation modes were classified into three types and the core layer deformation was divided into three regions. For the same value of impulse, a localized impulse led to severely localized deformation mode. A relatively evenly distributed impulse resulted in largely global bending deformation. Under the same loading, graded panels with the core of the largest relative density placed near the impact face suffered a smaller deflection than the panels with uniform core. Furthermore, for the same deformation mode the normalized back face sheet deflection increased linearly with impulse.

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https://doi.org/10.1016/j.compstruct.2017.04.027  
ABSTRACT: Based on theory of elasticity, static analysis of functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical shell imbedded in piezoelectric sensor and actuator layers under thermoelectro-mechanical load is carried out. Thermo-elastic constants of the CNTRC cylindrical shell is supposed to be independent of temperature difference. In this study, uniformly as well as different cases of functionally graded CNT distribution, along the radial coordinate of host layer is considered. Governing ordinary differential equations are derived by expanding all of quantities in term of axial coordinate and using state space technique along the radial direction and then they are solved analytically to compute temperature, stress and displacement fields as well as induced electric voltage in sensor layer. Validity of the present approach is assessed by comparing the obtained numerical results with the available results in literature. Influence of CNT volume fraction, kind of CNT distribution along the radial coordinate, surface thermal, mechanical and electrical boundary conditions on static behavior of hybrid FG-CNTRC cylindrical shell are evaluated.

ABSTRACT: The stability failure of the axially loaded cylindrical shell is considered as the last unresolved classical stability problem, although it has been investigated for over 100 years. Therefore designers rely on the
application of empirical knockdown factors from the 1960s like the NASA SP-8007 for cylindrical shells and the NASA SP-8019 for truncated conical shells which are very conservative for modern shell structures. Perturbation approaches for the design of axially loaded cylindrical and conical shells are presented in this paper. These approaches deliver knockdown factors for a physical based estimation of the lower-bound buckling load and are suitable for research and industrial applications as they are independent from imperfection measurements and easy to implement. The corresponding numerical models are validated by means of high-fidelity buckling experiments and it shows that experimental buckling loads can be calculated very precisely in contrast to the previous methodology. Additionally, new robust knockdown factors are proposed for preliminary shell design which are based on curve fitting of numerical knockdown factors of the perturbation approaches. Thus, it is possible to utilize the load bearing capability of launch-vehicle primary structures up to 40% more effectively, resulting in considerable weight saving potentials for composite shell structures.

References listed at the end of the paper:
Experimental and numerical crushing analysis of circular CFRP tubes under axial impact loading

ABSTRACT: In this paper, a prospective simulation method for composite crushing under axial crash loading is presented. To this end carbon fibre-reinforced plastic (CFRP) circular crash tubes are investigated in drop tower tests. Flat specimen tests are performed to determine calibration parameters and are used for efficient re-parameterization of a transversally isotropic material card used in finite element (FE) simulation. An existing material card for CFRP based on basic tension and compression tests is used as a starting point and only a small set of material parameters is numerically reasonable adjusted to account for crushing. Once calibrated by means
of flat specimens the material model is able to cover a variety of different composite layups and specimen geometries, e.g. tube specimens. Therefore, numerical simulation of drop tower testing is carried out and results show good agreement between numerical and experimental results. In addition to these tests, it can be shown that the presented approach is leading to equally good results when the material and geometry of the specimens are changed to a glass fibre-reinforced plastic (GFRP) tube structure.

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ABSTRACT: The object of this paper is to present a novel semi-analytical method and its associated applications for linear vibration analyses of functionally graded carbon nanotube reinforced composite (FG-CNTRC) doubly-curved panels and shells of revolution on with arbitrary boundary conditions. Distribution of the carbon nanotubes through the thickness of the structures may be uniform or functionally graded and four types of the CNTs distribution are considered in this paper. Properties of the composite media are determined by a refined rule of mixtures approach which contains the efficiency parameters. The translation and rotation displacements of the doubly-curved structures are uniformly expressed as the superposition of a standard cosine Fourier series and several auxiliary functions introduced to eliminate all potential discontinuities of the original displacement function and its derivatives at the edges. Based on that, the energy expression of the FG-CNTRC doubly-curved panels and shells of revolution is examined where the first-order shear deformation elasticity theory is considered. Lastly, to solve the natural frequencies as well as the associated mode shapes by means of the Ritz-variational energy method. Unlike other existing methods, the proposed method is capable of handling various combinations of boundary constraints in a unified fashion, including free, simply-supported, clamped and elastic-supported boundary conditions. Comprehensive studies on the convergence, accuracy, stability and efficiency of the method are derived via the comparison with existing results reported in publications. The parametric studies concerning the influence of the geometrical parameters, CNTs distributions, volume fraction of CNTs as well as boundary restraint parameters on free vibration of FG-CNTRC doubly-curved panels and shells of revolution is also investigated in detail.


ABSTRACT: In this study, the crush behaviour and the energy absorption capability of an aluminium honeycomb core is discussed. A three-dimensional finite-element model of a honeycomb-core structure was developed using the commercial code Abaqus. Flatwise and edgewise experimental compressive tests were
made to validate the numerical model and good agreement was found between the experimental data and the numerical results. Virtual compressive tests varying the cell size, cell-wall thickness, and material properties were performed. The deformation mode, compressive core behaviour and its energy-absorption capacity were examined. The crushing parameters at in-plane directions were more affected by the variations of the characteristic core parameters; although, in general, increasing the cell-wall thickness and the yield stress of the aluminium alloy give higher crush loads, and therefore the absorbed energy increases. However, if the cell size increases, the energy-absorption capacity decreases.

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“Buckling and post-buckling analysis of geometrically non-linear composite plates exhibiting large initial imperfections”, Composite Structures, Vol. 174, pp 134-141, August 2017
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ABSTRACT: This paper discusses the buckling and post-buckling of thick composite plates having large initial geometrical imperfections. Within the theory of large transformations, the proposed formulation uses generalised forces and deformations derived from the energy conjugacy of the second Piola-Kirchhoff stress and Green-Lagrange strain. In addition, it provides partial differential equations of equilibrium that are easy to solve using common techniques such as the Galerkin-Ritz method. Unlike existing contributions, which are (i) limited to imperfections that are proportional to current deformations, (ii) address small to moderate initial imperfections only, and/or (iii) require advanced and time consuming numerical methods, the present approach is based on analytical solution and takes into account large initial imperfections. Despite the complexity of the energy balance formulation, the resulting governing equations are simple and applicable to design practical composite structures. The proposed model was compared to numerical results obtained using the finite element method. Overall, good agreements have been obtained when the assumptions fall within the range of validity of the commercial software used for simulation.


ABSTRACT: An analytical approach is presented to investigate nonlinear dynamic responses of sandwich plates. To obtain governing differential equations of motion, the higher order shear deformation theory is employed together with Hamilton’s principle. The Navier’s solution and Runge-Kutta method using available mathematical package software MAPLE 14 are used to solve the governing equations. This method can consider any required number of layers through the sandwich plate thickness. To evaluate the method validity a sandwich plate with FGM face sheets and the FRC core resting on an elastic foundation is subjected to the blast load due to the burst of 5 kg charge. The maximum plane-normal displacement is obtained by the analytical method and numerical approach. Comparison between results shows good agreement. Thereafter, time histories obtained from both analytical and numerical approaches are compared. The interlaminar stresses are obtained through the sandwich plate thickness. The results show that neither material failure nor delamination occurs.
ABSTRACT: Due to the existence of sweepback angle of aircraft, the stringers of the stiffened panels in some parts may be declined instead parallel to the boundary. The paper deals with stability experiment investigation on the stiffened composite panels with tilting stringers. Two panels stiffened by six tilting stringers were manufactured and tested. Attempts were made to obtain the buckling load, ultimate load carrying capability and failure state of the panels. Finite element analysis was performed to investigate the tests and FE models were calculated by ABAQUS. The numerical results were assessed by comparing with the test data and good agreement was observed for both buckling and ultimate collapse load as well as the failure modes of the structure. Further investigation was performed to explore the influence of tilting angles on stability behavior of the panels which revealed that the buckling load exhibited a continuous decrease with the increasing tilting angles while the ultimate load showed an initial rise from 0° to 1° and then decreased.

ABSTRACT: Compressing a stiff film bonded to a compliant substrate with finite thickness can lead to various instabilities, including global buckling, local wrinkling, delamination or their concomitant buckling. This paper proposed an analytical model, which integrates global and local interactive effects due to the finite thickness, to reveal the growth from buckling to buckling-driven delamination. The resulting governing non-linear equations (non-autonomous fourth-order ordinary differential nonlinear equations with integral conditions) are then solved by introducing a continuation algorithm, which offers considerable advantages to detect multiple bifurcations and trace a complex post-buckling path. The critical conditions for global buckling, local wrinkling and buckling-driven delamination are carefully studied. Two different growth processes from destabilization to restabilization (snap-back) are captured in the post-buckling range. Moreover, it is found that the interface toughness and the pre-existing delamination crack length dominates the critical strain for the onset of buckling-driven delamination, and further decide the initial instability mode. Finally, two phase diagrams are plotted to predict both initial and advanced instability modes in such a bilayer system. The phase diagrams can be used to guide the design of film/substrate systems to achieve desired modes of instabilities.
ABSTRACT: A large body of work has studied the energy absorption of metallic and composite tubes undergoing crushing. Similarly, reinforcements of metallic structures with composites have also been studied. By contrast, composite tubes with metallic reinforcements (composite-intensive) have not been investigated, although they may offer benefits in terms of robustness or cost over both composite as well as metallic tubes. Here, composite materials with metallic reinforcements were tested under dynamic axial loading in order to study the effects of major design parameters on the energy absorption and load uniformity behavior. Significant benefits could be identified, particularly when considering cost aspects. Two numerical approaches for modeling the adhesive interface between the two discrete material phases were evaluated in terms of accuracy and efficiency in crash simulations. The simplified modeling technique comprising two layers of shell elements rigidly tied at the interface proved to be generally applicable to the evaluation of structural concepts in an early vehicle development stage.

ABSTRACT: In the framework of a unified 2D continuum formulation of the fully coupled thermomechanical laminated plate with von Karman nonlinearities, a consistent model with third order shear deformability and cubic temperature distribution along the thickness is proposed. Focusing on symmetric cross-ply laminates, an effective minimal dimension reduction is then pursued by expressing both in-plane displacement components and shear angles in terms of transverse displacement and thermal variables via kinematic condensations. The ensuing compact reduced order model with different coupling features allows to account for nonlinear mechanical and thermal phenomena, along with their interactions, under a variety of thermomechanical assumptions, boundary conditions and excitations. Upon proper validation in linear free dynamics and critical buckling, numerical investigation of the nonlinear dynamic response under different thermal conditions is accomplished, focusing on the variable features of its transient and post-buckled response, where the thermomechanical interaction plays a meaningful role.

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ABSTRACT: Mechanical response and energy absorption of aluminum foam-filled and empty circular tubes with different geometries were investigated experimentally and theoretically. All specimens including foam-filled circular and empty circular tubes were compressed laterally by two rigid plates. Effects of the geometrical characteristics of specimens and densities of aluminum foam on deformation and energy absorption of the foam-filled and empty circular tubes were considered. Experimental results show that the presence of aluminum foam filled in the circular tubes changes the deformation modes and increases the energy absorption of the
foam-filled circular tubes. An analytical model for the plastic deformation of the foam-filled circular tubes under the lateral loading was proposed. The relations of lateral loading and energy absorption of the foam-filled circular tubes were obtained. Comparisons between the analytical predictions and the experimental results were performed and good agreement was achieved.

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“Exact solutions for free vibration analysis of laminated, box and sandwich beams by refined layer-wise theory”, Composite Structures, Vol. 175, pp 28-45, September 2017
https://doi.org/10.1016/j.compstruct.2017.05.003
ABSTRACT: The present work addresses a closed-form solution for the free vibration analysis of simply supported composite laminated beams via a refined one-dimensional (1D) model, which employs the Carrera Unified Formulation (CUF). In the framework of CUF, the 3D displacement field can be expanded as any order of generic unknown variables over the cross section, in the case of beam theories. Particularly, Lagrange expansions of cross-sectional displacement variables in conjunction with layer-wise (LW) theory are adopted in this analysis, which makes it possible to refine the kinematic fields of complex cross section by arbitrary order and accuracy. As a consequence, the governing equations can be derived using the principle of virtual work in a unified form and can be solved by a Navier-type, closed-form solution. Numerical investigations are carried out to test the performance of this novel method, including composite and sandwich beams ranging from simple to complex configurations of the cross section. The results are compared with those available in the literature as well as the 3D finite element method (FEM) solutions computed by commercial codes. The present CUF model is proved to be able of achieving high accurate results with less computational costs. Besides, they may serve as benchmarks for future assessments in this field.

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ABSTRACT: Metal/composites hybrid structures, which combine low-density composites with low-cost metallic materials, are gaining increasing attention for meeting higher and higher requirements of lightweighting and crashworthiness in automotive and aerospace engineering. This study explores the crushing characteristics involving energy absorption and damage behaviors of three different configurations of hybrid aluminum/CFRP under quasi-static axial loading. For a comparative purpose, empty aluminum tube and CFRP tube were tested as well. Based on the experimental results, effects of different configurations on crashworthiness characteristics were studied; and it was found that the hybrid tube H-I (i.e. the aluminum tube internally filled with a CFRP tube) offers the best results. Finally, the advantages of hybrid tube H-I were further investigated from the perspectives of cost and lightweight by using the analytical models derived. It was found that for the same energy absorption, hybrid tube H-I saves the cost by 32.1% compared with the pure
CFRP tube, and leads to the weight saving of 33.6% compared with the pure aluminum tube. Such a hybrid structure would be of considerable potential to be used as an efficient energy absorber.

Salvatore Brischetto (Department of Mechanical and Aerospace Engineering, Politecnico di Torino, corso Duca degli Abruzzi, 24, 10129 Torino, Italy), “A general exact elastic shell solution for bending analysis of functionally graded structures”, Composite Structures, Vol. 175, pp 70-85, September 2017
ABSTRACT: This new work proposes a three-dimensional (3D) exact shell model for the static analysis of simply-supported structures embedding Functionally Graded Material (FGM) layers when they are subjected to harmonic transverse normal loads. Results are proposed in terms of displacement and stress amplitudes through the thickness direction. One-layered FGM plates and cylinders, and sandwich cylindrical and spherical shell panels embedding an internal FGM core and external classical skins have been analyzed. Proposed results give a complete 3D description of FGM structures in terms of displacement and stress states. Such results can be used to validate new refined 2D shell models proposed in numerical or analytical form. Different geometries, lamination schemes, thickness ratios, materials and FGM laws through the thickness have been analyzed in order to have a general overview of the problem. The proposed 3D shell model uses the spherical 3D equilibrium equations developed in general orthogonal curvilinear coordinates. These equations automatically degenerate in those for cylindrical and plate structures via opportune considerations made about the radii of curvature. Equilibrium equations are solved in closed form considering simply supported boundary conditions and harmonic applied loads. The exponential matrix method has been employed to solve the second order partial differential equations in z. These equations have constant coefficients because of the introduction of opportune mathematical layers for the FGM description and for the curvature evaluation. A layer-wise approach has been identified with the direct imposition in the 3D shell model of equilibrium conditions for transverse stresses and compatibility conditions for displacements.

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ABSTRACT: In the present work, experimental and numerical studies were conducted on the in-plane uniaxial behavior of a fiberglass/phenolic honeycomb core to investigate the effects of the node bond adhesive fillet. A non-linear finite element model (FEM) with large displacements of the repetitive unit cell of the hexagonal cell honeycomb core is employed to study the in-plane behavior numerically. The model was used to conduct a parametric study on the effects of the adhesive fillet and its geometry. To validate the numerical model, a series of in-plane quasi-static tensile and compressive tests was carried out. Numerical analysis showed that increased node bond adhesive fillet size significantly induces higher tangent stiffness of the honeycomb core. Good agreement was observed between the model predictions and test results. Analytical models from the literature without adhesive or adhesive fillet were also used for comparison.

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ABSTRACT: Research is limited with respect to load-deflection behavior of slender concrete columns internally reinforced with Fiber Reinforced Polymer (FRP) spirals and longitudinal bars. An analytical buckling model based on numerical integration is presented to predict the load versus deflection performance of slender concrete columns reinforced with FRP spirals and longitudinal bars, subjected to eccentric loads. The model can be used to predict the behavior of slender concrete columns with various configurations including FRP and/or steel reinforcement, single or double spiral, and number of longitudinal bars. The longitudinal bars considered include steel, FRP, or hybrid reinforcement consisting of steel and FRP bars. The model is found to predict the experimental performance of slender concrete columns reinforced with Glass FRP longitudinal bars and spirals with satisfactory accuracy. The model is used to create interaction diagrams for FRP spiral-confined circular concrete columns with various slenderness ratios, reinforced with steel, FRP or hybrid reinforcement.

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ABSTRACT: To construct weight efficient aerospace sandwich structures, interlocked orthogrid sandwich composite panels reinforced by carbon fibers were designed, made and tested. The orthogrid is weight efficient in flatwise compression for its strength is greater than usual three-dimensional (3D) lattice truss composite structures. Progressive crushing of the ribs endows the orthogrid long deformation plateau and great mean crushing force (MCF) while most of 3D lattice truss composite structures are usually brittle. Crushing models of lattice truss materials were developed to predict the MCF and it is found that the orthogrid composite has comparable or even better specific energy absorption (SEA) compared with 3D metallic lattice trusses. Forming continuous resin adhesive layers between the facesheets and the orthogrid, the orthogrid sandwich panel has stronger shear strength and is more weight efficient than usual 3D lattice truss sandwich panels jointed by adhesive joints in shear resistance. Through the research, it is concluded that interlocking orthogrid provides a simple but efficient way to construct lightweight sandwich composite.

Mehdi Darabi and Rajamohan Ganesan (Concordia Center for Composites, Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Blvd. W., Montreal, Quebec, Canada),
“Non-linear vibration and dynamic instability of internally-thickness-tapered composite plates under parametric excitation”, Composite Structures, Vol. 176, pp 82-104, September 2017
https://doi.org/10.1016/j.compstruct.2017.04.059
ABSTRACT: Internally-tapered composite plates are formed by terminating or dropping-off some of the plies in the laminates at pre-determined locations, which is an important method for stiffness tailoring and weight saving in these structures. In the present work, the dynamic instability of internally-thickness-tapered laminated composite plates subjected to harmonic in-plane loading is studied based on non-linear vibration analysis. The non-linear von Karman strains associated with large deflections and curvatures are considered. The in-plane displacements are determined from the two in-plane force-equilibrium equations of motion of non-linear large
deflection tapered plate. Consequently, the in-plane force-resultants can be obtained from the in-plane displacements and further applying the boundary conditions. Then the general Galerkin method is used for the moment-equilibrium equation of motion to satisfy spatial dependence in the partial differential equation of motion to produce a set of non-linear Mathieu-Hill equations. These equations are ordinary differential equations, with time-dependency. By applying the Bolotin’s method to these equations, the dynamically-unstable regions, stable-, and unstable-solutions amplitudes of the steady-state vibrations are obtained. The non-linear dynamic stability characteristics of symmetric cross-ply laminates with different taper configurations are examined. A comprehensive parametric study is carried out to examine and compare the effects of the taper angles, magnitudes of both tensile and compressive in-plane loads, aspect ratios of the tapered plate including length-to-width and length-to-average-thickness ratios on the instability regions and the parametric resonance particularly the steady-state vibrations amplitude. For linear vibrations, the present results show good agreement with that available in the literature which were obtained based on linear analysis.

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ABSTRACT: This paper explores the compression behavior of eco-friendly natural fiber-based isogrid lattice cylinder made of pineapple leaf fibers and phenol formaldehyde resin matrix. The filament winding method and an appropriate curing system was used to prepare specimens. The mechanical behavior of the structure was determined by axial compressive test. The interfacial adhesions between pineapple leaf fibers and phenol formaldehyde resin contain physical and chemical bonding by analyzing Fourier transform infrared spectroscopy. For the lattice cylinder, corresponding theoretical and finite element models were proposed to simulate the mechanical properties. Compared with the measured values, the predicted values for the theory and the finite element method were approximately 77–96% of the values of the experimental data. The failure forms of lattice cylinders focus on delamination and fracture of circular rib segments adjacent to the crossover, in agreement with the analytical position of shear failure based on the finite element method, indicating the validity of the predicted model. After that, an orthogonal test was designed to explore the impacts of structural parameters on the mechanical behavior of the lattice cylinder. The results indicated that the main influence factor of special load and stiffness is the number of equal divisions of the circumference. The lattice cylinder can be treated as a truss core combined with skins to manufacture a hierarchical sandwich structure, for use in the construction of some parts of buildings, like the floor.

Ning Liu and Ann E. Jeffers (Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA), “Isogeometric analysis of laminated composite and functionally graded sandwich plates based on a layerwise displacement theory”, Composite Structures, Vol. 176, pp 143-153, September 2017 https://doi.org/10.1016/j.compstruct.2017.05.037
ABSTRACT: A multi-layered shell formulation is developed based on a layerwise deformation theory (Reddy, 2004) within the framework of isogeometric analysis (IGA). IGA utilizes Non-Uniform Rational B-splines (NURBS) to represent the geometry as well as to describe the field variables (Hughes et al., 2005). The high-order smoothness of NURBS offered the opportunity of capturing the structural deformation efficiently in a
rotation-free manner. The derivation also follows a layerwise theory, which assumes a separate displacement field expansion within each layer, and considers transverse displacement component as $C^0$-continuous at layer interfaces, thus resulting in a layerwise continuous transverse strain states. Since the in-plane and through-thickness integrations are carried out individually, this approach is capable of capturing the complete three-dimensional stress states in a two-dimensional setting, which improves the computational efficiency. A knot insertion technique is utilized for the discretization in the through-thickness direction, and $C^0$-continuity is enforced by means of knot repetition at dissimilar material interfaces. The performance of the proposed model is demonstrated using multiple laminated composites and sandwich plates (including functionally graded material core) as examples. Numerical results prove the accuracy of the proposed formulation and show that the isogeometric layerwise shell is superior to its finite element counterpart.

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ABSTRACT: Elastoplastic buckling behaviors of rectangular plates made from functionally graded materials (FGMs) are investigated in this paper. The elastoplastic material properties are assumed to vary smoothly through the thickness of the plates. The three dimensional material constitutive relation of FGMs is found by introducing the material homogenization method, named Tamura-Tomota-Ozawa(TTO) model, into $J_2$ deformation theory or $J_2$ flow theory. The uniform strain hypothesis helps to simplify the prebuckling state and derive the analytical expression of the position of the material elastoplastic interface. The buckling governing equations and the buckling critical condition of the structures are formulated under the framework of the classical plate theory. An iterative algorithm is designed to obtain the elastoplastic buckling critical load, a converging result between the prebuckling and the buckling critical internal forces. ABAQUS simulation well verifies the present theoretical predictions from $J_2$ flow theory, and is resorted to investigate the postbuckling behaviors of FGM plates. Discussions are addressed for the effects of the constituent distribution, the material plastic flow, the preloaded states of the plates, and the regions of buckling types are plotted as well.

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ABSTRACT: This paper discusses the thermal buckling analysis of composite plates and sandwich panels by means of a Ritz-based variable-kinematic formulation. Main feature of the proposed formulation consists in the representation of the structure by means of sublaminates, i.e. arbitrary groups of plies composing the panel. Each sublamine is associated with an independent, arbitrary kinematic description, so that the use of refined, high-order theories can be restricted to specific regions, such as the core of sandwich panels. Monolithic plates can be studied as a special case where the structure is modeled using only one sublamine. Presented are the critical temperatures, with and without accounting for the nonlinear pre-buckling effects, for a set of monolithic and sandwich configurations. When pre-buckling effects are neglected, the problem is solved as a standard
eigenvalue problem. On the other hand, the introduction of pre-buckling effects leads to a nonlinear eigenvalue problem, which is solved with an iterative procedure. The results are validated against 3D solutions, and highlight the importance of accounting for pre-buckling deformations, especially in the case of sandwich panels. As demonstrated, high-fidelity predictions are obtained while keeping at minimum the amount of degrees of freedom.

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ABSTRACT: Radomes with traditional splicing structure has non-entirety failures of joins and rivets, so it cannot give full play to the structure’s carrying efficiency after shocking. A new kind of radome is put forward, an improved version of the traditional splicing structure, with Carbon Fiber Reinforced Polymer (CFRP) structure. We combined theoretical analysis, finite element simulation and experimental test as well as compared and analyzed compressed cloud picture of displacement and stress distribution of radomes with two braided angles structures (90° and 60°) in order to study the deformation and stress capacity of radome after stressing. Simulation result: the compressed displacement of two kinds of radomes increases linearly, compressed stress diagram increases in a jagged way liking a parabola. Under the same compressed displacement, braided angle of 90° enjoys bigger compressed stress than that of 60°; under the same load, braided angle of 90° enjoys smaller compressed displacement than that of 60° with less joints cracking. The experiment shows that some of the joints cracked because the connection between braiding joints coupled. But the stressing deformation and stress development of radome match the simulation results basically.

ABSTRACT: Nitsche’s method had recently demonstrated its potential for a seamless and continuity-preserving coupling of NURBS patches in isogeometric shell analysis. Trimmed and non-conforming patches and even blended models including classical thin-shell and solid-shell formulations can be coupled successfully while preserving a continuous flux along the coupling interfaces. In this paper, we take advantage of the method’s modeling flexibility for an extension to NURBS-based laminate composite shell structures. We introduce a global-local model coupling approach to enrich laminate composite thin-shell Kirchhoff-Love models locally with a full three-dimensional continuum solution. The approach provides a reliable coupling of the classical lamina theory with a layerwise formulation revealing the full interlaminar stress state at reduced computational cost. The layerwise shell model is based purely on a mid-surface NURBS description of the shell body thus supporting the direct application of a surface-defined CAD data representation of shells. We apply a refined finite cell approach to handle efficiently trimmed geometries, as common in CAD models. We demonstrate reliability, accuracy of the coupling approach and efficiency in terms of numerical costs and modeling effort of our approach with several examples.
ABSTRACT: This paper investigates the energy-absorbing characteristics of a lightweight honeycomb core containing embedded carbon fibre reinforced plastic (CFRP) tubes. Initial tests are undertaken on the plain aluminum honeycomb material in order to characterize its specific energy absorption (SEA) capability and to identify the prevailing failure mechanisms. Tests are then conducted on honeycomb cores reinforced with increasing numbers of composite tubes in order to establish the influence of varying the density of the tubular array on the measured SEA. Finally, a series of drop-weight impact tests are conducted in order to characterize the dynamic response of these materials and assess their overall rate-sensitivity. Tests on the plain aluminum honeycomb cores resulted in the characteristic plastic wrinkling of the cell walls, yielding an average value of SEA of 14 kJ/kg. Embedding CFRP tubes into the honeycomb served to greatly enhance the energy-absorbing properties of the core, with quasi-static values of SEA reaching as high as 105 kJ/kg. An examination of the failed samples indicated that the previously-observed wrinkling mode of failure was largely absent, with the composite tubes being reduced to fine debris. Increasing the areal density of tubes in the honeycomb to relatively high values proved to be counterproductive, due to unwanted interactions between the individual tubes. Dynamic tests on the tube-reinforced honeycombs yielded SEA values that exceeded the quasi-static results with values reaching 112 kJ/kg for a moderately-reinforced core. Given the simplicity of the preparation process, it is believed that these lightweight structures represent an attractive cost-effective energy-absorbing material for use in dynamic applications.

References listed at the end of the paper:

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ABSTRACT: A new dynamic modeling and free vibrational analysis of double-layered nanoplates made of functionally graded (FG) materials in hygro-thermal environments is presented for the first time. A better description of size-dependent phenomena is presented using a nonlocal stress-strain gradient theory. The double-layered nanoplate is subjected to hygro-thermal loading and it is resting on elastic medium. The gradation of material properties is considered using power-law model. Modeling of double-layered nanoplate is conducted according to a refined four-variable plate theory with fewer field variables than first order plate theory. The governing equations and related classical and non-classical boundary conditions are derived based on Hamilton’s principle. These equations are solved for hinged nanoplates via Galerkin’s method. It is indicated that type of vibration, moisture rise, temperature rise, nonlocal parameter, strain gradient parameter, material gradation, elastic foundation and side-to-thickness have a remarkable influence on vibration behavior of double-layered nanoscale plates.

Bekir Akgoez and Oemer Civalek (Akdeniz University, Civil Engineering Department, Division of Mechanics, Antalya, Turkiye), “A size-dependent beam model for stability of axially loaded carbon nanotubes surrounded by Pasternak elastic foundation”, Composite Structures, Vol. 176, pp 1028-1038, September 2017,
https://doi.org/10.1016/j.compstruct.2017.06.039

ABSTRACT: Microstructure-dependent buckling behavior of single-walled carbon nanotubes (SWCNTs) surrounded by a two-parameter elastic foundation is investigated. The governing equations and corresponding
boundary conditions in buckling are achieved by implementing minimum total potential energy principle via modified strain gradient theory and several beam theories. The resulting equations are analytically solved by employing Navier’s solution procedure for simply supported boundary conditions. A detailed parametric study is performed to indicate effects of diameter-to-length scale parameter ratio, diameter-to-length ratio, shear deformation, shear correction factor and foundation parameters on buckling loads of SWCNTs. Numerical results reveal that the classical buckling loads evaluated by all shear deformation beam theories agree well with each other while a discrepancy occurs between the size-dependent buckling loads of parabolic beam theory (PBT), sinusoidal beam theory (SBT) and Timoshenko beam theory with proposed shear correction factor (TBT*), and those of Timoshenko beam theory (TBT).

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ABSTRACT: A theoretical procedure for dynamic response of metal foam core sandwich beams struck by a heavy mass with low-velocity is developed to consider the combined local denting and global deformation. Analysis focuses on effect of local denting on global deformation and inertial effect of the structure. Large deflection effects are determined by using the membrane factor method. A set of finite element simulations is carried out to validate the model predictions. It is demonstrated that the model predictions are in good agreement with the finite element computations. The sandwich beam is strengthened with the deflection increasing.

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ABSTRACT: The hygro-thermal effects on vibration and buckling analysis of functionally graded beams are presented in this paper. The present work is based on a higher-order shear deformation theory which accounts for a hyperbolic distribution of transverse shear stress and higher-order variation of in-plane and out-of-plane displacements. Equations of motion are obtained from Lagrange’s equations. Ritz solution method is used to solve problems with different boundary conditions. Numerical results for natural frequencies and critical buckling temperatures of functionally graded beams are compared with those obtained from previous works.
Effects of power-law index, span-to-depth ratio, transverse normal strain, temperature and moisture changes on the results are discussed.

ABSTRACT: This paper investigates the three-dimensional (3-D) vibration characteristics of sandwich and multilayered plates with general ply stacking sequences and arbitrary restraints based on a spectral-sampling surface method. The theoretical formulation is undertaken by the 3-D theory of elasticity such that it is able to study the dynamic behavior of sandwich and multilayered plates very well, even in the presence of soft layers. Under the current framework, a set of sampling surfaces along the thickness direction of each plate layer are primarily selected and the displacements of these surfaces are chosen as basic plate variables. Consequently, vibration solutions for sandwich and multilayered plates with different thicknesses, material properties and ply stacking sequences can be derived up to desired accuracy by selecting sufficient number of sampling surfaces. In addition, the penalty technique and Lagrange multiplier method are adopted to relax the enforcement of the boundary conditions. As a result, the proposed formulation can be applied efficiently to the 3-D vibration analysis of sandwich and multilayered plates with general restraints. The final solutions are determined by a modified variational principle, in which each of the basic plate variables is approximated by the spectral method. Results show that the present method is capable of calculating highly accurate numerical results for thick sandwich and multilayered plates with general ply stacking sequences and arbitrary boundary conditions.

ABSTRACT: The paper describes an invariant-based formulation of a triangular finite element for geometrically nonlinear analysis of shear flexible composite shells subjected to thermal loads. Transverse shear deformation is taken into account using the first order shear deformation theory. The focus is on the representation of the strain energy of the shell in terms of invariant quantities which depend on the components of the strain tensor and elastic constants of the material. Based on the invariant expression for the strain energy density, algorithmic relations are derived for computing the stiffness matrix of the shell finite element. The finite element formulation is used to study stability of equilibrium configurations in the region of large thermal displacements. A positive definite second variation of the total energy is used as a sufficient criterion for stability of equilibrium configurations. A series of numerical examples are given to estimate performance of the finite element in solving nonlinear problems of composite plates and shells under uniform temperature rise. Solution of some classical problems of laminated plates and shells shows that there exist equilibrium configurations not previously reported in the literature.

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ABSTRACT: Variable Angle Tow (VAT) composites remove the constraint of having straight fibers, typical of traditional composite structures. This dramatically increases the design space and allows a more effective tailoring of the material properties to minimize the weight and increase structural performance. To provide an accurate prediction of the displacement and stress fields in an efficient computational framework, a multi-theory architecture based on the Generalized Unified Formulation (GUF) is proposed. In particular, Equivalent Single Layer, Zig-Zag, and Layer Wise theories with different orders of expansions for the different variables are generated with a theory-invariant mathematical model. This feature allows the user to tailor the computational accuracy and cost to the needs of the case under investigation and is inherently well suited for optimization and reliability problems. For the in-plane discretization, a fourth-order triangular shell element presenting 15 nodes is adopted. The interlaminar displacement continuity is imposed in the finite element assembling in the thickness direction of the layer stiffness matrices, whereas the inter-element displacement compatibility is enforced with the penalty method. This approach allows one to use independent GUF discretization for any desired direction within each element, providing significant versatility (accuracy vs computational time) in the structural modeling. A transverse stress recovery procedure taking into account the variability of the structural properties due to the fibers’ curvilinear paths is also presented. Results are compared with the literature and a commercial software (NX NASTRAN) featuring 3D finite elements.

A. Alibeigloo (Department of Mechanical Engineering, Faculty of Engineering, Tarbiat Modares University, 14115-143 Tehran, Iran), “Three dimensional coupled thermoelasticity solution of sandwich plate with FGM core under thermal shock”, Composite Structures, Vol. 177, pp 96-103, October 2017, https://doi.org/10.1016/j.compstruct.2017.06.046

ABSTRACT: Based on the Lord–Shulman formulation, time dependent response of sandwich plate with functionally graded material (FGM) core is performed by using generalized coupled thermoelasticity. Governing partial differential thermoelasticity equations are reduced to ordinary differential equations by applying Fourier series state space technique and then are solved analytically via Laplace transform. Solutions are then converted to time domain by using inverse Laplace transform. Validation of the present approach is assessed by comparing the numerical results with the available results in literature. Finally influence of time constant, applied temperature, mid radius to thickness ratio and time history on transient thermoelastic behavior of sandwich plate are studied.

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ABSTRACT: A novel sandwich element design consisting of two facings made of carbon reinforced Textile Reinforced Concrete (TRC), a low density foamed concrete (FC) core and glass fibre reinforced polymer
(GFRP) connecting devices was experimentally investigated according to quasi-static and cyclic quasi-static four-point bending. Optical measurements based on Digital Image Correlation (DIC) were taken during testing to enable a detailed analysis of the bending behaviour and level of composite action. A model, verified by the experiments, was developed based on non-linear finite element analysis (NLFEA) to gain further insight on the failure mechanisms. Under both loading conditions, the bending behaviour of the TRC-FC composite elements was characterized by favourable load bearing capacity, partial composite action, superior ductility and multiple fine cracking. The connecting devices were found to be the critical elements causing the initial failure mechanism in the form of localized pull-out within an element.

ABSTRACT: Polymer matrix nanocomposites reinforced with uniformly dispersed and randomly oriented multi-walled carbon nanotubes (MWCNTs) are identified as excellent candidates for functionally graded structural members. This paper presents static and dynamic behavior of functionally graded polymer composite plates reinforced by randomly oriented multi-walled carbon nanotubes using novel layer-wise formulation concept. The weight fraction of MWCNTs in functional graded plate is represented by layer-wise variation along the thickness and MWCNTs are considered as uniformly dispersed in each layer. The effective elastic modulus of nanocomposite plate is predicted with modified Halpin-Tsai model, while the Poisson’s ratio and density are determined by rule of mixtures. System of governing equations are derived based on generalized higher order shear deformation (HSDT) plate theory and Navier technique is employed to obtain the solution for free-vibration, buckling and static bending problems of simply supported plates under axial and transverse loading conditions at various aspect-ratios. In order to understand the effect of important reinforcement and plate parameters on the natural frequencies, critical buckling loads and bending deflections, different parametric studies are conducted. Results reveal that different types of weight distributions have significant influence on structural characteristics.

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ABSTRACT: This study reports thermal buckling analyses of functionally graded material (FGM) sandwich plates using an improved mesh-free radial point interpolation method (RPIM). The buckling formulation of FGM sandwich plates is derived from the improved RPIM which employs a new radial basis function enabling the shape functions to be built without any supporting fixing parameters based on the higher-order shear deformation plate theory. Two types of FGM sandwich plates with different composition scheme, i.e. one with FGM skins and homogenous core and the other composed of homogenous skins and FGM core are considered in the analyses. The simulated results by the improved RPIM are compared with the analytical solutions found in the literature for the verification purpose. Detailed parametric studies are then carried out to scrutinize the
effects of the volume fraction, plate length-to-thickness ratio, aspect ratio, boundary condition and FGM constituents on the critical buckling temperature changes of the FGM sandwich plates under various types of temperature variation through the thickness. Results demonstrate that the improved mesh-free RPIM can effectively predict the thermal buckling behavior of the FGM sandwich plates.

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ABSTRACT: This paper presents a comprehensive review on the development of higher-order continuum models for capturing size effects in small-scale structures. The review mainly focus on the size-dependent beam, plate and shell models developed based on the nonlocal elasticity theory, modified couple stress theory and strain gradient theory due to their common use in predicting the global behaviour of small-scale structures. In each higher-order continuum theory, various size-dependent models based on the classical theory, first-order shear deformation theory and higher-order shear deformation theory were reviewed and discussed. In addition, the development of finite element solutions for size-dependent analysis of beams and plates was also highlighted. Finally a summary and recommendations for future research are presented. It is hoped that this review paper will provide current knowledge on the development of higher-order continuum models and inspire further applications of these models in predicting the behaviour of micro- and nano-structures.

S. Sahmani and M.M. Aghdam (Department of Mechanical Engineering, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran), “A nonlocal strain gradient hyperbolic shear deformable shell model for radial postbuckling analysis of functionally graded multilayer GPLRC nanoshells”, Composite Structures, Vol. 178, pp 97-109, October 2017, https://doi.org/10.1016/j.compstruct.2017.06.062

ABSTRACT: The present study addresses the size dependency in nonlinear instability of functionally graded multilayer graphene platelet-reinforced composite (GPLRC) nanoshells under hydrostatic pressure including jointly the nonlocal elastic and strain gradient stress fields. For this objective, the new unconventional continuum theory namely as nonlocal strain gradient theory of elasticity is utilized within the framework of a refined hyperbolic shear deformation shell theory. Via stacking up a number of individual layers, the graphene platelet (GPL) nanofillers are distributed uniformly and three different functionally graded patterns based upon a layerwise change of the GPL weight fraction through the shell thickness direction. The effective material properties corresponding to uniform (U-GPLRC) and X-GPLRC, O-GPLRC, A-GPLRC functionally graded patterns of dispersion are extracted by Halpin-Tsai micromechanical scheme. By employing jointly the boundary layer theory of shell buckling and a two-stepped perturbation technique, explicit analytical expressions are achieved for nonlocal strain gradient stability curves of functionally graded multilayer GPLRC
nanoshells. It is indicated that by increasing the value of GPL weight fraction for the U-GPLRC and O-GPLRC nanoshells, the significance of the both nonlocal and strain gradient size dependencies reduces, while for the X-GPLRC and A-GPLRC nanoshells, it increases.

ABSTRACT: In this study, an improved formulation is presented for the spatially coupled free vibration analysis of Al/Al2O3 thin-walled functionally graded (FG) sandwich beams with non-symmetric open, single- and double-cell sections. The thin-walled beam model is based on the Euler-Bernoulli beam theory for bending and the Vlasov theory for torsion. The FG beam consists of ceramic (Al2O3) and metal (Al) phases varying through the wall thickness. Three types of material distribution, which leads to the material coupling, are considered. The strain and kinetic energies are derived by introducing displacement parameters defined at the arbitrary chosen axis considering the effects of axial-flexural-torsional coupling and restrained warping. For finite element analysis, cubic polynomials are utilized as the shape functions of two-noded Hermitian beam element. Elastic stiffness and mass matrices for the non-symmetric cross-sections are precisely evaluated. In order to illustrate the accuracy of this formulation, the present finite element solutions of thin-walled sandwich beams with non-symmetric open, single- and double-cell sections are presented and compared with available results. Especially, the effects of various structural parameters of thin-walled FG sandwich beams such as gradient index, thickness ratios of ceramic in flanges and webs, and non-symmetricity of cross-section on the warping to torsion ratio of cross-section and the spatially coupled natural frequencies are parametrically investigated.

Zhong-Kui Cai, Daiyu Wang and Zhenyu Wang (Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China; and Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, China; and School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China), “Full-scale seismic testing of concrete building columns reinforced with both steel and CFRP bars”, Composite Structures, Vol. 178, pp 195-209, October 2017, https://doi.org/10.1016/j.compstruct.2017.06.020
ABSTRACT: This paper presents an experimental study of an innovative concrete building column which is longitudinally reinforced with both steel bars and fiber-reinforced polymer (FRP) composite bars. The main objectives of this study include: (1) investigating the seismic failure mechanism of such FRP-steel reinforced concrete (FSRC) columns under relatively large gravity load and (2) analyzing the effects of the FRP bars on the seismic performance of the FSRC columns. To this end, a total of six full-scale cantilever columns with variable carbon FRP (CFRP) bar and steel reinforcement ratios were tested under combined constant axial load and lateral displacement reversals. The specimens had 400 mm square sections and effective heights of 1800 mm. Test results showed that adding additional CFRP bars into the conventional steel reinforced concrete (SRC) columns was efficient in improving the post-yield stiffness ratios and mitigating the residual displacements, while the hysteretic energy dissipation could be maintained. Failure modes of the tested FSRC specimens were characterized by crushing of FRP bars and buckling of steel bars at drift ratios larger than 2.4%. Furthermore, confining the FSRC column with external CFRP wraps was effective in delaying the crushing of internal CFRP bars and reducing the post-earthquake residual displacement.
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“Experimental investigation on different positional impact damages and shear-after-impact (SAI) behaviors of stiffened composite panels”, Composite Structures, Vol. 176, pp 232-245, October 2017,
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ABSTRACT: Buckling and postbuckling performances of stiffened composite panels with different positional impact damage under in-plane shear load were investigated. Barely visible impact damage (BVID) was introduced into three different positions with the same impact energy of 50 J. Damage areas and impact crater depths were both measured and their relationship in each impact position was affirmed. Shear after impact (SAI) experiments were conducted on the damaged specimens. Compared with pristine panels, the impact damaged panels showed a similar buckling mode during the shear process, which was three buckling waves in each skin bay without buckling transition, but had a far different failure mode. Additionally, the changes in buckling and failure load both were different depending on the impact position. The most serious decline in buckling and failure load was caused by the combination of material properties degradation and debonding due to the impact damage.


ABSTRACT: In this paper, free in-plane vibration of elastically restrained annular plate made of functionally gradient material (FGM) is investigated by an improved Fourier series method. The material property is assumed to be gradually changed in power law along the radial direction. The energy equation is formulated for the in-plane free vibration description of FGM annular plate, with the admissible functions constructed as the superposition of standard Fourier series and boundary smoothed polynomials to make the spatial differential continuous enough in the entire solving domain. In conjunction with the Rayleigh-Ritz procedure, system characteristic equation in matrix form is straightforwardly derived. Several numerical examples are then presented to validate the proposed model, and study the in-plane vibration characteristics of FGM annular panel with various boundary conditions. Based on the model established, the influence of important parameters, such as FGM power-law exponent and boundary restraints, on the in-plane vibration characteristics of FGM annular panel is addressed and investigated in detail. This work can shed some light for a better understanding on the in-plane dynamic characteristics of such complex structure.


ABSTRACT: Sandwich structures have been widely used in marine applications due to their properties such as high weight/strength ratio. In contrast, the failure mechanism of these structures has a significant effect on the local and global dynamic responses. In the present study, sandwich panels with polymeric skins and PVC foam cores subjected to slamming impact are investigated experimentally and numerically. A high speed shock
machine is used to keep approximately a constant velocity during the impact event. The dynamic resistance was analysed in terms of hydrodynamic loads, dynamic deformation and failure mechanisms for different impact velocities. On the other hand, the slamming model was implemented in Abaqus/Explicit software based on Coupled Eulerian Lagrangian model approach. In addition, different damage modes are incorporated in the numerical model, including the intralaminar, debonding in skin/core interface, and core shear to cover all possible damage modes throughout structures. Two failure criteria (Hashin criteria for the laminate composite and Christensen criteria for the core in sandwich structure) are defined and integrated into VUMAT sub-routine. In addition, the cohesive zone model is used to predict the debonding skin/core. A good agreement in both hydrodynamic loads and damage prediction were found between numerical and experimental results.


ABSTRACT: In a recent paper by Shafiei, Mirjavadi, Afshari, Rabby, and Hamouda [1], for the first time the nonlinear mathematical formulations of axially functionally graded (AFG) micro/nano-beams under non-uniform temperature distribution in the thickness direction based on the classical theory as well as the non-classical theories (modified couple stress and nonlocal theories) were developed to study the thermal buckling of system. In this comment, it is indicated that the governing equations and associated boundary conditions of system were incompletely established not only for the non-classical models but also for the classical model. The main reason for the inaccuracy of mathematical formulations proposed by Shafiei et al. [1] is to neglect the influence of thermal moment at both the governing equations and boundary conditions. In addition, it is discussed that the size-dependent and -independent buckling temperature rise predicted by Shafiei et al. [1] is meaningless for both the simply supported and fully clamped case studies.


ABSTRACT: The fire stability of carbon fiber reinforced polymer (CFRP) shell structures was investigated using an intermediate-scale test setup. The shell specimens are representative of typical load-bearing CFRPs in modern civil aviation. The CFRP shell specimens were exposed to a fully developed fire with direct flame impingement to one side at a heat flux of 182 kW/m². Specimens were simultaneously loaded with constant compressive force equal to 40% of the ultimate failure load. CFRP shells and four different fire retarding configurations, using integrated protective layers, were investigated. Unprotected CFRP specimens failed after just 27 s. Specimens with integrated protective layers with low heat conductivity and high burn-through resistance showed the most promising results. An integrated titanium foil decelerated the decomposition of the epoxy matrix and increased the time to failure by 68% compared to the unprotected CFRP shell.

ABSTRACT: The paper deals with four-point bending tests of thin-walled channel section beams, made of eight-layer GFRP laminate. In the performed tests two scenarios were investigated: beams were bent in the plane with lowest second moment of area and beams were subjected to bending in the plane passing through the geometrical centre of the flanges of channel section profile and parallel to the plane with the highest second moment of area. Six arrangements of layers were analysed: \[0/−45/45/90\]_S, \[90/−45/45/0\]_S, \[90/0/90/0\]_S, \[0/90/0/90\]_S, \[45/−45/45/−45\]_S, \[45/−45/90/0\]_S. The experimental research was conducted with the use of the ultimate testing machine, additionally designed test stand and the digital image correlation system Aramis®. Numerical analyses have been performed in the Ansys® software, based on the finite element method. In geometrically nonlinear analysis two algorithms, indicating failure mechanisms, were applied: progressive failure analysis with material property degradation method and anisotropic Hill potential theory with assumption of perfect plasticity.

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ABSTRACT: This paper presents free vibration of composite beams under axial load using a four-unknown shear and normal deformation theory. The constitutive equation is reduced from the 3D stress-strain relations of orthotropic lamina. The governing differential equations of motion are derived using the Hamilton’s principle. A two-node C^1 beam element is developed by using a mixed interpolation with linear and Hermite-cubic polynomials for unknown variables. Numerical results are computed and compared with those available in the literature and commercial finite element software (ANSYS and ABAQUS). The comparison study illustrates the effects of normal strain, lay-ups and Poisson’s ratio on the natural frequencies and load-frequency curves of composite beams.

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ABSTRACT: The aim of this paper is to develop a robust layer-wise theory for structural analysis of curved glass and photovoltaic panels. By the analogy to the existing theories of plates, governing equations for doubly curved layers including kinematic relations, equilibrium conditions and constitutive equations are introduced. Applying assumptions of shear rigidity of skin layers and moments-free core layer as well as approximations of
thin shallow shell, a reduced form of governing differential equations is proposed. Compared to the classical theories of shells the derived system includes an additional second order differential equation. As a result, additional boundary conditions should be satisfied for any edge of the shell. The importance of these extensions is demonstrated for long cylindrical panel with for two examples of simple supports: one with free edges, where relative in-plane displacements of skins are allowed, and one with framed edges, where cross-section rotations of all layers are assumed the same. For both cases closed-form analytical solutions related to a shell strip approximation are presented. Displacement bounds in monolithic and layered cases are derived, and the dependence of deformation and stress characteristics on the radius of curvature and types of supports are illustrated.

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ABSTRACT: Functionally graded materials (FGMs) and porous materials are two special and new branches of materials with unique applications and properties. Emerging nano-/micro-science is growing every day and for this purpose, FGMs and porous materials can be used in small-scale systems. In this study, the nonlinear buckling characteristics of functionally graded nano-/micro-beams which are made of porous materials are studied based on Euler-Bernoulli beam theory for the first time. Considering the von Kármán geometric nonlinearity, governing equations of nano-beam are derived using Eringen’s nonlocal theory and the modified couple stress theory is utilized to obtain the governing equations of microbeam. The generalized differential quadrature method (GDQM) is used along with the iteration technique to obtain the nonlinear results. The results are depicted to show the effects of different parameters on the nonlinear buckling behavior of the functionally graded (FG) porous micro-/nano-beams for clamped boundary condition.

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ABSTRACT: The paper presents the failure analysis of thin-walled channel section composite beams made of GFRP laminate. Six arrangements of layers were analysed. Two scenarios were investigated in the performed tests: pure bending and bending with torsion. In order to characterise the process of failure, the following techniques were used: ultrasonic non-destructive testing, computed microtomography and scanning electron microscopy. The conducted failure analysis based on macro and microscopic tests allow to identify the location, geometry and the character of the failure areas. Furthermore, occurrence of characteristic forms and mechanisms of failure was revealed. Based on the conducted analyses it was concluded that the failure of reinforcing fibres, as a result of compressive and shearing stresses, is a major/dominant form of failure for most of the studied configurations. Detailed analysis of the failure areas allowed to determine the influence of
orientation and position of particular layers on the character of damage of the tested beams. The type and
distribution of the observed forms of failure indicate that the character of degradation of particular layers with
different orientations remains heterogeneous to a large extent.

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“An isogeometric finite element approach for thermal bending and buckling analyses of laminated composite
plates”, Composite Structures, Vol. 179, pp 35-49, November 2017,
https://doi.org/10.1016/j.compstruct.2017.07.056

ABSTRACT: Temperature rise in a plate structure produces non-zero transverse normal strain. Thus, a six-
variable quasi-3D model with one additional variable in transverse displacement of higher-order shear
defformation theory (HSDT) is developed in this paper to take into account the effects of transverse shears and
normal strain in a laminated composite plate. The governing equation is discretized by isogeometric analysis
(IGA), which naturally fulfills the $C^1$-continuity requirement of the plate model. Due to the presence of
bending-extension coupling, two kinds of thermal plate issues are considered – thermal buckling and thermal
bending phenomena. Several numerical examples are provided to show the accuracy of the present method
compared to reference results. Furthermore, it has been confirmed that the transverse normal strain cannot be
discarded, especially for thick plates under a temperature environment.

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“Free vibration of FGM sandwich doubly-curved shallow shell based on a new shear deformation theory with
stretching effects”, Composite Structures, Vol. 179, pp 50-60, November 2017,
https://doi.org/10.1016/j.compstruct.2017.07.032

ABSTRACT: Free vibration of the functionally graded material (FGM) sandwich doubly-curved shallow shells
under simply supported conditions is presented. Three common types of the shell, namely, the shell with
homogeneous hardcore and FGM facesheet (type A), the shell with homogeneous softcore and FGM facesheet
(type B) and the shell with FGM core and homogeneous facesheet (type C), are discussed. The dynamics model
is derived according to a new shear deformation theory with stretching effects. The dimensionless natural
frequency is obtained by Navier method. Numerical examples of the FGM sandwich doubly-curved shallow
shells are provided for different gradient material parameters, core thicknesses, radii of curvature, aspect ratios,
side-to-thickness ratios and vibration modes to demonstrate the accuracy of the present theory.

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ABSTRACT: Aerothermoelastic characteristics of composite laminated panels with time-dependent boundary conditions are investigated. The macro fiber composite (MFC) which is more adaptive and effective than the traditional monolithic piezoelectric materials is applied to control the structural vibration. The MFC actuator and sensor are bonded on the top and bottom surfaces of the panel so that the active flutter control can be conducted. Aerodynamic pressure is evaluated by the supersonic piston theory. The governing equation of the electromechanical and thermal coupling system is established by the extended Hamilton’s principle with the assumed modes method. By solving the eigenvalue problem, natural frequencies of the structural system are obtained. Frequency- and time-domain responses are computed to analyze the aerothermoelastic properties of the laminated panel. The influences of ply angle and aspect ratio of the laminated panel on the flutter behaviors are investigated. The displacement feedback control (DFC) and linear quadratic Gaussian (LQG) methods are performed to design the controllers. The active control effects under the two different controllers are compared. It is observed that both the DFC and LQG methods can suppress the vibration, and the LQG is more effective than the DFC controller in flutter suppression of the laminated panel with time-dependent boundary conditions.

ABSTRACT: In the current study, a nonlocal strain gradient beam model with third-order distribution of shear deformation is established to explore the nonlinear vibration of axially-loaded multilayer functionally graded graphene platelet-reinforced composite (GPLRC) nanobeams in both of the prebuckling and postbuckling domains. The dispersion of graphene platelet (GPL) nanofillers changes layerwise based upon different functionally graded patterns while it remains constant within each individual layer. The effective mechanical properties of multilayer functionally graded GPLRC nanobeams are estimated using Halpin-Tsai model of micromechanics. Hamilton's principle is utilized to construct the size-dependent differential equations of motion. Subsequently, an improved perturbation technique in conjunction with the Galerkin method is employed to present explicit analytical expression for nonlocal strain gradient nonlinear frequency in terms of applied axial load. It is observed that at the critical buckling point, the significance of the nonlocality and strain gradient size dependency on the nonlinear frequency remains constant for all values of maximum deflection. However, within the prebuckling and postbuckling regimes, by increasing the maximum deflection of the axially-loaded multilayer GPLRC nanobeam, both types of size effects on the nonlinear frequency reduce. Also, it is seen that similar to the type of GPL dispersion pattern, the value of GPL weight fraction has also no influence on the significance of size dependencies in the nonlinear frequency of axially-loaded multilayer functionally graded GPLRC nanobeams.

ABSTRACT: The paper presents an effective numerical approach for modeling and optimizing the ceramic volume fraction distribution of functionally graded (FG) plates in the thermo-mechanical environment. Ceramic volume fraction design variables at control points whose coordinates are located along the plate thickness by Greville abscissae are used to describe the material distribution using the B-spline basis functions. Continuously altering macroscopic material properties can therefore be easily captured by selecting a proper order of these B-spline functions without any extra terms. The temperature-dependent material properties are then evaluated by either the rule of mixture or the Mori-Tanaka scheme. A non-uniform rational B-splines (NURBS)-based isogeometric finite element model associated with the third-order shear deformation theory (TSDT) is utilized for the static analysis of the FG plates. A recently proposed adaptive hybrid evolutionary firefly algorithm (AHEFA) is employed to solve compliance minimization problems with volume constraints. This algorithm effectively enhances the trade-off between the global and local search abilities, the solution accuracy and the convergence speed are thus improved dramatically. Several numerical examples are examined to confirm the effectiveness and robustness of the present method.

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ABSTRACT: In this study, wave propagation in functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical microshell is investigated by taking into consideration nonlocal constant and material length scale parameter. For this purpose, FG-CNTRC cylindrical microshell is modeled using shear deformable shell theory as well as nonlocal strain gradient theory. The classical governing equations are extracted using Hamilton’s principle. Carbon nanotubes are distributed in UD and FG-X shapes in FG-CNTRC cylindrical microshells. The results demonstrate that the rigidity of FG-CNTRC cylindrical microshell is higher in the strain gradient theory and lower in the nonlocal theory compared to that in the classical theory. In addition, the effect of manner of distribution of carbon nanotubes in the FG-CNTRC cylindrical microshell as well as the effect of volume fraction of the carbon nanotubes on the phase velocity of the FG-CNTRC cylindrical microshell is investigated. The results demonstrate that the effects of nonlocal constant and material length scale parameter, thickness, and wavenumber on the phase velocity of FG-CNTRC cylindrical microshell are considerable.

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ABSTRACT: Automated fiber placement (AFP) is one of the recently developed robot-assisted composite manufacturing techniques. Steering fibers along optimal curvilinear paths enables tailoring the multifunctional properties of laminated composites to fully exploit all potentials of composite materials. This type of advanced composites, called variable stiffness laminates, can optimize the structural performance of composites. In this
paper, we aim at developing a novel semi-analytical methodology to conduct hygro-thermo-mechanical analysis on thin to relatively-thick fiber-steered composite panels. The principle of minimum total potential energy, and Layer-wise method are employed to explore the effects of fiber steering on the hygro-thermal and mechanical buckling loads, natural frequency, bending deformation, and stress distributions of conical and cylindrical panels as well as circular plates made by AFP technology without considering manufacturing defects. The numerical results show that the buckling loads and fundamental frequencies of composite conical panels could be improved up to 57% and 44%, respectively, by using a constant curvature fiber-steered lay-up instead of a corresponding quasi-isotropic composite.

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ABSTRACT: An analytical approach is proposed to determine delamination threshold loads of fiber-reinforced laminated composite plates with arbitrary stacking sequences under transverse loading conditions. Following the concept of cohesive zone modeling, a laminated plate is considered as an assembly of two sub-laminates connected by a virtual elastic-brittle layer with infinitesimal thickness. The problem is formulated and solved by the Rayleigh-Ritz method based on first-order shear deformation theory. The problem of quasi-static face-on (transverse) indentation test is analyzed as an example. The results, including elastic stiffness of flexural response, traction distributions over the potential crack interface, and threshold loads and initiating locations of delamination, are found to be in very good agreement with finite element simulations using cohesive elements. The modeling strategy, therefore, is useful for aerospace structural engineers at the preliminary design stage of laminated composite aerospace structures.


ABSTRACT: In the present study, finite element formulations are derived for static bending, linear buckling and free vibration analysis of nanobeam structures by utilizing the integral form of Eringen nonlocal model. Formulations are developed according to the minimum total potential energy principle by presenting the differentiation operations explicitly. As being distinct from other studies, a non-uniform mesh distribution is proposed for the corresponding analytical expressions of the beam deflections. With this aid, the discontinuous nature of rotation angle, which is encountered at boundaries of the beam, is aimed to be captured. Many numerical examples are solved, and compared with the exact solutions reported in the literature to demonstrate the versatility of the non-local finite element method with the proposed mesh configuration. It is found out that, with the suggested mesh distribution, the number of elements can be decreased dramatically without sacrificing from the accuracy, which consequently leads to a considerable reduction in the computational cost.
Nonlinear aeroelastic analysis of curved laminated composite panels

ABSTRACT: Nonlinear aeroelastic behaviors of curved laminated composite panels are investigated in this paper. The finite element co-rotational theory is applied to model geometrically nonlinear shell panels, and an Euler solver, instead of piston theory or other simplified aerodynamic theories, is utilized to solve for the unsteady aerodynamic pressure. Aeroelastic responses for thin panels, with which have two different sizes of curvature $H/h = 5$ and $H/h = 10$, as well as two different layer orientations, $[0°/90°/0°/90°/0°]$ and $[45°/−45°/45°/−45°/45°]$ are simulated under four Mach numbers at 0.76, 0.96, 1.2 and 1.67. The results, comprising the static aeroelastic deformation, limit cycle oscillation, non-periodic oscillation and chaotic behaviors are obtained and studied. Flutter dynamic pressure, amplitudes, and spectra of limit cycle oscillation are analyzed, and the nonlinear characteristics are discussed.

Optimal design of thin-walled functionally graded beams for buckling problems

ABSTRACT: This paper presents a modeling as well as a numerical approach for geometric and material optimization of thin-walled functionally graded I-shaped cross-section beam focusing on lateral and flexural–torsional buckling problems. Material properties are assumed to be varied through the shell thickness by a non-monotonic function in which volume fractions of constituent phases have been estimated according to a piecewise cubic interpolation. Governing buckling equations, also a finite element method based on Vlasov’s thin-walled theory are developed. Genetic algorithm (GA) is utilized as an optimal tool that preserving the computational efficiency of the overall analysis. N-point volume fraction through-the-thickness, as well as width-to-thickness, span-to-height ratios are simultaneously considered as design variables. The obtained critical buckling parameters are verified via several benchmark problems. Optimum results are found to be beneficial for a specific design of thin-walled functionally graded beams.

Equivalent single layer theories for composite and sandwich structures: A review

ABSTRACT: This article describes one type of plate theories called equivalent single layer theories that are characterized by a single approximation of the displacements through the thickness. This approach is also used for beams and for shells. The presentation focuses on the basic assumptions of the theories to bring out similarities and differences and to organize the existing approaches in a logical manner. Two broad categories are retained. In the first one the displacement field is expressed in terms of polynomials functions of the transverse variables while in the second category, non-polynomial functions are used. In each category, theories
are grouped in terms of the number of unknown variables to be determined. This is a very active research area and it is shown that most theories retain only three, four or five variables even though more terms can be added.

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ABSTRACT: The inverse finite element method (iFEM) is an innovative framework for dynamic tracking of full-field structural displacements and stresses in structures that are instrumented with a network of strain sensors. In this study, an improved iFEM formulation is proposed for displacement and stress monitoring of laminated composite and sandwich plates and shells. The formulation includes the kinematics of Refined Zigzag Theory (RZT) as its baseline. The present iFEM methodology minimizes a weighted-least-squares functional that uses the complete set of strain measures of RZT. The main advantage of the current formulation is that highly accurate through-the-thickness distributions of displacements, strains, and stresses are attainable using an element based on simple C⁰-continuous displacement interpolation functions. Moreover, a relatively small number of strain gauges is required. A three-node inverse-shell element, named i3-RZT, is developed. Two example problems are examined in detail: (1) a simply supported rectangular laminated composite plate and (2) a wedge structure with a hole near one of the clamped ends. The numerical results demonstrate the superior capability and potential applicability of the i3-RZT/iFEM methodology for performing accurate shape and stress sensing of complex composite structures.


ABSTRACT: Functionally graded materials (FGMs) and fluid-conveying nanopipes may find significant applications in nanotechnology. In this paper, the size-dependent free vibration and stability of multi-span viscoelastic FGM nanopipes conveying fluid are investigated by nonlocal elasticity theory. And a hybrid method which combines reverberation-ray matrix method and wave propagation method is developed to determine the natural frequencies. Present analysis is verified by comparing results with those in existing literature. Then, the effects of fluid velocity, nonlocal parameter, volume fraction exponent and internal damping on stability of multi-span FGM nanopipes conveying fluid are discussed. It is found that the stability decreases with the increase of nonlocal parameter and increases with increasing volume fraction exponent. It is also found that distributions of natural frequencies of FGM nanopipes can be modulated by designing the volume fraction exponent.

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ABSTRACT: The vibro-acoustic responses of the laminated composite flat panel in an infinite rigid baffle under the influence of central and eccentric harmonic point excitation are investigated numerically. A general mathematical model of the flat panel is developed in the framework of the higher order shear deformation theory to compute the vibrational properties. The system governing equations are obtained using Hamilton’s principle and discretised through suitable finite element steps. An in-house computer code is developed based on a coupled finite and boundary element formulation in MATLAB environment and employed to compute the associated acoustic radiations from the vibrating plates. Lab scale experiments (modal analysis) are performed to validate the natural frequencies obtained using the present scheme. The proposed formulation is validated for acoustic responses by comparing the present sound power level with the results available in published literature alongside the results obtained using commercial finite element package (ANSYS). The validation study demonstrated the inevitability of the present formulation in predicting the vibro-acoustic response of the layered composite plate. The geometrical parameters (aspect ratio, thickness ratio), composite material properties, laminate scheme and support conditions are found to have significant influence on the vibro-acoustic behaviour of laminated composite flat panel.

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ABSTRACT: The problems of a multi-mode buckling approach which is based on Koiter’s theory of a hybrid column are presented in this paper. An interaction of global buckling modes with the local ones is discussed. There are many different local and global buckling modes. Their selected combinations are dangerous and cause a reduction in the load-carrying capacity. All walls of the hybrid column were plane and made of many layers. The outer layers were thermal barriers and made of a TiC ceramic layer or an AL-TiC-type FGM. The inner layers were composed of aluminium layers and a few carbon-epoxy laminate layers. The classical laminate theory is used to define the ABD matrix which described the relations between applied loads and the associated deformations. The layup configuration of the hybrid column is general, so the coupling submatrix B is non-trivial. This submatrix has a significant impact on the value of local buckling load, whereas its effect on the value of global buckling load can be neglected. The main topic discussed in this paper is whether and how individual elements of the B submatrix can change the load-carrying capacity of a hybrid column. A detailed discussion is conducted for simple supported columns with opened cross-sections subjected to mechanical loads only. Thermal effects are neglected.

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ABSTRACT: Protecting building, critical infrastructure and military vehicles from Improvised Explosive Devices (IEDs) has become a critical task. This study aims to examine the performance of a new protective system utilizing auxetic honeycomb-cored sandwich panels for mitigation of shock loads from close-in and contact detonations of high explosives. Both field blast tests and drop weight tests were performed using the proposed sandwiches as a shield for concrete panels in combination with conventional steel protective plates. The combined shield was found to be effective in protecting reinforced concrete structures against severe impact and close-in blast loadings. The honeycomb core with re-entrant hexagonal cells shows evident auxetic characteristics which contribute substantially to outstanding force mitigation and blast-resistance performances of such sandwich panels. Numerical simulations showed good agreement with the experimental results. The proposed auxetic panels were found to perform better than conventional honeycomb panels of the same size, areal density and material. Both were found to boost the energy absorption of the monolithic steel plate by a factor of 2.5 by changing its deformation pattern under close-in blast loading. In addition, a combination of the steel plate and an auxetic sandwich panel has aeria specific energy absorption (ASEA) higher than either of them, showing great potential for the development of lightweight blast protection of civil, mining, military, nuclear infrastructure and vehicles.

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ABSTRACT: This study presents a size-dependent continuum model for the nonlinear buckling of magneto-electro-elastic (MEE) hybrid nanoshells in thermal environment. The nanocomposite cylindrical shell is composed of a carbon nanotube (CNT), a microtube (MT) and a MEE nanoscale layer which are coupled by polymer or filament matrix. The hybrid nanostructure is subjected to thermo-electro-magnetic loads. The small scale effect is taken into consideration based on the nonlocal elasticity theory. The Pasternak model is used to simulate the normal and shear behavior of the coupling elastic medium. Using the principle of virtual work and von Karman’s strain-displacement relations, the nonlinear governing differential equations are derived. The non-dimensional postbuckling loads of the hybrid nanoshells are obtained using the Galerkin’s approach. The validity of the present model and method of solution is verified by comparing the results with available experimental data and the molecular dynamics simulation results from the literature. It is found that the nonlinear buckling loads of MEE hybrid nanoshells are strongly sensitive to the small scale coefficient. In addition, the non-dimensional buckling loads decrease with increasing the external electric voltage, while the applied magnetic potential has an increasing effects on the critical buckling loads.
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ABSTRACT: In this study, free vibration analysis of smart sandwich plate rested on Winkler-Pasternak foundation is investigated. Sandwich plate is made of electro-rheological (ER) fluid core embedded within two nanocomposite layers which are included ZnO matrix and carbon nanotubes (CNTs) fiber. Due to electrical properties of core and nanocomposite facesheets, the external electric fields are applied to them, separately. The material properties of ER core are determined by Don and Yalcintas models. Also, Eshelby-Mori-Tanaka approach is used to obtain the material properties of nanocomposite facesheets. Hamilton’s principle is utilized to derive the governing equations of motion. Numerical characteristics of the differential quadrature method (DQM) are shown through solving selected ER sandwich plate with CCCC and SSSS boundary conditions, core to facesheets thickness ratios, volume fractions of CNTs, external voltage and Winkler-Pasternak foundation coefficients. The results obtained for ER sandwich plate show that DQM has very good accordance with results of finite element method available in literature. Also, it is observed that increasing the volume fraction of CNTs in facesheets leads to increase the stability of ER sandwich plate. These finding can be employed to design building smart structures and machines.


ABSTRACT: The application of the sampling surfaces (SaS) method to the three-dimensional (3D) stress analysis of laminated composite plates is presented in a companion paper (Kulikov GM, Plotnikova SV. Strong sampling surfaces formulation for laminated composite plates. Compos Struct 2017;172:73–82). In this paper, we extend the strong SaS formulation to the 3D vibration analysis of laminated plates. The SaS formulation is based on choosing the arbitrary number of SaS parallel to the middle surface in order to introduce the displacements of these surfaces as basic plate unknowns. Such choice of unknowns with the use of the Lagrange polynomials in spatial approximations of displacements through the layer thicknesses leads to a robust laminated plate formulation. The feature of the proposed approach is that all SaS are located inside the layers at Chebyshev polynomial nodes. The use of outer surfaces and interfaces is avoided that makes it possible to minimize uniformly the error due to the Lagrange interpolation. Therefore, the strong SaS formulation based on direct integration of equations of motion of the elastic body can be applied efficiently for the 3D free and forced vibration analyses of laminated composite plates.


ABSTRACT: Given the widespread use of FGM shell elements in numerous industrial fields and their extreme vulnerability to crack formation, the present work is directed towards investigating the vibrational behavior of
cracked FGM shells. A general XFEM formulation, with tested accuracy and performance, is presented due to its intrinsic capability to handle problems with discontinuities, such as cracks. To demonstrate the performance of the adopted approach, multiple examples are introduced and analyzed and the effects of various parameters such as the length and angle of the crack and different distribution patterns of material stiffness and density across the thickness of the shell, are extensively studied. Five cracked FGM models, including a rectangular plate, a circular plate with four radial cracks, a cylindrical shell, a conical shell and a spherical dome are simulated by the proposed approach and the results are discussed.

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ABSTRACT: A novel analytical model that accurately represents the free vibration response of intact/damaged composite plates accounting for the bending-torsional coupling is developed. Unlike the existing models for the bending-torsion vibrations of composite plates, in the present model, the equations of motion are derived in an uncoupled form. It is then easier to derive analytical solutions for composite plates under coupled bending-torsion vibrations. In addition, for the first time, analytical solutions for the free bending and torsional vibrations of cantilever and clamped-clamped laminated composite plates with discontinuities including circular holes, rectangular holes, notches, and internal and edge cracks are easily obtained. Shifts in the natural frequencies due to discontinuities are modeled where the reductions in the plate stiffnesses are related to the amount of the energy release rate due to a defect formation. In order to verify the accuracy of the proposed model and the derived solutions, the proposed model is compared to the available conventional models. Moreover, experimental measurements of the free bending and torsional vibrations of carbon-fiber-laminated composite plates with circular holes is performed. A set of finite element analyses are carried out and compared to the experimental and the proposed model results. Then, a parametric study is presented in order to investigate the effects of the discontinuity size and location on the bending and torsional natural frequencies of laminated composite plates with various forms of discontinuities. The performed analyses demonstrate the accuracy of the proposed models to represent the free vibrations of laminated composite plates with discontinuities.

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ABSTRACT: It is well known that the high-order elements have significantly improved the accuracy of solutions in the traditional finite element analysis, but the performance of high-order elements is restricted by the shear-locking and distorted meshes for the plate problems. In this paper, a linear smoothed eight-node Reissner-Mindlin plate element (Q8 plate element) based on the first order shear deformation theory is developed for the static and free vibration analysis of laminated composite plates, the computation of the interior derivatives of shape function and isoparametric mapping can be removed. The strain matrices are modified with a linear smoothing technique by using the divergence theorem between the nodal shape functions and their derivatives in Taylor’s expansion. Moreover, the first order Taylor’s expansion is also employed for the construction of stiffness matrix to satisfy the linear strain distribution. Several numerical examples indicate that the novel Q8 plate element has good performance to alleviate the shear-locking phenomenon and improve the quality of the solutions with distorted meshes.

ABSTRACT: A geometrically exact approach is employed to formulate the equations of motion of thin multi-layered composite shells subject to excitations that cause large strains, displacements, and rotations. Ad hoc truncated kinematic approximations of the obtained semi-intrinsic theory delivers, as a by-product, the kinematics of the Koiter and the Naghdi theories of shells, respectively. Numerical simulations are carried out both for cylindrical and spherical shells: nonlinear equilibrium paths are constructed considering a quasi-static load increase. The comparisons between the results furnished by the geometrically exact theory and those obtained by Koiter and Naghdi theories show the high accuracy of the proposed nonlinear approach. Classical theories become increasingly inaccurate at deflection amplitudes of the order of the shell thickness, evidencing that significant misrepresentations of the system behavior are possible if reduced-order kinematics are taken into account.

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ABSTRACT: In the present paper, the snap buckling of the shallow SMA hybrid composite (SMAHC) cylindrical shells is investigated proposing the new algorithm with regard to the spatial and time variations of martensite volume fraction along the wires. The Crisfield-Ramm arc-length technique is employed to solve the nonlinear finite element formulations via FORTRAN code. In the current study, the spacing of the SMA wires is assumed to be changed gradually across the length and the width of the panel. As the thickness is very small, the volume gradient in the same direction should be tuned with changing of the wire diameters in each lamina. So far, the advantage of grading the SMA wires in all directions has never been cylindrical reported. The effect of the volume fraction of the SMA, type of the composite substrate, pre-tension of wires and the direction of the distribution of SMA wires, on snap instability modification are discussed in details. The results demonstrate the
role of embedding SMA wires on the snap instability modification of shallow laminated shells in terms of increase of the upper limit load and the amount of the dissipated energy during the instability.

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ABSTRACT: Present research aims to analyse the thermal buckling response of composite laminated plates reinforced with graphene sheets. Volume fraction of graphene in each layer may be different which results in a piecewise functionally graded material. All of the thermomechanical properties of the matrix and graphene sheets are assumed to be temperature dependent. A micromechanical approach is used to estimate the thermomechanical properties of the composite media. Using the first order shear deformation plate theory, the strain energy of the plate and the work done by the thermally induced prebuckling forces are obtained. Afterwards, a non-uniform rational B-spline (NURBS) based isogeometric finite element method is used to study the thermal buckling response of the graphene reinforced composite plates. A detailed study is provided to investigate the effects of boundary conditions, functionally graded pattern, aspect ratio and side to thickness ratio of the plate.

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ABSTRACT: This study focuses on the effect of temperature on the mechanical behavior of closed-cell aluminum-alloy foam filled tubes (FFTs) under quasi-static compressive loads. The results of the compressive testing indicated that at each tested temperature the closed-cell aluminum foam improves the mechanical properties of the empty steel tubes. This behavior is related to the interaction effect between the aluminum foam as filler material and the empty tubes. Also, it was observed that the deformation mechanism of FFTs at all tested temperatures is axisymmetric concertina mode with formation of two folds. Due to the softening phenomenon of the steel tube matrix with increasing of temperature the distribution and size of propagated micro-cracks on both loading surfaces and peripheral folds decreased significantly from the order of millimeters up to micrometers. Finally, it was observed that the increasing of the working temperature reduces the ability FFTs to absorb energy during compression test.

ABSTRACT: In the paper, the dynamic stiffness method based on the HSDT and FSDT plate theories is applied to study free vibration characteristics of composite stiffened and cracked plate assemblies. The dynamic
stiffness matrices for transverse vibration of laminated composite plate based on the HSDT and FSDT previously derived by authors have been coupled with the dynamic stiffness matrix of laminated composite plate undergoing in-plane vibration. The numerical analysis has been carried out through several illustrative examples in order to check the applicability and accuracy of the proposed method in the free vibration analysis of stiffened plate assemblies. The effects of transverse shear deformation, boundary conditions, side-to-thickness ratios, crack length or reinforcement amount within the GFRP beam on the free vibration characteristics have been discussed, and the variety of new results has been provided as a benchmark for future investigations.

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ABSTRACT: Dynamic response of sandwich structures subjected to in-plane axial impact loading is investigated experimentally and numerically. A comprehensive set of impact test results on sandwich panels with various configurations is presented. Experimental observation is made using high-speed cameras to closely examine the detailed temporal responses of the sandwich columns before the collapse of the entire structures. It is found that the failure mode is significantly affected by the core thickness. Finite-element based simulation is also performed to have a better understanding of the failure mechanism. Discrete cohesive zone model (DCZM) is utilized to model delamination failure at the interface between the skins and core. The interfacial failure is driven by dynamic buckling of the skin, competing against the bonding strength at the interface.

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ABSTRACT: A large deflection geometrically nonlinear analysis of functionally graded (FG) multilayer graphene platelet-reinforced polymer composite (GPL-RPC) rectangular plates subjected to uniform and sinusoidal transverse mechanical loadings is performed in this article. Based on the sinusoidal shear deformation plate theory and von Kármán nonlinear strain-displacement relations, the nonlinear governing equilibrium equations and boundary conditions are developed by using the principle of virtual work. It is assumed that the weight fraction of GPL nanofillers layer-wisely changes across the thickness of plate. The effective Young’s modulus of FG-GPL-RPCs is approximately calculated via the modified Halpin-Tsai model. Also, the effective Poisson’s ratio and mass density are determined by employing the rule of mixture. The investigation is performed by using a numerical solution approach. To evaluate the nonlinear bending stiffness of FG multilayer GPL-RPC plate, the discretization of governing equations and boundary conditions is carried out using the generalized differential quadrature (GDQ) method, and the pseudo arc-length continuation technique is employed to solve the set of nonlinear algebraic discretized equations to obtain the load-deflection curve. Numerical problems are given to reveal the influences of GPL distribution pattern, weight fraction,
geometry of GPL nanofillers, length-to-thickness and edge conditions on nonlinear bending responses of the GPL-RPC plates.

Zhan Zhao, Chuang Feng, Yu Wang and Jie Yang (School of Engineering, RMIT University, PO Box 71, Bundoora, VIC 3083, Australia), “Bending and vibration analysis of functionally graded trapezoidal nanocomposite plates reinforced with graphene nanoplatelets (GPLs)”. Composite Structures, Vol. 180, pp 799-808, November 2017, https://doi.org/10.1016/j.compstruct.2017.08.044

ABSTRACT: This paper investigates the bending and vibration behaviors of a novel class of functionally graded trapezoidal plates reinforced with graphene nanoplatelets (GPLs) by employing the finite element method. Modified Halpin-Tsai model and the rule of mixture are used to determine the effective material properties including Young’s modulus, mass density and Poisson’s ratio of the nanocomposites. A comprehensive parametric study is conducted to examine the effects of the distribution, concentration and dimension of GPL and the plate geometry on the static and dynamic behaviors of GPL reinforced functionally graded trapezoidal plates. The results demonstrate that adding a small amount of GPLs as reinforcing nanofillers can significantly enhance the stiffness of the plate and the most effective reinforcing effect can be achieved by distributing more GPLs with a larger surface area near the top and bottom surfaces of the plate. Also, the bending and vibration behaviors of trapezoidal plates with such a distribution pattern are more sensitive to the GPL weight fraction and plate geometry compared to the other distribution patterns. Moreover, it is found that the static and dynamic deflections of the plate tend to be lower as either of the two base angles becomes smaller.


ABSTRACT: Variable stiffness composites, where fibre angles are spatially varied by steering the tows in curvilinear paths to optimise the structural response, have been a subject of intensive study. In this paper, experimental validation of the variable stiffness composite technology is carried out for a panel representing a wing lower-skin with a large access hole designed against material failure. An idealised flat panel with a large cut-out under tension or combined tension and shear is modeled using finite elements. In addition to a quasi-isotropic laminate, constant stiffness and variable stiffness laminates are designed to maximise the failure load using a multi-step optimisation framework. Three panels, one for each type of laminate, are built from thermoset prepreg material using automated fibre placement. All three panels are tested in pure tension. The failure loads, failure modes and weights of the tested panels are compared. The results indicate that the variable stiffness laminate is capable of sustaining significantly larger loads, before failure, than the constant stiffness and quasi-isotropic laminates of equal weight.

ABSTRACT: An analytical method is presented in this paper to solve the energy absorption capacity of composite reinforced metal hemispherical shells undergoing axial compression. Here, finite element method is also applied to simulate the collapse process, employing the software ABAQUS, to verify the feasibility of the analytical model. The effects of composite layer (viz. fiber layer thickness proportions and fiber reinforced orientation), loading velocity and geometric parameter of hemispherical shells (R/t) are described and investigated in examples respectively.

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ABSTRACT: In this paper, an analysis method for the determination of displacement, strain and stress fields in cylindrically curved cross-ply laminates under bending load is presented. The considered cross-ply laminates may be either symmetrically or unsymmetrically laminated and are clamped at one end while the other end is loaded by an evenly distributed bending moment. The analysis method employs a layerwise plane strain approach in the inner regions of the laminate in which the stresses in each layer are represented by adequate formulations for Airy’s stress function. In the regions of the free laminate edges where significant three-dimensional and possibly singular interlaminar stress fields are to be expected, the plane-strain approach is upgraded by a layerwise displacement-based formulation wherein the physical laminate layers are discretized into a number of mathematical layers with respect to the thickness direction. The governing differential equations for the unknown additional displacement functions with respect to the width coordinate in the form of the Euler-Lagrange equations stemming from the underlying variational statement can be solved exactly and eventually lead to an eigenvalue problem that needs to be solved numerically. Usage of continuity conditions between the individual laminate layers and formulation of adequate boundary conditions at the free edges in an integral sense then lead to complete representations for displacements, strains and stresses at every location in the considered laminate. While the analysis approach relies on a discretization of the laminate into a number of mathematical layers with respect to the thickness direction and further requires a numerical solution of a quadratic eigenvalue problem, it provides closed-form analytical solutions concerning the width direction and can thus be classified as being a semi-analytical solution. The presented analysis method is compared to the results of comparative finite element simulations and is shown to be in good agreement, however with only a fraction of the computational effort that is required for according finite element simulations.

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ABSTRACT: This study consists of a numerical investigation on the nonlinear flutter oscillations of composite panels on multiple supports (multibay panels) in high supersonic flow. In contrast to what is done in the majority of studies, direct time-domain integration is used here instead of linearized updated mode approximations or modal decomposition techniques. The main goal is to study the interaction between adjacent bays in the nonlinear regime in order to identify aeroelastic phenomena that are not predicted by the usual single-panel approach. Multiple lamination schemes and multibay arrangements are considered, and new important results have been found. In nearly all cases simulated, severe jump discontinuities have been detected in the limit cycle oscillation amplitudes when the dynamic pressure reaches certain values. Such jumps, observed here for the first time, occur due to the nonlinear coupling between neighboring bays and consist of very abrupt amplitude elevations that happen when there are inversions in the motion phase of one or more bays. Furthermore, this study has been able to show that single-panel analysis may be unsafe for structural design as it drastically underestimates the maximum displacements of the bays located in rear (downwind) positions.

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ABSTRACT: Wind Loads are one of the main loads causing the instability of the ground-based radome. Due to the existence of joints and riveting solid and other non-integer defects, traditional mosaic structure of the radome affects the radome strength, stiffness and electromagnetic properties. Based on the research results of buckling behavior of CFRP meshed shell radome, the overall stressed-skin structure radome is further proposed. In order to study the deformation and stress performance under WL and to use the method of theoretical analysis and experiment simulation, ANSYS and MATLAB are used to analyze the braided angle of 90° and 60° of stress, strain performance and wind pressure of the radome, the turbulence law of wind speed under the condition of wind angle of 45° from Grade 1, 3 to 17 of wind loads. The results show that stress and strain of the two-kind radomes change as WL change and the change rate is close. The largest difference of wind pressure and wind speed between the two kinds of radomes is about 11.54%, which can provide reference for the design of wind load stability of the structure-function integral radome in actual engineering.

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ABSTRACT: A novel anti-icing/de-icing system composed of bi-stable laminate composite structures with superhydrophobic surface and soft electrothermal patch is investigated in this paper. In this system, the superhydrophobic surface has superior performance in anti-icing and de-icing by reducing the adhesion of the ice-skin interface; meanwhile, a thermo-mechanical way to remove ice is conducted by deforming the bi-stable
structures using heating actuation method. The superhydrophobic layer is fabricated by decreasing the free energy of copper oxide on the copper surface. The water contact angle of the superhydrophobic surface is tested by an optical contact angle measuring device, which reaches above 155° and the sliding angle is less than 10°. In addition, the microstructure of superhydrophobic layer is characterized by using a scanning electron microscope (SEM) to illustrate the superhydrophobic mechanism. Moreover, outstanding self-cleaning properties and UV-durability are obtained on the prepared surface. Experimental results indicate that the system has good performances in both anti-icing and de-icing processes when working at the subzero temperature. Meanwhile, there is no liquid water left on the surface after the snap-through process of bi-stable structures. Besides, the factors that affect the anti-icing and de-icing performance of system are discussed, including the superhydrophobic property, morphing characteristic of bi-stable laminate composite structures and actuating method. Finally, the finite element method is used to simulate the factors that affect the deformation of bi-stable structures independently, including the single layer thickness, stacking sequence of the laminate and the embedment of the electrothermal alloy.

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“Effect of temperature on aeroelastic behavior of stiffened composite laminated panel with embedded SMA wire using the hierarchical Rayleigh-Ritz method”, Composite Structures, Vol. 181, pp 26-45, December 2017,
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ABSTRACT: This work investigates the effects of temperature in the shape memory alloy hybrid composites (SMAHC) cylindrical stiffened panels’ aeroelastic stability. The SMAHC is modelled using a micromechanical formulation embedding carbon fiber, SMA wire and resin to the same lamina and taking into account the martensite/austenite phases of transformation in the material response. Virtual work principle formulation is implemented with classical laminate plate theory (CLPT) panel formulation and one-dimensional Euler-Bernoulli beam theory formulation for the stiffener. Numerical results are obtained by using an energy based semi-analytical method applying hierarchical polynomials to approximate the membrane and out of plane displacement fields. Different geometric configurations, laminate stacking sequences, boundary conditions and radii of curvature are investigated. The study shows that the variation of temperature induce stiffening due to changes in the martensite/austenite fractions of the SMA, increasing the critical flutter dynamic pressure. Therefore, it can be achieved certain control in the flutter critical boundary by increasing the temperature of the shape memory alloy (SMA) wire. The effects due to the SMA wire stiffening with the temperature are more pronounced for cross-ply stiffened cylindrical panels with unitary aspect ratio and for angle-ply panels with aspect ratio higher than one.

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“Third order theory based quadrilateral element for delaminated composite plates with a hybrid method for satisfying continuity at delamination fronts”, Composite Structures, Vol. 181, pp 84-95, December 2017,
https://doi.org/10.1016/j.compstruct.2017.08.074
ABSTRACT: We present a four-node quadrilateral element based on the third order theory for analysis of composite plates with multiple delaminations, by employing a novel hybrid method for satisfying the continuity conditions at the delaminated fronts. In this method, the continuity of inplane displacement variables is satisfied by directly satisfying them at the midplanes of the sublaminates separated by delaminations, and employing the least squares method with respect to the shear rotation variables. The element is shown to yield very good accuracy in general, in comparison with experimental and three dimensional finite element (FE) solutions, and yield superior results to the other available analytical and FE solutions for static and free vibration responses of delaminated composite beams, and rectangular and skew composite plates under different boundary conditions. It is seen that the results from the existing continuity methods can have large error for thick beams/plates and for higher vibration modes, while the proposed hybrid method is generally very accurate and much superior to the existing methods.

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ABSTRACT: To give a precise prediction of piezolaminated smart structures under strong electric field resulting in large displacements and rotations, the paper develops various geometrically nonlinear models with taking into account the electroelastic material nonlinear effect. The present nonlinear FE formulations are derived based on the first-order shear deformation theory (FSDT) with taking into account various geometric nonlinearities, which include von Kármán type nonlinearity, moderate rotation nonlinearity, and large rotation nonlinearity. The constitutive equations with consideration of piezoelectric material nonlinearity are integrated into the present FE formulations. The proposed nonlinear FE models are first validated by experimental and numerical examples in the literature, and later on implemented into numerical analysis for piezolaminated smart plates and shells with applied strong electric field.

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ABSTRACT: The paper presents a simplified model of damage of composite plates (SDM) subjected to low-velocity impact testing. The damage model assumes reduced thickness of laminate plies versus impact energy.
The decrease in strength of the lay-up was measured by Compression-After-Impact (CAI) tests. The numerical analysis was performed on composite plates made of CFRP laminate subjected to uniform compression, with represented regions of damage caused by different impact energies. The numerical results show the behaviour of the laminate during compression, taking into account the damage process evaluated by a progressive damage criterion. The numerical analysis was performed using the ABAQUS programme. The results were verified based on experimental findings reported in the literature and the numerical results of the tested composite plates subjected to CAI testing.

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ABSTRACT: As an excellent heat-resistant material with broad potential application, the mechanical behavior of functionally graded material (FGM) is of research focus in many fields. However, the thermal buckling behavior of FGM thin-walled shell has been widely investigated, but little work was done for the cylindrical shell with FGM coating due to more complex material distribution and mathematical expressions. Therefore, the present work mainly carried out the theoretical derivation and buckling behavior analysis for a cylindrical shell with FGM coating subjected to a thermal load. The results show that the theoretical solution of the critical buckling temperature rise is in good agreement with the developed numerical approach. In addition, an empirical engineering formula of the critical buckling temperature rise with a more concise mathematical expression is proposed for solving this practical complex engineering application based on the significant amount of numerical calculation and theoretical analysis.

ALSO SEE:
Zewu Wang, Quanfeng Han, David H. Nash and Hongxin You, “Thermal buckling analysis for IMPERFECT cylindrical shell with functionally graded material coating”, (publisher and date not given in the pdf file)

ABSTRACT: The shell with functionally graded material (FGM) coating is a novel high temperature resistant structure, which has been increasingly applied in the aerospace, nuclear, turbo machinery and other engineering fields. However, there are some defects for practical structure due to the limitation of manufacturing technique. But relevant theoretical research on the thermal buckling behavior of the imperfect cylindrical shell is rather limited in most open literature. Therefore, this work proposed to establish the theoretical solution of the critical buckling temperature rise of the cylindrical shell with an axisymmetric imperfect and FGM coating based on the Donnell shell theory, Koiter model and Galerkin method. The result shows that the theoretical solution is in exact agreement with the literature. In addition, the influences of the profile of the axisymmetric imperfection, the volume fraction of the ceramic phase and the types of the thermal loading on the thermal buckling behavior of the imperfect cylindrical shell with FGM coating are analyzed comprehensively. The study provides a scientific solution and better understanding for the thermal buckling problem of the imperfect cylindrical shell with FGM coating.

References listed at the end of the paper:


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ABSTRACT: In this paper, post-buckling behavior of geometrically imperfect porous beams reinforced with graphene platelets (GPLs) and resting on nonlinear hardening foundation is investigated. GPLs are uniformly and non-uniformly distributed throughout the thickness direction. Different porosity distributions called uniform, symmetric and asymmetric are considered. The elastic properties of the nanocomposite are obtained by employing Halpin-Tsai micromechanics model. The present refined beam model satisfies the shear deformation effect needed of any shear correction factor. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin’s method needed of any iteration process. New results show the importance of porosity coefficient, porosity distribution, GPL distribution, GPL weight fraction, geometrical imperfection and foundation parameters on nonlinear buckling behavior of porous beams. Specially, porosities and GPL reinforcement have a great impact on post-buckling configuration of both ideal and imperfect nanocomposite beams.

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“Buckling optimization of variable-stiffness composite panels based on flow field function”, Composite Structures, Vol. 181, pp 240-255, December 2017, [https://doi.org/10.1016/j.compstruct.2017.08.081](https://doi.org/10.1016/j.compstruct.2017.08.081)

ABSTRACT: Due to the non-uniform in-plane stress distribution, variable-stiffness panel with curvilinear fiber paths is a promising structural concept for cutout reinforcement of composite structures under axial compression, due to the more diverse tailorability opportunities than simply choosing the best straight stacking sequence. However, traditional representation methods of curvilinear fiber path are usually not flexible for cutout reinforcement. In this study, the flow field function containing a uniform field and several vortex fields is utilized to represent the fiber path due to its inherent non-intersect and orthotropic features, and a bi-level optimization framework of variable-stiffness panels considering manufacturing constraints is then proposed. A typical rectangular composite panel with multiple cutouts is established to demonstrate the advantage of proposed framework by comparison with other fiber path functions. Results indicate that the flow fiber path only needs few variables to finely represent the fiber path, which can provide satisfying and manufacturable fiber paths by combination use of curvature constraint.

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ABSTRACT: This paper presents the results of an experimental program investigating flexural creep and creep buckling behavior of pultruded glass fiber reinforce polymer (pGFRP) plate specimens. In this study (a) short-term material properties were determined; (b) 1000 h flexural creep tests at three load levels were conducted from which Findley power law parameters describing creep strain behavior were obtained; (c) creep buckling tests of slender concentrically loaded specimens were conducted; and (d) results from the buckling tests were compared with the predictions of the Findley power law which is shown to predict results reasonably well. Provided the flexural creep tests have relatively small loads and sufficient duration to pass through the primary creep stage of the material, reliable creep parameters were established. The intent of this study is to demonstrate a framework for establishing creep behavior and creep buckling performance of pGFRP materials.

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ABSTRACT: The structural beams with a uniform cross section of hat-shape were manufactured through a high-cycle compression molding technique, by using randomly oriented chopped thermoplastic composites. The crash tubes were obtained by vibration welding of those two hat-section beams at their flanges. And the axial
compressive impact tests were carried out for them. It followed that the compressive failure was progressive crushing caused by the delamination and local buckling of walls and welded flange while the specific energy absorption was so high. The finite element model was constructed to predict the axial progressive crushing and energy absorption. The important key concept for designing the numerical model was to incorporate some hypothetical inter-layers even in randomly oriented composites and assign them with the failure model as cohesive zone elements, which can perform non-linear characteristics with failure criterion. The material parameters for the model tried to be obtained by direct measurement test methods. The reproducibility of the numerical modeling was validated against the results from axial compressive crushing. The progressive damage mode and energy absorption prediction agreed well with the experimental results. It was also clarified that the out-of-plane failure influenced the energy absorption performance of the crush tubes.

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ABSTRACT: Some Lamb waves in a plate and some circumferential waves in a one-layer cylinder are characterized by the resonance frequencies where the group velocity is vanishing while the phase velocity remains finite. This paper investigates on the existence of these special waves which call zero group velocity waves (ZGV waves) in the case of the copper/polymer composite cylindrical shell immersed in water and filled with air. The acoustic scattering of a plane wave from this composite cylindrical shell is analyzed in the reduced frequency range (0.1 <k1a1<200; k1 is the wave number and a1 is the outer radius of the composite cylindrical shell). The study of the respective influence of the inner layer thickness (polymer) and the outer layer thickness (copper) shows that the existence of these waves is a function of these thicknesses. Moreover, this study depicts that the dispersion curves of the considered bilayer shell tend towards the dispersion curves of the one-layer cylindrical shell made from the material of the thicker layer of the bi-layer cylindrical shell (polymer or copper). The time-frequency representation of smoothed pseudo Wigner-Ville (SPWV) is used to extract some properties of the circumferential waves propagating in and around the bi-layer cylindrical shell. The obtained results by this representation are in good agreement with those obtained by the theoretical approach.


ABSTRACT: Free vibration of laminated viscoelastic composite plates on Pasternak viscoelastic medium with simply supported edge conditions is investigated. The composite plate consists of linear viscoelastic polymeric matrix reinforced by transversely isotropic elastic fibers. Multi-cell micromechanical approach together with relaxation functions of bulk/shear moduli and Boltzmann superposition principle are adopted to establish time-dependent stiffness coefficients of laminates. The coupled integro-PDEs of motions are derived based on third-order shear deformation theory by Laplace transformation and Hamilton principle. Complex frequencies and
closed form solutions for transient response are achieved by weighted residual method, iterative numerical algorithm and Fourier transform. To verify, the results are compared for thick elastic composite plates on Pasternak elastic foundation and thick viscoelastic composite sandwich plates without foundation that represent acceptable accuracy. By parametric study, effects of materials, lamination scheme, geometry and medium on dynamic characteristics are scrutinized.


ABSTRACT: Static behavior of thin-walled laminated composite closed cross-section beams having variable stiffness is investigated in this study. The analytical model used accounts for flexural–torsional coupling and warping effects as well as the variable stiffness along the contour of the cross-section of the beam. The variable stiffness is acquired by constructing the laminates with curvilinear fibres having certain specific paths. The orientation of fibres varies by depending on the fibre path along the contour of the cross-section in each layer. Equilibrium equations are derived by use of minimum potential energy principle. Although the formulation given can be applied to any shape of the closed cross-section with straight or curved edges, preliminary numerical results are presented only for box-beams. A displacement based finite element method is developed to solve the analytical model and to predict displacements and rotations under the effect of different types of loading conditions. Numerical results are obtained for different fibre paths and lay-up configurations and compared with the available solutions in the literature also with the results of a finite element analysis software using shell element.

Mohammad Reza Barati (1) and Ashraf M. Zenkour (2,3) (1) Aerospace Engineering Department & Center of Excellence in Computational Aerospace, AmirKabir University of Technology, Tehran, Iran (2) Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia (3) Department of Mathematics, Faculty of Science, Kafrelsheikh University, Kafr El-Sheikh 33516, Egypt “Investigation on post-buckling of geometrically imperfect metal foam nanobeams with symmetric and asymmetric porosity distributions”, Composite Structures, Vol. 182, pp 91-98, December 2017, https://doi.org/10.1016/j.compstruct.2017.09.008

ABSTRACT: In this research, analysis of post-buckling behavior of porous metal foam nanobeams is performed based on a nonlocal nonlinear refined shear deformation beam model with geometric nonlinearity and imperfection. In the metal foam nanobeam, porosities are dispersed by uniform, symmetric and asymmetric models. The present nanobeam model satisfies the shear deformation effect needless of any shear correction factor. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin’s method needless of any iteration process. New results show the importance of porosity coefficient, porosity distribution, geometrical imperfection, nonlocal parameter, foundation parameters and slenderness ratio on nonlinear buckling behavior of porous nanoscale beams. Specially, porosities have a great impact on post-buckling configuration of both ideal and imperfect nanobeams.

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ABSTRACT: Low velocity impact responses of a newly developed sandwich panel with aluminium foam core and fibre metal laminate (FML) skins, comprised of aluminium sheets and plain woven E glass fibres, are investigated in this paper. Drop weight impact tests were conducted and the effect of the thickness of foam core and FML skin on the impact response of the panels was investigated via the experimental study. A finite element model is also developed and validated against the experiments to prove the effectiveness and accuracy for analyzing the impact responses of the sandwich panels under low-velocity impact. The research findings are summarized and concluded finally.


ABSTRACT: This work explores the relationship between different failure mechanisms and compression after impact (CAI) strength through an advanced finite element analysis. A Continuum Damage Mechanics (CDM) approach is used to model intra-laminar failure and Cohesive Zone Modelling (CZM) for inter-laminar failure. The FE progressive failure analysis is performed in two consecutive steps. The first is a low-velocity impact analysis in which the induced damage maps are obtained. In the second step, the boundary conditions are modified and an analysis of CAI is performed. The effect of change in ply layup sequence, sub-laminate scaling and ply blocking are investigated and a link between failure and CAI strength is established. Results suggest that changes in ply layup sequence affect delamination sizes, positions and shapes during impact, which in turn result in either global or sub-laminate buckling failure during compression. A global buckling mode results in higher CAI strength compared to failure by sub-laminate buckling for quasi-isotropic laminates of the same thickness. Ply-blocking increases tendency towards delamination, causing a decrease in CAI strength. Sub-laminate scaling causes a transition in failure mode from out-of-plane buckling to in-plane compressive fiber failure. These results suggest a strong correlation between failure mechanism and CAI strength.


ABSTRACT: In this work, explicit equations to determine local buckling critical stress of thin-walled fiber reinforced polymer (FRP) profiles in pure bending or compression are proposed. Interaction between flange and web is considered and the expressions allow for different orthotropy ratios and ranges of flange-to-web widths and thicknesses. To obtain the equations, Rayleigh Quotient energy method is adopted for assumed approximate buckled shapes. As quality of selected functions affects the accuracy, different shapes are investigated and the results are compared with those obtained with Generalized Beam Theory (GBT) for typical I-section
dimensions and material properties. A comparison is made to the solutions based on discrete plate with simplified support conditions as well as to a recently proposed equation for major-axis bending. Finally, a general form for the local buckling critical coefficient is also presented along with tabulated parameters for prompt assessment of critical stresses, consisting in a simple and reliable alternative for design approach.

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“Low velocity impact performance investigation on square hollow glass columns via full-scale experiments and finite element analyses”, Composite Structures, Vol. 182, pp 311-325, December 2017,
https://doi.org/10.1016/j.compstruct.2017.09.055
ABSTRACT: Taking advantage of two full-scale experimental tests carried out on square hollow glass columns under low velocity impacts, the paper aims to further assess via Finite Element models the structural performance of such structural systems. In them, the resisting cross-section consists of four adhesively bonded laminated glass panes. Adhesive joints are also used for the connection between glass columns and top/bottom restraints. As a result, careful consideration in the analysis and design of these innovative systems is required, to guarantee appropriate fail-safe design principles for a typically tensile brittle material, as well as to account for possible accidental or exceptional loading conditions. Simplified but computationally efficient FE models are validated in the paper towards the available full-scale test results. Key aspects in the observed overall performances under low velocity impact are then emphasized, with careful consideration for several loading configurations, including variations in the release distance for the impacting mass as well as in the type of impact (hard/soft body). In conclusion, a FE sensitivity analysis is also carried out, giving preliminary evidence of the effects of some main input parameters on the overall performance of the examined systems, including possible localized damage in glass, as well as geometrical and mechanical features in the column restraints.

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“Vibration analysis of the functionally graded carbon nanotube reinforced composite shallow shells with arbitrary boundary conditions”, Composite Structures, Vol. 182, pp 364-379, December 2017,
https://doi.org/10.1016/j.compstruct.2017.09.043
ABSTRACT: The aim of this paper is to firstly present the free vibration analysis of functionally graded carbon nanotube reinforced composite (FG-CNTRC) shallow shells with arbitrary boundary conditions. The first-order shear deformation theory and the artificial spring boundary technique are introduced to achieve the general theoretical modeling and arbitrary boundary conditions, respectively. Then according to the energy variational principle, the energy expression of the FG-CNTRC shallow shells is obtained. Furthermore, the admissible displacement functions of the FG-CNTRC shallow shells are chosen as an improved Fourier series which combines the standard double cosine Fourier series and several auxiliary functions which are introduced to remove any potential discontinuity of the displacement function and its derivatives at the edges. In the current framework, the vibration analysis of the FG-CNTRC shallow shells with arbitrary boundary conditions can be
conducted by a unified model, and the calculation core code derived from the MATLAB software does not need changing while the boundary conditions or geometric parameters change. The good accuracy, reliability and efficiency of the current approach are validated by several numerical examples. Simultaneously, a comprehensive parametric investigation concerning the effects of elastic restraint parameters, shear deformation and rotary inertia, shallowness and material properties is performed.

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ABSTRACT: Due to its tailorability intrinsic characteristics, composite materials are an effective option in structural design or on its reengineering, especially when the ratios stiffness and/or strength to weight are relevant. Dual-phase or multiphase fibre reinforced composites can thus be found in many engineering and science applications. However, in the majority of the cases these composites are made from unidirectional plies stacking. The possibility of building fibre reinforced composite structures, wherein these fibres follow curvilinear paths, may be an important enhancement to structural mechanical response and in particular to its dynamic stability, as variable fibre orientation is responsible for variable elastic stiffness within a generic layer. This work aims characterizing the dynamic instability response of variable stiffness composite plates, according to different material and geometrical parameters. To this purpose one considers Rayleigh-Ritz method to perform buckling, free vibrations and dynamic instability analyses, using orthogonal polynomials. The dynamic instability problem is solved considering Bolotin’s method. A set of verification and illustrative case studies is considered and discussed.

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ABSTRACT: This paper presents an investigation on the nonlinear vibration behavior of graphene-reinforced composite (GRC) laminated cylindrical shells in thermal environments. The material properties of the GRCs are temperature-dependent and the functionally graded (FG) materials concept is adopted which allows a piecewise variation of the volume fraction of graphene reinforcement in the thickness direction of the shell. An extended Halpin-Tsaia micromechanical model is employed to estimate the GRC material properties. The motion equations for the nonlinear vibration of FG-GRC laminated cylindrical shells are based on the Reddy’s third order shear deformation theory and the von Kármán-type kinematic nonlinearity, and the effects of thermal

ABSTRACT: Elastostatics of laminated and functionally graded (FG) sandwich open cylindrical shells is studied using a refined higher order shear and normal deformation theory. Displacement based approach with twelve middle surface displacement parameters representing bending and membrane response of cylindrical shell is considered. An extended thickness criterion, \((h/R)^2 \ll 1\), is used to make the present theory more reliable over large range of thickness ratios of shell. Basic equations are obtained using minimum potential energy principle and solved subsequently with Navier solution method for cylindrical shells with all edges diaphragm supported. Two kinds of FG sandwich panels are considered having FG layer with Voigt’s rule of mixture following power law gradation of volume fraction. Results show an excellent accuracy with the three dimensional results available in literature for laminated shells. Also, superiority of present formulation over other higher order theories is shown by carrying out a number of comparative studies.
ABSTRACT: Nomex honeycomb has very low relative density, thus there is a lot of the air entrapped within the cells of Nomex honeycomb sandwich structures. The air has a significant effect on the mechanical response under flatwise compression, and it was investigated herein. Firstly, experiments of the honeycomb with and without facesheets were performed to study the entrapped air effect. Secondly, the unit cell model and multi-cell model of the honeycomb were proposed, in which, two methods of modeling the entrapped air using commercial software LS-DYNA were developed. In the first method, six cell walls and two facesheets as well as the air entrapped by them are simulated as an air-filled cavity using Airbag tools. In the second method, the entrapped air is simulated by ALE (Arbitrary Lagrangian Eulerian) elements, which realize the grid deformation and material flow. Interaction between the entrapped air and cell walls under compression is analyzed using fluid-structure coupling algorithm. It is found in this paper that energy absorption capacity of Nomex honeycomb sandwich can be enhanced through the effect of the entrapped air on the cell walls folding process. The ALE method is superior to the airbag method in the unit cell models as regard to the energy absorption capacity and the energy absorbing process.


ABSTRACT: In this paper, a pseudo spectral approach based on Legendre Basis Functions (LBF) is developed for geometrically nonlinear analysis of laminated composite plates with and without geometric imperfections. Both classical plate theory (CPT) and first-order shear deformation plate theory (FSDT) are investigated and the field variable shape functions are constructed using Point Interpolation Method (PIM). Boundary conditions are enforced easily and directly on each boundary nodes. Due to sharp fluctuations at the boundaries and the occurrence of Runge’s phenomenon in the case of the uniform points, in the present study the domain is discretized with Legendre-Gauss-Lobatto nodes. The system of equations is introduced by discretizing the von-Karman’s equilibrium equations and also boundary conditions with finite Legendre basis functions that are substituted into the displacement fields. The nonlinear system of equations is solved by using the Newton-Raphson technique, and since the number of equations is always more than the number of unknown parameters, the least squares technique is used. Some examples involving various boundary conditions and initial imperfections are solved to demonstrate the validity and capability of the proposed method.


ABSTRACT: Free vibration analysis of curved structural components such as truncated conical shells, circular cylindrical shells and annular plates has been investigated numerically in this paper. The method of discrete
singular convolution (DSC) and the method differential quadrature (DQ) are used for numerical simulations, respectively. Related partial differential equations governed the motion of the structures obtained from higher-order shear deformation theory have been solved by using these two methods in the space domain. Different material properties have been considered such as isotropic, laminated and functionally graded material (FGM). Four-parameter power law and simple power law distributions have been used for ceramic volume fraction in FGM cases. The numerical results related to free vibration of conical shells have obtained by the present two techniques compare well with the results available in the literature. Results for circular cylindrical shells and annular plates have also been presented for different geometric and material parameters. The effects of grid number and types of the grid distribution have also been investigated for annular plate and shells.

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ABSTRACT: The study is devoted to thin-walled simply supported sandwich beams: three and seven-layer beams. Seven-layer beams are composed of a trapezoidally crosswise corrugated main core and two three-layer facings with trapezoidally lengthwise corrugated cores. Essential difference between such a structure and classical three-layer beams consists in the fact that the facings are of three-layer structure too. Hence, the structure is a seven-layer beam, the layers of which are distinguished by different properties. The thin-walled beam with three trapezoidally corrugated cores is an innovatory orthotropic structure, not referred to in the literature. Characteristic feature of the beam consists in differentiation of shear effects in particular layers, according to the core corrugation direction. Deformation of the cross section of the beam depends on the direction too. An original mathematical model is formulated, which includes the hypothesis of deformation of the cross section of the beam, inclusive of the displacement and strain fields, and rigidities of the layers in particular directions. The adequate model of three-layer beam with steel foam core is also formulated. Basing on the principle of the total potential energy the equations of equilibrium are derived for three and seven-layer beams, respectively. Then the equations are analytically solved. In case of seven-layer beams the deflections and the critical axial force are determined for different values of the trapezoidal corrugation pitch of the main core. The results are compared with adequate for three-layer beam and presented in Tables. It is concluded that such seven-layer beam – plate band with three-layered facings is more resistant to the load than the classical three-layered beams of the same mass with regard to strength and stability. Additional effect of the research consists in generalization of classical theories of sandwich plates.

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ABSTRACT: This work investigates the effects of composite materials and non-structural masses on the dynamic behavior of space structure components and whole space vehicle. A refined one-dimensional model has been used in the analyses, and the effects of composite materials and of the fuel mass introduced as non-structural masses have been considered. The adopted refined one-dimensional Finite Element Model has been developed using the Carrera Unified Formulation. This numerical tool allows to develop a variable kinematic displacement field over the beam cross-section, that is, a set of Lagrange (LE) expansions polynomials was adopted for the cross-sectional displacement field approximation. The use of such one-dimensional models
leads to the so-called component-wise (CW) approach in which stiffeners and plate are modeled using the same one-dimensional kinematic. Static and free vibration analysis of space structural components and complete space structures have been performed. Both compact and thin-walled structural configurations have been considered. The results have been assessed using analytical solutions or refined three-dimensional Finite Element Models. Composite materials and non-structural masses, e.g. the fuel mass or payload, have been included in the analysis. The results show the capability of the present model to provide a quasi three-dimensional solution with a low computational cost. The refined kinematic allows composite materials to be investigated accurately.

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ABSTRACT: This paper presents some solutions for mechanical responses of angle-ply laminated plates under transverse distributed loads, which are obtained by using refined finite element models adopting variable kinematics based on Carrera’s Unified Formulation (CUF). Plates with several types of stacking sequence under different boundary conditions are considered. Layer-wise (LW) models based on Chebyshev polynomials (first kind) and Equivalent Single Layer (ESL) models based on Trigonometric series are used in the analysis. To compare the performances of different displacement-based kinematic models, a set of simply supported boundary conditions and mixed clamped-free boundaries are adopted in the numerical study. A nine-node MITC (Mixed Interpolated of Tensorial Components) plate element is employed to contrast the shear locking phenomenon of thin plates. CUF-based variable kinematic models are used in the numerical study and the number of expansion terms in the thickness direction is increased until the requisite numerical accuracy is achieved. By comparing the numerical results obtained with CUF-based refined models and ABAQUS 3D models as well as reference solutions from literature, the effectiveness of the adopted models is verified. The newly studied numerical cases can be taken as benchmarks for future research.

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ABSTRACT: This study analyzes the mechanical behaviors of conical composite tubes, considering fiber orientation errors, under static loads. Fiber orientation errors are defined as fiber orientation changes that occur due to the taper angle of conical composite tubes during the wrapping process. Such fiber orientation errors are one of many important parameters in predicting mechanical properties, and must be taken into account for the design of conical composite tubes. Thus, this study derived the theoretical equations to analyze the mechanical behaviors of conical composite tubes under static loads considering fiber orientation errors according to the laminate plate theory. For verification of the derived equations, the calculation results were compared with the results of other research that did not take fiber orientation errors into account as well as experimental results that did include fiber orientation errors. As a result, the derived equations could predict the static behaviors of conical composite tubes 5.5% errors. Also, we performed parametric studies such as taper angles, sizes, and stacking sequences. The effect of taper angles on the static behaviors was the most important and the static deformations with and without the consideration of fiber orientation errors had a 500% difference over 10\(^6\) of the taper angle.

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ABSTRACT: The paper is devoted to the strength analysis of a simply supported three layer beam. The sandwich beam consists of: two metal facings, the metal foam core and two binding layers between the faces and the core. In consequence, the beam is a five layer beam. The main goal of the study is to elaborate a mathematical model of this beam, analytical description and a solution of the three-point bending problem. The two different nonlinear hypotheses of the deformation of the cross section of the beam are formulated. Based on the principle of the stationary potential energy the two systems of four equations of equilibrium are derived. Then deflections and stresses are determined. The results of the solutions of the bending problem analysis are shown in the tables and figures. The analytical model is verified numerically using the finite element analysis, as well as experimentally.

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ABSTRACT: A two-way coupling global-local finite element approach which has demonstrated its potential on the basis of representative test cases in earlier work, is used for the progressive failure analysis of large stiffened composite panels. In order to realize the capability of the approach to analyze larger panels, the efficiency of the analysis is enhanced and improved rules for the choice of the size of local models are developed. The potential to carry out a progressive failure analysis for large stiffened panels is illustrated firstly through the analysis of a two-stringer panel with a local defect, in which the adjusted rules to define the local models are applied, and subsequently concretized by applying the approach to a large stiffened composite panel with five stringers. A comparison between the results of the global-local coupling analysis and a reference analysis with shell elements including degradation is presented and the results are discussed. The results of the numerical analyses of the large panel are also compared with experimental results available.

Listed at the end of the paper:

ABSTRACT: Multistable structures used in morphing applications are conventionally achieved by using bistable shapes having different values of out orientation on the multistable shapes. A rich nonlinear finite element analysis. A parametric study is further conducted to analyze the effect of changing fiber check the accuracy and robustness of the proposed method, the results for different cases are compared with a

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ABSTRACT: The objects of consideration are thin linearly elastic Kirchhoff-Love-type open circular cylindrical shells having a functionally graded macrostructure and a tolerance-periodic microstructure in circumferential direction. The aim of this contribution is to formulate and discuss a new mathematical averaged model for the analysis of selected dynamic problems for these shells. This, so-called, combined asymptotic-tolerance model is derived by applying the combined modelling technique which includes both the asymptotic and tolerance non-asymptotic procedures. Contrary to the starting exact shell equations with highly oscillating, non-continuous and tolerance-periodic coefficients, governing equations of the proposed combined model have continuous and slowly varying coefficients depending also on a cell size. Hence, this model can be applied to study the effect of a microstructure size on dynamic behaviour of the shells (the length-scale effect). An important advantage of this model is that it makes it possible to analyse micro-dynamics of tolerance-periodic shells independently of their macro-dynamics.

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ABSTRACT: Buckling of composite plates with linearly varying in-plane loads has been studied. Loaded edges are assumed as simply supported and the remaining ones are arbitrary. First order and third order shear deformation plate theories are used in the formulation of the problem. Ritz method has been utilized with simple polynomials in displacement field. By modifying displacement field components, the continuity of transverse stresses is satisfied among the layers of cross-ply symmetric lay-up composite plates. Results are obtained for different material, geometrical properties and loading conditions.

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Auxetic panels demonstrate interesting crushing behaviour, effectively adapting to the dynamic loading by symmetrically modelled with shell elements and the CONWEP model is used to simulate the blast loading parameters including the geometrical factors and the effective Poisson’s ratio. The transmitted reaction forces and maximum stresses on the protected structure are quantified for various design evaluations to evaluate the performances of different design crushing strengths of the representative panels at different impact velocities. Parametric studies are conducted to investigate the behaviours of these structures are numerically investigated, taking into account the rate-dependent effects. The Johnson-Cook model is employed to describe the dynamic responses of the composite sandwiches subjected to high strain-rate loadings. Analytical models are derived correlating unit cell geometrical parameters and type buckling analyses to remain flat under in-plane pure bending. The dynamic behaviours of these structures are numerically investigated, taking into account the rate-dependent effects. The Johnson-Cook model is employed to describe the dynamic responses of the composite sandwiches subjected to high strain-rate loadings. Analytical models are derived correlating unit cell geometrical parameters and type buckling analyses to remain flat under in-plane pure bending.
progressively drawing material into the locally loaded zone to thereby enhance the impact resistance. Meanwhile, conventional honeycomb panels deform plastically without localised stiffness enhancement.

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ABSTRACT: In this study, a numerical and experimental study was carried out to determine the effects of variables such as curvature and foam properties on the natural frequencies of the sandwich panels. Sandwich panels consist of laminated E/glass epoxy face sheets with [0°/90°/−45°/+45°] stacking sequences and PVC−foam cores with AIREX C70.55, C70.90, C70.200 and C70.250. A group of sandwich panels with radii of curvature ranging from 90 to 200 mm were analysed by ANSYS software. Vibration characteristics were obtained for clamped square sandwich panels. The results indicate that the natural frequencies increase with the increasing curvature and foam density. However, the increment in the natural frequency due to an increase in the magnitude of curvature decreases with increasing foam density. The highest increase in natural frequency due to increasing foam properties is seen in the flat panels. Also, it is found that in values beyond a specific curvature; increasing of the foam properties causes reduction in the natural frequencies.

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ABSTRACT: The paper describes buckling of rectangular plate made of polyethylene. The plate is built of three layers. External faces are solid and the core is porous. The plate is described with broken line hypothesis.

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causes that induced force in the pockets is also changed. In the paper critical states are obtained for static load and equation of motion are solved for equilibrium paths for example plates.

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ABSTRACT: Exact eigensolutions for flutter of two-dimensional symmetric cross-ply composite laminated panel with all combinations of simply supported (S), guided (G), clamped (C) and free (F) boundaries are derived according to classical laminate theory (CLT) and first-order piston theory. The flutter mechanism is revealed with the benefit of eigenvalue properties from both mathematical and physical senses. It is concluded that the coupled-mode flutter, zero-frequency single-mode flutter and buckling can be observed in 2D composite panel. The effects of aerodynamic damping, chord-thickness ratio, in-plane loads, boundary conditions and orthotopic modulus ratio on flutter properties are examined, and in-plane loads and boundary conditions are stressed since they affect both flutter boundary and type. The exact solutions are compared with the results of Galerkin method and the comparison results show that the Galerkin method using the first three modes gives accurate flutter solutions.

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ABSTRACT: In this work a finite element model is developed for vibration analysis of pure functionally graded material (FGM) structures, and for passive damped sandwich structures, with a soft viscoelastic core between the FGM layers. The FGM layers are modeled using the classical plate theory and the core is modeled using Reddy’s third-order shear deformation theory. The finite element is obtained by using specific assumptions on the displacement continuity at the interfaces between layers. The dynamic analysis of these types of structures is conducted in the frequency domain to obtain the natural frequencies and, for the case of a viscoelastic core, the respective modal loss factors. It is also conducted in the time domain for steady state harmonic motion. For both analyses, the finite element code is implemented. The model is applied in the solution of some illustrative examples and the results are presented and discussed.

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ABSTRACT: This paper studies the vibration behaviours of laminated plates with consideration of the influences of surface and interface energies. Geometric nonlinearity is taken into account in this model to obtain the results of large amplitude vibrations. Approximate closed-form solutions for simply supported plates,
clamped plates and clamped circular plates are provided. Numerical results show that the surface/interface effect can affect the dynamic behaviours of laminated plates at nanometer scale. This is especially for nonlinear (large-amplitude) vibration. In addition, the ratio of the thickness to length of the plate, the external load and number of layers also affect the surface/interface effects for large amplitude vibration. This study is helpful for designing and examining the non-linear dynamic behaviour of laminated nanoplates and nanoscale devices.

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sheets. The specially designed and manufactured platens with four round
simultaneously cut and crush square bare CFRP tubes and CFRP tubes wrapped externally with aluminium

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Rafea Dakhil Hussein, Dong Ruan, Guoxing Lu and Rodney Thomson (Primarily from: Faculty of Science, Engineering and Technology, Swinburne University of Technology, John Street, Hawthorn, VIC 3122, Australia), “An energy dissipating mechanism for crushing square aluminium/CFRP tubes”, Composite Structures, Vol. 183, pp 643-653, January 2018, \url{https://doi.org/10.1016/j.compstruct.2017.08.033}

ABSTRACT: A platen with cutting blades was introduced as a new energy dissipating mechanism to simultaneously cut and crush square bare CFRP tubes and CFRP tubes wrapped externally with aluminium sheets. The specially designed and manufactured platens with four round tip blades, four sharp tip blades and
eight round tip blades were used to reduce the initial peak crushing force and increase the energy absorption of CFRP tubes. Notches were introduced at one end of tubes to control the location of the initial failure. Experimental results showed that the deformation mode of CFRP tubes and aluminium sheet-wrapped CFRP tubes that were crushed by platens with blades was a combination of splaying progressive and transverse shearing failure mode. More damage was observed to CFRP plies when tubes were crushed by using round tip blades. Tubes cut and crushed by a platen with eight round tip blades had a lower initial peak crushing force, higher mean crushing force, larger energy absorption and higher specific energy absorption in comparison with counterpart tubes crushed by flat platens. A comparison between the new trigger mechanism proposed in this study (cutting blades) and other different trigger mechanisms used in published literature was made.

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Contour maps provide new insights into buckling performance improvements that are non-orientations. The contour maps are applicable to two recently developed databases containing symmetric and factors, which are superimposed on the lamination parameter design spaces for laminates with standard supported edges. The equations are used to generate contour maps, representing non-shear buckling to assess the effect of

ABSTRACT: This article describes the development of closed form polynomial equations for compression and shear buckling and the numerical prediction of their energy absorption capabilities. The equations are applicable to two recently developed databases containing symmetric and non-symmetric laminates with either Bending-Twisting or Extension-Shearing Bending-Twisting coupling. The contour maps provide new insights into buckling performance improvements that are non-intuitive and facilitate...
comparison between hypothetical and practical designs. The databases are illustrated through point clouds of lamination parameter coordinates, which demonstrate the effect of applying common design heuristics, including ply angle, ply percentage and ply contiguity constraints.

Guohua Zhu, Guangyong Sun, Guangyao Li, Aiguo Cheng and Qing Li, “Modeling for CFRP structures subjected to quasi-static crushing”, Composite Structures, Vol. 184, pp 41-55, January 2018
ABSTRACT: Carbon fiber reinforced plastic (CFRP) composite materials demonstrate significant promise to further improve weight to performance in automotive engineering. Nevertheless, design of CFRP components for crashworthiness criteria remains rather challenging and typically requires laborious trial-and-error processes. This study aims to promote computational design of CFRP structures by establishing effective constitutive model that is implemented in the commercial finite element code Abaqus/Explicit. Two different numerical models (namely, the single layer shell model and the stacked shell model) were developed to simulate experimental crushing tests on the square CFRP tube. The effects of key parameters for these two FE models were analyzed, respectively. The comparisons of numerical results with experimental data indicated that the 9 layers stacked shell model is capable of reproducing experimental results with relatively higher accuracy. Based on the validated modeling approach, crushing behaviors of several CFRP thin-walled structures with different cross sectional geometries and thicknesses were further explored. The failure modes and key indicators in relation to the structural crashworthiness were investigated for identifying a best possible sectional configuration. It is found that the circular tube shows superior specific energy absorption capacity of all different tubal configurations with the same wall thickness, meaning that the tube with circular section is of good potential as a crashworthy CFRP structure.

ABSTRACT: Grout (SRG) jackets under monotonically increasing uniaxial compression. A total of 24 specimens of short RC columns of square cross section were designed to fail due to longitudinal reinforcement buckling. Single-layered SRG jackets were applied to 18 of these specimens, whereas the rest served for control without SRG jackets. Parameters of this investigation were the type and density of the steel fabric as well as the corner radius of the cross section. The employed SRG jacketing managed to increase the strength and strain capacity and postpone the buckling of the longitudinal steel bars to occur at higher compressive strain level. Confinement effectiveness with respect to the lateral confining pressure exerted by the used SRG jacketing is discussed along with the observed mode of failure.

Zhibo Xin, Xiaohui Zhang, Yugang Duan and Wu Xu, “Nacre-inspired design of CFRP composite for improved energy absorption properties”, Composite Structures, Vol. 184, pp 102-109, January 2018
ABSTRACT: Discontinuous unidirectional fiber-reinforced composites are shown to possibly exhibit pseudoductile failure that is lacking in continuous fiber composites. The aim of this paper is to use a discontinuous and interdigitated design strategy which mimicks the nacre structure to improve the specific energy absorption (SEA) of a carbon/expoxy composite tube. Quasi-static axial compressive experiment is combined with a digital image correlation system to analyze the failure process of the specimens. Four kinds of tubular specimens which are based on different ply cut intervals and distributions are fabricated and crushed. The load-crushed displacement curves and the SEA values are obtained showing that circular shaped continuous ply cuts result is the highest fluctuation of the compressive force. Moreover, the tubes with helical and nacre mimicking ply cut structures result in a flatter load-crushed displacement curve. This work demonstrates that in a crush process,
unidirectional composites with a well-designed discontinuity at the ply level can improve the SEA over 51% as compared to the unidirectional continuous tubes.

Guangyong Sun, Dongdong Chen, Xintao Huo, Gang Zheng and Qing Li, “Experimental and numerical studies on indentation and perforation characteristics of honeycomb sandwich panels”, Composite Structures, Vol. 184, pp 110-124, January 2018
ABSTRACT: Aluminum sandwich panels with honeycomb core have been widely used as energy absorption structure in lightweight design. This study aimed to characterize the indentation and perforation behaviors of sandwich structures with different geometric configurations. The specimens with four characteristic geometric variables, namely, facesheet thickness, core height, honeycomb core thickness and side length of hexagon cell were tested experimentally. Photographs of cross-sectional view near the loading area and failure modes in the tests were investigated in detail. For the first time, digital image correlation (DIC) technique through an ARAMIS™ real-time optical strain measurement system was adopted for capturing the deformation process of lower skin by acquiring the displacement-time data. Three typical damage modes were identified from the force-displacement curves with different geometric parameters and configurations. It was found that the thickness of facesheet has the most significant effects on both force-displacement curves and energy absorption capacity. Changes in the core parameters have relatively small influences in total energy absorption but sizeable effects on the force-displacement curve and failure modes. A finite element model for predicting damage evolution was also developed and validated through the force-displacement relation and deformation process on the bottom skin. The damage mechanisms of the sandwich panel subject to quasi-static indentation and perforation were analyzed through the numerical models. The present study contributed on understanding how the geometric parameters affect the characteristics of indentation and perforation, thereby providing useful guidelines for its potential applications in impact engineering.

ABSTRACT: The deflection responses of the damaged doubly curved shallow shell panels under the combined thermomechanical loading are investigated numerically in this article. The debonded layered structures are modeled mathematically using two higher-order displacement kinematic theories and solved via finite element method. The separation between the consecutive layers is included using two sub-laminate approaches in the current model including the intermittent displacement continuity conditions. Further, the weak form of the equilibrium equation for the deflected shell panel structure under the combined action of loading is achieved via two-dimensional nine noded isoparametric Lagrangian elements. The responses are obtained by minimising the total potential energy expression with the help of an original computer code (MATLAB) in association with the currently developed mathematical models. The consistency of the present numerical solutions is demonstrated by conducting the convergence test and the validity of the models checked through the proper comparison test. Lastly, some new examples are solved using the current models to show the consequence of the delamination (size and position) including the other structural parameters (the side to thickness ratio, the length to width ratio, the curvature ratio and the boundary condition) on the deflection responses under the influence of thermomechanical loading.

ABSTRACT: Fiber steering is one of the promising capabilities of Automated Fiber Placement (AFP) technology in manufacturing of advanced composite structures with spatially tailored properties. The so-called variable stiffness (VS) composites have considerable scope to outperform their traditionally made constant stiffness (CS) counterparts. However, there are several design and manufacturing challenges to be addressed before practically using them as structural components. In this work we demonstrate the design, manufacturing and testing procedure of a variable stiffness (VS) composite cylinder made by fiber steering. The improved bending-induced buckling performance is the objective of the VS cylinder to be compared with its CS counterpart. The experimental results show that the buckling capacity of the VS cylinder is about 18.5% higher than its CS counterpart.

ABSTRACT: Honeycombs are versatile structures. They have been widely employed in industries where the characteristics of high stiffness, high buckling resistance, large shock absorption and light weight are required. To explore the potential of honeycombs in various mechanical applications, this paper proposes a novel honeycomb with composite laminate cell walls in order to provide wider selection of constituent materials, improved specific stiffness and distinct cell wall surfaces. Analytical homogenization model of this special type of honeycombs is established by modeling the locally heterogeneous honeycomb as a homogeneous orthotropic bulk. Both full-detailed and homogenized models are built and tested using finite element analysis, and the results showed that the analytical model has excellent accuracy in property prediction at a relatively small computational cost. Parametric studies are also conducted to investigate the effect of thickness and elastic moduli of the cell wall plies on the structure’s overall mechanical response. Based on the results, suggestions on property optimizations are discussed.

ABSTRACT: Effect of stiffener damage caused by Low Velocity Impact (LVI) on compressive buckling and failure load of the three T-stiffened composite panel was studied by experiment in this paper. Stiffener damages were introduced at four impact energy levels with the impact position located on the panel side over the middle stiffener. The impact experimental results show that the impact energy inducing the initial damage of the stiffened panel is about 34 J. With the increase of impact energy, the damage of the panel is slighter than Barely Visible Impact Damage (BVID), while the stiffener damage and stiffener/panel debonding are serious. The panel dent will not be visible until the stiffener is completely fractured under a higher energy impact. Compression after Impact (CAI) experimental results show that although the initial compression stiffness of the stiffened panel is not affected by the stiffener damage, the compressive stiffness decreases with the increase of compressive load due to the damage propagation of the impacted stiffener and buckling of panel. The failure loads decrease significantly when the damage of stiffener and the stiffener/panel debonding occur as the result of LVI, with a maximum drop of 44% compared to the undamaged specimen.

Qingshan Wang, Dong Shao and Bin Qin, “A simple first-order shear deformation shell theory for vibration analysis of composite laminated open cylindrical shells with general boundary conditions”, Composite Structures, Vol. 184, pp 211-232, January 2018
ABSTRACT: This paper presents, for the first time, a simple first-order shear deformation shell theory (SFSDST) for free and transient vibration analysis of composite laminated open cylindrical shells with general boundary conditions. By partitioning the radial displacement into bending and shear components, the present
theory contains only four unknowns and can be regarded as an enhanced classical shell theory with the consideration of the effects of shear deformation and rotary inertia terms. The governing equations and appropriate boundary conditions are derived from Hamilton’s principle. To obtain natural frequencies and transient responses accurately, the method of reverberation ray matrix (MRRM) is employed based on the obtained exact closed-form solutions. The artificial spring technology is adopted to achieve the general boundary conditions. Accordingly, the scattering matrix is redefined in MRRM to make it suitable for different boundary cases. The excellent accuracy, reliability and efficiency of the present theory and approach are verified by examining the free and transient vibrations of composite laminated open cylindrical shells under various combinations of classical and non-classical boundary conditions. Meanwhile, a variety of new parameter studies regarding the influence of the boundary conditions, geometry parameters, lamina number, material properties and loading forms are performed in detail.

ABSTRACT: Failure modes and critical loads for adhesively bonded steel corrugated sandwich structure under three-point bending in both longitudinal and transverse direction are investigated. An analytical model considering both adhesive joint effects and classic beam theory is developed for predicting the failure modes and stresses in each member of the sandwich structure. Then the corresponding experiments and the numerical analysis by using cohesive zone model are also carried out. The experimental data, numerical results and the analytical predictions are all agree well with each other. Furthermore, based on the analytical expressions, the failure mechanism maps for three-point bending are constructed to get better understanding of failure modes and minimum weight design. Besides, the effects of adhesive parameters on failure modes and stress distribution are further studied by using the analytical model.

ABSTRACT: The integration of microchannels within structural composites enables a range of multifunctional responses such as thermal management and self-healing. In this work, we investigate how microchannels affect the crashworthiness of the host material. Corrugated panels are fabricated with aligned microchannels (ca. 400 µm diameter) at different channel spacing (10 mm and 1.2 mm), orientation with respect to the loading direction, and alignment with respect to the surrounding fiber-reinforcement. Specific energy absorbed (SEA) is measured by compression testing of samples with a chamfer edge trigger. SEA was preserved within 10% for all test cases. Flat (non-corrugated) panels are also tested to demonstrate that microchannels can serendipitously trigger stable, energy absorbing failure modes that lead to improved crashworthiness. Non-vascular panels without an edge chamfer fail catastrophically when compressed. In dramatic contrast, vascular panels fail in a stable fashion triggered by crack initiation at the microchannels, yielding ca. 10 times more energy absorption.

Mohammad Reza Barati and Ashraf M. Zenkour, “Post-buckling analysis of imperfect multi-phase nanocrystalline nanobeams considering nanograins and nanopores surface effects”, Composite Structures, Vol. 184, pp 497-505, January 2018
ABSTRACT: In this paper, a size-dependent nonlinear higher order refined beam model is developed based on modified couple stress theory. Then, it is applied to investigate post-buckling behavior of multi-phase nanocrystalline silicon nanobeams with geometrical imperfection. Nanocrystalline materials (NcMs) are multi-phase composites with the contribution of nanopores, nanograins and interface phase. Because of experimental
observation of strain gradients near interface phase, the nanobeam is modeled via strain gradient based couple stress theory. A micromechanical model based on Mori-Tanaka scheme is employed to incorporate the size of nanograins/nanopores and their surface energies. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin’s method needless of any iteration process. New results show the importance of porosity percentage, nanograins size, geometrical imperfection, couple stress parameter, foundation parameters and surface phase of nanograins/nanopores on nonlinear buckling behavior of NcM nanoscale beams.


ABSTRACT: In this paper, the nonlinear vibrations and energy exchange of single-walled carbon nanotubes (SWNTs) are analysed. The Sanders-Koiter shell theory is used to model the nonlinear dynamics of the system in the case of finite amplitude of vibration. The SWNT deformation is described in terms of longitudinal, circumferential and radial displacement fields. Simply supported, clamped and free boundary conditions are applied. The resonant interaction between radial breathing (axisymmetric) modes (RBMs) is analysed. An energy method, based on the Lagrange equations, is considered in order to reduce the nonlinear partial differential equations of motion to a set of nonlinear ordinary differential equations, which is then solved applying the implicit Runge-Kutta numerical method. The present model is validated in linear field comparing the RBM natural frequencies numerically predicted with data reported in the literature from experiments and molecular dynamics simulations. The nonlinear energy exchange between the two halves along the SWNT axis in the time is studied for different amplitudes of initial excitation applied to the two lowest frequency resonant RBMs. The influence of the SWNT aspect ratio on the numerical value of the nonlinear energy beating period under different boundary conditions is analysed.


ABSTRACT: In this paper, we present for the first time a size-dependent model based on the modified couple stress theory (MCST) and isogeometric analysis (IGA) for the static and free vibration behaviors of functionally graded carbon nanotube reinforced composite (FG-CNTRC) nanoplates. By using higher order shear deformation theory for displacement fields, the shear correction factor is omitted when determining the stiffness matrix. Based on the rule of mixture, the effective Young’s and shear moduli of carbon nanotube (CNT) are established. For verifying the accuracy and trustworthiness of the proposed method, the present results are compared with those of analytical solutions, and excellent agreement is obtained. The proposed model can capture the small scale effect for FG-CNTRC nanoplates. The effect of length scale on stresses and natural frequencies of FG-CNTRC nanoplates is discussed in details.


ABSTRACT: This paper presents a new shear deformation theory including the stretching effect for free vibration of the simply supported functionally graded plates. The theory accounts for parabolic distribution of the transverse shear strains and satisfies the zero traction boundary conditions on the surfaces of the functionally graded plate without using shear correction factors. This theory has only five unknowns, which is even less than the other shear and normal deformation theories. The present one has a new displacement field which
introduces undetermined integral variables. The equation of motion of the vibrated structure obtained via the classical Hamilton’s principle and solved using Navier’s steps. The validation of the proposed theoretical model is performed to demonstrate the efficacy of the model. It can be concluded that the present theory is not only accurate but also simple in predicting the natural frequencies of functionally graded plates with stretching effect.


ABSTRACT: In the present work, vibration analysis of curved nanobeams is investigated using nonlocal elasticity approach based on Eringen formulation coupled with a higher-order shear deformation theory accounting for through thickness stretching effect. The formulation developed here is general in the sense that it can be deduced to examine the influence of different structural theories and analyses of nanobeams. The governing equations derived are solved employing finite element method by introducing a 3-nodes curved beam element. The formulation is validated considering problems for which solutions are available. A comparative study is made using various structural models. The effects of various structural and material parameters such as thickness ratio, beam length, rise of the curved beam, boundary conditions, and size-dependent or nonlocal parameter are brought out on the vibration behaviours of curved nanobeams.


ABSTRACT: Laminated composites with a core layer sandwiched between orthogonal mechanically-prestrained laminae exhibit two weakly-coupled cylindrical shapes where each shape is influenced only by one prestrained lamina. This study investigates the domain of bistability and actuation requirements of such bistable laminated composites. An analytical model is constructed as follows: point-wise displacements and areal dimensions are scaled; strain energy and actuation work are computed using high-order displacement polynomials; and net energy is minimized using the Rayleigh-Ritz method to calculate stable shapes as a function of actuation force. Shape transition is shown to be a multi-stage phenomenon through an experimental procedure involving friction-free tensile tests and 3D motion capture. The simulated actuation energies agree with measurements within 12%. Square laminates are shown to be bistable only when the ratios of laminae prestrains are greater than 0.2. The aspect ratio limit for bistability can be improved by maximizing both prestrains while maintaining a prestrain ratio of one. It is shown that in-plane forcing requires 100 times more energy than an equivalent moment. A parametric study reveals that the composite’s performance parameters are more sensitive to the core’s thickness than its modulus; the sensitivity of actuation energy is minimal relative to that of deformation and stiffness.


ABSTRACT: In this work, nonlocal nonlinear finite element analysis of laminated composite plates using Reddy’s third-order shear deformation theory (TSDT) (Reddy, 1984) and Eringen’s nonlocality Eringen and (Edelen, 1972) is presented. The governing equations of third order shear deformation theory with the von Kármán strains are derived employing the Eringen’s (Eringen and Edelen, 1972) stress-gradient constitutive model. The principle of virtual displacement is used to derive the weak forms, and the displacement finite element models are developed using the weak forms. Four-noded rectangular conforming element with 8 degrees of freedom per node has been used. The coefficients of stiffness matrix and tangent stiffness matrix are presented along with nonlocal force vector. The developed finite element model can be employed to capture
the small scale deviations from local continuum models caused by material inhomogeneity and the inter atomic and inter molecular forces. Numerical examples are presented to illustrate the effects of nonlocality, anisotropy, and the von Kármán type nonlinearity on the bending behaviour of laminated composite plates.

Farzad Ebrahimi and Mohammad Reza Barati, “Damping vibration analysis of graphene sheets on viscoelastic medium incorporating hygro-thermal effects employing nonlocal strain gradient theory”, Composite Structures, Vol. 185, pp 241-253, February 2018

ABSTRACT: In the present article, a nonlocal strain gradient plate model is developed for damping vibration analysis of viscoelastic graphene sheets under hygro-thermal environments. For more accurate analysis of graphene sheets, the proposed theory contains two scale parameters related to the nonlocal and strain gradient effects. Graphene sheet is modeled via a two-variable shear deformation plate theory needless of shear correction factors. Governing equations of a nonlocal strain gradient graphene sheet on viscoelastic substrate are derived via Hamilton’s principle. Differential Quadrature Method (DQM) is implemented to solve the governing equations for different boundary conditions. Effects of different factors such as temperature rise, nonlocal parameter, length scale parameter, elastic foundation and aspect ratio on vibration characteristics a graphene sheets are studied.

Habiburrahman Ahmadi and Hayder A. Rasheed, “Lateral torsional buckling of anisotropic laminated thin-walled simply supported beams subjected to mid-span concentrated load”, Composite Structures, Vol. 185, pp 348-361, February 2018

ABSTRACT: In this paper, a generalized semi-analytical approach for lateral-torsional buckling of simply supported anisotropic, thin-walled, rectangular cross-section beams under concentrated load at mid-span/mid-height was developed using the classical laminated plate theory as a basis for the constitutive equations. A closed form buckling expression was derived in terms of the lateral, torsional and coupling stiffness coefficients of the overall composite. These coefficients were obtained through dimensional reduction by static condensation of the general 6x6 constitutive matrix mapped into an effective 2×2 coupled weak axis bending-twisting relationship. The resulting two coupled stability differential equations are manipulated to yield a single governing differential equation in terms of the twisting angle. This differential equation with variable coefficients, subjected to applicable boundary conditions, was solved numerically using Mathematica. The resulting solution was found to correlate with the effective lateral-flexure, torsional and coupling stiffness coefficients to yield a general semi-analytical solution. An analytical formula was possible to extract, which was verified against finite element buckling solutions using ABAQUS for a wide range of lamination orientations showing excellent accuracy. The stability of the beam under different geometric and material parameters, like length/height ratio, layer thickness, and ply orientation, was investigated.

Ye Tang and Tianzhi Yang, “Post-buckling behavior and nonlinear vibration analysis of a fluid-conveying pipe composed of functionally graded material”, Composite Structures, Vol. 185, pp 393-400, February 2018

ABSTRACT: The post-buckling behavior and nonlinear vibration of a fluid-conveying pipe composed of a functionally graded material were analytically studied. The power-law material property was considered as continuously varying across the direction of the pipe wall thickness. A nonlinear governing equation for the pipe and relevant boundary conditions were derived based on Hamilton’s principle. The post-buckling configurations of the pipe were analytically predicted. The closed-form expression of the nonlinear free vibration of the pipe was determined using the homotopy analysis method. Numerical results are presented to display the dependence of the flow velocity, fluid density, and the initial stress on the post-buckling configurations. It was concluded that the statics and dynamics are significantly changed by the material
properties, which suggests that the dynamic behavior of pipes may be tailored by use of man-made functionally graded materials.


ABSTRACT: The Carrera Unified Formulation (CUF) is a technique that, in addition to eliminate the imperfections of other theories, allows us to achieve a large class of models, such as equivalent single layer, layer wise, and mixed formulation in a unified manner. For this reason, this formulation can be very effective in different analyses, and according to the desired analysis, an appropriate model could be chosen. In this research, for the first time, the Carrera Unified Formulation is extended in the polar coordinates for analyzing the sandwich circular plate with the functionally graded material core. In order to apply variations in the properties of the functionally graded material, the variable kinematic method is used in the frame work of CUF, which ultimately leads to a reduction in degrees of freedom and an increase in the accuracy of the results. The functionally graded material is modeled as a mixture of ceramics and metal, whose properties change according to a power distribution in the direction of thickness. In this research, the generalized differential quadrature (GDQ) method is used to solve the governing equations. The obtained results are compared with the existing three-dimensional results as well as the generalized Zig-Zag theory, which indicates the high accuracy of the CUF formulation for circular plates in the polar coordinates. In addition, new results are provided for different geometries, thickness ratios, boundary conditions as well as deflection, radial displacements, annular and radial stresses, and transverse stresses along the thickness.


ABSTRACT: Nonlinear dynamic behavior of double curved shallow shells with negative Poisson’s ratios in auxetic honeycombs on elastic foundations subjected blast, mechanical and damping loads is investigated in the present article. This study considers double curved shallow shells with auxetic core which have three layers in which the top and the bottom outer skins are isotropic aluminum materials; the central layer has honeycomb structure using the same aluminum material. Based on the analytical solution, Reddy’s third order shear deformation theory (TSDT) with the geometrical nonlinear in von Karman and Airy stress functions method, Galerkin method and the fourth-order Runge-Kutta method, the resulting equations are solved to obtain expressions for nonlinear motion equations. The effects of geometrical parameters, material properties, elastic foundations, imperfections, blast loads, mechanical and damping loads on the nonlinear dynamic analysis of double curved shallow shells with negative Poisson’s ratios in auxetic honeycombs are studied.

Hui Zhou, Ping Xu, Suchao Xie, Zhejun Feng, Da Wang, “Mechanical performance and energy absorption properties of structures combining two Nomex honeycombs”, Composite Structures, Vol. 185, pp 524-536, February 2018

ABSTRACT: To study the mechanical performance and energy absorption property of two-layer Nomex honeycombs of different types, compressive tests on different combinations were conducted and the experimental results compared with those from tests on single honeycomb specimens. The types of combinations include combinations of two honeycombs of the same specification without a clapboard (HSSWC), combinations of two honeycombs of the same specification containing a clapboard (HSSCC), combinations of two honeycombs of different specification without a clapboard (HDSWC), and combinations of two honeycombs of different specification containing a clapboard (HDSCC). The results showed that
different combinations were suitable for different situations. It was advisable to apply the combinations containing clapboard as crashworthy structures which call for large collapse stress. It is necessary to reduce the initial collapse stress in the damping and energy-absorbing structures, so combinations without clapboards can be used. The structures combining different honeycomb specifications can be adopted to control the ordered deformation and ladder energy levels.

M.R. Bambach, “Geometric optimization and compression design of natural fibre composite structural channel sections”, Composite Structures, Vol. 185, pp 549-560, February 2018
ABSTRACT: Public concerns about the environment, climate change, energy consumption and greenhouse gas emissions have placed increasing demands for the use of sustainable materials in the built environment. Natural fibres such as flax, jute and hemp have recently been considered for fibre-resin composites, with a major motivation for their implementation being their notable sustainability attributes. However, many studies have noted the relatively modest mechanical properties of natural fibre composites. Despite this, a recent paper by the author demonstrated that the compression strength of flat plates and plain channel sections may be suitable for light structural applications. This paper presents the geometric optimisation of channel sections via the inclusion of complex web, flange-edge and flange-interior stiffeners. It is demonstrated that the inclusion of geometric stiffeners restricts the development of local buckling, creating less slender channel sections with greater compression strength. Compression strengths are compared with steel and timber wall stud strengths and shown to be suitable for residential building applications. The combined plain channel and stiffened channel experimental data covers a broad range of section slenderness values, and design models are developed to predict their compression strength.

ABSTRACT: A numerical approach is adopted for the multiscale analysis of vibrations of single-walled carbon nanotubes (SWCNTs). The SWCNT is modeled by a hyperelastic membrane whose kinematics is described using the higher-order Cauchy-Born rule. The constitutive model is formulated exclusively in terms of the interatomic potential, so, it inherits the atomistic information and involves no other phenomenological input. The variational differential quadrature (VDQ) method is employed in which the continuum model is discretized using DQ, and a weak form of equation of motion is obtained via a variational approach. VDQ is computationally advantageous since it has a fast rate of convergence and can reproduce the results of molecular dynamics simulations. Detailed investigations into frequencies and mode shapes of SWCNTs with different geometrical parameters, boundary conditions and chiralities are carried out. It is found that short nanotubes display a coupling between the axial/torsional and bending modes. Also, as the tube diameter or length increases, mode transitions are made at several critical points. If the edge supports are more flexible and tube length is longer, the critical diameters are larger. Eventually, the vibration characteristics of axially strained nanotubes are analyzed, and it is concluded that SWCNTs with smaller radii have higher strain sensitivity.

Huagang Lin, Dengqing Cao, Chonghui Shao, “An admissible function fo vibration and flutter studies of FG cylindrical shells with arbitrary edge conditions using characteristic orthogonal polynomials”, Composite Structures, Vol. 185, pp 748-763, February 2018
ABSTRACT: A general approach for the vibration and aeroelastic stability of the functionally graded cylindrical shell with arbitrary boundary conditions is firstly presented. The Sanders' shell theory, a steady-state heat transfer equation and the piston theory are employed to establish the motion equation, where the thermomechanical properties of material are set to be location- and temperature-dependent. The orthogonal
polynomials series generated by employing the Gram–Schmidt process are taken as the admissible functions to express the general formulations of displacement. Moreover, the artificial spring technique is introduced to simulate the elastic constraints imposed on the cylinders’ edges. The frequency equations are derived considering the strain energy of artificial springs during the Rayleigh–Ritz procedure, and the motion equation of cylindrical shells subjected to combined thermal and aerodynamic loads is established based on the Hamilton principle. A few comparisons for the frequency and critical flutter pressure are performed to validate the proposed approach. The influences of the volume fraction, thermal gradient, boundary conditions and spring stiffness on the flutter characteristics are highlighted. This paper overcomes the limitations of previous vibration and flutter studies which are confined to the structure under simply supported or clamped boundaries.


ABSTRACT: An analytical-experimental study of the shear wrinkling behavior of plain woven composite preforms under bias extension test (BET) and picture frame test (PFT) is presented. The intentionally induced tension in the PFT has been regarded in a large portion of the literature as the source of delay in fabric wrinkling initiation as compared to the BET. Through this study, however, it is demonstrated that shear within yarns – known as intra-yarn shear – could be another cause of the delayed wrinkling in the PFT, even when the tension level in yarns is kept at zero. To better explain this hypothesis, an analytical model has been developed and the meso-level nature of wrinkle formation in the BET and PFT is compared. Analytical equations are provided to predict both the fabric locking and wrinkling onsets under these characterization tests, and verified experimentally on a carbon fiber plain woven fabric.


ABSTRACT: The ability to accurately predict the crashworthiness performance is crucial to the use of composites in the primary energy absorbing structures in vehicles. Such predictions require material models that consider not only the initial failure but also the responses of severely damaged composites. The latter requirement exceeds the boundary of any existing physics based models. To address this problem, an enhanced continuum damage mechanics (ECDM) model has been developed. ECDM employs two sub-models, i.e. a pre-failure model and a post-failure model, to describe the stress–strain behavior in the pre-peak and post-peak regions. This setup allows one to consider the growth of damage and irreversible strains in the two regions under different evolution laws corresponding to different damage/deformation mechanisms. The ECDM model was evaluated in quasi-static and dynamic tube crash simulations of triaxial braided composites. The results show that the irreversible strains and residual stiffness are critical to the energy absorption prediction of composites. The ECDM model provides much improved correlations with the experimental results than the existing models.


ABSTRACT: This paper develops a nonlocal theory of elasticity for the thermoelastic vibration of nanoplates. A mixed variational formula based upon Hamilton’s principle is extended to deal with nanoplates. The present nonlocal first-order shear deformation theory does not need any shear correction factors. Equations of motion and boundary conditions are obtained simultaneously through the mixed variational formula. Governing equations of a mixed nonlocal smart nanoplate are obtained and their solutions are given. The accuracy of the present results is investigated through many comparison examples in the literature. The influences of different
factors such as nonlocal parameter, aspect ratio, side-to-thickness ratio, and mode numbers on the natural vibration characteristics of nanoplates are studied.

ABSTRACT: Free vibration analysis of laminated composite and functionally graded materials (FGM) composite annular plates is investigated. The equations of motion of annular plates have been obtained via conical shell equations. Shear deformation theory is used for shell equation of motion. After the implementation of the Regularized Shannon delta (RSD) kernel and Lagrange delta sequence (LDS) kernel, the method of discrete singular convolution (DSC) is used for numerical solution of the governing equations to obtain the frequency values. To verify the accuracy of this method, comparisons of the present results are made with results available in the open literature. Some parametric results for annular plates and conical panels have depicted for isotropic, laminated composite and functionally graded composite materials. It is found that the convergence and accuracy of the present DSC method is very good for vibration problem of annular plates with functionally graded materials (FMG) and laminated composite cases. Some results about carbon nanotube reinforced (CNTR) composite plate have also been approved.

ABSTRACT: This paper presents the dynamic behavior of a sandwich circular cylindrical shell with a constrained fractional viscoelastic layer. Based on the Donnell-Moshtari theory, the structural formulation of the cylinder is obtained using the Lagrange method and the Rayleigh–Ritz method is implemented to solve the discretized governing equations. To describe the mechanical properties of the viscoelastic layer, the fractional order standard solid model is applied. The effects of variation of the governing parameters such as the length to radius ratio, the radius to total thickness ratio, ratio of core to facing thickness, fractional order parameter and the ratio of non-relaxed to relaxed modulus on the frequency and loss factor of sandwich cylindrical shells are investigated and some conclusions are outlined.

ABSTRACT: The transient response of composite laminated cylindrical shells with convex and concave shapes, subjected to low-velocity impact, was numerically investigated. Geometrically linear analysis without consideration of the membrane effect demonstrated the same contact force and central deflection histories for convex and concave shells. This unexpected numerical result could be explained by the detailed investigation of all stiffness matrix terms of the finite element equation. Furthermore, in the geometrically linear analysis, the dynamic strain distribution on the top surface of the convex shell exhibited the same contour shapes as those on the bottom surface of the concave shell, with the exception of only a reversed value between the tensile and compressive strains. This unique numerical result could also be explained by the detailed investigation of each term of the strain-displacement relation. Finally, we can conclude that geometrically nonlinear analysis must be performed with consideration of the membrane effect of the curved shell, in order to accurately analyse its impact response.
Wei Sun, Zhidong Guan, Zengshan Li, Tian Ouyang and Ye Jiang, “Modelling and simulating of the compressive behavior of T-stiffened composite panels subjected to stiffener impact”, Composite Structures, Vol. 186, pp 221-232, February 2018

ABSTRACT: In this paper, an equivalent damage model was proposed to predict the compressive behavior of three T-stiffened composite panels subjected to low velocity stiffener impact. A softening inclusion model combined with the reduction of material properties was used to describe the impacted stiffener damage. The progressive damage of the impacted stiffener and the failure of the panels under compression were simulated within the finite element software package ABAQUS. Compression-After-Impact (CAI) numerical results show that the compressive buckling modes of the stiffened panels are influenced by the damage degree of the impacted stiffener, and the fracture of the impacted stiffener triggers the global buckling of the panel. The buckling and failure loads of the panels predicted by this paper are in good agreement with the experimental results, which proves the validity of the model.


ABSTRACT: A general analytical procedure is proposed to design tapered laminated composite structures. It is based on: 1) the introduction of two variables representing a laminate configuration, 2) the analytical determination of the lower bound of the number of layers in each of the segments constituting the construction, 3) the definition of the reference sublamine which configuration is transferred to all segments/parts of the construction, 4) the gradual building of configurations for symmetric balanced laminates having odd or even number of plies. The solution is verified by the comparison with results existing in the literature for both inner and outer tapers. A multi-panel composite structure is considered to demonstrate the applicability of the proposed method. As usual, in a such class of problems, the whole construction is divided into segments/panels. The individual segments are subjected to the simultaneous action of in-plane, tensile or compressive and shear loads. The present results demonstrate the simplicity and effectiveness of the method and non-uniqueness of solutions. The paper intends to clarify the physical sense of the discussed problem.


ABSTRACT: This work aims to develop a nonlinear layerwise shell element formulation for shear-deformable laminated composite plate and shell structures. The element is formulated based on a zigzag theory in presence of individual local coordinates in the thickness direction for separate layers. In order to properly employ the zigzag theory, the considered local coordinates have different ranges of variation for middle, upper and lower layers. Using Mindlin-Reissner theory a convenient displacement field is derived for each layer and an ordered algorithm is adapted to calculate increments in the director vector of each layer due to relative finite rotations of its adjacent layers. Employing this shear deformable displacement field in the principle of virtual displacement leads to integral governing equations with various through-the-thickness parameter ranges. To overcome this challenge, the stress and strain tensors are rewritten in terms of through-the-thickness parameters and an explicit integration is performed in thickness direction. In this way, the nonlinear formulation is derived using the updated Lagrangian approach in accompany with a particular linearization scheme. To assess the performance of the present finite element formulation, a proprietary nonlinear finite element program is developed. Some illustrative problems are solved and comparisons with available solutions are presented.

This paper investigates the strength and ductility of concrete confined by Glass/Epoxy ±55° Filament Wound Pipes (GFRP) under axial compression. A total of 24 cylindrical specimens were prepared with expansive and Portland cements, properly compacted and un-compacted for different composite fresh concrete matrix. Test results showed that compressive strength and axial deformation at failure of concrete confined with GFRP tubes increased by an average of 2.85 and 5.57 times these of unconfined concrete, respectively. Macro and micro analyses of GFRP pipes after failure were also investigated. Debonding, whitening, matrix/transfer cracking, delamination and splitting mechanisms were detected at failure, respectively. The experimental results were also employed to assess the reliability of design models available in the literature for confined concrete compressive strength.


Hierarchical anisogrid stiffened panels (HASPs) have two-level stiffeners. The primary stiffeners improve the global stiffness of the HASP and the sub-stiffeners enhance the local stiffness of the mono-cell skin supported by the primary stiffeners. A smearing method was proposed to homogenize the HASP into a homogenous panel, based on two-step equivalences of extensional rigidities and bending rigidities. Dynamic responses of blast-loaded HASPs were analyzed based on the homogenous panel and the mode superposition method and validated by finite element (FE) analysis. Commonly the HASP vibrates like a homogenous panel and the theoretical prediction is accurate. Local mono-cell vibration appears only when the skin and the sub-stiffeners are weak enough. The model was applied to analyze the blast response of a composite protective door. Failure criterion based on maximum strain was proposed to predict the peak blast pressure the HASP can bear. The equivalent theory has good accuracy, providing a feasible way to analyze blast responses of HASPs.

Yue Zhang, Wei Sun, Jian Yang and Qingkai Han, “Analytical analysis of forced vibration of the hard-coating cylindrical shell with material nonlinearity and elastic constraint”, Composite Structures, Vol. 187, pp 281-293, March 2018

In this paper, the nonlinear vibration characteristics of the hard-coating cylindrical shell with the base excitation and un-classical elastic constraint are investigated based on the Rayleigh-Ritz method. A continual variable stiffness elastic constraint is presented to introduce the actual uneven distribution of connection stiffness into the analytical vibration analysis. The nonlinear governing equations of motion are formulated by the Love’s first approximation theory and von Karman-type nonlinear strain-displacement relationship. The admissible displacement functions are constructed by the Gram-Schmidt orthogonal polynomials. To effectively consider the effects of the strain dependences of storage modulus and loss factor of hard coating on the vibration characteristics of the shell, a modified domain decomposition method is employed to determine the equivalent strain of hard coating under the action of base excitation. By extending the Newton-Raphson iterative scheme, a unified iterative solution method is developed for solving the nonlinear resonant frequencies and responses of the hard-coating cylindrical shell. The numerical and experimental examples of the cylindrical shell coated with NiCoCrAlY + YSZ are performed to validate the accuracy and reliability of the developed analytical model. The mechanism of soft nonlinearity displayed in the amplitude-frequency curves of the hard-coating cylindrical shell is discussed as well.


In this paper, the dynamic instability of variable angle tow (VAT) plates with a single rectangular delamination is studied using an analytical model. The analytical model is derived from the principle of
potential energy based on the classical laminated plate theory. Both global and local behavior of delaminated VAT plates in the dynamic instability analysis are accurately captured by the use of multiple Legendre polynomial series. The equations for the motion in dynamic instability problem are derived using Hamilton’s principle. The dynamic instability regions are determined from the resulting Mathieu differential equations, which are solved using Bolotin’s approach. To validate the proposed analytical model, both critical buckling loads and natural frequencies of delaminated VAT plates are evaluated and compared with FEM results. The influence of delamination on the buckling load, natural frequency and dynamic instability region (DIR) of delaminated VAT plates is examined by numerical examples. A parametric study is subsequently carried out to analyze the effect of linearly varying fibre orientation angles on the dynamic instability response of delaminated VAT plates. Finally, the mechanism of applying variable angle tows to improve the dynamic stability performance of delaminated composite plates is studied.


ABSTRACT: Quasi-unidirectional E-glass/polyester semi-hexagonal composite structures manufactured by different processes (vacuum assisted infusion, hand lay-up and ultraviolet (UV) cured pultrusion) have been studied for automotive crash applications. In order to evaluate the effect of the manufacturing process in energy absorption capability of the material, the interlaminar shear strength (ILSS) and the specific energy absorption (SEA) capability of the material have been characterised. Hand lay-up and UV cured pultrusion samples have shown similar ILSS values, around 43 MPa. However, the ILSS of the infusion samples is 33 MPa due to the uneven distribution of the fibres along the thickness of the samples. Furthermore, the lower values of ILSS have resulted in the lowest SEA values for the infusion samples; 31 kJ/kg. Hand lay-up samples have shown the highest SEA values (52 kJ/kg) and UV pultrusion samples slightly lower (49 kJ/kg) values due to a higher void content. Nonetheless, the material manufactured continuously by UV curing pultrusion process has shown high energy absorbing capabilities for crashworthiness applications.

Ge Qi and Li Ma, “Experimental investigation of composite pyramidal truss core sandwich panels with lightweight inserts”, Composite Structures, Vol. 187, pp 336-343, March 2018

ABSTRACT: Composite sandwich structures with lattice truss cores have both lightweight characteristics and multifunctional potential, which attract a large number of studies on topological optimization, manufacture process and performance evaluation in recent years. However, reliability study on the joint is an inevitable research subject for engineering application, and few studies on inserts within sandwich panels with lattice truss cores are published. In this paper, composite pyramidal truss core sandwich panels with lightweight metallic quadrangular-prism inserts are designed and fabricated. Pull-out and shear tests are carried out to investigate their load capability and failure behaviors, respectively. It is observed that, compared to the honeycomb panels, the present sandwich panels with quadrangular-prism inserts normally can obtain a similar level of pull-out strength but a higher level of shear load capabilities.


ABSTRACT: A hybrid discontinuous finite element method based on Delta function is developed for skewed and curved laminated beams/plates. Equal-order interpolations for displacement field and interface stress field are obtained without numerical oscillations. For the displacement field, the Consistent Orthogonal Basis Function Space is applied. For the interface stress field, the Delta function is used as basis functions. Two types
of Delta functions are discussed. For the first type, the Delta function is defined uniformly on the interface. For the second type, the Delta function is defined on the Gauss points. It is observed that the numerical oscillation occurs in the first type for a large deformation analysis. For the second type, it is always numerical stable. The effect domain of the Delta function is discussed such that the stress on the interface is able to be calculated. The laminated plate and beam with clamped boundary conditions are studied. The interface shear stress is compared with ANSYS. Numerical oscillation is not observed for the second type Delta function with equal-order interpolations of displacement and interface stress. Skewed and curved laminated plates are also analyzed. The accuracy is still good for various angles between adjacent edges and various curvatures.


ABSTRACT: The square honeycomb core is compressed quasi-statically and dynamically in order to investigate the mechanical properties of it. The plastic collapse stress under static compression is mathematically discussed by investigating the collapse mechanisms of cells from numerical simulations. Results show that the plastic collapse stress in the y direction is larger than that in the x direction under mult-cell condition, which agrees with the conclusion of numerical simulations. This difference is insensitive to the relative density within a specific range under quasi-static compression. However, it turns to be insignificant when the crushing velocity reaches or exceeds a critical velocity. A reverse method is proposed to estimate this critical velocity. For the equi-biaxial compression analysis, deformation process of the honeycomb is defined to three modes, and the deformation map is drawn. Compared with true stresses in both x and y directions in uniaxial compression, performances of them in equi-biaxial compression are reinforced. To represent the true stress in mathematical way, empirical formula for high velocity compression is derived. The energy absorption capacity is also enhanced, and the process is smoother around the stage of full densification than that under uniaxial compression.


ABSTRACT: This study gives a numerical work on dynamic response of cylindrical shells submerged in an incompressible fluid subjected to earthquake, thermal and moisture loads. The cylindrical shell is reinforced by carbon nanotubes (CNTs) where the Mori-Tanaka model is used for calculating the effective material properties of the structure considering agglomeration effects. The effect of the fluid is assumed using the acoustic wave equation. The structural damping effect is considered using Kelvin-Voigt model. Sinusoidal shear deformation shell theory (SSDT) is utilized in the shell dynamical equations based on energy method and Hamilton’s principle. The problem is framed combining shell motion equations with the acoustic wave equation where the fluid-loaded terms are considered with Hankel function of second kind. Differential quadrature method (DQM) and Newmark approach are employed to solve the shell problem. The influences of fluid, boundary condition, thermal load, moisture changes, boundary condition, structural damping parameter, length to thickness ratio of shell, CNTs volume percent and agglomeration are shown on the dynamic deflection of the structure. The results show that increasing the CNTs volume percent, the dynamic deflection decreases while considering the CNTs agglomeration leads to increase in the dynamic deflection of the structure.

ABSTRACT: The full dynamic response of FG-CNT reinforced composite plates with arbitrary geometry subjected to impact loading is considered in the present paper. The CNT reinforcement distribution is considered either uniform or functionally graded along the plate thickness and the equivalent mechanical properties of reinforced composite plates are estimated according to the extended rule of mixtures. The derived governing equations are based on high-order shear deformation theory, using Hamilton’s principle. An integration scheme appropriate for calculating double integral with variable limits is developed based on the Simpson’s rule to evaluate the components of Hamilton’s equation. A two-dimensional Ritz formulation appropriate for general boundary conditions is incorporated in the nonlinear Hertzian contact law to establish the equations of motion. A well-known fourth-order Runge-Kutta method is employed to solve the resulting equations in time domain. The validation of the proposed model is accomplished by comparing its results and those published in the literature and good agreement is achieved. A comprehensive sensitivity analysis is conducted to study the effect of various involved parameters such as CNT volume fraction and its distribution profile along the thickness, boundary conditions, temperature rising and in-plane loading on impact characteristics of both circular and triangular plates.


ABSTRACT: A novel approach using scaled boundary finite element method (SBFEM) associated with the precise integration technique (PIT) is proposed for the analysis of laminated composite and sandwich plates. The governing equation is derived strictly following the three-dimensional theory of elasticity, nevertheless, the formulation uses two-dimensional modeling in terms of translational displacements only. Unlike most theories presented in the literature, where to account for shear deformation effects in laminated composite plates, a variety of functions have been assumed to simulate the in-plane and the transverse displacements through the thickness, in the proposed approach, by virtue of the SBFEM, the displacements along the thickness direction are solved analytically and the PIT ensures high accuracy of the results. Numerical examples show that excellent agreement with the exact solutions applying three-dimensional theory of elasticity is reached. As a result, the predicted displacement and stress fields along the thickness direction of the plate can achieve very high accuracy, better than other models available in the literature. In addition, the proposed approach requires least nodal unknowns. The computational effort is saved to a great extent.

Martin Pietrek and Peter Horst, “Analysis and numerical prediction of the delamination behaviour of debonded asymmetric sandwich shells with a thin-walled skin considering plastic deformation”, Composite Structures, Vol. 188, pp 220-232, March 2018

ABSTRACT: This paper analyzes the delamination behavior of asymmetric sandwich shells with one thin-walled aluminum skin. In-plane compression tests of specimens with a delamination of the aluminum skin show high dependencies of the failure loads and the debond behavior on the delamination size and its in-depth position relative to the adhesive layer. All delaminations proceed in an unstable manner within the foam core close to the adhesive interface. A FE model is created and correctly reproduces the specimen’s deformation and buckling behavior. Its predictions of failure loads are conservative but show some deviations. Furthermore, the numerical simulations are used for the analysis of occurring plastic strains in the aluminum skin. As shown, they have major influence on the delamination behavior. Large portions of the debonded areas are plastically deformed and relatively large amounts of deformation energy are dissipated by the plastic deformation.

Xiang Ou, Xiaoqing Zhang, Run Zhang, Xiaohu Yao and Qiang Han, “Weak form quadrature element analysis on nonlinear bifurcation and post-buckling of cylindrical composite laminates”, Composite Structures, Vol. 188, pp 266-277, March 2018
ABSTRACT: This paper presents a weak form quadrature element formulation in the analysis of nonlinear bifurcation and post-buckling of cylindrical composite laminates subjected to transverse loads. A total Lagrangian updating scheme is used in combination with arc-length method and the branch switching method is adopted to identify the whole post-buckling procedure of the laminates. The formulation of the shell model is based on the basic concept of Ahmad. The coincidence of discrete nodes and integration points in quadrature element endows it with compactness and conciseness in the nonlinear buckling analysis of cylindrical laminates. Shear and membrane locking problems are avoided in the quadrature element formulation for its high-order approximation property. Several numerical examples are firstly presented to verify the effectiveness and accuracy of the present formulation. Parametric studies of the effects including rise, thickness, boundary conditions and lamination scheme of the cylindrical composite laminates on the bifurcation and post-buckling behaviors are performed.


ABSTRACT: In this study the free vibration problem of laminated orthotropic conical shells (LOCSs) based on the modified version of first order shear deformation theory (FSDT) is investigated. Based on the physical and mathematical reasoning, the motion equations for LOCSs are derived and obtained formula for the frequency parameters using the Galerkin's method. In order to prove the validity of the formulas, the specific cases of this study were compared with the results of other studies in the literature. Finally, the influence of various parameters; stacking-sequence, shear stresses (SSs) and aspect ratio on the fundamental frequency parameters (FFPs) of LOCSs are examined.


ABSTRACT: In this study, the free vibration characteristics of variable stiffness laminated composite shells is numerically studied using a higher-order accurate theory. The unique feature of the variable stiffness composites is that the fiber orientation within the lamina changes continuously leading to spatial variation of stiffness of the resulting laminate. A systematic parametric study is conducted to bring out the influence of fiber orientation within and across the laminae, shell geometry and the structural theory on the fundamental frequency. The influence of environmental factors such as the temperature and the presence of moisture is also considered. It is inferred that the spatial variation of stiffness due to curvilinear fibres introduces additional flexibility in designing structures made of such materials.


ABSTRACT: A multi-scale model is proposed to investigate arbitrarily functionally graded hollow cylinders (discs), with fibers, particles, or disc-shaped reinforcements, subjected to harmonic loading conditions. The stress analyses are performed by dividing the cylinders (discs) into several layers each with homogeneous properties, which are functionally graded through the thickness of the structures, with varying microstructural details. Good agreement can be obtained by comparing the present stress distributions against other analytical solutions used as boundary conditions or obtained for homogeneous and continuously graded structures. Furthermore, the Mori-Tanaka model is used to generate effective properties of each layer reinforced with fibers, particles or disc-shaped inclusions. The stress distributions in the cylinders along the radial direction are effectively investigated with the influence of either the shape or the volume fraction of reinforcements. Finally,
the particle swarm optimization technique is combined with the present framework to provide inverse calculations for microstructural details, in the effort of finding proper inclusion volume fractions or minimizing the shear stress along the radial direction, which are necessary for the design of functionally graded structures. The present analysis for arbitrarily FG cylinders under arbitrary loading conditions provides benchmark solutions for other future analytical and numerical methods.


ABSTRACT: This paper aims to investigate the low-velocity impact response and post-impact flexural behaviour of hybrid sandwich structures consisting of carbon fibre-reinforced polymer (CFRP) face sheets and aluminium alloy corrugated cores. A combined experimental and numerical study is carried out over a range of impact energies and impact sites to evaluate the effects of the abovementioned factors on the impact damage and residual flexural strength. Low-velocity impact tests are performed to investigate the impact resistance of such structures with respect to impact load, absorbed energy and failure mode. Subsequently, three-point bending tests are conducted to determine and quantify the effects of impact damage on the residual properties of post-impact sandwich structures. Meanwhile, a procedure to numerically simulate the low-velocity impact tests and residual flexural strength tests of sandwich structures is developed by the VUMAT subroutine in ABAQUS/Explicit. Reasonably good agreement is achieved when comparing the impact response and flexural behaviour between experimental measurements and numerical predictions. These studies reveal that the damage depends on the impact energy and impact location. The residual flexural strength decreases significantly even though the impact energy is lower than 10 J, while there is a slight reduction with a further increase in the impact energy.

Wanli Yang and Dan He, “Bending, free vibration and buckling analyses of anisotropic layered micro-plates based on a new size-dependent model”, Composite Structures, Vol. 189 pp 137-147, April 2018

ABSTRACT: A new size-dependent composite laminated plate model is proposed in this study based on a re-modified couple stress theory (RMCST) and a zigzag theory. In contrast to the published size-dependent models for composite laminated plates, present model a priori satisfies the continuity conditions of transverse shear stresses (TSSs) at the interfaces. In the present formulation, the discontinuous TSSs obtained from the constitutive relations are replaced by the new continuous TSSs by using the Reissner’s Mixed Variational Theorem (RMVT). In addition, the RMVT is utilized to obtain the governing equations and corresponding boundary conditions. Subsequently, the deflections, stresses, frequencies and critical loads of cross-ply simply supported plates are considered to verify the present formulation. The results prove that the scale effects of present size-dependent models are effectively investigated. Moreover, the results predicted by present size-independent models are in accordance with the exact solutions. Eventually, the differences of the mechanical performance among the following three models, i.e. present, Mindlin and Reddy for composite laminated plates are discussed in different modulus and span-to-thickness ratios.

Yanchun Zhai, Mengjiang Chai, Jianmin Su and Sen Liang, “Dynamics properties of composite sandwich open circular cylindrical shells”, Composite Structures, Vol. 189 pp 148-159, April 2018

ABSTRACT: This paper deals with the dynamic properties of three-layered composite sandwich open circular cylindrical shells (CSOCCS). First, the equations of motion that govern the free vibrations of CSOCCS are derived by applying Hamilton’s principle based on the first-order shear deformation shell theory. Owing to considering the effect of rotary inertias and shear deformation, thin-to-moderately thick shells can be analyzed. Next, these equations are solved by means of the closed-form Navier method. The calculated results are
compared with the findings of previous studies and those obtained by the finite element method, and a good agreement is observed. The variation of modal loss factor and frequency with system parameters is evaluated and presented graphically. It is the first time to study the dynamic properties of composite open circular cylindrical shells with constrained viscoelastic core.

ABSTRACT: This paper analyses the numerical and experimental results to evaluate the dynamic properties of pultruded GFRP (Glass-Fiber Reinforced Polymers) buckled columns. The profiles are made of glass fiber reinforcement and thermosetting vinyl ester matrix with thin-walled open or closed cross section. The buckling phenomena of the column with fixed ends were evaluated with a non-destructive method based on experimental modal data through dynamic identification procedure. Numerical analysis has been carried out through Finite Element models calibrated considering two consecutive stages that involve the local and global scale: i) parametric natural frequencies analysis to model the different cross sections taking into account the stiffness of the rotational constraint between the wall segments of the thin walled pultruded profiles; ii) buckling analysis to identify the inaccuracies in the specimen or in the experimental apparatus through global flexural displacements which increase continuously with the axial load. Experimental, theoretical and numerical results were compared in order to know the wall segment effects of GFRP columns in free vibration field when affected by buckling phenomena. The results allow to investigate the significant role that the manufacturing imperfections of pultruded material play in the structural performance of GFRP buckled columns.

Francesco Tornabene, Nicholas Fantuzzi, Michele Bacciocchi and Erasmo Viola, “Mechanical behavior of damaged laminated composites plates and shells: Higher-order shear deformation theories”, Composite Structures, Vol. 189 pp 304-329, April 2018
ABSTRACT: The paper aims to present a novel mathematical formulation for the modelling of damage. In particular, the decay of the mechanical properties of the elastic media is modeled by means of two-dimensional smooth functions, which are the Gaussian and the ellipse shaped ones. Various damaged configurations are obtained as concentrated variations of the elastic properties of the materials by setting properly the parameters that define the distributions at issue. This approach is employed to investigate the dynamic behavior of damaged plates and shells made of composite materials. In particular, a massive set of parametric studies is presented for this purpose. The results are obtained numerically by means of the Generalized Differential Quadrature (GDQ) method and are presented in terms of natural frequencies. Several Higher-order Shear Deformation Theories (HSDTs), which can include also the Murakami’s function to capture the so-called zig-zag effect, are used and compared.

Xiaobin Deng, Chen Zhang, Voulong Chen, Yuan Yan, . . . Xi Chen, “Crush behaviors of polyvinyl chloride cellular structures with liquid filler”, Composite Structures, Vol. 189 pp 428-434, April 2018
ABSTRACT: In this work, the crush behaviors of hemi-ellipsoid polyvinyl chloride cellular structures (PVC-CS) with liquid filler (i.e. water) are experimentally studied. The load capacity and energy absorption characteristics of the liquid filled PVC-CS are significantly enhanced due to the additional support of liquid filler and the lateral expansion of PVC-CS, compared with the hollow PVC-CS without sealing. Besides, both the hollow and liquid filled PVC-CS are flexible and their deformations are fully reversible upon compression (for compressive strain up to 0.8) owing to the superelasticity of PVC. The effects of PVC hardness and strain rate on the crush behaviors of hollow and liquid filled PVC-CS are also explored. A homogeneous material model is developed by incorporating viscosity into the hyperelastic Yeoh model, which can describe the impacting behaviors of the liquid filled PVC-CS. The results presented in this work provide guidelines for
designing and engineering high-performance energy absorption structures that are resilient, flexible, and of high energy absorption density.

ABSTRACT: An experimental program investigating the flange local buckling (FLB) behavior of pGFRP box-sections is reported. The commonly accepted design equation based on plate theory was validated although importance of accurate assessment of the rotational stiffness of the web-flange junctions was identified. It is concluded that the lower bound solution, assuming the flange is a simply-supported plate subject to uniform compressive stress, results in uniformly conservative predictions of the critical FLB moments. The theoretical solution accounting for flange plate edge support stiffness based only on web stiffness, material and geometric properties of the cross section over predicts the support stiffness resulting in unconservative predictions of FLB behavior. The rotational stiffness of flange-web junction of the pGFRP box-section is also investigated experimentally. It is found that the actual rotational stiffness of flange-web junction is relatively low, closer to the simply-supported boundary condition. The role of fiber architecture at the web-flange junction is identified as affecting this behavior. The conclusions of this study support the use of the lower bound solution for design of pGFRP box-sections.

Dongying Liu, Sritawat Kitipornchai, Weiqiu Chen and Jie Yang, “Three-dimensional buckling and free vibration analyses of initially stressed functionally graded graphene reinforced composite cylindrical shell”, Composite Structures, Vol. 189 pp 560-569, April 2018
ABSTRACT: The buckling and free vibration of initially stressed functionally graded cylindrical shell reinforced with non-uniformly distributed graphene platelets (GPLs) are investigated using the state-space formulation based on three-dimensional elasticity theory. The shell is under an axial initial stress and composed of multilayers with GPLs uniformly dispersed in each individual layer but its weight fraction changing layer-by-layer along the thickness direction. The modified Halpin-Tsai model and rule of mixtures are employed to evaluate the effective elastic properties of the GPL-reinforced shell. Analytical buckling and frequency solutions are obtained for simply supported shells. Numerical results are presented for functionally graded GPL-reinforced cylindrical shells with five GPL dispersion patterns (GPL-UD, GPL-V, GPL-A, GPL-X, and GPL-O). The effects of GPL weight fraction, dispersion pattern, geometry, and size as well as the influence of initial stress on the buckling and free vibration characteristics of the shell are discussed in detail. It is found that the addition of a small amount of GPLs significantly increases the critical buckling stress and natural frequencies. The GPL-X pattern outperforms other patterns for thin composite shells while the uniform pattern GPL-UD works better for thick composite shells.

W. Zhang, S.W. Yang and J.J. Mao, “Nonlinear radial breathing vibrations of CFRP laminated cylindrical shell with non-normal boundary conditions subjected to axial pressure and radial line load at two ends”, Composite Structures, Vol. 190 pp 52-78, April 2018
ABSTRACT: The cylindrical shell structure is an important kind of the primary structures in many engineering community. Under axial excitation and radial line load, the nonlinear radial breathing vibrations of a carbon fiber reinforced polymer (CFRP) laminated cylindrical shell with different temperature is investigated in this paper. Based on von Karman type nonlinear geometric relationship, the first-order shear deformation shell theory is applied to model the kinematics of deformations, and Hamilton’s principle is used to drive the differential governing equations. Galerkin method is utilized to obtain the nonlinear ordinary differential governing equations along the radial displacement of the system under the non-normal boundary conditions that one generatrix of the cylindrical shell is clamped and both ends of the shell are free. The bifurcation diagrams,
maximum Lyapunov exponent diagrams, phase portraits, the time history diagrams, three-dimensional phase portraits and poincare maps are obtained by using the fourth-order Runge-Kutta algorithm. The influences of the radial line load, the axial excitation as well as the ratio of length to thickness on the nonlinear radial breath vibrations characteristics of the CFRP laminated cylindrical shell are studied in detail by numerical calculations. The results show that the radial line load, axial excitation and ratio of length to thickness can be used to control the nonlinear dynamic motions.

Hooman Aminipour, Maziar Janghorban and Li Li, “A new model for wave propagation in functionally graded anisotropic doubly-curved shells”, Composite Structures, Vol. 190 pp 91-111, April 2018
ABSTRACT: This research is devoted to an investigation on the wave propagation in doubly-curved shell made of Functionally Graded Anisotropic materials in the framework of an accurate higher order shear deformation theory. In this recently developed theory, an exponential formula in combination with a trigonometric function are used for modeling the displacement field. This type of theory has only five unknowns but it seems that it can have precise results in various conditions for thick and thin shells. In the functionally graded anisotropic material, all components of the elastic stiffness tensor and density are varied exponentially through the thickness direction. Hamilton’s principle is utilized with the purpose of deriving the governing equations in orthogonal curvilinear coordinates. The analytical dispersion relations are obtained by solving an eigenvalue problem. These methods are validated by comparing authors’ results with other papers available in open literature for isotropic and functionally graded plates. Detailed parametric studies are then carried out to scrutinize the influences of wave number, geometrical shape, exponential factor and volume fraction index on the circular frequencies, phase velocities and group velocities. From the best knowledge of authors, it is the first time that functionally graded anisotropic doubly-curved shells are investigated in open literature.

ABSTRACT: The linear dynamics of axially functionally graded (AFG) cantilevered pipes conveying fluid is studied, aiming at enhancing the dynamic stability of such fluid-interaction systems. Either the elastic modulus or the density of the AFG cantilevered pipe is assumed to be varied from the clamped to the free ends. The governing equation of the AFG pipe is derived first and then discretized by using the differential quadrature method (DQM). The effects of elastic modulus gradient and density gradient on the critical flow velocity for flutter instability are analyzed. It is found that, compared with uniform pipes, the decrease of density along the pipe length leads to a more stable system, while the opposite result may be obtained for the decrease of elastic modulus for small values of mass ratio. From the boundary curves of critical flow velocity versus density gradient and of critical flow velocity versus elastic modulus gradient, it is shown that the occurrence of Z-shape segments is possible when the mass ratio becomes large. Furthermore, the phenomenon of mode exchange has also been detected with increasing density gradient or elastic modulus gradient within a certain range of mass ratio.

ABSTRACT: The nonlinear dynamic behaviours of functionally graded (FG) cylindrical shells under combined parametric and external excitations are presented in this paper. Based on the von Kármán nonlinear theory, Galerkin’s method and the static condensation method, the coupled nonlinear differential equations with two modes are derived. The method of multiple scales is applied to solve the coupled nonlinear differential equations having both quadratic and cubic nonlinearities, and the principal resonance and internal resonance of the system are investigated by the frequency response curves. The dynamic stability of parametric excitations is
also investigated by time responses of the fundamental mode. The effects of different parameters on the nonlinear vibration are discussed by numerical simulation. Some comparisons are made with the available published work and good agreement is obtained.

Matin Latifi, Mahsa Kharazi and Hamid Reza Ovesy, “Nonlinear dynamic instability analysis of sandwich beams with integral viscoelastic core using different criteria”, Composite Structures, Vol. 191 pp 89-99, May 2018
ABSTRACT: This paper deals with the nonlinear dynamic instability analysis of three-layered composite beams with viscoelastic core subjected to combined lateral and axial loadings. The Full-Layerwise theory (FLWT) based on the assumptions of advanced first-order shear deformation theory (AFSDT) is employed to model the sandwich beam. The viscoelastic constitutive equation is considered as the Boltzmann’s integral form with the Koltunov-Rzhanitsyn kernel. The obtained nonlinear integro-partial differential equations (IPDEs) of motion are solved by using Galerkin’s discretization method in combination with Newton-Raphson algorithm. The dynamic instability is analysed by using the Budiansky-Hutchinson, modified-Budiansky and Volmir criteria in conjunction with the phase-plane analysis of the studied cases. It is observed that, the modified-Budiansky criterion and the phase-plane analysis are more appropriate to investigate the dynamic instability of the beams especially with the viscoelastic cores. In addition, the effects of different rheological parameters (R-Ps) of viscoelastic core on the dynamic instability of sandwich beams are investigated by using modified-Budiansky criterion and the phase-plane analysis.

ABSTRACT: Wave behavior is investigated in a piezoelectric coupled laminated fiber-reinforced composite cylindrical shell by considering the transverse shear effects and rotary inertia. A mathematical model is presented for analysis of wave propagation in a laminated fiber-reinforced composite cylindrical shell coated with the piezoelectric layer. By solving an eigenvalue problem, dispersion characteristics for different wave modes are obtained. Piezoelectric effect on dispersion curve is investigated. The effects of material properties of host substrate shell, laminate stacking sequence, and fiber orientation on dispersion curve are examined as well. In addition, a comparison of dispersion solutions from different shell theories with different axial and circumferential wave numbers and piezoelectric layer thickness is provided to illustrate the transverse shear and rotary inertia effects on wave behavior of a laminated fiber-reinforced composite shell. The results of this paper can be used for studies on wave propagation in piezoelectric coupled laminated composite shell structures and in design of smart composite shell structures with the piezoelectric material for health monitoring and dynamic stability evaluation.

ABSTRACT: Through-the-Thickness Jacketing (TTJ) is a technique for repairing and retrofitting shell structures by inducing in the shell core a beneficial confining stress state created by a net of broadly distributed retrofitting links crossing the shell thickness and tying externally applied layers. The paper presents the derivation, the algorithmic implementation and the numerical assessment of a predictor-corrector computational strategy for the integration of a shell FE-model obtained by combining a discrete MITC quadrilateral element with a layered continuum-based generalized shell theory of TTJ-reinforced structures, essentially based upon a
Winkler-like idealization of TTJ. This theory of Through-the-Thickness-Jacketed Shells (TTJS) captures the onset of complex triaxial stress states originated by the interaction between core and TTJ reinforcements. Results of benchmark numerical applications in OpenSees with flat and curved elastic-plastic shell structures are presented in order to assess and illustrate the consistency and the general modelling features of the proposed TTJS-MITC framework endowed with the Drucker-Prager elastic-perfectly-plastic idealization of the nonlinear behavior of the material composing the shell. Numerical results exhibit quadratic convergence and show that the model captures marked strength increments over the in-plane membrane response, albeit these are lower when the response is predominantly of out-of-plane flexural type.


ABSTRACT: This work presents the free vibration analysis of tapered aircraft structures made of composite and metallic materials, with reference to global and local damage. A refined one-dimensional model, developed in the framework of the Carrera Unified Formulation, has been used to provide a detailed description of structures. Multi-component aeronautical structures have been modeled adopting Lagrange polynomials to evaluate the displacement field over the cross-section. Each component has been described through the component-wise approach, with its own geometrical and mechanical characteristics. The effects of localized damage have been investigated, thanks to the accuracy of the layer-wise models adopted. The model has been assessed by comparing the results with classical FE models. The results show that the present approach provides an accurate solution for the free vibration analyses of complex structures and is able to predict the consequences of a global or local failure of a structural component. The computational efficiency and the accuracy of the model used in this work can be exploited to characterize the dynamic response of complex composite structures considering a large number of damage configurations.


ABSTRACT: To assess a load-carrying capacity of compressed thin-walled plate structures in the paper the coupling buckling phenomenon of compressed columns was analyzed. The columns were of open cross-sections and made of coupled laminate. Selected configuration of laminate layers enables different types of coupling between membrane and bending states which describes the coupling stiffness submatrix B. Element values of stiffness matrix ABD were determined with application of classical laminate plate theory CLPT. The main aim of the work is to estimate an influence of chosen submatrix B elements on buckling, postbuckling and load-carrying capacity of analyzed thin-walled structures. The problem was solved with the Koiter’s theory application. The detailed computations were performed for uniformly compressed lip channel and top hat channel. The dimensions of both columns were chosen in a way which allowed to observe the strong coupling effect among different buckling modes. It were two laminate configurations considered which differed in value of stiffness reduction coefficients.


ABSTRACT: This paper presents the results of an experimental work carried out to fabricate and characterise the in-situ foam filled tubes (FFTs) made of aluminium alloys prepared by powder metallurgy method, using aluminium alloy tubes with extremely thin walls (~0.6 mm). The fabrication procedure demonstrates that thin-walled tubes with extremely thin walls can support temperatures near to its melting temperature (~700 °C)
required to form a closed-cell aluminium alloy foam, consequently in-situ filling the tube. The mechanical performance of fabricated structures was evaluated using uniaxial compressive tests and infrared thermography. Results demonstrate that the benefits of the manufacturing process and its product, the FFTs (composite structures). Additionally, they reveal that this is a cost-effective solution to prepare efficient energy absorbing lightweight structures, allowing to adjust the weight and levels of the energy absorption, simultaneously. The results demonstrate that the promising in-situ FFTs with thinner outer tubes axially deform in an efficient mixed mode, showing superior energy absorption capability compared to the empty thin-walled tubes.


Abstract: This paper presents a size-dependent four-unknown shear deformable model for static bending, free vibration and buckling analyses of isotropic and sandwich functionally graded (FG) microplates based on the modified strain gradient theory (MSGT). The MSGT requires three material length scale parameters instead of five parameters as well known in the original strain gradient theory. The material parameters of isotropic and sandwich FG microplates are directly derived from a rule of mixture. The governing equations are derived from the principle of virtual work. Since the present method contains the higher-order gradients in the weak form, NURBS-based isogeometric analysis is suitable for the solution procedure. The effects of geometrical parameters, boundary conditions, volume fraction and material length scale parameters are investigated through isotropic and sandwich FG microplate examples. Obtained results indicate that the consideration of strain gradients leads to a rise of the plate stiffness, and a reduction of displacement and an increase in natural frequency as well as critical buckling load of FG microplates are therefore remarked. Moreover, the present model can be degenerated into the modified couple stress model or classical model when a few material length-scale parameters are neglected.

Dahai Zhang, Qingguo Fei, Dong Jiang and Yanbin Li, “Numerical and analytical investigation on crushing of fractal-like honeycombs with self-similar hierarchy”, Composite Structures, Vol. 192 pp 289-299, May 2018

Abstract: The out-of-plane crushing resistance of fractal-like honeycombs with self-similar hierarchy are investigated numerically and analytically. The hierarchical honeycombs are developed via replacing each three-edge vertex of a regular hexagonal honeycomb by a smaller hexagon. Hierarchical honeycombs with higher orders are constructed by repeating this process. Theoretical solutions are derived based on the Super Folding Element (SFE) theory to predict the mean crushing forces (MCFs) of the hierarchical honeycombs. Numerical simulations are also conducted in conjunction with the theoretical solutions. Crushing resistances of three groups of hierarchical honeycombs with different relative densities are explored subsequently. Good agreement between results obtained using theoretical and numerical methods indicates that the theoretical predictions are reliable. The results show that hierarchy can significantly improve the crushing resistance of honeycombs. It is found that the MCFs of first to fourth order hierarchical honeycombs are improved by 71%, 114%, 201% and 309% compared with the regular honeycomb under the same relative density, respectively. It reveals that the amplification of the MCF from one generation to the next approaches a constant ($\xi_n \approx 1.26$) when the hierarchical order is sufficiently large. The potential maximum achievable amplifications of the MCF for hierarchical honeycombs of different relative densities are also discussed.


Abstract: Bistable composite cylindrical shells have attracted many attentions thanks to their lightness, simple structure and high packaging efficiency. The ploy region between the two stable states of a bistable
cylindrical shell affects the structural properties and overall compactness significantly. An analytical model is proposed assuming that the longitudinal and transverse curvatures are two dominant factors for the two different zones of the ploy region respectively. The model can be used to predict the length and the curvature distributions of the ploy region conveniently. Results obtained from the analytical model agree with numerical and experimental results. The influences of geometric parameters and bending stiffnesses on the ploy region are discussed according to the proposed analytical model.


ABSTRACT: In this paper insights are provided into the implementation and use of the Ritz method for free vibration and buckling analysis of composite plates. Focus is given on the choice of the trial functions in relation to the degree and the kind of anisotropy exhibited by the plates. The Ritz approximation is applied to models based both on the classical lamination theory and a more advanced variable-kinematic formulation, capable of dealing with several higher order plate theories within an unified framework. A very efficient computation of the Ritz integrals is proposed, which allows to handle hundreds of admissible functions. In this way, accurate upper bound solutions can be obtained even for problems where the convergence rate of the Ritz method is low due to extreme levels of anisotropy. The effect of different forms of elastic couplings, boundary conditions and amount of material anisotropy on the convergence and accuracy of the solution is investigated when different sets of admissible functions – Legendre and Chebyshev polynomials, as well as of trigonometric type – are adopted. Important remarks about the completeness and numerical efficiency of the selected basis are also provided.

Hanfeng Yin, Xiaofei Huang, Fabrizio Scarpa, Guilin Wen, . . . Chao Zhang, “In-plane crashworthiness of bio-inspired hierarchical honeycombs”, Composite Structures, Vol. 192 pp 516-527, May 2018

ABSTRACT: Biological tissues like bone, wood, and sponge possess hierarchical cellular topologies, which are lightweight and feature an excellent energy absorption capability. Here we present a system of bio-inspired hierarchical honeycomb structures based on hexagonal, Kagome, and triangular tessellations. The hierarchical designs and a reference regular honeycomb configuration are subjected to simulated in-plane impact using the nonlinear finite element code LS-DYNA. The numerical simulation results show that the triangular hierarchical honeycomb provides the best performance compared to the other two hierarchical honeycombs, and features more than twice the energy absorbed by the regular honeycomb under similar loading conditions. We also propose a parametric study correlating the microstructure parameters (hierarchical length ratio r and the number of sub cells N) to the energy absorption capacity of these hierarchical honeycombs. The triangular hierarchical honeycomb with N=2 and r=1/8 shows the highest energy absorption capacity among all the investigated cases, and this configuration could be employed as a benchmark for the design of future safety protective systems.

Fei Wu, Xiaoting Xiao, Yong Dong, Jie Yang and Yeqi Yu, “Quasi-static axial crush response and energy absorption of layered composite structure formed from novel crochet-sintered mesh tube and thin-walled tube”, Composite Structures, Vol. 192 pp 592-604, May 2018

ABSTRACT: This work investigates the quasi-static crush response and energy absorption of the layered composite circular tubes formed by matching thin-walled tubes with novel crochet-sintered mesh tubes (CSMTs). The matching effect existed between the CSMT and the thin-walled tube have been observed. The CSMTs are suitable for application as energy absorption components to improve the load-bearing capacity and energy absorption of thin-walled tubes. The load-carrying capacity, energy absorption, effective stroke ratio and crushing force efficiency of layered composite tubes all increases, compared to those of metal thin-walled tube.
The increment scale of energy absorption can be reach 106%. The load-carrying capacity, energy absorption, crushing force efficiency and specific energy absorption of the three-layered structure are higher than those of the two-layered structures. The initial impact effect of the three-layered tubes is weaker than that of the two-layered tubes. These show that the former have better structure crashworthiness than the latter. The layered composite tubes show great potential for application as energy absorbers.

ABSTRACT: Present investigation deals with the nonlinear vibration of a sandwich plate with a homogeneous core and graphene-reinforced composite (GRC) face sheets supported by an elastic foundation under thermal environmental conditions. The material properties of GRC face sheets are assumed to be piece-wise functionally graded by changing the volume fraction of graphene in the thickness direction. The material properties of both the homogeneous core and the GRC face sheets are assumed to be temperature-dependent, and are estimated by the extended Halpin-Tsai micromechanical model. Reddy’s higher order shear deformation plate theory and the von Kármán-type kinematic nonlinearity are used to derive the motion equations which account for the plate-foundation interaction and the thermal effects. The nonlinear vibration solutions for the sandwich plate can be obtained by using a two-step perturbation technique. The effects of distribution type of reinforcements, core-to-face sheet thickness ratio, temperature variation, foundation stiffness and in-plane boundary conditions on the nonlinear vibration characteristics of sandwich plates with piece-wise functionally graded GRC face sheets are discussed in detail.

ABSTRACT: A numerical stochastic strategy for optimising composite elastic shells undergoing buckling is presented. Its scope is to search for the best stacking sequence that maximises the collapse load considering the post-buckling behaviour. Its feasibility is due to a reduced order model built for each material setup starting from a hybrid solid-shell finite element model exploiting a multimodal Koiter method. The approach has no limitations concerning geometry, boundary conditions and material properties distribution. The collapse load is evaluated using a Monte Carlo simulation able to detect the worst imperfection shape, including a posteriori the imperfections in the reduced order model. For a limited number of parameters the proposal allows to analyse all the possible layups. In the general case, it uses a Monte Carlo scanning of the design parameters with different levels of adaptability. The optimisation of curved panels, also with stiffeners, confirms the feasibility and reliability of the proposed strategy.

ABSTRACT: The present study deals with vibration of functionally graded viscoelastic open-cell foam plates resting on three parameters orthotropic visco-Pasternak foundation. The kinematic and constitutive relations are described by classical plate theory and separable kernels framework, respectively. Viscoelastic treatment of bulk and shear moduli of plates are modeled by standard solid and Kelvin-Voigt models. Also, nonlinear non-symmetric porosity distribution through thickness is obtained using power law and neutral surface decoupling. The integro-PDE of motion with frequency-dependent coefficients is figured out by weighted residual method and iterative numerical algorithm to obtain natural frequencies and modal loss factors. In elastic domain, frequencies are compared with those reported for thin functionally graded plates resting on isotropic Pasternak foundation while in the viscoelastic domain, complex frequencies are compared for standard solid and Kelvin-
Voigt viscoelastic plates where acceptable correlation is observed. Influences of various boundary conditions including fully clamped and fully free edge conditions, aspect ratio, coefficients and orthotropy angle of medium on dynamic characteristics are scrutinized via a comprehensive parametric study which could be used as benchmark results in future studies.

ABSTRACT: Free vibration of layered circular cylindrical shell filled with fluid with an anti-symmetric angle-ply walls including first-order shear deformation theory is presented. The fluid is assumed to be quiescent and inviscid. The permeability condition on the fluid-shell interface is applied to ensure the contact between the fluid and shell wall. The governing equations are obtained in terms of displacement and rotational functions. These functions are assumed in a separable form, resulting into a system of ordinary differential equation. Bickley-type spline of order three is applied to the problem, along with the equations of boundary conditions, bringing out into the system of homogeneous equations and become as a generalized eigenvalue problem. This problem is solved for frequency parameter with an associated eigenvectors. The effect of shell geometry, types of material, ply-orientations, number of layers and boundary conditions on frequencies are studied.

Jie Yang, Da Chen and Sritawat Kitipornchai, “Buckling and free vibration analyses of functionally graded graphene reinforced porous nanocomposite plates based on Chebyshev-Ritz method”, Composite Structures, Vol. 193 pp 281-294, June 2018
ABSTRACT: This paper is concerned with the buckling and free vibration behaviors of functionally graded (FG) porous nanocomposite plates reinforced with graphene platelets (GPLs). The porous plates are constructed based on a multiplayer model with GPLs uniformly or non-uniformly distributed in the metal matrix containing open-cell internal pores. The modified Halpin-Tsai micromechanics model, the extended rule of mixture, and the typical mechanical properties of open-cell metal foams are used to determine the effective properties of the porous nanocomposite. By using the first-order shear deformation plate theory (FSDT) to account for the transverse shear strain and Chebyshev-Ritz method to discretize the displacement fields, the governing equations are derived and then solved to calculate the critical uniaxial, biaxial and shear buckling loads and natural frequencies of the plates with different porosity distributions and GPL dispersion patterns. After a convergence and validation study to verify the present analysis, a comprehensive parametric investigation on the influences of the weight fraction and geometric parameters of GPL nanofiller and the porosity coefficient is conducted to identify the most effective way to achieve improved buckling and vibration resistances of the porous nanocomposite plate.

Xiang Xu, Yong Zhang, Jin Wang, Feng Jiang and Chun H. Wang, “Crashworthiness design of novel hierarchical hexagonal columns”, Composite Structures, Vol. 194 pp 36-48, June 2018
ABSTRACT: Self-similar hierarchical structures are widely observed in nature, and have been credited with superior mechanical properties. In this paper, a novel self-similar hierarchical hexagonal columns (HHC) is proposed to improve structural crashworthiness performance. The self-similar hierarchical hexagonal columns are constructed by iteratively adding sub-hexagons at the corners of primary hexagon. To investigate the crashworthiness of HHC, the nonlinear finite element model is first developed and validated against experimental data obtained from 1st order HHC. Numerical investigations of 1st and 2nd order hierarchical hexagonal columns with different hierarchical levels are performed to compare with 0th order HHC, the results show that 1st and 2nd order hierarchical hexagonal columns improve the energy absorption and crush force efficiency by governing the material distribution, especially, 2nd order HHC exhibits significant advantage for
energy absorption. In addition, parametric designs of 2nd order HHC are carried out to explore crashworthiness effect on hierarchical size ratio, cell wall thickness and impact velocity. The significant effects on both specific energy absorption (SEA) and the peak crushing force (PCF) are observed. The findings of this study offer a new route of designing novel crashworthiness structure with highly energy absorption capacity.

Qiang Liu, Hao Shen, Yinghan Wu, Zhencong Xia, . . . Qing Li, “Crash responses under multiple impacts and residual properties of CFRP and aluminum tubes”, Composite Structures, Vol. 194 pp 87-103, June 2018

ABSTRACT: This study aimed to explore the impact responses and residual properties of thin-walled carbon fiber reinforced plastics (CFRP) tubes and aluminum (Al) tubes subjected to multiple axial impacts. Five repeated impacts with the same impact energy were first conducted to evaluate the effect of repeated impact number, and then the crushing tests were performed to explore the post-impact residual behavior. Regardless of number of repeated impacts, the progressive end crushing modes for the CFRP tubes and stable progressive folding mode for aluminum tubes were identified under repeated dynamic impacts. The CFRP tubes exhibited the highest specific energy absorption (SEA) under the 1st impact, then the similar SEA values in the other four subsequent impacts; whereas the SEA of aluminum tubes fluctuated with the repeated impact numbers which were related to formation of different folds. The quasi-static crushing tests revealed that the residual SEAs of the CFRP tubes and aluminum tubes were not much influenced by the impact number, only within a difference of 5% under the 5 repetitive impacts conducted. It was demonstrated that the CFRP tubes had much better performance in energy absorption capability in comparison with the aluminum tubes in terms of repeated impacts and residual crushing tests.


ABSTRACT: Composite pipes have become a viable alternative to metallic pipes in several applications. Flow-accelerated erosion and internal surface attack often result in thickness thinning that may compromise the structural integrity of the pipe and lead to its failure. In this paper, we investigate how the internal surface damage is reflected on the vibration behavior of a composite pipe conveying fluid. The defected pipe-fluid system is modeled using the extended Hamilton’s approach and discretized using the wavelet-based finite element method. The modal characteristics of the pipe vibrations have been obtained by solving the generalized eigenvalue problem. The developed model was validated and some benchmark solutions are presented to highlight the effects of the internal wall-thinning on the vibrational behavior of composite pipes conveying fluid. The obtained results facilitate the future research by revealing the potential of using the vibration signature as a basis for detection of erosion-induced internal defects in pipelines.


ABSTRACT: In this paper, a unified Jacobi-Ritz method is presented and implemented to study the free vibration analysis of coupled composite laminated axis-symmetric doubly-curved revolution shell structures with general boundary conditions in the framework of the first-order shear deformation theory. The substructure of coupled structures mainly contains the laminated elliptical, hyperbolical, paraboloidal and cylindrical shells. In the theoretical analysis model, the multi-segment partitioning strategy is adopted. The displacement functions of each shell segment are uniformly expanded in the form of a double mixed series in which Jacobi polynomials are along the meridional direction and the standard Fourier series is along the circumferential direction, regardless of the shell components and the boundary conditions. The vibration results including frequency parameters and mode shapes of coupled composite laminated axis-symmetric doubly-curved revolution shell
structures are easily obtained by means of the Ritz method. The major advantages of the present solutions for coupled structure are to eliminate the need of changing the displacement or the equations of motion and to improve the efficiency of modeling. The accuracy and reliability of the proposed method are verified with the FEM and literature results, and various numerical examples are presented for the free vibration of the various coupled structures of composite laminated axis-symmetric shell, and these results can be used as reference data.

Guangyong Sun, Zhen Wang, Jiaying Hong, Kai Song and Qing Li, “Experimental investigation of the quasi-static axial crushing behavior of filament-wound CFRP and aluminum/CFRP hybrid tubes”, Composite Structures, Vol. 194 pp 208-225, June 2018
ABSTRACT: This study aims to investigate the effects of winding angles (25°, 50°, 75°, 90°; the 0° winding angle is along the axial direction of the tube) and thicknesses (3-ply, 6-ply, 9-ply) on crashworthiness characteristics of carbon fiber reinforced plastics (CFRP) tube and aluminum/CFRP hybrid tube molded by the filament winding technique through quasi-static crushing tests. The interaction between the outer CFRP tube and inner aluminum tube in a hybrid configuration was explored by comparing the sum of energy absorption of individual components with the hybrid form. It was found that both winding angle and wall thickness had significant influence on failure modes and crushing characteristics of both CFRP and hybrid tubes. With the same laminate thickness, increasing the winding angle decreased the specific energy absorption (SEA), energy absorption (EA) and peak crushing force (PCF) of pure CFRP and hybrid tubes. With the same winding angle of CFRP tube, increasing the thickness of CFRP tube increased the SEA, EA and PCF of both the CFRP and hybrid tubes. The SEA of 9-ply CFRP tube with winding angle of 25° and 9-ply CFRP/aluminum hybrid tube with winding angle of 25° were the highest of all the CFRP and hybrid tubes (48.74 J/g and 79.05 J/g), respectively. Moreover, EA of the hybrid tube exceeded the sum of that of the individual components thanks to the positive interaction between these components; making the hybrid tubes better crashworthiness than individual components.

Matteo Brunetti, Stefano Vidoli and Angela Vincenti, “Bistability of orthotropic shells with clamped boundary conditions: An analysis by the polar method”, Composite Structures, Vol. 194 pp 388-397, June 2018
ABSTRACT: Multistable shells have been recently proposed as an effective solution to design morphing structures. We describe a class of shallow shells which are bistable after one of their sides, initially curved, is clamped along a flat line. Supposing the shell being assembled as a composite laminate, we show how the anisotropy of the material can influence the multistable behaviour and the robustness of stable configurations. Specifically, we focus on orthotropic laminated shells using the polar method for a complete representation of the anisotropic elastic properties. Two experimental prototypes have been produced and tested to validate our analytical and numerical results.

Kwangnam Choe, Jinyuan Tang, Cijujn Shui, Ailun Wang and Qingshan Wang, “Free vibration analysis of coupled functionally graded (FG) doubly-curved revolution shell structures with general boundary conditions”, Composite Structures, Vol. 194 pp 413-432, June 2018
ABSTRACT: In this paper, free vibration behavior of coupled functionally graded (FG) doubly-curved revolution shell structures with general boundary conditions is studied by the using unified Jacobi-Ritz method. The first-order shear deformation theory in conjunction with a multilevel partition technique is adopted to establish the theoretical model. The substructure of the theoretical model mainly includes the FG elliptical, hyperbolical, paraboloidal and cylindrical shells and three kinds of coupled FG shell structures containing paraboloidal-cylindrical shells, elliptical-cylindrical shells and hyperbolical-cylindrical shells are also considered in actual calculation. To obtain the continuous conditions at the interface and satisfy the arbitrary boundary conditions, the boundary and coupling spring techniques are adopted in this paper. In despite of the
shell components and the boundary conditions, a mix function which is with the Jacobi polynomials along the meridional direction and the standard Fourier series along the circumferential direction is used as the admissible displacements of each shell segment. The convergence and comparison studies for the FG doubly-curved revolution shell structures with different boundary conditions, coupling parameters and Jacobi parameters are carried out to verify the reliability and accuracy of the present solutions. To enhance the understanding of the titled problem, some mode shapes of coupled FG shell structure are provided. Through comparative analysis, including the experimental and numerical comparison, it is obvious that the current method has good stability and rapid convergence properties and the present results agree closely with those reference results no matter what the frequency parameters or mode shapes are. The influence of the geometric dimensions and material constants on the vibration behavior of coupled FG shell structure is also reported.


ABSTRACT: In this paper, the effect of T, I and J stiffer configurations on post-buckling response of composite stiffened panels with impact damage is investigated through experiments and numerical simulations. Two identical panels in all three configurations were designed and manufactured. Each panel has four stringers of the same type. All panels were designed to have a skin buckling load of 92 kN ± 5 kN and weight of 1.45 kg ± 0.05 kg to separate the effect of impact damage irrespective of stiffener type. One panel from each configuration is impacted with 50 J energy above stiffener flange from skin side to create a Barely Visible Impact Damage (BVID) and followed by a compression test till collapse. A comparative study between pristine and impacted panels is presented. The effect of impact damage on buckling load, post-buckling response, collapse load and end-shortening were investigated. Moreover, finite element numerical models were developed for all panels which include intra-laminar and inter-laminar damage initiation and growth models. Impact damage area measured from ultrasonic C-scan was modelled in commercial finite element software Abaqus®. Failure modes in pristine and impacted panels such as disbond, tearing of stiffener web and locations from experiments are discussed and validated by numerical simulations.


ABSTRACT: Composite, sandwich and functionally graded materials are frequently utilized for different applications. Thus, numerous optimization studies have been conducted on structures made up of these materials to improve their mechanical or thermal behavior such as buckling resistance, stiffness and strength along with reducing weight, cost and stress under various types of loadings. This work which is the first part of two sequential review papers attempts to review most of the studies carried out from 2000 on optimizing composite structures by representing a classification based on the type of structures. Important parameters of these optimization approaches namely objective functions, design variables, constraints and the applied algorithms are highlighted. The influential factors including boundary conditions, orientation of curved fibers, piezo electric patches, Shape Memory Alloy (SMA) fibers and stiffeners as well as the effect of design variables on the determined objectives are also noticed. Moreover, the examined outperformance of developed algorithms in case of accuracy and pace over their common counterparts is mentioned. The second part will be allocated to the publications on optimization of sandwich and functionally graded structures.

ABSTRACT: Structural hierarchy in nature can be mimicked in order to develop novel composites and structures with desirable properties. In this study, hierarchy is introduced at multiple length scales into tubular sections that can be utilised as energy absorbing systems in various industries. The proposed hierarchical tubular section is inspired by the micro- to nano-architecture of biological materials, such as tendon and muscle, which can be mimicked by packing smaller tubes into a tube of a higher hierarchical level. The process can be repeated for creating tubular sections of higher orders of structural hierarchy, regardless of size or choice of materials. Numerical experiment has revealed that the impact energy absorption capability can be improved significantly when hierarchy is introduced and greater enhancement is achieved for higher-order hierarchical sections. A parametric study has been undertaken, and with the use of dimensionless parameters, the robustness and the generality of the phenomenon are demonstrated.


ABSTRACT: Post-buckling analysis of micro-composite films (MCF) has been extensively investigated in recent years. However, the literature of composite elements at micro/nanoscale has been mainly focused on buckling response without lateral confinements. This paper takes one step forward to theoretical studying of static and dynamic post-buckling response of MCF constrained by irregularly bilateral walls using the modified couple stress theory. A discretization algorithm is developed to convert the irregular constraints into normalized gap vectors. An energy method is presented to solve the proposed model by minimizing the total energy with respect to the gap vectors. Numerical simulations are carried out to validate the theoretical model. Satisfactory agreements are obtained between the theoretical and FE results. The proposed theoretical model is used to study the effect of the material length factor $\varsigma$ on the buckling mode transition force $P$ and highest achievable buckling mode of the irregularly constrained micro-films. The presented model can be used to predict and tune the post-buckling response of the axially loaded MCF subjected to irregularly bilateral constraints.


ABSTRACT: Analytical closed-form solutions for thermos-mechanical stability and explicit expressions for free- and forced-vibration of thin functionally graded sandwich shells with double curvature resting on elastic bases are investigated for the first time in this study. A core layer of ceramic and two cover layers of functionally graded materials constitute the shell structure. Governing equations are derived from the classical shell theory using Hamilton’s principle admitting Volmir assumption and von Karman nonlinear displacement fields. Theoretical solutions are achieved by using the Bubnov-Galerkin procedure in solving differential equations. Parametric studies showing the effects of temperature-dependent features, material constituents, initial geometry imperfections, external thermos-mechanical loadings, elastic bases, and geometry configuration on static and dynamic behaviors of the shells are performed. Thin functionally graded sandwich spherical, cylindrical, and hyperbolic paraboloid shells are studied. Snap-through phenomena under load-control conditions are recognized in thin functionally graded sandwich cylindrical shells. The fourth-order Runge-Kutta method is employed to numerically solve dynamic problems and four analogies are drawn to validate theoretical formulations.


ABSTRACT: This research presents a parametric study by using ABAQUS/Explicit and analytical analysis of rectangular sandwich plates with Miura-ori folded core. Two loading conditions are studied: three-point...
bending and uniformly distributed pressure loading. Load-displacement curves are obtained and energy absorption performance is assessed. Under three-point bending and uniformly distributed pressure loading of small magnitude, performance of such sandwich plates has been found to be better than that of corresponding monolithic plates of the same mass. In addition, analytical modelling has been conducted based on the plastic hinge theory, which results in a good agreement with those from the finite element analysis (FEA). It has been found that the maximum bending strength is governed by the incipience or fully plastic yielding of the core material for relatively thick cores, or elastic buckling of the core compression for thin cores. Furthermore, the yielding moment, fully plastic bending moment and elastic buckling moment of the incipience of core buckling have been evaluated.


ABSTRACT: The aim of this study is to experimentally investigate the stability behavior and failure characteristics of carbon fibre reinforced polymer (CFRP) composite panels with secondary bonded blade stiffener under compression. Various experimental techniques like 3D-digital image correlation (DIC), acoustic emission (AE), strain gaging and infrared thermography were employed together for capturing the buckling, post-buckling response and failure characteristics of test panels. The 3D-DIC technique was employed for determining the buckling and post-buckling displacement fields of the test panel. The strain gage data was used for accurate prediction of the onset of buckling phenomenon of the test panels. Parametric data obtained from the AE technique was analysed for identifying and classifying the various damage events encountered in the test panel. In addition, finite element simulation of the CFRP stiffened panel under compression was performed to validate the experimental post-buckling results. In this work, Hashin’s failure criteria was used to study the initiation of various failure modes in the critical regions of the stiffened panel. The proposed unified experimental approach can provide more insights on the post-buckling behavior and failure characteristics of single blade stiffened CFRP panels, thereby helping engineers in designing damage tolerant composite structures.


ABSTRACT: The present article investigates the thermoelastic vibration and stability characteristics of carbon nanotube-reinforced composite (CNTRC) plates in thermal environment. The CNTRC plates are made up of four different types of uniaxially aligned reinforcements. The single-walled carbon nanotubes (SWCNTs) reinforcement is either uniformly distributed (UD) or functionally graded (FG) according to linear functions of the thickness direction. The material properties, of both matrix and CNTs, are temperature-dependent and the effective elastic coefficients are evaluated by using a micromechanical model. The governing equations (GEs) are derived in their weak-form by using Hamilton’s Principle in conjunction with the method of the power series expansion of the displacement components. The Ritz method, based on highly stable trigonometric trial functions, is used as solution technique. Convergence and stability of the proposed formulation have been thoroughly analyzed by assessing many higher-order plate models. Thermal and mechanical pre-stresses are taken into account. Moreover, the effect of significant parameters such as length-to-thickness ratio, volume fraction, aspect ratio, loading-type, CNTs distribution as well as boundary conditions is discussed.

Subodh Kumar, Vinayak Ranjan and Prasun Jana, “Free vibration analysis of thin functionally graded rectangular plates using the dynamic stiffness”, Composite Structures, Vol. 197 pp 39-53, August 2018
ABSTRACT: In this paper, free vibration behavior of thin functionally graded rectangular plates is investigated by using the dynamic stiffness method (DSM). Classical plate theory along with the concept of physical neutral surface of the functionally graded plate is used to formulate the dynamic stiffness matrix. The dynamic stiffness matrix is finally solved by using the Wittrick-Williams algorithm to compute the natural frequencies. DSM frequencies are compared with those available in the literature. Some inaccurate published results are pointed out and possible reasons for these inaccuracies are discussed. Results for several plate parameters are given and the influence of these parameters on natural frequencies of the functionally graded plate is highlighted. The present study shows that the dynamic stiffness method provides very accurate results for vibration analysis of thin functionally graded plates and these results can be used as benchmark solutions for comparison purposes.

Yu Wang, Chuang Feng, Zhan Zhao, Fangzhou Lu and Jie Yang, “Torsional buckling of graphene platelets (GPLs) reinforced functionally graded cylindrical shell with cutout”, Composite Structures, Vol. 197 pp 72-79, August 2018

ABSTRACT: This paper studies the torsional buckling of functionally graded cylindrical shells reinforced with graphene platelets (GPLs) through finite element method (FEM). The cylindrical shell is consisted of a number of layers in the thickness direction, in which the GPL concentration varies from layer to layer. The Young’s modulus and Poisson’s ratio of the composites are determined by Halpin-Tsai model and rule of mixture, respectively. The FEM model is validated by comparing present results with theoretical predictions for homogeneous shells. Parametric study is carried out to investigate the effects of the number of layers, the GPL distribution patterns, the dimensions of shell, the weight fraction and size of GPLs, and the existence of cutout on torsional buckling. The results demonstrate using multi-layers is accurate enough to obtain functionally graded structures. GPL distribution plays a significant role in the buckling. Increasing the number of layers significantly decreases the stress gradient between two adjacent layers. Square shaped GPLs with fewer layers are preferred as reinforcements. With the increase of cutout size, the buckling load decreases and the structure undergoes the transition from global to local buckling mode. Moreover, the effects of the slenderness, orientation and position of the cutout on buckling are examined.

Jing Tang and Xiao Chen, “Experimental investigation on ultimate strength and failure response of composite box beams used in wind turbine blades”, Composite Structures, Vol. 198 pp 19-34, August 2018

ABSTRACT: This study focuses on the ultimate strength and failure response of composite box beams under three-point bending. The box beams consist of spar caps and shear webs and they are typically used in wind turbine blades as load-carrying members. Different spar cap configurations and loading directions are examined experimentally to investigate structural behavior associated with multiple nonlinearities leading to structural collapse. Global displacements, local strains and video images are recorded throughout the loading history to capture failure initiation, propagation and the strain state contributing to post-collapse characteristics. The failure mechanisms of the box beams involving geometric, material and contact nonlinearities are discussed in detail. The study shows that compressive crushing failure, driven by local buckling of shear webs, determines the ultimate strength of the box beams under flapwise loading, and adhesive joint debonding, initiated by local adhesive cracking and spar cap buckling, is the critical failure mode of the box beams under edgewise loading. The Brazier effect and shear nonlinearity contribute to the initial failure depending on the loading directions. Debonding rather than delamination characterizes post-collapse behavior of all box beams examined in this study.

ABSTRACT: This paper develops a three-dimensional (3D) isogeometric analysis (IGA) and meshfree coupling approach to investigate the static, dynamic and buckling behaviors for plates and shells of functionally graded material (FGM). The meshfree method and IGA are coupled using the higher-order consistency condition in the physical domain so that the higher-order continuity of basis functions is guaranteed, and the topological complexity of the global volumetric parameterization for IGA to build the 3D geometry can be overcome. By employing IGA elements on the domain boundary and meshfree nodes in the interior domain, the approach preserves the advantages of the exact geometry and flexible discretization in the problem domain. Based on the coupling approach, the analyses for FGM plates and shells are carried out, and the effects of the material volume fraction, the side-to-thickness ratio and the curvature of the cylindrical shell on the deflection, natural frequency, and buckling load are investigated. The coupling approach is verified by comparing with the solutions obtained from other existing theories.

References listed at the end of the paper:


Saeid Sahmani, Mohammad Mohammadi Aghdam and Timon Rabczuk, “Nonlocal strain gradient plate model for nonlinear large-amplitude vibrations of functionally graded porous micro/nano-plates reinforced with GPLs”, Composite Structures, Vol. 198 pp 51-62, August 2018

ABSTRACT: Because of rapid development of manufacturing technology, functionally graded porous materials have gained commercially attraction in promoted engineering applications. It is common to reinforce the porous materials with nanofillers to improve their mechanical properties efficiently. The prime objective of the present investigation is to explore the size dependency in nonlinear large-amplitude vibrational response of functionally graded porous micro/nano-plates reinforced with graphene platelets (GPLs). To accomplish this purpose, the newly proposed unconventional continuum theory namely as the nonlocal strain gradient theory incorporating size effects more comprehensively is adopted to the refined exponential shear deformation plate theory. Based upon the closed-cell Gaussian-Random field scheme in conjunction with the Halpin-Tsai micromechanical modelling, the mechanical properties of the porous material with uniform and three different functionally graded patterns of porosity dispersion reinforced with GPLs are extracted. Using Hamilton's principle, the non-classical form of differential equations of motion are derived. Thereafter, an improved perturbation technique is put to use to construct analytical expression for the nonlocal strain gradient nonlinear frequency associated with the large-amplitude vibration of functionally graded porous micro/nano-plates reinforced with GPLs. It is indicated that by increasing the plate deflection, the significance of the both size effects on the nonlinear frequency of the porous micro/nano-plates decreases. Also, it is displayed that for vibrations with higher amplitude, the role of porosity dispersion pattern in the significance of size effects on the nonlinear frequency of functionally graded micro/nano-plates becomes more important.


ABSTRACT: By applying a quasi-static transverse load, shallow cylindrical shells can be snapped between two inverted stable states. This dynamic transition, initiated at either a limit point (fold) or a subcritical bifurcation, traverses a region of instability. The ensuing large displacements are attractive for shape adaptation of multi-functional engineering structures. Previous research on isotropic cylindrical shells has indicated the presence of isolated regions of stability in the otherwise unstable transition region. While these regions are theoretically attractive for multi-stage snap-morphing, they are difficult to attain in practice by means of a single control parameter. In this paper, we study the effect of orthotropic material properties on the structural stability and snap-through behavior of shallow cylindrical shells. In addition, we explore complex stability phenomena created by material orthotropy, which are attractive for multi-stage morphing. The problem is analyzed in a robust manner using a technique known as generalized path-following, which combines the mathematical domains of finite element analysis and numerical continuation. The present study shows, in particular, that laminates comprising layers of different directional material properties provide the ability to tailor the elastic bifurcation behavior of cylindrical shells. For example, the lamination scheme can be varied to add isolated regions of stability or entirely remove them; to induce snaking that allows transitioning between the two inverted cylindrical shapes through a series of snaps; and finally, to create groupings of multiple unique stable configurations that can be attained via additional shape control.
Zhi-Min Li, Tao Liu and De-Qing Yang, “Postbuckling behavior of shear deformable anisotropic laminated cylindrical shell under combined external pressure and axial compression”, Composite Structures, Vol. 198 pp 84-108, August 2018

ABSTRACT: Structural design of composite shells are more challenging than conventional metals due to the complex mechanical behavior and damage mechanisms which composite materials exhibit. Postbuckling analysis for a moderately thick anisotropic laminated cylindrical shell subjected to combined loadings of external pressure and axial compression is presented which extends the boundary layer theory of shell buckling. The governing equations are based on Reddy’s higher order shear deformation shell theory with von Kármán-Donnell-type of kinematic nonlinearity. Both nonlinear prebuckling deformations and initial geometric imperfections of the shell are taken into account. A two-step singular perturbation method is used to determine interactive buckling loads and postbuckling equilibrium paths. A verification study is conducted, and the validity of the formulation is established through comparison with results of nonlinear finite element software such as ABAQUS®. The internal physical mechanism of the shell geometric parameters on the buckling load and the postbuckling equilibrium path is obtained. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, anisotropic laminated cylindrical shells with different load-proportional parameters. The analytical model can provide an effective tool to investigate postbuckling of composite shell structures.

Sigong Zhang and Lei Xu, “Exact static analysis of eccentrically stiffened plates with partial composite action”, Composite Structures, Vol. 198 pp 117-125, August 2018

ABSTRACT: Stiffened plates are common forms used in engineering structures. Extensive research efforts have been devoted to investigating the behavior of stiffened plates under static loading. In the existing models, two issues have not been always appropriately addressed. One is the eccentricity of the stiffeners and the other is the composite action between the plate and stiffeners. In the present paper, static deformation of an eccentrically stiffened plates with partial composite action was analyzed by using the variational approach. In order to investigate the eccentricity and composite action issues, the stiffened plates were idealized as assemblies of plate and beam elements, in such way the stiffeners are discretely connected to the plate elements. Based on the principle of the minimum potential energy, the governing differential equations were derived by using the variational approach with taking into consideration of strain energy of connectors between plate and stiffeners and associated boundary conditions as well. Five displacement functions were defined as double Fourier series to solve the static deflection of simply-supported eccentrically stiffened plates. A relative stiffness factor $K$ with a range of zero to one was introduced to represent the composite action between the plate and stiffeners from no interaction (i.e., ) to rigidly connected (i.e., $K = 1$ ). Finally, the proposed energy approach was compared with previously published methods through numerical examples of the plates reinforced by one to fourteen stiffeners in two orthogonal directions.


ABSTRACT: In this paper, the wave propagation in magneto-electro-elastic (MEE) nanoshells is investigated via two nonlocal strain gradient shell theories, namely, the Kirchhoff–Love shell theory and the first-order shear deformation (FSD) shell theory. By using Hamilton’s principle, we derive the governing equations, which are then solved analytically to obtain the dispersion relations of MEE nanoshells. Results are presented to highlight the influences of the temperature change, external electric potential, external magnetic potential, external load, nonlocal parameter and length scale parameter on the wave propagation characteristics of MEE nanoshells. It is
found that the electro-magneto-mechanical loadings can lead to the cut-off wave number at which the frequency reaches to zero.


ABSTRACT: In this work, a Boundary Element Method formulation for stress analysis of symmetrically laminated composite thick shallow shells is presented. The proposed formulation was obtained by coupling the boundary element formulation of shear deformable symmetrically laminated composite plates and the boundary element formulation for two-dimensional anisotropic plane stress analysis. Formulation uses the elastostatic anisotropic fundamental solutions proposed for these formulations. Domain integrals are transformed to the boundary by using the Radial Integration Method. Numerical examples are presented to demonstrate the efficiency and accuracy of the formulation. Obtained results concur with results available in the literature as well as with finite element results.


ABSTRACT: The paper presents the model of progressive failure analysis of laminates incorporated into the 6-field non-linear shell theory with non-symmetrical strain measures of Cosserat type. Such a theory is specially recommended in the analysis of shells with intersections due to its specific kinematics including the so-called drilling rotation. As a consequence of asymmetry of strain measures, modified laminates failure criteria must be used in the prediction of the failure initiation. The model is implemented into the noncommercial numerical code of finite element method. Several examples are examined and the obtained solutions are compared with analytical, numerical and experimental results.


ABSTRACT: Engineering structures in marine and vehicle are frequently subjected to repeated impact loadings. The damage can’t be neglected during the accumulation of deflection caused by the repeated impacts. In this paper, the dynamic behaviour of aluminum foam sandwich plate (AFSP) under repeated impacts was investigated by impact tests using INSTRON 9350 Drop Tower. The penetration behavior of front face and back face are compared. Meanwhile, the relationships between deflections of face sheets with impact number as well as the loading-unloading process during repeated impacts are analyzed. Results showed that, the permanent deflections of the front face and back face increased gradually, while the increments decreased until the crack occurred on the front face sheet. The damage modes of front face and back face were different. The impact number \(N_p\) for penetration of front fact and residual number \(N_r\) for perforation of back face both decreased in exponential form with the increase of impact energy. It implied that the back face sheet still has residual load-carrying capacity even if the front face sheet became cracked.


ABSTRACT: This paper deals with the free vibration analysis of two kinds of five-layered composite sandwich plates with two-layered viscoelastic cores based on the first-order shear deformation theory for the first time. To fulfill this purposes, first, the Hamilton’s principle is employed to derive the equations of motion that govern
the free vibrations of the sandwich plates, and solved by employing the method of the closed-form Navier method. Then, the present solutions are compared with those available in the previous literature to confirm their validity. Next, the variations of frequency and loss factor with system parameters are evaluated and presented graphically. Owing to considering the effect of rotary inertias and shear deformation, thin-to-moderately thick shells can be analyzed. New results for free vibration analysis of five-layered composite sandwich plates with two-layered viscoelastic cores are also presented for the first time and they may be served as benchmark for researchers in this field.


ABSTRACT: A novel approach for creating highly detailed finite element models of wind turbine blades is presented. The approach is implemented as a software tool which handles all the different steps of the model creation process. The novel approach considers the blade to consist of a collection of parametric pre-defined blocks. This allows wind turbine blade models consisting of shell elements, solid elements or combinations to be created. By including the tools to accurately partition the outer mold layer, create the required offset surfaces and calculate accurate element-wise material orientations, a high level of detail and fidelity can be achieved.


ABSTRACT: An extensive analytical model to determine behaviour of curved sandwich plates with variable stiffness cores and face-sheets under low velocity impact with foam core is presented in this paper. A developed method is introduced to determine effective dynamic stiffness of the face-sheets and core with variable stiffness. A modified spring-mass-dashpot model was used to obtain the contact force function related to effective dynamic stiffness and effective dynamic frequency to determine the contact force histories by impact of a hemispherical-nose impactor. A parametric study was also performed to understand the effects of several factors such as impactor velocity, face-sheet thickness, core thickness (constant and variable stiffness), layup orientation and curvature on the contact force histories of curved sandwich plates. Different geometries of curved sandwich plates are analysed to study their performance under impact loading. Numerical analysis was performed in LS-DYNA to further validate with the developed analytical models.


ABSTRACT: We carried out a dynamic instability assessment of carbon nanotube reinforced composite (CNTRC) and carbon nanotubes/fiber/polymer composite (CNTFPC) skew plates with delamination based on the high-order shear deformation plate theory (HSDT). The multiscale interactions between carbon nanotube (CNT) ratios, skew angles and delamination sizes on the dynamic instability for various length-thickness ratios are studied using a two-dimensional finite element delamination model developed for this study. The results were verified by those reported in the literature for undelaminated cases show the interactions between the CNT reinforcement and delamination sizes in the skew laminate. Numerical examples show the importance of CNT reinforcement when assessing the dynamic instability of CNTRC and CNTFPC skew plates with delamination.
ABSTRACT: A layer-wise sandwich model is employed for vibration analysis of symmetric sandwich plates with two thin carbon nanotube-reinforced composite (CNTRC) face-sheets, in which a new polynomial refined plate theory is proposed for the core and the classical plate theory is adopted for the face-sheets. By virtue of symmetry, the in-plane displacements are neglected. By maintaining the displacement continuity conditions at the interfaces, the displacement fields are expressed with only two transverse displacement components, which are given in summations of products of beam characteristic functions in one direction and unknown functions in the other. Then, the multi-term Kantorovich-Galerkin method (MTKGM) is extended to obtain semi-analytical solutions for vibration response of symmetric CNTRC sandwich plates resting on elastic foundation. Non-dimensional natural frequencies are obtained for CNTRC sandwich plates, and the effects of the number of approximate terms, boundary conditions, sandwich configurations, volume fractions of carbon nanotube, plate aspect ratio, core-to-skin thickness ratio, and foundation stiffness are examined. The new polynomial refined plate theory presented provides an improved yet relatively simple model for vibration analysis of sandwich structures.

ABSTRACT: In this paper, we propose an original FEM strategy to consider stiffening honeycomb-shaped cells, filled or not, to the simulation of sandwich plates and shells. The strategy combines three-dimensional membrane elements (called active face) with solid prismatic elements. This approach is different from the usual ones that use solid elements to discretize all parts of a panel or use equivalent macroscopic properties to simulate honeycomb-shape laminated composites. In the proposed technique, the composition of elements is done by means of direct nodal correspondence, defined in the mesh generation procedure, not interfering in the number of degrees of freedom of the models. Thus, introduction of reinforcements does not increase the number of degrees of freedom, which makes the technique highly economical from the numerical point of view. Positional finite element (Positional FEM) procedure is adopted, resulting in a total Lagrangian description that allows general applications including large displacements of laminated plate and shell problems. Positional FEM adopts as main variables the current nodal positions instead of displacements as classical finite elements do. The proposed stiffening cell element is tested regarding stress and displacements calculations, comparing results with literature. Results for large displacements in reinforced honeycomb laminated shells are also presented.

ABSTRACT: In this work, an analytical solution for layered magneto-electro-elastic (MEE) cylindrical shell adhesively bonded by viscoelastic interlayer is developed to predict its time-dependent mechanical, electric and magnetic behaviors. The viscoelastic characteristic of the interlayer is modelled by the standard linear solid model. Each MEE layer is governed by the equations of magneto-electro-elasticity. The imperfect electric conditions between adjacent MEE layers are also considered. Using the Pseudo-Stroh formalism, a general solution with unknown coefficients is derived for each MEE layer. The Laplace transformation is applied to the constitutive equations of the viscoelastic interlayer. The coefficients are determined by the surface conditions as well as the interface conditions. The present solution can be used as the benchmark to assess results from
numerical approaches. It is shown that the finite element solution converges to the present one as the mesh density increases; however, the finite element method is time-consuming in mesh division and calculation. Finally, the effects of time, shell angle, interlayer thickness and imperfect electric coefficient on the mechanical, electric and magnetic behaviors are investigated.


ABSTRACT: Lightweight architected cellular cores have been introduced as an advanced alternative to improve the overall performance of sandwich structures. In this study, we implement semi-analytical and finite element approaches and conduct experimental impact tests to evaluate the performance of 3D printed lightweight sandwich panels with architected cellular cores of programmable six-sided cells. Changing the geometrical parameters of the cells leads to cellular cores of hexagonal, rectangular and auxetic topologies. A semi-analytical methodology is developed for conducting structural and low-velocity impact analyses based on a modified higher-order shear deformation theory. The standard mechanics homogenization is implemented through finite element modelling to accurately predict the effective mechanical properties of architected cellular cores. We apply explicit large deformation finite element analysis using ANSYS to analyze the elasto-plastic behavior of architected sandwich panels under a low-velocity impact. To experimentally corroborate the developed theoretical and computational models and to evaluate the manufacturability of the architected sandwich panels, we use the fused deposition modeling to 3D print samples of polylactic acid biopolymers. Uniaxial tensile test is first used to characterize the polymer. We then conduct low-velocity impact tests to investigate the energy absorption capability of architected sandwich panels. X-ray micro-tomography is finally employed to study the microstructural features of panels before and after the impact. The experimental and numerical results show that the auxetic sandwich panel is potentially an appropriate candidate for energy absorption applications due to its high-energy absorption capability and a minimum response force transferred from the 3D printed panel.

Son Thai, Huu-Tai Thai, Thuc P. Vo and Seunghye Lee, “Postbuckling analysis of functionally graded nanoplates based on nonlocal theory and isogeometric analysis”, Composite Structures, Vol. 201, pp 13-20, 1 October 2018, https://doi.org/10.1016/j.compstruct.2018.05.116

ABSTRACT: This study aims to investigate the postbuckling response of functionally graded (FG) nanoplates by using the nonlocal elasticity theory of Eringen to capture the size effect. In addition, Reddy’s third-order shear deformation theory is adopted to describe the kinematic relations, while von Kármán’s assumptions are used to account for the geometrical nonlinearity. In order to calculate the effective material properties, the Mori-Tanaka scheme is adopted. Governing equations are derived based on the principle of virtual work. Isogeometric analysis (IGA) is employed as a discretization tool, which is able to satisfy the C1-continuity demand efficiently. The Newton-Raphson iterative technique with imperfections is employed to trace the postbuckling paths. Various numerical studies are carried out to examine the influences of gradient index, nonlocal effect, ratio of compressive loads, boundary condition, thickness ratio and aspect ratio on the postbuckling behaviour of FG nanoplates.


ABSTRACT: The bending responses of porous functionally graded (FG) single-layered and sandwich thick rectangular plates are investigated according to a quasi-3D shear deformation theory. Both the effect of shear
strain and normal deformation are included in the present theory and so it does not need any shear correction factor. The equilibrium equations according to the porous FG single-layered and sandwich plates are derived. The solution of the problem is derived by using Navier’s technique. Numerical results have been reported, and compared with those available in the open literature for non-porous single-layered and sandwich plates. Effects of the exponent graded and porosity factors are investigated.


ABSTRACT: In this paper, a unified Jacobi-Ritz method is present to analyze the free vibration of composite laminated doubly-curved shells of revolution with general boundary conditions. The composite laminated doubly-curved shells of revolution are divided into their segments in the axial direction, and the theoretical model for vibration analysis is formulated by applying first-order shear deformation theory. The Jacobi polynomials along the axial direction and the standard Fourier series along the circumferential direction make up the displacement functions of shell segments. The boundary conditions at the ends of the composite laminated doubly-curved shells of revolution and the continuity conditions at two adjacent segments were enforced by penalty method. The results including frequency parameter and mode shapes of composite laminated doubly-curved shells of revolution are easy obtained by Ritz method. The major advantage of presented solutions for solving the vibration characteristics of composite laminated doubly-curved shells of revolution is no need to change the mathematical model or the displacement functions. The accuracy and reliability of the proposed method are verified by the results of literature and finite element method (FEM), and various numerical examples are presented for free vibration analysis of composite laminated doubly-curved shells of revolution.


ABSTRACT: A derivation and validation of an analytical formula for the calculation of the fundamental frequency of a composite anisogrid lattice cylindrical panel with clamped edges is presented in this paper. Free vibration analysis is performed based on the continuous model of a lattice structure using the equations of engineering theory of orthotropic cylindrical shells. The problem was solved using the Galerkin method in which the displacements of the panel were approximated by the clamped-clamped beam functions. The analytical formula derived from this solution was employed to study the effects of the structural parameters of composite lattice panels on their fundamental frequencies. The results of these parametric analyses were successfully verified by comparisons with the finite-element solutions. It is shown that the analytical model that only takes into account the inertia of the transverse motion of the panel in the direction normal to its surface provides a reasonable estimate of the value of fundamental frequency. It is also demonstrated how the formula works in the calculations delivering the required fundamental frequency when designing the composite lattice panels.


ABSTRACT: In composite component, confined concrete is widely used in civil engineering due to its excellent performance, such as high compressive strength and good plasticity. In this study, an actively-confined concrete model is developed using current published models and test data, the stress-strain behavior of
Concrete in active confinement and fiber-reinforced polymer confinement are compared, then the influence of loading path on concrete is quantified. An analytical model is developed to predict the mechanical behavior of confined concrete columns, and validated using previously published test results. The analytical model is found to provide satisfactory predictions in short concrete columns confined by FRP or steel tubes.


ABSTRACT: This paper investigates the eccentric low-velocity impact of Fiber metal laminates (FMLs) subjected to spherical projectile using a unified Zig-Zag plate theory. The presented zig-zag plate theory enforces transverse shear stress continuity through the thickness and can be reduced to conventional plate theories using appropriate shape function. The governing equations and suitable boundary conditions are obtained using the principle of minimum total potential energy. Runge-Kutta method is employed to solve initial value problem resulted by the method of Ritz. The present model is validated by comparison and good agreement between its results and those of reports in open literature. Influence of various specifications of impact phenomenon such as laminate thickness, projectile radius, projectile velocity, in-plane load and eccentricity parameter is examined on deflection and contact force time history. The obtained results indicate that continuity of transverse shear stress is required to achieve accurate contact force even for moderately thin FMLs.


ABSTRACT: In this paper, we propose an efficient and accurate approach to investigate the post-buckling behavior of sandwich structures. In this framework, a novel one-dimensional layer-wise model using Euler-Bernoulli beam theory in the skins and higher-order kinematics in the core is proposed. The resulting nonlinear governing equations are then solved by the Asymptotic Numerical Method (ANM) with a bifurcation indicator, which is more reliable and efficient than the classical iterative methods, e.g., Newton-Raphson method, in terms of detecting critical points and computing bifurcated branches. Several numerical tests, i.e., global buckling, local wrinkling and global-local-coupling instability phenomena of sandwich beams, are performed and the results show that the proposed approach is able to efficiently and precisely characterize the critical loads and the post-buckling behaviors of sandwich structures. Finally, the effect of three aspects, i.e., kinematics, strain-displacement relationships and interpolation functions on the computational accuracy of predicting these instability phenomena are investigated.


ABSTRACT: In this paper, the dynamic response of functionally graded viscoelastic hollow cylinder subjected to thermo-mechanical loads is studied using the meshless local Petrov-Galerkin method. The material is assumed to be graded in the radial direction with aluminum as viscoelastic constituent and alumina as the elastic constituent. The macroscopic viscoelastic properties are evaluated using the rule of mixtures and the inverse rule of mixtures, whilst that of the cylinder is computed by employing the Mori-Tanaka homogenization scheme. A systematic parametric study is carried out to bring out the influence of material gradient index, the viscoelastic properties and the boundary conditions on the dynamic/transient response of the cylinder.

ABSTRACT: The static axial crushing and energy absorption of density-graded aluminum foam-filled square metal columns are experimentally and theoretically investigated. Typical deformation modes are observed in experiments, such as symmetric, asymmetric, extension and rupture modes. Theoretical analysis is carried out and the predictions are in good agreement with the experimental results. The effects of gradient pattern, density difference, average density of foam, and wall thickness on the crushing of foam-filled columns are discussed. It is shown that the density-graded aluminum foam-filled square metal column is a novel topological structure with higher energy absorption, higher load-carrying capacity and much higher crushing force efficiency.


ABSTRACT: This paper proposes a novel analytical model to study the nonlinear dynamics of cross-ply bi-stable composite plates. Based on Hamilton’s principle, in conjunction with the Rayleigh-Ritz method, an advanced analytical model with only 17 unknown terms is developed to predict the entire nonlinear dynamic response of bi-stable composite plates, which are excited by an electrodynamic shaker. The coupling between the bi-stable plate and the shaker is considered in the development of the analytical model. This work, for the first time, simulates the full dynamics of bi-stable plates using an analytical model, including the prediction of the nonlinear characteristics of single well vibration and cross well vibration. Numerical results on three vibrational patterns of two standard cross-ply composite plates are obtained to study the nonlinear dynamics of bi-stable plates. The prediction accuracy on the dynamic characteristics of different vibrational patterns of bi-stable plates are verified by both finite element analysis (FEA) and experimental results. Large amplitude cross-well vibrations due to the transitions between different stable states of bi-stable plates are also characterized accurately. Applying this 17-term analytical model for the dynamic analysis of bi-stable plates is straightforward, as the mass and stiffness properties are obtained directly from the geometry and material properties. Only the damping coefficients for different plates need to be determined from experiments. Furthermore, this proposed 17-term analytical model has much higher computational efficiency than FEA.


ABSTRACT: Modal analysis is the basis of the structural dynamics design and optimization. When operating in a thermal environment, the structure may be affected by the temperature in diverse aspects. In this paper, a sandwich structure composed of carbon fiber woven skins and a Nomex honeycomb core is taken as the research object. Temperature effects on its modal characteristics are investigated by experiments and simulations. During the test, natural frequencies and modal damping ratios of the specimen change with temperature dramatically, while each mode exhibits a particular trend. Although the temperature-dependent material property of the skin is identified as the essential factor of the variations in the modal parameters, the modulus components of the skin material have different sensitivities to the temperature change. As a result, correlations between the natural frequencies and modulus components are related to the corresponding mode shapes. And these correlations are studied by the finite element analysis.

ABSTRACT: The rise in moisture concentration and temperature reduces both strength and stiffness of composites. A thorough understanding of the effects of temperature and moisture concentration in composite structures is critical in ensuring safety design. There seems to be no such solutions available for multilayered composite cylindrical shells. This paper is therefore devoted to the three-dimensional hygrothermal vibration analysis of multilayered cylindrical shells under general boundary conditions for the first time. The formulation is based on the 3-D elasticity theory. The vibrational displacement field is numerically discretized by the sampling surface technique in the transfer domain and approximated by the spectral method in the remaining domains. The transverse deformations and interlaminate continuities are taken into account in combination with differential-quadrature concept. The governing equations are finally derived in a modified variational form for constrained system and the boundary conditions are taken into account in a unified form by utilizing penalty functions and Lagrange multipliers. The boundary conditions may be free, simply-supported, clamped or/and elastically restrained. The solutions match well with those reported in the literature in verification. The effects of hygrothermal environment, boundary conditions, shell geometry, lamination are brought out and discussed through parametric study.


ABSTRACT: This paper presents size-dependency effects on nonlinear transient dynamic response of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) nanoplates under a transverse uniform load in thermal environments. To consider the length scale and size-dependency effect of nanostructures, a nonlocal continuum theory of Eringen is adopted. The nonlocal governing equations for nanoplate theory are derived from the Hamilton’s principle and approximated by using isogeometric analysis associated with the higher-order shear deformation theory. A numerical model based on the von Kármán strains and Newmark time integration scheme is employed to solve geometrically nonlinear transient problems. The material properties of the FG-CNTRC nanoplate are assumed to be graded and temperature-dependent in the thickness direction, which are expressed through a micromechanical model. Effects of nonlocal parameter, carbon nanotube volume fraction, length-to-thickness ratio, distributions of carbon nanotubes and temperatures through thickness are investigated in detail. Several numerical results show the reliability of the present method. References listed at the end of the paper: (none given in this short pdf file)


ABSTRACT: In this paper a carbon fiber reinforced composite cantilever cylinder under gravity was designed using the cantilever beam theory. The finite element model of the composite cantilever cylinder was established using software ANSYS. The static and dynamic bending responses of the cantilever cylinder were investigated with the aid of the finite element method and theory of flexible multi-body dynamics. The deflection calculated using fully constraints at the root of the cantilever cylinder under gravity satisfies the design requirements. Moreover, the response curves of deflections of the cantilever cylinder with time were obtained in terms of the step motion and sinusoidal motion, respectively, using software ADAMS. The deflections of the cantilever cylinder were also evaluated for various motions. The results indicate that the maximum deflections of the
The cantilever cylinder for the both motion modes do not exceed the allowable design values. The present models and methods are able to provide a useful reference for design and production of carbon fiber composite cantilever cylinders.


ABSTRACT: This work deals with the problem of the least-weight design of a composite stiffened panel subject to constraints of different nature (mechanical, geometrical and manufacturability requirements). To face this problem, a multi-scale two-level (MS2L) design methodology is proposed. This approach aims at optimising simultaneously both geometrical and mechanical parameters for skin and stiffeners at each characteristic scale (mesoscopic and macroscopic ones). In this background, at the first level (macroscopic scale) the goal is to find the optimum value of geometric and mechanical design variables of the panel minimising its mass and meeting the set of imposed constraints. The second-level problem focuses on the laminate mesoscopic scale and aims at finding at least one stacking sequence (for each laminate composing the panel) meeting the geometrical and mechanical parameters provided by the first-level problem. The MS2L optimisation approach is based on the polar formalism to describe the macroscopic behaviour of the composites and on a special genetic algorithm to perform optimisation calculations. The quality of the optimum configurations is investigated, a posteriori, through a refined finite element model of the stiffened panel making use of elements with different kinematics and accuracy in the framework of the Carrera’s Unified Formulation (CUF).


ABSTRACT: An extended Ritz formulation for the analysis of buckling and post-buckling behaviour of cracked composite multilayered plates is presented. The formulation is based on: (i) the First-order Shear Deformation Theory to model the mechanics of the multilayered plate; (ii) the von Kármán’s theory to account for geometric nonlinearities; (iii) the use of an extended set of approximating functions able to model the presence of an embedded or edge crack and to capture the crack opening fields as well as the global behaviour within a single cracked domain. The numerical results of the buckling analyses and the equilibrium paths in the post-buckling regime are compared with the results from finite elements simulations, confirming the accuracy and potential of the formulation.


ABSTRACT: The paper is focused on the evaluation of the critical speed of rotating doubly-curved multilayered shell structures. The theoretical framework developed to this aim is based on a general formulation capable to define several Higher-order Shear Deformation Theories (HSDTs) in a unified manner. The current approach can deal easily with angular velocities applied about a generic axis of the structure. This aspect represents a clear advancement with respect to the formulations available in the literature, which are developed mainly to investigate the dynamic behavior of rotating shells of revolution (disks, circular cylinders and conical shells), in which the angular velocity is applied about their revolution axis. It is important to underline that the effects of both Coriolis and centripetal accelerations on the dynamic response of shell structures, characterized by various geometric shapes, are included in the model. The quadratic eigenvalue problem that lies behind the
free vibration analysis in hand is solved numerically by means of the well-known Generalized Differential Quadrature (GDQ) method. The critical speed is obtained as a result of many parametric investigations, which are defined for increasing values of the applied angular velocities. Finally, it should be mentioned that the current research falls within the aim of the study of the dynamic stability of rotating structures. For this purpose, several considerations concerning the flutter and divergence phenomena are presented.

ABSTRACT: The compressive kinking behavior of non-sledger unidirectional glass fiber-reinforced polymer (GFRP) specimens has been analyzed by finite element (FE) models. The experimentally observed imperfections, including the initial fiber waviness throughout the entire specimen volume and the scattered resin/interface defects, were taken into account in the FE models. The birth-and-death method was employed to simulate the progressive damage to the material. The consideration of the coexistence of initial fiber waviness and initial resin/interface defects was found to be essential for accurate modeling of the kinking failure process. Kinking was initiated due to the disproportional increase of the fiber microbuckling at the locations of initial defects. The numerically obtained peak load, fiber microbuckling amplitudes, kink band angle and width, and compressive strain concentrations at the kink band edges were well predicted compared to the experimental results. The number of defects was less significant than the fact that defects existed that served as initiation points of the kink band formation.

ABSTRACT: The work provides an analysis of paperboard tubes subjected to transversal compression force. The investigations were performed for 8 tubes of different radii and different wall thicknesses. The number of layers for detailed pipe ranged from 4 up to 13. The each layer of the paper was modelled with orthotropic material properties. To compare the obtained results of experimental tests, numerical simulations of considered tubes in Ansys 16.2® software were conducted. The calculations were carried out for total failure of pipes using the anisotropic Hill potential theory to implement progressive phase of damage. The scores of investigations were compared with each other and discussed.

ABSTRACT: Chiral-type cells consisting of rigid nodes and rotatable ligaments provide an opportunity to develop lightweight engineering structures with unique mechanical performances. For a 2D or 3D chiral-type cellular structure system with a periodic arrangement of chiral cells, a distinct rotational response will present because of the asymmetrical and geometrical configuration. In this article, a tetra-chiral cylindrical shell is proposed on the basis of natural plant architecture. This shell exhibits a reversible bi-directional twisting deformation in the axial compression and tension processes. A theoretical model is proposed via the geometrical parameters of cells to describe the relationship between twist angle and axial displacement. Two categories of tetra-chiral cylindrical shell specimens are fabricated utilizing additive manufacturing technique involving the application of nylon and AISI10Mg materials. Uniaxial compressive tests and finite element simulation are conducted to reveal the twist deformation mechanism. Results verify that the twist characteristics of the chiral-type shell, which are adjustable in terms of the rotational direction and angle, are only related to the distribution
and geometrical sizes of ligaments. The innovative chiral-type cylindrical shell provide a new design strategy which can be used in engineering applications as compress- or stretch-twist coupled smart actuators, biomechanical devices, and micro sensors.


ABSTRACT: Foam core sandwich structure has excellent insulation and specific strength and is widely used in the aerospace, aviation, navigation and military fields. The hemispherical shell of this kind sandwich structure is often used as energy and load carrying component due to its energy absorption ability. Some foam core sandwich hemispherical structures work in particular ultra-low temperature environments which undergo both temperature and mechanical loads. The research on the load carrying capacity of such structures in ultra-low temperature environment is essential for design and verify its properties. In this paper, the low-temperature mechanical properties of the face sheet and core materials were tested. The thermo-mechanical coupling numerical model was established and verified by comparison with the experimental results. Through the numerical simulation, the compressive behavior of the foam core hemispherical shells with different sizes was obtained under three different low-temperature loading situations. The effect of temperature loading on the deformation mode, load carrying capacity and deformation accumulation is further studied. It is suggested that the cooling of the out sheet is a relatively preferred low-temperature loading method. It also provides advice and ideas for the use of such structures.


ABSTRACT: We in this paper present an effective computational approach for static and free vibration analyses of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) shells. The governing equations are approximated based on the first-order shear deformation shell theory (FSDT) and non-uniform rational B-Spline (NURBS) basis functions. The advantage of NURBS in modeling exact geometries of shell structures is exploited. Material properties of FG-CNTRC shells are assumed to be graded through the thickness and estimated according to an equivalent continuum model based on the rule of mixture. The high accuracy and reliability of the present formulation is verified through several numerical examples in comparison with various reference solutions. In addition, some numerical results of FG-CNTRC panels and cylinders are provided. This may be useful for future references.

Xiang Ou, Xiaohu Yao, Run Zhang, Xiaqing Zhang and Qiang Han, “Nonlinear dynamic response analysis of cylindrical composite stiffened laminates based on the weak form quadrature element method”, Composite Structures, Vol. 203, pp 446-457, 1 November 2018, https://doi.org/10.1016/j.compstruct.2018.06.114

ABSTRACT: This paper presents a weak form quadrature element formulation for the analysis of nonlinear dynamic response of cylindrical composite stiffened laminates subjected to impact loads. A total Lagrangian updating scheme in combination with Newmark’s numerical integration is adopted to solve the nonlinear governing equations. The formulation of present shell and beam model stems from the basic concept of Ahmad (1970). Several numerical examples are firstly presented to verify the effectiveness and accuracy of the weak form quadrature element formulation. Parametric studies on the effects of the impact as well as geometric parameters, boundary conditions and lamination sequences of the laminates are performed. It shows that lamination sequences, geometric parameters, impact load type and duration have remarkable influence on the dynamic response of structures.

ABSTRACT: Modeling and numerical solution of free vibration problem of annular and annular sector plates with carbon nanotube reinforced (CNTR) composites have been presented. First-order shear deformation theory has been used for modeling of laminated composite and CNTR composite materials. The method of discrete singular convolution (DSC) is used for solution of equations of motion for shells and plate. Verification of the accuracy of the present DSC results is verified by appropriate convergence study and checked with the results available in the open literature for isotropic, laminated and CNTR cases. The influence of volume fraction index, boundary conditions, types of CNTR and geometrical parameters on results have been investigated in details.


ABSTRACT: In this paper, the variability of natural frequencies of laminated composite structures modeled by finite elements is studied using the Modal Stability Procedure (MSP) probabilistic approach. This stochastic method is based on the modal stability assumption and associates a metamodel of natural frequencies with a fast Monte Carlo Simulation (MCS). The uncertain parameters of the structure may be material properties (elastic properties, densities) and physical properties (thicknesses and fiber orientations). A simple error indicator which is able to estimate the error level using a small number of Monte Carlo trials is proposed. Two examples are studied: an eight-layer composite square plate and a stiffened ten-layer composite rectangular plate. The statistical results obtained by the MSP and the direct MCS are compared, the latter being considered as a reference. The comparison shows that the MSP provides quite accurate results with high computational efficiency.


ABSTRACT: In this paper, aiming at better understanding the damage tolerance of T-stiffened composite panels, impact damage and the influences on compression behaviors were studied with experiment methods using single T-stiffened panels. Low velocity impact (LVI) was conducted on the stiffener flange tip from the smooth side. Serious impact damage, including stiffener/skin interface debonding, fibre breakage and delamination, was observed. After the impact test, compression experiment was performed to characterize both the buckling behavior and compression failure mechanism. The compression results revealed that the buckling was promoted by the impact damage and induced bending moments which drove delamination inside the skin to propagate beneath the stiffener and led to the failure of the stiffened panel. Consequently, the impact damage decreased the buckling load and failure load of the single T-stiffened panel by 9.62% and 34.1%, respectively.


ABSTRACT: Auxetic materials and structures as a class of metamaterials have been extensively studied and evaluated for many applications. This paper focuses on the fabrication and vibration damping of the carbon
fiber composite auxetic double-arrow corrugated sandwich panels (DACSPs). The negative Poisson’s ratio effects of the composite auxetic DACSPs are analytically studied based on energy method. 3D finite element (FE) models combined with Modal Strain Energy (MSE) approach are developed to investigate their vibration and damping characteristics. To validate the numerical models in the present study, the composite auxetic DACSPs and such structures inserted with high damping layer are designed and manufactured. Modal vibration and three-point bending tests are conducted to investigate their vibration damping and bending responses. The results show that the 3D FE models combined with MSE approach are valid to predict the modal properties of the composite auxetic DACSPs. The influence of the different inclined corrugated angles on the natural frequencies and damping loss factors are plotted and discussed. Meanwhile, the effect of Poisson’s ratio on the nominal Young’s modulus, natural frequencies and damping loss factors of the composite auxetic DACSPs are also revealed. It is observed from the results that it is possible to obtain both increased stiffness and high damping capacity of such composite auxetic DACSPs by optimizing the inclined corrugated angles and inserting suitable damping layers.


ABSTRACT: Graphene reinforcements can obviously enhance the piezoelectric properties as well as the mechanical properties of the polyvinylidene fluoride (PVDF). This paper investigates the linear and nonlinear vibration behaviors of the smart piezoelectric composite plate reinforced by uniformly and non-uniformly dispersing graphene platelets (GPLs). The effective Young’s modulus is predicted by the Halpin Tsai’s parallel model while the effective mass density, Possion’s ratio and piezoelectric properties are calculated by the rule of the mixture. Based on the first-order shear deformation plate theory, von Karman nonlinear geometric relationship and Hamilton’s principle, the governing equations of motion under different boundary conditions are derived for the smart piezoelectric composite plate. The governing equations of motion are solved to obtain the nonlinear eigenvalue equations by the differential quadrature (DQ) method. The analysis is validated by comparing with the current results of the smart piezoelectric composite plate. The effects of the GPL distribution pattern, stratification number, concentration and geometry of GPLs, plate geometry, external voltage and piezoelectric properties of GPLs as well as boundary conditions on the linear and nonlinear vibration behaviors are discussed in detail. The numerical results clearly illustrate that there exists the great potential for using GPLs in achieving smart structures with significantly improved structural stiffness.


ABSTRACT: In this paper, the nonlinear bending and vibrational characteristics of porous tubes are analyzed for the first time. Within the framework of the nonlocal strain gradient theory, a size-dependent model for the tubes with radial inhomogeneity is formulated. It is assumed that the tube is made from functionally graded materials (FGM). Employed a new model for tubes which takes into account of the shear deformation effects, the motion equations are derived with the help of Hamilton variational principle and determined by the two-step perturbation technique. The validity and feasibility of the method are verified by actual examples. The effects of different parameters such as scaling parameters, porosity volume fraction, power law index and inner-to-outer radius ratio on the nonlinear bending and vibration behaviors of the porous tubes are particularly discussed.

ABSTRACT: In this paper, a shell based finite element (FE) model previously introduced for capturing the face-on impact and compressive strength after impact (CSAI) response of composite laminated structures is evaluated for predicting the dynamic response and damage due to edge-on impact and the resulting CSAI. The model utilizes an in-plane progressive damage and failure material model, Enhanced Schapery Theory (EST), for modeling the full field damage and failure of a single lamina in the 1–2 plane. The material model captures the pre-peak matrix non-linearity due to micro cracking using Schapery Theory (ST). The Bažant-Oh Crack Band (CB) model is utilized for matrix cracking and fiber rupture at the lamina level. Discrete cohesive elements are used for delamination initiation and propagation. Edge-on impact data for a range of impact energies is used for evaluating the models capability. The predicted impact damage state of the laminate is used for acquiring predictions of the CSAI of the laminate. The model predictions show promising results for the impact and CSAI response of an edge-on impacted coupon. The paper discusses the strengths of the model, the issues encountered, as well as topics for future study.


ABSTRACT: The problem of a delaminated composite plate subjected to in-plane compressive loading is investigated by employing a novel analytical framework previously developed by the authors. The framework is capable of modelling the post-buckling behaviour considering damage growth by using a set of generalized coordinates only. Therefore, in order to model the post-buckling responses of delaminated composite plates a Rayleigh–Ritz formulation is employed. Thus, the post-buckling behaviour as well as the delamination growth characteristics are determined by solving a set of non-linear algebraic equations only. For the cases investigated, the study reveals that delamination growth is associated with the global buckling response. So long as stable delamination growth is present, the post-buckling response remains also stable. However, unstable delamination growth may be caused which would occur unexpectedly yielding sudden failure of the structure. This underlines the importance of considering delamination growth when studying the structural stability behaviour of these structures.


ABSTRACT: In this paper, variable angle tow (VAT) composite plates tailored to enhance buckling performance are studied with the use of stochastic finite element method to quantify uncertainties in buckling measures arising from variations in material properties and fibre tow path. Detailed formulations for predicting buckling statistics in terms of mean value and standard deviation are derived to enable a perturbation-based stochastic finite element analysis. The derivations are built on a linear variation formula for fibre tow path and plate element based on the first order shear deformation theory. They are integrated with Taylor series expansion to propagate uncertainties from inputs to buckling performance measures, including buckling eigenvalues, critical buckling coefficients, etc. A twelve-layer VAT composite plate, with optimally designed fibre tow paths under various boundary conditions, has been investigated to illustrate the uncertainty quantification procedure. The performance of the perturbation-based stochastic finite element method has been validated using Monte Carlo simulation. Influences of variations in material properties and fibre tow path are thoroughly examined to understand the variability of buckling performance of VAT composites.

ABSTRACT: In this paper, a unified solution is developed to analyze the vibration and flutter behaviors of supersonic porous functionally graded material (FGM) plates with general boundary conditions, in which the classical and non-classical boundary conditions can be dealt with. The one-dimensional Fourier equation of heat conduction is employed to calculate the temperature distribution through the thickness direction of the plate and the properties of temperature dependent materials can be further obtained. The first-order shear deformation theory (FSDT) and supersonic piston theory considering the yawed flow angle effect are employed to formulate the strain energy, kinetic energy and external work functions of the system. The motion equations of the supersonic porous FGM plate are derived by using the Hamilton’s principle and the displacement components of the plate are expanded by the Fourier series combined with auxiliary functions. A considerable number of numerical examples concerning the vibration and flutter of the supersonic porous FGM plate are carried out to show the accuracy and efficiency of the described method. Finally, the effects of the boundary condition, material property distribution, elastic foundation, temperature field, porosity volume fraction and yawed flow angle on the flutter characteristics of the supersonic FGM plate are analyzed in detail.


ABSTRACT: The purpose of this research is to analyse the free vibration of composite laminated conical shells based on higher order shear deformation theory. The vibrational behavior of multi-layered conical shells are analyzed for simply supported end condition. The coupled differential equations in terms displacement and rotational functions are obtained. These displacement and rotational functions are invariantly approximated using cubic and quartic spline. A generalized eigenvalue problem is obtained and solved numerically for an eigenfrequency parameter and an associated eigenvector of spline coefficients. The different materials are used to show the parametric effects of shell’s length ratio, cone angle, stacking sequence and number of lamina on the frequency of the conical shells. The numerical results obtained using spline approximation are validated through existing literature.


ABSTRACT: The study is devoted to thin-walled clamped symmetrical three-layer circular plate. The sandwich plate consists of two facings, and a metal foam core. The mechanical properties of the core plate vary along its radius, remaining constant in the facings. The main goal of the study is to elaborate a mathematical model of the compressed circular plate in its middle plane, analytical description and solution of the global buckling problem. The nonlinear hypothesis of deformation of the normal to the middle plane of the plate is formulated. The equations of equilibrium are derived based on the principle of stationary total potential energy. The proposed mathematical model of the displacements considers the shear effect. The analytical model is verified numerically with the use of Finite Element Analysis.

ABSTRACT: The paper describes a numerical and experimental study investigating the load carrying capacity of thin-walled composite columns with a top-hat cross section under axial compression. The tested columns were made of carbon-epoxy laminate with symmetrical lay-up and ply orientation [0/90/0/90]. The experiments were performed on a universal testing machine, Zwick Z100, under full load conditions until total failure of the structure. In the experiments, post-critical equilibrium paths of the structure were determined, defining the relationship between compressive force and deflection and enabling the validation of the numerical models. Based on the obtained post-critical equilibrium paths, the critical load of the structure was determined by approximation methods. Simultaneously, a numerical analysis was performed by the finite element method using the Abaqus® software. The critical state was determined via a linear eigenvalue analysis, and the critical load and a corresponding buckling mode were estimated. The next stage of the numerical analysis involved solving a nonlinear stability problem for a structure with initialized geometric imperfection reflecting the lowest buckling mode. The geometrically non-linear problem was solved by the Newton-Raphson method. The load carrying capacity of the composite structure in the post-buckling state was determined by the progressive failure criterion which estimates damage initiation in the composite material based on the Hashin criterion, while the progression of damage is described with the energy criterion describing the degradation of stiffness of finite elements. The numerical and experimental results show high agreement, which confirms the adequacy of the developed numerical models of composite structures.


ABSTRACT: The subject of the paper is a cylindrical panel with symmetrically varying mechanical properties in the thickness direction. The nonlinear hypothesis of deformation of the straight line normal to the panel neutral surface is assumed. Based on the principle of stationary potential energy differential equations of equilibrium are obtained. The system of the equations is analytically solved and the critical loads of cylindrical panel are derived. Moreover, a simplified model of the cylindrical panel without shear effect is formulated. The results of critical loads for example structures are calculated and presented in Tables.


ABSTRACT: Low velocity impact events significantly reduce the mechanical performance of composite structures even though the damage might be barely visible. Numerical simulations can be used to understand and improve the damage resistance and tolerance of composite structures. However, numerical simulations are usually computationally intensive and their application in large composite structures is limited. Furthermore, the numerical models require many parameters that affect their efficiency, accuracy, objectivity and robustness. The present work describes a methodology to simulate low velocity impact and compression after impact which is applied to a composite stiffened panel undergoing visible impact damage. The key definitions are discussed and special attention is devoted to the computational efficiency. The numerical results are compared with experimental data, and the suitability of the proposed methodology is discussed.


ABSTRACT: A new hyperbolic tangent shear deformation theory (HTSDT) for the static, free vibration and buckling analysis of laminated composite plates is presented. In the present theory, shear stresses disappear at
the top and bottom surfaces of the plates and shear correction factors are no longer required. Weak forms of the static, free vibration and buckling analysis for laminated composite plates based on the HTSDT are then derived and are numerically solved using the isogeometric analysis (IGA). The proposed formulation requires $C^1$ continuity generalized displacements, whereas the basis functions used in IGA can perfectly fulfill this requirement. Based on the available solutions in the literature, the present method shows high accuracy and efficiency when numerical examples are solved.


ABSTRACT: A buckling structure is a crucial element for materials used in wearable electronics by taking a topographical approach to solve a spatial constraint. This review introduces various buckling structures, with the corresponding theory and fabrication, for the latest materials or devices, including secondary batteries, supercapacitors, sensors, organic thin film transistors, polymer light-emitting diodes, and organic light emitting diodes, all of which have attracted much attention recently in journals. This review demonstrates how various buckling structures can be practically integrated into functional materials to enlarge the active area, to enhance flexibility or stretchability, and to improve unique functionality itself without loss.


ABSTRACT: Structural optimisation of a wind turbine blade is presented in this work. The optimisation was performed using a multi-objective genetic algorithm and finite element modelling to determine the optimal structural design for a glass fibre-reinforced polypropylene composite blade. A candidate blade design from the Pareto efficient set was manufactured and tested for a range of structural characteristics, including: mass, centre of gravity, deflections, strains and natural frequencies. Static testing was carried out using a Whiffle tree test rig and a laser scanner was used to determine the deflection of the blade to a high degree of accuracy. The finite element model results for the custom-made design are compared to the measured blade response. The FE model predictions for strains, mass and natural frequencies are in relatively good agreement with the test results; however, notable deviations in the deflections predictions are attributed to modifications to the blade for manufacture and the shell-based modelling approach. The differences are discussed in detail and recommendations for future design work are outlined. The test results of the bespoke blade are also compared to two additional designs to determine the level of improvement afforded by the genetic algorithm approach. The bespoke glass fibre blade demonstrated an improvement in tip deflection of 16% relative to the original blade design, with a slight decrease in mass.

Bin Han, Wei-Wei Hui, Qian-Cheng Zhang, Zhen-Yu Zhao, Feng Jin, Qi Zhang, Tian Jian Lu and Bing-Heng Lu, “A refined quasi-3D zigzag beam theory for free vibration and stability analysis of multilayered composite beams subjected to thermomechanical loading”, Composite Structures, Vol. 204, pp 620-633, 15 November 2018, https://doi.org/10.1016/j.compstruct.2018.08.005

ABSTRACT: A refined four-unknown quasi-3D zigzag beam theory is developed to model the free vibration and buckling behaviors of multilayered composite beams subjected to axial mechanical loading (e.g., distributed load and terminal force) and uniform temperature variation. Types of the composite beams considered include laminated composite beams, sandwich beams with composite face sheets, and fiber metal laminates. The proposed theory accounts for not only thickness stretching but also interlaminar continuity of transverse shear stresses and displacements. Associated eigenvalue problems for various boundary conditions are derived using
the Ritz method. Accuracy and effectiveness of the theoretical predictions are verified by comparison with existing results and present finite element simulations. The theory is employed to quantify the effects of axial distributed load/terminal force and temperature variation on free vibration and buckling for different boundary conditions, geometric parameters and material properties. The present theory could produce sufficiently accurate predictions of natural frequencies and buckling capacities of multilayered beams at a very low computational cost.


ABSTRACT: Hybrid fibre-reinforced polymer (FRP)-concrete-steel double-skin tubular columns (DSTCs) consist of an outer FRP tube and an inner steel tube, with the space inbetween filled with concrete. In hybrid DSTCs, the outward buckling of the steel inner tube is constrained by the surrounding concrete and the outer FRP tube, but its inward buckling is still possible. Existing research has shown that such inward buckling can become significant in non-circular hybrid DSTCs due to the non-uniform confinement, in hybrid DSTCs with a strong FRP tube due to the large axial deformation of the columns, and/or in hybrid DSTCs with a thin steel tube. In these cases, the stiffening of the inner steel tube is necessary to prevent or delay its inward buckling and to minimize its negative consequences to the column behavior. Against this background, a variation of hybrid DSTCs (hybrid R-DSTCs), in which the inner steel tube is stiffened by a number of vertical rib stiffeners, was recently developed at the University of Wollongong, Australia. This paper presents an experimental study on the axial compressive behavior of the new form of columns. The experimental program included a total of 12 R-DSTC specimens and two DSTC specimens for comparison, with the test variables being the number, thickness and width of rib stiffeners as well as the number of plies of fibres in the FRP tube. The test results confirmed that the additional rib stiffeners on the steel tube are effective in delaying the local buckling of the steel tube and in improving the performance of the columns. The test results also clarified the effects of the tested parameters of the rib stiffeners.


ABSTRACT: In order to accurately predict the static and dynamic behavior of composite box beam, the Geometrically Exact Nonlinear Model (GENM) of composite box beams with arbitrary material distribution and large deflection was performed based on the Hodges’ neralized Timoshenko beam theory. The strain of any point in the deformed beam was calculated by the rotational tensor decomposition. Then, the asymptotic variational method was used to determine the arbitrary sectional warping. The generalized Timoshenko strain energy was derived from the second-order asymptotically exact strain energy using the equilibrium equation. The motion equations of GENM were established by using the Hamilton’s generalized principle. Finally, the proposed model was applied to the static and dynamic analysis of the composite box beam and verified by comparison with the experimental data. The influence of non-classical effects of sectional warping and transverse shear deformation on the composite box beam were further investigated. The results show that the sectional warping has significant effects on the static deformation and natural frequencies of composite box beams, and the influence of transverse shear deformation on the static deformation and the natural frequencies are related to the aspect ratio of beam length to section dimension.

ABSTRACT: This work shows possibilities and limitations of the refined zigzag theory (RZT) that has been used in different structural (beam, plate and shell) finite elements. The refined zigzag theory can deal with composite laminates, adding only one nodal degree of freedom per spatial dimension of the laminate, obtaining very good accuracy. It assumes that the in-plane displacements have a piece-wise linear shape across the thickness depending on the shear stiffness of each composite layer. This paper presents the main aspects of a beam/shell of revolution element used for the numerical simulations. The details of the refined zigzag theory are given also in order to discuss some limitations that occur when dealing with the non-linear phenomenon of delamination. Two examples are presented and discussed, including different inhomogeneities that show the limitations of the RZT for the treatment of partially delaminated beams.


ABSTRACT: This paper presents an investigation on free vibration of functionally graded (FG) porous nanocomposite plates reinforced with a small amount of graphene platelets (GPLs) and supported by the two-parameter elastic foundations with different boundary conditions. Four different porosity distributions of the parent metal were reinforced by four various GPLs dispersion patterns (evenly or unevenly) along the thickness direction. To obtain graded distribution in both porosity and GPLs, the Young’s modulus, shear modulus and density of nanocomposites are assumed to vary through the thickness direction due to variation of internal pores and the volume fraction of GPLs. By employing Halpin-Tsai micromechanics model, effective elastic modulus of the nanocomposites is obtained according to the assumption of closed-cell cellular solids under Gaussian Random Field scheme. The governing equations of FG GPLs-reinforced metal foams resting on elastic foundations are derived from Hamilton’s principle by the means of classic plate theory with the consideration of von Kármán strain-displacement relation. Applying the differential quadrature method, the dimensionless natural frequencies of porous nanocomposite plates with different boundary conditions are obtained and present method is thoroughly validated with the results in open literature. The comprehensive parametric studies on different porosity coefficients, GPL dispersion patterns, weight fraction of GPL, aspect ratios, thickness ratios and parameters of elastic foundation on free vibration of FG GPLs-reinforced porous plates with various boundary conditions. An interesting finding is that the increase of porosity coefficients would lead to the linearly decrease of both mass density and stiffness of the plates, but the increase of porosity coefficients does not always induce the decrease of natural frequencies. Moreover, both porosity distribution and GPL dispersion pattern have a distinct effect on dynamic characteristics, the former plays a more important role than the latter in analysing mechanical properties of FG GPLs-reinforced plates.


ABSTRACT: The feasibility and performance of standard and boundary layer perturbation techniques in nonlinear analyses of cylindrical shells are investigated. To this end, the nonlinear axisymmetric behavior of short and long functionally graded (FG) cylindrical shells is considered. The nonlinear governing equations of shell theory with first-order approximation and the von Karman nonlinearity are decoupled. This uncoupling makes it possible to present an analytical solution. A new boundary layer perturbation solution is presented by reducing the governing equations to a normalized form of boundary-layer type. Also, the uncoupled governing
equations are solved using standard one-, two-, and three-parameter expansions. Findings indicate that the boundary layer technique cannot predict the post-buckling behavior of cylindrical shells for any geometric ratios R/h and L/R, since after occurrence of instability, the behavior of shell is not boundary-layer type and it is impossible to satisfy the matching conditions. Hence, this technique is only valid for the analysis of long shells before buckling occurs. Furthermore, the standard perturbation series in terms of output parameters can predict the buckling load and the static equilibrium path with acceptable accuracy only under consideration of the deflection of points at an area near enough to the ends of the shell. On the other hand, the standard expansions in loading parameters are able to predict the snap-through post-buckling behavior accurately by considering higher-order terms (around 30th order) in expansion series.


ABSTRACT: In this work, a mathematical model of multilayer orthotropic shells with the account of both the 3rd-order generalized model (the so-called Grigoluk-Kulikov model) and a temperature field is presented. An asymptotically stable modified model is proposed. The reported conservative difference schemes associated with the considered models are developed based on the variational-difference method. The stability of a symmetric/non-symmetric pack of layers is addressed. In particular, the influence of the number of layers on the shell stability properties is illustrated and discussed.


ABSTRACT: Composite pipes with unidirectional fiber-reinforced layers at different fiber orientations are used in many industrial applications. When they carry pressurized fluids, water hammer may occur during any rapid change in the momentum of the fluid flow. Water hammer produces a travelling pressure wave and causes pipe vibration. This vibration, in turn, affects the water hammer so that fluid-structure interaction may play an important role in the pipe design calculations. In this paper, governing equations for the fluid-structure interaction of water hammer in thin laminated pipes were derived by assuming longitudinal vibration of the pipe. The resulting system of partial differential equations (PDEs) was solved numerically using an implicit least squares technique. The method uses radial basis functions locally in function approximations leading to a sparse and symmetric coefficient matrix. Two problems were solved using the proposed numerical method and the effect of the number of layers on the travelling pressure wave characteristics was investigated.


ABSTRACT: The objects of consideration are thin linearly elastic Kirchhoff-Love-type circular cylindrical shells having a periodically microheterogeneous structure in circumferential and axial directions (biperiodic shells). The aim of this contribution is to formulate and discuss a new mathematical averaged model for the analysis of selected dynamic problems for these shells. This, so-called, general combined asymptotic-tolerance model is derived by applying a certain extended version of the known tolerance (non-asymptotic) modelling procedure. This version is based on a new notion of weakly slowly-varying functions. Contrary to the starting exact shell equations with highly oscillating, non-continuous and periodic coefficients, governing equations of the proposed combined model have constant coefficients depending also on a cell size. Hence, this model can be applied to study the effect of a microstructure size on dynamic behaviour of the shells (the length-scale effect).
An important advantage of this model is that it makes it possible to analyse micro-dynamics of biperiodic shells independently of their macro-dynamics. The differences between the proposed general combined model and the corresponding known less accurate standard combined model derived by means of the more restrictive concept of slowly-varying functions are discussed. As an example there are determined and analysed cell depending micro-vibrations of the biperiodic shells under consideration.


ABSTRACT: A p-version curved composite laminated shell element has been developed using the modified high order bases of a differential quadrature hierarchical finite element method (DQHFEM). The theoretical model of the shell is based on a layerwise theory with linear expansion in each layer. Exact geometry is established using the CAD technique of Non-Uniform Rational B-splines. As a result, the FEM discretization errors of geometry are eliminated. To solve the coupling difficulty of elements with different parameterization that commonly exists in complicated models, a novel method based on interpolation on arc length coordinates is proposed in this work. Even though the computational efficiency based on a layerwise theory is not as fast as those based on the equivalent single-layer theory, it produces as accurate results as the 3D theory and uses less DOFs as well as less input data than the 3D model. Additionally, because of the high convergence rate of the p-version FEM and the exact representation of the geometric model, the present elements are expected to produce more accurate results than the conventional h-version flat shell elements with the same number of DOFs. Numerical examples are provided to illustrate the accuracy as well as versatility of the present elements.


ABSTRACT: This paper studies buckling and post-buckling behaviours of multi-layered plates under in-plane compression based on Reissner-Mindlin plate theory. The governing equations are derived from a kinematic nonlinearity based on the von-Kármán assumptions and are thereafter discretized by isogeometric analysis (IGA), which utilizes the NURBS basis functions. For the symmetrically laminated plates, stability analysis consists of three steps: pre-buckling, buckling and post-buckling analyses. In fact, the pre-buckling stresses must be first determined in the pre-buckling analysis and become an important factor in accurate estimation of the critical buckling and post-buckling loads. Otherwise, in the imperfect or unsymmetrically stacked plates, there is no buckling bifurcation phenomenon. The Newton-Rapshon method is hence adopted to solve the geometrically nonlinear problem. Numerical examples are supplied to investigate the effect of an initially geometrical imperfection, which is possible imperfection type such as sine-type, global-type or local-type imperfection, on the post-buckling response of the plates.


ABSTRACT: High velocity impact on laminated composite panels is investigated by modeling, simulation, and experiments. Impact velocities of 100, 200, and 300 m/s are considered and normal as well as oblique impacts are studied. FEM simulations are conducted to design three different laminate configurations to achieve the cases of a reflecting, almost sticking, and fully perforating impactor, respectively. Within a domain where material nonlinearities are expected the shell-based ply-scale approach is used. Every ply is modeled by a layer of shell elements which are connected via cohesive zone elements. Both element types are assigned nonlinear
constitutive laws to capture their mechanical behavior appropriately. Outside this domain, a single layer of composite shell elements is used. Corresponding laminated plates are produced and tested using a gas gun setup, where energy absorption and damage patterns are assessed. The comparison of simulations and experiments shows excellent agreement. The three cases are predicted well, and also the damage patterns and the energy absorptions match very well.

ABSTRACT: The main objective of the present study is to develop a hexahedral continuous element for the three-dimensional nonlinear free vibration analysis of rectangular nano-plates with circular cutout based on the strain gradient elasticity theory. In the proposed element, in addition to the values of displacement components, the corresponding first, mixed second and mixed third order derivatives are taken into account as nodal values. Since arbitrary-shaped hexahedral elements are considered, spatial derivatives are presented using isoparametric formulation. To derive the nonlinear governing equations, the matrix form of kinetic and strain energies are written based on the three-dimensional strain gradient elasticity theory which can be reduced to the modified strain gradient theory (MSGT) and the modified couple stress theory (MCST). The accuracy and convergence of the numerical results are first investigated. In the parametric study, the nonlinear free vibration response of nano-plate is studied for different length scale parameters, geometrical factors and boundary conditions.

ABSTRACT: Dynamic response of a cylindrical tube surrounded by an unbounded elastic medium due to plane harmonic SH-Waves is studied. A two-dimensional mathematical model is considered. Cylindrical coordinates are used for convenience. The surrounding medium is assumed to be homogeneous, isotropic and linear elastic. The tube is assumed to be made of linear elastic functionally graded materials (FGMs) such that shear modulus and shear wave velocity are assumed to change linearly from inner surface to outer surface. Material properties are constant along circumferential direction. It is assumed that the inner surface of the tube is traction-free and there is a welded contact between the tube and the surrounding medium. Governing equations are slightly different in the tube region and the unbounded region. Both of the governing equations are solved by applying Finite Fourier Transform in circumferential direction. The exact solution series are presented in terms of Fourier-Bessel series in the unbounded region and power series in the tube region. The presented numerical results show that when the incoming wave lengths decrease, shear stresses at the tube increase significantly. It was shown that for the shorter incoming wave lengths, tubes made of FGMs are subjected to smaller shear stresses compared to the tubes homogeneously made of outer surface material of the FG cases.

ABSTRACT: The vibration characteristics of a sandwich plate with viscoelastic periodic cores are examined analytically and experimentally, which extends the previous research of corresponding periodic sandwich beam structure. Closed-form solutions for forced response and band structure of periodic sandwich plate are theoretically derived, providing computational support on the attenuation analysis. In the theoretical model, a new admissible displacement function for sandwich plate is proposed. Although it is used in free boundary condition in this paper, it is also suitable for clamped, simply supported, slipping, and elastic boundary
conditions. The formation of the band gap is carefully studied, showing that the overall band gap is proved to be the intersection of all the cross-stream modal band gaps, which is quite different from a corresponding periodic beam structure. The parametric analysis shows further that the overall band gap could disappear when length ratio, element width, or core thickness exceeds a cut-off value, which provides a guidance in the band-gap design. The attenuation in a sandwich plate with viscoelastic periodic cores is mainly dominated by Bragg scattering mechanism in the band gap and by energy dissipation out of the band gap. Owing to the combined effect of both mechanisms, the sandwich plate with viscoelastic periodic cores provides better attenuation performance than that with a uniform viscoelastic core. This research could possibly provide useful guidance for the researchers and engineers on the design of plate-type damping structures.

ABSTRACT: Buckling of axially functionally graded and nonuniform Timoshenko beams is examined based on the nonlocal Timoshenko beam theory. Small scale effect on the buckling is taken into account via the length scale parameter often referred as the nonlocal parameter. The material properties vary in the axial direction and the nanobeam is modelled as a nonuniform Timoshenko beam which rests on a Winkler-Pasternak foundation. Rayleigh quotients for the buckling load are derived for Euler-Bernoulli and Timoshenko beams. Chebyshev polynomials based on the Rayleigh-Ritz method is used to obtain the numerical solution of the problem for a combination of clamped, simply supported and free boundary conditions. Accuracy of the method is verified by comparing the buckling loads obtained by the present approach with those available in the literature. Numerical results for the problem are given in the form of contour plots to study the effect of nonlocal parameter, cross-sectional non-uniformity, axial grading and the boundary conditions on the buckling loads.

ABSTRACT: The purpose of this study is to investigate the dynamic stability of heterogeneous orthotropic visco-elastic cylindrical shells (HTOVECSs) under an axial load. The hereditary theory is used for heterogeneous (HT) orthotropic cylindrical shells over the entire thickness. The behavior of HTOVECSs is described by integro-differential equations with heterogeneous elastic parameters. The method is proposed for calculating the critical time parameter (CTP) of HTOVECSs by using the linear visco-elasticity theory. Finally, the influences of heterogeneity, rheological parameter and shell characteristics on the critical time parameter of the orthotropic visco-elastic cylindrical shells (OVECSs) are discussed in detail.

ABSTRACT: A higher-order beam theory suitable for accurate analysis of composite thin-walled box beams is developed. Because anisotropic and laminate effects in composite beams produce deformation patterns that do not appear in isotropic beams, accurate analyses for composite beams require elaborately defined sectional shape functions that describe local cross-sectional deformations. Here, we present a new systematic method to define these functions and establish a one-dimensional finite element based on a higher-order beam theory for composite thin-walled box beams. The validity of the developed approach is checked by solving static and eigenvalue problems with composite thin-walled box beams, and by comparing the obtained numerical results with those obtained by ABAQUS shell elements.

ABSTRACT: This paper investigates the postbuckling behavior of a novel glass-protection film system under thermal environment using the element-free kp-Ritz method. The governing formulation is derived based on the first-order shear deformation plate theory considering small strains and the nonlocal elasticity theory which takes small scale effect into account. The modified Newton-Raphson method incorporated with the arc-length continuation technique is used to trace the nonlinear response of the film-foundation system. The influences of boundary conditions, nonlocal parameters, geometry and elastic foundation on the nonlinear response of glass-protection film are examined. The results show that adhesion force between graphene sheets (GSs) film and the elastic substrate can significantly enhance thermal buckling resistance of GSs film. It is also concluded that van der Waals forces between GSs film lead to consistent post-buckling behavior of individual GSs. Present study can provide suggestions on firefighting design, such as setting alarm temperature based on transition temperature.


ABSTRACT: The metaheuristic optimization methods have been widely used in complex composite material design. However, it is still difficult to apply these methods to complicated problems due to expensive cost of evaluations. Therefore, to reduce the expensive cost of finite element (FE) analysis in the composite laminate optimization problems, the surrogate assisted optimization (SAO) method has been well developed. However, considering the low accuracy of surrogate model for complicated cases, the SAO is always difficult to converge to the global optimum. In this study, a fast and accurate solver, the reanalysis algorithm is extended to vibration problem and integrated to improve the efficiency of metaheuristic optimization of composite laminates instead of surrogate model. In the proposed method, the shifting method is used in each iterative step. To validate the performance of suggested method, several numerical examples are presented. The results demonstrate that reanalysis assisted particle swarm optimization (RPSO) is much more efficient for free vibration problems of composite laminates than the PSO. Moreover, such strategy can be extended to other metaheuristic algorithms easily.


ABSTRACT: The snapthrough and free vibration response of bistable cross-ply [] composite laminates is investigated. Thin unsymmetric composite laminates possess more than one equilibrium position when cooled to room temperature due to the difference in thermal expansion of the plies. Bistable cross-ply laminates have cylindrical shapes at room temperature provided appropriate side-length-to-thickness ratio is used. The laminate is modelled according to the classical lamination plate theory taking into account the von Karman geometric nonlinearity. The strains and displacements are approximated via a simplified Rayleigh-Ritz model that depends on only four time-dependent parameters for the general dynamic response. The simplified model is validated against experimental and finite element results and an acceptable agreement is obtained. The laminate’s length-to-thickness ratio is key to assess the existence of bistability. The model is used to investigate the snapthrough response of an 8-ply [90sub4/0sub4] laminate that is subjected to three loading schemes: concentrated moments, normal forces, and tangential forces. The variations of the principal curvatures and the lateral displacement of
the laminate with the applied forces are shown. The significance of the force location is also found a crucial element in finding the snapthrough force. The free vibration that takes place in the vicinity of a stable equilibrium position is studied and the variation of the fundamental frequency with the laminate size is presented.


ABSTRACT: The different applications of micro/nano scale structures increase daily, and using new developed theories accounting size-reduction effect can be useful to study mechanical behaviors of such structures. The size dependent theory of modified strain gradient is capable for considering micro/nano structures. In the current work a new model based on the modified strain gradient and three dimensional elasticity theories is developed for free vibration of functionally graded (FG) micro/nano plates, and an exact analytical solution is carried out for extracting the natural frequencies of it. The present three-dimensional elasticity model contains three length scale parameters. Analytical solution is based on the state space method. In order to achieve the analytical solution, the distribution of material properties through the plate thickness follows an exponential law. Finally, some exact numerical results are tabulated for both homogeneous and FG plates that can be used as an exact three dimensional elasticity benchmark for validate other two dimensional models.


ABSTRACT: To obtain a strong and weight-efficient cylindrical shell, a novel foam-core sandwich cylinder was proposed with glass fibre-reinforced plastic (GFRP) stiffeners inserted between the faces and the foam core. This novel cylinder possessed the advantages of both stiffened cylinders and sandwich cylinders to resist buckling. A cost-effective vacuum-assisted resin infusion (VARI) method was used to manufacture the structure. We performed axial compression tests on two representative samples to investigate the compression strength and failure modes of the novel structure. Thereafter, a theoretical model was developed to predict the collapse strengths associated with three typical failure modes. The analytically predictions showed great agreement with the experimentally observed failure mode and load. Results indicated that, benefitting from the combination advantage of stiffened cylinder and sandwich cylinder, this novel cylinder can resist or postpone various buckling failure, instead failing via face crushing with high strength. Combined with the simplified manufacturing technology, this novel cylinder is a desirable alternative in engineering structures.


ABSTRACT: Natural fiber reinforced composites may have a great potential applications in the automotive and aerospace industries. Hydrothermal ageing in natural fiber reinforced composites leads to significantly degradation of their mechanical properties. This paper proposes a theoretical model for predicting the mechanical responses of bidirectional natural fiber reinforced composites under hydrothermal loading. Nine elastic coefficients of orthotropic composites after hydrothermal reaction and moisture absorption are obtained. Based on the present model, closed-form solutions for buckling load and frequency of a simply supported composite plate are derived. It is found that the elastic module and buckling load decrease monotonously with time, and approaches to a certain value with time. However, the frequency decreases with time firstly, and then increases with time, finally approaches to a certain value with time. In addition, the degradation of elastic
modulus, buckling load and frequency for the composites with high fiber content are larger than those with low fiber content. This research may be helpful for designing natural fiber reinforced composites for applications in humid environments.


ABSTRACT: The variable-stiffness fiber composite plates which have an enhanced design flexibility, largely rely on laminate optimizations to maximize the buckling performance. The corresponding computational efficiency becomes a key issue, in particular when the nonlinear structural behavior is considered. The finite element method based on a full nonlinear analysis is a standard technique for nonlinear structural analysis, however the high computational complexities generated from both the incremental-iterative procedure and the very refined mesh needed for the discrete modeling of curved fibers, are still a decisive cost factor on modern computers. In this work, the Koiter-Newton method is further extended to nonlinear buckling analysis, including the pre and post buckling stage, of variable stiffness composite plates. A four-node quadrilateral element based on the classical laminated plate theory is developed in framework of the von Kármán kinematics, for the finite element implementation of the proposed asymptotic method. The reduced order model, with or without imperfections, is constructed using the improved Koiter’s asymptotic expansion, for both the symmetrical and unsymmetrical laminates. The nonlinear response curve of loaded structure can be traced automatically, using the nonlinear predictor and corrections both generated from the reduced order model. This leads to a fairly large step size in the path-tracing process, compared to that for the classical Newton method. The reduced order model largely reduces the computational burden produced by the high-density FE mesh for the varied fiber path. Numerical results indicate the overall high quality and efficiency of the proposed method.


ABSTRACT: The result of an experimental programme investigating a novel technique to strengthen web plates against breathing fatigue is presented in this paper; the programme was divided into five phases, including: (1) the development of a novel preformed corrugated FRP panel for strengthening thin-walled steel plate girder webs against buckling, (2) selecting the adequate adhesive and epoxy using double-lap shear and tension specimens, (3) producing the FRP panel, and (4, 5) testing its performance in two main experimental series; the initial (static) series and the final (cyclic) series. Only the initial series which involved tests on 13 steel plates strengthened with the proposed preformed corrugated FRP panel and subjected to in-plane shear will be reported in this paper. This series investigated the performance of different forms of strengthening under static load, in preparation for a subsequent series of cyclic tests to investigate their fatigue performance. Test results showed the efficiency of the technique at increasing the stiffness of the strengthened specimens in comparison to the unstrengthened ones and reducing the critical stresses which will serve as a precursor for the anticipated increase in the fatigue life of the girders.


ABSTRACT: In this article, the nature of instability in architected cellular materials is explored through computational modelling and experimental testing. The in-plane and out-of-plane buckling as two major instability mechanisms in cellular materials are distinguished and the effects of their microarchitectural
parameters on the buckling behavior are demonstrated. Different architected cellular materials in the form of cellular plates are analysed with a finite element method (FEM) by eigen buckling and nonlinear analyses, while a few samples of elastomeric architected cellular materials are prototyped and experimentally tested to corroborate our numerical predictions for the buckling load. We show that an appropriate gradient of cell architecture within the cellular plates could lead to an increase in both out-of-plane and in-plane buckling loads. The experimental tests conducted on the casted cellular plates with uniform and graded microarchitectures, made of a two-component silicone elastomer, confirm that different buckling mode shapes can be observed by tailoring the microarchitectures of cellular plates. This idea can pave the path for devising advanced reconfigurable materials, for shape matching and energy absorption applications, whose mode shapes and resistance to buckling can be programmed based on the desirable functionalities without compromising their total mass.


ABSTRACT: The design of morphing structures requires attaining concurrently light-weight, load-carrying and shape adaptable systems that minimize complexity, actuation requirements and part count. Exploiting the external loads to produce local stiffness variations induced by elastic instabilities offers the potential to activate shape deformations purely passively. Following this approach, we present the structural response study of wings capable of attaining compliant buckling-induced twisting deformations. The structure is designed such that a specific level of aerodynamic load triggers the elastic instability in a shear web part of the wing box. The buckling-induced variation in effective shear stiffness, resulting from the development of a stable, reversible diagonal tension field, leads to a twisting deformation. The structural behaviour is characterized by two drastically different mechanical responses, delimited by the onset of elastic instability. The influence of the buckling component design on the attainable change in spanwise angle of attack is investigated for the specific case of a finite composite wing structure under aerodynamic loads. The type of composite material, its thickness, and the fibre orientation are the considered design parameters. The buckling-induced variation in twist angle, and the corresponding aerodynamic pressure redistribution on the wing, is exploited for achieving load alleviation, reducing the global lift coefficient and decreasing the wing root bending moment.


ABSTRACT: This paper investigates the thermal and mechanical buckling analysis of functionally graded carbon nanotube reinforced composite (FG-CNTRC) plates by using isogeometric analysis (IGA) based on modified couple stress theory (MCST). A refined hyperbolic shear deformation theory is used for buckling analysis, which satisfies free transverse shear stress conditions on the top and bottom surfaces of plate without a need for shear correction factor. The material properties of carbon nanotube reinforced composite plates are assumed to be temperature-dependent. For numerical analysis the IGA method using B-Spline or Non-Uniform Rational B-Spline (NURBS) functions is employed. The obtained results are compared with those available in the literature. Also, the influence of different parameters on mechanical and thermal buckling analysis is investigated. These parameters include material length scale parameter, boundary conditions, aspect and length-to-thickness ratios of plate, different types of FG-CNTRC distribution, volume fraction of CNTs and temperature dependency.

ABSTRACT: The purpose of this paper was to investigate the failure behaviors of composite stiffened panels with skin low-velocity impact (LVI) damage under axial compression. Barely visible impact damage (BVID) was introduced into the L-shaped and T-shaped stiffened panels within the skin between stiffeners. Compression after impact (CAI) tests were performed and delamination growth of specimens was observed directly. The results show that there are two types of delamination growth processes, which are unstable and stable respectively. Due to the restriction effect of the stiffener, the delamination growth is easier to initiate in the outer sublaminates on the smooth side of the skin compared to the ones on the stiffener side. In addition, according to the thermal-deply result, adjacent impact delaminations can be connected by matrix cracks, which results in a larger area of the sublaminates. It is revealed that buckling of the sublaminates and subsequent transverse delamination propagation in large area are the triggers leading to the final failure of the stiffened panel.


ABSTRACT: This paper studies the nonlinear dynamical characteristic of a composite plate made of new three-phase materials which include the graphene (GP) combined with macro fiber composite (MFC) in the polymer. The GP is supposed to be uniformly dispersed in the upper and lower surfaces of the composite laminated plate with 1–3 mode of macro fiber. The cross-ply MFC composite laminated plate is subjected to transversal excitations. The constitutive laws for the MFC-GP composite material are obtained based on the rule of mixture for multi-components of composite material. The nonlinear governing equations of motion of the MFC-GP plate are derived by Hamilton’s principle and the von Kármán geometrical kinematics. Galerkin’s approach is employed to discretize the partial differential governing equations into a two-degree-of-freedom nonlinear system. Then, stability analysis is conducted to investigate the influences of various parameters on natural frequencies of the MFC-GP plate, with a particular focus on the effects of GP volume fraction, initial conditions and damping coefficients on nonlinear vibration behaviours of the composite plate.


ABSTRACT: In this paper, a novel numerical method based on the Walsh series (WS) is proposed for free vibrations of functionally graded material (FGM) cylindrical shells. Based on the first order shear deformation theory, the governing equations of the FGM cylindrical shells are derived via the Hamilton’s principle. After converting the governing equations into a set of ordinary differential equations (ODEs) by the separation of variables, the proposed Walsh series method (WSM) is utilized to transform the ODEs to algebraic equation sets, which results to a standard linear eigenvalue problem. The natural frequencies of the FGM cylindrical shell are calculated by solving the obtained algebraic equations. The convergence and accuracy analyses of the present method are performed by comparing the obtained results with those available in the existing literature. The results show that the solution of the proposed WSM is stably converged with the numerical convergence rate close to 2 and the good agreement of the obtained results with those in the available literature is also observed. Finally, the parametric study is conducted to investigate the effects of several geometrical and material parameters of the FGM cylindrical shells with various boundary conditions on the natural frequencies.

ABSTRACT: For composite panels with cutouts, curvilinear fiber path can adjust the in-plane stiffness distribution to increase the buckling resistance, but it results in huge computational cost for the buckling analysis when FEA is employed. In this study, variable-stiffness panels with cutouts are analyzed via isogeometric method, where cutouts are represented by the level set method. The method for suppressing artificial buckling modes is proposed to improve the prediction accuracy. Moreover, the analytical sensitivity is derived to facilitate fiber path optimization, and a new bi-level optimization framework considering manufacturing constraints is established. Finally, the proposed method is verified by variable-stiffness aircraft panel with multiple cutouts, which can not only provide an accurate prediction of buckling load, but also exhibit high convergence rate and low computational cost for fiber path optimization.


ABSTRACT: In this article, the results for compressed channel section profiles made of glass and flax fiber reinforced polymer were presented. Six symmetric arrangements of layers were tested: [0/-45/45/90]s, [90/-45/45/0]s, [90/0/90/0]s, [0/90/0/90]s, [45/-45/−45/−45]s, [45/-45/90/0]s. The study concerns the buckling and failure modes and loads determination. To obtain load capacity of analyzed structures the ANSYS program based on finite element method was employed. Linear (LBA) and nonlinear buckling analyses (NBA) with an implementation of the progressive failure algorithm (PFA) with the Hashin criterion as the damage onset criterion, were performed. Structures made of natural fibers were characterized by small differences in relation to the successive buckling loads, similar load carrying capacity values determined for the implementation of successive buckling modes and, in opposition to GFRP channel section profiles, by a lack of or a small range of deformations in the postbuckling stage. Wherefore, the obtained results with results for analogous profiles made of GFRP were compared. Furthermore, the effect of laying the laminate layers on the magnitude of the critical force and the occurrence of a specific failure mechanism depending on the number of degraded layers were presented.

More papers published in the journal, Composite Structures (2017 and on).


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ABSTRACT: This paper examines static, free and forced vibration of functionally graded (FG) sandwich beams under the action of double moving harmonic loads travelling with constant velocities using Timoshenko beam theory (TBT). Three different sandwich beam models with various cross-sectional shape and various boundary conditions are considered. It is assumed that in FG part of sandwich beams, the material properties vary continuously through the thickness of the beam according to simple power-law form. The problem is formulated based on the energy approach. For this purpose, the unknown displacement functions are approximated by using the simple polynomials together with the auxiliary functions for satisfying the essential boundary conditions. The equations of the motion are obtained by using the Lagrange's equations, and solved with the help of the implicit time integration method of Newmark-. In this study, the effects of the different sandwich beam models, boundary conditions, gradient index, the velocity, excitation frequency and the phase angles of the two successive harmonic loads, and the distance between the loads on the mechanical behavior of sandwich beams are discussed in detail. At the same time, extensive static and free vibration results are presented to check the reliability of the present formulation. Good agreement is observed.

M. Mohammadimehr and S. Shahedi (Department of Solid Mechanics, Faculty of Mechanical Engineering, University of Kashan, 87317-53153, Kashan, Iran), “High-order buckling and free vibration analysis of two types sandwich beam including AL or PVC-foam flexible core and CNTs reinforced nanocomposite face sheets using GDQM”, Composites Part B: Engineering, Vol. 108, pp 91-107, January 2017
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ABSTRACT: In the present study, the high-order buckling and free vibration behaviors of two types sandwich beams including AL or PVC-foam flexible core and CNTs reinforced nanocomposite face sheets using generalized differential quadrature method (GDQM) are investigated. The high-order sandwich panel theory (HSAPT) for AL or PVC-foam flexible is employed and also the modified couple stress theory (MCST) for the face sheets is used. It is noted that the core of first sandwich beam is Aluminum alloy foam with variable mechanical properties and the other consists of PVC-foam core with temperature dependent mechanical properties. The governing partial differential equations of motion for two types sandwich beam are derived using Hamilton's principle and then discretized by using GDQM. These formulations yield nine partial differential equations which are coupled in axial and transverse deformations. A parametric study is carried out to investigate the effect of some important parameters such as slenderness ratio, face sheet thickness, temperature rise. Although increasing slenderness ratio, reduce the 1st natural frequency and also critical buckling load, but the treatment is different for AL-FCSB and PVC-FCSB. It is found that at high temperatures, the PVC-FCSB frequency decreases with increasing face sheet thickness whereas for AL-FCSB at high-temperatures although the frequency is less for low slenderness ratio and high face sheet thickness, but with increasing slenderness ratio frequency increases. This behavior is due to the large effect of face sheet and their temperature dependence in short sandwich beams compared with long ones.

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ABSTRACT: The need for high-performance lightweight materials for the design of aerospace structures predicts a remarkable future role of carbon nanotubes (CNTs). In particular, thin curved fuselage panels are widely employed. However, the theoretical difficulties in the underlying differential problem induced by the curvature, as well as a still under development technology of CNT-based composites, the number of studies
dealing with buckling behavior of this structural typology is limited. The present study aims to provide some insight into the linear buckling analysis of functionally graded carbon-nanotube reinforced (FG-CNTRC) cylindrical curved panels under compressive and shear loading. Effective properties of materials of the panels reinforced by single-walled carbon nanotubes (SWCNTs) are estimated through a micromechanical model based on either the Eshelby-Mori-Tanaka approach or the extended rule of mixtures. A series of numerical simulations have been carried out to inspect the influence of curvature, panel aspect ratio, the distribution profile of reinforcements (uniform and three non-uniform distributions) and CNTs orientation angle on the buckling critical load under compressive and shear loading in uniform thermal environments. Results demonstrate that the change of fiber orientation, CNTs distribution, panel aspect ratio, loading condition and temperature have noticeable effects on the buckling strength and buckling modes of FG-CNTRC curved panels.

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ABSTRACT: In this study, the thermoelastic buckling of functionally graded material (FGM) conical shells under non-linear temperature rise across the thickness in the framework of the shear deformation theory (SDT) is investigated. To the derivation of basic equations is used modified Donnell-type shell theory. The Galerkin method is used to obtain the formula for non-linear buckling temperature difference of freely supported FGM truncated conical shell in the framework of the SDT. By changing the properties of FGMs and volume fraction index, the effect of transverse shear deformations on the non-linear buckling temperature difference is evaluated by comparing with the results of the classical shell theory (CST). Meanwhile, the effect of geometric parameters on the non-linear buckling temperature difference of the shear deformable FGM conical shells is discussed in detail.

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ABSTRACT: Sandwich structures with lattice core are novel composite structures, but the aeroelastic behaviors of them have not been fully studied. This paper is devoted to investigate the flutter and buckling properties of sandwich panels with triangular lattice core in supersonic airflow, and the active flutter and buckling control are also carried out, which can provide theoretical basis for the use of sandwich structures in the design of aircrafts. The unsteady aerodynamic pressure is evaluated by the supersonic piston theory in which the yawed flow angle is taken into account. Hamilton's principle with the assumed mode method is applied to formulate the equation of motion of the structural system. The active controller is designed by the displacement feedback method. Aeroelastic characteristics of the sandwich panels are studied, and the influences of the aerodynamic pressure on the frequency and mode shape of the panel are analyzed. The effects of yawed flow angle on the flutter properties of the sandwich panel are also analyzed. When considering the external in-plane load, the buckling behaviors of the sandwich panel are investigated. Moreover, the flutter and buckling properties between the sandwich and equivalent isotropic panels are compared to show the superior aeroelastic properties of the sandwich panels. The optimal locations of piezoelectric patch placements on the active flutter control are analyzed. The present study verifies that the sandwich structures have different aeroelastic and flutter suppression properties, which is useful in the research of lightweight sandwich materials.

References listed at the end of the paper:


ABSTRACT: This paper presents a finite element model based on the first-order shear deformation theory for free vibration and buckling of functionally graded beams. The present element has five nodes and ten degrees-of-freedom. Material properties vary continuously through the beam thickness according to the power-law form. Governing equations are derived with the aid of Lagrange's equations. Natural frequencies and buckling loads are calculated numerically for different end conditions, power-law indices, and span-to-depth ratios. Accuracy of the present element is demonstrated by comparisons with the available results.

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ABSTRACT: We present a nonlinear finite element method to investigate the nonlinear stability of stiffened functionally graded materials (FGM) plates considered as a whole unit. The plates are subjected to mechanical and thermal loads. The material properties are assumed to be temperature dependent and varied gradually across the thickness according to a power law distribution. The nonlinear equations of FGM plates are based on the first-order shear order plate theory. The influence of material, geometrical properties of stiffeners and initial deflections on the buckling and post-buckling response of the stiffened plates are studied in detail. Including the latest information no work has been oriented towards post-buckling analysis of stiffened FGM plates considered as a whole unit.

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ABSTRACT: Various bifurcation behaviors, including asymmetric axial buckling induced by end thrust, bifurcation under external pressure, and eversion without any loading, of a soft circular hollow cylinder (or cylindrical shell) composed of functionally graded incompressible elastomeric material are considered in a unified way. Based on the nonlinear elasticity theory of a deformable continuous body undergoing large deformation and the linearized incremental theory for a superimposed infinitesimal deformation, an efficient approach for buckling analysis is developed and applied to the cylinder subjected to a combination of axial end thrust and internal/external pressure. It is based on the state-space formalism, which naturally avoids the derivatives of instantaneous material constants, enabling a convenient and accurate numerical implementation. Along with the layerwise method, an analytical characteristic equation (i.e. the bifurcation criterion) governing the general asymmetric buckling of the cylinder is derived. Detailed parametric studies are then carried out for a pressurized soft functionally graded hollow cylinder using an incompressible Mooney-Rivlin material model. The effects of material gradient on bifurcation induced either by end thrust or external pressure are discussed through numerical examples. Not only does this study provide an efficient tool for buckling analysis of soft cylinders, some findings that are unique to a functionally graded material are also highlighted. All in all, it is found highly possible to tune the bifurcation behavior of soft elastomeric cylindrical shells by tailoring material composition and/or adjusting the pressures acting on the surfaces of the cylinder.

ABSTRACT: In this paper, the authors study periodic vibrations of variable stiffness composite laminates excited by a harmonic force. The plates have geometrical imperfection in the form of various sinusoidal out-of-
plane initial deflections associated with zero stress. The angle of the curvilinear fibre path is introduced as a function of the horizontal Cartesian coordinate. The theory used to extract equations of motion for VSCLs is a third order shear deformation theory that retains rotary inertia. The relations of von Kármán for elastic large deflection are used. A $p$-version finite element is employed and, to find the solution of the equations of motion, the shooting method is applied; frequency response curves are obtained. Static condensation and a modal summation method are applied to reduce the number of degrees of freedom. A damage analysis based on Tsai-Wu criterion is carried out during the studies on vibration. The effects of curvilinear fibres and the influence of modal interactions on the vibration of imperfect VSCLs are investigated. The stability of the periodic solutions is determined by applying Floquet's theory. The effect of geometric imperfections on the vibrational behaviour is studied.

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ABSTRACT: This paper presents a family of beam higher-orders finite elements based on a hierarchical one-dimensional unified formulation for a free vibration analysis of three-dimensional sandwich structures. The element stiffness and mass matrices are derived in a nuclear form that corresponds to a generic term in the displacement field approximation over the cross-section. This fundamental nucleus does not depend upon the approximation order nor the number of nodes per element that are free parameters of the formulation. Higher-order beam theories are then obtained straightforwardly. Timoshenko's classical beam theory is obtained as a special case. Short and slender beams are investigated. Simply supported, cantilevered and clamped-clamped boundary conditions are considered. Several natural frequencies as well as the corresponding modes are investigated. Results are validated in terms of accuracy and computational costs towards three-dimensional finite element solutions. The proposed hierarchical models, upon an appropriate choice of approximation order, yield accurate results with a reduced computational cost.

Nam-Li Kim and Jaehong Lee (Department of Architectural Engineering, Sejong University, 209, Neungdongo-ro, Gwangjin-gu, Seoul 05006, South Korea), “Coupled vibration characteristics of shear flexible thin-walled functionally graded sandwich I-beams”, Composites Part B: Engineering, Vol. 110, pp 229-247, February 2017
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ABSTRACT: This paper presents the general shear flexible thin-walled beam theory to study the coupled vibration characteristics of sandwich I-beams made of functionally graded materials (FGMs). This model accounts for the structural coupling coming from the material anisotropy and the transverse shear and the restrained warping induced shear deformation. The mechanical properties of beam such as Young's and shear moduli and material density are assumed to be continuously graded through the wall thickness according to a power law distribution of volume fraction of ceramic and metal. The seven coupled equations of motion are derived from Hamilton's principle. To solve the dynamic problems, three different types of finite beam elements, namely, linear, quadratic and cubic elements are employed with the scope to discretize the equations of motion. For the purpose of model validation, the results obtained in the present analysis are verified against
those given in literature. Through numerical examples, two types of material distributions are considered to investigate the effects of shear deformation, gradient index, thickness ratio of ceramic, boundary conditions, and span-to-height ratio on the dynamic responses of FGM bisymmetric and mono-symmetric I-beams. Particularly, the crossover phenomenon in vibration modes is investigated with respect to changes in gradient index and thickness ratio of ceramic.

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ABSTRACT: Nowadays, there has been an increasing interest in the study of cellular structures under non-ideal loading situation. In this study, comprehensive investigations of honeycomb structure embedded with the inclined cells were carried out to understand the mechanical behavior subjected to compression. Factorial analyses in several of inclined angles ranging from 0 to 90° were conducted both experimentally and numerically, from which excellent correlation has been observed. Three patterns of deformation modes of various inclined cell honeycomb structures with different tilt angle were categorized, some key spinodals of off-axis angle have been determined. In addition, theoretical relationship between inclined angle and strength of honeycomb has been successfully constructed, and validated with experiments as well as numerical simulation. Excellent agreement has been observed between them. According to this study, the mean plateau stress is not only related with the out-of-plane crush strength, but also related to in-plane crush strength. In general, it shows a cosine-like function with the tilt angle before 45°. These provide significant guidelines to characterize the mechanical properties of the honeycomb under non-ideal loading situation, so as to combine them in kinds of equivalent constitutive model in finite element simulation.


ABSTRACT: A phenomenological-based mechanical finite element model is developed for the prediction of ultimate compression loads and failure modes of wing relevant composite panels stiffened with I-shaped stiffeners, of which the edge is subjected to impact loading. The initiation of intralaminar failure including fiber and inter-fiber fracture is evaluated by Puck criteria, and its evolution is assumed to be controlled by equivalent strains. The interlaminar failure, namely delamination, is simulated by employing a surface-based cohesive contact model. For R-sections of the impacted stiffener, interfacial delamination, which may cause premature failure and to some extent reduce the load carrying capacity, is efficiently considered. A good correlation between the experimental and numerical results shows correctness and effectiveness of the proposed mechanical method for predicting CAEI response. Furthermore, numerical results reveal that not only failure propagation of the impacted site but that of the other undamaged side dominate the compressive mechanism of the edge impacted stiffener, of which complete fracture determines the ultimate failure load of the I-stiffened composite panel.

ABSTRACT: In this study, free vibration analysis of conical and cylindrical shells and annular plates made of composite laminated and functionally graded materials (FGMs) is investigated. Carbon nanotubes reinforced (CNTR) composite case is also taken consideration for FGM. The equations of motion for conical shell are obtained via Hamilton's principle using the transverse shear deformation theory. To obtain the eigenvalue problem of the system, the method of discrete singular convolution is employed. Material properties are graded in the thickness direction according to a volume fraction power law and four-parameter power law indexes for FGM cases. Five types of distributions of CNTR material are also considered. To verify the accuracy of this method, comparisons of the present results are made with results available in the open literature. Free vibrations of cylindrical shells and annular plates with FGM are treated as special cases. Results are also presented for carbon nanotubes reinforced (CNTR) composite cylindrical shells and annular plates. It is found that the convergence and accuracy of the present DSC method is very good for vibration problem of shells with functionally graded materials (FMG) and CNTR functionally graded materials.

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ABSTRACT: In this paper transient thermo-elastic analysis of a thick hollow finite length cylinder made of two dimensional functionally graded materials (2D-FGMs) has been investigated. The transient heat conduction and the thermo-elastic equations have been solved for the cylinder subjected to thermal loading utilizing finite element method. The higher order Lagrange shape function elements have been used to improve the accuracy of the temperature and thermal stress distribution in the axisymmetric thermo-elastic analysis. In addition, a new effective material model according to the Mori-Tanaka scheme for 2D-FGM has been developed and implemented. The nonlinear temperature-dependency of material properties as well as their variation along two directions led into highly nonlinear equations. In consequence, the temperatures and stresses have been evaluated in the different time frames and the effects of the material distributions in two radial and axial directions have been investigated. The results mainly indicate that the variation of the material distribution along the axial direction significantly influence the temperature and stress distributions. Also the material distribution along the z-direction increases the design variables, so it will be helpful to achieve more desirable results.


ABSTRACT: Several efforts have been made in the last years to improve the efficiency and the effectiveness of structural models for the analysis of laminated shell structures. Among the others, many recent and past works in the literature have been aimed at formulating theories of structures that maximize the accuracy of analysis
meanwhile reducing the computational costs. In this paper, this objective is pursued by implementing advanced shell theories with through-the-thickness variable kinematic capabilities. By employing the Carrera Unified Formulation (CUF), the proposed shell model is obtained by expressing the displacement field as an arbitrary and, eventually, hierarchical expansion of the primary unknowns along the thickness. Thus, Equivalent-Single-Layer (ESL), Layer-Wise (LW) models as well as variable kinematic models which combine ESL and LW approaches within the shell thickness can be obtained in a straightforward and unified manner. After the unified shell model is formulated, the governing equations and the related finite element arrays are obtained by employing the principle of virtual work. A nine node finite element is implemented to approximate the solution field, and the Mixed Interpolation of Tensorial Components (MITC) method is used to contrast the membrane and shear locking phenomena. Some numerical examples are discussed, including three- and ten-layered cross-ply shells under bi-sinusoidal load and simply-supported boundary conditions, a multilayered spherical panel subjected to bi-sinusoidal load and a sandwich cylinder undergoing bi-sinusoidal pressure. Moreover, various thickness and radius-to-thickness ratios are considered. Whenever possible, the results are compared with those from the literature and from exact elasticity solutions. The analysis of the results clearly shows the enhanced capabilities of the present variable-kinematic shell element, which allows the analyst to opportunely reduce the computational costs and enhance the accuracy of the model only in those regions of the thickness domain where an accurate evaluation of the stress/strain field is needed.

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ABSTRACT: The paper discusses nonlinear buckling and failure analysis of FML thin-walled structures under axial compression. Study was carried out on Fibre Metal Laminates (FMLs) made of alternating thin layers of aluminium and glass fibre-reinforced unidirectional prepreg. Various 3/2 symmetrical lay-ups were investigated and depending on fibres alignment 7 stacking sequences of FML were considered when subjected to axial compression in laboratory buckling tests. The behaviour of thin walled compression members was investigated with main focus on buckling and post-buckling response and various failure mechanisms. Experimental procedures included macroscopic and microscopic examination performed by means of stereoscopic, optical and scanning electron microscope (SEM). The results of experimental investigations were compared with finite element simulations wherein Tsai-Wu, Hashin and Puck failure criteria were applied. Failure assessment by FEM included also an attempt to estimate particular regions of laminate's fracture within buckling and post-buckling state.

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ABSTRACT: Nonlinear and linear vibrations of fluid conveying carbon nanotubes considering thermal effects are studied. It is assumed that the nanotube conveying fluid flow has a general type of boundary conditions and is supported on a nonlinear Winkler-Pasternak foundation. The nonlocal Euler-Bernoulli beam theory is implemented to develop the governing differential equation of motion of the nanotube system. Furthermore, the surface effect is considered in the vibration modelling of the carbon nanotubes. The influence of the thermal effect combined with the applied longitudinal force on the vibration performance of the system is examined.
The Galerkin procedure is employed to obtain the nonlinear ordinary differential equation and the multiple time-scales method is utilized to study the primary vibration resonance of the system. A parametric sensitivity analysis is carried out to reveal the influence of different parameters on the vibration primary resonance and linear natural frequency. The effects of temperature variation, boundary conditions, foundation coefficients and the fluid flow velocity on the primary resonance and natural frequency of the nanotube are investigated. The effect of temperature on the material properties of carbon nanotube is originally combined with the vibration model. Different types of Zigzag carbon nanotubes are considered and the effects of different parameters, namely, the fluid flow velocity and the temperature variations are compared.

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ABSTRACT: The paper proposes a generalized shell formulation devised for the triaxial stress analysis of Through-the-Thickness (TT) confining mechanisms induced by TT Jacketing (TTJ) devices in laminated composite structures, such as masonry walls retrofitted by stirrups-tied FRP sheets and TT jacketed concrete sandwich panels. Assuming a smeared description of TT reinforcements, the proposed shell formulation is constructed as an enhancement of the classical laminated shell formulation based on the Equivalent Single Layer Mindlin First-order Shear Deformation Theory (ESL-FSDT). This enhancement captures TT stretching by adding the TT displacement field among the kinematic variables and permits to describe the smeared TTJ interaction between transverse uniaxial reinforcements and confined layers in terms of continuum equilibrium and compatibility equations. Statics and kinematics of the shell are developed by following standard work-association arguments and encompassing both TT-laminated and TT-functionally graded structures. A nonlinear elasto-plastic constitutive behavior of the core material and of the TT reinforcements is considered and explicit representations of the elasto-plastic tangent operator are derived. The TTJ formulation is combined with a MITC finite element formulation and implemented in the research FE code Opensees. Results of nonlinear structural analyses of walls subject to in-plane and out-of-plane bending show that the proposed TTJ approach provides physically meaningful predictions of the structural response and is capable to efficiently track a complex triaxial confining interaction which ultimately results into marked global structural effects of increased stiffness, strength and ductility.

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ABSTRACT: In order to understand the formation of one-dimension periodic structures by electrospinning, an approximate mechanical approach for the critical load and the number of half waves in the buckled shape have been conducted based on the energy method. Diameter of circular cross-section electrospun fiber is assumed to be equal to the length of the rectangular cross-section spitted fiber. Fiber with rectangular cross section buckles more easily than that with circular cross section because of the different flexural rigidity. For rectangular-section fiber, increase of length to width ratio can result in the increase of the number of half waves. Detailed simulation results for buckling responses of circular-section fiber and rectangular-section fiber have been conducted by commercial finite element analysis software (ABAQUS).

Kadir Mercan and Oemer Civalek (Akdeniz University, Engineering Faculty, Civil Engineering Dept., Division of Mechanics, 07058 Antalya, Turkey), “Buckling analysis of silicon carbide nanotubes (SiCNTs) with surface effect and nonlocal elasticity using the method of HDQ”, Composites Part B: Engineering, Vol. 114, pp 34-45, April 2017, https://doi.org/10.1016/j.compositesb.2017.01.067

ABSTRACT: As the parallel to the advancement of technology in nano-sizes, the importance of nanotubes is rising every day. The mostly worked and used nanotubes are Carbon Nanotubes (CNT) due to their superior mechanical and electrical properties. On the other hand, the technology always needs better materials with superior mechanical, electrical conductivity and thermal properties. After a couple years of working with Carbon nanotubes, scientists have discovered different types of nanotube such boron nitride and Silicon carbide nanotubes (SiCNTs). In this work, the stability of the Silicon carbide nanotube is investigated in the static buckling case with surface effect. Nonlocal continuum theory is also used in order to see the difference between two higher-order elasticity theories. The stability of nanotubes has an important role since it is used in high-tech equipment. Buckling behavior of SiCNTs is discussed by using the continuum model based on the Euler-Bernoulli beam theory for different boundary conditions in conjunctions with the surface effect and nonlocal elasticity theory. The harmonic differential quadrature method (HDQ) is used for numerical simulations. Some parametric values for critical buckling loads have been obtained with different geometrical quantities of SiCNTs. The size effects on results have been also investigated by the surface elasticity and Eringen's nonlocal elasticity parameters.


ABSTRACT: This paper copes with the statistical dynamic behaviors of nonlinear vibration of the single-walled carbon nanotubes (SWCNTs) under longitudinal magnetic field by considering the effects of the geometric nonlinearity and nonlinear damping. Both the Young's modulus of elasticity and mass density of the SWCNTs are considered as stochastic with respect to the position to actually characterize the random material properties of the SWCNTs. Based on the theory of nonlocal elasticity, the small scale effects of the nonlinear vibration of the SWCNTs are investigated. By using the Hamilton's principle, the nonlinear governing equations of the single-walled carbon nanotubes subjected to longitudinal magnetic field are derived. The Monte Carlo Simulation, Galerkin's method and the multiple scale method are adopted to solve the nonlinear governing equation and to calculate the statistical response of the SWCNTs. Some statistical dynamic responses of the SWCNTs such as the mean values and standard deviations of the midpoint deflections are computed, the effects of the small scale coefficients, magnetic field, nonlinear damping and the elastic stiffness of matrix on the statistical dynamic responses of the SWCNTs are investigated and discussed.
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ABSTRACT: In the present work, a new class of finite elements (FEs) for the analysis of metallic and composite plates is proposed. By making use of node-by-node variable plate theory assumptions, the new finite element allows for the simultaneous analysis of different subregions of the problem domain with different kinematics and accuracy, in a global/local sense. As a consequence, the computational costs can be reduced drastically by assuming refined theories only in those zones/nodes of the structural domain where the resulting strain and stress states present a complex distribution. On the contrary, computationally cheaper, low-order kinematic assumptions can be used in the remaining parts of the plate where a localized detailed analysis is not necessary. The primary advantage of the present variable-kinematics element and related global/local approach is that no ad-hoc techniques and mathematical artifices are required to mix the fields coming from two different and kinematically incompatible adjacent elements, because the plate structural theory varies within the finite element itself. In other words, the structural theory of the plate element is a property of the FE node in this present approach, and the continuity between two adjacent elements is ensured by adopting the same kinematics at the interface nodes. In this paper, the novel variable-kinematics plate element is implemented by utilizing the Carrera Unified Formulation (CUF), whose main advantage consists in the possibility of keeping the order of the expansion of the state variables along the thickness of the plate as a free parameter of the model. According to CUF, Taylor polynomial expansions are used to describe the through-the-thickness unknowns to develop classical to higher-order Equivalent Single Layer (ESL) plate theories. Furthermore, the Mixed Interpolated Tensorial Components (MITC) method is employed to contrast the shear locking phenomenon. Several numerical investigations are carried out to validate and demonstrate the accuracy and efficiency of the present plate element, including comparison with various closed-form and FE solutions from the literature.

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ABSTRACT: Composite materials has recently been widely used in the automotive, aerospace and other fields due to its lightweight and good performance. At the same time, biological materials are also being paid more attentions in industrial application fields because of its economic, environmental, renewable and other advantages. Coconut mesocarp was chosen to be the core of composite sandwich structures with sheets of glass fiber reinforced plastics and carbon fiber reinforced composite were studied. Energy absorption behaviors were analyzed and compared. The thickness of all composite sheets is 1mm and the thickness of coconut mesocarp core is 20mm. Static compression tests were made by using universal testing machine. Results show that the composite sandwich structure with glass fiber reinforced plastic sheets and coconut mesocarp core has 1.0J/g of per weight energy absorption, which is higher than 0.91J/g of the composite sandwich structures with carbon
fiber reinforced composite sheets and coconut mesocarp core. However, the peak crushing force of the former is less than the latter. Therefore, composite sandwich structures with glass fiber reinforced plastic sheets were selected for three points bending tests to study mechanical bending properties. By contrast with metal sheets sandwich structure and aluminum sheets sandwich structure, specific energy absorption of glass fiber reinforced plastic sheets sandwich structure is 2 times as much as metal sheets sandwich structure and 3–7 times as much as aluminum sheets sandwich structure, which shows an excellent crashworthiness performance of sandwich structures with composite sheets and bio coconut core.


ABSTRACT: The size-dependent radial buckling and postbuckling behavior of functionally graded cylindrical shells at nanoscale integrated with piezoelectric nanolayers is studied in this paper on the basis of nonlocal elasticity theory within the framework of exponential shear deformation shell theory to capture the influence of transverse shear deformation in a refined form. By introducing a new reference surface, the stretching-bending coupling terms due to unsymmetrical material characteristics related to the functionally graded substrate of nanoshell are removed. After that, with the aid of boundary layer of shell buckling, the non-classical partial nonlinear differential equations are constructed to describe the nonlocal instability of nanoscaled shells. Finally, a perturbation-based solution methodology is utilized to propose explicit expressions for the nonlocal equilibrium paths associated with the both prebuckling and postbuckling domains of hybrid functionally graded nanoshells subjected to the combination of hydrostatic pressure and lateral electric field. It is seen that the nonlocality size effect causes to reduce the critical hydrostatic pressure, but it leads to increase the associated shortening of the movable ends of hybrid functionally graded nanoshells.

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ABSTRACT: By means of Non-Uniform Rational B-Splines (NURBS) curves, it is possible to describe arbitrary shapes with holes and discontinuities. These peculiar shapes can be taken into account to describe the reference domain of several nanoplates, where a nanoplate refers to a flat structure reinforced with Carbon Nanotubes (CNTs). In the present paper, a micromechanical model based on the agglomeration of these nanoparticles is considered. Indeed, when this kind of reinforcing phase is inserted into a polymeric matrix, CNTs tend to increase their density in some regions. Nevertheless, some nanoparticles can be still scattered within the matrix. The proposed model allows to control the agglomeration by means of two parameters. In this way, several parametric studies are presented to show the influence of this agglomeration on the free vibrations. The considered structures are characterized also by a gradual variation of CNTs along the plate thickness. Thus, the term Functionally Graded Carbon Nanotubes (FG-CNTs) is introduced to specify these plates. Some additional parametric studies are also performed to analyze the effect of a mesh distortion, by considering several geometric and mechanical configurations. The validity of the current methodology is proven through a comparative assessment of our results with those available from the literature or obtained with different
numerical approaches, such as the Finite Element Method (FEM). The strong form of the equations governing a plate is solved by means of the Generalized Differential Quadrature (GDQ) method.

ABSTRACT: This paper deals with analysis and optimization of rectangular and skew composite plates with embedded Shape Memory Alloy (SMA) wires with respect to thermal buckling. The governing equations are derived based on First Order Shear Deformation Theory (FSDT) and the critical buckling temperatures are calculated using Generalized Differential Quadrature (GDQ) method. The influences of SMA volume fraction, lay-up orientation, pre-strain of SMA fibers, dependency of material properties on temperature, and geometrical parameters like skew angle on thermal buckling of the structure are examined. Results demonstrate that SMAs can play a significant role in delaying buckling when the structure is under thermal loads. Then, in the second part of results, optimization of shape memory alloy hybrid composite (SMAHC) plates is presented in order to maximize critical buckling temperatures. A four-layer composite plates with two SMA-reinforced layers is considered for the optimization problem in which the orientations of fibers are the optimization variables. As the critical buckling temperatures cannot be obtained through a closed-form solution, the optimization process takes a lot of time. Therefore, a powerful meta-heuristic algorithm called Firefly Algorithm (FA) is implemented to find the best answers. A comprehensive verification study is also performed to indicate the accuracy and efficiency of both GDQ solution and optimization process.

ABSTRACT: This work is motivated by the self-powered component of biomedical nano-robotic device which is expected to move in arterial blood vessels. The transverse vibrations and steady-state responses of axially moving viscoelastic piezoelectric two-dimensional nanostructures are investigated based on the nonlocal viscoelasticity thin plate theory. The constitutive relations of viscoelastic piezoelectric nanoplate containing the thermal effect are performed and the governing partial differential equations of the problem model are derived using the Hamilton's principle. The natural frequencies are numerically determined via the Galerkin method, the complex mode method, as well as the finite element method for comparison. Moreover, the theoretical calculations are compared with those in previous literature to verify effects in nonlocal nanoscale framework and average speed on natural frequency. Afterwards, the instable behaviors of axially non-uniformly moving viscoelastic piezoelectric nanoplate characterized as a sine variation about the constant average speed are addressed using the method of multiple scales. The analyses are mainly focused on the boundaries of instable regions in combination parametric resonance and principal parametric resonance. The non-dimensional numerical results imply the existences of nonlocal nanoscale parameter and average speed contribute to reduce the rigidity, and further produce the coupled vibrations and flutter instabilities for complex frequencies. Additionally, the instable regions of combination and principal parametric resonances decrease with increases in the biaxial compression, change of temperature, positive electric voltage and viscoelastic coefficient. The dynamic responses of axially moving viscoelastic piezoelectric nanoplate under the coupling of thermo-electro-mechanical multi-fields are expected to play significant roles in designing biomedical nano-robots.

ABSTRACT: The non-linear free vibration behavior of functionally graded (FG) orthotropic cylindrical shells interacting with the two-parameter elastic foundation is investigated. The major goal of this research was to obtain a solution for the non-linear frequencies associated with the problem outlined above. The dynamic stability and compatibility equations of FG orthotropic cylindrical shells surrounded by an elastic foundation are derived within the first order shear deformation theory (FSDT) and von Kármán strain displacement relationships, and then superposition and Galerkin methods are adopted to convert the above equations into a nonlinear ordinary differential equation. The expression for non-linear frequency of FG orthotropic cylindrical shell surrounded by an elastic foundation within the FSDT is obtained using the homotopy perturbation method (HPM). In particular, similar expression in the framework of the classical shell theory (CST) is obtained, also. The results are compared and validated with the results available in the literature. Finally, the calculation and presentation of the effect of many parameters included in the analysis conclude the goals to be reached in the study.


ABSTRACT: A closed form three-dimensional (3D) free vibration solution for a rectangular laminated plate with Levy-type support conditions is presented first time using recently developed extended Kantorovich method. Hamiltons principle is extended to develop a mixed formulation in terms of displacements and stresses as primary variables. The present solution will serve as a benchmark for assessing two-dimensional (2D) theories and 3D numerical solutions. Natural frequencies are tabulated for composite and sandwich laminates (first time) for different boundary conditions. It is found that single term solution is sufficient enough for obtaining accurate natural frequencies. But stresses near the clamped edge are accurately predicted by multi-term solution ($n = 2$). The effect of the span to thickness ratio and in-plane modulus ratios on the natural frequency is also studied.

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ABSTRACT: This paper proposes an efficient and accurate thermal stress analysis method based on the conventional first-order shear deformation theory (FSDT). The transverse shear strain energy is modified through the mixed variational theorem. The independent transverse shear stresses are obtained from a third-order zigzag model to improve the accuracy, whereas the FSDT displacements are employed to improve the numerical efficiency. The transverse displacement field includes higher-order terms without introducing additional unknown variables by superimposing a prescribed thermal field. This allows one to consider the thermal transverse normal strain effect under the plane stress condition. The resulting strain energy expressions are collectively referred to as the enhanced first-order shear deformation theory including the transverse normal effect based on the mixed variational theorem (EFSDTM_TN). The EFSDTM_TN offers the same computational advantages as the conventional FSDT while allowing for improved local variations of stresses and displacements via a post-processing procedure. In this procedure, in-plane correction factors are introduced and determined by applying equivalent stress resultants so that the improved stresses satisfy the plate equilibrium. Finally, the obtained displacements and stress distributions are compared with the data available in the literature.

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ABSTRACT: This study investigates nonlinear dynamic thermoelastic response of functionally graded material (FGM) plates with longitudinal velocity for the first time. The large amplitude motion of FGM plates is considered so that the present model includes both geometry and material nonlinearities. Based on the D'Alembert's principle, the out-of-plane equation of motion of the system is obtained by considering the thermal effect and the longitudinal velocity. After that, the Galerkin method is employed to discretize the partial differential equation of motion to a set of ordinary differential equations. The method of harmonic balance is used to solve analytically the time-varying set of ordinary differential equations. The approximately analytical solutions are verified by numerical solutions utilizing an adaptive step-size fourth-order Runge-Kutta technique. Furthermore, the stability of steady-state response is analyzed for the approximately analytical solutions. The linear frequency characteristics and nonlinear frequency-response characteristics are both presented for the system. The nonlinear frequency-response relationships demonstrate strong hardening-type behavior of the system. Results are shown to examine the influences of different parameters including longitudinal velocity, temperature, constituent volume distribution, in-plane pretension, damping and force amplitude on the nonlinear dynamic thermoelastic response of FGM plates with longitudinal velocity.

ABSTRACT: In order to get a strong, stiff and lightweight structure, a novel glass fiber reinforced composite (GFRC) lattice sandwich panel (LSP) was designed and manufactured. The lattice core consists of orthogonal corrugated GFRC truss and foam cubes. A modified vacuum assisted resin infusion (VARI) method was used to manufacture the LSP. Flatwise compression test, theoretical analysis and finite element analysis were carried out to reveal the modulus and failure modes of the structure. A local buckling failure and delamination at the corner of strut were observed in compression. Experimental, theoretical and simulation result show great agreement with each other on the modulus of the structure. The experimental modulus and ultimate failure strength are about 1.798 GPa and 5.59 MPa, respectively.

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ABSTRACT: The objective of this research is to investigate the aeroelastic buckling and flutter instability of a pressurized functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical shell subjected to supersonic airflow. The dynamic model of the FG-CNTRC cylindrical shell is established in accordance with the first-order shear deformation theory, Donnell kinematic theory along with the von Karman geometrical nonlinearity. The quasi-steady Krumhaar's modified piston theory by considering the effect of the panel curvature is used to estimate the aerodynamic pressure induced by the supersonic airflow. The dynamic equations are discretized using trigonometric expansion through the circumferential direction and harmonic differential quadrature (HDQ) method through the meridional direction. Effects of boundary conditions, geometrical parameters, volume fraction and distribution of CNTs and the Mach number on the flutter instability, onset of the buckling and deformation shapes of the cylindrical shell are put into evidence through a set of parametric studies. The simulation indicates that the critical flutter dynamic pressure may be significantly enhanced through functionally graded distribution of CNTs in a polymer matrix. Furthermore, it is found that presence of the aerodynamic pressure may completely change deformation shapes of the FG-CNTRC cylindrical shell.

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ABSTRACT: Introducing gradient into cellular materials has been envisioned as an effective way to improve their performance. In this study, a novel in-plane graded honeycomb is proposed and its dynamic behavior under out-of-plane compression is investigated using numerical simulation and theoretical analysis. The in-plane gradient is introduced by changing the thickness of each cell wall of honeycomb unit cell along its side length. Numerical results show that the crushing strength and energy absorption capacity of honeycombs with positive gradient are substantially enhanced compared to those of honeycombs without gradient. To explore the
enhancement, theoretical and numerical analyses on the energy absorption mechanism of honeycombs are performed. It is found that severe plastic deformation is mainly concentrated near the intersecting edge of cell walls, and the energy absorption can be further improved by distributing more material near the intersecting edge when the total mass remains constant. In addition, analytical formulas for the crushing strength and energy absorption of graded honeycombs are developed, and good agreement is obtained with numerical results.

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ABSTRACT: We find thermal stresses developed in Ceramic Matrix Composite (CMC) cylindrical shells reinforced with aggregated Carbon Nanotubes (CNTs) with heat flux prescribed on the inner surface and temperature on the outer surface. Null surface tractions are prescribed on these two surfaces and the cylinder edges are clamped. The material properties are homogenized by using a two-parameter Eshelby-Mori-Tanaka (EMT) approach. Material properties of the ceramic are assumed to depend upon the temperature, and the smooth variation of the CNT volume fraction through the shell thickness is assumed to be described either by a sigmoidal function or profile-O or profile-X often used in the literature. The one-way coupled thermo-mechanical problem is analyzed by first numerically solving the nonlinear heat equation with the Generalized Differential Quadrature Method (GDQM), and then the linear mechanical problem by using Reddy's Third-order Shear Deformation Theory (TSDT) and the GDQM. For the same thermal boundary conditions and the volume fraction of CNTs, the maximum hoop, the in-plane shear and the transverse normal stresses developed in the cylinder are highest for the profile-X of CNTs. The aggregation factor noticeably influences the maximum transverse normal and the maximum hoop stresses developed in the cylinder.

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“Vibration analysis of quadrilateral graphene sheets subjected to an in-plane magnetic field based on nonlocal elasticity theory”, Composites Part B: Engineering, Vol. 118, pp 96-103, June 2017
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ABSTRACT: Graphene sheets have wide application, in which the integration of multiple disparate fields for the realization of expanded functionalities is of great significance. This study investigates the vibration behavior of quadrilateral single-layered graphene sheets (SLGSs) in a magnetic field using classic plate theory and incorporating nonlocal elasticity theory, concerning the small scale effect. The element-free kp-Ritz method is
employed to perform the numerical simulation. The efficiency of the proposed numerical tool is verified by published results. The effect of nonlocal parameters, skew angles, magnetic parameters and boundary conditions on the vibration behavior of parallelogram SLGSs is studied. The results show that skew angles and the magnetic field help increase the fundamental frequencies of SLGSs, which indicates the potential application of SLGSs as highly sensitive mass detectors. Moreover, 14 different quadrilateral SLGSs, with different nonlocal parameters and magnetic parameters for different boundary conditions, are simulated.

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ABSTRACT: This paper aims to investigate the lateral planar crushing and bending responses of carbon fiber reinforced plastic (CFRP) square tube filled with aluminum honeycomb. The various failure modes and mechanical characteristics of filled tube were experimentally captured and numerically predicted by commercial finite element (FE) package LS-DYNA, comparing to the hollow tubes. The filled aluminum honeycomb effectively improved the stability of progressive collapse during crushing, leading to both hinges symmetrically occurred along the vertical side. The experimental results showed that energy absorbed (EA) and specific energy absorption (SEA) of the filled CFRP tubes could be significantly increased to 6.56 and 4 times, respectively, of those measured for the hollow tubes without fillings under lateral crushing. Although an improvement of 32% of EA and 0.9% of SEA were obtained for the lateral bending, still the design using aluminum honeycomb as filling was remarkably capable to improve the mechanical characteristics of CFRP tube structure. A good agreement was obtained between experimentally measured and numerically predicted load-displacement histories. The FE prediction was also helpful in understanding the initiation and propagation of cracks within the filled CFRP structure.

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ABSTRACT: In the present investigation, a suitable and simple computational formulation based on Isogeometric Analysis (IGA) integrated with higher-order shear deformation theory (HSDT) is introduced for size-dependent geometrically nonlinear transient analysis of functionally graded material (FGM) nanoplates. The material properties of FGM based on the Mori–Tanaka schemes and the rule of mixture are used. The nonlinear transient nonlocal governing equations approximated according to IGA based on HSDT, which satisfies naturally the higher-order derivatives continuity requirement in weak form of the FGM nanoplates, are formed using the von Kármán strains and solved by Newmark time integration scheme. The effect of nonlocal approach on the behaviors of the FGM nanoplates with several volume fraction exponents is investigated. Several numerical results are presented to demonstrate the reliability of the proposed method.

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“Buckling and postbuckling of functionally graded graphene-reinforced composite laminated plates in thermal environments”, Composites Part B: Engineering, Vol. 119, pp 67-78, June 2017
https://doi.org/10.1016/j.compositesb.2017.03.020
ABSTRACT: Modeling and analysis of the postbuckling behavior of graphene-reinforced composite (GRC) laminated plates are presented in this paper. The GRC plates are in a thermal environment, subjected to uniaxial compression and resting on an elastic foundation. The temperature-dependent material properties of functionally graded graphene-reinforced composites (FG-GRCs) are assumed to be graded in the plate thickness direction with a piece-wise type, and are estimated through a micromechanical model. The postbuckling problem of FG-GRC laminated plates is modeled using a higher order shear deformation plate theory and the plate-foundation interaction and thermal effects are taken into consideration. A two-step perturbation technique is employed to determine the buckling loads and the postbuckling equilibrium paths. The compressive buckling and postbuckling behavior of perfect and imperfect, geometrically mid-plane symmetric FG-GRC laminated plates under different sets of thermal environmental conditions is obtained and is also compared with the behavior of uniformly distributed GRC laminated plates. The results show that the buckling loads as well as the postbuckling strength of the GRC laminated plates may be enhanced through piece-wise functionally graded distribution of graphene.

ABSTRACT: In the present work, families of equivalent singe layer and layer-wise models for the static and free vibrations analysis of magneto-electro-elastic multilayered plates are developed. The models are defined in the framework of a unified formulation, which offers a systematic approach for generating refined plate theories through suitable expansions of the through-the-thickness components of the relevant fields, considering the
expansion order as a free parameter. The key features of the developed formulation are: a) the condensation of the electric and magnetic description into the mechanical representation, based on the quasi-static electric-magnetic approximation, which allows to reduce the computation of the analysis for both layer-wise and equivalent single layer models; b) the employment of the Reissner Mixed Variational Theorem, in which the displacements and transverse stress components are used as primary variables, thus allowing the explicit fulfilment of the transverse stress interface equilibrium. The proposed methodology is assessed by generating different layer-wise and equivalent single layer models for the analysis of thick magneto-electro-elastic plates and comparing their solution against available three-dimensional analytic results.

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ABSTRACT: This new work proposes an exact three-dimensional static analysis of plates and shells. One-layered and multilayered isotropic, orthotropic, sandwich and composite structures are investigated in terms of displacements and in-plane and out-of-plane stresses through the thickness direction. Proposed structures are completely simply-supported and a transverse normal load is applied. The proposed method is based on the 3D equilibrium equations written using general orthogonal curvilinear coordinates which are valid for spherical shells. Cylindrical shell, cylinder and plate results are obtained as particular cases of 3D spherical shell equations. All the considered structures are analyzed without any geometrical approximation. The exact solution is possible because of simply-supported boundary conditions and harmonic form for applied loads. The shell solution is based on a layer-wise approach and the second order differential equations are solved using the redouble of variables and the exponential matrix method. A preliminary validation of the model is made using reference results in the literature. Thereafter, the proposed exact 3D shell solution is employed with confidence to provide results for one-layered and multilayered plates, cylinders, cylindrical shell panels and spherical shell panels. All these geometries are analyzed via a unified and general solution, and the obtained results can be used to validate future numerical methods proposed for plates and shells (e.g., the finite element method or the differential quadrature method). Proposed results allow to remark substantial features about the thickness of the structures, their geometry, the zigzag effects of displacements, the interlaminar continuity of displacements and transverse stresses, and boundary loading conditions for stresses.

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“Buckling, postbuckling and progressive failure analyses of composite laminated plates under compressive loading”, Composites Part B: Engineering, Vol. 120, pp 143-151, July 2017
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ABSTRACT: In this study, buckling, post-buckling and progressive failure of composite laminated plates have been investigated numerically and experimentally. Buckling load, load-displacement relations for post buckling and maximum out-of-plane displacements of the plates are determined. Furthermore, the numerical results are compared with experimental findings for two different laminates made of woven fabric and uni-directional tapes. The comparisons show that there is a good agreement between numerical and experimental results obtained for buckling load and post-buckling behavior especially for the laminates with uni-directional tapes.
ABSTRACT: The paper presents an effective plate formulation based on isogeometric analysis (IGA) and a novel simple quasi-3D hyperbolic shear deformation theory (S-Q3HSDT) to study static bending, free vibration, and buckling behaviors of functionally graded plates. In S-Q3HSDT fashion, five unknowns per node are included; both shear deformation and thickness-stretching effects across the thickness are taken into account; and the awkward shear locking phenomenon is avoided. The requirement for \( C^1 \)-continuity in terms of the S-Q3DHSDT is straightforwardly possessed with the aid of inherent high-order continuity of non-uniform rational B-spline (NURBS), which serve as basis functions in our IGA formulation. The superior performance and accuracy of the proposed method is demonstrated through numerous numerical examples. The calculated results are then compared with reference solutions, investigating the effects of boundary conditions, gradient index, and other aspect ratios on mechanical responses of functionally graded plates.

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“A free vibration of sandwich truncated conical shells containing functionally graded layers within the shear deformation theory”, Composites Part B: Engineering, Vol. 120, pp 197-211, July 2017
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ABSTRACT: This study demonstrates the effectiveness of functionally graded coatings in the vibration of sandwich truncated conical shells. First order shear deformation shell theory (FOSDT) and Donnell kinematics assumptions are used to establish the governing equations. The problem is solved for piecewise and continuous through-the-thickness coatings stiffness variations. The closed-form solution is obtained for frequency parameters of homogeneous truncated conical shells coated by functionally graded (FG) layers within the FOSDT. The analysis is extended to account for the influences of transverse shear deformations and functionally graded material (FGM) layers on the frequency parameters of sandwich truncated conical shells. Parametric studies are conducted for two configurations, different volume fraction index and different geometrical parameters of FGM sandwich truncated cones.
Oemer Civalek (Akdeniz University, Engineering Faculty, Civil Engineering Dept., Division of Mechanics, 07058, Antalya, Turkiye), “Vibration of laminated composite panels and curved plates with different types of FGM composite constituent”, Composites Part B: Engineering, Vol. 122, pp 89-108, August 2017
https://doi.org/10.1016/j.compositesb.2017.04.012
ABSTRACT: Free vibration analysis of truncated conical panels and annular sector plates with functionally graded materials (FGM) is carried out. Governing equations of motion are obtained based on two different shell theories such as Love's shell theory and first-order shear deformation theory (FSDT). The resulting governing differential equations have been solved using the differential quadrature (DQ) and discrete singular convolution (DSC) methods. As the FGM cases two different material properties of structures are assumed to change continuously in the thickness direction according to the volume fraction power law and the general four-parameter power-law distributions in terms of the volume fractions of constituents. Accuracy, convergence and reliability of these two methods have been validated by comparing the obtained results with the existing results available in the open literature. Furthermore, the effects of the grid numbers on results for each method have been also investigated for different boundary conditions and mode numbers for conical panel vibrations. Then, using the DQ and DSC methods, the frequencies values have been calculated for different material and geometric parameters, modes and boundary cases for truncated conical panels with FGM. The effects of material power-law distribution are also discussed. The convergence, advantages and accuracy of the present two methodologies are examined in conjunctions with the vibration problem of truncated conical panels with functionally graded materials (FMG). Some results for annular sector plates and circular cylindrical panels have also been obtained via conical panel equations.

ABSTRACT: In this study, the exact solutions for coupled responses of thin-walled FG (functionally graded) sandwich beams with non-symmetric cross-sections are derived. Material properties of beam are assumed to be graded through the wall thickness of flanges and web. Three types of material distributions are considered. The Euler-Bernoulli beam theory and the Vlasov one are employed for bending and torsional problems, respectively. The explicit expressions for displacement parameters are derived from equilibrium equations based on the displacement state vector consisting of 14 displacement parameters. The exact member stiffness matrix is determined using the force-displacement relations. As a special case, the analytical solutions for decoupled flexural response of FG sandwich beams with various boundary conditions are presented. To demonstrate the accuracy and validity of this study, numerical solutions are presented and compared with results from the finite element method and other available results.

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ABSTRACT: A new method based on the \( C^0 \) type efficient higher-order zigzag theory (EHOZT) is proposed for the efficient and accurate thermomechanical analysis of laminated composite plates. In this method, the transverse shear strain energy is modified according to the mixed variational theorem (MVT). The transverse stress field is defined by the arbitrary \( m \) -th order zigzag model including the transverse normal strain effect to improve the accuracy, while the displacement field is obtained from the \( C^0 \) -type EHOZT to amplify the benefits of the numerical efficiency. The transverse displacement field is assumed to be a smooth parabolic distribution to consider the transverse normal strain effect, which has a significant role in predicting the thermal deformation. Derivative components of the transverse displacement field are eliminated from the in-plane displacement field of the \( C^0 \)-type EHOZT by the transverse shear stress condition. The resulting strain energy expressions are collectively referred to as the \( C^0 \)-type EHOZT via the MVT. The proposed theory has the computational advantage of utilizing the \( C^0 \)-continuity condition for finite element implementation while allowing local distributions of the transverse stress to be improved via the recovery procedure. The obtained displacements and stress distributions were compared with data available in the literature for validation.

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ABSTRACT: This paper presents a new computational method for stress-strain analysis of simply supported rectangular cross-ply laminated composite plates subjected to transverse loads which was applied in the authors FORTRAN program code. The algorithm of the program is based on the layerwise theory of Reddy. Equations obtained by applying the principle of virtual displacements were solved in a closed form using double trigonometric series. Convergence control and numerical stability of the program's outputs: displacements and stresses, with appropriate comments, are discussed. Comparison and verification of the presented computational method was carried out in relation to the results given in the available literature. Also, a comparison with the values calculated using the ANSYS program which is based on finite element method was performed. The paper presents and provides comments on edge dimensionless displacements and \( \bar{v} \) of a laminated plate. For the adopted simply supported rectangular four-layer plate with antisymmetric layer an analysis of dimensionless deflection change in the middle of the plate and displacement \( \bar{u} \) on the edge of the plate was performed, as well as the analysis of the ratio between the maximum values \( \sigma_{xx}/\sigma_{yy} \) and \( \sigma_{xz}/\sigma_{yy} \) due to the change of the aspect ratio \( a/b \), the side-to-thickness ratio \( b/h \) and elastic modulus ratio \( E_1/E_2 \). The results of the proposed computational model based on the layerwise theory are given in a tabular and graphical form.

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ABSTRACT: This paper presents the first known mechanical behavior of laminated CNT-reinforced composite skew plates subjected to a transverse sudden dynamic load. The plate is composed of multilayers of nanocomposite reinforced with single-walled carbon nanotubes (SWCNTs). The problem is formulated using the first-order shear deformation theory (FSDT), and solution to the problem is obtained through the element-free IMLS-Ritz method. The elastodynamic behavior is furnished by employing the Newmark-β method. Material properties of CNT-reinforced composites are predicted through the Mori–Tanaka approach. The stability and precision of the IMLS-Ritz method are validated by convergence and comparison studies. The effects of skew angles, width-to-thickness ratio, CNT-volume fraction, CNT-distribution along the layer thickness, CNT-fiber orientation and boundary conditions on the elastodynamic responses of laminated CNT-reinforced composite skew plates are examined.

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ABSTRACT: Nonlocal theories of Continuum Mechanics are widely used in order to assess size effects in nano-structures. In this paper, free vibrations of nano-beams are investigated by making recourse to the novel stress-driven nonlocal integral model (SDM). Equations of motion governing the dynamics of a Bernoulli-Euler nano-beam are consistently formulated and numerically integrated by Matlab. Selected case studies involving structures of nanotechnological interest are examined. Natural frequencies, evaluated according to the SDM, are compared with those obtained by the Eringen differential law (EDM) and by the gradient elasticity theory (GradEla). SDM provides an effective methodology to describe nonlocal phenomena in NEMS.

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ABSTRACT: Nonlinear harmonic vibration of a piezoelectric-layered nanotube conveying fluid flow is investigated. The mathematical modeling of the structure is developed by means of the nonlocal theory and energy approach. The piezoelectric layer is assumed to be slender and the fluid flows through the nanotube at a uniform velocity. The forced vibration of the system is resulted from an external loading and hence, the parametric excitation is analyzed. Three different scenarios for its resonance conditions, known as the primary, parametric, and the simultaneous primary-parametric resonances, employing a strong perturbation technique known as the multiple time-scales method, are investigated. The effects of the variation of different parameters, such as the applied voltage, piezoelectric layer, nonlocal parameter and the fluid flow velocity, on both the
frequency-amplitude relationship and the frequency response of the system are studied. Finally, a detailed discussion on the numerical results obtained were fully presented.

ABSTRACT: This paper investigates the sensitivity of nonlinear flexural and vibration response of shear deformable functionally graded material (FGM) plates to the initial geometrical imperfections. The formulations are based on recently developed non-polynomial higher-order shear and normal deformation theory by authors. The theory accounts for nonlinear variation in the in-plane and transverse displacement through the thickness. It also accommodates thickness stretching effect without employing shear correction factor. The novelty of this theory is that it contains only four unknowns, unlike several other shear deformation theories which contain five or more unknowns. The equations of motion are derived using variational principle. The initial geometric imperfections have been incorporated using generic imperfection function. Material properties of the FGM plates are assumed to be varying continuously in the thickness direction according to a simple power law and exponential law. Convergence and comparison studies have been carried out to establish the authenticity and reliability of the solution. The numerical results are highlighted with various geometric imperfections and system parameters.

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ABSTRACT: Composite laminates are generally characterized by poor mechanical properties along the thickness direction, therefore they are highly susceptible to delaminations. A potential increase in structural efficiency may be obtained by using 3D reinforcements technologies. In this paper, an experimental/numerical study is presented focusing on the effects of a single reinforcement seam of stitches along the edge of a stringer foot, in a stiffened composite panel. Three-point bending tests have been performed on a skin-stringer configuration by considering variations of the skin thickness, the stitching technique, the pitch and the yarn diameter. Then, a Finite Element Model has been developed capable to simulate the mechanical behaviour of stiffened composite panels with selective stitching and to assist the design of more complex geometrical configurations by estimating the damage behaviour, as well as the onset and the propagation of delamination taking into account the effect of the selective stitching. The numerical results, in terms of load vs applied displacements, have been found in good agreement with the experimental data proving the effectiveness of the introduced numerical model. The numerical results have confirmed the potential beneficial effects of stitching in terms of delay of the crack initiation and growth, of smoother delamination profile, of increase in the stiffness of the structure with a reduction of the delamination area.

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ABSTRACT: In this paper, based on Third-order Shear Deformation Theory (TSDT), the mechanical buckling behavior of the continuously graded Carbon Nano-Tube (CNT)-reinforced shells stiffened by stringer and rings is studied. A two-parameter Eshelby-Mori-Tanaka (EMT) approach, which is capable of dominating the aggregation degree of CNTs within ceramic matrix phase, is proposed to estimate the effective material properties of the nanocomposite. In the present work, the equilibrium equations are obtained using variational approach based on TSDT of Reddy. The stability equations of the continuously graded CNRTC Stiffened Cylindrical Shell (SCS) are extracted via the concept of the adjacent equilibrium criterion. Opposed to most available works in which the stiffener effects were smeared out over the respective stiffener spacing, in the present paper, the stiffeners are modeled as Euler-Bernoulli beams. A semi-analytical solution employing the Generalized Differential Quadrature Method (GDQM) along with the trigonometric expansion is implemented to solve the stability equations. A detailed parametric study is conducted to highlight the impacts of various geometrical and material parameters involved on the critical mechanical buckling of the SCS aggregated by graded CNTs. The results obtained showed that the graded distribution of the CNTs close to the surface, where contains higher amount of CNT volume fraction, results in increasing the critical mechanical buckling load. Furthermore, it has been inferred that the aggregation tendency of the CNTs has a negative effect on the mechanical buckling behavior of the continuously graded SCS.

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“Size-dependent behaviour of functionally graded sandwich microplates under mechanical and thermal loads”, Composites Part B: Engineering, Vol. 124, pp 218-241, September 2017
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ABSTRACT: This paper presents the static bending, free vibration and buckling behaviours of functionally graded sandwich microplates under mechanical and thermal loads. Governing equations of both higher-order shear deformation and quasi-3D theories are derived based on the variational principle and modified couple stress theory. Apart from mechanical load, the temperature profiles considered are either uniform or linear distribution through the thickness, which results in changes of material properties and stress resultants. Numerical results are obtained using Navier solutions. The difference between quasi-3D and 2D models in dealing with mechanical and thermal load is discussed. Temperature-dependent and temperature-independent material properties are examined. The effects of geometry and power-law index together with mechanical loads and various temperature distributions on the size-dependent behaviours of functionally graded sandwich plates are also investigated.
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ABSTRACT: Laminated composite structures consisting of load-carrying and multifunctional materials represent a rather powerful material system. The passive, load-carrying layers can be made of isotropic material or fiber-reinforced composites, while piezoelectric materials represent the most common choice of multifunctional materials for active layers. The multifunctionality of piezoelectric layers is provided by their inherent property to couple mechanical and electric fields. The property can thus be used to sense deformations or produce actuating forces. A highly efficient 3-node shell element is developed for modeling piezoelectric laminated composite shells. The equivalent single-layer approach and Mindlin-Reissner kinematics are used in the element formulation together with the discrete shear gap (DSG) technique to resolve the shear locking and strain smoothing technique to improve the performance. Piezoelectric layers are assumed to be polarized in the thickness direction thus coupling the in-plane strains with the electric field oriented in the thickness direction. The co-rotational FE formulation is used to account for geometrically nonlinear effects. Numerical examples cover linear and geometrically nonlinear static and dynamic cases with piezoelectric layers used as actuators and sensors.

ABSTRACT: Three-dimensional thermo-elastic analysis of a multi-directional functionally graded skew plate on elastic foundation under thermo-mechanical loading is carried out for the first time. Numerical results of displacement and stresses are obtained using differential quadrature method (DQM). Some material properties of the plate assumed to be temperature-dependent and graded in all three spatial directions according to a power law function. The results for various boundary conditions are obtained and the effects of grading index of material properties, temperature distribution, elastic foundation parameters and angle of skew plate are presented. Moreover, the dynamic response of a multi-directional functionally graded material skew plate on elastic foundation is obtained using 4D DQM for the first time. The results show that the material grading direction has a noticeable effect on plate behavior especially for the plates under thermal loading as well as for the dynamic response of the plate.

A. Aliyari Parand and A. Alibeigloo (Mechanical Engineering Department, Faculty of Engineering, Tarbiat Modares University, 14115-143 Tehran, Iran), “Static and vibration analysis of sandwich cylindrical shells with functionally graded core and viscoelastic interface using DQM”, Composites Part B: Engineering, Vol. 126, pp 1-16, October 2017, https://doi.org/10.1016/j.compositesb.2017.05.071
ABSTRACT: In the present paper, elasticity solution for static and free vibration analysis of sandwich cylindrical shell with functionally graded (FG) core and viscoelastic interface is carried out. Variation of Young's Module and material density of FGM core layer are assumed to obey power-law of radial coordinate
with the Poisson's ratio holds to be constant. Imperfect interfaces are modeled according to the Kelvin-Voigt viscoelastic law. State space differential equations are derived using differential equations of motion as well as stress-displacement relations. For sandwich cylindrical shell with simply supported boundary conditions, these equations are solved analytically by using Fourier series expansion along the axial and circumferential direction. Whereas they are solved semi-analytically for the other cases of boundary conditions by using one dimensional differential quadrature method (DQM) along the axial coordinate. Time-dependent behavior is determined by solving first-order differential equation of sliding displacement at the viscoelastic interfaces. Numerical results are computed and compared with the reported results in literature to validate the present approach. In addition, effects of solid, elastic interfaces, different boundary conditions, time and mid radius to thickness ratio on the bending and vibration behavior of the sandwich shell are studied.

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“A posteriori stress and strain recovery procedure for the static analysis of laminated shells resting on nonlinear elastic foundation”, Composites Part B: Engineering, Vol. 126, pp 162-191, October 2017
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ABSTRACT: The numerical analysis of laminated composite plates and shells resting on nonlinear elastic foundation is the main topic of the paper. The generalized differential quadrature (GDQ) technique and the Newton-Raphson iteration are employed to obtain the solution of the static problems under consideration. The nonlinear elastic foundation is modeled using the Winkler-Pasternak model embedded with quadratic and cubic nonlinearities in order to have a more complete description of the interaction. The structural behavior is modeled by means of higher-order displacement fields developed in the framework of a unified formulation. Several lamination schemes are studied. The class of sandwich structures with an inner soft-core is also taken into account with the help of the Murakami’s function, which correctly captures the so-called zig-zag effect. The presented approach can deal with doubly-curved surfaces characterized by two radii of curvature that can vary in each point of the reference domain, whereas most of the examples available in the literature considers only shells with constant curvature, such as spherical and cylindrical shells. Solutions are presented in terms of through-the-thickness variations of strains, stresses, and displacements. For these purposes, a posteriori recovery procedure based on the GDQ method is introduced. The accuracy and effectiveness of the proposed approach are proven by means of the comparison with the numerical results obtained by a three-dimensional finite element model.

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ABSTRACT: This paper presents an experimental investigation on impact response of sandwich composite panels with thermoplastic and thermoset face-sheet. E-glass reinforced epoxy (thermoset) and polypropylene (thermoplastic) have been used to produce polymer composite face-sheets. PVC foam was used as a core material. Several low velocity impact tests were performed under various impact energies. Besides to the
individual impact behavior of the thermoset and thermoplastic sandwich composites, the impact response of sandwich composites having hybrid sequences was also investigated. Along with images of damaged samples, variations of the impact characteristics such as absorbed energy, maximum contact force and maximum deflection of the samples are provided. Most particularly this study showed that sandwich composites must have the harmony between core and the face sheet material. The deformation required for core densification must be able to compensate by the face sheet material.


ABSTRACT: This paper presents an analytical approach to analyze the nonlinear static buckling of imperfect functionally graded carbon nano-reinforced composite (FG-CNTRC) plates subjected to axial compression. The material properties of the FG-CNTRC are assumed to be graded through the thickness direction according to several linear distributions of the volume fraction of carbon nanotubes. The theoretical formulations are based on the classical plate theory (Kirchhoff plate) with von Karman-type of nonlinearity and the initial geometrical imperfection. The approximate solution is developed for simply supported and freely movable boundary conditions. By applying the traditional Galerkin method and the Airy stress function, the results for the critical load are obtained in closed-form solutions, which are convenient to be used in engineering design. Some illustrative examples are also presented in details to investigate the effects of the imperfection, carbon nanotubes, and geometrical parameters on the nonlinear static behavior the plates.

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ABSTRACT: The optimal design of viscoelastic laminated composite panels with active piezoelectric patches is addressed in this paper. Constrained optimization is conducted to determine optimal distributions of piezoelectric patches on the top and bottom surfaces of laminated plates with viscoelastic layers. The design variables are the number and position of these patches, and the objectives are the minimization of the number of patches, the maximization of the fundamental modal loss factor and the maximization of the fundamental natural frequency. The problem is solved using the Direct MultiSearch (DMS) solver for derivative-free MultiObjective Optimization (MOO). The objective functions are evaluated by a finite element model that was developed for laminated sandwich plates incorporating piezoelectric or viscoelastic layers. Trade-off Pareto optimal fronts and the respective optimal active patch configurations are obtained and the results are analyzed and discussed.

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ABSTRACT: The aim of this study was to determine the effect of impact energy and impactor size on basalt filament wound composite tubes with different winding angles. Tubes with four different winding angles \([\pm 45^\circ]_3, [\pm 55^\circ]_3, [\pm 65^\circ]_3\), and \([\pm 75^\circ]_3\) were subjected to various impact energy levels, 4, 6, 8 and 10 J, using four different impactor diameters, 6.35, 10, 12.7 and 15.9 mm. The results obtained revealed the significant effect of energy levels, despite the limited range purposely studied. In particular, not only maximum damage diameter (MDD) but also the geometry of damage area is influenced by impact energy. MDD also increases the higher the winding angles. In addition, basalt tubes with higher winding angles absorb less energy than the tubes with smaller winding angles for any given impact energy: this may be also the effect of them being slightly thinner. Impact damage typically propagates in the fibre direction of the tubes. Impact using larger impactors increases the dimensions of damage area, hence reducing the penetration. In comparison with E-glass tubes with similar amount of reinforcement, damage area of basalt tubes is significantly smaller at all impact energies.


ABSTRACT: This paper deals with the vibration and buckling behaviour of orthotropic double-layered graphene sheets with various boundary conditions in a hygrothermal environment. Two graphene sheets are coupled by an elastic media and also limited to the external Pasternak elastic foundations. The governing equations of motion and equilibrium are derived using Hamilton's principle and then solved using Galerkin's method. The general equations for transverse vibration and buckling of orthotropic double-layered graphene sheets subjected to in-plane edge hygrothermal loadings are formulated on the basis of Eringen's differential nonlocal elastic law and the new first order shear deformation theory. The accuracy of the present solutions is demonstrated by comparison with solutions available in the literature. Numerical results are presented to show variations of the frequency and critical buckling load corresponding to various values of the nonlocal parameter, temperature rise, moisture rise, elastic foundation parameter, and aspect ratio. Also, seven different boundary conditions are discussed in the paper.


ABSTRACT: Carbon nanotubes have drawn enormous attention in recent years due to their outstanding mechanical and multifunctional properties. In addition, the growing tendency of aeronautical engineering to incorporate advanced composite materials in aircraft structures suggests carbon nanotube reinforced composites as ideal materials for high-performance fuselage panels. Nevertheless, due to the theoretical difficulties in the underlying differential problem induced by curvature, along with the technology of carbon nanotube based composites that is still under development, the number of research works on the post-buckling behavior of carbon nanotube reinforced composite curved panels is still scant. Furthermore, numerous experimental results in the literature report about the wavy state of nanotubes in polymer matrices, as well as their tendency to gather...
in bundles due to their high van der Waals force attraction. Therefore, advanced homogenization approaches are needed to account for these phenomena and assist the structural design. In this context, this paper presents detailed parametric analyses of the post-buckling behavior of functionally graded carbon nanotube reinforced curved panels under uniaxial compression. In particular, the effects of filler content, fiber orientation, distribution along the thickness, and misalignment of fibers are investigated. To this aim, the overall elastic moduli of carbon nanotube reinforced composites are computed by the Eshelby-Mori-Tanaka method with consideration of waviness and agglomeration effects. The presented results prove the essential role of the micromechanical variables in the design of high-strength composite curved panels. Notably, the theoretical simulations highlight the detrimental effect of waviness and agglomeration on the mechanical response of these composites. In light of this study, it is concluded that the incorporation of the considered micromechanical variables is essential for the study of the post-buckling response of functionally graded carbon nanotube reinforced curved panels under axial compression.

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ABSTRACT: The tailorable mechanical properties and high strength-to-weight ratios of composite sandwich panels make them of interest to the commercial marine and naval sector, however, further investigation into their blast resilience is required. The experiments performed in this study aimed to identify whether alterations to the composite skins or core of a sandwich panel can yield improved blast resilience both in air and underwater. Underwater blast loads using 1.28 kg TNT equivalent charge at a stand-off distance of 1 m were performed on four different composite sandwich panels. Results revealed that implementing a stepwise graded density foam core, with increasing density away from the blast, reduces the deflection of the panel and damage sustained. Furthermore, the skin material affects the extent of panel deflection and damage, the lower strain to failure of carbon-fibre reinforced polymer (CFRP) skins reduces deflection but increases skin debonding. A further two panels were subjected to a 100 kg TNT air blast loading at a 15 m stand-off to compare the effect of a graded density core and the results support the underwater blast results. Future modelling of these experiments will aid the design process and should aim to include material damage mechanisms to identify the most suitable skins.

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2. M. Kelly, “Comparing the blast tolerance of different composite structures”, Imperial College London (2016)
ABSTRACT: In this paper, thermal and shear deformation effects on the vibrational response of non-homogeneous microbeams made of functionally graded (FG) materials are carried out. It is assumed that the temperature-dependent material properties of FG microbeams change smoothly and gradually throughout the height according to the classical rule of mixture. The governing differential equations and related boundary conditions are derived by implementing Hamilton's principle on the basis of hyperbolic shear deformation beam and modified couple stress theories and they are analytically solved. The results are given together with other beam theories. A detailed parametric study is performed to indicate the influences of slenderness ratio, material length scale parameter, gradient index, shear correction factors and temperature rise on natural frequencies of FG microbeams. It is revealed that the use of modified shear correction factor can provide more accurate and valid results for first-order shear deformable microbeam model.

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ABSTRACT: This paper aimed to experimentally understand the effects of Expanded Polypropylene (EPP) foam filling on the mechanical properties of aluminum (Al) honeycomb panels. The process of lightweight EPP foam with different densities filling in Al honeycomb composites was first studied, then a series of axial (out-of-plane) and lateral (in-plane) compression tests were carried out on the bare and filled honeycombs. It is showed that the peak strength, mean crushing strength and total energy absorption (EA) in the axial tests increased with foam filler (increased by approximately 2.310–43.069%, 34.791–120.219% and 46.765–179.474% with respect to bare honeycomb, respectively); and the higher foam density, the greater filling effect, whereas the specific energy absorption (SEA) remained unchanged with increase in the foam density. Interestingly, more significant improvement in total energy absorption and SEA were found under lateral crushing. All the foam filled panels were of even greater energy absorption than the sum of bare honeycomb and EPP foam separately under both axial and lateral crushing. The foam filler had no significant effect on its deformation pattern under axial crushing, whereas it helped decrease local densification in honeycomb, leading the filled panels to deform in uniform rhombus shapes under lateral crushing.

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ABSTRACT: In the present work, a close-form solution based on a unified one-dimensional model is proposed and then applied to static response analyses of cross-ply laminated and sandwich beams subjected to simply supported boundary conditions. The hierarchical beam model is derived within the framework of the Carrera Unified Formulation (CUF), which makes use of Lagrange polynomials to express the three-dimensional (3D) displacement field via arbitrary order approximation of pure displacement variables at each layer over the cross section, in a Layer-Wise (LW) sense. The governing equations are derived via the principle of virtual work and a Navier-type close-form solution is employed to solve the resulting boundary value problem. Four benchmark numerical examples are carried out to demonstrate the efficiency of this novel method, including compact multi-layered cross-ply laminated beams, a thin-walled composite box beam and a composite sandwich-box beam. The results show that accurate displacement and stress components can be obtained as the order of the expansion increases, accompanied by a significant reduction in computational costs in comparison with the 3D finite element solutions. Besides, numerical cases in this research may be taken as benchmarks for future assessments in this field.


ABSTRACT: Multi-cell metallic thin-walled tubes have gained wide popular in recent years, due to their significantly improvements in mechanical behaviors comparing with general single sample. In this investigation, some attempts to learn of the mechanism of folding process of multi-cell thin-walled square tubes were carried out. The half-wave length has been fully determined theoretically by the means of Super Folding Element. The relationship between the half-wave length as well as mean load versus cell amounts has been given. Afterwards, comprehensive numerical simulations were also conducted after necessary experimental validation, with the cell amounts range from $1 \times 1$ to $15 \times 15$ which have the equal weight but different thickness. Detailed evolitional process of deformation mode, half-wave length, and energy absorption capability were analyzed parametrically. The results turned out that the vital influence factor on mechanical properties of multi-cell tubes directly lies in the half-wave length caused by different cell amounts. With the increasing of cells, the half-wave length decreases while the energy absorption capability promotes. Evidently promotion can be observed compared with general single cell tube. All these achievements shed a light on disclosing the multi-cell effect on mechanical properties.

References listed at the end of the paper:

ABSTRACT: The excitation frequencies of parametric vibration of laminated non-homogeneous orthotropic conical shells (LNHOCSs) under axial load periodically varying with time, are determined using the classical shell theory (CST). The basic equations are found using the Donnell-Mushtari shell theory and reduce to the Mathieu-Hill type differential equation, in which the instability is examined by the Bolotin method. To validate of current results was made a comparison with the previous studies. The effects of stacking sequences, axial load factors, non-homogeneity, as well as the variation of geometric characteristics on the backward and forward excitation frequencies (BFEFs) of conical shells are studied in detail.

References listed at the end of the paper:

12 A.H. Sofiyev, N. Kuruoglu, “Natural frequency of laminated orthotropic shells with different boundary conditions and resting on the Pasternak type elastic foundation”, Compos B Eng, 42 (2011), pp. 1562-1570
ABSTRACT: The present study deals with the size-dependent nonlinear buckling and postbuckling characteristics of magneto-electro-elastic cylindrical composite nanoshells incorporating simultaneously the both of hardening-stiffness and softening-stiffness size effects. To accomplish this purpose, the nonlocal strain gradient elasticity theory is applied to the classical shell theory. Via the virtual work's principle, the size-dependent governing differential equations are constructed including the coupling terms between the axial mechanical compressive load, external magnetic potential and external electrical potential. The nonlinear prebuckling deformations and the large postbuckling deflections are taken into consideration based upon the boundary layer theory of shell buckling. Finally, an improved perturbation technique is employed to achieve explicit analytical expressions for nonlocal strain gradient stability curves of magneto-electro-elastic nanoshells.
under various surface electric and magnetic voltages. It is seen that a positive electric potential and a negative magnetic potential cause to increase both of the nonlocality and strain gradient size dependencies in the nonlinear instability behavior of axially loaded magneto-electro-elastic composite nanoshells, while a negative electric potential and a positive magnetic potential play an opposite role.

References listed at the end of the paper:
3 A.H. Sofiyev, E. Osmancebioglu, “The free vibration of sandwich truncated conical shells containing functionally graded layers within the shear deformation theory”, Compos Part B Eng, 120 (2017), pp. 197-211

ABSTRACT: To maximize the controllable energy absorption of corrugation troughs as observed in the single sided corrugated (SSC) tube, we proposed and tested a new structure design, i.e., double-sided corrugated (DSC) tube made of Al 6060-T6 aluminum alloy or CF1263 carbon/epoxy composite. Finite element models were developed to test the mechanical advantage of the DSC tube in comparison with both SSC and classical straight (S) tubes under axial crushing. Results have shown that the total absorbed energy of the DSC aluminum tube with 14 corrugations was 330% and 32% higher than that of the SSC tube with 14 corrugations and the S-tube, respectively. The initiation and progression of the crushing process for different tube configurations were characterized, leading to the mechanism of energy absorption. Plastic deformation in terms of PPEQ is the key parameter correlating with the energy absorption capacity. To overcome the lower specific absorbed energy (SAE) in the DSC tube compared to that in the S-tube, the CF1263 carbon/epoxy composite laminate was adopted and the corresponding SAE was 5.9 times higher than that of the aluminum one. Moreover, the influence of the number of corrugations on the crushing behaviors of the DSC tube was also inspected. A minimal straight tube section was suggested for a controllable smooth crushing behavior regardless of its advantage in SAE. This work might shed light on designing future thin-walled energy absorber devices with better control of crushing behaviors for minimal injuries and damages.


ABSTRACT: This paper presents static bending and compressive buckling analyses of functionally graded multilayer graphene nanoplatelet (GPL)/polymer composite plates within the framework of the first-order shear deformation theory. The GPL weight fraction shows a layer-wise change along the thickness direction with GPLs uniformly dispersed in the polymer matrix in each individual layer. The effective Young's modulus of the nanocomposites is estimated through the Halpin-Tsai micromechanics model while the effective Poisson's ratio is determined by the rule of mixture. Analytical solutions are obtained for the static deflection and critical buckling load of the simply supported functionally graded GPL/polymer plates by using the Navier solution technique. Numerical results show that GPL distribution pattern, weight fraction, and geometry and size have significant influences on the bending and buckling behaviors of the functionally graded GPL reinforced nanocomposite plate.


ABSTRACT: Present investigation deals with the buckling and postbuckling behavior of a sandwich plate with a homogeneous core and graphene-reinforced composite (GRC) face sheets resting on an elastic foundation in thermal environments. The material properties of GRC face sheets are assumed to be piece-wise functionally graded by changing the volume fraction of graphene in the thickness direction. The material properties of both the homogeneous core layer and the GRC face sheets are assumed to be temperature-dependent, and are estimated by the extended Halpin-Tsai micromechanical model. The higher order shear deformation plate theory and the von Kármán-type kinematic nonlinearity are used to derive the governing equations which account for the plate-foundation interaction and the thermal effects. The buckling loads and the postbuckling equilibrium paths are obtained by using a two-step perturbation technique. The impacts of the distribution type of reinforcements, core-to-face sheet thickness ratio, plate aspect ratio, temperature variation, foundation stiffness and in-plane boundary conditions on the postbuckling behavior of sandwich plates with functionally graded GRC face sheets are studied in detail.

ABSTRACT: Buckling analyses of laminated truncated conical shells subjected to external hydrostatic compression are carried out by employing the Abaqus finite element program. The critical buckling loads of these truncated conical shells with a given material system are maximized with respect to fiber orientations by using the golden section method. Through parametric studies, the influences of the end condition, shell thickness, shell length, shell radius ratio and cutout size on the optimal buckling loads, the associated optimal fiber orientations and the associated buckling modes are demonstrated and discussed.


ABSTRACT: Recently, cellular-filled structure has gained popularity due to its evident promotion in energy absorption capacity of absorber. In this study, a new pattern of compositied filling structure—honeycomb cells filled with circular tubes (HFCT) has been put forward. Comprehensive experimental investigations have been conducted in terms of ten types of HFCT structures with hollow and different fillers including circular carbon fiber reinforced polymer (CFRP) tubes as well as circular Al tubes in different filling patterns. Detailed mechanical performances on energy absorption, deformation mode and interaction between inside circular CFRP filler and outside hexagonal honeycomb container were determined. The analyses show that, when undergoing axial loading, the HFCT structure not only maintains the same excellent mechanical properties with conventional hollow honeycomb core, but also gains evident promotion in energy absorption when filled in appropriate filling pattern. Obvious filling effect and matching effect were extensively discussed around the kind patterns of filling structures, which have significant influence on HFCT structure's performance. All the achievements prove that the HFCT structure can be considered as a perfect choice in aid to design of energy absorption device.


ABSTRACT: This paper studies the small and large amplitude vibration behaviors of graphene-reinforced composite (GRC) laminated cylindrical panels supported by an elastic foundation under thermal environmental conditions. The temperature dependent material properties of GRC are assumed to be functionally graded in a piece-wise pattern by changing the volume fraction of graphene in the panel thickness direction and are estimated by the extended Halpin-Tsai micromechanical model. The motion equations for the nonlinear vibration problem of the panels are obtained from the higher order shear deformation shell theory and take into consideration of the effects of the von Kármán geometric nonlinearity, the elastic foundation and the temperature change. The nonlinear vibration solutions for the FG-GRC laminated cylindrical panels can be obtained by applying a two-step perturbation technique. We observe that the natural frequencies of FG-GRC panel with symmetrical distribution of graphene reinforcements are higher, whereas the nonlinear to linear frequency ratios of the same panel are lower than those of panels with uniform or unsymmetrical distribution of graphene reinforcements.


ABSTRACT: The present article investigates the free vibration and elastic stability behaviour of three-dimensional functionally graded sandwich beams featured by two different types of porosity, with arbitrary
boundary conditions and resting on Winkler-Pasternak elastic foundations. The investigation is carried out by using the method of series expansion of displacement components. Various hierarchical refined exponential, polynomial, and trigonometric higher-order beam theories are developed in a generalized manner and are validated and assessed against 3D FEM results. The weak-form of the governing equations (GEs) is derived via Hamilton's Principle. The GEs are then solved by using the Ritz method, whose accuracy is significantly enhanced by orthogonalizing the algebraic Ritz functions by virtue of the Gram-Schmidt process. Convergence and accuracy are comprehensively analysed by testing 86 quasi-3D beam theories. Moreover, the effect of significant parameters such as slenderness ratio, volume fraction index, porosity coefficient, elastic foundation coefficients, FG sandwich beam typology as well as boundary conditions, on the circular frequency parameters and critical buckling loads, is discussed.

ABSTRACT: Free vibration and buckling of double-walled carbon nanotubes embedded in an elastic medium with simply supported boundary conditions are studied. Doublet Mechanics (DM) is used in the analysis. Macro level strains and stresses are defined in terms of micro level strains and stresses in the DM theory. These micro deformations and micro stresses are expanded in Taylor series and the number of terms in the Taylor series defines degree of the approach. Double-walled carbon nanotubes are modelled as Euler-Bernoulli beams embedded in an elastic medium. Critical buckling loads and free vibration frequencies are obtained by using DM and compared with the classical elasticity solutions. It is obtained that for some frequencies carbon nanotubes move noncoaxially. Noncoaxial vibration and buckling affect the physical properties of carbon nanotubes. The present results show that a length scale dependent DM can be used in the design of nano electro-mechanical systems.

ABSTRACT: This paper presents a numerical study about the thermal behaviour of pultruded GFRP profiles with square tubular cross-section exposed to fire. Two-dimensional and three-dimensional numerical models of previous fire tests of GFRP profiles were developed using the commercial software ANSYS Fluent 14.5. The efficacy of using different fire protection systems (passive and active) and the influence of the number of sides exposed to fire (one or three) in the thermal response of the GFRP profiles was studied. The models developed consider the heat exchanges by means of conduction, internal radiation and convection of the air and/or water enclosed in the cavity of the GFRP tubular profiles. A general good agreement was obtained between numerical temperatures and test data. The results obtained highlight (i) the relative efficiency of the different fire protection systems and (ii) the remarkable influence of exposing GFRP profiles to fire in three sides, and (iii) show the importance of the heat exchanges due to internal radiation and convection inside the cavity of the GFRP cross-section in this type of thermal simulations. The thermal models were further validated through the simulation of previous fire resistance experiments on multicellular slab panels.

ABSTRACT: A structural analysis and an optimization method for anisogrid composite lattice shell structures is proposed, considering cylindrical structures simultaneously subjected to different external loads and multiple stiffness constraints. A discrete approach is used to exactly estimate the critical buckling load of the anisogrid lattice structure, independently of the buckling failure mode. The method makes use of a full FE parametric
modeling technique able to manage all the geometrical parameters of the anisogrid composite lattice structure. Then an optimization procedure based on the genetic algorithm NSGA-II has been performed; it allows to analyze different alternatives in terms of geometrical variables, both continuous and discrete, driving the search towards the optimal solution in term of mass and conformity with all structural and stiffness constraints, aiming at the preliminary design of an actual structure. The practical usefulness and applicability of the proposed procedure to industrial cases was demonstrated through numerical examples where the anisogrid lattice structure was subjected to multiple external loads and stiffness constraints simultaneously applied.


ABSTRACT: The carbon nanotubes (CNTs) are well known for its application in the areas of advanced composite materials for their improved elastic properties. The large specific interfacial surface area owing to tiny dimensions of CNTs may greatly escalation the interfacial sliding which may promote the dissipation of energy in a dynamic situation that makes them very ideal for damping applications in engineering structures/systems. The present article investigates the viscoelastic modelling and dynamic responses of the CNTs – based carbon fiber reinforced two dimensional woven fabrics (CNTs-CFRP-2DWF) composite spherical shell panels where CNTs are reinforced in the polymer matrix phase. The Mori – Tanaka (MT) micromechanics in conjunction with weak interface (WI) theory has been developed for the mathematical formulations of the viscoelastic modelling of CNTs-based polymer matrix phase. Further, strength of material (SOM) method has been employed to formulate viscoelastic material behavior of the yarn and finally the viscoelastic properties of the representative unit cell (RUC) is established based on the unit cell method (UCM). An eight-node shell element with five degree of freedom per node has been formulated to study the vibration damping characteristics of spherical shell structures made by CNTs-CFRP-2DWF composite materials. The shell finite element formulation is based on the transverse shear effect as per the Mindlin's hypothesis, and stress resultant-type Koiter's shell theory. Frequency and temperature dependent material properties of such CNTs-CFRP-2DWF composite materials have been obtained and analysed. Impulse and frequency responses of such structures have been performed to study the effects of various important parameters such as volume fraction of CNTs, interfacial condition, agglomeration, temperature, geometries of shell panel on the material properties and such dynamic responses. Obtained results demonstrate that quick vibration mitigation may be possible using such CNTs-CFRP-2DWF composite material which is desirable to overcome the drawbacks of conventional CFRP woven fabric composite materials.


ABSTRACT: This paper presents an investigation on the nonlinear bending behaviors of nanocomposite laminated cylindrical panels made of graphene-reinforced composites (GRCs) supported by an elastic foundation under thermal environmental conditions. The extended Halpin-Tsai micromechanical model together with results from MD simulations is employed to obtain the material properties of GRCs which are temperature dependent. A piece-wise functionally graded distribution of graphene fillers along the panel thickness direction is adopted in order to maximize the effect of graphene reinforcement to the panels. The Reddy's third order shear deformable shell theory is applied to derive the governing equations for the bending problem of the panels and the von Kármán geometric nonlinearity, the foundation support and the temperature effect are also included in the derivation. The governing equations are solved by applying a two-step perturbation approach to obtain the panel load-deflection and load-bending moment curves of FG-GRC laminated cylindrical panels subjected
to a transverse uniform or sinusoidal load. The influences of loading conditions and temperature variation on the nonlinear bending behaviors of FG-GRC laminated cylindrical panels are discussed in details.

ABSTRACT: Bending properties play a significant role in the forming of textile composites reinforcements, particularly in determining the shape of wrinkles. The physics related to the bending of fibrous reinforcements is specific. Bending is due to slippage between the fibers and since the fibers are quasi-inextensible, standard plate and shell theories are irrelevant. To measure bending characteristics, three experimental tests (and their variants) have been developed in the last decades, and efforts are currently devoted to extending and improving these tests. From their results, simulations can be performed by introducing a flexural energy related to the bending moment and the curvature. In particular, wrinkles during forming can be simulated. In the case of 3D modeling of thick reinforcements, the use of generalized continuum mechanics model is necessary because of the bending stiffness of each fiber and the slippage between fibers. In order to simulate textile reinforcements with shells, some shell approaches, different of the standard theories, can correctly calculate the rotations of textile reinforcement normals.

Nebojsa Radic and Dejan Jeremic, “Analytical solution for buckling of orthotropic double-layered graphene sheets exposed to unidirectional in-plane magnetic field with various boundary conditions”, Composites Part B Engineering, Vol. 142, pp 9-23, June 2018
ABSTRACT: In this article, the analyses of the buckling behaviour of orthotropic double-layered graphene sheets (DLGSs), resting on Pasternak's elastic foundation with various boundary conditions and subjected to unidirectional in-plane magnetic field are presented. The governing equations of equilibrium of the nonlocal model are derived in terms of generalized displacement using the new first-order shear deformation theory (NFSDT) and Maxwell's equations in conjunction with the Eringen's differential nonlocal elastic law. An explicit solution for buckling loads is obtained for orthotropic DLGSs under biaxial and uniaxial loads. The effectiveness of the present formulation and solutions are firstly validated by executing the comparison studies with results available in the literature. The effects of nonlocal parameter, magnetic field strength, a different type of load and boundary conditions, aspect ratio, side length and number of half waves on the buckling behaviour of DLGSs are investigated.

M.H. Jalaei and A. Ghorbanpour Arani, “Size-dependent static and dynamic responses of embedded double-layered graphene sheets under longitudinal magnetic field with arbitrary boundary conditions”, Composites Part B Engineering, Vol. 142, pp 117-130, June 2018
ABSTRACT: This paper deals with the static and dynamic response of orthotropic double-layered graphene sheets (DLGSs) resting on visco-Pasternak foundation subjected to longitudinal magnetic field as well as mechanical transverse load with arbitrary boundary conditions based on first order shear deformation theory (FSDT) in the framework of Eringen's differential constitutive model. In order to obtain more accurate results in dynamic response, the properties of each single layer graphene sheet (SLGS) are assumed to be viscoelastic. The governing equations of motion are obtained via energy method and Hamilton's principle. Two solution procedures are proposed to solve the governing equations of motion. In the first method, the equations are solved analytically by means of Navier's and Laplace inversion technique in the space and time domains only for simply supported boundary conditions. In the second method, the governing equations are discretized numerically on the space and time domains via Ritz method and Newmark scheme, respectively, which are suitable for arbitrary boundary conditions. Employing the second solution procedure as the main approach,
parametric studies are carried out to explore the effects of the magnetic parameter, nonlocal parameter, boundary conditions, structural damping, stiffness and damping coefficient of the foundation, aspect ratio, length to thickness ratio and van der Waals (vdW) interaction. Results indicate that with increasing the value of vdW interaction, the deflection of upper layer decreases while it increases for lower layer. Moreover, it is observed that when one edge of the nanoplate changes from free to simply supported or from simply supported to clamped, the deflection amplitude and time of response decrease and therefore the nanoplate reaches the equilibrium state much faster. The presented results can be used in practical design and manufacturing of graphene reinforced nanocomposites.

Yuan Chen, Kunkun Fu, Shujuan Hou, Xu Han and Lin Ye, “Multi-objective optimization for designing a composite sandwich structure under normal and 45-degree impact loadings”, Composites Part B Engineering, Vol. 142, pp 159-170, June 2018

ABSTRACT: With their lightweight character and high energy absorption capacity, composite sandwich structures have attracted increasing attention in the transportation industry. The aim of this work is to present a new approach to investigate and optimize a composite sandwich structure by taking into account both normal and 45° low-speed impact loadings. First, a finite element model considering elastic-plastic, damage, and failure behaviours of the composites by using continuum damage mechanics is developed and validated by a normal low-speed impact test. Second, dynamic effects of normal and 45° impacts on energy absorption and failure behaviours of the composite sandwich structures are investigated. Then, a parametric study is performed to systematically understand the influences of core depth and cell thickness on the impact resistance of the sandwich composite structures subjected to both normal and 45° impacts. In contrast to their metal counterparts, it is interestingly found that absorbed energy generally increases with cell thickness, with a small extent of fluctuation, whereas core depth jumps, and the energy absorption capacity remains almost steady under normal impact but varies irregularly under the 45° impact. Afterwards, a multi-objective optimization is performed to enhance the energy absorption under both normal and 45° loadings. The energy absorption capability of the optimal composite sandwich structure can remarkably be improved by 12.447% for normal impact, and 7.9% for 45° impact. This method provides a new manner and systematic guidance for designing a lightweight composite sandwich structure more practical for engineering application.


ABSTRACT: A high order shear deformation theory is used to develop a discrete model for the structural and sensitivity analyses allowing for the material distribution and sizing optimization of functionally graded material (FGM) structures. The finite element formulation for general FGM plate-shell type structures is presented, and a non-conforming triangular flat plate/shell element with 24° of freedom for the generalized displacements is used. The formulation accounts for geometric and material nonlinear behaviour, free vibrations and linear buckling analyses, and their analytical gradient based sensitivities. The p-index of the power–law material distribution and the thickness are the design variables. Mass, displacement, fundamental frequency and critical load are the objective functions or constraints. The optimization solutions, obtained by a Feasible Arc Interior Point gradient-based algorithm, for some plate-shell examples are presented for benchmarking purposes.

ABSTRACT: The review outlines modern trends in theoretical developments, novel designs and modern applications of sandwich structures. The most recent work published at the time of writing of this review is considered, older sources are listed only on as-needed basis. The review begins with the discussion on the analytical models and methods of analysis of sandwich structures as well as representative problems utilizing or comparing these models. Novel designs of sandwich structures is further elucidated concentrating on miscellaneous cores, introduction of nanotubes and smart materials in the elements of a sandwich structure as well as using functionally graded designs. Examples of problems experienced by developers and designers of sandwich structures, including typical damage, response under miscellaneous loads, environmental effects and fire are considered. Sample applications of sandwich structures included in the review concentrate on aerospace, civil and marine engineering, electronics and biomedical areas. Finally, the authors suggest a list of areas where they envision a pressing need in further research.


ABSTRACT: Carbon fibers (CFs) have high specific tensile strength, high modulus, and outstanding wear resistance, and are widely used for the reinforcement of advanced composite materials. CF-reinforced thermoplastic composites have received much attention because of their easy processability and recycling convenience compared with thermosetting composites. Surface treatment of CFs is generally employed to increase the surface functional groups and interfacial adhesion between the CFs and the surrounding polymer matrix. In this review, we explore recent advances in the surface treatment of CFs and preparation of CF/thermoplastic composites. The thermal, mechanical, and electrical properties of the composites are also discussed.

Zheyi Zhang, Wei Sun, Yongsheng Zhao and Shujuan Hou, “Crashworthiness of different composite tubes by experiments and simulations”, Composites Part B Engineering, Vol. 143, pp 86-95, June 2018

ABSTRACT: Composite tubes show a good energy absorbing ability and they have great potential as energy absorbing components to replace traditional metal structures in automobiles, aircrafts and other transportation. This paper aims to investigate the impacts of geometrical parameters, including intermediate diameter, wall thickness and upper end diameter, on the specific energy absorption (SEA) of composite tubes, metal tubes, foam-filled tubes and hybrid tubes. The mechanical characteristics (axial compression response) of these tubes were numerically predicted by commercial finite element (FE) package LS-DYNA. Quasi-static axial compression tests were performed to determine failure parameters of glass fiber reinforced polymer (GFRP) used in this paper. Stress-strain curves of polyurethane foam and aluminum foam were also obtained by tests. Finite element models of hollow GFRP, aluminum and aluminum-FRP tubes and polyurethane foam-filled and aluminum foam-filled composite tubes were established respectively. Configurations of these numerical models include circular, square and tapered (5 different upper end diameters) tubes. In optimization part, structural parameters optimization was carried out by response surface method (RSM). Results review that in general, SEA of circular tubes increases with smaller diameter-thickness ratio. In comparison part, SEA of circular, square and tapered tubes were compared. Results show that changing upper end diameter of tubes has great impacts on their energy absorption capacity, but sensitivities of SEA to geometrical parameters and cross-section shapes differ depending on materials of tubes and foam filling.

ABSTRACT: In this study, the buckling problem of functionally graded materials (FGMs) sandwich truncated conical shells (STCSs) under hydrostatic pressure was solved using the modified form of first-order shear deformation theory (FOSDT). The FGM properties of the constituents are graded in the thickness direction in accordance with a power-law distribution. The basis equations of FGM sandwich truncated conical shells (FGMSTCSs) are derived from the Donnell kinematics assumptions. Using the Galerkin method to the partial differential governing equations, the formula for the dimensionless hydrostatic buckling pressure (DHBP) in the framework of the FOSDT is obtained to demonstrate the buckling response of FGMSTCSs. A numerical analysis is performed for various types and geometry of FGMSTCSs under FOSDT and the classical shell theory (CST).


ABSTRACT: Lightweight cores, based on an egg-box core design, have been manufactured using a simple compression-moulding technique. Two types of composite prepreg were used to manufacture the core materials, these being a woven carbon fibre reinforced epoxy and a woven glass fibre reinforced epoxy. The resulting cores were of a high quality, exhibiting little or no wrinkling following the manufacturing procedure. Subsequent compression tests at quasi-static rates of loading showed that the compression strength of the core depended strongly on the level of constraint applied during testing, with sandwich panels based on composite skins bonded to an egg-box core offering a load-bearing capability that was more than double that of its unconstrained counterpart. The quasi-static compression strength of the carbon-based cores has been shown to be slightly higher than the glass fibre systems, particularly at higher core densities. Local splitting damage at cell joining regions and crushing of the cell of the egg-box structure was identified as the primary failure mechanism in the sandwich panels. Impact tests, conducted using a drop-weight impact tower, have shown that the compression strength of the egg-box cores is higher at dynamic rates of loading than at quasi-static rates. Here again, the local splitting and crushing was the primary mode of failure in the sandwich structures. Finally, the finite element technique has been used to model the mechanical response of these core designs under both quasi-static and impact loading testing conditions. Here, agreement between the predicted and observed responses was found to be good for both extremes of loading-rate.


ABSTRACT: This paper is concerned with free vibration characteristics of the functionally graded graphene reinforced porous nanocomposite cylindrical shell with spinning motion. It is assumed that the graphene platelet (GPL) nanofillers and internal pores are randomly oriented and uniformly dispersed in each concentric cylindrical shell, and both the GPL weight fraction and the porosity coefficient vary continuously along the thickness direction. Effective material properties of the nanocomposite which are position-dependent are derived employing the modified Halpin-Tsai model and the rule of mixture. Three types of the GPL patterns and four types of the porosity distributions are considered. Frequencies of forward and backward travelling waves and critical spinning speeds are derived from the equations of motion which are established based on the first order shear deformation theory and the Hamilton's principle. Detailed parametric studies on dimensionless natural frequencies and critical spinning speeds of the GPL reinforced porous nanocomposite cylindrical shell are carried out, especially, effect of initial hoop tension on vibration characteristics of the spinning cylindrical shell is numerically discussed.
Guangyong Sun, Shunfeng Li, Guangyao Li and Qing Li, “On crashing behaviors of aluminium/CFRP tubes subjected to axial and oblique loading: An experimental study”, Composites Part B Engineering, Vol. 145, pp 47-56, July 2018

ABSTRACT: Thin-walled energy-absorbing structures rarely experience in pure axial loading in real crash events, but rather a combination of axial and off-axial loads. In this perspective, it is critical to understand the oblique crushing process of thin-walled structures. To address this issue, circular aluminum and carbon fiber reinforced plastics (CFRP) tubes were experimentally investigated for characterizing their crashworthiness subject to quasi-static axial and oblique compression in this study. The tests were conducted at five different loading angles (θ) of 0°, 5°, 10°, 20° and 30° to the tubal axis. Five sets of specific fixtures were fabricated to apply the desired axial and off-axial loads onto the aluminum and CFRP specimens, respectively. The failure modes, load-displacement curves, crushing force and energy absorption of all the specimens were analyzed; and the effects of loading angle were explored. It is found from the experiments that with the increase in loading angle, aluminum tubes were more prone to collapse in an irregular diamond mode (I_d) instead of axisymmetric concertina mode (A_c), while the CFRP tubes collapsed in much more complex failure modes which included splaying mode (S_p), tearing mode (T_e), socking mode (S_o), micro-fragmentation mode (M_f) and catastrophic failure (C_f). As for the energy absorption characteristics, the loading angle (θ) ranged from 0° to 10° had little impact on the energy absorption for the both aluminum and CFRP tubes, nevertheless, the energy absorption of the CFRP tubes decreased more significant from θ = 10° to 30°, while that of aluminum tubes declined fairly steadily.


ABSTRACT: This paper investigates the impact behaviors of filament wound carbon fiber/epoxy (CFRP) nanocomposite tubes at cryogenic temperatures. As nanofiller, multi-walled carbon nanotubes (MWCNT) were introduced to epoxy resin. (±55°)_4 carbon fiber/epoxy nanocomposite specimens were manufactured using the filament winding method. Low velocity impact tests at 15 J energy level were performed on the neat and MWCNT added CFRP tubes at different temperatures (23 °C, 0 °C, −50 °C, −100 °C, −196 °C). The contact force-time, contact force-displacement histories and absorbed energy values by the specimens were obtained from the low velocity impact tests for each test samples. The effects of temperature change to impact response of neat and MWCNT added CFRP tubes were evaluated. Damage zones on the specimens were also examined in detail. It was observed that damages on the specimens increased when the temperature decreased for all test samples. Furthermore, the addition of nanoparticles to the specimens resulted in higher contact force values for the same temperature and less damage in the sample sections.


ABSTRACT: Double layered graphene sheets (DLGSs) have attracted increasing attention due to its unique excellent properties. The present work studies the geometrically nonlinear vibration behavior of DLGSs using von Kármán plate model incorporated with nonlocal elasticity theory accounting for the small scale effect. The element-free kp-Ritz method is then employed to solve the obtained coupled partial differential equations. The effectiveness of the present nonlocal element-free kp-Ritz method is verified through comparison with the published results. The influence of side length, boundary condition, aspect ratio and nonlocal parameter on the geometrically nonlinear vibration behavior of DLGSs are investigated. Ultimately, it is found that the effect of boundary conditions, side length, aspect ratio and nonlocal parameter can approximately be neglected, when compared with that of vdW interaction which exists between adjacent layers of DLGSs.

ABSTRACT: Hierarchical sandwich structures have been popularly investigated due to its promotion in structural stress and stiffness. A composite Honeycomb structure Filled with Circular Tubes (short as HFCT) was proposed in the previous study. In this paper, the blast resistance performances of sandwich plate filled with HFCT core (short as SP-HFCT) are investigated numerically by considering plastic dissipation energy, deflection of back face-sheet and deformation modes. The comparisons of performance between the general honeycomb sandwich plate (short as GHP) and the SP-HFCT illustrate that the composited filling mode can effectively improve blast resistant capacity by reducing the maximum deflection of the back plate and improving the ratio of plastic energy dissipated by cellular core to the total plastic energy dissipated by sandwich plate. Parametric analyses are performed to evaluate the influence of matching effect between container and filler, filling mode and blast loading on the resistance performance of SP-HFCT. The results show that a stronger honeycomb container filled with weaker circular tubes is a more favorable configuration of HFCT core. Meanwhile, by filling circular tubes into a buckling area, a considerable mass efficiency improvement with respect to deflection resistance can be obtained. With the increasing of stand-off distance, the effectiveness of SP-HFCT against blast loads will be boosted.


ABSTRACT: This paper presents the seismic response of laminated composite cylindrical tank in the framework of the first-order shear deformation theory. A random microstructure of composite material results in transversely isotropic properties at the meso-scale. The analysis of composites with random microstructure is done by using of a fictitious hexagonal microstructure. The laminated representative volume element is assumed for obtaining the effective material properties of the laminated composite. Seismic analysis of liquid storage laminated composite tank is different from the analysis of typical structures. The fluid exerts hydrodynamic impulsive and hydrodynamic convective pressures together with hydrostatic pressure on tank walls and bottom of the ground-supported fluid filling container during an earthquake. The knowledge of pressures and forces acting onto walls and bottom of the container and total hydrodynamic effects of liquid on storage tank during earthquake loading plays fundamental role in the design of an earthquake resistance of fluid filling container. The seismic response of a fluid filling laminated composite container was solved for Slovakia region respecting recommendations of Eurocode 8 Part. 4. We considered only horizontal seismic load by using the elastic response spectrum.


ABSTRACT: This paper presents a finite element model based on the first-order shear deformation theory for free vibration and buckling analyses of functionally graded (FG) sandwich beams. The present element has 3N + 7 degrees-of-freedom for an N-layer beam. Lagrange's equations are employed for derivation of the equations of motion. Two types of FG sandwich beams are considered: (a) Type A with FG faces and homogeneous ceramic core, and (b) Type B with homogeneous ceramic and metal faces and FG core. Natural frequencies and buckling loads are calculated numerically for different boundary conditions, power-law indices, and span-to-height ratios. Accuracy of the present element is demonstrated by comparisons with the results available, and discussions are made on the results given in graphs and tables for the sandwich beams considered.
Salvatore Brischetto and Francesco Tornabene, “Advanced GDQ models and 3D stress recovery in multilayered plates, spherical and double-curved panels subjected to transverse shear loads”, Composites Part B Engineering, Vol. 146, pp 244-269, August 2018

ABSTRACT: The present work shows a systematic comparison between different shell models in the case of static analysis of multilayered composite and sandwich plates and spherical shells. Transverse shear loads are applied on these structures. The behavior through the thickness direction is analyzed in terms of the three displacement components and the six stress components. Such evaluations allow to remark the typical zigzag effect of displacements and the interlaminar continuity conditions in terms of congruence and equilibrium equations in the multilayered plates and shells. The boundary load conditions at the external surfaces are also verified. The proposed 3D models are closed form solutions of 3D shell theories developed in the framework of analytical and semi-analytical approaches for differential equations in the thickness direction. The 2D numerical shell models are classical and refined models developed in both equivalent single layer and layer wise viewpoints. 2D numerical theories are solved by means of the Generalized Differential Quadrature (GDQ) model, which allows general solutions for different boundary conditions, load applications, lamination schemes and geometries. The advantages of this methodology are also clearly shown and discussed for complicated geometries such as double-curved shells.

A. Gliszczynski, T. Kubiak and L. Borkowski, “Experimental investigation of pre-damaged thin-walled channel section column subjected to compression”, Composites Part B Engineering, Vol. 147, pp 56-68, August 2018

ABSTRACT: Experimental investigations of channel-section profiles subjected to compression after low-velocity impacts (20 J) leading to global failure are presented. The columns under discussion were made of an eight-layer GFRP laminate with quasi-isotropic, quasi-orthotropic and angle ply arrangements of layers. The profiles were impacted in mid-width of the web or mid-width of the flange in various locations along the profile length. An influence of the impact position and the layer arrangement on buckling and failure phenomena, post-buckling behaviour for impacted and non-impacted columns was thoroughly examined and described. It was found that the local degradation introduced by low-velocity impacts did not affect the global behaviour of the analysed structures to a considerable extent. Moreover, it was noted that the failure mechanism was initiated in the impact location in none of the cases analysed. Additionally, it was stated that a number of fracture points did not have any significant impact on the capacity reduction.

Yaser Kiani, Rossana Dimitri and Francesco Tornabene, “Free vibration of FG-CNT reinforced composite skew cylindrical shells using the Chebyshev-Ritz formulation”, Composites Part B Engineering, Vol. 147, pp 169-177, August 2018

ABSTRACT: In the present research, the free vibration characteristics of a skew cylindrical panel made of functionally graded carbon nanotube reinforced composites (FG-CNTRCs) is investigated. A dual distribution of CNTs is considered across the panel thickness, namely a uniform and a nonuniform distribution. A refined rule of mixtures approach is applied to estimate the mechanical properties of the composite body, by means of the introduction of some efficiency parameters. A first order shear deformation shell theory (FSDT) is also combined with the Donnell's kinematic assumptions to determine the basic governing equations of the problem for thin-to-moderately thick shells. The governing equations are here referred to an oblique coordinate system, in order to handle any kind of boundary conditions. With the aid of the Ritz method, a system of homogeneous equations governs the eigenvalue problem, whose shape functions are built on Chebyshev polynomials. This system allows to compute the natural frequencies of the shell. A comparative evaluation of the formulation is performed to demonstrate its accuracy and efficiency. Further parametric studies are aimed at exploring the
sensitivity of the response to some reinforcement parameters, as the volume fraction or the distribution of CNTs within the matrix.


ABSTRACT: The compressive failure behavior of defected periodic fiber-reinforced composites subjected to macroscopic biaxial loadings is here analyzed from both the theoretical and numerical point of view. The coupled effects of local fiber buckling and matrix or fiber/matrix interface microcracks under unilateral self-contact are included in the analysis by adopting an original full finite deformation approach. The obtained uniqueness and stability conditions associated with a continuum rate formulation of the microscopic equilibrium problem, contain unusual nonlinear contributions arising from crack interface self-contact mechanisms whose significance for an accurate evaluation of macroscopic critical loads at the onset of instability and bifurcation is then investigated in an innovative way. To this end by using a nonlinear FE model and analytical developments, the composite failure domains are determined for radial macroscopic loading paths, ranging from biaxial compression to combined axial compression and lateral expansion, and for different microgeometrical parameters. Comparisons with stability and uniqueness domains obtained when simplified crack contact interface approaches are adopted, show the notable role of the above mentioned crack interface contributions for a realistic prediction of the real failure behavior of the composite solid.


ABSTRACT: This paper presents a stochastic dynamic analysis of functionally graded plates by following an efficient neural network based approach coupled with the finite element method. An isoparametric quadratic element having eight nodes is considered for the finite element analysis of pre-twisted functionally graded cantilever plates subjected to variation in geometric parameters, material properties and temperature. Both individual and compound effects of stochasticity in the uncertain input parameters are accounted to quantify their influence on the first three natural frequencies, mode shapes, and frequency response functions of functionally graded plates. A sensitivity analysis is conducted to ascertain the relative effects of various prospective sources of uncertainty. Latin hypercube sampling is utilised to train the efficient surrogate models, which are employed as a medium of uncertainty propagation. The comparative performance of artificial neural network and polynomial neural network is assessed in the stochastic dynamic analysis of the pre-twisted functionally graded plates from the viewpoint of accuracy and computational efficiency. The results are validated with respect to direct Monte Carlo simulation based on the finite element model of the functionally graded plates. It is observed that the artificial neural network based algorithm can achieve a significant level of computational efficiency without compromising the accuracy of results. The results presented in this article reveal that the source uncertainties of functionally graded plates have a significant effect on the dynamic responses of the structure.


ABSTRACT: Lightweight phenolic resin-impregnated aramid paper honeycombs, commercially known as Nomex® honeycombs, are promising cores for sandwich structures in aerospace applications due to their high ratios of stiffness and strength to density. The out-of-plane compressive properties of the Nomex honeycombs
have been widely investigated under quasi-static and low strain rates (up to 300 s⁻¹). There is a need to understand the behaviour of this structure under higher strain rate compression. This will widen the applicability of these structures to more areas such as debris impact and other impacts which induce high strain rates. This paper reports the out-of-plane compressive responses of Nomex honeycombs subject to quasi-static loading and high strain rate dynamic loading up to 1500 s⁻¹. The work involves experimental measurements and numerical modelling and validation. The compressive responses of the honeycombs were measured using a sensitive magnesium alloy Kolsky bar setup with front and back face impacts. The failure modes of the Nomex honeycombs were identified to be different under quasi-static and dynamic compressions. Under quasi-static compression, the honeycombs failed with local phenolic resin fracture after the elastic buckling of the honeycomb walls. For the dynamic compression, the honeycombs failed with the stubbing of cell walls at the ends of specimens. A finite element (FE) numerical model was devised and validated with the experimental data. The FE model considered the strain rate effect of phenolic resin material. The model predictions were in good agreement with the experimental measurements and facilitated interpreting the out-of-plane compressive response of the Nomex honeycombs. It was shown that there was a linear compressive strength enhancement up to 30% from quasi-static to strain rate of 1500 s⁻¹. The strength enhancement was governed by two mechanisms: the strain rate effect of the phenolic resin and inertial stabilization of the honeycomb unit cell walls, where 61%–74% of the enhancement was contributed by the inertial stabilization of the unit cell walls. In addition, it was shown that the impact method and initial imperfections had negligible effect on the compressive response of the Nomex honeycombs.

ABSTRACT: In the oil&gas field, common steel pipelines experience well-known problems of corrosion and maintenance. The design with composite materials could avoid these problems and provide lightness to the overall structures. Standards and regulations guide the designer through the qualification steps, but they are constantly under review based on the increasing knowledge of the long term mechanical behaviour of these materials. The aim of this work is to provide the designer with an analytical tool for the optimal design of a composite plain pipe, i.e. minimizing the wall thickness. The paper presents considerations useful in the design stage for the selection of the optimal fiber, matrix, volume fraction Vf, and winding angle θ. The study simulates tests with inner pressure and axial loads, in accordance with the main applicable standards. Based on the analytical estimations, we found a locus of optimal technological parameters with volume fraction 40% < Vf
< 60% and winding angle ±44.5°<θ<±52.5°. From these considerations, we can suggest a customization in the pipe production, based on the estimated axial loads in exercise.


ABSTRACT: Nowadays, filament wound composite pipes (GRP) are used as a structural element in many applications such as natural gas and oil transmission lines, and portable bridge constructions for military purposes. GRP pipes can expose to impact loading from various causes. This loading can cause an invisible level of damage. Thus, the detection and evaluation of such damages are of great importance. In this study, the low velocity impact response of (±55°) filament wound E-glass/epoxy composite pipes has been studied. The pipes have been subjected to drop weight impact loading with various impact energies. The force-time and force-displacement relations have been examined. The impact damage formation was also evaluated. It is concluded that the damage development in the pipes is controlled by displacement trough radial direction. The obtained results were evaluated statistically by means of Weibull approach. Microscopy analysis of impacted region revealed that debonding, radial cracks, transfer cracks and delamination damage modes are the main observed damage modes.


ABSTRACT: This paper aims to investigate the single and repeated impact behaviors of bio-sandwich structures consisting of E-glass fiber – reinforced thermoplastic face sheets and balsa cores. Low velocity impact tests were performed using a drop-weight impact machine under a hemispherical impactor. Preliminary single low velocity impact loadings were applied to the bio-sandwich composites with different core thicknesses (namely 15 and 25 mm) so as to obtain the energy limits which were ranged from fully elastic level (10 J) to perforation energy level (80 J). Impact behaviors and damage mechanisms which occurred at both face sheets and internal parts of the balsa core were elucidated through the energy profile diagrams and force – deformation (F-D) curves under low velocity single impact loadings. Besides, low velocity repeated impact tests of the bio-sandwich structures were performed with the same impact energy levels. Repetitive impact behaviors were also investigated with F-D curves at some specific repeated impact numbers. Impact failures which occurred in the upside and bottom of composite structures were detected with digital camera. According to the experimental findings, it was concluded that the total number of impact loads under impact energy level of 10 J until perforation were 38 for the sandwich structures with 15 mm balsa core thickness while it was 98 for the sandwich structures with 25 mm balsa core thickness. Based upon the test results, the number of impacts for perforation (Np) under smaller impact energies without testing was easily predicted with the derived equation in the form of (math), where Ec represents the impact energy while a and b are the constants.


ABSTRACT: The low-velocity impact behaviors of aeroelastic functionally graded CNT (carbon nanotube) reinforced composite panels in supersonic airflow are investigated. Thermal effects are taken into account. Reddy's higher-order shear deformation theory is applied in the structural modeling. The effective material properties of the functionally graded CNT reinforced composite panel are calculated by the rule of mixture. The
aerodynamic pressure is evaluated by the first-order piston theory. The contact force between the panel and the impactor is simulated by the Hertz law. Hamilton's principle and the assumed modes method are used to formulate the equation of motion which is then solved by the numerical method because of the high nonlinearity. A simplified mass-damping-spring model is also introduced to solve the problem. Influences of the aerodynamic pressure, CNTs distribution and volume fraction and thermal effects on the impact responses of the functionally graded CNT reinforced composite panels are investigated. The simulating results using the numerical model and the mass-damping-spring model are compared. The affect factor considering the inertial effect of the panel in the low-velocity impact for the CNT reinforced composite panel is given out.

ABSTRACT: The size-dependent static, free vibration and buckling behaviours of functionally graded (FG) sandwich plates are analysed in this study. Utilising the modified couple stress theory and variational principle, governing equations of motion are developed with a refined shear deformation theory. The rectangular plates embedded on two opposite simply-supported edges with the arbitrary combinations of the other two. Based on the state-space Levy solution, the deflections, stresses, natural frequencies and critical buckling loads are analytically solved for the closed-form formulations. The effects of material distribution and graded schemes, geometric parameters and boundary conditions are also investigated to examine the size-dependent behaviours of FG sandwich microplates.

ABSTRACT: Quasi-static compressive behavior of different density glass microballoon (GMB) reinforced high density polyethylene (HDPE) syntactic foams are investigated in the present work. Reducing the weight of thermoplastic components has been always a high priority in transportation, aerospace, consumer products and underwater vehicle structures. Despite continued interest in developing lightweight thermoplastic syntactic foams, they have not been studied extensively for quasi-static response with focus on wall thickness and volume fraction variations. Compression molded GMB/HDPE sheets are subjected to 0.001, 0.01 and 0.1 s$^{-1}$ strain rates. Compressive modulus of foams is higher compared to neat HDPE. Increasing strain rates and decreasing filler content increases yield strength for all the foams investigated compared to neat HDPE. Yield strain and energy absorption of GMB/HDPE foams increases with an increasing strain rate and wall thickness. Specific modulus and strength of GMB/HDPE foams are superior and are comparable to neat HDPE. GMB/HDPE foam achieved high stiffness to weight ratio making them suitable for wide variety of applications. Theoretical model based on differential scheme predicts a good estimate of elastic modulus for all the type of GMB/HDPE foams. Finally, property map is exhibited to present comparative studies with existing literature.

ABSTRACT: One of the most applications of stiffened composite panels is the marine application. In this study, a new sandwich structure consists of long E-glass fibers reinforced Balsa composites is evaluated. The use of this material in marine applications for long periods and under different environmental conditions leads to degradation of mechanical properties of structures and the adhesive. Therefore, in order to guarantee the best
functioning of structures for long time periods, an experimental characterization procedure is required. For this purpose, the dynamic mechanical behavior of top-hat bonded stiffened composite panels used in marine applications is studied. A special fixture was designed and fabricated for the impact testing of stiffened structures. Manufactured specimens were tested until final failure and the effect of impact velocities on the load-displacement and strain-displacement behaviors are compared. We have also interested to the effect of impact velocity on the dynamic behavior and damage kinetics.


ABSTRACT: Identification of the boundary between failure by buckling, collapse and material failure in cylindrical tubes under axial compression is still challenging. The focus of this research is to investigate the response of carbon/epoxy filament wound cylindrical tubes under axial compression. Three approaches have been studied: (i) linear buckling; (ii) nonlinear buckling; and (iii) progressive damage modeling (PDM). For that, analytical, numerical and experimental approaches have been followed. Key results show that thinner tubes fail by buckling followed by a post-buckling field, whereas material failure due to transverse compression and in-plane shear stresses occur for thicker tubes. Both analytical and linear numerical models predicted very well the critical buckling load for all [±α] tubes, and nonlinear buckling model satisfactorily predicted axial displacement over the loading history. For multilayered tubes, the developed damage model provided better predictions compared to the nonlinear buckling model. Furthermore, for thicker tubes, a hoop layer at the outermost, instead of middle or innermost, improves buckling/compressive resistance.


ABSTRACT: In the present work, thermo-elastic vibrational behavior of thick microbeams embedded in a two-parameter elastic foundation is studied. A Winkler-Pasternak type elastic foundation model is employed to simulate the interactions between microbeam and elastic medium. Size-dependent constitutive equations and associated boundary conditions are obtained by applying dynamic version of virtual work’s principle based on modified couple stress and various beam theories. Several numerical examples are presented to examine the sensitivity of various parameters associated with slenderness ratio, temperature rise, length scale, Winkler and shear layer parameters on the natural frequencies and critical temperature point of embedded microbeams.


ABSTRACT: In the present paper, advanced numerical methodologies have been adopted to investigate the structural behaviour of a composite subcomponent for aerospace applications subjected to quasi-static compression and dynamic loads. The analysed structural component, made of laminated carbon fibres reinforced polymers, is part of the floor support system in the cargo area of a commercial aircraft. The interlaminar and intra-laminar damage onset and propagation has been preliminary monitored under a quasi-static compressive displacement application. Then, the effects on the structural integrity of two impact energy levels have been analysed: 42 J energy has been applied to study the dynamic behaviour in an elastic linear rate while 585 J energy has been considered to assess the crashworthiness behaviour. The adopted numerical model has been validated by comparisons between the numerical results and analytical mass-spring model results and
experimental data in terms of stiffness, strain, and ultimate load. The simultaneous assessment of numerical results and experimental data has allowed to provide a comprehensive insight on the damage onset and propagation leading to the structural collapse of the investigated sub-floor support system.


ABSTRACT: In the present study, the effects of nonlinear van der Waals forces on the bending analysis of orthotropic bilayer conical graphene panels are investigated. In order to model the nano-sized panels, the first-order shear deformation shell theory is used to obtain the governing equations by applying energy method in nonlocal form. Semi-analytical polynomial method (SAPM) is utilized to solve the resulting nonlinear governing equations. Due to cover a wide range of geometric shapes, the geometry is considered as a conical panel, so the results can be simulated for cylindrical panels, annular sectors, and even rectangular plates. The van der Waals force between upper and lower layers of graphene panel is simulated by an extension spring with the linear and nonlinear stiffness. It is easy to obtain the results of single-layer panels by eliminating the van der Waals force, and also for macroscopic plates, with neglecting the nonlocal effects. Finally, the affecting parameters on the results are examined in detail such as the plate size, orthotropic effects of material, nonlocal effects, van der Waals force including its nonlinear term and various types of boundary conditions, even the free edges.


ABSTRACT: The main aim of this paper is to investigate the mechanical buckling behavior of functionally graded materials and carbon nanotubes-reinforced composite plates and curved panels. The governing equations are established using a double directors finite element shell model which induces a high-order distribution of the displacement field and takes into account the effect of transverse shear deformations. The effective material properties of functionally graded materials are estimated using a power law distribution and those of nanocomposites by an extended rule of mixture with some efficiency parameters. Uniform and four profiles of carbon nanotubes are considered to describe the distribution of these reinforcements through the thickness of the nanocomposite shell structure. A comparison study of the present results with those available in the literature is carried out for the isotropic case in order to prove the validity as well as the accuracy of the present model. Then, the results are extended to functionally graded materials and nanocomposites. The results reveal that the critical buckling load of plates and curved panels can be significantly increased as a result of a functionally graded reinforcement. They also show that the mechanical buckling behavior of such structures is significantly influenced by the plate aspect ratio, the length-to-thickness ratio, radius-to-thickness ratio, boundary conditions, power law index as well as the carbon nanotubes profiles and their volume fractions.


ABSTRACT: A methodology for structural analysis and optimal design of conical anisogrid composite lattice shell structures subject to different external loads concurrently applied and multiple stiffness constraints is presented. The critical buckling load of the anisogrid lattice conical structure is exactly assessed, independently of the buckling failure mode, by means of a discrete approach. The method makes use of a full FE parametric modeling technique able to manage all the geometrical parameters of the anisogrid composite lattice structure.
Additionally, the genetic algorithm NSGA-II is employed to set up an optimization procedure which allows to analyze different sets of geometrical variables, both continuous and discrete, to reach the optimal solution in terms of mass amount and fulfilling of structural and stiffness requirements, aiming at the preliminary design of an actual structure. Numerical case-studies are outlined in order to demonstrate the practical usefulness and versatility of the proposed procedure to industrial cases where the anisogrid lattice conical structure undergoes multiple external loads and various stiffness constraints must be satisfied.

ABSTRACT: Thin-walled structures hold primacy among modern engineering structures. All the advantages offered by the curved geometry and thinness of the walls come even more to the fore when combined with exquisite properties of fiber-reinforced composite laminates. Directionally dependant material properties open vast possibilities for tailoring global structural properties and, therewith, optimization. Successful design of such structures calls for high performance shell type finite elements. This paper presents a linear triangular shell element based on the equivalent single-layer approach and the first-order shear deformation theory. The shear locking effect is resolved by the discrete shear gap (DSG) approach combined with the cell smoothing technique. To improve the element performance with respect to the membrane behavior, the assumed natural deviatoric strains (ANDES) formulation is applied, with necessary modifications to meet the requirements of curved structures with anisotropic material properties. Geometric nonlinearities are addressed by the co-rotational formulation. Examples demonstrate the element applicability and performance.

ABSTRACT: The main objective of this research work is focused on sound transmission loss analysis of corrugated core functionally graded material (FGM) sandwich plates filled with porous material, wherein two types of FGM sandwich structures are considered, which include one with FGM face sheets and homogeneous ceramic or metal core, and the other with FGM core and homogeneous face sheets. To model the process of sound propagation between fluid and solid, the equivalent fluid model with effective density and bulk modulus is used to describe the sound wave propagation through porous sound absorptive material. The corrugated cores are approximated as a series of uniformly distributed translational and rotational springs to link the sandwich structure. Fluid-structure coupling is considered by imposing velocity continuity condition at fluid-structure interfaces. By using the space harmonic approach and virtual work principle, the sound transmission loss is described analytically. The validity of the proposed theoretical model is verified by comparisons with previously published numerical results. Based on the developed theoretical model, the influences of the FGM properties, gradient index, sandwich type, skin-core-skin ratios and porous material type on sound transmission loss are subsequently presented.

ABSTRACT: In this paper, linear and nonlinear vibration analyses are carried out on flax fibre reinforced composites with and without an interleaved natural viscoelastic layer. Experimental analysis was done in a clamped-free configuration on two stacking sequences of composites, [0]_8 and [0_2/90_2]. The procedure consists
on exciting the specimens with different amplitude levels for the first six bending modes. The dynamic properties as frequencies and damping factors were studied, and the results obtained were analyzed and compared. Then, the amplitudes of deformations were determined and discussed for the different excitation levels. The presence of the non-linearity generated by the viscoelastic layer was clearly identified by the shift observed in the values of natural frequencies and loss factors with increasing excitation levels. The linear and nonlinear, elastic and dissipative parameters were calculated and compared.


ABSTRACT: Compared with conventional steel spiral reinforced concrete (SRC) or concrete filled fiber reinforced polymer tube (CFFT) columns, the fiber reinforced polymer (FRP) tube and inner steel spiral reinforcement (SR) dual-confined concrete hybrid columns (shortened as FRP-SR-concrete) showed higher load-bearing capacity and ductility in static compressive loading. In literature, very few studies have considered the dynamic behavior of FRP-SR-concrete columns under impact loading when using such hybrid structures under seismic-induced axial dynamic loading. This study investigated the axial impact behavior of carbon FRP-SR-concrete (CFRP-SR-concrete) columns subjected to a drop-weight impact test. The experimental parameters considered were CFRP tube thickness, the SR volumetric ratio, height and the weight of the impact hammer of the drop-weight test. The axial impact resistance of conventional CFFT and SRC columns was further used for a comparison. The test results showed that the CFRP-SR-concrete had higher dynamic impact load and better cracking resistance compared with the SRC or CFFT counterparts. The impact resistance of the CFRP-SR-concrete columns was enhanced with an increase in the CFRP tube thickness and the volumetric ratio of the SR. Additionally, numerical simulation was performed to predict the failure process and the impact resistance of the CFRP-SR-concrete columns.


ABSTRACT: An ultrathin film is flexible but tends to buckle when subjected to compression and temperature variation. The buckling behavior will adversely affect its mechanical performance, therefore, it should be accurately evaluated and under controlled. Accordingly, it is vital to study thermal buckling behavior of ultrathin films. In the present work, thermal buckling of bilayer graphene sheets (GSs) embedded in Pasternak-type foundations is studied based on the nonlocal elastic theory and classical plate theory (CLPT). We have examined three types of thermal distribution, namely linear, nonlinear and uniform temperature distributions through the thickness of GSs. The effects of boundary condition, aspect ratio, nonlocal parameter, elastic foundation parameter, geometric size, stacking types on the critical buckling temperature loads are investigated.


ABSTRACT: Filament wound hybrid composite pipes can expose to impact loading from various causes during their service life which can cause an invisible level of damage. Thus, revealing the effect of impact damage gains great importance to design hybrid composite pipes with enhanced damage tolerance. Based on this motivation, the low velocity impact (LVI) response of carbon/glass hybrid filament wound composite pipes has been studied. Hybrid pipes were produced with the winding angle of ±55° by using glass and carbon fiber layers
in various stacking sequences by filament winding method. The stacking sequence configurations were set as Carbon/Glass/Glass (CGG), Glass/Carbon/Glass (GCG) and Glass/Glass/Carbon (GGC). Before generating impact damage, an internal pressure of 32 bar was applied to the hybrid pipes in accordance with ANSI/AWWA C950 standard and pre-stress was generated in the pipes. Following, the hybrid pipes subjected to internal pressure were subjected to low velocity impact tests at energy levels of 5, 10, 15 and 20 J. The variation of contact force versus time, contact force versus displacement and energy versus time were obtained. After the testing, the effects of stacking sequence upon damage formation and damage progression under LVI loading have been evaluated based on the obtained data and microscopic analysis. It has been found that the damage formation such as matrix cracking on outer/inner surfaces, radial cracks, delamination, transfer cracks, splitting and leakage can take place. Moreover, the hybrid pipes with CGG stacking represents higher impact resistance while the GCG stacking has a better response of damage formation since this stacking does not show leakage damage.


ABSTRACT: Size-dependent vibrational behavior of functionally graded (FG) Timoshenko nano-beams is investigated by strain gradient and stress-driven nonlocal integral theories of elasticity. Hellinger-Reissner's variational principle is preliminarily exploited to establish the equations governing the elastodynamic problem of FG strain gradient Timoshenko nano-beams. Differential and boundary conditions of dynamical equilibrium of FG Timoshenko nano-beams, with nonlocal behavior described by the stress-driven integral theory, are formulated. Free vibrational responses of simple structures of technical interest, associated with nonlocal stress-driven and strain gradient strategies, are analytically evaluated and compared in detail. The stress-driven nonlocal model for FG Timoshenko nano-beams provides an effective tool for dynamical analyses of stubby composite parts of Nano-Electro-Mechanical Systems.


ABSTRACT: This paper investigates the nonlinear bending of graphene nanoplatelet (GPL) reinforced laminated composite quadrilateral plates using the element-free IMLS-Ritz method. The effective material properties including Young's modulus, mass density and Poisson's ratio are determined by the modified Halpin-Tsai model and rule of mixture. The first-order shear deformation theory (FSDT) and the IMLS-Ritz approximation are employed to obtain the discrete nonlinear governing equation of quadrilateral plates with large deformation. The Newton-Raphson method is used to solve the nonlinear equation. The accuracy of the IMLS-Ritz results is examined by comparing with the published values. A comprehensive parametric study is carried out, with a particular focus on the effects of geometric parameters of quadrilateral plates and GPLs distribution pattern, weight fraction, total number of layers, and geometry and size of GPLs on the nondimensional deflection of GPLs reinforced laminated composite quadrilateral plate.


ABSTRACT: Based on the first-order shear deformation and Donnell's shell theory with von Karman nonlinearity, one decoupled stability equation for buckling analysis of functionally graded (FG) and multilayered
cylindrical shells with transversely isotropic layers subjected to various cases of combined thermo-mechanical loadings is developed. To this end, the equilibrium equations are uncoupled in terms of the transverse deflection, the force function and a new potential function. Using the adjacent equilibrium method, one decoupled stability equation which is an eighth-order differential equation in terms of transverse deflection is obtained and conveniently solved to present analytical expressions for buckling loads of cylindrical shells under any type of loading. These analytical expressions can be used in design and as a benchmark in numerical studies. For numerical purpose, the formulation is applied to FG shells, a three-layer shell laminated of transversely isotropic layers, and sandwich shells with an isogrid lattice core and transversely isotropic face sheets. The results are validated with the existing ones in the literature. Finally, the effect of different parameters on the buckling loads in the presence of combined loadings is discussed in detail. Numerical results show that the existence of an initial hoop stress as a main type of initial imperfection has significant influence on the buckling behavior (including buckling values and mode shapes) of long cylindrical shells subjected to axial loading and this effect reduces for cylindrical shells with a lattice core. Furthermore, the critical values of torsion significantly reduce under combined loading.


ABSTRACT: The coupled effect of manufacturing uncertainty and a critical service-life damage condition (delamination) is investigated on the natural frequencies of laminated composite plates. In general, delamination is an unavoidable phenomenon in composite materials encountered often in real-life operating conditions. We have focused on the characterization of dynamic responses of composite plates considering source-uncertainty in the material and geometric properties along with various single and multiple delamination scenarios. A hybrid high dimensional model representation based uncertainty propagation algorithm coupled with layer-wise stochastic finite element model of composites is developed to achieve computational efficiency. The finite element formulation is based on Mindlin's theory considering transverse shear deformation. Numerical results are presented for the stochastic natural frequencies of delaminated composites along with a comprehensive deterministic analysis. Further, an inevitable effect of noise is induced in the surrogate based analysis to explore the effect of various errors and epistemic uncertainties involved with the system.


ABSTRACT: An improved layerwise theory is established for the bending and vibration responses of multi-layered functionally graded doubly curved shells with material properties varying gradually and continuously across the whole shell thickness. The theory accounts for shear deformation and normal strain effects by assuming for each layer, a displacement field with zigzag first-order in-plane displacements and through-the-thickness parabolic transverse displacement. Moreover, it is assumed a stress field satisfying the loading conditions on the external shell faces and the continuity conditions of the internal stresses at the layers interfaces, so, there is no need for introducing in the present formulation any shear correction factor. For this purpose, a mixed variational statement is used. The continuity conditions for the displacements at the layers interfaces are used to decrease the degrees of freedom of the theory. Bending and free vibration problems are solved for FGM single- and three-layered sandwich open cylindrical and spherical shells with completely simply supported or clamped edges. Comparisons for some present results with numerical results obtained by other authors due to advanced 2D and 3D elasticity solutions are made showing the high efficiency of the

ABSTRACT: Based on the nonlocal strain gradient theory (NLSGT), and various higher order shear deformation beam theories a formulation for buckling and free vibration of size dependent functionally graded sandwich micro-beams resting on two parameter elastic foundation including Winkler and Pasternak shear layer springs with thermal effects is presented. The sandwich FG micro-beams are assumed to be formed with homogenous ceramic core and ceramic-metal FG skins. According to the Mori-Tanaka homogenization scheme and the classical rule of mixture the material properties of the FG part of the sandwich size dependent beam changes continuously through the thickness of the beam. Equations of motion and the associated boundary conditions are derived via Hamilton's principle. Static buckling loads and natural frequencies are obtained by using generalized differential quadrature method (GDQM) for size dependent sandwich FG beam with different boundary conditions. As original contributions to the literature, the effects of the nonlocal parameter, the length scale parameter, aspect ratio, gradient index, different cross-section shapes, temperature change and stiffnesses of Winkler and shear layer springs, respectively on the buckling and free vibration of the sandwich FG micro-beam are investigated, reported and discussed in detail. To verify the present formulation present results (buckling and free vibration) are compared with the previously published results. Good agreement is observed between the present solutions and the previously published results. (There is math in the abstract that I have ignored. Please do not put math in abstracts!)


ABSTRACT: The paper introduces an analysis of flexural-torsional vibration and buckling of thin-walled bi-directional FG beams. Several cross sections have been conducted such as mono-symmetric I-shaped and channel sections in which material properties are assumed to vary across blade thickness and along axial direction. Governing equations and finite element model are developed. The model is capable of capturing all complex eigenvalue problems, also provides a highly accurate prediction of vibrational shapes and buckling capacity. Since the material changes, the obtained results reflect the relative relation between the behaviors of the beam and the transformation of internal properties, for example, Young's modulus, density, etc. Effects of gradient parameters on the vibrational frequencies or limit loads of a thin-walled bi-directional FG beam under various configurations and boundary conditions have also been parametrically studied.


ABSTRACT: Polyethylene (PE) pipes are widely used in gas transmission projects due to their excellent performances. Earthquake is destructive and difficult to predicted, which is one of the major disasters caused PE pipe failure. The study was conducted on the mechanical behaviors and failure mechanisms of buried PE pipes under fault movement, and the effects of gas pressure, fault dislocation, soil and pipe size on the mechanical behavior of PE pipes were discussed. The study indicates that gas pressure has a less effect on the mechanical behavior of PE pipe. Under faults, the flatness curve of PE pipe is distributed symmetrically with respect to the
fault plane. Deformation rules of PE pipe in different stratums are similar, while the pipe deformation is the largest in clay and it is smallest in sand. The greater the standard pipe size, the greater the diameter flatness coefficient is. The larger the diameter, the smaller the pipe diameter flattening parameter is. PE pipes with a larger standard dimension ratio of a fitting (SDR) and a smaller diameter are prone to failure in fault zone. The results can provide a basis for gas pipe design, laying, testing, and evaluation.


ABSTRACT: The paper is a continuation of [1] where the formulation of the elastic constitutive law for functionally graded materials (FGM) on the grounds of nonlinear 6-parameter shell theory with the 6th parameter (the drilling degree of freedom) was presented. Here the formulation is extended to the elasto-plastic range. The material law is based on J2 Cosserat plasticity and employs the well-known Tamura-Tomota-Ozawa (TTO) [2] mixture model with additional formulae for Cosserat material parameters. Formulation is verified by solving a set of demanding analyses of plates, curved and multi-branched shells, including geometry, thickness and material distribution variation parameter analyses.


ABSTRACT: This article investigates the effect of the magnetic field on the thermomechanical buckling and vibration of viscoelastic sandwich nanobeams in humid environment. The nanoscale beam is composed of a homogeneous core integrated with two functionally graded (FG) carbon nanotube (CNT) reinforced face sheets. The present sandwich nanobeam is subjected to in-plane compressive load as well as in-plane axial magnetic field and embedded in visco-Pasternak substrate that contains Kelvin-Voigt viscoelastic layer and Pasternak shear layer. The motion equations for the deformable sandwich nanobeam are deduced based on a shear and normal deformations beam theory incorporated with the modified couple stress theory that captures the size effect by involving a material length scale parameter. The present results are verified by comparing them with the previously published ones. Moreover, parametric studies have been performed to illustrate the impacts of material parameter, viscoelastic damping for the structure and the foundation, the magnetic field parameter, humidity concentration and other parameters on the buckling load and frequency of the FGCNT reinforced viscoelastic sandwich nanobeams.


ABSTRACT: In this study, the size and location of delamination effects to layered composites' mechanical properties in buckling behavior are inspected experimentally. Composite plates were produced in accordance with the different dimensions of delaminations and the positions between the layers. These plates consist in delamination rates of \( a/L = 0.3, 0.5, 0.7 \) (\( a \): Delamination width and \( L \): Buckling length). The specimens were subjected to buckling tests with placed on its two edges, while the others are free. In the experiments two results are considered. First, we determined load-displacement graphs. Critical buckling loads (Pcr) were determined from the obtained load-displacement graphs. Second, we acquire lateral displacements, which occurred with the effect of applied load in the delamination area in direction of plate thickness. By comparing Pcr with each other, an optimum delamination dimension was determined for composite materials with delamination zones. In the
applications, the negative effect on the mechanical properties due to delaminations can be seen, proportionally according to the delamination location.

ABSTRACT: In this study, the compressive properties and failure mode of reinforced composite skin structures having different delamination deficiencies were investigated systematically. Different kinds of delamination deficiencies were presented at specific locations in the specimens. The compressive mechanical properties of the materials were performed by axial compression testing, and strain distribution in different parts of the specimen and bearing capacity were monitored during the compressing processes. The ultimate compression bearing capacity, the failure mode and the expansion of internal damage were investigated as well. Results showed that the existence of delamination deficiencies have effects on the ultimate loading capacity of the specimens in different degree, in which the influence of delamination deficiencies in the skin is the most serious. Comparing with the specimen without deficiencies, the ultimate load-carrying capacity of the specimen with delamination deficiencies in the skin and in the stiffener under compressive load reduced by 38.58% and 22.34%, respectively. The failure modes of specimens with and without delamination deficiencies are similar. Compression failure is the main form of fracture for the stiffener, and the skin having different degree of buckling and delamination.

ABSTRACT: In this paper, a novel three-dimensional exact solution is performed for vibration analysis of thick functionally graded porous rectangular plates subject to arbitrary boundary conditions. The theoretical model is based on the three-dimensional elastic theory. Three kinds of porosity distributions including even, uneven and the logarithmic-uneven are performed. Non consideration boundary conditions, all displacements of the rectangular plate are unified expanded as a improve Fourier series, which consists of standard three-dimensional (3-D) Fourier cosine series supplemented with closed-form auxiliary functions introduced to eliminate all the relevant discontinuities with the displacements and its derivatives at the edges. As the displacement field is sufficiently smooth in the entire solution domain, the exact solution of the energy function of the plate is obtained through the Rayleigh Ritz process. The numerical examples are given to verify the accuracy and reliability of the present method, in which both the present results and those reported in the literature are provided. Besides, several numerous new results for thick FGP plates with elastic boundary conditions are also presented.

End of more papers published in the journal, Composites Part B Engineering (2017 and on).


ABSTRACT: A path-following method that is based on controlling plastic dissipation or plastic work in an inelastic solid or structure is presented. It can be effective for highly nonlinear materially and geometrically problems. In particular, it can be applied for elasto-plastic problems where the standard arc-length methods fail, or to avoid artificial and undesirable elastic unloading of a complete solid or structure during the computation. The essential ingredients, the plastic dissipation and the plastic work based constraint equations, are derived by using either explicit or implicit pseudo-time integration. These constraint equations are valid for geometrically nonlinear small strain elasto-plasticity with hardening. Their implementation in the framework of the path-following method is described. Several numerical examples are presented in order to illustrate very satisfying performance of the derived path-following method. It performed very well for some challenging shell problems.

References listed at the end of the paper:

ABSTRACT: Analysis using Cartesian background mesh with the geometry embedded or immersed in the mesh is gaining popularity. The primary advantage of this approach is that a traditional mesh, which conforms to the geometry, is not needed. Instead a background mesh that is independent of the geometry and has regular shaped undistorted elements is used because it is easy to generate automatically. Many methods for imposing Dirichlet boundary conditions on immerse boundaries have been studied. In this work step boundary method, where the trial and test functions are weighted using approximate step functions, has been used for imposing Dirichlet boundary conditions on boundaries that do not have nodes on them. This method has been shown to be effective for static problems in the past but has not been studied for dynamics. Step boundary method is extended to modal analysis and modal superposition as well as problems involving base excitation where the Dirichlet boundary conditions are functions of time. Several test examples are used to verify and validate the method.

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ABSTRACT: The principle of mass detection using carbon nanotube (CNT) resonators is based on the detection of the resonant frequency shift due to an attached mass. Although CNT resonators can easily show a
nonlinear oscillation behavior, there is a lack of studies on the influence of the design parameters and the nonlinear dynamic behavior on the detection sensitivity of CNT-based mass sensors. In addition, most of the finite element method (FEM) analysis models that are used to predict the resonant frequency shift due to attached masses have been implemented in the linear oscillation regime. In order to enhance the sensing performance of the CNT-based mass sensor, a parametric study of the resonant frequency shift is conducted herein with respect to the attached mass, the electrostatic force, the initial tension and the CNT length, using an FEM-based nonlinear analysis model. The FE model is applied to solve the nonlinear dynamic behavior of CNT resonators using direct time integration and the solution is verified by its comparison to the corresponding analytical solution that had been validated in previous studies. The analysis results of the nonlinear dynamic behavior of the CNT resonator indicate that the CNT length plays a key role in the detection sensitivity, and the amount of electrostatic force determines the linear or nonlinear oscillation behavior of the resonator. It is shown that the detection sensitivity can be improved using the nonlinear oscillation behavior and this improvement is more effective with longer CNTs. This study's results justify the possibility and validity of FEM use for the analysis of the nonlinear behavior of CNT resonators and elucidate the relationship between the design parameters and the nonlinear behavior of the CNT-based mass sensor in enhancing the sensing performance.

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ABSTRACT: This work presents a general formulation and implementation in solid-shell elements of the refined zigzag theory and the trigonometric shear deformation theory in an unified way. The model thus conceived is aimed for use in the analysis, design and verification of structures made of composite materials, in which shear strains have a significant prevalence. The refined zigzag theory can deal with composite laminates economically, adding only two nodal degrees of freedom, with very good accuracy. It assumes that the in-plane displacements have a piece-wise linear shape across the thickness depending on the shear stiffness of each composite layer. The trigonometric theory assumes a cosine variation of the transverse shear strain. A modification of this theory is presented in this paper allowing its implementation with $C^0$ approximation functions. Two existing elements are considered, an eight-node tri-linear hexahedron and a six-node triangular prism. Both elements use a modified right Cauchy-Green deformation tensor $C^\circ$ where five of its six components are linearly interpolated from values computed at the top and bottom surfaces of the element. The sixth component is computed at the element center and it is enhanced with an additional degree of freedom. This basic kinematic is improved with a hierarchical field of in-plane displacements expressed in convective coordinates. The objective of this approach is to have a simple and efficient finite element formulation to analyze composite laminates under large displacements and rotations but small elastic strains. The assumed natural strain technique is used to prevent transverse shear locking. An analytic through-the-thickness integration and one point integration on the shell plane is used requiring hourglass stabilization for the hexahedral element. Several examples are considered on the one hand to compare with analytical static
solutions of plates, and on the other hand to observe natural frequencies, buckling loads and the non-linear large displacement behavior in double curved shells. The results obtained are in a very good agreement with the targets used.

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ABSTRACT: In structural engineering, many problems present nonlinear behavior associated to a large number of sources, ranging from the presence of large displacements and large strains to the constitutive material behavior. The simulation of such complex structural systems with the finite element method often requires the use of analysis control schemes, called continuation methods. These schemes aim at depicting equilibrium paths, associated with system stiffness loss and to the occurrence of load and displacement limit points. Among them, the arc length and the strain control methods are very popular. However, under certain conditions, these methods either fail to provide the full system response or require a large number of iterations for convergence. In the present work, a continuation method with combined restrictions is proposed to provide the full system response in the presence of both geometric nonlinearities and material elasto-plastic softening. Two or more restrictions are combined resulting in a more robust scheme for the solution of the nonlinear system of equilibrium equations. Consistency of the extended system is reached through the least squares method. The efficiency of the combined control is compared to the application of the restrictions individually in a Newton-Raphson solution scheme. An automatic increment adaptation strategy for the control parameters is introduced which helps stabilize the incremental process with multiple restrictions. In the analysis of the highly non-linear problems studied in this paper, the proposed method with combined restrictions proves to be more robust than the standard procedure with single restrictions. In the cases where the single restrictions failed, the combined restriction was able to provide the full solution.

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ABSTRACT: This paper presents a new four-node quadrilateral finite element for composite plates. A large number of displacement-based, variable kinematics plate models are formulated in the framework of Carrera's Unified Formulation, which encompass Equivalent Single Layer as well as Layer-Wise models with a displacement field that is defined by polynomials up to 4th order along the thickness direction z. The main novelty consists in the formulation of a field compatible approximation for the transverse shear strain field, referred to as QC4 interpolation, which eliminates the shear locking pathology by constraining only the z–z– constant transverse shear strain terms. Extensive numerical studies are proposed that demonstrate the absence of spurious modes and of locking problems as well as the enhanced robustness with respect to distorted element shapes in comparison to classical isoparametric approaches. The new QC4 variable kinematics plate element displays excellent convergence rates under different boundary and loading conditions, and it yields accurate displacement and stresses for both, thick and thin composite plates.

ABSTRACT: In this paper, we present a new ANM continuation algorithm with a predictor based on a new Padé approximant and without the use of a correction process. The ANM is a numerical method to obtain the solution of a nonlinear problem as a succession of branches [1–7]. Each branch is represented by a vectorial series which is obtained by inverting only one tangent stiffness matrix. The series representation can be replaced by a rational representation which reduces the number of branches necessary to obtain the entire branch of desired solution. In this work, we discuss the use of a new vectorial Padé approximants in the ANM algorithm. In previous works [1, 2, 4, 5], the Padé approximants have been introduced after an orthonormalization of the terms of the vectorial series. In a recent article [8], we have demonstrated that the coefficients of the Padé approximants can be chosen in an arbitrary manner. For this purpose, we propose a new choice of vectorial Padé approximants at order $M$ which minimizes the relative error between two consecutive vectorial Padé approximants at order $M$ and at order $M−1$. This minimization has been made by a judicious choice of the coefficients of the Padé at order $M$ as a function of coefficients of the Padé approximants at order $M−1$ obtained by the classical process of Gram-Schmidt orthonormalization. A comparison of the obtained results with those computed by the use of classical Padé approximants is presented.


ABSTRACT: The deployment of a thin, one-segment, large membrane space structure is examined by the means of a real time quasi-static inflation experiment with photogrammetry and finite element analysis with the explicit and implicit schemes applied to control volume, corpuscular and arbitrary Lagrangian-Eulerian inflation methods. The numerical solutions comparison is based on mesh size, energy ratio, number of particles, bleed-through leak coefficient, fluid pressure - surface depth stiffness coupling, accuracy and computational efficiency. An optimization of the number of particles and minimization of the bleed-through effects is effectively implemented in corpuscular and ALE approaches. The corpuscular and arbitrary Lagrangian-Eulerian are found to be most resembling the experimental results in the dynamic shape changes and the time history of the gas properties, but computationally expensive. The control volume, although computationally efficient, is lacking the adequate fluid-structure interaction, thus less accurately recreating the overall dynamics of the morphing surface. Only 0.2%–1.75% and 0.5%–2.5% difference is observed between the experimental, analytical and finite element inflation results respectively.

References listed at the end of the paper:


ABSTRACT: This paper deals with a new approach using both the variable separation and a robust C⁰ eight-node finite element for the modeling of composite plates. The displacement field is approximated as a sum of separated functions of the in-plane coordinates x, y and the transverse coordinate z. This choice yields to an iterative process that consists of solving a 2D and 1D problem successively at each iteration. In the thickness direction, a fourth-order expansion in each layer is considered. For the in-plane description, the main novelty consists in the formulation of a field compatible approximation for the transverse shear strain field, referred to as the CL8 interpolation. This latter has to be adapted to the particular framework of the separated representation. It allows us to eliminate the shear locking pathology by constraining only the z-constant transverse shear strain terms. Numerical assessments show the absence of locking problems as well as the enhanced robustness with respect to distorted element shapes in comparison to classical isoparametric approaches. This new CL8 plate element provides excellent convergence rates under different boundary and
loading conditions, and it yields accurate displacements and stresses for both thick and thin composite and sandwich plates.


ABSTRACT: This paper presents topology optimization of viscoelastic damping layers attached to shell structures for attenuating the amplitude of transient response under dynamic loads. The transient response is evaluated using an implicit time integration scheme. Dynamic performance indices are defined to measure the transient response. In the optimization formulation, three different types of the performance indices are considered as the objective function. The density-based topology optimization scheme is applied to find the optimal distribution of the viscoelastic material. The artificial densities of the shell elements of the viscoelastic layers are taken as the design variables. The constraint is the maximum volume fraction of the viscoelastic material. A sensitivity analysis method of the transient response is developed based on the adjoint variable method. Several numerical examples are presented to demonstrate the validity of the proposed method. The transient responses of the optimized structures are compared to those of the uniformly distributed structures to show the effectiveness of the proposed method. Also, the influences of the performance indices are discussed.


ABSTRACT: This paper deals with certain aspects related to the dynamic behaviour of isotropic shell-like structures analysed by the use of a higher order transversely deformable shell-type spectral finite element newly formulated and the approach known as the Time-domain Spectral Finite Element Method (TD-SFEM). Although recently this spectral approach is reported in the literature as a very powerful numerical tool used to solve various wave propagation problems, its properties make it also very well suited to solve static and dynamic modal problems. The robustness and effectiveness of the current spectral approach has been successfully demonstrated by the authors in the case of thin-walled spherical shell structures through a series of numerical tests comprising the analysis of natural frequencies and modes of vibration of an isotropic spherical shell as well as the wave propagation analysis in the case of the same spherical shell and a half-pipe shell-like structure.


ABSTRACT: This study deals with the development of a new solid-shell element using the Cosserat point theory for the linear and nonlinear analysis of laminated elastic structures. Generally speaking, the Cosserat point approach considers the element as a structure with a strain energy function that characterizes its response. This strain energy function is additively decomposed into two parts, where the first part depends on an average measure of the deformation and the second part, which is referred to as the inhomogeneous strain energy, controls the element's response to any inhomogeneous deformation. Due to the coupling nature between homogeneous and inhomogeneous deformation in laminated structures, the inhomogeneous strain energy is further additively decomposed into two parts. The first part quadratically depends on the inhomogeneous strain measures, while the second part accounts for the coupling between the homogeneous and inhomogeneous deformations. In the present study, a methodology for the determination of the constitutive coefficients for the two parts of the inhomogeneous strain energy function is presented. The resulting constitutive coefficients
ensure an accurate modeling of the inhomogeneous deformations and also ensure that the element has a control on all the inhomogeneous modes of the deformation. Both linear and nonlinear example problems are considered, which demonstrate that the developed laminated Cosserat point element (LSSCPE) is accurate, efficient, robust, and applicable in modeling laminated structures with one element through the structure's thickness.


ABSTRACT: The classic snap-through problem of shallow arches is revisited using the so-called generalised path-following technique. Classical buckling theory is a popular tool for designing structures prone to instabilities, albeit with limited applicability as it assumes a linear pre-buckling state. While incremental-iterative nonlinear finite element methods are more accurate, they are considered to be complex and costly for parametric studies. In this regard, a powerful approach for exploring the entire design space of nonlinear structures is the generalised path-following technique. Within this framework, a nonlinear finite element model is coupled with a numerical continuation solver to provide an accurate and robust way of evaluating multi-parametric structural problems. The capabilities of this technique are exemplified here by studying the effects of four different parameters on the structural behaviour of shallow arches, namely, mid span transverse loading, arch rise height, distribution of cross-sectional area along the span, and total volume of the arch. In particular, the distribution of area has a pronounced effect on the nonlinear load-displacement response and can therefore be used effectively for elastic tailoring. Most importantly, we illustrate the risks entailed in optimising the shape of arches using linear assumptions, which arise because the design drivers influencing linear and nonlinear designs are in fact topologically opposed.

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ABSTRACT: In the present work, elastic stability analysis of curved nanobeams is investigated using the differential constitutive law consequent to Eringen's strain-driven integral model coupled with a higher-order shear deformation theory accounting for through thickness stretching effect. The formulation developed here is general in the sense that it can be deduced to realise the influence of different structural theories and analyses of nanobeams. The governing equations derived are solved employing finite element method using a 3-nodes curved beam element. The model developed here is validated considering problems for which analytical/numerical solutions are available in the literature. For comparison purpose, results are also presented for various structural theories obtained from the present formulation. The influence of structural and material parameters such as thickness ratio, beam length, rise of the curved beam, boundary conditions, and size-dependent or nonlocal parameter are brought out on the buckling behaviours of curved nanobeams. It is observed that the type of buckling mode pertaining to the lowest critical value can be different depending on geometrical and internal material length scale parameter, and boundary conditions.


ABSTRACT: A new hyperelastic material model is proposed for graphene-based structures, such as graphene, carbon nanotubes (CNTs) and carbon nanocones (CNC). The proposed model is based on a set of invariants obtained from the right surface Cauchy-Green strain tensor and a structural tensor. The model is fully nonlinear and can simulate buckling and postbuckling behavior. It is calibrated from existing quantum data. It is implemented within a rotation-free isogeometric shell formulation. The speedup of the model is 1.5 relative to the finite element model of Ghaffari et al. [1], which is based on the logarithmic strain formulation of Kumar and Parks [2]. The material behavior is verified by testing uniaxial tension and pure shear. The performance of the material model is illustrated by several numerical examples. The examples include bending, twisting, and wall contact of CNTs and CNCs. The wall contact is modeled with a coarse grained contact model based on the Lennard-Jones potential. The buckling and post-buckling behavior is captured in the examples. The results are compared with reference results from the literature and there is good agreement.


ABSTRACT: Mechanically lined pipe consists of a load bearing carbon steel outer pipe with a thin corrosion resistant alloy (CRA) liner and is a proven and economical solution for oil and gas pipelines. The bond between the two pipes is purely mechanical and under large bending loads plastic deformation of the liner results in non-reversible liner wrinkling. This wrinkling impedes flow and significantly reduces the performance of the pipeline. This study uses non-linear finite element techniques to describe the wrinkling of lined pipe under pure bending and examines the effect of initial material stresses and contact surface friction. This model is then used to test a design failure criterion equation of DNV GL for design of mechanically lined pipelines. In single directional bending to failure the DNV GL failure criterion proves to be conservative in predicting the onset of liner wrinkling for all initial conditions and pipe geometries tested. Under low cycle repeated loading the safety factor in the predicted DNV GL failure curvature is sensitive to the magnitude of initial pre-stress. The results
presented herein provide evidence that the magnitude of initial material pre-stress in mechanically lined pipe needs to be considered in designing the CRA lined pipeline even at relatively low curvatures.


ABSTRACT: Thin-walled shells of revolution under circumferentially uniform pre-buckling stress states are important fundamental systems, often serving as reference ‘base cases’ to which the behaviour of more complex unsymmetrical systems can be related. However, the same simplicity that often permits closed-form algebraic expressions for the critical buckling load is also often responsible for a lack of localisation and significant ambiguity in the critical buckling mode. The computation of the linear or nonlinear buckling loads requires the systematic trial of many potential buckling modes to identify the one which minimises the necessary strain energy. In times when researchers used custom-written tools usually based on circumferential Fourier series expansions, this operation was relatively straightforward. However, today’s analysts using ‘general’ commercial 3D finite element packages must apply careful safeguards to correctly identify the correct buckling load and associated mode in axisymmetric shell systems. This paper presents a detailed computational strategy to accurately and efficiently investigate the correct buckling load and mode number of axisymmetric shell systems using the technique of a ‘panel analysis’. This is implemented in the ABAQUS finite element solver controlled by the SIMULIA Isight automation software and the Python object-oriented programming language. The methodology is illustrated on three classical benchmark problems from the scientific literature on the buckling of cylindrical shells under meridional compression, with special attention given to meshing considerations.

References listed at the end of the paper:

ABSTRACT: In this paper, a prismatic solid is developed. The element is intended to the analysis of shells during forming process and consolidation stage. To correctly perform the simulation of this step, the
proposed element provides an accurate calculation of stress/strain through the thickness. The bending stiffness of the element is based on the formulation of a DKT plate element which leads to good numerical efficiency. An additional degree of freedom at the center of the element, allows at the same time, the use of a complete 3D constitutive law, to avoid the thickness locking and a variation of the normal stress in the thickness which makes it possible to check the load boundary conditions on the upper and lower surfaces. This is very important for process simulation, and in particular for consolidation. A set of examples shows the good precision of the proposed element in many of the classical shell tests and its ability to calculate with accuracy the normal strain/stress in thickness.


**ABSTRACT:** Thin-walled shells of revolution under circumferentially uniform pre-buckling stress states are important fundamental systems, often serving as reference ‘base cases’ to which the behaviour of more complex unsymmetrical systems can be related. However, the same simplicity that often permits closed-form algebraic expressions for the critical buckling load is also often responsible for a lack of localisation and significant ambiguity in the critical buckling mode. The computation of the linear or nonlinear buckling loads requires the systematic trial of many potential buckling modes to identify the one which minimises the necessary strain energy. In times when researchers used custom-written tools usually based on circumferential Fourier series expansions, this operation was relatively straightforward. However, today's analysts using 'general' commercial 3D finite element packages must apply careful safeguards to correctly identify the correct buckling load and associated mode in axisymmetric shell systems.

This paper presents a detailed computational strategy to accurately and efficiently investigate the correct buckling load and mode number of axisymmetric shell systems using the technique of a ‘panel analysis’. This is implemented in the ABAQUS finite element solver controlled by the SIMULIA™ Isight automation software and the Python object-oriented programming language. The methodology is illustrated on three classical benchmark problems from the scientific literature on the buckling of cylindrical shells under meridional compression, with special attention given to meshing considerations.

(No appropriate papers in January or February 2019)

**End of more papers published in the journal, Finite Elements in Analysis and Design (2017 and on).**

**More papers published in the journal, Computer Methods in Applied Mechanics and Engineering (2017 and on):**
http://www.sciencedirect.com/science/journal/00457825

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ABSTRACT: This paper investigates the impact responses of carbon nanotube (CNT) reinforced functionally graded composite cylindrical shells. The effective material properties of the CNT-reinforced composite cylindrical shell are modeled by the extended rule of mixture. Reddy’s high-order shear deformation theory is employed in the modeling, in which thermal effects are taken into account. In order to simulate the contact load, a linearized contact law is used to obtain a linearized contact coefficient. Fourier series expansion and Laplace transforms are utilized during the solving process. The analytical expression of transverse displacement is furnished, and the impact responses of CNT-reinforced composite cylindrical shell are analyzed. From the numerical results, it is observed that the amplitude of the impact responses of FG-X CNT-reinforced composite cylindrical shell is lower than that of the shell with FG-O and UD CNT-distributions. The increase in CNT volume fraction reduces the amplitude of the impact response. Meanwhile, temperature change affects both the material properties and stiffness of the structure. It is also observed that with an increased temperature, the impact amplitude of the cylindrical shell increases.

References listed at the end of the paper:

ABSTRACT: In this paper we show how to significantly improve the robustness and the efficiency of the Newton method in geometrically non-linear structural problems discretized via displacement-based finite elements. The strategy is based on the relaxation of the constitutive equations at each integration point. This leads to an improved iterative scheme which requires a very low number of iterations to converge and can withstand very large steps in step-by-step analyses. The computational cost of each iteration is the same as the original Newton method. The impressive performances of the proposal are shown by many numerical tests. In geometrically non-linear analysis, the proposed strategy, called MIP Newton, seems worthy to replace the standard Newton method in any finite element code based on displacement formulations. Its implementation in existing codes is very easy.

References listed at the end of the paper:


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ABSTRACT: This paper uses a divergence-conforming B-spline fluid discretization to address the long-standing issue of poor mass conservation in immersed methods for computational fluid-structure interaction (FSI) that represent the influence of the structure as a forcing term in the fluid subproblem. We focus, in particular, on the immersogeometric method developed in our earlier work, analyze its convergence for linear model problems, then apply it to FSI analysis of heart valves, using divergence-conforming B-splines to discretize the fluid subproblem. Poor mass conservation can manifest as effective leakage of fluid through thin solid barriers. This leakage disrupts the qualitative behavior of FSI systems such as heart valves, which exist specifically to block flow. Divergence-conforming discretizations can enforce mass conservation exactly, avoiding this problem. To demonstrate the practical utility of immersogeometric FSI analysis with divergence-conforming B-splines, we use the methods described in this paper to construct and evaluate a computational model of an in vitro experiment that pumps water through an artificial valve.


ABSTRACT: In this article we present advanced computational models of the respiratory system with a special focus on approaches that are able to tackle the interaction between flow and tissue components which is necessary to accurately represent the underlying physics of the lung. We review complexity of this new generation of so-called coupled models and present strategies for sensible and target-oriented dimensional reduction. From this inherent complexity it becomes clear that there is no “one-size-fits-all” approach in the modelling of respiratory mechanics but one has to choose from a variety of different concepts to solve the problem at hand. We present four suitable coupled approaches introducing their underlying modelling idea and assumptions, their novelty against previous methods, possible scenarios of application, and limitations in a clinical practice. The quality of presented lung models is extended via regional validation against clinical measurements. This validation is performed using temporal highly resolved electrical impedance tomography monitoring. This detailed and for the first time dynamic regional validation generates further trust in the presented mathematically derived approaches. Finally the article closes with further steps towards simulation of gas exchange and local lung perfusion as the ultimate goal of respiratory modelling when ventilation is sufficiently understood.

A. Frikha and F. Dammak (Mechanical Modeling and Manufacturing Laboratory (LA2MP), National School of Engineers of Sfax, B.P 1173-3038, Sfax, University of Sfax, Tunisia), “Geometrically non-linear static analysis
https://doi.org/10.1016/j.cma.2016.10.017

ABSTRACT: A general shell model, including both theories of thin and thick shells, Kirchhoff–Love and Reissner–Mindlin undergoing finite rotations is presented. Based on Higher-order shear theory, where the fiber is cubic plane, the developed model does not need any transverse shear coefficients. The implementation is applicable to the analysis of isotropic and functionally graded shells undergoing fully geometrically nonlinear mechanical response. Material properties of the shells are assumed to be graded in the thickness direction according to a simple power-law and sigmoid distribution. The accuracy and overall robustness of the developed shell element are illustrated through the solution of several non trivial benchmark problems taken from the literature. The effect of the material distribution on the deflections and stresses is analyzed.


ABSTRACT: This paper presents a general non-linear computational formulation for rotation-free thin shells based on isogeometric finite elements. It is a displacement-based formulation that admits general material models. The formulation allows for a wide range of constitutive laws, including both shell models that are extracted from existing 3D continua using numerical integration and those that are directly formulated in 2D manifold form, like the Koiter, Canham and Helfrich models. Further, a unified approach to enforce the $G^1$-continuity between patches, fix the angle between surface folds, enforce symmetry conditions and prescribe rotational Dirichlet boundary conditions, is presented using penalty and Lagrange multiplier methods. The formulation is fully described in the natural curvilinear coordinate system of the finite element description, which facilitates an efficient computational implementation. It contains existing isogeometric thin shell formulations as special cases. Several classical numerical benchmark examples are considered to demonstrate the robustness and accuracy of the proposed formulation. The presented constitutive models, in particular the simple mixed Koiter model that does not require any thickness integration, show excellent performance, even for large deformations.

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ABSTRACT: We present an isogeometric thin shell formulation for multi-patches based on rational splines over hierarchical T-meshes (RHT-splines). Nitsche’s method is employed to efficiently couple the patches. The RHT-splines have the advantages of allowing a computationally feasible local refinement, are free from linear dependence, possess high-order continuity and satisfy the partition of unity and non-negativity. In addition, the C1 continuity of the RHT-splines avoids the rotational degrees of freedom. The good performance of the present method is demonstrated by a number of numerical examples.

References listed at the end of the paper:


clamped and cantilevered boundary conditions are found. It is shown that selecting the correct fiber orientation investigated. The optimum fiber orientations for CNT formulation of the plate is based on Reddy’
reinforced functionally graded composite skew plates using the isogeometric analysis is performed. The

ABSTRACT: A first attempt to investigate bending and vibration behaviors of carbon nanotube (CNT) reinforced functionally graded composite skew plates using the isogeometric analysis is performed. The formulation of the plate is based on Reddy’s higher order shear deformation theory (HSDT). The effect of CNT orientation angle on the mechanical behavior of CNT-reinforced composite plates with varying skew angles is investigated. The optimum fiber orientations for CNT-reinforced composite skew plates with simply supported, clamped and cantilevered boundary conditions are found. It is shown that selecting the correct fiber orientation

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ABSTRACT: A first attempt to investigate bending and vibration behaviors of carbon nanotube (CNT) reinforced functionally graded composite skew plates using the isogeometric analysis is performed. The formulation of the plate is based on Reddy’s higher order shear deformation theory (HSDT). The effect of CNT orientation angle on the mechanical behavior of CNT-reinforced composite plates with varying skew angles is investigated. The optimum fiber orientations for CNT-reinforced composite skew plates with simply supported, clamped and cantilevered boundary conditions are found. It is shown that selecting the correct fiber orientation
angle is of crucial importance in obtaining the desired static and dynamic responses of CNT-reinforced composite skew plates.

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ABSTRACT: This paper is devoted to the study of a micro–macro LaTIn-based Domain Decomposition Method for which the partitioning, the geometry and the boundary conditions play a major role in the number of iterations to convergence and in the scalability. To confront these obstacles, an analysis of the macroscopic space and of the search direction—two parameters of the strategy—is proposed for traction, bending and buckling examples. Then, we propose a new search direction which takes into account the global stiffness of the structure and that limits the need to enrich the macroscopic space. This choice leads to a minimal number of iterations, a reduced computation time and the scalability of the strategy. The enhanced parameter is then applied to the simulation of combined buckling and delamination of a composite 3D plate.

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ABSTRACT: This paper presents a Fourier-related double scale analysis to study the instability phenomena of sandwich plates. By expanding the displacement field into Fourier series, the sandwich plate model proposed by Yu et al. (2015), using the classical plate theory in the skins and high-order kinematics in the core, is transformed into a new Fourier-based reduced two-dimensional sandwich plate model with the slowly varying Fourier coefficients as macroscopic unknowns. The resulting nonlinear equations are solved by the Asymptotic Numerical Method (ANM), which is very efficient and reliable to capture the bifurcation point and the post-buckling path in wrinkling analyses. Both antisymmetrical and symmetrical wrinkling for sandwich plates under uni-axial and equi-biaxial compressive loads are studied and the numerical results demonstrate that the Fourier-based finite element model can accurately yet efficiently predict wrinkling patterns and critical loads, especially when dealing with wrinkling phenomena with extremely large wavenumbers.

ABSTRACT: The paper is to develop stochastic isogeometric analysis for the free vibration of functionally graded plates with spatially varying random material properties. The isogeometric analysis method is employed in the new stochastic analysis scheme which is called Stochastic IsoGeometric Analysis (SIGA). The elastic modulus and mass density are modeled as homogeneous Gaussian random fields along the plane of structure. The governing equation of stochastic isogeometric analysis for free vibration of functionally graded plates is derived in conjunction with perturbation expansions to predict the first and second moments of eigenvalues. In order to verify proposed method, the brute force Monte Carlo simulation is employed. The mean, variance, and COV (Coefficient of Variation) predicted by SIGA and those predicted by Monte Carlo simulation show good agreement. The numerical examples demonstrate that the randomness of material properties affects significantly the structural responses of the functionally graded plates. The correlation between elastic modulus and mass density is also observed to have significant effect on the response COV of eigenvalue.

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ABSTRACT: As a first endeavor, the aeroelastic responses of functionally graded carbon nanotube reinforced composite (FG-CNTRC) truncated conical curved panels subjected to aerodynamic load and axial compression are investigated. The nonlinear dynamic equations of FG-CNTRC conical curved panels are derived according to Green’s strains and the Novozhilov nonlinear shell theory. The aerodynamic load is estimated in accordance with the quasi-steady Krumhaar’s modified supersonic piston theory by taking into account the effect of the panel curvature. Matrix transform method along with the harmonic differential quadrature method (HDQM) are employed to solve the nonlinear equations of motion of the FG-CNTRC truncated conical curved panel. The advantage of the matrix transform method is that we only need to discretize the meridional direction. Effects of semi-vertex angle of the cone, subtended angle of the panel, boundary conditions, geometrical parameters, volume fraction and distribution of CNT, and Mach number on the aeroelastic characteristics of the FG-CNTRC conical curved panel are put into evidence via a set of parametric studies and pertinent conclusions are outlined. The results prove that the panels with different FG distributions have different critical dynamic pressure. It is found that the semi-vertex and subtended angles play a pivotal role in changing the critical circumferential mode number of the flutter instability. Besides, the research shows that the superb efficiency of proposed method with few grid points, which requires less CPU time, are attributed to the matrix transform method and the higher-order harmonic approximation function in the HDQM.

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ABSTRACT: This paper deals with the large amplitude vibration of functionally graded graphene-reinforced composite laminated plates resting on an elastic foundation and in thermal environments. The temperature-dependent material properties of piece-wise functionally graded graphene-reinforced composites (FG-GRCs) are assumed to be graded in the thickness direction of a plate, and are estimated through a micromechanical model. Based on a higher-order shear deformation plate theory, the motion equations are developed with geometric nonlinearity taking the form of von Kármán strains. The plate–foundation interaction and thermal effects are also included. The motion equations are then solved by a two-step perturbation technique to determine the nonlinear frequencies of the FG-GRC laminated plates. The numerical illustrations concern the nonlinear vibration characteristics of FG-GRC laminated plates under different sets of thermal environmental conditions, from which results for uniformly distributed GRC laminated plates are obtained as comparators. The effects of distribution type of reinforcements, temperature variation, foundation stiffness and different in-plane boundary conditions are also investigated.

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ABSTRACT: Laminated composites are prone to delamination failure due to the lack of reinforcement through the thickness. Therefore, during the design process the initiation and propagation of delaminations should be accounted for as early as possible. This paper presents computationally efficient nine degree-of-freedom (dof) and eight-dof shear locking-free beam elements using the mixed form of the refined zigzag theory (RZT(m)). The corresponding nine-dof and eight-dof elements use the anisoparametric and constrained anisoparametric interpolation schemes, respectively, to eliminate shear locking in slender beams. The advantage of the present element over previous RZT beam elements is that no post-processing is required to accurately model the transverse shear stress while maintaining the computational efficiency of a low-order beam element. Comparisons with high-fidelity finite element models and three-dimensional elasticity solutions show that the elements can robustly and accurately predict the displacement field, axial stress and transverse shear stress through the thickness of a sandwich beam or a composite laminate with an embedded delamination. In fact, the accuracy and computational efficiency of predicting stresses in laminates with embedded delaminations make the present elements attractive choices for RZT-based delamination initiation and propagation methodologies available in the literature.

ABSTRACT: New basis functions were developed for isogeometric analysis (IGA) to overcome the difficulties of IGA using NURBS (Non-Uniform Rational B-Splines) on coping with Dirichlet boundary conditions. The new basis functions were constructed through nesting rational local Lagrange interpolations like the T-split and were evaluated in similar procedure as the finite difference method. Explicit expressions for the new basis functions were presented. Due to their equivalence to the NURBS, the new basis functions were named as non-uniform rational Lagrange (NURL) basis. IGA using NURL includes the finite element method as a special case but the geometry in IGA using NURL is exact. IGA using NURL can carry out pp-refinement that has the nesting feature of the kk-refinement of NURBS. Dirichlet boundary conditions can be directly imposed in IGA using NURL because the NURL are interpolation basis functions. A method of directly transforming the tensor product basis of triangular patches to area coordinates was presented and the singularity problem at the edge degenerated to a single point was solved. The methods developed in this work were applied to in-plane and flexural vibration of thin plates. Comparisons with available results in literatures showed the fast convergence and high accuracy of IGA using NURL and the transformation method for triangular patches. Introduction of a MATLAB toolbox of the NURL was appended.


ABSTRACT: Two novel hierarchic finite element formulations for geometrically nonlinear shell analysis including the effects of transverse shear are presented. Both methods combine a fully nonlinear Kirchhoff–Love shell model with hierarchically added linearized transverse shear components. Thus, large rotations can be taken into account while circumventing the peculiar task of finding a corresponding parametrization of the rotation tensor. The two formulations differ in the way the transverse shear effects are included, either using hierarchic rotations or hierarchic displacements. The underlying assertion is that in most practical applications the transverse shear angles are small even for large deformations. This is confirmed by various numerical experiments. The hierarchic construction results in an additive strain decomposition into parts resulting from membrane and bending deformation and additional contributions from transverse shear. It requires at least \( C^1 \)-continuous shape functions, which can be easily established within the isogeometric context using spline based finite elements. As reported earlier, this concept is intrinsically free from transverse shear locking. In the nonlinear case it dramatically facilitates representation of large rotations in shell analysis.

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“Calibration of developed nonlocal anisotropic shear deformable plate model for uniaxial instability of 3D metallic carbon nanosheets containing interlocking hexagonal

ABSTRACT: In comparison with semiconducting carbon structures, the metallic carbon exhibits more novel properties due to their high density of states as well as superconductivity. As a result, prediction of mechanical properties associated with three-dimensional (3D) carbon structures is very attractive. In this paper, the size-dependent nonlinear uniaxial instability of 3D metallic carbon nanosheets containing interlocking hexagonal
carbon bonds is investigated based on a novel calibrated nonlocal anisotropic plate model. To accomplish this purpose, Eringen’s nonlocal continuum elasticity is incorporated to an exponential shear deformation plate theory. To extract the proper value of nonlocal parameter, the critical buckling loads and associated postbuckling equilibrium curves obtained by the established size-dependent plate model are compared with those of molecular dynamics (MD) simulations corresponding to various nanosheet side lengths and different boundary conditions. It is displayed that the calibrated nonlocal plate model with the proposed proper value of nonlocal parameter equal to 1.12 nm for fully simply supported edge supports and 1.26 nm for fully clamped edge supports has a very good capability to anticipate accurately both of the buckling and postbuckling characteristics of the uniaxially loaded 3D metallic carbon nanosheets.

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ABSTRACT: This study presents analysis on the vibration behavior of the two-dimensional functionally graded (2D-FG) nano and microbeams which are made of two kinds of porous materials for the first time, based on Timoshenko beam theory. The material of the nano and microbeams is modeled as 2D-FGMs according to the power law. The Eringen’s nonlocal elasticity and the modified couple stress theories are used, respectively in case of nano and microbeams. The boundary conditions are considered as clamped (CC), simply supported (SS), clamped–simply supported (CS), and cantilever (CF). The governing equations are solved using the generalized differential quadrature method (GDQM). The effects of FG power indexes along length and thickness are studied along each other and also exclusively. The parametric studies are presented for functionally graded along thickness (FG), functionally graded along length (AFG) and 2D-FG, porous and perfect, micro/nanobeams under different boundary conditions.

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ABSTRACT: In this paper, a practical and robust Riks-like path following method is developed to automatically trace the nonlinear equilibrium path for initial-finite-strain-induced snap-through phenomena in soft solids. The deformation gradient is decomposed into an elastic part and an initial-strain part, where the initial strain is characterized through a prescribed pattern tensor and an unknown strain factor describing the magnitude. In the non-linear finite element (FE) solution scheme, an equivalent body force proportional to the increment of the strain factor is derived, which varies in each iteration step due to its dependence on deformed configuration and stress. Both the displacement and the strain factor increments are introduced as unknowns in the linearized equation, which permits to predict the critical equilibrium states before and after the snap-through. Several examples with various configurations and strain histories are constructed, including multilayer beams and film-substrate systems, which demonstrate the effectiveness and robustness of the algorithm to capture the strain-induced snap-through phenomena.


ABSTRACT: Due to axisymmetric fundamental vibrational mode shape, the most studies on the large-amplitude free vibration of annular plates have been presented based on the axisymmetric formulation. However, the initial thermal loading can change the vibration behavior of annular plates. To analyze this effect, the nonlinear free vibration of carbon nanotube (CNT) reinforced composite annular plates is investigated under thermal loading based on the asymmetric formulation. The material properties of the CNT-reinforced composites are assumed to vary continuously along the thickness direction and estimated through a micromechanical model by which the temperature-dependency is taken into account. The governing equations are derived on the basis of first-order shear deformation theory, and an efficient numerical variational method is employed to solve the problem. In this regard, the quadratic form of the energy functional is directly discretized using numerical differential and integral operators, and the pseudo-arc length continuation method is then applied to find the frequency response of the structure. The numerical results of asymmetric and axisymmetric formulations are compared and it is observed that in the presence of initial thermal loading, the axisymmetric analysis leads to inaccurate results and complete asymmetric formulation should be considered.


ABSTRACT: An equivalent continuum model for multilayer graphene sheets (MLGSs) and its plate model are developed to analyze the deformation behavior of MLGSs. Hyperelastic material models are introduced for the MLGS continuum model by examining the atomistic structures of MLGSs and obtaining their mechanical properties by means of molecular statics simulations. The MLGS plate model, a structural model for MLGSs, is developed by applying kinematics assumptions to the MLGS continuum model subjected to infinitesimal deformation. Finite element methods (FEM) with the corotational formulation are adopted to analyze the mechanical behavior of MLGSs under small-strain deformation and large rotation conditions. The MLGS plate element passes several basic numerical tests, including patch tests, eigenvalue analyses, and geometrically nonlinear benchmark problems. Finally, the deflections of a plane-strain cantilever and spherical indentations
are analyzed by the proposed MLGS plate element and molecular dynamics (MD) simulations. These results show that the MLGS plate element properly represents the deformation behaviors of MLGSs from the atomic scale to the macroscopic continuum scale.

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ABSTRACT: We examine the aeroelastic behavior of a cylindrical nanocomposite (i.e. CNT-reinforced composite) shell in a supersonic airflow under thermal environments. Meanwhile, using piezoelectric materials, active flutter control of the cylindrical nanocomposite shell is conducted. Reddy’s high-order shear deformation theory is applied in the structural modeling, and the displacement fields of piezoelectric patches are derived according to the geometrical deformation relationship. The partial differential equation of motion is formulated by way of Hamilton’s principle and then is discretized by the assumed mode method. The active controller is designed by the displacement feedback and linear quadratic regular (LQR) methods. The aerothermoelastic properties of the cylindrical shell are analyzed using the frequency-domain method. The flutter bounds of the cylindrical shell are computed using the third-order shear deformation theory (TSDT), and the first-order shear deformation theory (FSDT) is compared in order to verify the necessity of the high-order shear deformation theory in the vibration analysis of thick nanocomposite structures. The influences of temperature change, CNT distribution and CNT volume fraction on the aeroelastic stability of the nanocomposite cylindrical shell are investigated. The active flutter control effects of different control methods are performed. The influence of thickness of the cylindrical shell on the flutter control effects is examined.


ABSTRACT: This paper presents a flexible method for coupling NURBS patches in isogeometric Kirchhoff–Love shell analysis. The required C1-continuity in such a shell formulation significantly complicates the patch coupling (as compared to typical C0-cases). In the present work, the C0-part of the coupling is a global coupling in a weak sense, whereas the C1-continuity is enforced by a strong point-wise coupling in well-chosen collocation points along the interface. The coupling conditions can be derived using only mesh information, without the need for suitable penalty or stabilisation parameters. They are expressed using a master–slave formulation between the interface variables. A static condensation approach to enforce these continuity constraints results in a reduced system matrix. The proposed method can be employed for both conforming and non-conforming patch configurations, and for G1-continuous structures as well as for patches meeting at a kink. This is demonstrated for a set of problems of (dynamic) shell analysis, including both eigenvalue and boundary-value problems.
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ABSTRACT: We present an isogeometric collocation formulation for the Reissner–Mindlin shell problem. After recalling the necessary basics on differential geometry and the shell governing equations, we show that the standard approach of expressing the equilibrium equations in terms of the primal variables is not a suitable way for shells due to the complexity of the underlying equations. We then propose an alternative approach, based on a stepwise formulation, and show its numerical implementation within an isogeometric collocation framework. The formulation is tested successfully on a set of benchmark examples, which comprise important aspects like locking and boundary layers. These test show that locking effects can be conveniently avoided by using high polynomial degrees. An accompanying study on the computational time also confirms that high polynomial degrees are preferable in terms of computational efficiency.

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ABSTRACT: For error-free computation of higher-order derivatives of a complex mathematical expression composed of elementary functions, hyper-dual numbers (HDNs) are receiving close attention in computational engineering and sciences. Differently from conventional finite differences, HDNs numerically evaluate, for instance, the exact first-order and second-order derivatives of the stiffness matrix with respect to nodal degrees-of-freedom (dof) in nonlinear finite element (FE) analysis. One of the most promising applications of HDNs is the asymptotic structural stability theory, which usually requires, in conventional series expansions, an unrealistically large number of second-order derivative of the stiffness matrix to predict the instability behavior of large-scale FE models. This computational bottleneck may be avoided along with so-called classical Lyapunov–Schmidt–Koiter condensation by a novel idea proposed in the present study. The proposed two-mode computational asymptotic theory is implementable in engineering practice to algebraically identify snap-through and path-branching in stability problems. One more associated innovation is a graphical solution of two simultaneous equations resulting from the asymptotic expansions. This sophisticated solution idea utilizing a popular mathematical tool (MATLAB) is widely applicable to quickly visualize the location and number of existing solutions. More specifically, the present paper formulates a two-mode asymptotic bifurcation theory in combination with HDNs and presents an examination of the proposed computational theory on stability problems of plates and shells. Near a precisely computed singular point on the equilibrium path, the incremental displacement field is represented in two modes: and . One mode is the critical eigenvector corresponding to the zero eigenvalue of the singular tangent stiffness matrix. The other one is a linear combination of all other non-critical eigenvectors, and respectively constitute the homogeneous and particular solutions of the linearized
equilibrium equations established in the singular point. Two perturbation parameters, and , work as weights of and , respectively, to find possible equilibria around the singular point. The nonlinear equilibrium equations are expanded into asymptotic series of and to use HDNs to compute 20 coefficients including first-order and second-order derivatives of the stiffness matrix in polynomials. The simultaneous polynomial equations of and are solved by using the MATLAB graphic operations. The obtained results in numerical examples well predict the stability behavior in excellent agreement with solutions available in conventional FE stability analysis. The two-mode asymptotic bifurcation theory combined with HDNs is sufficient to diagnose snap-through, asymmetric branching, unstable and stable symmetric bifurcation in structural stability problems.

ABSTRACT: In this paper we propose a Finite Element model for analyzing closed membranes (“bags”) interacting with internal and external (surrounding) fluids. The approach is based on embedding a Lagrangian monolithic model describing the membrane containing an internal fluid into an Eulerian external fluid model. The combination of kinematic frameworks allows us to accurately track the location of the membrane and naturally represent flow variables discontinuities across it. In order to obtain stable coupling for membrane materials with low density, a slight fluid compressibility is assumed. The coupling between the membrane and the internal fluid is automatically accounted for by a monolithic set-up. The filled membrane and the external fluid are coupled in a Dirichlet–Neumann fashion. The model is validated in several numerical examples and its potential application to a civil engineering problem of coast protection via water-filled bag reefs is shown.

ABSTRACT: Present paper deals with layered shells subjected to static loading. The basic equations include besides the global equilibrium formulated in terms of stress resultants, the local equilibrium in terms of stresses, the geometric field equations, the constitutive equations, a constraint which enforces the correct shape of the superposed displacement field through the thickness and the boundary conditions. Thereby an interface to three-dimensional material laws is created. The weak form of the boundary value problem is derived and a finite element formulation for quadrilaterals is specified. The mixed hybrid shell element possesses the usual 5 or 6 nodal degrees of freedom. This allows standard geometrical boundary conditions and the elements are applicable also to shell intersection problems. For linear elasticity the computed transverse shear stresses are automatically continuous at layer boundaries and zero at the outer surfaces. In comparison to fully 3D computations present element formulation needs only a fractional amount of computing time.

ABSTRACT: This study presents a three-dimensional nonlinear dynamic formulation based on a co-rotational (CR) approach for solid elements. The CR formulation is relatively efficient, but it is based on the assumption of small strains during large displacement. The novel idea of the present formulation involves the use of the CR formulation through a three-dimensional solid element for inertial quantities in addition to an internal force vector and a stiffness matrix. The present dynamic formulation is derived from Lagrange’s equation of motion. In this procedure, the CR formulation, (i.e., element-independent CR) is one of the most attractive features that is strongly manifested in an efficient manner. Consequently, this obtains the governing equation of motion including motion-driven inertial components (physical quantities induced by the prescribed motion). Four examples are presented to demonstrate the accuracy of the present dynamic formulation. Finally, the results are compared with those obtained by ABAQUS, and the findings reveal that the proposed dynamic formulation is in good agreement with existing predictions.

References listed at the end of the paper:
ABSTRACT: This paper presents a neural network (NN)-based surrogate modeling approach suitable for the geometrically nonlinear analysis of carbon nanotubes (CNTs). In this work we propose an NN-based equivalent beam element (NN-EBE) which is capable of accurately predicting the high-order phenomena caused by size-effects that characterize the behavior of CNTs at the nano-scale and can only be predicted by micro-mechanical models. The basic idea is to approximate the residual forces of the Newton–Raphson incremental-iterative formulation of the classical Euler or Timoshenko beam theory: Implementation of a strain-invariant finite element for static and dynamics", Comput. Methods Appl. Mech. Engrg., 171 (1999), pp. 141-171


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ABSTRACT: In this paper, we address the extension of the Kirchhoff shell model to non-linear analysis of functionally graded carbon nanotubes-reinforced thin composite shells (FG-CNTRCs). The present model can bring up two levels of analysis: geometrically non-linearities and nanostructures with the possibilities of two type of discretization. Either, three and four nodes finite shell elements are implemented to analyze as well as predict the non-linear bending behavior of FG-CNTRC shell structures. Uniform (UD) and three graded distributions of carbon nanotubes (CNTs) which are FG-V, FG-O and FG-X are considered. These distributions are uniaxially aligned in the axial direction of the shell and functionally graded along the thickness direction. The material properties of CNTs are estimated using the modified rule of mixture and the size dependence of these CNTs is taken into account via the introduction of some efficiency parameters. Three numerical examples of FG-CNTRC plates, hyperboloidal and cylindrical shells are presented to highlight the applicability and effectiveness of the present finite element model notably for thin structures. The effect of CNT profiles, CNT volume fractions and others geometrical parameters on non-linear behavior of such structures are also examined.


ABSTRACT: With the emergence of isogeometric analysis (IGA), the Galerkin rotation-free discretization of Kirchhoff–Love shells is facilitated, enabling more efficient thin shell structural analysis. High-order shape functions used in IGA also allow the collocation of partial differential equations, avoiding the time-consuming numerical integration of the Galerkin technique. The goal of the present work is to apply this method to NURBS-based isogeometric Kirchhoff–Love plates and shells, under the assumption of small deformations. Since Kirchhoff–Love plate theory yields a fourth-order formulation, two boundary conditions are required at each location on the contour, generating some conflicts at the corners where there are more equations than needed. To remedy this overdetermination, we provide priority and averaging rules that cover all the possible combinations of adjacent edge boundary conditions (i.e. the clamped, simply-supported, symmetric and free supports). Greville and alternative superconvergent points are used for NURBS basis of even and odd degrees, respectively. For square, circular, and annular flat plates, convergence orders are found to be in agreement with a-priori error estimates. The proposed isogeometric collocation method is then validated and benchmarked against a Galerkin implementation by studying a set of problems involving Kirchhoff–Love shells.


ABSTRACT: A hybrid NURBS-based isogeometric-finite element discretization technique is presented to take advantages of IGA for problems with regions demanding higher geometric accuracy or interpolation order. The validity of this coupled discretization is tested through standard patch test. Also, for demonstrative purposes, the proposed methodology is then applied to 2D interface contact/debonding of fiber–matrix as well as a 2D double cantilever beam peeling problem. Adopting a novel approach, the mortar method is used to account for both cohesive behavior and non-penetration constraint in the interface. Non-penetration constraint is enforced via Lagrange multiplier technique along with a mixed-mode cohesive law. The validity of the proposed unified contact/debonding formulation is tested against a contact/tension patch test. The stress contours after
simulations show a smooth variation across IG and FE domains further demonstrating the coupling’s eligibility. Moreover, smooth contact pressure distributions are obtained along the interfaces resulting from higher-order NURBS basis functions. Having significantly less DOFs, the hybrid IG–FE discretization also behaved more robustly compared with linear FEIs.


ABSTRACT: The present paper deals with postbuckling characteristics of carbon nanotube reinforced composite (CNTRC) rectangular plates with integrated piezoelectric layers subjected to in-plane compressive loads. The von Karman type of geometrical nonlinearity is taken into consideration to account for the large deformations of the plate. The dispersion of CNTs may be uniform or functionally graded and the distribution of electric potential across the thickness of piezoelectric layers is simulated by a combination of linear and sinusoidal functions. Generalized differential quadrature method is employed to discretize nonlinear stability equations, boundary conditions and Maxwell equation and then nonlinear system of equations is solved using a displacement control strategy. A comprehensive parametric study is presented to provide an insight into effects of CNT dispersion and volume fraction, geometrical parameters, type of in-plane load, boundary conditions, thickness of piezoelectric layers and external applied voltages on the postbuckling behaviors of the nanocomposite plate. It is shown that snap-through type of instability, which is known as secondary instability, occurs during postbuckling regime. It is revealed that both volume fraction and dispersion of the CNTs could affect the snap-through characteristics of the plate. It is found that snap-through instability is sensitive to thickness of the piezoelectric layers.


ABSTRACT: In this work an isogeometric solid-shell model for geometrically nonlinear analyses is proposed. It is based on a linear interpolation through the thickness and a NURBS interpolation on the middle surface of the shell for both the geometry and the displacement field. The Green–Lagrange strains are linearized along the thickness direction and a modified generalized constitutive matrix is adopted to easily eliminate thickness locking without introducing any additional unknowns and to model multi-layered composite shells. Reduced integration schemes, which take into account the high continuity of the shape functions, are investigated to avoid interpolation locking and to increase the computational efficiency. The relaxation of the constitutive equations at each integration point is adopted in the iterative scheme in order to reconstruct the equilibrium path using large steps and a low number of iterations, even for very slender structures. This strategy makes it possible to minimize the number of stiffness matrix evaluations and decompositions and it turns out to be particularly convenient in isogeometric analyses.


ABSTRACT: Recent years have seen a research revival in structural stability analysis. This renewed interest stems from a paradigm shift regarding the role of buckling instabilities in engineering design—from detrimental sources of catastrophic failure to novel opportunities for functionality. Novel nonlinear structures take the form of optimised thin-walled structures that operate safely in the post-buckling regime; shape-morphing structures that exploit multi-stability to snap and pop between different configurations; and meta-materials that derive novel material properties from a cascade of choreographed instabilities. Hence, elastic instabilities are no longer
considered as structural failures but rather exploited for repeatable well-behaved adaptations. In this article we focus on shape-morphing—a bio-inspired design strategy that intends to conform structures to different operating conditions. Computational tools that integrate easily with established methods used in industry, and that are capable of capturing the full phase diagram of compound instabilities and entangled post-buckling paths typical of these structures, are limited. Such a capability is crucial, however, as confidence in predictive tools can be key in enabling non-conventional designs. One potential candidate in this regard is generalised path-following, which combines the computational robustness of numerical continuation algorithms with the geometric versatility of the finite element method. In this paper we collate an array of successful computational tools introduced by other researchers, and introduce our own developments, to present a modelling framework fit for analysing and designing with well-behaved nonlinear structures in industry and academia. Particularly, we show that the full complexity of multi-snap events of morphing composite laminates is robustly captured by generalised path-following algorithms, and that the ability to determine loci of singular points with respect to a set of parameters is especially useful for tracing the boundaries of bistability in parameter space. Furthermore, we shed new insight into the mechanics of multi-stable laminates, showing that the multi-stability and snapping behaviour of these structures is much richer than previously assumed, featuring many unstable post-buckling branches and localised regions of stability.

ABSTRACT: This article presents original work combining a NURBS-based inverse analysis with both kinematic and constitutive nonlinearities to recover the applied loads and deformations of thin shell structures. The inverse formulation is tackled by gradient-based optimization algorithms based on computed and measured displacements at a number of discrete locations. The proposed method allows accurately recovering the target shape of shell structures such that instabilities due to snapping and buckling are captured. The results obtained show good performance and applicability of the proposed algorithms to computer-aided manufacturing of shell structures.

ABSTRACT: This study proposes an extension of the isogeometric approach for the dynamic response of laminated carbon nanotube reinforced composite (CNTRC) plates integrated with piezoelectric layers. The mechanical displacement field is approximated according to the higher-order shear deformation theory (HSDT) using the formulation based on Non-Uniform Rational B-Spline (NURBS) basis functions. The single-walled carbon nanotubes (SWCNTs) are assumed to be uniformly distributed (UD) or functionally graded (FG) distributed along the thickness direction. The material properties of carbon nanotube-reinforced composite plates are estimated according to the extended rule of mixture, while the electric potential is assumed to be a linear function through the thickness of each piezoelectric sub-layer. A velocity feedback control algorithm is used for the active control of the plate through a closed-loop control with piezoelectric sensors and actuators. The reliability and efficiency of the proposed technique are verified by comparing its numerical results with available references in literature.

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ABSTRACT: Present study proposes a nonlinear formulation to study the large amplitude free vibration of composite laminated plates reinforced by graphene sheets. Volume fraction of graphene sheets as reinforcements may be different in the layers. Material properties of the constituents are assumed to be temperature dependent. Properties of the composite media are obtained using a refined Halpin–Tsai approach where the auxiliary parameters are included into the formulation to capture the size dependency of the nanocomposite media. With the aid of third order shear deformation plate theory and the von Kármán type of kinematic assumptions, the basic governing equations of the plate are established. Afterwards, a non-uniform rational B-spline (NURBS) based isogeometric finite element method is used to study the large amplitude free vibration response of the graphene reinforced composite plates in thermal environment. Large amplitude frequencies as a function of centre point deflection are provided for different functionally graded patterns, aspect ratios, side to thickness ratios and boundary conditions.


ABSTRACT: An efficient assumed strain formulation for avoiding the membrane locking of non polar shells is developed in the context of B-spline interpolation. Assumed membrane strains are introduced locally in each element with a local projection, and then a spline reconstruction algorithm, developed by Thomas et al. (2015), is employed for reconstructing the membrane strain at the global patch level. In this way, a banded stiffness matrix is obtained that strongly reduces the computational cost with respect to the standard formulation for isogeometric analysis. The main advantages of the proposed method are: the reproduction of regular membrane strain fields, an accurate membrane locking-free solution and an high computational efficiency with respect to standard formulation. The method can be applied for any polynomial degree of the B-spline interpolation. The effectiveness of the proposed method is demonstrated analyzing some bending and membrane dominated problem, commonly employed as benchmark in the shell literature.


ABSTRACT: Engineering design via CAD software relies on Non-Uniform Rational B-Splines (NURBS) as a means for representing and communicating geometry. Therefore, in general, a NURBS description of a given design can be considered the exact description. The development of isogeometric methods has made the geometry available to analysis methods Hughes et al. (2005). Isogeometric analysis has been particularly successful in structural analysis; one reason being the wide-spread use of two-dimensional finite elements in this field. For fluid dynamics, where three-dimensional analysis is usually indispensable, isogeometric methods are more complicated, yet of course not impossible, to apply in a general fashion. This paper describes a method
that enables the solution of fluid–structure-interaction with a matching spline description of the interface. On the structural side, the spline is used in an isogeometric setting. On the fluid side, the same spline is used in the framework of a NURBS-enhanced finite element method (extension of Sevilla et al. (2011)). The coupling of the structural and the fluid solution is greatly facilitated by the common spline interface. The use of the identical spline representation for both sides permits a direct transfer of the necessary quantities, all the while still allowing an adjusted, individual refinement level for both sides.


ABSTRACT: The expansion of a bacterial biofilm on an agar substrate is modeled as a system of Föppl–von Kármán equations modified to include growth and coupling to a viscoelastic substrate. Analysis shows that wrinkles appear on the biofilm as a result of growth incompatibility and their frequency increases due to interaction with the agar layer. Simple cases of homogeneous radial and azimuthal growth are approximated by cone and corona solutions of the Monge–Ampère equation that are corrected by corner and boundary layers. A weak formulation of the problem allows us to express in-plane elastic strains and Airy potential solely in terms of the vertical displacement. We have developed a numerical method based on finite elements and simulated biofilm deformation for wide spectra of different growths. For heterogeneous growth, we find wrinkled patterns that are combinations of cones and coronas.


ABSTRACT: In this article, we explore an embedded shell finite element method for the unfitted discretization of solid–shell interaction problems. Its core component is a variationally consistent approach that couples a shell discretization on the surface of an embedded solid domain to its unfitted discretization with hexahedral solid elements. Derived via an augmented Lagrangian formulation and the formal elimination of interface Lagrange multipliers, our method depends only on displacement variables, facilitated by a shift of the displacement-dependent traction vector entirely to the solid structure. We demonstrate that the weighted least squares term required for stability of the formulation triggers severe surface locking due to a mismatch in the polynomial spaces of the shell element and the embedding solid element. We show that reduced quadrature of the stabilization term that evaluates the kinematic constraint at the nodes of the embedded shell elements completely mitigates surface locking. For coarse discretizations, our variationally consistent method achieves superior accuracy with respect to a locking-free nodal penalty method. We illustrate the versatility of embedded shell finite elements for image-based analysis, including patient-specific stress prediction in a vertebra and local rind buckling in a plant structure.


ABSTRACT: In this work, a framework based on the differential quadrature (DQ) method for the free vibration analysis of functionally graded carbon nanotube reinforced composite (FG-CNTRC) quadrilateral spherical panels with surface-bonded piezoelectric layers is developed. The higher-order shear deformation theory is used to model the displacement fields of quadrilateral thin-to-moderately thick spherical panels. Hamilton’s principle together with Maxwell’s equation is applied to drive the differential governing equations and the related boundary conditions. The transformed differential quadrature (TDQ) method for the case of quadrilateral panels
is established to discretize the governing partial differential equations. The benefit of this method is the usage of the transformed weighted coefficients, which are able to discretize partial differential equations in physical domain. This study exhibits that the TDQ approximation method shows a good convergence rate for quadrilateral curved panels. Furthermore, the accuracy and reliability of the proposed method are verified by comparing the results with the existing reference solutions or the results calculated by ANSYS software. The effects of CNTs volume fractions, CNTs distributions through the thickness, different boundary conditions and various panel geometrical parameters such as the panel thickness, piezoelectric thickness, side angle, and radius to length ratio on the natural frequency parameters are demonstrated. The article presents useful results for the design purpose of curved panels with complex geometries, for instance, achieving the optimal panel shape in order to pursuit the maximum structural stiffness.


ABSTRACT: Following a series of recent innovations, isogeometric shell analysis based on trimmed CAD surfaces is currently being developed into an accurate, efficient and mature design-through-analysis methodology. This work contributes to this emerging technology with respect to the following aspects. On the analysis side, we present a robust variationally consistent Nitsche-type formulation for thin shells at large deformations that weakly enforces coupling constraints at trimming curves. On the geometry side, we present a set of algorithms that enable automatic interaction of trimmed shell analysis with CAD data structures based on the STEP exchange format. We integrate these methodologies in a comprehensive framework for isogeometric trimmed shell analysis. We demonstrate that our framework is able to seamlessly perform large-deformation stress analysis of an industry-scale 76-patch surface model of a Dodge RAM hood, while delivering comparable accuracy with respect to Simulia’s commercial software package Abaqus.


ABSTRACT: This paper develops a novel coupling approach of the isogeometric analysis (IGA) method and the meshfree method for geometrically nonlinear analysis of thin-shell structures. The Kirchhoff–Love (KL) thin-shell theory is employed without the consideration of rotational degrees of freedom. Both parametric domain and physical domain are utilized for the thin-shell structures, and the former one is used to couple the IGA and meshfree methods and to obtain the later one via mapping. The domain is divided into three subdomains: the subdomain described by the IGA method to ensure geometry exactness, the subdomain described by the meshfree method to achieve local refinement, and the coupling subdomain described by both methods. In the coupling subdomain, the reproducing points are obtained based on the consistency conditions to realize smoothness between the IGA and meshfree subdomains. The coupling approach can achieve a higher convergence rate than the IGA and meshfree methods because of the realization of local refinement. The accuracy and robustness of the coupling approach are validated by solving shell benchmark problems.


ABSTRACT: Numerical formulations of the Koiter theory allow the efficient prediction, through a reduced model, of the behavior of shell structures when failure is dominated by buckling. In this work, we propose an isogeometric version of the method based on a solid-shell model. A NURBS interpolation is employed on the
middle surface of the shell to accurately describe the geometry and the high continuity typical of the displacement field in buckling problems and to directly link the CAD model to the structural one. A linear interpolation is then adopted through the thickness together with a modified generalized constitutive matrix, which allows us to easily eliminate thickness locking and model multi-layered composites. Reduced integration schemes, which take into account the continuity of the shape functions, are used to avoid interpolation locking and make the integration faster. A Mixed Integration Point strategy makes it possible to transform the displacement model into a mixed (stress–displacement) one, required by the Koiter method to obtain accurate predictions, without introducing stress interpolation functions. The result is an efficient numerical tool for buckling and initial post-buckling analysis of composite shells, characterized by a low number of DOFs and integration points and by a simple and quick construction of the reduced model.


ABSTRACT: In this paper, we significantly improve the membrane behavior of the previously published 3-node triangular MITC3+ shell element through the use of interpolation covers. We give the formulation of the improved MITC3+ element for linear and nonlinear large displacement analyses. The 3-node shell element passes the basic tests, namely the isotropy, patch, and zero energy mode tests, and we illustrate the excellent performance of the element in various standard test problems.


ABSTRACT: A new class of refined curved beam elements is proposed for the accurate stress analysis of composite structures. The element possesses three-dimensional capabilities and it is suited for the study of curved laminates and fiber-reinforced composites at the microscopic scale. The numerical issues associated with membrane and shear lockings are overcome by means of assumed interpolations of the strain components based on the mixed interpolation of tensorial components method (MITC). Higher-order expansions with only displacement unknowns are employed for the cross-section assumptions at the component level, enabling the computation of component-wise stress fields. For this purpose, a hierarchical set of Legendre functions is implemented, which allows the user to tune the kinematics of the element through the polynomial order input. The detrimental effects of locking in composite modeling are investigated and the robustness and efficiency of the beam element is assessed through comparison against solutions from the literature and refined solid models.


ABSTRACT: Controllable wrinkles in terms of amplitude, wavenumber and onset torsional angle are realized by using a twisting way of circular graphene sheets. A parametric study is carried out to investigate several factors, i.e., graphene size (inner radius and outer radius) and torsional angle, on the wrinkle formation of graphene. The effects of both wavenumber and amplitude are investigated in detail, because they are the most critical parameters in tuning the surface morphology that is finally reflected on the electrical properties of graphene. It is found that the onset torsional angle on the formation of wrinkles decreases as the graphene size increases. When the torsional angle increases continuously, the amplitude will abruptly jump due to a sudden change in the wrinkle pattern. The wrinkle wavenumber of graphene can also be controlled by changing the ratio of the inner and outer radii (i.e., r1/Ro). The variation of the strain energy shows that the structural
transformation is reversible, this is mainly caused by the superelastic property of graphene. Hence, the formation of recyclable wrinkles can be realized by loading and unloading processes.

ABSTRACT: Low density cellular materials may offer excellent mechanical properties and find wide applicability in lightweight design and infill structures for additive manufacturing, yet currently existing material structures are still far away from their theoretical limit in terms of compressive strength. To explore the existing potential, this paper presents a topology optimization framework for designing periodic cellular materials with maximized strength under compressive loading. Under this condition, the limiting factor of strength is the failure mechanism of buckling instability in the microstructure. In order to predict microstructural buckling, a simplified model based on homogenization theory, a linearized stability criterion and Floquet–Bloch theory is employed. Subsequently, a gradient-based topology optimization problem is formulated to maximize the buckling strength of the most critical failure mode. The framework is utilized to optimize square, triangular and hexagonal microstructures for three different macroscopic load conditions including biaxial, uniaxial and shear loading, and performance assessments are conducted by computation of associated failure surfaces in macroscopic stress space. In all cases, the optimized designs turn out to be first-order hierarchical type microstructures which offer major improvements of strength compared to the initial zero-order designs, however, the gains come at the cost of reductions in stiffness. Furthermore, it is illustrated how imposing geometric symmetry constraints can be exploited to control the shape of the failure surfaces.

ABSTRACT: Isogeometric analysis (IGA) is particularly suitable for the prediction of buckling load and design optimization of variable-stiffness composite panels, since curvilinear fiber path can be described exactly to improve the analysis efficiency, moreover, analytical sensitivity can be derived to improve the optimization efficiency. In this study, an integrated framework of exact modeling, isogeometric analysis and optimization for variable-stiffness panels is developed for the global optimum. Due to the inherent feature of multiple local optima for this type of problems, a novel multi-start gradient-based strategy is developed to enhance the global optimization capacity, and multiple initial designs for gradient-based optimization are determined by space tailoring method, which can guarantee the convergence rate and efficiency. Once the constraint aggregation and parallel computing methods are employed, the computational efficiency will be further improved. For typical illustrative example, it can be demonstrated that the proposed method is able to provide a more efficient optimum design with significant less computational cost compared to other traditional methods, including FEA-based optimization, direction optimization using genetic algorithm, gradient-based optimization without K–S function, gradient-based optimization based on difference method.

ABSTRACT: An isogeometric thin shell formulation allowing for large-strain plastic deformation is presented. A stress-based approach is adopted, which means that the constitutive equations are evaluated at different integration points through the thickness, allowing the use of general 3D material models. The plane stress constraint is satisfied by iteratively updating the thickness stretch at the integration points. The deformation of
the shell structure is completely described by the deformation of its midsurface, and, furthermore, the formulation is rotation-free, which means that the discrete shell model involves only three degrees of freedom. Several numerical benchmark examples, with comparison to fully 3D solid simulations, confirm the accuracy and efficiency of the proposed formulation.


ABSTRACT: In this paper, a transformed differential quadrature method (TDQM) for the free vibration analysis of functionally graded (FG) multilayer nanocomposite eccentric annular plates reinforced by graphene nanoplatelets (GPLs) and embedded in piezoelectric layers is developed. In this regards, a suitable conformal mapping is utilized to calculate the transformed weighting coefficients of the differential quadrature method (DQM) in physical domain which enables one to directly discretize the partial differential equations in the reference domain. The modified Halpin–Tsai model is employed to estimate the effective mechanical properties of the nanocomposites. The governing equations are derived based on the first-order shear deformation theory (FSDT) using Hamilton’s principle and Maxwell’s equation. The numerical results show that the TDQM has a very good convergence rate. Furthermore, the accuracy and reliability of the proposed method are verified by comparing the results with those obtained by simulating some problems via ABAQUS software and also, in the limit cases with those available in the literature. The effects of GPLs weight fractions, number of GPLs reinforced layers, distribution types of GPLs, different boundary conditions and various plate geometrical parameters such as the plate thickness, piezoelectric layers thickness, external electrical voltage and off-set parameter on the natural frequency parameters are investigated.


ABSTRACT: We introduce a novel meshfree Galerkin method for the solution of Reissner–Mindlin plate problems that is written in terms of the primitive variables only (i.e., rotations and transverse displacement) and is devoid of shear-locking. The proposed approach uses linear maximum-entropy basis functions for field variables approximation and is built variationally on a two-field potential energy functional wherein the shear strain, written in terms of the primitive variables, is computed via a volume-averaged nodal projection operator that is constructed from the Kirchhoff constraint of the three-field mixed weak form. The meshfree approximation is constructed over a set of scattered nodes that are obtained from an integration mesh of three-node triangles on which the meshfree stiffness matrix and nodal force vector are numerically integrated. The stability of the method is rendered by adding bubble-like enrichment to the rotation degrees of freedom. Some benchmark problems are presented to demonstrate the accuracy and performance of the proposed method for a wide range of plate thicknesses.


ABSTRACT: We present a fully isogeometric modeling and simulation method for geometrically exact, nonlinear 3D beams with spatially varying geometric and material distributions, both along the beam axis and through its cross-section. The approach is based on the modeling of 3D beams using the Cosserat rod theory and the numerical discretization using B-Spline and NURBS parameterizations in an isogeometric collocation
method. Transversally varying material constitutions are represented using non-homogeneous, functionally graded beam cross-section definitions such as laminates and continuously graded cross-sections. Furthermore, to model the axial variation of material and geometry, we introduce the parameterization of cross-section properties as spline curves along the beam centerlines. This fully isogeometric modeling and analysis concept, which is based on spline parameterizations of initial beam centerline curves, kinematic unknowns and axially varying material and geometric parameters, has various practical applications enabled by advances in manufacturing technology, including multi-material 3D printing and advanced manufacturing of composites with automated fiber placement. We verify and demonstrate the modeling and simulation approach using several numerical studies and highlight its practical applicability.


ABSTRACT: This paper presents a novel methodology of local adaptivity for the frequency-domain analysis of the vibrations of Reissner–Mindlin plates. The adaptive discretization is based on the recently developed Geometry Independent Field approximation (GIFT) framework, which may be seen as a generalization of the Iso-Geometric Analysis (IGA). Within the GIFT framework, we describe the geometry of the structure exactly with NURBS (Non-Uniform Rational B-Splines), whilst independently employing Polynomial splines over Hierarchical T-meshes (PHT)-splines to represent the solution field. The proposed strategy of local adaptivity, wherein a posteriori error estimators are computed based on inexpensive hierarchical h-refinement, aims to control the discretization error within a frequency band. The approach sweeps from lower to higher frequencies, refining the mesh appropriately so that each of the free vibration mode within the targeted frequency band is sufficiently resolved. Through several numerical examples, we show that the GIFT framework is a powerful and versatile tool to perform local adaptivity in structural dynamics. We also show that the proposed adaptive local h-refinement scheme allows us to achieve significantly faster convergence rates than a uniform h-refinement.


ABSTRACT: Challenging problems of computational mechanics may often be characterized by large deformations that are common in manufacturing processes such as forging. The finite element method faces difficulties in simulating large deformations, due to severe mesh distortion. A solution to overcome these difficulties is to use meshless methods like Smoothed Particle Hydrodynamics (SPH). This paper presents a thermomechanical SPH in total Lagrangian formulation to simulate efficiently large deformations thermomechanical problems. The continuum is modeled as a Hamiltonian system of particles (energy-based framework) when dissipative effects are considered where the constitutive equation is represented via an internal energy term. A comparison with an Eulerian SPH formulation and FEM is presented to assess the accuracy of the total Lagrangian formulation through examples of high velocity Taylor impact test and hot forging test.

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Guochang Li, Ranrui Zhang, Zhijian Yang and Bing Zhou (School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China), “Finite element analysis on mechanical performance of middle long CFST column with inner I-shaped CFRP profile under axial loading”, Structures, Vol. 9, pp 63-69, February 2017 https://doi.org/10.1016/j.istruc.2016.09.007
ABSTRACT: The mechanical performance of middle long concrete-filled square steel tube (CFST) column with I-shaped CFRP profile inside was studied in this paper. The numerical model of middle long CFST column with I-shaped CFRP profile inside was established by ABAQUS finite element software on the basis of the reasonable constitutive relationship model of material. The whole process curve of load deformation was analyzed, which can be divided into four stages: elastic stage, elastic-plastic rise stage, elastic-plastic decline stage and rebound stage. The model damaged because of buckling in the mid-span. The effect of steel strength and concrete strength, CFRP profile ratio and thickness of steel tube on mechanical performance of middle long column was studied. The bearing capacity of model increased with the increase of steel strength. With the increase of the concrete strength, the ultimate bearing capacity increased, but the ductility decreased. The ultimate bearing capability increased with the increase the CFRP profile ratio and steel tube thickness.

ABSTRACT: The multi-scale model which combined the fiber beam element with the fine element was used to investigate the progressive collapse performance of steel beam to concrete-filled steel tubular (CFST) column connections. By using the nonlinear static analysis method and taking into account the influence of the adjacent framework of joints, the resistance of progressive collapse, the failure modes and the stress distribution revealed the resistance mechanism of these joints during the process of progressive collapse. And the vertical displacement time history curves of joints which displayed the progressive collapse resistance demands of these joints were obtained by using the nonlinear dynamic analysis method. The relationship between resistance capacity and resistance demand of these joints were obtained by analyzing the nonlinear static analysis results and the nonlinear dynamic analysis results. These analysis results showed that the frame structure with these joints which enabled to form the resistance mechanism and new alternate path of unbalanced loads can prevent the occurrence of progressive collapse after the failure of column connected to joints. And the adjacent framework can improve the ability of anti-progressive collapse of these joints.

ABSTRACT: Concrete filled double skinned steel tubes (CFDST) are proved to have good structural performance in terms of strength, stiffness, ductility and fire resistance. Long CFDST columns find application in elevated corridors, bridge piers and also in buildings. However, the behaviour of CFDST long columns is still not fully understood and there is limited research in this area. In this paper, axial capacity equations for long
Column CFDST sections are proposed based on strength super-position method of design. Column capacity computed using the proposed equation is validated through experimental studies conducted by the authors (for columns having \( L/D \) ratio of 20) as well as additional tests reported in literature. Tests were conducted on CFDST, Concrete Filled Steel Tube (CFST) and Concrete Filled Hollow Single skinned Steel Tube (CFHSST) cross-sections. Parameters considered in the test include (i) length of the column, (ii) shape of the inner tube, and (iii) absence of inner tube. Results from the test viz., (a) load carrying capacity, (b) load vs. axial deformation curves, and (c) load vs. lateral deflection curves, have been reported. Test result shows that the contribution of inner tube on the axial capacity of long column is less than the predicted value, as the column undergoes elastic buckling prior to yielding. A reduction factor is proposed to account for the reduced contribution of inner steel tube, and it is applied as a correction to the initially proposed equations. The results from proposed capacity equation are compared with experimental results and are found to be in good agreement. It is concluded that the long column axial capacity equation specified for CFST in AISC-360 and EC4 could be extended for CFDST sections after incorporating the new reduction factor.


ABSTRACT: A numerical investigation on the shear characteristics of Lean Duplex Stainless Steel (LDSS) rectangular hollow beams are presented in this paper, through a parametric study, using the commercial finite element software, Abaqus. Effects of key cross sectional parameters viz., flange thickness \((t_f)\), flange width \((w_f)\), web thickness \((t_w)\) and shear span \((a)\) have been considered, keeping the height of the web \((h_w)\) constant. It is observed that increasing flange thickness for the same web thickness, can enhance both shear capacity and ductility. The shear capacity of the beam is seen to decrease with increasing shear span, the decrease being \(\sim 32-36\%\), for 100% increase in shear span \((a/h_w)\). The effect of increasing flange width is found to be relatively significant for stockier cross sections as compared to that of slender sections. Three failure mechanisms have been identified viz., 1) shear dominant, 2) bending dominant, and 3) combined shear and bending. In general, both EN 1993-1-4 (2006/A1:2015) and DSM are found to be applicable for the shear design of LDSS rectangular hollow beams. Possible modifications to both EN 1993-1-4 (2006/A1:2015) and DSM have been suggested by bifurcating into two span ratios: 1) \( a / h_w \leq 1.0 \) and 2) \( 1 < a / h_w \leq 2.0 \).


ABSTRACT: The full plastic resistance under a combination of bending and axial force of tubes of all possible wall thicknesses, from thin cylinders to circular solid sections, does not ever seem to have been thoroughly studied, despite the fact that this is a relatively simple analysis. The first part of this paper presents a formal analysis of the state of full plasticity under longitudinal stresses in a right circular tube of any thickness free of cross-section distortions. The derivation leads to relatively complicated algebraic expressions which are unsuitable for design guides and standards, so the chief purpose of this paper is to devise suitably accurate but simple empirical descriptions that give quite precise values for the state of full plasticity whilst avoiding the complexity of a formal exact analysis. The accuracy of each approximation is demonstrated. The two limiting cases of a thin tube (cylindrical shell) and circular solid section are shown to be simple special cases. The approximate expressions are particularly useful for the definition of the full plastic condition in tension members subject to small bending actions, but also applicable to all structural members and steel building
structures standards, as well as to standards on thin shells where they provide the full plastic reference resistance. These expressions are also useful because they give simple definitions of the orientation of the plastic strain vector, which can assist in the development of analyses of the plastic collapse of arches and axially restrained members under bending.

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ABSTRACT: A concrete filled elliptical steel tubular, abbreviated as CFEST, member consists of an elliptical hollow steel tube and in-filled concrete. The CFEST member is a family of concrete filled steel tubular (CFT) member having large deformability and toughness due to the confinement effect between the steel tube and the in-filled concrete. When the CFEST member is applied to bridge piers in the river, reduction of the bottom scouring due to the water flow can be expected. The present study aims to investigate, experimentally, the bending shear characteristics of CFEST deep beams through asymmetric four-point loading test method. The selected testing parameters are diameter-to-thickness ratio and two loading directions, namely the major and the minor axes. The results showed that shear capacity of CFEST members is strongly affected by the diameter-to-thickness ratio. The observed failure modes were cracking of the tube and/or shear failure of the in-filled concrete. A method to predict simple shear capacity of the CFEST deep beam is mainly discussed. Additionally, elasto-plastic principal stress behavior of the steel tube is also mentioned.

ABSTRACT: A simple numerical method capable of determining the $M$-$P$-$\Phi$ interaction diagrams of metal beam-columns sections subjected to axial load and bending moment (axial or biaxial) is presented. The effects of residual stresses, strain hardening and local buckling can be included. Tubular beam-columns and other shapes made of steel, aluminum or other metals can be analyzed by dividing the cross section in rectangular segments or in discrete areas. The method is based on the classic Euler-Bernoulli assumption that plane cross sections remain plane after deformations take place. The effects of shear stresses and strains are not taken into account. The maximum bending moment of the moment-curvature relationship for a given level of axial load is used to construct the failure surface for short beam-columns. The proposed model can be easily programmed by end users becoming an alternative to more refined and complex finite element models available in the technical literature and its validity and is verified against experimental results as well as those obtained using other analytical methods available in the technical literature.

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ABSTRACT: Moment–curvature–thrust relationships \((M-\kappa-N)\) are a useful resource for the solution of a variety of inelastic and geometrically non-linear structural problems involving elements under combined axial load and bending. A numerical discretised cross-section method is used in this research to generate such relationships for I-sections, rectangular box-sections and circular or elliptical hollow sections. The method is strain driven, with the maximum strain limited by an a priori defined local buckling strain, which can occur above or below the yield strain depending on the local slenderness of the cross-section. The relationship between the limiting strain and the local slenderness has been given for aluminium, mild steel and stainless steel cross-sections through the base curve of the Continuous Strength Method. Moment-curvature-thrust curves are derived from axial force and bending moment interaction curves by pairing the curvatures and moments for a given axial load level. These moment–curvature–thrust curves can be transformed into various formats to solve a variety of structural problems. The gradient of the curves is used to find the materially and geometrically non-linear solution of an example beam-column, by solving numerically the moment–curvature ordinary differential equations. The results capture the importance of the second order effects, particularly with regard to the plastic hinge formation at mid-height and the post-peak unloading response.


ABSTRACT: Small diameter steel tubes are used in many civil engineering applications. Recently, the behaviour of concrete columns reinforced with small diameter steel tubes was experimentally and analytically investigated. This study explores the effect of unsupported length to the outside diameter \((L/D)\) ratio on the axial compressive behaviour of small diameter steel tubes, which has not yet been adequately investigated. Galvanized and cold-formed steel tube specimens with \(L/D\) ratio of 2 to 12 were tested. It was observed that for specimens with \(L/D\) ratio of 2 and 4, the compressive failure occurred due to local elephant's foot buckling. However, the compressive failure mode changed to global buckling for specimens with \(L/D\) ratio \(\geq 6\). The ultimate compressive strength was found to be lower than the ultimate tensile strength for specimens with \(L/D\) ratio \(\geq 6\).


ABSTRACT: This paper analyses the lateral torsional buckling (LTB) behaviour of cantilever and two-span steel beams. The structural behaviour in terms of load-deflection curves, plasticisation of the cross section, ultimate capacities and failure modes of these beams is compared to the corresponding behaviour of simple beams, which are often considered as a basis for developing simplified models for design purposes. The results of the numerical study show that the ultimate capacity of steel beams is strongly affected by the yield-zone development and limited by four different failure criteria, namely the cross section failure, the eigenvalue-failure of the partially plastic system, the rotation limit and the eigenvalue-failure of the elastic system. Different ranges of slenderness are crucial for each failure criteria and these ranges vary for the different structural systems.
ABSTRACT: In this study, nonlinear behavior of concrete stiffened steel plate shear walls (CSPSW) with an opening is investigated. The study is divided into two separate parts in order to understand the effect of an unstiffened opening—locations and sizes. In phase one: four square opening sizes—small, medium, large, and very large—are selected to study the location of the opening. When the size of square opening is fixed, the location is changed over the infill wall. The pattern is also repeated with a new square size. In phase two: shear walls with a centrally located circular opening are considered and the opening ratio varies from 10% to 65%. In the study, the degradations of seismic factors—the initial stiffness, the ultimate shear strength, the ductility ratio, and the energy absorption—in terms of opening ratio are calculated. According to obtained results, the behavior of CSPSWs with an opening is utterly different from corresponding SPSWs. Initial elastic stiffness of CSPSWs with an opening is independent of the opening location and ultimate shear strength is slightly affected by location. Moreover, a linear degradation in the initial elastic stiffness and the ultimate shear strength of the infill composite wall is observed due to increasing the opening ratio.


ABSTRACT: The externally bonded CFRP strengthened steel C channel beams were tested in this study to understand the improvement in failure modes. Two different CFRP strengthening methods were proposed: 1) surface strengthening (wrapping around perimeter); 2) closed strengthening in which the open cross section of the steel channel section is infilled with cardboard and converted into a closed rectangular cross section followed by CFRP wrapping to improve the buckling mode. In addition, the effectiveness of CFRP strengthening under environmental exposure is also studied by conducting the durability test with artificial rain. The results indicate that the CFRP strengthening technique employed in the present research work can significantly improve the flexural moment capacity compared to the unstrengthened specimen by converting the lateral torsional buckling (LTB) mode of failure to failure due to yielding. The durability test indicates that the infill cardboard material is not affected due to moisture exposure.


ABSTRACT: Prestressed stayed columns have an enhanced resistance to buckling through the effective use of crossarms and pretensioned stays when compared to conventional columns. An analytical derivation of the minimum, linear optimum and maximum initial pretension forces for configurations of prestressed stayed columns with multiple crossarms and additional stays is presented for the first time. The findings are validated through comparisons with finite element models developed in the commercial package ABAQUS. The
influence of the initial pretension on the load-carrying capacity of the configurations considered is also analysed, providing insight into the actual optimum initial pretension force for the configurations accounting for the significance of geometric nonlinearities.


ABSTRACT: Recently conducted experimental and numerical investigations have shown that mobilisation of composite action within systems comprising cold-formed steel beams and wood-based floorboards is feasible and can lead to substantial improvements in structural performance. However, no design rules have yet been established for these systems in order to allow the beneficial effect of composite action to be exploited. In this paper, proposals for the design of such systems are devised and their theoretical basis is presented. At the core of the proposals is the calculation of the attained degree of partial shear connection and the shear bond coefficient for the composite members as a function of the geometric and material properties of their components and connectors. The accuracy of the devised design method for the prediction of moment capacity and flexural stiffness is demonstrated through comparisons with the results of 12 physical tests and about 80 numerical simulations reported in the literature. The proposals provide practical design rules for composite cold-formed steel floor beams, which are suitable for incorporation into future revisions of the Eurocodes.


Recent advances in timber production industries have enabled production of new innovative laminated timber products having layers with grain inclination angle. This paper is aimed to study influence of grain inclination angle in the laminated veneer lumber (LVL) and plywood sheathings on their shear buckling loads. Two extreme edge conditions of simply supported and clamped edges are considered. First, an accurate differential quadrature (DQ) computational code is developed using MAPLE programming software to obtain eigen buckling values and their corresponding eigen mode shapes. Next, for convenience of engineering calculations, approximate algebraic formulae are presented to predict critical shear buckling loads and mode shapes of LVL and plywood panels having layers with grain inclination angle, with adequate accuracy. Furthermore, finite element (FE) modelling is conducted for several cases using ANSYS software to show validity and accuracy of the predicted results for the problem. It is shown that the highest shear buckling loads of LVL sheathings is achievable when the inclination angle of about 30° with respect to the shorter edges is considered for production of LVL panels, whereas the same angle with respect to the long edges of the LVL sheathings results in a relatively lower buckling load. Considering similar inclination angle with respect to any edges of a plywood sheathing will also result in its highest pre-buckling capacity. It is also demonstrated that, under optimal design and certain loading circumstances, LVL shows a higher shear buckling capacity compared to a similar plywood sheathing.


ABSTRACT: In this article, the newly developed optimization method, so-called the Lion Pride Optimization Algorithm (LPOA), is applied to optimal design of double-layer space barrel vaults. In order to demonstrate the performance of the LPOA, three large-scale benchmark optimization design problems of double-layer barrel vaults are optimized and the results are compared with those of some metaheuristics from literature. The second aim of this article is to solve these examples using three other robust metaheuristic algorithms, namely Artificial
Bee Colony (ABC), Cuckoo Search (CS), and Particle Swarm Optimization (PSO). A comparative study of these algorithms shows the suitability of the LPOA for solving real-world practical spatial truss structures.

ABSTRACT: The beam-column members are widely used in civil structures. These members are subjected simultaneously to the axial load and the bending moment. In this paper, the buckling strength and the bracing stiffness requirement of the mono-symmetric beam-columns with discrete lateral bracing have been investigated. For this purpose, a numerical method based on the finite element analysis is developed to calculate the buckling load-set of the mono-symmetric beam-columns. This proposed method is capable to consider the initial geometric imperfection. The proposed method is compared with the results of experimental and numerical studies obtained by previous researchers and the spatial finite element analysis, which it shows good agreement. Also, by using the matrix form of the energy equation, a closed form solution of the bracing stiffness requirement is suggested for an arbitrary number of bracing points. The P-M interaction curve and formula are presented for mono-symmetric beam-columns. The results show that the peak point of the curve occurs at the $P = P_{ey}$ and $M = P_{ey}y_0$, where $P_{ey}$ is Euler's buckling load. Finally, a parametric study is done to investigate the effects of the eccentricity and degree of mono-symmetry on the buckling strength and bracing stiffness requirement.

ABSTRACT: The existence of initial imperfections in manufacturing or assemblage of real structures is inevitable. Many of these imperfections in double-layer space structures, such as the curvature and length imperfections, are random in nature. In this paper, the effect of initial curvature imperfection in the load carrying capacity of double-layer space structures is investigated. For this purpose, three different types of supports are considered. The curvature imperfection is considered as a random number by gamma distribution. The probabilistic model is used to distribute random imperfections among all members of the structure. Collapse behavior and the ultimate capacity of the structures are determined using nonlinear analysis and this procedure is repeated by Monte Carlo simulation method. The results show that the collapse behavior of double-layer grid space structures is sensitive to the random distribution of initial imperfections.

ABSTRACT: The distribution and intensity of blast pressure from far-field and near-field blasts can produce remarkably different patterns of loading on a reinforced concrete (RC) panel and can cause the panel to experience different modes of failure. Behaviour of RC panels, designed without consideration for extreme loading was investigated to analyse their damage and failure modes under different blast scenarios. The damage and failure modes of RC panels tested in two different full scale open air blast trials are presented. One of the tests was conducted in far-field condition with 40 m standoff distance. The other test was conducted on panels in near-field condition with standoff distances up to 2 m. These tested RC panels were subsequently modelled and analysed using the non-linear finite element (FE) code, LS-DYNA. Developed finite element models were used to conduct further parametric study to investigate damage behaviour and failure modes of RC panels under different blast loading conditions. The effect of blast pressure distribution and intensity on the failure modes of different RC elements were studied and blast pressure distribution and shock density were found to influence the mode of failure of a RC element significantly. Based on parametric study results, specific values of incident
angle and shock density of blast pressure were suggested which can be used to predict the transition between failure modes of RC panels from shear to flexure for far-field and near-field blasts.


ABSTRACT: Concentrically braced structures are one of the most common resistant systems in steel buildings due to their high stiffness and lateral strength. These systems have a good performance under mild earthquakes that behave in the elastic range. However, when these structures are subjected to moderate and severe earthquakes, their main weakness is being revealed. Under these earthquakes, the structure enters the inelastic zone and thus the braces that are pressurized begin to buckle. This makes it impossible to use the full capacity of braces in the energy dissipation exerted on the structure. In the past decades, researchers have conducted a variety of studies to improve the behavior of concentric bracing systems. This paper introduces a method for improving the post-buckling behavior of concentric braces. In this method, a side-mounted fuse is used in the middle of the brace to modify the post-buckling behavior of concentric braces. The results of experimental and numerical researches of this study indicate the better performance of this structural system in terms of ductility and energy dissipation capacity compared to the common concentric braces. The suggested system can be utilized to reduce the capacity of bracing connection which results in reduced costs of the project.


ABSTRACT: Concrete-filled double-skin tubular (CFDST) columns are formed by sandwiching concrete between two concentric hollow steel tubes. The result is a composite column with the benefits of both steel and concrete properties. When compared to a traditional concrete-filled steel tube (consisting of a single hollow steel tube instead of two), CFDST column is found to have greater axial, flexural and torsional strengths as well as improved strength-to-weight ratios. However, developments in CFDST column configurations can be made by altering the cross-section shape of the steel tubes, which is generally formed from square and circular ones. This paper considers the square CFDST short columns with inner square hollow sections (i.e. SHS outer and SHS inner tubes). This is because; in addition to their advantages shown above, they were seldom considered in literature especially by virtual testing. Accordingly, this paper is devoted for the finite element (FE) modelling of this type of composite columns by using ABAQUS program. Innovatively, this paper, rather than different investigations in literature, uses the most accurate constitutive models of both the cold-formed steel (i.e. Ramberg-Osgood model) and the confined concrete infill in double-skin tubes. Prior to parametric studies, the program has been validated using previous experimental results to ensure that the chosen combination of the materials could provide accurate and reliable results for the proposed models. The paper is then extends through parametric studies to investigate the effects of the key parameters affecting the general behaviour of this column under axial compressive loading, which exceeds the range of materials currently available in the available experiments. The paper additionally explores the effect of the eccentric loads on the behaviour of such columns, rarely done in literature, and comparisons with available theoretical moment-interaction curves have been considered. Overall, this paper provides new results that might aid in widening the practical usage of such column.


ABSTRACT: The statistical evaluation of the experimental and numerical results is an essential task in case of resistance model development for civil engineering structures. If a design model is developed which has
analytical or empirical background, its safety level has to be confirmed and it should be proved that the developed design method fits the safety requirements of the EN 1990 [1]. However, in the EN 1990 and also in the international literature there are several different safety factor evaluation methods that can be used to check the necessary safety level of the analyzed design method (e.g.: 5% quantile level, 2.3% quantile level, 1‰ quantile level, \( \gamma_M \) partial safety factor, \( \gamma_M^* \) partial safety factor, \( \beta \) reliability index). In the international literature different calculation methods can be found even for the calculation of the same partial safety factor as well. In the present study the flexural buckling resistance of high strength steel (HSS) welded box sections is analyzed and the application of different safety approaches are demonstrated and compared. The authors investigated the buckling resistance of the analyzed columns by laboratory tests and by numerical simulations and the necessary partial safety factors are determined by different approaches. Based on the comparison tendencies are identified and the differences between the statistical evaluation methods are demonstrated.

ABSTRACT: Shells have the potential to considerably reduce material consumption in buildings due to their high structural efficiency compared to equivalent structures acting in bending. Textile reinforced concrete (TRC) is a promising material for the construction of thin concrete shells due to its strength, geometric versatility, and durability. Existing design methods for TRC shells predicts the local capacity by linear interpolation between experimentally determined values of strength in pure tension, pure bending, and pure compression. This simplification leads to a significant underestimation of strength in combined bending and compression. Relying entirely on physical test results also effectively prohibits exploration and optimisation of the shell design. This paper proposes a new analytical design approach for TRC which is instead derived from the properties of the concrete and reinforcement, and for the first time captures the highly non-linear interaction between axial and bending forces. A series of pure tension, pure bending, and combined bending and compression tests were carried out on TRC specimens of 15 mm and 30 mm thickness. The predicted strengths were conservative under combined compression and bending but otherwise accurate. For the specimens tested, the proposed method increases the predicted strength by a factor of up to 3.7 compared to existing methods, whilst remaining conservative, and hence its use could lead to significant material savings and new applications for TRC shells.

ABSTRACT: The adequacy of rubberised concrete (RuC) for use in structural columns is, currently, investigated experimentally through the use of cold-formed double-skin circular steel tube confinement. The RuC is of particular interest because the aggregate can be sourced from recycled tyres, so it is a form of sustainable concrete, and it possesses superior mechanical properties to conventional concrete such as increased ductility and energy absorption. Rubberised concrete does have one major issue in that it has a low compressive strength compared to normal concrete, which limits its application. The aim of this study is to evaluate the effectiveness of confinement in overcoming this mechanical deficiency by using rubberised concrete-filled double-skin tubes (RuCFDST). The experimental program involves testing and measurements of key mechanical properties including compressive strength, hoop and axial strains, and compressive load-deflection curves. A total of 15 composite specimens were examined to ascertain the varying properties of single-skin, double-skin, confined, unconfined, standard and rubberised concrete. Recycled rubber particles ranging from two to seven millimeters in size were used to replace 15% and 30% of the fine and coarse concrete aggregate by weight. The rubber particles were treated with sodium hydroxide solution resulting in increased bonding
strength to the concrete. Circular hollow section (CHS) configurations of different internal and external dimensions were also examined to further understand the mechanics of double-skin confinement. Confinement in RuCFDST showed significant improvements in strength and ductility properties. Experimental results proved to be in agreement with design ultimate axial strength predictions proposed by existing methods and design codes. Given the exceptional ductility, energy dissipation and improved strength of RuCFDST, this study shows the potential viability of RuCFDST as structural columns particularly in areas that are prone to seismic activity.


ABSTRACT: This study investigates the buckling performance of tubular glass columns under axial compression. A total of two cases are considered (i) single glass tubular column and (ii) bundled column constructed using structural silicone sealants. A series of compression test were carried out on different geometrical dimensions of these two cases to determine their failure mechanism, load carrying capacity and to evaluate the buckling performance. Prior to the load carrying capacity (LCC) that was measured at the ultimate, a distinctive remaining structural capacity (RSC) was characterized especially for bundled glass based on the first crack. The shear connection in the bundled system was justified in comparison to the monolithic glass. This study showed that the failure mechanisms depended strongly on the slenderness ratio of the columns and that the failure occurred either by crushing or by buckling depending on the lengths of the column. The scatter in the failure load for specimens that had a higher slenderness ratio was much lower than for those that had a lower slenderness ratio. In order to justify the variability of the glass strength, a Weibull statistical distribution was used. Finite element modelling (FE) based on the simplified Riks method was performed using ABAQUS v6.10 to compliment the test results and to provide methods of analysis which could be used as a guideline for structural engineers to predict structural behaviour of tubular glass columns in general. An overestimation was predicted in the FE models which suggested modification of the imperfection factor.


ABSTRACT: This paper exploits the accuracy and versatility of additive manufacturing to display interesting buckling behavior in slender elastic columns. A set of parallel columns were printed to relatively high precision, and then subjected to axial loading. The load-deflection behavior is influenced by the post-buckled mutual contact between adjacent columns. Given the capability of incorporating prescribed (but small) initial geometric imperfections using additive manufacturing it is feasible to seed post-buckling behavior, effectively tailoring stiffness.


ABSTRACT: In this study, the buckling behaviour of a cable-stiffened steel column with a four-branch pin-connected crossarm system is investigated. A new geometric imperfection distribution is constructed with a nonlinear buckling analysis to trigger interactive buckling, and a method to obtain the actual load carrying capacity of the cable-stiffened steel column is proposed. The effects of different parameters, including the stay diameter, crossarm length, pretension in cables, and imperfection size, have also been analysed and discussed in this article. The findings of this study show that the interactive buckling of steel column stiffened by the four-branch pin-connected crossarms must be taken into account for accurate analysis. It is also demonstrated that the cable-stiffened steel columns are imperfection sensitive, particularly when the critical buckling mode is
located at the transition between symmetric and antisymmetric buckling, though the corresponding configuration is proved to be optimal with respect to the material utilisation rate.


ABSTRACT: The use of lightweight aggregate concrete (LWC) is the most obvious way to reduce the self-weight of concrete-filled steel tube (CFST) columns. This paper reports an investigation of the properties of reinforced lightweight aggregate concrete-filled steel tube (RLWCFST) columns subjected to axial compression. Eighteen specimens with three length-to-diameter ($L/D$) ratios (short, medium, and long) and two diameter-to-thickness ($D/t$) ratios (thin and thick) were tested. The LWC compressive strength is 30.58 MPa. The test results are given in terms of the compression loading against end shortening curves, and the failure modes of eighteen specimens are compared and discussed. In addition, the predictions of AISC360-16 and EC4 design specifications were compared to the test results to confirm the predictions of these specifications hold for RLWCFST columns. According to the experimental results, the use of the steel-bar reinforcement improves the mechanical behavior of LWC and increases the compressive strength capacity, toughness, and ductility of the composite column. The failure modes of the columns were affected by the behavior of the reinforced and unreinforced LWC and the geometric properties of the steel tube ($L/D$ and $D/t$ ratios). Steel-bar reinforcement combined with thinner steel tube provided excellent performance and using larger-diameter steel-bars instead of thick steel tube can offer improvement in compression capacity and ductility for short, medium, and long columns.


ABSTRACT: In cold-formed steel structures, such as trusses, wall frames and portal frames, the use of back-to-back built-up cold-formed steel channel sections are becoming increasingly popular. In such an arrangement, intermediate fasteners are required at discrete points along the length, preventing the channel-sections from buckling independently. Current guidance in the AISI & AS/NZS for such back-to-back built-up cold-formed steel channel sections requires the use of modified slenderness in order to take into account the spacing of the fasteners. Limited research has been done on back-to-back built-up cold-formed steel columns to understand the effect of column thickness and slenderness's on axial capacity. This issue is addressed herein. This paper presents the results of 60 experimental tests performed on back-to-back built-up cold-formed steel channel sections under compression. Detailed observations on different failure modes and column strengths were made through varying thickness, length and cross section of columns. A non-linear finite element model was developed which includes material non-linearity, geometric imperfections and explicit modelling of web fasteners. The finite element model was validated against experimental results. A comprehensive parametric study consisting of 204 models has been carried out covering a wide range of thickness and slenderness for the considered back-to-back built-up columns. Axial capacities obtained from the numerical study were used to assess the performance of the current AISI & AS/NZS standards when applied to cold-formed back-to-back built up columns; obtained comparisons showed that AISI & AS/NZS standards are un-conservative for stub and short columns which were failed by local buckling whereas standards were over-conservative for the strength of intermediate and slender columns which were failed mainly by overall member buckling. This paper has therefore proposed improved design rules and verified their accuracy using finite element analysis and test results of back-to-back built-up cold-formed channel sections, subjected to axial compression.
End of more papers published in the journal, Structures (2017 and on).


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ABSTRACT: Instabilities in bilayered systems can generate a wide variety of patterns ranging from simple folds, wrinkles, and creases to complex checkerboards, hexagons, and herringbones. Physics-based theories traditionally model these systems as a thin film on a thick substrate under confined compression and assume that the film is orders of magnitude stiffer than the substrate. However, instability phenomena in soft films on soft substrates remain insufficiently understood. Here we show that soft bilayered systems are highly sensitive to the stiffness ratio, boundary conditions, and mode of compression. In a systematic analysis over a wide range of stiffness ratios, from $0.1<\beta<1000.1<\beta<1000$, for eight different compression modes including whole-domain compression, substrate prestretch, and film growth, we observe significantly different instability characteristics in the low-stiffness-contrast regime, for $\beta<10$. While systems with inverse stiffness ratios under whole-domain compression are unstable for a wide range of wrinkling modes, under film-only compression, the same systems display distinct wrinkling modes. Strikingly, these discrepancies disappear when using measures of effective strain, effective stiffness, and effective wavelength. Our study suggests that future instability studies should use these effective measures to standardize their findings. Our results have important applications in soft matter and living matter physics, where stiffness contrasts are low and small environmental changes can have large effects on morphogenesis, pattern tabselection, and the evolution of shape.

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ABSTRACT: In this paper, we study the interplay between macroscopic and microscopic instabilities in 3D periodic fiber reinforced composites undergoing large deformations. We employ the Bloch-Floquet analysis to determine the onset of microscopic instabilities for composites with hyperelastic constituents. We show that the primary mode of buckling in the fiber composites is determined by the volume fraction of fibers and the contrast between elastic moduli of fiber and matrix phases. We find that for composites with volume fraction of fibers exceeding a threshold value, which depends on elastic modulus contrast, the primary buckling mode corresponds to the long wave or macroscopic instability. However, composites with a lower amount of fibers experience microscopic instabilities corresponding to wavy or helical buckling shapes. Buckling modes and critical wavelengths are shown to be highly tunable by material composition. A comparison between the
instability behavior of 3D fiber composites and laminates, subjected to uniaxial compression, reveals the significant differences in critical strains, wavelengths, and transition points from macro- to microscopic instabilities in these composites.

ABSTRACT: Nematic elastomers are rubbery solids which have liquid crystals incorporated into their polymer chains. These materials display many unusual mechanical properties, one such being the ability to form fine-scale microstructure. In this work, we explore the response of taut and appreciably stressed sheets made of nematic elastomer. Such sheets feature two potential instabilities – the formation of fine-scale material microstructure and the formation of fine-scale wrinkles. We develop a theoretical framework to study these sheets that accounts for both instabilities, and we implement this framework numerically. Specifically, we show that these instabilities occur for distinct mesoscale stretches, and observe that microstructure is finer than wrinkles for physically relevant parameters. Therefore, we relax (i.e., implicitly but rigorously account for) the microstructure while we regularize (i.e., compute the details explicitly) the wrinkles. Using both analytical and numerical studies, we show that nematic elastomer sheets can suppress wrinkling by modifying the expected state of stress through the formation of microstructure.

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ABSTRACT: Metamaterials are composed of structural elements and derive their properties mainly from the inner structure of the elements, rather than the properties of their constituent material. By designing an unstable structural element as the building block of a metamaterial, many interesting effective material properties can be obtained. The deformation and dissipation mechanisms of such a material built from unstable structural elements is studied in detail. To do so a combination of analytical, semi-analytical, and numerical models are applied to a single buckling element, a periodic cell, and finite size combinations of buckling elements including gradients in the properties of the building blocks. This not only provides insight into the micromechanics and the resulting effective behavior of such metamaterials, but also makes them accessible on the different relevant length scales. A metamaterial built from these building blocks shows programmable or switchable properties and can display energy dissipation with fully reversible deformation, distinguishing it from plastic materials, and timescale independent behavior, distinguishing it from viscoelastic materials.

ABSTRACT: Thin membrane structures would experience wrinkling due to local buckling deformation when compressive stresses are induced in some regions. Using the stress criterion for membranes in wrinkled and taut states, this paper proposed a new stress-based topology optimization methodology to seek the optimal wrinkle-free design of macro-scale thin membrane structures under stretching. Based on the continuum model and linearly elastic assumption in the taut state, the optimization problem is defined as to maximize the structural stiffness under membrane area and principal stress constraints. In order to make the problem computationally tractable, the stress constraints are reformulated into equivalent ones and relaxed by a cosine-type relaxation scheme. The reformulated optimization problem is solved by a standard gradient-based algorithm with the adjoint-variable sensitivity analysis. Several examples with post-bulking simulations and experimental tests are given to demonstrate the effectiveness of the proposed optimization model for eliminating stress-related wrinkles in the novel design of thin membrane structures.

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ABSTRACT: Wide beams can exhibit subcritical buckling, i.e. the slope of the force-displacement curve can become negative in the postbuckling regime. In this paper, we capture this intriguing behaviour by constructing a 1D nonlinear beam model, where the central ingredient is the nonlinearity in the stress-strain relation of the beams constitutive material. First, we present experimental and numerical evidence of a transition to subcritical buckling for wide neo-Hookean hyperelastic beams, when their width-to-length ratio exceeds a critical value of 12%. Second, we construct an effective 1D energy density by combining the Mindlin–Reissner kinematics with a nonlinearity in the stress-strain relation. Finally, we establish and solve the governing beam equations to analytically determine the slope of the force-displacement curve in the postbuckling regime. We find, without any adjustable parameters, excellent agreement between the 1D theory, experiments and simulations. Our work extends the understanding of the postbuckling of structures made of wide elastic beams and opens up avenues for the reverse-engineering of instabilities in soft and metamaterials.

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ABSTRACT: Combining atomistic simulations and continuum modeling, a comprehensive study of the out-of-plane compressive deformation behaviors of equilateral three-dimensional (3D) graphene honeycombs was performed. It was demonstrated that under out-of-plane compression, the honeycomb exhibits two critical deformation events, i.e., elastic mechanical instability (including elastic buckling and structural transformation) and inelastic structural collapse. The above events were shown to be strongly dependent on the honeycomb cell size and affected by the local atomic bonding at the cell junction. By treating the 3D graphene honeycomb as a continuum cellular solid, and accounting for the structural heterogeneity and constraint at the junction, a set of analytical models were developed to accurately predict the threshold stresses corresponding to the onset of
those deformation events. The present study elucidates key structure–property relationships of 3D graphene honeycombs under out-of-plane compression, and provides a comprehensive theoretical framework to predictively analyze their deformation responses, and more generally, offers critical new knowledge for the rational bottom-up design of 3D networks of two-dimensional nanomaterials.

ABSTRACT: We study the in-plane damped oscillations of a finite lattice of particles coupled by linear springs under distributed harmonic excitation. Strong nonlinearity in this system is generated by geometric effects due to the in-plane stretching of the coupling spring elements. The lattice has a finite number of nonlinear transverse standing waves (termed nonlinear normal modes – NNMs), and an equal number of axial linear modes which are nonlinearly coupled to the transverse ones. Nonlinear interactions between the transverse and axial modes under harmonic excitation give rise to unexpected and extreme nonlinear energy exchanges in the lattice. In particular, we directly excite a transverse NNM by harmonic forcing (causing simultaneous indirect excitation of a corresponding axial linear mode due to nonlinear coupling), and identify three energy transfer mechanisms in the lattice. First, we detect the stable response of the directly excited transverse NNM (despite its instability in the absence of forcing), with simultaneous stability of the indirectly excited axial linear mode. Second, by changing the system and forcing parameters we report extreme nonlinear “energy explosions,” whereby, after an initial regime of stability, the directly excited transverse NNM loses stability, leading to abrupt excitation of all transverse and axial modes of the lattice, at all possible wave numbers. This strong instability is triggered by the parametric instability of an indirectly excited axial mode which builds energy until the explosion. This is proved through theoretical analysis. Finally, in other parameter ranges we report intermittent, intense energy transfers from the directly excited transverse NNM to a small set of transverse NNMs with smaller wavelengths, and from the indirectly excited axial mode to a small set of axial modes, but with larger wavelengths. These intermittent energy transfers resemble energy cascades occurring in turbulent flows. Our results show that nonlinear mechanical systems can support extreme energy transfer phenomena, with features resembling “mechanical turbulence”.

ABSTRACT: In this paper, a consistent finite-strain plate theory for growth-induced large deformations is developed. The three-dimensional (3D) governing system of the plate model is formulated through the variational approach, which is composed of the mechanical equilibrium equation and the constraint equation of incompressibility. Then, series expansions of the unknown functions in terms of the thickness variable are adopted. By using the 3D equilibrium equations and the surface boundary conditions, recursion relations for the expansion coefficients are successfully established. As a result, a 2D vector plate equation with three unknowns is obtained and the associated edge boundary conditions are proposed. It can be verified that the plate equation ensures the required asymptotic order for all the terms in the variations of the total energy functional. The weak formulation of the plate equation has also been derived for future numerical calculations. As applications of the plate theory, two examples regarding the growth-induced deformations and instabilities in thin hyperelastic plates are studied. Some analytical results are obtained in these examples, which can be used to describe the large deformations and reveal the bifurcation properties of the thin plates. Furthermore, the results obtained
from the current plate theory are compared with those obtained from the classical Föppl-von Kármán plate theory, from which the efficiencies and advantages of the current plate theory can be demonstrated.

ABSTRACT: Mechanically-guided 3D assembly based on controlled, compressive buckling represents a promising, emerging approach for forming complex 3D mesostructures in advanced materials. Due to the versatile applicability to a broad set of material types (including device-grade single-crystal silicon) over length scales from nanometers to centimeters, a wide range of novel applications have been demonstrated in soft electronic systems, interactive bio-interfaces as well as tunable electromagnetic devices. Previously reported 3D designs relied mainly on finite element analyses (FEA) as a guide, but the massive numerical simulations and computational efforts necessary to obtain the assembly parameters for a targeted 3D geometry prevent rapid exploration of engineering options. A systematic understanding of the relationship between a 3D shape and the associated parameters for assembly requires the development of a general theory for the postbuckling process. In this paper, a double perturbation method is established for the postbuckling analyses of planar curved beams, of direct relevance to the assembly of ribbon-shaped 3D mesostructures. By introducing two perturbation parameters related to the initial configuration and the deformation, the highly nonlinear governing equations can be transformed into a series of solvable, linear equations that give analytic solutions to the displacements and curvatures during postbuckling. Systematic analyses of postbuckling in three representative ribbon shapes (sinusoidal, polynomial and arc configurations) illustrate the validity of theoretical method, through comparisons to the results of experiment and FEA. These results shed light on the relationship between the important deformation quantities (e.g., mode ratio and maximum strain) and the assembly parameters (e.g., initial configuration and the applied strain). This double perturbation method provides an attractive route to the inverse design of ribbon-shaped 3D geometries, as demonstrated in a class of helical mesostructures.

ABSTRACT: Micro-electromechanical systems (MEMS) that rely on structural vibrations have many important applications, ranging from oscillators and actuators, to energy harvesters and vehicles for measurement of mechanical properties. Conventional MEMS, however, mostly utilize two-dimensional (2D) vibrational modes, thereby imposing certain limitations that are not present in 3D designs (e.g., multi-directional energy harvesting). 3D vibrational micro-platforms assembled through the techniques of controlled compressive buckling are promising because of their complex 3D architectures and the ability to tune their vibrational behavior (e.g., natural frequencies and modes) by reversibly changing their dimensions by deforming their soft, elastomeric substrates. A clear understanding of such strain-dependent vibration behavior is essential for their practical applications. Here, we present a study on the linear and nonlinear vibration of such 3D mesostructures through analytical modeling, finite element analysis (FEA) and experiment. An analytical solution is obtained for the vibration mode and linear natural frequency of a buckled ribbon, indicating a mode change as the static deflection amplitude increases. The model also yields a scaling law for linear natural frequency that can be extended to general, complex 3D geometries, as validated by FEA and experiment. In the regime of nonlinear vibration, FEA suggests that an increase of amplitude of external loading represents an effective means to enhance the bandwidth. The results also uncover a reduced nonlinearity of vibration as the static deflection amplitude of the 3D structures increases. The developed analytical model can be used in the development of
new 3D vibrational micro-platforms, for example, to enable simultaneous measurement of diverse mechanical properties (density, modulus, viscosity etc.) of thin films and biomaterials.


ABSTRACT: Surface acoustic wave (SAW) devices have found a wide variety of technical applications, including SAW filters, SAW resonators, microfluidic actuators, biosensors, flow measurement devices, and seismic wave shields. Stretchable/flexible electronic devices, such as sensory skins for robotics, structural health monitors, and wearable communication devices, have received considerable attention across different disciplines. Flexible SAW devices are essential building blocks for these applications, wherein piezoelectric films may need to be integrated with the compliant substrates. When piezoelectric films are much stiffer than soft substrates, SAWs are usually leaky and the devices incorporating them suffer from acoustic losses. In this study, the propagation of SAWs in a wrinkled bilayer system is investigated, and our analysis shows that non-leaky modes can be achieved by engineering stress patterns through surface wrinkles in the system. Our analysis also uncovers intriguing bandgaps (BGs) related to the SAWs in a wrinkled bilayer system; these are caused by periodic deformation patterns, which indicate that diverse wrinkling patterns could be used as metasurfaces for controlling the propagation of SAWs.


ABSTRACT: The prenatal development of the human brain is characterized by a rapid increase in brain volume and a development of a highly folded cortex. At the cellular level, these events are enabled by symmetric and asymmetric cell division in the ventricular regions of the brain followed by an outwards cell migration towards the peripheral regions. The role of mechanics during brain development has been suggested and acknowledged in past decades, but remains insufficiently understood. Here we propose a mechanistic model that couples cell division, cell migration, and brain volume growth to accurately model the developing brain between weeks 10 and 29 of gestation. Our model accurately predicts a 160-fold volume increase from 1.5 cm$^3$ at week 10 to 235 cm$^3$ at week 29 of gestation. In agreement with human brain development, the cortex begins to form around week 22 and accounts for about 30% of the total brain volume at week 29. Our results show that cell division and coupling between cell density and volume growth are essential to accurately model brain volume development, whereas cell migration and diffusion contribute mainly to the development of the cortex. We demonstrate that complex folding patterns, including sinusoidal folds and creases, emerge naturally as the cortex develops, even for low stiffness contrasts between the cortex and subcortex.


ABSTRACT: In this paper, a periodic configuration of V-shaped double peeling process is investigated. Specifically, an elastic thin film is detached from a soft elastic material by applying multiple concentrated loads periodically distributed with spatial periodicity $\lambda$. The original Kendall’s idea is extended to take into account the change in elastic energy occurring in the substrate when the detachment fronts propagate. The symmetric configuration typical of a V-peeling process causes the energy release rate to be sensitive to variations of the elastic energy stored in the soft substrate. This results in an enhancement of the adhesion strength because part of the external work required to trigger the peeling mechanism is converted in substrate elastic energy. A key role is played by both spatial periodicity $\lambda$ and elasticity ratio $E/E_h$, between tape and substrate elastic moduli, in
determining the conditions of stable adhesion. Indeed, the presence of multiple peeling fronts determines a modification of the mechanism of interaction, because deformations close to each peeling front are also affected by the stresses related to the other fronts. Results show that the energy release rate depends on the detached length of the tape so that conditions can be established which lead to an increase of the supported load compared to the classical peeling on rigid substrates. Finally, we also find that for any given value of the load per unit length, an optimum value of the wavelength \( \lambda \) exists that maximizes the tolerance of the system, before unstable propagation of the peeling front can occur.


ABSTRACT: In recent years, shape design of graphene sheets (GSs) by introducing topological defects for enhancing their mechanical behaviors has attracted the attention of scholars. In the present work, we propose a consistent methodology for optimal shape design of GSs using a combination of the molecular mechanics (MM) method, the non-parametric shape optimization method, the phase field crystal (PFC) method, Voronoi tessellation, and molecular dynamics (MD) simulation to maximize their fundamental frequencies. At first, we model GSs as continuum frame models using a link between the MM method and continuum mechanics. Then, we carry out optimal shape design of GSs in fundamental frequency maximization problem based on a developed shape optimization method for frames. However, the obtained optimal shapes of GSs only consisting of hexagonal carbon rings are unstable that do not satisfy the principle of least action, so we relocate carbon atoms on the optimal shapes by introducing topological defects using the PFC method and Voronoi tessellation. At last, we perform the structural relaxation through MD simulation to determine the final optimal shapes of GSs. We design two examples of GSs and the optimal results show that the fundamental frequencies of GSs can be significantly enhanced according to the optimal shape design methodology.


ABSTRACT: The buckling and post-buckling behaviour of slender structures is increasingly being harnessed for smart functionalities. Equally, the post-buckling regime of many traditional engineering structures is not being used for design and may therefore harbour latent load-bearing capacity for further structural efficiency. Both applications can benefit from a robust means of modifying and controlling the post-buckling behaviour for a specific purpose. To this end, we introduce a structural design paradigm termed modal nudging, which can be used to tailor the post-buckling response of slender engineering structures without any significant increase in mass. Modal nudging uses deformation modes of stable post-buckled equilibria to perturb the undeformed baseline geometry of the structure imperceptibly, thereby favouring the seeded post-buckling response over potential alternatives. The benefits of this technique are enhanced control over the post-buckling behaviour, such as modal differentiation for smart structures that use snap-buckling for shape adaptation, or alternatively, increased load-carrying capacity, increased compliance or a shift from imperfection sensitivity to imperfection insensitivity. Although these concepts are, in theory, of general applicability, we concentrate here on planar frame structures analysed using the nonlinear finite element method and numerical continuation procedures. Using these computational techniques, we show that planar frame structures may exhibit isolated regions of stable equilibria in otherwise unstable post-buckling regimes, or indeed stable equilibria entirely disconnected from the natural structural response. In both cases, the load-carrying capacity of these isolated stable equilibria is greater than the natural structural response of the frames. Using the concept of modal nudging it is possible to
“nudge” the frames onto these equilibrium paths of greater load-carrying capacity. Due to the scale invariance of modal nudging, these findings may impact the design of structures from the micro- to the macro-scale.


ABSTRACT: Through a combination of experiments, theoretical modeling, and finite element simulation, we explore the mechanics governing the formation and evolution of periodic buckle-delamination on both micro- and macro-scale by bonding a thin film to an extremely pre-strained soft elastomeric substrate over 400%. We find that upon the large substrate pre-strain release, the deformation in the film follows a three-stage deformation regime, i.e. onset of localized blisters (Stage I), growth through delamination crack propagation to form periodic sinusoidal blisters (Stage II), and transition to post-buckled jig-saw-like blisters under fixed-end compression after crack arrest (Stage III). Related energy-based mechanics models on predicting the evolution and geometry of periodic blisters under moderate and large compression are developed and validated through both experiments and finite element simulation. Finally, we discuss the potential applications of harnessing spontaneous buckle-delamination for interfacial toughness measurement through the metrology of blisters, as well as design of extremely stretchable electronics by achieving an extremely lower value of maximum tensile strain in the buckle-delaminated film.


ABSTRACT: This work is concerned with the characterization of the macroscopic response of soft elastomeric composites following the onset of ‘macroscopic’ (long wavelength) instabilities. For this purpose, the special case of laminated composites made of two neo-Hookean phases of different stiffneses subjected to plane strain loading is considered. Indeed, it is known that the macroscopic response of such elastic composites can lose strong ellipticity when the stiff layers are subjected to sufficiently high compressive loads and their volume fraction is large enough. However, their post-bifurcation response is not yet known. Here it will be shown that the laminates can in fact lose (global) strict rank-one convexity, and do so well before losing (local) strong ellipticity. This will be accomplished by first constructing the rank-one convexification of the ‘principal’ solution for the stored-energy function at finite strains. It will then be shown that the rank-one convexification of the energy is polyconvex, and therefore corresponds to the quasiconvexification or ‘relaxation’ of the energy. Consequently, the post-bifurcation response corresponds to the formation of lamellar or ‘striped’ domains, which, in turn, gives rise to ‘soft modes’ of deformation. One important implication of this work for more general soft elastic composites is that the commonly accepted practice of using loss of strong ellipticity to predict the onset of macroscopic instabilities can significantly overestimate their stability. Instead, the relaxation of the energy should be computed in order to get more accurate (and conservative) estimates for their macroscopic stability, as well as the correct post-bifurcation response.


ABSTRACT: The multiplicative decomposition model is widely employed for predicting residual stresses and morphologies of biological tissues due to growth. However, it relies on the assumption that the tissue is initially in a stress-free state, which conflicts with the observations that any growth state of a biological tissue is under a significant level of residual stresses that helps to maintain its ideal mechanical conditions. Here, we propose a modified multiplicative decomposition model in which the initial state (or reference configuration) of a biological tissue is endowed with a residual stress instead of being stress-free. Releasing theoretically the initial
residual stress, the initially stressed state is first transmitted into a virtual stress-free state, thus resulting in an initial elastic deformation. The initial virtual stress-free state subsequently grows to another counterpart with a growth deformation, while the corresponding free energy density should depend on the initial residual stress and the total deformation. Three key issues including the explicit expression of the free energy density, the predetermination of the initial elastic deformation, and the initial residual stress are addressed. Finally, we consider a tubular organ as a representative example to demonstrate the effects of the proposed initial residual stress on stress distribution and on shape formation through an incremental stability analysis. Our results suggest that the initial residual stress exerts a major influence on the growth stress and the morphology of biological tissues. The model bridges the gap between any two growth states of a biological tissue that is endowed with a certain level of residual stresses.


ABSTRACT: Even if still little known, the most significant nonlinear effect during nonlinear vibrations of continuous systems is the increase of damping with the vibration amplitude. The literature on nonlinear vibrations of beams, shells and plates is huge, but almost entirely dedicated to model the nonlinear stiffness and completely neglecting any damping nonlinearity. Experiments presented in this study show a damping increase of six times with the vibration amplitude. Based on this evidence, the nonlinear damping of rectangular plates is derived assuming the material to be viscoelastic, and the constitutive relationship to be governed by the standard linear solid model. The material model is then introduced into a geometrically nonlinear plate theory, carefully considering that the retardation time is a function of the vibration mode shape, exactly as its natural frequency. Then, the equations of motion describing the nonlinear vibrations of rectangular plates are derived by Lagrange equations. Numerical results, obtained by continuation and collocation method, are very successfully compared to experimental results on nonlinear vibrations of a rectangular stainless steel plate, validating the proposed approach. Geometric imperfections, in-plane inertia and multi-harmonic vibration response are included in the plate model.


ABSTRACT: We show that a smooth giant voltage actuation of soft dielectric plates is not easily obtained in practice. In principle one can exploit, through pre-deformation, the snap-through behavior of their loading curve to deliver a large stretch prior to electric breakdown. However, we demonstrate here that even in this favorable scenario, the soft dielectric is likely to first encounter the plate wrinkling phenomenon, as modeled by the onset of small-amplitude sinusoidal perturbations on its faces. We provide an explicit treatment of this incremental boundary value problem. We also derive closed-form expressions for the two limit cases of very thin membranes (with vanishing thickness) and of thick plates (with thickness comparable to or greater than the wavelength of the perturbation). We treat explicitly examples of ideal dielectric free energy functions (where the mechanical part is of the neo-Hookean, Mooney–Rivlin or Gent form) and of dielectrics exhibiting polarization saturation. In addition to the expected buckling mode coming from the purely elastic case, we discover a second mode occurring at large voltages in extension. We find that plates always wrinkle anti-

ABSTRACT: Recent work demonstrates that finite-deformation nonlinear elasticity is essential in the accurate modeling of wrinkling in highly stretched thin films. Geometrically exact models predict an isola-center bifurcation, indicating that for a bounded interval of aspect ratios only, stable wrinkles appear and then disappear as the macroscopic strain is increased. This phenomenon has been verified in experiments. In addition, recent experiments revealed the following striking phenomenon: For certain aspect ratios for which no wrinkling occurred upon the first loading, wrinkles appeared during the first unloading and again during all subsequent cyclic loading. Our goal here is to present a simple pseudo-elastic model, capturing the stress softening and residual strain observed in the experiments, that accurately predicts wrinkling behavior on the first loading that differs from that under subsequent cyclic loading. In particular for specific aspect ratios, the model correctly predicts the scenario of no wrinkling during first loading with wrinkling occurring during unloading and for all subsequent cyclic loading.


ABSTRACT: This paper studies the buckling behavior and imperfection sensitivity of geodesic and stellated shells subject to external pressure. It is shown that these structures can completely eliminate the severe imperfection sensitivity of spherical shells and can achieve buckling pressure and mass efficiency higher than the perfect sphere. Key results of this paper are as follows. First, a shell with the shape of an icosahedron can carry external pressure significantly higher than a spherical shell, when the effects of geometric imperfections are considered. Second, stellated shells are generally insensitive to imperfections. For pyramids with height-to-radius ratios greater than 35% the buckling pressure is greater than for a perfect sphere. The specific ratio 45% gives the highest buckling pressure, 28% higher than the perfect sphere. Third, stellated icosahedra with concave pyramids have higher mass efficiency than the perfect sphere. Fourth, in terms of volume efficiency, geodesic shells are comparable to spherical shells with a knockdown factor of 0.2 and convex stellated shells are comparable to spherical shells with a knockdown factor of 0.65.


ABSTRACT: The dynamic collapse of hollow and foam-filled double hull composite cylinders is investigated experimentally. Concentric carbon-fiber/epoxy double cylinders with and without parametrically-graded PVC foam cores are collapsed in a large-diameter pressure vessel under critical hydrostatic pressure as well sub-critical hydrostatic pressure and shock loading. Dynamic pressure data is used in conjunction with underwater Digital Image Correlation (DIC) to determine the effect of the double hull structure on implosion mechanics. Buckling initiation and overall collapse behavior are studied, as well as the pressure pulses released during the dynamic event. Incidents of partial collapse are reported, in addition to cases where the entire structure collapses. The physical mechanisms responsible for this behavior are identified, and the time between inner and outer cylinders collapsing is related to buckling phase angle. For hydrostatically initiated implosions, results show heavier foam cores increase critical collapse pressure linearly with foam crushing strength. Pressure
pulses emitted during collapse are shown to occur in distinct phases, with an additional under- and overpressure region present if the inner cylinder collapses. Impulse is demonstrated to be primarily a function of collapse pressure, with energy released increasing with core density. For shock initiated cases, specimens are shown to implode below their natural collapse pressure when subject to explosive loading, with the addition of a foam core substantially increasing structural stability and sometimes preventing collapse. Specimens with foam cores are shown to undergo prolonged vibrations before collapsing. Post-mortem specimens are used to elucidate fracture and failure mechanisms.

https://doi.org/10.1016/j.jmps.2018.07.024
ABSTRACT: We investigate the non-linear buckling patterns produced by the elastic Rayleigh-Taylor instability in a hyper-elastic slab hanging below a rigid horizontal plane, using a combination of experiments, weakly non-linear expansions and numerical simulations. Our experiments reveal the formation of hexagonal patterns through a discontinuous transition. As the unbuckled state is transversely isotropic, a continuum of linear modes become critical at the first bifurcation load: the critical wavevectors form a circle contained in a horizontal plane. Using a weakly non-linear post-bifurcation expansion, we investigate how these linear modes cooperate to produce buckling patterns: by a mechanism documented in other transversely isotropic structures, three-modes coupling make the unbuckled configuration unstable with respect to hexagonal patterns by a transcritical bifurcation. Stripe and square patterns are solutions of the post-bifurcation expansion as well but they are unstable near the threshold. These analytical results are confirmed and complemented by numerical simulations.

https://doi.org/10.1016/j.jmps.2018.08.008
ABSTRACT: Membrane structures with symmetry often exhibit geometric instability under finite inflation. We observe and study this phenomenon in the case of a flat toroidal membrane with axisymmetry and reflection symmetry. The membrane is modeled as a Mooney-Rivlin hyperelastic material. The stability of the symmetric inflation path is studied perturbatively which reveals a zone of instability. Using higher order perturbation, the asymmetric shape is subsequently determined. As the inflation proceeds, first the axisymmetry is broken spontaneously through a supercritical pitchfork bifurcation, and is later restored at a reverse subcritical pitchfork bifurcation. The extent of the symmetry breaking zone depends on the material and geometric parameters of the toroidal structure. It is found that a stout torus can completely eliminate the occurrence of such symmetry breaking bifurcations on its inflation path.

Shi-Lei Xue, Si-Fan Yin, Bo Li and Xi-Qiao Feng, “Biochemomechanical modeling of vascular collapse in growing tumors”, Journal of the Mechanics and Physics of Solids, Vol. 121, pp 463-479, December 2018,
https://doi.org/10.1016/j.jmps.2018.08.009
ABSTRACT: The collapse of blood vessels are widely observed in solid tumors, but the mechanisms underpinning this abnormal behavior remain unclear. In this paper, we investigate the stability of blood vessels embedded in a growing solid tumor by using a chemomechanical poroelastic theory. Linear stability analysis is first made to give the critical condition of vascular buckling. Thereby, pattern diagrams are provided to predict the collapsed shape of a blood vessel from the mechanical and geometric parameters of the system. Due to the mechano-chemo-biological coupling effect in tumors which involve both fluid transport and tissue growth, the
The buckling of blood vessels exhibits distinctly different features from such previously reported tubular tissues as airways and esophagi. We show that interstitial fluid pressure tends to drive blood vessels to buckle with a lower buckling mode, while perivascular cell proliferation favors a higher mode. Furthermore, a nonlinear biochemomechanical finite element method is formulated to track the morphological evolution of blood vessels during postbuckling. It is found that the blood vessels with the second mode of buckling may readily evolve into a crack-like shape. This method can reproduce the essential features of vascular collapse observed in vivo tumors and provide clues for vascular normalization and stress alleviation in cancer treatments.


NOTE: The page numbers are not given in order. Instead the articles are grouped by category, with page numbers within each category in order, but a following category generally starts at a much lower page number than that at the end of the previous category.


ABSTRACT: A Mindlin plate subjected to a pair of inertial loads traveling at a constant high speed in opposite directions along arbitrary trajectory, straight or curved, is presented. The masses represent vehicles passing a bridge or track plates. A numerical solution is obtained using the space–time finite element method, since it allows a clear and simple derivation of the characteristic matrices of the time-stepping procedure. The transition from one spatial finite element to another must be energetically consistent. In the case of the moving inertial load the classical time-integration schemes are methodologically difficult, since we consider the Dirac delta term with a moving argument. The proposed numerical approach provides the correct definition of force equilibrium in the time interval. The given approach closes the problem of the numerical analysis of vibration of a structure subjected to inertial loads moving arbitrarily with acceleration. The results obtained for a massless and an inertial load traveling over a Mindlin plate at various speeds are compared with benchmark results obtained for a Kirchhoff plate. The pair of inertial forces traveling in opposite directions causes displacements and stresses more than twice as large as their corresponding quantities observed for the passage of a single mass.

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ABSTRACT: Subjected to external lateral excitations, large-amplitude sloshing may take place in propellant tanks, especially for spacecraft in low-gravity conditions, such as landers in the process of hover and obstacle avoidance during lunar soft landing. Due to lateral force of the order of gravity in magnitude, the amplitude of liquid sloshing becomes too big for the traditional equivalent model to be accurate. Therefore, a new equivalent mechanical model, denominated the “composite model”, that can address large-amplitude lateral sloshing in partially filled spherical tanks is established in this paper, with both translational and rotational excitations considered. The hypothesis of liquid equilibrium position following equivalent gravity is first proposed. By decomposing the large-amplitude motion of a liquid into bulk motion following the equivalent gravity and additional small-amplitude sloshing, a better simulation of large-amplitude liquid sloshing is presented. The effectiveness and accuracy of the model are verified by comparing the slosh forces and moments to results of the traditional model and CFD software.

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ABSTRACT: We explore the use of structure-embedded Acoustic Black Holes (ABH) to design thin-walled structural components exhibiting broadband vibration attenuation characteristics. The ABH is a geometric taper with a power-law profile fully integrated into the structural component and able to induce a smooth and progressive decrease of both the velocity and the wavelength of flexural waves. Previous studies have shown these characteristics to be critical to enable highly efficient vibration attenuation systems. The performance of ABH thin-walled structures is numerically and experimentally evaluated under both transient and steady state excitation conditions. Both numerical and experimental results suggest that the proposed approach enables highly efficient and broadband vibration attenuation performance.

ABSTRACT: The effect of the shear correction coefficient on the branches of the frequency spectrum for the free vibrations of Mindlin plates is studied. Each of the three branches of the frequency spectrum for the Mindlin plate is associated with its corresponding branch of the frequency spectrum of the infinite elastodynamic plate through direct comparison. The use of branch dependent shear correction coefficients is proposed, and is utilized to bring each of the three branches of the Mindlin plate into best agreement with their corresponding elastodynamic branches. Conclusions with respect to the accuracy and range of applicability of the Mindlin frequency spectrum are drawn, with emphasis on the second flexural (Mindlin \( w_2 \)) frequency branch. For the plate that is simply-supported on all of its edges, each of the three frequency branches contributes to the motion of the plate independently of the other two branches. Hence, only one of the branches is active for a given vibration mode, which allows one to solve for unique natural frequencies for each of the branches and to quantify their accuracy as well as to study the motion of each branch separately. This is not, however, the case for plates with other support conditions. In these cases, the vibrational motion corresponding
to each of the branches of the frequency spectrum contributes to a given vibration mode. This, in turn, alters
the implementation of Mindlin theory for these plates. Results for natural frequency predictions are compared to
those of other studies in the literature as well as to those of the classical case when a single shear correction
coefficient is employed. It is shown that natural frequency predictions are improved for the plate with all of its
dges simply-supported, while the accuracy of the mode shape is improved for other boundary conditions.

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https://doi.org/10.1016/j.jsv.2016.12.030
ABSTRACT: The vibration in tyres submitted to random forces in the contact zone is investigated with the
model of prestressed orthotropic plate on visco-elastic foundation. It is shown that beyond a cut-on frequency a
single wave propagates whose speed is directional-dependent. A systematic numerical exploration of the
governing equation solutions shows that three regimes may exist in such plates. These are modal field, diffuse
field and free field. For actual tyres which present a high level of damping, the passage from low to high
frequencies generally explores the modal and free field regimes but not the diffuse field regime.

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“Bifurcation and response analysis of a nonlinear flexible rotating disc immersed in bounded compressible
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ABSTRACT: Use of heavy gases in centrifugal compressors for enhanced oil extraction have made the
impellers susceptible to failures through acousto-elastic instabilities. This study focusses on understanding the
dynamical behavior of such systems by considering the effects of the bounded fluid housed in a casing on a
rotating disc. First, a mathematical model is developed that incorporates the interaction between the rotating
impeller - modelled as a flexible disc - and the bounded compressible fluid medium in which it is immersed.
The nonlinear effects arising due to large deformations of the disc have been included in the formulation so as
to capture the post flutter behavior. A bifurcation analysis is carried out with the disc rotational speed as the
bifurcation parameter to investigate the dynamical behavior of the coupled system and estimate the stability
boundaries. Parametric studies reveal that the relative strengths of the various dissipation mechanisms in the
coupled system play a significant role that affect the bifurcation route and the post flutter behavior in the
acousto-elastic system.

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ABSTRACT: This paper presents a case study in which the finite element model for a curved circular plate is calibrated to reproduce both the linear and nonlinear dynamic response measured from two nominally identical samples. The linear dynamic response is described with the linear natural frequencies and mode shapes identified with a roving hammer test. Due to the uncertainty in the stiffness characteristics from the manufactured perforations, the linear natural frequencies are used to update the effective modulus of elasticity of the full order finite element model (FEM). The nonlinear dynamic response is described with nonlinear normal modes (NNMs) measured using force appropriation and high speed 3D digital image correlation (3D-DIC). The measured NNMs are used to update the boundary conditions of the full order FEM through comparison with NNMs calculated from a nonlinear reduced order model (NLROM). This comparison revealed that the nonlinear behavior could not be captured without accounting for the small curvature of the plate from manufacturing as confirmed in literature. So, 3D-DIC was also used to identify the initial static curvature of each plate and the resulting curvature was included in the full order FEM. The updated models are then used to understand how the stress distribution changes at large response amplitudes providing a possible explanation of failures observed during testing.


ABSTRACT: This paper presents an analytical solution for sound transmission through a multilayered cylindrical shell with bonded-unbonded (BU) configuration. The multilayered cylindrical shell, which is composed of an outer layer of functionally graded material (FGM) and an inner isotropic layer with a poroelastic core and an air gap, is assumed to be infinitely long and is subjected to a plane wave on its external sidewall. To describe the poroelastic core, the extended full method (EFM) is applied based on Biot’s theory. Contrary to previous methods, the EFM completely models the poroelastic cylindrical shell in three dimensions. In addition, the motions of both FGM and isotropic shells are described with the first order shear deformation theory (FSDT). Unlike the simplified method, the EFM does not need to identify the frequency ranges where one of the airborne or frame waves is dominant in BU configuration. In fact, utilizing the EFM for BU configuration permits obtaining the sound transmission loss (TL) irrespective of the dominant wave, which significantly reduces the computational work. Moreover, comparing with the previous models, the EFM provides more accurate results as it does not ignore any term in the modeling. Furthermore, the advantages of the BU-FGM shell in enhancing the TL are demonstrated with respect to the BB-isotropic configuration. It is shown that presence of the FGM in addition to the poroelastic material in a structure yields thermal insulation and improves soundproofing characteristics in a broadband frequency range.

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ABSTRACT: The far-field acoustic radiation of a cylindrical shell with finite length submerged at finite depth from the water surface is studied. Two steps are utilized to solve the problem. The first step is to determine the
vibration response of the submerged cylindrical shell by using an analytical method and the second one is to
determine the far field sound radiation with the boundary element method. To address the vibration responses of
the shell analytically, the cylindrical shell and surrounding fluid are described by the Flügge shell equations and
Laplace equation in the cylindrical coordinate system respectively. The free surface effect is taken into
consideration by using the image method and the Graf’s addition theorem. The reliability and efficiency of the
present method are validated by comparison with the finite element method. Then, based on the vibration
responses of the shell obtained from the first step, the far-field sound pressure is computed by using the
boundary element method. It is found that the vibration of the cylindrical shell submerged at finite depth from
the free surface tends to be the same as that in infinite fluid when the submerged depth exceeds a certain value.
The frequency and the submerged depth have crucial effects on the fluctuation of the far-field sound pressure,
while for the curve of sound pressure level versus immersion depth, the ratio of the distance between the
adjacent peak points of sound pressure to the wavelength is independent of the frequency. Moreover, the petal
number of the directivity of the far-field sound pressure increases with the increase of the frequency and the
submerged depth. The work provides more understanding on the vibration and acoustic radiation behavior of a
finite cylindrical shell submerged at finite depth.

Reza Okhovat and Anders Bostroem (Chalmers University of Technology, Department of Applied Mechanics,
SE-412 96 Göteborg, Sweden), “Dynamic equations for an isotropic spherical shell using the power series
https://doi.org/10.1016/j.jsv.2017.01.025
ABSTRACT: Dynamic equations for an isotropic spherical shell are derived by using a series expansion
technique. The displacement field is split into a scalar (radial) part and a vector (tangential) part. Surface
differential operators are introduced to decrease the length of all equations. The starting point is a power series
expansion of the displacement components in the thickness coordinate relative to the mid-surface of the shell.
By using the expansions of the displacement components, the three-dimensional elastodynamic equations yield
a set of recursion relations among the expansion functions that can be used to eliminate all but the four of
lowest order and to express higher order expansion functions in terms of those of lowest orders. Applying the
boundary conditions on the surfaces of the spherical shell and eliminating all but the four lowest order
expansion functions give the shell equations as a power series in the shell thickness. After lengthy
manipulations, the final four shell equations are obtained in a relatively compact form which are given to
second order in shell thickness explicitly. The eigenfrequencies are compared to exact three-dimensional theory
with excellent agreement and to membrane theory.

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University/University of the Federal Armed Forces Hamburg, Holstenhofweg 85, D-22048 Hamburg,
Germany), “Adaptive support for aircraft panel testing: New method and its experimental verification on a
https://doi.org/10.1016/j.jsv.2017.02.004
ABSTRACT: Acoustic transmissibility of aircraft panels is measured in full-scale test rigs. The panels are
supported at their frames. These boundary conditions do not take into account the dynamic influence of the
fuselage, which is significant in the frequency range below 300 Hz. This paper introduces a new adaptive
boundary system (ABS). It combines accelerometers and electrodynamic shakers with real-time signal
processing. The ABS considers the dynamic effect of the fuselage on the panel. The frames are dominating the
dynamic behaviour of a fuselage in the low-frequency range. Therefore, the new method is applied to a beam
representing a frame of the aircraft structure. The experimental results are evaluated and the precision of the ABS is discussed. The theoretical apparent mass representing the cut-off part of a frame is calculated and compared with the apparent mass, as provided by the ABS. It is explained how the experimental set-up limits the precision of the ABS.

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https://doi.org/10.1016/j.jsv.2017.01.033
ABSTRACT: Dynamic deformations of beams and plates under moving objects have extensively been studied in the past. In this work, the dynamic response of geometrically nonlinear rectangular elastic plates subjected to moving mass loading is numerically investigated. A rectangular von Karman plate with various boundary conditions is modeled using specifically developed geometrically nonlinear plate elements. In the available finite element (FE) codes the only way to distinguish between moving masses from moving loads is to model the moving mass as a separate entity. However, these procedures still do not guarantee the inclusion of all inertial effects associated with the moving mass. In a prepared finite element code, the plate elements are developed using the conventional nonlinear methods, i.e., Total Lagrangian technique, but all inertial components associated with the travelling mass are taken into account. Since inertial components affect the mass, damping, and stiffness matrices of the system as the moving mass traverses the plate, appropriate time increments shall be selected to avoid numerical instability. The dynamic response of the plate induced by the moving mass is evaluated and compared to previous studies. Also, unlike the existing FE programs, the different inertial components of the normal contact force between the moving mass and the plate are computed separately to substantiate the no-separation assumption made for the moving mass. Also, it is observed that for large moving mass velocities, the peak plate deformation occurs somewhere away from the plate center point. Under the two extreme in-plane boundary conditions considered in this study, it is shown that if the geometrical nonlinearity of plate is accounted for, the deformations obtained would be less than the case with classical linear plate theory.

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ABSTRACT: This study combined theoretical, experimental, and numerical analysis to investigate the vibration characteristics of a thin rectangular plate positioned horizontally at the bottom of a rectangular container filled with liquid. Flow field pressure was derived using an equation governing the behavior of incompressible fluids. Analytic solutions to vibrations in a thin plate in air served as the fundamental function of the thin plate coupled with liquid. We then used liquid pressure, and the out-of-plane deflection of the thin plate for the construction of frequency response functions for the analysis of vibration characteristics in the liquid-plate coupling system. Two experimental methods were employed to measure the vibration characteristics of the thin plate immersed
in water. The first involved using sensors of polyvinylidene difluoride (PVDF) to measure transient signals of fluid-plate system subjected an impact at the thin plate. These were then converted to the frequency domain in order to obtain the resonant frequencies of the fluid-plate coupling system. The second method was amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI), which was used to measure the dynamic characteristics of the thin plate in the flow field. This method was paired with the image processing techniques, temporal speckle pattern interferometry (TSPI) and temporal standard deviation (TSTD), to obtain clear mode shapes of the thin plate and resonant frequencies. Comparison of the results from theoretical analysis, finite element method, and experimental measurements confirmed the accuracy of our theoretical analysis, which was superior to the conventional approach based on beam mode shape functions. The experimental methods proposed in this study can be used to measure the resonant frequencies of underwater thin plates, and clear mode shapes can be obtained using AF-ESPI. Our results indicate that the resonant frequencies of thin plates underwater are lower than those in air. To a limited extent, increasing the depth of water enhanced the reduction of resonant frequencies.

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ABSTRACT: The system of the hypersingular integral equations with respect to the aerodynamic derivatives of the shell pressure drop is obtained to analyze the interaction of the shallow shell with three-dimensional incompressible potential air flow. This system of the integral equations is very applicable to analyze aeroelastic vibrations of thin-walled structures. The numerical approach based on the discrete vortices method is suggested to solve the system of the hypersingular integral equations. Using the assumed-mode method, the finite degrees of freedom dynamical system is derived to analyze the shallow shell dynamic instability. The dynamic instability of the shallow shell equilibrium in the subsonic air flow is analyzed numerically. This type of instability results in flutter. The influence of the structure parameters on the dynamic instability is analyzed. The parameters of the dynamic instability are compared with the data, which are calculated by the software ANSYS.
vibraphone. It is the novel contribution of this paper to provide a systematic approach for synthesizing sound from vibrating structures with arbitrary geometries just from their surface vibrations. In case of musical instruments, the resulting sound can be evaluated and rated by psychoacoustic criteria to define a target function for their numerical optimization. The method is applied to a bar modeled according to the design of typical vibraphone bars. The sound resulting from the synthesis algorithm is validated against the boundary element approach and results from microphone measurements.


ABSTRACT: Recent reports exemplify both the potential and the concerns encountered in implementing post-buckled structures in diverse applications. By numerical and experimental methods, characterizations have provided useful insights on the dynamic sensitivities of such bi- or multistable structures subjected to either harmonic or stochastic excitations. Yet, the more realistic scenario of combined harmonic and stochastic loading has not been closely examined so that such sensitivities might be fully illuminated. To provide a more complete understanding on the robustness and susceptibility of multistable structures to dynamic state transitions, this research establishes new analytical and experimental methods to quantify the likelihood of triggering transitions among dynamic regimes of an archetypal post-buckled structure as a result of combined harmonic and stochastic loading. It is discovered that persistent periodic snap-through dynamics are rapidly disabled by additional noise excitation when the harmonic excitation contribution occurs at frequencies close to the linearized resonance. The extra noise may also drastically compromise the integrity of small-amplitude periodic responses that occur at frequencies around one-half of the linearized resonance. Particular relative proportions of the noise standard deviation and harmonic excitation amplitude are uncovered that most readily compromise the robustness of a given steady-state dynamic regime. The analytical method also complements prior developments focused on stochastic resonance by uncovering the broader perspective of dynamic sensitivities of post-buckled structures under arbitrary combinations of harmonic and random driving loads.


ABSTRACT: In deformable shells conveying pulsatile flow, oscillatory pressure changes cause local movements of the fluid and deformation of the shell wall, which propagate downstream in the form of a wave. In biomechanics, it is the propagation of the pulse that determines the pressure gradient during the flow at every location of the arterial tree. In this study, a woven Dacron aortic prosthesis is modelled as an orthotropic circular cylindrical shell described by means of the Novozhilov nonlinear shell theory. Flexible boundary conditions are considered to simulate connection with the remaining tissue. Nonlinear vibrations of the shell conveying pulsatile flow and subjected to pulsatile pressure are investigated taking into account the effects of the pulse-wave propagation. For the first time in literature, coupled fluid-structure Lagrange equations of motion for a non-material volume with wave propagation in case of pulsatile flow are developed. The fluid is modeled as a Newtonian inviscid pulsatile flow and it is formulated using a hybrid model based on the linear potential flow theory and considering the unsteady viscous effects obtained from the unsteady time-averaged
Navier-Stokes equations. Contributions of pressure and velocity propagation are also considered in the pressure drop along the shell and in the pulsatile frictional traction on the internal wall in the axial direction. A numerical bifurcation analysis employs a refined reduced order model to investigate the dynamic behavior of a pressurized Dacron aortic graft conveying blood flow. A pulsatile time-dependent blood flow model is considered by applying the first harmonic of the physiological waveforms of velocity and pressure during the heart beating period. Geometrically nonlinear vibration response to pulsatile flow and transmural pulsatile pressure, considering the propagation of pressure and velocity changes inside the shell, is here presented via frequency-response curves, time histories, bifurcation diagrams and Poincaré maps. It is shown that traveling waves of pressure and velocity cause a delay in the radial displacement of the shell at different values of the axial coordinate. The effect of different pulse wave velocities is also studied. Comparisons with the corresponding ideal case without wave propagation (i.e. with the same pulsatile velocity and pressure at any point of the shell) are here discussed. Bifurcation diagrams of Poincaré maps obtained from direct time integration have been used to study the system in the spectral neighborhood of the fundamental natural frequency. By increasing the forcing frequency, the response undergoes very complex nonlinear dynamics (chaos, amplitude modulation and period-doubling bifurcation), here deeply investigated.

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ABSTRACT: Damping parameters of fiber-reinforced composite possess significant uncertainty due to the structural complexity of such materials. Considering the parameters as random variables, this paper uses the generalized polynomial chaos (gPC) expansion to capture the uncertainty in the damping and frequency response function of composite plate structures. A spectral stochastic finite element formulation for damped vibration analysis of laminate plates is employed. Experimental modal data for samples of plates is used to identify and realize the range and probability distributions of uncertain damping parameters. The constructed gPC expansions for the uncertain parameters are used as inputs to a deterministic finite element model to realize random frequency responses on a few numbers of collocation points generated in random space. The realizations then are employed to estimate the unknown deterministic functions of the gPC expansion approximating the responses. Employing modal superposition method to solve harmonic analysis problem yields an efficient sparse gPC expansion representing the responses. The results show while the responses are influenced by the damping uncertainties at the mid and high frequency ranges, the impact in low frequency modes can be safely ignored. Utilizing a few random collocation points, the method indicates also a very good agreement compared to the sampling-based Monte Carlo simulations with large number of realizations. As the deterministic finite element model serves as black-box solver, the procedure can be efficiently adopted to complex structural systems with uncertain parameters in terms of computational time.

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ABSTRACT: Piezoelectric sensors are effective for distributed health monitoring and sensing of structures. The signals of piezoelectric sensors are related to the orientation of the sensors. In this study, a diagonal piezoelectric sensor is proposed for cylindrical shells. The sensor is made of a rectangular piezoelectric patch and diagonally attached on the shell surface; and piezoelectric actuators are used for excitation. An analytical model of the sensor is derived based on thin shell assumption with simply-supported boundary conditions. The orientation angle of the piezoelectric sensor is introduced as an independent variable. The proposed model consists of an integral term over the electrode area, which is divided into three regions for calculation. The sensing signal is decomposed into six components to evaluate the contributions of the strain components. Case studies on signals with respect to the orientation and aspect ratios are accomplished. The cylindrical shell with piezoelectric actuators and diagonal sensors is fabricated and tested under laboratory condition. Comparison of theoretical results with experimental data is conducted, and the model of the diagonal sensors is validated. The errors between the predictions and experimental results are less than 10% for all evaluated modes.

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ABSTRACT: The flexural-wave attenuation performance of traditional constraint-layer damping in a sandwich beam is improved by using periodic constrained-layer damping (PCLD), where the monolithic viscoelastic core is replaced with two periodically alternating viscoelastic cores. Closed-form solutions of the wave propagation constants of the infinite periodic sandwich beam and the forced response of the corresponding finite sandwich structure are theoretically derived, providing computational support on the analysis of attenuation characteristics. In a sandwich beam with PCLD, the flexural waves can be attenuated by both Bragg scattering effect and damping effect, where the attenuation level is mainly dominated by Bragg scattering in the band-gaps and by damping in the pass-bands. Affected by these two effects, when the parameters of periodic cores are properly selected, a sandwich beam with PCLD can effectively reduce vibrations of much lower frequencies than that with traditional constrained-layer damping. The effects of the parameters of viscoelastic periodic cores on band-gap properties are also discussed, showing that the average attenuation in the desired frequency band can be maximized by tuning the length ratio and core thickness to proper values. The research in this paper could possibly provide useful information for the researches and engineers to design damping structures.

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ABSTRACT: This paper presents a simulation study concerning the low and mid frequencies control of flexural vibration in a lightly damped thin plate equipped with five time-varying shunted piezoelectric patch absorbers. The panel is excited by a rain-on-the-roof broad frequency band stationary disturbance. The absorbers are composed by piezoelectric patches connected to time-varying RL shunt circuits. Discrete or continuous variations over time of the shunts are implemented in such a way as to either switch, between given values, or
sweep, within certain ranges, the natural frequency and damping factor of the electro-mechanical absorbers to control either the resonant response of targeted flexural modes of the plate with natural frequency comprised between 30 Hz and 1 kHz or to control the resonant responses of all flexural modes with natural frequencies comprised between 30 Hz and 1 kHz. The proposed system is firstly presented; then, the vibration control effects produced by a single patch and by the array of five patches implementing the switching and sweeping shunts are investigated. Both time-varying operation modes produce significant vibration control effects, with reductions of the resonance peaks of the target resonances or target frequency band up to 12 dB. The piezoelectric patch absorbers with sweeping shunts offer an interesting practical solution since they are operated blindly, thus they do not require a system identification during installation and effectively work without on line tuning also on systems whose response may vary substantially in time.

ABSTRACT: Structural model for a slender and uniform pipe conveying fluid, with axially moving supports on both ends, immersed in an incompressible fluid, is formulated. Free vibration and stability of the system are studied through numerical calculation. First, the equations of motion of the system are derived in an absolute coordinate system. An "axial added mass coefficient" is adopted to amend the forces caused by the external fluid. Boundary conditions are fixed by using coordinated conversion. Then, numerical results of the natural frequency are obtained via the Galerkin method, both for pinned-pinned and clamped-clamped supports. The critical speeds of supports and several instability types are discussed. Last, the effects of the system parameters on the dynamics and instability of the system are investigated.

M.R. Delfani (Faculty of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran), “Extended theory of elastica for free torsional, longitudinal, and radial breathing vibrations of single-walled carbon nanotubes”, Journal of Sound and Vibration, pp 104-128, September 2017 https://doi.org/10.1016/j.jsv.2017.05.020
ABSTRACT: Single-walled carbon nanotube (SWCNT) can be viewed as a two-dimensional elastica obtained from rolling up graphene into a cylinder. By extending the formulation of elastica to dynamic problems, the present study provides an analysis for free torsional, longitudinal, and radial breathing vibrations of SWCNTs. With incorporating the effects of both geometrical and material nonlinearities, the exact closed-form expressions are obtained for the deformation field and the natural angular frequency of the elastica corresponding to the freely vibrating SWCNT. It is shown that torsional, longitudinal, and radial breathing modes of deformation are coupled to each other in free vibration of SWCNTs. However, for the special cases of zigzag and armchair SWCNTs as well as the limiting case of large-radius SWCNTs, torsional mode of deformation is decoupled from the other two modes.

ABSTRACT: In many applications, lightweight structures need to combine outstanding component properties and low weight. Here, fibre-reinforced polymers offer particular advantages, as their material-inherent anisotropic material damping behaviour facilitates the design of lightweight structures with both low sound
radiation levels and low mass. At the same time, composite structures often have to fulfil a high level of stiffness and strength. These manifold requirements result in a complex design process with optimisation scenarios often involving contrary objectives in terms of weight, stiffness and sound radiation. Those objectives are in turn accompanied by many different design variables. The aim of the work presented in this paper was therefore to develop a material-specific design strategy for scenarios of this type. The authors developed semi-analytical models for the calculation of structural dynamics and sound radiation in composite structures before combining them with optimisation algorithms in order to perform effective sensitivity analyses. Parametric studies were used to define material-specific input parameters for physical characteristics, which in turn provided a basis for the detailed numerical simulation of the vibro-acoustic behaviour of complex geometries. This paper uses a trough-shaped structure as an application-oriented example of the optimisation of vibro-acoustic behaviour with the aid of the numerical model developed by the authors.


ABSTRACT: This paper is focused on the analysis of complex rotating structures subjected to plausible operating conditions. Effects of the temperature gradient and the centrifugal stiffening contribution have been evaluated. In particular, the analyses have been performed considering disks with constant and variable thicknesses, which have been assumed either clamped at the bore or supported by a deformable shaft. The prestress contributions have been obtained through the integration of the three-dimensional stress state, which is generated by centrifugal and thermal loads, multiplied by the non-linear terms of the strain field. The weak form of the governing equations has been solved using the Finite Element method. High-fidelity one-dimensional elements have been developed according to the Carrera Unified Formulation. The comparisons between the current results and those obtained from solid finite element solutions have demonstrated that the proposed methodology can represent a valuable alternative to the three-dimensional modelling technique by ensuring a comparable accuracy with a lower computational effort.

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ABSTRACT: This paper presents the dynamical model involved with load of fluid pressure, electric-solid coupling simulation and experimental performance of the piezoelectric diaphragm fabricated and applied in valveless micropump. The model is based on the theory of plate-shell with small deflection, considering the two-layer structure of piezoelectric ceramic and elastic substrate. The high-order non-homogeneous vibration equation of the piezoelectric diaphragm, derived in the course of the study, was solved by being divided into a homogeneous Bessel equation and a non-homogeneous static equation according to the superposition principle. The amplitude of the piezoelectric diaphragm driven by sinusoidal voltage against the load of fluid pressure was obtained from the solution of the vibration equation. Also, finite element simulation of electric-solid coupling between displacement of piezoelectric diaphragm due to an applied voltage and resulting deformation of
membrane was considered. The simulation result showed that the maximum deflection of diaphragm is 9.51 μm at a quarter cycle time when applied a peak-to-peak voltage of 150V_{p-p} with a frequency of 90 Hz, and the displacement distribution according to the direction of the radius was demonstrated. Experiments were performed to verify the prediction of the dynamic modeling and the coupling simulation, the experimental data showed a good agreement with the dynamical model and simulation.


ABSTRACT: The objective of this investigation is to develop a new total Lagrangian continuum-based liquid sloshing model that can be systematically integrated with multibody system (MBS) algorithms in order to allow for studying complex motion scenarios. The new approach allows for accurately capturing the effect of the sloshing forces during curve negotiation, rapid lane change, and accelerating and braking scenarios. In these motion scenarios, the liquid experiences large displacements and significant changes in shape that can be captured effectively using the finite element (FE) absolute nodal coordinate formulation (ANCF). ANCF elements are used in this investigation to describe complex mesh geometries, to capture the change in inertia due to the change in the fluid shape, and to accurately calculate the centrifugal forces, which for flexible bodies do not take the simple form used in rigid body dynamics. A penalty formulation is used to define the contact between the rigid tank walls and the fluid. A fully nonlinear MBS truck model that includes a suspension system and Pacejka's brush tire model is developed. Specified motion trajectories are used to examine the vehicle dynamics in three different scenarios – deceleration during straight-line motion, rapid lane change, and curve negotiation. It is demonstrated that the liquid sloshing changes the contact forces between the tires and the ground – increasing the forces on certain wheels and decreasing the forces on other wheels. In cases of extreme sloshing, this dynamic behavior can negatively impact the vehicle stability by increasing the possibility of wheel lift and vehicle rollover.

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ABSTRACT: A random vibration analysis of an axially compressed cylindrical shell under a turbulent boundary layer (TBL) is presented in the symplectic duality system. By expressing the cross power spectral density (PSD) of the TBL as a Fourier series in the axial and circumferential directions, the problem of structures excited by a random distributed pressure due to the TBL is reduced to solving the harmonic response function, which is the response of structures to a spatial and temporal harmonic pressure of unit magnitude. The governing differential equations of the axially compressed cylindrical shell are derived in the symplectic duality system, and then a symplectic eigenproblem is formed by using the method of separation of variables. Expanding the excitation vector and unknown state vector in symplectic space, decoupled governing equations are derived, and then the analytical solution can be obtained. In contrast to the modal decomposition method (MDM), the present method is formulated in the symplectic duality system and does not need modal truncation,
and hence the computations are of high precision and efficiency. In numerical examples, harmonic response functions for the axially compressed cylindrical shell are studied, and a comparison is made with the MDM to verify the present method. Then, the random responses of the shell to the TBL are obtained by the present method, and the convergence problems induced by Fourier series expansion are discussed. Finally, influences of the axial compression on random responses are investigated.

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ABSTRACT: Tire vibration characteristics influence noise, vibration, and harshness. Hence, there have been many investigations of the dynamic responses of tires. In this paper, we present new formulations for the prediction of tire tread vibrations below 150 Hz using a three-dimensional flexible ring-based model. The ring represents the tread including the belt, and the springs represent the tire sidewall stiffness. The equations of motion for lateral, longitudinal, and radial vibration on the tread are derived based on the assumption of inextensional deformation. Many of the associated numerical parameters are identified from experimental tests. Unlike most studies of flexible ring models, which mainly discussed radial and circumferential vibration, this study presents steady response functions concerning not only radial and circumferential but also lateral vibration using the three-dimensional flexible ring-based model. The results of impact tests described confirm the theoretical findings. The results show reasonable agreement with the predictions.

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ABSTRACT: This work presents an experimental and numerical study on the flexural vibration of horizontal circular tubes partially filled with liquid. The tube is configured as a free-free beam with attention being directed to the case of small amplitudes of transverse oscillation whereas the axial movements of the tube and liquid are disregarded. At first vertical and horizontal polarizations of the flexural tube are investigated experimentally for different amounts of filling liquid. In contrast with the empty and fully-filled tubes, it is
observed that natural frequencies of the vertical and horizontal polarizations are different due to asymmetry induced by the liquid layer, which acts like an added mass. Less mass of liquid is added to the tube when oscillating horizontally; as a consequence, eigenfrequencies for the horizontal polarization are found to be greater than the case of the vertically polarized tube. A simple method to calculate the natural vibration frequencies using coefficients of added mass of liquid is proposed. It is shown that the added mass coefficient increases with the liquid's level and viscosity. At last a numerical investigation of the interaction between the liquid and the tube is carried out by solving in two-dimensions the full Navier-Stokes equations via a finite volume method, with the free-surface flow being modeled with a homogeneous multiphase Eulerian-Eulerian fluid approach. Vertical and horizontal polarizations are imposed to the tube with pressure and shear stresses being determined numerically to assess the liquid's forcing onto the tube's wall. The coefficient of added mass of liquid is then estimated by the ratio between the resulting force and the acceleration imposed to the wall. A good agreement is found between experimental and numerical results, especially for the horizontally oscillating tube. It is also shown that viscosity can noticeably affect the added mass coefficients, particularly at low filling levels.

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ABSTRACT: Structurally radiated sound power is a critical design parameter. The acoustic radiation mode approach for computing sound power was developed in the early 1990s and has since been widely used. It has been shown to be a rather efficient approach for determining the radiated sound power. In previous research, radiation mode expressions have been developed for planar and spherical structures, as well as axisymmetric modes of internal and external radiation from cylinders. In this work, the radiation modes for external radiating cylinders which account for both axial and circumferential dependence are presented. The expressions are uniquely developed using cylindrical basis functions which are a more natural match to the geometry than past developments, which have been based on spherical harmonics. Higher order radiation modes than have been previously presented are shown. The “leapfrog effect”, whereby higher order modes leapfrog over lower modes in terms of their radiation efficiencies as the frequency goes above the cut-on frequency for those modes, is discussed in detail. The relationships between the mode efficiency and the coincidence effect associated with the cut-on frequencies of the vibration modes are described.

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ABSTRACT: In future, wings will be deployed in the span direction during flight. The deployment system improves flight ability and saves storage space in the airplane. For the safe design of the wing, the deployment motion needs to be simulated. In the simulation, the structural flexibility and aerodynamic unsteadiness should be considered because they may lead to undesirable phenomena such as a residual vibration after the
deployment or a flutter during the deployment. In this study, the deployment motion is simulated in the time
domain by using a nonlinear folding wing model based on multibody dynamics, absolute nodal coordinate
formulation, and two-dimensional aerodynamics with strip theory. We investigate the effect of the structural
flexibility and aerodynamic unsteadiness on the time-domain deployment simulation.

Amit Yadav, Sarat Kumar Panda and Tanish Dey (Department of Civil Engineering, Indian Institute of
Technology (ISM), Dhanbad, India), “Non-linear dynamic instability analysis of thin-walled stiffener beam
subjected to uniform harmonic in-plane loading”, Journal of Sound and Vibration, Vol. 408, pp 383-399,
ABSTRACT: Present analysis deals with nonlinear flexural-torsional vibration and dynamic instability of thin-
walled stiffener beam with open section subjected to harmonic in-plane loading. The static and dynamic
components of the applied harmonic in-plane loading are assumed to vary uniformly. A set of nonlinear partial
differential equations (PDEs) describing the vibration of system is derived. Using Galerkin's method, these
partial differential equations are reduced into coupled Mathieu equations. The steady state response of the
system is determined by solving the condition for a non-trivial solution. The principal regions of parametric
resonance are determined using the method suggested by Bolotin. The numerical results are presented to
investigate the effect of aspect ratios, boundary conditions and static load factor on the frequency-amplitude
responses and instability regions.

Julia Winroth, Wolfgang Kropp, Carsten Koever and Patrik Hoestmad (Division of Applied Acoustics,
Department of Civil and Environmental Engineering, Chalmers University of Technology, SE-41296 Göteborg,
Sweden), “Contact stiffness considerations when simulating tyre/road noise”, Journal of Sound and Vibration,
ABSTRACT: Tyre/road simulation tools that can capture tyre vibrations, rolling resistance and noise generation
are useful for understanding the complex processes that are involved and thereby promoting further
development and optimisation. The most detailed tyre/road contact models use a spatial discretisation of the
contact and assume an interfacial stiffness to account for the small-scale roughness within the elements. This
interfacial stiffness has been found to have a significant impact on the simulated noise emissions but no
thorough investigations of this sensitivity have been conducted. Three mechanisms are thought to be involved:
The horn effect, the modal composition of the vibrational field of the tyre and the contact forces exciting the
tyre vibrations. This study used a numerical tyre/road noise simulation tool based on physical relations to
investigate these aspects. The model includes a detailed time-domain contact model with linear or non-linear
contact springs that accounts for the effect of local tread deformation on smaller length scales. Results confirm
that an increase in contact spring stiffness causes a significant increase of the simulated tyre/road noise. This is
primarily caused by a corresponding increase in the contact forces, resulting in larger vibrational amplitudes.
The horn effect and the modal composition are relatively unaffected and have minor effects on the radiated
noise. A more detailed non-linear contact spring formulation with lower stiffness at small indentations results in
a reduced high-frequency content in the contact forces and the simulated noise.

Ali Loghmani, Mohammad Danesh, Moon K. Kwak and Mehdi Keshmin (Primarily from: Department of
Mechanical Engineering, Isfahan University of Technology, 84156-83111, Isfahan, Iran), “Vibration
suppression of a piezo-equipped cylindrical shell in a broad-band frequency domain”, Journal of Sound and
ABSTRACT: This paper focuses on the dynamic modeling of a cylindrical shell equipped with piezoceramic sensors and actuators, as well as the design of a broad band multi-input and multi-output linear quadratic Gaussian controller for the suppression of vibrations. The optimal locations of actuators are derived by Genetic Algorithm (GA) to effectively control the specific structural modes of the cylinder. The dynamic model is derived based on the Sanders shell theory and the energy approach for both the cylinder and the piezoelectric transducers, all of which reflect the piezoelectric effect. The natural vibration characteristics of the cylindrical shell are investigated both theoretically and experimentally. The theoretical predictions are in good agreement with the experimental results. Then, the broad band multi-input and multi-output linear quadratic Gaussian controller was designed and applied to the test article. An active vibration control experiment is carried out on the cylindrical shell and the digital control system is used to implement the proposed control algorithm. The experimental results show that vibrations of the cylindrical shell can be suppressed by the piezoceramic sensors and actuators along with the proposed controller. The optimal location of the actuators makes the proposed control system more efficient than other configurations.


ABSTRACT: An analytical model is developed to study the sound transmission loss through a general double-walled cylindrical shell system with one or two walls perforated, which is excited by a plane wave in the presence of external mean flow. The shell motion is governed by the classical Donnell's thin shell theory, and the mean particle velocity model is employed to describe boundary conditions at interfaces between the shells and fluid media. In contrast to the conventional solid double-walled shell system, numerical results show that perforating the inner shell in the transmission side improves sound insulation performance over a wide frequency band, and removes fluctuation of sound transmission loss with frequency at mid-frequencies in the absence of external flow. Both the incidence and azimuthal angles have nearly negligible effect on the sound transmission loss over the low and middle frequency range when perforating the inner shell. Width of the frequency band with continuous sound transmission loss can be tuned by the perforation ratio.


ABSTRACT: The paper summarises the experimental investigations and numerical simulations of non-planar parametric vibrations of a statically deformed pipe. Underpinning the theoretical analysis is a 3D dynamic model of curved pipe. The pipe motion is governed by four non-linear partial differential equations with periodically varying coefficients. The Galerkin method was applied, the shape function being that governing the beam's natural vibrations. Experiments were conducted in the range of simple and combination parametric resonances, evidencing the possibility of in-plane and out-of-plane vibrations as well as fully non-planar vibrations in the combination resonance range. It is demonstrated that sub-harmonic and quasi-periodic vibrations are likely to be excited. The method suggested allows the spatial modes to be determined basing on results registered at selected points in the pipe. Results are summarised in the form of time histories, phase trajectory plots and spectral diagrams. Dedicated video materials give us a better insight into the investigated phenomena.

ABSTRACT: In most of the active flutter controls, the feedback control gains are selected arbitrarily or by trial and error. These methods are inaccurate and time-consuming. In the present study, a smart and optimal method is proposed to investigate the thermal flutter control of composite laminated panels in supersonic airflow based on a genetic algorithm (GA), in which the feedback control gains of all the piezoelectric actuators are represented by the chromosomes and the fitness is set to be the difference between the present flutter bound and the expected one. Then, according to the GA process, a set of optimal feedback control gains can be obtained, and the flutter bounds of the structural system can be suppressed to any expected values by means of the optimal control gains. Furthermore, the maximum flutter bound of the panel and the corresponding feedback control gains can also be obtained. In the investigations, the aerodynamic pressure is evaluated by the supersonic piston theory and the controller is designed by the displacement feedback method. The influences of the placements of piezoelectric patches on the active flutter control effects are analyzed. Some interesting phenomena are obtained and discussed.

Kang Gao, Wei Gao, Di Wu and Chongmin Song, “Nonlinear dynamic stability of the orthotropic functionally graded cylindrical shell surrounded by Winkler-Pasternak elastic foundation subjected to a linearly increasing load”, Journal of Sound and Vibration, Vol. 415, pp 147-168, February 2018

ABSTRACT: This paper focuses on the dynamic stability behaviors of the functionally graded (FG) orthotropic circular cylindrical shell surrounded by the two-parameter (Winkler-Pasternak) elastic foundation subjected to a linearly increasing load with the consideration of damping effect. The material properties are assumed to vary gradually in the thickness direction based on an exponential distribution function of the volume fraction of constituent materials. Equations of motion are derived from Hamilton's principle and the nonlinear compatibility equation is considered by the means of modified Donnell shell theory including large deflection. Then the nonlinear dynamic buckling equation is solved by a hybrid analytical-numerical method (combined Galerkin method and fourth-order Runge-Kutta method). The nonlinear dynamic stability of the FG orthotropic cylindrical shell is assessed based on Budiansky-Roth criterion. Additionally, effects of different parameters such as various inhomogeneous parameters, loading speeds, damping ratios and aspect ratios and thickness ratios of the structure on dynamic buckling are discussed in details. Finally, the proposed method is validated with published literature.


ABSTRACT: The conditions under which significant modal cross-coupling occurs in dynamical systems responding to high-frequency, broadband forcing that excites many modes is studied. The modal overlap factor plays a key role in the analysis of these systems as the modal density (the ratio of number of modes to the frequency bandwidth) becomes large. The modal overlap factor is effectively the ratio of the width of a resonant peak (the damping ratio times the resonant frequency) to the average frequency interval between resonant peaks (or rather, the inverse of the modal density). It is shown that this parameter largely determines whether substantial modal cross-coupling occurs in a given system's response. Here, two prototypical systems are considered. The first is a simple rectangular plate whose significant modal cross-coupling is the exception rather than the norm. The second is a pair of rectangular plates attached at a point where significant modal cross-coupling is more likely to occur. We show that, for certain cases of modal density and damping, non-negligible cross coupling occurs in both systems. Under similar circumstances, the constraint force between the two plates
in the latter system becomes broadband. The implications of this for using Asymptotic Modal Analysis (AMA) in multi-component systems are discussed.

Feng Liang, Xiao-Dong Yang, Wei Zhang and Ying-Jing Qian, “Dynamical modeling and free vibration analysis of spinning pipes conveying fluid with axial deployment”, Journal of Sound and Vibration, Vol. 417, pp 65-79, March 2018
ABSTRACT: In this paper, a dynamical model of simply-supported spinning pipes conveying fluid with axial deployment is proposed and the transverse free vibration and stability for such a doubly gyroscopic system involving time-dependent parameters are investigated. The partial differential equations of motion are derived by the extended Hamilton principle and then truncated by the Galerkin technique. The time-variant frequencies, mode shapes and responses to initial conditions are comprehensively investigated to reveal the dynamical essence of the system. It is indicated that the qualitative stability evolution of the system mainly depends on the effect of fluid-structure interaction (FSI), while the spinning motion will enhance the pipe rigidity and eliminate the buckling instability. The dynamical evolution of a retracting pipe is almost inverse to that of the deploying one. The pipe possesses different mode configurations of spatial curves as the pipe length increases and some modal and response characteristics of the present system are found rather distinct from those of deploying cantilevered structures.

ABSTRACT: The paper addresses the classical problem of time-harmonic forced vibrations of a fluid-filled cylindrical shell considered as a multi-modal waveguide carrying infinitely many waves. The forced vibration problem is solved using tailored Green's matrices formulated in terms of eigenfunction expansions. The formulation of Green's matrix is based on special (bi-)orthogonality relations between the eigenfunctions, which are derived here for the fluid-filled shell. Further, the relations are generalised to any multi-modal symmetric waveguide. Using the orthogonality relations the transcendental equation system is converted into algebraic modal equations that can be solved analytically. Upon formulation of Green's matrices the solution space is studied in terms of completeness and convergence (uniformity and rate). Special features and findings exposed only through this modal decomposition method are elaborated and the physical interpretation of the bi-orthogonality relation is discussed in relation to the total energy flow which leads to derivation of simplified equations for the energy flow components.

Jie Hong, Xueqing He, Dayi Zhang, Bing Zhang and Yanhong Ma, “Vibration isolation design for periodically stiffened shells by the wave finite element method”, Journal of Sound and Vibration, Vol. 419, pp 90-102, April 2018
ABSTRACT: Periodically stiffened shell structures are widely used due to their excellent specific strength, in particular for aeronautical and astronautical components. This paper presents an improved Wave Finite Element Method (FEM) that can be employed to predict the band-gap characteristics of stiffened shell structures efficiently. An aero-engine casing, which is a typical periodically stiffened shell structure, was employed to verify the validation and efficiency of the Wave FEM. Good agreement has been found between the Wave FEM and the classical FEM for different boundary conditions. One effective wave selection method based on the Wave FEM has thus been put forward to filter the radial modes of a shell structure. Furthermore, an optimisation strategy by the combination of the Wave FEM and genetic algorithm was presented for periodically stiffened shell structures. The optimal out-of-plane band gap and the mass of the whole structure can be achieved by the optimisation strategy under an aerodynamic load. Results also indicate that geometric
parameters of stiffeners can be properly selected that the out-of-plane vibration attenuates significantly in the frequency band of interest. This study can provide valuable references for designing the band gaps of vibration isolation.

S. Oberst, S.L. Tuttle, D. Griffin, A. Lambert and R.R. Boyce, “Experimental validation of tape springs to be used as thin-walled space structures”, Journal of Sound and Vibration, Vol. 419, pp 558-570, April 2018

ABSTRACT: With the advent of standardised launch geometries and off-the-shelf payloads, space programs utilising nano-satellite platforms are growing worldwide. Thin-walled, flexible and self-deployable structures are commonly used for antennae, instrument booms or solar panels owing to their lightweight, ideal packaging characteristics and near zero energy consumption. However their behaviour in space, in particular in Low Earth Orbits with continually changing environmental conditions, raises many questions. Accurate numerical models, which are often not available due to the difficulty of experimental testing under 1g-conditions, are needed to answer these questions. In this study, we present on-earth experimental validations, as a starting point to study the response of a tape spring as a representative of thin-walled flexible structures under static and vibrational loading. Material parameters of tape springs in a singly (straight, open cylinder) and a doubly curved design, are compared to each other by combining finite element calculations, with experimental laser vibrometry within a single and multi-stage model updating approach. While the determination of the Young’s modulus is unproblematic, the damping is found to be inversely proportional to deployment length. With updated material properties the buckling instability margin is calculated using different slenderness ratios. Results indicate a high sensitivity of thin-walled structures to miniscule perturbations, which makes proper experimental testing a key requirement for stability prediction on thin-elastic space structures. The doubly curved tape spring provides closer agreement with experimental results than a straight tape spring design.


ABSTRACT: The present study examines the nonlinear behaviour of a cantilevered carbon nanotube (CNT) resonator and its mass detection sensitivity, employing a new nonlinear electrostatic load model. More specifically, a 3D finite element model is developed in order to obtain the electrostatic load distribution on cantilevered CNT resonators. A new nonlinear electrostatic load model is then proposed accounting for the end effects due to finite length. Additionally, a new nonlinear size-dependent continuum model is developed for the cantilevered CNT resonator, employing the modified couple stress theory (to account for size-effects) together with the Kelvin-Voigt model (to account for nonlinear damping); the size-dependent model takes into account all sources of nonlinearity, i.e. geometrical and inertial nonlinearities as well as nonlinearities associated with damping, small-scale, and electrostatic load. The nonlinear equation of motion of the cantilevered CNT resonator is obtained based on the new models developed for the CNT resonator and the electrostatic load. The Galerkin method is then applied to the nonlinear equation of motion, resulting in a set of nonlinear ordinary differential equations, consisting of geometrical, inertial, electrical, damping, and size-dependent nonlinear terms. This high-dimensional nonlinear discretized model is solved numerically utilizing the pseudo-arclength continuation technique. The nonlinear static and dynamic responses of the system are examined for various cases, investigating the effect of DC and AC voltages, length-scale parameter, nonlinear damping, and electrostatic load. Moreover, the mass detection sensitivity of the system is examined for possible application of the CNT resonator as a nanosensor.

ABSTRACT: A dynamic model of a coupled rotating drum-disk system with elastic support is developed in this paper. By considering the effects of centrifugal and Coriolis forces as well as rotation-induced hoop stress, the governing differential equation of the drum-disk is derived by Donnell's shell theory. The nonlinear amplitude-frequency characteristics of coupled structure are studied. The results indicate that the natural characteristics of the coupling structure are sensitive to the supporting stiffness of the disk, and the sensitive range is affected by rotating speeds. The circumferential wave numbers can affect the characteristics of the drum-disk structure. If the circumferential wave number, the vibration response of the drum keeps a stable value under an unbalanced load of the disk, there is no coupling effect if . Under the excitation, the nonlinear hardening characteristics of the forward traveling wave are more evident than that of the backward traveling wave. Moreover, because of the coupling effect of the drum and the disk, the supporting stiffness of the disk has certain effect on the nonlinear characteristics of the forward and backward traveling waves. In addition, small length-radius and thickness-radius ratios have a significant effect on the nonlinear characteristics of the coupled structure, which means nonlinear shell theory should be adopted to design rotating drum's parameter for its specific structural parameters.


ABSTRACT: Soft materials can be designed with a functionally graded (FG) property for specific applications. Such material inhomogeneity can also be found in many soft biological tissues whose functionality is only partly understood to date. In this paper, we analyze the axisymmetric guided wave propagation in a pressurized FG elastomeric hollow cylinder. The cylinder is subjected to a combined action of axial pre-stretch and pressure difference applied to the inner and outer cylindrical surfaces. We consider both torsional waves and longitudinal waves propagating in the FG cylinder made of incompressible isotropic elastomer, which is characterized by the Mooney-Rivlin strain energy function but with the material parameters varying with the radial coordinate in an affine way. The pressure difference generates an inhomogeneous deformation field in the FG cylinder, which dramatically complicates the superimposed wave problem described by the small-on-large theory. A particularly efficient approach is hence employed which combines the state-space formalism for the incremental wave motion with the approximate laminate or multi-layer technique. Dispersion relations for the two types of axisymmetric guided waves are then derived analytically. The accuracy and convergence of the proposed approach is validated numerically. The effects of the pressure difference, material gradient, and axial pre-stretch on both the torsional and the longitudinal wave propagation characteristics are discussed in detail through numerical examples. It is found that the frequency of axisymmetric waves depends non-linearly on the pressure difference and the material gradient, and an increase in the material gradient enhances the capability of the pressure difference to adjust the wave behavior in the FG cylinder. This work provides a theoretical guidance for characterizing FG soft materials by in-situ ultrasonic nondestructive evaluation and for designing tunable waveguides via material tailoring along with an adjustment of the pre-stretch and pressure difference.


ABSTRACT: The present study develops a new three-dimensional nonlinear model for investigating vortex-induced vibrations (VIV) of flexible pipes conveying internal fluid flow. The unsteady hydrodynamic forces associated with the wake dynamics are modeled by two distributed van der Pol wake oscillators. In particular, the nonlinear partial differential equations of motion of the pipe and the wake are derived, taking into account the coupling between the structure and the fluid. The nonlinear equations of motion for the coupled system are
then discretized by means of the Galerkin technique, resulting in a high-dimensional reduced-order model of the system. It is shown that the natural frequencies for in-plane and out-of-plane motions of the pipe may be different at high internal flow velocities beyond the threshold of buckling instability. The orientation angle of the postbuckling configuration is time-varying due to the disturbance of hydrodynamic forces, thus yielding sometimes unexpected results. For a buckled pipe with relatively low cross-flow velocity, interestingly, examining the nonlinear dynamics of the pipe indicates that the combined effects of the cross-flow-induced resonance of the in-plane first mode and the internal-flow-induced buckling on the IL and CF oscillation amplitudes may be significant. For higher cross-flow velocities, however, the effect of internal fluid flow on the nonlinear VIV responses of the pipe is not pronounced.


ABSTRACT: The sound-structure coupling problem of a cylindrical shell submerged in a quarter water domain is studied. A semi-analytical method based on the double wave reflection method and the Graf's addition theorem is proposed to solve the vibration and acoustic radiation of an infinite cylindrical shell excited by an axially uniform harmonic line force, in which the acoustic boundary conditions consist of a free surface and a vertical rigid surface. The influences of the complex acoustic boundary conditions on the vibration and acoustic radiation of the cylindrical shell are discussed. It is found that the complex acoustic boundary has crucial influence on the vibration of the cylindrical shell when the cylindrical shell approaches the boundary, and the influence tends to vanish when the distances between the cylindrical shell and the boundaries exceed certain values. However, the influence of the complex acoustic boundary on the far-field sound pressure of the cylindrical shell cannot be ignored. The far-field acoustic directivity of the cylindrical shell varies with the distances between the cylindrical shell and the boundaries, besides the driving frequency. The work provides more understanding on the vibration and acoustic radiation behaviors of cylindrical shells with complex acoustic boundary conditions.


ABSTRACT: · Computationally efficient multiscale modelling based on Cauchy–Born rule in conjunction with finite element method is employed to study static and dynamic characteristics of graphene sheets, with/without considering initial strain, involving Green–Lagrange geometric and material nonlinearities. The strain energy density function at continuum level is established by coupling the deformation at continuum level to that at atomic level through Cauchy–Born rule. The atomic interactions between carbon atoms are modelled through Tersoff–Brenner potential. The governing equation of motion obtained using Hamilton's principle is solved through standard Newton–Raphson method for nonlinear static response and Newmark's time integration technique to obtain nonlinear transient response characteristics. Effect of initial strain on the linear free vibration frequencies, nonlinear static and dynamic response characteristics is investigated in detail. The present multiscale modelling based results are found to be in good agreement with those obtained through molecular mechanics simulation. Two different types of boundary constraints generally used in MM simulation are explored in detail and few interesting findings are brought out. The effect of initial strain is found to be greater in linear response when compared to that in nonlinear response.

ABSTRACT: This paper is focused on the resonant responses and chaotic dynamics of a composite laminated circular cylindrical shell with radially pre-stretched membranes at both ends and clamped along a generatrix. Based on the two-degree-of-freedom non-autonomous nonlinear equations of this system, the method of multiple scales is employed to obtain the four-dimensional nonlinear averaged equation. The resonant case considered here is the primary parametric resonance-1/2 subharmonic resonance and 1:1 internal resonance. Corresponding to several selected parameters, the frequency-response curves are obtained. From the numerical results, we find that the hardening-spring-type behaviors and jump phenomena are exhibited. The jump phenomena also occur in the amplitude curves of the temperature parameter excitation. Moreover, it is found that the temperature parameter excitation, the coupling degree of two order modes and the detuning parameters can effect the nonlinear oscillations of this system. The periodic and chaotic motions of the composite laminated circular cylindrical shell clamped along a generatrix are demonstrated by the bifurcation diagrams, the maximum Lyapunov exponents, the phase portraits, the waveforms, the power spectrums and the Poincaré map. The temperature parameter excitation shows that the Pomeau-Manneville type intermittent chaos occur under certain initial conditions. It is also found that there exist the twin phenomena between the Pomeau-Manneville type intermittent chaos and the period-doubling bifurcation.

ABSTRACT: Parametric non-linear vibrations of flexible cylindrical panels subjected to additive white noise are studied. The governing Marguerre equations are investigated using the finite difference method (FDM) of the second-order accuracy and the Runge-Kutta method. The considered mechanical structural member is treated as a system of many/infinite number of degrees of freedom (DoF). The dependence of chaotic vibrations on the number of DoFs is investigated. Reliability of results is guaranteed by comparing the results obtained using two qualitatively different methods to reduce the problem of PDEs (partial differential equations) to ODEs (ordinary differential equations), i.e. the Faedo-Galerkin method in higher approximations and the 4th and 6th order FDM. The Cauchy problem obtained by the FDM is eventually solved using the 4th-order Runge-Kutta methods. The numerical experiment yielded, for a certain set of parameters, the non-symmetric vibration modes/forms with and without white noise. In particular, it has been illustrated and discussed that action of white noise on chaotic vibrations implies quasi-periodicity, whereas the previously non-symmetric vibration modes are closer to symmetric ones.

ABSTRACT: In this paper, sound radiation modes of baffled cylinders have been derived by constructing the radiation resistance matrix analytically. By examining the characteristics of sound radiation modes, it is found that radiation coefficient of each radiation mode increases gradually with the increase of frequency while modal shapes of sound radiation modes of cylindrical shells show a weak dependence upon frequency. Based on understandings on sound radiation modes, vibro-acoustics behaviors of cylindrical shells have been analyzed. The vibration responses of cylindrical shells are described by modified Fourier series expansions and solved by Rayleigh-Ritz method involving Flügge shell theory. Then radiation efficiency of a resonance has been determined by examining whether the vibration pattern is in correspondence with a sound radiation mode possessing great radiation efficiency. Furthermore, effects of thickness and boundary conditions on sound radiation of cylindrical shells have been investigated. It is found that radiation efficiency of thicker shells is greater than thinner shells while shells with a clamped boundary constraint radiate sound more efficiently than simply supported shells under thin shell assumption.
ABSTRACT: The paper studies the transverse nonlinear vibration of an isotropic and homogeneous annular membrane spinning at constant angular velocity, under the action of a uniform transverse load. The equilibrium configuration of the membrane, clamped along the inner edge and free along the outer edge, and the natural frequencies of vibration of the membrane are calculated. A Galerkin procedure is used to determine a reduced order model describing the weakly nonlinear vibration of the membrane, and it is shown that near-resonance vibration can be modeled as a single degree of freedom Helmholtz-Duffing oscillator. A detailed study at vibration frequencies close to the fundamental, axisymmetric vibration mode shows a transition from softening to hardening behavior, and jump phenomena or hysteretic behavior depending on the angular velocity, the transverse load, the amplitude of dynamic excitation and the damping ratio. The results are in agreement with dynamic implicit finite element simulations in Abaqus/Standard and direct experimental measurements.

ABSTRACT: In this paper, the multi pocket structure is regarded as a combination of Kirchhoff plates. A semi analytical solutions for the vibration of this thin walled structure are obtained by the subdomain decomposition method which is proposed by the authors earlier. Thereafter, a dynamic cutting model concerning the cutting position and the vibration states is adopted to modelling the milling force. Both the vibration model and the dynamic cutting model are integrated together to establish the governing equation which fully consider the dynamic features for the thin wall milling process. Based on the quasi static hypothesis, the stability of the milling of thin walled structure can be regarded as the stability of cutting at a series of discrete points. And the semi discretization method is applied to analysis the stability for this thin wall milling process. It is found that the critical depth of cut is appropriately inversely proportional to the square of mode shape for each single mode. In addition, the influence of the multimode and the mode coupling effects on the milling stability are discussed. It gives clearer insight into the dynamics and stability for the milling processes of thin walled structure.

ABSTRACT: This paper studies optimum distributions of damping material in shell structures subject to impact loads by topology optimization. The optimization aims at reducing the residual vibration responses after the application of impact loads. In particular, the dependence of both structural forced vibration and residual vibration on the damping layer distribution is considered by transient dynamic responses based optimization approach. Until now, optimum distributions of damping material are always carried out based on frequency domain responses or structural dynamic characteristics. But for the studied problem, transient responses based optimization is more straightforward when the impact loads are known. When involving transient responses, the calculations of structural responses and sensitivities are always difficult and time-consuming. To deal with these problems, we use an integrated square performance measure of residual vibration as the objective function, which can be greatly simplified by Lyapunov equation, and use an efficient adjoint method to calculate the sensitivities. The topology optimization is implemented using the common solid isotropic material with penalization (SIMP) method. Numerical examples are carried out to illustrate the validity and utility of the proposed approach, and the numerical results also show the advantages of transient dynamic responses based optimization for the studied problem.

ABSTRACT: In this article, the vibroacoustic responses of laminated composite curved panels subjected to harmonic point excitation in a combined temperature and moisture environment are investigated numerically using a novel higher-order finite-boundary element model. The hygrothermal dependent composite material properties are incorporated macroscopically in the formulation. The governing equations are derived using the higher-order shear deformation shell theory coupled with finite and boundary element approach. First, the Hamilton's principle is employed to obtain the stiffness, mass tensors and modal values of the vibrating structure subjected to hygrothermal stresses. The acoustic radiation responses are then computed by solving the Helmholtz wave equation discretized on the structure boundary using boundary elements coupled with the structural finite elements. Compared to those reported in open literature, the results for natural frequencies, critical buckling temperature, critical buckling moisture and sound power level values computed using the present scheme are found to be more accurate. The sound power values are also acquired via a simulation model implemented using commercial tools ANSYS and LMS. Virtual Lab and compared with present numerical results. The scheme is further extended to solve numerous numerical examples highlighting the influence of hygrothermal loads, geometry, curvature ratio, modular ratio, support conditions and lamination scheme on the hygro-thermo-acoustic responses of laminated composite shell panels.


ABSTRACT: Nonlinear travelling wave vibrations of a rotating thin cylindrical shell are studied in the paper. Taking into account the effects of centrifugal and Coriolis forces as well as the initial hoop tension due to rotation, governing equations of the nonlinear rotating cylindrical shell with simply supported conditions are derived by using Lagrange equations. The model described by the governing equations is exact, which means no simplification procedures like neglecting all inertia terms on in-plane directions are carried out. Based on the exact model, numerical simulations are carried out to reveal some complex dynamic characteristics of nonlinear travelling wave vibrations, which are different from nonlinear (standing wave) vibrations in generic stationary shells. These results are presented in detail, including amplitude-frequency curves, bifurcation diagrams, time histories, phase portraits, poincaré maps and frequency spectrums.


ABSTRACT: This paper deals with the problem of applying electromagnetic devices of the motional type to improve the dynamic stability of a pipe conveying air. When the flow velocity reaches a critical value, the steady equilibrium position becomes unstable, and self-excited lateral vibrations arise. In contrast, electromagnetic devices of the transformer type have been demonstrated to be highly effective in the passive stabilization of such a system, as well as the active stabilization of similar non-conservative systems with a follower force. In the present paper, we apply a pair of motional devices made of a conducting plate which is attached to the pipe and moves together with it within the perpendicular magnetic field generated by the controlled electromagnets. This motion generates eddy currents in the plates and a drag force of a viscous character. In this setting, we first investigate the possibility of designing a stabilizing control within the region of the magnetic field where every passive solution results in an unstable or conservative state. For that purpose, we determine a practical condition justifying the existence of a stabilizing control for a given set of system
parameters. Later we pose and solve an optimal control problem aiming at stabilizing the system with the optimal rate of decrease of the system's energy. The solution is examined by means of numerical simulations performed within the three regions of the flow velocity: low subcritical, where the Coriolis acceleration of the conveyed fluid generates the predominate damping force; high subcritical, where the inertia of the fluid begins to dominate the dynamics of the system; and low supercritical, where unstable flutter vibrations start to arise. The effectiveness of the designed optimal controller is validated by comparisons with the corresponding passive solutions.


ABSTRACT: Comprising rigid bars and spring systems at the joints and in the cells, the Hencky bar-net model (HBM) has been shown to be a physical structural representation of the finite difference plate model (FDM). In this paper, the HBM is extended for the vibration analysis of rectangular plates with rectangular cutouts. This extension addresses the rotationally elastic and transverse spring stiffnesses for the HBM at the cutout corners. After verifying the HBM model by comparing the vibration results with existing solutions for some plate problems, the model is used to obtain some new free vibration solutions for plates having various boundary conditions including cracked corners modelled by free small rectangular cutouts.


ABSTRACT: This paper deals with the investigation of normal modes change of metallic structures, when subjected to geometrical nonlinearities in the large displacement/rotations field. Namely, a unified framework based on the Carrera Unified Formulation (CUF) and a total Lagrangian approach are employed to formulate higher order beam theories including geometric nonlinearities. Thus, a finite element approximation is used along with a path-following method to perform nonlinear analyses. Linearized vibration modes around equilibrium states and along the whole equilibrium path of structures subjected to bending and compression loadings are evaluated by solving a classical eigenvalue problem. In order to show the capabilities of the proposed methodology, both solid and thin-walled cross-section beams are considered. The analyses demonstrate that, with some differences depending on the geometry and both boundary and loading conditions, natural frequencies and modal shapes may change significantly as the structure is subjected to large displacements and rotations.


ABSTRACT: Most widely studied Structural Health Monitoring methods need baseline data from the undamaged state and a high number of sensors attached to the structure, which makes these methods difficult to be applied in real structures for on-line monitoring. In order to deal with that, the NOde DISplacement (NODIS) method is proposed by considering the structural damage indicator. The idea of the present work is to develop a baseline-free damage location and quantification method based on the node displacement of structural mode shapes. The damage location procedure is developed by combining the nodes from different mode shapes and the damage quantification is achieved by the proposed Transfer-Function-based Damage Indicator (TFDI). The advantages of this method are: (1) baseline-free, in terms of the comparison with a reference signal is not needed, (2) only a relatively small number of sensors is required for real-time damage location and (3) with the
proposed TFDI, the damage detection result can be quantified. In the present paper, the baseline-free damage location algorithm is proposed and validated on a steel beam with an analytical model, a numerical model and experiments. In addition, the influence of temperature, the additional weight of the sensor and the error in sensor location on the NODIS method are studied. After that, the TFDI is developed and improved for the experiment. Finally, the method is applied to a supporting structure of a sailplane under complex boundary condition and different environmental temperatures.


ABSTRACT: In this study, sound transmission through a thin-walled cylindrical shell is investigated both analytically and experimentally. A theoretical model based on statistical energy analysis (SEA) is developed in order to calculate the noise reduction and sound transmission loss of the cylindrical shell. The procedure to obtain the parameters involved in the SEA model, such as radiation efficiency and loss factors, is explained in detail. An experimental setup was constructed in a reverberation chamber to evaluate the transmission loss of the cylinder using two experimental methods. First the transmission suite method which includes measurements of the sound pressure levels inside and outside of the cylinder using microphones was used. Then the sound intensity method was used in which the transmitted sound intensity is measured with a sound intensity probe. The experimental results are compared with the analytical results obtained from the SEA theory, which shows good agreement. By comparing both experimental techniques, the transmission suite method is found to have advantages over the other method at low frequencies. However, the sound intensity method is more applicable in the medium and high frequency regions between the ring and critical frequencies in order to predict the noise transmission characteristics of the cylindrical shell. Another experiment was conducted with absorbing materials placed inside the cylinder. The use of sound absorbing material produced a significant reduction in the noise level in the cylinder specifically in the high frequency range. The effects of the absorption coefficient on the acoustical behavior of the cylindrical shell were also investigated theoretically.


ABSTRACT: Aircraft and spacecraft skin can undergo potentially destructive aeroelastic motions in high-speed flight. Reliable mathematical modelling is crucial for understanding such phenomena and aiding aerospace structural design. The panels of real skin structures are normally thin-walled elements riveted to beams and frames that act as stiffeners. In panel flutter literature, however, such stiffening components are normally idealised as perfectly immovable supports or, at best, as linear springs, which restricts the level of information to be obtained from the analyses. Aiming to better understand how the flexibility and mobility of stiffeners affect the aeroelastic behaviour of reinforced panels, the present work employs a more realistic model for skin structures. The Mindlin theory is used for the panel, and the stiffener is modelled as an eccentric Timoshenko beam. Geometrical non-linearity is added to both models, and the supersonic aerodynamic loads are calculated via linear piston theory. The Finite Element Method is employed for spatial discretisation, and an iterative Newmark-type scheme is used for time marching. Differently from what is typically done in the literature, the results are discussed not only from the standpoint of oscillation amplitudes, but also using energy distribution assessment. Solutions have been generated for several flow conditions and stiffener cross-sections. Comparison between the present results and those from a structurally-idealised model has demonstrated that modelling stiffeners as immovable boundaries overestimates flutter onset conditions and underestimates post-flutter amplitudes, thus being an unconservative simplification. Energy distribution analysis has shown that, for
reasonably flexible stiffeners, the aeroelastic system can bifurcate and move between two stable limit cycles, one of which displays larger energy levels. Furthermore, it has been shown that the total energy can be unevenly distributed along the structure during flutter, which can be used to determine suitable locations for control devices or energy sinks.


ABSTRACT: We operate a perturbation approach on the finite field equations for clamped slender arches with compact symmetric cross-section and parabolic centre curve under a uniform line load parallel to their symmetry axis. We study small vibration superposed on the relevant stress, assumed of membrane nature. We find the fundamental angular frequency in terms of the aspect ratio of the arch and of the pre-load; the possibility of buckling is examined. This is a first step towards monitoring such structures, and evaluating pre-loads and structural integrity by dynamic measurements.


ABSTRACT: In this paper, the coupled axial and transverse non-linear vibrations of a simply supported pipe, subjected to motion-limiting constraints, conveying pulsating fluid are investigated. The equations of motion are discretized into a set of coupled ordinary differential equations via Galerkin's method, which are then solved using Houbolt's method combined with Newton-Raphson iterative technique. The bifurcation diagrams are constructed to present the global dynamics of the system. Phase-plane portraits, Poincaré maps and power spectrum diagrams are plotted to show the characteristics of some typical motions, such as quasi-periodic and chaotic motions. Finally, the influence of axial motion on the system dynamics is investigated.


ABSTRACT: Environmental issues and energy crisis have caused the world attention to the renewable energies; especially the wind power, since they have low cost and high reliability. To achieve higher capacity, wind turbines have increased in their size over the years. However, the large size of the modern turbines has exacerbated the problem of vibrations, which results in lower efficiency and power generation. Because of the large deformations, the conventional linear theories cannot model the blades accurately, due to the importance of nonlinear effects in large scale wind turbines. In this research, a nonlinear kinematic model of the wind turbine blade is developed using the Hamilton's principle. This model is then simplified to three modal equations, two in flapwise direction and one in edgewise direction. These equations are then solved analytically using the multiple scales perturbation method, under the free vibration conditions including the non-resonance and internal resonance cases. In the non-resonance case, the accuracy of the perturbation method is compared with the numerical solutions. In the internal resonance case, the phenomenon of energy transfer between the modes is shown in three different conditions.

ABSTRACT: This paper presents a new approach to amplify the acoustic field generated by a uniform thickness piezoelectric cylindrical shell by introducing a stepped thickness variation at predetermined axial locations. The acoustic field and corresponding mode shapes of a uniform thickness piezoelectric tube are analyzed first and then, axial thickness variations are machined within the specified designed regions of the tube. The machining leads to the formation of thin-walled regions in the tube which localize the vibration amplitude within the machined spaces with higher amplitude. This results in a conspicuous increase of approximately 85% on average in the strength of the resultant acoustic field, though both specimens the uniform and stepped-thickness tubes have the same power consumption. The results of the simulations and experiments are in good agreement.


ABSTRACT: This paper presents an analytical study on linear and nonlinear free vibration characteristics and dynamic responses of spinning functionally graded (FG) graphene reinforced thin cylindrical shells with various boundary conditions and subjected to a static axial load. The weight fraction of graphene platelet (GPL) nanofillers in each concentric cylindrical layer is constant but follows a layer-wise variation through thickness direction, resulting in position-dependent elastic moduli, mass density and Poisson's ratio along the shell thickness. Based on the Donnell's nonlinear shell theory, the nonlinear partial differential equations of motion for the cylindrical shell are established by using the Hamilton's principle with the effects of centrifugal and Coriolis forces as well as the spin-induced initial hoop tension taken into account. The governing equations for nonlinear vibration of the nanocomposite cylindrical shell with different GPL dispersion patterns are derived from a set of nonlinear ordinary differential equations which are derived by employing the Galerkin approach. Dynamic responses of forward and backward travelling waves are investigated by analyzing the wave form and the frequency spectrum. Special attention is given to the effects of the weight fraction, dispersion patterns and the geometrical size of GPLs, the external axial load and spinning speeds of the cylindrical shell on the linear and nonlinear free vibrations of the nanocomposite cylindrical shell.


ABSTRACT: This paper presents theoretical and experimental investigations into nonlinear flexural vibrations of a structure composed of a host beam with piezoelectric ceramic actuators symmetrically bonded to its top and bottom surfaces. The composite beam is supported at its ends to completely restrain axial displacements or to impose the displacement of one or both ends. Applying voltage to piezoelectric actuators one creates prestress which can stabilize the structure when the external compressive force appears. The analytical model for describing flexural vibration of a beam under both the external load and piezoelectric actuation is based on the Euler–Bernoulli beam. The piezo material exhibits linear piezoelectricity with constitutive equations including electromechanical coupling. Due to geometrical nonlinearity, the solution to the problem has been obtained by using the Lindstedt-Poincare perturbation method. The main results concern the effect of the residual piezo force on the non-linear vibration frequency of the structure. In the experimental part of the study two laboratory stands have been designed and built for three and five segmented beams to find out and prove the effect of the electric field on the residual force and the natural frequency of both systems. Very good agreement between theoretical and experimental results has been observed.

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The following sub-section is from the 17th International Conference on Sheet Metal (SHEMET17)

ABSTRACT: The formation of wrinkling in deep drawing processes generally occurs in the two area of flange and cup wall. In this paper, a geometric method based on FEM simulation has been developed to investigate the wrinkling in the wall area of conical cups. Wrinkling wave variation was considered as the criterion of wrinkle defect. The forming process in this study is hydrodynamic deep drawing assisted by radial pressure with inward flowing liquid. The effects of radial pressure and cavity pressure on wrinkle phenomenon have been investigated. To verify the results of the simulation, experiments were performed on the steel sheets. Good agreement between the simulation and experimental results shows the reliability of this method in the wrinkling study. Results showed that radial pressure and cavity pressure have significant impacts on creation or prevention of wrinkling in the side wall.
References listed at the end of the paper:

ABSTRACT: Folding is a process of forming cellular structures out of a flat raw material. Through this technology it is possible to create sharp-edged structures with high depths and multiple bending axes and for this reason it is part of the technical origami. Current research work at the IFU focuses on applying this technique to sheet metals with thicknesses between 0.5 – 2mm. These kinds of structures can be used for optically appealing claddings, heat exchangers or sandwich panel core materials. In previous projects, it was
shown that it is necessary to pre-crease the bending axis on the flat raw material to achieve a defined folding process. For sheet metals, in particular the embossing of grooves is a promising approach. The general challenges for folding sheet metals are the forming of radii, the hardening effects emerging in the bending axis, and well-ordered design of appropriate tool concept. Also appropriate FEA models are necessary for a sufficient development of this process. The embossing of grooves itself is a bulk metal forming process and, therefore requires volume elements. Folding itself, however, is a forming process of large blanks, which is why simulations based on tetrahedral elements are extremely time-consuming. For this reason, two different models are necessary. The first model, which has integrated volume elements, simulates the folding of single folding cells targeting to detect the interaction of the embossing and the subsequent bending process. In the second model, shell elements are used, with a focus on the effect of the grooves’ run rather than the effects of the embossing itself. In this paper, a FEA model for the folding of a mono cell is presented, which shows that a defined folding with small radii for sheet metals with blank thicknesses larger than 0.5mm is possible as well. 

References listed at the end of the paper:

The following sub-section is on Structural and Physical Aspects of Construction Engineering

Ondrej Pesek and Jindrich Melcher (Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, Brno 602 00, Czech Republic), “Lateral-torsional buckling of laminated structural glass beams. Experimental study”, Procedia Engineering, Vol. 190, pp 70-77, 2017
https://doi.org/10.1016/j.proeng.2017.05.309

ABSTRACT: This paper deals with experimental research of stability behaviour of laminated structural glass beams. The purpose of the research is the evaluation of lateral-torsional buckling resistance and actual behaviour of the beams due to absence of standards for design of glass load-bearing structures. The experimental research follows the previous one focusing on measuring of initial geometrical imperfections of glass members and experimental evaluation of flexural buckling resistance of structural glass columns. Within the frame of the research 9 specimens were tested. All of them were of the same dimensions - length 2400 mm and width 280 mm but different thicknesses - 12, 16, 20 mm. All the beams were composed of two annealed glass panes bonded together by PVB foil. Beams were loaded by couple of forces symmetrically situated to the mid-span and supports complied with fork boundary conditions. Specimens were loaded by constantly increasing force up to failure. During testing lateral deflection, vertical deflection, angle of torsion and normal stresses at mid-span were measured. Maximum bending moment achieved during testing has been adopted as lateral-torsional buckling resistance. From these values were calculated characteristics and design values according to the EN 1990. Experiment results were compared with lateral torsional buckling resistance calculated according to the buckling curves approach.

References listed at the end of the paper:

ABSTRACT: Currently used methods of solution of Lateral Torsion buckling which are implemented in design codes are based on solution of critical moment. This method can be correctly used only for minimally single symmetric cross sections. Also FEM based numerical models cannot be generally used because of problematic specification of all imperfections. Usually it is very difficult to define all boundary conditions and also effect of loading during the iteration process. The goal of presented research is an experimental and theoretical analysis of selected types of cross-sections of elements subjected to bending with focus on lateral torsional buckling problems. Those experiments are focused on differences between real behaviour of single symmetric cross section and slightly non symmetric cross section.

References listed at the end of the paper:

Martin Vild and Miroslav Bajer (Brno University of Technology, Faculty of Civil Engineering, Veveří 95, Brno 602 00, Czech Republic), “Strengthening under load: Numerical study of flexural buckling of columns”, Procedia Engineering, Vol. 190, pp 118-125, 2017, https://doi.org/10.1016/j.proeng.2017.05.316

ABSTRACT: The paper refers to the strengthening of doubly symmetric columns under load by welded plates. A validated numerical study containing more than 500 models was performed to question the currently used design procedures. These procedures are not unified but vary greatly in different countries. The overly conservative design approach used in the Czech Republic contrasts with the approach completely neglecting the effect of preload commonly used in the USA. The effect of various parameters on the flexural buckling resistance of columns strengthened under load was investigated. The selected parameters were the thickness of
the strengthening flange, the column length, the initial bow imperfection, the preload magnitude and the direction of the axis which is pinned while the other axis is fixed. Several conclusions were reached from provided results and a simple analytical method is proposed. The load under which the column is strengthened weakens the column but only slightly.

References listed at the end of the paper:


ABSTRACT: Elastic very shallow shell subjected to the external pressure is analysed in the paper numerically by FEM. Nonlinear equilibrium paths are calculated for the different boundary conditions. ANSYS system was used for nonlinear analysis, arc-length method was chosen to obtain fundamental load-displacement path of solution. Effects of geometrical imperfections on equilibrium paths are investigated. Presented results confirm the fact that the nonlinear approach is necessary. The difference between the critical load of buckling analysis and the load value at the limit point of load-displacement path of nonlinear solution is in the tens of percent (depending on the boundary conditions).

References listed at the end of the paper:

ABSTRACT: The paper presents information about one part of the theoretical research oriented to determine the impact of loss the stability of rectangular concrete-filled steel tubes in terms of their resistance. This part deals with the theoretical analysis of the influence of imperfections on the local buckling and carrying capacity of short axially compressed cold-formed rectangular steel tubes. The numerical models of the mentioned above structures in software ABAQUS were presented in the work. The different support conditions of loaded edges of the steel section were considered in the models. The results of modelling were compared with the results of calculation of the carrying capacity of such structures according to standard Eurocode 3.

References listed at the end of the paper:

ABSTRACT: The paper describes two methods of FEM modelling of I-section beams loaded by bending moments. Series of random realizations with initial imperfections following the first eigenmode of lateral-torsional buckling were created. Two independent FEM software products were used for analyses of resistance. At the end the difference and correlation between the results as well as advantages and disadvantages of both methods are discussed.

References listed at the end of the paper:

ABSTRACT: Snap-through effect i.e. sudden change of buckling surface is an unpleasant phenomenon in behavior of structures especially in thin-walled structures. Geometric non-linear theory (The Total Lagrange Description) must be used. In geometric non-linear solution we have more results and snap-through effect can be explained as a jump between branches of solutions. It can be smooth but mostly this effect is sudden and accompanied with big noise. Examples of imperfect columns, von-Mises truss, shallow arch and steel thin-walled panels are presented.

References listed at the end of the paper:

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ABSTRACT: Influence lines of torsion and distortion internal forces of large concrete and steel cable-stayed bridges with continuous box-girders. Application for real bridges: (i) steel SNP bridge over river Danube in Bratislava, Slovak Republic, (ii) concrete Harp bridge over pond Jordán near Tábor, Czech Republic.

References listed at the end of the paper:

ABSTRACT: Structural designing of reinforced concrete structures consists in determination of the cross section height and amount of the vertical and horizontal reinforcement on the basis of the internal forces. These forces are not determined correctly without considering the structure deformation. It means that the geometric type nonlinearity should be regarded at least. In the case of compression the buckling and the so called “second order effects” should be taken into account. The EC2-1-1 code gives the general rules for such effects, but they are described in details only for columns and buildings. Therefore the aim of this paper is to formulate recommendations which will be useful for reinforced concrete cylindrical tanks for liquids and particulate solids compressed vertically (meridional compression) and horizontally (hoop compression). These recommendations are formulated on the basis of nonlinear FEM analysis, which is preceded by analysis of expressions describing the critical stress of cylinders, formulated by theory of elasticity.

References listed at the end of the paper:


ABSTRACT: Given that the conventional view in engineering design is to regard nonlinearity as either unwanted or detrimental—a “nuisance” to be at most tolerated and “designed around”—or as a mere perturbation of the predominantly linear dynamics, the two standard approaches of nonlinear structural dynamics were developed: The linearized and weakly nonlinear approaches. Yet, recent work has revealed the important benefits that strong nonlinearity offers over broad areas, from turbulent flows, fluid-structure interactions, vibration and shock isolation, and acoustic metamaterials, to energy harvesting, blast and acoustic mitigation, and nano/micro design. Indeed, it is the author’s view that accounting for, understanding of, and designing with strong nonlinearity will become a cornerstone of future engineering practice. This work focuses on constructive utilization of intentional strong nonlinearity to enable passive energy management in dynamical systems across
spatial and temporal scales. After a brief review of recent applications, emphasis is given to passive blast mitigation of large-scale infrastructure.

References listed at the end of the paper:


ABSTRACT: In the present paper, the problem of evaluation natural frequencies of a transversely isotropic circular plate is considered and the impact of the material properties of the plate on its natural frequencies is studied. The classical Kirchhoff-Love (KL) theory only takes into account material properties of the midplane. That is why the fundamental frequencies for isotropic and transversely isotropic plates are equal for the classical theory. The Ambartsumyan (A) theory of anisotropic shells takes into account the impact of the shear deformation in the thickness direction on the stress-strain state of the plate. In the general case, the theory of anisotropic plates and shells developed by Rodionova, Titaev, and Chernykh (RTC) permits one to take into account not only the transverse shears, but also the deformation of normals to the midplane. In the present paper, the problem of determining the fundamental frequencies is solved both with A and RTC theories, which improve the KL theory. To study the impact of the radial inhomogeneity on the plate fundamental frequencies, the calculations are carried out using the commercial finite element software COMSOL Multiphysics (v. 5.0). It
is shown that the inhomogeneity of the plate affects greatly the fundamental (lowest) frequency of the plate, while the plate non-isotropy has a greater influence on the second and higher vibration modes.

References listed at the end of the paper:


ABSTRACT: This paper presents the analysis of the dynamic response of a steel overground pipeline to a strong seismic shock. The scientific motivation of this study was to identify the response of connections of steel pipeline sections to a strong seismic shock. A 105-metre-long steel pipeline was the subject of this investigation. A submodelling technique was used in the numerical analysis. All details, such as bolts, flanges and the support pillar, were modelled. Both models were subjected to non-uniform kinematic excitation. An actual seismic shock was used for the excitation of the pipeline. The excitation was applied to the structure as accelerations of particular supports acting in three dimensions. The three tested values of seismic wave velocity were 250m/s, 500m/s and 1500m/s; numerical calculation was conducted for each wave speed. During analyses, the normal stresses at representative points were calculated. The analysed points were located at the top, at the bottom and at the middle bolt. The values of stresses obtained for each analysis were compared. On the basis of this comparison, it can be noted that the stresses obtained for selected points reflected the complex state of stress in the connection. The bolt deformations also show the strong bending that occurred in connection elements.


ABSTRACT: In the past, a number of investigations have been performed on the seismic behaviour of storage tanks. At the University of Auckland, a number of shake table experiments on tanks with different aspect ratios have been recently performed. The earthquake ground excitation was simulated based on a design spectrum from the New Zealand code NZS 1170.5, classification D for soft soils. The results show that the base plate stiffness of storage tanks may play a significant role in the magnitude of hoop stresses caused by the passage of the earthquake. To incorporate a low-damage seismic design philosophy, the tank is allowed to separate partially at the base. This temporary separation initiates rigid body like motion of the tank and thus reduce the wall local deformations. Consequently, the stress development along the wall can be reduced from that occurring with full base plate contact. This research focuses on the effect of the base plate thickness on the hoop stress development along the height of the tank wall for five radial directions.

References listed at the end of the paper:

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ABSTRACT: Free vibration and Ljapounov stability of compressed open thin-walled beams with a cross-section reduction are studied by a in-house finite differences numerical code, based on a refined direct beam model and allowing for investigating elastic stability of non-trivial equilibrium paths in a dynamic setting. The benchmark is a beam with doubly symmetric cross-section and non-zero warping rigidity, under free, semi-, and fully restrained warping at its ends. In all cases, the results of the direct model are compared to finite element
and/or experimental ones. The reduction in the cross-section rigidity induces a weakening that may model a local damage; thus, the present investigation may be useful with an outlook to damage monitoring and identification.

References listed at the end of the paper:
5. Error! Hyperlink reference not valid.


ABSTRACT: Despite the significant amount of research effort devoted to understanding the structural behavior of grain-silos, each year a large number of silos still fails due to bad design, poor construction, with a frequency much larger than other civil structures. In particular, silos frequently fails during large earthquakes, as occurred during the 1999 ChiChi, Taiwan earthquake when almost all the silos located in Taichung Port, 70 km far from the epicenter, collapsed. The EQE report stated that “the seismic design of practice that is used for the design and construction of such facilities clearly requires a major revision”. The fact indicates that actual design procedures have limits and therefore significant advancements in the knowledge of the structural behavior of silo structures are still necessary. The present work presents an analytical formulation for the assessment of the natural periods of grain silos. The predictions of the novel formulation are compared with experimental findings.

References listed at the end of the paper:


ABSTRACT: Elevated water tanks are one of the essential components of water supply networks that are expected to remain functional after severe earthquakes. In this paper, the effect of earthquake site-source distance on the dynamic response of reinforced concrete elevated water tanks with shaft type support is investigated. Six different pairs of near and far-field earthquake records each consisting of horizontal and vertical components are selected for the dynamic analyses. A two-dimensional structural system is numerically simulated using finite element method. The fluid-structure interaction is taken into account using single mass and two-mass analogies. This method is capable of considering both impulsive and convective responses of fluid-tank systems. The structure is assumed to be fixed at the base. Comparisons are made on base shear, base moment and sloshing responses under different near and far-field ground motions and simultaneous effects of their horizontal and vertical components. The results are verified and compared with those obtained from current code provisions. It is concluded that the dynamic behavior of the system is highly sensitive to site-source distance of the earthquake records. Moreover, two different simplified methods for modeling of fluid-structure interaction are studied and compared considering various dynamic responses.

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SAMPLE TEXT


ABSTRACT: Small free low-frequency vibrations of ring-stiffened cylindrical shells are considered. This problem is reduced to solution of the eigenvalue problems of linear differential equations. The equations describing the vibration of thin shells contain the dimensionless shell thickness as a small parameter. It allows to find the solution of the initial eigenvalue problem as the sum of slowly varying functions and edge effect integrals. Thus the initial system of differential equations is transformed into an approximate system of the smaller order. The simple asymptotic formulas for low frequencies are derived. Numerical results are obtained with the help of a shooting procedure. The asymptotic and numerical results converge.

References listed at the end of the paper:

Jianxin Yu (1,2), Huifeng Tan (1) and Jianzheng Wei (2)
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ABSTRACT: Dynamic testing of an inflatable wrap-rib reflector antenna with carbon fiber reinforced polymer (CFRP) supporting ribs was conducted. The inflatable reflector antenna was made of thin film, and the precision of off-set parabolic reflector was maintained by tension tailored CFRP ribs with a central hub and an outer inflatable torus. The effects of inner gas pressure and gravity on structural natural frequencies, modal shapes, and modal damping ratios were evaluated experimentally, inflatable wrap-rib reflector antenna with cup-up and cup down configurations with 10kPa and 20kPa inner inflation pressures were tested respectively. In ground vibration test based on experimental modal analysis, the whole antenna was fully deployed and hanged with a rope at central hub in lab environment. A series of impulse tests were conducted with high sensitive load cell to record input force, and several mini tri-axial accelerometers were instrumented on inflatable torus and supporting ribs to monitor the global vibration response, the excitation point was reinforced with a lightweight Alumina thin shell to minimize local deformation. Ground modal analysis results could be used as reference for predicting dynamic characteristics of inflatable wrap-rib reflector antenna on orbit.

References listed at the end of the paper:

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(2) Mohammed V University in Rabat, Ecole Mohammadia d’Ingénieurs, LERSIM, Agdal, 10090 Rabat, Morocco
ABSTRACT: Geometrically nonlinear free vibration of Functionally Graded thin Annular Plates (FGAP) with porosities subjected to thermal environment is investigated. A semi-analytical model based on an extension of the Rayleigh Ritz method to nonlinear vibrations is considered. A homogenization procedure has been employed to reduce the problem to that of an isotropic homogeneous annular plate. The material properties are assumed to be temperature-dependent and graded in the thickness direction. The rule of mixture has been
modified in order to take into account the effect of porosity and approximate the material properties. The problem is solved by a numerical iterative method. The effects of the porosity volume fraction, the temperature distribution through the plate thickness and temperature-dependency of material properties on the nonlinear free vibrations responses of the FGAP at large amplitudes are examined and discussed in detail.

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12. Y.S. Touloukian, Thermo physical properties of high temperature solid materials, McMillan, New York (1967)


ABSTRACT: Seismic protection of wine storage tanks has become a very important issue due to the boom of the winery industry in some seismic countries such as, the U.S, Italy, New Zealand, Chile and Argentina. Wine storage tanks are classified in two major groups: continuously supported tanks and legged tanks. Previous research has developed fragility curves for continuously supported tanks, with and without seismic protection devices, in order to establish the seismic reliability of this kind of tanks. However, fragility curves of legged wine tanks have not been reported. Therefore, in this study, the fragility curves of a typical stainless steel legged wine storage tank (one of 3,000 litres capacity), used for fermentation and wine storage, are assessed by means of numerical simulation. The fragility curves were developed by the results obtained from a mathematical model capable to perform the nonlinear time history analysis of the tank subjected to several artificial ground motions. The artificial ground motions are based on ground motion prediction from earthquakes recorded in Chile. Finally, the seismic fragility for a typical legged wine storage located in Chile was presented. Furthermore, the seismic fragility of a same damage state for a typical legged wine storage tank with and without a novel isolation device were compared.

References listed at the end of the paper:

Zenon J.G.N. del Prado (1), Marco Amabili (2) and Paulo B. Goncalves (3)
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ABSTRACT: In this work the effect of geometric imperfections on the non-linear dynamics of simply supported viscoelastic fluid-filled circular cylindrical shells subjected to lateral harmonic load is studied. Donnell’s non-linear shallow shell theory is used to model the shell, assumed to be made of a Kelvin-Voigt material type, and a modal solution with eight degrees of freedom is used to describe the lateral displacements. The Galerkin method is applied to derive a set of coupled non-linear ordinary differential equations of motion. The influence of shell geometry, flow velocity and dissipation parameter are studied and special attention is given to resonance curves and bifurcation diagrams. Obtained results show that geometric imperfections together with the viscoelastic dissipation parameter and internal fluid have significant influence on the nonlinear dynamic behavior of the shells as displayed in resonance curves.

References listed at the end of the paper:

ABSTRACT: Cylindrical shells exhibit a dense frequency spectrum, especially near the lowest frequency range. In addition, due to the circumferential symmetry, frequencies occur in pairs. So, in the vicinity of the lowest natural frequencies, several equal or nearly equal frequencies may occur, leading to a complex dynamic behavior. The aim of the present work is to investigate the influence of several modal geometrical imperfections on the nonlinear vibration of simply supported transversally excited cylindrical shells with multiple equal or nearly equal natural frequencies. The shell is modelled using the Donnell nonlinear shallow shell theory and the discretized equations of motion are obtained by applying the Galerkin method. For this, a modal solution that takes into account the modal interaction among the relevant modes and the influence of their companion modes (modes with rotational symmetry), which satisfies the boundary and continuity conditions of the shell, is derived. Several numerical strategies are used to study the nonlinear behavior of the imperfect shell. Special attention is given to the shape and the magnitude of the initial geometric imperfection on the resonance curves and bifurcations of simply supported transversally excited cylindrical shells with 1:1:1:1 internal resonance (four interacting modes).

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ABSTRACT: In this paper the method based on results of numerical simulation, using Pam-Stamp 2G (ESI Group) solution, and on the results of theoretical solution of the functional, allowing achievement of minimal thickness fluctuation of the barrel-shaped shells, is presented. The friction coefficient is selected as variable parameter. Its calculated values serve as prerequisites for the simulation.

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5. E.G. Demyanenko, “A Technique of Shaping the Barrel-Type Parts”, Russian Aeronautics., 57 (2014), pp. 204-211.

ABSTRACT: Aluminum tubes are efficient energy absorbing components and are widely used as framework and reinforcement members of structures. This paper deals with the influence of the axial length, cross-sectional shape and reinforcing rib on a dynamic axially compressed aluminum polygonal tube in order to obtain basic data on buckling. The axial impact test of an aluminum square tube was carried out with a drop-hammer testing machine. The dynamic deformation process of a polygonal tube was analyzed by a finite element method. The specimen used in this analysis is an aluminum polygonal tube (square, hexagonal, octagonal and decagonal). The result shows that even when the axial length was changed, there was no difference in the trend of the compressive load-time curve in each cross-sectional shape. The trend of the compressive load-time curve was affected by the reinforcing ribs. The buckling was generated partially in each axial length and cross-sectional shape. In the case of a square tube without ribs, the deformation shape was concave-convex in adjoining surfaces, and crushed in a bellows-like manner. As for the deformation shape, the experimental results approximately agreed with those of the finite element method analysis.
References listed at the end of the paper:


ABSTRACT: Modern high and ultra-high strength steels often require extensive alloy concepts and complex processing routes. To tailor the properties of low alloy steel accordingly, strain hardening combined with a subsequent local heat treatment presents a promising alternative. As a result, the final annealing step of the whole steel strip after cold rolling can be omitted. This process combination can be used to locally increase the formability of semi-finished parts as well as to improve the functionality of final parts. In this work, local heat treatment strategies are applied to increase the energy absorption capacity of a structural component. A high strength low alloy steel is strain hardened by cold rolling and heat-treated locally via laser irradiation. To identify suitable parameters for the laser heat treatment, the material is subjected to a short time heat treatment followed by a tensile test in a dilatometer. The determined mechanical properties are used for an FE study of a crash test. The FE model is used to develop potential local heat treatment strategies and to evaluate their crashworthiness. To validate the model, the developed heat treatment strategies are applied on real crash boxes. In dynamic impact tests, it is shown that the combination of strain hardening and local heat treatment can be used to improve the energy absorption capacity compared to a globally heat-treated crash box and to control the crash behaviour of structural components.


ABSTRACT: The nonlinear response of K8 pattern single-layer reticulated domes of different rise-span ratios under vertical rare earthquakes are analyzed by using the dynamic time-history analysis method and the pseudo static elasto-plastic analysis method. Comparison of these analysis results indicates that the structural members would be in different plastic deformation states under vertical rare earthquakes because of different rise-span ratios. The analysis results of the dynamic time-history method indicate that the vertical displacement response decreases with the increase of the rise-span ratio in condition of the same member section. Through the comparison the analytical results of pseudo static elasto-plastic analysis with the analytical results of dynamic time-history analysis, it is found that the difference of plastic members and region and error of the vertical displacement response, which may be a reference for future vertical seismic study of single-layer reticulated domes.
References listed at the end of the paper:


ABSTRACT: Double-layer grid structures with long span are widely applied by complex buildings such as airport terminal halls, super high-way train stations, conference & exhibition halls, sport studios, warehouses and so on. As the area of the fire source located in the large volume space is rather smaller than that of floor, this kind of fire scenario is named as localized fire with non-uniform temperature distribution. In present paper, a new temperature-time curve has been firstly developed to describe the transient non-uniform temperature distribution in localized fire, which is dependent on the space size, heat release rate of fire source. Then, the mechanical behaviors of global double-layer grid structures subjected to localized fire have been investigated by using numerical method. As a part of the structure is subjected to heating strongly and the heated members are restrained by the adjacent members which are heated slightly, some chords hold the characteristic of axially restrained members. The mechanical behaviors of chords with different axial restraint stiffness due to different non-uniform temperature distribution which can be described by the new temperature-time curve have been deeply studied. The initial imperfection can strongly improve the buckling resistance for axially restrained chords. An analytic method has been developed to estimate the fire resistance of double-layer grid structures exposed to localized fire.

Procedia Engineering, Vol. 211, 2018, no “buckling shell” papers
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DOI: 10.1016/j.euromechsol.2016.08.008
ABSTRACT: In the present article the mechanical instability and free vibration of FGM micro-plate based on the modified strain gradient theory were studied using the spline finite strip method. By daily increase in the application of micro-scale structures, developing theories were become essential to account in a way for the size-reduction effect. The modified strain gradient theory based on three length scale parameters, has the capability of evaluating structures at the micro size level. Considering the obtained results, it was clear that increasing the length-scale parameter would increase the critical buckling load and the vibration frequency, similar to the macroscopic case. In addition, increasing the power of volume fraction module decreases the critical load and the natural frequency of micro plate. Finally, the effect of length-scale parameter, boundary conditions, volume fraction module and dimensions of the micro-plate on critical loading and natural frequency of micro-plate were studied.

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[https://doi.org/10.1016/j.euromechsol.2016.09.012](https://doi.org/10.1016/j.euromechsol.2016.09.012)
ABSTRACT: This paper describes the development of high fidelity solutions for the study of homogeneous (elastic and inelastic) spherical shells subject to dynamic loading and undergoing finite deformations. The goal of the activity is to provide high accuracy results that can be used as benchmark solutions for the verification of computational physics codes. The equilibrium equations for the geometrically non-linear problem are solved through mode expansion of the displacement field and the boundary conditions are enforced in a strong form. Time integration is performed through high-order implicit Runge-Kutta schemes. Accuracy and convergence of the proposed method are evaluated by means of numerical examples with finite deformations and material non-linearities and inelasticity.
References listed at the end of the paper:

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ABSTRACT: Based on the Lagrange series interpolation, the Finite Block Petrov-Galerkin Method (FBPGM) has been developed to the non-linear analysis of Reissner plate theory with Functionally Graded Materials
(FGMs). By introducing the mapping technique, a quadratic type block is mapped into a normalized domain with 8 seeds. Then the domain nodes distribution can be determined by using shape functions. The load incremental technique and displacement control scheme are adopted to solve nonlinear problems including large deformation and post buckling of plates under pressure load and in-plane compressive forces. Numerical examples are given to demonstrate the efficiency and accuracy of proposed method in comparing with the Boundary Element Method (BEM), point collocation method (PCM) and Finite Element Method (FEM).

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Fengxian Xin and Tian Jian Lu (State Key Laboratory for Strength and Vibration of Mechanical Structures and MOE Key Laboratory for Multifunctional Materials and Structures, Xi’an Jiaotong University, Xi’an, 710049, PR China), “A plane strain elasticity model for the acoustical properties of rib-stiffened composite plates”, European Journal of Mechanics – A/Solids, Vol. 62, pp 1-13, March-April 2017
ABSTRACT: A theoretical elasticity model is established to study the noise reduction performance of a compliant coating layer that is attached to a periodically rib-stiffened plate under time-harmonic mechanical excitation. The general case of the structure immersed in two different fluids is considered so as to accurately simulate the interior and exterior fluid media of hull structures in underwater environment. The theory of plane strain elasticity is employed to model the dilatational and shear motions of the compliant coating layer and the elastic plate, while the scalar Helmholtz equation is adopted to describe the motions of the two fluids. Vibroacoustic coupling is realized by enforcing displacement and stress continuity at adjacent layer interfaces, with the reaction forces of the rib-stiffeners accounted for by introducing them as discretely distributed stresses. The resultant boundary value equations of the system are solved by applying the Fourier transform technique, based upon which the noise reduction due to the compliant coating layer can be favorably calculated. Numerical investigations are implemented to explore the effects of coating thickness, coating material properties, radiation angle, and excitation location on noise reduction. The theoretical results presented in this study provide valuable guidance for experimental research and structural design related to the decoupling effects of coating layers affixed to elastic structures in underwater environment.

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https://doi.org/10.1016/j.euromechsol.2016.10.006
ABSTRACT: Static bending and free vibration of cross-ply laminated plates with simply supported boundary conditions are studied using layerwise description for field variables. The layerwise approach accounts for the through-the-thickness deformations. The equations of motion and the boundary conditions are obtained by the Carrera's unified formulation. The stiffness matrix is computed by using the Reissner mixed variational theorem (RMVT), in which the transverse stresses are also treated as independent variables apart from the displacements. To this end, a mixed form of Hooke's law is defined. A cell-based smoothed finite element method is employed to compute the terms in the stiffness matrix. The influence of various parameters on the static bending and free vibration are numerically studied.

Xuexia Wei and Lingtong Yan (State Key Laboratory of Explosion Science and Technology, Department of Mechanics and Engineering, School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China), “Core-shell spheres under diametrical compression: An analytical solution”, European Journal of Mechanics – A/Solids, Vol. 62, pp 39-49, March-April 2017,

https://doi.org/10.1016/j.euromechsol.2016.11.005
ABSTRACT: The analytical solution for the stress distributions within core-shell spheres or layered spheres under diametrical compression is obtained. The solution reduces analytically to the classical solution for solid spheres by Hiramatsu and Oka (1966) and the analytical solution for hollow spheres by Wei et al. (2015) in the two limiting special cases. The numerical results of the present solution show that a drastic increase of tensile stress is usually observed for a core-shell sphere with a stiff shell or a shell with the same stiffness but a small Poisson's ratio, while a drastic decrease of tensile stress is usually observed for a core-shell sphere with a soft
shell or a shell with the same stiffness but a large Poisson's ratio. The maximum tensile stress may be either
induced at the interface or near the loading areas, which is more likely induced at the interface of a core-shell
sphere with a thin and stiff shell, otherwise it is more likely induced near the loading areas of a core-shell
sphere. Moreover, the maximum tensile stress is affected by the size of loading areas, the ratio of the Young's
moduli of the core and the outer shell, Poisson's ratio and the thickness of the shell. Since more and more
composite materials made up of core-shell spheres are used for some advanced devices to achieve multi-
functions or some intelligent abilities, the present solution can be used as a benchmark or a basic solution for
analyzing the failure mechanism of composite materials made up of core-shell spheres or layered spheres.

Saeed Sarkheil and Mahmoud Saadat Foumani (School of Mechanical Engineering, Sharif University of
Technology, Iran), “An improvement to motion equations of rotating truncated conical shells”, European
https://doi.org/10.1016/j.euromechsol.2016.11.003
ABSTRACT: In this paper, an improved formulation has been presented to study the vibrations of a truncated
conical shell under rotating condition. This formulation considers the Coriolis and centrifugal forces and the
initial hoop tension resulting from rotation. The conical shell discussed in this paper is the shell of revolution
modeled by the Novoshilov theory. The equations which have been derived in the present paper differ from and
are more complete than the equations in the existing papers published on the vibrations of conical shells under
rotating condition. For validation, first, the solution method used in this paper was evaluated and then the
conditions that highlight the difference between the equations obtained in the present paper and the former
equations were considered. In this way, it was demonstrated that when the cone angle and rotation speed have
large values, the backward frequencies obtained from the two equations differ from each other, and this
difference becomes more pronounced as the circumferential wave number increases. After validating the
presented equations and the solution method, the effects of different important parameters such as the rotation
speed, cone angle and the circumferential wave number on the forward and backward waves' frequencies have
been evaluated. The results reveal that with increase in the rotation speed of the cone, the discrepancy between
the frequencies of the forward and backward waves gets larger. Also, the difference between the forward and
backward waves’ frequencies diminishes with the increase of the cone angle.

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“Dynamic inversion characteristics of composite reinforced tubes”, European Journal of Mechanics –A/Solids,
ABSTRACT: An analytical solution is presented to study the energy absorption properties of composite
reinforced tubes undergoing freely dynamic external inversion. A finite element method is used to indirectly
validate the analytical solution for dynamic inversion characteristics of composite reinforced tubes. Compared
with finite element results, the feasibility of the analytical method is simply verified. The effects of composite
layer (viz. fiber layer thickness and fiber reinforced orientation), dynamic loading and section shape of tube on
the inversion characteristics of composite reinforced tubes are described and investigated in examples,
respectively.
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ABSTRACT: This paper deals with the analysis of free vibration and biaxial buckling of double-magneto-electro-elastic nanoplate-systems (DMEENPS) subjected to initial external electric and magnetic potentials, using nonlocal plate theory. It is supposed that the two nanoplates are bonded with each other using a visco-Pasternak medium, and are also limited to the external elastic substrate. Hamilton's variational principle is applied to acquire the partial differential equations of motion and corresponding boundary conditions for three modes (out-of-phase, in-phase and one nanoplate fixed) and solved analytically to determine clear closed-form phrase for complex natural frequencies and buckling loads. Numerical examples are performed to demonstrate the changes of the vibration frequency and buckling load ratio NL/L of DMEENP against to different values of the nonlocal parameters, initial external electric and magnetic potentials, aspect ratio, damping and transverse stiffness coefficients of the viscoelastic foundation, shear stiffness coefficient of Pasternak medium, length to thickness ratio, nanoplate thickness and higher modes. Also, the effect of biaxial compression ratio on the buckling load is investigated. Results of this study show that considering the interaction between two Magneto-electro-elastic nanoplates lead to achieving greater frequencies and biaxial buckling loads. Moreover, the influences of the nonlocal parameter become more pronounced when the half wave number, initial external electric potential and aspect ratio increase, while the effect of the length to thickness ratio and initial external magnetic potential has the opposite trend.

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ABSTRACT: The cyclic performance of cylindrical SMA actuators are investigated, taken into account the individual effects of the (1) selected SMA material, (2) geometric configuration of the actuator, and (3) prior mechanical load path taking to a targeted stressed preload state before starting thermal cycles. The “ordinary”, commercially-available, binary Ni_{49.9}Ti_{50.1} and a developmental “high temperature” ternary Ni_{50.3}Ti_{29.7}Hf_{20} alloys are used for comparison. The responses of these alloys are characterized using a multimechanism SMA model. Cylindrical actuator geometries, ranging from thin tubular configuration, where there is more uniformity in stress distribution, to a solid section, having significant non-homogeneities in stress, are utilized. Both proportional and non-proportional loading conditions are examined under limited stress levels and thermal cycles. Based on the results obtained for the alternative actuator designs, the conclusions are: (i) high actuation strokes are produced by Ni_{49.9}Ti_{50.1} actuators, (ii) the Ni_{50.3}Ti_{29.7}Hf_{20} actuators show relatively more dimensionally stable actuation performance, (iii) there is a marked difference in the degree of mechanical load-path dependency on cyclic behavior between the Ni_{49.9}Ti_{50.1} and Ni_{50.3}Ti_{29.7}Hf_{20} actuators, (iv) the cyclic response of the Ni_{50.3}Ti_{29.7}Hf_{20} is far less sensitive to the actuator geometry in comparison to the Ni_{49.9}Ti_{50.1}, and (v)
differences in actuator performance are connected to the intrinsic transformation behavior of the selected shape memory alloys.

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ABSTRACT: In this paper, a simple to use and single variable refined theory for free vibrations of a plate is proposed by incorporating inertia related terms in displacements. To the best of the authors' knowledge, no such approach has been reported in the literature pertaining to plate theories. The theory has only one fourth-order governing differential equation involving a single variable. Moreover, the expressions for displacements, strains, stresses, moments and shear forces of the theory are also expressed in terms of a single variable. It is worthwhile to note that, the expressions for shear forces of the present theory obtained by using strain-displacement and constitutive equations also involve inertia related terms. Whereas, the other first-order and higher-order shear deformation plate theories would result in the inconsistency of the expressions for shear forces obtained by using strain-displacement and constitutive equations and those obtained by using equilibrium equations. Efficacy of the proposed theory is demonstrated through illustrative examples for free vibrations of simply supported isotropic rectangular plates. Results obtained by using present theory are compared with three-dimensional theory of elasticity results, and also with those obtained by other first-order and higher-order shear deformation plate theories. Results obtained are quite accurate.

ABSTRACT: In this paper, a hybrid method which combines reverberation-ray matrix method and wave propagation method is developed to investigate the stability of multi-span viscoelastic functionally graded material (FGM) pipes conveying fluid. The material properties of FGM pipes are considered as graded distribution along thickness direction according to a power-law. A parametric study is conducted to verify the effectiveness of present method and investigate effects of volume fraction exponent, fluid velocity, internal pressure and internal damping on stability of the FGM pipes conveying fluid. The numerical results demonstrate that the present method provides accurate results by using only a small number of elements and the viscoelastic FGM pipes exhibit some special dynamic behaviors. Moreover, the results also reveal that the natural frequencies of FGM piping system could be adjusted by devising the volume fraction exponent. This particular feature of FGM pipes can be tailored to fulfill the special applications in engineering.

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ABSTRACT: We investigate the surface instability of a curved film interacting with a curved contactor through the action of van der Waals forces. Any one of the two curved boundaries of the film can be subjected to surface interactions while the other is bonded to a curved rigid substrate. In each case, the corresponding bifurcation is governed by the critical value of the relative film thickness. The effects of Poisson's ratio, surface energy and film thickness on the film's instability are discussed in detail leading to a complete picture of stability and bifurcation in the system.


ABSTRACT: In terms of the interaction between buckling and snap-through for shallow structures affected by geometrical imperfections results have shown that, after the nonlinear bifurcation, load reductions occur accompanied with a predictable tendency. In order to do it, the tracing of interaction domains and interaction curves presented in recent papers by the same Authors, has been proposed. In this study, every simple structural arrangement has been analyzed with regards to different shallowness ratios, slenderness, restraining conditions and imperfection patterns. It has been observed how the driving parameters could be led back to two original interaction and form factors. This procedure could shed new light on the application of the more burdensome imperfection pattern for the instability of geometrically nonlinear structures. Possible implications of these results have been presented, with a special attention to sensors and structural identification. The study accomplished numerous numerical simulations and showed good agreement with the theoretical expected results.


ABSTRACT: Nanocrystalline materials (NcMs) are multi-phase composites containing nanograins, nanovoids and interface. A softening mechanism due to the interface phase and nanovoids is observed in NcMs. For the first time, vibration behavior of double-layered nanocrystalline silicon nanoplates on elastic substrate is analyzed based on a two-variable refined plate model. Due to the experimentally observation of grains micro-rotation and strain gradients near interfaces, the strain gradient based couple stress theory is employed to describe the size-dependent behavior of the nanocrystalline nanoplate. A micromechanical model is employed to incorporate the effects of inclusions and their surface energies. Galerkin's method is implemented to obtain the natural frequencies of nanocrystalline nanoplate with different boundary conditions. One can see that the nanograins size, nanograins surface energy, nanovoids size, void percentage, interface region, scale parameter, foundation constants and boundary conditions have a great influence on the vibration behavior of a double-layered nanocrystalline nanoplate.
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ABSTRACT: This paper presents a theoretical study and finite element simulation for the buckling of a thin film on the compliant substrate. First, we develop a continuum mechanics approach for large deformation buckling analysis based on minimizing the total energy of the film/substrate structures, and considering the precise curvature of the buckled film and the Poisson's ratio of the substrate. The predicting results using this proposed theory agree quite well with previous experimental results. Then, we make a modification for the model to simplify the expressions for the wavelength and amplitude of the buckled geometry. Furthermore, considering a thin Si film on shape memory polymer (SMP) substrate, we investigate the buckling behavior of the thin film through theoretical analysis and finite element method. Through the investigation, it is found that the evolution rate of the buckling geometry of thin film depends on the temperature of the SMP substrate, and the buckling geometry changes faster at a higher temperature. Finally, a programmed method to control the buckling of thin Si film on the SMP substrate is proposed and is realized with finite element simulation in ABAQUS.

ABSTRACT: In this paper, the electro-elastic surface/interface model is introduced to investigate the surface energy effect on the nonlinear free vibration behavior of orthotropic piezoelectric cylindrical nano-shells. On the basis of classical shell theory and von-Karman-Donnell-type geometric nonlinearity, the fundamental equations for vibration are given. By considering the constitute relations for surfaces, the total energy of the orthotropic piezoelectric cylindrical nano-shell is obtained. The governing equations of motion are derived from Hamilton's principle and solved by using the homotopy perturbation method (HPM). Afterwards, the results without surface effect are compared and validated with the datum available in the literature, and the influences of surface parameters and geometric characteristics on the nonlinear free vibration of the orthotropic piezoelectric cylindrical nano-shell are examined.

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ABSTRACT: This paper presents an effective plate formulation coupling the merits of isogeometric analysis (IGA) and a new non-classical simple first-order shear deformation theory (SFSDT) for static bending, free vibration, and buckling of functionally graded (FG) moderately thick microplates. In contrast to the conventional first-order shear deformation theory (FSDT), the new SFSDT adopted here inherently owns several advantages such as free from shear-locking, capturing the shear-deformation effect, and fewer unknowns. In order to capture the small scale effects, we thus introduce a non-classical SFSDT based on a modified couple stress theory. The requirement for C^2-continuity in terms of the non-classical SFSDT is straightforwardly treated with the aid of inherent high-order continuity of non-uniform rational B-spline (NURBS), which serves as basis functions in our IGA framework. Numerical examples are presented and the obtained numerical results reveal that the deflection decreases while the frequency and buckling load increase with decreasing the plate thickness. Results also show that the small size effect can lead to an increase of microplate stiffness.


ABSTRACT: A stack of two identical flat circular membranes, bonded along the periphery can be inflated to form a reflector. To maintain the desired shape of the reflector surface, a supporting outer rim is required. An inflatable membrane reflector supported by an outer inflated toroidal rim structure is considered. Both the reflector and the toroidal rim are considered to be geometrically flat in the uninflated state. Initially, the circular membranes are pre-stretched and joined with the inner equator of the inflated torus, causing an inward radial force on the toroidal rim. The inflated shapes of the circular membranes (reflectors) under uniform pressure are obtained by an iterative solution scheme. The inflation problem is solved to determine the inflated shapes and the possible occurrence of wrinkling instability of the reflector or pull-in instability of the toroidal rim. The shape of the reflector is found to be close to a paraboloid whose focal length depends on the level of inflation and pre-stretch. Lower inflation pressure of the inflatable reflector is found to result in a better parabolic approximation of the reflecting surface.


ABSTRACT: The stochastic dynamic stability analysis of laminated composite curved panels under non-uniform partial edge loading is studied using finite element analysis. The system input parameters are randomized to ascertain the stochastic first buckling load and zone of resonance. Considering the effects of transverse shear deformation and rotary inertia, first order shear deformation theory is used to model the composite doubly curved shells. The stochasticity is introduced in Love's and Donnell's theory considering dynamic and shear deformable theory according to the Sander's first approximation by tracers for doubly curved laminated shells. The moving least square method is employed as a surrogate of the actual finite element model to reduce the computational cost. The results are compared with those available in the literature. Statistical results are presented to show the effects of radius of curvatures, material properties, fibre parameters, and non-uniform load parameters on the stability boundaries.


ABSTRACT: The present paper is focused on the size-dependent shear buckling of nanoplates embedded in Winkler-Pasternak foundation and hygrothermal environment. Hence, the refined higher-order plate theories
(Polynomial, Exponential, and Hyperbolic) needless of any shear correction factor are used in the formulations. The equations of motion are derived based on the mentioned theories in conjunction with the nonlocal strain gradient theory employing Hamilton's principle. The four unknown functions denoting the buckling load of plates are defined in a modal manner, and Navier solution method is used to find the shear buckling response. Results for the shear buckling and thermal buckling analysis of nanoplates are approved by existing literature to demonstrate the accuracy of present formulation and solution method. From our knowledge, it is the first time that the hygrothermal environment and also the nonlocal strain gradient theory are applied to study on shear buckling of nanoplates. Hence, the influence of nanoplate geometry, various hygrothermal conditions, elastic medium, nonlocal parameter and gradient parameter on the shear buckling load are obtained and discussed using different plate theories. The numerical results indicate that the shear buckling of nanoplate in the absence of strain gradient parameter is significantly affected by the temperature and moisture variations.


ABSTRACT: Dynamic modeling of nanoplates constructed from porous functionally graded (FG) and metal foam materials is presented based on nonlocal strain gradient theory (NSGT). In this model, both stiffness-softening and stiffness-hardening effects are considered for more reliable forced vibration analysis of nanoplates. The present nano-resonator is based on a vibrating higher order nanoscale plate subjected to transverse uniform dynamic load. Porosities inside FG material are incorporated to the model based on a modified rule of mixture. Also, porosities inside metal foam nanoplate are non-uniformly distributed thorough the thickness. Applying Galerkin's method, the resonance frequencies and dynamic deflections are obtained. It is indicated that the forced vibration characteristics of the nanoplate are significantly influenced by the excitation frequency, porosities, nonlocal parameter, strain gradient parameter, elastic foundation and dynamic load characteristics.


ABSTRACT: A 90° back-to-back pipe bend structure subjected to cyclic in-plane bending moment and steady internal pressures is analysed by means of the Linear Matching Method (LMM) in order to create the limit, shakedown, and ratchet boundaries. The analyses performed in this work demonstrate that the cyclic moment has a more significant impact upon the structural integrity of the pipe bend than the constant pressure. Full cyclic incremental analyses are used to verify the structural responses either side of each boundary and confirm correct responses. In addition, the shakedown boundary produced by the LMM is compared to another shakedown boundary of an identical pipe bend computed by the simplified technique and it is shown that the LMM calculates results more accurately. Parametric studies involving a change of geometry of the pipe bends and loading type are carried out. From the studies of the geometry, two semi-empirical equations are derived from correlations of the reverse plasticity limit and the limit pressure with the bend characteristic. Finally, the results presented in this paper provide a comprehensive understanding of post-yield behaviours of the 90° back-to-back pipe structure under the combined loading as well as offering essential points to be concerned for the life assessment of the piping system.

ABSTRACT: Time depended deformation and critical buckling load of viscoelastic thick plates were studied using finite strip method with the trigonometric functions in longitudinal direction and the polynomial functions in transverse direction. The plates were considered to be thick and the third order shear deformation theory was used to consider the effect of shear stresses in thickness. The mechanical properties of the material were considered to be linear viscoelastic by expressing the relaxation modulus in terms of Prony series. Time history of maximum deflection of viscoelastic plates subjected to transverse loading and unloading on plates was calculated using a fully discretized formulation. In addition, the critical in–plane load of plates was calculated by a nonlinear procedure in different times of loading. Moreover, the effect of thickness and the interaction of biaxial in–plane loading on critical load of plate were studied.

ABSTRACT: An original and consistent first-order shear deformation theory that retains all the nonlinear terms in the in-plane displacements and rotations is presented here. The theory is developed for dynamics and is applied to study large-amplitude, geometrically nonlinear vibrations. The numerical application to a simply supported, composite laminated circular cylindrical shell is implemented for illustration and validation purposes. Initially the theory is compared to an accurate third-order nonlinear shear deformation theory for the case of pressurized shell. This comparison validates the theory for buckling, which arises in case of external pressure, and post-buckling. The pressure is accurately modelled as displacement-dependent. Then, the nonlinear vibrations due to harmonic forcing around a resonance are studied in detail. The coupling between driven and companion mode gives a chaotic oscillation region near the linear resonance associated to a travelling-wave vibration. Results are presented in the frequency and time domains, in addition to sections of Poincaré maps.

ABSTRACT: In this study, a geometrically nonlinear analysis of thin-walled Al/Al₂O₃ functionally graded (FG) sandwich I-beams with mono-symmetric cross-section is presented. The FG beam consists of ceramic (Al₂O₃) and metal (Al) phases varying through the wall thickness. The Euler-Bernoulli beam theory and the Vlasov one are applied for bending and torsional problems, respectively. The analysis model considers the elastic couplings and constrained warping, and the geometric nonlinearity is accounted for in the von Kármán sense. The nonlinear governing equations are derived and the finite beam element model considering the Hermite cubic interpolation polynomials is employed with the scope to discretize the nonlinear governing equations. The results of Al/Al₂O₃ FG sandwich I-beams with mono-symmetric cross-section are validated with available results. In all cases, good correlation has been observed. Two types of material distributions are considered to investigate the influences of geometric nonlinearity, gradient index, thickness ratio of ceramic, material ratio, and span-to-height ratio on the coupled nonlinear responses of FG sandwich I-beams. Numerical results show that the above mentioned effects play an important role on the nonlinear structural responses.

ABSTRACT: A 4-node, 8-DOF non-conforming quadrilateral element with four internal modes, denoted as iQ8, is developed. It takes the four edges' midpoints of the linear element Q4 as the internal virtual nodes, whose shape functions are the same as those of the mid-side nodes of the quadratic element Q8. In order to deal with the rank deficiency of the new element stiffness matrix under 2 × 2 Gaussian quadrature, a new reduced 5-
point integration scheme is constructed. By both the eigenvalue analysis of the element stiffness matrix and the example for the patch test, the weight of the central integration point is determined to a value close to 4, correspondingly the 5-point quadrature converges to 1-point quadrature. The non-central integration points are far away from the element domain, which is much different from conventional quadratures. Finally, some typical numerical examples are tested, and the results show that, except for only passing the weak patch test, the new element achieves the best performance of other 4-node quadrilateral elements in the aspects of anti-distortion, being free of trapezoidal locking, and exactness in pure bending.

ABSTRACT: The shell with functionally graded material (FGM) thermal barrier coating is a novel high temperature resistant structure, which has been increasingly applied in the aerospace, nuclear, turbo machinery and other engineering fields. However, there are some defects for the practical structures due to the limitation of manufacturing technique. But relevant theoretical research on the thermal buckling behavior of the imperfect cylindrical shell is limited in most open literature. Therefore, this work proposed to establish the theoretical solution of the critical temperature of buckling for the cylindrical shell with an axisymmetric imperfect and FGM coating based on the Donnell shell theory, Koiter model and Galerkin method. The theoretical solution deduced in this work agrees well with the existing literature. In addition, the influences of the profile of the axisymmetric imperfection, the volume fraction of the ceramic phase and the types of the thermal loading on the thermal buckling behavior of the coated imperfect cylindrical are further analyzed. The study provides a scientific solution and better understanding for the thermal buckling problem of the coated imperfect cylindrical shells.

ABSTRACT: The essence of nonlocal elasticity for vibration analysis of multi-layer graphene sheets (MLGSs) is investigated in the following study. The van der Waals interactions of every two adjacent layers are considered in analysis which results in interlayer shear effect. The proposed formulation is according to sandwich model (SM). Molecular Dynamic (MD) simulation is implemented to verify our model. We present an investigation to obtain the consistent values for SM parameters to comply with MD results. Afterward, the SM is integrated with nonlocal elasticity. The new calibrated values for nonlocal parameter lead to the best conformity of nonlocal SM with MD.

ABSTRACT: Nonlocal electro-elastic bending analysis of a doubly curved nano shell is studied in this paper based on nonlocal elasticity theory and first order shear deformation theory. Nonlocal piezo-elasticity relations are used for analysis of the problem. The doubly curved piezoelectric nano shell is subjected to transverse loads and applied voltage. In addition, the structure is resting on Winkler-Pasternak foundation. The governing equations of nonlocal electro-elastic bending are derived based on principle of virtual work. The nonlocal electro-elastic bending results of doubly curved nano shell are investigated using Navier's method. Influence of nonlocal parameter, applied electric potential, Winkler and Pasternak's parameters of foundation is studied on the mechanical and electrical components of the piezoelectric doubly curved nano shell.
ABSTRACT: Realistic multi-span fluid-conveying pipe may contain various accessories such as valves, clamps, flanges, elastic supports and vibration absorbers under complex boundary conditions in engineering applications. The dynamic response of the multi-span pipe may be affected by the presence of accessories, giving rise to complex mode shapes. Simplified and reliable methods for multi-span mode shapes calculation from eigenvector of the characteristic equation are widely applied in the pipeline engineering community. However, current methods are not valid when it comes to the amplitude of the eigenvector with a resonance frequency. Consequently, corresponding stresses cannot be further evaluated exactly. To address the above mentioned issues, a novel Frequency Response Function (FRF)-based method is proposed in this paper for the calculation of the mode shapes exactly. Furthermore, a method combining the Spectral Analysis Method (SAM) and Transfer Matrix Method (TMM) is first proposed in this paper to obtain the natural frequencies and transient response for the cascaded pipeline. The results calculated by the present method are validated by comparing them with those obtained from existing literature and conventional Finite Element Method (FEM). The effects of the accessories on the vibration characteristics of the multi-span pipes are further analyzed.

ABSTRACT: In this paper, we analyzed the stochastic stability of a single-layer graphene sheet resting on a viscoelastic foundation and influenced by the in-plane magnetic field. The mechanical model of a graphene sheet is given as an orthotropic and viscoelastic nanoplate while the viscoelastic foundation is of the Kelvin-Voigt type. We assume that the graphene sheet is influenced by the in-plane random forces variable with time and exerted in-plane magnetic field. Based on the Eringen's nonlocal continuum theory and Kirchhoff–Love plate theory, the governing equation of motion is derived by considering the influence of the Lorentz forces obtained from the classical Maxwell relations. In order to investigate the stochastic stability of such system, the maximal and moment Lyapunov exponents are considered by using the perturbation method. The predicted approximated analytical results for the p-th moment Lyapunov exponents are validated by the Monte Carlo method. Moreover, the boundaries of almost-sure and moment stability of the viscoelastic nanoplate are determined as functions of different system parameters. The influences of the nonlocal and magnetic field parameters, stiffness and damping coefficients and spectral density on the moment Lyapunov exponents are investigated through several numerical examples. Presented results reveal that the applied in-plane magnetic field could be successfully used to improve stability performances of nano-electromechanical systems based on graphene sheets.

ABSTRACT: In the present work, a shell finite element with a variable kinematic field based on a new zig-zag power function is proposed for the analysis of laminated shell structures. The kinematic field is written by using an arbitrary number of continuous piecewise polynomial functions. The polynomial expansion order of a generic subdomain is a combination of zig-zag power functions depending on the shell thickness coordinate. As in the classical layer-wise approach, the shell thickness can be divided into a variable number of mathematical subdomains. The expansion order of each subdomain is an input parameter of the analysis. This feature enables the solution to be locally refined over generic regions of the shell thickness by enriching the kinematic field. The advanced finite shell elements with variable kinematics are formulated in the framework of the Carrera Unified Formulation. The finite element arrays are formulated in terms of fundamental nuclei, which are invariants of the theory approximation order and the modelling technique (Equivalent-Single-Layer, Layer-Wise). In this work, the attention is focused on linear static stress analyses of composite laminated shell structures. The governing equations are obtained by applying the Principle of Virtual Displacements, and they are solved using the Finite Element method. Furthermore, the Mixed Interpolated Tensorial Components (MITC) method is employed to contrast the shear locking phenomenon. Several numerical investigations are carried out to validate and demonstrate the accuracy and efficiency of the present shell element.


ABSTRACT: The deflection of the composite laminates and their maximum tensile strain in bending conditions are investigated in this study. For this purpose, different equivalent single layer and layerwise theories based on polynomial shape functions are used. Then Rayleigh–Ritz approximation technique and principle of minimum potential energy are applied to obtain the unknown coefficients of the displacement fields. The results are compared with the three dimensional finite element analysis and the experimental investigation. Also the process of obtaining material properties in tensile condition is explained completely. Regarding to the computational costs and agreement of the analytical and numerical results with the experimental ones, for both CCFF and SSFF boundary conditions the deflection prediction by layerwise HSDT is in a good consistency with the experimental results than the other plate theories and FEM method in this study. Although for obtaining strains in SSFF boundary conditions precisely FEM is more applicable.


ABSTRACT: The divergence and flutter instabilities of the thin-walled spinning pipes reinforced by single-walled carbon nanotubes in thermal environment are investigated. The material properties of carbon nanotube-reinforced composites are assumed to be uniform distribution as well as two types of functionally graded distribution patterns. The thermal effects are also considered and the material properties of carbon nanotube-reinforced composites are assumed to be temperature-dependent. The cantilever pipe conveying fluid is spinning along its longitudinal axis and subjected to an axial force at the free end. Based on the thin-walled Timoshenko beam theory, the governing equations of motion are derived using the extended Hamilton's principle and discretized via the Galerkin method. The resulting thermal-structural-fluid eigenvalue problem is solved and the frequency and the critical fluid velocities are calculated. The effects of carbon nanotubes distributions, volume fraction of carbon nanotubes, compressive axial force, spinning speed, gravity and fluid mass ratio on the critical divergence and flutter velocities of the thin-walled spinning pipe conveying fluid are studied.

ABSTRACT: The nonlinear buckling and postbuckling behavior of Multilayer functionally graded (FGM) cylindrical shells reinforced by ring, stringer and/or spiral stiffeners made of isotropic material under torsional loads and thermal load is proposed by an analytical approach. The thin shell is composed of three layers: isotropic layer – FGM layer – isotropic layer and surrounded by Pasternak type elastic foundation. The governing equations are based on the Donnell shell theory with von Kármán-Donnell-type geometrical nonlinearity, combining the improvability of Lekhnitskii's smeared stiffeners technique for spiral stiffeners. The effects of mechanical and thermal loads are considered in this paper. The number of spiral stiffeners, angle stiffeners, temperature change, and volume fraction index of shells, foundation and stiffeners are numerically investigated. A very large effect of spiral stiffeners on buckling behavior of shell in comparison with orthogonal stiffeners is approved in numerical results.


ABSTRACT: In this work, a shear deformable viscoelastic sandwich shell element is proposed for doubly curved sandwich shell panels with passive constrained layer damping (PCLD) treatment. The transverse displacements of the constraining layer and base layer are considered to be independent, besides the in-plane displacements. The transverse and in-plane displacements of the viscoelastic core are considered to be varying linearly through the thickness. Shear as well as normal deformations of the core are included in the analysis. The equation of motion of the doubly curved sandwich shell panel under free vibration is derived via Hamilton’s principle. The modal frequencies and modal loss factors of the Isotropic elastic-Viscoelastic-Isotropic elastic (IVI) sandwich shell panel and Laminated elastic-Viscoelastic-Laminated elastic (LVL) sandwich panel are obtained from numerical solutions, using finite element method in conjunction with Hamilton's principle. Parametric studies are carried out to ascertain the effects of shell geometries, aspect ratio, orthotropy of the skins, core layer thickness, constraining layer thickness, core loss factor on the natural frequencies and system loss factors under different boundary conditions.


ABSTRACT: This study concerns with transverse vibrations of magnetically-thermally affected vertically aligned arrays of single-walled carbon nanotubes (SWCNTs) using nonlocal elasticity theory of Eringen. Using nonlocal Rayleigh and Timoshenko beam theories, both discrete and continuous versions of equations of motion are presented. In contrast to the discrete models, the continuous models do not suffer from huge time and labor costs for nanosystems with high population. The capability and efficiency of the continuous models in capturing the frequencies of the discrete models are displayed, and a reasonably good agreement is obtained. Subsequently, the influences of radius of SWCNTs, slenderness ratio, population, small-scale parameter, strength of magnetic field, and variation of the temperature on the fundamental frequency are explained and discussed. Additionally, the role of shear deformation on the obtained results is explained and the limitations of the nonlocal Rayleigh beam model are revealed.
ABSTRACT: We present in this study a size-dependent computational approach based on the modified strain gradient theory (MSGT) and higher-order shear deformation theory for static bending and free vibration analyses of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) microplates. Three material length scale parameters (MLSPs) are taken into account in MSGT to capture size effects of microplate behavior. The effective material properties of FG-CNTRC microplates are obtained by an extended rule of mixture. Four types of carbon nanotube distributions, which are either uniform or functionally graded (FG) through the plate thickness, are considered. The governing equations are derived from the principle of virtual work and are then solved by isogeometric analysis (IGA). The IGA is suitable for a numerical implementation of the size-dependent models since it requires higher-order gradients in the weak form. The inclusion of geometrical parameters, boundary conditions, distributed types of carbon nanotube and material length scale parameters are studied to evaluate the displacement and natural frequency of FG-CNTRC microplates. In addition, the present size-dependent model can be retrieved into the modified couple stress model or classical model when a few MLSPs are ignored.


ABSTRACT: Based on the classical theory of thin plate and Biot theory, a precise model of the transverse vibrations of a thin rectangular porous plate is proposed. The first order differential equations of the porous plate are derived in the frequency domain. By considering the coupling effect between the solid phase and the fluid phase and without any hypothesis for the fluid displacement, the model presented here is rigorous and close to the real materials. Owing to the use of extended homogeneous capacity precision integration method and precise element method, the model can be applied in higher frequency range than pure numerical methods. This model also easily adapts to various boundary conditions. Numerical results are given for two different porous plates under different excitations and boundary conditions.

ABSTRACT: This paper deals with the study of the temperature effect on the nonlinear vibration behavior of nanoplate-based nano electromechanical systems (NEMS) subjected to hydrostatic and electrostatic actuations. Using Eringen's nonlocal elasticity and Gurtin–Murdoch theory, the nonlocal plate model is derived through
Hamilton's principle. The governing equation which is extremely nonlinear due to the geometrical nonlinearity and electrostatic attraction forces is solved numerically using the differential quadrature method (DQ M). The accuracy of the present method is verified by comparing the obtained results with the experimental data and those in the literature and very good agreement is obtained. Finally a comprehensive study is carried out to determine the influence of temperature on the nonlinear vibration characteristics of NEMS made of two different materials including aluminum (Al) and silicon (Si) and some conclusions are drawn.


ABSTRACT: The objective of the present investigation is to predict the nonlinear buckling and postbuckling characteristics of cylindrical shear deformable nanoshells with and without initial imperfection under hydrostatic pressure load in the presence of surface free energy effects. To this end, Gurtin-Murdoch elasticity theory is implemented into the first-order shear deformation shell theory to develop a size-dependent shell model which has an excellent capability to take surface free energy effects into account. A linear variation through the shell thickness is assumed for the normal stress component of the bulk to satisfy the equilibrium conditions on the surfaces of nanoshell. On the basis of variational approach and using von Karman-Donnell-type of kinematic nonlinearity, the non-classical governing differential equations are derived. Then a boundary layer theory of shell buckling is employed incorporating the effects of surface free energy in conjunction with nonlinear prebuckling deformations, large deflections in the postbuckling domain and initial geometric imperfection. Finally, an efficient solution methodology based on a two-stepped singular perturbation technique is put into use in order to obtain the critical buckling loads and postbuckling equilibrium paths corresponding to various geometric parameters. It is demonstrated that the surface free energy effects cause increases in both the critical buckling pressure and critical end-shortening of a nanoshell made of silicon.


ABSTRACT: In this paper, a 3-node triangular element for couple stress theory is proposed based on the assumed stress quasi-conforming method. The formulation starts from polynomial approximation of stresses. Then the stress-function matrix is treated as the weighted function to weaken the strain-displacement equations. Finally, the string-net functions are introduced to calculate strain integration and the stress smooth technique is adopted to improve the stress accuracy. Numerical results show that the proposed new model can pass the $C^{0-1}$ patch test with excellent precision, does not exhibit extra zero energy modes and can capture the scale effects of microstructure.

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ABSTRACT: Two grades of Dyneema® composite laminates with the commercial designations of HB26 and HB50 were cut into blocks with or without an edge crack and compressed in the longitudinal fiber direction. The cracked and uncracked specimens show similar compressive responses including failure pattern and failure load. The two grades of Dyneema® composites exhibit different failure modes: a diffuse, sinusoidal buckling pattern for Dyneema® HB50 due to its weak matrix constituent and a kink band for Dyneema® HB26 due to its relatively stronger matrix constituent. An effective finite element model is used to simulate the collapse of Dyneema® composites, and the sensitivity of laminate compressive responses to the overall effective shear modulus, interlaminar shear strength, thickness and imperfection angle are investigated. The change of failure mode from kink band to sinusoidal buckling pattern by decreasing the interlaminar shear strength is validated by the finite element analyses.

ABSTRACT: The vibrational frequency analysis of finite elastic tube filled with compressible viscous fluid has received plenty of attention in recent years. To apply frequency analysis to defect detection for example, it is necessary to investigate the vibrational behavior under appropriate boundary conditions. In this paper, we present a detailed theoretical study of the three dimensional modal analysis of compressible fluid within an elastic cylinder. The dispersion equations of flexural, torsional and longitudinal modes are derived by elastodynamic theory and the unsteady Stokes equation. The symbolic software Mathematica is used in order to find the coupled vibration frequencies. The dispersion equation is deduced and analytically solved. The finite element results are compared with the present method for validation and an acceptable match between them are obtained.

ABSTRACT: The nonlinear free vibration around the postbuckling configuration of nonlocal nanobeams with pinned–pinned boundary conditions are analytically investigated, considering the geometric nonlinearity arising from the mid-plane stretching and particularly the effect of a longitudinal magnetic field. When the applied axial force is small, the nanobeam is stable and its free vibration is around the straight equilibrium position. As the axial force becomes large and is beyond a certain critical value (critical axial force), however, either positive or negative non-trivial equilibrium configuration occurs and the free vibration is around the buckled configuration. The governing equation for the nanobeam before buckling exhibits a cubic nonlinearity while for a buckled nanobeam it contains both cubic and quadratic nonlinearities. Based on the nonlinear governing equations, approximate analytical solutions for the postbuckling configuration in terms of the applied axial force are evaluated, showing that the magnetic field parameter has a great effect on the critical axial force, buckled displacement and linear frequencies of the nanobeam system. More interestingly, the nonlinear frequency is found to be generally higher than the linear frequency in the case of prebuckling regime while it could be lower than the linear one in the case of postbuckling regime. The nonlinear frequency can be significantly influenced by the magnetic field, the nonlinear coefficient associated with the mid-plane stretching, and the initial vibration amplitude.
ABSTRACT: In this paper, we investigate the microfluid induced vibration of a nanotube in thermal environment. Attention is focused on a special case that the law of energy equipartition is unreliable unless the quantum effect is taken into account. A nonlocal Euler–Bernoulli beam model is used to model the transverse vibration of a single-walled nanotube (SWCNT). Results reveal that the root of mean squared (RMS) amplitude of thermal vibration of the fluid-conveying SWCNT predicted from the quantum theory is lower than that predicted from the law of energy equipartition. The quantum effect on the thermal vibration of the fluid-conveying SWCNT is more significant for the cases of higher-order modes, lower flow velocity, lower temperature, and lower fluid density.

ABSTRACT: In this paper, we consider the dynamic response of a pre-stressed sandwich plate-strip with a piezoelectric core and elastic layers under the action of a time-harmonic force resting on a rigid foundation. The investigation is carried out within the framework of the piecewise homogeneous body model by utilizing the exact equations of motion and relations of the linear theory of electro-elasticity. It is assumed that there is a shear-spring-type imperfect contact between the layers, but a complete contact between the plate-strip and the rigid foundation. A mathematical model of the problem is constructed, and the governing equations of motion are solved by employing the finite element method (FEM). Numerical results illustrating the influence of a change in the value of the shear-spring parameter on the dynamic response of the plate-strip are then presented.

(Seemingly there are no 2018 issues. The list of issues ends with December 2017. The search for new papers in this journal is not included in Part 2.)


SUMMARY: A differential quadrature hierarchical finite element method (DQHFEM) is proposed by expressing the hierarchical finite element method matrices in similar form as in the differential quadrature finite element method and introducing interpolation basis on the boundary of hierarchical finite element method
elements. The DQHFEM is similar as the fixed interface mode synthesis method but the DQHFEM does not need modal analysis. The DQHFEM with non-uniform rational B-splines elements were shown to accomplish similar destination as the isogeometric analysis. Three key points that determine the accuracy, efficiency and convergence of DQHFEM were addressed, namely, (1) the Gauss–Lobatto–Legendre points should be used as nodes, (2) the recursion formula should be used to compute high-order orthogonal polynomials, and (3) the separation variable feature of the basis should be used to save computational cost. Numerical comparison and convergence studies of the DQHFEM were carried out by comparing the DQHFEM results for vibration and bending of Mindlin plates with available exact or highly accurate approximate results in literatures. The DQHFEM can present highly accurate results using only a few sampling points. Meanwhile, the order of the DQHFEM can be as high as needed for high-frequency vibration analysis.

SUMMARY: The contribution of this work is the implementation of a new elastic solution method for thick laminated composites and sandwich structures based on a generalized unified formulation using finite elements. A quadrilateral four-node element was developed and evaluated using an in-house finite element program. The C-1 continuity requirements are fulfilled for the transversal displacement field variable. This method is tagged as Caliri's generalized formulation. The results employing the proposed solution method yielded coherent results with deviations as low as 0.05% for a static simply supported symmetric laminate and 0.5% for the modal analyses of a soft core sandwich structure.

SUMMARY: In this paper, a simple locking-free triangular plate element, labeled here as Mindlin-type triangular plate element with nine degrees of freedom (MTP9), is presented. The element employs an incompatible approximation with nine degrees of freedom (DOFs) independent of the nodes and the shape of the triangle to define the displacements $u/v/w$ (which is similar to a general solid element) along the $x/y/z$ axes. It is free of shear locking, has a proper rank, and provides stable solutions for thick and thin plates. Moreover, the paper provides a new way to develop simple and efficient locking-free thick–thin-plate/shell elements. A variety of numerical examples demonstrate the convergence, accuracy, and robustness of the present element MTP9.

SUMMARY: A shear-flexible isogeometric Reissner–Mindlin shell formulation using non-uniform rational B-splines basis functions is introduced, which is used for the demonstration of a coupling approach for multiple non-conforming patches. The six degrees of freedom formulation uses the exact surface normal vectors and
The shell formulation is implemented in an isogeometric analysis framework for computation of structures composed of multiple geometric entities. To enable local model refinement as well as non-matching domains coupling, a conservative multi-patch approach using Lagrange multipliers for structured non-uniform rational B-splines patches is presented. Here, an additional border frame mesh is used to couple geometries during structural analyses. This frame interface approach avoids the problem of excessive constraints when multiple patches are coupled at one point. First, the shell formulation is verified with several reference cases. Then the influence of the frame interface discretization and frame penalty stiffness on the smoothness of the results is investigated. The effects of the perturbed Lagrangian method in combination with the frame interface approach is shown. In addition, results of models with T-joint interface connections and perpendicular stiffener patches are presented.

SUMMARY: The paper deals with two main advantages in the analysis of slender elastic structures both achieved through the mixed (stress and displacement) format with respect to the more commonly used displacement one: (i) the smaller error in the extrapolations usually employed in the solution strategies of nonlinear problems and (ii) the lower polynomial dependence of the problem equations on the finite element degrees of freedom when solid finite elements are used. The smaller extrapolation error produces a lower number of iterations and larger step length in path-following analysis and a greater accuracy in Koiter asymptotic method. To focus on the origin of the phenomenon, the two formats are derived for the same finite element interpolation. The reduced polynomial dependence improves the Koiter asymptotic strategy in terms of both computational efficiency, accuracy and simplicity.

SUMMARY: In isogeometric analysis, identical basis functions are used for geometrical representation and analysis. In this work, non-uniform rational basis splines basis functions are applied in an isoparametric approach. An isogeometric Reissner–Mindlin shell formulation for implicit dynamic calculations using the Galerkin method is presented. A consistent as well as a lumped matrix formulation is implemented. The suitability of the developed shell formulation for natural frequency analysis is demonstrated by a numerical example. In a second set of examples, transient problems of plane and curved geometries undergoing large deformations in combination with nonlinear material behavior are investigated. Via a zero-thickness stress algorithm for arbitrary material models, a $J_2$-plasticity constitutive law is implemented. In the numerical examples, the effectiveness, robustness, and superior accuracy of a continuous interpolation method of the shell director vector is compared with experimental results and alternative numerical approaches.

Nicholas Fantuzzi, Francesco Tornabene, Michele Bacciocchi, Ana M.A. Heves and Antonio J.M. Ferreira (DICAM–Department, School of Engineering and Architecture, University of Bologna, Italy), “Stability and
SUMMARY: In the present paper, strong form finite elements are employed for the free vibration study of laminated arbitrarily shaped plates. In particular, the stability and accuracy of three different Fourier expansion-based differential quadrature techniques are shown. These techniques are used to solve the partial differential system of equations inside each computational element. The three approaches are called harmonic differential quadrature, Fourier differential quadrature and improved Fourier expansion-based differential quadrature methods. The improved Fourier expansion-based differential quadrature method implements auxiliary functions in order to approximate functional derivatives up to the fourth order, with respect to the Fourier differential quadrature method that has a basis made of sines and cosines. All the present applications are related to literature comparisons and the presentation of new results for further investigation within the same topic. A study of such kind has never been proposed in the literature, and it could be useful as a reference for future investigation in this matter.


SUMMARY: Lobatto elements are high order or spectral elements featured by non-equispaced Lobatto nodes and the Lobatto nodal quadrature. The tensor product nature of the element interpolation allows the derivatives at the node be computed through the derivatives along the nodal line which involve only 1D interpolations. In this paper, generic schemes for formulating assumed natural strain and stabilized Lobatto Lagrange C0 plate/shell elements of order $\geq 2$ are presented. Two assumed natural strain schemes are devised. Both schemes sample the normal membrane and transverse shear natural strain components at the 1D reduced-order Gaussian quadrature points along the nodal lines. The difference is that the first and second schemes sample the membrane shear natural strain component at the Lobatto nodes and the 2D reduced-order Gaussian quadrature points, respectively. Meanwhile, all the other natural strain components in both schemes can be obtained by 1D interpolation along the nodal lines. In the stabilization scheme for reduced-integrated elements, only five stabilization vectors are required regardless of the element order. The new elements outperform the standard Lobatto element except when membrane-dominated curved thin-shell problems with strong boundary layer effect are considered by coarse meshes.


ABSTRACT: For a Mindlin–Reissner plate subjected to transverse loadings, the distributions of the rotations and some resultant forces may vary very sharply within a narrow district near certain boundaries. This edge effect is indeed a great challenge for conventional finite element analysis. Recently, an effective hybrid displacement function (HDF) finite element method was successfully developed for solving such difficulty [1, 2]. Although good performances can be obtained in most cases, the distribution continuity of some resulting resultants is destroyed when coarse meshes are employed. Moreover, an additional local coordinate system must be used for avoiding a singular problem in matrix inversion, which makes the derivations more complicated.
Based on a modified complementary energy functional containing Lagrangian multipliers, an improved HDF (IHDF) element scheme is proposed in this work. And two new special IHDF elements, named by IHDF-P4-Free and IHDF-P4-SS1, are constructed for modeling plate behaviors near free and soft simply supported boundaries, respectively. The present modeling scheme not only greatly improves the precision of the numerical results but also avoids usage of the additional local Coordinate system. The numerical tests demonstrate that the new IHDF element scheme is an effective way for solving the challenging edge effect problem in Mindlin–Reissner plates.


SUMMARY: In this paper, we present an effective 6-node triangular solid-shell element (MITC-S6), with particular attention on shear locking and thickness locking. To alleviate shear locking, the assumed transverse strain field of the MITC3+ shell element is used while modifying the bending enhancement mechanism. Thickness locking is treated using the assumed and enhanced strain methods for thickness strain. Two independent enhancements of strains are applied: The in-plane and transverse shear strain fields are enhanced using the strain fields obtained from a bubble interpolation function for in-plane translations, and the thickness strain field is enhanced for linear variation in the thickness direction. The general three-dimensional material law is employed. The proposed element passes all the basic tests including zero-energy mode, patch, and isotropy tests. Excellent performance is observed in various linear and nonlinear benchmark tests, wherein its performance is compared with that of existing 6-node triangular and 8-node quadrilateral solid-shell elements.


SUMMARY: Numerical integration techniques are commonly employed to formulate the system matrices encountered in the analysis of variable stiffness beams and plates using a Ritz based approach. Computing these integrals accurately is often computationally costly. Herein, a novel alternative is presented, the Recursive Analytical Polynomial Integral Definition (RAPID) formulation. The RAPID formulation offers a significant improvement in the speed of analysis, achieved by reducing the number of numerical integrations that are performed by an order of magnitude. A common Legendre Polynomial basis is employed for both trial functions and stiffness/load variations leading to a common form for the integrals encountered. The Legendre Polynomial basis possesses algebraic recursion relations that allow these integrals to be reformulated as triple-products with known analytical solutions, defined compactly using the Wigner (3j) coefficient. The satisfaction of boundary conditions, calculation of derivatives and transformation to other bases is achieved through combinations of matrix multiplication, with each matrix representing a unique boundary condition or physical effect, therefore permitting application of the RAPID approach to a variety of problems. Indicative performance studies demonstrate the advantage of the RAPID formulation when compared to direct analysis using Matlab's ‘integral’ and ‘integral2’.
SUMMARY: A true integration-free meshless method based on Taylor series named Taylor meshless method (TMM) has been proposed to solve two-dimensional partial differential equations (PDEs). In this framework, the shape functions are approximated solutions of the PDE, and the discretization concerns only the boundary. In this paper, the applicability of TMM to solve large-scale problems is discussed under two aspects. First, as in some other meshless methods, ill-conditioned matrices and round-off error propagation could lead to a loss of accuracy when the number of unknowns increases. This point will be investigated in the case of large-scale problems. Second, the computation time and its distribution are analyzed from numerical experiments for PDEs in a 3D domain. It is established that the TMM method is efficient and robust, even in the case of large-scale problems, while the finite element numerical model involves more than 3 million degrees of freedom.

SUMMARY: This paper presents a novel formulation based on Hellinger–Reissner variational principle in the framework of quasi-conforming method for static and free vibration analysis of Reissner–Mindlin plates. The formulation starts from polynomial approximation of stresses, which satisfy the equilibrium equations of Reissner–Mindlin plate theory. Then the stress matrix is treated as the weighted function to weaken the strain-displacement equations after the strains are derived by using the constitutive equations. Finally, the string-net functions are introduced to calculate strain integration. As examples, two new plate bending elements, a 4-node quadrilateral element QC-P4-11/β and a 3-node triangular element QC-P3-7/β, are proposed. Several benchmark examples are demonstrated to show the performance of the elements, and the results obtained are compared with other available ones. Numerical results have proved that both elements possess excellent precision. In particular, the quadrilateral element performs well even when the element shape degenerates into a triangle or concave quadrangle.

SUMMARY: This study proposed geometrically nonlinear quadratic solid/solid-shell elements applicable for moving structures. Coordinates in the corotational (CR) formulation were established for a solid element. The proposed CR formulation was consistent with other hexahedral or tetrahedral solid type finite elements. The study involved an explicit description of relevant quantities induced during the derivation. Centrifugal and inertial terms were derived to analyze the behavior of moving structures. The formulation derived in the study was applicable for various solid type elements. Thus, an assumed-strain 18-node solid-shell element was developed based on the Hellinger–Reissner principle to avoid locking in the local element. In addition, quadratic solid elements (i.e., a 10-node tetrahedron and a 20-node hexahedron) were developed in the CR solid formulation. Finally, the results were compared with those derived by previous researches involving typical static benchmark problems and commercial software. The findings indicated a good agreement between the comparisons and validated the proposed finite elements.

ABSTRACT: The Koiter-Newton method had recently demonstrated a superior performance for nonlinear analyses of structures, compared to traditional path-following strategies. The method follows a predictor-corrector scheme to trace the entire equilibrium path. During a predictor step, a reduced-order model is constructed based on Koiter's asymptotic postbuckling theory that is followed by a Newton iteration in the corrector phase to regain the equilibrium of forces. In this manuscript, we introduce a robust mixed solid-shell formulation to further enhance the efficiency of stability analyses in various aspects. We show that a Hellinger-Reissner variational formulation facilitates the reduced-order model construction omitting an expensive evaluation of the inherent fourth-order derivatives of the strain energy. We demonstrate that extremely large step sizes with a reasonable out-of-balance residual can be obtained with substantial impact on the total number of steps needed to trace the complete equilibrium path. More importantly, the numerical effort of the corrector phase involving a Newton iteration of the full-order model is drastically reduced thus revealing the true strength of the proposed formulation. We study a number of problems from engineering and compare the results to the conventional approach in order to highlight the gain in numerical efficiency for stability problems.


ABSTRACT: We introduce a coupled finite and boundary element formulation for acoustic scattering analysis over thin-shell structures. A triangular Loop subdivision surface discretisation is used for both geometry and analysis fields. The Kirchhoff-Love shell equation is discretised with the finite element method and the Helmholtz equation for the acoustic field with the boundary element method. The use of the boundary element formulation allows the elegant handling of infinite domains and precludes the need for volumetric meshing. In the present work, the subdivision control meshes for the shell displacements and the acoustic pressures have the same resolution. The corresponding smooth subdivision basis functions have the $C^1$ continuity property required for the Kirchhoff-Love formulation and are highly efficient for the acoustic field computations. We verify the proposed isogeometric formulation through a closed-form solution of acoustic scattering over a thin-shell sphere. Furthermore, we demonstrate the ability of the proposed approach to handle complex geometries with arbitrary topology that provides an integrated isogeometric design and analysis workflow for coupled structural-acoustic analysis of shells.


ABSTRACT: The Koiter-Newton (KN) method is a combination of local multimode polynomial approximations inspired by Koiter's initial postbuckling theory and global corrections using the standard Newton method. In the original formulation, the local polynomial approximation, called a reduced-order model, is used to make significantly more accurate predictions compared to the standard linear prediction used in conjunction with Newton method. The correction to the exact equilibrium path relied exclusively on Newton-Raphson method using the full model. In this paper, we proposed a modified Newton-type KN
method to trace the geometrically nonlinear response of structures. The developed predictor–corrector strategy is applied to each predicted solution of the reduced–order model. The reduced–order model can be used also in the correction phase, and the exact full nonlinear model is applied only to calculate force residuals. Remainder terms in both the displacement expansion and the reduced–order model are well considered and constantly updated during correction. The same augmented finite element model system is used for both the construction of the reduced–order model and the iterations for correction. Hence, the developed method can be seen as a particular modified Newton method with a constant iteration matrix over the single KN step. This significantly reduces the computational cost of the method. As a side product, the method has better error control, leading to more robust step size adaptation strategies. Numerical results demonstrate the effectiveness of the method in treating nonlinear buckling problems.


ABSTRACT: Three–dimensional hybrid–Trefftz stress finite elements for plates and shells are proposed. Two independent fields are approximated: stresses within the element and displacement on their boundary. The required stress field derived from the Papkovitch–Neuber solution of the Navier equation, which a priori satisfies the Trefftz constraint, is generated using homogeneous harmonic polynomials. Restriction on the polynomial degree in the coordinate measured along the thickness direction is imposed to reduce the number of independent terms. Explicit expressions of the corresponding independent polynomials are listed up to the fifth order. Illustrative applications to evaluate displacements and stresses are conducted by hexahedral hybrid–Trefftz stress element models. The hierarchical p– and h–refinement strategy are exploited in the numerical tests.


ABSTRACT: In this paper, we present a novel scheme to generate trimmed quadrilateral shell meshes using a paving and cutting algorithm. Paving with well–shaped quadrilateral shell elements is initiated from a seed element placed in the interior of a geometric surface and proceeds around the boundary of the paved mesh in all directions. The paved all–quadrilateral mesh covering the entire domain is cut by the boundaries of a geometric surface. Pentagonal shell elements are created by cutting the corners of quadrilateral shell elements at the domain boundaries. Pentagonal shape functions are constructed using Wachspress coordinates, and assumed natural strains in the form of the mixed interpolation of tensorial components approach are employed to avoid the transverse shear locking of pentagonal shell elements. Several numerical examples are investigated to show the effectiveness of the present method.


ABSTRACT: Single–curvature plates are commonly encountered in mechanical and civil structures. In this paper, we introduce a topology optimization method for the stiffness–based design of structures made of curved plates with fixed thickness. The geometry of each curved plate is analytically and explicitly represented by its location, orientation, dimension, and curvature radius, and therefore, our method renders designs that are
distinctly made of curved plates. To perform the primal and sensitivity analyses, we use the geometry projection method, which smoothly maps the analytical geometry of the curved plates onto a continuous density field defined over a fixed uniform finite element grid. A size variable is ascribed to each plate and penalized in the spirit of solid isotropic material with penalization, which allows the optimizer to remove a plate from the design. We also introduce in our method a constraint that ensures that no portion of a plate lies outside the design envelope. This prevents designs that would otherwise require cuts to the plates that may be very difficult to manufacture. We present numerical examples to demonstrate the validity and applicability of the proposed method.

ABSTRACT: In this paper, we extend to Reissner-Mindlin plate bending problems a technique, originally proposed in the context of two-dimensional and three-dimensional continua, for recovering fully equilibrated stresses from the solution of a compatible finite element model. The technique involves partition of unity functions and the analyses of overlapping star patches modelled with hybrid equilibrium plate elements. The patches are subjected to balanced systems of loads composed of partitioned and fictitious loads, where the latter are derived from the stresses of the compatible solution. The special case of assumed linear displacement fields of both deflection and rotation for the compatible model is included. This case requires additional fields of stress resultants to correct possible rotational imbalances of star patches, and these are derived elementwise. Other cases of nonconforming elements are briefly considered. Numerical examples are presented to illustrate the effectiveness of these techniques in terms of the deviation of the recovery, which compares the complementary strain energy of a recovered solution with that obtained by a global equilibrated analysis based on the same stress approximations.

ABSTRACT: The concept of energy-sampling stabilization is used to develop a mean-strain quadratic 10-node tetrahedral element for the solution of geometrically nonlinear solid mechanics problems. The development parallels recent developments of a “composite” uniform-strain 10-node tetrahedron for applications to linear elasticity and nonlinear deformation. The technique relies on stabilization by energy sampling with a mean-strain quadrature and proposes to choose the stabilization parameters as a quasi-optimal solution to a set of linear elastic benchmark problems. The accuracy and convergence characteristics of the present formulation are tested on linear and nonlinear benchmarks and compare favorably with the capabilities of other mean-strain and high-performance tetrahedral and hexahedral elements for solids, thin-walled structures (shells), and nearly incompressible structures.

ABSTRACT: We present a variational method for problems in solid and structural mechanics that is designed to be intrinsically free from locking when using equal-order interpolation for all involved fields. The specific feature of the formulation is that it avoids all geometrical locking effects (as opposed to material locking effects, for instance Poisson locking) for any type of structural or solid model, independent of the underlying
discretization scheme. The possibility of employing equal-order interpolation for all involved fields circumvents the task of finding particular function spaces to remove locking and avoid artificial stress oscillations. This is particularly attractive, for instance, for isogeometric analysis using unstructured meshes or T-splines. Comprehensive numerical tests underline the promising behavior of the proposed method for geometrically linear and nonlinear problems in terms of displacements and stress resultants using standard finite elements, isogeometric finite elements, and a meshless method.


ABSTRACT: A recent unsymmetric 4-node, 8-DOF plane element US-ATFQ4, which exhibits excellent precision and distortion-resistance for linear elastic problems, is extended to geometric nonlinear analysis. Since the original linear element US-ATFQ4 contains the analytical solutions for plane pure bending, how to modify such formulae into incremental forms for nonlinear applications and design an appropriate updated algorithm become the key of the whole job. First, the analytical trial functions should be updated at each iterative step in the framework of updated Lagrangian formulation that takes the configuration at the beginning of an incremental step as the reference configuration during that step. Second, an appropriate stress update algorithm in which the Cauchy stresses are updated by the Hughes-Winget method is adopted to estimate current stress fields. Numerical examples show that the new nonlinear element US-ATFQ4 also possesses amazing performance for geometric nonlinear analysis, no matter whether regular or distorted meshes are used. It again demonstrates the advantages of the unsymmetric finite element method with analytical trial functions.

Shuguang Li, Jiayi Yan, Guofan Zhang and Shihui Duan, “Commutativity of the strain energy density expression for the benefit of the FEM implementation of Koiter’s initial postbuckling theory”, International Journal for Numerical Methods in Engineering, Vol. 114, No. 9, pp 955-974, 1 June 2018

ABSTRACT: The concept of full commutativity of displacements in the expression for strain energy density for the geometrically nonlinear problem has been introduced for the first time and fully established in this paper. Its consequences for the FEM formulation have been demonstrated. As a result, the strain energy, equilibrium equation, and incremental equilibrium equation for the geometrically nonlinear problem can all be presented in a unified manner involving various stiffness matrices that are all symmetric, unique, and explicitly expressed. As an important application, the framework has been employed in the FEM implementation of Koiter’s initial postbuckling theory, which has been handicapped by its mesh sensitivity in evaluating one of the initial postbuckling coefficients. This has largely prevented it from being incorporated in mainstream commercial FEM codes. Based on the outcomes of this paper, the mesh sensitivity problem has been completely resolved without the need to use any specially formulated element. As a result, Koiter’s theory can be practically and straightforwardly implemented in any FEM code. The results have been verified against those found in the literature.


ABSTRACT: The analysis of the Kirchhoff plate is performed using rational Bézier triangles in isogeometric analysis coupled with a feature-preserving automatic meshing algorithm. Isogeometric analysis employs the same basis function for geometric design as well as for numerical analysis. The proposed approach also features an automatic meshing algorithm that admits localized geometric features (eg, small geometric details and sharp
corners) with high resolution. Moreover, the use of rational triangular Bézier splines for domain triangulation significantly increases the flexibility in discretizing spaces bounded by complicated nonuniform rational B-spline curves. To raise the global continuity to $C^1$ for the solution of the plate bending problem, Lagrange multipliers are leveraged to impose continuity constraints. The proposed approach also manipulates the control points at domain boundaries in such a way that the geometry is exactly described. A number of numerical examples consisting of static bending and free vibration analysis of thin plates bounded by complicated nonuniform rational B-spline curves are used to demonstrate the advantage of the proposed approach.


ABSTRACT: In this paper, a triangular thin flat shell element without rotation degrees of freedom is proposed. In the Kirchhoff hypothesis, the first derivative of the displacement must be continuous because there are second-order differential terms of the displacement in the weak form of the governing equations. The displacement is expressed as a linear function and the nodal rotation is defined using node-based smoothed finite element method. The rotation field is approximated using the nodal rotation and linear shape functions. This rotation field is linear in an element and continuous between elements. The curvature is defined by differentiating the rotation field, and the stiffness is calculated from the curvature. A hybrid stress triangular membrane element was used to construct the shell element. The penalty technique was used to apply the rotation boundary conditions. The proposed element was verified through several numerical examples.


ABSTRACT: A nine-node corotational curved quadrilateral shell element with novel treatment for rotation at intersection of folded and multishell structures is presented. The element's corotational reference frame is defined by the two bisectors of the diagonal vectors generated using the four corner nodes and their cross product. In reference frame, the element rigid-body rotations are excluded in calculating the local nodal variables from the global nodal variables. Rotations are not represented by axial (pseudo) vectors but by components of polar (proper) vectors, of which additivity and commutativity lead to symmetry of the tangent stiffness matrix. In the global coordinate system, the two smallest components of the midsurface normal vector at each node of a smooth shell or at nodes away from the intersection of nonsmooth shells are defined as rotational variables. In addition, of the two nodal orientation vectors at intersections of folded and multishell structures, two smallest components of one vector, together with one smaller component of another vector, are employed as rotational variables, leading to the desired additive property for all nodal variables in a nonlinear incremental solution procedure. In the local coordinate system, the two smallest components of the midsurface normal vector(s) at any node of a smooth shell or in each smooth patch of nonsmooth shell are defined as rotational variables. Different from other existing corotational finite-element formulations, the resulting element tangent stiffness matrix is symmetric owing to the commutativity of the local nodal variables in calculating the second derivative of strain energy with respect to these nodal variables. To alleviate membrane and shear locking phenomena, the membrane strains and the out-of-plane shear strains are replaced with assumed strains, using the Mixed Interpolation of Tensorial Components approach, for obtaining the element tangent stiffness matrices and the internal force vector. Finally, a series of benchmark, challenging smooth, folded, and multishell structures undergoing large displacements and large rotations are analyzed to demonstrate the reliability and computational accuracy of the proposed formulation.

ABSTRACT: A locking-free unsymmetric 8-node solid-shell element with high distortion tolerance is proposed for general shell analysis, which is equipped with translational degrees of freedom only. The prototype of this new model is a recent solid element US-ATFH8 developed by combining the unsymmetric finite element method and the analytical solutions in three-dimensional local oblique coordinates. By introducing proper shell assumptions and assumed natural strain modifications for transverse strains, the new solid-shell element US-ATFHS8 is successfully formulated. This element is able to give highly accurate predictions for shells with different geometric features and loading conditions and is quite insensitive to mesh distortions. In particular, the excellent performance of US-ATFH8 under membrane load is well inherited, which is an outstanding advantage over other shell elements.


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“Harnessing Seeded Geometric Imperfection to Design Cylindrical Shells With Tunable Elastic Postbuckling Behavior”, Journal of Applied Mechanics, Vol. 84, No. 1, January 2017 (or is it October 2016?)
doi:10.1115/1.4034827.

ABSTRACT: Geometric imperfection, known as a detrimental effect on the buckling load of cylindrical shells, has a new role under the emerging trend of using buckling for smart purposes. Eigenshape-based geometries were designed on the shell surface with the aim of tailoring the postbuckling response. Fourteen seeded geometric imperfection (SGI) cylinders were fabricated using polymer-based 3D printing, and their postbuckling responses were numerically simulated with a general-purpose finite element program. Results on the prototyped SGI cylinders showed a tunable elastic postbuckling response in terms of initial and final stiffness, the maximum load drop from mode switching, and the number of snap-buckling events. A response contour and discrete map is presented to show how the number of waves in the axial and circumferential directions in the seeded eigenshape imperfection can control the elastic postbuckling response. SGI cylinders provide diverse design opportunities for controllable unstable response and are good candidates for use in smart and adaptive materials/structures.

References listed at the end of the paper:


ABSTRACT: This paper illustrates the effectiveness of a functionally graded core in preventing wrinkling in sandwich structures. The problem is solved for piecewise and continuous through-the-thickness core stiffness variations. The analysis is extended to account for the effect of temperature on wrinkling of a sandwich beam with a functionally graded core. The applicability of the developed theory is demonstrated for foam cores where the stiffness is an analytical function of the mass density. In this case, a desirable variation of the stiffness can be achieved by varying the mass density through the thickness of the core. Numerical examples demonstrate that wrinkling stability of a facing can significantly be increased using a piecewise graded core. The best results are achieved locating the layers with a higher mass density adjacent to the facing. A significant increase in the wrinkling stress can eliminate wrinkling as a possible mode of failure, without noticeably increasing the weight of the structure. In the case of a uniform temperature applied in addition to compression, wrinkling in a sandwich beam with a functionally graded core is affected both by its grading as well as by the effect of temperature on the facing and core properties. Although even a moderately elevated temperature may significantly lower the wrinkling stress, the advantage of a graded core over the homogeneous counterpart is conserved.

Zhichao Fan, Jian Wu, Qiang Ma, Yuan Liu, Yewang Su and Keh-Chih Hwang, “Post-buckling analysis of curved beams”, Journal of Applied Mechanics, Vol. 84, No. 3, March 2017 (or is it January 2017?)

doi: 10.1115/1.4035534

ABSTRACT: Stretchability of the stretchable and flexible electronics involves the post-buckling behaviors of internal connectors that are designed into various shapes of curved beams. The linear displacement–curvature relation is often used in the existing post-buckling analyses. Koiter pointed out that the post-buckling analysis needs to account for curvature up to the fourth power of displacements. A systematic method is established for the accurate post-buckling analysis of curved beams in this paper. It is shown that the nonlinear terms in curvature should be retained, which is consistent with Koiter’s post-buckling theory. The stretchability and strain of the curved beams under different loads can be accurately obtained with this method.

ABSTRACT: We explore the effect of precisely defined geometric imperfections on the buckling load of spherical shells under external pressure loading, using finite-element analysis that was previously validated through precision experiments. Our numerical simulations focus on the limit of large amplitude defects and reveal a lower bound that depends solely on the shell radius to thickness ratio and the angular width of the defect. It is shown that, in the large amplitude limit, the buckling load depends on a single geometric parameter, even for shells of moderate radius to thickness ratio. Moreover, numerical results on the knockdown factor are fitted to an empirical, albeit general, functional form that may be used as a robust design guideline for the critical buckling conditions of pressurized spherical shells.

References listed at the end of the paper:

ABSTRACT: Mechanics of tympanic membrane (TM) is crucial for investigating the acoustic transmission through the ear. In this study, we studied the wrinkling behavior of tympanic membrane when it is exposed to mismatched air pressure between the ambient and the middle ear. The Rayleigh–Ritz method is adopted to analyze the critical wrinkling pressure and the fundamental eigenmode. An approximate analytical solution is obtained and validated by finite element analysis (FEA). The model will be useful in future investigations on how the wrinkling deformation of the TM alters the acoustic transmission function of the ear.


ABSTRACT: Attributed to its significance in a wide range of practical applications, the post-buckling behavior of a beam with lateral constraints has drawn much attention in the last few decades. Despite the fact that, in reality, the lateral constraints are often flexible or deformable, vast majority of studies have considered fixed and rigid lateral constraints. In this paper, we make a step toward bridging this gap by studying the post-buckling behavior of a planar beam that is laterally constrained by a deformable wall. Unfortunately, the interaction with a compliant wall prevents derivation of closed-form analytical solutions. Nevertheless, careful examination of the governing equations of a simplified model reveals general properties of the solution, and let us identify the key features that govern the behavior. Specifically, we construct universal “solution maps” that do not depend on the mode number and enable simple and easy prediction of the contact conditions and of the mode-switching force (the force at which the system undergoes instantaneous transition from one equilibrium configuration (or mode) to another). The predictions of the mathematical model are validated against finite element (FE) simulations.


ABSTRACT: In this work, the surface wrinkle modulation of the film/substrate system caused by eigenstrain in the film is studied. A theoretical model is proposed which shows the change of the wrinkle amplitude is completely determined by four dimensionless parameters, i.e., the eigenstrain in the film, the plane strain modulus ratio between the film and the substrate, the film thickness to wrinkle wavelength ratio, and the initial wrinkle amplitude to wavelength ratio. The surface wrinkle amplitude becomes smaller (even almost flat) for the contraction eigenstrain in the film, while for the expansion eigenstrain it becomes larger. If the expansion eigenstrain exceeds a critical value, secondary wrinkling on top of the existing one is observed for some cases. In general, the deformation diagram of the wrinkled film/substrate system can be divided into three regions, i.e., the change of surface wrinkle amplitude, the irregular wrinkling, and the secondary wrinkling, governed by the
four parameters above. Parallel finite element method (FEM) simulations are carried out which have good agreement with the theoretical predictions. The findings may be useful to guide the design and performance of stretchable electronics, cosmetic products, biomedical engineering, soft materials, and devices.

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ABSTRACT: Elastic spherical shells loaded under uniform pressure are subject to equal and opposite compressive probing forces at their poles to trigger and explore buckling. When the shells support external pressure, buckling is usually axisymmetric; the maximum probing force and the energy barrier the probe must overcome are determined. Applications of the probing forces under two different loading conditions, constant pressure or constant volume, are qualitatively different from one another and fully characterized. The effects of probe forces on both perfect shells and shells with axisymmetric dimple imperfections are studied. When the shells are subject to internal pressure, buckling occurs as a non-axisymmetric bifurcation from the axisymmetric state in the shape of a mode with multiple circumferential waves concentrated in the vicinity of the probe.

Exciting new experiments by others are briefly described.

References listed at the end of the paper:
Ming Li, Yanglun Luo, HuaPing Wu, Kai Zhu, Yanzhuang Niu, Tengfei Zhao, Jian Xing and Zhan Kang, “A prenecking strategy makes stretched membranes with clamped ends wrinkle-free”, Journal of Applied Mechanics, Vol. 84, No. 6, June 2017, doi: 10.1115/1.4036416
ABSTRACT: For both polyimide membranes in aerospace and graphene membranes in nanoelectronics with surface accuracy requirements, wrinkles due to the extreme out-of-plane flexibility yield inverse influences on the properties and applications of membranes. In this study, on the basis of discrete topology optimization, we propose a prenecking strategy by adopting elliptical free edges to suppress the stretch-induced wrinkling. This prenecking strategy with the computer-aided-design (CAD)-ready format is versatile to eliminate wrinkles in stretched membranes with clamped ends and achieve wrinkle-free performances. The wrinkle-free capability of the prenecking strategy, capable of satisfying the shape accuracy requirements, indicates that by suffering insignificant area loss, concerning of wrinkling problems in membranes is no further required. As compared with the existing researches focusing on studying wrinkling behaviors, the prenecking strategy offers a promising solution to the stretch-induced wrinkling problem by eliminating wrinkles through design optimization.

ABSTRACT: Wrinkles are widely found in natural and engineering structures, ranging from skins to stretchable electronics. However, it is nontrivial to predict wrinkles, especially for complicated structures, such as multilayer or gradient structures. Here, we establish a symplectic analysis framework for the wrinkles and apply it to layered neo-Hookean structures. The symplectic structure enables us to accurately and efficiently solve the eigenvalue problems of wrinkles via the extended Wittrick–Williams (w–W) algorithm. The symplectic analysis is able to exactly predict wrinkles in bi- and triple-layer structures, compared with the benchmark results and finite element simulations. Our findings also shed light on the formation of hierarchical wrinkles

ABSTRACT: The nonaxisymmetric transverse free vibrations of radially inhomogeneous circular Mindlin plates with variable thickness are governed by three coupled differential equations with variable coefficients, which are quite difficult to solve analytically in general. In this paper, we discover that if the geometrical and material properties of the plates vary in generalized power form along the radial direction, then the complicated governing differential equations can be reduced into three uncoupled second-order ordinary differential equations which are very easy to solve analytically. Most strikingly, for a class of solid circular Mindlin plates with absolutely sharp edge, the natural frequencies can be expressed explicitly in terms of elementary functions, with the corresponding mode shapes given in terms of Jacobi polynomials. These analytical expressions can serve as benchmark solutions for various numerical methods.

ABSTRACT: A new one-dimensional high-order sandwich panel theory for curved panels is presented and compared with the theory of elasticity. The theory accounts for the sandwich core compressibility in the radial direction as well as the core circumferential rigidity. Two distinct core displacement fields are proposed and investigated. One is a logarithmic (it includes terms that are linear, inverse, and logarithmic functions of the radial coordinate). The other is a polynomial (it consists of second and third-order polynomials of the radial coordinate), and it is an extension of the corresponding field for the flat panel. In both formulations, the two thin curved face sheets are assumed to be perfectly bonded to the core and follow the classical Euler–Bernoulli beam assumptions. The relative merits of these two approaches are assessed by comparing the results to an elasticity solution. The case examined is a simply supported curved sandwich panel subjected to a distributed transverse load, for which a closed-form elasticity solution can be formulated. It is shown that the logarithmic formulation is more accurate than the polynomial especially for the stiffer cores and for curved panels of smaller radius.

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ABSTRACT: A modified Fourier–Ritz approach is developed in this study to analyze the free in-plane vibration of orthotropic annular sector plates with general boundary conditions. In this approach, two auxiliary sine functions are added to the standard Fourier cosine series to obtain a robust function set. The introduction of a logarithmic radial variable simplifies the expressions of total energy and the Lagrangian function. The improved Fourier expansion based on the new variable eliminates all the potential discontinuities of the original displacement function and its derivatives in the entire domain and effectively improves the convergence of the results. The radial and circumferential displacements are formulated with the modified Fourier series expansion, and the arbitrary boundary conditions are simulated by the artificial boundary spring technique. The number of terms in the truncated Fourier series and the appropriate value of the boundary spring retraining stiffness are discussed. The developed Ritz procedure is used to obtain accurate solution with adequately smooth displacement field in the entire solution domain. Numerical examples involving plates with various boundary conditions demonstrate the robustness, precision, and versatility of this method. The method developed here is found to be computationally economic compared with the previous method that does not adopt the logarithmic radial variable.


ABSTRACT: The energy absorption capacity of origami crash boxes (OCB) subjected to oblique loading is investigated in the present study. A conventional square tube (CST) with identical weight is employed as benchmark. The comparative study reveals that the origami crash box is more desirable than the conventional square tube in most of the range of load angle. A parameter study is performed to assess the effect of geometry parameters on the energy absorption characteristics. The geometry parameters are tube length L, tube width b, module length l, and width of folded lobe c. Considering that bamboo with large slenderness ratio could
effectively resist wind load, a bulkhead-reinforced origami crash box is proposed as a high-performance energy absorption device. And an optimum structure designed based on the parameter study is investigated. The result suggests that the proposed tube performs much better than the original design.


ABSTRACT: The ribbons selectively bonded to a prestrained elastomeric substrate may buckle into three-dimensional (3D) microstructures after the prestrain release, leading to three possible deformation modes, global, local, and no buckling, depending on the adhesion between the ribbons and substrate. This note establishes analytically the critical length-to-thickness ratio of ribbons, above which the global buckling mode (preferred for mechanically guided 3D deterministic assembly) occurs without material failure.


ABSTRACT: Thin metal-polymer laminates make excellent materials for use in inflatable space structures. By inflating a stowed envelope using pressurized gas and by increasing the internal pressure slightly beyond the yield point of the metal films, the shell rigidizes in the deployed shape. Structures constructed with such materials retain the deployed geometry once the inflation gas has either leaked away, or it has been intentionally vented. For flight, these structures must be initially folded and stowed. This paper presents a numerical method for predicting the force required to achieve a given fold radius in a three-ply metal-polymer-metal laminate and to obtain the resultant springback. A coupon of the laminate is modeled as a cantilever subject to an increasing tip force. Fully elastic, elastic–plastic, relaxation, and springback stages are included in the model. The results show good agreement when compared with experimental data at large curvatures.

Raudel Avila and Yeguang Xue, “Torsional buckling by joining prestrained and unstrained elastomeric strips with application as bilinear elastic spring”, Journal of Applied Mechanics, Vol. 84, No. 10, October 2017, DOI: 10.1115/1.4037347

ABSTRACT: Controlled formation of complex three-dimensional (3D) geometries has always attracted wide interest especially in micro/nanoscale where traditional fabrication techniques fail to apply. Recent advances employed buckling as a promising complementary assembling technique and the method can be used for high-performance electronics materials, such as silicon. This paper describes a new buckling pattern generated by joining multiple prestrained and unstrained elastomeric strips. After releasing, periodic twisting of the system along the releasing direction is generated and bilinear force–displacement relationship is revealed from finite element analysis (FEA). The finding enriches the classes of geometries that can be achieved from structural buckling. Also, compared to other buckling phenomena, the lateral dimension of the system does not change during the buckling process, which makes the structure perfect for elastic spring elements that can be arranged closely to each other without interference.

ABSTRACT: Conformability of bio-integrated electronics to soft and microscopically rough biotissues can enhance effective electronics–tissue interface adhesion and can facilitate signal/heat/mass transfer across the interface. When biotissues deform, for example, when skin stretches or heart beats, the deformation may lead to changes in conformability. Although a theory concerning just full conformability (FC) under deformation has been developed (i.e., the FC theory), there is no available theory for partially conformable (PC) systems subjected to deformation. Taking advantage of the path-independent feature of elastic deformation, we find that the total energy of a PC system subjected to stretching or compression can be analytically expressed and minimized. We discover that the FC theory is not sufficient in predicting FC and a full energy landscape obtained by our PC theory is needed for searching for the equilibrium. Our results reveal that stretching enhances conformability while compression degrades it. In addition to predicting the critical parameters to maintain FC under deformation, our PC theory can also be applied to predict the critical compressive strain beyond which FC is lost. Our theory has been validated by laminating poly(methyl methacrylate) (PMMA) membranes of different thicknesses on human skin and inducing skin deformation.


ABSTRACT: The nonlinear response of a flexible structure, subjected to generally supported conditions with nonlinearities, is investigated for the first time. An analytical procedure is proposed first. Moreover, a simulation technique usually employed in static analysis is developed for confirmation. Generally, ordinary perturbation methods could analyze dynamics of flexible structures with linear boundary conditions. As nonlinear boundaries are taken into account, they are out of operation for the modal shape that is hardly to be obtained, which is the key to the analysis. In order to overcome this, nonlinear boundary conditions are rescaled and the technique of modal revision is employed. Consequently, each governing equation with different time-scales could be analyzed exactly according to corresponding rescaled boundary conditions. The total response of any point at the flexible structure will be composed by harmonic responses yielded by the analytical method. Furthermore, the differential quadrature element method (DQEM), a numerical simulation technique could satisfy boundary conditions strictly, is introduced to certify analytical results. The comparison shows a reasonable agreement between these two methods. In fact, the accuracy of the analytical method for nonlinear boundaries could be explained in theory. Based on the certification, boundary nonlinearities are discussed in detail analytically and found to play an important role in responses. Because of the important role played by the nonlinear factors in the vibration and control of the flexible structure, this paper will open the vibration analysis and numerical study of the flexible structure with nonlinear constraints.


ABSTRACT: We study the buckling of hemispherical elastic shells subjected to the combined effect of pressure loading and a probing force. We perform an experimental investigation using thin shells of nearly uniform thickness that are fabricated with a well-controlled geometric imperfection. By systematically varying the indentation displacement and the geometry of the probe, we study the effect that the probe-induced deflections have on the buckling strength of our spherical shells. The experimental results are then compared to finite element simulations, as well as to recent theoretical predictions from the literature. Inspired by a nondestructive technique that was recently proposed to evaluate the stability of elastic shells, we characterize the nonlinear load-deflection mechanical response of the probe for different values of the pressure loading. We demonstrate that this nondestructive method is a successful local way to assess the stability of spherical shells.

ABSTRACT: Benefits of a functionally graded core increasing wrinkling stability of sandwich panels have been demonstrated in a recent paper (Birman, V., and Vo, N., 2017, “Wrinkling in Sandwich Structures With a Functionally Graded Core,” ASME J. Appl. Mech., 84(2), p. 021002), where a several-fold increase in the wrinkling stress was achieved, without a significant weight penalty, using a stiffer core adjacent to the facings.

In this paper, wrinkling is analyzed in case where the facings are subject to biaxial compression and/or in-plane shear loading, and the core is arbitrary graded through the thickness. Two issues addressed are the effect of biaxial or in-plane shear loads on wrinkling stability of panels with both graded and ungraded core, and the verification that functional grading of the core remains an effective tool increasing wrinkling stability under such two-dimensional (2D) loads. As follows from the study, biaxial compression and in-plane shear cause a reduction in the wrinkling stress compared to the case of a uniaxial compression in all grading scenarios. Accordingly, even sandwich panels whose mode of failure under uniaxial compression was global buckling, the loss of strength in the facings or core crimpling may become vulnerable to wrinkling under 2D in-plane loading. It is demonstrated that a functionally graded core with the material distributed to increase the local stiffness in the interface region with the facings is effective in preventing wrinkling under arbitrary in-plane loads compared to the equal weight homogeneous core.

References listed at the end of the paper:


ABSTRACT: Stretchable electronics based on inorganic materials are an innovative technology with potential applications for many emerging electronic devices, due to their combination of stretchable mechanics and high electronic performance. The compliant elastomeric substrate, on which the brittle electronic components are mounted, plays a key role in achieving stretchability. However, conventional elastomeric substrates can undergo excessive mechanical deformation, which can lead to active component failure. Here, we introduce a simple and novel strategy to produce failure-resistant stretchable electronic platforms by bonding a thin film of stiff material, patterned into a serpentine network layout, to the elastomeric substrate. No prestraining of the substrate is required, and these systems offer sharp bilinear mechanical behavior and high ratio of tangent-to-elastic moduli. We perform comprehensive theoretical, numerical, and experimental studies on the nonbuckling-based prestrain-free design, and we analyze the key parameters impacting the mechanical behavior of a strain-limiting substrate. As a device-level demonstration, we experimentally fabricate and characterize skin-mountable stretchable copper (Cu) electrodes for electrophysiological monitoring. This study paves the way to high performance stretchable electronics with failure-resistant designs. References listed at the end of the paper:


ABSTRACT: Wrinkles can be often observed in dielectric elastomer (DE) films when they are subjected to electrical voltage and mechanical forces. In the applications of DEs, wrinkle formation is often regarded as an indication of system failure. However, in some scenarios, wrinkling in DE does not necessarily result in material failure and can be even controllable. Although tremendous efforts have been made to analyze and calculate a variety of deformation modes in DE structures and devices, a model which is capable of analyzing wrinkling phenomena including the critical electromechanical conditions for the onset of wrinkles and wrinkle morphology in DE structures is currently unavailable. In this paper, we experimentally demonstrate controllable wrinkling in annular DE films with the central part being mechanically constrained. By changing the ratio between the inner radius and outer radius of the annular films, wrinkles with different wavelength can be induced in the films when externally applied voltage exceeds a critical value. To analyze wrinkling phenomena in DE films, we formulate a linear plate theory of DE films subjected to electromechanical loadings. Using the model, we successfully predict the wavelength of the voltage-induced wrinkles in annular DE films. The model developed in this paper can be used to design voltage-induced wrinkling in DE structures for different engineering applications.

References listed at the end of the paper:

ABSTRACT: In the analysis of origami structures, the deformation of shells usually couples with the rotation of creases, which leads to the difficulty of solving high-order differential equations. In this study, first the deformation of creased shell is solved analytically. Then, an approximation method named virtual crease method (VCM) is employed, where virtual creases are used to approximate the deformation of shells, and then a complex structure can be simplified into rigid shells connected by real and virtual creases. Then, VCM is used to analyze the large deflection of shells as well as the bistable states of origami structures, such as single creased shell and cell of Miura-Ori. Compared with experiment results, the deformed states given by VCM are quite accurate. Therefore, this generalized method may have potential applications in the analysis of origami structures.

References listed at the end of the paper

ABSTRACT: The control of geometric shapes is well acknowledged as one of the facile routes to regulate properties of graphene. Here, we conduct a theoretical study on the evaporation-driven self-folding of a single piece of graphene nanoribbon that is immersed inside a liquid droplet prior, and demonstrate the folded pattern, which is significantly affected by the surface wettability gradient of the graphene nanoribbon. On the basis of energy competition among elastic bending deformation, liquid–graphene interaction and van der Waals force interaction of folded nanoribbons, we propose a theoretical mechanics model to quantitatively probe the relationship among self-folding, surface wettability gradient, and pattern and size of ultimate folded graphene. Full-scale molecular dynamics (MD) simulations are performed to validate the energy competition and the self-folded patterns, and the results show good agreement with theoretical analyses. This study sheds novel insight on folding graphene nanoribbons by leveraging surface wettability and will serve as a theoretical guidance for the controllable shape design of graphene nanoribbons.


ABSTRACT: In this study, the plastic deformation mechanism of a fully clamped beam under oblique loading at its free end is analyzed. Supposing the cross sections are variable along the beam length, a characteristic length $L^* \equiv MP/NP$, defined as the ratio between fully plastic bending moment $MP$ and fully compression force $NP$, is employed to estimate the load carrying capacity of each cross section. By finite element (FE) simulations of the conical tubes, it is validated that if the initial failure position locates in the middle of the beam, it will not change with the total beam length. Then, based on the analytical analysis and FE simulation, a progressive deformation mechanism triggered by bending, notated as progressive bending, is proposed for the first time. From the optimization result of maximizing loading force that the unit mass can withstand, the tubes with constant thickness are found to be better than tubes with graded thickness, when they are used as supporting structures. The multi-objective optimization for tubes with varying cross sections under oblique loading with different angles is also given. Then, two methods to improve the load carrying capacity of tubes are given: (1) to design the cross section of the tube, which is corresponding to let the critical loading force of all the cross sections be equal; (2) to optimize the initial failure point, so as to produce repeated failure modes.

References listed at the end of the paper:
were obtained. The free point forces. Some physical insights into the cantilevered beam response at the first and second resonant modes and computational results previously published show good agreement for responses to both static and dynamic point forces. Some physical insights into the cantilevered beam response at the first and second resonant modes were obtained. The free–free beam condition was investigated at the first and third resonant modes, and the
nolinearity (primarily inertia) was shown to shift the resonant frequency significantly from the linear natural frequency and lead to hysteresis in both modes.

References listed at the end of the paper:


ABSTRACT: Through the analysis of a model problem, a thin elastic plate bonded to an elastic foundation, we address several issues related to the miniature bulge test for measuring the energy-release rate associated with the interfacial fracture of a bimaterial system, where one of the constituents is a thin foil. These issues include the effect of the substrate compliance on the interpretation of the energy release rate, interfacial strength, and the identification of the boundary of the deforming bulge or the location of the interfacial crack front. The analysis also suggests a way for measuring the so-called foundation modulus, which characterizes the property of the substrate. An experimental example, a stainless steel thin foil bonded to an aluminum substrate through hot-isostatic-pressing (HIP), is used to illustrate and highlight some of the conclusions of the model analysis.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: Buckling of multilayer graphene sheets (MLGSs) subjected to an axial compressive load in plane-strain condition is studied. Closed-form solutions for buckling load of MLGSs are obtained based on a continuum model for MLGSs. Two different kinematic assumptions, which lead to MLGS beam, which was recently proposed by the authors, and the Euler beam, are used to obtain the buckling loads. The obtained solutions yield significantly different buckling loads when the axial length is small. To validate obtained results, molecular dynamics (MD) simulations are conducted, and they show that the MLGS beam model well captures the buckling load of MLGSs. The buckling solution of MLGS beam model provides two interesting facts. First, the buckling load of MLGSs coincides with the Euler buckling load when the length is large. Second, when the number of layers is large, the buckling strain converges to a finite value, and could be expressed as a linear combination of the buckling strain of single-layer graphene and the ratio between the shear rigidity of interlayer and the tensile rigidity of graphene layer. We validate the asymptotic behavior of buckling strain through MD simulations and show that buckling occurs even when the overall thickness is larger than the axial length.
Finally, we present a diagram that contains buckling strain of MLGSs according to the boundary conditions, the number of layers, and the axial length.

References listed at the end of the paper:

ABSTRACT: The membrane structure has been applied throughout different fields such as civil engineering, biology, and aeronautics, among others. In many applications, large deflections negate linearizing assumptions, and linear modes begin to interact due to the nonlinearity. This paper considers the coupling effect between vibration modes and develops the theoretical analysis of the free vibration problem for orthotropic rectangular membrane structures. Von Kármán theory is applied to model the nonlinear dynamics of these membrane structures with sufficiently large deformation. The transverse displacement fields are expanded with both symmetric and asymmetric modes, and the stress function form is built with these coupled modes. Then, a
reduced model with a set of coupled equations may be obtained by the Galerkin technique, which is then solved numerically by the fourth-order Runge–Kutta method. The model is validated by means of an experimental study. The proposed model can be used to quantitatively predict the softening behavior of amplitude-frequency, confirm the asymmetric characters of mode space distribution, and reveal the influence of various geometric and material parameters on the nonlinear dynamics.

References listed at the end of the paper:

ABSTRACT: This paper presents a novel application of multiparameter spectral theory to the study of structural stability, with particular emphasis on aeroelastic flutter. Methods of multiparameter analysis allow the development of significant new solution and analysis algorithms for aeroelastic flutter problems; including direct solvers for polynomial problems of arbitrary order and size, and a pseudospectral method for characterizing the nature of the flutter point and its local modal damping gradient. Two variants of the flutter point direct solver are presented, their computational characteristics are compared, and an efficient hybrid method of direct spectral solution and iterative pseudospectral solution is developed. This method is well suited to the analysis of problems arising in reduced-order modeling and preliminary design optimization and has the advantage of computing all the system flutter points and their characteristics with minimal user oversight. The aeroelastic inverse problem, with applications in parameter identification and system optimization, is also shown to be solvable via multiparameter analysis. Extensions and improvements to this new conceptual framework and associated solvers are discussed.

References listed at the end of the paper:

ABSTRACT: Understanding the buckling and post-buckling behavior of rods confined in a finite space is of both scientific and engineering significance. Under uniaxial compression, an initially straight and slender rod confined in a tube may buckle into a sinusoidal shape and subsequently evolve into a complicated, three-dimensional (3D) helical shape. In this paper, we combine theoretical and numerical methods to investigate the post-buckling behavior of confined rods. Two theoretical models, which are based on the inextensible and extensible rod theories, respectively, are proposed to derive the analytical expressions for the axial compressive stiffness in the sinusoidal post-buckling stage. The former is concise in formulation and can be easily applied in engineering, while the latter works well in a broader scope of post-buckling analysis. Both methods can give a good approximation to the sinusoidal post-buckling stiffness and the former model is proved to be a zeroth-order approximation of the latter. The flexible multibody dynamics method based on the Timoshenko's geometrically exact beam theory is used to examine the accuracy of the two models. The methods presented in this work can be used in, for example, drilling engineering in oil and gas industries.

References listed at the end of the paper:


ABSTRACT: Viscoelasticity plays an important role in the instability and performance of soft transducers. Wrinkling, an instability phenomenon commonly observed on soft materials, has been studied extensively. In this paper, we theoretically investigate the viscoelastic effect on the wrinkle formation of a dielectric-elastomer (DE) balloon subjected to combined electromechanical loads. Results show that the critical voltage for the wrinkle formation of a DE balloon gradually decreases as the material undergoes viscoelastic relaxation and finally reaches a stable value. The wrinkles in the lateral direction always have critical voltages equal to or lower than those in the longitudinal direction. What is more, the nucleation sites of wrinkles always move from the apex to the rim of DE balloon with the viscoelastic relaxation of DE. Higher pressure also leads to the stable wrinkle nucleation site moving closer to the fixed edge of the DE balloon. An experiment is conducted to illustrate the effect of viscoelasticity on the wrinkle propagation of a DE balloon, and the results agree well with the model predictions. This study provides a guide in the wrinkling control of a DE balloon and may help the future design of DE transducers.

References listed at the end of the paper:

https://doi.org/10.2118/55039-PA

ABSTRACT: In this work, the surface wrinkle modulation mechanism of the three-dimensional (3D) film/substrate system caused by biaxial eigenstrains in the films is studied. A theoretical model based on the energy minimization of the 3D wrinkled film/substrate system is proposed which shows that the change of the surface wrinkle amplitude is determined by four dimensionless parameters, i.e., the eigenstrain in the film, plane strain modulus ratio between the film and substrate, film thickness to wrinkle wavelength ratio, and initial wrinkle amplitude to wavelength ratio. The surface wrinkle amplitude decreases (even almost flat) upon contraction eigenstrain in the film, while increases for that of expansion eigenstrain. Parallel finite element method (FEM) simulations are carried out which have good agreements with the theoretical predictions, and experimental verifications are also presented to verify the findings. Besides, different patterns of 3D surface wrinkles are studied and the similar surface wrinkle modulation is also observed. The findings presented herein may shed useful insights for the design of complex stretchable electronics, cosmetic products, soft devices and the fabrication of 3D complex structures.

References listed at the end of the paper:


ABSTRACT: This is a series of two papers in which the nonlinear stability behavior of sandwich panels is investigated. This part presents the buckling behavior and focuses on the critical load and the buckling mode. The buckling analysis is based on the extended high-order sandwich panel theory (EHSAPT) which takes transverse compressibility and axial rigidity of the core into account. It allows for the interaction between the faces and the core. The geometric nonlinearity, i.e., large displacement with moderate rotation, is considered in both faces and core. The weak form governing equations are derived based on the EHSAPT-based element. Detailed formulations and analysis procedures are provided. It presents a general approach for arbitrary buckling type without decoupling it into isolated global buckling and wrinkling. There are no additional assumptions made about the prebuckling state and buckling mode shape, which are commonly presumed in the literature. In addition, edge effects which are also commonly neglected are included. The prebuckling state is determined via a nonlinear static analysis. Solving an eigenvalue problem yields the critical load and the corresponding eigenvector gives the buckling mode. Sandwich panels with different lengths are studied as examples. Both global buckling and wrinkling are observed. It shows that the axial rigidity of the core has a pronounced effect on both the critical load and the buckling mode.

References listed at the end of the paper:

Furthermore, this could destabilize the post-localized effects may be easily initiated by imperfections after the sandwich structure has buckled globally. The corresponding to global buckling and wrinkling buckling response with imperfections is studied. The numerical examples discuss the post-rigidity, and the shear effect of the core. Both faces and core are considered undergoing large displacements sandwich panel theory (EHSAPT) is presented. The model includes the transverse compressibility, the axial rigidity, and the shear effect of the core. Both faces and core are considered undergoing large displacements with moderate rotations. Based on the nonlinear weak form governing equations, the post-buckling response is obtained by the arc-length continuation method together with the branch switching technique. Also, the post-buckling response with imperfections is studied. The numerical examples discuss the post-buckling response corresponding to global buckling and wrinkling. It is found that due to the interaction between faces and core, localized effects may be easily initiated by imperfections after the sandwich structure has buckled globally. Furthermore, this could destabilize the post-buckling response. The post-buckling response verifies the critical
load and buckling mode given by the buckling analysis in part I. The axial rigidity of the core, although it is very small compared to that of the faces, has a significant effect on the post-buckling response.


ABSTRACT: This paper investigates issues that have arisen in recent efforts to revise long-standing knockdown factors for elastic shell buckling, which are widely regarded as being overly conservative for well-constructed shells. In particular, this paper focuses on cylindrical shells under axial compression with emphasis on the role of local geometric dimple imperfections and the use of lateral force probes as surrogate imperfections. Local and global buckling loads are identified and related for the two kinds of imperfections. Buckling loads are computed for four sets of relevant boundary conditions revealing a strong dependence of the global buckling load on overall end-rotation constraint when local buckling precedes global buckling. A reasonably complete picture emerges, which should be useful for informing decisions on establishing knockdown factors. Experiments are performed using a lateral probe to study the stability landscape for a cylindrical shell with overall end rotation constrained in the first set of tests and then unconstrained in the second set of tests. The nonlinear buckling behavior of spherical shells under external pressure is also examined for both types of imperfections. The buckling behavior of spherical shells is different in a number of important respects from that of the cylindrical shells, particularly regarding the interplay between local and global buckling and the post-buckling load-carrying capacity. These behavioral differences have bearing on efforts to revise buckling design rules. The present study raises questions about the perspicacity of using probe force imperfections as surrogates for geometric dimple imperfections.

References listed at the end of the paper:
In this paper, we propose a new mechanism of DE fluid pumping for high pressure and large volume via synergistic snap-through. This pumping mechanism is customizable for various pressure gradients and enables a new approach to design DE-based soft pumping devices such as a DE total volume pumping over a wide range of large adverse pressure gradients. In comparison, the conventional single DE pump's pumping volume rapidly decreased beyond a low adverse pressure gradient, and large deformation provided by an electromechanical instability, for large volume pumping under high adverse pressure gradient by a DE pump has not been realized. However, the output volume of snap-through pumping is drastically reduced by adverse pressure gradient, and large-volume pumping under high adverse pressure gradient by a DE pump has not been realized. In this paper, we propose a new mechanism of DE fluid pumping that can address this shortcoming by connecting DE pumps of different membrane stiffnesses serially in a pumping circuit and by harnessing synergistic interactions between neighboring pump units. We build a simple serial DE pump to verify the concept, which consists of two DE membranes. By adjusting the membrane stiffness appropriately, a synergistic effect is observed, where the snap-through of membrane 1 triggers the snap-through of membrane 2, ensuring that a large volume (over 70 ml/cycle) can be achieved over a wide range of large adverse pressure gradients. In comparison, the conventional single DE pump's pumping volume rapidly decreased beyond a low adverse pressure gradient of 0.196 kPa. At the pressure difference of 0.98 kPa, the serial DE pump's pumping volume is 4185.1% larger than that of the conventional DE pump. This pumping mechanism is customizable for various pressure ranges and enables a new approach to design DE-based soft pumping devices such as a DE total artificial heart, which requires large-volume pumping over a wide range of pressure difference.


ABSTRACT: Harnessing reversible snap-through of a dielectric elastomer (DE), which is a mechanism for large deformation provided by an electromechanical instability, for large-volume pumping has proven to be feasible. However, the output volume of snap-through pumping is drastically reduced by adverse pressure gradient, and large-volume pumping under high adverse pressure gradient by a DE pump has not been realized. In this paper, we propose a new mechanism of DE fluid pumping that can address this shortcoming by connecting DE pumps of different membrane stiffnesses serially in a pumping circuit and by harnessing synergistic interactions between neighboring pump units. We build a simple serial DE pump to verify the concept, which consists of two DE membranes. By adjusting the membrane stiffness appropriately, a synergistic effect is observed, where the snap-through of membrane 1 triggers the snap-through of membrane 2, ensuring that a large volume (over 70 ml/cycle) can be achieved over a wide range of large adverse pressure gradients. In comparison, the conventional single DE pump's pumping volume rapidly decreased beyond a low adverse pressure gradient of 0.196 kPa. At the pressure difference of 0.98 kPa, the serial DE pump's pumping volume is 4185.1% larger than that of the conventional DE pump. This pumping mechanism is customizable for various pressure ranges and enables a new approach to design DE-based soft pumping devices such as a DE total artificial heart, which requires large-volume pumping over a wide range of pressure difference.
ABSTRACT: An analytical model is derived for the delamination of a thin film from a rigid substrate by a cylindrical shaft with a flat end and finite radius. We show that, within certain limitations, a point-load model can be applied to the system, to give simple relations between the film-substrate energy of adhesion and the measured variables of applied shaft force, blister height, and blister radius. The results are applicable to systems where a finite size cylindrical shaft or disk generates delamination of the film from the substrate.


ABSTRACT: Vibrational microplatforms that exploit complex three-dimensional (3D) architectures assembled via the controlled compressive buckling technique represent promising candidates in 3D microelectromechanical systems (MEMS), with a wide range of applications such as oscillators, actuators, energy harvesters, etc. However, the accuracy and efficiency of such 3D MEMS might be significantly reduced by the viscoelastic damping effect that arises from material viscosity. Therefore, a clear understanding and characterization of such effects are essential to progress in this area. Here, we present a study on the viscoelastic damping effect in complex 3D structures via an analytical model and finite element analysis (FEA). By adopting the Kelvin–Voigt model to characterize the material viscoelasticity, an analytical solution is derived for the vibration of a buckled ribbon. This solution then yields a scaling law for the half-band width or the quality factor of vibration that can be extended to other classes of complex 3D structures, as validated by FEA. The scaling law reveals the dependence of the half-band width on the geometries of 3D structures and the compressive strain. The results could serve as guidelines to design novel 3D vibrational microplatforms for applications in MEMS and other areas of technology.


ABSTRACT: The cruciforms are widely employed as energy absorbers in ships and offshore structures, or basic components in sandwich panel and multicell structure. The kirigami approach is adopted in the design of cruciform in this paper for the following reasons. First, the manufacture process is simplified. Second, it can alter the stiffness distribution of a structure to trigger desirable progressive collapse modes (PCMs). Third, the kirigami pattern can be referred as a type of geometric imperfection to lower the initial peak force during impact. Experiments and numerical simulations were carried out to validate the effectiveness of kirigami approach for cruciform designs. Numerical simulations were carried out to perform comparative and parametric analyses. The comparative studies among single plate (SP), single plate with kirigami pattern (SPKP), and kirigami cruciform (KC) show that the normalized mean crushing force of KC is nearly two times higher than those of SP and SPKP, whereas the normalized initial peak force of KC reduces by about 20%. In addition, the parametric analyses suggest that both the parameters controlling the overall size (i.e., the global slenderness and local slenderness) and those related to the kirigami pattern (i.e., the length ratio and the relative position ratio) could significantly affect the collapse behavior of the cruciforms.

References listed at the end of the paper:


(There are only one or two review papers per issue. There are none on the subject of buckling/vibration, etc. of plates and shells from January 2017 to June 2017)


ABSTRACT: Instabilities in solids and structures are ubiquitous across all length and time scales, and engineering design principles have commonly aimed at preventing instability. However, over the past two decades, engineering mechanics has undergone a paradigm shift, away from avoiding instability and toward taking advantage thereof. At the core of all instabilities—both at the microstructural scale in materials and at the macroscopic, structural level—lies a nonconvex potential energy landscape which is responsible, e.g., for phase transitions and domain switching, localization, pattern formation, or structural buckling and snapping.
Deliberately driving a system close to, into, and beyond the unstable regime has been exploited to create new materials systems with superior, interesting, or extreme physical properties. Here, we review the state-of-the-art in utilizing mechanical instabilities in solids and structures at the microstructural level in order to control macroscopic (meta)material performance. After a brief theoretical review, we discuss examples of utilizing material instabilities (from phase transitions and ferroelectric switching to extreme composites) as well as examples of exploiting structural instabilities in acoustic and mechanical metamaterials.

References listed at the end of the paper (291 of them!):


No “buckling/vibration” reviews in 2018 up to July 2018

End of more review papers published in the journal, ASME Applied Mechanics Reviews (2017 and on).

Google the string: “Journal of Composite Materials”, then click on the third entry, which is: “Journal of Composite Materials – All Issues – SAGE Journals”

DOI: 10.1177/0021998316651482
ABSTRACT: In the present article, the variational energy principle is used to derive the expression for energy release rate in buckled composite laminate containing through-the-width delamination, subjected to in-plane strains. Boundary conditions are clamped at both edges. Buckling and post-buckling solutions are obtained and expressions for critical buckling load and post-buckling deflection have been developed. A through-the-width delamination model has been considered and formulations are based on higher order shear deformation theory. The effects of considering the higher order shear deformation theory on equivalent bending rigidity, buckling load, and energy release rate have been investigated. Finally, the results of current study have been compared with the results of finite element method analysis by Abaqus/CAE and those available in the literature.

DOI: 10.1177/0021998316658966
ABSTRACT: In this article, static and dynamic responses of cross-ply bi-stable composite plates were studied. To accurately predict the natural frequencies and snap-through load, a set of higher order shape functions were proposed. In static analysis, the stable configurations, the deflection of corners, and the midpoint of the plate were calculated. For dynamic analysis, Hamilton’s principle is used to provide approximate solutions to the vibration problem under study. The responses of the plate under ramp and harmonic applied forces were determined, the effect of shape functions on the prediction of the first natural frequency of the plate and the required force for snap-through were investigated. A finite element model is also developed to study the static and vibration characteristics of bi-stable composite plate. The qualitative and quantitative comparisons between the finite element method results and those obtained from the present analysis are generally good and satisfactory. The developed analytical model can also be used for parametric study and further design modification.

ABSTRACT: Filament-wound composite pressure vessels, owing to the advantages of their high specific strength, specific modulus and fatigue resistance, as well as excellent design performance, have been widely used in energy engineering, chemical industry and other fields. A filament-wound composite pressure vessel generally consists of two parts, a cylindrical drum part and the dome parts. In the cylindrical drum part, the filament winding angle and the winding layer thickness can be easily determined due to the regular shape. In the dome parts, however, both the winding angle and the thickness vary along the meridian line. Performance of the dome parts, which strongly depends on the effect of end-opening and the winding mode, dominates the performance of a pressure vessel. In this paper, optimum design of the dome parts is studied by considering both geodesic
winding and non-geodesic winding patterns. A hyperelliptic function is adopted as the basis function for describing the meridian of the dome shape. The dome contour is optimized by taking the shape factor (S.F.) as the objective and parameters in the basis function as the design variables. A specific composite pressure vessel is taken as the numerical analysis example with varying dome shape which is to be optimized. The optimum design solution is obtained through the particle swarm optimization algorithm. It shows that an optimized dome with non-geodesic winding has better S.F. as compared with geodesic winding. Influences of the slippage coefficient and the polar opening on the S.F. are also discussed.

ABSTRACT: Scope of the presented work is a detailed comparison of a macroscopic draping model with real fibre architecture on a complex non-crimp-fabric preform using a new robot-based optical measurement system. By means of a preliminary analytical process design approach, a preforming test centre is set up to manufacture dry non-crimp-fabric preforms. A variable blank holder setup is used to investigate the effect of different process parameters on the fibre architecture. The real fibre architecture of those preforms is captured by the optical measurement system, which generates a three-dimensional model containing information about the fibre orientation along the entire surface of the preform. The measured and calculated fiber orientations are then compared with the simulation results in a three-dimensional overlay file. The results show that the analytical approach is able to predict local hot spots with high shear angles on the preform. Macroscopic simulations show a higher sensitivity towards changes in blank holder pressure than reality and limit the approach to precisely predict fibre architecture parameters on complex geometries.

ABSTRACT: In this paper, a simple four-variable first-order shear deformation theory is further applied to solve the bending and free vibration problems of antisymmetrically laminated functionally graded carbon nanotube (FG-CNT)-reinforced composite plates. The adopted four-variable theory contains only four unknowns in its displacement field which is less than the Reddy’s first-order theory. The equations of motion are derived from the Hamilton’s principle with the help of specific boundary conditions. Laminated FG-CNT-reinforced plates with different distribution types of carbon nanotube through the thickness are considered. The material properties of individual layer are estimated by using the extended rule of mixture. Analytical solutions of various simply supported antisymmetric cross-ply and angle-ply laminates are given for case study. The effects of carbon nanotube volume fraction, length to width ratio and thickness to width ratio on the non-dimensional fundamental frequency and the central deflection are investigated for antisymmetrically laminated FG-CNT-reinforced plates.

ABSTRACT: Laminated composite structures manufactured via the automated fiber placement process inherently contain process defects know as gaps and overlaps. These defects raise concerns when they are
located on or near holes intended for mechanical fastening. This investigation attempts to predict the effect of automated fiber placement-generated defects on the open-hole compression strength by combining both experimental tests and numerical simulation. Tested open-hole compression specimens containing gaps and overlaps oriented at 0° or 90° and centered on or shifted near the hole show that, depending on their location, the gaps and overlaps may have negative, negligible, or positive effects on the open-hole compression strength. The better than expected effects are compatible with microscopic observations that clearly show the rearrangement of the plies during the consolidation process, which prevent the formation of deleterious discontinuities. Incorporating these observations in a numerical model, which simulates gaps and overlaps embedded inside the composite laminates, and applying a progressive failure analysis, confirms that the effects of automated fiber placement defects depend as much on their type as on their location relative to the hole center. Finally, the results obtained from a parametric study provided further explanation on the effects of automated fiber placement defects on the failure strength of perforated composite laminates.


ABSTRACT: The aim of this study is to determine the ballistic impact response of a novel sandwich structure consisting of aluminum honeycomb and Al/SiC functionally graded face sheets and develop a compatible numerical model with experiments. The experiments were carried out by a single-stage gas gun system and numerical simulations were performed using the explicit finite element code, LS-DYNA®. The mechanical properties of the functionally graded face sheets through the thickness were considered in accordance with a power-law distribution. The Mori–Tanaka scheme was used in order to determine the effective material properties of the functionally graded face sheets at a local point. In order to simulate the elastoplastic behavior of the functionally graded face sheets, Tamura–Tomota–Ozawa model was implemented in the numerical model. The ballistic performance of the sandwich structure was investigated for metal-rich \( n = 0.1 \), linear \( n = 1.0 \), and ceramic-rich \( n = 10.0 \) compositions of the functionally graded face sheets. The results indicated that the ceramic fraction of the functionally graded face sheets was quite influential on energy absorption capability, damage mechanism, and impact resistance of the sandwich structure. The sandwich structure with linear functionally graded face sheets showed the highest ballistic performance in terms of damage and deformation shapes of the entire sandwich structure among investigated material compositions.


ABSTRACT: More fundamental test methods are needed to assist the development of physically based and truly predictive simulation tools for composite materials under crash conditions. In this paper, a unidirectional flat specimen that can be used to validate the predicted behaviour from a simulation to the physical behaviour in the experiment is developed. A systematic experimental investigation is conducted to evaluate the influence of the trigger geometry on the crushing response by selecting two trigger types and different trigger angles. For longitudinal crushing, the traditional bevel trigger leads to out-of-plane failure by splaying with a limited amount of in-plane fracture, while the proposed trigger achieves a high amount of compressive fragmentation failure. For transverse crushing, the symmetry of the proposed new trigger improves the specimen stability during the crushing process. It is also observed that the weft threads of the unidirectional fabric reinforcement used for the tests have a strong influence on the longitudinal crushing response. The boundary conditions of the test and the information on the specimen failure gleaned from video recordings and microscopic inspections are discussed in order to facilitate a future correlation with modelling results.

ABSTRACT: The aim of the present work is to study the vibration behavior of sandwich composites with shear damages on the foams. The effect of the densities of damage on the linear and nonlinear vibration parameters is studied. The sandwich materials used in this study is constructed with glass fiber laminates as skins and with PVC closed-cell foams with density 60 and 100 kg m$^{-3}$ as core. After a series of vibration tests, the change of natural frequencies and modal damping due to the damage and the foam densities. For an intact specimen, the resonance frequency was constant when we increase the excitation amplitude. For damaged specimens, the resonance frequencies decrease and the loss factors increase proportionally with the increasing excitation amplitude. The nonlinear parameters corresponding to the elastic modulus and damping were determined for each frequency modes and each damage and foam densities. The results showed that nonlinear dissipative parameters were more sensitive to damage than linear elastic and dissipative parameters.


ABSTRACT: Separation of skin and stringer is likely to be a failure mode in co-cured composites stiffened panels where there is considerable out-of-plane deformation. Such deformations are possible when a stiffened skin structure is loaded in compression/shear beyond buckling or in structures which contain a disbond/delamination at the skin–stringer interface. Prediction of damage initiation and progressive growth in numerical simulations require parameters such as interface fracture toughness which have to be obtained through specimen tests. Since interface toughness is generally mode dependent, this study deals with the design and testing of three different configuration of blade stiffened co-cured composite skin–stringer specimens under mode-I and mode-II dominated loading. Finite element numerical models are developed using three-dimensional cohesive elements to predict the disbond growth under mode-I and mode-II dominated loading. The work also addresses the complexities in the convergence of numerical simulations that arise due to cohesive elements. A systematic way to obtain the best values for cohesive element parameters while finding a balance between accuracy of the results, computation time and numerical stability is presented. The present cohesive element modelling and analysis methodology successfully predicted the disbond growth in skin–stringer specimen and can be used to predict disbond/delamination onset or growth in composite stiffened structures subjected to high bending.


ABSTRACT: Sandwich structures, due to their high stiffness versus lightness ratio, are used progressively in high performance products. In order to design these structures with the most appropriate dimensions and material combinations, relevant mechanical properties must be well understood. This work aims to estimate the elastic properties of composite sandwiches from a curved structure taking into account the manufacturing process. In the case of filament winding process, specimens are necessarily cylindrical or barrel extracted. In our case, these types of structures are tested in 3- and 4-point bending to analyze their behavior experimentally using predictive models and design rules. Different configurations are adopted for bending tests to analyze and discuss global mechanical behavior. Furthermore, the acoustic emission technique is used to detect the initial appearance of damage mechanisms and to examine their evolution in terms of amplitude peaks and localization.
Finally, a correlation between these acoustic emission signals and the damage initiation mechanisms is proposed, considering their effects on the mechanical behavior of each tested material.

ABSTRACT: The fatigue life and damage tolerance of composite stiffened panels with indentation damage are investigated experimentally using single-stringer compression specimens. The indentation damage was induced to one of the two flanges of the stringer of every panel. The advantages of indentation compared to impact are the simplicity of application, less dependence on boundary conditions, better controllability, and repeatability of the imparted damage. The tests were conducted using advanced instrumentation, including digital image correlation, passive thermography, and in situ ultrasonic scanning. Specimens with initial indentation damage ranging between 32 and 56 mm in length were tested quasi-statically and in fatigue, and the effects of cyclic load amplitude and damage size were studied. A means of comparison of the damage propagation rates and collapse loads based on a stress intensity measure and the Paris law is proposed. The stress intensity measure provides the means to compare the collapse loads of specimens with different damage types and damage sizes, while the Paris law is used to compare the damage propagation rates in specimens subjected to different cyclic loads. This approach enables a comparison of different tests and the potential identification of the effects that influence the fatigue lives and damage tolerance of postbuckled structures with defects.

Youming Chen, Raj Das and Mark Battley, “Experimental study on in-plane compressive response of irregular honeycombs”, Journal of Composite Materials, Vol. 52, No. 8, April 2018

ABSTRACT: Compared with regular honeycombs, irregular honeycombs are more representative of real foams, and thus more suitable for the study of foam mechanics. In this paper, the deformation and failure progression in the irregular honeycombs are investigated by analysing the images captured in order to gain an improved understanding on foam failure. Irregular honeycombs with varying cell wall thickness, cell size and cell shape were manufactured using a three-dimensional printer and tested under compression. The behaviour of irregular honeycombs is found to be different from that of regular honeycombs. In irregular honeycombs, cell walls start to fracture at some point, initially at a low speed from multiple locations. The global stress reaches its maximum value shortly after the first fracture of cell walls. Only a few cell walls buckle in the specimens with cells of irregular shape. Fracture is more likely to occur to thin and long cell walls aligned within a medium angle (around 30 to 60°) to the compressive load. However, the susceptibility of a cell wall is to fracture is also affected by its neighbouring cell walls. Strong and stiff neighbouring cell walls could shield load away and protect it from breaking. Because of this, it is better to think of a weak spot as a region, rather than an individual cell or cell wall. Overall, the more uniform cell wall size and thickness are, the better the mechanical performance of cellular solids is.

Qianqian Sui, Changliang Lai and Hualin Fan, “Buckling analyses of double-shell octagonal lattice truss composite structures”, Journal of Composite Materials, Vol. 52, No. 9, April 2018

ABSTRACT: To reveal the compression failure modes of one-dimensional hierarchical double-shell octagonal lattice truss composite structures (DLTCSs), finite element modeling and equivalent continuum models were developed. DLTCS has three typical failure modes: (a) fracture of the strut, (b) global buckling, and (c) local buckling. Failure mode maps were constructed. It is found that column of long enough length will collapse at global buckling. When the column length decreases, the failure mode will turn to local buckling and strut fracture successively. Bay length greatly influences the buckling mode. Longer bay length could change the buckling mode from global buckling to local buckling. Compared with single-shell lattice truss composite structure, DLTCS has advantage in load carrying when the column fails at strut fracture or global buckling, while local buckling tolerance of DLTCS is smaller.

ABSTRACT: The paper presents an efficient numerical optimization approach to deal with the optimization problem for maximizing the fundamental frequency of laminated functionally graded carbon nanotube-reinforced composite quadrilateral plates. The proposed approach is a combination of the cell-based smoothed discrete shear gap method (CS-DSG3) for analyzing the first natural frequency of the functionally graded carbon nanotube reinforced composite plates and a global optimization algorithm, namely adaptive elitist differential evolution algorithm (aeDE), for solving the optimization problem. The design variables are the carbon nanotube orientation in the layers and constrained in the range of integer numbers belonging to \([-90^\circ, 90^\circ]\). Several numerical examples are presented to investigate optimum design of quadrilateral laminated functionally graded carbon nanotube reinforced composite plates with various parameters such as carbon nanotube distribution, carbon nanotube volume fraction, boundary condition and number of layers.

References listed at the end of the paper:

1. Lei ZX, Zhang LW and Liew KM. Analysis of laminated CNT reinforced functionally graded plates using the element-free kp-Ritz method. Compos B Eng 2016; 84: 211–221.


ABSTRACT: This work deals with experimental buckling and free vibration behavior of silane-treated cenosphere/epoxy syntactic foams subjected to axial compression. Critical buckling loads are computed from compressive load–deflection plots deduced using universal testing machine. Further, compressive loads are applied in the fixed intervals until critical loading point on different set of samples having similar filler loadings to estimate natural frequency associated with the first three transverse bending modes. Increasing filler content increases critical buckling load and natural frequency of syntactic foam composites. Increasing axial compressive load reduce structural stiffness of all the samples under investigation. Syntactic foams registered higher stiffness compared to neat epoxy for all the test loads. Similar observations are noted in case of untreated cenosphere/epoxy foam composites. Silane-modified cenosphere embedded in epoxy matrix registered superior performance (rise in critical buckling load and natural frequencies to the tune of 23.75% and 11.46%, respectively) as compared to untreated ones. Experimental results are compared with the analytical solutions that are derived based on Euler–Bernoulli hypothesis and results are found to be in good agreement. Finally, property map of buckling load as a function of density is presented by extracting values from the available literature.

Jamshid Fazilati, “Panel flutter of curvilinear composite laminated plates in the presence of delamination”, Journal of Composite Materials, Vol. 52, No. 20, pp 2789-2801, August 2018
ABSTRACT: The effect of variable fiber placement angle on the supersonic linear flutter of rectangular composite panels containing square delamination zone is investigated using an enhanced spline version of finite strip method (FSM). The location dependent stiffness characteristics and mass matrices due to variable fiber orientation angles within every ply are extracted. The structural formulation is based on the higher-order shear deformation theory while the first-order piston theory is utilized to predict the loading effects of the supersonic airflow. Laminated composite material with varying fiber orientation angles along the axial direction is considered. The effect of aerodynamic damping is overlooked. The flutter coalescence of vibration modes is then traced using a standard eigenvalue procedure. Some representative results are provided to show the accuracy and capability of the developed formulation. The effects of material layup as well as geometry on the flutter behavior of laminated panels are then studied and the variation of critical aerodynamic pressure considering different delamination size, delamination depth, and boundary conditions are examined.

ABSTRACT: The present work proposes a closed-form solution based on refined beam theories for the static analysis of fiber-reinforced composite and sandwich beams under simply supported boundary conditions. The higher-order beam models are developed by employing Carrera Unified Formulation, which uses Lagrange-polynomials expansions to approximate the kinematic field over the cross section. The proposed methodology allows to carry out analysis of composite structure analysis through a single formulation in global-local sense, i.e. homogenized laminates at a global scale and fiber-matrix constituents at a local scale, leading to component-wise analysis. Therefore, three-dimensional stress/displacement fields at different scales can be successfully detected by increasing the order of Lagrange polynomials opportune. The governing equations
are derived in a strong-form and solved in a Navier-type sense. Three benchmark numerical assessments are carried out on a single-layer transversely isotropic beam, a cross-ply laminate $[0^\circ/90^\circ/0^\circ]$ beam and a sandwich beam. The results show that accurate displacement and stress values can be obtained in different parts of the structure with lower computational cost in comparison with traditional, enhanced as well as three-dimensional finite element methods. Besides, this study may serve as benchmarks for future assessments in this field.


ABSTRACT: Three-dimensional fiber-reinforced foam cores may have improved mechanical properties under specific strain rates and fiber volumes. But its performance as a core in a composite sandwich structure has not been fully investigated. This study explored different manufacturing techniques for the three-dimensional fiber-reinforced foam core using existing literature as a guideline to provide a proof of concept for a low-cost and easily repeatable method comprised of readily available materials. The mechanical properties of the fiber-reinforced foam were determined using a three-point bend test and compared to unreinforced polyurethane foam. The foam was then used in a sandwich panel and subjected to dynamic loading by means of a gas gun ($10^3$ s$^{-1}$). High-strain impact tests validated previously published studies by showing, qualitatively and quantitatively, an 18–20% reduction in the maximum force experienced by the fiber-reinforced core and its ability to dissipate the impact force in the foam core sandwich panel. The results show potential for this cost-effective manufacturing method to produce an improved composite foam core sandwich panel for applications where high-velocity impacts are probable. This has the potential to reduce manufacturing and operating costs while improving performance.


ABSTRACT: This paper investigates the effect of moisture on bistable characteristics of antisymmetric composite cylindrical by using experimental and finite element method. The bistable characteristics are characterized by the curvatures of antisymmetric composite cylindrical shells in different stable states and snap processes between the two stable states which are indicated by the load–displacement curve and snap load. The manufactured specimens after dried in the oven are immersed in distilled water to full saturation and the saturated salt solutions ($\text{MgCl}_2$) to full saturation. The specimen achieves different moisture that is immersed in distilled water at the different period until full saturation and in the saturated salt solution ($\text{MgCl}_2$) with the same period of saturation in distilled water. Specimens with different moisture are then mechanically loaded on a testing machine to transform between two stable states. Load–displacement curves are recorded in the computer, from which the snap loads can be found. After the test, the principal and twisting curvatures are captured by a digital image processing. The results are contrasted with hygroscopic influence on another kind of bistable composite structure (asymmetric cross-ply laminates) in this paper. The results show that the shapes and snap loads of antisymmetric composite cylindrical shells are influenced by the moisture increasing.


ABSTRACT: Fiber reinforced composites are often subjected to severe thermal-mechanical coupling loads. In order to predict the stiffness and strength of the designed composites, thermal buckling response of the delaminated fiber reinforced composite plates and fracture analysis along the delamination front under thermo-
mechanical coupling are investigated based on the generalized layerwise plate theory. Delamination between individual layers is considered as discontinuities in the displacement field using Heaviside step functions in the finite element model of delaminated composite plates. Governing equations are derived using virtual work principle and fracture analysis is performed by calculation of the strain energy release rate along the delamination front by means of the virtual crack closure technique. The effect of laying angle, delamination size, and delamination position on the critical thermal buckling temperature of laminated composite plates are investigated. Numerical results reveal that the critical thermal buckling temperature is insensitive to the delamination size less than an ‘irrelevant size’ and then significantly decreases with the increase of delamination sizes. The inside delamination has a greater influence on the critical thermal buckling temperature than the outside delamination. The maximum values of strain energy release rate always occur in the ‘equivalent material direction’ when the delamination is located in the middle of composite plates, while it is determined by laying angle and delamination position together for non-middle plane delamination.


ABSTRACT: A de-homogenization multi-scale computational method is proposed for the virtual performance simulation of chopped fibers composites under crush loadings. The novel approach led to the development of a multi-scale material characterization procedure for composite systems, comprising of: (1) chopped fibers homogenization based on the Eshelby and Mori–Tanaka inclusion theories, (2) orientation tensor stiffness averaging technique, (3) micro- and macro-mechanics damage and failure theories, and (4) crush resistance evaluation, as a part of the durability and damage tolerance analysis. The chopped fibers material model developed in this work is then employed in a finite element analysis, interfaced with a multi-scale progressive failure technique to track damage and fracture evolution. Comparison of the simulation results obtained for two tubes, manufactured by injection and compression molding respectively, shows good agreement with the crush test data within 10% accuracy. The proposed de-homogenization method offers a superior load resistance prediction over commercially available techniques. Furthermore, the implementation of the proposed approach in our in-house software provides traceable damage evolution and visualization of the contributing failure mechanisms, valuable sources for the design and development of new composite structures.


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ABSTRACT: The kinematic contribution to the hardening of ultra-thin metallic sheets characterized by monotonic and reversed simple shear tests is of high interest in the sheet metal forming industry, because of its influence on the accurate prediction of springback. However, ultra-thin sheets are very sensitive to buckling when submitted to shear stress because of the large gauge width to thickness ratio, the stress perturbations induced by the clamping and the alignment of sample, which thus limit the attainable strain levels using conventional simple shear devices. In this paper, a new simple shear test dedicated to ultra-thin metallic sheets is proposed through the development of a specific support. A transparent glass part enables the application of a normal tightening force to prevent the out-of-plane buckling of the sheets whilst also allowing full field strain measurements to be taken. Firstly, the capabilities of the device are shown by comparing the mechanical behavior in a simple shear test on an austenitic stainless steel with and without the support. A good reproducibility of the flow curves is observed with the support and large shear strains are reached without buckling. Secondly, the influence of friction due to the contact between the sample and the support is checked by finite elements simulations and shown to be negligible compared to the shearing force. Finally, monotonic and reversed shear tests on a pure copper sheet with a thickness of 0.1 mm were performed up to rupture without buckling, these were not previously conceivable on such a low thickness, and demonstrate the potential of the proposed device.

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ABSTRACT: This paper reports the development of a vibration monitoring system for wind turbine blades. This system is used to estimate the deflection at the tip blade on a wind turbine tower. Technical accidents of wind turbine blades have become increasingly common. Thus, regular monitoring of the blades is very important to prevent breakdowns, especially in cases when the blades begin to vibrate excessively. The monitoring system developed in this study satisfies two main objectives for practicality. First, our system is easy to install on existing wind turbines. Second, blade deflection is measured in real time. Our system can be operated using a few strain gages attached at the blade root, and the deflection is calculated based on the monitored stress. Thus, direct measurement of deflection at the blade tip is unnecessary. An estimation algorithm for this purpose is adopted based on the experimental modal analysis. This paper focuses on the evaluation of the estimation algorithm to investigate the feasibility of our system. Basic experiments were conducted using a simple blade model of a 300 W scaled wind turbine under rotation. Signals from the strain gages were acquired by a sensor network and sent to a computer through a wireless connection. The results show that the estimation accuracy is acceptably high. Therefore, we conclude that our proposed system is practical.


ABSTRACT: This study presents an evaluation of the static and dynamic mechanical behavior of low porosity, ductile two-dimensional auxetic metamaterials. The full in-plane displacement fields and the eigenmodes of different geometric structures were investigated and compared with finite element simulations using speckle interferometry and digital image correlation. The results showed strong agreement, validating the theoretical approach used and establishing a method for testing and quantitatively assessing the performance of negative
Poisson ratio structures, and metamaterials in general, for different purposes and fields. The findings of this study also increase our knowledge of elastic instabilities in metallic auxetic structures, with further applications in several engineering fields that can benefit from combining the qualities of ductile materials with additional features typical of these smart structures.


ABSTRACT: The Murray Lecture that was delivered in 2011 included a historical perspective on salient features of research conducted and published by Arun Shukla. A review of experimental work since the Murray Lecture is presented in this paper on the topic of imploding underwater structures. Specifically, the dynamic underwater collapse of metallic structures was studied under free-field and confined environments using novel applications of the Digital Image Correlation (DIC) technique. During these implosion experiments, the implodable volumes became unstable under hydrostatic and combined hydrostatic-explosive conditions. Moreover, there are two types of confinements explored in this paper. A semi-confinement, where a large tubular structure is open to a reservoir at one end and closed at the other end, which leads to water hammer waves on the closed end after implosions. Also, a full-confinement, where a large tubular structure is closed at both ends, which leads to limited hydrostatic potential energy during the implosion. For accurate displacement and velocity measurements of the collapsing structures, the 3D DIC technique is calibrated for underwater measurements in a small-scale setup for each experimental configuration. High-speed cameras are then used to record the dynamic implosion event while dynamic pressure transducers measure the emitted pressure pulses. The results of these experimental series show that the 3D DIC technique can be successfully used for displacement measurements of submerged objects by extracting intrinsic and extrinsic parameters using a submerged calibration grid. The implodable volume in an open-ended semi-confining structure displays a reduced collapse velocity with respect to a free-field configuration. This is primarily caused by a near-field pressure drop from the superposition of low-pressure implosion waves inside confining structure. Semi-confined implosion also exhibits high-pressure hammer pulses at the closed end. Implosions in fully confined vessels show significant reduction/delays in the implosion process due to limited energy present in the vessel. Lastly, during fully confined explosive experiments, the shock wave impact leads to structural vibrations in the implodable volume. The amplitude of these vibrations increases with higher hydrostatic pressures until the implodable volume shows an instability.


“Mechanical characterization of a convex shell (Contact Lens) with meridional thickness variation”

ABSTRACT: Contact lenses are hydrogel shells of spherical cap geometry, and their meridional thickness variation determines their optical power. To characterize the lens mechanical behavior, a rigid shaft was used to apply a quasi-static load to the apex while the central displacement and deformed profile were monitored in-situ. Loading-unloading cycles were performed. In contrast to classical shells of uniform thickness, contact lenses show distinct mechanical response signatures, depending upon their optical power. Typical hyperopic lenses show a local maximum and minimum, attributable to the expanding-contracting dimple across the changing meridional thickness. In addition, deformation-driven water efflux-influx suggest poroelastic behavior of the gel. The measurements have significant impacts on contact lens design.

ABSTRACT: In this study, a suitable method to simulate pipe-manufacturing processes (i.e., bending, unbending, and flattening) was developed to reproduce the process and the mechanical properties of the pipe. To verify the reliability of the strain distribution and plastic deformation behavior predicted by the proposed method, experimentally-derived strain by digital image correlation (DIC) and finite element analyses were employed. Hardness and tensile tests were performed on bent-flattened specimens. The finite element method confirmed that the proposed method can predict the yield strength of pipes.

W. Wang, J.V. Gray, S.E. Julien and K.-T. Wan, “Mechanical characterization of a convex shell (Contact Lens) with meridional thickness variation”, Experimental Mechanics, Vol. 58, No. 6, pp 997-1002, July 2018

ABSTRACT: Contact lenses are hydrogel shells of spherical cap geometry, and their meridional thickness variation determines their optical power. To characterize the lens mechanical behavior, a rigid shaft was used to apply a quasi-static load to the apex while the central displacement and deformed profile were monitored in-situ. Loading-unloading cycles were performed. In contrast to classical shells of uniform thickness, contact lenses show distinct mechanical response signatures, depending upon their optical power. Typical hyperopic lenses show a local maximum and minimum, attributable to the expanding-contracting dimple across the changing meridional thickness. In addition, deformation-driven water efflux-influx suggest poroelastic behavior of the gel. The measurements have significant impacts on contact lens design.

References listed at the end of the paper:


ABSTRACT: Appropriate representation of the displacement field is important to establish proper stress distribution including shear-free condition at free surfaces for a laminated composite shell used in real engineering applications. The present study attempted to develop a more accurate higher-order displacement field for the analysis of a doubly curved laminated composite shell with C0 finite element model based on higher-order shear deformation theory. A new displacement function is proposed for static and free vibration analysis of such a shell. The accurate strain displacement relationship is applied in the analysis of a shell structure with exactly zero shear-free condition at top and bottom surfaces. The proposed model is capable of determining the accurate shear stress distribution across the thickness of the laminate. Moderately deep and thick shells can be analyzed very accurately as the ratio of thickness coordinate to radius of curvature is incorporated in the formulation. An eight-noded isoparametric shell element with seven degrees of freedom at each node is used to formulate the finite element model. The numerical results in terms of deflection, stresses and natural frequencies obtained by the present formulations are compared with those available in the published literature to validate the accuracy of the proposed model.

References listed at the end of the paper:

3. Hildebrand, F.B., Reissner E, Thomas GB.: Note on the foundations of the theory of small displacement of orthotropic shells. NACA TN 1833 (1949)
ABSTRACT: Electrostatically actuated circular micro-/nanoplates are commonly used in micro-/nanoswitches and pumps. This paper models the thermal and size effects on the nonlinear vibration behavior of electrostatically actuated circular micro-/nanoplates. Surface elasticity and modified couple stress theories are simultaneously applied to the modeling. A reduced-order model incorporating temperature change is derived.
and solved numerically. Results show that the material length scale, surface energy, negative temperature change, and geometry nonlinear strain increase frequency and pull-in voltage of the plate. However, Casimir force and positive temperature change reduce the frequency of the plate. Moreover, the effects of surface energy, material length scale and temperature change on frequency become more obvious for thinner plates. The influence of the geometrically nonlinear strain on the frequency is significant for large initial gap to thickness ratio of the plate.

References listed at the end of the paper:

ABSTRACT: The present research develops a general formulation for thermo-elastic analysis of a functionally graded thick shell of revolution with arbitrary curvature and variable thickness subjected to thermo-mechanical loading by using higher-order shear deformation theory. Mechanical properties except Poisson’s ratio are assumed to vary along a two-dimensional coordinate system with arbitrary functional distribution. Given that the thick shell is divided into some virtual disks and replacing various variable terms by their constant values, a set of differential equations for constant thickness are obtained for each virtual disk. By applying continuity conditions between the virtual disks, the general solution of the thick shell is obtained. The final relations are derived in general state for every arbitrary structure and material property distributions. Although previous publications presented a general formulation for thick shells of revolution, to the best of the authors’ knowledge, a closed-form solution is not provided.

References listed at the end of the paper:


ABSTRACT: A validated multi-scale computational mechanics framework for progressive failure modeling of composite structures is developed. Zhang and Waas (Acta Mech 225(4–5):1391–1417, 2014) proposed a micromechanics-based two-scale multiscale model which is able to predict the nonlinear response of a composite. Their proposed micromechanics analysis uses the analytical solutions derived from the concentric cylinder model along with the generalized self-consistent model to find the effective properties of the unidirectional fiber reinforced composites, which are dependent on constituent level fiber–matrix mechanical properties and fiber volume fraction. In this model, the composite material is represented by an inner fiber core and an outer matrix annulus. It should be noted that the 2–CYL fiber–matrix concentric cylinder micromechanics model can be extended to a concentric fiber and any number of \((N–1)\) matrix layers in general, keeping the volume fraction constant, hence called the \(N\)-cylinder model (NCYL), which can analytically calculate the strain and stress field within the fiber and matrix cylinders for a given applied remote composite strain field, acting on the outer boundary of the matrix cylinder. The spatial variation of strain and stress fields within the cylinder are the key determinants for progressive damage and failure analysis of composite structures and hence, they need to be predicted accurately. The advantage of the NCYL concentric cylinder model is that the matrix strain and stress fields can be found in a discrete manner for each layer and the evolution of damage can be localized at a particular layer of matrix. These results can be used at the sub-scale in a multi-scale analysis to calculate the effective nonlinear composite response at a global scale. This work is based on a full analytical solution, and hence, it delivers a distinct computational advantage in composite failure analysis. That is, high fidelity and computational efficiency are gained at the same time.

References listed at the end of the paper:

DOI: 10.1007/s00707-016-1702-6

ABSTRACT: In this paper, we derive a general closed-form solution for the static, axisymmetric bending of solid and annular microstructure-dependent Mindlin plates based on the modified couple-stress theory. The solution is developed by employing a suitable change in displacement variables. The couple-stress solution contains modified Bessel functions which do not appear in the classical case. The stress distributions of the annular microstructure-dependent plate are obtained in terms of load resultants by using the general closed-form solution. Analytical and numerical examples considering solid and annular circular plates are presented. The examples include simply supported and clamped solid and annular plates subjected to a uniformly distributed load and annular plates attached to a point-loaded rigid shaft.

References listed at the end of the paper:

ABSTRACT: Thermo-electro-mechanical transient analysis of a sandwich nanoplate is studied in this paper. The sandwich nanoplate consists of a Kelvin–Voigt viscoelastic nanoplate and two integrated piezoelectric face sheets resting on a visco-Pasternak foundation. The sandwich nanoplate is subjected to thermal and mechanical loads, and the piezoelectric face sheets are subjected to an applied electric potential. Two-variable sinusoidal shear deformation plate theory is used for the description of the displacement components. The governing equations of motion are derived using Hamilton’s principle by calculation of strain and kinetic energies and energy due to external forces. The natural frequencies of the sandwich nanoplate are calculated in terms of three parameters of foundation, structural viscoelastic damping parameter and excitation frequency. Also, bending results of the problem in terms of the parameters of the temperature loadings are presented.

References listed at the end of the paper:


ABSTRACT: The natural frequencies of a circular cylindrical shell closed with a hemi-spherical dome are determined by the Ritz method using a three-dimensional (3-D) analysis instead of two-dimensional (2-D) thin shell theories or higher-order thick shell theories. The present analysis is based upon the circular cylindrical coordinates, while in the traditional shell analyses 3-D shell coordinates have been usually used. Using the Ritz method, the Legendre polynomials, which are mathematically minimal or orthonormal, are used as admissible functions instead of ordinary simple algebraic polynomials. Natural frequencies are presented for different boundary conditions. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the
combined shell. The frequencies from the present 3-D method are compared with those from 2-D thin shell theories. The present method is applicable to very thick shells as well as thin shells.

References listed at the end of the paper:


ABSTRACT: A thermo-elastic analysis of a multi-directional functionally graded thick rectangular plate with different boundary conditions is carried out in this study. Some material properties are assumed to be temperature dependent and graded in all three spatial directions following a power law function. The differential quadrature method (DQM) is employed to obtain the temperature distribution throughout the 3D-FGM plate. The governing partial differential equations based on the three-dimensional thermo-elasticity theory are obtained, and the DQM is employed to discretize the resulting equations. Comparisons are made with the available results of 1D-FGM and 2D-FGM plates in the literature and an Abaqus model. Numerical results are obtained for different gradient indices, plate dimensions, and various thermal and mechanical boundary conditions.

References listed at the end of the paper:

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ABSTRACT: Understanding the complex nonlinear dynamics of carbon nanotubes (CNTs) is essential to enable utilization of these structures in devices and practical applications. We present in this work an investigation of the global nonlinear dynamics of a slacked CNT when actuated by large electrostatic and electrodynamic excitations. The coexistence of several attractors is observed. The CNT is modeled as an Euler–Bernoulli beam. A reduced-order model based on the Galerkin method is developed and utilized to simulate the static and dynamic responses. Critical computational challenges are posed due to the complicated form of the electrostatic force, which describes the interaction between the upper electrode, consisting of the cylindrically shaped CNT, and the lower electrode. Toward this, we approximate the electrostatic force using the Padé expansion. We explore the dynamics near the primary and superharmonic resonances. The nanostructure exhibits several attractors with different characteristics. To achieve deep insight and describe the complexity and richness of the behavior, we analyze the nonlinear response from an attractor-basins point of view. The competition of attractors is highlighted. Compactness and/or fractality of their basins are discussed. Both the effects of varying the excitation frequency and amplitude are examined up to the dynamic pull-in instability.

References listed at the end of the paper:
ABSTRACT: As a first endeavor, the thermal buckling of rotating pre-twisted functionally graded microbeams with temperature-dependent material properties is studied based on the modified strain gradient theory in conjunction with the first-order shear deformation theory of beams. The adjacent equilibrium criterion and Chebyshev–Ritz method are employed to derive the nonlinear algebraic eigenvalue equations governing the thermal buckling behavior of the microbeams, which are solved iteratively. The fast rate of convergence and accuracy of the method are numerically demonstrated. Then, the effects of the twist angle, rate of twist angle (as an important geometrical design parameter), material length scale parameter, material gradient index and angular velocity on the thermal load-bearing capacity of rotating pre-twisted FG microbeams under different boundary conditions are studied. It is shown that by increasing the hub radius, the angular velocity and the length scale parameter, the thermal buckling load increases, but an increase of the material gradient index reduces the critical thermal buckling load. In addition, the formulation can be easily degenerated to those of large-scale rotating pre-twisted FG beams.
References listed at the end of the paper:


Jiazhao Huang, Nhon Nguyen-Thanh and Kun Zhou, Extended isogeometric analysis based on Bézier extraction for buckling analysis of Mindlin-Reissner plates, Acta Mechanica, April 2017

ABSTRACT: In this paper, the buckling analysis for the Mindlin-Reissner plates is performed by applying the isogeometric analysis (IGA) coupled with Bézier extraction operator. The Bézier extraction operator allows the incorporation of non-uniform rational B-spline (NURBS) based IGA into the existing finite element method (FEM) work frame. For cracked plates, the extended IGA (XIGA) is employed. Unlike previous FEM approaches, the present method is expected to be more accurate and achieve higher convergence as the polynomial order increases. Discrete shear gap (DSG) is applied to address shear locking. The results obtained by the present method for the plates with and without crack are compared with the reference solutions. It is found that the present method processes the following desirable properties: (1) the simulation results are found to be in good agreement with the reference solutions; (2) the present method is able to preserve exact geometry of complicated surfaces and (3) the method can be applicable to both moderately thick and thin plates straightforwardly. The effects of various plate shapes, side-to-thickness ratio, aspect ratio, crack length and boundary conditions (BCs) are also studied.

References listed at the end of the paper:


Y. Kiani (Shahrekord University, Shahrekord, Iran), “Buckling of FG-CNT-reinforced composite plates subjected to parabolic loading”, Acta Mechanica, Vol. 228, No. 4, pp 1303-1319, April 2017

DOI: 10.1007/s00707-016-1781-4

ABSTRACT: It is known that the distribution of stresses in a rectangular plate is the same as the applied stresses on the boundaries when the loading is uniform or linearly varying. For other types of compressive loads, for instance parabolic compressive loading, the distribution of stresses in the plate is different from the applied loads at the boundaries of the plate. For such conditions, to obtain the buckling loads of the plate, an
accurate prebuckling analysis should be performed. The present research aims to obtain the buckling loads and buckling pattern of composite plates reinforced with carbon nanotubes with uniform or functionally graded distribution across the plate thickness. The properties of the composite media are obtained based on a modified rule of mixtures approach with the introduction of efficiency parameters. First-order shear deformation plate theory is used to approximate the plate kinematics. The plate is subjected to uniaxial compressive loads which vary as parabolic functions across the width of the plate. At first, using the Ritz method and Airy stress function formulation, the distribution of stress resultants in the plate domain is obtained as a two-dimensional elasticity formulation. Afterwards, by means of the Chebyshev polynomials as the basic functions of the Ritz solution method, an eigenvalue problem is established to obtain the buckling load and buckling shape of the plate. Comparison studies are provided to assure the accuracy of the presented formulation for isotropic homogeneous and cross-ply laminated plates. Afterwards, parametric studies are performed for composite plates reinforced with carbon nanotubes.

References listed at the end of the paper:

ABSTRACT: In this paper, the nonlinear vibration behavior of an electrically actuated microbeam is investigated at various levels of direct current (DC) and alternating current (AC) voltages. The governing equations are developed using Euler–Bernoulli beam theory and used to derive the frequency response of the beam. The mid-plane stretching is accounted for using von Kármán nonlinear strain, and the effects of fringing field, damping, residual axial force, and boundary conditions are also included in the model formulations. The governing equations are solved using the method of multiple scales. The results of our work reveal that the applied DC and AC voltages determine the characteristic feature of the frequency response of the microbeam. A design chart in terms of the dimensionless DC voltage and AC voltage amplitude is developed to show the domains of different characteristic frequency responses. Our results also reveal the significant effect of mid-plane stretching, damping, residual axial force, and boundary conditions on the frequency response of the microbeam. Moreover, our results further identify the effect of mid-plane stretching, damping, and residual axial force on the critical DC voltages separating the hardening and softening frequency response regions in the newly developed design chart of the micro-resonator.
ABSTRACT: This paper presents an analytical investigation on buckling and postbuckling of eccentrically stiffened functionally graded thin truncated conical shells subjected to axial compressive load and resting on elastic foundations. Shells are reinforced by rings and stringers attached to their inside. The shell material properties are graded in the thickness direction according to a volume fraction power law distribution. The change in spacing between stringers in the meridional direction is taken into account. The theoretical formulations based on the Donnell shell theory with von Karman geometrical nonlinearity and the smeared stiffeners technique are derived. The resulting equations, which are a coupled set of three variable coefficients nonlinear partial differential equations in terms of displacement components, are solved by the Galerkin method. The closed-form expressions for determining the critical buckling load and for analyzing the postbuckling load–deflection curves are obtained. The influences of various parameters such as stiffeners, foundations, material properties and geometric dimensions on the stability of shells are considered in detail. References listed at the end of the paper:


13. Huang, H., Han, Q.: Nonlinear dynamic buckling of functionally graded cylindrical shells subjected to a time-dependent axial load. Compos. Struct. 92, 593–598 (2010)


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ABSTRACT: The present research deals with the nonaxisymmetric buckling behaviour of isotropic homogeneous annular plates subjected to simultaneous effects of uniform temperature rise and constant angular speed. First-order shear deformation plate theory is used to obtain the complete set of governing equations and the associated boundary conditions. Pre-buckling deformations and stresses of the plate are obtained using the solution of a plane stress formulation, neglecting the rotations and lateral deflection. Applying the adjacent equilibrium criterion, the linearised stability equations are obtained. The resulting equations are solved using a hybrid method, including the exact trigonometric functions through the circumferential direction and generalised differential quadrature method through the radial direction. The resulting eigenvalue problem is solved to obtain the critical conditions of the plate and the associated circumferential mode number. Numerical results reveal that, only for annular plates with exterior edge clamped, rotation may enhance the critical buckling temperature of a plate under special circumstances. Furthermore, asymmetric stability analysis should be performed to extract the critical state and buckled shape of a rotating annular plate subjected to uniform heating. Otherwise, the critical buckling temperature is overestimated and the buckling pattern is wrongly predicted.

References listed at the end of the paper:
ABSTRACT: Based on an axisymmetric layerwise approach, the differential quadrature method (DQM) is adopted in axial direction to analyse a hollow cylindrical shell made of functionally graded material (FGM) with piezoelectric actuator rings under dynamic load. The mechanical properties are regulated by volume fraction as a proper function of the radial coordinate. The FGM shell and piezo-rings are divided into mathematical sub-layers in thickness direction, then the general layerwise theory is formulated through introducing piecewise continuous approximations across each sub-layer. This accounts for any discontinuity in derivatives of the displacement at the interface of the rings and the cylinder. The virtual work statement including structural and electrical potential energies yields the 3-D governing equations which are reduced to 2-D differential equations, which then are discretized by using DQM in both the spatial and time domains. By inserting the boundary conditions into the DQ form of the equations and incorporating the initial conditions, a system of algebraic equations is obtained that delivers the unknown degrees of freedom. Static and dynamic responses of the FG shell to electrical and mechanical loads with different exponents of material in homogeneity ‘n’ and boundary conditions as well as the effects of size, number and interval between actuated piezo-rings on the induced deformation in the FG shell are investigated. The accuracy and computational efficiency of the proposed approach are verified by comparing the results with those obtained using the finite element method and similar problems in the literature.

References listed at the end of the paper:


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ABSTRACT: Based on a new modified couple stress theory for composite laminates, considering geometric nonlinear theory and Timoshenko beam hypothesis, the governing equations for size-dependent composite laminated microbeams in thermal environment are derived using Hamilton’s principle. Analytical and numerical solutions are employed in solving the present problem, respectively. An auxiliary function is introduced to reduce the governing equations to a single fourth-order integral-differential equation, and the exact solutions for the thermal buckling and postbuckling of microbeams with combination of in-plane immovable simply supported boundary conditions are obtained. By introducing the differential quadrature method, the governing equations are transferred into a system of nonlinear algebraic eigenvalue equations. In numerical examples, comparison between the present results and those obtained in the literature verifies the validity and efficiency of the present analytical and numerical methods. The effects of thermal expansion coefficients and material length scale parameter are discussed. Numerical results indicate that the above-mentioned effects play very important roles for the thermal buckling and postbuckling of the composite laminated microbeams.

References listed at the end of the paper:


frequency is significant. The frequency shift at an initial tensile load is larger than that at an initial compressive load. These results are consistent with the previously reported ones.

References listed at the end of the paper:


Rajesh Kumar, L.S. Ramachandra and Biswanath Banerjee (Dept. of Civil Engineering, Indian Institute of Technology, Karagpur, India), “Semi-analytical approach for thermal buckling and postbuckling response of
ABSTRACT: A semi-analytical solution of thermal buckling and postbuckling equilibrium paths of rectangular composite plates subjected to localized thermal heating over the plate area with uniform temperature rise through its thickness is reported here. The plate is either simply supported or clamped for out-of-plane displacements and immovable for in-plane displacements. The thermal buckling of the composite plate subjected to localized thermal loading is solved in two steps as the prebuckling stress distributions within the plate are not known a priori. In the first step the explicit analytical expressions for these in-plane prebuckling stress distributions within the composite plate are developed by solving the thermoelasticity problem using Airy’s stress function. Using the computed in-plane stress distributions within the plate, the plate nonlinear stability equations are formulated using a variational principle. First-order shear deformation theory incorporating von-Kármán geometric nonlinearity is used to model the plate. The generalized differential quadrature method in conjunction with the modified Newton–Raphson method is used to solve the nonlinear governing partial differential equations for nonlinear thermal stability of composite plates. The influence of aspect ratio, area of heated region, and the boundary conditions on the critical buckling temperature and equilibrium paths are examined.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: Based on the first-order shear deformation plate theory, two approaches within the extended Kantorovich method (EKM) are presented for a bending analysis of functionally graded annular sector plates with arbitrary boundary conditions subjected to both uniform and non-uniform loadings. In the first approach, EKM is applied to the functional of the problem, while in the second one EKM is applied to the weighted integral form of the governing differential equations of the problem as presented by Kerr. In both approaches, the system of ordinary differential equations with variable coefficients in \( r \) direction and the set of ordinary differential equations with constant coefficients in \( \theta \) direction are solved by the generalized differential quadrature method and the state space method, respectively. The material properties are graded through the plate thickness according to a power-law distribution of the volume fraction of the constituents. The results are verified with the available published works in the literature. It is observed that the first approach is applicable to all supports with an excellent accuracy while the second approach does not give acceptable results for a plate.
with a free edge. Furthermore, various response quantities in FG annular sector plates with different boundary conditions, material constants, and sector angles are presented which can be used as a benchmark.


ABSTRACT: As a first endeavor, the free vibration behavior of functionally graded carbon nanotubes-reinforced composite (FG-CNTRC) skewed cylindrical panels, as a most general geometry of panels in practical applications, is investigated. The first-order shear deformation shell theory is used to model the kinematics of deformations, and Hamilton’s principle is applied to drive the differential governing equations and the related boundary conditions. An analytical transformation together with the differential quadrature method, namely transformed differential quadrature method, is employed to discretize the governing equations subjected to general boundary conditions. This method offers superior practicality and applicability in directly discretizing the governing differential equations for an arbitrary physical domain. The correctness of the computational method is investigated through several numerical examples that include FG-CNTRC skew plates, homogeneous skewed cylindrical panels and FG-CNTRC cylindrical panels. Eventually, the effects of geometrical shape parameters like thickness/radius-to-length and aspect ratios, different distributions and volume fractions of CNTs and boundary conditions on the non-dimensional frequency parameters of the FG-CNTRC skewed cylindrical panels are studied.


ABSTRACT: This paper presents the vibro-acoustic modeling and analysis of sandwich plates with metal–ceramic functionally graded (FG) core using a simplified first-order shear deformation theory and elemental radiator approach. A simply supported rectangular plate having functionally graded core, metal and ceramic facesheets is considered with aluminum as metal and alumina as ceramic. The material properties of the core are assumed to vary according to a power law distribution of the volume fraction of the constituents. The sound radiation due to point load and uniformly distributed load is computed by numerically solving the Rayleigh integral. The effective material properties of the sandwich plate are presented as a function of core thickness. The vibration parameters in terms of natural frequencies, plate displacement and velocity, and acoustic parameters such as radiated sound power level, radiated sound pressure level and radiation efficiency are computed for various values of the power law index. A comprehensive study of the influence of core thickness on vibro-acoustic performance is presented in terms of mean-squared velocity and overall sound power level. It is found that, for the plate being considered, the sound power level increases with increase in the power law index of the core at lower frequency segment. Increased vibro-acoustic response is observed in the high-frequency band for ceramic-rich FG core and in the low-frequency band for metal-rich FG core, respectively. A sandwich plate with metal-rich FG core configuration has shown improved flexural stiffness, compared to an FG plate with no significant rise in overall radiated sound. It is possible with this analysis to suitably tailor and optimize the sandwich FG plates for multifunctional performance and desired vibro-acoustic interaction.

ABSTRACT: In this paper, the Gurtin–Murdoch continuum theory is applied to develop a new continuum mechanics model for static and dynamic analyses of nanoscale rectangular plates. The relevant governing equations are established from basic principles. Analytical solutions for static and free vibration of nanoscale rectangular plates are presented for selected boundary conditions. A finite element method for the analysis of rectangular nanoplates is also developed to solve general cases that cannot be solved analytically. Expressions for stiffness and mass matrices and the load vector are derived by using a weighted residual formulation. A selected set of numerical results is presented to investigate the size-dependent static and free vibration response of plates and the influence of surface material properties and boundary conditions.


ABSTRACT: Free vibration of pre-/postbuckled circular functionally graded piezoelectric (FGP) plates is studied in this research. The buckled configurations are considered to be resulting from either thermoelectrical bifurcation buckling or limit load buckling due to lateral loading of thermally preloaded plates. The nonlinear governing equations of motion and associated boundary conditions are extracted by the generalized form of Hamilton’s principle. The Ritz finite element method is then implemented to construct the matrix representation of governing equations which are solved by two different strategies including Newton–Raphson scheme and cylindrical arc-length method. The thermoelectromechanical properties of FGPM plates are considered to be graded in the thickness direction on the basis of a power law function. Moreover, two cases of thermal loading, i.e., uniform temperature rise and heat conduction across the thickness as well as two types of boundary conditions, including clamped and simply supported, are considered. Comparison studies are presented to validate the numerical results. Furthermore, extensive parametric studies are conducted to assess the influence of involved parameters.


ABSTRACT: Based on the three-dimensional theory of elasticity, the transient response of variable stiffness composite laminated (VSCL) plates with curvilinear fibers subjected to time-dependent concentrated load on elastic foundation is investigated. The fiber orientation angle varies linearly with respect to the in-plane coordinate in each layer. The layerwise theory in conjunction with a mixed integral–differential quadrature method is used to discretize the equations of motion and relevant boundary conditions in the spatial domain with arbitrary boundary conditions. Then, a novel multi-step method based on B-spline curves is presented to obtain a solution for the resulting system of ordinary differential equations in the temporal domain. Simplicity, accuracy and reliability of the novel combined I-DQ approach and in particular the multi-step techniques with respect to the Newmark time integration scheme are demonstrated. By performed comparison studies with available solutions in the open literature, the convergence and accuracy of the presented technique are demonstrated. Finally, the effects of fiber orientation, different geometric parameters, boundary conditions and elastic foundation coefficients on the transient behavior of the VSCL plates are parametrically studied. It is expected that the presented multi-step technique is to be used in a variety of science and engineering problems in future studies.

ABSTRACT: The dynamic response of physically asymmetric rectangular sandwich plates with metal foam core subjected to blast loading is investigated analytically and numerically. The so-called ‘bounds’ of analytical solutions for the maximum central deflection of back face-sheets and the structural response time are obtained, respectively, by employing the yield criteria for an asymmetric sandwich structure including core compression. Furthermore, an improved membrane mode analysis considering the ‘residual’ bending moment for asymmetric sandwich plates is presented and the membrane mode solutions are given. It is shown that there is a good agreement between the theoretical predictions and the numerical results. Based on the analytical formulae, optimal design charts are constructed to maximize the impulsive resistance of physically asymmetric sandwich plates for a given mass. Finally, the performances of optimally designed sandwich plates with various face-sheet material combinations are discussed.

Xu Wang and Peter Schiavone, “Multilayered cylindrical panels with interface diffusing and sliding under thermomechanical loads”, Acta Mechanica, Vol. 228, No. 8, pp 3285-3296, September 2017

ABSTRACT: We investigate the time-dependent deformations of multilayered isotropic elastic cylindrical panels with interfacial diffusion and rate-dependent sliding under thermomechanical loads. The state-space approach is found to be extremely effective for the analysis of a cylindrical panel composed of an arbitrary number of layers. We show that when a particular condition is met, the thermal loading will not induce any thermal stresses in the cylindrical panel. To demonstrate our results, we present the evolving displacements and stresses in a three-layered panel induced by sinusoidal temperature variation and normal traction applied to its upper surface. In addition, we present all 198 relaxation times corresponding to a 100-layered panel.

D.V. Dung and Pham Minh Vuong, “Analytical investigation on buckling and postbuckling of FGM toroidal shell segment surrounded by elastic foundation in thermal environment and under external pressure using TSDT”, Acta Mechanica, Vol. 228, No. 10, pp 3511-3531, October 2017

ABSTRACT: In this paper, FGM toroidal shell segments surrounded by elastic foundation and subjected to uniform external pressure are investigated by analytical method. A novelty of the study is that the Reddy’s third-order shear deformation shell theory (TSDT) with von Karman geometrical nonlinearity combined with deflection function selected with three terms is used to investigate the nonlinear stability of thicker FGM toroidal shell segments. In addition, the thermal element in the shell is also taken into account. The FGM shell is a convex and concave toroidal shell segment. It is a general form for a circular cylindrical shell. Closed-form expressions for determining the static critical external pressure load and postbuckling load–deflection curves are obtained. Effects of temperature field, foundations, material and dimensional parameters on the stability of shells are considered. This paper also shows that the use of TSDT to analyze the nonlinear stability of thicker toroidal shell segments is necessary and more suitable.

References listed at the end of the paper:
8. Huang, H., Han, Q.: Nonlinear dynamic buckling of functionally graded cylindrical shells subjected to a time-dependent axial load. Compos. Struct. 92, 593–598 (2010)

ABSTRACT: This paper deals with the exact calculation of natural frequencies of a plate with two opposite edges simply supported considering three versions of the Uflyand–Mindlin plate theory: the original Uflyand–Mindlin plate theory, the truncated version of this model as suggested by Elishakoff, and the recently proposed Uflyand–Mindlin plate theory based on slope inertia. The comparison between the frequencies using the different models and with those found in the literature using numerical methods shows the efficiency of the models and the methods presented hereinafter.

References listed at the end of the paper:


ABSTRACT: The nonlinear buckling of thin shell-type structures is sensitive to the initial geometric imperfection. In this study, the imperfection sensitivity of the nonlinear instability of cylindrical nanopanels made of functionally graded material (FGM) is addressed including surface elasticity, aiming to present a background for axial postbuckling behavior of imperfect FGM nanopanels. The material properties are supposed to be graded across the panel thickness in accordance with a simple power law function of the volume fractions of the silicon and aluminum constituents with considering the physical neutral plane position. The non-classical governing differential equations are constructed and then they are deduced to boundary layer-type ones. Afterward, a perturbation-based solution methodology is employed to extract explicit expressions for the size-dependent postbuckling equilibrium paths of FGM nanopanels with and without initial geometric imperfection and corresponding to various panel thicknesses, geometrical parameters, temperature changes and material property gradient indexes. It is displayed that through reduction of the surface elasticity effects for
thicker FGM nanopanels, the influence of the initial geometric imperfection on the minimum load of the postbuckling regime increases. This pattern is more significant for FGM nanopanels with a lower value of the material gradient index.

References listed at the end of the paper:
ABSTRACT: In the present article, the buckling of a fluid-infiltrated porous plate is investigated using Mindlin plate theory and an analytical procedure. A cosine rule for the pore distribution across the plate thickness is
assumed with a coefficient defining porosity level. The governing stability equations are rewritten in terms of four auxiliary functions and decoupled with the aid of some mathematical manipulations. The decoupled partial differential equations are solved analytically by assuming simply supported radial edges for the plate. The critical buckling loads are calculated by considering fluid-saturated and fluid free conditions for the interconnected network of pores for different sector angles, thickness–radius ratios, coefficients of plate porosity, aspect ratios, and boundary conditions. It is found that the pore fluid compressibility affects the buckling load significantly.

References listed at the end of the paper:
ABSTRACT: In this research, by using displacement potential functions, the exact solution is presented for free vibration analysis of transversely isotropic thick rectangular plates. The governing differential equations are derived by the substitution of the displacement components in Navier’s equations. The two governing partial differential equations of fourth and second order are solved using the separation of variables method and satisfying the exact boundary conditions. Having no simplifying assumptions for the strain or stress distribution in the plate thickness, the obtained results in this paper are applicable to any arbitrary plate thickness with no limitation on its thickness ratio. Due to absence of available research on thick transversely isotropic plates, the obtained results are compared with other analytical works for thin and moderately thick plates and the finite element method for thick plates, showing remarkable agreement. Accurate natural frequencies are presented for different ranges of thickness ratio and aspect ratio and different materials. It is observed that with increasing thickness the ratio and aspect ratio of the plate, the non-dimensional natural frequencies decrease and increase, respectively. In addition, comparative results of isotropic material and four different transversely isotropic materials also illustrate that the shear modulus in transverse direction has important influence on the vibrational behavior of plates.

References listed at the end of the paper:

A. Alibeigloo and A. Rajaee Piteh Noee, Acta Mechanica, Vol. 228, No. 12, pp 4123-4140, December 2017

ABSTRACT: In this paper, static and free vibration analysis of a sandwich cylindrical shell is performed using theory of elasticity formulation. The core layer is made of functionally graded material with material properties varying along the thickness direction according to a simple power law. For the case of simply supported boundary conditions, equations of motion and equilibrium equations are solved analytically by applying a state-space technique along the radial direction and Fourier series expansion along the axial and circumferential direction. When boundary conditions are not simply supported, a semi-analytically solution is performed by
using the differential quadrature method along the axial direction. The present approach is validated by comparing the obtained numerical results with those published in the available literature. Moreover, effects of boundary conditions, graded direction, mid-radius to thickness and length to mid-radius ratios on bending and vibration behavior are considered.

References listed at the end of the paper:

ABSTRACT: This paper presents the results of the dynamic stability analysis of a flexible spinning launch vehicle subjected to thrust modeled as a thin-walled composite beam with circular cross section. Due to the presence of gyroscopic forces, we mainly aimed to find divergence and/or flutter instabilities and establish the stability boundaries of the spinning beam. For this purpose, we implemented a circumferentially uniform stiffness (CUS) layup configuration to exhibit the coupled motion of bending–bending–shear. The solution of the eigenvalue problem is handled by the extended Galerkin method (EGM), and we computed the results addressing the effects of various parameters such as spin speed, axial load, ply angle, aspect ratio and transverse shear on the dynamic stability of the beam. Insights revealed by this study contribute to the design of advanced aerospace structures modeled as thin-walled composite beams reflecting the potential influence of transverse shear and aspect ratio on dynamic stability characteristics. A notable contribution is that we show that divergence/flutter instabilities can be delayed or even avoided using the directionality property of composite materials.

Soo-Min Ko and Jae-Hoon Kang, “Free vibration analysis of shallow and deep ellipsoidal shells having variable thickness with and without a top opening”, Acta Mechanica, Vol. 228, No. 12, pp 4391-4409, December 2017

ABSTRACT: A three-dimensional (3-D) method of analysis is presented for determining the natural frequencies and the mode shapes of hemi-ellipsoidal domes having non-uniform thickness with and without a top opening by the Ritz method. Instead of mathematically two-dimensional (2-D) conventional thin shell theories or higher-order shell theories, the present method is based upon the 3-D dynamic equations of elasticity by the Ritz method. Mathematically minimal or orthonormal Legendre polynomials are used as admissible functions in place of ordinary simple algebraic polynomials which are usually applied in the Ritz method. The analysis is based upon the circular cylindrical coordinates instead of the shell coordinates which are normal and tangential to the shell mid-surface. Potential (strain) and kinetic energies of the hemi-ellipsoidal dome having variable thickness with and without a top opening are formulated, and the Ritz method is used to solve the eigenvalue problem, thus yielding upper bound values of the frequencies by minimizing the frequencies. As the degree of the Legendre polynomials is increased, the frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies. Numerical results are presented for a variety of shallow and deep hemi-ellipsoidal domes having variable thickness of five values of aspect ratios with and without a top opening, which are completely free and fixed at the bottom. The frequencies from the present 3-D analysis are compared with those from other 3-D analysis and a 2-D thin shell theory.

References listed at the end of the paper:


ABSTRACT: This article presents vibration characteristics of a piezoelectric viscoelastic nanoplate under various boundary conditions embedded in a visco-Pasternak’s medium using nonlocal plate theory. The piezo-hygrotherm effects are all included. The hygrothermal piezoelectric nanoplate is made of orthotropic viscoelastic material. Also, the visco-Pasternak’s medium is modeled according to a Kelvin–Voigt foundation. A Two-variable sinusoidal shear deformation plate theory is presented. The imaginary and real parts of the eigenfrequency of piezoelectric viscoelastic nanoplates which are associated with viscoelastic foundation, nonlocal parameter, as well as the viscoelastic structural damping coefficient, are obtained. The effects of other parameters such as aspect ratio, side-to-thickness ratio, temperature change, and moisture concentration are all investigated. The predicted results are compared with the corresponding ones in the literature to check their validation. Additional results are presented and suitable discussions are made.

References listed at the end of the paper:


ABSTRACT: The general thin-walled beam model is presented to study the flexural-torsional coupled buckling behavior of shear flexible sandwich I-beams made of functionally graded materials based on an orthogonal Cartesian coordinate system. The derived beam model includes the transverse shear, the restrained warping induced shear deformations, the structural coupling coming from the material anisotropy, and the variable axial force effect. Material properties of the beam such as Young’s and shear moduli are assumed to be graded across the wall thickness. The strain energy and the potential energy due to the variable axial force are introduced. The seven coupled instability equations are derived from the energy principle. To solve the instability problem, three types of finite beam elements, namely, linear, quadratic, and cubic elements are employed with the scope to discretize the governing equations. In order to verify the accuracy and efficiency of the beam model presented by this study, numerical results are presented and compared with results from other researchers. By numerical examples, the bisymmetric and mono-symmetric I-beams with two types of material distributions are considered to investigate the effects of shear deformation, variable axial force, gradient index, thickness ratio of ceramic, boundary conditions, material ratio, and span-to-height ratio on the buckling behavior of FG sandwich I-beams. Particularly, the crossover phenomenon in buckling modes with changes in gradient index and thickness ratio of ceramic in flanges is investigated.

References listed at the end of the paper:


ABSTRACT: In the present study, the problem of stability and vibration of a square single-layer graphene sheet under body force is studied using Eringen’s theory. The body force is constant and parallel with the plate. The boundary conditions correspond to the dynamical model of a nonplate clamped at all its sides. Classical plate theory, upgraded with nonlocal elasticity theory, is used to formulate the differential equation of stability and vibration of the nonplate. Natural frequencies of transverse vibrations, depending on the effects of body load and nonlocality, are obtained using Galerkin’s method. Critical values of the body load parameter, i.e., the values of the body load parameter when the plate loses its stability, are determined for different values of nonlocality parameter. The mode shapes for a square nonplate under influences of body load and nonlocality are presented as well.

References listed at the end of the paper:


ABSTRACT: In this paper, a geometrically nonlinear formulation for a six-node triangular shell element is proposed. Total Lagrangian formulation is utilized to consider large displacements and rotations in the shell analysis. To avoid shear and membrane locking, a proper interpolation function for the strain field is implemented. Both algorithm and flowchart of the nonlinear solution, which are utilized in the author’s computer program, are presented. To validate the suggested formulation, several popular benchmark problems are solved. Moreover, the obtained results are compared with those of the other well-known elements. Findings demonstrate the ability of the suggested shell element.

References listed at the end of the paper:

ABSTRACT: In this paper, the boundary element method (BEM) is developed for the flutter analysis of thick anisotropic plates modeled by Mindlin’s theory. Such plates describe the response of laminated plates consisting of layers of anisotropic materials, which are extensively used in various modern engineering applications. The plate is subjected to aerodynamic pressure due to supersonic air flow, a follower-type load. The governing equations are three coupled linear partial differential equations of second order subjected to three boundary conditions besides the initial conditions. The boundary value problem is solved using the analog equation method. Thus, following the principle of the analog equation, the original equations are substituted by three uncoupled Poisson’s equations under fictitious loads, which are subsequently, solved using the conventional BEM for Poisson’s equation. Various thick and thin laminated plate problems are studied using the proposed method. The obtained numerical results demonstrate the efficiency of the solution procedure, validate its accuracy and give a revealing insight into the dynamic response of the thick laminated plates under follower loads.

References listed at the end of the paper:

ABSTRACT: Weakly clamped uniformly stretched thin elastic plates can experience edge buckling when subjected to a transverse pressure. This situation is revisited here for a circular plate, under the assumption of finite rotations and negligible bending stiffness in the pre-buckling range. The eigenproblem describing this instability is formulated in terms of two singularly perturbed fourth-order differential equations involving the non-dimensional bending stiffness $\varepsilon \theta$. By using an extension of the asymptotic reduction technique proposed by Coman and Haughton (Acta Mech 55:179–200, 2006), these equations are formally reduced to a simple second-order ordinary differential equation in the limit $\varepsilon \to \theta^+$. It is further shown that the predictions of this reduced problem are in excellent agreement with the direct numerical simulations of the original bifurcation equations. (Abstract contains math)

References listed at the end of the paper:

ABSTRACT: This paper studies the free vibrational behavior of porous functionally graded nanoshells using nonlocal strain gradient theory. A nonlocal parameter and a strain gradient parameter are employed to describe both stiffness reduction and stiffness enhancement of nanoshells. Porosities are evenly and unevenly distributed thorough the thickness of the nanoshell. The gradation of material properties having porosities is described using a modified power-law function. The nanoshell is modeled via first-order shear deformation theory, and Galerkin’s method is implemented to obtain vibration frequencies. Shape functions which satisfy available classical and nonclassical boundary conditions in nonlocal strain gradient theory are proposed. It is shown that the vibrational behavior of the nanoshell is influenced by the porosity volume fraction, porosity distribution, nonlocal coefficient, strain gradient coefficient, boundary conditions and radius-to-thickness ratio.

References listed at the end of the paper:


ABSTRACT: The present article deals with the viscoelastic modeling and dynamic responses of the carbon nanotubes (CNTs)-based carbon fiber-reinforced polymer (CNTs-CFRP) composite spherical shell panels where CNTs are reinforced in the polymer matrix phase. The Mori–Tanaka micromechanics in conjunction with
weak interface theory has been developed for the mathematical formulations of the viscoelastic modeling of CNTs-based polymer matrix phase. Further, the strength of material method has been employed to formulate the viscoelastic material behavior of the homogenized hybrid CNTs-CFRP composite materials. An eight-node shell element with five degrees of freedom per node has been formulated to study the vibration damping characteristics of spherical shell structures made by CNTs-CFRP composite materials. Frequency- and temperature-dependent material properties of such hybrid composite materials have been obtained and analyzed. Impulse and frequency responses of such structures have been performed to study the effects of various important parameters on the material properties and such dynamic responses. Obtained results demonstrate that quick vibration mitigation may be possible using such CNTs-based proposed composite materials.

References listed at the end of the paper:
A. Kaveh, A. Dadras and N. Geran Malek, “Buckling load of laminated composite plates using three variants of the biogeography-based optimization algorithm”, Acta Mechanica, Vol. 229, No. 4, pp 1551-1566, April 2018 ABSTRACT: This paper presents the application of the biogeography-based optimization (BBO) and some of its variants in the optimization of stacking sequence of laminated composites. Harmony search is also implemented to compare its results with those of the BBO. The optimization objective is to maximize the buckling load of a symmetric and balanced laminated plate. Four laminated composites with different loadings and dimensions are studied, and the statistical comparison of the obtained configurations and buckling load capacities shows the high capability of the BBO with quadratic migration model in terms of robustness and global search.

References listed at the end of the paper:


ABSTRACT: Geometrically nonlinear forced vibrations of a cantilever shallow shell are analyzed. A finite degree of freedom nonlinear dynamical system is derived using the assumed mode method. The Neimark–Sacker bifurcations are detected close to the first principal resonance. The quasi-periodic vibrations, which originate from these bifurcations, are investigated numerically. These vibrations are transformed into chaotic motions as a result of the forcing frequency variation. Sub-harmonic vibrations with large amplitudes are analyzed in a wide forcing frequency range close to the second principal resonance.

References listed at the end of the paper:

ABSTRACT: Delamination is a well-known defect mode that can arise in the manufacturing process of laminated composite plates. Due to the importance of analyzing the destructive effects of delamination on the mechanical behavior of composite plates, the flexural analysis of circular laminated composite plates with circular delamination is presented here. The governing equilibrium equations of laminated plates are first determined using third-order shear deformation theory. Both the linear and geometrically nonlinear strain states are considered, and the variational approach with a moving boundary is employed to derive the equilibrium equations. The governing equations in terms of the displacement field are then solved using the Galerkin method and the spectral homotopy analysis method to obtain the linear and nonlinear strain states, respectively. The effect of the variations of the elastic material properties on the strain energy release rate is also comprehensively studied. The results of the present study are consistent with the results of other methods found in the literature.
Kármán through a micromechanical model. The governing equations are based on classical shell theory taking von temperature dependent, graded in the thickness direction, and ar properties of functionally graded carbon nanotube (SWCNTs) structures in general and composite cylindrical panels in particular. This paper investigates the nonlinear thermomechanical nonlinear response of pressure


ABSTRACT: Initial geometrical imperfection and elasticity of tangential edge constraints are inherent in real structures in general and composite cylindrical panels in particular. This paper investigates the nonlinear response of functionally graded nanocomposite cylindrical panels reinforced by single-walled carbon nanotubes (SWCNTs), exposed to thermal environments and subjected to uniform external pressure. The material properties of functionally graded carbon nanotube-reinforced composites (FG-CNTRC) are assumed to be temperature dependent, graded in the thickness direction, and are estimated by the extended rule of mixture through a micromechanical model. The governing equations are based on classical shell theory taking von Kármán–Donnell nonlinearity, initial geometrical imperfection and tangential constraints of boundary edges


into consideration. Approximate solutions of deflection and stress functions are assumed to satisfy simply supported boundary conditions, and the Galerkin method is applied to obtain closed-form expressions of load–deflection relations. An analysis of separate and simultaneous influences of carbon nanotube volume fraction and distribution types, geometrical parameters, varying degree of tangential edge constraints, thermal environments, geometrical imperfection and temperature dependence of material properties on the buckling behavior and load-carrying capacity of FG-CNTRC cylindrical panels results in interesting remarks and novelty of the present study.

References listed at the end of the paper:
5. Tung, H.V.: Postbuckling behavior of functionally graded cylindrical panels with tangential edge constraints and resting on elastic foundations. Compos. Struct. 100, 532–541 (2013)

ABSTRACT: The elastic buckling of square and skew thin functionally graded material (FGM) plates with cutout resting on an elastic foundation is investigated using the isoparametric spline finite strip method. It is assumed that the material properties of FGM plates vary smoothly through the thickness according to the power law model. The elastic foundation is simulated by the Winkler and two-parameter Pasternak models. The isoparametric spline finite strip method is also applied to investigate initial inelastic local buckling loads of skew homogenous plates with cutout based on the Ramberg–Osgood representation of the stress–strain curve using the deformation theory of plasticity. The critical buckling load of the plate is achieved by minimizing its total potential energy and solving the corresponding eigenvalue problem. In addition, the effects of elastic foundation coefficients and hole size on the local buckling of plates with different boundary conditions are determined and discussed.

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Mokhtar Bouazza, Ashraf M. Zenkour and Noureddine Benseddiq, Closed-form solutions for thermal buckling analysis of advanced nanoplates according to a hyperbolic four-variable refined theory with small-scale effects”, Acta Mechanica, Vol. 229, No. 5, pp 2251-2265, May 2018

ABSTRACT: A four-variable plate model is successfully extended here to investigate the thermal buckling analysis of advanced nanoplates. The advanced nanoplate is fabricated from a functionally graded material mixed of ceramic and metal with continuously varying material properties through the nanoplate thickness. Two types of thermal loadings, uniform and nonlinear temperature rises along the nanoplate thickness are taken into consideration. The present model contains four unknown functions as against five or more in other alternative models. The through-the-thickness distributions of transverse shear stresses of the nanoplate are considered to vary parabolically and vanish at upper and lower surfaces. The present model does not require any problem-dependent shear correction factor. Comparison examples are made between results obtained via this model and those via available solutions in the literature.

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5. Matsunaga, H.: Thermal buckling of functionally graded plates according to a 2D higher-order deformation theory. Compos. Struct. 90, 76–86 (2009)
G. Ruta and I. Elishakoff, “Suitable radial grading may considerably increase buckling loads of FGM circular plates”, Acta Mechanica, Vol. 229, No. 6, pp 2477-2493, June 2018

ABSTRACT: In this paper, we study buckling of radially FGM circular plates. In a previous study, a fourth-order polynomial expressing the exact solution of a linear elastic problem was used as buckling mode shape. To generalise such investigation, in this contribution the buckling mode is postulated to take the shape of a fifth-order polynomial expressing the exact solution of a linear elastic problem. To realise such investigation, in this contribution the buckling mode is postulated to take the shape of a fifth-order polynomial expressing the exact solution of a linear elastic problem was used as buckling mode shape. To generalise such investigation, in this contribution the buckling mode is postulated to take the shape of a fifth-order polynomial function of the radial coordinate. The flexural rigidity is consequently sought as a polynomial of suitable order, expressing the functional grading. New solutions in closed form are then obtained by a semi-inverse method. It is found that suitable choices of functional grading may increase the buckling load up to 246% with respect to the homogeneous and uniform cases.

References listed at the end of the paper:

ABSTRACT: The present research considers the free vibration characteristics of a joined shell system that consists of three segments. The joined shell system contains two conical shells at the ends and a cylindrical shell at the middle. All shell elements are made from isotropic homogeneous material. The shell elements are unified in thickness. With the aid of the first-order shear deformation shell theory and the Donnell type of kinematic assumptions, the equations of motion of a conical shell and the associated boundary conditions are obtained. These equations are valid for each segment. The obtained equations are then discreted using the generalised differential quadratures (GDQ) method. Applying the intersection continuity conditions for displacements, rotations, forces, and moments between two adjacent shells, and also boundary conditions at the ends of the joined shell system, a set of homogeneous equations is obtained, which governs the free vibration motion of the joined shell. Comparisons are made with the available data in the open literature for the case of thin conical–cylindrical–conical shells with special types of geometry or boundary conditions. Afterwards, numerical results are provided for moderately thick shells with different geometric and boundary conditions.

References listed at the end of the paper:

ABSTRACT: In this article, we investigate the mechanical behavior of initially curved microplates under electrostatic actuation. Microplates are essential components of many Micro-Electro-Mechanical System devices; however, they commonly undergo an initial curvature imperfection, due to the microfabrication process. Initial curvature imperfection significantly affects the mechanical behavior of microplates. In this work, we derive a dynamic analogue of the von Kármán governing equation for such plates. These equations are then used to develop a reduced order model based on the Galerkin procedure to simulate the static and dynamic behavior of the microplate. Two profiles of initial curvature commonly encountered in microfabricated structures are considered, where one assumes a variation in shape along one dimension of the plate only (cylindrical bending shape) while the other assumes a variation in shape along both dimensions of the plate. Their effects on both the static and dynamic responses of the microplates are examined and compared. We validate the reduced order model by comparing the calculated static behavior and the fundamental natural frequency with those computed by a finite element model over a range of the initial plate rise. The static behavior of the microplate is investigated when varying the DC voltage. Then, the dynamic behavior of the microplate is examined under the application of a harmonic AC voltage superimposed to a DC voltage.

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ABSTRACT: The hot spot caused by frictional heat and thermal contact resistance is one of the most important reasons for hot-cracks and brake failure in brake systems. This paper simulates the brake system as a functionally graded material (FGM) coated half-plane sliding against a homogeneous half-plane. The motivation of using the FGM coating is to improve the coupled thermoelastic instability (TEI) of the brake system due to the thermal contact resistance and frictional heat. The thermoelastic properties of the FGM coating are assumed to vary arbitrarily along the thickness direction. The homogeneous multi-layered model is employed to simulate arbitrary properties of the coating. The perturbation method and transfer matrix method are used to derive the characteristic equation of the coupled TEI problem. The effects of the thermal contact resistance, friction coefficient, heat generation factor and different gradient types of the FGM coating on the stability boundaries are discussed in detail. The results show that the stability boundary is sensitive to the varying thermal parameters of the FGM coating, and an appropriate gradient type can adjust the coupled TEI of the sliding system.

ABSTRACT: Non-classical continuum theories are able to capture the size-dependent behavior of microscale structures. Among them, strain gradient modeling is one of the most accurate ones. The objective of this paper is to develop for the first time a nonlinear strain gradient formulation for the vibrational analysis of electrostatically actuated shear deformable microarches. The normalized equations of motion and the corresponding boundary conditions are derived based on Hamilton’s principle. Novel closed form expressions are derived for the mode shapes of the system using the perturbation technique. These mode shapes are then utilized in a Galerkin projection method to reduce the partial differential equations of motion to time domain nonlinear ordinary differential equations. Multiple time scales perturbation technique is then employed to derive analytical solutions for the nonlinear vibration of the system resulting from a DC step voltage excitation. The analytical results are compared with numerical simulations, and excellent agreement is observed. The formulations and the results presented in this paper can be utilized for design, analysis and synthesis of microscale bistable structures with pre-deformed thick microbeams as their main operating element.

References listed at the end of the paper:


ABSTRACT: This paper presents a size-dependent, nonlinear beam model for bending, buckling and free vibrations of electrically actuated viscoelastic clamped–clamped microbeams. The modified couple stress theory is used to model the size effect. The Euler–Bernoulli beam model including von Karman geometric nonlinearity and intermolecular van der Waals and Casimir forces is adopted. The Boltzmann superposition viscoelastic model is used to simulate the linear behavior of the viscoelastic material. The governing integral–differential equation and corresponding boundary conditions are obtained using Hamilton’s principle. Galerkin’s discretization is used to obtain a reduced-order model of the problem. The quasi-elastic method is used to approximate the viscoelastic behavior. The model has been verified by comparing some results with those available in the literature, and a good agreement is obtained. The influence of the small size, creep modulus, relaxation time and intermolecular forces on the electrostatic bending, buckling and free vibrations are investigated and found significant.


ABSTRACT: In this article, two types of higher-order kinematic theories are adopted to evaluate the nonlinear bending and the stress values of the internally damaged layered composite flat panel structure numerically including the thickness stretching effect. The structural distortion is modeled by Green–Lagrange strain kinematics including all of the nonlinear higher-order strain terms to maintain the required generality. Additionally, the internal debonding between the adjacent layers is introduced via two sub-laminate approaches by maintaining the intermittent link as a priori by the continuity condition. Subsequently, the static equilibrium equations of the debonded structure under the influence of uniform mechanical loading are obtained using a variational principle and solved iteratively in association with the isoparametric finite element steps. Further, the accuracy of the derived model is established by comparing the deflection and stress values with available published results including own experimental data (three-point bend test on artificially debonded layered composite). Finally, a suitable number of numerical examples is solved using the derived higher-order nonlinear models to reveal the operational strength and effect of the debonding (size, position, and location) on the nonlinear static deflection values of the debonded structure.

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Jianxun Zhang, Yang Ye and Qinhua Qin, “Large deflections of multilayer sandwich beams with metal foam core under transverse loading”, Acta Mechanica, Vol. 229, No. 9, pp 3585-3599, September 2018

ABSTRACT: In this paper, large deflections of fully clamped multilayer sandwich beams with metal foam cores are investigated. Based on the yield criteria, analytical solutions are derived for the plastic behavior of fully clamped multilayer sandwich beams loaded by a punch, in which the effects of local denting and core strength on the overall bending are considered. The finite element method is employed to predict the large deflection behavior of multilayer sandwich beams, and the analytical model captures numerical results reasonably well. The effects of core strength, multilayer factor, the size of the loading punch and loading location on the plastic analysis of multilayer sandwich beams are discussed. It is demonstrated that the load-carrying capacity of multilayer sandwich beams increases with a decrease in the multilayer factor and an increase in the core strength and that loading location and the size of the loading punch play important roles in plastic analysis.

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Pham Hong Cong and Nguyen Dinh Duc, “New approach to investigate the nonlinear dynamic response and vibration of a functionally graded multilayer graphene nanocomposite plate on a viscoelastic Pasternak medium in a thermal environment”, Acta Mechanica, Vol. 229, No. 9, pp 3651-3670, September 2018

ABSTRACT: This paper presents an analytical approach to investigate the nonlinear dynamic response and vibration of functionally graded multilayer nanocomposite plates reinforced with a low content of graphene platelets (GPLs) using first-order shear deformation theory and a stress function with full motion equations (not using Volmir’s assumptions). The weight fraction of GPL nanofillers is assumed to be constant in each individual GPL-reinforced composite (GPLRC). The modified Halpin–Tsai micromechanics model that takes into account the GPL geometry effect is adopted to estimate the effective Young’s modulus of the GPLRC layers. The plate is assumed to rest on a viscoelastic Pasternak medium and to be subjected to dynamic mechanical load in a thermal environment. Numerical results for the nonlinear dynamic response and vibration of functionally graded (FG) multilayer GPLRC plates are obtained by the Runge–Kutta method. The results show the influences of the GPL distribution pattern, weight fraction, geometry, foundation models, mechanical and temperature loads on the nonlinear dynamic response and vibration, natural frequencies and frequency–amplitude curves of FG multilayer GPLRC plates.

References listed at the end of the paper:


ABSTRACT: Cylindrical shells are widely used in engineering practice; in particular, one of the special applications is a tire, which can be modeled as a cylindrical shell on an elastic foundation (CSEF). To investigate influences of related parameters on the dynamic characteristics of the shell and help engineers to gain insights into the tire dynamics, a unified formulation for vibration analysis of the cylindrical shell with general boundaries has been developed; this unified formulation includes (i) formulations for CSEF governing equations based on the Donnell–Mushtari theory and Hamilton’s principle; (ii) a unified approach for the solutions of the characteristic equation; and (iii) a general treatment of the boundary conditions by adjusting the foundation spring coefficients. All nine sets of possible solutions of the characteristic equation are clarified and examined. Five case studies have been conducted to validate and verify the developed algorithm. The results based on the developed method generally have good agreement with those of the finite element method and experiment; missed solutions can be recovered.

References listed at the end of the paper:
ABSTRACT: This study presents nonlinear buckling analyses of functionally graded (FG) circular plates in thermal environments using a mesh-free method. The thermal buckling response is formulated based on higher-order shear deformation plate theory in which a new transverse shear function is incorporated to better represent the displacement fields. An enhanced mesh-free radial point interpolation method (RPIM) in which the shape functions are constructed without any fitting parameters by virtue of the radial basis function in a compactly supported form is developed and utilized to explore the thermal buckling behavior. A radial basis function in a compactly supported form is proposed and included in the RPIM. Two types of FG circular plates with different FGM orientation, i.e., metal–ceramic FG circular plates and ceramic–metal FG circular plates, are considered in the analyses. The effectiveness and accuracy of the enhanced RPIM based on the higher-order shear deformation theory is first confirmed by simulating a numerical example found in the literature and comparing the results with the analytical solutions. Detailed parametric studies are then performed to investigate the effects of the volume fraction, plate thickness-to-radius ratio and metallic surface temperature on the critical buckling temperatures of FG circular plates subjected to various through-thickness temperature distributions. Results demonstrate that the enhanced mesh-free RPIM based on the higher-order shear deformation plate theory with the proposed transverse shear function can effectively predict the thermal buckling responses of FG circular plates, and that the volume fraction, plate thickness-to-radius ratio, bottom surface temperature and FGM orientation have considerable effects on the critical buckling temperatures.

References listed at the end of the paper:
25. Matsunaga, H.: Thermal buckling of functionally graded plates according to a 2D higher-order deformation theory. Compos. Struct. 90, 76–86 (2009)
ABSTRACT: In this paper, the nonlinear forced vibration properties of the lattice sandwich beam with pyramidal truss core and viscoelastic surfaces are investigated. The nonlinear dynamic model of the lattice sandwich beam is formulated based on the Kelvin–Voigt viscoelastic model and discretized into nonlinear ordinary equations with multiple degrees of freedom by using the assumed mode method. The nonlinear amplitude–frequency curves of the steady-state responses of the beam are obtained by an iterative algorithm. The effects of the external excitation amplitude, the inclination angle of the truss core, and the viscoelastic coefficient of the surface material on the nonlinear forced vibration behaviors of the beam are analyzed. From the research results, it can be seen that the lattice sandwich beam shows very rich and novel nonlinear dynamic behavior. The viscoelastic damping of the surfaces can decrease the resonance amplitudes of most modes of the beam. An acceptable optimal inclination angle considering the equivalent mass density of the
pyramidal truss core and the resonance amplitude of the beam is obtained. The evolution rules of the lattice sandwich beam with the material and structural parameters obtained from the preset study are helpful for the engineering applications of this kind of lightweight sandwich structures.

References listed at the end of the paper:


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ABSTRACT: A reconstructed edge-based smoothed triangular element, which is incorporated with the discrete shear gap (DSG) method, is formulated based on the global coordinate for analysis of Reissner–Mindlin plates. A symbolic integration combined with the smoothing technique is implemented to calculate the smoothed finite element matrices, which is integrated along the boundaries of each smoothing cell. Numerical results show that the proposed element is free from shear locking, and its results are in good agreement with the exact solutions, even for very thin plates with extremely distorted elements. The proposed element gives more accurate results than the original DSG element without smoothing, and it can be taken as an alternative element for analysis of Reissner–Mindlin plates. The prominent feature of the present element is that the integration scheme is unified in the smoothed form for all of the finite element matrices.

References listed at the end of the paper:


ABSTRACT: Free transverse vibration of monolayer graphene, boron nitride (BN), and silicon carbide (SiC) sheets is investigated by using molecular dynamics finite element method. Eigenfrequencies and eigenmodes of these three sheets in rectangular shape are studied with different aspect ratios with respect to various boundary
conditions. It is found that aspect ratios and boundary conditions affect in a similar way on natural frequencies of graphene, BN, and SiC sheets. Natural frequencies in all modes decrease with an increase of the sheet’s size. Graphene exhibits the highest natural frequencies, and SiC sheet possesses the lowest ones. Missing atoms have minor effects on natural frequencies in this study.

References listed at the end of the paper:

ABSTRACT: This paper elucidates the interactive buckling behaviors of an inflated envelope under coupled mechanical and thermal loads. Unlike the mechanical case, thermal load leads to a hoop negative ovalization buckling. In addition, it can accelerate the longitudinal coupled bifurcation and resist the hoop coupled ovalization buckling. Moreover, the bending resistance of the inflated envelope will be improved when the length of the structure is increased, resulting in the difficulty of it to become wrinkled. These results provide a new insight into the buckling behaviors of an inflated envelope under coupled external loads, and give a reference for the design of the inflated envelope.

References listed at the end of the paper:


ABSTRACT: This paper presents a 3D topology optimization approach for designing shell structures with a porous or void interior. It is shown that the resulting structures are significantly more robust towards load perturbations than completely solid structures optimized under the same conditions. The study indicates that the potential benefit of using porous structures is higher for lower total volume fractions. Compared to earlier work dealing with 2D topology optimization, we found several new effects in 3D problems. Most notably, the opportunity for designing closed shells significantly improves the performance of porous structures due to the sandwich effect. Furthermore, the paper introduces improved filter boundary conditions to ensure a completely uniform coating thickness at the design domain boundary.

Hong-Ling Ye, Wei-Wei Wang, Ning Chen and Yun-Kang Sui (College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, China), “Plate/shell structure topology optimization of orthotropic material for buckling problem based on continuous topological variables”, Acta Mechanica Sinica, Vol. 33, No. 5, pp 899-911, October 2017

ABSTRACT: The purpose of the present work is to study the buckling problem with plate/shell topology optimization of orthotropic material. A model of buckling topology optimization is established based on the independent, continuous, and mapping method, which considers structural mass as objective and buckling critical loads as constraints. Firstly, composite exponential function (CEF) and power function (PF) as filter functions are introduced to recognize the element mass, the element stiffness matrix, and the element geometric stiffness matrix. The filter functions of the orthotropic material stiffness are deduced. Then these filter functions are put into buckling topology optimization of a differential equation to analyze the design sensitivity. Furthermore, the buckling constraints are approximately expressed as explicit functions with respect to the design variables based on the first-order Taylor expansion. The objective function is standardized based on the second-order Taylor expansion. Therefore, the optimization model is translated into a quadratic program. Finally, the dual sequence quadratic programming (DSQP) algorithm and the global convergence method of moving asymptotes algorithm with two different filter functions (CEF and PF) are applied to solve the optimal
model. Three numerical results show that DSQP&CEF has the best performance in the view of structural mass and discretion.

References listed at the end of the paper:


ABSTRACT: A nonlocal continuum orthotropic plate model is proposed to study the vibration behavior of single-layer graphene sheets (SLGSs) using an analytical symplectic approach. A Hamiltonian system is established by introducing a total unknown vector consisting of the displacement amplitude, rotation angle, shear force, and bending moment. The high-order governing differential equation of the vibration of SLGSs is transformed into a set of ordinary differential equations in symplectic space. Exact solutions for free vibration are obtained by the method of separation of variables without any trial shape functions and can be expanded in series of symplectic eigenfunctions. Analytical frequency equations are derived for all six possible boundary conditions. Vibration modes are expressed in terms of the symplectic eigenfunctions. In the numerical examples, comparison is presented to verify the accuracy of the proposed method. Comprehensive numerical examples for graphene sheets with Levy-type boundary conditions are given. A parametric study of the natural frequency is also included.

References listed at the end of the paper:
functions of a series of harmonic amplitudes of plate displacement, which are then solved by employing the space harmonic method and Fourier transforms are applied to a one-layer and multilayer plate structures considering the vibration effects are first developed. Then approaches of the space harmonic method and Fourier transforms are applied to a one-layer plate, and finally the cascade connection method is utilized for a multilayer plate structure. Based on fundamental acoustic formulas, the vibroacoustic responses of microperforated stiffened plates are expressed as functions of a series of harmonic amplitudes of plate displacement, which are then solved by employing the


ABSTRACT: The vibroacoustic response and sound absorption performance of a structure composed of multilayer plates and one rigid back wall are theoretically analyzed. In this structure, all plates are two-dimensional, microperforated, and periodically rib-stiffened. To investigate such a structural system, semianalytical models of one-layer and multilayer plate structures considering the vibration effects are first developed. Then approaches of the space harmonic method and Fourier transforms are applied to a one-layer plate, and finally the cascade connection method is utilized for a multilayer plate structure. Based on fundamental acoustic formulas, the vibroacoustic responses of microperforated stiffened plates are expressed as functions of a series of harmonic amplitudes of plate displacement, which are then solved by employing the
numerical truncation method. Applying the inverse Fourier transform, wave propagation, and linear addition properties, the equations of the sound pressures and absorption coefficients for the one-layer and multilayer stiffened plates in physical space are finally derived. Using numerical examples, the effects of the most important physical parameters—for example, the perforation ratio of the plate, sound incident angles, and periodical rib spacing—on sound absorption performance are examined. Numerical results indicate that the sound absorption performance of the studied structure is effectively enhanced by the flexural vibration of the plate in water. Finally, the proposed approaches are validated by comparing the results of stiffened plates of the present work with solutions from previous studies.

References listed at the end of the paper:

ABSTRACT: This paper deals with the three-dimensional dynamics and postbuckling behavior of flexible supported pipes conveying fluid, considering flow velocities lower and higher than the critical value at which the buckling instability occurs. In the case of low flow velocity, the pipe is stable with a straight equilibrium position and the dynamics of the system can be examined using linear theory. When the flow velocity is beyond the critical value, any motions of the pipe could be around the postbuckling configuration (non-zero equilibrium position) rather than the straight equilibrium position, so nonlinear theory is required. The nonlinear equations of perturbed motions around the postbuckling configuration are derived and solved with the aid of Galerkin
discretization. It is found, for a given flow velocity, that the first-mode frequency for in-plane motions is quite different from that for out-of-plane motions. However, the second- or third-mode frequencies for in-plane motions are approximately equal to their counterparts for out-of-plane motions, keeping almost constant values with increasing flow velocity. Moreover, the orientation angle of the postbuckling configuration plane for a buckled pipe can be significantly affected by initial conditions, displaying new features which have not been observed in the same pipe system factitiously supposed to deform in a single plane.

References listed at the end of the paper:


ABSTRACT: The seemingly contradictory understandings of the initial crush stress of cellular materials under dynamic loadings exist in the literature, and a comprehensive analysis of this issue is carried out with using
direct information of local stress and strain. Local stress/strain calculation methods are applied to determine the initial crush stresses and the strain rates at initial crush from a cell-based finite element model of irregular honeycomb under dynamic loadings. The initial crush stress under constant-velocity compression is identical to the quasi-static one, but less than the one under direct impact, i.e. the initial crush stresses under different dynamic loadings could be very different even though there is no strain-rate effect of matrix material. A power-law relation between the initial crush stress and the strain rate is explored to describe the strain-rate effect on the initial crush stress of irregular honeycomb when the local strain rate exceeds a critical value, below which there is no strain-rate effect of irregular honeycomb. Deformation mechanisms of the initial crush behavior under dynamic loadings are also explored. The deformation modes of the initial crush region in the front of plastic compaction wave are different under different dynamic loadings.

References listed at the end of the paper:


ABSTRACT: Using Reddy’s high-order shear theory for laminated plates and Hamilton’s principle, a nonlinear partial differential equation for the dynamics of a deploying cantilevered piezoelectric laminated composite plate, under the combined action of aerodynamic load and piezoelectric excitation, is introduced. Two-degree of freedom (DOF) nonlinear dynamic models for the time-varying coefficients describing the transverse vibration of the deploying laminate under the combined actions of a first-order aerodynamic force and piezoelectric excitation were obtained by selecting a suitable time-dependent modal function satisfying the displacement boundary conditions and applying second-order discretization using the Galerkin method. Using a numerical method, the time history curves of the deploying laminate were obtained, and its nonlinear dynamic characteristics, including extension speed and different piezoelectric excitations, were studied. The results suggest that the piezoelectric excitation has a clear effect on the change of the nonlinear dynamic characteristics of such piezoelectric laminated composite plates. The nonlinear vibration of the deploying cantilevered laminate can be effectively suppressed by choosing a suitable voltage and polarity.

References listed at the end of the paper:
Wei He, Meidong Han, Shibin Wang, Lin-An Li and Xiuli Xue, “Micromechanics of substrate-supported thin films”, Acta Mechanica Sinica, Vol. 34, No. 2, pp 381-391, April 2018

ABSTRACT: The mechanical properties of metallic thin films deposited on a substrate play a crucial role in the performance of micro/nano-electromechanical systems (MEMS/NEMS) and flexible electronics. This article reviews ongoing study on the mechanics of substrate-supported thin films, with emphasis on the experimental characterization techniques, such as the rule of mixture and X-ray tensile testing. In particular, the determination of interfacial adhesion energy, film deformation, elastic properties and Bauschinger effect are discussed.

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Yang Zhao, Shuhong Dong, Peishi Yu and Junhua Zhao, “Loading direction-dependent shear behavior at different temperatures of single-layer chiral graphene sheets”, Acta Mechanica Sinica, Vol. 34, No. 3, pp 542-548, June 2018

ABSTRACT: The loading direction-dependent shear behavior of single-layer chiral graphene sheets at different temperatures is studied by molecular dynamics (MD) simulations. Our results show that the shear properties (such as shear stress–strain curves, buckling strains, and failure strains) of chiral graphene sheets strongly depend on the loading direction due to the structural asymmetry. The maximum values of both the critical buckling shear strain and the failure strain under positive shear deformation can be around 1.4 times higher than those under negative shear deformation. For a given chiral graphene sheet, both its failure strain and failure stress decrease with increasing temperature. In particular, the amplitude to wavelength ratio of wrinkles for different chiral graphene sheets under shear deformation using present MD simulations agrees well with that from the existing theory. These findings provide physical insights into the origins of the loading direction-dependent shear behavior of chiral graphene sheets and their potential applications in nanodevices.

References listed at the end of the paper:
schemes are used to express the effective elastic module and Poisson's ratio. Moreover, the strength of the pressurized spherical or cylindrical vessel. Both the Mori–Tanaka and rule-of-mixtures homogenization schemes are used to express the effective elastic module and Poisson’s ratio. Moreover, the strength of the
composite is expressed based on the rule of mixtures. Besides, finite element simulation is carried out to verify the accuracy of the analytical solution. The effects of input parameters such as the internal pressure, strength of the SiC particles, ratio of in-plane shear stress to effective yield strength, and choice of homogenization scheme on the tailored distribution of the SiC volume fraction in the radial direction are also investigated.

Chengfu Shu and Shujuan Hou, “Theoretical prediction on corrugated sandwich panels under bending loads”, Acta Mechanica Sinica, First Online: 03 May 2018; published in Vol. 34, No. 5, pp 925-935, October 2018

ABSTRACT: In this paper, an aluminum corrugated sandwich panel with triangular core under bending loads was investigated. Firstly, the equivalent material parameters of the triangular corrugated core layer, which could be considered as an orthotropic panel, were obtained by using Castigliano’s theorem and equivalent homogeneous model. Secondly, contributions of the corrugated core layer and two face panels were both considered to compute the equivalent material parameters of the whole structure through the classical lamination theory, and these equivalent material parameters were compared with finite element analysis solutions. Then, based on the Mindlin orthotropic plate theory, this study obtain the closed-form solutions of the displacement for a corrugated sandwich panel under bending loads in specified boundary conditions, and parameters study and comparison by the finite element method were executed simultaneously.

References listed at the end of the paper:

ABSTRACT: A novel square honeycomb-cored sandwich beam with perforated bottom facesheet is investigated under three-point bending, both analytically and numerically. Perforated square holes in the bottom facesheet are characterized by the area ratio of the hole to intact facesheet (perforation ratio). While for large-scale engineering applications like the decks of cargo vehicles and transportation ships, the perforations are needed to facilitate the fabrication process (e.g., laser welding) as well as service maintenance, it is demonstrated that these perforations, when properly designed, can also enhance the resistance of the sandwich to bending. For illustration, fair comparisons among competing sandwich designs having different perforation ratios but equal mass is achieved by systematically thickening the core webs. Further, the perforated sandwich beam is designed with a relatively thick facesheet to avoid local indentation failure so that it mainly fails in two competing modes: (1) bending failure, i.e., yielding of beam cross-section and buckling of top facesheet caused by bending moment; (2) shear failure, i.e., yielding and buckling of core webs due to shear forcing. The sensitivity of the failure loads to the ratio of core height to beam span is also discussed for varying perforation ratios. As the perforation ratio is increased, the load of shear failure increases due to thickening core webs, while that of bending failure decreases due to the weakening bottom facesheet. Design of a sandwich beam with optimal perforation ratio is realized when the two failure loads are equal, leading to significantly enhanced failure load (up to 60% increase) relative to that of a non-perforated sandwich beam with equal mass.

References listed at the end of the paper:

Abstract: This research presents a finite element formulation based on four-variable refined plate theory for bending analysis of cross-ply and angle-ply laminated composite plates integrated with a piezoelectric fiber-reinforced composite actuators.
reinforced composite actuator under electromechanical loading. The four-variable refined plate theory is a simple and efficient higher-order shear deformation theory, which predicts parabolic variation of transverse shear stresses across the plate thickness and satisfies zero traction conditions on the plate free surfaces. The weak form of governing equations is derived using the principle of minimum potential energy, and a 4-node non-conforming rectangular plate element with 8 degrees of freedom per node is introduced for discretizing the domain. Several benchmark problems are solved by the developed MATLAB code and the obtained results are compared with those from exact and other numerical solutions, showing good agreement.

References listed at the end of the paper:


ABSTRACT: In the present paper, the isogeometric analysis (IGA) of free-form planar curved beams is formulated based on the nonlinear Timoshenko beam theory to investigate the large deformation of beams with variable curvature. Based on the isoparametric concept, the shape functions of the field variables (displacement and rotation) in a finite element analysis are considered to be the same as the non-uniform rational basis spline (NURBS) basis functions defining the geometry. The validity of the presented formulation is tested in five case studies covering a wide range of engineering curved structures including from straight and constant curvature to variable curvature beams. The nonlinear deformation results obtained by the presented method are compared to well-established benchmark examples and also compared to the results of linear and nonlinear finite element analyses. As the nonlinear load-deflection behavior of Timoshenko beams is the main topic of this article, the results strongly show the applicability of the IGA method to the large deformation analysis of free-form curved beams. Finally, it is interesting to notice that, until very recently, the large deformations analysis of free-form Timoshenko curved beams has not been considered in IGA by researchers.

References listed at the end of the paper:


ABSTRACT: Rotation-free shell formulation is a simple and effective method to model a shell with large deformation. Moreover, it can be compatible with the existing theories of finite element method. However, a rotation-free shell is seldom employed in multibody systems. Using a derivative of rigid body motion, an efficient nonlinear shell model is proposed based on the rotation-free shell element and corotational frame. The bending and membrane strains of the shell have been simplified by isolating deformational displacements from the detailed description of rigid body motion. The consistent stiffness matrix can be obtained easily in this form of shell model. To model the multibody system consisting of the presented shells, joint kinematic constraints including translational and rotational constraints are deduced in the context of geometric nonlinear rotation-free element. A simple node-to-surface contact discretization and penalty method are adopted for contacts between shells. A series of analyses for multibody system dynamics are presented to validate the proposed formulation. Furthermore, the deployment of a large scaled solar array is presented to verify the comprehensive performance of the nonlinear shell model.

References listed at the end of the paper:


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https://doi.org/10.2514/1.J055301

ABSTRACT: Although engineering sandwich panel theories can usually give accurate displacement, most of them cannot recover all stresses accurately, especially for the sandwich panels with nonhomogeneous soft cores. In this paper, a static analysis of sandwich panels with nonhomogeneous soft cores is performed by using the differential quadrature method. The material properties vary exponentially through the thickness according to a power-law form. To circumvent the difficulty in dealing with the discontinuity of the first-order derivative of material parameters encountered by point discrete methods, a novel modeling strategy is proposed. Only the top half of the core is analyzed, and the displacement and stress of the entire core are obtained by using the method of superposition. Detailed formulations are provided. Numerical results are presented to investigate the effect of the power-law exponent on the displacement and stress of the sandwich panels with nonhomogeneous soft cores. The computed displacement and the through-thickness distributions of the stress are found in good agreement with those obtained by Abaqus software with very fine meshes.

https://doi.org/10.2514/1.J055245
ABSTRACT: This research proposes a new design for a vertical strut used in aircraft fuselages. It consists of a hollow aluminum vertical strut filled with a glass-fiber-reinforced polymer honeycomb-shaped structure and polymeric foam. The design is optimized for crashworthiness of aircraft fuselage structures. The variables of the surrogate-based optimization procedures are the thicknesses of the aluminum and polymer, and the cell size and shape. The objective functions for the single-objective optimization are the specific energy absorption and the cost, whereas the metrics for the multiobjective optimization are the two aforementioned along with the peak force, mass, and absorbed energy. By using the polymeric foam, an improvement of 28% on the specific energy absorption is obtained when compared to a component without this reinforcement. Compared to a baseline model, the optimum also reduces the cost by 40%. Three Pareto fronts are obtained with different combinations of objective functions. When compared to different baseline models, the optimized models show substantial improvement, increasing the specific energy absorption while reducing peak force, mass, and costs. An important effect of the cell shape on the model’s performance is observed, with the optimum models having pseudorectangular cells.


ABSTRACT: A Ritz approach for the analysis of buckling and postbuckling of stiffened composite panels with through-the-thickness cracks and/or delaminations is presented. The structure is modeled as the assembly of plate elements of which the behavior is described by the first-order shear deformation theory and von Kármán’s geometric nonlinearities. Penalty techniques ensure continuity along the edges of contiguous plate elements and the enforcement of the restraints on the external boundaries. They are also used to avoid interpenetration problems. General symmetric and unsymmetric stacking sequences are considered. A computer code has been developed and used to validate the proposed method, comparing the results with literature and finite-elements solutions. Results are also presented for postbuckling of multilayered stiffened plates with through-the-thickness cracks and delaminations. The analyses carried out show the efficiency and potential of the method, which provides accuracy comparable to those of other techniques in conjunction with a reduction in the number of degrees of freedom and simplification in data preparation.


ABSTRACT: This paper presents an efficient finite element approach to study the prestressed vibration mode results of a curvilinearly stiffened composite panel subjected to various in-plane loads. The present method models the plate and the stiffener separately, which allows the stiffener element nodes to not coincide with the plate shell-element nodes. The stiffness and mass matrices of a stiffener are transformed to those of the plate through the displacement compatibility conditions at the plate–stiffener interface via finite element interpolation. Convergence and validation studies have been conducted to verify the present method in the finite element vibration analysis by using the examples from the existing literature. Prestressed vibration mode results are examined for a stiffened composite panel with arbitrarily shaped composite stiffeners in the presence of the in-plane normal and shear loads. Numerical results show the possible benefits of using curvilinear stiffeners to improve the vibration response by increasing both the fundamental frequency and the buckling load through changing the vibration and buckling mode shapes with a negligible or even no weight penalty. The stiffener depth ratio is found to increase both the fundamental frequency and the buckling load, but only up to a certain
value. Any further increase in the stiffener depth ratio causes stiffener buckling before plate buckling, and it leads the free and prestressed vibration mode results to behave as the vibration mode results for a plate with simply supported boundary conditions along the stiffeners.

References listed at the end of the paper:


https://doi.org/10.2514/1.J055021

ABSTRACT: This paper proposes the use of curvilinear stiffeners as a mechanism to control supersonic panel flutter. To account for transverse shear deformation, the plate and stiffeners are modeled according to the first-order shear deformation theory and Timoshenko beam theory, respectively. The Chebyshev polynomials are the basis of the deflection and rotation functions in the Ritz method. The aeroelastic load is formulated according to the first-order high-Mach-number approximation to linear potential flow theory. The minimum potential energy and Hamilton’s principle are used to solve the problem. Plots of frequency versus aerodynamic pressure and damping versus aerodynamic pressure are used to determine the critical aerodynamic pressure, and hence to predict flutter of various isotropic and composite, stiffened, and unstiffened plates. The results for the flutter of straight-stiffened plates are validated through comparison with published papers. Several numerical examples are discussed, for which parametric studies for the shape and number of stiffeners and fiber orientation are performed. The flutter mode shapes are also presented. The present study attests that the critical dynamic pressure can be enhanced, and flutter can be successfully suppressed by changing the stiffener’s shape and fiber orientation.


https://doi.org/10.2514/1.J055136

ABSTRACT: In this paper, geometrically exact fully intrinsic equations and variational asymptotic beam sections are used to study the buckling and postbuckling of a column under self-weight. Initial curvature effects both generalized one-dimensional beam equations and the cross-sectional stiffness properties. The effects of initial curvature have been studied on buckling and postbuckling in this paper. This problem is a valuable test case for the utility of the fully intrinsic equations and variational asymptotic beam sections.

ABSTRACT: Substructuring methods have been widely used in structural dynamics to divide large, complicated finite element models into smaller substructures. For linear systems, many methods have been developed to reduce the subcomponents down to a low-order set of equations using a special set of component modes, and these are then assembled to approximate the dynamics of a large-scale model. In this paper, a substructuring approach is developed for coupling geometrically nonlinear structures, where each subcomponent is drastically reduced to a low-order set of nonlinear equations using a truncated set of fixed-interface and characteristic constraint modes. The method used to extract the coefficients of the nonlinear reduced-order model is nonintrusive, in that it does not require any modification to the commercial finite element code but computes the reduced-order model from the results of several nonlinear static analyses. The nonlinear reduced-order models are then assembled to approximate the nonlinear differential equations of the global assembly. The method is demonstrated on the coupling of two geometrically nonlinear plates with simple supports at all edges. The plates are joined at a continuous interface through the rotational degrees of freedom, and the nonlinear normal modes of the assembled equations are computed to validate the models. The proposed substructuring approach reduces a 12,861-degree-of-freedom model down to only 23 degrees of freedom while still accurately reproducing the nonlinear normal modes.


ABSTRACT: A numerical model was developed for nonlinear vibro-acoustic analysis of a skin–core debonded sandwich plate immersed in an infinite fluid and subjected to time-varying loads. The structural model of the plate was formulated using a modified variational principle in conjunction with a multilevel partitioning procedure. The nonlinear contact constraints on the detached interfaces of the plate were imposed by using the Nitsche’s method. This led to a stable contact solution that does not depend on the penalty parameter as strongly as in the traditional penalty approach. A time-domain Burton–Miller boundary integral formulation was employed to couple with the structural model of the plate to determine the acoustic field, which avoids spurious instabilities in long-time simulations. Comparisons of the present results were made with solutions obtained from finite element analyses. The results show that both the structural and acoustic responses of a sandwich plate can be significantly affected by the presence of a debonding. For a debonded sandwich plate under harmonic excitation forces, the vibration and acoustic responses of the plate consist of not only the fundamental excitation frequencies, but also subharmonic and superharmonic components and combination harmonics of the excitation frequencies. The effect of the debonding size on the nonlinear vibration and acoustic-radiation responses of sandwich plates was investigated.


ABSTRACT: The nonlinear transient behavior of the delaminated composite curved shell panel under different kinds of mechanical loading is investigated in this analysis. The delaminated shell panel model is developed
mathematically using two higher-order midplane theories in conjunction with the Green–Langrage type of geometrical nonlinear strains including all the nonlinear higher-order terms. Further, the desired nonlinear responses are computed numerically with the help of a unique computer code developed in the MATLAB® environment. The nonlinear numerical responses are computed using Newmark’s time integration scheme together with the direct iterative method in conjunction with finite-element steps. Further, the convergence behavior of the present numerical results is checked. In addition, the validity of the present numerical responses is shown by comparing the results with those of the available published literature. Finally, the role of the size, location, and position of delamination as well as the effects of different design parameters (curvature ratio, aspect ratio, modular ratio, shell configuration, and constraint condition) on the nonlinear transient responses are computed through a wide variety of numerical examples and discussed in detail.

https://doi.org/10.2514/1.J055567

ABSTRACT: The natural frequencies of a hermetic capsule of a circular cylinder closed with hemispheroidal caps at both ends and having variable thickness are determined by the Ritz method using a three-dimensional analysis. However, in the traditional shell analysis, mathematically two-dimensional thin-shell theories or higher-order thick-shell theories, which make very limiting assumptions about the displacement variation through the shell thickness, have usually applied. Although most researchers have used three-dimensional shell coordinates that are normal and tangent to the shell midsurface, the present analysis is based upon the circular cylindrical coordinates. Using the Ritz method, the Legendre polynomials, which are mathematically orthonormal, are used as admissible functions instead of ordinary simple algebraic polynomials. The potential and kinetic energies of the hermetic capsule are formulated, and upper bound values of the frequencies are obtained by minimizing the frequencies. As the degree of the Legendre polynomials is increased, frequencies converge to the exact values. Convergence to four-digit exactitude is demonstrated for the first five frequencies. The frequencies from the present three-dimensional method are compared with those from other three-dimensional approaches and two-dimensional shell theories by previous researchers. The present three-dimensional analysis is applicable to very thick shells as well as thin shells.

https://doi.org/10.2514/1.J055763

ABSTRACT: For the structural dynamic analysis of complicated beam-type structures, a detailed finite element model with large number of degrees of freedom is almost impossible to be used due to the huge computational cost and storage requirements. Therefore, a novel reduced-order model is proposed to determine the natural frequencies of the beam-type structures in this study, which is established by using a reduction basis along with the polynomial interpolation function. The basic idea is to convert the displacements of finite element model nodes in each cross section to a small set of nodes with a few generalized degrees of freedom. The proposed reduced-order model can gain a significant reduction of computational cost without sacrifice of accuracy; moreover, it has the ability to identify shell lobe-type modes and coupled modes. Several numerical case studies for different beam-type structures, including thin-walled cylinder, stiffened shells, and thin-walled cylinder with cutouts, are studied, and the outcomes are validated by benchmark studies.
ABSTRACT: The linear elasticity problem formulation and solution for a generally asymmetric sandwich curved beam/panel consisting of orthotropic core and face sheets, which is subjected to a top face sinusoidal distributed transverse loading, is presented. The displacement approach is used along with a plane strain assumption, and the panel is assumed to be simply supported at the ends. Closed-form solutions for the displacements and stresses are derived, and results for realistic material systems are presented for the transverse and hoop displacements as well as the core transverse normal and shear stresses and the face hoop stresses. A comparison of the results between the elasticity, the first-order shear deformation theory with an equivalent shear modulus, and the classical sandwich theories is presented. In addition, a comparison is presented with results from the compressive high-order sandwich panel theory. This closed-form elasticity solution can be used as a benchmark in assessing the accuracy of the various sandwich panel theories or numerical approaches.

ABSTRACT: Pillow distortion has become one significant limiting factor to the development of space mesh reflector antennas toward large-scale extension and high surface accuracy. However, the current state of the art about pillow distortion have great limitations in practical application, because they are mostly based on the assumptions that the stress applied on the mesh membrane is uniformly distributed and that the reflector is segmented into regular convex polygons by cable net. To improve the applicability and simplicity of the current state of the art, an alternative approach has been developed for the pillow distortion analysis of space mesh reflector antennas without limiting assumptions in this paper. First of all, the triangular and quadrilateral cable-membrane elements are selected as conventional base units for space mesh reflector antennas. Second, equations and the calculation method were derived to investigate the pillow distortion of space mesh reflector antennas composed of triangular cable-membrane elements, based on the differential equations of membranes and cables, and then extended for that composed of other polygonal elements. To verify the validity and robustness of the proposed analytical method, some cable-membrane elements and a space mesh reflector antenna were taken as numerical examples. Eventually, the surface error distribution, root mean square error, and far-field electrical performance of an antenna influenced by the pillow distortion were conducted.

ABSTRACT: Probabilistic design methods may be used to account for inherent variability in the manufacturing quality of aerospace structures. Two different probabilistic approaches are compared alongside a deterministic method for the aeroelastic design of composite plate wings with uncertain ply orientations. The instability speed is found to be a discontinuous function of the lamination parameters, which are themselves functions of the ply orientations. A surrogate modeling approach is presented in which Gaussian processes are combined with support vector machines to emulate the discontinuous instability speed to efficiently propagate uncertainty through the model. The surrogate model is used to calculate the objectives of two optimization strategies: a
reliability-based design, in which the probability of aeroelastic instability occurring within the design envelope is minimized, and a robust design, in which the mean and standard deviation of the instability speed are traded off. A genetic algorithm is used to optimize the layup, and reductions in the probability of failure of 94% are achieved in the reliability-based design using a 145 m/s design speed, relative to benchmark deterministic designs. A 74% reduction in the standard deviation is achieved in the robust design, at the expense of a 1% reduction in the mean.

https://doi.org/10.2514/1.J054787

ABSTRACT: In this paper, a new method to obtain a geometrically nonlinear structural dynamics model based on the full linear finite element model of slender structures is presented. For this purpose, a finite element model is divided into multiple segments along its span. For each segment, a modal analysis is carried out. Boundary grid points are defined on each segment and loaded by fictitious masses. The modal analysis produces a set of elastic modes and six rigid-body modes that have significant deformations near the boundary. These deformations facilitate high-accuracy integration of the segments into a coupled model, in which the fictitious masses are removed. The elastic modes are used as master modes that describe the deformation, whereas the rigid-body modes are used as slave modes to establish displacement compatibility between the segments. The modal analysis is carried out with the local segment attached to its own reference frame, yielding a local linear solution that is part of a global nonlinear analysis. Large rotations and displacements are provided by the rigid-body modes in a corotational framework.

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ABSTRACT: The industry has to resort to experiments for practical design of composite laminates when physical models/simulations are inadequate for desirable accuracy or require excessive computational resources. Surrogates are used to predict strength of composite laminates in the design space by conducting an array of tests. It has been reported that an exploration strategy to test as many different configurations as possible is more effective than replication of fewer points for reducing test noise. The observation was based on analytical test functions and synthetic Gaussian noise. This paper first studies real experiments to check whether the previous observation stands. Test results of open-hole tension for composite plates that included 18 replicates per configuration were examined. A resampling procedure was developed that compared exploration and replication, and it was found that exploration proved to be more accurate for prediction than replication. Second, the major source of uncertainty for surrogate prediction was examined, which is variability of strength. The distribution of experimental open-hole tension strength was found to be not unambiguously independent and was identically distributed normal distribution as commonly assumed. The variation of specimen strength is correlated rather than independent at different configurations due to the between-batch variability. Consequently, the influence of distribution type was then investigated on an analytical test function with three synthetic distributions. The exploration strategy proved to be better than the replication strategy for all three distributions. It was found that the exploration strategy allows for higher-order polynomial surrogate to be used, which is a key point to improve characterization of a function with complex dependence on design parameters.
ABSTRACT: In this study, the nonlinear free vibration responses of functionally graded curved (cylindrical, elliptical, and hyperbolic) shell panels are analyzed under heat conduction. For the present investigation, the effective material properties of each constituent are assumed to be the function of temperature and thermal conductivity. The functionally graded material kinematic model is developed using the higher-order shear deformation theory, and the geometrical nonlinearity is introduced through Green–Lagrange strain. The governing equation of the vibrated functionally graded panel model is derived using the classical Hamilton’s principle. The model is discretized based on the isoparametric finite element approach and solved using the direct iterative method. Finally, the variety of numerical examples are solved for different design parameters (geometrical and material), and their effects on the linear and the nonlinear frequency responses of the functionally graded curved shell panels are also discussed in details.

ABSTRACT: The natural frequencies of toroidal shells of revolution with a hollow elliptical cross section and variable thickness are determined by the Ritz method from a three-dimensional theory, whereas traditional shell theories are mathematically two-dimensional. Instead of ordinary algebraic polynomials, the Legendre polynomials, which are mathematically orthonormal, are used as admissible functions. The present analysis is based upon the circular cylindrical coordinates, whereas toroidal coordinates have been used in general. The potential and kinetic energies of the torus are formulated, and upper bound values of the frequencies are obtained by minimizing the frequencies. Convergence to a four-digit exactitude is demonstrated for the first five frequencies of the torus. Comparisons are made between the frequencies from the present three-dimensional method, a two-dimensional thin-shell theory, and thin- and thick-ring theories. The present method is applicable to very thick shells as well as thin shells.

ABSTRACT: Due to the curvature, the first-order shear deformation theory for curved sandwich panels is not a direct extension of the corresponding one for flat panels; thus, it is formulated accordingly, and its unique features, such as the reference curve, are discussed. Three versions of the first-order shear deformation theory are formulated: the one based on a direct variational formulation based on the assumed through-thickness displacement field (termed “basic”); one based on the definition of an equivalent shear modulus for the section (termed “$G_{eq}$”); and one based on derivation of a shear correction factor, which is considered in conjunction with the equivalent shear modulus. A comparison of the results between a previously formulated benchmark elasticity solution and the three variants of the first-order shear deformation theory is presented. In addition, the results are compared with the classical theory for curved sandwich panels, which does not include transverse shear. The shear correction factor formula derived for sandwich curved panels is proven to converge to the homogeneous flat-plate value of $5/6$. 
https://doi.org/10.2514/1.J055822
(Technical Note: cannot cut and paste the abstract)

https://doi.org/10.2514/1.J056314
ABSTRACT: A feasible, nonparametric, probabilistic approach for modeling and quantifying model-form uncertainties associated with a computational model designed for the solution of a generalized eigenvalue problem is presented. It is based on the construction of a stochastic, projection-based reduced-order model associated with a high-dimensional model using three innovative ideas: 1) the substitution of the deterministic reduced-order basis with a stochastic counterpart featuring a reduced number of hyperparameters, 2) the construction of this stochastic reduced-order basis on a subset of a compact Stiefel manifold to guarantee the linear independence of its column vectors and the satisfaction of any constraints of interest, and 3) the formulation and solution of a reduced-order inverse statistical problem to determine the hyperparameters so that the mean value and statistical fluctuations of the eigenvalues predicted using the stochastic, projection-based reduced-order model match target values obtained from available data. Consequently, the proposed approach for modeling model-form uncertainties can be interpreted as an effective approach for extracting from data fundamental information and/or knowledge that are not captured by a deterministic computational model, and incorporating them in this model. Its potential for quantifying model-form uncertainties in generalized eigencomputations is demonstrated for a natural vibration analysis of a small-scale replica of an X-56-type aircraft made of a composite material for which ground-vibration-test data are available.

https://doi.org/10.2514/1.J056384
ABSTRACT: The present paper proposes an approach that can be used to mix one-, two-, and three-dimensional refined models, derived using the Carrera Unified Formulation, to build a variable kinematic model that is able to deal with the static analysis of complex thin-walled structures. The adopted formulation, which only has displacements as degrees of freedom, allows these models to easily be connected to each other; that is, a variable kinematics model can be derived without ad hoc techniques. The refined models used in the present paper ensure high accuracy and low computational costs. The displacement continuity at the interface is guaranteed by the formulation, and no stress singularities appear in the kinematic model transition. The mixed interpolation tensorial component approach has been used, in a unified sense, for one-, two-, and three-dimensional models to avoid the shear locking effect. The accuracy of the present approach has been confirmed by comparing the results with those from the literature and with those obtained using commercial finite element codes. The static response of a reinforced panel and a section of an aircraft fuselage have been investigated to show the capabilities of the present approach. The use of refined structural models makes it possible to overcome the limits of classical structural models and, at the same time, to reduce the computational costs.

https://doi.org/10.2514/1.J056320
ABSTRACT: The free vibration analysis of laminated composite cylindrical, spherical, hypar, saddle, and elliptical shells with cutouts and concentrated mass is presented by developing a $C^0$ finite element formulation based on third-order shear deformation theory (TSDT). The proposed model satisfies the zero transverse shear stress conditions at shell top and bottom without using a shear correction factor. This is the first finite element implementation of the TSDT to solve the vibration problem of laminated composite shells with cutouts and concentrated mass incorporating cross curvature effects in shells. Parametric vibration study has been performed for different shells with cutouts and concentrated mass.


ABSTRACT: An investigation into the bistability of positively curved laminated composite slit tubes is presented, establishing a natural extension in this area that has previously been focused on straight tubes. Curved slit tubes are modeled as the surface segments of a torus. The design space is explored through a parametric study to investigate the effect on the second stable state, representing a small coil. This includes the effects of longitudinal curvature, cross-section subtending angles, nonuniform transverse curvature, and spatially varying laminate properties. The second equilibrium state is determined through strain energy minimization using the Rayleigh–Ritz method. To verify the model, samples are manufactured from glass-fiber braid and polypropylene resin. This investigation finds 1) the initial curvature along the length of the tube has little effect on coil radius, however, the coil has a distinct barrel shape; 2) highly enclosed and 3) highly curved cross-sections result in higher edge strains of the second equilibrium, enabling identification of practical bistable tubes; and 4) conversely, the greater the initial curvature along the length of the tube, the lower the second equilibrium strain.


ABSTRACT: Perturbation-based approximation methods are widely used in preliminary design studies of thin-walled structures. In this paper, postbuckling analysis of a variable-angle-tow composite plate is performed using the perturbation-based asymptotic numerical method, which transforms the nonlinear problem into a set of well-posed recursive linear problems. These linear problems are solved using a novel generalized differential-integral quadrature method, and the postbuckling solutions are sought over a finite load step size around the critical buckling point using asymptotic expansions. The accuracy of the asymptotic numerical method in evaluating the initial postbuckling of variable-angle-tow plates under compression is investigated. Subsequently, a novel postbuckling optimization approach based on asymptotic numerical method results is proposed for the design of variable-angle-tow laminates. The postbuckling features obtained from asymptotic numerical method are used in an efficient two-level optimization framework for the design of variable-angle-tow plates. At the first level, a globally convergent method of moving asymptotes is adopted to determine the optimal lamination parameter distributions that maximize the postbuckling performance of the variable-angle-tow plate. At the second level, a genetic algorithm is used to convert the optimal lamination parameter distributions into realistic variable-angle-tow layups. The optimization studies are performed for square variable-angle-tow plates for axial/biaxial compression under different in-plane boundary conditions.

(Technical note: no abstract)


ABSTRACT: A detection scheme to localize and quantify multiple damages in structures is proposed. At first, acceleration response histories at multiple sensor locations are collected experimentally from damaged and undamaged structures. Structures with single as well as multiple damages have been considered. The cross correlation between the acceleration histories at each sensor location is computed. The peak amplitudes of normalized cross-correlation outputs are used to form the damage indicators. The traditional threshold-based method of detecting damages from these damage indicators has been observed to be inadequate for the detection of multiple damages. Here, the drawback of threshold-based damage-detection method is overcome by using an artificial neural network. The accuracy of the damage-detection scheme has been shown for different damage cases.


ABSTRACT: An equivalent linearization technique has been incorporated into NASTRAN to predict the geometrically nonlinear random vibration responses of laminated plates subjected to acoustic excitation. The nonlinear equations of motion of laminated plates are obtained based on the classical laminated plate theory and large deflection finite element formulation. The existing internal variables in the modal frequency response solution sequence of NASTRAN are called directly by the direct matrix abstraction program, and the direct matrix abstraction program implements the iterative procedure for determining the modal equivalent linear stiffness matrix. In this way, the usual manner of computing variables is retained; that is, these variables are determined internally within NASTRAN using information provided in the bulk data file written by PATRAN. The numerical results for a thin, simply supported, aluminum plate are in good agreement with previously reported data, which confirms the proposed method has reasonable precision and high efficiency. Then, the proposed method is applied for analyzing the geometrically nonlinear random responses of thin, simply supported, laminated plates. It is shown that the geometric nonlinearity plays an important role in the vibration response of laminated plates, particularly at high acoustic pressure loading.


ABSTRACT: This study introduces a scaling law to explain wrinkle dissipation induced on a membrane under a shear load. Wrinkles in an isotropic rectangular membrane are fixed at the bottom edge and subjected to an in-plane shear stress at the upper edge. The wrinkle dissipation is simulated by an in-plane tension load applied at the upper edge, which is perpendicular to the shear load. A scaling law depicts that the ratio of residual wrinkles, which indicates the extent of wrinkle dissipation, is not affected by the membrane size but is uniquely determined by the ratio of the major principal strain to the in-plane shrinkage strain. This observation is verified by performing geometrical nonlinear finite element simulations using shell theory and tension-field theory. Additionally, a simplified equation is derived to directly estimate the ratio of tensile displacement to control membrane wrinkling. This equation reveals that the tensile displacement necessary to completely suppress
membrane wrinkling is dependent on the Poisson ratio and the aspect ratio of the membranes. Wrinkles can be perfectly dissipated by applying a tensile displacement equivalent to 64% of the shear displacement when the Poisson ratio is 0.3 and the aspect ratio is larger than 3. The measures used in this study are effective descriptions of membrane wrinkling that can be used to design future spacefaring gossamer structures.


ABSTRACT: A new higher-order zig-zag theory is proposed for the free and forced vibration analysis of laminated composite and sandwich beams with different thickness at each ply. In-plane displacements in the proposed model nonlinearly distribute through the thickness and exhibit an abrupt discontinuity of slope at interfaces, which coincide with three-dimensional analysis. Differing from previous approaches, the transverse shear stress satisfies the continuity condition at interface by integrating the three-dimensional equilibrium equations, whereas the higher-order derivatives of displacement parameters have been eliminated using the three-field Hu-Washizu (HW) mixed variational principle. Moreover, the accurate transverse shear stresses are introduced in the equations of motion by using Hamilton’s principle, which actively impact the accurate prediction of natural frequencies of the laminated composite beams with arbitrary layouts. The performance of the proposed model is tested with different examples. It is observed that the present model gives most accurate results with respect to two-dimensional elasticity solutions for the free and forced vibration analysis compared with the existing higher-order models recently reported in the literature.


ABSTRACT: Minimum-weight aircraft wing design, with an emphasis on avoiding aeroelastic instability, has been studied since the 1960s. The majority of works to date were posed as sizing problems; only a handful of researchers have employed a topology optimization approach. The aim of this study is to use the level set method for this purpose. The problem is formulated as one of plate thickness distribution, which takes on one of two prescribed values at every point on the wing planform. This is combined with constraints implemented on the eigenvalues of the flutter equation; such an approach is shown to be robust and versatile. Optimization results for rectangular plate wings at a range of sweep configurations studied previously are included to validate the present methods. Delta, high-aspect-ratio, and typical swept transport wing planforms are then optimized. All solutions demonstrate the ability to significantly reduce wing mass while maintaining flutter and divergence speed above a specified limit, which can be higher than that of the reference, maximum-thickness design. The proposed method can be used to provide insights into optimal aeroelastic wing structures and is particularly useful for developing unconventional aircraft structural configurations.


ABSTRACT: (Not given for Technical Notes)


ABSTRACT: Focusing on the aeroelastic stability of heated flexible panel in shock-dominated flows with arbitrary shock impingement location condition, a systematic theoretical analysis model is established. The von-Karman large deflection theory is used to account for the geometrical nonlinearity. Local first-order piston theory is employed in the region before and after shock to estimate the aerodynamic pressure. The results show
that the shock impingement location has a significant effect on the stability of the flexible panel. The change of the critical dynamic pressure (for which flutter onset occurs) is not a monotonic function of the shock impingement point from one endpoint to the other. Specifically, the nondimensional critical flutter dynamic pressure increases as the shock impingement points move from the left to the right in the middle region, and the value of the critical flutter dynamic pressure varies substantially as the shock is located near the boundary of the panel. The variation is larger for higher shock strength. For a large shock strength, panel can buckle (or diverge) rather than only flutter even without thermal stresses. The sensitivity of the panel dynamics to the shock impingement location may have interesting implications for the case of a moving incident shock.


ABSTRACT: (Not given for Technical Notes)


ABSTRACT: The concept of a curvilinearly stiffened panel is promising for aerospace and aircraft structures with cutouts, since the stiffness distribution and loading path can be flexibly tailored in terms of cutouts. However, uncertainties from the manufacturing process can significantly reduce the practical load-carrying capacity of a curvilinearly stiffened panel. Traditional nondeterministic design optimization methods would suffer from a high computational burden because numerous discrete-continuous variables, in which thousands of finite element analyses are usually required, are involved. Therefore, a hierarchical nondeterministic optimization framework of a curvilinearly stiffened panel is established, containing two steps (global search and local search) and four main parts (layout design, nondeterministic design optimization, reshape layout design, and stress validation). In the first-step deterministic optimization, all variables are considered, and a rough result set will be obtained by a global search. In the second-step nondeterministic optimization, all discrete-continuous layout parameters are fixed in the initial stage, and the efficient adaptive-loop method is applied to significantly increase the computational efficiency, in which the variations of material properties and geometric dimensions are considered as uncertainties. The layout also will be reshaped to explore the potential of the load-carrying capacity. Finally, the stress constraint and crippling constraint are verified for the optimum design. An illustrative example indicates the advantage of the proposed framework not merely provides a competitive efficiency and robustness over other nondeterministic approaches but also improves the rationality of deterministic design optimization.


ABSTRACT: (Abstract not given for technical notes.)

End of more papers published in the journal, AIAA Journal (2017 and on).

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ABSTRACT: In this paper, a procedure is developed to analyze long-distance free-spanning pipelines on an uneven seabed through the incorporation of the Vector Form Intrinsic Finite Element (VFIFE or V-5) method with the bubble model, which is also called the UWAPIPE model. A dynamic contacting scheme is proposed to model variations of the contact situation between a seabed and a deforming pipeline on it. Specifically, a high-efficiency Message Passing Interface (MPI) parallel scheme is adopted to reduce the computing time of the procedure. Through the use of the procedure, the configuration of a 10 km long-distance pipeline lying on a real irregular seabed in the South China Sea is simulated, and the results are compared with a Remotely Operated Underwater Vehicle (ROV) survey and Det Norske Veritas (DNV) recommendations. The effects of the submerged weight and internal pressure of the pipeline are evaluated. Subsequently, the unevenness ratio is defined, and its relation to the pipeline bending moment is presented. The effects of the seabed undulation and adjacent spans are proved to be significant for the examined case.

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ABSTRACT: In S-lay operations, the pipeline passes over the stinger and is laid on the seabed after welding and nondestructive tests. The high combined loadings of axial tension, bending moment, roller reaction force, and the pipelay vessel motion may result in plastic deformation in the pipeline, which is difficult to accurately quantify. A real-time onboard monitoring system is recommended to guarantee the safety of the pipelaying process in challenging projects that include very large strain in the pipeline. However, most of the current onboard monitoring systems focus on the submerged section and sagbend section of the pipeline. The overbend section is ignored because of the uncertainty resulting from the combined loadings and the dynamic process during the pipe passing over the stinger. The present paper proposes a novel online monitoring method based on the roller reaction force measurement, which can monitor the dynamic overbend pipe strain fluctuations in real time. Relevant analytical equations in the model are first derived, then a large-scale hybrid model test and numerical simulation are carried out to verify the proposed monitoring system.

ABSTRACT: In this paper, the dynamic ultimate hull girder strength analysis on a container ship subjected to impact bending moments was studied based on a 3-D nonlinear explicit finite element model (FEM). In general, the dynamic response of a container ship is studied by means of the hydroelasticity theory, so the nonlinear dynamic response of the hull girder cannot be considered. A nonlinear explicit finite element method can overcome this problem. First, a nonlinear finite element method is used to obtain ultimate strength and the nonlinear relationship between the bending moment and rotational angle of the hull girder, and the ultimate rotation ($\theta_u$) is used as a failure criterion to estimate the dynamic ultimate strength of the container ship under an impact bending moment. Then the impact bending moment is characterized as a sinusoidal pulse function, and the pulse duration and amplitude of the impact bending moment on the dynamic elastic-plastic response of the hull girder were estimated based on the nonlinear explicit finite element method. Some important conclusions can be obtained from this paper.


ABSTRACT: The interaction of water waves with multiple composite flexible membranes is studied based on the assumption of linear wave theory and small membrane response. The eigenfunction expansion method and the wide spacing approximation are used to obtain the reflection and transmission coefficients. The characteristics of Bragg reflection are investigated by changing various factors including the relative group spacing, the end condition, the number, the tension, the draft, and the protrusion of membranes. It is found that the multiple composite flexible membranes can enlarge the bandwidth of Bragg reflection. This study can provide guidance on the design of multiple composite flexible membranes as effective floating breakwaters by taking advantage of Bragg reflection.


ABSTRACT: The discrete-finite element coupling method is an effective approach to simulate the complex interactions between sea ice and offshore structures and ice-induced vibrations (IIVs) of structures. However, the small time step in the discrete element method, as the time step of the coupled method, is time-consuming. Adoption of a time multiscale strategy can solve this problem. This paper proposes a coupled discrete-finite element method based on a domain decomposition method to analyze the interactions between sea ice and a conical jacket platform. Moreover, IIVs of the platform were analyzed. The computational domain is split into several subdomains based on whether sea ice interacts with the platform. The subdomains directly impacted by sea ice use small time steps of the discrete element method. The numerical results show that the proposed time-efficient method is reliable and stable for the simulations of ice-platform interactions.


ABSTRACT: The objective of the present study is to investigate the ultimate hull girder strength of an asymmetrically damaged ship under a sagging condition. Two kinds of ships are taken as the object of analysis. The cross section of the ship is considered and assumed to have remained plane. The simply supported boundary condition is applied to both sides of the cross-section. The ultimate hull girder strength is attained when a plate and/or stiffened plate element at the specified location called “critical element” reach its ultimate strength. To investigate the ultimate hull girder strength, a simplified approach is proposed. The result obtained
by the simplified approach is compared with the progressive collapse analysis to determine effectiveness and for validation.


ABSTRACT: With the advent of higher steel grades for offshore pipelines and the reliance of the UOE forming process on trial and error, knowing the final yield strength of the pipe beforehand would be beneficial in terms of time and cost. However, predicting the yield strength of the UOE pipe constitutes a difficult task because of the alteration of the material properties throughout the forming process. Moreover, the yield strength is measured by tensile test executed on specimens obtained by flattening samples cut from the formed pipe, but this flattening process also alters the properties of the material. Accordingly, this study presents a 2-D finite element method (FEM) program considering both forming and flattening processes to predict the yield strength of the UOE pipe measured by tensile test. The results show that the simulation predicts the yield strength with good accuracy.

(No appropriate papers through December 2018)


ABSTRACT: This paper presents the crashworthiness design optimisation of a typical vehicle structure subjected to offset deformable barrier and full rigid barrier impact cases. Several approaches involving sampling techniques, surrogate model, multi-objective optimisation algorithm and reliability analysis are introduced and applied. Four correlation functions of Kriging are adopted for the design optimisation. It shows that the accuracy of the correlation functions is different and the best one is selected for the objective or constraint function. Both the deterministic optimisation and reliability-based design optimisation (RBDO) are conducted. In RBDO, the reliability levels of constraints are computed through the first-order reliability method (FORM) and second-order reliability method (SORM), and are compared with Monte Carlo simulation. It is found that SORM is more accurate than FORM when the constraint functions are highly nonlinear. Finally, the results demonstrate that RBDO solutions are more reliable than that of the deterministic optimisation for real engineering application. RBDO solutions are further validated by finite element analysis model, which shows the effectiveness of the proposed RRDO approach in obtaining the reliable optimal design of the vehicle structures.
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ABSTRACT: According to auto industry's interest for reducing fuel consumption, composite materials have gained lots of attention due to their superior characteristics. The available finite element model of the Toyota Yaris has been modified through the substitution of the steel roof with composite and aluminium solution, to evaluate the change in the static and dynamic stiffness of vehicle body and the change in the structural response of the vehicle in case of full frontal crash. ‘Piecewise Linear Plasticity’ and ‘Enhanced Composite Damage’ material models available with LS-DYNA are applied to model metal and composite roof panels, respectively. Analyses have been done based on the same and modified roof panel thickness. Results reveal that the composite solutions give comparable value of the body stiffness, although with lower energy absorption capacity of the roof in comparison with the steel solutions but they have large contribution, around 40%, to the weight reduction of vehicle roof panel along with the acceptable structural performance.

ABSTRACT: Square tubes have been widely used as energy absorption components. To investigate the influences of multi-cell configuration and loading arrangement on the crashworthiness of square tubes, eight kinds of multi-cell square tubes were numerically analysed under axial and oblique loads. Validation was performed against experimental data. According to the complex proportional assessment method, the T5-1 tube is found to have the best crashworthiness performance. Next, a parameter study was performed to analyse the effect of geometric parameters of the T5-1 tube on the crashworthiness. It was found that the s/b ratio and thickness have a significant influence on the energy absorption. The critical loading angle lies in the range of 10°–11°. Finally, a structural improvement design, with the straight tube changed to the taper tube, was implemented and the taper T5-1 tube was proposed. The results show that the taper T5-1 tube has better crashworthiness performance, compared with the original T5-1 tube.

ABSTRACT: Thin-walled structures have been widely used as energy absorbers due to their significant advantages on crashworthiness and light weight. Relatively few studies have been reported about thin-walled structures with variable diameter along the longitudinal direction in a nonlinear manner. In this paper, a new functionally graded thin-walled structure with variable diameter (functionally graded tapered tube, FGTT) is introduced; and its crashworthiness is comprehensively discussed in terms of specific energy absorption (SEA) and initial peak crushing force (IPCF). The results show that FGTT is of great advantages on energy absorption over the conventionally straight/tapered circular tubes under the same weight. Then, a parametric study is carried out to investigate the effects of wall thickness, gradient variations of section and diameter range between top and bottom diameters on the crashworthiness of FGTTs. Finally, the multiobjective non-dominated sorting genetic algorithm (NSGA-II) is used to further optimise the FGTTs for maximising SEA and minimising IPCF. The optimal FGTTs are found to have superior crashworthiness and great potential for energy absorber.

**ABSTRACT:** The purpose of this paper is to provide efficient lightweight design for improving the loading carrying efficiency and energy absorption capability of tailor-rolled blank thin-walled structure with top-hat section (TRB-TH) under transverse loading. First, a new finite-element (FE) modelling method for the TRB-TH structure is proposed. The FE model is validated by performing quasi-static bending tests on two kinds of typical specimens. Second, the validated FE model is used to study the loading carrying efficiency and energy absorption capability of TRB-TH structures with variations in the thicknesses of constant thickness zone, lengths and positions of thickness transition zone by using global sensitivity analysis. Finally, to determine the optimal thickness distribution, multiobjective optimisation design is performed by integrating response surface method and non-dominated sorting genetic algorithm (NSGA-II) algorithm. The results have demonstrated that the TRB-TH structures can not only produce much better Pareto solutions than the traditional designed uniform thickness (UF-TH) counterparts, but also provide a better balance between lightweight and crashworthiness of energy absorbers simultaneously. The proposed approach can provide some useful guidance for designing the TRB-TH energy absorbers of vehicle body.


**ABSTRACT:** The main subject of the study is the impact simulation of an elastic fuel tank reinforced with a polymer exoskeleton. Thanks to its lightweight and failure resistance, this type of design shows potential to be used in aerospace applications. The simulation emulates a drop test from the height of 20 m on a rigid surface, in accordance with Military Handbook testing guidelines for fuel tanks. The focus is on providing an example of modelling and solving this type of problems. The computational methods are tested on a generic model of a rectangular prismatic tank with rounded edges. The walls of the tank are made of orthotropic fabric reinforced polymer. The simulation is performed for a 70% and a 100% water-filled tank. All calculations are performed using the Altair HyperWorks 13.0 software suite, in particular, the nonlinear RADIOSS solver and OptiStruct Solver and Optimiser. The fluid inside the tank is modelled using the SPH (Smoothed Particle Hydrodynamics) approach. The model serves as a basis for establishing a design optimisation procedure, aiming at reduction of mass of the tank components while ensuring structural integrity. The main insights of the current study are the successful modelling of the liquid and the air inside the tank by means of smoothed-particle hydrodynamics elements, and the structural optimisation methodology of a composite fuel tank.


**ABSTRACT:** Multi-cell thin-walled structures have recently gained attentions in aerospace and automotive industries for their excellent energy absorption capacity with lightweight. This paper introduces a novel 3D-multi-cell design to enhance energy absorption capability of multi-cell thin-walled tubes by performing a new arrangement of the internal webs and dividing them into multilayers with different angles of orientation. A comparative study of energy-absorbing performance of single-cell, conventional multi-cell and the proposed three-dimensional multi-cell (3D-multi-cell) of thin-walled circular tubes under axial impact loading is carried
out using the non-linear finite element code ANSYS-WORKBENCH/LS-DYNA. The numerical results show that the 3D-multi-cell configuration can achieve a significant improvement in the energy absorption per unit mass (SEA) up to 40%, the crush force efficiency (CFE) up to 42.5%, and the energy absorption effectiveness factor ($\psi$) up to 30.7% in comparison with those of circular tube. Furthermore, it can significantly improve the SEA up to 20%, the CFE up to 36.8%, and the $\psi$ up to 20% in comparison with those of conventional multi-cell configuration. Furthermore, it is found that the number of layers and angle of orientations have a distinctive effect on the energy absorption capacity and the CFE.

ABSTRACT: Recent advancements in crashworthiness analysis of functionally graded foam-filled tubes are achieved by studying the energy absorption characteristics in lateral or axial directions, separately. In this paper, for the first time, two-directional (lateral and axial directions together) functionally graded foams (TDFGFs) under axial crushing loads are considered. The effect of variations of foam density on the specific energy absorption (SEA) and peak crushing force (PCF) is studied by controlling the gradient exponential parameters which give rise to significant effects on the crashworthiness of TDFGFs. Also, it is further analysed that how the mass of the TDFGF tube changes values of SEA in crushing process. In addition, as the result of performing multi-objective particle swarm optimisations, it is seen that the energy absorption characteristics of TDFGFs for higher values of gradient exponential parameters are improved significantly. The crashworthiness properties of optimum configurations for TDFGF are compared with the extreme cases of minimum, maximum densities and uniform foam-filled tubes with the same weight as the corresponding TDFGF tubes. Finally, a global sensitivity analysis is carried out. The results of this analysis reveal that the SEA and PCF functions are generally sensitive to the variations of the gradient exponential parameters.

ABSTRACT: This article investigates the effect of luggage on the crashworthiness of fuselage section with under-floor cargo compartment. Detailed nonlinear finite element models of an aircraft fuselage section with and without luggage were developed for crash simulations which were subjected to the velocity of 9.14 m/s. The overall deformation of the fuselage, the acceleration time histories at selected locations on the fuselage and the energy absorption of key structural components were studied. It was determined that the under-floor luggage and the fuselage frame play the most important roles in energy absorption during impact which account for 45.62% and 19.42%, respectively, and that the luggage markedly affects the deformation of the entire structure. Without luggage, the cabin structure would be damaged heavily, while with luggage loaded, the integrity of the cabin structure can be maintained. Besides, the luggage model had lower peak acceleration values and shorter pulse durations when compared with the absence of luggage model results. Furthermore, the effects of luggage stiffness, viscosity and the worst-case scenario on crashworthiness were also examined. It was shown that the strength and stiffer luggage could evoke the inherent ability of cargo floor structure to absorb more energy during impact.
ABSTRACT: Considering vehicle crash safety, gas emission and the improvement in the energy efficiency, carbon fiber reinforced plastic (CFRP) composite materials have been increasingly used in automotive applications. Bumper beam, as a main structural component of automobile bumper subsystem, is expected to protect occupants and its nearby components. It is an effective way to develop the bumper beam using CFRP to meet higher requirements of crash safety and lightweight. In this study, a stiffness degraded model is proposed to predict low-velocity impact behavior of CFRP bumper beam under two different loading conditions. Based on the simulation results, a novel design scheme of CFRP bumper beam with variable cross-sections is proposed to further improve material utilization. Finally, an optimization procedure incorporating the RBF modeling technique and NSGA-II algorithm was implemented to obtain the multi-objective optimal design. The results yielded from the optimization demonstrate that the optimized bumper beam with variable cross-sections is superior to its uniform counterpart in lightweight and crashworthiness and consequently is recommended as a better approach to replace the conventional metallic bumper beam.

ABSTRACT: Part of the work of AircraftFire, a project investigating the effects of fire and crash on aircraft survivability, is presented. This work compares the effect of changing the material model from metallic to composite on the impact damage and floor acceleration characteristics. First, the metallic two- and six-frame sections of an A320 are analysed, with drop test data to compare for reference and validation. The six-frame metallic and composite sections for a larger, A350-like aircraft are examined to compare the relative safety of newer composite fuselages. The composite model includes both a quasi-isotropic analysis with damage based on maximum allowable strain, and a ply-by-ply laminate model with Hashin damage. Energy dissipation and acceleration analyses follow, which show the potentially dangerous acceleration pulses for passengers seated in the cabin.

ABSTRACT: Stiffened metal fan casing was extensively utilised for containment system in fan blade out events. In this paper, ballistic impact tests were carried out on aluminium alloy plate with different types of stiffener. The ballistic limits and energy absorption of each type plate were determined and compared. The transformation of damage mechanism and failure modes of stiffened plate were also addressed. It is concluded that the failure modes of flat plate and stiffened plates are mainly petaling failure, and the shear plugging failure becomes evident with the increase of impact velocity. The ballistic limit of stiffened plate increase 25% higher than the flat plate and the critical impact energy is lifted by 56.3%-62.5% correspondingly with only 8.9% weight increment. There are very small differences of ballistic limit between different types of stiffened plates. The existence of the stiffened bar alters the failure modes and the cracking propagation direction decreases the deflection of target under impact, and further restricts the cracking propagation along the longitudinal direction. For L-type stiffened plate and T-type stiffened plate, the failure modes are dominated by ripping and petaling failure, while the shear plugging failure mode is more obvious for I-type stiffened plate.

ABSTRACT: To study the crashworthiness of single- and multi-cell, square structures under axial loads, the response surface models of these structures were established separately by using the polynomial response surface method (PRSM). The models describe the response surfaces of specific energy absorption (SEA), peak crushing force $F_{\text{max}}$ and mean crushing force $F_{\text{avg}}$ under the variation of the side-length $a$, wall thickness $t$ and number of cells $N$ in the structure. The results showed that for the square thin-walled structures with the same $N$, the SEA basically increases with wall thickness $t$ and decreases with side-length $a$; $F_{\text{max}}$ increases with $t$ and $a$, while $F_{\text{avg}}$ increases with $t$ but remained unchanged with $a$. Besides, under the same dimensional parameters (identical $a$ and $t$), the larger the value of $N$, the larger the values of SEA, $F_{\text{max}}$ and $F_{\text{avg}}$. When other parameters are the same, with the progress of the crushing distance in a collision, structures with large side-length $a$, wall thickness $t$ and number of cells $N$ are subjected to large crushing forces and therefore the kinetic energy generated in the collision, and absorbed by these structures, is large; however, for parameters $t$ and $N$, the crushing force and absorption energy change only slightly with $a$.


ABSTRACT: Triggers can be implemented in the design of crash box to help in achieving desired deformation pattern, energy absorption and peak force value. In this study, crashworthiness of glass fibre reinforced plastic (GFRP) composite crash box structures with novel geometrically intrinsic triggers has been studied extensively for different types of geometric cross sections. In this study, GFRP crash boxes with four types of cross sections: square, cylindrical, hexagonal and decagonal are considered. Six different types of novel triggers, namely; type-1 slot, type-2 slot, type-3 slot, thickness variation 1, thickness variation 2 and thickness variation 3 are applied to all the types of crash boxes. A comparative numerical analysis is done to study the effect of each trigger on the energy absorption of crash boxes in low velocity impact, based on the ‘Research Council for Automobile Repairs’ test popularly known as the ‘RCAR’ test. Force versus displacement curves were plotted for each case providing detailed insights into the force variation during deformation. The objective of this study is to highlight the effect of triggers on crashworthiness of GFRP crash boxes made of various cross sections and also to showcase the relative effect of each trigger type on the energy and force variation; with the variation of cross section of the crash boxes.


ABSTRACT: In the present work, an analytical model is proposed to obtain the damage area of the composite laminates at below ballistic limit velocities. The model is based on the fact that total kinetic energy of the projectile is absorbed by different energy absorbing mechanisms taking place in laminates during impact. Depending upon the projectile velocity, some or all energy absorbing mechanisms observed are: fibre breakage, deformation of fibres, delamination, matrix cracking and cone formation on the back face of the laminates. The accuracy of the model is then assessed by comparing its predictions for damage area and specific energy absorption with the experimental values for two different types of fibres (glass and kevlar) as well as glass/kevlar hybrid combinations. Experimental results are also used to quantify and compare the specific energy absorption capacity of the glass/epoxy, kevlar/epoxy and glass/kevlar/epoxy laminates. It is observed
that the glass/kevlar/epoxy laminates in which kevlar percentage is 27.5% w/w showed 20% improvement in specific energy absorption as compared to the glass/epoxy laminates.

ABSTRACT: A novel crashworthy aircraft strut system with corrugated composite plate and hinge joints is proposed and investigated. The hinge joints could transfer axial impact load to the corrugated composite plate (CCP). The best crashworthy CCP is guaranteed to enhance the energy absorption ability. To verify the impact dynamic performance, the progressive failure model is adopted. Both of the fibre and matrix failure modes are considered in the failure criterion. To give a better failure behaviour, the single shell and stacked shell approaches are researched and compared. Based on the validated model, the sensitivities of layer number, layer angle and cross-sectional size are given. Numerical results show that the proposed crashworthy fuselage structure could enhance the energy absorption ability. The intra-laminar and delamination could be simulated by the stacked shell model. A similar energy absorption ability is demonstrated for the different CCPs with progressive failure behaviour. An unstable failure behaviour may be exhibited if the lateral stiffness and strength is not enough to support the impact process.

ABSTRACT: Lightweight cellular materials such as honeycombs and foams can absorb energy efficiently, and are therefore used as filler materials in thin-walled structures. This paper aims to explore the merits of various filling fashions on the crashworthiness of multi-cell square structures, namely honeycomb filling, foam filling and compound filling of honeycomb and foam. First, finite element models of different filling structures are validated by the theoretical model. Then, the numerical analysis is carried out using nonlinear finite element code LS-DYNA. The results reveal that partially filling the corner cells of the multi-cell square tube using honeycombs (H40) yields best crashworthiness performance. While for foam filling, filling two diagonally opposed corner cells (F20) produces the best results. Finally, the compound filling schemes were implemented, and found that filling the corner cells with honeycombs, and the central cell with foams (H40F01) generates promising crashworthiness performance. Finally, multi-objective particle swarm optimisation algorithm is adopted to maximise the specific energy absorption and minimise peak crushing force of the three novel structures. The results show that partially filling the four corner cells with honeycombs (H40) yields the most desirable crashworthiness performance.

ABSTRACT: Passenger safety is an important aspect in the design and construction of automobiles. This is achieved in frontal collisions by introducing energy absorbing (EA) structures known as crumple zones or crush cans within the frontal structures that absorb impact energy by controlled plastic deformation and attenuate the intensity of impact during collisions. Although considerable research is carried out till date in developing a variety of EA structures, major limitations in most structures is that they exhibit high initial peak force ($F_{peak}$) and low stroke efficiency (SE). This paper aims to develop thin walled EA structural configurations that can weaken the intensity of impact-induced decelerations while maximising the energy absorbed. It initially presents finite element analysis (FEA) of an existing EA structure taken from a literature whose experimental
results are available for validation of numerical modelling and analysis procedures. Subsequently, it presents five EA structural configurations, their numerical analyses and assessment of their crashworthiness based on important parameters such as crush force efficiency (CFE), SE and specific energy absorption (SEA). Aluminium alloy AA7005 in T6 state is used for the proposed EA structures. The relative merits of each configuration are discussed based on results of numerical analyses and the best configuration with all-round performance in crashworthiness is recommended.

ABSTRACT: Induced delamination due to low velocity impact results in degradation of load-carrying capacity of composite structures especially when loading is predominantly in compression. In this paper, size, shape and orientation of delamination that occur due to low velocity impact is obtained by numerical modelling and results are validated through experiments. Initially, numerical model is validated for single-mode fracture tests like double cantilever beam and end-notch flexure. Multimode failure phenomenon like low velocity impact was also simulated for different lay-ups such as cross-ply, angle-ply and quasi-isotropic and validated through experiments. Low velocity impact testing of laminates was done using drop weight impactor, and experimentally obtained force–time and energy–time history were compared with numerical results. Good match is obtained between simulations and experiments. Delamination size was also compared and it is found that numerical model correctly predicts the size, shape and orientation of delamination for all lay-ups.

ABSTRACT: Due to their inherently brittle behaviour, carbon fibre reinforced plastics (CFRP) structures demand for a specific design to achieve appropriate crash energy absorption compared to classical metallic fuselage designs. In this paper, experimental as well as numerical studies on two different crashworthy designs are presented. The first concept aims to absorb the crash energy by crushing of CFRP components below a reinforced cargo cross beam in combination with further energy absorbing devices in the lower side shell. The feasibility of this concept was in the meantime proven by tests at the coupon and structural element level. An alternative crash concept making use of energy absorption in so-called tension absorbers in the passenger and cargo floor structure was developed and assessed with the focus on a reduction of structural mass in combination with improved concept robustness. This paper provides a summary of the performed research work and discusses the context of the concept development. Details on the individual research tasks can be found in further publications which are given in the references.

ABSTRACT: This paper deals with explicit numerical simulation of fixed-wing aircraft ditching using a coupled approach of Smoothed Particle Hydrodynamics and Finite Elements. Particular focus is put on recent advances toward simulation of flexible full aircraft models, which comprises significant challenges with respect to the numerical efficiency as well as the model complexity. First, the pursued numerical approach is briefly presented. In order to deal with aforementioned challenges, an automated modular tool, which generates numerical models and launches ditching simulations, is presented. The paper provides a brief explanation of state-of-the-art aircraft as well as fluid modelling techniques used and furthermore presents an integrated model
that computes aerodynamic loads during the simulation. The developed tool is used to conduct various numerical studies. First, the improved efficiency of such simulations over the state of the art is shown. Next, results of parameter studies are presented, demonstrating the effects of impact conditions on the aircraft motion. Finally, the structural deformation experienced during ditching of a detailed finite element aircraft model is analysed and its effects on the aircraft motion are discussed.

ABSTRACT: Very fast full vehicle simulations through the use of effective, but drastically simplified digital models is a topic of great interest to automotive manufacturers and research communities. A non-conventional modelling and simulation approach using the macro-element methodology, embedded in Visual Crash Studio (VCS), is assessed. Modelling practices for converting finite element models to macro-element models are developed and presented. A large number of automotive systems, ranging from components and sub-systems to full vehicle models, is investigated. Numerical results obtained from VCS and the finite element code LS-DYNA compared moderately in the majority of the cases. The accuracy and efficiency of the macro-element methodology for vehicle crashworthiness analysis as well as the necessity for model corrections are discussed. Through improved functionality and accuracy, the macro-element methodology could potentially enable engineers to evaluate multiple conceptual designs in shorter times and revolutionise the vehicle development phase.

ABSTRACT: Energy-dissipating structures are widely used in automotive and aerospace engineering. Novel design for energy-dissipating structures using gradient auxetic cellular material is proposed. The structure is built by layers of auxetic cellular units with varying heights. Compared with cellular structure with uniformly sized cells, the gradient structure has lower resistant force together with better energy absorption ability. A crash box for low-speed collision is designed with the proposed pattern. Optimisation to minimise the mass of crash box with constrains on the crash-resistant force and energy absorption is conducted. Validations with standard collision tests are carried out and results show the obtained structure with gradient auxetic cellular structure passes the test and performs effectively as an energy dissipating structure.

ABSTRACT: The circular tube is one of the most widely used energy absorbers in structure crashworthiness. To improve the energy absorption performance of the said tube, a foam-filled tri-tube is proposed. Axial quasi-static crushing experiments are conducted to investigate the energy absorption characteristics of the foam-filled tri-tube. Other tube configurations, such as empty single tubes, foam-filled single tubes, empty double tubes, foam-filled double tubes and empty tri-tubes, are also tested for comparison with the foam-filled tri-tube. Results show that the foam-filled tri-tube has better energy absorption performance than other tubes. A finite element model is developed to perform a parametric study on the effect of tube diameter, wall thickness and foam density on the energy absorption characteristics of the foam-filled tri-tube. The results show that parameters, such as outer tube diameter, wall thickness and foam density, have significant influence on the energy absorption characteristics of the foam-filled tri-tube, whereas the inner tube diameter has less influence.

ABSTRACT: Due to extraordinary energy absorption capacity as well as light weight, functionally graded foam-filled cellular structure (FGFCS) has gained considerable attention. Using nonlinear finite element method through LS-DYNA, this work studied the bending crashworthiness of nine FGFCSs with different cross-sectional configurations. The results demonstrate that the bending crashworthiness of the FGFCSs is significantly affected by the design parameter of the graded functional parameter \( q \). Thus, in order to find the optimal gradient exponential parameter, the FGFCSs with different cross sections were optimised using the radial basis function metamodel and the Non-dominated Sorting Genetic Algorithm II. Meanwhile, the corresponding uniform foam-filled cellular structures (UFCSs) with the same weight as above FGFCSs were also optimised in our study. In the optimisation process, the aim is to achieve maximum value of specific energy absorption and minimum value of peak crushing force. By comparing the Pareto fronts obtained by multi-objective optimisation, it can be found that FGFCSs have better crashworthiness than the corresponding UFCSs in most considered cases. Thus, the optimal design of FGFCS has exactly an excellent energy absorption capacity under lateral impact and can be used in the future vehicle body.


ABSTRACT: As a common type of energy absorbers, thin-walled structures have been extensively used in crashworthiness application in many industries. The goal of this research is the optimisation of the crushing parameters of corrugated tubes in terms of the number and shape of corrugations. Six different configurations were experimentally investigated; one refers to the straight tube without configurations and the others to corrugated tubes with different geometrical parameters. First, lateral compression tests were carried out and the experimental results were used to validate the finite element models. Other six different configurations of corrugated tubes were analysed by means of finite element simulations. The obtained results demonstrate the advantage of the corrugated tubes with respect to the straight tube in terms of the total absorbed energy and the crushing load. Moreover, the geometrical shape of corrugation (i.e. the ratio of corrugation base to its depth) plays an important role in enhancing the efficiency of the corrugated tubes.


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INTRODUCTION: This Special Issue of the International Journal of Computational Methods in Engineering Science and Mechanics, (IJCMESM) is devoted to the theme, Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures. Its publication is directly linked to the 3rd International Conference on Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures that was held in Braunschweig, Germany on 25–27 March 2015. Total 84 presentations covered new achievements in the following topics of buckling, postbuckling, and collapse behavior of composite laminated shell structures were presented: 1. Influence of imperfections, 2. Experimental methods and results, 3. Design guidelines, 4. Advanced finite element tools for certification, 5. Fast design tools, 6. Degradation models, 7. Failure criteria, and 8. Structural optimization. All topics focused on various composite laminated shell structures under different states of loading. Ten conference papers (including one technical note) were selected for publication in this special issue. The conference was primarily organized as final event of the finished EU project DESICOS demonstrating its results. DESICOS stands for new robust DESign guideline for Imperfection sensitive COmposite launcheR Structures. DESICOS started in 2012 and was finished in July 2015. The main objective of DESICOS was the development of a new future design scenario for imperfection sensitive composite structures that are understood as parts of real launchers. The project developed different analysis-based methods to exploit further the reserves in the capacities of imperfection sensitive shells. The final results comprise an assessment of the methods for different kinds of structure type (cylindrical, conical, monolithic, sandwich, . . .). More details can be also found at www.desicos.eu.

J. Blachut (Faculty of Management, AGH University of Science and Technology, Krakow, Poland), “Composite spheroidal shells under external pressure”, International Journal for Computational Methods in Engineering Science and Mechanics, Vol.18, No.1, Special Issue: Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures, pp 2-12, January 2017

http://dx.doi.org/10.1080/15502287.2016.1276336

ABSTRACT: Buckling, collapse, and first ply failure pressures have been obtained for a range of spheroidal FRP shells under static external pressures. Comparisons of the load carrying capacities are made for like geometries. It is shown that some prolate ellipsoids can be stronger, for up to 70% than the equivalent spheres. The effect of boundary conditions in the equatorial plane on the buckling strength is assessed for the diameter-to-wall-thickness ratio ranging from 100 to 500. Regions where the strength (FFP) rather than asymmetric bifurcation control the failure have been identified. Small perturbations in ply orientations, ±5°, have been introduced in order to assess their influence on the buckling strength. Both symmetric and asymmetric stacking with respect to the mid-plane have been analyzed (including random stacking). Initial shape imperfection positioned at the apex of a hemispherical head has been examined. The latter aimed at assessing the sensitivity of buckling pressure to deviations from perfect geometry. Results have been obtained for the lower bound approach based on the local flattening using the increased-radius. Imperfections in ellipsoids have also been studied. Axisymmetric modeling of all shells was used throughout in this study. Only the upper half of shells was modeled, and the issue of boundary conditions at the equatorial plane was also explored.

References listed at the end of the paper:


ABSTRACT: This article deals with numerical calculations of thin-walled composite laminate beams with closed cross-section subjected to pure bending. Thin-walled beams with square cross-section made of eight-layer GFRP laminate have been taken into consideration. An FEM model has been prepared using four-node multi-layered shell elements governed by first-order shear deformation theory. Linear buckling analysis and nonlinear static analysis including large displacements have been performed. A Newton–Rapson algorithm has been employed. The FEM calculations have been conducted using Ansys® software. Three following layer arrangement were considered: [45/−45/0/0]s, [45/−45/45/0]s and [45/−45/45/0/0/−45/45/−45]t. The influence of number of load steps and geometrical initial imperfection on course of equilibrium paths has been checked. The results of calculations have been compared with experimentally performed four-point bending tests. Comparing results of tests and numerical calculations, it was observed that, in some cases, the deflection of beams does not correspond to the bifurcation buckling mode but corresponds to the lowest buckling load; the geometrical imperfection that corresponds to the higher buckling mode should be taken into consideration to obtain similar postbuckling equilibrium paths from tests and FEM calculations. As is well known, the buckling load and failure load for real structures depend on course of equilibrium paths. Taking above considerations into account, the author of this article tries to show some problems in obtaining numerical calculations results that are similar to experimental tests.

References listed at the end of the paper:
http://dx.doi.org/10.1080/15502287.2016.1276340

ABSTRACT: The buckling and postbuckling behavior of composite struts under uniaxial compression is investigated. A geometrically nonlinear model comprising only four generalized coordinates is applied to multi-layered struts built up of transversally isotropic unidirectional layers. Laminates with a cross-ply layup are investigated. By minimizing the total potential energy of the system, equilibrium paths and critical buckling loads for varying lengths and depths of delamination are determined. Thus, the response of the system in the postbuckling range is analyzed and areas of stable and unstable behavior are determined. The outcome of the work provides detailed information about the influence of delaminations on the buckling behavior of composite struts.

References listed at the end of the paper:

ABSTRACT: Thin-walled stiffened shell structures are used in primary structures of space launcher vehicles. These structures are prone to buckling and thus fail due to a loss of structural stability. Generally, it has to be distinguished between two major modes of instability for stiffened shell structures: a global buckling of the entire structure and a local buckling of skin fields, longitudinal and circumferential stiffeners. Due to the large number of variables when designing stiffened shell structures, their preliminary design is a demanding task. To allow an efficient preliminary design, sizing strategies can be developed. For this purpose, analytical methods, which allow to assess the local and global instability of stiffened shell structures, are employed. In this article, sizing strategies based on efficient analytical methods are introduced and applied to identify suitable designs of stringer stiffened and orthogrid stiffened shell structures. To study the imperfection sensitivity of stringer and orthogrid stiffened shell structures, numerical computations are performed using the single perturbation load approach and mode shape imperfections. Finally, weight strength curves are derived for stringer and orthogrid stiffened shell structures.

References listed at the end of the paper:

ABSTRACT: Asymmetric meshing technique (AMT) is a perturbation method to introduce disturbances (i.e., imperfections) in a finite-element model without changing geometry, boundary conditions, or loading conditions. For cylindrical shells under axial compression, asymmetric meshing in the form of a square patch of three different surface areas and a band in axial and/or circumferential directions with different areas is discussed in the first half of the article. The element size in the patch or band is lowered to a varying degree as compared to the rest of the shell in order to produce the asymmetry. The reduction in the buckling load was observed from 15% to 20%, which depends mainly on the total area of asymmetric meshing, and less on the amplitude of asymmetry, i.e., reduction in element size. While loading the shell, an isolated dimple formed near the bifurcation point that increased in size to reach a stable state in the postbuckling range; overall buckling behavior depends on the directionality of asymmetric meshing employed in the model.

References listed at the end of the paper:

ABSTRACT: In this work, the influence of uniaxial and biaxial nonuniform edge loads on buckling characteristics of laminated composite panels with and without cutout is investigated by using a finite element method. Furthermore, this investigation addresses the effects of different degree of edge restraints on buckling analysis. Regarding this, a nine node heterosis plate element has been adapted by employing the effects of shear deformation and rotary inertia. The influence of different parameters, such as ply-orientations, nonuniform edge loads, boundary conditions, and cutout sizes, has been considered and studied in detail. It is clearly illustrated that cutout sizes under different loading conditions have remarkable effects on buckling behavior of composite laminates.

References listed at the end of the paper:

ABSTRACT: The objective of the running EU project DESICOS (New Robust DESign Guideline for Imperfection Sensitive COMposite Launcher Structures) is to formulate an improved shell design methodology in order to meet the demand of aerospace industry for lighter structures. Within the project, this article discusses the development of a probability-based methodology developed at Politecnico di Milano. It is based on the combination of the Stress–Strength Interference Method and the Latin Hypercube Method with the aim to predict the buckling response of three sandwich composite cylindrical shells, assuming a loading condition of pure compression. The three shells are made of the same material, but have different stacking sequence and geometric dimensions. One of them presents three circular cut-outs. Different types of input imperfections, treated as random variables, are taken into account independently and in combination: variability in longitudinal Young’s modulus, ply misalignment, geometric imperfections, and boundary imperfections. The methodology enables a first assessment of the structural reliability of the shells through the calculation of a probabilistic buckling factor for a specified level of probability. The factor depends highly on the reliability level, on the number of adopted samples, and on the assumptions made in modeling the input imperfections. The main advantage of the developed procedure is the versatility, as it can be applied to the buckling analysis of laminated composite shells and sandwich composite shells including different types of imperfections.

References listed at the end of the paper:
1. J. P. Peterson, P. Seide, and V. I. Weingarten, NASA SP-8007 - Buckling of Thin-Walled Circular Cylinders, National Aeronautics and Space Administration, Washington, DC, USA, 1968.
ABSTRACT: Simplified methods have been derived to analyze load introduction problems of orthotropic stiffened shells. Axisymmetric shell elements based on the transfer matrix method have been proved to solve load introduction problems precisely and effectively. In the case of nonaxisymmetric cylindrical shell structures, the model is based on analytical derived element stiffness matrices of curved shear panels that are connected with ring frame elements (curved beam elements) and stringer (rod elements). The element stiffness matrices are based on analytical solutions, the set of linear equations of the system (entire structure) is solved numerically. Due to the analytical description of the element stiffness matrices, a significant reduction of number of equations of the system is possible that allows a rapid analysis.

References listed at the end of the paper:


http://dx.doi.org/10.1080/15502287.2016.1276355


http://dx.doi.org/10.1080/15502287.2016.1276359

ABSTRACT: The novel methodology for imperfection sensitivity analysis, presented in Barbero et al. [E.J. Barbero, A. Madeo, G. Zagari, R. Zinno, and G. Zucco, Imperfection Sensitivity Analysis of Laminated Folded Plate, Thin-Wall. Struct., vol. 90, pp. 128–139, 2015], is here applied for the evaluation of limit load of composite cylindrical shells. Koiter’s perturbation method is used to calculate the imperfection paths emanating from mode interaction bifurcations, and the Monte Carlo method is used to test a large number of modes and all possible interactions among them. The computational cost is low because of the efficiency of Koiter’s method. The demands of Koiter’s method for accurate evaluations of higher order derivatives of the potential energy are met by a mixed, corotational element.

References listed at the end of the paper:
ABSTRACT: Over a period of more than 45 years, an extensive research program has allowed a series of very simple propositions, relating to the safe design of shells experiencing imperfection sensitive buckling, to be recast in the form of a series of lemmas. These are briefly summarized and their practical use is illustrated in relation to the prediction of safe lower bounds to the imperfection sensitive buckling of axially loaded, fiber reinforced polymeric, laminated cylinders. With a fundamental aspect of the approach, sometimes referred to as the reduced stiffness method, being the delineation of the various shell membrane and bending stiffness (or perhaps more appropriately energy) components contributing to the buckling resistance, the method will be shown to also provide a powerful way of making rational design decisions to optimize the use of fiber reinforcement.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: This article provides a combined computational and analytical study to investigate the lateral impact behavior of pressurized pipelines and inspect all the parameters such as the outside diameter and internal pressure and evaluate how they affect such behavior. In this study, quartic polynomial functions are applied to formulate the maximum crushing force ($F_{\text{max}}$), maximum permanent displacement ($W$), and absorbed energy ($E$) of the pressurized pipelines during the impact problem. The effects of the diameter and pressure on $F_{\text{max}}$, $W$, and $E$ are therefore illustrated through analyzing these functions. Response surfaces are also plotted based on the generated quartic polynomial functions and the quality (accuracy) of these functions are verified through several techniques.


ABSTRACT: This work concerns with buckling and vibration analysis of composite plates based on a transverse shear theory. A numerical scheme is introduced to determine the angular frequencies and critical buckling loads of such plates. Moving least square differential quadrature method is employed to reduce the problem to that of eigen value problem. The accuracy and efficiency of the proposed scheme is examined with different computational characteristics, (radius of support domain, basis completeness order, and scaling factors). The obtained results agreed, at less execution time, with the previous ones. Further, a parametric study is introduced to investigate the influence of elastic and geometric characteristics, (Young's modulus gradation ratio, shear modulus gradation ratio, Poisson's ratio, loading parameter, and aspect ratio), of the composite on the values of critical buckling load, natural frequencies, and behavior of mode shape functions.

ABSTRACT: In the present work, buckling analysis of orthotropic thin rectangular plates with uniform thickness resting on Pasternak foundation are investigated for eight types of boundary conditions: SSSS, CCCC, SCSC, SSSC, SSCC, CCCC, SSFC, and CFCF. Based on classical plate theory, governing differential equation in buckling are solved numerically using generalized differential quadrature method (GDQM) to obtain critical buckling loads and corresponding modes. The kinds of nonlinear loading are presented in six cases including symmetrical and unsymmetrical distribution. In addition, the effects of aspect ratio, orthotropic moduli ratio and coefficients of foundation on the buckling load are illustrated. The present work is the first attempt to consider the influence of the nonlinearity of distributed in-plane bi-directional loading in determination of buckling load and representation of the corresponding shape modes. Some numerical examples are provided to demonstrate good accuracy of the GDQ method to evaluate the critical buckling load in case of nonlinear distributed bi-directional compressive loads. As shown, profile of distributed in-plane loading plays an important role on buckling behavior of the rectangular plate.


ABSTRACT: The paper presents the study of low velocity impact response of delaminated composite stiffened shell with pretwist employing finite element method for different combination of stiffeners. An eight noded isoparametric shell element along with a three noded isoparametric beam element are employed to model the shell and the stiffener, respectively. The modified Hertzian contact law is considered to compute the contact force, while the Newmark's time integration algorithm is used to solve the time dependent equations of both impactor and shell. The multipoint constraint algorithm is used to model delamination. Finally, the parametric studies are reported.

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More papers published in the journal, Marine Structures (2017 and on):
http://www.sciencedirect.com/science/journal/09518339

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ABSTRACT: Spherical shells are presently the most extensively used shapes for pressure hulls in the deep manned submersible. However, it is known that the spherical pressure hull has disadvantages of difficult interior arrangement/low space efficiency, and is highly sensitive to geometric imperfections. These limitations have prevented further developments of the deep manned submersible to some extent. In order to overcome these limitations, two egg-shaped pressure hulls respectively with the constant and variable thickness are proposed in this paper, where the equivalent spherical pressure hull is also presented for comparison. Buckling of these pressure hulls with geometric imperfections are further studied using numerical analyses at a given design load. It is found that, with respect to hull strength, buoyancy reserve, and space efficiency etc., egg-shaped pressure hulls could be optimally coordinated, which appear to be leading to overall better performance than the spherical pressure hull. Especially, the egg-shaped pressure hull is quite less sensitive to the geometric imperfections, making it more convenient and low costly to form the hull in manufacturing or to open holes in applications. It is anticipated that egg-shaped pressure hulls will play a key role in the future development of deep-sea manned submersibles.

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ABSTRACT: Closed-form analytical solutions for the energy released for deforming and crushing of structures and the impact impulse during ship collisions were developed and published in Marine Structures in 1998 [1]. The proposed mathematical models have been used by many engineers and researchers although the methods were only validated with time domain numerical simulation results at that time. Since then, model and full-scale measurements have been carried out and experimental results are available in the public domain. The purpose of the present paper is to use such experimental results to further analyze the validity and robustness of the closed-form analytical methods as well as to further improve some parameter's accuracy. In total, 60 experimental results have been analyzed and compared with the analytical results and this paper presents the outcome. It can be concluded that the analytical methods give a reasonable agreement with the experimental results. The paper also introduces a simple concept to account for the effective mass of liquids with free surface carried on board of a ship and it is shown how the analytical analysis procedure can be expanded to take into account the effect of ship roll on the energy released for crushing.

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ABSTRACT: Fluid filled structure widely exists in the field of ship and ocean engineering, but the investigation concerned with the whipping response of a fluid filled structure subjected to an underwater explosion is very
less. A numerical model considering the effect of an internal fluid is established in this paper. In the implementation of the numerical model, the doubly asymptotic approximation for the external fluid is used to model the external fluid domain, the doubly asymptotic approximation for the internal fluid is used to model the internal fluid domain, and the dynamic response of the structure is simulated by the finite element method. After that, the numerical model is validated against the analytical solution. The numerical result agrees well with the analytical result. Finally, the whipping response of a fluid filled cylindrical shell subjected to an underwater explosion is investigated and the influence of the internal fluid on the whipping response is analyzed. The main results are as follows. The existence of the internal fluid makes the maximum relative displacement decrease, as the density of the internal fluid and the sound speed within the internal fluid increase, the maximum of the maximum relative displacement decreases.


ABSTRACT: Umbilical cables are fundamental equipment used in deep and ultra-deep water oil and gas production systems. The complexity of such structures usually enforces the use of numerical tools. This paper presents and compares two different numerical approaches for prediction of stress and strain fields in the umbilical cable components under crushing loads, which are imposed to the umbilical during laying operation. The first approach, presented in a previous work [1], is based on a joint analysis using a two-dimensional finite element model fed by analytical models, which represent three-dimensional effects. The second approach, used here as a paradigm, is based on a full three-dimensional finite element model, in which the three-dimensional effects are intrinsically considered. An armoured Steel Tube Umbilical Cable is used as a case study in order to compare both methodologies. It is shown that, while being much faster, the two-dimensional approach yields consistent results when focus is directed onto the components of the central core, as steel tubes. Elastic-plastic behavior is adopted for the steel tubes in both models.


ABSTRACT: The double-plated structure is extensively applied to the surface ships and submarines. Between the two plates there always exists liquid such as water or oil. When it is exposed to the attack by underwater weapon, the shock wave firstly hits the outer plates, and then it is transmitted into the internal liquid, subsequently to the inner plates. The mechanism in this process is so complex that has been a troublesome problem for a long time. In this paper, a numerical method is developed to solve this problem. The second-order doubly asymptotic approximations (DAA) is used to analyze the external fluid-structure interaction (FSI) effect for the outer fluid field with the outer plates, and cavitation acoustic finite element (CAFE) is used to model the internal FSI effect. Results obtained by this approach show good agreement with results of the excitation problem of 3D fluid-filled shell by a plane step wave. Last, two experiments are implemented to validate the method. From the comparative results, it shows that the simulation results coincide well with tests.

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ABSTRACT: Designs of flexible pipe utilized in offshore dynamic riser applications need to be subjected to strength assessment over the entire length in relation to the dynamic motion of the connected floater. Such assessment includes many uncertain factors including soil properties, internal pressure, ocean metadata and others. Failure of flexible pipe, moreover, leads to serious financial loss and environmental degradation. Thus, flexible pipe failure modes and safety need to be evaluated in terms of ultimate strength under various loads. Ultimate strength assessment of flexible pipe is quite complicated and time-consuming compared with that of a steel catenary riser, due to the composite materials, geometric complexity and the contact mechanism between layers. The material nonlinearity and large deformation, moreover, render stable convergence of nonlinear analysis to a solution problematic. This paper proposes practical and stable methods of ultimate-strength assessment using 8-layered and 5-layered 3D FE models subjected to axial tensile and compressive loads, respectively. In the 5-layered model, four inner layers (carcass, pressure sheath, pressure armour, and anti-friction tape) are replaced by one equivalent pressure layer which plays a role of withstanding pressure applied together with the axial compression. It aims to improve the convergence of nonlinear analysis by simplifying the interactions between layers. For each analysis, the failure mechanisms and the interactions between layers are investigated in detail with incremental loading. The effect of initial imperfection, i.e. ovalizations are also examined. In the compressive strength analysis, the influence of various external pressure are additionally studied.

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ABSTRACT: The behaviour and failure of stiffened steel plates subjected to transverse loading by an indenter is studied in this paper. Low-velocity dynamic and quasi-static tests of stiffened plates with geometry adopted from a typical external deck area on an offshore platform were conducted. The results show that the quasi-static tests provide a good reference for impact loading situations, although they displayed a larger displacement at fracture. Finite element simulations of the steel panel tests were performed, using the elastic-viscoplastic J2 flow theory and a one-parameter fracture criterion. A relatively fine spatial discretization in the load application area was needed to capture accurately the onset of fracture. In order to locally refine the mesh, a method for automatic mesh refinement based on damage driven h-adaptivity was implemented and evaluated against results obtained with fixed meshes of various element sizes.

ABSTRACT: Instability in structural components has been widely studied to understand the elastic and inelastic behaviors of materials because of the risks associated with sudden failure of components under equilibrium conditions. However, most studies have been performed for various monotonic load configurations without considering the instability as a final step in a process induced by irreversible deformations that can arise even for small vibrations. This work investigates instability problems that may be caused by plastic strain during cyclic loading. This type of instability is difficult to study with conventional plasticity models because they fail in predicting irreversible deformation for changes in the stress state within the elastic domain. In contrast, unconventional theories abolish the distinction between plastic and elastic domains, allowing the material to exhibit a smooth elastoplastic response for every change in the stress state during a loading.

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ABSTRACT: The Arbitrary Lagrangian Eulerian (ALE) fluid-structure interaction (FSI) method is widely used to simulate ship-ship/ship-ice collisions, in which hydrodynamics are incorporated to estimate a more realistic and reliable collision response. The purpose of this paper was to use the ALE FSI method for parametric studies on ship collision results, in which the contact force and the ship motions were calculated simultaneously. Numerical simulations of a collision between two identical ships have been conducted using the ALE FSI analysis technique of the LS-DYNA code, in which the surrounding fluid flow was explicitly modeled. The effects of the forward velocity of the struck ship, the mass of the struck ship and the collision angle on collision response were investigated. Furthermore, the analytical method based on momentum conservation and the constant added mass (CAM) method in which the hydrodynamic effects were treated as a constant added mass were applied to calculate energy dissipation. The results were compared with those in the FSI method. Discussions and conclusions are presented.


ABSTRACT: The paper gives an overview of the current status of the methods and methodologies which are in use for the evaluation of the structural response induced by sloshing impacts. First the overall problem (seakeeping, sloshing, impacts, statistics…) is discussed and then the accent is put on the modeling of hydro-structure interactions which occur during the severe sloshing impacts in the tanks of the Liquefied Natural Gas (LNG) Carriers of membrane type. The main conclusion is that the sloshing assessment procedures are still under investigations and there are still no fully satisfactory methods and methodologies available to solve the problem fully consistently within the so called direct calculation approach. That is why, for the time being, a relatively simplified procedures are used in practice.

ABSTRACT: In this paper, the flexural response of extruded wrought aluminium girders is presented. This structural element is intended for usage in marine structures such as light docks, marinas and yacht ports. Ease of use, durability, reduced weight, manoeuvrability and the potential development of bespoke sections are appealing properties in such structures that are fulfilled satisfactorily by this type of aluminium elements. Both experimental and numerical analyses are presented. Experimentally, modules of the girders are tested with loading about both minor and major axes. Numerically, the tests are satisfactorily reproduced for the sake of validation and a subsequent exploitation of the model is addressed for further study of the structural response of the girders. A discussion of the results is presented with some design recommendations of these particular structural elements.


ABSTRACT: Pitting corrosion can cause the ultimate strength degradation of hull structure. This research aims at the development of ultimate strength calculation formula of pitted stiffened plates under uniaxial compression. Firstly, the relative parameters (such as sizes of stiffened plates, sizes and shape of pits, initial geometric imperfection and residual stresses of stiffened plates, boundary condition and type and size of finite element) of pitted stiffened plates in the finite element analysis were analyzed and assumed. Secondly, the effects of a few factors (such as distribution status, depth and position of pits, number of longitudinal stiffeners and sizes of stiffened plates) on the ultimate strength with respect to the corroded volume loss were discussed. Lastly, the ultimate strength reduction formulae of pitted stiffened plates based on corroded volume loss were obtained by the data analysis from lots of nonlinear finite element analyses.


ABSTRACT: Fluid-structure interaction solutions for the air and water blast response of marine composite sandwich panels with crushable foam cores are presented in this paper. Reflected and radiated acoustic pressure waves were introduced using Taylor's FSI method into Lagrange's equations of motion for the sandwich plate. In comparison to air blast, water-structure interactions diminished deflection and slowed down the response of the sandwich panel for a given pressure pulse loading. The predicted elastic-plastic transient response of the sandwich panel from the analytical model was shown to be fairly consistent results with ABAQUS Explicit. Pressure amplitudes to initiate damage in a sandwich panel with E-glass/Vinyl Ester facesheets and PVC H250 foam core were calculated under water blast/air back, water blast/water back, and air blast/air back conditions. It took significantly higher pressures to initiate damage in the panels under water blast/air back and water blast/water back conditions than in the air blast/air back plate because of fluid damping and higher plastic work dissipation in the core. A parametric study showed that on a per unit areal weight basis, panels with softer, more ductile foams were more blast resistant than panels with strong and stiff cores because of work dissipation during core plasticity. In the water blast cases, foam yielding was affected by transverse compression and not only transverse shear, as is usually case in air blast-loaded sandwich panels.

ABSTRACT: This paper presents the experimental and numerical investigation results of the residual strengths of damaged ring-stiffened cylinders subjected to external hydrostatic pressure. The damage generation procedure adopted in this paper could represent the collision accidents of marine ring-stiffened cylinders with floating subjects or support vessels. Three steel ring-stiffened cylinder models were fabricated and among them two were damaged by drop testing using a rigid knife-edge indenter. Hydrostatic pressure tests were conducted on one intact model and two damaged ones. The test results demonstrated that the ultimate strengths of the two damaged models were significantly reduced compared with that of the intact model. The denting and collapse processes were simulated using the Abaqus FEA software package. The numerical predictions show a good agreement with the test results. Further analyses were also conducted on ring-stiffened cylinders using various striker headers with knife-edge, rectangular and hemispherical indenters to clarify the effect of damage shapes on the residual strengths of damaged ring-stiffened cylinders.


ABSTRACT: This paper focuses on the buckling of titanium alloy spherical pressure hulls subjected to uniform external pressure. Hulls were spherical shells with 1000 mm median radius and had uniform wall thickness of 25–80 mm. The linear and nonlinear buckling of geometrically perfect hulls were examined numerically and verified analytically in linear range. The nonlinear buckling of hulls with eigenmode geometrical imperfections were evaluated numerically using the modified Riks method, in which imperfection size ranged from 2 to 10 mm. The critical buckling load of geometrically perfect and imperfect hulls was obtained based on elastic-perfectly plastic material modelling, in which the yield strength varied from 800 to 1300 MPa. A semi-analytical formula to predict the load carrying capacity of hulls was derived based on the numerical computations, which was verified against previous laboratory experiments conducted years ago and numerical benchmark study. Results of analytical, numerical, and experimental investigations were given in tables and figures.

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Experimental perforated tubular member's samples in terms of axial load capacity and life-time shortening of the structures. The aim of this paper is to present an experimental campaign and a numerical finite element model to obtain the ultimate strength of tubular structures with circular perforated damage subjected to axial compression. In the experimental program fifteen tubular scaled specimens are tested and results are compared with the ones from geometrical and material non-linear finite element model considering reconstructed geometries, variable thickness distribution and actual material stress-strain curves. hell elements are used and the finite element meshes are obtained from detailed external wall 3D laser scanning of the experimental samples and ultrasonic thickness measurements in several cross-sections. Spatial thickness interpolation is performed to define the thickness in all meshed nodes. Results from numerical model analyses demonstrate considerable accuracy and good agreement with those directly measured from experimental perforated tubular member's samples in terms of axial load-displacement and strains. From the results, it has been concluded that the perforation size is the most important variable in determining the extent of the compressive strength degradation.
ABSTRACT: Ship collisions may be critical to the operational safety of ships and offshore structures, and should be carefully designed against. This paper investigates the response of offshore tubular members subjected to vessel bow and stern impacts with the nonlinear finite element code LS-DYNA. Two 7500 tons displacement supply vessels of modern design are modeled. Force-displacement curves for bow and stern indentation by rigid tubes are compared with design curves in the DNV-GL RP C204. Next, both the ship structure and the tubular braces/legs are modeled using nonlinear shell finite elements, and the effect of ship-platform interaction on the damage distribution is investigated. A parametric study of the denting mechanics with respect to the length, diameter and wall thickness of tubular members is described. An existing analytical denting model is extended to account for distributed loads and is verified against simulation results. Existing requirements to resist excessive local denting are discussed, and a new concept ‘transition indentation ratio’ is introduced. The concept helps to understand the governing deformation patterns of tubular members given different tube dimensions, and is useful to unify existing cross section compactness criteria for braces/legs, providing a theoretical support for the $R_c$ criterion in the new version DNV-GL RP C204 standard. Finally, new design compactness requirements for tubular members against impacts from ship bow, stern corner and stern end are proposed.

ABSTRACT: Unburied subsea pipelines operating under high temperature and high pressure (HT/HP) conditions tend to relieve their axial compressive force by forming lateral buckles in an uncontrolled manner. In order to control lateral buckling, a distributed buoyancy section is often employed. In this study, analytical solutions are deduced for lateral buckling of unburied subsea pipelines with a distributed buoyancy section. An energy analysis is employed to investigate the stability of the buckled pipeline. The influence of the length and weight of the distributed buoyancy section on pipeline buckled configurations, typical lateral buckling behaviour and the minimum critical temperature difference is illustrated and analysed. The results are shown to be in good agreement with experimental data in the literature. The effect of imperfections is also discussed and an error analysis is conducted for one of the main assumptions of the proposed analytical method. The results show that increasing the length or decreasing the weight of the distributed buoyancy section can both be used to decrease the minimum critical temperature difference. The maximum compressive stress will decrease with decreasing weight of the distributed buoyancy section. However, the influence of the length of the distributed buoyancy section on the maximum compressive stress is complicated.

ABSTRACT: On the basis of an experimental investigation [1], numerical investigation is conducted in this paper on damaged seamless metallic pipelines with metal loss (diameter-to-thickness ratio around 21) through nonlinear finite element method (FEM). Numerical models are developed and validated through test results by using the measured material properties and specimen geometry, capable of predicting the residual ultimate strength of pipes in terms of bending capacity (Mcr) and critical curvature (kappacr). By changing the metal loss parameters, i.e. length (lm), width (wm) and depth (dm), a series of numerical simulations are carried out. Results show that the larger the dm or lm is, the less the bending capacity will be. The increase of notch width slightly reduces the pipe strength, presenting a linear tendency. Based on the FEM results, empirical formulas
are proposed to predict the residual ultimate strength of metallic pipes with metal loss under pure bending moment. The prediction results match well with the results from the tests, the numerical simulations as well as the theoretical derivation. Such formulas can be therefore used for practice purposes and facilitate the decision-making of pipe maintenance after mechanical interference.


ABSTRACT: The intersection between stiffeners and primary supporting members is one of the most critical details in ship hull structures. Learning from the lessons of actual damages experienced in the past, many formulae to estimate stresses around the slot cut-out structures have been developed. However, good agreement with finite element analysis or experiments has not been achieved, and the formulae have been used with empirical correction coefficient, introduced using actual damage and no-damage records or calibration based on finite element analysis results. In this study, the authors develop a consistent theoretical formula taking account of all the structural components affecting the load share of each member, in combination with the combined load effect of direct force from the longitudinal stiffener and shear force on the primary supporting member. The derived formula was verified through comparison with the results of finite element analysis and past experiments, and good accuracy was confirmed. Then, using the proposed theoretical formula, various parametric studies are carried out, and effective countermeasures to enhance the strength of slot cut-out structures are discussed. Finally, critical review on IACS CSR formulae on the slot cut-out structures is conducted. Because the rules take account of only the direct load from the longitudinal stiffeners, and do not consider the effect of the shear force on the primary supporting member, it is probable that the rules give insufficient strength when the effect of the shear force on the primary supporting member superimposes the effect of the load from the longitudinal stiffener. On the other hand, the rules may be too conservative when they cancel each other. It is shown that rational evaluation of the strength of slot cut-out structure is possible using the proposed theoretical formula.


ABSTRACT: This paper presents a benchmark study on collision simulations that was initiated by the MARSTRUCT Virtual Institute. The objective was to compare assumptions, finite element models, modelling techniques and experiences between established researchers within the field. Fifteen research groups worldwide participated in the study. An experiment involving a rigid indenter penetrating a ship-like side structure was used as the case study. A description of how the experiment was performed, the geometry model of it, and material properties were distributed to the participants prior to their simulations. The paper presents the results obtained from the fifteen FE simulations and the experiment. It presents a comparison of, among other factors, the reaction force versus the indenter displacement, internal energy absorbed by the structure versus the indenter displacement, and analyses of the participants' ability to predict failure modes and events that were observed in the experiment. The outcome of the study is a discussion and recommendations regarding mesh size, failure criteria and damage models, interpretation of material data and how they are used in a constitutive material model, and finally, uncertainties in general.

ABSTRACT: The dynamic response and failure modes of carbon/epoxy laminates subjected to underwater impulsive loading are experimentally investigated in this work. The effects of impulse intensity and fluid-structure interaction (FSI) on the failure modes of the clamped laminates were also assessed. A lab-scale underwater explosive simulator was utilized to impart the controlled impulsive loading with three different decay times on the laminates. The 3D Digital Image Correlation method with high speed photography was used to capture the dynamic response of the laminates. A series of microscopic examinations was conducted to analyze the failure mechanism of the laminates. The results show that the composite laminates provided higher blast resistance than aluminum plates in the same thickness. The fiber breakage, delamination and matrix crack were the main failure modes of the laminates subjected to underwater impulsive loading. The fiber breakage occurring at the center and the boundary of the plate was mainly caused by the stretching and shear-off, respectively. The damage extent of the laminates was increased with the impulsive loading increasing or FSI parameter decreasing. The results obtained in this study provide a potential application guidance for laminates in marine structure lightweight design.


ABSTRACT: Stability analysis of curved pipes conveying fluid is of significant interest in many engineering applications such as floating and moored system dynamics. The aim of this paper is to develop a new formulation based on the Isogeometric Analysis (IGA) for vibration and stability analyses of curved pipes conveying fluid. Both divergence and flutter instabilities of curved pipes are investigated. IGA uses B-Splines and Non-Uniform Rational B-Splines (NURBS) as basis functions. The main feature of IGA, as required in dynamic analysis of curved structures, is the ability of the NURBS functions to represent the exact geometry of the problem with fewer control points. This method provides several advantages including high-order continuity of the solution and better accuracy. The governing differential equations of the problem are obtained using the Hamiltonian's principle. The effects of rotary inertias of both pipe and fluid are also included in the mathematical formulation. It is shown that the present formulation can provide accurate results with small number of degrees of freedom. It is concluded that IGA can be used efficiently to predict the instability of curved pipes conveying fluid with the advantage of considering the exact curvature of the pipe.


ABSTRACT: This paper presents a simplified formulation for the assessment of large deformation resistance of stiffened panels subjected to lateral loading. The method is based on rigid plastic material assumptions and the use of yield functions formulated in terms of stress resultants. The method considers the flexibility of the panel ends with respect to inward motion, while the rotational boundary conditions are free or clamped. Concentrated and distributed loads are considered, as is patch loading. The resistance-deformation curves predicted by the proposed method are compared with results from experiments and using LS-DYNA, and good agreement is obtained for panels that are not dominated by shear failure and tripping or local buckling of stiffeners at the early stage of deformation. The formulation provides a useful tool for quick estimates of panels subjected to abnormal or accidental static and transient lateral loads such as ship collisions, dropped objects, explosions, slamming, hydrostatic pressure and ice actions.

ABSTRACT: Owing to its structural efficiency stiffened steel curved panels are increasingly used in structural applications in civil, naval and offshore engineering. However, design provisions to predict their strength are practically non-existent. Consequently, the aim of this paper is to present a robust semi-analytical procedure for the prediction of the post-buckling behaviour of unstiffened cylindrically curved steel panels under uniform uniaxial compression. Nonlinear stability models based on large deflection theory incorporating initial imperfections and geometric nonlinearity are implemented. The problem is solved through the Rayleigh-Ritz method and the post-buckling solutions are obtained in order to assess local buckling of isotropic panels. Two distinct simply supported boundary conditions are considered, depending on the in-plane restraints of edges. The validity of these computational models is assessed with the results of finite element analyses for different curvatures and aspect ratios, yielding good results. Finally, design-oriented closed-form analytical expressions are derived based on single degree of freedom approximations.


ABSTRACT: Lateral buckling of pipelines with closely spaced imperfections laid on even seabed with nonlinear soil-pipe interaction is investigated using finite element analysis (FEA). An analytical solution for lateral buckling of pipeline with single imperfection is proposed and is used to validate the FEA. Effects of amplitude, half wave-length and spacing of imperfections as well as soil resistance on lateral buckling response are presented. It is found that at imperfection spacing greater than half the imperfection half wave-length, there will be no interaction between the buckle lobes. Using validated FEA, the collapse of the pipe-wall due to the interaction between lateral buckling and external pressure is studied. Buckle interaction envelopes are developed and compared to recommendations of the DNV standard. It is shown that in pipeline with closely spaced imperfections, the lateral curvature at the onset of buckling is as large as the critical collapse curvature under combined bending and external pressure.


ABSTRACT: In this paper, a new approximate method based on analytical formulas is proposed to estimate the ultimate strength of stiffened panels by investigating collapse mechanisms of the stiffened panels. In this respect, firstly, a series of detailed elastoplastic large deflection Finite Element Analysis (FEA) is performed to investigate the collapse behavior and the ultimate strength of the stiffened panels. In the analysis, the initial deflections are considered in the form of thin-horse mode plus overall buckling mode for the plates, and flexural buckling mode plus tripping mode for the stiffeners. On the basis of the observed FEA results, an efficient method is proposed to estimate the ultimate strength of stiffened panels based on Elastic Large Deflection Analysis (ELDA) with the initial yielding concept. In the ELDA, the deflection modes are defined as the sum of overall buckling mode plus local plate buckling mode. The welding residual stresses are not taken into account in this study. The ultimate strength is predicted by examining yielding at several critical points. The calculated results by the proposed method and the nonlinear FEA are compared, and a very good agreement is obtained for all collapse scenarios investigated.
ABSTRACT: Buried subsea pipelines under high temperature conditions tend to relieve their axial compressive force by forming localised upheaval buckles. This phenomenon is traditionally studied as a kind of imperfect column buckling problem. We study upheaval buckling as a genuinely localised buckling phenomenon without making any ad hoc assumptions on the shape of the buckled pipeline. We combine this buckling analysis with a detailed state-of-the-art nonlinear pipe-soil interaction model that accounts for the effect of uplift peak soil resistance for buried pipelines. This allows us to investigate the effect of cover depth of subsea pipelines on their load-deflection behaviour. Furthermore, the influence of axial and uplift peak soil resistance on the localised upheaval behaviour is investigated and the maximum axial compressive stress during the buckling process is discussed. Parameter studies reveal a limit to the temperature difference for safe operation of the pipeline. Localised upheaval buckling may then occur if the pipe is sufficiently imperfect or sufficiently dynamically perturbed.

ABSTRACT: This paper carries out an experimental and numerical study on the buckling behavior of a biologically evolving longan-shaped shell under external pressure. Such a shape, following Cassini oval formula, is determined based on the measurements of 171 actual dried longan shells. On this basis, three nominally identical longan-shaped shells with the shape index of 0.11 are fabricated using stamping and welding process, measured for geometry, slowly tested to destruction, and numerically evaluated for their buckling behaviour. A good agreement between experiments and numerical evaluations is obtained.

ABSTRACT: This paper investigates elevated temperature resistance of circular hollow section X-joints reinforced with collar plates subjected to brace compression. A finite element (FE) model was developed and the results were validated against the data available from seven experimental tests. Also, the results of the present FE model were compared with the numerical results of other researchers. Afterwards, several 3-D FE-models of the collar plate reinforced X-joints were generated to investigate the effect of joint geometry and collar plate size on the initial stiffness, ultimate strength, and failure mechanisms at different elevated temperatures. Results showed that the use of the collar plates in X-joints at elevated temperatures (200 °C, 400 °C, and 600 °C, and 800 °C) leads to the significant increase of the initial stiffness and ultimate strength. Also, the increase of the plate length results in the less reduction in ultimate strength, at all elevated temperatures. But, the effect of the plate thickness on the reduction factor can be ignored. Moreover, the decrease of the β in the plate reinforced X-joints at elevated temperature can lead to the shifting of the maximum plastic strain from joint intersection to the toe of the weld joining the collar plate to chord member. The parametric investigation was followed by the non-linear regression analysis to propose a parametric equation for determining the ultimate strength of the collar plate reinforced X-joints under brace compression at elevated temperatures.

Composites steel-concrete construction utilising the benefits of both materials has extensively been used in structural engineering with the ability to be used in onshore and offshore applications. One of these elements is the concrete-filled double-skin tubes (CFDST), which is a concept that has been developed in recent years. In this column, the steel tubes can support considerable amounts of loads while providing permanent formwork to the concrete. Likewise, the steel tubes add confinement to the concrete whereas the concrete infill delays the local buckling of the steel tubes. This paper provides the behaviour of CFDST short columns under concentric compressive loads. The specimens studied consist of an outer skin, which is a circular hollow section (CHS), and an inner skin, which is a square hollow section (SHS), with the annulus filled with concrete while the inner tube is completely empty. A finite element (FE) analysis is generated in order to analyse the performance of such columns. Therefore, to assure the accuracy of the modelling of these specimens, FE models with concentric axial loads are developed and compared against results from past experiments. In view of this, different stress-strain curves for structural steel and concrete infill are identified, and those that provided the best curve fittings were selected for the parametric study. Accordingly, the best combination of the constitutive models of both the steel (suiting the cold-formed tubes) and the concrete (filled in double-skin tubes) is found based on previous research and considered herein. The study aims at examining the effect of various diameter-to-thickness ($D_o/t_o$) ratios, width-to-thickness ($B_i/t_i$) ratios and material properties such as nominal compressive strength and nominal yield strength on the fundamental behaviour of CFDST. In the parametric study, high nominal compressive strengths are tested, and the steel tubes are cold-formed from different design yield strengths. Overall, this paper provides important conclusions for current circular CFDST short columns with an inner SHS and an outer CHS.


The paper aims at assessing the probabilistic characteristics of the hull girder target safety level of a Suezmax tanker derived from a cost-benefit analysis. The target safety level is obtained considering as risk control option the change in the cross section scantlings of the tanker and its effect on risk reduction expressed by the total expected cost of the hull girder failure. The approach involves the evaluation of the effect of the risk control on the hull girder failure probability assessed by means of a structural reliability analysis, and the assessment of the expected cost of hull girder failure in terms of property damage of the ship, pollution due to spillage of oil and loss of life of the ship's crew, as proposed by the International Maritime Organization (IMO). The uncertainties in the costs related to the loss of human life and environmental damages are characterised using available statistics and included into the probabilistic framework. Moreover, a probabilistic model is proposed that explicitly accounts for labour and material costs when evaluating the cost of the risk control option. The hull girder failure probability is calculated using the First-Order Reliability Method, considering the ultimate collapse of the midship cross section under vertical bending moment as the failure event. Uncertainty propagation and sensitivity analyses are conducted for different operational scenarios to assess the contribution of the model parameters on the uncertainty of the target safety level of the tanker with the objective of identifying the range of the variation and the characteristic target safety level of the hull girder that would be adequate for risk-based design and reliability-based code calibration studies.


The combination damage induced by mechanical interference, in reality, is more likely to happen. In this paper, numerical models on pipes with combined dent and metal loss in terms of a notch are developed
and validated through tests (diameter-to-thickness ratio of test pipes around 21), capable of predicting the residual ultimate strength of pipes in terms of bending moment () and critical curvature (). The effect of residual stress is explored, assuming a linear distribution in the pipe hoop direction. Investigations of damaged pipes with different (15–50) are carried out. Through changing damage parameters in the combinations, i.e. dent depth () or metal loss depth (), the corresponding effects of damage are clarified. Results show that the combined dent and notch damage is a more severe type of damage on pipe strength compared with other damage types (excluding fracture). The dent in combined damage plays a more dominant role on the pipe residual strength. Empirical formulas are proposed to predict residual ultimate strength of damaged metallic pipes (around 21) with combined dent and metal loss under bending moment, which can be used for practical purposes. The application domain can be expanded to pipes with up to 30 based on simulations. (Math symbols in the abstract are ignored)

ABSTRACT: The development of oil and gas fields in deepwater challenges the design of flexible pipes due to high pressures, temperatures and dynamic loads. Amongst the known failure modes, lateral buckling of tensile armor layers in flexible pipes has attracted extensive interest for its complicated mechanisms. The present paper addresses lateral buckling behavior of tensile armor wires in flexible pipes when armor annulus is flooded. Based on the thin curved beam theory, a single armor wire is modeled on a cylindrical surface without considering the effect of friction and bending through a system of six order nonlinear differential equations. Then, by applying a perturbation technique, analytical solutions are obtained which reveal a series of potential lateral buckling modes. An estimate for the lateral buckling is obtained under conditions given herein. Case studies are performed comparing the proposed model with the results obtained through a numerical program and alternative analytical model available in the literature.

ABSTRACT: This paper aims to study the structural behavior of tubular KT-joints subjected to axial loading at fire induced elevated temperatures. At first, a finite element (FE) model was developed and validated against the data available from experimental tests. Then, a set of 810 FE analyses were performed to study the influence of temperature and dimensionless geometrical parameters (β, γ, θ, and τ) on the ultimate strength and initial stiffness. The joints were analyzed under two types of axial loading and five different temperatures (20 °C, 200 °C, 400 °C, 550 °C, and 700 °C). Up to now, there has not been any design formula available for determining the ultimate strength of KT-joints at elevated temperatures. Hence, after parametric study, a new equation was developed through nonlinear regression analyses, for calculating the ultimate strength of KT-joints subjected to axial loading at elevated temperatures.

ABSTRACT: Subsea pipelines are occasionally struck and hooked by objects such as anchors or trawl gear. The initial denting, followed by potential hooking and displacement of the pipeline, give rise to a complex load and deformation history. Transverse displacements cause a simultaneous increase in tensile axial forces, further complicating the load sequence. This study examines the effect of applying one of three different axial loads
(zero, constant, and linearly increasing) to a pipe while simultaneously deforming it transversely. The three tests were repeated with an internal pressure of 10 MPa (100 bar), and all tests were recreated numerically in finite element simulations using both iterative (implicit) and non-iterative (explicit) approaches. As expected, adding an axial load increased the pipe's resistance to bending in terms of force-displacement, and the same can be said of including internal pressure. However, a more localised dent was observed in the pressurised pipes, which in turn could affect the onset of failure. The experimental results were well captured by the finite element simulations.


ABSTRACT: Offshore pipelines are occasionally subjected to accidental impact loads from trawl gear or anchors, which may damage the pipe. In this study, a series of indentation experiments carried out on offshore steel pipes covered by a multi-layer polymeric coating solution is presented. Polymeric coating solutions are often applied to pipelines to act as corrosion protection and thermal insulation. Despite not being designed for it, the polymeric coatings are experienced to have an energy absorbing capacity, which is the main topic of the investigation herein. In design codes and guidelines, coatings are traditionally not accounted for when determining the energy absorbed by a pipeline during impact. This makes estimates overly conservative. The main goal of this experimental work is thus to investigate the contribution a typical polymeric coating makes to the energy absorption in a pipeline during impact. To this end, a series of indentation experiments carried out on offshore steel pipes covered by a multi-layer polymeric coating solution is performed. The test program includes quasi-static and dynamic denting experiments on both coated and uncoated full-scale pipe cross-sections. All pipes tested have a length of approximately 1 m. The sharpest indenter from the relevant guidelines is used, as a sharp indenter is more likely to penetrate the coating compared with a blunter one. Based on the outcome of the tests, the polymeric coating is found to absorb a considerable amount of the kinetic energy delivered by an impacting object.

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More papers published in the journal, Ocean Engineering (2017 and on):
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ABSTRACT: In this paper, an analytical method to study the free and forced vibration behaviors of a submerged finite elliptic cylindrical shell is proposed. The vibration equations are derived based on Flügge shell
theory. Unlike the vibration equations of a circular cylindrical shell, the coefficients of state variables in the vibration equations of the elliptic cylindrical shell are variable with the circumferential curvature, which causes that the vibration equations are rather difficult to solve. To solve this problem, the shell's displacements are expanded in double Fourier series in the view of wave propagation and the circumferential curvature is expanded in single Fourier series. The partial differential equations with variable coefficients are converted into a set of linear equations which couple with each other about the circumferential modal parameters. The fluid around the shell is considered as an ideal acoustic medium and the sound pressure is described by the Helmholtz Equation. Free and forced vibration responses of the submerged finite elliptic cylindrical shell are obtained by solving the coupled equations and are also compared with those of circular cylindrical shell and infinite elliptic cylindrical shell. The present results show good agreements with published results and FEM results. The influences of main parameters of the shell, such as ellipticity parameter, shell thickness ratio, shell length ratio and exciting force's position, on the vibration characteristics are also discussed in detail.

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ABSTRACT: Based on the previous work of the variable wall thickness pipe element Li (2016), an orthogonal polynomial pipe element is developed in this paper. The orthogonal polynomial theory is applied in the displacement basis functions. By choosing some particular orthogonal polynomials as the basis function, the element mass matrix and total mass matrix are both tri-diagonal matrix, which is meaningful for the explicit dynamical analysis. This paper presents a systematical method of how to design the basis functions. Given the pipe configuration and boundary conditions, a unique basis function can be obtained to generate a tri-diagonal mass matrix accurately. The values of the non-zero terms of the tri-diagonal mass matrix can be pre-calculated. In order to satisfy the displacement circumferential periodical condition and the contact constraint condition, the Lagrangian multiplier method or MPC (multi-points constraint) is applied. The additional force degree is eliminated in the element level so that the tri-diagonal mass matrix is maintained. Since the orthogonal polynomial is applied, a high-order resolution is obtained. To prove the accuracy of this orthogonal polynomial pipe element, the problems of the pipe dynamical buckling propagation are analyzed. The numerical simulation results are compared with experiment results from other papers.

References listed at the end of the paper:
ABSTRACT: The ultimate strength assessment method of corroded plates based on corroded volume loss had been proposed by the theoretical derivation and Finite Element Analysis in the previous researches. The method still needs to be validated by experiments before it is applied in engineering. Firstly, the jigs were designed and made for being suitable for the present testing machine system and simulating the simply-supported boundary. Secondly, ultimate strength experiments of plates with no corrosion were carried out in order to validate the assumptions about the plates in Finite Element Analysis. Thirdly, the corrosion parameters of the corroded plates were measured and the corroded volume loss was calculated in order to validate the proposed calculation method of the corroded volume loss. Lastly, ultimate strength experiments of plates with corrosion were carried out in order to validate the assumptions about corrosion damage in Finite Element Analysis and the ultimate strength assessment method of corroded plates based on corroded volume loss.

ABSTRACT: Offshore pipelines are often buried to protect the pipeline from external loads and upheaval buckling. Models for pipe uplift resistance in clay soils are based predominantly on homogenous backfill conditions. In practice, however, there will be significant soil disturbance during installation. With certain trenching techniques this may produce a backfill more akin to a matrix of lumps of intact soil connected by weaker remoulded interfaces. This research uses centrifuge modeling to assess the resistance provided by a representative lumpy clay backfill that has experienced self-weight consolidation. A model pipe is then uplifted through this model backfill in order to assess the soil uplift resistance. Results show that the uplift resistance in this material is governed strongly by the size of the lumps and, to a lesser extent, by the rate at which displacement occurs. When interpreted in terms of the strength reduction $\eta$, that may be used to correct between theoretical and measured uplifts, lower values were derived than those currently used based on intact soils. The value of $\eta$ is seen to be controlled by a non-dimensional drainage parameter, but may be practically estimated based on an estimate of the size of lumps relative to the pipe diameter.

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ABSTRACT: Corrosion takes place in the life cycle of ships, resulting in degradation of structural strengths. Corrosion effects with uncertainty on ultimate strength for container ship structures are studied in this paper. On one hand, the ultimate strength of container ship hull girder subject to combined moments of bending and torsion is studied by Nonlinear Finite Element Analysis (NFEA), and the limit state of failure is derived through Minimum Square Error (MSE) technique based on a series of NFEAs, and the probabilistic characteristics under simultaneous uniform corrosions (however, with different scales) in longitudinal structures are studied for the cases of pure bending, pure torsion and combination of both, which can be a useful reference for the scheduled maintenance of container ships. On the other hand, the ultimate strength of bottom stiffened panel under longitudinal thrust derived from hogging conditions is studied considering effects of key factors such as initial deflection, element sizes, simplified boundary conditions, and lateral seawater pressure etc. Uniform and not simultaneous corrosion across different structures is studied, and surrogate models by Gaussian Process (GP) are built, and the corresponding ultimate strength probabilistic characteristics and its dependency on correlation between different structures’ corrosion are studied.

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ABSTRACT: Submarine pipelines are often operated under conditions of high temperature and high pressure, which may induce considerable axial compressive force. If the lateral movement is constrained, for instance, burying pipe or dumping gravel, upheaval buckling may happen. Pipe-soil interaction affects the upheaval buckling behavior of submarine pipelines. However, pipe-soil interaction models currently existing fail to reflect the drop process of uplift resistance when the vertical displacement is over mobilization distance. To solve this problem, a new nonlinear pipe-soil interaction model is presented and the governing differential equation of an imperfect pipeline on soft foundation is deduced. The solution to the governing differential equation is proposed based on nonlinear perturbation expansions. The effect of soil conditions, burial depth and initial imperfections on critical force as well as localization pattern of upheaval buckling are discussed. Results show that the capacity of pipeline against thermal buckling increases with the burial depth or maximum uplift resistance and decreases with the OOS of pipeline or mobilization distance. Critical buckling force is almost unaffected by pipe-soil interaction form, but the post-buckling response depends on pipe-soil interaction forms. The pipe-soil interaction model can be used not only in pre-buckling design but also in post-buckling control.

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ABSTRACT: There has been an increasing interest in using reliability–based approaches in ship structural design. The methods and numerical tools presently available to solve structural reliability problems are capable of representing in a rational manner the uncertainties involved in the design of structures and their consequences on the safety level. With these methods, the uncertainties in the design variables involved in a given strength requirement can be rationally quantified through probabilistic models. As a result, the probability of failure, or the probability of violation of the strength requirement can be computed and used as the safety measure. The objective of the present paper is to use novel longitudinals of Y–stiffener profiles instead of the conventional T–stiffeners profile in double hull oil tanker's bottom and deck panels under axial compressive loads considering the structural degradation due to corrosion effects. The Y–stiffener profile is a fabricated section and simply can be produced by attaching the lower end the conventional stiffener's web to the top of the hat part. The Y–stiffener utilizes the advantages of having more effective plate that allows increasing the stiffener spacing, which in turn drops the required number of stiffeners. Time–variant reliability analyses were performed using VaP (Variable Processor) software via applying the Second–Order Reliability Method (SORM) for both conventional and novel Y–stiffener profiles. The ultimate strength and the applied load formulations were derived based on the International Association of Classification Societies–Common Structural Rules (IACS–CSR) for oil tankers. With the Y–stiffeners, a significant improvement in the panel's safety level was achieved in comparison with the conventional profiles in terms of providing higher safety index, larger safety index to weight ratio over the vessel entire lifetime and more structural weight saving.

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ABSTRACT: Load carrying capacity is of importance in the evaluation of the stability of submarine pressure shell structure. During the buckling process of cylindrical shell under hydrostatic pressure, the total potential energy of ring-stiffened cylindrical shell can be divided into constant component, linear component and square nonlinear component. Based on the derivations of buckling loads of smooth cylindrical shell and ring-stiffened cylindrical shell, the reduced stiffness method (RSM) is applied to assess the role of different stiffness reductions in the evaluation of stable load carrying capacity of cylindrical shell. This study shows: (1) the circumferential membrane stiffness is influence the stability of cylindrical shell largest; (2) the ring ribs have a significant effect on the overall stability of ring-stiffened cylindrical shells under hydrostatic pressure; (3) the circumferential buckling wave number of ring-stiffened cylindrical shell may not depend on the membrane stiffness reduction of shell, but it increases with the bending stiffness reduction of ring ribs.

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ABSTRACT: The collapse behaviour of stiffened panels under uniaxial compression load and lateral pressure are investigated in the FE analysis, in which two spans model with periodical boundary conditions are adopted. Fourier components including symmetric and asymmetric shapes are used to estimate the half-wave number of collapse for local plate by using nonlinear finite element analysis. The comparisons of the results between the FE analysis and analytical method are performed. The influences of half-wave number, direction and magnitude of initial deflection, lateral pressure as well as constraint conditions along longitudinal edges on the collapse behaviour and the ultimate strength of the stiffened panels are discussed. The ultimate strength and collapse deformation of stiffened panels are affected by not only the magnitude but also the half-wave number of initial imperfections. The lateral pressure caused by water head might increase the load carrying capacity of the stiffened panels, which depends on the collapse mode that relates with the configurations of stiffener and plate.

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ABSTRACT: The free vibration response of a thin rectangular plate in contact with fluid is experimentally studied by Acoustic and Modal tests. To this purpose, a series of experiments are done on rectangular plates contacting fluid, with different dimensions and materials, wherein the plate is connected on one side of a heavy solid container by certain number of bolts, where are situated near to each other on the boundaries of the plate to make clamped support. In Acoustic test, the plate in contact with an inviscid fluid is stimulated by a hammer and the produced sound from free vibration of the plate is sampled by microphone. Thereafter by transforming of sound pressure signal to frequency domain, the natural frequencies of the plate are acquired in different spectrum. To verify the method, some Modal tests are performed and also an analysis is done via Rayleigh-Ritz method. Comparing results of experiments and theory shows good agreement between them. Finally by considering frequency response function, natural frequency of the plate is extracted in different height of the fluid and effects of some parameters on the natural frequencies such as fluid height and dimensions of the plate are studied.

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(3) Technip Asia Pacific, Kuala Lumpur, Malaysia
ABSTRACT: There are several methods such as experimental, numerical, and analytical methods which are the mostly adopted in the verification of proposed design code or guidelines to calculate the ultimate strength performance of stiffened panel structures. This study proposes an advanced empirical formula shape, which is a function of plate slenderness ratio and column slenderness ratio with two (2) correction coefficients ($C_1, C_2$), used to predict the ultimate strength performance of stiffened panel structures in ships. In addition, the two aforementioned correction coefficients were decided and verified by obtaining the result of an ANSYS nonlinear finite element analysis. An average level of initial imperfection and 2 bay – 2 span (1/2 – 1 – 1/2) model were adopted in the proposed empirical formula. The effects of residual strength were not considered in this study. A total of 124 stiffened panels with four different plate slenderness ratios ($\beta$) and changing column slenderness ratio ($\lambda$) were selected for the simulation scenarios. To confirm the accuracy of the obtained formula, a statistical analysis was also conducted on the ANSYS results and other existing formulas. The proposed method and its details were documented.

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ABSTRACT: Dynamic analysis and design of slender structures subject to different types of applied forces is of considerable practical interest in ocean engineering and aerospace applications. In this paper, the stability of pipes subjected to influences induced by fluid flow is investigated by using IsoGeometric Analysis (IGA). IGA aims to use the exact Computer-Aided Design (CAD) geometry and reduce the geometrical errors introduced by approximation of the physical domain of the problem. It uses B-Splines and Non-Uniform Rational B-Splines (NURBS) as basis functions and provides several advantages, which make it suitable for efficient and accurate simulations. The mathematical formulation of the problem is developed based on the Euler-Bernoulli beam theory (EBT) and the plug-flow model for the fluid forces. Both divergence and flutter instabilities are investigated. The numerical results are compared with those obtained by other available methods and it is shown that the results are in good agreement with lesser number of degrees of freedom, which is a fundamental criterion for the computational cost of an analysis. It is also confirmed that the IGA as described in the present paper, can be used efficiently to predict the possibility of divergence and coupled-mode flutter in dynamic analysis of pipes conveying fluid.


ABSTRACT: The construction cost of subsea oil pipelines takes rather high portion in the overall developing investment in offshore oilfield, thus an effective design of subsea oil pipelines is one of the main measurements to decrease the cost in offshore oilfield. In this paper, a new method for design and optimization of subsea pipelines is proposed, which conjunctly analyzes thermal-hydraulic performance and structural integrity, and
uniformly solves main parameters for pipeline design, such as internal diameter, wall thickness, insulation layer thickness and pipeline inlet pressure and temperature. A complex non-linear mathematical model is established to minimize the total construction investment and operation costs while ensuring that the system meets minimum structural integrity standards and operation requirements over its anticipated service life; the model also analyzes the uncertainties in operation parameters, such as environmental temperature, overburden pressure and delivery flow fluctuations. Four multi-swarm cooperative improved particle swarm optimization algorithms (MC-GPSO, MC-LPSO, MC-FIPSO and MC-SLPSO) are employed for calculation. Monte Carlo method is introduced into the algorithms to determine the uncertain parameters. Through comparison, MC-SLPSO algorithm can optimally solve this type of model when 5 slave swarms are employed. Finally, a virtual oil pipeline and a practical multiphase subsea pipeline are set as two examples to demonstrate the performance of the optimization schemes.


ABSTRACT: A multi-layered composite pipe finite element is developed, in which the wall thickness and the reference surface of each layer can be arbitrary functions of circumferential and axial directions. The kinematics of this multi-layered composite pipe element is set up. Explicit formulations for the Jacobian matrix and its determinant are obtained. The high-order modal displacement test/trial function are applied. To satisfy the compatibility condition between adjacent layers, the interface traction DOF (degree of freedom) is induced and the mixed formulation is obtained. The Dirac's Delta function defined on the interfaces is used as the interpolation function of the traction field. The static condensation technique is applied so that the DOFs of traction are eliminated on the element level. The implementation details of the nonlinear finite element for the multi-layered composite pipe element are also presented. Large deformation and finite strain are both considered. The UL (Updated Lagrangian) form is applied. This multi-layered composite pipe element is applied to solve the multi-layered pipe buckling problem. The results are compared with those from ANSYS.


ABSTRACT: The load assessment in water impacts problems involving complex geometries is generally a quite challenging task for numerical solvers. Indeed, the occurrence of large free-surface deformation, air cushioning and possible compressibility effects strain the standard Computational Fluid Dynamics (CFD) codes to their limits. In the present work, an enhanced Smoothed Particle Hydrodynamics (SPH) model is adopted to evaluate the pressures acting on the surface of smooth and corrugated panels impacting water and the numerical outcomes are compared to experimental data and analytical solutions. Specifically, the water entry of a flat panel at four inches is firstly studied in order to highlight the main critical aspects underlying the numerical solution of water impacts with small deadrise angles. Then, the water impact of a Mark III type panel (a corrugated insulation panel) adopted in LNG tanks is considered. Experimental data involving wet drop tests of both flat and corrugated panels have been performed and the pressures during the impact have been measured at several points along the panel surface. Complex features of the flow, such as 3D effects and air-cushioning, have been addressed by a developing the numerical study in steps of increasing complexity.

ABSTRACT: This paper aims to propose a design of using the revised PIP system to control vortex induced vibrations (VIV) of cylindrical structural components. Analytical studies are carried out to examine the effectiveness of the proposed method. To this end, the fluid-induced vibration of a single pipe is investigated and the equation of motion of the system is solved and validated by the experimental data. This single pipe system is then extended to the proposed PIP system and its dynamic behaviour under the excitation of vortex shedding is simplified as a Two-Degree-of-Freedom (2DoF) system. The optimal damping ratio and tuning frequency of the revised PIP system are obtained through a series of numerical searching technique and sensitivity analyses. Explicit formulae are also derived for practical ease of use. The governing equation of the system under VIV is solved in the time domain using the MATLAB/Simulink program. The responses of the single pipe system and the proposed PIP system due to vortex shedding are calculated and compared. Analytical results demonstrate that the proposed PIP system can significantly suppress the VIV of offshore cylindrical components. It could be then a cost-effective passive solution to suppress vibration of offshore cylindrical components.


ABSTRACT: A single wave of extreme height can damage ship structures in the ocean by generating buckling midship, thus destabilizing the ship girder and causing rupture. The probability of such an extreme wave is low in reality. On the one hand, it is very costly to recreate a real ship test for the study of extreme wave conditions. On the other hand, it is difficult to carry out tests on a scale model in tank waves, because such waves are too small to damage the ship model. In this paper, a hydroelasto-buckling experiment is performed on a ship model to study the dynamic ultimate strength of the ship and dynamic course of collapse of the structure. Thus far, no method of simulation has been proposed to study this problem because the dynamic ultimate strength of the ship involves strong coupling between the nonlinearity in the ship structure and waves. Here, a hydroelasto-buckling ship model is first designed, and a test programme is determined. A buckling hinge that can collapse under the load of the tank wave is used to connect two ship girders with a hinge joint. Then, a number of single tank waves are generated by changing their wave patterns to simulate an extreme ocean wave. The dynamic rotation angle, bottom water press and acceleration at midship are measured in the experiment. Importantly, the relationship between structural response and wave patterns is analyzed. The structural response involves encountering the VBM/rotation deformation induced by the wave load and whipping the VBM/rotation deformation induced by natural structural oscillations. It is found that the ultimate strength of the ship girder can be generated by both encountering waves and the structural flutter response caused by changing wave height. Lastly, the midship water pressure and acceleration are also analyzed to discuss the influence of a large deformation of the ship structure on the fluid load. Some conclusions are presented in the paper.


ABSTRACT: The free flexural vibration of a cylindrical shell horizontally immersed in shallow water is analyzed in low frequency range using the wave propagation approach. The effects of both the upper and lower fluid boundaries, i.e., free surface and seabed, are considered with the image method, and the scattering effect of cylindrical shell is neglected. Motions of cylindrical shell and fluid are modeled with the Flügge shell theory and wave equation, respectively. The accuracy of present method is verified through comparison with available experimental works. The modal added mass is introduced to show the influence of shallow water on coupled modal frequency. The influence of shallow water is significant in the case of small water depth and it's the
contributions from fluid boundaries. The presence of free surface (seabed) will make negative (positive) contribution to the modal added mass and finally result in the increase (reduction) of coupled modal frequency. But the individual fluid boundary effect will be reduced gradually and finally negligible when the distance between cylindrical shell and fluid boundary increases. The influence of shallow water can not be negligible when the water depth is less than 8 times of shell radius. This work will help to select proper test environment for submerged cylindrical shell.


ABSTRACT: In the present study, the selection of a pipe-in-pipe (PIP) system which includes an installation analysis modelling technique is investigated. The PIP system has become the standard pipeline design for subsea field developments, especially for deep water fields. One of the most important design challenges for engineers is the pipeline installation design. A design underestimation of loads could result in serious damage, while overestimation would result in high operation costs. An accurate or improved modelling method is definitely required for the PIP system. The modelling of a finite element single pipe-lay simulation has been studied and discussed by many authors, and is very much understood by the people in the industry. However, modelling complex PIP systems for pipe laying simulations in order to obtain accurate results is quite challenging. To build the most economic finite element (FE) model for the pipe-lay simulation of PIP systems, various modelling aspects of the installation have been studied separately. In this work, three types of FE models which are two models with different simplifications and one actual PIP model were established and compared. Finally, a systematic approach selection for performing a PIP installation is presented.


ABSTRACT: This paper proposes design principles of a new concept prismatic pressure vessel that is primarily constructed of plane surfaces. These principles were compared with those of conventional pressure vessel which is primarily constructed of revolutionary surfaces. Considering structural characteristics of prismatic pressure vessel, membrane force and bending moment were calculated individually. Formulas including maximum bending moment and membrane force effects were illustrated by applying Levy's method and superposition method. For total stress at the plate of the pressure vessel, membrane force effects obtained from the shear loads of adjacent plates were included to enable to get more accurate solutions. The proposed simplified formulas for prismatic pressure vessel were suggested so that they can be applied for all dimensions and thicknesses. Case studies were conducted to verify the formulas by comparing with FEM results. By providing an overview of the stress relations of a non-stiffened type prismatic pressure vessel, the design principle of a prismatic pressure vessel shows distinctive concept to the conventional cylindrical pressure vessel. The membrane force effect studied in this research will be useful in the design of larger pressure vessels that require stiffeners.


ABSTRACT: The paper presents partitioned tightly coupled fluid-structure interaction (FSI) simulations for composite panel slamming of a high-speed planing hull, including comparison with full-scale experiments. Panels with different layout/stiffness are investigated. Computational fluid dynamics (CFD) is performed using the URANS code CFDShip-Iowa. Computational structural dynamics (CSD) uses modal expansion by ANSYS
finite elements. One- and two-way tightly coupled FSI is performed. The complexity of sea-trial conditions is reduced by statistical/frequency analysis, allowing for a simplified representation by one regular wave. Simulations provide details of slamming, including correlation of re-entering pressure peaks with motions and strain peaks. Numerical/modeling issues are discussed. Expected value and associated uncertainty of experimental pressure/strain peak and duration are used for validation. The difference of panels’ dynamics is well predicted. Validation errors and uncertainties (average 25% and 14%) are quite large. Nevertheless, errors always fall within one standard deviation of experimental-data individual readings. Results are promising especially if compared to earlier slamming studies for regular/irregular waves in controlled towing tank tests, which show average error and validation uncertainty of 25% and 10%. The current study lays the groundwork for research on high-fidelity CFD/CSD FSI of real-world geometry slamming and ultimately multidisciplinary design optimization of structural and hull-form parameters.

ABSTRACT: This study combines a mixed finite element formulation and a boundary element procedure for the free vibration analysis of Mindlin plates resting on Pasternak foundation and interacting with a quiescent fluid with a free surface on the other side. The plate-foundation system is represented by a two field mixed finite element formulation, based on the Hellinger-Reissner variational principle, and the fluid-structure interaction is incorporated into the analysis through a boundary element solution. The proposed formulation provides the added mass matrix in terms of the plate deflection, which is appended into the plate equation of motion. The method is applied to the free vibration problem of circular and elliptical bottom plates of rigid fluid storage tanks supported by elastic foundation. Effects of system parameters, such as thickness to width and fluid depth ratios, foundation parameters and plate ellipticity, are extensively studied.

ABSTRACT: The purpose of this paper is to present optimal designs for variable stiffness laminated composite truncated cones under lateral external pressure. The objective is to maximize the failure load which is defined as the minimum of the buckling load and the first-ply failure (FPF) load. The numerical results are obtained using a semi-analytical degenerated shell element based on a refined first-order shear deformable shell theory and the influences of the pressure stiffness (PS) and the thickness/radius ratio are taken into account. A 2D degenerated shell element is also used for verification purposes. Results are presented for the related verification problems solved and the semi-analytical shell element is validated. Optimal designs, where FPF and buckling are imposed as design constraints, are presented for laminated composite thin and relatively thick cones having variable thickness and ply-angle. A simple graphical optimization technique and a modified Micro-Genetic Algorithm are employed. It is shown that, FPF constraint may be active for thicker cones having lower cone angles, PS slightly decreases the buckling pressures, and the stacking sequence has considerable influence on the failure load. The numerical results presented show that restraining the large end against rotation significantly increases the failure load.

ABSTRACT: For pipelines on uneven seabed, upheaval buckling may occur if the axial compressive force reaches the critical force of upheaval buckling. The critical axial force is sensitive to the seabed undulation. However, the effect of the seabed undulation on the critical force has not been completely discussed. Moreover, effect of the initial stress which accumulates in the pipe wall when the pipeline conforms to the seabed undulation under self-weight has been rarely examined. This paper mainly focuses on the effect of the initial stress. Using numerical tools developed with the Vector Form Intrinsic Finite Element (VFIFE) method, effect of the initial stress is proved significant. Subsequently with the theory of dimensional analysis, a formula of the critical axial force is derived. This formula covers the dimensionless undulation length and the Out-of-Straight (OOS) of the seabed undulation. Considering three seabed undulation shapes, coefficients in the formulas are determined with numerical results from the VFIFE simulations. Finally, the proposed formulas are proved applicable for pipes with different properties and within the error range of ±10% for pipelines in continuous contact with the seabed in a large dimensionless scope.


ABSTRACT: Unburied subsea pipelines operating under high temperature and high pressure (HT/HP) conditions tend to relieve their axial compressive force by forming lateral buckles. Uncontrolled lateral buckling can lead to pipeline failure. In order to control lateral buckling phenomenon, distributed buoyancy method is employed as buckle initiation technique. In this study, analytical solutions for lateral buckling of unburied subsea pipelines with distributed buoyancy section are derived. Fitting method is used to get the relationship between the equivalent axial compressive force and the half-length of the buckled section. The influence of the length and the weight of the distributed buoyancy section over typical behaviors of lateral buckling is illustrated and analyzed. The results show that increasing the length of distributed buoyancy section or decreasing the weight of distributed buoyancy section can all be used to decrease the minimum critical temperature difference and reduce the maximum axial compressive stress. However, the corresponding lateral displacement amplitude increases. The best selection of the weight of distributed buoyancy section is about half reduction of the original weight of pipeline.


ABSTRACT: Unburied subsea pipelines designed to operate under high temperature and high pressure (HT/HP) conditions tend to relieve their axial compressive force by forming lateral buckles. Uncontrolled lateral buckling can lead to pipeline failure, such as collapse. Thus, controlled lateral buckling is an effective and inexpensive method to accommodate axial thermal expansion and to control pipeline lateral buckling. In this study, analytical solutions for uncontrolled and controlled lateral buckling of unburied subsea pipelines are derived. And the interaction between two adjacent buckles for controlled lateral buckling is considered. The typical behaviors of uncontrolled and controlled lateral buckling with different lengths of feed-in zone are illustrated and analyzed. The effects of length of feed-in zone and lateral soil resistance on controlled lateral buckling are also presented. The results show that shorter length of feed-in zone and smaller lateral soil resistance will lead to smaller lateral buckling amplitude, maximum bending moment and maximum axial compressive stress. Therefore, reducing the length of feed-in zone or lateral soil resistance can be an appropriate method to be used to control lateral buckling. Finally, the analytical solutions are validated by use of the finite element modelling. The analytical results show good agreement with finite element analysis results.
ABSTRACT: The exploratory frontier of offshore oil and gas industry comes into deeper waters, with the 3000 m water depth barrier hurdled in the US Gulf of Mexico in 2003. At these water depths, the extremely high external pressures, low temperatures, long distance tie-backs and high environmental loads due to waves, currents, and wind combined brings the employed equipment to its operational limit. This paper presents a literature review on failure events experienced by the industry concerning pipelines, risers, and umbilical cables, describing their causes, consequences, and severity. From the several failure modes reported up to now, it is possible to select the ones that are more frequent and deserves attention from academia and industry. Concerning pipelines, the main failure modes reported are due to mechanical damage, corrosion, construction defect, natural hazards and fatigue. Additionally, a vast review of published researches concerning the pipeline-seabed interaction is presented. With regard to floating risers, approximately 85% of them are of flexible type. Although flexible risers may fail in different ways, collapse due to external pressure is reported as the most frequent failure mode. For umbilical cables, the major failure modes are found to occur under tension or compression, torsion, fatigue, wear and sheaving.

ABSTRACT: Reliability-based safety factors for metallic strip flexible pipes (MSFP) subjected to external pressure are calibrated in this paper. The partial safety factors of such pipes are obtained by introducing a target reliability index and using a combination of Monte-Carlo simulation and FORM. The relationship between the safety factors and the coefficient of variation for key basic variables as well as the impact of different distribution types for both the resistance and load effect parameters on the calibrated results are investigated. Recommended design safety factor for MSFP is given similar to the widely used design safety factor for conventional metallic pipes. The calibration process presented in this paper is relatively easy to understand and to carry out. This also applies to cases with multiple components and even requiring complex iterations in relation to the mechanical model. The results obtained here can provide some guidance in connection with manufacturing procedures at the initial design stage of the MSFP.

ABSTRACT: The main objective of this research paper is to investigate the positive influence of the stiffeners on the vibration of functionally graded plates based on an exact approach via Navier solution. The plate is reinforced by stiffeners in both longitudinal and transversal directions. The material properties of functionally graded materials (FGMs) media are distributed across the thickness based on a sigmoid-law form and are assumed to be temperature-dependent. By using the Hamilton's principle and the classical plate theory (CPT), the governing equations of motion are obtained. Based on the Navier solution, an exact solution is proposed for natural frequencies of simply supported rectangular plates. In addition, the effects of related parameters on natural frequencies are also addressed in detail. Finally, numerical examples are presented and compared with existing results.

ABSTRACT: The plastic collapse loads of cracked circular hollow section (CHS) T/Y-joints under in-plane and out-of-plane bending are investigated using finite element (FE) analyses. An in-house 3D FE mesh generator is specifically developed to create the mesh models of the cracked joints containing a semi-elliptical surface crack located at the weld toe of the chord. Mesh convergence tests are then carried out to check the accuracy of the generated mesh models. The in-plane and out-of-plane plastic collapse moments of uncracked CHS T/Y-joints are calculated and compared with results obtained from three codes and experimental data. The comparison shows that the plastic collapse moments of uncracked CHS T/Y-joints obtained in this study are accurate and reliable. Subsequently, an extensive parametric study is carried out to investigate the plastic collapse moments of cracked CHS T/Y-joints under in-plane and out-of-plane bending. It is found that the in-plane and out-of-plane plastic collapse moments may decrease by up to 35.1% and 33.6% respectively when the crack area \( A_{nc} \) reaches 25% of the intersectional area, \( t_w l_w \). Finally, two lower bound strength reduction factor \( F_{AR} \) equations for cracked CHS T/Y-joints under in-plane and out-of-plane bending are proposed.


ABSTRACT: This paper focuses on the effect of initial imperfections and corrosion wastage on the age related strength degradation of bulk carriers. At the beginning, the initial imperfections including initial distortions and residual stresses, are employed to assess the ultimate bending moment reduction. Then, the effect of thickness degradation due to corrosion wastage on the ultimate hull girder strength is investigated. Finally, the combination of initial imperfections and corrosion wastage is considered to evaluate the residual hull girder strength. To do that, the initial imperfections of the unperfected structures and a corrosion rate estimation model for bulk carriers are introduced. A simplified method is also proposed to determine the ultimate vertical bending moment of ship hull girder subjected to initial imperfections and corrosion wastage. Additionally, the design and construction considerations for bulk carriers are made.


ABSTRACT: A modular floating concept for oil storage is proposed. The concept is composed of several modular floating tanks and barges. The floating tanks are self-stable and designed for storage of oil and hydrocarbon material. The barges provide platforms for equipment and workers quarters, and enclose the floating tanks through mooring fender systems. The whole concept is then moored by mooring dolphins. This concept is designed for finite water depth application, however, potential application for deep water condition is also investigated. In this study, only single floating tank is investigated with both empty and full tank conditions considered. Different mooring fender configuration designs are the focus. It is assumed that the barges are fixed in the study of single tank dynamic properties, and multi-body hydrodynamic is neglected. Different regular wave conditions are used for the study of the dynamic performance of the tank under various fender mooring system parameters. Irregular wave together with wind and current for 100 year return period are also applied for the study of the tank dynamic performance. At last, sensitivity study of the viscous effects is performed.

ABSTRACT: Vortex-Induced Vibration (VIV) of flexible risers under unsteady flows is receiving increasing attention over the recent years. In this paper, an alternative time domain force-decomposition model for flexible risers is proposed to predict VIV response under both steady and oscillatory flows. Non-dimensional frequency range of [0.125, 0.25] is deemed as lock-in region. When lock-in occurs, the riser will be synchronized onto its own natural frequency closest to the non-dimensional frequency of 0.17. The hydrodynamic forces are time-varying and will be updated at each time step according to the riser’s response amplitude and frequency. Firstly, the adopted lock-in region is verified well for uniform and sheared flow cases. Next, the same numerical model is also validated against experimental measurements when expanding to oscillatory flow conditions. VIV response with different \( KC \) numbers and maximum reduced velocities presents quite individual features, which can be reasonably explained from the VIV mechanism level. Then, the comparisons of VIV response between uniform and oscillatory flows are discussed and analyzed in essence. Finally, another large-scale riser is simulated under the designed oscillatory flows, and some new conclusions different from the small-scale risers are obtained.


ABSTRACT: Ultra large container ship (ULCS) structures feature large deck openings and low torsional rigidity. It is essential to accurately evaluate the maximum loading carrying capacity of ship structures. When the ship sails at an oblique heading in rough sea, the horizontal and torsional moments may approach or even exceed the magnitude of vertical bending moment. In such cases, hull girder ultimate strength assessment of container ships under load combinations comprising of vertical bending moment, horizontal bending moment and torsion is necessary in their structural design stage. In this paper, special attentions are thus paid to the hull girder ultimate strength of an ULCS (i.e., a typical 10,000 TEU container ship) subjected to combined three load components mentioned above, which is also a common load case in ships and ship-shaped offshore structures and it is assumed that the three kinds of main loads can be combined each other freely. A series of nonlinear finite element analyses (NFEA) is carried out. Effects of fabrication related initial imperfections are investigated in the present study. Based on the computed numerical results, the 3D hull girder ultimate strength envelope considering initial deformation and incorporating the interaction relationships among three kinds of load components mentioned above is established.


ABSTRACT: The three-dimensional nonlinear dynamic model of a long marine riser with Kelvin-Voigt viscoelasticity properties under vortex-induced vibration is proposed and investigated. The objective is to find the appropriate viscoelastic coefficients to suppress the nonlinear dynamic response of a marine riser. The pipe is placed in a uniform cross flow and geometric nonlinearities are considered. Two distributed and coupled Van der Pol wake oscillators are applied to characterize the fluctuating lift and drag coefficients, respectively. The highly nonlinear fluid-structure interaction equations are directly coupled and solved by the finite element method. Firstly, the model is validated by comparing with published experimental data and numerical simulation results. Then, modal analysis is performed to determine the impact of viscoelastic coefficients on the natural frequency for different damping values. A nonlinear dynamic analysis is carried out to determine the
impacts of the viscoelastic coefficients on displacements, stresses, modal variation and phase portraits. The results show that the viscoelastic coefficients have a significant effect on the natural frequency of the studied marine riser. It is also demonstrated that appropriate viscoelastic coefficients are very important to effectively suppress the maximum displacements and stresses.

ABSTRACT: A top-tensioned riser is a slender pipe that conveys fluids between a floater and a subsea system. High top-tension keeps its straight configuration and helps to prevent compressive loads. Because of the floater's heave motion, the tension on the riser fluctuates giving rise to dynamic buckling. This paper examines the dynamic buckling characteristics of a top-tensioned riser analyzing the governing equation with nonlinear damping. The equation is discretized in space by the finite difference method and then is numerically integrated by the Runge-Kutta method. As main objective, an ultimate limit state function for risers is used to investigate its reliability during parametric excitation. While the short-term stationary Gaussian random motion of a floater can be described by a response spectrum, the uncertainties of a long-term response are considered by Monte Carlo simulation. In view of an applied example, it is found that the dynamic buckling would occur often, and although the probability of failure is acceptable, it can cause serious failure when axial excitation is of significance in harsher sea states. This study aims to contribute in clarifying the role of parametric vibrations (dynamic buckling) in the reliability of risers for ultimate limit state.

ABSTRACT: This study attempts to explore and distinguish the effects of internal flow induced centrifugal force and Coriolis force on the parametric instability of deepwater drilling risers. The governing equation of a fluid-conveying flexible riser subjected to parametric excitations is established at first, which is then reduced into a system of first-order linear equations by use of the Galerkin method with attention to the Coriolis-related skew-symmetric matrix. The stability charts of a deepwater drilling riser at different internal flow velocities are plotted by applying the Floquet theory, and the effects of the centrifugal force and Coriolis force on the primary instability have been identified, distinguished and exemplified. Owing to the centrifugal force effect which can reduce the effective tension and decrease the natural frequencies of the riser, the simple instability zones are enlarged and shifted in the stability chart, and more modes can be triggered in the chosen excitation domain. On the other hand, the simple resonance zones become narrower ascribed to the Coriolis force's damping effect. The most notable finding is that the Coriolis force creates and/or strengthens the coupling effect of excited modes, which can make the combination resonance much more profound.

ABSTRACT: A series of nonlinear finite element analyses were carried out for varying levels of initial deflections, welding residual stresses as well as the length and location of cracks to investigate their combined effects on the ultimate strength of intact and cracked steel plates. The effects of plate slenderness are also considered. Based on numerical results, it is found out that when the three factors are included in the plate together, they will have combined effect on the ultimate strength of the plate rather than a simple superposition of their influences. The meaningful phenomenon is revealed that cracks will change the effect of residual stress
on the ultimate strength, depending on the crack's location and length. The crack's breaking effect on residual stress are discussed for three typical crack locations and different crack lengths in the paper. The breaking effect will reduce the effect of residual stress where crack is located.

ABSTRACT: In order to reduce the structural failure and accident occurrence of the offshore wind turbine, the researches on structural operational safety of offshore wind turbine based on the measured data during the operation periods should be carried out and considered as the key way to solve these problems. However, the current researches are only focused on numerical simulation, model experiment and theoretical analysis and ignore the structural vibration characteristics analyzed from condition monitoring and prototype observation data from the actual wind turbine structure. To compensate for this study defect, the structural vibration displacement signals of one Chinese offshore wind power prototype under different conditions were obtained based on a long-term prototype observation in order to achieve the comprehensive and systematic research on vibration response characteristics and operational modal analysis of measured structure. Considering the complicated operational environment of offshore wind turbines, the structural response regular pattern and vibration safety are also discussed emphatically under different conditions such as standstill, normal operational, startup, shutdown and extreme typhoon status. Simultaneously, the integral operational modal identification method of offshore wind turbine in the range of full power is proposed based on traditional and modified stochastic subspace identification technologies, and further the modal identification results and the relationship between structural modal parameters and environmental/operational factors are also illustrated in this paper. The researches on the structural vibration characteristics and operational modal analysis of offshore wind turbine not only provide powerful data and technology support for the operation safety evaluation, but also provide the necessary theoretical and practical bases for the design and maintenance of wind turbine structures.

ABSTRACT: It is common for subsea pipelines to operate at high pressures and high temperatures (HPHT) conditions. The build-up of axial force along the pipeline due to temperature and pressure differences from as-laid conditions coupled with the influence of the seabed soil that restricts free movement of the pipeline can result in the phenomenon called ‘lateral buckling’. The excessive lateral deformation from lateral buckling may risk safe operation of the pipeline due to local axial strains that potentially could be severe enough to cause fracture failure of welds or collapse of the pipeline. Engineered buckles may be initiated reliably during operation by using special subsea structures or lay methods which are expensive. This paper introduces and exemplifies a novel method that involves continuously deforming the pipeline prior to or during installation with prescribed radius and wavelength to control lateral buckling that could be a valuable modification of the practical design of offshore pipelines. Previous published work has shown that installation of a pipeline with such continuous deformations is feasible. The results from an example pipeline case described here show that the pipeline can be installed and operated safely at elevated temperatures without the need for other expensive buckle initiation methods.

ABSTRACT: In this paper the ultimate strength characteristics of stiffened panels with cracks under longitudinal compressive loading are investigated. The influences of various geometrical characteristics of cracks, especially the location of cracks, are studied by a numerical method. It is found out that the influence of crack location on the residual ultimate strength is very much depended on where the crack locates. Based on the numerical results, an empirical formula as a function of crack length, orientation angle and location, is proposed to predict the ultimate strength of cracked stiffened panels under longitudinal compressive loading.


ABSTRACT: Offshore structures are often founded on long, slender piles that extend for a substantial distance above the ground surface. This paper presents a novel unified model to analyze the free vibration and buckling of partially embedded end-bearing piles subjected to axial compressive load. Consideration is given to the tapered piles of variable cross-sectional shape with constant volume. The governing differential equation of the motions is derived, and solved by using the Runge-Kutta method in combination with the Regula-Falsi method. The accuracy of the proposed model is confirmed by comparing the obtained calculations with existing closed-form and numerical solutions. Numerical results for the natural frequency, buckling load and corresponding modal displacements are provided, which are analyzed to highlight the effects of the parameters related to the cross-sectional shape, taper ratio and embedment of the pile, soil stiffness and compressive force as well as the end constraint. The geometry and material parameters that statically and dynamically yield the strongest piles with fixed volume are identified. The analytical model is beneficial for the optimum design of the soil-pile system in engineering applications.


ABSTRACT: Numerical simulation is an effective method to study the global buckling of submarine pipelines under high temperature and high pressure. The length of the pipeline model has a significant effect on the global buckling during the numerical simulation. This paper outlines the global buckling regularity of different pipes of various lengths and proposes a method to determine the pipe model length for the numerical simulation of pipe buckling by using theoretical analysis and the FEA method. A method of calculating the pipeline's critical length and upper-limit critical length is proposed based on the characteristics of the short pipe and long pipe. The numerical analysis results indicate that the global buckling amplitude of the short pipe increases with the length of the pipeline model. Therefore, the model length of a short pipeline in the numerical simulation should be equal to the actual length of the research object. In contrast, the buckling amplitude of pipes with a length greater than the critical length does not vary with the pipe length. Thus, the model length only needs to be equal to or slightly larger than the critical length. A method to determine the length of the pipe model for the numerical simulation of pipe buckling is proposed for various pipelines with different laying modes in practical engineering.


ABSTRACT: A modal space based direct method is developed for vortex-induced vibration (VIV) prediction of flexible risers. A VIV response solution model is established in modal space, consisting of a hydrodynamic force equation and a dynamic response equation. Adopting a non-iterative root-search method in modal space, the equation set gets solved directly without power-balance iterations. This direct method is compared against
conventional empirical models, with its validity and applicability verified. This method entirely gets rid of convergence problems during predictions, which is conducive to practical engineering applications and puts forward fresh ideas for further development of empirical models for VIV prediction.


ABSTRACT: This paper describes numerical simulations of the vortex-induced vibrations (VIVs) of a long flexible riser in a step current. We consider the model vertical riser tested at the Delta Flume. The simulation is carried out by our in-house computational fluid dynamics (CFD) solver viv-FOAM-SJTU, which was coupled with the strip method and developed in OpenFOAM platform. The vibration modes in both in-line (IL) and cross-flow (CF) directions are accurately predicted. The numerically predicted maximum mean IL displacement and its location differed marginally from the experimental results. The good agreement between the numerical and experimental results proved that this solver was reliable for predicting the VIV response. A large number of numerical tests were then carried out to study the effects of various parameters on VIV responses further. Three main parameters are considered in this study: current velocity, top tension and mass ratio. The intrinsic relationship between the natural frequency and oscillating frequency was analyzed to explain the occurrence of the dominant mode. Based on the numerical results, the regular characteristics of the VIV response with the reduced velocity were pointed out. The curvatures and the maximum mean offset values were proportional to the squares of the reduced velocities.


ABSTRACT: Submarine pipe-in-pipe flowline have become a common pipeline arrangement to achieve a significant thermal insulation capacity. A pipe-in-pipe system generally contains four structural components: jacket pipe, carrier pipe, spacers and bulkheads. Global response of the system depends on both the behaviour of each constituent part and interactions between them. Existing design approaches to consider this system are either too simplistic resulting in loss of accuracy or significantly complicated Finite Element Analysis demanding expensive highly skilled manpower. This paper proposes cost effective design methods which provide accurate prediction with minimum increase in modelling complexity through simplified Finite Element Analysis models. Pipe-in-pipe system S-lay, thermal expansion and spool arrangement design have been investigated. ABAQUS or AutoPIPE based methods have been proposed to cover each application and excellent performance has been observed. In addition to cost-effectiveness, ABAQUS based method for S-lay is able to capture twisting and residual stresses which are generally ignored by traditional approach but important in deep-water applications.


ABSTRACT: In present paper, a hybrid analytical-numerical approach is developed to investigate vibration characteristics of a finite cylindrical shell with interior structures, e.g. plates and other complicated structures. The cylindrical shell is analyzed through exact wave based method (WBM). Flügge theory is adopted to describe motion equations of the shell and displacement functions are expressed as wave functions. Interior structures are modelled by means of finite element method (FEM) and coupled to the shell through the artificial spring technique. By allowing a wide variation range of spring stiffness constants, different coupling conditions between the shell and interior structures can be easily simulated. Comparisons of results individually obtained
from this hybrid method and FEM demonstrate the high accuracy of the hybrid method. Some numerical examples are given herein to further study effects of coupling conditions and boundary conditions on vibration responses of the shell with interior structures.


ABSTRACT: Over the past decades, the offshore oil and gas industry has developed rapidly. A large number of offshore structures, notably jacket and jack-up platforms, were constructed and installed worldwide. As they are often exposed to safety threats from impacts by visiting vessels and dropped objects, there has been a continuous interest in understanding the impact mechanics of tubular structures and proposing practical design standards to protect from collisions. This paper reviews the state-of-the-art with respect to the response dynamics and mechanics of offshore tubular structures subjected to mass impacts, covering material modelling, ship impact loading, energy absorption in the ship and platform, global and local responses of tubular structures, the residual strengths of damaged tubular members and design considerations to mitigate against ship impacts. A wealth of information is available in the literature, and recent findings and classical references, which have a wide influence, are prioritized. The collected information is compared and discussed. The findings in this paper will help understand the impact response of offshore tubular structures and assessment procedures, and provide useful indications for future research.

Wanhai Xu, Yexuan Ma, Chunning Ji and Chao Sun, “Laboratory measurements of vortex-induced vibrations of flexible cylinder at different yaw angles”, Ocean Engineering, Vol. 154, pp 27-42, April 2018, https://doi.org/10.1016/j.oceaneng.2018.01.113

ABSTRACT: Laboratory tests were carried out to characterize the multi-mode vortex-induced vibrations (VIV) of a yawed flexible cylinder in a uniform flow. Five yaw angles in relation to the direction orthogonal to the oncoming flow were adopted, i.e. \(a = 0^\circ, 15^\circ, 30^\circ, 45^\circ \text{ and } 60^\circ\) in this paper. In order to simulate the uniform flow, the flexible cylinder model with a mass ratio of 1.90 and an aspect ratio of 350 was towed by a carriage with the towing velocity varying from 0.05 m/s to 1.0 m/s in a towing tank. The corresponding Reynolds numbers approximately fell in the range of 800–16000. The effects of yaw angle on the multi-mode response of the yawed flexible cylinder subjected to VIV were investigated and discussed based on the experimental results. It can be found that the maximum values of response amplitudes in both cross-flow (CF) and in-line (IL) directions show a slight upward trend when the yaw angle increases from 0° to 60°. The peak value of Strouhal number of the yawed cylinder is about 5% larger than that of the normal-incidence one \((a = 0^\circ)\). The multi-mode VIV response occurs even at a yaw angle as high as 60°. In addition, particular attention was paid to the validity of the independence principle (IP) which assumes that the yawed and normal-incidence cylinder cases are comparable if only the oncoming flow velocity normal component is applied to scale the physical quantities. The experimental results indicate that the IP seems to be a reasonable hypothesis for examining the multi-mode VIV of a yawed flexible cylinder for \(a \leq 30^\circ\), and some discrepancies gradually appear as the yaw angle increases from 45° to 60°.


ABSTRACT: The present study investigates the design buckling capacities of a Gaztransport and Technigaz (GTT) NO96-type liquefied natural gas (LNG) cargo containment system (NO96 CCS), one of the most critical failure modes for a box-type LNG cargo containment system, against sloshing dynamic loads from an LNG carrier cargo tank. The design load for NO96 CCS (sloshing) is a typical dynamic event; hence, the dynamic
effect on the buckling capacity is investigated as the defining dynamic strength factor. A series of finite-element (FE) analyses for the insulation system are performed using commercial FE software (i.e., ABAQUS and ANSYS) and considering the environmental temperature and material properties of the system. The design buckling strength under both static and dynamic conditions is provided based on the FE calculations and compared with the as-designed criteria of DNV GL for a membrane-type LNG cargo tank.


ABSTRACT: A novel method of pipeline pigging is that Coiled Tubing (CT) connected with a pig, and then CT is injected into the SCR to clean up pipelines. The CT needs enough axial force so that it would not be stuck in the SCR during the pipeline pigging operation. To analyze the axial load transfer characteristic, paper built the force analysis of the micro element on the straight and curved section, amended effective axial force and the friction between the CT and SCR, and built the mathematical model of SCR pipe-in-pipe system considering impacts of the coiled tubing's buckling. The axial force of the random micro section can be calculated through iterative method. In order to verify the correctness of the theory, the SCR pipe-in-pipe system's indoor platform was built. The experimental platform can study different effects which affect the CT’s load transfer behavior within the unfixed SCR. The experimental results of two different phases which inclined angles were 2.0° and 30.0° show that CT’s transfer efficiency of axial load is less than 85.0% in SCR pipe-in-pipe system, and it will increase with the inclined angle increasing. Through comparing experimental and theoretical calculation results, the mathematical model of SCR pipe-in-pipe system is validated. Paper calculated the axial force results on the inclined angle 2.0°, 10.0°, 18.0°, 26.0° and 30.0° by the theoretical mechanical model. The theoretical calculation results show that the transfer efficiency would increase with the increasing of the inclined angles. To ensure more axial force to be transferred to the CT’s bottom-end, the inclined angle should be as big as possible. The above research can provide theoretical support to the SCR’s pigging operation.


ABSTRACT: An investigation in conducted on the dynamic ultimate strength of ship bottom stiffened plates under uniaxial compression and lateral pressure. The nonlinear finite element method is adopted, considering both material and geometric non-linearities. The dynamic ultimate strength of a tested specimen is calculated based on the nonlinear finite element method, and the comparison with test results shows the applicability of the present numerical method. The static ultimate strength of stiffened plate structures obtained with the numerical method is compared with an empirical formulation and the error is within the allowable range. Then, the influence of modes and magnitudes of initial imperfections, boundary conditions, lateral pressure, strain rate and structural dimensions, on the dynamic ultimate strength are discussed.


ABSTRACT: During the fabrication of lightweight ship panel, thin plates are usually employed and welding induced buckling may be generated, which will significantly influence the manufacturing integrity and performance. Computational approach based on inherent deformation was proposed, and its framework and application were introduced in this study. In detail, typical fillet welded joint was experimentally conducted and its solid elements FE model was numerically examined with experimental validation. Then, welding inherent
deformation was evaluated based on computational results; elastic FE analysis with welding inherent deformations as input parameters was implemented to predict out-of-plane welding distortion and critical welding buckling condition. As the practical technique, intermittent welding procedure was employed to decrease the magnitude of welding inherent deformation, and sequentially avoid the occurrence of welding induced buckling. With this holistic investigation, welding induced buckling during thin plate section assembly was represented; critical welding buckling condition and mitigation technique were also demonstrated.


ABSTRACT: In the present article, nonlinear static deflections of internally damaged shear deformable laminated composite curved (single and doubly) shell panel are investigated numerically under the quasi-static loading and validated with experimental results. For the numerical analysis, a general nonlinear mathematical model of the laminated composite curved shell panel including the effect of the internal damage is derived with the help of two higher-order kinematic theories and Green-Lagrange nonlinear strain. The desired governing equation is obtained by minimizing the energy expression and solved via nonlinear finite element steps. The numerical responses are computed via a generic MATLAB code developed based on the present mathematical formulation. The degree of accuracy of the current numerical model has been checked and the subsequent validation is established by comparing the present results with available published results. In addition, an experimental investigation has also been carried out for the comparison purpose via three-point bend test on the laminated Glass/Epoxy composite with artificial delamination. Lastly, numbers of numerical examples are solved to demonstrate the implicit behavior of the currently developed higher-order nonlinear model for the analysis of the pre-damaged layered structure.


ABSTRACT: Stability analysis of a composite thin-walled cantilever pipe conveying fluid supported at free end by linear translational and rotational springs is considered in this paper. The governing equations of the system are developed by extended Hamilton's principle for open systems. Applying extended Galerkin technique, eigenvalue analysis is implemented and the critical fluid velocity and consequently stability of the system are obtained. The critical velocity and eigenvalue are validated by comparison with the results in available literature. The numerical results are presented to investigate the effects of fiber orientation angle, volume fraction of fiber, composite lay-up, size of fiber, structural damping coefficient, mass fluid ratio and elastic boundary conditions on eigenvalue and critical fluid velocity of the system. It is revealed that by increasing the value of fiber orientation angle, the critical fluid velocity of the system is decreased. Furthermore, it is found that the volume fraction of fiber and size of fiber have stabilizing effects on the dynamic behavior of the system. Moreover, it is demonstrated that by increasing the value of linear spring constant at the free end, the pipe loses stability by either divergence or flutter.


ABSTRACT: Digital fringe projection profilometry (FPP) was used to study the mechanical behavior and failure mode of an I-shaped stiffened panel of carbon fiber reinforced polymer (CFRP) composites subjected to axial compression. The fabrication process of the I-type stiffened CFRP panel is described in this paper. A
special fixture was designed and fabricated to apply a compressive load to the CFRP panel. Furthermore, strain gauges and the FPP technique were used to monitor the failure process of the panel when compressed. Strain measurement results revealed that a bifurcation phenomenon appeared on the panel surface. Moreover, full-field deflection results indicate that local skin buckling occurs on the stiffened CFRP panel, which can be used to explain the strain bifurcation. Results from the experiment show that the design and fabrication process of the stiffened panel is reasonable and can be used to study the failure mechanism of stiffened CFRP panel.


ABSTRACT: Free vibration characteristics of a flexible non-rectangular bottom of a fluid-filled rectangular tank are investigated using a semi-analytical technique. Element free Galerkin method (EFG) based on moving kriging (MK) shape functions is used along with the Mindlin plate theory to model the flexible plate. Two different types of non-rectangular structural domains, viz., skew and trapezoidal configurations are considered in the present study. The fluid is assumed to be incompressible, inviscid and the effect of surface waves is ignored. Potential flow theory is assumed and the velocity potential is used to calculate the kinetic energy of the fluid. The results obtained are first validated with available solutions in the literature for elastic rectangular plates in contact with the fluid. Thereafter, the effects of various structural and fluid domain parameters on natural frequencies of thin isotropic and laminated composite skew/trapezoidal bottom of a rectangular tank filled with fluid are investigated in detail. New results on the vibration of non-rectangular plates in contact with the fluid, hitherto not found in the literature are presented here for the first time.


ABSTRACT: This paper outlines empirical formulas to provide adequate predictions of the ultimate strength of ring-stiffened cylinders under hydrostatic pressure. The ultimate strength formulation was derived from published test data found in the open literature. The formulas consider the failure mode interactions, which include the parameter of shell yielding, inter-frame buckling, overall buckling, and stiffener tripping. The failure modes were inserted in the quadratic Merchant-Rankine formula. Afterward, the knockdown factors were empirically derived to best fit the actual collapse pressure. It is found that the proposed formulation can predict the ultimate strengths of ring-stiffened cylinders more accurately and consistently than other codified rules (PD5500, GL, ABS, API). The simple criterion for the assessment of failure modes was also provided. Furthermore, parametric studies were conducted to observe the effect of the design parameter on sizing the ring-stiffened cylinder when the failure modes can be predicted.


ABSTRACT: Marine risers are dynamic sensitive systems and robust numerical models that describe their complex behavior are needed. The vector form intrinsic finite element (VFIFE) method is adopted to analyze the nonlinear behavior of marine risers with large deformations in three dimensional space. The method is based on vector mechanics theory and numerical calculation. The structural behavior is described by a simple physical model and strong-formed particle governing equations of motion. Three kinds of marine risers are presented to demonstrate the performance of VFIFE on analyzing marine risers under complex conditions. Hydrostatic and hydrodynamic loadings due to internal and external fluid acting on each element are considered. The modeling
process is introduced in detail and the results are compared with the published literature. It is proved that the application of the VFIFE method in the nonlinear analysis of the three-dimensional marine risers is feasible and simply verified that loads outside of the plane have a more obvious impact on the risers, it is necessary to conduct three-dimensional analysis.


ABSTRACT: The influence of lateral pressure and stiffener type on the collapse behaviours of steel stiffened panels are investigated in the FE (finite element) analysis. Based on the numerical results, the empirical expressions are derived for the ultimate strength assessment of stiffened panels under combined in-plane axial compression and different levels of lateral pressure. The regression formulae only include the plate slenderness ratio and column (stiffener) slenderness ratio. Hence, to consider the influence of stiffener type, the databases of sample points are separately grouped for various cross sections in the regression process. At the same time, for the convenient of utilizing the regression model, the coefficients are expressed as water head in meters. To investigate the approximating accuracy of regression model, the statistical measurement analyses are conducted by comparing with FE analysis, simplified analytical method and experiments.


ABSTRACT: This paper numerically investigated the residual ultimate strength of large opening box girders with crack damage under individually or jointly applied torsion and bending loads. Series of nonlinear finite element analyses were carried out with varying the crack length, location, and orientation angle to assess their effects on the residual ultimate strength of large opening box girders. Three types of cracks, namely longitudinal crack, transverse crack and inclined crack, are considered in this paper. The residual ultimate strength are obtained and discussed for the three types of cracks under torsional or bending moment loading condition. Based on the numerical results under individually applied torsion or bending moment, two of the most dangerous crack damage situations are adopted for analyzing the residual ultimate strength of large opening box girders with crack damage under combined loads. An interaction equation is proposed for predicting the residual ultimate strength of large opening box girders with crack damage under combined loads. The validity of this simple equation is verified by some crack damage cases of varying crack length.


ABSTRACT: This paper analyzes the dynamic behavior of a fluid-conveying pipe with different pipe end boundary conditions. The pipe is considered to be an Euler-Bernoulli beam, and a motion equation for the pipe is derived using Hamilton's principle. A semi-analytical method, which includes the differential quadrature method (DQM) and the Laplace transform and its inverse, is used to obtain a model for the dynamic behavior of the pipe. The use of DQM provides a solution in terms of pipe length whereas use of the Laplace transform and its inverse produce a solution in terms of time. An examination of the results of sampling pipe displacement at different numbers of sample points along the pipe length shows that the method we developed has a fast convergence rate. The frequency and critical velocity of the fluid-conveying pipe derived by DQM are exactly the same as the exact solution. The numerical results given by the model match well with the result obtained using the Galerkin method. The effect on pipe displacement of the pipe end boundary conditions is investigated,
and it increases with an increase in the edge degrees of freedom. The results obtained in this paper can serve as benchmark data in further research.

ABSTRACT: Corrosion degradation of ship plates is predicted at different ship locations based on limited information on the local environmental conditions. The ship spaces are classified according to their chemical and physical characteristics that affect the corrosion behaviour. The parameters of the calibrated models, expressing the corrosion degradation from both sides of ship plates, are used to derive other parameters for corrosion models expressing the corrosion degradation at each side of the corresponding plates. The derived models are then used to develop corrosion models for other ship spaces, where no real corrosion measurement data are available.

ABSTRACT: A thorough stability analysis of submerged pipeline dynamics has been performed. The problem of current-induced vibrations in a free spanning pipeline was analyzed using both linear and non-linear methodologies. While most investigations dedicated to the analysis of this type of problem use either approximate analytical methods or traditional numerical methods, two alternative approaches are presented: Linear Stability Analysis (LSA) and the Generalized Integral Transform Technique (GITT). Although strictly valid when the pipeline is subject to small amplitude disturbances, LSA is simple to apply and yields accurate either explicit or transcendental analytical relations that predict dominant pipeline vibration frequencies and wavelengths as well as the onset of buckling. On the other hand, the GITT can predict pipeline behavior for arbitrary disturbance amplitudes more efficiently than traditional numerical methods. These features are illustrated by considering the problem of a submerged pipeline subjected to soil conditions and ocean currents. This problem was solved using LSA, the GITT and the Finite Element Method (FEM) for comparison purposes. Moreover, the DNV-RP-F105 standard was also used for verifying the proposed methods. The alternative methods offered in this paper can overcome limitations associated with traditional analytical and numerical approaches, and are employed to produce previously unreported results.

ABSTRACT: In this paper, the size-effect and fluid-structure interaction on the vibrational characteristics of a simply supported rectangular microplate is investigated. The influences of rotary inertia and transverse shear deformation which have the remarkable role in the analysis of moderately thick microplates are considered. The first order shear deformation theory along with the modified couple stress theory has been used to perform the free vibrational analysis of the considered problem. The Hamilton's principle is employed to derive the governing differential equations of motion and the corresponding boundary conditions. The fluid is assumed to be incompressible, inviscid and irrotational. The fluid velocity potential is obtained using the boundary and compatibility conditions. Then the Rayleigh-Ritz method has been applied to calculate the natural frequencies of the system. A convergence study is carried out. The obtained results are compared against available data in the published papers and very good agreements have been observed. Finally by referring to the numerical
results, the effects of dimensionless thickness, side to thickness ratio, aspect ratio, material length scale parameter and fluid depth ratio on the natural frequencies are discussed in details.


ABSTRACT: The aim of this paper is to put forward a semi-analytical solution to conduct the free vibration analysis of thick orthotropic annular sector plates with general boundary conditions, internal radial line and circumferential arc supports for the first time. Based on the Mindlin plate theory, stationary energy principle and Rayleigh-Ritz method, the governing eigenvalue equation is derived for thick orthotropic annular sector plates of different radii, sector angles, thickness ratio, line/arc supports and various boundary conditions along the radial and circumference edges. The main innovation point of this paper lies in breaking the classical boundary barrier by using an improved Fourier series to replace the traditional Fourier series. By comparing with those results in open reported literature, the present method proves to be of excellent accuracy and reliability. In addition, in order to enrich the research, some results involving thick orthotropic annular sector plates with various boundary conditions are presented firstly, which can be acted as benchmark data for the future research.


ABSTRACT: Underwater explosives that left in ports and harbors during World War II, which may not be inspected in reconnaissance surveys could threat submerged pipelines seriously. This paper developed a three-dimensional numerical model for dynamic response of pipelines induced by underwater explosion. Both FSI (Fluid-Structure interaction) and PSI (Pipeline-Seabed interaction) are taken into consideration simultaneously in current research. The proposed integrated model has been validated against experiment data available in previous literature. It has been found that the pipeline laid on the seabed tends to roll away from detonation rather than to deform in the pipeline section. The semi-buried pipeline is the most vulnerable due to combined action of reloading effect and trench constraint. Based on the numerical results, shallow buried installation is an effective method to enhance the anti-blast ability of submerged pipelines. The stress level of the pipeline increases slightly due to enhancement of the surrounding soil for shallow buried pipelines, while the integral lateral displacement and element pressure decrease with increase of burial depth.


ABSTRACT: Numerical investigation is conducted in this paper on both intact and dented seamless metallic pipelines (diameter-to-thickness ratio around 21), deploying nonlinear finite element method (FEM). A full numerical model is developed, capable of predicting the residual ultimate strength of pipes in terms of bending capacity () and critical curvature (). The simulation results are validated through test results by using the measured material properties and specimen geometry. An extensive parametric investigation is conducted on the influences of material anisotropy, initial imperfection, friction of the test set-up and dent parameters. It is found that the structural response is quite sensitive to the frictions that have been introduced by the test configuration. For a pipe with a considerable dent size, the effect of manufacturing induced initial imperfection is insignificant and can be neglected in the FEM simulation. The material yield stress in the pipe longitudinal
direction dominates the bending capacity of structures. In the end, formulas are proposed to predict the residual ultimate strength of dented metallic pipes under pure bending moment, which can be used for practical purposes. A satisfying fit is obtained through the comparison between the formulas and FEM methods.


ABSTRACT: Flexible risers are being required to be installed in a water depth of over 3000 m for fewer remaining easy-to-access oil fields nowadays. Their innermost carcass layers are designed for external pressure resistance since the hydrostatic pressure at such a water depth may cause the collapse failure of flexible risers. Determining a critical collapse pressure for the carcass is of great importance to the whole structural safety of flexible risers. However, the complexity of the carcass profile always makes FE analysis computational intensive. To overcome that problem, the treatment of the interlocked carcass as an equivalent layer is adopted by researchers to accelerate the anti-collapse analyses. This paper presents an equivalent layer method to enable that treatment, which obtains the equivalent properties for the layer through strain energy and membrane stiffness equivalences. The strain energy of the carcass was obtained through FE models and then used in a derived equation set to calculate the geometric and material properties for the equivalent layer. After all the equivalent properties have been determined, the FE model of the equivalent layer was developed to predict the critical pressure of the carcass. The result of prediction was compared with that of the full 3D carcass model as well as the equivalent models that built based on other existing equivalent methods, which showed that the proposed equivalent layer method performs better on predicting the critical pressure of the carcass.


ABSTRACT: This study evaluates the structural feasibility of a prismatic pressure vessel using strength assessments. A prismatic pressure vessel, which differs from a cylindrical or spherical pressure vessel, is proposed. A prismatic pressure vessel can be used to ship liquefied gas. A prototype of the prismatic pressure vessel was designed, manufactured and tested in accordance with the ASME Boiler and Pressure Vessel Code. Its design uses the “design-by-analysis” method, including protection against plastic collapse. The prototype of the prismatic pressure vessel uses typical construction materials considering their linear elastic and nonlinear plastic behaviors. The vulnerable components of the structure were obtained through numerical analysis using the finite element method. A pressure test with strain gauges was conducted, and the results demonstrate the feasibility of the prismatic pressure vessel as a suitable vessel for high-pressure fluids with high volume efficiencies. The prismatic pressure vessel has potential for general applicability in the shipping of liquefied gas.


ABSTRACT: An energy-based formulation is developed to investigate the vibro-acoustic behaviors of the submarine hull immersed in heavy fluid in the present paper. The conical-cylindrical-hemispherical coupled shell with bulkheads and ring stiffeners is considered as the theoretical model of the hull structure, which is discretized into a number of spectral elements according to the structure type. Displacement components of each spectral element are invariably expressed by a set of modified Fourier series. The external acoustic field is described by one-dimensional Helmholtz integral formulation that can be solved by the means of discretization
along the generator line of the hull structure. Subsequently, the full vibro-acoustic model for the submerged hull is established by taking into account the energy of the acoustic field acting on the hull surface. The reliability and accuracy of the present method is validated by comparison of vibration and acoustic responses with those from the commercial softwares. Several examples are conducted to understand the effects of bulkheads, ring stiffeners and coupling stiffneces on the vibro-acoustic behavior of the submerged hull, which provides some helpful information in the design of underwater hull structures.

ABSTRACT: The dynamics of an underwater explosion bubble interacting with a moveable plate with basic characteristics of a sandwich structure are investigated numerically using boundary element method. The response of sandwich structures is assumed to be a moveable plate with a given velocity profile. The influence of the plate velocity profile, the standoff distance and the scale of the plate on the bubble behaviors are discussed. Within the scope of discussions, the bubble volume and period are a decreasing function of the maximum crushing velocity, the core compression, and the plate dimension, and an increasing function of the standoff distance. Three different regimes of bubble behaviors are distinguished: (1) jet directing towards the plate; (2) the bubble splitting into multiple bubbles or oscillating spherically without jet; (3) jet directing away from the plate. The results indicate that the sandwich plate which can provide larger deformation and larger maximum deformation velocity is beneficial for altering the jet direction to direct away from the plate.

ABSTRACT: Third party threats from accidentally dropped objects could cause external impact loading that may potentially affect the integrity and safety of a subsea pipeline system. These incidents may occur during installation, construction and operation phases of the project. To evaluate the structural integrity of carbon steel (CS) subsea pipelines due to dropped objects events, risk assessment is conducted following the procedure detailed in DNV-RP-F107, which gives a closed-form formula for predicting the impact-energy capacity of the CS pipeline and assumes an acceptance criterion of limiting the dent-depth ratio to 5% of pipe diameter for a no-leakage condition. In the case of CS pipelines mechanically-lined with corrosion resistant alloy (CRA), the applicability of the impact-energy formula and the acceptance criterion is, however, largely unknown considering that CRA-lined pipes involve additional modes of failure in the form of liner separation and its potential for subsequent fatigue failure during operation. This paper discusses finite element modelling undertaken to evaluate the structural response of a CRA-lined pipeline subjected to external impact loads. Results confirm that liner separation is of minor importance and the use of the established acceptance criterion derived for plain carbon steel pipes can be justified to apply to CRA-lined pipelines.

ABSTRACT: Unburied submarine pipelines might buckle laterally under the conditions of high temperature and high pressure. As an important design parameter of submarine pipelines, the lateral buckling critical force (LBCF) is affected by the maximum amplitude, wavelength, shape of the initial imperfection, and etc. However, the exact relationship between the LBCF and the initial imperfection shape is not clear at present. In this paper, the lateral buckling behaviors of submarine pipelines with different initial imperfection shapes are studied using 3D finite element (FE) analysis. A parametric study is conducted and the characteristic parameter of the initial
imperfection shape is found. It is the characteristic parameter that makes the LBCF greatly affected by the initial imperfection shape. A unified formula is proposed to reveal the exact relationship between the LBCF and the initial imperfection shape. An application of the unified formula is carried out and the results show the accuracy of the unified formula.


ABSTRACT: This work experimentally investigates the influence of different opening sizes and shapes, different steel materials and structural configurations on the ultimate strength of steel plates. A series of experiments have been carried out for unstiffened plates and stiffened panels having an opening of different shape and size in addition to different constructional steels; high tensile and mild steel. The effect on the ultimate load carrying capacity of the opening sizes and shapes, different steels and structural configurations, post-collapse deformations and strain energy density are investigated and analysed. Several relationships of the ultimate stress ratio, ultimate load carrying capacity ratio for different steels as a function of the residual breadth ratio are presented and discussed. A relationship showing the effect of different structural configurations on the ultimate load carrying capacity ratio is presented. Several observations and concluding remarks are derived from the experimental results.


ABSTRACT: This paper examines the free vibration of laminated composite plates in contact with a water-filled cavity. The fluid compressibility is considered in the analysis. The main objective is to evaluate the natural frequencies of the plate-fluid coupled system, compare the results with those obtained assuming an incompressible fluid domain, and examine the influence of the laminate stacking sequence. Classical and refined plate theories are considered in a compact manner. The Ritz method is used to obtain approximations of the kinetic and potential energy of both the fluid and the plate. The accuracy of the formulation is demonstrated by comparing the results to 3D finite element solutions obtained via commercial software. Parametric studies are carried out to examine the influence of the geometry, lamination angles and boundary conditions on the natural frequencies and the error incurred due to neglecting fluid compressibility. The error is higher when thick, stiff plates with rigid supports are considered. The effect of the fluid domain depth on the natural frequencies depends on the symmetric or antisymmetric nature of the mode shape. The orientation of the laminas becomes highly relevant when rectangular plates with mixed supports are considered.


ABSTRACT: A benchmark study, devoted to systematically investigate the ultimate strength of simply supported platings under uniaxial compression, is performed to develop unified design formulas, accounting for geometrical imperfections, welding residual stresses and pitting corrosion wastage. Particularly, two boundary conditions for the in-plane motion of longitudinal edges, namely free and fully restrained, are considered as they significantly affect the plating behaviour in the post-buckling regime. Several practical design equations for uncorroded platings are derived to account for different levels of initial deflections and residual stresses, based on a wide and systematic series of elasto-plastic large deflection analyses performed by Ansys Mechanical APDL. Subsequently, proposed formulas are extended to platings affected by pitting corrosion wastage, on the
basis of a new series of FE analysis, where the pitting intensity and corrosion degrees are systematically varied based on random distribution of the corrosion wastage on the plate panel. Finally, the goodness of proposed formulas is checked against current Rule equations, as well as several experimental collapse tests and FE results available in literature.

ABSTRACT: High resolution bathymetry combined with structural modelling is used to estimate changes in the on-bottom stability of an offshore pipeline due to scour and sedimentation over an 11 year period. Detailed observations of post-lay embedment changes have been combined with the pipeline structural characteristics and an elastic-plastic model of soil resistance to estimate the vertical and horizontal stability of the pipeline using a finite difference solution to the beam bending equation. Application of the design approach indicates that post-lay increases to the critical (break-out) velocity of 1–2 m/s occur along the full 19 km of surveyed pipeline due to scour and sedimentation, which act to reduce load and increase soil resistance. The rate at which this increase in stability occurs with time is found to vary along the pipeline, and is dependent on the mechanism of pipeline lowering (i.e. whether the pipe lowered due to sagging into widely spaced scour holes, or by sinking into the shoulders between many closely spaced scour holes). By incorporating sediment transport into the pipeline design, the present results suggest potential for significant improvements in pipeline on-bottom stability and associated reductions in minimum required specific gravity and/or secondary stabilisation.

ABSTRACT: This study focusses on deriving a formulation to predict the permanent damage of steel ring-stiffened cylinders subjected to dynamic lateral mass impact and their ultimate strength in both intact and damaged conditions under hydrostatic pressure. The damage scenario considered in this study can represent the collision accidents of offshore ring-stiffened cylinder structures with supply vessels or floating objects. To validate the numerical modelling and analytical techniques, six small-scale ring-stiffened cylinder models were fabricated. Drop tests with a knife-edge indenter were performed to generate the damage on four cylinder models. Then, all the models were subjected to hydrostatic pressure tests for assessing their ultimate strength in damaged and intact conditions. Next, rigorous parametric studies on the actual design of full-scale ring-stiffened cylinder examples were performed by changing the design variables. Simple design equations were derived for predicting the extent of local denting damage and the residual strength of the damaged ring-stiffened cylinders. The accuracy of the derived formulation has been established by comparison with the results of tests and finite element analyses, showing a good agreement for all the loading cases. This formulation can be useful for the purposes of design of ring-stiffened cylinders under the risk conditions of marine structures.

ABSTRACT: Currently, ship inner shell (SIS) design models which are being used widely in shipyards do not have good changeability. To improve the changeability of ship inner shell model and design efficiency, a new method for parametric design and optimization of ship inner shell is proposed. The method is based on the parametric expression model of different types of ship inner shell. The computing system of hold capacity is developed to calculate the floating status and stability. Furthermore, a parametric ship inner shell optimization
model is established, including objective function for optimization, constraints, optimization model solving etc. The optimization objective is maximum hold capacity. The requirements and rules for ship inner shell design are made constraints. The particle swarm optimization (PSO) algorithm is improved to solve this optimization model. To evaluate the applicability of the proposed method, the correctness and efficiency of the method is verified through 2 ships. Finally, the sensitivity analysis procedure is adopted to estimate the influence of the value of the key calculation parameters in the optimization algorithm on the calculation process and results.


**ABSTRACT:** This study intends to numerically analyze post-buckling behavior of functionally graded material (FGM) sandwich plates under mechanical edge compression. A simple yet accurate meshless approximation based on the radial point interpolation method (RPIM) and the higher-order shear deformation theory (HSDT) is presented and used to predict the post-buckling responses. The HSDT constructs a von Kármán type nonlinear equation which accounts for both the large deformation and the initial geometric imperfection for imperfect FGM sandwich plate. The field variables are approximated by introducing the radial basis function in a compactly supported form through which the shape functions are constructed without any fitting parameters. A solution procedure which utilizes the modified Newton-Raphson iterative scheme is designed to solve the discretized system equations needed to obtain the post-buckling path. Performance accuracy of the mesh-free approximation is confirmed by the comparative studies, followed by the detailed parametric investigations to elucidate the post-buckling characteristics of FGM sandwich plates subjected to in-plane mechanical compression. Results illustrate that the proposed mesh-free method can be used as a simple and accurate numerical tool for predicting the post-buckling responses of FGM sandwich plates, and the initial geometric imperfection and loading type have significant effects on the post-buckling behavior.

**End of more papers published in the journal, Ocean Engineering** (2017 and on).


Reza Ansari, Jalal Torabi and Amir Hosein Shakouri (Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran), “Vibration analysis of functionally graded carbon nanotube-reinforced composite elliptical plates using a numerical strategy”, Aerospace Science and Technology, Vol. 60, pp 152-161, January 2017, [https://doi.org/10.1016/j.ast.2016.11.004](https://doi.org/10.1016/j.ast.2016.11.004)

**ABSTRACT:** A numerical meshless discretization technique is developed within the framework of variational formulation to present the linear free vibration analysis of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) elliptical plates. The effective material properties of nanocomposite plate are continuously varied across the thickness direction and are evaluated based on the extended rule of mixture. The governing equations are derived on the basis of the first order shear deformation theory. To this end, the matrix form of Hamilton's principle is first presented. Then, based on the moving least-squares (MLS) approximation and background cells approach, the meshless differential and integral operators are constructed to perform the discretization process. After conducting the comparison and convergence study, various numerical results are reported to explore the effects of concerned parameters on the natural frequencies of composite elliptical plates.
reinforced with carbon nanotubes (CNTs). Results reveal that functionally grading of CNTs through the thickness direction can considerably improve the vibrational characteristics of FG-CNTRC elliptical plates. References listed at the end of the paper:


ABSTRACT: In this study, the free and forced vibration responses of rotating delaminated thickness tapered composite thick plates resting on elastic foundations using the element-free IMLS-Ritz method, Appl. Math. Comput., 256 (2015), pp. 488–504


natural frequencies of delaminated composite plate when compared to intact composite plate at lower modes is lesser than those compared to higher modes irrespective taper models and rotating speeds considered. Further, it was noticed that the decreasing percentage of natural frequencies of the mid-plane delaminated different taper models of composite plate over intact plate increase in the order of TM2, TM1, TM3 and uniform composite.

References listed at the end of the paper:

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ABSTRACT: Influenced by numerous local features, the post-buckling analysis and optimization for hierarchical stiffened shells suffer from heavy computational costs. By smearing the minor stiffeners based on a novel numerical implementation of asymptotic homogenization (NIAH) method, a novel hybrid model for hierarchical stiffened shells is presented. Then, the high prediction accuracy and efficiency of the hybrid model for post-buckling analysis and imperfection sensitivity analysis are validated. Furthermore, a grid-pattern optimization framework of novel hierarchical stiffened shells allowing for imperfection sensitivity is established. The illustrative examples indicate that, the hierarchical stiffened shell with candidate sub-structures is more competitive in load-carrying capacity than that with the fixed grid-pattern, and the presence of imperfections would greatly affect the results of grid-pattern optimizations.

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ABSTRACT: In this article, free vibration of the hard-coating cantilever cylindrical shell is investigated considering the elastic constraints at the clamped end. Love's first approximation theory and Rayleigh–Ritz method are applied to build the analytical model of hard-coating cylindrical shell. In the modeling process, orthogonal polynomials are used as admissible displacement functions to formulate the displacement field, and the elastic constraints are simulated by constrained springs whose stiffness values are determined using model updating technique. The developed model has been validated by the comparison between the natural frequencies obtained by analytical calculation and by experiment respectively. Finally, the influences of hard-coating parameters, including thickness, Young's modulus and loss factor, on the vibration characteristics of the cylindrical shell are studied.

Qilin Jin and Weian Yao (State Key Laboratory of Structure Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China), “Hygrothermal analysis of laminated composite plates in terms of an improved C0-type global-local model”, Aerospace Science and Technology, Vol. 63, pp 328-343, April 2017, https://doi.org/10.1016/j.ast.2017.01.004

ABSTRACT: In this paper, an efficient improved C0-type global–local model (IGLM) considering transverse normal strain is proposed to study the hygrothermal response of thick cross-ply laminated composite plates. Based on the interlaminar continuity conditions of in-plane displacement and transverse shear stresses, layer-dependent variables could be reduced. Employing shear stress free condition at the upper and the lower surfaces, derivatives of transverse displacement are eliminated from the displacement field, so that C0 interpolation functions are only required for the finite element implementation. As a result, the number of variables is independent of the number of layers of the laminate. To assess the proposed model, the classical quadratic eight-node isoparametric element is presented, in which the interelement C0 continuity conditions are satisfied. Comparing the results from available three-dimensional elasticity theory and those computed from the ninth-order model, it is found that the simple C0 finite elements could produce promising deformations and stresses for thick cross-ply laminated composite plates with different boundary conditions under hygrothermal loadings.

Hui-Shen Shen and Hai Wang (School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China), “Nonlinear vibration of compressed and thermally postbuckled

ABSTRACT: This paper investigates the small- and large-amplitude vibrations of compressed and thermally postbuckled carbon nanotube-reinforced composite (CNTRC) plates resting on elastic foundations. For the CNTRC plates, uniformly distributed (UD) and functionally graded (FG) reinforcements are considered where the temperature-dependent material properties of CNTRC plates are assumed to be graded in the thickness direction and estimated through a micromechanical model. The motion equations containing plate–foundation interaction are derived based on a higher order shear deformation plate theory and von Kármán nonlinear strain–displacement relationships. The initial deflections caused by compressive or thermal postbuckling are included. The numerical illustrations concern small- and large-amplitude vibration characteristics of compressed postbuckled CNTRC plates in thermal environments and thermally postbuckled CNTRC plates under uniform temperature field. The effects of CNT volume fraction and distribution patterns as well as foundation stiffness on the vibration characteristics of CNTRC plates are examined in detail.

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ABSTRACT: This research presents an exhaustive analysis on the buckling behavior of two-dimensional functionally graded (2D-FG) tapered Euler–Bernoulli beams made of porous materials in nano- and micro-scales. The imperfect nanobeams are studied based on the Eringen's nonlocal elasticity theory and the governing equations of micro-scaled imperfect beams are derived using the modified couple stress theory. The 2D-FG composition of the material is considered using the power law function. The generalized differential quadrature method (GDQM) is used for the solution process. The buckling behavior of 2D-FG porous micro- and nano-beams is studied in different porosity volume fractions (α), FG indexes (nx and nz ) and rates of cross section change along thickness (βh) and width (βb).


ABSTRACT: The present study focuses on performing a free vibration analysis of a functionally graded (FG) porous cylindrical shell subject to different sets of immovable boundary conditions. It is assumed that the modulus of elasticity of the porous composite is graded in the thickness direction. The open-cell metal foam provides a typical mechanical feature to determine the relationship between coefficients of density and porosity. A sinusoidal shear deformation theory (SSDT) in conjunction with the Rayleigh–Ritz method is employed to derive the governing equations associated with the free vibration of the circular cylindrical shell. Two types of graded porosity distributions in the thickness direction are considered. The study investigates the effects of FG porosity, boundary conditions, and geometrical parameters on free vibration characteristics of the FG porous cylindrical shell.

ABSTRACT: In this paper, bending, buckling and buckling of embedded nano-sandwich plates are investigated based on refined zigzag theory (RZT), sinusoidal shear deformation theory (SSDT), first order shear deformation theory (FSDT) and classical plate theory (CPT). In order to present a realistic model, the material properties of system are assumed viscoelastic using Kelvin–Voigt model. The elastic medium is simulated by orthotropic visco-Pasternak medium. Based on energy method and D'Alembert's principle, the derivation of the nonlinear equations of motion is presented. A novel numerical method namely as differential cubature (DC) method is applied for obtaining the static response, the natural frequencies and the buckling loads of nano-sandwich plates. The effects of different parameters such as nonlocal parameter, structural damping, viscoelastic foundation, geometrical parameters, stiffness of core and boundary conditions are shown on the bending, buckling and vibration behaviors of nanostructure. The accuracy of the proposed method is verified by comparing its numerical predictions with other published works as well as solution of system with differential quadrature (DQ) and harmonic differential quadrature (HDQ) methods. The numerical investigation shows that RZT is highly accurate in predicting the deflection, frequency and buckling load of nano-sandwich plates without requiring any shear correction factors.

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ABSTRACT: In this study, the effects of uncertain material properties on the buckling response of laminated composite structures based on the isogeometric analysis will be presented. The target modulus of elasticity fields are assumed to be a stochastic field and case studies are considered for laminated composite structures including beams and plates. The spectral representation is employed as the crucial method of generating samples. Numerical results show a successful establishment of spectral representation method based on Monte Carlo simulation and isogeometric analysis for evaluating accurately the effects of uncertain material property on the buckling responses. It is demonstrated that linear-like relations between the standard deviation of modulus of elasticity and the standard deviation of critical buckling load of composite beams and plates are accomplished. In addition, isogeometric analysis, which is employed as a solver for the analysis of composite plate based on C¹ four-unknown refined plate theory, remarkably outweighs the finite element analysis approach in terms of computational cost of the simulations.

M.M. Shokrieh and A. Nouri Parkestani (Composites Research Laboratories, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Iran), “Post buckling analysis of shallow composite shells based on the third order shear deformation theory”, Aerospace Science and Technology, Vol. 66, pp 332-341, July 2017
ABSTRACT: In the present paper, a higher-order shear deformation theory of elastic shells was developed for geometrically nonlinear analysis of laminated shells of orthotropic layers. The theory can better represent the kinematics, may not require shear correction factors and can yield more accurate interlaminar stress distributions. The nonlinear mathematical model is derived using the Green–Lagrange type geometric nonlinearity in the framework of the higher order shear deformation theory. The developed model accounts for parabolic distribution of the transverse shear strains through the thickness and tangential stress-free boundary conditions on the boundary surfaces of the shell. Therefore, shear correction factors of the usual shear deformation theory are not required in the present theory. The principle of the virtual work forms the basis to derive the nonlinear finite element equations. The nonlinear equilibrium equations are solved using an incremental iterative technique based on the arc length method.

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Thermomechanical buckling and post-buckling of cylindrical shell with functionally graded coatings and reinforced by stringers”, Aerospace Science and Technology, Vol. 66, pp 392-401, July 2017

ABSTRACT: The cylindrical shells reinforced by stringers have been widely used in modern engineering structures such as storage tanks, missile, submarine hull, oil-transmitting pipeline, etc. In this present article, the thermomechanical buckling and post-buckling behaviors of a cylindrical shell with functionally graded (FG) coatings are investigated by an analytical approach. The cylindrical shell is reinforced by outside stringers under torsional load in the thermal environment. The layers of FG coatings are assumed to be made by functionally graded materials (FGMS) combining of ceramic and metal phases and the core of the shell is made from homogeneous material. The classical shell theory based on the von-Karman assumptions is used to model the thin cylindrical shell. Using Galerkin's procedure and Airy stress function, the governing equations can be solved to obtain the closed-form solution for the critical buckling load and postbuckling load-deflection curves of simply supported shells. Moreover, many important parametric studies of stringers, temperature field, material volume fraction index, the thickness of metal layer, etc. are taken into investigation. According to numerical examples, it is revealed that the outside strings have considerably impact on thermomechanical buckling and postbuckling behaviors of the shells.


ABSTRACT: In this paper, displacement based new hyperbolic higher-order shear and normal deformation theory (HHSNDT) is introduced for the geometrically nonlinear vibrations response of FGM plates. The proposed theory accounts for nonlinear in-plane and transverse displacement through the plate thickness. Unlike
any other theory, the number of unknown functions involved in the present theory is only four, as against five or higher in the case of other well-known shear deformation theories. It also accounts the stretching effects across the thickness and does not require any shear correction factor. The fundamental equations of FGM plate are obtained using variational principle and von Karman theory is employed for large transverse deflection. Voigt and Mori–Tanaka model is used with the conjunction of exponential law and power law to estimate the graded material properties. The accuracy of the present theory is ascertained by comparing it with various available results in the literature. A comprehensive numerical study is carried out based on the present theory to examine the influence of the homogenization techniques, geometrical parameter, amplitude ratio and boundary conditions on the vibration response of the graded plate.

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ABSTRACT: In recent years, with the development of the space structures, thin film reflector structures have the feature of lightweight, high compact ratio, easy to fold and unfold and so on. Its form has received wide attention from researchers and a broad application prospect. In this paper, the nonlinear finite element software ABAQUS was used to carry out the numerical simulation of the deployment of membrane structures based on Miura-ori, by taking advantage of the variable Poisson's ratio model to revise the stress distribution of membrane elements. Then the uniaxial tension tests were carried out to study the material properties of the polyimide film. The effective elastic modulus was used to simulate the crease of the membrane. The deployment of a membrane structure based on Miura origami pattern was studied. Moreover, effects of some parameters, such as the number of loading nodes and the loading rate on the numerical results were discussed.

ABSTRACT: The thermal buckling and post-buckling behavior of laminated composite beam reinforced with Shape Memory Alloy (SMA) wires is explored. The thermo-mechanical behavior of embedded SMA wires is formulated based on one-dimensional Brinson SMA model. Using a variational approach, the Layer-Wise Theory (LWT) of beams is employed to develop the governing equations. The von Karman strain–displacement relations are used to account for the large deflection effects. A closed-form solution of the resulting systems of nonlinear equations is represented. Exemplary case studies are assessed by comparing with available literature. Considering symmetric and antisymmetric layups, the influence of thickness/span ratio, degree of anisotropy, SMA pre-strain and volume fraction upon the buckling and post-buckling of thick composite and hybrid composite beams are examined and discussed in detail.
ABSTRACT: This paper details an experiment that was used to validate the frame deformation of three vacuums lighter than air vehicle finite element models composed of a frame with a skin covering. The experiment consisted of a simplified one directional loading to determine the behavior of a 3D printed frame, which was compared to a corresponding finite element model. A 3D printed icosahedron frame was loaded in compression using a mechanical testing machine to record the load versus displacement of the structure. It was discovered that the material properties of the printed structure were significantly lower than the quoted values from the manufacturer. The modulus property was extracted from the finite element model that best matched the experiment. The behavior of the frame from the experiment shows that the beams do buckle. The model matches the frame buckling and load retention. The feasibility of a vacuum lighter than air vehicle using an icosahedron, hexakis icosahedron, and celestial frame and skin were then analyzed since the method of analysis was proven through the experiment. The icosahedron showed failure due to material limits and the hexakis icosahedron showed definite feasibility using modern material properties.

ABSTRACT: This paper presents Best Theory Diagrams (BTDs) constructed from various non-polynomial terms to identify best plate theories for metallic and functionally graded plates. The BTD is a curve that provides the minimum number of unknown variables necessary to obtain a given accuracy or the best accuracy given by a given number of unknown variables. The plate theories that belong to the BTD have been obtained using the Axiomatic/Asymptotic Method (AAM). The different plate theories reported are implemented by using the Carrera Unified Formulation (CUF). Navier-type solutions have been obtained for the case of simply supported plates loaded by a sinusoidal transverse pressure with different length-to-thickness ratios. The BTDs built from non-polynomial functions are compared with BTDs using Maclaurin expansions. The results suggest that the plate models obtained from the BTD using non-polynomial terms can improve the accuracy obtained from Maclaurin expansions for a given number of unknown variables of the displacement field.
ABSTRACT: In this study, the reliability-based design optimization (RBDO) of rotating functionally graded cylindrical shells (FGCSs) subjected to temperature dependent probabilistic frequency constraints is investigated. The uncertain parameters such as FG material properties and the shell thermo-mechanical loads are considered as random variable in RBDO. To decrease model uncertainty, the effect of initial thermal stresses are efficiently included in elasticity-based vibration equations of the shell and the powerful differential quadrature method (DQM) is employed to accurately determine the shell frequency parameters. An efficient RBDO framework based on the hybrid weighted average simulation method (WASM) and DQM together with the particle swarm optimization (PSO) method is then presented for design optimization of the FGCSs. A key feature of proposed hybrid DQ-WASM-PSO is that only one simulation run is required for WASM during entire optimization process of the FGCS, even if the distribution type of input variables and/or the system target reliability level be changed. The influence of temperature rise, temperature-dependence of FGM properties, annular velocity, PDFs of the random variables, and convection heat transfer coefficient of the shell inside fluid on the RBDO results are carried out. Parametric study indicates that exact evaluation of the initial thermal stresses, temperature-dependence of the FGM properties and convection heat transfer coefficient have considerable effect on optimization results.

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ABSTRACT: In the present article, static response and free vibration of functionally graded carbon nanotube reinforced composite (FG-CNTRC) rectangular plate resting on Winkler–Pasternak elastic foundations using an analytical approach are studied. The rectangular plates are reinforced by single-walled carbon nanotubes (SWCNTs) which are assumed to be graded through the thickness direction with four types of distributions. The mathematical model of the FG-CNTRC plate is developed based on the first-order shear deformation plate theory (FSDT) and Hamilton principle. By using Navier solution, the governing equations are solved to obtain the central deflection and the natural frequency parameters. Several examples are verified to have higher accuracy than those from the previous method in the literature. Also, the effects of different parameters on static response and natural frequency of FG-CNTRC plate are highlighted by solving numerous examples. Finally, these new results may serve as benchmarks for future investigations.

References listed at the end of the paper:
[31] L.W. Zhang, Z.X. Lei, K.M. Liew, Vibration characteristic of moderately thick functionally graded carbon nanotube reinforced
functions

ABSTRACT: The present work deals with prediction of bending and free vibration analysis of laminated composite and sandwich plates using non-polynomial zigzag theories inline with C⁰ finite element formulation. The assumed mathematical model is the combination of zigzag parameters and non-polynomial shear strain functions with constant variation of transverse displacement. It represents continuous form of out-plane stresses

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and parabolic variation across the plate thickness. Moreover, improved form of in-plane responses also achieved. The mathematical model is layer independent and consist of less number of unknowns like in the case of first order theory. Hence, the present theory required less computational efforts. Higher mode shapes of frequencies are obtained for the multilayered sandwich plates and composite plates. By ranging the geometrical parameters, loading conditions, material properties and boundary conditions the numerical examples are carried out to establish the superiority of the current zigzag models than the available results.


ABSTRACT: This paper develops a unified semi-analytical method for the free vibration analysis of moderately thick doubly curved open shells with arbitrary geometry and classic boundary conditions. The only restriction on the shell's geometry is that boundaries are being coincided by the principal curvature lines of the shell. The formulation is based on the first order shear deformation theory by considering effects of curvature in the evaluation of stress resultants. Differential geometry method is used to represent the arbitrary shape of the middle surface of the shell. The Ritz method with algebraic polynomials as trial functions is employed to obtain the natural frequencies and mode shapes of the shell. To demonstrate the efficiency and accuracy of the solution, convergence and comparison studies are carried out for a cantilevered shallow shell and a parabolic panel. Furthermore, a variety of new vibration results including frequencies and mode shapes of ellipsoid and Enneper panels with various boundary conditions are presented which may be used as benchmark results for future studies.


ABSTRACT: The current formulation applies Non-dominated Sorting Genetic Algorithm (NSGA-II) as well as First-order Shear Deformation Theory (FSDT) to optimize Sound Transmission Loss (STL) of the laminated composite cylindrical shell lined with a porous material subjected to a plane sound wave. Therefore, in the first part of the paper, the Extended Full method [29] is employed to provide an exact solution based on three dimensional elasticity theory as well as investigating the well-known Helmholtz decomposition to present fluid pressure, the displacement fields and the solid stresses. Subsequently, some configurations are brought up to illustrate the accuracy of the present results. Furthermore, this paper also clarifies the importance of applying porous layer by demonstrating the direct influence between porous layer thicknesses and STL of the structure particularly in high frequency region. Consequently, in the second part of the paper the NSGA-II method is applied to multi objective optimize of sound transmission into such structure taking account the appropriate Pareto front which result in substantial improvement on the performance of the system based on minimizing the weight as well as maximizing sound transmission. Therefore, this procedure is followed by considering suitable design variables to designate what combination of design variables could result in a composite shell satisfying the sound insulation.


ABSTRACT: Free vibration behaviour of a shear deformable conical shell with intermediate ring support is analysed in this research. It is assumed that the conical shell is made from a linearly elastic isotropic
homogeneous material. To capture the through-the-thickness shear deformations and rotary inertia effects, first order shear deformation theory of shells accompanied with the Donnell type of kinematic assumptions are adopted to establish the general equations of motion and the associated boundary conditions with the aid of Hamilton's principle. The resulting system of equations are discreted using the semi-analytical generalised differential quadratures (GDQ) method. The shell is divided into two sections, where the continuity conditions are satisfied at the ring position. Considering various types of boundary conditions for the shell ends and continuity conditions at the ring position, an eigenvalue problem is established to examine the natural frequencies of the shell reinforced with an intermediate ring support. After proving the efficiency and validity of the present method for the case of thin isotropic homogeneous cylindrical shell with intermediate ring support, parametric studies are carried out for the case of shear deformable conical shells with intermediate ring support.

ABSTRACT: Considering Functionally Graded Material (FGM) plates composed of elastoplastic Ramberg–Osgood metal and elastic ceramic parts, the buckling phenomenon is studied. Plastic flows are formulated by the methods of Incremental Theory (IT) and Deformation Theory (DT). Using proper homogenization tactics and minimum potential energy principle, inclusive forms of governing equations are derived for the elastoplastic buckling of FGM plates. Using the Generalized Differential Quadrature (GDQ) technique a suitable solution algorithm is schemes and programmed in Matlab. Comparing the results with similar studies in buckling of elastoplastic homogeneous plates or elastic FGM plates, the methodology is assessed. The developed analytical IT and DT methodologies are used to analyze the elastoplastic buckling of plates with different boundary conditions. In different in-plane longitudinal and transversal loading conditions, the buckling load of plates with different thickness and aspect ratio are obtained. The effect of other several important factors such as the exponent of power law distribution function and the type of boundary conditions are studied in an extensive range of loads. Between similar FGM rectangular plates, the effect of aspect ratio and thicknesses upon the buckling loads are studied.

ABSTRACT: A first known study is conducted on the vibrations of functionally graded material (FGM) rectangular plates with porosities and moving in thermal environment. The FGM plates contain porosities owing to the technical issues during the preparation of FGMs. Two types of porosity distribution, namely, even and uneven distribution, are considered. The geometric nonlinearity is taken into account by using von Kármán nonlinear plate theory. The out-of-plane equation of motion of the system is derived based on the D'Alembert's principle with the consideration of the thermal effect and longitudinal speed. Then the Galerkin method is employed to discretize the partial differential equation of motion to a set of ordinary differential equations. These time-varying ordinary differential equations are solved analytically by means of the method of harmonic balance. The accuracy of approximately analytical solutions is verified by the adaptive step-size fourth-order Runge–Kutta technique. Additionally, the stability of steady-state solutions is analyzed for the analytical solutions. Vibration characteristics such as natural frequency and nonlinear frequency response are shown. The present model is a hardening-spring system based on the nonlinear frequency response results. Effects of some key parameters are investigated on the vibration of rectangular FGM plates with porosities and moving in thermal environment.

ABSTRACT: To solve the linear and nonlinear dynamic equation of motion, a family of explicit higher-order time integration algorithms is presented. The differential transformation method in conjunction with the state–space concept is used. In this study, four members of this family are considered thoroughly. To validate the performance of the new algorithms, comparison studies are accomplished with the well-known time integration schemes. By solving some linear and nonlinear dynamic problems, the merits of the authors' formulations will be clearly demonstrated.


ABSTRACT: This paper is concerned with the analysis of active constrained layer damping (ACLD) of geometrically nonlinear vibrations of doubly curved sandwich shells with facings composed of fuzzy fiber reinforced composite (FFRC). FFRC is a novel composite where the short carbon nanotubes (CNTs) which are either straight or wavy are radially grown on the periphery of the long continuous carbon fiber reinforcements. The plane of waviness of the CNTs is coplanar with the plane of carbon fiber. The constraining layer of the ACLD treatment is composed of the vertically/obliquely reinforced 1–3 piezoelectric composites (PZCs) while the constrained viscoelastic layer has been sandwiched between the substrate and the PZC layer. The Golla–Hughes–McTavish (GHM) method has been implemented to model the constrained viscoelastic layer of the ACLD treatment in time domain. A three dimensional finite element (FE) model of smart doubly curved FFRC sandwich shells integrated with ACLD patches has been developed to investigate the performance of these patches for controlling the geometrically nonlinear vibrations of these shells. This study reveals that the performance of the ACLD patches for controlling the geometrically nonlinear vibrations of the doubly curved sandwich shells is better in the case of the facings composed of laminated FFRC than that in the case of the facings made of conventional orthotropic laminated composite. The research carried out in this paper brings to light that even the wavy CNTs can be properly utilized for attaining structural benefits from the exceptional elastic properties of CNTs.


ABSTRACT: Multilayered composite and sandwich plates and shells are typical aerospace structures. They introduce complicating effects such as in-plane and transverse anisotropy which lead to zigzag forms of displacement and interlaminar continuity problems. The present closed-form 3D shell solution allows the static analysis of simply-supported cross-ply laminated and sandwich plates, cylinders and cylindrical/spherical shell panels subjected to different harmonic load types. It is possible to consider transverse normal and transverse shear loads simultaneously or separately applied at the top and at the bottom of the considered structure. The present work extends the previous exact 3D shell model developed for the static analysis of plates and shells in the case of transverse normal load applied at the top or at the bottom of the investigated structure. This new extension is still based on the 3D equilibrium equations written in general orthogonal curvilinear coordinates. The obtained system is solved using simply supported boundary conditions, harmonic forms for loads and displacements, a general layer wise approach and the exponential matrix method for the solution of the differential equations in z. However, the load boundary conditions introduced in the proposed shell model have
been opportunely modified in order to allow the combination of different transverse normal and transverse shear loads applied at the external surfaces. The new proposed benchmarks fill the gap present in the literature where the proposed 3D exact models always use a transverse normal load applied at the external surfaces. The present paper investigates the zigzag effects, the interlaminar continuity, the equilibrium and compatibility conditions, the load boundary conditions, the symmetry characteristics, the thickness ratio effect and the 3D behavior in laminated and sandwich plates and shells in the case of different load applications. The new proposed benchmarks will be fundamental for the validation of those new refined 2D shell models which want to capture all these features for different load types.


ABSTRACT: In the present work, the thermo-mechanical response characteristics of cross-ply as well as angle-ply laminated composite plates in closed form are investigated. The laminated composite plates are modelled in an axiomatic framework based on an inverse hyperbolic shear deformation theory (IHSDT). The governing differential equations are yielded by implementing the principle of virtual work. These governing equations are solved separately for cross-ply and angle-ply plates by consideration of stiffness characteristics of these plates. The sinusoidal and uniform transverse mechanical loading is considered with the linear and non-linear distribution of temperature across the depth of the plate. The simply supported composite plates are considered and Navier solutions satisfying the associated boundary constraints are developed. The mechanical and thermo-mechanical response characteristics of cross-ply and angle-ply plates under such conditions are investigated and the results are presented in the non-dimensional form. A comparison of the obtained results with the existing results for a variety of examples is presented and based on this comparison study, the validity, applicability and accuracy of IHSDT for such analysis is ensured. The applicability and accuracy of IHSDT for thermo-mechanical responses of laminated composite plates is ascertained on the basis of results presented. The effects of span thickness ratio, lamination sequence, loading and thermal conditions, material anisotropy ratio, and aspect ratio on the thermo-mechanical response characteristics are also concluded.


ABSTRACT: As a first attempt, finite element (FE), genetic algorithm (GA) and particle swarm optimization (PSO) methods are mixed to maximize buckling load of stiffened laminated composite plate via finding optimum fibers orientation of the plate. The FE method is used to solve the higher-order shear deformation based equations of the plate. To improve the performance of genetic algorithms for solving the problem, the particle swarm optimization technique is added as an operator of the GA. Accuracy, convergence and applicability of the proposed approach are shown. Effects of the dimensions of the plate, the cross section shapes of the stiffener(s), number of layers of the plate and boundary conditions on the optimum results are investigated.


ABSTRACT: The main goal of this study is using analytical solution to investigate the nonlinear dynamic response and vibration of sandwich auxetic composite cylindrical panels. The sandwich composite panels have
three layers in which the top and bottom outer skins are isotropic aluminum materials, the central auxetic core layer – honeycomb structures with negative Poisson's ratio using the same aluminum material. The panels are resting on elastic foundations and subjected to mechanical, blast and damping loads. Based on Reddy's first order shear deformation theory (FSDT) with the geometrical nonlinear in von Karman and using the Airy stress functions method, Galerkin method and fourth-order Runge–Kutta method, the resulting equations are solved to obtain expressions for nonlinear motion equations. The effects of geometrical parameters, material properties, elastic Winkler and Pasternak foundations, mechanical, blast and damping loads on the nonlinear dynamic response and the natural frequencies of sandwich composite cylindrical panels are studied.


ABSTRACT: The solid-shell elements can simplify the modeling process of the three-dimensional thin-walled structures that are commonly used in aerospace engineering. In this work, an efficient locking-free 8-node solid-shell element, termed SolSh8, is developed for geometrically nonlinear buckling analysis of shell structures. The solid-shell element is developed based on the conventional brick solid element with only translational degrees of freedom. The Assumed Natural Strain (ANS) method and the Enhanced Assumed strain (EAS) method are used to improve the linear performance of the element formulation. The proposed element is implemented into the co-rotational formulation of the Koiter–Newton method. The geometrically nonlinear equilibrium path of the structure can be traced efficiently benefiting from the reduced order model used in the Koiter–Newton method. Numerical examples demonstrate the excellent performance of the proposed method.


ABSTRACT: Under uniaxial compression, carbon fiber reinforced composite (CFRC) orthogrid sandwich cylinder has four potential failure modes, including global buckling, monocell buckling, rib buckling and material failure. The smearing method was applied to predict the equivalent stiffness and calculate the stresses of the skins and the orthogrid, providing fundamentals to build the failure criteria. Theoretical models were established to reveal the failure modes and predict the ultimate load of the compressed orthogrid cylinder by the way of failure maps, providing a feasible way to optimally design CFRC anisogrid cylinder.


ABSTRACT: This paper presents a new approach – using analytical solution to investigate nonlinear dynamic response and vibration of imperfect functionally graded carbon nanotube reinforced composite (FG-CNTRC) double curved shallow shells. The double curved shallow shells are reinforced by single-walled carbon nanotubes (SWCNTs) which vary according to the linear functions of the shell thickness. The shells are resting on elastic foundations and subjected to blast load and temperature. The shell's effective material properties are assumed to depend on temperature and estimated through the rule of mixture. By applying higher order shear theory, Galerkin method and fourth-order Runge–Kutta method and the Airy stress function, nonlinear dynamic response and natural frequency for thick imperfect FG-CNTRC double curved shallow shells are determined. In numerical results, the influences of geometrical parameters, elastic foundations, initial imperfection, temperature increment and nanotube volume fraction on the nonlinear vibration of the FG-CNTRC double
curved shallow shells are investigated. The proposed results are validated by comparing with those of other authors.


ABSTRACT: A novel quasi-3D hyperbolic theory is presented for the free vibration analysis of functionally graded (FG) porous plates resting on elastic foundations by dividing transverse displacement into bending, shear, and thickness stretching parts. The elastic foundation can be chosen as Winkler, Pasternak or Kerr foundation. Three different patterns of porosity distributions (including even and uneven distribution patterns, and the logarithmic-uneven pattern) are considered. A Galerkin method is developed for the solution of the eigenvalue problem of the presented quasi-3D hyperbolic plate model. The presented quasi-3D hyperbolic theory is simple and easy to implement since it uses only five-unknown variables to determine fourfold coupled (axial-shear-bending-stretching) vibration responses. A comprehensive parametric study is carried out to assess the effects of volume fraction index, porosity fraction index, stiffness of foundation parameters, mode numbers, and geometry on the natural frequencies of imperfect FG plates.

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ABSTRACT: An analytical model is developed to investigate the sound transmission loss from orthogonally rib-stiffened plates structure under diffuse acoustic field excitation. The validity and feasibility of the model are verified by comparing the present theoretical predictions with numerical and experimental results published previously. The influences of modal coupling terms, boundary condition and stiffener spacing on sound power and sound transmission loss are subsequently presented. Numerical discussion of the model demonstrates the significant influence of both boundary conditions and stiffener spacing upon the mode shape, sound power and sound transmission loss for stiffened plate, wherein sound power decreases and sound transmission loss increases as the amount of constraint increases.
ABSTRACT: This paper investigates the micro- and nano-mechanical behavior of orthotropic doubly curved shells by considering the New Modified Couple Stress Theory (NMCST). The higher order continuum assumed by the NMCST includes three material length scale parameters in order to capture the size-effect of anisotropic and orthotropic materials. The governing equations of the problem are based on the First-order Shear Deformation Theory (FSDT). According to the proposed NMCST, the expressions of the physical components for the strain and curvature tensors are obtained in an orthogonal curvilinear coordinate system. Then, the governing differential equations and boundary conditions are derived by applying the energy method and Hamilton's principle. A comparative investigation between our numerical results and the ones available in the literature proves the capability of the proposed formulation in predicting the micro- and nano-mechanical behavior of orthotropic doubly curved shells.

ABSTRACT: An analytical model is performed across the aerospace composite structure to interpret acoustic transmission of the infinitely long doubly curved shell considering the effect of mean flow with the aid of Higher-order Shear Deformation Theory (HSDT). Accordingly, the displacements are extended up to cubic order of thickness coordinate based on Third-order Shear Deformation Theory (TSDT) known as HSDT including no effect of shear correction factor. Consequently, in order to present the Sound Transmission Loss (STL) of the present model, the excitation of the structure with an oblique plane sound wave is set in order. However, the acoustic transmission is performed by incorporating the both of shell equations and acoustic wave equations simultaneously. In the next step, the accuracy as well as the reliability of the present model is provided by comparing the achieved results with those available in literature. Moreover, the present results illustrate the importance of investigating TSDT due to clarifying the more precise outcomes. Finally, the important of the present model is cleared as a result of improving the mechanical and sound insulation properties particularly in low frequency zone by illustrating the STL comparison between the current structure and those structures without any curvature.

ABSTRACT: Solids that exhibit negative Poisson's ratio are called auxetic materials. Static behavior of the auxetic-porous structures has not been investigated so far, especially for structures composed of multi directional heterogeneous materials. The two parameter elastic foundation (Pasternak type) is developed by taking into account the torsional interaction and horizontal friction force. The material properties of the plate except the Poisson's ratio are assumed to be graded in the thickness and radial directions according to exponential functions. The governing state equations are derived in terms of displacements based on 3D poroelasticity theory. These equations are semi-analytically solved using state-space based differential quadrature method. A detailed parametric study is carried out to highlight the influences of key parameters on the static response of non-uniform bi-directional functionally graded auxetic-porous material (FGAPM) circular plates to compound mechanical tractions. Finally, the static response of circular plates composed of various
functionally graded materials to compound mechanical loads is compared. Results reveal that the auxeticity of the material, torsional couples on the plate and rotary interaction of the elastic foundation play important roles on the static behavior of the plate.


ABSTRACT: In this paper, a comprehensive numerical study is presented on the large-amplitude free vibration of sandwich annular plates integrated with functionally graded carbon nanotube-reinforced composite (FG-CNTRC) face sheets resting on elastic foundation. The sandwich plate is made of a homogeneous core and two FG-CNTRC face sheets whose material properties are estimated through a micromechanical model. Since the fundamental vibrational mode shapes of annular plates are axisymmetric, the governing equations are derived assuming the axisymmetric formulation. For this purpose, the quadratic form of total potential energy of the structure is presented based on the higher-order shear deformation theory (HSDT) of plates along with von-Karman nonlinear kinematic relations. The numerical differential and integral operators are then employed to discretize the energy functional in space and time domains. Finally, using the response of linear analysis and applying the pseudo-arc length continuation method, the nonlinear frequencies are obtained. After validating the results of proposed approach, detailed numerical results are given to analyze the effects of geometrical and material parameters on the nonlinear vibration of FG-CNTRC sandwich annular plates.


ABSTRACT: Present research deals with the shear buckling behaviour of composite skew plates reinforced with aligned single walled carbon nanotubes (CNTs). Distribution of CNTs across the thickness of the skew plate are assumed to be uniform or functionally graded. Two different types of shear loads are considered. The case of rectangular shear which produces pure shear and the case of skew shear which results in a combined uniform shear and uniaxial tension/compression. Suitable for moderately thick plates, first order shear deformation plate theory is used to estimate the displacement field of the plate. The equivalent properties of the composite media are obtained by means of the refined rule of mixtures approach which contains efficiency parameters to capture the size dependent properties of the CNTs. With the aid of the Hamilton principle, transformation of the orthogonal coordinate system to an oblique one and the conventional Ritz method whose shape functions are constructed according to the Gram–Schmidt process, the stability equations of the plate are established and solved for two different types of loading, namely rectangular and skew shear loads. As shown, through introduction of a proper functionally graded pattern, i.e., FG-X pattern, the buckling load of the plate may be increased, significantly.


ABSTRACT: This work presents an analytical approach to investigate buckling and post-buckling behavior of FGM plate with porosities resting on elastic foundations and subjected to mechanical, thermal and thermomechanical loads. The formulations are based on Reddy’s higher-order shear deformation plate theory taking into consideration Von Karman nonlinearity, initial geometrical imperfections, and Pasternak type of elastic foundations. By applying Galerkin method, closed-form relations of buckling loads and post-buckling equilibrium paths for simply supported plates are determined. Numerical results are carried out to show the
effects of porosity distribution characteristics (Porosity-I and Porosity-II), geometrical parameters, material properties and elastic foundations on the mechanical, thermal and thermomechanical buckling loads and post-buckling resistance capacity of the porous FGM plates.


ABSTRACT: In the present research, dynamic buckling of a shallow arch subjected to transient type of thermal loading is investigated following the Budiansky–Hutchinson criterion. Arch is subjected to thermal shock on one surface while the other surface is kept at reference temperature. Transient heat conduction equation across the arch thickness is established and solved analytically. The induced bending moment and compressive thermal force are obtained and inserted into the equations of motion of the arch. To model the arch, classical arch theory suitable for thin arches is employed. The von Kármán type of strain-displacement relation suitable for small strains and large deformations is used. The governing nonlinear equations of motion are presented as the coupled nonlinear algebraic equations. These equations are established using the conventional Ritz method, where the shape functions are constructed employing the polynomial functions. The resulting equations are solved by means of the Newmark time marching scheme and the Newton–Raphson linearization technique. By means of the Budiansky criterion, critical thermal shock parameters are distinguished. Dynamic buckling temperatures are also verified using the phase-plane presentation, also known as the Hoff–Hsu criterion. It is verified that the shallow arches may undergo dynamic snap-through type of motion under rapid surface heating when certain geometrical constrains are met.


ABSTRACT: The paper presents an investigation of electro-thermo-mechanical vibration of functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical shells surrounded by an elastic medium by an analytical approach. The uniform and functionally graded CNTs are used to reinforce through the thickness of the shell. Based on geometrical nonlinearity in von Karman–Donnell's sense within the classical thin shell theory, the governing equations of motion are proposed. By using the Galerkin's method to solve the equations of motion, analytical solutions with three approximate functions of deflection are given to analyze thermal vibration of the piezoelectric actuated FG-CNTRC shells. Piezoelectric layers are bonded onto the outer and inner surfaces of the cylindrical shell to act as the actuators, respectively. The Dormand/Prince Runge–Kutta pairs are used as a semi-analytical approach to solve differential equations of the problem. The fundamental frequencies, relation of frequency ratios–amplitudes and responses of vibration are researched. Furthermore, the effects of CNT volume fraction, piezoelectric layers, thermal environment, distribution type of the reinforcement, geometrical parameters and elastic foundation are analyzed. It is expected that the obtained results can be used as benchmark solutions for an analytical approach to serve in further research as well as in industrial applications.


ABSTRACT: This paper presents the studies carried out for improving the acoustic behavior of truss core sandwich panel, which is mostly used in aerospace structural applications. The empty space of the truss core is filled with polyurethane foam (PUF) to achieve better vibro-acoustic and sound transmission loss characteristics. Initially equivalent elastic properties of the foam filled truss core sandwich panel are calculated.
Then, the vibration response of the panel under a harmonic excitation is obtained based on the equivalent 2D finite element model. Finally, the vibration response is given as an input to the Rayleigh integral code built in-house to obtain the acoustic and sound transmission loss characteristics. The results revealed that PUF filling of the empty space of the truss core, significantly reduces resonant amplitudes of both vibration and acoustic responses. It is also observed that foam filling reduces the overall sound power level significantly. Similarly, sound transmission loss studies revealed that, sudden dips at resonance frequencies are significantly reduced. Also an experiment is conducted on forced vibration response of honeycomb core sandwich panel to show that equivalent 2D model can be used for predicting sound power level and transmission loss behavior.


ABSTRACT: This work deals with the numerical investigation of the geometrically nonlinear resonant dynamics of carbon nanotube/fiber/polymer multiscale laminated composite (CNT-FPMLC) rectangular plates with different boundary conditions. It is assumed that a uniform distributed harmonic excitation load in the transverse direction is applied to the CNT-FPMLC plates. The material properties of multiscale composite are estimated by means of the fiber micromechanics and Halpin–Tsai relations. Furthermore, it is assumed that the carbon nanotubes (CNTs) are distributed uniformly and oriented arbitrarily through the epoxy resin matrix. Based upon the Mindlin plate theory and using the von Kármán hypotheses, the governing equations of motion for the in-plane and out-of-plane motions including the effects of geometric nonlinearity, rotary inertia and shear deformation are achieved by means of the Hamilton's principle. In the solution process, the nonlinear partial differential equations of motions and associated boundary conditions are discretized via the generalized differential quadrature (GDQ) and afterward converted into a Duffing-type nonlinear time-varying set of ordinary differential equations via a numerical Galerkin approach. Then, the time periodic discretization method and the pseudo-arc length continuation technique are employed to solve the obtained equations in order to achieve the frequency–response curves associated with nonlinear free and forced resonances for the CNT-FPMLC rectangular plates with various edge supports. Finally, the influences of important design parameters including the weight percentage of single-walled and multi-walled CNTs, volume fraction of fibers, CNT aspect ratio, plate geometry and boundary conditions on the nonlinear resonant dynamics and linear natural frequencies of CNT-FPMLC rectangular plate are investigated in the numerical results.


ABSTRACT: A first order shear deformation theory based finite element approach is used in this paper to investigate the free vibration behaviour of functionally graded thin, moderately thick and thick multi-layer composite plates reinforced with graphene nanoplatelets (GPLs). The effect of four different layer-wise variations of GPL distribution along the thickness and all possible plate edge boundary condition combinations on the natural frequencies of the plate are investigated. The effective Young's modulus for each layer and distribution type is determined using the modified Halpin–Tsai model, and mass density and Poisson's ratio are calculated based on the rule of mixture. Initially, present results are verified by comparing with available reported results. Thereafter, the method is used to conduct a parametric study, focusing on the effect of length to thickness ratio, different boundary conditions, GPL distribution patterns, percentage weight fraction of GPL, and geometry and size of GPL on the natural frequencies and percentage increase in natural frequencies.

ABSTRACT: This paper investigates a diffuse acoustic field to analyze the wave propagation on infinite doubly curved laminated composite shell sandwiching a porous material which is extensively used in aerospace structures. In fact, the main goal is to study the influence of embedded porous core on Sound Transmission Loss (STL) of the structure. Accordingly, Biot's theory is employed to model the poroelastic material which considers three types of wave propagation including two compression and one shear terms. In addition, Shear Deformation Shallow Shell Theory (SDSST) is applied to derive the wave propagation through double-walled laminated composite shell. Moreover, a numerical process is prepared to investigate a random incidence STL in a diffuse acoustic field which results in presenting the Limiting angle of incidence in which no incident wave is transmitted through structure. Then, in order to show the accuracy and the reliability of the present results, some comparisons are made between the achieved results and those of analytical as well as experimental results available in literature. Besides, the importance of using porous material as a core has been presented. Finally, some effective parameters have been studied in numerical results to inspect the insulation property of the current composite structure.


ABSTRACT: Smart control and vibration analysis of laminated sandwich truncated conical shells with piezoelectric layers as sensor and actuator are presented in this paper. The core of the sandwich structure is reinforced by carbon fibers and carbon nanotubes (CNTs) where the effective material properties are obtained by Halpin–Tsai model. The actuator layer is subjected to external voltage and a Proportional-Derivative (PD) controller is used for sensor output control. Based on Kelvin–Voigt model, the structural damping effects are assumed. The formulation of the problem is based on the layerwise first order shear deformation theory (FSDT). Considering the continuity of the displacements and the internal stress fields at the interfaces of the layers, the motion equations are derived utilizing Hamilton's principle. The solution of the problem is carried out by differential quadrature method (DQM) for calculating the frequency of the smart sandwich structure. The effects of different parameters such as structural damping, weight percent of CNTs, boundary conditions, geometrical parameters of the structure, semi vertex angle of the cone, external voltage, temperature and moisture changes are examined on the vibration response of the smart sandwich structure. Numerical results indicate that using a PD controller can increase the frequency of the structure. In addition, the hygrothermal load decreases the vibration frequency of the system.


ABSTRACT: The present paper aims at the study of the dynamic behavior of functionally graded carbon nanotubes-reinforced composite shell structures (FG-CNTRC) via forced vibration analysis. The governing equations of motion are developed using a linear discrete double directors finite element model. The elaborated model is based on high-order-distribution of displacement field and uses a cubic variation of the vector position along the thickness direction. A zero transverse shear stress at top and bottom surfaces is also imposed. Four types of distributions of carbon nanotubes (CNTs) such that uniformly and three functionally graded distributions are considered. The extended rule of mixture is used to estimate the effective material properties of
carbon nanotube-reinforced composite (CNTRC) shell. The applicability and the performance of the present model are illustrated by three numerical examples of FG-CNTRC square plates, spherical caps and annular ring plates. The transient center deflections of the studied shell structures are computed and depicted for different volume fractions and profiles of CNTs, various boundary conditions and other geometrical parameters in order to show the effect of these parameters on dynamic behavior of FG-CNTRC shells.

ABSTRACT: In this paper, buckling analysis of two-directionally porous beam is conducted. Based on the available results of Young’s modulus and mass density via Gaussian random field theory, a new two-directionally porous beam model is developed. With the help of Euler–Bernoulli beam theory and minimum total potential energy principle, the equilibrium equations for nonlinear and linear buckling are derived. The numerical solutions of critical buckling loads for different porosity distribution patterns can be obtained by generalized differential quadrature method. The final numerical results exhibit that more porosities near the middle surface or the two edges of beam can lead to a larger critical buckling load when the same total volume fraction of porosity is in different porosity distribution patterns. The effect of porosity distribution in thickness direction is more dominated on the critical buckling load than that of the axial porosity distribution. Moreover, the critical buckling load becomes more sensitive to aspect ratio of beam and total volume fraction of the porosity when increasing mode number. The critical buckling load of two-directionally porous beam depends not only on bending coefficient (like the one-directionally porous beam), but also on first and second derivatives of the bending coefficient.

ABSTRACT: The aim of this research paper is to present the elastic buckling and free vibration analyses of porous-cellular plates based on the first-order shear deformation theory (FSDT). In the porous-cellular plate model, porosities are dispersed by uniform and non-uniform (symmetric and asymmetric) distribution patterns. The material properties, such as Young's modulus and mass density of the porous-cellular plates are assumed to vary along the thickness direction in term of porosity coefficient. First, the dynamic version of Hamilton's principle is applied to derive the Euler–Lagrange equations. Then, in the case of simply supported boundary condition, the critical buckling load and natural frequency of the porous-cellular plates are obtained using the Navier procedure. Furthermore, the reliability of the current formulation is validated by several examples. Finally, a comprehensive examination into the influence of porosity coefficient, porosity distributions, and the geometric parameters on the buckling behavior and vibration response of the porous-cellular plates are performed. Numerical results indicate that the effect of porosity distributions on the structural performance and provide the useful insights into the porosity design to achieve appropriately natural frequency and buckling resistance.

ABSTRACT: Viscoelastic sheets, moving in an inviscid gas with initial varicose disturbances, have been investigated by performing a second-order temporal weakly nonlinear instability analysis based on the perturbation technique. The Oldroyd-B equation is considered as the rheological model of viscoelastic fluid. The solutions of the second-order disturbances have been derived, including the second-order dispersion
relation and the corresponding interface displacement. The results showed that the second-order interface displacement of the varicose mode was also varicose, which interacts with the fundamental varicose wave, causing disintegration of sheets at full-wavelength intervals and resulting in ligaments consisting of two connected swells. Much smaller satellite ligaments were also formed soon after breakup within such ligaments. Different breakup behaviors and mechanisms between sheets with initial varicose and sinuous disturbances are displayed and analyzed. It is found that the eventual shape of sheets depends mainly on three factors, the first-order and second-order temporal growth rates and the second-order disturbance amplitude. The breakup time has been calculated to assess the extent of nonlinear instability. The influence of dimensionless rheological parameters on instability, i.e. elasticity number and time constant ratio, are examined via comparison of the three key factors, breakup time and wave deformation at the shortest breakup time.


ABSTRACT: This paper presents an analytical approach to study nonlinear response and buckling analysis of FGM toroidal shell segments reinforced by FGM stiffeners surrounded by elastic foundations in thermal environment and under external pressure. The formulations are based on Reddy's third-order shear deformation shell theory (TSDT) with von Karman nonlinearity, Pasternak type elastic foundations and smeared stiffener technique. By applying Galerkin's method and using stress function, closed-form expressions for determining the static critical external pressure load and postbuckling load–deflection curves are determined. Finally, the influences of geometrical parameters, volume fraction index, elastic foundations, and the effectiveness of stiffeners on the stability of shells are considered.


ABSTRACT: In present paper, bending and buckling analysis of functionally graded material (FGM) annular microplate integrated with piezoelectric layers is investigated. The annular sandwich microplate is subjected to radial compressive and uniform transverse load. Considering the nonlocal elasticity theory for small scale effect is developed. In order to mathematical modeling of annular sandwich microplate, layerwise theory, is employed. Furthermore, the surrounding elastic medium is simulated by Pasternak foundation model, in which both compression and tension are assumed. The material properties of FGM annular microplate are supposed to vary through the thickness according to power law. Using energy method and principle of minimum potential energy, the size dependent governing motion equations are derived. In this study, the governing motion equations are solved numerically using differential quadrature (DQ) method. The present numerical solutions are validated through comparisons against those available in open literature for the reduced cases. Also, different boundary conditions at the edges of the annular sandwich microplate are considered. A parametric study is conducted to examine the effects such as elastic foundation, small scale effect, various boundary conditions, number of grid point, external voltages of piezoelectric layers, outer–inner radius ratio on the critical buckling load, are developed. The results clarify that external voltages are effective parameter on the critical buckling load and the bending behavior of the system. In addition, the effects of elastic foundation is very remarkable on the buckling and deflection of the annular sandwich plate.
ABSTRACT: Mixed zig-zag plate theories are derived from a recently developed 3-D five d.o.f. zig-zag “adaptive” theory ZZA (a priori fulfillment of interfacial stress constraints) under steadily growing limiting assumptions on displacement, strain and stress fields. The intended aim is trying to save computational costs simultaneously preserving accuracy. Lower-order theories assume a uniform or a polynomial transverse displacement, out-of-plane stresses are derived from local equilibrium equations or retaken from higher-order theories. The focus of this study is twofold: (i) to assess whether and for which cases a higher-order through-thickness zig-zag transverse displacement representation is essential, or vice versa a simpler kinematics can be assumed; (ii) to compare accuracy of theories based on Murakami's and Di Sciuva's zig-zag functions with the same expansion order across the thickness. A number of challenging benchmarks are retaken from literature and new benchmarks with a strong variation of material properties (damaged layers), distributed or localized step loading and some different boundary conditions are considered to assess accuracy of theories and of FEA 3-D (constituting the reference solution in lack of exact results). For these benchmarks, closed-form solutions are obtained assuming the same expansion order across the thickness and the same in-plane trial functions for all theories. The numerical illustrations show that lower order and Murakami's based theories fail for cases having the strongest layerwise and transverse anisotropy effects, or a marked through-thickness asymmetry. The Hu–Washizu highest-order theory HWZZ is shown to be always the only as accurate as ZZA, despite it reduces the computational effort.

ABSTRACT: The current work deals with the assessment of dynamic stability behavior of laminated composite and sandwich plates subjected to in-plane static and periodic compressive loads based on a recently developed zigzag theory by the authors. This theory satisfies the traction-free boundary conditions at top and bottom surfaces of the laminate as well as the inter-laminar stress continuity at layer interfaces. Also, it obviates the need of artificial shear correction factor. The theory is based upon shear strain shape function assuming non-linear distribution of transverse shear stresses. An efficient C^0 continuous, eight-noded isoparametric element with seven field variables is employed for the dynamic stability analysis of laminated composite and sandwich plates. The boundaries of principal instability domains are obtained following Bolotin’s approach and are represented either in the non-dimensional load amplitude-excitation frequency plane or load amplitude-load frequency plane. A series of numerical examples on the dynamic stability analysis of laminated composite and sandwich plates are studied to demonstrate the effects of modular ratio, span to thickness ratio, boundary conditions, thickness ratio, static load factor and various load parameters on the principal instability regions. The predicted results are compared with the available existing results in order to ensure the performance of the proposed model.

ABSTRACT: A two-variable sinusoidal shear deformation theory (SSDT) and a nonlocal elasticity theory are applied in this paper to analyze the free vibration behavior of functionally graded (FG) polymer composite nanoplates reinforced with graphene nanoplatelets (GNPs), resting on a Pasternak foundation. Based on the proposed theory, the transverse deflection is assumed as summation of bending and shear transverse
deformations. Four different FG reinforcement patterns are here employed, namely a uniform distribution UD, and non-uniform distributions FG-O, FG-X and FG-A. The effective elastic modulus, the Poisson's ratio and the density of composite nanoplates are computed using the Halpin–Tsai model and the rule of mixture, respectively. The numerical results are validated through a comparative assessment of the results with respect to predictions from literature, including nanoplates and FG polymer composite plates. A wide parametric investigation shows the influence of some significant parameters, such as nonlocal parameters, total number of layers, weight fraction, as well as parameters related to the Pasternak foundation and geometry, on the free vibration response of FG polymer composite nanoplates reinforced with GNP.

ABSTRACT: In this work, postbuckling behaviors of grid-stiffened cylinders under compressive loads are examined in an attempt to establish an analytical method to derive the shell Knockdown factor for space launch vehicle structures. Two grid systems using stiffeners – traditional orthogrid and hybrid-grid systems – are considered for the stiffened cylinders. The hybrid-grid system consists of major and minor stiffeners, which have two different cross-sectional sizes. Additionally, the baseline and minimum weight models are considered for each grid-stiffened cylinder model. The single perturbation load approach is used to represent the geometrical imperfection of cylinders. A commercial finite element analysis code, ABAQUS, is used for the postbuckling analyses. The present numerical simulations investigate the global and local instabilities for both stiffened cylinders using orthogrid and hybrid-grid systems. The global buckling load for the hybrid-grid stiffened cylinder is higher than that for the traditional orthogrid stiffened cylinder for both the baseline and minimum weight models. However, the postbuckling behaviors for the hybrid-grid stiffened cylinders are more complex, as compared to those for the orthogrid stiffened cylinders. Additionally, the shell Knockdown factors are derived using obtained numerical analysis results for the grid-stiffened cylinders. Since the shell Knockdown factor of the hybrid-grid stiffened cylinder is higher than that of the traditional orthogrid stiffened cylinders for both the baseline and minimum weight models, the hybrid-grid stiffened cylinder is more efficient in terms of the buckling design when compared to a traditional orthogrid stiffened cylinder. Furthermore, the derived Knockdown factors in the present work are higher than the values by NASA's buckling design criteria.

ABSTRACT: The main objective of this research work is focused on sound transmission loss analysis of stiffened double laminated composite sandwich plate structures subjected to plane sound wave excitation, wherein the laminated composite plates are composed of perfectly bonded functionally graded carbon nanotubes (CNTs) reinforced composite layers, and in each layer, the carbon nanotubes is uniform or functionally graded along with the thickness direction of structures, and three types of the CNTs distributions are studied. The extended rule of mixture is employed to determine the properties of the composite material. The compatibility of displacements on the interface between the plate and the stiffeners is employed to derive the governing equation of each stiffener. Then fluid–structure coupling is considered by imposing velocity continuity condition at fluid–structure interfaces. By using the space harmonic approach and virtual work principle, the sound transmission loss is described analytically. Since no existing results of sound insulation can be found for such composite material plate structure, comparison studies can only be made with the isotropic and laminated case. Good agreement is found from these comparison studies. Based on the developed
theoretical mode, the influences of the volume fractions of CNTs, distribution type of CNTs, structural damping, lamination angle and the number of layers on sound transmission loss are subsequently presented.


ABSTRACT: This study introduces a new quasi-3D (three-dimensional) higher-order shear deformation theory (HSDT) capable of accounting for the through-thickness deformations with only four unknowns, which is suited to the numerical method for buckling analysis of functionally graded material (FGM) plates in thermal environments. The refined quasi-3D HSDT is incorporated into the improved meshless radial point interpolation method (RPIM) in order to scrutinize the thermal buckling responses of FGM plates. In the improved RPIM, the radial basis function is presented in a compactly supported form to build the shape functions without any fitting parameters. Parametric studies on the buckling behavior of FGM plates under various types of through-thickness temperature changes are conducted and the effects of temperature distribution on the plate surface are investigated. Results illustrate the accuracy of the proposed meshless method based on the refined quasi-3D HSDT and the improved RPIM for predicting the thermal buckling behavior of FGM plates.


ABSTRACT: This paper investigates the buckling behavior of functionally graded graphene reinforced porous nanocomposite cylindrical shells with spinning motion and subjected to a combined action of external axial compressive force and radial pressure. The weight fraction of graphene platelet (GPL) nanofillers and porosity coefficient are constant in each concentric cylindrical shell but vary layer-wise through the thickness direction, resulting in position-dependent elastic moduli, mass density and Poisson's ratio along the shell thickness. The first-order shear deformation theory incorporated with the von Kármán's geometrical nonlinearity is employed to describe the pre-buckling deformation. The governing equations of the cylindrical shell are established by using the minimum potential energy principle where the centrifugal effect due to the spinning motion of the cylindrical shell is considered. The pre-buckling deformation is derived by adopting the Galerkin method, then the axial critical buckling force, radial critical buckling pressure and critical buckling hydrostatic pressure are obtained with the effect of pre-buckling deformation being taken into account. Special attention is given to the effects of the porosity coefficient, the weight fraction, the dispersion pattern, the geometrical size of the GPL and spinning speed of the cylindrical shell on the pre-buckling deformation and different types of critical buckling loads of the porous nanocomposite cylindrical shell.


ABSTRACT: This paper presents a model which is effective and simple based upon Second Order Shear Deformation Theory (SSDT) to comprehensive study of Functionally Graded Carbon Nanotube Reinforced Composite (FG-CNTRC) plates including size effects for the first time. Also it is the first time that the size-dependent static, stability and dynamic response of FG-CNTRC plates considering Winkler–Pasternak elastic foundation effects are investigated. It is assumed that the material properties of FG-CNTRC are varied through the thickness direction using four different distributions of carbon nanotubes (CNTs). In order to include the size effects in our modeling, the nonlocal elasticity theory presented by Eringen is utilized. The influences of different parameters such as volume fraction of carbon nanotubes, nonlocality and elastic foundation effects on
the response of FG-CNTRC plates are studied. Numerical results prove high accuracy and reliability of the present method in comparison with other available numerical or analytical methods.


ABSTRACT: This paper is devoted to investigate the aerothermoelastic flutter and thermal buckling characteristics of composite laminated cylindrical shells with elastic boundary conditions. In the structural modeling, Donnell’s shell theory is employed, and the supersonic piston theory is applied to evaluate the aerodynamic pressure. The elastic boundary constraints for the cylindrical shell are simulated by a series of distributed artificial springs. The shape functions of the laminated cylindrical shell with elastic boundary conditions are composed of characteristic orthogonal polynomials which are derived by the Rayleigh–Ritz method. The equation of motion of the structural system is established using Hamilton's principle. The high accuracy of the present method is verified by comparing the natural frequencies and flutter bounds with published results. Based on the frequency domain method, the aerothermoelastic properties of the laminated cylindrical shell with elastic boundary conditions are analyzed. The influences of different types of spring stiffnesses on the flutter and thermal buckling bounds are studied in detail. In addition, the influences of several parameters including the length to radius ratio, ply angle and boundary condition on the aerothermoelastic behaviors of the laminated cylindrical shell with elastic boundary conditions are researched.

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ABSTRACT: A semianalytical method hybridizing hierarchical theory and finite-strip method (FSM) is developed to analyze buckling behavior of composite laminate shells in this paper. The Legendre orthogonal polynomial series are chosen as the hierarchical shape functions for the shell strips. The critical buckling loads and modes of cylinder shells with various radiuses subjected to axial loads are calculated by the proposed hierarchical finite-strip method (HFSM). The efficiency of HFSM is noted as the method combines the advantages of both hierarchical theory and FSM. The convergence and precision of HFSM are also demonstrated by several numerical examples.
Guotao Yang and Mark A. Bradford (Civil Engineering, Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, UNSW Australia, UNSW Sydney, NSW 2052, Australia), “Postbuckling snaking of axially loaded infinite beam on nonlinear foundation with restabilizing effects”, ASCE Journal of Engineering Mechanics, Vol. 143, No. 6, June 2017 https://doi.org/10.1061/(ASCE)EM.1943-7889.0001217

ABSTRACT: Long slender elastic structures, such as railroad tracks, pipelines, and pavements, may experience buckling owing to axial compressive forces developed in them as a result of thermal or other effects, and in many cases these structures can be simplified as a beam on an elastic foundation. This paper presents an investigation of the critical buckling and postbuckling of such an elastic structure on a nonlinear foundation that has softening and restabilizing effects. The method of minimization of the total potential energy of the beam-foundation system is invoked to develop a differential equation of equilibrium and a differential equation of critical buckling (or bifurcation) of the beam. The analysis shows that critical buckling may be in a symmetric or in an antisymmetric mode, depending on the length of the beam, and when the length is extremely large, the two buckling modes are indistinguishable. The equations of the postbuckling equilibrium of the beam are highly nonlinear. To elucidate the response of the beam, a multiple-scale perturbation technique as used in modal analysis and a numerical solution based on a shooting technique are developed. It is shown that the postbuckling equilibrium of the beam has two stages after its critical buckling: a postbuckling localization stage that is unstable, and a subsequent postbuckling snaking stage characterized by a zigzag of the equilibrium configuration, and this snaking stage is dependent on the relative effects of the softening and restabilizing parameters. Comparisons of the perturbation solutions with the results of the numerical formulation show that the former semianalytical technique is accurate in the initial stages of postbuckling during which localization develops, but not in the subsequent snaking stage. The effect of the foundation parameters is also investigated in the paper.

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ABSTRACT: In this paper the influence of bimoment, induced by external axial loads, on the global buckling of thin-walled Z-section beams, subjected to different boundary conditions, is studied. Since bimoment varies along the beam axis, the problem of torsional and torsional-flexural buckling of thin-walled beams is defined by linear homogeneous differential equations of the second-order theory with a variable coefficient. To obtain the buckling load numerically, a finite-difference method is employed for discretizing the governing differential equations. To verify the validity and the accuracy of this study, numerical solutions are presented and compared with those calculated by simulation software.


ABSTRACT: For the standard extended finite-element method (XFEM), the degrees of freedom (DOFs) at nodes around the surfaces and tips of cracks are enriched to represent the discontinuity and the singularity of
cracks. However, for the incremental approach, the XFEM encounters some troubles as the total number of DOFs increases with the crack growth. This leads to difficulties of the matrix algorithm. In this paper, a multidimensional space method for geometrically nonlinear problems under the total Lagrangian formulation is presented to simulate the crack growth and coalescence. The multidimensional space method is developed from the XFEM. The core concept is that the two-dimensional domain containing cracks is placed into the 12-dimensional space. Each node has $12n$ DOFs in the domain containing $n$ cracks. The total Lagrangian formulation is applied to analyze the two-dimensional (2D) geometrically nonlinear problems, especially for large deformation. Moreover, three numerical experiments are presented to verify the efficiency and robustness of the proposed method.

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ABSTRACT: This paper presents an analysis of thermal-mechanical snap-through instabilities in structures using a hybrid load-controlled/displacement-controlled algorithm. The derivation uses the finite element method with a combination of modified Newton-Raphson and arc-length methods, aimed at providing a robust and efficient means for modeling the buckling response of structures that exhibit instability in the presence of nonuniform time-varying temperature fields and temperature-dependent material response. Load control is used to model the system’s response up to the point of instability, which is identified using the method of bisections. During the instability, the analysis switches to displacement control to capture the load-shedding behavior. Once a stable point is reached, the algorithm switches back to load control. The novelty lies in the ability of the hybrid algorithm to model instabilities that are caused by material degradation under nonuniform transient temperature fields, which is particularly important in the study of structural response under fire hazards. Numerical analyses are carried out using a two-dimensional (2D) fiber-based corotational beam element. Verifications at room temperature and at elevated temperature demonstrate that the proposed approach exhibits a high level of accuracy. A brief study of toggle frames subjected to various types of heating and loading conditions is presented to illustrate the kinds of behaviors that can be captured with the proposed modeling approach.

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ABSTRACT: Natural frequencies and mode shapes of a complex shell composed of a circular cylindrical shell and hemispherical shell with variable thickness are determined by the Ritz method using a mathematically three-dimensional (3D) analysis instead of two-dimensional (2D) thin-shell theories or higher-order thick-shell theories. The present analysis is based upon the circular cylindrical coordinates, whereas in traditional shell analyses, 3D shell coordinates have usually been used. Using the Ritz method, Legendre polynomials, which are mathematically orthonormal, are used as admissible functions instead of ordinary simple algebraic polynomials. Natural frequencies are presented for different boundary conditions. Convergence to four-digit exactitude is demonstrated for the first five frequencies of the combined shell. The frequencies from the present
3D method are compared with those from three types of 2D thin-shell theories found by previous researchers. The present method is applicable to very thick shells as well as thin shells and complex shells with variable thickness.

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ABSTRACT: The load-carrying capacity of circular sandwich panels under the quasi-static loading applied in the central area is investigated in this paper. The panels consist of two metallic face sheets and a metallic foam core, and they are simply supported or fully clamped at the edges. A velocity field is assumed to estimate the large deflection response, which is defined according to the initial deformation mode of the flat panel and boundary condition. In order to validate the analytical solution a finite-element simulation has been performed. Good agreement confirms that the quasi-static behavior of circular sandwich plates is well captured by the analytical model. A parametric study is then carried out to examine the effect of the boundary condition, face-to-core thickness ratio, and core strength on the structural response. It is shown that membrane effect caused by large deflection has a significant influence on the postyield response, especially in the case of a fully clamped boundary. Using the analytical model, a comparative study is carried out between the sandwich panels and monolithic plates, on their energy-dissipating performance.

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ABSTRACT: This study investigates propagation buckling of subsea pipe-in-pipe (PIP) systems under hydrostatic pressure. Unlike in previous studies, PIP systems consisting of carrier pipes with a diameter-to-thickness (Do/to) ratio in the range 26–40 are examined here. Experimental results from ring squash tests (RSTs), confined ring squash tests (CRSTs), and hyperbaric chamber tests are presented and compared with a modified two-dimensional (2D) analytical solution and with numerical results using three-dimensional (3D) finite-element (FE) analysis. The comparison indicates that the proposed modified analytical expression provides a more accurate lower-bound estimate of the propagation buckling pressure of PIP systems compared with the existing equations, especially for higher Do/to ratios. The novel RST and CRST protocols proposed for PIP systems give lower-bound estimates of the propagation pressure. The FE analysis outcomes demonstrate that the lengths of PIP system transition zones are almost twice the corresponding lengths in single pipes. New modes of buckling are discovered in the hyperbaric chamber tests of PIP systems with Do/to=26.

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ABSTRACT: Multistable structural members are extensively used in various fields, including microelectromechanical systems (MEMS) actuation, sensing, and energy harvesting. The multistable configuration of elements can be obtained through their elastic postbuckling response. Under quasi-static excitations, the snap-through transitions of buckled elements constitute a useful tool to generate high-rate excitations for piezoelectric transducers. Yet, more efficient energy harvesting and accurate sensing requires that buckling events happen at specific loading levels. This paper investigates the control of snap-through events by using beam assemblies. Multiple bilaterally constrained beams were arranged in parallel and subjected to axial displacement–controlled loading. Experimental studies show that snap-buckling transitions can be controlled by changing the geometry of the assembled beams. An analytical model was developed to investigate the effect of system parameters on its postbuckling response. Results show that transitions are mainly controlled by the beams' thicknesses and lengths. By tuning both parameters, the system can be designed to snap at a desired axial displacement. In this paper, the assemblies were designed to transition at equally spaced axial displacements. However, other displacement combinations can be achieved.

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ABSTRACT: An energy-based solution is developed for the lateral torsional buckling analysis of wooden beams with a midspan lateral brace subjected to uniformly distributed loads or midspan point load. The predicted critical moments and mode shapes are shown to agree with results based on three-dimensional finite-element analysis. The study indicates that such beams are prone to two buckling patterns: a symmetric mode and an antisymmetric mode. Whether the symmetric or the antisymmetric mode governs the critical moment capacity is shown to depend on the bracing height. A technique is developed to determine the threshold bracing height required to maximize the critical moment. A parametric study is conducted to investigate the effect of lateral bracing and load height effects on the critical moments. Simple design equations are developed to predict critical moments for a practical range of cases. The limitations of the simplified procedure are discussed. For cases outside the scope of the simplified procedure, designers are recommended to adopt the more detailed energy-based solution. Design examples are provided to illustrate the merits and applicability of the proposed procedure in practical situations.


ABSTRACT: This article investigates the structural stability of prismatic columns with elastically restrained ends under axial compressive force. An emphasis is placed on the analysis of the effect of Engesser’s and Haringx’s hypotheses on buckling. Based on the Timoshenko beam theory and a higher-order shear-deformable beam theory, simple characteristic equations were derived for buckling of an axially loaded elastic column with two ends linked to translational and rotational springs. By introducing orientation factor $\alpha$, a buckling load falls
between those corresponding to Engesser’s ($\alpha=0$) and Haringx’s ($\alpha=1$) models. For freely standing, simply supported, and clamped columns, explicit expressions for each critical load were obtained. The effects of Engesser’s and Haringx’s hypotheses as well as of the translational and rotational spring rigidities at the elastically restrained end on buckling loads are analyzed in detail. Obtained results indicate that Engesser’s and Haringx’s hypotheses hardly affect buckling loads for a column with strong shear rigidity, and they have a significant influence on buckling loads for a column with weak shear rigidity. The effect of translational spring rigidity on buckling loads is more pronounced than that of rotational spring rigidity.


ABSTRACT: In this paper, the static and dynamic behaviors of a finite microstructured rectangular membrane were studied. The microstructured membrane model comprised an equal number of elastic springs in both directions forming a rectangular lattice membrane. The authors considered the out-of-plane displacement of each node of this two-dimensional lattice. The rectangular lattice membrane was fixed at its boundary. A nonlocal continuous membrane model was developed to approximate the behavior of the finite lattice model. A continualization procedure was applied to the discrete equations in which the difference operators were approximated by differential operators. The resulting nonlocal continuum was governed by some length scales in each direction that depended on the size of the microstructure. This nonlocal continuum exactly coincided with the one elaborated by Rosenau in the 1980s in the dynamics range. The authors showed that such a nonlocal medium also can be used for static deflection of microstructured membranes. A comparison of both discrete (the reference lattice model) and continualized nonlocal responses brought out the effectiveness of this micromechanics-based approach. The continualized nonlocal continuum also was compared with a phenomenological Eringen’s nonlocal model.


ABSTRACT: In this study, the weak-form finite-element model has been developed for bending of plates considering the rotation gradient–dependent potential energy along with the conventional strain energy in the case of moderate rotation for Cosserat solid. The microrotation of the material point is considered to be constrained with the macrorotation of the continua. First, the governing equations are obtained from the principle of virtual displacements considering the displacement field as general power (Taylor) series expansion about the displacement of the midplane of the plate, and then the formulations are specialized for the general third-order, first-order, and the classical plate theory. The nonlinear finite-element models have been developed for all the plate theories considered. Further, the analytical solution for a simply supported linear plate is presented. In the numerical examples, the stiffening and anisotropic effects in response to oriented microstructures in the continuum of a microplate are illustrated. The parametric effect of the material length scale on the various components of stress is also studied.


ABSTRACT: It is well established that the lateral bending stiffness of thin panels is considerably enhanced by judicious use of ribs or stiffeners. This increase in stiffness is primarily due to a disproportionate increase in the second moment of area, and because relatively little mass is added, stiffened panels are especially appealing in
an aerospace engineering context. In experiments it is relatively straightforward to measure bending deflections (especially in a cantilever configuration) and natural frequencies using laser vibrometry and associated signal-processing tools. This paper reports on a parametric study in which bending stiffness and natural frequencies are measured for a set of rectangular panels, conveniently manufactured using a three-dimensional (3D) printer. Both isogrid (stiffeners in a triangular configuration) and orthogrid (stiffeners in a rectangular configuration) structures were made and tested, with certain nondimensional parameters held constant (for example, total mass and length-to-width ratio) to facilitate easier comparison. The boundary condition considered was one edge clamped and the other edges free (simple cantilever) with a consistent plan area aspect ratio, and with the height and arrangement of stiffening ribs providing the major parametric variation.

ABSTRACT: This paper investigates the nonlinear elastic in-plane dynamic buckling of a fixed shallow circular arch that was subjected to an arbitrarily located step radial point load, which has not been previously reported in the literature. The arbitrary step load produced unsymmetrical deformations of the arch and unsymmetrical internal forces in the arch and caused the arch to oscillate unsymmetrically. Because the unsymmetrical equilibrium path was nonlinear and consisted of a primary stable branch, an unstable branch, and a remote stable branch, when the step load reached a critical value, the arch could oscillate to reach the unstable equilibrium branch and subsequently lose its in-plane stability in a dynamic buckling mode. Hence, the first condition for dynamic buckling of the arch was that the load could induce oscillation of the arch sufficiently large to reach an unstable equilibrium position. The second condition was derived on the basis of the principle of the conservation of energy: the total potential energy of the system needed to vanish for its possible dynamic buckling. This condition could be used in conjunction with the nonlinear equilibrium path to derive the analytical solution for the dynamic buckling load of shallow arches under an arbitrary step radial point load. The unsymmetrical effects of the load position on the dynamic buckling load were found to be significant. First, if the load was not applied at the crown of the arch, there was only one dynamic buckling load. This was different from the case of a fixed arch subjected to a step point load at its crown, in which an upper and a lower dynamic buckling load exist. Second, the dynamic buckling load first decreased and then increased as the point of the application of the load moved away from the crown. Third, when the load position exceeded a specific value from the crown, the arch did not experience dynamic buckling but oscillated around a stable equilibrium point under the step load. The effects of the modified slenderness on the dynamic buckling were also investigated, and it was found that the dynamic buckling load increased with an increase of the modified slenderness. Finally, the comparisons with the nonlinear elastic static in-plane buckling showed that the nonlinear elastic dynamic buckling load of an arch was lower than its static counterpart.

ABSTRACT: Models, typically given by systems of mathematical equations, are built to help represent, understand, and further characterize physical phenomena. The choice of a model for a particular phenomenon is made based on user judgment, evidence from measurement data, and/or the ease of its use. Generally, many linear and nonlinear models are available to describe a particular structural dynamical system. Bayesian model selection is a probabilistic tool to help select suitable mathematical model(s) among a possible set of models using Bayes’ theorem. To simplify the analysis, linear structural dynamical models are often used, regardless of whether the dynamical system behaves linearly or not. However, linear models are not always adequate to
accurately compute structural responses. When the models also involve some nonlinearity, the required computation for Bayesian model selection increases significantly. An important class of nonlinear problems consists of models that are mostly linear except for some spatially localized nonlinearities. For example, in a building with base isolation, the superstructure is designed to behave essentially linearly in an earthquake excitation and only the isolation layer behaves nonlinearly. Similarly, spacecraft may be modeled with linear components that are connected by spatially localized nonlinearities. To lessen this increased computational burden, a method is proposed in this paper, combining the senior authors’ previously developed efficient dynamic response algorithm for locally nonlinear systems and an intelligent sampling algorithm, to calculate the evidence for, or marginal likelihood of, a model. The efficient dynamic response algorithm helps achieve significant gains in computational efficiency by exactly transforming the potentially high-dimensional state-space equation of the structural dynamical system into a low-order nonlinear Volterra integral equation. This algorithm is embedded into a nested sampling algorithm, which samples parameters more frequently from the high likelihood region (even if the region of higher likelihood is very different from the region where the prior parameter density function is large), resulting in a computationally efficient framework for Bayesian model selection with locally nonlinear systems; a (moderately) alternate derivation of nested sampling is developed. The approach is demonstrated using three numerical examples. The first two examples consider building models mounted on a hysteretic isolation layer that are subjected to an earthquake excitation. Both single and 99-degree-of-freedom superstructure models are investigated. Different candidate linear and nonlinear models representing the hysteretic behavior of the isolation layer are used. The third example consists of a three-dimensional wind-excited 1,623-degree-of-freedom building structure with tuned mass dampers (TMDs) attached to its roof, where different linear and nonlinear candidate damping models are considered in the TMDs. All three examples include cases in which the true model is not among the models evaluated. The application of the proposed synergistic approach, consisting of an intelligent sampling and an efficient dynamic response algorithm, demonstrates gains in Bayesian model selection computational efficiency of up to three orders of magnitude relative to conventional approaches with comparable accuracy, reducing days of computation to minutes or hours.


ABSTRACT: This paper investigates the effect of long-range interaction forces in the longitudinal vibration of an axial linear elastic lattice. The eigenfrequencies of this axial lattice with direct and indirect linear elastic interactions are expressed in closed-form solutions for fixed-fixed and fixed-free boundary conditions. The paper starts with the two-neighbor interaction problem, and then generalizes the result to the more general N-neighbor interaction problem. Starting from a continualization of the higher-order difference equations, a nonlocal elastic continuum is constructed to approximate the behavior of the axial lattice with generalized short and long-range interactions. It is shown, while preserving the definite positiveness of the generalized lattice strain energy, that the associated nonlocal continuum is equivalent to a stress gradient type of Eringen’s nonlocal model, which is able to capture the main scale phenomena of the generalized lattice. The length scale factor of the nonlocal model is calibrated to the size of the influence domain for the long-range interaction. The paper ends with a discussion about the effect of the discrete interaction kernel on the sensitivity of the eigenfrequencies with respect to scale effects. Exact analytical natural frequencies are calculated for discrete power law or exponential-based kernels. The stress gradient nonlocal theory offers an efficient engineering continuum framework, which accurately fits the response of generalized lattice with N-neighbor interaction.

Ye Feng, Zi-Xiong Guo and Yi-Chao Gao, “An unconditionally stable explicit algorithm for nonlinear
ABSTRACT: An unconditionally stable explicit algorithm with second-order accuracy is proposed in state space. Stability, relative period error, and amplitude decay of the proposed algorithm are studied. It is shown that the proposed algorithm is unconditionally stable for linear systems and nonlinear systems whether the stiffness of the structure is the softening or hardening type. This stability property is appealing because currently, explicit algorithms cannot be unconditionally stable when the stiffness is the hardening type. In addition, the stability and accuracy of the proposed algorithm are demonstrated by several nonlinear numerical examples.

ABSTRACT: This paper enhances the available generalized beam theory (GBT) geometrically nonlinear (elastic) formulations by including (1) the whole set of nonlinear membrane strain terms, and (2) the nonlinear bending strain terms. Initially, the main steps involved in the derivation, development, and numerical implementation of the novel/enhanced GBT geometrically nonlinear formulation are presented in detail. Then, after comparing the proposed and available GBT nonlinear formulations, numerical results concerning two illustrative examples are presented and discussed. They make it possible (1) to better understand the concepts and procedures involved, and (2) to assess the relevance of the added nonlinear membrane and bending strain terms. Such results (1) concern a Z-column and a lipped channel beam under uniform stress resultant diagrams and buckling in distortional and local modes, respectively, and (2) comprise several equilibrium paths obtained from approximate or rigorous analyses, relevant displacement profiles, modal participation diagrams, and deformed configurations. For validation, the GBT-based results are compared with values yielded by shell finite-element analyses.

ABSTRACT: This paper analytically investigates the buckling and postbuckling of functionally graded composite plates reinforced by single-walled carbon nanotubes (SWCNTs), supported by elastic foundations and loaded by edge-compressive and thermomechanical loadings. The effective properties of a functionally graded carbon nanotube-reinforced composite (FG-CNTRC) plate were assumed to be graded in the thickness direction and were determined by the extended mixture rule. The basic equations for a geometrically imperfect plate were established according to the classical plate theory (CPT) incorporating nonlinear terms, a two-parameter elastic foundation, and elastic constraints of the in-plane boundary condition. The deflection and stress functions were assumed to satisfy the simply supported condition of the boundary edges, and the Galerkin procedure was adopted to obtain the explicit form results of the critical buckling loads and nonlinear relations of load and deflection. The important effects played by the tangential edge restraints on the nonlinear stability response of the FG-CNTRC plates were highlighted. In addition, the separate and combined influences of the volume percentage and the distribution patterns of the carbon nanotubes, aspect ratios, stiffness of foundations, thermal environments, and imperfection size on the buckling resistance capacity and postbuckling strength of FG-CNTRC plates were analyzed through a variety of numerical examples.

L.N. Yshii, E. Lucena Neto, F.A.C. Monteiro and R.C. Santana, “Accuracy of the buckling predictions of

ABSTRACT: The aim of this work is to explore the potential of two hierarchic sets, one polynomial and the other trigonometric, in the construction of versatile Ritz bases to accurately solve the linear buckling of anisotropic Kirchhoff plates. Focus is placed on reporting the basis ability to surmount numerical degrading effects associated with anisotropy. Several examples are presented to illustrate the merits and demerits of each set in terms of accuracy and rate of convergence, mainly by comparing their results with those obtained from traditional Ritz bases and finite-element models.


ABSTRACT: Four-point bending tests have been a staple in many structural engineering experiments as a reliable way of assessing the bending resistance of circular hollow sections, tubes and cylindrical shells, and they continue to be widely performed. However, relatively little attention appears to have been paid to quantify the effects of different boundary conditions on the test outcome. In particular, the restraint or freedom given to the cross-section at the ends of the specimen to ovalize can have a significant impact when the specimen is in an appropriate length range. Ovalization is an elastic geometrically nonlinear phenomenon that is known to reduce the elastic bending resistance by as much as half in long tubes or cylinders.

References listed at the end of the paper:

ABSTRACT: This paper investigates the axisymmetric free vibrations of annular single-layered graphene sheets with different boundary conditions using nonlocal elasticity theory. The analysis procedure is based on the first-order shear deformation theory and small deflections assumption to derive the equations of motion which are a system of partial differential equations with variable coefficients. In order to determine the transverse natural frequencies as well as the radial natural frequencies analytically, the perturbation technique is applied to solve these equations. The transverse natural frequencies are calculated using classical plate theory. The results of both theories are compared with those obtained from the literature. A parametric study is performed and the effects of nonlocal parameter, geometry, and boundary conditions on the natural frequencies are investigated.


ABSTRACT: A semianalytical method is developed to obtain the dynamic response of laterally loaded piles in a multilayered soil. In the analysis, the soil is modeled as a three-dimensional viscoelastic continuum with frequency-independent hysteretic material damping and the pile as a circular elastic Timoshenko beam. Unlike the Euler-Bernoulli beam that is conventionally used to model laterally loaded piles in various analytical, semianalytical, and numerical studies, the Timoshenko beam theory accounts for the effect of shear deformation and rotatory inertia within the pile cross-section that might be important for modeling short stubby piles with solid or hollow cross-sections and piles subjected to high frequency of loading. In the analysis, the soil displacements in the horizontal direction are expressed as products of separable functions, and the extended Hamilton’s principle in conjunction with the calculus of variations is used to obtain two sets of coupled differential equations governing pile and soil motions along with the relevant boundary conditions. The coupled equations are solved analytically and numerically following an iterative algorithm. The differential equation and boundary conditions governing pile motion are progressively reduced to model the pile as a Rayleigh beam and a Euler-Bernoulli beam; thus, a unified framework incorporating various beam theories for the dynamic soil-structure interaction of laterally loaded piles in a multilayered soil is developed. The accuracy of the present analysis is verified against the results of several analytical and numerical solutions available in the literature. It is shown from the solved example problems that rotatory inertia has practically no effect on the dynamic response of piles, whereas there is some effect of shear deformation on the response of piles with hollow cross-sections.

Kulmani Mehar, Trupti Ranjan Mahapatra, Subrata Kumar Panda, Pankaj V. Katariya and Umesh Kumar Tompe, “Finite-element solution to nonlocal elasticity and scale effect on frequency behavior of shear
ABSTRACT: In this article, the eigenfrequency responses of a nanoplate structure are evaluated numerically via a novel higher-order mathematical model and finite-element method including nonlocal elasticity theory. A new computer program has been prepared based on the present model to compute the frequencies of the nanoplate structure. The accuracy of the numerical solutions has been checked through proper convergence and comparison with available published data by evaluating an adequate number of examples. The conclusions related to the capability of solving nanoplate structural problem and subsequent accuracy of the current higher-order finite-element model have been demonstrated by solving several illustrations. Also, the numerical examples are solved by considering the nonlocal elasticity as well as the scale effect and other geometrical and material parameters (aspect ratio, size, and nonlocal parameter) that may directly affect the final solutions are discussed.

ABSTRACT: Modern structural analysis necessitates numerical formulations with advanced nonlinear attributes. To that end, numerous finite elements have been proposed, spanning from classical to hybrid standpoints. In addition to their individual features, all formulations originally stem from an underlying variational principle, which can be deemed as a unified energy metric of the system. The corresponding equations of structural equilibrium define a stationary point of the assumed principle. Following this logic in this work, the total potential energy is directly treated as an objective function, subject to some kinematic compatibility constraints, within the conceptions of nonlinear programming. The only approximated internal field is curvature, whereas displacements occur solely as nodal entities and Lagrange multipliers serve compatibility. Thereby, a new nonlinear programming hybrid element formulation is derived, which uses exact kinematic fields, can incorporate nonlinear assumptions of any extent, and is amenable to various applicable nonlinear programming algorithms. The suggested nonlinear program is presented in detail herein, together with its consistent second-order iterative solution procedure. The results obtained in benchmark nonlinear structural problems are validated and compared with OpenSees flexibility-based elements, showcasing notable performance in terms of accuracy, mesh density discretization, computational speed, and robustness.

ABSTRACT: In this paper, a mechanistic model for nanobeams with surface energy effects is developed by using a variational formulation. This work is motivated by the unusual response of nanocantilevers predicted by models based on the Young-Laplace equation for surface stress. The governing equation and boundary conditions derived from the variational methods are compared with the governing equations and boundary conditions used in the Young-Laplace models and other formulations. A key difference in the shear force boundary condition is noted. Analytical solutions for simply supported, cantilevered, and fixed-fixed beams are reexamined. It is shown that the unusual behavior of nanocantilevers predicted by the Young-Laplace models is due to the shear force boundary condition used. The current formulation leads to consistent solutions for beams under different boundary conditions.

No appropriate papers in December 2018 issue.
More papers published in the journal, Curved and Layered Structures (2017 and on):


ABSTRACT: This paper presents the efficient modeling and analysis of laminated composite plates using an eightnode quasi-conforming solid-shell element, named as QCSS8. The present element QCSS8 is not only lockingfree, but highly computational efficiency as it possesses the explicit element stiffness matrix. All the six components of stresses can be evaluated directly by QCSS8 in terms of the 3-D constitutive equations and the appropriately assumed element strain field. Several typical numerical examples of laminated plates are solved to validate QCSS8, and the resulting values are compared with analytical solutions and the numerical results of solid/solidshell elements of commercial codes computed by the present authors in which fine meshes were used. The numerical results show that QCSS8 can give accurate displacements and stresses of laminated composite plates even with coarse meshes. Furthermore, QCSS8 yields also accurate transverse normal strain which is very important for the evaluation of interlaminar stresses in laminated plates. Since each lamina of laminated composite plates can be modeled naturally by one or a few layers of solidshell elements and a large aspect ratio of element edge to thickness is allowed in solidshell elements, the present solid-shell element QCSS8 is extremely appropriate for the modeling of laminated composite plates.

References listed at the end of the paper:

(in Chinese)


ABSTRACT: Static and kinematic matrix operator equations are revisited for one-, two-, and three-dimensional deformable bodies. In particular, the elastic problem is formulated in the details in the case of arches, cylinders, circular plates, thin domes, and, through an induction process, shells of revolution. It is emphasized how the static and kinematic matrix operators are one the adjoint of the other, and then demonstrated through the definition of stiffness matrix and the application of virtual work principle. From the matrix operator formulation it clearly emerges the identity of the usual Finite Element Method definition of elastic stiffness matrix and the classical definition of Ritz-Galerkin matrix.

References listed at the end of the paper:


ABSTRACT: The purpose of this content is to investigate the free vibration of functionally graded parabolic and circular panels with general boundary conditions by using the Fourier-Ritz method. The first-order shear deformation theory is adopted to consider the effects of the transverse shear and rotary inertia of the panel structures. The functionally graded panel structures consist of ceramic and metal which are assumed to vary continuously through the thickness according to the power-law distribution, and two types of power-law distributions are considered for the ceramic volume fraction. The improved Fourier series method is applied to construct the new admissible function of the panels to surmount the weakness of the relevant discontinuities with the original displacement and its derivatives at the boundaries while using the traditional Fourier series method. The boundary spring technique is adopted to simulate the general boundary condition. The unknown
coefficients appearing in the admissible function are determined by using the Ritz procedure based on the energy functional of the panels. The numerical results show the present method has good convergence, reliability and accuracy. Some new results for functionally graded parabolic and circular panels with different material distributions and boundary conditions are provided, which may serve as benchmark solutions.

References listed at the end of the paper:


ABSTRACT: In this paper, free vibration analysis of annular sector plates has been presented via conical shell equations. By using the first-order shear deformation theory (FSDT) equation of motion of conical shell is obtained. The method of discrete singular convolution (DSC) and method differential quadrature (DQ) are used for solution of the vibration problem of annular plates for some special value of semi-vertex angle via conical shell equation. The obtained numerical results based on the two numerical approaches for annular sector plates compare well with the results available in the literature. The effects of some geometric parameters, grid numbers and types of the grid distribution have been discussed for curved plates.

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ABSTRACT: A simple analytical model to estimate the longitudinal strength of ship hulls in composite materials under buckling, material failure and ultimate collapse is presented in this paper. Ship hulls are regarded as assemblies of stiffened panels which idealized as group of plate-stiffener combinations. Ultimate strain of the plate-stiffener combination is predicted under buckling or material failure with composite beam-column theory. The effects of initial imperfection of ship hull and eccentricity of load are included. Corresponding longitudinal strengths of ship hull are derived in a straightforward method. A longitudinally framed ship hull made of symmetrically stacked unidirectional plies under sagging is analyzed. The results indicate that present analytical results have a good agreement with FEM method. The initial deflection of ship hull and eccentricity of load can dramatically reduce the bending capacity of ship hull. The proposed formulations provide a simple but useful tool for the longitudinal strength estimation in practical design.

References listed at the end of the paper:

ABSTRACT: Fiber reinforced anisotropic material abounds in biological world. It has been demonstrated in previous theoretical and experimental works that growth of biological soft tubular tissue plays a significant role in morphogenesis and pathology. Here we investigate growth-induced buckling of anisotropic cylindrical tissue, focusing on the effects of type of growth(constraint/unconstraint, isotropic/anisotropic), fiber property(orientation, density and strength), geometry and any interaction between these factors. We studied one-layer and two-layer models and obtained a rich spectrum of results. For one-layer model, we demonstrate that circumferential fiber orientation has a consistent stabilizing effect under various scenarios of growth. Higher fiber density has a destabilizing effect by disabling high-mode buckling. For two-layer model, we found that critical buckling strain at inner boundary is an invariant under same isotropic growth rate ratio between inner/outer layer($g_i/g_o$). Then we applied our model to wound healing and illustrate the effects of skin residual stress, fiber property, proliferation region width and wound size on the wound edge stability. We conclude that fiber-reinforcement is an important factor to consider when investigating growth induced instability of anisotropic soft tissue.
References listed at the end of the paper:


ABSTRACT: This paper presents the free vibration response of piezo laminated composite geometrically nonlinear conical shell panel subjected to a thermo-electrical loading. The temperature field is assumed to be a uniform distribution over the shell surface and through the shell thickness and the electric field is assumed to be the transverse component \(E_z\) only. The material properties are assumed to be independent of the temperature and the electric field. The basic formulation is based on higher order shear deformation plate theory (HSDT) with von-Karman nonlinearity. A \(C^{0}\) nonlinear finite element method based on direct iterative approach is outlined and applied to solve nonlinear generalized eigenvalue problem. Parametric studies are carried out to examine the effect of amplitude ratios, stacking sequences, cone angles, piezoelectric layers, applied voltages, circumferential length to thickness ratios, change in temperatures and support boundary conditions on the nonlinear natural frequency of laminated conical shell panels. The present outlined approach has been validated with those available results in the literature.

References listed at the end of the paper:


ABSTRACT: The main goal of the present paper was to study the physical response of a double side skin...
(DSS) structure under impact load in a collision event between two ships. Collision energy and damage extent (size and location) during the collision process were observed together with damage patterns on side structure. The ships were modeled after a Ro-Ro passenger ship and cargo reefer which were involved in a ship collision on the Sunda Strait while the analyses were performed using non-linear simulations FEM to produce virtual simulation data. Several cases were proposed to be investigated in this work with involvement of parameters i.e. penetration location and ship materials which were embedded on the structure model. A series of material experiments and testing was conducted to obtain detailed material properties which were to be deployed in simulation. It was shown that, after penetration at the transition location, the striking ship was successfully deforming and forming tears to the inner skin. On the other hand, with identical structure and identical mass of construction, the use of high-strength low-alloy (HSLA) steel as the repair material offered considerably better capacity in absorbing the impact load than plain-carbon steel.

References listed at the end of the paper:


ABSTRACT: Based on the transfer matrix theory and precise integration method, the precise integration transfer matrix method (PITMM) is implemented to investigate the free vibration characteristics of isotropic coupled conical-cylindrical shells. The influence on the boundary conditions, the shell thickness and the semivertex conical angle on the vibration characteristics are discussed. Based on the Flügge thin shell theory and the transfer matrix method, the field transfer matrix of cylindrical and conical shells is obtained. Taking continuity conditions at the junction of the coupled conical-cylindrical shell into consideration, the field transfer matrix of the coupled shell is constructed. According to the boundary conditions at the ends of the coupled shell, the natural frequencies of the coupled shell are solved by the precise integration method. An approach for studying the free vibration characteristics of isotropic coupled conical-cylindrical shells is obtained. Comparison of the natural frequencies obtained using the present method with those from literature confirms the validity of the proposed approach. The effects of the boundary conditions, the shell thickness and the semivertex conical angle on vibration characteristics are presented.

References listed at the end of the paper:


ABSTRACT: This paper describes the behaviour of axially loaded long and eccentrically loaded short thin-walled steel channels, strengthened with transversely bonded carbon fibre reinforced polymer (CFRP) sheets. Seven long members, each 1400 mm long, and seven short members, each 750mm long, were tested. The main parameters were the number of CFRP plies (one or two) and the clear spacing between the CFRP strips (50, 100 or 150 mm). The effect of CFRP sheet layer and clear spacing was studied. All the ultimate load capacity of the reinforced members was improved in different extent. A maximum strength gain of 9.13% was achieved for long members with two CFRP layers and 50 mm spacing of CFRP strips. The experimental results show that the global buckling happens to all the long specimens. For short members, the maximum strength gain of 12.1% was achieved with two CFRP layers and 50 mm spacing of CFRP strips. With the exception of the most heavily reinforced (2 plies at 50 and 100 mm), local buckling was observed prior to global buckling for short members, which was completely opposite of the control specimens. Meanwhile, when the clear spacing of CFRP strips is greater than the web height of steel channel, the transversely bonded CFRP does not have a significant improvement in buckling load capacity of the short- and long-channel components. While the clear spacing is less than the web height, the more number of CFRP layer, the more enhancement of buckling load capacity.

References listed at the end of the paper:


ABSTRACT: This paper presents the first known vibration characteristics of moderately thick functionally graded carbon nanotube reinforced composite rectangular plates on Pasternak foundation with arbitrary boundary conditions and internal line supports on the basis of the firstorder shear deformation theory. Different distributions of single walled carbon nanotubes (SWCNTs) along the thickness are considered. Uniform and other three kinds of functionally graded distributions of carbon nanotubes along the thickness direction of plates are studied. The solutions carried out using an enhanced Ritz method mainly include the following three points: Firstly, create the Lagrange energy function by the energy principle; Secondly, as the main innovation point, the modified Fourier series are chosen as the basic functions of the admissible functions of the plates to eliminate all the relevant discontinuities of the displacements and their derivatives at the edges; Lastly, solve the natural frequencies as well as the associated mode shapes by means of the Ritz-variational energy method. In this study, the influences of the volume fraction of CNTs, distribution type of CNTs, boundary restrain parameters, location of the internal line supports, foundation coefficients on the natural frequencies and mode shapes of the FG-CNT reinforced composite rectangular plates are presented.

References listed at the end of the paper:


ABSTRACT: In this paper, an efficient and unified approach for free vibration analysis of the moderately thick
functionally graded carbon nanotube reinforced composite annular sector plate with general boundary supports is presented by using the Ritz method and the first-order shear deformation theory. For the distribution of the carbon nanotubes in thickness direction, it may be uniform or functionally graded. Properties of the composite media are based on a refined rule of the mixture approach which contains the efficiency parameters. A modified Fourier series is chosen as the basic function of the admissible function to eliminate all the relevant discontinuities of the displacements and their derivatives at the edges. To establish the general boundary supports of the annular sector plate, the artificial spring boundary technique is implemented at all edges. The desired solutions are obtained through the Ritz-variational energy method. Some numerical examples are considered to check the accuracy, convergence and reliability of the present method. In addition, the parameter studies of the functionally graded carbon nanotube reinforced composite annular sector plate are carried out as well.

References listed at the end of the paper:


ABSTRACT: In this paper, a unified solution for vibration analysis of the functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical panels with general elastic supports is carried out via using the Ritz method. The excellent accuracy and reliability of the present method are compared with the results of the classical boundary cases found in the literature. New results are given for vibration characteristics of FG-CNTRC cylindrical panels with various boundary conditions. The effects of the elastic restraint parameters, thickness, subtended angle and volume fraction of carbon nanotubes on the free vibration characteristic of the cylindrical panels are also reported.

References listed at the end of the paper:


ABSTRACT: A hybrid-mixed functionally graded material (FGM) piezoelectric four-node solid-shell element through the sampling surfaces (SaS) method is proposed. The SaS formulation is based on choosing inside the shell N SaS parallel to the middle surface in order to introduce the displacements and electric potentials of these surfaces as fundamental shell unknowns. Such choice of unknowns with the use of Lagrange polynomials of degree N-1 in through-thickness interpolations of the displacements, strains, electric potential, electric field and material properties leads to a robust FGM piezoelectric shell formulation. The inner SaS are located at Chebyshev polynomial nodes that make it possible to minimize uniformly the error due to Lagrange interpolation. To implement the effective analytical integration throughout the element, the extended assumed natural strain (ANS) method is employed. As a result, the piezoelectric four-node solid-shell element exhibits a superior performance in the case of coarse meshes. To circumvent shear and membrane locking, the hybrid stress-strain solid-shell formulation via the Hu-Washizu variational principle is employed. The developed solid-shell element could be useful for the 3D stress analysis of FGM structures because the SaS method allows obtaining the solutions with a prescribed accuracy, which asymptotically approach the exact solutions of electroelasticity as the number of SaS tends to infinity.

References listed at the end of the paper:


ABSTRACT: The evaluation of the stress field within a nonlocal version of the displacement-based finite element method is addressed. With the aid of two numerical examples it is shown as some spurious oscillations of the computed nonlocal stresses arise at sections (or zones) of macroscopic inhomogeneity of the examined structures. It is also shown how the above drawback, which renders the stress numerical solution unreliable, can be viewed as the so-called locking in FEM, a subject debated in the early seventies. It is proved that a well known remedy for locking, i.e. the reduced integration technique, can be successfully applied also in the nonlocal elasticity context.

References listed at the end of the paper:

ABSTRACT: During ship collision, hull crashworthiness is an important data which needs to be assessed as rapid development of hull structure has taken into consideration since several notable dangerous events. After catastrophic accidents cause both tragic loss of life and destruction of maritime environment, double skin system is applied for almost all ships, including RoRo passengers. This work aimed to assess effects of selected internal parameters to crashworthiness criteria, considering a passenger vessel as the target of a series of impact loads. A set of collision scenario was numerically designed using finite element (FE) method by involving single and double skin structures, target location and material grade to obtained estimation of hull
crashworthiness. Assessment was focussed on the energy absorption, crushing force, stress level and failure strain of the target ship after experiencing side collisions. It was obtained from the analyses regarding role of the inner skin on tendency of the energy absorption. Failure progress on the proposed structures was successfully quantified based on stress expansion. Minimum value of material strength was concluded in final discussion to reduce more massive failure.

ABSTRACT: Bending of functionally graded plate with two reverse simply supported edges is studied based upon a refined quasi three-dimensional (quasi-3D) shear and normal deformation theory using a third-order shape function. The present theory accounts for the distribution of transvers shear stresses that satisfies the free transverse shear stresses condition on the upper and lower surfaces of the plate. Therefore, the strain distribution does not include the unwanted influences of transverse shear correction factor. The effect of transverse normal strain is included. Unlike the traditional normal and shear deformation theories, the present theory have four unknowns only. The equilibrium equations are derived by using the principle of virtual work. The influence of material properties, aspect and side-to-thickness ratios, mechanical loads and inhomogeneity parameter are discussed. The efficiency and correctness of the present theory results are established by comparisons with available theories results.

ABSTRACT: In this paper, Differential Quadrature Method (DQM) is applied to investigate free vibration of Single Walled Carbon Nanotubes (SWCNTs) with exponentially varying stiffness based on non-local Euler-Bernoulli beam theory. Application of DQ method in the governing differential equation converts the problem to a generalized eigenvalue problem and its solution gives frequency parameters. Convergence of the results show that DQM solutions converge fast. In this article, a detailed investigation has been reported and MATLAB code has been developed to analyze the numerical results for different scaling parameters as well as for four types of boundary conditions. Present results are compared with other available results and are found to be in good agreement.

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ABSTRACT: This paper presents numerical and experimental investigations of the in-plane strength and design of pin-ended circular arches having a sinusoidal corrugated web under combined in-plane loads. Finite-element models are developed that account for the effects of the corrugated web, initial geometric global and local imperfections of the arch and its web and flanges, residual stresses, the included angle and curvature of the arch, and different combined load cases. These are validated by test results and used together with the experiments to investigate the failure modes and strengths of such arches. It is found that an I-section arch with a corrugated web may fail in a global mode or in a web shear buckling mode. There are two types of global failure modes for arches under combined loads. In most cases, corrugated arches may fail in an elastoplastic buckling mode. However, when wind load plays an important role in the combined loads, corrugated arches may fail in a plastic yielding mode. An interaction design equation is proposed for predicting the global in-plane strength of steel arches with a sinusoidal corrugated web under combined axial and bending actions. The design equation provides lower bound predictions for the strengths of corrugated arches. General procedures are also proposed for the practical strength design of steel I-section arches with a sinusoidal corrugated web.


ABSTRACT: This paper presents a new design methodology for equal-width rectangular hollow section (RHS) X-joints failing by sidewall buckling. In the new approach, a slenderness parameter is defined based on the elastic local buckling stress of the sidewall, idealized as an infinitely long plate under patch loading. A Rayleigh-Ritz approximation is thereby used to obtain a closed-form solution. The proposed design equation is verified against experimental results over a wide range of wall slenderness values obtained from the literature and complemented by a brief experimental program carried out by the authors. It is demonstrated that the new design equation yields excellent results against the experimental data. Finally, a reliability analysis is performed within the framework of both the Eurocode and the AISI standards to ensure that the proposed design equation possesses the required level of safety. The newly proposed equation strongly outperforms the current Comité International pour le Développement et l’Etude de la Construction Tubulaire (CIDECT) design rule for sidewall buckling and also further extends the range of applicability to a wall slenderness ratio of up to 50.


ABSTRACT: Reinforced structural walls are often implemented as a lateral force resisting system in multistory buildings, designed to deform elastically under wind loads and form plastic hinges at their base under seismic excitation. Past research suggests plastic tensile demands and subsequent load reversals can cause a plastic, localized lateral instability in walls. Although lateral stability is addressed by some building codes, plastic buckling is rarely directly addressed. In 2010 and 2011, New Zealand experienced earthquakes that damaged many structural wall buildings, and plastic buckling was observed. This paper re-examines two existing local buckling models using a range of data sources. A review of prior experimental work assesses the models’ accuracy at predicting plastic buckling capacities. A parametric study on a range of walls examines the
variables most influential to affect plastic buckling capacities. Additionally, three nonlinear time history analyses of buildings subjected to the 2010 and 2011 New Zealand earthquakes are presented and compared with field observations to assess each buckling model’s accuracy. The findings’ impacts are discussed and revisions to the buckling models are suggested. Recommendations are provided for future research on local instability of structural walls.

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ABSTRACT: Ultimate shear strengths of 20 unstiffened I-girder specimens from the literature and seven new specimens designed to fill gaps in the experimental data are compared with predictions from models recommended by Basler, Höglund, and Lee and colleagues. Basler’s model, which is based solely on an idealized web shear buckling resistance, is shown to be accurate for webs with slenderness between 60 and 100. However, it is very conservative for members with typical plate girder web slenderness ratios. Höglund’s methods, which aim to characterize the shear postbuckling capacity of unstiffened webs, are found to be accurate to conservative. The method by Lee and colleagues, which aims to predict the shear postbuckling strength of webs with widely spaced stiffeners, is accurate on average. However, this method significantly overpredicts the strength of several specimens. A proposed adaptation of Höglund’s recommendations from a 1997 article matches the current AISC shear buckling strength equations for stocky web panels, is very simple to apply, and provides predictions that are in between those of Höglund’s methods. This adaptation of Höglund’s equations gives shear resistances that are as high as 3.66 times the capacity from Basler’s model. The specific characteristics of the different shear resistance equations are discussed, and recommendations for potential further improvement are offered. The interaction between the shear and moment capacities is found to be insignificant, although many of the specimens are subjected simultaneously to shears and moments close to the calculated nominal strengths. Resistance factors are computed to facilitate potential inclusion in modern specifications.

Lakshmi Subramanian and Donald W. White (Georgia Institute of Technology, Atlanta, GA 30332),
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001686

ABSTRACT: The I-section member lateral torsional buckling (LTB) resistance equations of the unified provisions underlying the current AISC and AASHTO specifications are a fit to a large body of experimental test data. It has been observed that finite-element (FE) test simulations commonly predict smaller capacities than the AISC/AASHTO LTB equations, especially in the inelastic LTB region. One reason for this disconnect is the fact that the residual stresses and geometric imperfections are often approximated by conservative nominal values in test simulations. Another reason for the discrepancy is the common lack of consideration of inelastic effective length effects within calibrations to experimental test results. This paper recommends improvements to the current LTB resistance equations to address these shortcomings. The impact of inelastic end restraint in representative beam LTB experimental tests is illustrated through FE test simulations. In
addition, extensive test simulation results are presented, based on reduced residual stresses and geometric
imperfections determined in separate research, which illustrate the quality of the proposed prediction equations
for I-section members of various cross section types subjected to uniform moment.

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https://doi.org/10.1061/(ASCE)ST.1943-541X.0001690
ABSTRACT: The existing design expressions for the lateral-torsional buckling behavior of castellated beams
conflict. Furthermore, they do not take into account the detrimental effect of the residual stress modification
attributable to the fabrication process, which was only recently demonstrated by the authors. This makes these
design rules possibly unsafe. In this paper, the lateral-torsional buckling behavior of doubly symmetric
castellated beams loaded by a constant bending moment is investigated numerically. The numerical model,
including the modified residual stresses, was validated by comparing its results with experimental results. A
preliminary design approach is proposed based on the current European guidelines for the calculation of the
lateral-torsional buckling resistance of I-section beams. According to the proposed approach, the lateraltorsional buckling resistance of castellated beams can be determined using the cross-sectional properties
calculated at the center of the web opening. The modification of the residual stresses during the fabrication
process results in resistances that lie approximately one buckling curve lower.

Lakshmi Subramanian and Donald W. White (Georgia Institute of Technology, Atlanta, GA 30332),
“Reassessment of the lateral torsional buckling resistance of rolled I-section members: Moment gradient tests”,
ASCE Journal of Structural Engineering, Vol. 143, No. 4, April 2017
https://doi.org/10.1061/(ASCE)ST.1943-541X.0001687
ABSTRACT: The lateral torsional buckling (LTB) equations in some current standards are based on unified
equations that are a fit to a large body of experimental test data. However, these curves tend to overestimate the
capacities from finite-element (FE) simulations based on typical idealized end conditions, residual stresses, and
geometric imperfections. Uniform moment tests conducted on various types of cross sections have led to
proposed modifications of the current specification for LTB equations. This paper investigates and
recommends, by means of FE test simulations, the use of the modified equations with additional improvements
for moment gradient cases. The emphasis of the studies is on rolled I-section members. Specifically, the paper
demonstrates an inelastic Cb effect that can be particularly significant for beams in which the maximum
moment occurs within the unbraced length rather than at a braced point. A new way of applying the LTB
modification factor, Cb, in the inelastic LTB region for these cases is recommended for ordinary application of
current standard resistance equations. Also, it is shown that this effect can also be captured seamlessly via an
explicit inelastic buckling analysis using stiffness-reduction factors (SRFs) derived from the design resistance
curves.

Lakshmni Subramanian and Donald W. White (Georgia Institute of Technology, Atlanta, GA 30332),
“Improved noncompact web-slenderness limit for steel I-girders”, ASCE Journal of Structural Engineering,
Vol. 143, No. 4, April 2017, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001722
ABSTRACT: The noncompact web-slenderness limit in current design specifications is based on an assumed
value of the plate buckling coefficient for a web subjected to flexure that is between the values for fixed and
simply-supported edge conditions. While the limit provided in current specifications is a good representation in many situations, there is evidence that the limit overestimates the magnitude of the restraint provided by smaller flanges. This paper shows that the ratio of the area of the compression flange to the area of the web in compression is a good indicator of the restraint provided to the bend-buckling of the web plate. The overestimation of the plate buckling coefficient can result in the classification of cross sections having relatively small flanges as noncompact web sections when their behavior is more akin to that of slender web sections. Slender web sections have a maximum possible flexural resistance, referred to as the plateau strength, less than the yield moment \( M_{yc} \), because of load shedding from the web. Furthermore, the St. Venant torsional stiffness contribution to the lateral torsional buckling resistance is neglected for these sections due to web distortional flexibility. This paper evaluates the appropriate noncompact web-slenderness limit via test simulation of a targeted set of short girder specimens in which the calculated resistance is governed by the plateau strength and proposes a modified equation to rectify the problem. The impact of this change on the prediction of a broad range of member limit states is illustrated via comparison to other test simulations and to experimental results.

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ABSTRACT: This paper presents a comprehensive parametric study on the ultimate strength of perforated cold-formed steel columns using the finite element (FE) package ABAQUS. FE models were developed for columns predisposed to local (L), distortional (D), and global (G) buckling failures. The parametric study involved five cross-section types (i.e., C, stiffened C, Z, rack, and hat sections), five widths of holes, four lengths of holes, four different sizes of hole spacings, three material properties, two magnitudes and various directions of geometric imperfections, and three buckling modes (i.e., L, D, and G) and all of the possible interactions between them (i.e., LD, LG, DG, and LDG). Ultimate strengths, as well as failure modes, were obtained from the analyses and are plotted against the current codified direct strength method (DSM) in AS/NZS 4600. Significant discrepancies between the numerical results and the DSM-predicted strengths were observed due to the influence of holes, the interaction of buckling modes, and occasionally the inherent limitations of the DSM itself. The effects of column length, material properties, and centroid shift due to perforation are also discussed. A data pool including 146,207 column-ultimate strengths were obtained, most of which were used to formulate new design equations for perforated thin-walled columns based on the direct strength method, as presented in a companion paper.

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ABSTRACT: The parametric study of the ultimate strength of perforated cold-formed steel columns is presented in a companion paper. The parameters include five cross-section types (i.e., C, stiffened C, Z, rack, and hat sections), five hole widths, four hole lengths, four hole spacings, three material properties, two magnitudes and various directions of geometric imperfections, and three buckling modes (i.e., L, D, and G) and all the possible interactions between them (i.e., LD, LG, DG, and LDG). Based on the extensive range of
strength data obtained, four design methods based on the direct strength method (DSM) are evaluated, including the existing AS/NZS 4600 DSM (Australia Standard 2005), Design Option 4 by Moen and Schafer (2011), and two sets of proposed methods. All these methods are complemented by a reliability analysis deriving appropriate resistance factors. The proposed methods are based on Design Option 4 and include DG interaction. They only require the inputs of elastic local and distortional buckling loads based on gross section properties, which is a significant simplification compared to the methods based on net section properties. Additionally, Proposed Method 1 uses a uniform penalty factor to ensure the satisfaction of the overall resistance factor of 0.85, while Proposed Method 2 adopts a factor based on a regression analysis involving parameters such as the dimensions of holes and cross-sections. Proposed Method 2 outperforms all the other methods in terms of a reduced overall scatter in prediction and an increased overall reliability. This method can also be used for nonperforated columns with a better performance than the current AS/NZS 4600 DSM (Australia Standard 2005).

Song Hong Pham, Cao Hung Pham and Gregory J. Hancock (School of Civil Engineering, Univ. of Sydney, Sydney, NSW 2006, Australia), “Direct strength method of design for channel sections in shear with square and circular web holes”, ASCE Journal of Structural Engineering, Vol. 143, No. 6, June 2017 https://doi.org/10.1061/(ASCE)ST.1943-541X.0001765

ABSTRACT: The direct strength method (DSM) design rules for cold-formed steel members in shear have been incorporated recently into the North American specification for the design of cold-formed steel structural members and are being implemented in the Australian cold-formed steel structures standard. The method, which was calibrated for unperforated members only, requires two inputs including the buckling load \( V_{cr} \) and the shear yielding load \( V_y \). For members with square web cutouts, \( V_{cr} \) can be computed by either the spline finite strip method or the tabulated values based on the shear buckling coefficients \( k_v \) as in previous studies or the finite element method. However, \( V_y \) has not been accurately formulated including holes. This paper represents a practical model to obtain \( V_y \) for members with central openings subjected predominantly to shear. The model ranges from very small holes where traditional shear yielding predominates to large holes where Vierendeel action dominates. The model is verified with the DSM design formulas using the predominantly shear tests recently conducted at the University of Sydney and Queensland University of Technology with both square and circular web openings and for shear spans with aspect ratio of 1.0.

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ABSTRACT: Tension field theory assumes that after elastic shear buckling has occurred, compressive stresses in the web plate do not increase; therefore, postbuckling shear strength solely results from the development of tensile stresses within a defined diagonal tension field. Finite-element analyses have found this fundamental assumption to be invalid and a new theory (compression theory) was proposed that bases the development of postbuckling shear strength mostly on the compressive response of the plate (tension plays a secondary role). Previous work has validated compression theory against a wide variety of published experimental data at ambient temperature. This paper shows that compression theory can predict the ultimate postbuckling shear strength of steel web plates up to temperatures of 1,100°C. This finding is significant because steel plate girders subjected to fire loading are highly susceptible to web shear buckling. Experimentally validated finite-element
models are used to develop temperature-dependent multiplicative parameters to permit the use of compression theory to calculate ultimate postbuckling shear strength at elevated temperatures. Comparisons with published experimental data show that predictions of ultimate postbuckling shear strength from compression theory closely agree with the literature.

https://doi.org/10.1061/(ASCE)ST.1943-541X.0001763
ABSTRACT: An experimental and numerical study of the flexural buckling behavior of hot-finished high-strength steel (HSS) square and rectangular hollow section (SHS and RHS, respectively) columns is described in this paper. A total of 30 hot-finished S460 and S690 hollow section column specimens have been tested in compression with pin-ended boundary conditions. Finite element (FE) models have been developed to replicate the experiments and employed in a subsequent parametric study considering a range of member geometries. Based on the test and FE results, the applicability of the current column design curves in European, North American, Chinese and Australian structural steel design standards to hot-finished HSS SHS and RHS columns has been verified by means of reliability analyses.

https://doi.org/10.1061/(ASCE)ST.1943-541X.0001779
ABSTRACT: Research was conducted to investigate how the inclination angle of the diagonal tension field action varies in steel plate shear walls (SPSWs) and to determine what optimum constant angle best matches the demands obtained from finite-element (FE) analysis. An FE model was first calibrated against experimental results that surveyed inclination angles across the web plate of an idealized SPSW as a function of drift and that showed significant differences in inclination angles at different locations across the web plate. Then, four real SPSWs with varying aspect ratios and numbers of stories were designed and modeled for FE analyses. The variations in angle in the web plate and along the boundary elements were documented as a function of drift and showed significant variations. Combined moment–axial force demand ratios in the SPSW boundary elements were calculated and compared for all real SPSWs to determine the preferable value of single angle that could be used in design. Overall, using 45° was found to be a reasonable compromise for both horizontal and vertical boundary element (HBE and VBE, respectively) design if a single constant angle is desired. Furthermore, the demand on the web plate is not sensitive to the variation of inclination angle. Consequently, the single angle of 45° is recommended for the design of the entire SPSW.

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ABSTRACT: Composite columns of various sectional configurations are studied to maximize the contribution of high-strength steel under compression-flexural loading. For concrete-encased steel (CES) columns, steel angles were placed at four corners of the cross-section and connected by various types of transverse reinforcements. In the case of a concrete-filled steel tube (CFT) column, a slender steel tube was stiffened by welding longitudinal bars. To verify structural capacities, eccentric axial load tests were performed for three concrete-encased steel angle (CES-A) columns and a stiffened concrete-filled slender steel tube (S-CFT) column, using Grade 800 MPa steel and 100 MPa concrete. The CES-A columns showed good structural performance in strength, flexural stiffness, and ductility due to the high contribution and good confinement effect of the corner steel angles and transverse reinforcement. In the S-CFT column the welded longitudinal bars successfully restrained local buckling of the slender steel tube so that the full plastic strength of the composite section developed.

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ABSTRACT: In this study, the behavior of high-strength steel circular hollow section (CHS) X-joints was systematically investigated by experimental and test-validated numerical analysis. A total of nine CHS X-joints fabricated from cold-formed tubes were tested under axial compression. The key test variables included different grades of steels and geometrical configuration of the joint. The joint strength observed was mostly governed by the widely accepted 3% indentation criteria before reaching the peak strength. All of the high-strength steel X-joints tested in this study exceeded the nominal strength with sufficient margin found in the Eurocode. Supplemental numerical results also corroborated this experimental observation, implying that the joint strength reduction factor of 0.8, which currently used for high-strength steels in the Eurocode, may be too conservative and needs to be re-examined. Overall, the experimental and supplemental numerical results of this study indicated that high-strength steel CHS X-joints show satisfactory performance, just slightly inferior to ordinary steels, in terms of serviceability, ultimate strength and ductility, even when the yield strength of steel is as high as 800 MPa.

ABSTRACT: Ten full-scale concrete deep beams reinforced with glass fiber-reinforced polymer (GFRP) with a cross section of 1,200×300mm were tested to failure under two-point loading. The test variables were the configuration of web reinforcement (horizontal and/or vertical) and shear span-to-depth ratio (a/d=1.47, 1.13, and 0.83). All specimens exhibited sufficient deformation required to develop arch action, which was confirmed by crack propagation and an almost linear strain profile in the main longitudinal reinforcement, in addition to the typical failure mode of crushing in the concrete diagonal strut. The results show that the vertical web
reinforcement had no clear impact on ultimate capacity, while the configuration with horizontal-only web reinforcement unexpectedly resulted in a lower ultimate capacity compared to the specimens without web reinforcement. The web reinforcement’s main contribution was significant crack-width control.

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ABSTRACT: Progressive collapse accidents of single-layer latticed domes seriously threaten public safety and social security. Structural integrity and progressive collapse–resisting capacity are gradually becoming essential requirements in structural design. The Kiewitt Lamella and geodesic single-layer latticed domes are typical of domes used in large-scale public facilities. In this paper, an experimental study and a numerical simulation were carried out to understand the mechanism of internal force redistribution in the progressive collapse of domes. Three effective methods to evaluate progressive collapse resistance and critical displacement were determined and verified. The results indicate that both the Kiewitt Lamella dome and the geodesic dome exhibit undergo snap-through collapse. The collapse of the Kiewitt Lamella dome was induced by unexpected local instability around the initial failure members, whereas that of the geodesic dome was the result of a rapid change in nodal displacement and a sharp decline in structural stiffness.

ABSTRACT: Steel arches are applied in many engineering structures because of their excellent capacity to resist various transverse loadings. Modified (or normalized) slenderness plays an important role in the strength design of steel arches. The elastic lateral-torsional buckling load of steel arches is essential in calculating the modified slenderness for the out-of-plane strength design. This paper is concerned with analytical investigations of the elastic lateral-torsional buckling of steel pin-ended arches having in-plane rotationally restrained ends under an arbitrary radial concentrated load, which has not been reported in the literature. Nonuniform unsymmetrical distributed internal actions are produced by the arbitrary load and are significantly influenced by the load position. The arch suddenly reaches its ultimate resistance in a lateral-torsional buckling mode when the internal actions reach certain values. This paper conducts a theoretical investigation into the elastic lateral-torsional buckling of steel arches and derives the analytical solution for the buckling load based on accurate internal forces obtained by an exact prebuckling analysis. The fourth-order differential equations in terms of axial and radial displacements, which are successfully used for the prebuckling analysis of steel arches under symmetric loads, are found to be difficult to solve for steel arches under an arbitrary concentrated load. A proper method is explored and found useful for accurately determining the prebuckling internal forces. The analytical solutions for the elastic lateral-torsional buckling load based on the accurate prebuckling internal forces are compared with the independent finite-element results, and the comparisons show very good agreements between them. The effects of the load position on the lateral-torsional buckling loads of arches are investigated. It is found that the buckling loads are significantly influenced by changes in load position. The lateral-torsional buckling load increases as the load position moves away from the crown of the arch. The influence of the load position on the lateral-torsional buckling load of steel arches with a rectangular section is
slightly significant than that of steel arches with an I-section. The elastic lateral-torsional buckling load obtained in this paper provides a sound basis for out-of-plane strength studies of steel arches in the future.

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ABSTRACT: Recent experimental and computational studies have shown that the inelastic behavior of deep steel columns, where the cross-section depth is substantially greater than the flange width, is not yet well understood. To address this shortcoming, detailed finite element models that are validated using available experimental data, are used to study the response of deep steel columns subjected to combined axial and lateral loading. Two loading protocols are considered: (1) members that undergo monotonic lateral loading under a constant compressive force until failure (load then drift, i.e., LTD protocol); and (2) members that are subjected to various initial axial loads, displaced to a specified drift and then further loaded until failure (drift then load, i.e., DTL protocol). The loading protocols are designed to determine the effect that initial axial load, axial shortening, and local buckling effects play in predicting the failure mode and axial resistance of the member. Regression analysis is performed on the results to determine which parameters are most significant. The simulation studies show that global out-of-plane slenderness is a key parameter influencing behavior and that the effective buckling length of deep steel columns could be substantially greater than its initial value, a finding that has implications for seismic design.

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ABSTRACT: Concrete-filled steel tube (CFT)–RC composite members consist of multiple CFT columns connected by RC plates or webs. CFT-RC composite members have been used in different types of structures, for example, as ribs in long-span arch bridges and as tall piers supporting long-span bridges. However, there is limited knowledge regarding their fundamental axial load-displacement behavior, and a general lack of behavior-based design equations for estimating their axial compressive strength. This paper addresses these knowledge gaps by presenting experimental results from axial loading tests conducted on 14 short (stub) column specimens. These include seven CFT-RC columns, four CFT columns, and three RC plates. The parameters included in the tests are the thickness of the steel tube wall (ts) and RC plates (tp). An experimental database of 104 CFT column tests conducted around the world is also compiled. The experimental results from the tests conducted in this research are combined with those from the compiled database and used together to develop behavior-based design equations for estimating the axial compressive strength of short CFT-RC columns.
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ABSTRACT: The dual-hazard inelastic behavior of concrete-filled double-skin steel tubes (CFDSTs) is experimentally investigated as a substitute to reinforced concrete columns for bridge piers in multihazard applications. Results demonstrate that CFDSTs exhibit substantial toughness and ductility that can help achieve satisfactory performance when exposed to seismic and blast hazards. Under cyclic loading, for all specimens designed as part of this testing program, yielding of the section preceded buckling of the outside tube. The onset of local buckling of the outside tube was not observed until well beyond 4% drift, and failure of all the sections happened generally beyond 7% drift, even when compactness of the outside tube met only the AISC seismic provisions requirements for moderately ductile behavior. In the cyclic tests, although pinching of the hysteresis curve happened during the test, the curves remained stable. For the blast tests, all sections behaved in a ductile manner when subjected to near-contact charges; but for extreme conditions, sections having large voids in their cross section experienced significant denting. Overall, these tests validated the viability of CFDSTs in compliance with AISC compactness requirements for bridge columns in the dual-hazard application considered here.

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ABSTRACT: Behavior of concrete-filled steel tubular (CFST) columns can be predicted accurately using detailed finite-element (FE) modeling, but such models are tedious to build and impractical for frame analysis. In contrast, computationally efficient fiber beam element (FBE) models can achieve the balance between accuracy and simplicity, and can be utilized for advanced analysis of structural systems. In FBE models, however, the material models themselves have to account for the interaction between the steel tube and core concrete. Therefore the accuracy of a FBE model depends mainly on the input material models. Although there are a few FBE models available in the literature for CFST columns, these models may not be suitable for some cases, especially when considering the rapid development and application of high-strength materials and/or thin-walled steel tubes. This paper proposes versatile, computationally simple, yet accurate steel and concrete models based on detailed FE modeling results of circular CFST stub columns under axial compression. The material models are then implemented in FBE modeling and the prediction accuracy is verified with a wide range of test data.

M.V. Anil Kumar and V. Kalyanaraman, “Interaction of local, distortional, and global buckling in CFS lipped channel compression members”, ASCE Journal of Structural Engineering, Vol. 144, No. 2, February 2018,
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ABSTRACT: The strength of thin-walled cold formed steel (CFS) lipped channel compression members may be governed by yielding, local, distortional, or global buckling or any possible interaction among these buckling modes. The interaction between buckling modes reduces the strength of thin-walled members to values below
its strengths as affected by any one of the independent buckling modes. The direct strength method (DSM), which significantly simplified the evaluation of design strength of CFS members, recognizes this reduction in strength caused by interaction of buckling modes, but explicitly handles local-global interaction only. A simple and accurate interaction equation that accounts for interaction between all possible buckling failure modes for CFS lipped channel compression members is proposed in this paper. The method requires the use of modified DSM equations for evaluating the strength under the different independent buckling modes (local and distortional). The proposed interaction equation is validated with both experimental as well as numerical results.

ABSTRACT: The objective of this study is to develop and validate a practical finite-element modeling protocol for predicting the flexural strength and collapse behavior of thin-walled spirally welded tapered tubes that can be used as steel wind turbine towers. The overall modeling protocol consists of two parts: (1) a meshing protocol is developed considering the effects shell element type, aspect ratio, inclination angle, and density on the buckling moment relative to theoretical predictions; and (2) two patterns of geometric imperfections (eigenmode-affine and so-called weld depression) scaled to the thresholds of fabrication tolerance quality classes in Eurocode 3 are considered in nonlinear collapse shell finite-element models and the results are compared to a series of eight large-scale flexural tests of spirally welded tubes. The computational results are compared with test results in terms of moment-rotation response, stiffness, and buckling modes and show sufficient agreement to justify the further development of nonlinear analysis methods for the design of steel wind turbine towers made from thin-walled spirally welded tapered tubes.

ABSTRACT: A three-dimensional (3D) noncontact laser-scanning method to quantify the deviations in cold-formed steel (CFS) channel sections (plain and lipped) is presented. The methodologies to segregate the different categories of imperfections from the deviations in the geometry of CFS member are also presented. A total of 24 different C-sections (minimum of six samples in each section) with varying cross-sectional parameters totaling 188 specimens were studied. The nature of imperfections in the CFS members was found to correlate with geometric properties such as slenderness ratios, torsional constant, and plate slenderness. The bow and camber imperfection (global out-of-straightness) in the members is presented with respect to the minor and major axis slenderness ratios. A new combined global and cross-sectional parameter (J/L) is introduced against the deviation caused by twisting of the CFS member. To predict the imperfection magnitudes based on their geometrical properties, a new set of expressions are suggested.

ABSTRACT: The rivet-fastened rectangular hollow flange channel beam (RHFCB) is a new cold-formed steel section and is considered to be a substitute for welded hollow flange channel beams. This monosymmetric channel section is made from two torsionally rigid rectangular hollow flanges connected to a web plate using rivets at intermittent spacing. This fabrication process allows great flexibility in selecting different combinations of web and flange element sizes to attain optimum design capacities. Although the shear behavior of the
commonly used lipped channel beam (LCB) and welded hollow flange beam (HFB) sections, with and without web openings, has been investigated previously, the shear strength and behavior of rivet-fastened RHFCBs with web openings have not been investigated yet. Therefore a series of shear tests was conducted to investigate the shear behavior and strength of rivet-fastened RHFCBs with circular web openings. Simply supported test specimens with aspect ratios of 1.0 and 1.5 were loaded at midspan until failure. The shear capacities determined from the tests were compared with those predicted by current cold-formed steel design standards. The results revealed that the existing design equations were not able to accurately predict the shear capacities of rivet-fastened RHFCBs with circular web openings. This is mainly due to the shear buckling capacity improvements provided by the rectangular hollow flanges and associated postbuckling strength. Hence the shear strength capacity results were used to propose improved design equations for rivet-fastened RHFCBs with circular web openings. This paper presents the details of the shear tests, observations, design capacity comparison, and proposed design equations.


ABSTRACT: Instability failure (also referred to as out-of-plane instability) has been observed in several experimental studies conducted on seismic performance of rectangular structural walls under in-plane loading. Observation of this failure pattern in some well-confined modern walls during the 2010 Chile and the 2011 Christchurch earthquakes has raised concerns about the reliability of current design code provisions. In this study, a numerical model composed of nonlinear shell-type finite elements was proposed and validated for seismic performance prediction and simulation of out-of-plane instability failure in rectangular walls. The plane sections are not enforced to remain plane in the planar direction in this type of model, and the in-plane axial-flexure-shear interaction can be simulated without requiring any empirical adjustment. The element used in the model (curved shell element) had integration points along the thickness unlike flat shell elements in which integration is performed in one plane only. This element was consequently able to capture the variation of strain along the thickness and simulate the deformation in the out-of-plane direction. Experimental results of cantilever wall specimens which failed in out-of-plane mode were used for verification of the adopted modeling and analysis approach. The numerical model was found to be able to predict the trend of initiation, increase, and recovery of out-of-plane deformation as well as the formation of out-of-plane instability that was observed during the tests. Development of this failure mechanism in the numerical model has been scrutinized using detailed response of the reinforcement and concrete elements positioned along the thickness of one of the specimens and at different stages of the failure mode. Also, the dependency of initiation and amount of the out-of-plane deformation on the maximum tensile strain developed in the longitudinal reinforcement during a specific loading cycle, and consequently all the parameters that influence its value (e.g., axial load, wall length, and cyclic loading protocol), as well as wall thickness has been confirmed by a set of parametric studies conducted on the models developed for one of the wall specimens.


ABSTRACT: This paper presents and discusses the results of experiments on the behavior of composite columns made of concrete-filled hollow sections subjected to fire and restrained thermal elongation. Several parameters that may influence the behavior of such columns in case of fire were tested, such as: slenderness, cross-sectional shape, and restraint caused by the surrounding structure on the column subjected to fire. In fire resistance tests, specimens were subjected to the standard fire curve, and critical time, critical temperature, and
corresponding buckling modes were assessed. The experimental results were also compared with results from available analytical models to determine whether they are safe and consistent for fire design. Finally, the results showed that column fire resistance may not be significantly affected by the stiffness of the surrounding structure, and that the simplified calculation method for the fire design of concrete-filled hollow sections presented in Annex H of Eurocode 4 part 1.2 is unsafe, except for elliptical columns.

ABSTRACT: Little research has been reported for the out-plane elastic-plastic buckling strength of high-strength steel (HSS) arches and no adequate code provisions are available for their strength design, despite HSS structures being increasingly used in engineering construction. This paper presents a study of out-plane elastic-plastic buckling strengths of HSS arches using a validated finite-element model. The out-plane elastic-plastic behavior of HSS arches is determined by considering the influences of pertinent characteristics of the steel, material inelasticity, large deformations, initial lateral bow and twist imperfections, and residual stresses. The high yield strength of the HSS is found to reduce the difference between the inelastic and elastic out-plane buckling loads of HSS arches. Design rules for the strength of HSS arches under uniform compression and under uniform bending are developed based on the results of the finite-element analysis. The influences of initial lateral bow and twist imperfections and residual stresses are also elucidated.

ABSTRACT: This paper presents the numerical investigation of the compressive behavior of cold-formed high-strength steel (HSS) tubular stub columns. The nominal 0.2% proof stresses of the high-strength steel are 700, 900, and 1,100 MPa. Experimental investigations have been conducted, and the numerical methodology has been verified against the test results in a complementary study. Parametric studies on the cold-formed HSS tubular stub columns were performed using the verified models, and additional data were generated to evaluate the structural performance of such compression members. The experimental and numerical results were then compared with the predictions from the design guidelines for square hollow sections (SHS), rectangular hollow sections (RHS), and circular hollow sections (CHS). The current codified slenderness limits and design methods were examined. Modifications to the design methods for resistances of SHS, RHS, and CHS stub columns against cross-sectional yielding or local buckling are proposed in this paper.

ABSTRACT: Large-scale tests on concrete-filled double-skin tubes, composed of pairs of concentric cold-formed rectangular hollow section members with the annulus between them filled with grout, are performed under air-blast loading. The recorded data from the field tests, along with further laboratory experimentation, are used to validate numerical models developed for single-degree-of-freedom and explicit finite-element analysis. The influence of several key variables on the response of concrete-filled double-skin tubes is ascertained by means of a parametric study. Overall, the ultimate moment capacity is found to have a stronger influence on the response than do mass, stiffness, hollowness ratio, or confinement factor. The results of this investigation are used to provide design guidance for the use of these members in protective design applications.

ABSTRACT: Wind tunnel tests were carried out in an open terrain to measure the wind pressure on six cylindrical roofs with the rise-span ratios of 1/4, 1/6, and 1/8 and length-span ratios of 1 and 2. Using the measured wind pressures on the roof, a parametric study using numerical simulation with finite-element (FE) models was conducted to investigate the effects of the structural span, rise-span ratio, length-span ratio, roof distributed mass, and mean wind velocity on the wind-induced response and equivalent static wind loads (ESWLs) of 432 single-layer cylindrical steel shells with supports along four edges. The results demonstrated that the wind directions of 0 and 45° were unfavorable in the view of the wind-induced response; the first several vibration modes made the most important contribution to the wind-induced response; and the background response was larger than the resonant response for most cases. In the balance of precision and simplicity of the parametric analysis for convenient application, the universal ESWLs realizing the equivalence of multiple peak response were expressed by two dominating vibration modes simplified as sine functions. With this method and parametric analysis, the pressure coefficients of the ESWLs were proposed as a function of reduced frequency for engineering applications.


ABSTRACT: Laboratory tests have shown that current standardized design rules lead to overly optimistic results for calculated ultimate loads of plated structures, especially for internal elements such as box beams. Additionally, the validity of applying equations to compute local buckling resistance might be restricted to steel grades for which the yield strength is less than 500–700 MPa. Both the literature survey and recent experimental buckling tests using ultrahigh-strength steel (UHSS) show that the current design equations can be extended to at least a nominal yield strength of 1,000 MPa. Additionally, a new simplified equation for the reduction factor \( \rho \) is proposed and a statistical calculation is presented to compare current and proposed calculation methods.


ABSTRACT: This paper comprehensively discusses the potential of applying elliptical hollow sections (EHSs) for seismic regions. The study commenced with an experimental investigation of 12 EHS beam-column specimens under combined compression and uniaxial cyclic bending, where the main test parameters were section slenderness, axial load ratio, and loading direction. Local buckling was found to be the main failure mode for all specimens, and strength, ductility, and energy dissipation greatly depended on the varying test parameters. The manufacturing of the specimens was also looked into, and the resulting material properties and residual stresses were examined. Following the experimental study, a numerical investigation was carried out. The numerical models were validated against the experimental data with good agreement observed, enabling a further parametric study to be conducted taking account of a wider range of parameter matrices. The influences of a spectrum of geometric and material properties on section behavior were evaluated, and, based on the available data, a ductility-oriented design approach for EHSs was proposed. The imperfection amplitude and imperfection shape were found to moderately affect the behavior of EHSs.

ABSTRACT: The web crippling strength of unlipped cold-formed ferritic stainless steel channels subject to interior-one-flange and end-one-flange loading is considered in this paper. A total of 144 results are presented, consisting of 36 laboratory and 108 numerical results. These results cover the cases of both flanges, restrained and unrestrained to the load and reaction plates. Unlike other work in the literature, the numerical analysis in this paper uses nonlinear quasi-static finite-element analysis with an implicit integration scheme, which has advantages over static and quasi-static with an explicit integration scheme analysis, particularly for postbuckling predictions of unlipped channels subject to web crippling. The laboratory and numerical investigations show the current stainless steel design guidance to be too conservative. In terms of design standards, although no cold-formed stainless steel standard distinguishes between flanges restrained and unrestrained to the load and reaction plates, with each standard providing only one equation to cover both restrained and unrestrained, the web crippling strengths for the flanges unrestrained case were found to be higher than those predicted from the current American specification by as much as 24%. In addition, the web crippling strengths for the flanges restrained case are shown to be higher than those predicted from equations found in the literature by as much as 14%. New web crippling design equations are proposed; the proposed equations are shown to be reliable when compared against laboratory and numerical results.


ABSTRACT: Recent research shows that shear walls with corrugated steel sheathing demonstrate high strength and high initial stiffness but low ductility. This paper presents an experimental study and numerical simulation aimed at improving the ductility of cold-formed steel shear walls sheathed with corrugated steel sheathing. A method of introducing slit openings in the field of sheathing is used to improve the shear wall’s ductility and control the failure mode and location. Ten full-scale shear wall specimens are tested, including six different slit configurations. The results show that with proper a slit pattern in the sheathing, the corrugated steel sheathed shear wall can yield significantly improved ductility while maintaining a high level of shear strength. Additionally, nonlinear dynamic analyses are carried out to verify the improvement of the building’s seismic performance when the innovative shear wall is installed. The dynamic analyses show that the new shear wall system can greatly reduce the seismic effects and decrease the collapse probability of cold-formed steel buildings.


ABSTRACT: Refined one-dimensional (1D) models are used to carry out free vibration analysis of civil engineering structures affected by local damages. The Carrera unified formulation (CUF) provides higher-order structural models to be formulated in a compact and, eventually, hierarchical manner. In the domain of the CUF, refined 1D models characterized by three-dimensional capabilities can be realized by using various function expansions of the generalized displacement field over the cross section. Recently, a component-wise (CW) approach was introduced by using CUF. CW gives a detailed physical description of multicomponent structures, since each component can be modeled with its geometrical and mechanical characteristics; that is, no reference surfaces, axes, or homogenization techniques are used. In the present work, combinations of quadratic Lagrange elements are used to describe the beam theory kinematics. This approach enables the highly-accurate
analysis of complex civil structures such as truss structures, industrial buildings, and a multifloor building. In this context, damage scenarios are introduced with no loss of accuracy in the mathematical formulation by deteriorating the single component of the structure. Effects of damages are, thus, evaluated by free vibration analyses.

ABSTRACT: Experimental testing was conducted on four large-scale, flexure-yielding walls with rectangular cross sections to investigate the impact of imposed axial load ratio (10, 14, and 20% of axial compression capacity) and transverse reinforcement detailing on the seismic performance, including damage and deformability. Variations in detailing included the inclusion or exclusion of crossties on web longitudinal reinforcement, the confined length of the boundary element, and the effectiveness of using full hoops versus 180–180° crossties in boundary elements. Failure was characterized by simultaneous crushing of the boundary element core concrete and buckling of the longitudinal reinforcement, except for one wall that failed by out-of-plane instability of the wall boundary element. The plastic rotations at lateral strength loss of 20% were on average 3.3, 2.7, and 2.1% for walls with axial load ratios of 0.1, 0.14, and 0.2, respectively. These rotations exceeded the codified limits used for assessment of structures in the United States but were below the codified limits used for design in New Zealand for axial load ratios exceeding 10%. A model for determining the plastic rotation capacity of rectangular walls as a function of the axial load is proposed.

ABSTRACT: Current standards require that, for moment-resisting frames, the strength degradation of a beam–column connection should not reduce flexural strength measured at a drift angle of 0.04 rad to less than 80% of the nominal flexural strength, $M_p$. This requirement is generally sufficient for special moment-resisting frames (SMFs) to prevent collapse due to instability. However, in other seismic force-resisting systems (SFRSs), such as special truss moment frames (STMFs), the chord members within the predefined yielding panel, referred to as a special segment, experience a much larger member rotation. The rotational capacity and ductility of a steel member are controlled by the interaction of three instabilities: flange local buckling (FLB), web local buckling (WLB), and lateral-torsional buckling (LTB). In this study, a new connection detail was developed which uses a center gusset plate and horizontal stitches to prevent global lateral-torsional buckling of double-channel built-up sections, thereby enhancing rotational capacity. For deeper channel sections, web stiffeners can be used to separate WLB and FLB and thus minimize their interaction. Component testing was carried out on members with various sizes of double-channel sections, as well as a reduced beam section (RBS). The test results showed that the new detailing allows double-channel (C310) sections to achieve a member rotation of 0.09 rad (0.065-rad moment frame story drift angle) with more than 80% of the nominal flexural strength. As a result, double-channel built-up sections are able to provide sufficient ductility to prevent the structures they support from deforming into a strength-degrading range under major earthquakes, which makes them a good candidate for STMFs and for potential use in other seismic force-resisting systems.

ABSTRACT: This paper presents a comprehensive experimental and numerical study on distortional buckling–moment resistance capacity of built-up cold-formed steel hybrid double-I-box beams (HDIBBs) under four-point bending. These built-up beams are fabricated by means of four press-braked channel sections that are fastened together using bolted connections. The cross section of this closed-form built-up beam resembles the shape of a double-I box. Three different parameters were considered: (1) a hybrid parameter ratio that is yield strengths of flange steel to web steel \( \phi_h = f_{yf} / f_{yw} \); (2) ratio of breadth to the overall depth of the section \( B/D \); and (3) flange thickness \( t_f \). All the tested beams failed in a sort of distortional buckling mode. The test results revealed that the use of higher-grade steel in the flanges had a significant influence on buckling failure modes and moment capacities of the built-up members. In the hybrid built-up beams, the use of thicker and stiffened flange plates enhanced the moment carrying capacity of HDIBBs. It was found that the flange plate slenderness \( \lambda_{pf} \) plays a major part in reducing the member moment resistance capacity due to local and distortional buckling of flanges. Appropriate nonlinear finite-element (FE) models were developed using commercially available software, and numerical analysis was performed. The FE and actual test results were in good agreement in terms of ultimate moment capacities and buckling modes. Therefore, the FE models were verified. The results were compared with the predicted member buckling resistance capacities from a standard design rule, which was found to slightly overestimate in its results.


ABSTRACT: A unified model that can be used to study both distortional buckling and global lateral buckling of cold-formed Z-purlins with sloping lips is presented. The model is composed of the compressive lipped flange and part of the web, upon which two interactive springs are attached, representing the restraints of remaining part of the cross section. The distortional and lateral buckling capacities are obtained by the Ritz method. The inclination angle of the lip, as well as widths of the flange and lip, are varied in the parametric study. The results show that the inclination angle has a significant influence on the distortional buckling coefficient but relatively less influence on lateral buckling. The distortional buckling coefficients increase as the flange and lip widths become larger. The results are also used to predict the load-carrying capacity of available tests, and good agreement is achieved with the test results. Formulas for distortional buckling coefficients of Z-purlins with sloping lips are presented and have been verified to have high accuracy compared with the numerical results.


ABSTRACT: This paper proposes a general approach for topology optimization of tensegrity structures. The optimization problem is formulated in the framework of a mixed-integer linear programming. Compared with previous approaches, more practical issues such as member overlapping, strut buckling, displacement limits, and multiple load cases are considered in the proposed approach. The member connectivities, internal forces, and cross-sectional areas are used as independent variables. The total weight of the final structure is used as the objective function. The maximum allowed number of struts connected to each node, the maximum allowed number of cross-sectional sizes for each type of members, and the minimum number of nodes used in the final structure can be actively controlled. A novel constraint formulation is proposed to avoid the member overlapping problem. Numerical examples are carried out to verify the proposed approach. The tensegrity
structures found by the proposed approach are much more suitable for practical applications, and the approach can be used as a general generator for new types of tensegrity structures for specific application scenarios.

ABSTRACT: This paper presents an experimental investigation of concrete-filled high-strength steel tubular X joints. The high-strength steel tubes were cold formed into square and rectangular hollow sections with nominal 0.2% proof stresses of 700 and 900 MPa. The cold-formed high-strength steel tubes were infilled with normal and high-strength concrete with nominal concrete cylinder strengths of 35 and 100 MPa, respectively. A total of 31 tests was conducted, covering chord sidewall slenderness ratios varying between 12.6 and 40.6. Two different types of load–deformation behavior were observed and are discussed in this paper. The obtained test strengths were compared with the nominal strengths calculated using Comité International pour le Développement et l’Étude de la Construction Tubulaire (CIDECT) design provisions. Overall, the nominal strengths predicted by the CIDECT design provisions are quite conservative for concrete-filled high-strength steel tubular X joints with chord sidewall slenderness ratios up to 40. However, the predictions for specimens with ductile load–deformation behavior are found to be overly conservative. Hence, modifications to CIDECT provisions are suggested for the design of concrete-filled high-strength steel tubular joints under transverse compression

ABSTRACT: Fiber-based elements are commonly used to simulate steel beam–columns because of their ability to capture $P$-$M$ interactions and spread of plasticity. However, when mechanisms such as local buckling result in effective softening at the fiber scale, conventional fiber models exhibit mesh dependence. To address this, a two-dimensional (2D) nonlocal fiber-based beam–column model is developed and implemented numerically. The model focuses on hot-rolled wide flange sections (W-sections) that exhibit local buckling-induced softening when subjected to combinations of axial compression and flexure. The formulation upscales a previously developed nonlocal formulation for single-fiber buckling to the full frame element. The formulation incorporates a physical length scale associated with local buckling along with an effective softening constitutive relationship at the fiber level. To support these aspects of the model, 43 continuum finite element (CFE) test problems are constructed. These test problems examine a range of parameters, including the axial load, cross section, and moment gradient. The implemented formulation is validated against CFE models as well as physical steel beam–column experiments that exhibit local buckling-induced softening. The formulation successfully predicts postpeak response for these validation cases in a mesh-independent manner, while also capturing the effects of $P$-$M$ interactions and moment gradient. To enable convenient generalization, guidelines for calibration and selection of the model parameters are provided. Limitations are discussed along with areas for future development.

ABSTRACT: Corrugated steel plate shear wall (CoSPSW) is a lateral load–resisting system in which corrugated infill steel wall panels are embedded inside a steel boundary frame. Compared to flat steel plate
shear walls (SPSWs), elastic buckling capacity and lateral stiffness could be enhanced considerably, and gravity loads could be avoided when the load is perpendicular to the rib, or resisted when the load is parallel to the rib, which solves the long-lasting problem of flat wall buckling under gravity loads during construction. Cyclic quasi-static tests were conducted on three, 1/3-scale, 2-story, single-bay CoSPSW specimens with different corrugation orientation and configuration. All specimens showed highly ductile behavior and stable cyclic postbuckling performance. Compared to the SPSW specimen, CoSPSW specimens had much higher lateral stiffness and elastic buckling capacity, with less pinching in the hysteric curves. Different from the tension field action mechanism in SPSW, the lateral load–resisting mechanism in CoSPSWs was shear yielding, or inelastic shear buckling, depending on the corrugation configuration. The experimental results and their implication on seismic design are summarized and discussed.


ABSTRACT: A number of experimental and analytical studies have been conducted on the axial compressive behavior of square concrete-filled steel tubular (CFST) columns, but there still exist several controversies on this issue because the loads sustained by the concrete infill and the steel tube cannot be accurately measured in a conventional axial loading test. In this study, an innovative test method was devised to directly measure the load components of square CFST columns under axial compression. Five specimens with different width-to-thickness ratios were fabricated and tested. The factors that may affect the compressive strength of concrete in square CFST columns were investigated, and it was found that the difference between the compressive strength of concrete in CFST columns and the corresponding cylinder strength was small and within the commonly accepted ranges. The measured compressive strengths of the steel tubes were compared to the available empirical formulas. It was determined that the ultimate strength of the steel tube can be reasonably estimated, but more research is needed to fully understand the post-local-buckling behavior of the steel tube and the effects of various factors. Design recommendations were proposed for the axial load capacity of square CFST columns. The existing stress-strain models for the concrete infill and the steel tube were assessed using the measured stress-strain relationships, and more credible stress-strain models were developed.

You-Fu Yang, Chao Hou and Min Liu, “Experimental study and numerical analysis of CFSST Columns subjected to lateral cyclic loading”, ASCE Journal of Structural Engineering, Vol. 144, No. 12, December 2018, ABSTRACT: An experimental study and numerical modeling were carried out to investigate the behavior of concrete-filled stainless-steel tube (CFSST) columns subjected to constant axial compression combined with lateral cyclic loading. Eighteen specimens with varied cross-sectional configuration, steel ratio, and axial compression ratio were tested. The failure pattern, load versus deformation curve, bearing capacity, stiffness degradation, accumulated energy dissipation, and ductility were comprehensively investigated. The experimental results revealed that the failure pattern of the stainless-steel tube is mainly a lantern-shape local buckling beside the rigid fixture along with crushing of core concrete at the buckling position. CFSST specimens under lateral cyclic loading generally possessed stable fusiform hysteretic curves, with their initial loading and unloading stiffness increased with increasing cross-sectional steel ratio and axial compression ratio. The axial compression ratio has a more evident influence on the mechanical response of the specimens than the steel ratio, whereas an increase of the bearing capacity, energy dissipation, and ductility index was detected when increasing the steel ratio or decreasing the axial compression ratio. Square specimens have lower ductility and more rapid stiffness degradation compared with circular ones. A finite-element analysis (FEA) model was also established to simulate the behavior of CFSST columns subjected to constant axial compression combined
with lateral cyclic loading. Good accuracy was achieved when comparing the predicted response and experimental observations.


**ABSTRACT:** Cold-formed steel sections are generally used as flexural members in lightweight steel construction. The SupaCee section is an innovative section introduced recently to the Australian building sector. It provides superior flexural strength than the traditional channel sections due to unique ribbed web and curved lip elements. However, the web crippling behavior and strength of the high strength SupaCee sections has not been investigated yet. Current web crippling design methods given in cold-formed steel design standards do not include any provision for SupaCee sections. Hence, detailed experimental and finite element studies were conducted to investigate the web crippling behavior and strengths of SupaCee sections under one-flange load cases with their flanges unfastened from the supports. Experimental and finite element analysis results showed that the web crippling capacities of SupaCee sections are reduced relative to lipped channel sections. Therefore, the current web crippling design equations in the American and Australian/New Zealand cold-formed steel design standards were modified by including suitable web crippling coefficients for SupaCee sections. Finite element models of tested SupaCee sections were also developed and validated using the experimental results. This paper presents the details of experimental and numerical web crippling studies of SupaCee sections under one-flange load cases and the results. It also presents the details of direct strength method-based design equations developed in this research.

**End of more papers published in the journal, ASCE Journal of Structural Engineering (2017 and on).**

**More papers published in the journal, Journal of Sandwich Structures and Materials (2017 and on):**


**ABSTRACT:** The objective of this study is to enhance the out-of-plane tensile and compressive performances of foam core sandwich composite via structural core modifications considering the ease of application and time consumption. The performances of single core perforated, single core stitched, divided core perforated, and divided core stitched sandwich composites are compared with each other and reference plain foam core sandwich composites. Results indicate that “perforated and stitched core” sandwich composites have superior strength, and in terms of performance modification, dividing the core is found very efficient for plain (non-perforated and non-stitched) core sandwich composites.

ABSTRACT: For sandwich beams with second-order hierarchical corrugated truss core under three-point bending, a correction factor of shear deflection was firstly proposed to improve the prediction accuracy of the bending analysis, which was verified by finite element analysis and compared with the original formula. Then, the failure modes of the sandwich beam under bending were analyzed, including four competing modes of the large struts (i.e. plastic yielding, buckling, wrinkling of facesheet, shear buckling) and two competing modes of the small struts (i.e. plastic yielding, buckling). Subsequently, the analytical expressions of critical load for each failure mode were derived. On this basis, the failure mechanism maps were constructed. Finally, several typical points from the map were selected and verified by finite element analysis, and a good agreement of predicted failure modes was observed.


ABSTRACT: Radar domes are the cover structures over the radar antenna systems to provide environmental protection to the sensitive parts such as electronics, steering hardware, wave guide, additional equipments, and antenna itself. Composite dielectric materials are preferred solutions for radome construction because of their negligible effects on electromagnetic transmission of enclosed antenna. Very recently, the effect of interlaminar stress distribution and radome geometry over the transmission capabilities is reported by several researchers. The aim of this study is to present an efficient solution methodology with minimized mathematical effort for the analytical solution of sandwich composite dielectric materials for radome structures with one and double core layers. Analytical solution methodology for the analyses of stresses and deformations is based on Third-Order Shear Deformation Theory (TSDT). Double Fourier series which are specialized for boundary discontinuity are used to solve highly coupled linear partial differential equations. Numerical solutions for the designed spherical radome geometry with one and double core layers are presented for laminated sandwich shells to provide benchmark results for the pre-design activities of radome structures.


ABSTRACT: An approach is introduced for determining accurate two-dimensional equivalent laminated models of sandwich laminates with honeycomb core and composite facesheets by optimization involving modal behavior. The approach relies on minimizing the objective function which is defined as the sum of the square of the differences between the natural frequencies of the honeycomb sandwich laminate estimated by the finite element analysis of the 3D detailed model with the actual honeycomb core geometry and by the 2D equivalent laminated model with the honeycomb core replaced by the equivalent 2D orthotropic material model. Equivalent elastic constants of the 2D orthotropic model of the honeycomb core are defined as the design variables of the optimization problem, and a finite element solver and genetic algorithm-based optimizer are coupled to perform the optimization task. Results show that with the optimization-based approach, very accurate 2D equivalent models of honeycomb sandwich laminates are obtained compared to equivalent models
obtained by replacing the honeycomb core with elastic constants of the 2D orthotropic material model obtained utilizing analytical models available in the literature.


ABSTRACT: Using harmonic differential quadrature method, an approach to analyze sandwich cylindrical shell panels with any sort of boundary conditions under a generally distributed static loading, undergoing elasto-plastic deformation is proposed. The faces of the sandwich shell panel are made of some isotropic materials with linear work hardening behavior while the core is assumed to be an isotropic material experiencing only elastic behavior. The faces are modeled as thin cylindrical shells obeying the Kirchhoff–Love assumptions. For the core material, it is assumed to be thick and the in-plane stresses are negligible. Upon application of an inner and outer general lateral loading, the governing equations are derived using the principle of virtual displacements. Using an iterative approach, named elasto-plastic harmonic differential quadrature method (EP-HDQM), the equations are solved. The obtained results are compared with the results from finite element software Ansys for different sandwich shell panel configurations. Then, the effects of changing different parameters on the stress and displacement components of sandwich cylindrical shell panels in different elasto-plastic conditions are investigated.


ABSTRACT: In this paper, a set of numerical and experimental studies are performed to improve mechanical and vibrational properties of carbon nanotubes-reinforced composites. First, at a design concept level, linear distribution patterns of multi-walled carbon nanotubes through the thickness of a typical beam is adopted to investigate its fundamental natural frequency for a given weight percent of multi-walled carbon nanotubes. Both Timoshenko and Euler-Bernoulli beam theories are used in the derivation of the governing equations. The finite element method is employed to obtain a numerical approximation of the motion equation. Next, based on the introduced distribution patterns, laminated multi-walled carbon nanotubes-reinforced polystyrene-amine composite beams are fabricated. Static and experimental modal tests are performed to measure the effective stiffness and fundamental natural frequencies of the fabricated composite beams. Also, in order to generate realistic model to investigate the material properties of fabricated composite beams, the actual tensile specimens of multi-walled carbon nanotubes/polystyrene-amine composites are successfully fabricated and the tensile behaviors of both pure matrix and composites are investigated. To better interfacial bonding between carbon nanotubes and polymer, a chemical treatment is performed on carbon nanotubes. It is seen that the addition of a few wt. % of multi-walled carbon nanotubes make considerable increase in the Young's modulus and the tensile strength of the composite. It is observed from the free vibration tests that the uniform distribution of multi-walled carbon nanotubes results in an increase of 9.5% in the fundamental natural frequency of the polymer cantilever beam, whereas using the symmetric multi-walled carbon nanotube distribution increased its fundamental natural frequency by 17.32%.

ABSTRACT: In this article, a three-dimensional solution based on the Fourier’s series and finite difference method has been presented to study the low-velocity impact on sandwich panels with foam core and composite face sheets. The Navier’s equations are derived and displacements are substituted by their corresponding Fourier’s series and three partial differential equations with coefficients of Fourier’s series are obtained. The contact force has been considered as a Fourier’s series of impactor displacement and deflection of top face sheet. Also, the model is verified by experiments performed on sandwich panel with epoxy/woven-fiberglass composites, face sheets and polyurethane foam core, and other researchers’ works. The history of contact forces and lateral displacement of contact point has been obtained experimentally and compared with theoretical model. Finally, the effects of impact energy and geometrical parameters including in-plane dimension ratio, core thickness, and face sheet thickness on contact force and lateral deflection histories have been investigated.


ABSTRACT: Sandwich panels with auxetic lattice cores confined between metallic facets are proposed for localized impact resistance applications. Their performance under localized impact is numerically studied, considering the rate-dependent effects. The behaviour of the composite structure material at high strain rates is modelled with the Johnson-Cook model. Parametric analyses are conducted to assess the performance of different designs of the hybrid composite structures. The results are compared with monolithic panels of equivalent areal mass and material in terms of deformations and plastic energy dissipation. Design parameters considered for the parametric analyses include the auxetic unit cell effective Poisson’s ratio, thickness of the facet, material properties and radius of the unit cell’s struts. Significant reduction in computational time is achieved by modelling a quarter of the panel, with shell elements for facets and beam elements for the auxetic core. With projectile impacts up to 200 m/s, the auxetic composite panels are found to be able to absorb a similar amount of energy through plastic deformation, while the maximum back facet displacements are reduced up to 56% due to localized densification and plastic deformation of the auxetic core.


ABSTRACT: This paper proposes an analytical formulation for torsional analysis of thin-walled and moderately thick-walled hollow members with sandwich wall. The sandwich rod can have a complicated cross-section including straight and curved edges. The material and thickness of the two faces of the sandwich are assumed the same. Prandtl’s stress function is used to formulate the problem for faces and core, while the continuity and compatibility conditions at the face–core interfaces are also used to complete the formulation. By the presented method, it is possible to find the torsional stiffness and the shearing stress in the cross-section. By presenting several numerical examples, the accuracy of the presented method is demonstrated. The accuracy of the solutions resulting from the proposed method is demonstrated by comparing the results with accurate solutions obtained from the finite element method with a fine mesh. The effects of different geometrical and
material parameters on the accuracy of the solutions are studied too. The presented formulation is quite practical and is employable for analyzing the torsion of thin- and moderately thick-walled sandwich members.

ABSTRACT: In this paper, the free vibration and buckling analyses of the cylindrical sandwich panel with magneto-rheological fluid layer for simply supported boundary conditions was performed based on an improved higher order sandwich panel theory. This paper deals with investigation of the effects of magnetic field, geometrical parameters such as the core thickness to the panel thickness ratio, MR layer thickness to the panel thickness ratio and the fiber angle on the natural frequencies, loss factors and buckling loads corresponding to the first four mode shapes. In order to validate the results obtained from the present study, the cylindrical sandwich panel was simulated and analyzed in finite element software ABAQUS. A good agreement was observed between the results of present method and those extracted from simulation.

ABSTRACT: Two kinds of innovative re-entrant and hexagonal cell honeycomb sandwich structures filled with reactive powder concrete were proposed, and the ballistic resistance and energy absorption of the sandwich structures were investigated by numerical simulations. The deformation and failure modes of the different structures were analyzed and evaluated in detail. The honeycomb sandwich structures filled with reactive powder concrete prisms improved the capacity of ballistic resistance and energy absorption significantly, compared to the normal reactive powder concrete plates and sandwich structures without reactive powder concrete prisms. The analysis shows that the auxetic re-entrant cell honeycomb sandwich structures have a better ballistic performance than the hexagonal cell honeycomb sandwich structures. The sandwich structures were subjected to impact by three kinds of projectiles: flat, hemispherical and conical nosed. The ballistic limit of the flat nosed projectile is the highest, while the impact performance of the conical and hemispherical nosed projectiles is obviously different from the flat nosed projectile, especially in a relative high velocity range. The sharper nose leads to a higher value of exit velocity and mass loss. In addition, effects of different design parameters on ballistic resistance were also studied by changing the thickness of honeycomb cell and face plates. Results indicate that the thickness of honeycomb walls and face plates have significant effect on the ballistic resistance and energy absorption in a relative low velocity range, while there are no big differences when the initial impact velocity exceeds 400 m/s.

ABSTRACT: The dynamic response of circular sandwich panels with aluminium honeycomb and corrugated cores under projectile impact was investigated experimentally and numerically. Impulse loaded on the panel
was controlled by projectile launching velocity and the deformation process of sandwich panels was recorded by a high-speed camera in the experiments. Typical deformation/failure modes of face-sheets and cores were obtained and analysed. The back face-sheet deflections and strain histories of face-sheets were measured and discussed. A parametric study was conducted by LS-DYNA 3D to analyse the effect of geometrical configuration on energy absorption mechanism and back face-sheet permanent deflection of circular sandwich panels. The results indicated that the impact resistance of the structure was sensitive to geometrical configuration. Increasing face-sheet thickness and core relative density significantly improved sandwich structure impact resistance. Increasing foil thickness improved the panel impact resistance more efficiently than decreasing wall side length. The results have important reference value to guide engineering application of the sandwich structure subjected to impact loading.

References listed at the end of the paper: (See Part 2)


ABSTRACT: The paper studied the dynamic response of square aluminum corrugated sandwich panels under projectile impact. The aluminum foam projectile was utilized to apply the impulse on the sandwich panels. In order to increase the applied impulse under controlled impact velocity ($V < 200$ m/s), a cylindrical Nylon mass was adhered to the back of foam projectile. Corrugated sandwich panels with two different configurations were tested and their typical deformation modes were obtained in the experiment. Based on the experiment, corresponding numerical simulations were presented. The energy absorption and deformation mechanism of corrugated sandwich panels were studied through the simulation. The influence of impact velocity, thickness of face sheet and wall thickness of corrugated core were discussed. The results indicated that the corrugated sandwich panels with smaller core height produce larger deformation than the panels with larger core height. The face sheets of corrugated sandwich panel absorbed comparable amount of energy with the corrugated core. The velocity histories show that under the combined action of aluminum foam projectile and nylon back mass, a second peak velocity of front face sheet can be produced during the impact process, which is defined as “accelerating impact stage” in current study. The influence of “accelerating impact stage” to the response of structures is sensitive to the impact velocity.


ABSTRACT: An accurate discrete model and analytical solutions thereof are presented for shear-deformable web-core sandwich plates. The face-plates are analyzed using the equations of three-dimensional elasticity, while the webs are accurately modelled using the classical plate theory with a plane stress solution for transverse bending and a Levy-type methodology for lateral bending. It is shown that this obviates the need for a complete three-dimensional analysis of the sandwich plate. Results obtained by this approach are used to highlight the effect of shear deformation of the face-plates.

ABSTRACT: Mechanical stability of the functionally graded rectangular plates bonded with functionally graded piezoelectric layers is studied in the present research. Classical plate theory is employed in the description of three components of the plate displacement. Geometric nonlinearity is considered in the strain–displacement relations using the von Karman equation. The constitutive relations are developed for the functionally graded material core and functionally graded plate material layers in the general state. The top and bottom of the piezoelectric layers is assumed to be short-circuited. Three equilibrium equations as well as Maxwell equation are constituted of four governing differential equations of the problem. Some important nondimensional parameters representing the geometries of the sandwich plate incorporated with nonhomogeneous index of the material properties are considered for this analysis. The results indicate that these parameters have important effects on the buckling loads.


ABSTRACT: In this work, biaxial buckling analysis of sandwich plates with symmetric composite laminated core and two functionally graded nanocomposite face sheets is carried out by a new improved high-order theory. The nanocomposite face sheets are carbon nanotube (CNT)-reinforced nanocomposites and the material properties of the nanocomposites plates are graded along the thickness and are estimated though the Mori–Tanaka approach. CNTs are assumed randomly oriented and aggregated into some clusters. The same third order theory is used for modeling of core and the faces sheets. The theory has third and second orders of z for in-plane and normal displacements, respectively. The principle of minimum potential energy is used to derive the equations of motion and boundary conditions. Analytical solution for static analysis of simply supported sandwich plates under biaxial in-plane compressive loads is presented using Navier’s solution. The effects of CNT volume fraction, CNT aggregation states, CNT distribution, biaxial loads ratio, and geometric dimensions of sandwich plate are investigated on the overall buckling of functionally graded carbon nanotube-reinforced nanocomposite sandwich plates.


ABSTRACT: In this paper, classical as well as various refined plate finite elements for the analysis of laminates and sandwich structures are discussed. The attention is particularly focussed on a new variable-kinematic plate element. According to the proposed modelling approach, the plate kinematics can vary through the thickness within the same finite element. Therefore, refined approximations and layer-wise descriptions of the primary mechanical variables can be adopted in selected portions of the structures that require a more accurate analysis. The variable-kinematic model is implemented in the framework of the Carrera unified formulation, which is a hierarchical approach allowing for the straightforward implementation of the theories of structures. In particular, Legendre-like polynomial expansions are adopted to approximate the through-the-thickness unknowns and develop equivalent single layer, layer-wise, as well as variable-kinematic theories. In this paper, the principle of virtual displacements is used to derive the governing equations of the generic plate theory and a mixed interpolation of tensorial components technique is employed to avoid locking phenomena. Various problems are addressed in order to validate and assess the proposed formulation, including multi-layer plates.
and sandwich structures subjected to different loadings and boundary conditions. The results are compared with those from the elasticity theory given in the literature and from layer-wise solutions. The discussion clearly underlines the enhanced capabilities of the proposed variable-kinematic mixed interpolation of tensorial component plate elements, which allows, if used properly, to obtain formally correct solutions in critical areas of the structure with a considerable reduction of the computational costs with respect to more complex, full layer-wise models. This aspect results particularly advantageous in problems where localized phenomena within complex structures play a major role.


ABSTRACT: Honeycomb sandwich structures are increasingly used in the automotive, aerospace and shipbuilding industries where fuel savings, increase in load carrying capacity, vehicle safety and decrease in gas emissions are very important aspects. The aim of this study was to develop the theoretical methods, initially proposed by the authors and by other researchers for the prediction of low-velocity impact responses of sandwich structures. The developed methods were applied to sandwich structures with aluminium honeycomb cores and glass-epoxy facings for the assessment of impact parameters and for the prediction of limit loads. The values of model parameters were compared with data reported in literature and the predictions of the limit loads were validated by means of the experimental data. Good achievement was obtained between the results of the theoretical models and the experimental data. The failure mode and the internal damage of the sandwich panels have been investigated using 3D computed tomography, which allowed the evaluation of parameters of energy balance model, and infrared thermography, which allowed the detection of the temperature evolution of the specimens during the tests. The experimental and theoretical results demonstrated that the use of glass-epoxy reinforcement on aluminium honeycomb sandwiches enhances the energy absorption and load carrying capacities.


ABSTRACT: In the present work, for the first time, the accuracy of the Refined Zigzag Theory in reproducing the static bending response of sandwich beams is experimentally assessed. The theory is briefly reviewed and an analytical solution of the equilibrium equations is presented for the boundary and loading conditions under investigation (four-point bending). The experimental campaign is described, including the material characterization and the bending tests. The experimentally measured deflections and axial strains are compared with those provided by Refined Zigzag Theory and by the Timoshenko Beam Theory with an ad hoc shear correction factor. The Refined Zigzag Theory is shown to be more accurate than the Timoshenko Beam Theory, in particular for beams with higher face-to-core thickness and stiffness ratios and with a reduced slenderness.


ABSTRACT: Shock tube experiments were performed to investigate the blast response of corrugated steel cellular core sandwich panels filled with a silicone based syntactic foam at room and high temperatures. The syntactic foam filler was prepared by mixing a two-part silicone mixture with glass microspheres; its microstructure, and mechanical properties were also characterized. The syntactic foam-filled sandwich panels
were loaded via air shock pressure by using the shock tube with a fixture capable of testing materials at temperatures up to 900°C. High-speed photo-optical methods, digital image correlation techniques, were used in tandem with optical band-pass filters and high intensity light sources for providing sufficient contrast at elevated temperatures. Back-face deformation images were captured using two synchronized high-speed cameras while a third camera captured the side view deformation images. The shock pressure profiles and digital image correlation analysis were used to obtain the impulse imparted to the specimen, transient deflection, in-plane strain and out-of-plane velocity of the back-face sheet. It was observed that using the syntactic foam as a filler material decreased the front face and back face deflections by 42% and 27%, respectively, as compared to the empty sandwich panel. At high temperatures, the silicone-based syntactic foam decomposes into silica, a stable and non-hazardous byproduct. The highest impulse was imparted to the specimen at room temperature and subsequently lower impulses with increasing temperatures were observed. Due to the increased ductility of steel at high temperatures, the specimens demonstrated an increase in back face deflection, in-plane strain and out-of-plane velocity with increased temperatures, with weld failure being the primary form of core damage.

ABSTRACT: Free vibration of laminated composite and soft core sandwich plates resting on Winkler–Pasternak foundations using four-variable refined plate theory are presented. The theory accounts for the hyperbolic distribution of the transverse shear strains through the plate thickness, and satisfies the zero traction boundary conditions on the surfaces of the plate without using shear correction factors. Equations of motion are derived from the dynamic version of the principle of virtual work. Navier technique is employed to obtain the closed-form solutions of antisymmetric cross-ply, angle-ply, and soft core laminates or soft core sandwich plates resting on elastic foundations. Numerical results obtained using present theory are compared with three-dimensional elasticity solutions and those computed using the first-order and the other higher-order theories. It can be concluded that the proposed theory is not only accurate, but also efficient in predicting the natural frequencies of laminated composite and soft core sandwich plates resting on Winkler–Pasternak foundations.

ABSTRACT: Used the Reddy's higher-order shear deformation plate theory, the nonlinear dynamic analysis and vibration of imperfect functionally graded sandwich plates in thermal environment with piezoelectric actuators (PFGM) on elastic foundations subjected to a combination of electrical, damping loadings and temperature are investigated in this article. One of the salient features of this work is the consideration of temperature on the piezoelectric layer, and the material properties of the PFGM sandwich plates are assumed to be temperature-dependent. The governing equations are established based on the stress function, the Galerkin method, and the Runge–Kutta method. In the numerical results, the effects of geometrical parameters; material properties; imperfections; elastic foundations; electrical, thermal, and damping loads on the vibration and nonlinear dynamic response of the PFGM sandwich plates are discussed. The obtained natural frequencies are verified with the known results in the literature.

ABSTRACT: Free vibration analysis of a sandwich beam with soft core and carbon nanotube reinforced composite face sheets, hitherto not reported in the literature, based on extended high-order sandwich panel theory is presented. Distribution of fibers through the thickness of the face sheets could be uniform or functionally graded. In this theory, the face sheets follow the first-order shear deformation theory. Besides, the two-dimensional elasticity is used for the core. The field equations are derived via the Ritz-based solution which is suitable for any essential boundary conditions. Chebyshev polynomials multiplying boundary R-functions are used as admissible functions and evidence of their good performance is given. A detailed parametric study is conducted to study the effects of nanotube volume fraction and their distribution pattern, core-to-face sheet thickness ratio, and boundary conditions on the natural frequencies and mode shapes of sandwich beams with functionally graded carbon nanotube reinforced composite face sheets and soft cores. Since the extended high-order sandwich panel theory can be used with any combinations of core and face sheets and not only the soft cores that the other theories demand, the results for the same beam with functionally graded carbon nanotube reinforced composite face sheets and stiff core are also provided for comparison. It is concluded that the sandwich beam with X and V distribution figures of face sheets, no matter what the boundary conditions, has higher vibration performance than the beam with UD-CNTRC face sheets.


ABSTRACT: Based on classical dynamic cylindrical cavity expansion theory, a nine-step penetration and perforation process of aluminum foam sandwich targets by truncated cone-nosed projectiles are developed theoretically. In the theoretical model, the friction, shear strength, and the force for tearing the cells in the core at the periphery of the projectile are considered, and the resistance force and instantaneous velocity are achieved from this process. On this basis, the effects of the geometry of projectiles, core thickness, and impact velocities of projectiles on absorbed energy are also analyzed. Simple composite failure criteria will be applied in the fracture and perforation of the face sheet, core, and back sheet. It is shown that the diameter of projectile and core thickness have significant influence on the ballistic velocity of the projectile, which is important for the impact response and absorbed energy of the sandwich. Numerical simulation at various impact velocities is also performed, and there is a good agreement between the numerical predictions and the analytical measurements.


ABSTRACT: The paper presents the experimental and numerical studies of sandwich panels with a hybrid core. The sandwich panel consists of external steel facings and a core, which is made of polyurethane foam or mineral wool or a combination of those two materials. The polyurethane foam material has a low weight and high thermal insulation properties, while the mineral wool material can provide high acoustic insulation and excellent fire resistance. Various proportions of the core materials are taken into account. It is assumed that a proper combination can provide the benefits of both materials. The structural behavior of a sandwich structure with a hybrid core is observed during laboratory tests. The failure mechanism is investigated in a four-point bending test. The material parameters of the core and facings are determined in standardized tests. The obtained parameters are used for FE simulations of the four-point bending tests. The criteria of damage initiation and propagation are defined in the interface layer of the numerical model. A satisfactory correlation between
laboratory tests and numerical results is reported. Additionally, the sensitivity analysis of the numerical model response to the variation of the parameters of the interface is presented.


ABSTRACT: In this paper, we study the nonlinear dynamic response of higher order shear deformable sandwich functionally graded circular cylindrical shells with outer surface-bonded piezoelectric actuator on elastic foundations subjected to thermo-electro-mechanical and damping loads. The sigmoid functionally graded material shells are made of the metal–ceramic–metal layers with temperature-dependent material properties. The governing equations are established based on Reddy’s third-order shear deformation theory using the stress function, the Galerkin method and the fourth-order Runge-Kutta method. Numerical results are given to demonstrate the influence of geometrical parameters, material properties, imperfection, elastic foundations, and thermo-electro-mechanical and damping loads on the nonlinear dynamic response of the shells. Accuracy of the present formulation is shown by comparing the results of numerical examples with the ones available in literature.


ABSTRACT: This paper presents experimental and analytical investigations about the elastic and viscoelastic (creep) behaviour of sandwich panels made of glass-fibre reinforced polymer faces and a polyethylene terephthalate foam core, produced by vacuum infusion for civil engineering structural applications. First, the elastic response of the panels’ constituent materials (glass-fibre reinforced polymer and polyethylene terephthalate) in tension, compression and shear was experimentally assessed; shear tests on the foam were carried out using a novel test method, the diagonal tension shear test. The creep behaviour in shear of the polyethylene terephthalate foam was evaluated for different load levels. The effective flexural properties of the full-scale sandwich panels as well as their flexural behaviour up to failure were experimentally assessed. Flexural creep and subsequent recovery experiments were also conducted for different load levels, to characterise the viscoelastic behaviour of the full-scale sandwich panels. Creep deformations of the polyethylene terephthalate foam and of the sandwich panels were found to be significantly lower than those corresponding to polyurethane foam and balsa wood reported in the literature; unrecoverable viscoelastic deformations were observed in the full-scale panels. In the analytical study, the creep response of the panels was modelled using Findley’s power law and the composite creep modelling approach. The composite creep modelling predictions were reasonably accurate and allowed assessing the relative contributions of bending and shear deformations to the total sandwich panel creep deflections.


ABSTRACT: The boundary layer hygrothermal stresses in the thick sandwich cylinder with laminated face are investigated. Uniform and through the thickness steady-state distribution for temperature and moisture content can be considered in the analysis. A displacement based layer-wise formulation is presented for analysis of thick sandwich composite cylinders subjected to hygrothermal loading conditions. Considering a general displacement field and employing a displacement based layer-wise theory, the governing equations of thick laminated sandwich cylinder are obtained. The displacement based formulation is derived for thick sandwich
cylinder, which is subjected to non-uniform hygrothermal loading conditions. The faces of the sandwich cylinder are made of laminated composite with general layer stacking. The governing equations of the system include a set of coupled differential equations on the displacement components of the numerical surfaces. A semi-analytical solution is developed and the governing equations are solved for free edge boundary conditions. The accuracy of the numerical results is validated by the results of the finite element simulation and good agreements are seen between the predicted results. The free edge interlaminar stresses distributions are presented for thin and thick sandwich composite cylinders for uniform and non-uniform loading conditions. It is concluded that the presented layer-wise formulation is efficient and accurate method for analysis of thermal and hygroscopic stresses in thick and thin sandwich cylinders with general layer stacking.


ABSTRACT: In this study, nonlinear free and forced vibration analysis of an embedded functionally graded sandwich micro-beam with a moving mass is investigated. The velocity of moving mass is assumed constant. The structure is resting on nonlinear Pasternak foundation. The governing equation of motion is obtained using Hamilton's principle based on the Euler–Bernoulli model with considering nonlinear terms in strain–displacement relation. Strain gradient elasticity theory is used to model the small scale effects. The micro-beam contains a homogenous core and two integrated functionally graded face-sheets. Mechanical properties except Poisson ratio are assumed to be variable based on the power-law distribution along the thickness direction. Galerkin's decomposition technique is implemented to convert nonlinear partial differential equation to a nonlinear ordinary differential equation. Multiple times scale method is applied to derive closed form approximate solution for free and forced vibration and nonlinear natural frequencies of the micro-beams. Accuracy of the obtained results using current issue may be justified by comparing with those obtained by existing results of the literature. The effect of some important parameters such as length scale parameter, power gradient index, nonlinear elastic foundation, aspect ratio, position, and velocity of moving mass and boundary conditions is studied on the various responses of the micro-beam such as nonlinear natural frequency, frequency response, and force–response curves.


ABSTRACT: The behavior of a simple and innovative multi-layer sandwich panels having a polypropylene honeycomb core has been investigated carefully, theoretically and experimentally. A four-point bending test was performed to detect the mechanical characteristics of the multi-layer core. The experimental results emphasize a better rigidity of the multi-layer structure compared to the weakness displayed by the single-layer configuration. In fact, a small increase in the final weight of the component leads to a significant increase of the mechanical properties. In the second part of this study, analytical and numerical homogenization approaches were developed to compute the effective properties of the single polypropylene honeycomb core. The numerical model complies with the experimental protocol, and the simulation conducted is aiming to reproduce a typical four-point bending test on a polypropylene honeycomb multi-layer sandwich panel. Both numerical and experimental results are presented in details and a good correlation between them is highlighted.
ABSTRACT: In order to investigate the impact resistance of the Nomex honeycomb sandwich structures skinned with thin fibre reinforced woven fabric composites, both drop-weight experimental work and meso-mechanical finite element modelling were conducted and the corresponding output was compared. Drop-weight impact tests with different impact parameters, including impact energy, impactor mass and facesheets, were carried out on Nomex honeycomb-cored sandwich structures. It was found that the impact resistance and the penetration depth of the Nomex honeycomb sandwich structures were significantly influenced by the impact energy. However, for impact energies that cause full perforation, the impact resistance is characterized with almost the same initial stiffness and peak force. The impactor mass has little influence on the impact response and the perforation force is primarily dependent on the thickness of the facesheet, which generally varies linearly with it. In the numerical simulation, a comprehensive finite element model was developed which considers all the constituent materials of the Nomex honeycomb, i.e. aramid paper, phenolic resin, and the micro-structure of the honeycomb wall. The model was validated against the corresponding experimental results and then further applied to study the effects of various impact angles on the response of the honeycomb. It was found that both the impact resistance and the perforation depth are significantly influenced by the impact angle. The former increases with the obliquity, while the latter decreases with it. The orientation of the Nomex core has little effect on the impact response, while the angle between the impact direction and the fibre direction of the facesheets has a great influence on the impact response.

ABSTRACT: This study investigates the effect of foam core density on the behaviour of sandwich panels with novel bio-composite unidirectional flax fibre-reinforced polymer skins, along with a comparison to panels of conventional glass-FRP skins. Eighteen 1000 mm long flexural specimens and 18 500 mm long stub column specimens were fabricated and tested. All specimens had a foam core of 100 × 50 mm² cross-section with symmetrical 100 mm wide skins. The study compares the effect of three separate polyisocyanurate foam cores when used in conjunction with either three layers of flax fibre-reinforced polymer or a single glass-FRP layer for each skin. Flexural specimens were tested in four-point bending and stub columns were tested under axial compression with pin–pin end conditions. Doubling the core density from 32 to 64 kg/m³ and tripling the density to 96 kg/m³ led to flexural strength increases of 82 and 213%, respectively, for flax fibre-reinforced polymer skinned panels, and comparable increases in glass-FRP skinned panels. Similarly, flax fibre-reinforced polymer-skinned columns showed similar increases in ultimate axial capacity of 85% and 196%, while glass-FRP-skinned columns experienced lower increases when core density was varied. The three-layered flax fibre-reinforced polymer skin, only 17% thicker than the single layer glass-FRP skin, was shown to provide equivalent flexural and axial strengths at all three core densities, within −5 to +13%.

ABSTRACT: This paper presents the studies carried out on bending and free vibration behavior of truss core sandwich panel filled with foam typically used in aerospace applications. Equivalent stiffness properties for foam-filled truss core sandwich panel are derived by idealizing 3D foam-filled sandwich panel to an equivalent
2D orthotropic thick plate continuum. The accuracy of the derived elastic property is ensured by the numerical comparison of free vibration response of 3D and its equivalent 2D finite element model. The derived stiffness constants were used in closed form solution to evaluate the maximum deflection of the continuum. The results show that the free vibration and static behavior of the sandwich panel can be enhanced in due consideration to the space constraint by filling foam in the empty space of core. The results also reveal that triangular core foam-filled sandwich panel deflects less compared to other cores. From the free vibration analysis, effect of filling foam is effective in cellular and trapezoidal core.

ABSTRACT: Titanium honeycomb sandwich structures are gradually used in several newly developed aircrafts in China. During the manufacturing process and aircraft service life, low-velocity impacts from foreign objects (typically stones, tools and hails, etc.), would quite likely happen and could not be completely avoided. In order to evaluate the influence of low-velocity impact damage on titanium honeycomb sandwich structures, unidirectional in-plane compression tests on both intact and impact damaged sandwich panels were conducted to obtain their failure modes and compressive failure strength. Test results showed that the low-velocity impact damage could cause the change in failure modes and a 9% to 15% decrease in the compressive failure strength. Different impact energy levels showed a limited influence on the compressive failure strength. Numerical analysis was conducted to study the compression after impact behavior of titanium sandwich panels. Parametric finite element models that contained all the geometric and the structural details of honeycomb core cells, as well as the indentation and the crushed core region, were developed in the analysis. The numerical results successfully exhibited the failure process of the intact and impact damaged titanium sandwich panels subjected to unidirectional in-plane compression, similar to what observed in the tests. The predicted compressive failure strength also agreed very well with the test data.

ABSTRACT: Auxetic cellular solids in the forms of honeycombs under blast load have great potential in a diverse range of applications, including core material in sandwich plates composite components. Based on Reddy’s first-order shear deformation plate theory, this paper presents an analysis of the nonlinear dynamic response and vibration of sandwich plates with negative Poisson’s ratio in auxetic honeycombs on elastic foundations subjected to blast and mechanical loads. A three-layer sandwich plate is considered discretized in the thickness direction by using analytical methods (stress function method, approximate solution), Galerkin method, and fourth-order Runge-Kutta method. The results show the effects of geometrical parameters, material properties, mechanical and elastic foundations on the nonlinear dynamic response, and vibration of sandwich plates.

ABSTRACT: Free vibration analysis of sandwich plates with non-monotonically graded flexible core is studied using a high-order sandwich panel theory. The non-monotonically graded flexible core is considered as two monotonically graded flexible core layers. In this high-order theory, the first-order shear deformation theory is
used for the face sheets and a 3D-elasticity solution of weak core is employed for each single core layer. The laminated two-layered core is analyzed and formulated by the mixed layer-wise theory. Based on the continuity of the displacements and transverse stresses at the interfaces of the face sheets and the core, equations of motion are derived by Hamilton’s principle. The accuracy of the present approach is validated by comparing with the numerical results obtained from finite element method and good agreements are reached. Parametric study is also conducted to investigate the effect of distribution of functionally graded material properties, the monotonically graded core thickness ratio, and the thickness-to-side ratio on the vibration frequency.

ABSTRACT: The buckling and postbuckling behaviors of eccentrically stiffened sandwich plates on elastic foundations subjected to in-plane compressive loads, thermal loads, or thermomechanical loads are presented analytically by using the Reddy’s third-order shear deformation plate theory with von Karman geometrical nonlinearity. Four cases of general Sigmoid and power laws are considered. The material properties of the facesheets, the core layer, and stiffeners are assumed to be temperature-dependent. Theoretical formulations based on the smeared stiffeners technique and third-order shear deformation plate theory are derived. The expressions of thermal parameters are found in the analytical form. Applying the Galerkin method, the expressions for determination of the critical buckling load and analysis of the postbuckling mechanical and thermal load-deflection curves are obtained. The iterative algorithm is presented for the case of temperature-dependent plate material properties. In addition, the influences of thermal element, functionally graded material stiffeners, the facesheet thickness to total thickness ratio, initial imperfection, and foundations are clarified in detail.

ABSTRACT: This paper investigates the nonlinear response of doubly curved functionally graded material sandwich panels resting on elastic foundations, exposed to thermal environments and subjected to uniform external pressure. The material properties of both face sheets and core layer are assumed to be temperature dependent, and effective material properties of functionally graded material layers are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. Formulations are based on first-order shear deformation shell theory taking geometrical nonlinearity, initial geometrical imperfection, Pasternak type elastic foundations, and tangential edge constraints into consideration. Approximate solutions are assumed to satisfy simply supported boundary conditions and Galerkin procedure is applied to derive expressions of buckling loads and nonlinear load-deflection relation. The effects of material, geometry and foundation parameters, face sheet thickness ratio, initial geometrical imperfection, thermal environments and degree of tangential restraint of edges on the snap-through instability, and nonlinear response of spherical and cylindrical functionally graded material sandwich panels are analyzed and discussed in detail.

ABSTRACT: Titanium honeycomb sandwich structures are gradually used in newly developed aircrafts in China. In this study, low-velocity impact tests on the titanium honeycomb sandwich structures were carried out to obtain the impact dynamic response and investigate the typical impact damage modes and parameters including the depths and diameters of the facesheet indentation and the core crushing region. The test results showed that the maximum contact force, the diameter and depth of the indentation had strong positive correlations to the impact energy. Numerical analysis was also conducted to study the low-velocity impact behaviour of the titanium honeycomb sandwich structures by using parametric finite element models that contained all the geometric and the structural details of the titanium honeycomb cores. The numerical results successfully captured the typical low-velocity impact damage modes of the titanium sandwich structures, similar to those observed in the tests. The predicted impact dynamic response also agreed very well with the test data. By using the validated finite element models, a parameter sensitivity study on the effects of the structural parameters on the low-velocity impact damage behaviour of the titanium sandwich structures was conducted. The parametric analysis results showed that the impactor diameter, the facesheet thickness and the core cell wall thickness had positive effect on the maximum contact force, and negative effect on the indentation depth, while the height of the honeycomb core had positive effect on the contact force, but little influence on the indentation depth.


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ABSTRACT: Circumferential ring stiffeners are commonly used to improve the buckling strength of cylindrical shells. Under special circumstances, stiffener ring needs to be partially cut in order to avoid interference with vessel attachments or surrounding structures. No clear guideline is available in rule-based method to deal with such case. This paper investigates the extent of reduction in buckling capacity for a range of cylindrical shell geometries with stiffener rings having different cross sections and different extents of circumferential cut. Finite-element (FE)-based analysis as per ASME Section VIII, Division 2, Part 5 has been employed to determine the permissible external pressure in each of the cases. Effects of ring cross section and extent of circumferential cut of stiffening ring on the maximum permissible external pressure have been presented. A total of 63 combinations of shell-stiffening ring configurations of different L/D, D/t ratios, cross section shape, and extent of cut have been investigated. Geometrical parameters for these combinations under study are so chosen that normal working range in industries is covered. The results obtained provide guidelines to design shells with partially cut stiffening rings.

ABSTRACT: When a crack is detected in a piping line during in-service inspections, failure estimation method provided in ASME Boiler and Pressure Vessel Code Section XI (ASME Code Section XI) or JSME Rules on Fitness-for-Service for Nuclear Power Plants (JSME FFS Code) can be applied to evaluate the structural integrity of the cracked pipe. The failure estimation method in the current codes accounts for the bending moment and axial force due to pressure. The torsion moment is not considered. Recently, analytical investigation was carried out by the authors on the limit load of cracked pipes considering multi-axial loads including torsion. Two failure estimation methods for multi-axial loads including torsion moment with different ranges were proposed. In this study, to investigate the failure behavior of cracked pipes subjected to multi-axial loads including the torsion moment and to provide experimental support for the failure estimation methods, failure experiments were performed on 20 mm diameter stainless steel pipes with a circumferential surface crack or a through-wall crack under combined axial force, bending moment, and torsion moment. Based on the experimental results, the proposed failure estimation methods were confirmed to be applicable to cracked pipes subjected to multi-axial loads.


ABSTRACT: The effect of welding residual stress on the buckling behavior of storage tanks subjected to the harmonic settlement was simulated using the shell-to-solid coupling method. In the numerical model of tanks coupled with the welding residual stress, the welding joint and its adjacent zone were modeled using the solid submodel and the zone far away from the welding joint was built by the shell submodel. Effects of welding parameters (e.g., welding velocities and welding passes) on the buckling behavior of tanks were analyzed systematically. Results indicate that the buckling strength of tanks is enhanced due to the welding residual stress. Comparatively, a slow welding velocity presents a more remarkable strengthening effect than the fast welding velocity due to a larger axial residual stress produced at the welding joint. Nevertheless, no significant difference between the double-side welding and the one-side welding for buckling strength enhancement is observed for the cases studied. This indicates that the current design method causes a conservative design without considering the welding residual stress.


ABSTRACT: This study aims to investigate the creep buckling behavior of a stainless steel column under axial compressive loading at extremely high temperatures. Creep buckling failure time of a slender column with a rectangular cross section was experimentally measured under three different temperature conditions, namely, 800, 900, and 1000 °C. At each temperature, axial compressive loads with magnitudes ranging between 15% and 80% of the buckling loads were applied to the top of the column, and the creep buckling failure time was measured to examine its relationship with the compressive load. The stainless steel column was found to fail within a relatively short time compared to that of creep deformation under tensile loading. An increase in the
temperature of the column was found to accelerate creep buckling failure. The in-plane and out-of-plane column displacements, which respectively, corresponded to the axial and lateral displacements, were monitored during the entire experiment. The creep buckling behavior of the column was also visualized by a high-speed camera. Based on the Larson–Miller parameters (LMP) determined from the experimental results, an empirical correlation for predicting the creep buckling failure time was developed. Another empirical correlation for predicting the creep buckling failure time based on the lateral deflection rate was also derived.


ABSTRACT: Technological advances have improved pipeline capacity to accommodate large ground deformation associated with earthquakes, floods, landslides, tunneling, deep excavations, mining, and subsidence. The fabrication of polyvinyl chloride (PVC) piping, for example, can be modified by expanding PVC pipe stock to approximately twice its original diameter, thus causing PVC molecular chains to realign in the circumferential direction. This process yields biaxially oriented polyvinyl chloride (PVCO) pipe with increased circumferential strength, reduced pipe wall thickness, and enhanced cross-sectional flexibility. This paper reports on experiments performed at the Cornell University Large-Scale Lifelines Testing Facility characterizing PVCO pipeline performance in response to large ground deformation. The evaluation was performed on 150-mm (6-in.)-diameter PVCO pipelines with bell-and-spigot joints. The testing procedure included determination of fundamental PVCO material properties, axial joint tension and compression tests, four-point bending tests, and a full-scale fault rupture simulation. The test results show that the performance of segmental PVCO pipelines under large ground deformation is strongly influenced by the axial pullout and compressive load capacity of the joints, as well as their ability to accommodate deflection and joint rotation. The PVCO pipeline performance is quantified in terms of its capacity to accommodate horizontal ground strain, and compared with a statistical characterization of lateral ground strains caused by soil liquefaction during the Canterbury earthquake sequence in New Zealand.


ABSTRACT: Pipelines can be subjected to bending loads due to a variety of factors such as seismic activity, slope instability, or discontinuous permafrost. Experimental studies of Sen et al. [1–3] showed that pipelines can fail under bending loads due to pipe body tension side fracture which is a mostly overlooked failure mode in pipelines. Recent numerical studies on the structural behavior of cold bent pipes [4–6] also confirmed the likelihood of the pipe body tension side fracture. Furthermore, it was shown that both the material properties and the level of internal pressure can have a considerable effect on the failure mode of the pipe. In this current work, the parametric studies of internal pressure and material properties are extended to straight pipes using finite-element analysis. The differences in the structural behavior due to using stress–strain curves from test specimens in longitudinal and circumferential direction of the pipe are demonstrated. Using failure criteria based on the equivalent plastic strain, different failure modes corresponding to different levels of internal pressure and yield strength are shown on straight pipes.

ABSTRACT: Piping lines in nuclear power plants may experience multi-axial loads including tensile force, bending, and torsion moments during operation. There is a lack of guidance for failure evaluation of locally wall-thinned pipes under the multi-axial loads including torsion moment. The ASME B&PV Code Section XI Working Group is currently developing fully plastic failure evaluation procedures for pressurized piping items containing local wall thinning subjected to multi-axial loads. A failure estimation method for locally wall-thinned pipes subjected to multi-axial loads including torsion moment has been proposed through numerical analyses. In this study, in order to investigate the failure behavior of the pipes with local wall thinning subjected to multi-axial loads including the torsion, failure experiments were performed on 20 mm diameter carbon steel pipes with a local wall thinning. Based on the experimental results, the proposed failure estimation method is confirmed to be applicable to pipes with local wall thinning.


ABSTRACT: Consideration of a geometrical nonlinearity is a common practice for thin-walled pressurized structures, especially when their cross section is not a perfectly circular one due to either initial imperfections or distortions caused by the nonsymmetrical loading. The application of inner pressure leads to so-called rerounding effect when decreasing of local flexibilities takes place. The crack can be also treated as the concentrated flexibility, so the goal of this work is the investigation of dependence of stress intensity factor (SIF) on applied pressure. Two cases of SIF calculation for 1D long axial surface crack in a pipe loaded by inner pressure are considered here: (a) cross section of pipe has an ideal circular form and (b) the form has a small distortion and crack is located at the place of maximal additional bending stresses. The theoretical analysis is based on: (a) well-known crack compliance method (CCM) (Cheng, W., and Finnie, I., 1986, “Measurement of Residual Hoop Stresses in Cylinders Using the Compliance Method,” ASME J. Eng. Mater. Technol., 108(2), pp. 87–92) and (b) analytically linearized solution for deformation of the curved beam in the case of action of uniform longitudinal stresses. It is shown that for moderately deep crack (crack depth to the wall thickness ratio of 0.5 and bigger) in thin-walled pipe (radius to thickness ratio of 25–40) and inner pressure which induce hoop stress up to 300 MPa, the effect investigated can be quite noticeable and can lead to 5–15% reduction of calculated SIF as compared with the linear case. The analytical results are supported by the geometrically nonlinear finite element method (FEM) calculations.


ABSTRACT: Design of the top wind stiffeners of aboveground storage tanks designed to the requirements of API 650 is investigated. The current design methodology is based on intuition and experience without a sound technical justification. This paper investigates a diameter limit to be used in the design of the top stiffener ring by using finite-element analysis (FEA) in a parametric study. Linear bifurcation analysis (LBA) and geometrically nonlinear analysis including imperfections (GNA) were performed on cylindrical storage tanks. By modeling tanks with different diameters and limiting the design of top stiffener ring for a diameter of 170-ft
(52-m), the buckling loads are investigated. It was found that the 170-ft (52-m) diameter is a suitable upper limit to design the top stiffener rings for larger diameters.


ABSTRACT: This paper presents a numerical study of the dynamic response and stability of a partially confined cantilever pipe under simultaneous internal and external axial flows in opposite directions. The onset of flow-induced vibrations is predicted by the developed numerical model, and moreover, limit-cycle motion occurs as the flow speed becomes larger than a critical value. The numerical results are in good agreement with existing experimental results. The simulation gives control over many physical parameters and provides a better insight into the dynamics of the pipe. A parametric study regarding the stability of the system for varying confinement length is performed. The current results show that there is an increase in the susceptibility of the system to instability as the extent of confinement is increased.


ABSTRACT: Shop–welded, flat-bottom tanks for storage of production liquids are designed and fabricated in specific dimensions and capacities for internal pressures close to atmospheric pressure in accordance with the API 12F specification. This study addresses the failure pressure on the eleven (11) current API 12F shop-welded steel tanks as well as two proposed sizes through finite element and stress analysis of more than 350 different tank models. An elastic analysis was carried out to determine the yielding pressure of the shell-to-bottom and roof-to-shell joints. An elastic buckling analysis and a post-buckling analysis including imperfections was performed to determine the buckling modes of the equipment. The redistribution of stresses due to inelastic deformations and plastic collapse were evaluated through a plastic stress analysis considering the stress–strain hardening of the ASTM A36 mild steel material. Moreover, the design pressure increase to failure pressure or 24 oz/in² (10.3 kPa) was investigated regarding the stress levels and bottom uplift of the 13 flat-bottom tanks. The presented research provides meaningful insights and engineering calculations to evaluate the current design of the API 12F shop-welded, flat-bottom tanks as well as to establish new design internal pressures guaranteeing a safe performance of the equipment.

Huan Sheng Lal and Kang Lin Liu (School of Chemical Engineering, Fuzhou University, Fujian, China), “Relationships between the proportional law and the charts used in ASME VIII-1 and EN13445-3 for designing shells and tubes under external pressure”, ASME Journal of Pressure Vessel Technology, Vol. 139, No. 4, August 2017, doi: 10.1115/1.4036531

ABSTRACT: Shells and tubes usually fail in the form of buckling under external pressure. Charts are used in the design of shells and tubes in the standards of ASME VIII-1 and EN13445-3 and these simplify the calculation process, while the proportional law is a more effective and simple method. In this paper, the relationships between the proportional law and the charts used in the standards were researched; finite element method (FEM) was used to compare the accuracies of the proportional law and the charts. It was theoretically proved that the proportional law and the charts were using essentially the same method to calculate the critical
buckling pressure; they were different forms of the same dimensionless tension stress–strain curves. The simulation results showed that the proportional law and the charts had effectively equal accuracies in calculated critical buckling pressures. Therefore, the proportional law can be a candidate method included in the standards for the design of shells and tubes under external pressure.

References listed at the end of the paper:

ABSTRACT: In this study, two failure modes, yield buckling of the compression ring section and strength failure in the roof-to-shell of the tank, have been proposed for a vertical vaulted tank. The failure criteria of the two failure modes in the roof-to-shell of vault tanks are established via finite element analysis of three tanks of 640 m³, 3200 m³, and 6800 m³ in volume. The finite element models are built with axisymmetric elements and spatial multi-elements. Based on the strength failure criterion, the failure pressure formula in the vaulted tank roof-to-shell is derived. The maximum relative error between the theoretical calculation and numerical simulation is 9.7%. Finally, we verify the strength failure criterion through a tank failure test; the maximum relative error between the test and theoretical calculation is 9.6%. The failure pressure of both failure modes has been compared and analyzed. The failure pressure of the yield buckling in the compression ring section is about 1.65 times that of the strength failure in the roof-to-shell of the tank.

ABSTRACT: In this paper, applicability of net-section collapse load approach to circumferential multiple-cracked pipe assessment is investigated using finite element (FE) damage analysis. The FE damage analysis based on the stress-modified fracture strain model is validated against limited fracture test data of two circumferential surface-cracked pipes. Then, the systematic parametric study is performed using the FE damage analysis for symmetrical and asymmetrical surface-cracked pipes. It is found that predictions using the net-section collapse load approach tend to be more accurate with increasing the distance between two symmetrical cracks. For asymmetrical cracks, it is found that the deeper crack plays a more important role and that the existing net-section collapse load expression can be potentially nonconservative. Idealization to symmetrical cracks based on the deeper crack is proposed.


ABSTRACT: Motivated by the fact that a leaking pipe can lose or gain energy from the leaking flow, this study attempts to explore the nonconservative leaking flow effect on the dynamic stability of a simply supported pipe with a constant velocity leakage. It employs a two-dimensional nonlinear longitudinal and lateral coupling model, and the leakage effect is accounted for by virtual work due to virtual momentum transport at the leaking point. The equations of motion are solved by Galerkin-based multimode approach and the Houbolt's finite difference time integration. It demonstrates that when there is a leaking flow, a stable pipe can be refined or destabilized via a static pitchfork bifurcation, and a buckling pipe can be stabilized or deteriorated into a worse divergence condition. The critical leaking flow velocities and the excited buckling modes depend on the leaking fluid mass and the leak's position. This study may provide some insights to assist the leak detection system (LDS) of a pipe transporting high-pressure oil or gas in modern engineering.


ABSTRACT: The paper describes burst pressures of eight mild steel toriconical shells and proposes a criterion for their ultimate loss of structural integrity based on true stress–strain material relationship. All test models were initially loaded by quasi-static external pressure until they buckled/collapsed. They were subsequently internally pressurized until burst. The details about the numerical process, which simulates the two-stage loading process, i.e., starting with buckling by external pressure being followed by reloading using internal pressure for up to the burst, are given. The paper concentrates on numerical procedure, which allows computation of the burst pressure using extensive plastic straining. It is shown that burst pressures based on the excessive plastic straining are closer to reality (and experiments) than those based on plastic instability.

ABSTRACT: In this paper, an analytical method is developed to obtain the solution for the two-dimensional (2D) \((r,\theta)\) transient thermal and mechanical stresses in a hollow sphere made of functionally graded (FG) material and piezoelectric layers. The FGM properties vary continuously across the thickness, according to the power functions of radial direction. The temperature distribution as a function of radial and circumferential directions and time is obtained solving the energy equation, using the method of separation of variables and Legendre series. The Navier equations are solved analytically using the Legendre polynomials and the system of Euler differential equations.

ABSTRACT: The stress states of elbow and tee pipes are complex and different from those of straight pipes. The low-cycle fatigue lives of elbows and tees cannot be predicted by Manson's universal slope method; however, a revised universal method proposed by Takahashi et al. was able to predict with high accuracy the low-cycle fatigue lives of elbows under combined cyclic bending and internal pressure. The objective of this study was to confirm the validity of the revised universal slope method for the prediction of low-cycle fatigue behaviors of elbows and tees of various shapes and dimensions under conditions of in-plane bending and internal pressure. Finite element analysis (FEA) was carried out to simulate the low-cycle fatigue behaviors observed in previous experimental studies of elbows and tees. The low-cycle fatigue behaviors, such as the area of crack initiation, the direction of crack growth, and the fatigue lives, obtained by the analysis were compared with previously obtained experimental data. Based on this comparison, the revised universal slope method was found to accurately predict the low-cycle fatigue behaviors of elbows and tees under internal pressure conditions regardless of differences in shape and dimensions.

ABSTRACT: In order to ensure safe operation and structural integrity of pipelines and piping systems subjected to extreme loading conditions, it is often necessary to strengthen critical pipe components. One method to strengthen pipe components is the use of composite materials. The present study is aimed at investigating the mechanical response of pipe elbows, wrapped with carbon fiber-reinforced plastic (CFRP) material, and subjected to severe cyclic loading that leads to low-cycle fatigue (LCF). In the first part of the paper, a set of LCF experiments on reinforced and nonreinforced pipe bend specimens are described focusing on the effects of CFRP reinforcement on the number of cycles to failure. The experimental work is supported by finite element analysis presented in the second part of the paper, in an attempt to elucidate the failure mechanism. For describing the material nonlinearities of the steel pipe, an efficient cyclic-plasticity material model is employed, capable of describing both the initial yield plateau of the stress–strain curve and the Bauschinger effect characterizing reverse plastic loading conditions. The results from the numerical models are compared with the experimental data, showing an overall good comparison. Furthermore, a parametric numerical analysis is conducted to examine the effect of internal pressure on the structural behavior of nonreinforced and reinforced elbows, subjected to severe cyclic loading.

ABSTRACT: In this paper, performance criteria for the seismic design of industrial liquid storage tanks and piping systems are proposed, aimed at introducing those industrial components into a performance-based design (PBD) framework. Considering “loss of containment” as the ultimate damage state, the proposed limit states are quantified in terms of local quantities obtained from a simple and efficient earthquake analysis. Liquid storage tanks and the corresponding principal failure modes (elephant's foot buckling, roof damage, base plate failure, anchorage failure, and nozzle damage) are examined first. Subsequently, limit states for piping systems are presented in terms of local strain at specific piping components (elbows, Tees, and nozzles) against ultimate strain capacity (tensile and compressive) and low-cycle fatigue. Modeling issues for liquid storage tanks and piping systems are also discussed, compared successfully with available experimental data, and simple and efficient analysis tools are proposed, toward reliable estimates of local strain demand. Using the above reliable numerical models, the proposed damage states are examined in two case studies: (a) a liquid storage tank and (b) a piping system, both located in areas of high seismicity.

Masanori Ando, Hiroki Yada, Kazuyuki Tsukimori, Masakazu Ichimiya and Yoshinari Anoda (primarily Research Institute of Nuclear Engineering, University of Fukui, Japan), “Experimental study on the deformation and failure of the bellows structure beyond the designed internal pressure”, ASME Journal of Pressure Vessel Technology, Vol. 139, No. 6, December 2017, doi: 10.1115/1.4037564

ABSTRACT: Bellows structure is used to absorb the thermal expansion maintaining the boundary of the inside to outside, and it is applied to constitute the containment vessel (CV) boundary of the nuclear power plant. In this study, in order to develop the evaluation method of the ultimate strength of the bellows structure subject to internal pressure beyond the specified limit, the failure test and finite element analysis (FEA) of the bellows structure were performed. Several types of the bellows structure made of SUS304 were tested using pressurized water. The failure modes were demonstrated through the test of five and six specimens with six and five convolutions, respectively. Water leakage was caused by contact of the expanded convolution and the neighbor structure in the specimens with the shipping rod mounts. On the other hand, local failure as leakage in the deformation concentrated location and ductile failure as burst in the expanded convolution were observed in the specimen without shipping rod mounts. The maximum pressures in the test observed local and ductile failure were over ten times larger than the estimated values of the limited design pressure for in-plane instability by the EJMA standard. To simulate the buckling and deformation behavior during the test, the implicit and explicit FEA were performed. Because the inversion of the convolution accompanied by convolution contact observed in the test was too difficult a problem for implicit analysis, the maximum pressures in the step of solution converged were compared to the maximum pressures in the tests. On the other hand, explicit analysis enabled to simulate the complex deformation during the test, and the results were evaluated considering ductile failure to compare the test results.


ABSTRACT: Linearized buckling analysis of functionally graded shells of revolution subjected to displacement-dependent pressure, which remains normal to the shell's middle surface throughout the
deformation process, is described in this work. Material properties are assumed to be varied continuously in the thickness direction according to a simple power law distribution in terms of the volume fraction of a ceramic and a metal. The governing equations are derived based on the first-order shear deformation theory, which accounts for through the thickness shear flexibility with Sanders type of kinematic nonlinearity. Displacements and rotations in the shell's middle surface are approximated by combining polynomial functions in the meridional direction and truncated Fourier series with an appropriate number of harmonic terms in the circumferential direction. The load stiffness matrix, also known as the pressure stiffness matrix, which accounts for the variation of load direction, is derived for each strip and after assembling resulted in the global load stiffness matrix of the shell, which may be unsymmetric. The load stiffness matrix can be divided into two unsymmetric parts (i.e., load nonuniformity and unconstrained boundary effects) and a symmetric part. The main part of this research is to quantify the effects of these unsymmetries on the follower action of lateral pressure. A detailed numerical study is carried out to assess the influence of various parameters such as power law index of functionally graded material (FGM) and shell geometry interaction with load distribution, and shell boundary conditions on the follower buckling pressure reduction factor. The results indicate that, when applied individually, unconstrained boundary effect and longitudinal nonuniformity of lateral pressure have little effect on the follower buckling reduction factor, but when combined with each other and with circumferentially loading nonuniformity, intensify this effect.

References listed at the end of the paper:


Mehdi Rastgar and Hossein Showkati (Dept. of Civil Engineering, Urmia University, Iran), “Buckling of cylindrical steel tanks with oblique body imperfection under uniform external pressure”, ASME Journal of Pressure Vessel Technology, Vol. 139, No. 6, December 2017, doi: 10.1115/1.4037808

ABSTRACT: Shell structures are built using a number of welded curved panel parts. Hence, some geometrical imperfections emerge. These imperfections have a direct impact on structural behavior of shells during the external compressive loading. In this research, a field study was accomplished on the implementation of the storage tanks in a refinery site, and then the resulted imperfections were identified and categorized. The survey of imperfections revealed that imperfection resulted from deviation with respect to the vertical direction has the highest number in tank bodies. This imperfection experimentally modeled, and the buckling behavior of these tanks was evaluated under uniform external pressure. The cylindrical tanks were examined using finite element analysis, and results obtained were compared with experimental results. Investigation of finding results demonstrated that such imperfection has a significant role in reducing the number of circumferential waves in body of the tanks under uniform external pressure. Comparing the results obtained by estimation, American Society of Mechanical Engineers (ASME) code, experimental research, and finite element method (FEM) represented a considerable difference in the amount of buckling load. Results show that tanks with oblique body imperfections exhibit high initial strength against buckling due to the uniform external pressure.

References listed at the end of the paper:

ABSTRACT: A containment of a nuclear power plant is a final barrier against the release of radioactive materials and withstands internal pressure due to an accident. Buckling is a critical failure mode of an ellipsoidal head of steel containment vessel under internal pressure. First, a vessel was designed to measure buckling pressure and shape of the ellipsoidal head. Second, an experiment was successfully performed on an ellipsoidal head which has a diameter of 4797 mm, a radius-to-height ratio of 1.728, and a thickness of 5.5 mm. The initial shape and deformations of the ellipsoidal head were measured by using three-dimensional (3D) laser scanners. The detailed buckling characteristics including shapes, deformations, strains of buckles, and buckling pressures were obtained. Finally, initial buckling pressures were predicted by nonlinear finite element analysis considering the initial measured and the initial perfect shapes of the ellipsoidal head, respectively. The agreement between the initial experimental buckling pressure and that predicted by the analysis considering the initial measured shape is good.

ABSTRACT: The accident at the Fukushima Dai-ichi Nuclear Power Plant (NPP) resulting from the 2011 Great East Japan Earthquake raised awareness as to the importance of considering Beyond Design Basis Events (BDBE) when planning for safe management of NPPs. In considering BDBE, it is necessary to clarify the possible failure modes of structures under extreme loading. Because piping systems are one of the representative components of NPPs, an experimental investigation was conducted on the failure of a pipe assembly under simulated excessive seismic loads. The failure mode obtained by excitation tests was mainly fatigue failure. The reduction of the dominant frequency and the increase of hysteresis damping were clearly observed in high-level input acceleration due to plastic deformation, and they greatly affected the specimens’ vibration response. Based on the experimental results, a procedure is proposed for calculating experimental stress intensities based on excitation test so that they can be compared with design limitations.


ABSTRACT: Aboveground vertical steel storage tanks use stiffener rings to prevent their shell wall from buckling under wind loading. The existing stiffener rings design rules from API 650 standard is known to be overly conservative. This study investigates the possibility of modifying the design rules by reducing the required size of the top stiffener ring to the same size as the intermediate stiffener ring. In this study, we used finite element analysis (FEA) to perform linear bifurcation analysis (LBA) and geometrically nonlinear analysis including imperfections (GNIA) to obtain failure load of modeled tanks. The buckling pressure load was obtained to ensure it is larger than the design pressure. Moreover, the effects of higher strength materials, different buckling modes, and various wind profiles were also studied to ensure the design suggested by this study is practical and universal to different situations. The results show that for cylindrical storage tanks, which only needs one intermediate stiffener ring, the size of the top stiffener ring can be set to the same size as the intermediate stiffener ring.


ABSTRACT: As an economical alternative to solid corrosion resistant alloy (CRA) and clad pipes, mechanically lined or sleeved CRA pipes are proven to be effective in the transport of corrosive fluids in oil and gas industry. A major issue with these pipes is that pressure drop or fluctuations may cause buckling of the liner, resulting in irreparable and costly damage. This issue should be resolved in order to fully implement this type of pipes in oil and gas industry. In this study, post-buckling analysis of liner pipe encased in carbon steel outer pipe is carried out following the hydraulic expansion manufacturing process. Commercially available ABAQUS finite element software is employed. The proposed model is partly verified with an analytical solution and other numerical results under the condition of no residual contact pressure. Results of the parametric study reveal that increasing the residual contact pressure and decreasing the magnitude of geometric imperfection can both contribute to enhancing the buckling resistance.


ABSTRACT: Pipe-in-pipes (PIPs) are generally applied to the extreme environments such as deep-sea and next-generation reactors due to their functionality and robustness. Thus, it is important to estimate the fracture behaviors of PIPs for integrity assessment of this unique piping system. In this work, the plastic collapse
behaviors of PIPs with circumferential through-wall cracks (TWCs) are investigated based on three-dimensional finite element (FE) limit analysis, where the crack is assumed to be located at the inner pipe of PIPs. As for loading conditions, internal pressure, axial tension, and global bending moment are considered. In particular, the bending restraint effect induced by interconnection between the inner and outer pipes of PIPs is quantified through the FE analyses considering a practical range of geometries of PIPs. Based on the FE analysis results, the tabular and closed-form solutions of the plastic limit loads of the circumferential through-wall cracked PIPs are proposed, and then, validated against numerical simulations.


ABSTRACT: The paper is a review work devoted to dished heads of various meridian shapes. Geometry of the shells of revolution, the membrane state, and the edge effect occurring in the shells are described. Exemplary analytical and numerical finite element method (FEM) studies of torispherical, ellipsoidal, Cassini-ovaloidal, and untypical special dished heads are presented. The results of the above-mentioned two methods are compared. Moreover, numerical research of elastic buckling of the above-mentioned selected heads under external pressure is carried out. Literature related to each of the considered head types is quoted and discussed, with special attention paid to the works developed in the 21st century. In concluding remarks, the stress concentration and buckling of these structures are commented, with consideration of the head meridian shapes.

References listed at the end of the paper:


ABSTRACT: Although the inner container of the cryogenic liquid semitrailer works under inner pressure, it needs to be vacuumed during the helium leak detection. Furthermore, the inner container usually cannot meet the stability requirements during the evacuation, though equipped with stiffening structures such as supporting rings for baffles inside the containe. Therefore, a kind of temporary local rigid clamping structure was proposed to improve the antibuckling ability of the inner container during the helium leak detection. “Lulu” can was taken as the thin-walled cylindrical shell specimen under external pressure and was clamped with the temporary local rigid ring on the outside surface. The critical pressures were experimentally and numerically studied for the specimen with local clamping rings of different sizes, in which eigenvalue buckling analysis and nonlinear analysis were employed with the aid of ANSYS. It indicates that the critical pressure of the specimen with the local clamping ring is higher than that without the clamping ring. Finally, the optimal clamping scheme including size and location of clamping rings for the inner container of DC18 type cryogenic liquid semitrailer was studied with the finite element method, which aimed to improve the antibuckling capacity of the inner container during the helium leak detection.


ABSTRACT: It is generally accepted that the presence of imperfections in pressure vessel components can significantly reduce their buckling strength. In fact, the discrepancies between theoretical predictions and experimental results have been attributed to various kinds of existing and unavoidable imperfections. This is not a new problem but despite of substantial research effort in this area over the recent decades, it is far from being satisfactorily resolved. This review provides insight into the past findings and current activities related to the role of different types of imperfections on the buckling strength. It aims to contribute to a better understanding of the influence of imperfections on the structural stability of cones, cylinders, and domes when these are
subjected to external loading conditions. The review concentrates not only on the prominent role of initial geometric imperfections of the shell's generator but also on less known defects. This includes uneven axial length of cylinders, eccentricities, and nonuniformities of applied load, inaccurately modeled boundary conditions, corrosion of the wall, influence of material discontinuity or crack, and effect of prebuckling deformation. The study examines: (i) how the data were obtained (analytically, experimentally, and/or numerically), (ii) the type of material from which the shell structures were made, and (iii) the importance of findings of the previous works. Metallic and composite components are considered.

References listed at the end of the paper:
ABSTRACT: In service pipelines exhibit bending loads in a variety of in-field situation. These bending loads can induce large longitudinal strains, which may trigger local buckling on the pipe's compressive side and/or lead to rupture of the pipe's tensile side. In this article, the post-buckling failure modes of pressurized X65 steel pipelines under monotonic bending loading conditions are studied via both experimental and numerical investigations. Through the performed full-scale bending test, it is shown that the post-buckling rupture is only plausible to occur in the pipe wall on the tensile side of the wrinkled cross section under the increased bending. Based on the experimental results, a finite element (FE)-based numerical model with a calibrated cumulative fracture criterion was proposed to conduct a parametric analysis on the effects of the internal pressure on the pipe's failure modes. The results show that the internal pressure is the most crucial variable that controls the ultimate failure mode of a wrinkled pipeline under monotonic bending load. And the post-buckling rupture of the tensile wall can only be reached in highly pressurized pipes (hoop stress no less than 70% SMYS for the investigated X65 pipe). That is, no postwrinkling rupture is likely to happen below a certain critical internal pressure even after an abrupt distortion of the wrinkled wall on the compressive side of the cross section.

References listed at the end of the paper:

ABSTRACT: Composite pipes are currently being used in a multitude of applications varying from civil to oil and gas applications. Pipes are generally connected together by means of pipe elbows that in turn are subjected to bending moment and pressure loading. This study looks into the effect of combined loading on the first ply and ultimate failure load of pipe elbows. The influence of pressure loading followed by a bending moment versus first applying bending moment followed by subsequent pressure loading, on the ultimate catastrophic failure load, is investigated through numerical models. The combined bending moment and pressure load ramping is also studied. Design by analysis finite element damage mechanics numerical methods are applied to investigate post first ply failure (FPF) and stress redistribution. The study shows that different loading combinations can give rise to different damage mechanisms and ultimately failure loads. A safe design load envelope for different fiber-reinforced pipe elbows based on FPF and ultimate catastrophic load is identified and discussed.

End of more papers published in the journal, ASME Journal of Pressure Vessel Technology (2017 and on).

More papers published in the journal, Advances in Structural Engineering (2017 and on)

Google the string: “Advances in Structural Engineering”, then click on the entry: “Advances in Structural Engineering – All Issues – SAGE Journals”


ABSTRACT: A method for monitoring the upheaval buckling of subsea buried pipelines by distributed optical fiber sensors is introduced. The proposed method originates from the fact that the bucked pipe has the deterministic patterns of the bending-induced and axial force–induced strains, which can be used to identify the pre- and post-buckling states of the pipe. The challenge for utilizing these features is that the distributed fiber optic sensor can only measure the compound strain created by both bending and axial compression. A monitoring scheme by placing three sensors with 2π/3 space around the circumference of the pipeline was proposed in this article. An approach was presented to extract the bending-induced and axial force–induced strains from the longitudinal strains measured by the distributed fiber optic sensors. The experimental programs were then designed to investigate the feasibility of the proposed method. It is demonstrated that the proposed method is possible to detect the occurrence of buckling in the pipe. However, further research is necessary in order to examine the efficiency of the proposed approach under the complex loading patterns at subsea levels.

ABSTRACT: Before being tensioned, the stiffness of the upper reticulated shell of a prestressed suspended dome is small, and the lower cable–strut system is completely flexible. The shape and stiffness of the structure constantly change during the construction process; therefore, a construction experiment needed to be performed to ensure the success and safety of the tensioning process for practical engineering. A tensioning experiment was performed on a reduced scale model of a large-span suspended dome. The safety, internal forces, joint displacements, and cable tensions during the tensioning process were studied. The effects of the sequence, times, and magnitudes of the loop cable tensioning were studied. The unfavorable factors of friction loss at the cable–strut joint, tensioning sequence loss, and out-of-sync tensioning on the tensioning points were evaluated, and measures to reduce the friction loss were then proposed. Two tensioning schemes were tested, compared, and used to predict the potential difficulties in practical engineering construction. An optimized tensioning scheme was developed for practical engineering.


ABSTRACT: Mode selection and modal coupling analysis are important to estimate wind-induced structural response of long-span roof structures. This article presents a framework for predicting wind-induced structural response of long-span roof structures based on modal analysis. This framework first identifies the dominant modes according to the correlation between the mode shape and the wind load spatial distribution on the structure as well as a proposed “modal participation coefficient.” Second, the concept of modal strain energy is introduced and a modal coupling coefficient is defined, based on which the dominant coupling modes are determined. A modified square root of the sum of the squares methodology is then developed to account for the modal coupling effects of the background and the resonant response components. The total responses can be obtained by combining the contributions of the dominant coupling modes and the square root of the sum of the squares results from the dominant modes. This avoids the use of the computation expensive complete quadratic combination method. Finally, an illustrative example of wind-induced response analysis of the China National Stadium roof structure is provided to demonstrate the effectiveness of the proposed framework.


ABSTRACT: To prevent lower-order local buckling of H-section steel core, an improved type of buckling-restrained braces named buckling-restrained brace with H-section steel core was proposed by the authors. This article further investigates the effect of configuration details on seismic performance of buckling-restrained braces with H-section steel core and compares two half-wavelength calculation methods for higher-order local buckling of H-section steel core. First, quasi-static cyclic tests are described on two newly designed buckling-restrained braces with H-section steel cores and another buckling-restrained brace with flat steel core. Then, Bleich’s and Lundquist’s methods are reviewed for evaluating half wavelength of higher-order local buckling based on elastoplastic buckling theory of plates and compared with the test results of four buckling-restrained braces with H-section steel core including the two from a previous test. It is found from the test results that due to H-section steel core’s higher self-stability, the compression force fluctuation was not observed on the hysteretic loops of buckling-restrained brace with H-section steel core with even larger clearance but on the buckling-restrained brace with flat core. The buckling-restrained brace with H-section steel core was also advantageous over the buckling-restrained brace with flat core in terms of having lower compression strength adjustment factor $\beta$. A stopper in the middle of the core member and the gradual change of cross section of the core plate around the end of stiffeners could help to improve the fatigue performance of buckling-restrained...
braces. The test results also confirmed that Lundquist’s theory was more reliable for evaluating the half wavelength of higher-order local buckling for H-section steel core.


ABSTRACT: This article presents a numerical investigation on the web crippling strength of cold-formed stainless steel lipped channel sections with circular web openings under end-one-flange loading condition. In order to take into account the influence of the circular web openings, a parametric study involving 1992 finite element analyses was performed, covering duplex EN1.4462, austenitic EN1.4404 and ferritic EN1.4003 stainless steel grades; from the results of the parametric study, strength reduction factor equations are proposed. The web crippling strengths predicted by the reduction factor equations are first compared to the strengths calculated using the equations recently proposed for cold-formed carbon steel lipped channel sections. It is demonstrated that the strength reduction factor equations proposed for cold-formed carbon steel are unconservative for the stainless steel grades by up to 7%. Unified strength reduction factor equations are then proposed that can be applied to all three stainless steel grades.


ABSTRACT: The bundled lipped channel-concrete composite wall is an innovative structural wall. This wall has a series of advantages, such as convenient construction and high bearing capacity. Seven full-scaled specimens were tested and subjected to cyclic lateral loads. ABAQUS, which is a finite-element software, was used to simulate the test process. Hysteretic curves and skeleton curves were obtained. This process proved that the simulation effect of finite element was good. A parametric analysis was conducted on this composite shear wall to determine the effect of the wall under different parameters, such as the axial load ratio, the shear span ratio, and the intensity of steel and concrete. The formula for the bending capacity of normal section was deduced. The failure mode and factors that affect the shear capacity of the composite shear wall at a low shear span ratio were analyzed to obtain the composition of the shear capacity. Based on the superposition theory and statistical regression, the formula for the shear capacity of the inclined section was obtained.


ABSTRACT: Thin-walled steel hollow flange channel beams are commonly used as joists and bearers in various flooring systems in buildings. A new rivet fastened rectangular hollow flange channel beam was proposed using an intermittently rivet fastening process as an alternative to welded beams. This flexible fastening process allows rectangular hollow flange channel beams to have greater section optimisation, by configuring web and flange widths and thicknesses. In the industrial applications of rectangular hollow flange channel beams as flooring, roofing or modular building systems, their flanges will be fastened to supports, which will provide increased capacities. However, no research has been conducted to investigate the web crippling capacities of rectangular hollow flange channel beams with flanges fastened to supports under two-flange load cases. Therefore, an experimental study was conducted to investigate the web crippling behaviour and capacities of rectangular hollow flange channel beams based on the new American Iron and Steel Institute S909 standard test method. The web crippling capacities were compared with the predictions from the design
equations in Australia/New Zealand Standard 4600 and American Iron and Steel Institute S100 to determine their accuracy in predicting the web crippling capacities of rectangular hollow flange channel beams. Test results showed that these design equations are considerably conservative for the end two-flange load case while being unconservative for the interior two-flange load case. New equations are proposed to determine the web crippling capacities of rectangular hollow flange channel beams with flanges fastened to supports. Test results showed that web crippling capacities increased by 78% and 65% on average for the end two-flange and interior two-flange load cases when flanges were fastened to supports. This article presents the details of this web crippling experimental study of rectangular hollow flange channel beam sections and the results.


ABSTRACT: In order to improve buildability of cold-formed steel structures, a series of research and development projects have been undertaken by the authors to examine structural behaviour of bolted moment connections between cold-formed steel sections. In this article, a systematic numerical investigation with advanced finite element modelling technique into the structural behaviour of high-strength cold-formed steel lapped Z-sections under gravity loads is presented, and details of the modelling techniques are presented thoroughly. It aims to examine deformation characteristics of these lapped Z-sections with different overlapping lengths. After careful calibration of advanced finite element models of lapped Z-sections against test data, it is demonstrated that the predicted moment rotation curves of these models follow closely the measured data not only up to the maximum applied moments but also at large deformations. In general, all of these lapped Z-sections are unable to resist sustained loadings after section failure under combined bending and shear, and they exhibit sudden unloadings once the maximum applied loads are attained. Hence, the proposed finite element models are able to simulate highly non-ductile deformation characteristics of these Z-sections. While long overlapping lengths over internal supports in multi-span cold-formed steel purlin systems are often advantageous in terms of both ‘stiffness and strength’, more steel materials are used at the same time. Hence, it is very desirable to establish an efficient use of the lapped Z-sections with optimal overlapping lengths. A total of six models with different overlapping lengths are then extended to simulate the structural behaviour of lapped double-span beams, and extensive material and geometrical non-linear analyses have been carried out. It is found that lapped double-span beams with practical overlapping lengths tend to behave superior to continuous double-span beams in terms of both load resistances and deformations. Depending on the overlapping lengths of the lapped Z-sections, different system failure mechanisms have been clearly identified after significant moment redistribution within the beams, and their structural behaviour has been compared in a rational manner. Consequently, these models will be readily employed to investigate the structural behaviour of high-strength cold-formed steel lapped Z-sections under a wide range of practical loading and boundary loading conditions for possible development of effective design rules.


ABSTRACT: Static and vibration characteristics of thin-walled straight and curved box beams were investigated experimentally. Three different beam configurations were considered for the tests: one straight and two curved box beams. The load was applied at the centroid of the box section for the straight and one curved beam specimens. However, for the other curved specimen, the load was applied eccentrically to investigate its behavior under the additional torsion induced by the eccentricity. Displacements and strains were obtained using linear variable displacement transducer, one-directional and rosette strain gages. The specimens were
excited using an impact at their free ends. The time history of strains was obtained to calculate natural frequencies and damping ratios. The experiment results were compared with those obtained from three-dimensional finite element analysis for all cases. The results obtained from implementing tests on the straight specimen were also used to validate an efficient numerical method recently developed by the authors.


ABSTRACT: The double rectangular tube assembled buckling-restrained brace is a new type of buckling energy consumption buckling-restrained brace. Because of its external restraining members, which are bound by high-strength bolts, its mechanical mechanism is more complicated and its failure modes are more varied. In this study, the double rectangular tube assembled buckling-restrained brace composition and three types of end constructions are introduced in detail. The influences of different design parameters on the performance of double rectangular tube assembled buckling-restrained brace are studied by numerical analysis methods; the possible failure modes and the influence of the end strengthening construction of double rectangular tube assembled buckling-restrained brace are also investigated, and a number of suggestions are proposed to improve this design. This study shows that the pinned double rectangular tube assembled buckling-restrained brace has four types of typical failure modes, namely, overall buckling failure, external end local pressure-bearing failure, bending failure of the extended strengthened core region and bolt threading failure. Rational design can prevent a buckling-restrained brace from losing its load-bearing capacity. In addition, compared with the end strengthening scheme with an external hoop, the end strengthening scheme with a strengthened bench can improve the load-bearing capacity of the double rectangular tube assembled buckling-restrained brace more effectively, and a reasonable design can also save materials.


ABSTRACT: This article presents a finite element investigation into the web crippling strength of cold-formed stainless-steel lipped channels with web perforations under end-two-flange loading. The cases of web openings located both centred and offset to the load bearing plates are considered. In order to take into account the influence of the circular web openings, a parametric study involving 2190 finite element analyses was performed, covering duplex EN 1.4462, austenitic EN 1.4404 and ferritic EN 1.4003 stainless-steel grades; from the results of the parametric study, strength reduction factor equations are determined. The strength reduction factor equations are first compared to equations recently proposed for cold-formed carbon-steel lipped channels. It is demonstrated that the strength reduction factor equations proposed for cold-formed carbon steel are conservative for the stainless-steel grades by up to 10%. New coefficients for web crippling strength reduction factor equations are then proposed that can be applied to all three stainless-steel grades.


ABSTRACT: A new type of thin-walled steel tube/bamboo plywood hollow composite column with binding bars was developed in which transverse binding bars were used as reinforcement. The compression performance of 12 specimens was tested to examine the failure modes of the steel tube/bamboo plywood hollow composite
column with binding bars, and the influences of the slenderness ratio, the net cross-sectional area of the bamboo plywood, the load eccentricity distance, and the binding bars on the ultimate load-bearing capacity were analyzed. The results indicated that the compression failure modes of the steel tube/bamboo plywood hollow composite column with binding bars were mainly bamboo plywood material failure and debonding failure of the adhesion interface; the ultimate bearing capacity of the steel tube/bamboo plywood hollow composite column with binding bars increased with an increasing net cross-sectional area of the bamboo plywood and decreased with an increasing slenderness ratio and eccentricity distance. Transverse binding bars were introduced to ensure the integrity of the composite column, to effectively reduce the debonding failure of the adhesion interface, to change the life-limiting damage mode, and to significantly improve the load-bearing capacity of the steel tube/bamboo plywood hollow composite column with binding bars. Finite element numerical simulations were performed to extend the influential factor analysis based on the test results. Furthermore, based on a non-linear regression analysis of the experimental data, a model for calculating the load-bearing capacity was formulated to determine the allowable compressive capacity of an steel tube/bamboo plywood hollow composite column with binding bar for engineering applications.


ABSTRACT: This article elaborates on experimental and analytical studies on the behavior of tube-confined steel-reinforced ultra-high-strength concrete short columns subjected to axial compressive load. A total of 22 specimens were fabricated and tested to investigate the failure mode and axial load behavior of tube-confined steel-reinforced concrete columns. The parameters for the tests include the following: (1) tube shape, (2) the shape of inner steel, (3) the thickness of the steel tube, and (4) tube tensile strength. The test results indicate that the confinement effect of the circular tube is greatly superior to that of the square tube, because the circular tube can prevent the ultra-high-strength concrete from brittle failure more efficaciously. The O-shape of the steel exhibited better mechanical performance than other shapes of the steel. The larger the area of the concrete that could be constrained by the steel shape, the better the performance it could provide. Elastic–plastic analysis of the tube was utilized to investigate the mechanism of tube-confined steel-reinforced concrete columns under axial compression. A bearing capacity formula for tube-confined steel-reinforced concrete columns was proposed based on the test results, which can be used as a reference for further study and guideline for engineering application.


ABSTRACT: In cold-formed steel structures, such as trusses, wall frames, and portal frames, the use of back-to-back built-up cold-formed steel channel sections for the column members is becoming increasingly popular. In such an arrangement, intermediate fasteners at discrete points along the length prevent the individual channel sections from buckling independently. Current guidance by the American Iron and Steel Institute and the Australian and New Zealand Standards for built-up sections describes a modified slenderness approach, to take into account the spacing of the screws. Limited experimental tests or finite element analyses, however, have been reported in the literature for such sections to understand the effect of screw spacing. This issue is addressed herein. The results of 30 experimental tests are reported, conducted on back-to-back built-up cold-formed steel channel sections covering stub columns to slender columns. A finite element model is then described which shows good agreement with the experimental test results. The finite element model is then used for the purposes of a parametric study comprising 144 models. It is shown that while the modified slenderness...
approach is in general conservative, for stub columns it can be unconservative by around 10%.

ABSTRACT: Monolithic and sandwich structures have been widely used as energy absorption structures in military and civil engineering. This article reviews theoretical analyses of monolithic beams and plates subjected to static loading, impulsive loading and impact by a mass systematically. Experimental data collected from the literatures are compared with these theoretical results. In addition, the critical impulses for the failure of the monolithic structures are also reviewed. Furthermore, sandwich structures under quasi-static, low-velocity impact, high-velocity impact and blast loading, as well as their failure modes, are also summarized. The research methodology involves experimental investigations, theoretical analyses and numerical simulations. References listed at the end of the paper: (See Part 2)

ABSTRACT: A numerical analysis based on previous experiment has been carried out on T-shaped concrete-filled steel tubular columns subjected to constant axial compressive load and cyclic lateral loads. Tensile bar stiffeners were introduced to be welded on inside surfaces of steel tube to postpone its local buckling and to enhance the confinement of steel tube for concrete. A modified fiber-based method was developed to establish numerical modeling program of specimens’ cyclic behavior, incorporating the effect of stiffeners on postponing steel tube’s local buckling and the confinement for concrete. The reciprocating movement of inflection point along frame column is also considered in the numerical program. A simplified arc-length method was employed as iterative control algorithm of the numerical model. Horizontal load–displacement hysteretic curves of specimens were calculated with the numerical model and verified with test results. A restoring force model based on experimental investigation was proposed as simplified method for engineering practice.

ABSTRACT: The increasing interest in timber as a sustainable construction material has led to the development of a new type of structures referred to as ‘hybrid fibre-reinforced polymer–timber thin-walled structures’. In these structures, thin layers of fibre-reinforced polymer are combined with timber veneers to create high-performance, lightweight and easy-to-construct structural members. This new type of structural members harnesses the orthotropic properties of both timber and fibre-reinforced polymer by appropriately orientating material fibre directions for optimal composite properties as well as efficient thin-walled cross-sectional shapes. Hybrid fibre-reinforced polymer–timber thin-walled members can be used in many applications such as load-bearing walls, roofs, floor panels and bridge decks. This article describes several novel hybrid fibre-reinforced polymer–timber structural member forms and presents results from a preliminary experimental investigation into the compressive behaviour of hybrid fibre-reinforced polymer–timber wall panels. A comparison of behaviour between a hybrid fibre-reinforced polymer–timber wall panel and a pure timber wall panel is presented to show that the hybrid fibre-reinforced polymer–timber system significantly outperforms the pure timber system in terms of both load resistance and axial strain at failure.

Zuo-Cai Wang, Wei-Xin Ren and Genda Chen, “Time-frequency analysis and applications in time-

ABSTRACT: Nonlinear dynamic behaviors of civil engineering structures have been observed not only under extreme loads but also during normal operations. Characterization of the time-varying property or nonlinearity of the structures must account for temporal evolution of the frequency and amplitude contents of nonstationary vibration responses. Neither time analysis nor frequency analysis method alone can fully describe the nonstationary characteristics. In this article, an attempt is made to review the milestone developments of time-frequency analysis in the past few decades and summarize the fundamental principles and structural engineering applications of wavelet analysis and Hilbert transform analysis in system identification, damage detection, and nonlinear modeling. This article is concluded with a brief discussion on challenges and future research directions with the application of time-frequency analysis in structural engineering.

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51 Shi ZY, Law SS and Xu X (2009) Identification of linear time-varying MDOF dynamic systems from forced excitation using

ABSTRACT: This article presents a new form of fibre-reinforced polymer-concrete-steel hybrid columns and demonstrates some of its expected advantages using results from an experimental study. These columns consist of a concrete-filled fibre-reinforced polymer tube that is internally reinforced with a high-strength steel tube and are referred to as hybrid double-tube concrete columns. The three components in hybrid double-tube concrete columns (i.e. the external fibre-reinforced polymer tube, the concrete infill and the internal high-strength steel tube) are combined in an optimal manner to deliver excellent short- and long-term performance. The experimental study included axial compression tests on eight hybrid double-tube concrete columns with a glass fibre–reinforced polymer external tube covering different glass fibre–reinforced polymer tube thicknesses and diameters as well as different high-strength steel tube diameters. The experimental results show that in hybrid double-tube concrete columns, the concrete is well confined by both the fibre-reinforced polymer tube and the high-strength steel tube, and the buckling of the high-strength steel tube is suppressed so that its high material strength can be effectively utilized, leading to excellent column performance. Due to the high yield stress of high-strength steel, the hoop stress developed to confine the core concrete is much higher than can be derived from a normal-strength steel tube, giving the use of high-strength steel in double-tube concrete columns an additional advantage.

Yong Yang, Lin Zhang, Yicong Xue, Dengpan Zhao, Hui Deng and Bo Wu, “Experimental research on the fire performance of a special cross-shaped composite column with a high-strength concrete-filled steel tubular core”, Advances in Structural Engineering, Vol. 21, No. 11, pp 1608-1619, August 2018, https://doi.org/10.1177/1369433218753426

ABSTRACT: To improve the mechanical performance of specially shaped reinforced concrete columns, which are widely applied in China, an innovative specially shaped composite column with high-strength concrete-filled steel tubular core was developed. To investigate the fire performance of this specially shaped composite column, two series of fire tests, including the fire resistance test series and the post-fire test series, were conducted on five full-scale specimens. The test parameters include the axial load level, the spacing of stirrups, and the fire exposure time. Compared to the test result of a controlled specimen that was axially compressed to fail without exposure to any fire, both the fire resistance under fire and the residual capacity after fire of this specially shaped composite column were analyzed and studied. The results indicated that the inner concrete-filled steel tubular core plays an important role in both the fire resistance and the post-fire performance, and that the post-fire residual capacities of three post-fire testing specimens were also largely increased.


ABSTRACT: This article proposes a new closed-form equation to determine the reduction factor for global buckling of concentrically loaded pultruded fiber-reinforced polymer struts based on the Ayrton–Perry formula and observed initial out-of-straightness of pultruded fiber-reinforced polymer members measured by other researchers, which makes the original solution recommended by Eurocode 3 easy to be used to predict the global buckling loads of doubly symmetric pultruded fiber-reinforced polymer members subjected to axial compression. The influence of the geometric imperfections of pultruded fiber-reinforced polymer profiles is considered in this new closed-form equation. Validation of the solution including the parameter of the reduction factor for global buckling of pultruded fiber-reinforced polymer columns is performed by comparison with published experimental evidence. In addition, compared with the five closed-form solutions available in the
literature, this solution exhibits higher accuracy in predicting the global buckling capacity of concentrically loaded pultruded fiber-reinforced polymer struts with doubly symmetric cross sections. The solution implemented into the new reduction factor equation for global buckling of pultruded fiber-reinforced polymer members can be conveniently used by structural engineers at the preliminary engineering design stage for accurately assessing the reliability and safety of composite structures under concentric compressive loading.

ABSTRACT: This article introduces a numerical model that simulates the bond-slip behaviour in axially loaded circular concrete-filled tube columns without applying double nodes required in the use of the classical bond-link element. After calculating the nodal displacements of in-filled concrete, the deformation in the steel tube at each node has been found through the back-substitution technique from the first to the final steel element using a governing equation constructed on the basis of the force equilibrium and displacement compatibility at each node. Finally, correlation studies between analytical and experimental results are conducted to verify the efficiency and applicability of the introduced model.

ABSTRACT: In this study, five 1/4 scaled shaking table tests were conducted to investigate the seismic performance of reinforced concrete coupled shear walls with single layer of web reinforcement and inclined steel bars. The five tested coupled shear walls included three models with normal opening ratio (19%) and two models with large hole ratio (27%). The three models with normal opening included one model with single layer of web reinforcement, two models with single layer of web reinforcement and 75° inclined steel bars in the limbs’ web or at the bottom. Two reinforced concrete coupled shear walls with large hole and single row of reinforcements also were tested with inclined reinforcements or without them. The dynamic characteristics, dynamic response, and failure mode of each model were compared and analyzed. The test and analysis results demonstrate that the inclined steel bars are identified as an efficient means of limiting overall deformation, increasing energy dissipation, and reducing the possible damage by earthquake for reinforced concrete coupled shear walls with single layer of web reinforcement. Thus, reinforced concrete coupled shear walls with inclined steel bars have better seismic performance than reinforced concrete coupled shear walls without inclined steel bars. With appropriate design, reinforced concrete coupled shear walls with single layer of web reinforcement and inclined steel bars can be applied in multi-story buildings.

ABSTRACT: Seismic reliability analysis of bridge structures during and succeeding an earthquake event is of significant importance. The more accurate and robust approach of seismic reliability analysis is based on direct Monte Carlo simulation technique. But it is computationally challenging due to the requirement of large number of nonlinear time history analyses. The response surface method–based metamodeling approach is a viable alternative in such situation. This study explores the advantage of moving least squares method–based adaptive response surface method compared to the usually applied least squares method–based response surface method for improved seismic reliability analysis of multi-span bridge pier. The nonlinear time history analyses of the
bridge pier are performed in the OpenSees with fibre sections considering a ground motion bin corresponding to the specified hazard level of the bridge site. The seismic reliability analysis results obtained by the usual least squares method and the proposed moving least squares method–based response surface method are compared with that of obtained by more accurate direct Monte Carlo simulation technique to elucidate the effectiveness of the proposed approach.

End of more papers published in the journal, Advances in Structural Engineering (2017 and on)

More papers published in the journal, Archive of Applied Mechanics (2017 and on)

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ABSTRACT: Based on the two-variable refined plate theory, free vibration of orthotropic plates is analyzed using the differential transform method (DTM) and the Taylor collocation method (TCM). The refined plate theory outperforms the classical plate theory, and its formulation is simpler than those of other higher-order theories. Without the need for any shear correction factor, the theory performs reliably. The plates considered have two opposite edges simply supported (Levy plates). The first part of the analysis considers three combinations of clamped, simply supported and free edge conditions for the other two edges, keeping one of them simply supported. Detailed formulations of DTM and TCM for the free vibration analysis are given and, consequently, used to predict the frequency parameters and the effect of various factors ranging from geometric to material parameters. Next, the paper presents analysis of some cases, the multi-span plates and plates with stepped thickness and end rotational springs, whose analytical solutions are not readily available, particularly based on the two-variable refined plate theory. In order to verify the results, formulations of three more plate theories, namely the classical or Kirchhoff plate theory, the first-order shear deformation theory of Mindlin and the high-order shear deformation theory of Sayyad and Gugal, were implemented and solved using the proposed methods.

References listed at the end of the paper:

ABSTRACT: This paper focuses on the buckling analysis of composite sandwich conical shells subjected to a uniform external lateral pressure based on the first-order shear deformation theory. Approximate analytical solutions are assumed to satisfy fully clamped boundary conditions and then Fourier decomposition and Galerkin method is applied to achieve closed-form relations of buckling loads. The closed analytical formula for the critical pressure has been verified by comparison with the finite-element solutions and a special case where the angle of the conical shell approaches zero, that is, a cylindrical shell. Based on this formula buckling analyses of sandwich conical shells with different types of core materials have been accomplished. The outcomes are achieved considering the effects of half-vertex cone angle, core thickness and indicating applicability, accuracy, and stability of the present method.

References listed and the end of the paper:

References listed at the end of the paper:


ABSTRACT: The subject of the study is an orthotropic thin-walled sandwich band plate with trapezoidal main core and three-layer facings. The external sheets of the faces are flat, whereas the core of the faces is trapezoidal corrugated. The directions of the corrugations of both cores are perpendicular to each other. The band plate considered in this paper has the crosswise corrugated main core and the lengthwise corrugated core of the faces. The main goal of the study is to solve the problem of buckling and vibrations of the band plates. The mathematical and physical model of this band plate has been formulated, in particular the field of displacement and rigidities of corrugated layers which are both original elements of the work. The system of equations of motion is analytically derived using the energy method. The obtained solutions are verified numerically. The finite element analysis of stability of the sandwich band plate is performed with the use of the ABAQUS and ANSYS systems.

References listed at the end of the paper:

ABSTRACT: In this work, the geometrically nonlinear deflection responses of glass/epoxy composite flat/curved shell panel structure have been analysed theoretically with the help of three different displacement field kinematics and Green–Lagrange strain–displacement relation. In this analysis, the numerical models are developed based on two higher-order shear deformation mid-plane kinematics and one simulation model with the help of commercial finite element package (ANSYS). The present mathematical model is general in the sense that it includes all the nonlinear higher-order terms arising due to Green–Lagrange strain–displacement relation to capture the exact flexural strength of the laminated structure. The present nonlinear model is so generic that it can be easily extended for solving different kinds of geometrical configurations (spherical, cylindrical, elliptical, hyperboloid and plate). The equilibrium equation of the transversely loaded panel is achieved by minimizing total potential energy expression and discretized using the suitable finite element steps. The required deflection values are computed numerically via a homemade MATLAB code in conjunction with Picard’s iterative method. Consequently, the stability of the present numerical solutions has been established through the convergence test and validated by comparing the results with those available published results. In addition, the transverse deflections are obtained experimentally via three-point bend test and utilized for the comparison purpose to demonstrate the significance of the newly developed higher-order finite element model. References listed at the end of the paper:

ABSTRACT: 3D braided composite plates and shells seem much more complicated for structural analysis than 2D laminated composite structures. In this article, a rather simpler and novel micro-/macromechanical theory is proposed for flexural analysis of 3D rectangular braided plates subjected to lateral loads. This theory is based on a novel micromechanically equivalent layerwise multi-unit cell, combined with the conventional macromechanical full layerwise theory, so-called here equivalent full layerwise/multi-unit cell theory. A 3D braided composite is considered as a cell system, where elastic properties of each cell depend on the position of cell along the thickness of cross section. Instead of acquiring global elastic constants of the 3D braided composite, three equivalent layers are established and the elastic constants for each layer are acquired separately. This micromechanical procedure makes this model consistent with macromechanical full layerwise theory. Based on this theory, the governing differential equations are derived for flexural analysis of rectangular 3D braided plate subjected to lateral loads. The problem is solved with Galerkin and finite element methods.

The stress distributions in 3D braided composite plates seem quite different from those of geometrically equivalent homogeneous and isotropic plates. The differences are discussed in this article.

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Chao Hu, Hanxiong Hu, Xiaowei Zhang and Fai Ma, “Refined theory for vibration of thick plates with the lateral and tangential loads”, Archive of Applied Mechanics, Vol. 87, No. 3, pp 439-455, March 2017

ABSTRACT: Based on the three-dimensional elastodynamics, without using the classical assumption, an operator method is established to refine the dynamic theory of an infinite homogenous isotropic plate by using the spectral decomposition of operators. By this method, the governing equations of the bending and stretching vibrations of plates with the lateral and tangential loads on the surface are derived from the Boussinesq–Galerkin solution of the three-dimensional elasticity, respectively. To effectively deduce the governing equations, a complex differential operator is introduced. Dispersion relations based on the refined equations and the three-dimensional elastodynamics are compared to verify the refined theory of plates. It is shown that the dispersion relation of the refined theory of plates agrees more with the result based on the three-dimensional elastodynamics than Mindlin’s theory. Therefore, the refined equations are accurate that can be used to solve the vibration of thick plates and determine high-order vibration modes of plates. The applicable conditions of the refined plate theory are analyzed and discussed.

References listed at the end of the paper:

ABSTRACT: While the structural analysis of straight beams is straightforward, the behavior of curved beams is more complex to predict. In the present work, a displacement approach of toroidal elasticity is used to analyze thick isotropic curved tubes subjected to axial load, torque, and bending moment. The governing equations are developed in a toroidal coordinate. The method of successive approximation is used to obtain the general solution. The accuracy of the present methodology is tested comparing the numerical results with those obtained by finite element method (FEM) and stress-based toroidal elasticity (SBTE). The proposed methodology is computationally cost-effective, and its results reveal good agreements with FEM and SBTE results. Finally, several numerical examples of stress distributions in thick isotropic curved tubes under axial load, torque, and bending moment are presented. By using the present methodology, displacements as well as stresses are obtained which are important information for fracture analysis.

References listed at the end of the paper:

This paper presents a theoretical and experimental analysis of buckling load of the circular tube with flattened ends. The buckling tests were conducted on the steel tubes with different length and diameter, and the critical buckling force was determined from the measured relation between the lateral displacement and axial force. Analytical solutions for the critical buckling force of the circular tubes were derived in the series form, and a numerical procedure based on the finite difference method and quasi-Newton method was developed to determine the critical buckling load. The results show that both analytical and numerical solutions were in agreement with those measured from the experiment. Moreover, the effect of flattened part length on the value of the critical buckling force was investigated there. The paper provides a mathematical model of the value of the critical buckling force was investigated there. The paper provides a mathematical model of

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Yunke Zhao, Dongyan Shi and Huan Meng, “A unified spectro-geometric-Ritz solution for free vibration analysis of conical-cylindrical-spherical shell combination with arbitrary boundary conditions”, Archive of Applied Mechanics, Vol. 87, No. 6, pp 961-988, June 2017

ABSTRACT: In the present article, a spectro-geometric-Ritz solution for free vibration analysis of conical–cylindrical–spherical shell combinations with arbitrary boundary conditions is presented. The classical theory of small displacements of thin shells is employed to formulate the theoretical model. The admissible functions of each shell components are described as a combination of a two-dimensional (2-D) Fourier cosine series and auxiliary functions. As an innovative point of this work, the auxiliary functions are introduced to accelerate the convergence of the series representations and eliminate all the relevant discontinuities with the displacement and its derivatives at the boundaries and the junction between the shell components. The artificial spring technique is adopted here to model the boundary condition and coupling condition, respectively. All the expansion coefficients are considered as the generalized coordinates and determined by Ritz procedure. Convergence and comparison studies for both open and closed conical–cylindrical–spherical shells with arbitrary boundary conditions are carried out to verify the reliability and accuracy of the present solutions. Some selected mode shapes are illustrated to enhance the understanding of the research topic. It is found the present method exhibits stable and rapid convergence characteristics, and the present results, including the natural frequencies and the mode shapes, agree closely with those solutions obtained from the finite element analyses and results in the literature. The effects of the geometrical dimensions of the shell combinations on the natural frequencies are also investigated.

References listed at the end of the paper:

ABSTRACT: An approximate analytic solution for torsion of thin-walled laminated composite beams of symmetrical open cross sections with influence of shear is presented. The solution based on the classical Vlasov’s thin-walled beam theory is modified for thin-walled laminated composite beams with orthotropic and symmetrical lay-up. It is shown that the beam subjected to torsion with influence of shear, caused by couples in the cross section planes, is also subjected to bending due to shear in the plane orthogonal to the plane of symmetry. If the cross section has two axes of symmetry, the beam will be subjected only to torsion with influence of shear. The expressions for the displacements and normal stresses are derived in closed analytic form. The material influence on shear is defined by factor that depends on the fibre orientations. Simply supported and clamped beams subjected to distributed couples are considered. Illustrative examples are provided, and the results for the displacements and stresses show very good agreement between analytical ones and numerically obtained results utilizing three-dimensional shell finite elements.

References listed at the end of the paper:
ABSTRACT: Beam, column, plate, and any other structure, under full or partial compressive loading, are prone to failure by the buckling phenomenon. At the instant of failure, the structure may be in unpredictable elastic, elastic–plastic, full plastic, cracked, or other forms of deterioration state. Therefore, in spite of so much study, there is no definite solution to the problem. In this paper a unified, simple, and exact theory is proposed where buckling is considered as the change of state of structure between intact and collapsed states, and then the buckling capacity is innovatively expressed via states and phenomena functions, which are explicitly defined as functions of state variable. The state variable is determined by calibration of the structure slenderness ratio. The efficacy of the work is verified via concise mathematical logics, and comparison of the results with those of the others via seven examples.

References listed at the end of the paper:
ABSTRACT: The meshless analog equation method, a purely meshless method, is applied to the buckling analysis of moderately thick plates described by Mindlin’s theory and resting on two-parameter elastic foundation (Pasternak type). The method is based on the concept of the analog equation, which converts the three governing second-order partial differential equations (PDEs) in terms of the three plate displacements (transverse displacement and two rotations) into three substitute equations, the analog equations. The analog equations constitute a set of three uncoupled Poisson’s equations under fictitious sources, which are approximated by multi-quadric radial basis functions (MQ-RBFs) series. This enables the direct integration of the analog equations and allows the representation of the sought solution by new RBFs series. These RBFs approximate accurately not only the displacements but also their derivatives involved in the governing equations. Then, inserting the approximate solution in the original PDEs and in the associated boundary conditions (BCs) and collocating at mesh-free nodal points, a generalized eigenvalue problem is obtained, which allows the evaluation of the buckling load and the buckling modes. The studied examples demonstrate the efficiency of the presented method that is its ability to solve accurately and in a straightforward way difficult engineering problems.

References listed at the end of the paper:

ABSTRACT: Toward improving conventional beam elements in order to include distortional effects in their analysis, in this paper, independent parameters have been taken into account. Beam’s behavior becomes more complex, especially for eccentric loading, due to the coupling between warping and distortion. Thus, the importance of including higher-order phenomena in the analysis arises in order to derive accurate results. Due to the fact that more degrees of freedom are employed, the computational cost of the problem is significantly
increased. Isogeometric tools (B-splines and NURBS), either integrated in the finite element method or in a boundary element-based method called analog equation method, are employed in this contribution for the static analysis of beams of open or closed (box-shaped) cross sections toward improving computational effort. Responses of the stresses, stress resultants and displacements to static loading have been studied.

References listed at the end of the paper:


ABSTRACT: This paper presents approximate solutions for the postbuckling behavior of a plate consisting of laminated composites with symmetrical, balanced lay-up loaded in longitudinal compression. The transversal edges of the plate are simply supported, one longitudinal edge is free and the opposite one is rotationally restrained. Key to obtain an explicit and thus highly computational efficient solution is the use of a shape function with only few variables. First, the shape function is inserted into the compatibility condition of in-plane strains to derive a closed-form solution of Airy’s stress function. Then, the equilibrium condition is approximated with the Galerkin procedure yielding a load-deflection relationship. Subsequently, other state variables such as in-plane displacements and stresses can be obtained. Overall, results for displacements and strains show very good agreement with detailed nonlinear finite element analyses.

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Gaurav Watts, M.K. Singha and S. Pradyumna, “A numerical study on the nonlinear behavior of corner supported flat and curved panels”, Archive of Applied Mechanics, Vol. 88, No. 4, pp 503-516, April 2018

ABSTRACT: The nonlinear behavior of corner supported plates and curved shell panels is investigated here using the first-order shear deformation theory based on Marguerre’s membrane strains for shallow shells and von Kármán’s nonlinearity. The nonlinear differential equations are transformed into a set of nonlinear algebraic equations by using the element-free Galerkin method. The moving kriging shape function with two different types of correlation formulae (Gaussian and quartic spline) is employed here. After studying the effectiveness of the method, a detailed parametric study is conducted to examine the effect of support size on the displacements and bending moments of corner supported rectangular plates. Thereafter, the numerical study is extended to the nonlinear bending and stability behaviors of corner supported shallow cylindrical and spherical shell panels.

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Xiangyang Li, Kaiping Yu and Rui Zhao, “Thermal post-buckling and vibration analysis of a symmetric sandwich beam with clamped and simply supported boundary conditions”, Archive of Applied Mechanics, Vol. 88, No. 4, pp 543–561, April 2018

ABSTRACT: Sandwich structures are widely used in aerospace, marine and other engineering industries. This paper is focused on the post-buckling and free vibration of the sandwich beam theoretically in thermal environments with simply supported and clamped boundary conditions. Firstly, nonlinear governing equations...
of the sandwich beam are obtained based on the principle of virtual work and natural frequencies are derived by linear equations. Secondly, buckling temperatures together with corresponding modes are addressed. Thirdly, the new equilibrium position of the sandwich beam is obtained after it loses the stability. Finally, free vibration analysis of a post-buckling sandwich beam is derived when the temperature exceeds the critical temperature. It is observed that the maximum deformation of the sandwich beam suddenly increases sharply once it loses the stability. The natural frequencies of a sandwich beam decrease with the increment of temperature, but the first-order natural frequency increases as the temperature rises once the temperature exceeds the critical buckling temperature. The theory of this paper will provide a theoretical support for the numerical method and engineering design.

References listed at the end of the paper:


ABSTRACT: This paper presents the analysis of simply supported rectangular laminated composite plates loaded perpendicularly to the middle plane using a new computational method based on Reddy’s layerwise theory. The stress–strain analysis was based on the analytical solution of equations of the layerwise theory, where the plates with an antisymmetric layer arrangement were analysed. Each of the layers contains continuous fibres oriented in one of two mutually orthogonal directions. The results obtained by applying above-mentioned computational procedure have been compared with the results obtained using three different
models of finite elements of the ANSYS software package. The quantified limits of the computational method in terms of the impact of plate thickness, the number of layers and the aspect ratio of the plate on the accuracy, convergence and stability of primary variables—components of displacement, and secondary variables—components of stress, have been analysed in the paper.

References listed at the end of the paper:

ABSTRACT: This paper investigates the free and forced vibration of moderately thick orthotropic plates in thermal environment and resting on elastic supports. Three kinds of elastic supports, namely non-homogeneous...
elastic foundations, point elastic supports and line elastic supports, are considered in the present study. The first-order shear deformation theory is employed to formulate the strain and kinetic energy functions of the structures, and then the stiffness and mass matrices can be obtained by applying the Hamilton’s principle. The modified Fourier method is adopted to solve the dynamic problems of moderately thick orthotropic plates with different combinations of temperature variations, elastic supports and boundary conditions. The accuracy and reliability of the proposed formulation are validated by comparing the obtained results with the finite element method results. Finally, the effects of some key parameters including temperature variation and stiffness values of the elastic supports on the modal and dynamic characteristics of the plates are analyzed in detail. In view of the versatility of the developed method, it offers an efficient tool for the structural analysis of moderately thick orthotropic plates under thermal environment and resting on elastic supports.

References listed at the end of the paper:

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ABSTRACT: Free vibration and buckling of a set of parallel Timoshenko beams joined by intermediate flexible connections under axial loading are assessed in this paper. The numbers of beams and intermediate connections are arbitrary. Through axial loading, a new set of equations is extracted, applicable in solving the axial loading problems. The existence of the intermediate connections and the related compatibility equations allow for the introduction of coupled partial differential equations. The solution involves a change of variables to uncouple the governing differential equations. The natural frequencies and mode shapes are calculated through the transfer matrix method. By presenting an appropriate equation, it is observed that the general formulation studied here, regarding the separated flexible connections, can easily cover the issue of parallel beams joined by Winkler elastic layers in a continuous manner presented in the literature. The effects of different parameters such as the number of beams, number and stiffness of elastic connections and axial loading are assessed on the natural frequencies and the critical buckling force.

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Sandipan Nath Thakur, Chaitali Ray and Subrata Chakraborty, “Response sensitivity analysis of laminated composite shells based on higher-order shear deformation theory”, Archive of Applied Mechanics, Vol. 88, No. 8, pp 1429-1459, August 2018

ABSTRACT: Laminated composite shells are widely used as structural components in important aerospace, marine, automobile engineering structures. Thus, appropriate evaluation of sensitivities of responses like deflection, frequency, buckling etc. due to changes in design variables is of great importance for efficient and safe design of such structures. The present paper deals with a comprehensive sensitivity analysis of laminated composite shells using finite element with more accurate theoretical model based on higher-order shear deformation theory (HSDT). The sensitivity analysis of deflection and natural frequency with respect to important design parameters such as material parameters, angle of fiber orientation, radius of curvature, density of materials and external load is presented. Furthermore, sensitivity-based importance factor for each parameter is obtained so that the most important parameters affecting the shell responses can be readily identified. The response sensitivities obtained by the proposed formulation are compared with those obtained by the finite difference procedure. An extensive parametric study has been carried out considering different variables to understand the performance of laminated shell.

References listed at the end of the paper:

ABSTRACT: An enhanced efficient zigzag theory is presented for the static response in elastic composite plates under mechanical loading. The number of variables is six, which is one more than the conventional zigzag theory. Transverse shear stresses have been obtained through the use of constitutive equations in both symmetric and antisymmetric laminates under uniformly and sinusoidally applied mechanical load. The theory has a good representation of all the three displacement components. This is obtained by using individual descriptions for each layer as is observed in three-dimensional elasticity solution. Interlaminar continuity conditions on all displacement components, all transverse stresses and on the gradient of transverse normal stress as well as transverse shear-free conditions on the top and the bottom surfaces have been utilized to make the primary variables independent of number of layers in the laminate. Equilibrium equations and boundary conditions are derived from variational principle. Navier solution is obtained for simply supported square and rectangular plates. The accuracy of the present theory is assessed by comparison with three-dimensional (3D) elasticity solution. It is found that refinement of the transverse displacement alone is not sufficient to make the new theory capable of providing good accuracy in calculation of transverse stresses from constitutive equations, though some improvement is obtained in case of symmetric laminates.

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No appropriate papers in October or November 2018

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More papers published in the journal, Meccanica (2017 and on)
Google the string: “Meccanica”, then click on the entry: “Meccanica – Springer – Springer Link”; then click on “Browse Volumes & Issues”.


ABSTRACT: This study comprehensively investigates tensile-compressive and shear effects of van der Waals (vdWs) interactions on free vibration of cantilever bilayer graphene nanoribbons (CBGNRs) to be answered to this question that how and how much the effects of each of these factors are in comparison with the other one when they are considered simultaneously. To this end, the CBGNRs are modeled based on sandwich beam theory in which each nanoribbon plays role of sandwich layer and vdWs interactions are equivalent to the sandwich core. At the first step a geometrical–analytical method is presented to calculate the equivalent tensile-compressive and shear moduli of vdWs interactions. After that, a set of coupled governing equations of motion and boundary conditions are derived and solved numerically by the harmonic differential quadrature method. This study shows that for designing multi-layer GNR based applications, such as resonators, the shear effect of vdWs interactions must be considered.

References listed at the end of the paper:
ABSTRACT: In the present investigation, an analytical solution is proposed to predict the postbuckling characteristics of nanobeams made of functionally graded materials which are subjected to thermal environment and surface stress effect. To this end, a non-classical beam model on the basis of Gurtin–Murdock elasticity theory in the framework of Euler–Bernoulli beam theory and concept of physical neutral surface is utilized which has the capability to consider the effect of surface stress and von Karman-type of kinematic nonlinearity. The size-dependent nonlinear governing equations are solved analytically for different end supports. The postbuckling equilibrium paths corresponding to various boundary conditions are given in the presence of surface stress corresponding to various beam thicknesses, material gradient indexes, temperature changes and buckling mode numbers. It is found that by increasing the values of temperature change, the equilibrium path is
shifted to right and the normalized applied axial load decreases indicating that the effect of surface stress diminishes.

References listed at the end of the paper:


ABSTRACT: Stochastic linearization technique is a versatile method of solving nonlinear stochastic boundary value problems. It allows obtaining estimates of the response of the system when exact solution is unavailable; in contrast to the perturbation technique, its realization does not demand smallness of the parameter; on the other hand, unlike the Monte Carlo simulation it does not involve extensive computational cost. Although its accuracy may be not very high, this is remedied by the fact that the stochastic excitation itself need not be known quite precisely. Although it was advanced about six decades ago, during which several hundreds of papers were written, its foundations, as exposed in many monographs, appear to be still attracting investigators in stochastic dynamics. This study considers the methodological and pedagogical aspects of its exposition.

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ABSTRACT: Free in-plane vibration analysis of plates is carried out by a differential quadrature hierarchical finite element method (DQHFEM). The NURBS (Non-Uniform Rational B-Splines) patches of geometries were first transformed into differential quadrature hierarchical (DQH) patches, and then the elastic field was discretized by the same DQH basis. The DQHFEM solved the compatibility problem caused by different parametrization of neighbouring patches of isogeometric analysis using NURBS. And mesh refinement in DQHFEM does not propagate from patch to patch. The DQHFEM matrices also have the embedding property as the hierarchical finite element method (HFEM). In-plane vibration analyses of plates of several planforms showed that the DQHFEM is similar as the fixed interface mode synthesis method that can analyse a structure using a few nodes on the boundary of substructure elements and only several clamped modes inside each substructure element, but the DQHFEM does not need modal analysis and is of high accuracy. The accuracy and convergence of the DQHFEM were validated through comparison with exact and approximate results in literatures and computed by the authors.

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S. Sahmani, M. M. Aghdam and M. Bahrami, “Surface free energy effects on the postbuckling behavior of cylindrical shear deformable nanoshells under combined axial and radial compressions”, Meccanica, Vol. 52, No. 6, pp 1329-1352, April 2017

ABSTRACT: In the traditional continuum mechanics, the effects of surface free energy are generally ignored. However, this cannot be the case for nanostructures because of their high surface to volume ratio; surface energy plays an important role in the mechanical responses. In the present study, the nonlinear buckling and postbuckling characteristics of cylindrical nanoshells subjected to combined axial and radial compressions are investigated in the presence of surface energy effects. To this end, Gurtin–Murdock elasticity theory is implemented into the classical first-order shear deformation shell theory to develop an efficient size-dependent shell model incorporating surface free energy effects. Subsequently, a boundary layer theory is employed including surface effects in conjunction with the nonlinear prebuckling deformations, the large postbuckling deflections and the initial geometric imperfection. Finally, a solution methodology based on a two-stepped singular perturbation technique is utilized to obtain the size-dependent critical buckling loads and equilibrium postbuckling paths corresponding to the both axial dominated and radial dominated loading cases. It is observed that for the both axial dominated and radial dominated loading cases, surface free energy effects cause to increase the both critical buckling load and critical end-shortening of shear deformable nanoshell made of silicon.

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17. Li YS, Cai ZY, Shi SY (2014) Buckling and free vibration of magnetoelctroelastic nanoplate based on nonlocal theory. Compos Struct 111:522–529


ABSTRACT: Chebyshev polynomial functions are used in the Lagrangian multipliers method to study the free vibration characteristics of rectangular moderately thick composite plates reinforced with carbon nanotubes (CNTs). Plate is resting on point supports. Distribution of CNTs across the plate thickness is considered to be either uniform or functionally graded. Properties of the plate are obtained using a refined rule of mixtures approach which includes the efficiency parameters to capture the size dependent characteristics of the composite plate. Using a Ritz solution method, an eigenvalue problem is established which results in natural frequencies and mode shapes of the plate. Based on the developed solution method, number and position of point supports are arbitrary and also various boundary conditions may be assumed for the four edges of the plate. After performing comparison studies for isotropic homogeneous plates on point supports, parametric studies are provided to explore the vibration characteristics of the carbon nanotube reinforced composite plates on point supports. It is shown that, frequencies of the plate increase as the volume fraction of CNTs increases.

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N. M. Anoop Krishnan and Debraj Ghosh, “Buckling analysis of cylindrical thin-shells using strain gradient elasticity theory”, Meccanica, Vol. 52, No. 6, pp 1369-1379, April 2017

ABSTRACT: The stability problem of cylindrical shells is addressed using higher-order continuum theories in a generalized framework. The length-scale effect which becomes prominent at microscale can be included in the continuum theory using gradient-based nonlocal theories such as the strain gradient elasticity theories. In this work, expressions for critical buckling stress under uniaxial compression are derived using an energy approach. The results are compared with the classical continuum theory, which can be obtained by setting the length-scale parameters to zero. A special case is obtained by setting two length scale parameters to zero. Thus, it is shown that both the couple stress theory and classical continuum theory forms a special case of the strain gradient theory. The effect of various parameters such as the shell-radius, shell-length, and length-scale parameters on the buckling stress are investigated. The dimensions and constants corresponding to that of a carbon nanotube, where the length-scale effect becomes prominent, is considered for this investigation.

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M. Hosseini, A. Jamalpoor and A. Fath, “Surface effect on the biaxial buckling and free vibration of FGM nanoplate embedded in visco-Pasternak standard linear solid-type of foundation”, Meccanica, Vol. 52, No. 6, pp 1381-1396, April 2017

ABSTRACT: In this study, nonlocal elasticity theory in conjunction with Gurtin–Murdock elasticity theory is employed to investigate biaxial buckling and free vibration behavior of nanoplate made of functionally graded material (FGM) and resting on a visco-Pasternak standard linear solid-type of the foundation. The material characteristics of simply supported FGM nanoplates are assumed to be varied continuously as a power law function of the plate thickness. Hamilton’s principle is implemented to derive the non-classical governing equations of motion and related boundary conditions, which analytically solved to obtain the explicit closed-form expression for complex natural frequencies and buckling loads. Finally, attention is focused on considering the influences of various parameters on variation of damped natural frequency and buckling load ratio such as nonlocal parameter, surface effects, geometric parameters, power law index and properties of visco-Pasternak foundation and it is clearly demonstrated that these factors highly affect on vibration and buckling behavior.

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Moijtaba Asgari, Mohammad Reza Permoon and Hassan Haddadpour, Stability analysis of a fractional viscoelastic plate strip in supersonic flow under axial loading”, Meccanica, Vol. 52, No. 7, pp 1495-1502, May 2017

ABSTRACT: The stability of a viscoelastic plate strip, subjected to an axial load with the Kelvin–Voigt fractional order constitutive relationship is studied. Based on the classical plate theory, the structural formulation of the plate is obtained by using the Newton’s second law and the aerodynamic force due to the fluid flow is evaluated by piston theory. The Galerkin method is employed to discretize the equation of motion into a set of ordinary differential equations. To determine the stability margin of plate the obtained set of ordinary differential equations are solved using the Laplace transform method. The effects of variation of governing parameters such as axial force, retardation time, fractional order and boundary conditions on the stability margin of fractional viscoelastic panel are investigated and finally some conclusions are outlined.

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1. Fung Y (1960) A summary of the theories and experiments on panel flutter. Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena
Xuebin Li, Zhiqiang Wang and Lihua Huang, Study of vibration characteristics for orthotropic circular cylindrical shells using wave propagation approach and multivariate analysis”, Meccanica, Vol. 52, No. 10, pp 2349-2361, August 2017

ABSTRACT: A study of free vibration of orthotropic circular cylindrical shells is presented. The vibration control equations of shells are based on Flügge classical thin shell theory. Wave approach is used in the analysis, in which the boundary conditions of shells can be simplified according to the associated beam. The free vibration frequencies of shells can be obtained from a frequency polynomial equation of order 6. The parametric analysis of the free vibration of orthotropic cylindrical shells is investigated using a statistical method. The effects of geometrical parameters and material characteristics upon frequencies are investigated here. Multivariate analysis (MVA) can be a useful tool for this parametric study. Some statistical characteristics, including correlation analysis and ANOVA are applied. ANOVA has been conducted to predict the statistical significance of the various factors. Calculations are performed in the Minitab statistical software. The results show that the $L/R$, $h/R$ and $m$ have larger effects on the lowest frequency. The importance of input parameters is
ranked according to their contributions to the total variance. A knowledge and data visualization approach, Self-organizing mapping (SOM) is also adopted here for mining some intrinsic characteristics of shells.

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Thao-An Huynh, Anh-Tuan Luu and Jaehong Lee, “Bending, buckling and free vibration analyses of functionally graded curved beams with variable curvatures using isogeometric approach”, Vol. 52, No. 11-12, pp 2527–2546, September 2017

ABSTRACT: A study on the bending, buckling and free vibration of functionally graded curved beams with variable curvatures using isogeometric analysis is presented here. Non-uniform rational B-splines, known from computer aided geometric design, are employed to describe the exact geometry and approximate the unknown fields of a curved beam element based on Timoshenko model. Material properties of the beam are assumed to vary continuously through the thickness direction according to the power law form. The numerical examples investigated in this paper deal with circular, elliptic, parabolic and cycloid curved beams. Results have been verified with the previously published works in both cases of straight functionally graded beam and isotropic curved beam. The effects of material distribution, aspect ratio and slenderness ratio on the response of the beam with different boundary conditions are numerically studied. Furthermore, an interesting phenomenon of changing mode shapes for both buckling and free vibration characteristics corresponding to the variation in the parameters mentioned above is also examined.

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9. Simsek M (2015) Bi-directional functionally graded materials (BDFGMs) for free and forced vibration of Timoshenko beams with various boundary conditions. Compos Struct 133:968–978

ABSTRACT: In this article, a novel method, namely full modified nonlocal (FMNL) theory, for bending and buckling analysis of simply supported rectangular nano plates has been proposed. In this theory, a complete representation of strong-form of governing equation and boundary conditions are derived based on the infinite series of modified nonlocal constitutive equations by applying the variational principle. It is shown that by rearranging and then computing the sum of the infinite series which appears in the maximum bending deflection and critical buckling load, the truncation errors will be eliminated. A radius of convergence for the computed series is calculated to make sure the analyses are valid and reliable. In addition, the results of the presented method are compared with MD simulations to confirm the validity of FMNL theory. One of the advantages of the FMNL theory is that the defect of nonlocal theory in vanishing of small scale effect for some problems can be resolved. Furthermore, the FMNL theory will be a criterion for accuracy of the primary modified nonlocal theory that considers only two terms of the series of the modified nonlocal constitutive equation in predicting critical buckling loads and maximum bending deflections.

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M. D. Gilchrist, J. G. Murphy, B. Pierrat and G. Saccomandi, “Slight asymmetry in the winding angles of reinforcing collagen can cause large shear stresses in arteries and even induce buckling”, Meccanica, Vol. 52, No. 14, pp 3417-3429, November 2017

ABSTRACT: Many models of the mechanical response of arteries assume a reinforcement with two families of helically wound fibres of collagen of opposite pitch. Motivated by experimental observations, the consequences for the internal pressurisation of arteries of a slight asymmetry in the winding angles is investigated here. It is shown that a torsional shear stress is generated as a result of this flaw, with some common models of the mechanical response of arteries exhibiting significant shear stresses. If the shear stress is significant, then the corresponding model would not seem to be robust, given that an infinitesimal change in a model parameter results in a large change in system response, although it is also shown that there is a ‘magic-angle’ for fibre winding that eliminates torsional shear stress for many of the commonly used models. Finite Element simulations are used to further illustrate the main consequences of fibre asymmetry for some of the more common models of arterial response. If the fibre asymmetry is localised in a region, then simulations show that there is the possibility of significant bending of the artery centred in this region at physiological blood pressure.

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ABSTRACT: Nonlinear responses of a single pile with soil-structure interaction under primary resonance and two-to-one internal resonance are investigated. Considering the effect of soil-structure interaction and geometric
nonlinearity, the Hamilton principle is applied to derive the equation of motion of the pile subjected to a lateral excitation and axial load. Then, the effective nonlinear coefficient and the frequency-response equation are presented by employing the multimode discretization and the method of multiple scales. Moreover, the nonlinear frequencies are obtained for the analysis of the nonlinear dynamic characteristics of the pile. The equilibrium and dynamic solutions of modulation equations are examined by using the Newton-Raphson, shooting, and continuation methods. The nonlinear responses of the pile are explored by means of the backbone curves and the frequency (force)-response curves. Meanwhile, the effect of the axial load on the nonlinear dynamic characteristics of the pile is discussed. The numerical results show that the nonlinear responses of the pile exhibit some rich and complex nonlinear phenomena.

References listed at the end of the paper:


ABSTRACT: Thin periodic plates with uncertain properties in a periodicity cell are investigated. To describe dynamics of these plates the non-asymptotic tolerance modelling method, cf. Woźniak and Wierzbicki (Averaging techniques in thermomechanics of composite solids. Wydawnictwo Politechniki Częstochowskiej, Częstochowa, 15), Woźniak et al. (eds.) (Thermomechanics of microheterogeneous solids and structures. Tolerance averaging approach. Wydawnictwo Politechniki Łódzkiej, Łódź, 16), for those plates is applied. The governing equations of tolerance models based on this method take into account the effect of period lengths on the overall behaviour of the plate. Hence, the additional effects of the periodicity can be analysed, as higher order vibrations. Moreover, properties of the plate in the periodicity cell are determined uncertainly. To analyse an influence of random variables of the properties with a fixed probability distribution on vibrations of the plate the Monte Carlo analysis is applied.


ABSTRACT: Supersonic flutter behaviors of functionally graded material (FGM) shallow conical panel with steady thermal stress are investigated. It is assumed that temperature dependent material properties are graded along the radial direction following power law form. The shallow conical panel is formulated with the aid of first-order shear deformation theory and von-Karman geometrical nonlinearity. The aerodynamic loads are evaluated by using the first-order piston theory. The equations of motion in the form of nonlinear partial differential are derived by applying the Hamilton’s principle. In order to get a high dimensional dynamic discrete system, the Galerkin’s method is utilized and this system includes the effect of steady thermal stress due to considering the thermal stress. Newton–Raphson method and continuation method are applied to obtain the equilibrium points, and flutter boundaries are analyzed by solving the eigenvalue problem. The influences of damping, ratio of length to thickness and volume fraction index on the flutter characteristics of the simply supported FGM shallow conical shell panel are studied.

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ABSTRACT: We present some results about the asymptotic behavior of a Kirchhoff plate with viscoelastic dissipative effects, making use of the concept of minimal state. This approach allows to obtain results in a larger class of solutions and data with respect to the classical one, based on the histories of the deformation gradient. Recently, a lot of attention has been paid to find unified approaches to study the asymptotic behavior with memory kernels exhibiting a temporal decay containing the exponential and polynomial decay as special cases. Here we extend this unified approach to the Kirchhoff plate model in presence of supplies within the minimal state formalism.

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ABSTRACT: A numerical state-space approach is proposed to examine the natural frequencies and critical buckling limits of marine risers. A large axial tension in the riser model causes numerical limitations. These limitations are overcome by using the modified Gram–Schmidt orthonormalization process as an intermediate step during the numerical integration process with the fourth-order Runge–Kutta scheme. The obtained results are validated against those obtained with other numerical methods, such as the finite-element, Galerkin, and power-series methods, and are found to be in good agreement. The state-space approach is shown to be
computationally more efficient than the other methods. Also, we investigate the effect of a high applied tension, a high apparent weight, and higher-order modes on the accuracy of the numerical scheme. We demonstrate that, by applying the orthonormalization process, the stability and convergence of the approach are significantly improved.

References listed at the end of the paper:


ABSTRACT: The aim of the present work is to investigate the nonlinear vibration response and stability of a pre-stretched rectangular hyperelastic membrane resting on a nonlinear elastic foundation. The membrane is composed of an isotropic, homogeneous and hyperelastic material, which is modeled with four different constitutive laws, specifically: neo-Hookean, Mooney–Rivlin, Yeoh and Ogden hyperelastic models. The elastic foundation is described by a Winkler type nonlinear model with cubic hardening or softening nonlinearity. First the exact solution of the membrane under a biaxial stretch is obtained. Then the equations of motion of the pre-stretched membrane resting on the nonlinear foundation are derived. From the linearized equations, the natural frequencies and mode shapes of the membrane are obtained analytically. Then the natural modes are used to approximate the nonlinear deformation field using the Galerkin method. A detailed parametric analysis shows the strong influence of the stretching ratios and foundation parameters on the linear and nonlinear oscillations of the membrane. Frequency-amplitude relations and resonance curves are used to illustrate its nonlinear dynamics. The present results are favorably compared with the results evaluated for the same membrane, whenever possible, using a nonlinear finite element formulation.

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ABSTRACT: A deep understanding of both guided propagating and evanescent waves is very essential for non-destructive evaluation. Guided propagating waves have received considerable attention, but the research on guided evanescent waves is quite limited, especially for functionally graded structures. This paper presents an analytical approach, based on the orthogonal function technique, to solve the evanescent waves in a spherical curved plate with functionally graded material in the radial direction. The proposed approach can obtain all the real, imaginary and complex solutions but without iterative process. The validity of the proposed approach is illustrated by comparison with available results. The convergence of the approach is also discussed through a numerical example. Dispersion characteristics of the guided waves in various graded spherical curved plates are studied and three dimensional dispersion curves are plotted in frequency-complex wavenumber space. The effects of different radius-thickness ratios and graded fields on the dispersion curves of the guided evanescent waves are illustrated. The displacement distributions are also discussed to analyze the characteristics of the guided evanescent waves.

References listed at the end of the paper:


ABSTRACT: In this contribution, a novel type of piezoelectric tubular energy harvester based on fluctuating fluid pressure is investigated. Analytic model of the proposed energy harvester is built under the assumption of
axisymmetric radial vibration. Exact solution of the piezoelectric vibrating tube is obtained with its output performances formulated. A series of numerical simulations are conducted to investigate the influences of geometrical parameters, input mechanical load parameters and output electrical load parameters upon the output performances of the proposed piezoelectric tubular energy harvester. The model and simulation results indicate the potential of the proposed piezoelectric tubular energy harvester. It is expected that the energy harvester be useful in powering wireless sensor network for the health monitoring of hydraulic systems, where fluid conveying pipe vibration is omnipresent.

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Jin Zhang, “A nonlocal continuum model for the buckling of carbon honeycombs”, Meccanica, Vol. 53, No. 11-12, ppp 2999-3013, September 2018

ABSTRACT: Using molecular dynamics (MD) simulations and Eringen’s nonlocal elasticity theory, in this paper we comprehensively study the small-scale effects on the buckling behaviours of carbon honeycombs (CHCs). The MD simulation results show that the small-scale effects stemming from the long-range van der Waals interaction between carbon atoms can significantly affect the buckling behaviours of CHCs. To incorporate the small-scale effects into the theoretical analysis of the buckling of CHCs, we develop a nonlocal continuum mechanics (CM) model by employing Eringen’s nonlocal elasticity theory. Our nonlocal CM model is found to fit MD simulations well by setting the nonlocal parameter in the nonlocal CM model as 0.67. It is shown in our MD-based nonlocal CM model that when the cell length of CHCs is smaller than 7.93 Å the influence of small-scale effects on the buckling of CHCs becomes unnegligible and the small-scale effects can greatly reduce the critical buckling stress of CHCs. This reduction in critical buckling stress induced by the small-scale effects becomes more significant as the length of the cell wall decreases. Moreover, CHCs are found to display two different buckling modes when they are under different states of loading. The critical condition for the transition between these two buckling modes of CHCs can be greatly affected by the small-scale effects when the vertical cell wall and the inclined cell wall of CHCs have different lengths.

References listed at the end of the paper:

In this study, a multiplate shear model is developed for dynamic analysis of multilayer graphene sheets utilizing a variational approach based on the Kirchhoff plate model. The essential and natural boundary conditions are also obtained. Accordingly, the weak interlayer van der Waals interaction cannot maintain the integrity of carbon atoms in adjacent layers. Therefore, it is required that the interlayer shear effect is accounted to study multilayer graphene mechanical behavior. The governing differential equation of motion is derived for the multilayer graphene sheets utilizing a variational approach based on the Kirchhoff plate model. The essential and natural boundary conditions are also obtained at both the smooth periphery parts of the multilayer graphene sheets and the possible sharp corners. By considering cantilever and simply supported multilayer rectangular graphene sheets as two case studies, the results for the free-vibration analysis are presented based on the developed model, and these results are compared with those

M. Nikfar and M. Asghari, “A novel model for analysis of multilayer graphene sheets taking into account the interlayer shear effect”, Meccanica, Vol. 53, No. 11-12, pp 3061-3082, September 2018
of molecular dynamics simulations as some sort of verification. These results show that when the layers number increases, the natural frequency also increases up to a specific number, and afterward the influence of layers number on the natural frequency significantly decreases. Moreover, the natural frequency decreases with increase in the sheet aspect ratio up to a specific value, then the changes in the aspect ratio have no considerable effect in the natural frequency.

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ABSTRACT: This article is aimed to investigate the geometrically nonlinear wave propagation of nano-beams on the basis of the most comprehensive size-dependent elasticity theory. To this end, the integral model of nonlocal elasticity theory in the most general form without any simplification in conjunction with the modified strain gradient theory is implemented in the analysis. Also, the Timoshenko beam model is utilized in the presented nonlocal strain gradient elasticity theory. By Hamilton’s principle, the governing integro-partial differential equations of motion are derived. Employing numerical integration and an efficient method called as periodic grid technique, a semi-analytical approach is presented for the solution procedure. To detect the impacts of nonlocality and small scale effects on the nonlinear wave propagation characteristics of beams at nanoscale, adequate numerical examples and comparison studies are presented.

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Meghashyam Panyam, Mohammed F. Daqaq and Samir A. Emam, “Exploiting the subharmonic parametric resonances of a buckled beam for vibratory energy harvesting”, Meccanica, Vol. 53, No. 14, pp 3545-3564, November 2018
ABSTRACT: The potential of harvesting vibratory energy via a bistable beam subjected to subharmonic parametric excitations is investigated. The vibrating structure is a buckled beam with two stable equilibria separated by a potential barrier. The beam is subjected to a superposition of a static axial load beyond its buckling load and a harmonic axial excitation whose frequency is around twice the frequency of the buckled beam’s first vibration mode. A macro-fiber composite patch is attached to one side of the beam to convert the strain energy resulting from the beam’s oscillation into electricity. The study considers two regimes of excitations: an amplitude sweep and a frequency sweep. In the first regime, the amplitude of excitation is quasi-statically varied while the excitation frequency is tuned at twice the natural frequency of the first vibration mode. In the second regime, the excitation frequency is swept forward and backward around the subharmonic resonant frequency while the amplitude of excitation is kept constant. A theoretical model which governs the electromechanical coupling of the transverse vibrations of the beam and the output voltage is used to monitor the response as the excitation parameters are changed. An experimental setup is also built and a series of tests is performed to validate the theoretical findings. It is shown that, depending on the amplitude and frequency of excitation, the harvester can perform small-amplitude periodic intra-well motion, intra- and inter-well chaotic motions, as well as periodic inter-well motions. Experimental results also show that, as compared to the classical linear resonance, utilizing the sub-harmonic resonance of a bistable energy harvesters can result in a broadband frequency response.

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ABSTRACT: In this work, the modal characteristics, including modal damping, of FRP composite skin, honeycomb core sandwich panels with arbitrary geometries are computed using a mixed finite element-meshless method. By using the meshless node distribution scheme in conjunction with the Lagrangian quadrilateral interpolating functions, the continuity of inter-elemental displacements is assured. Since the distribution of the elements is not limited to the geometry of the problem, any arbitrary geometry can be readily analysed by using the same node and element distributions. Using the first order shear deformation plate theory, together with a structural damping model, modal response results are produced for a number of sandwich panel geometries, including triangular, trapezoidal, circular as well as rectangular plates with different combinations of free and clamped edges. Results are compared with those reported in the literature, showing the viability and the accuracy of the method.


ABSTRACT: In this paper, non-linear dynamics analysis of functionally graded material (fgm) shell structures is investigated using the higher order solid-shell element based on the enhanced assumed strain (eas). With this
element, a quadratic distribution of the shear stress through the thickness is considered in an enhancing part. Material properties of the shell structure are varied continuously in the thickness direction according to the general four-parameter power-law distribution in terms of the volume fractions of the constituents. Performance and accuracy of the present higher order solid-shell element are confirmed by comparing the numerical results obtained from finite element analyses with results from the literature.

ABSTRACT: This article presents the results of numerical investigation on modeling buckling behavior and ultimate strength of corroded multi-planar tubular joints. Finite element method was used in order to simulate the behavior of dx multi-planar tubular joints under axial compressive loading. Three different patterns were chosen for corrosion modeling and effects of corrosion-related parameters such as age and depth of corrosion were evaluated. The results indicate differences in the ultimate strength concluded from different patterns. It was found that conventional methods are conservative in evaluating the strength of corroded tubular joints of jacket platforms. Amongst 3 methods used for modeling corrosion, two had similar results to each other and closer to reality. It was also shown that corrosion is ineffective in braces.

ABSTRACT: State-of-the-art studies of impact crushing circular stepped tube (inversion tube) introduce various approaches to improve the energy absorption capacities. Adding external longitudinal stiffeners on the circular stepped tubes is one of these parameters that have a great effect and interest. In the current study, finite element analysis using (ls-dyna/workbench ansys) is performed on a series of numerical models of aluminum circular stepped tubes that are externally stiffened by a constant number of longitudinal stiffeners distributed around the cross section of the circular stepped tube. The numerical models are implemented under an axial impact crushing scenario. Furthermore, a new improved formula for prediction of steady inversion load is proposed. The theoretical predictions are found to be in good agreement with the numerical results with an error within 12%. A comparative study is conducted to compare the energy absorption characteristics and inversion mechanism between the newly proposed tubes and the conventional stepped tube. The results showed that addition of external longitudinal stiffeners on circular stepped tubes could imply greatest improvement for the energy absorption up to 104%, specific energy absorption capability (energy absorption per unit mass) up to 54.9%, the crush force efficiency up to 40.3% and increase the inversion stroke length in comparison with the unstiffened circular stepped tubes. A newfound role of external longitudinal stiffeners added to the stepped tubes that controls the inversion and deformation mechanism is presented.

ABSTRACT: The nonlinear vibration and normal mode shapes of fg cylindrical shells are investigated using an efficient analytical method. The equations of motion of the shell are based on the Donnell’s nonlinear shallow shell, and the material is assumed to be gradually changed across the thickness according to the simple power law. The solution is provided by first discretizing the equations of motion using the multi-mode Galerkin method. The nonlinear normal mode of the system is then extracted using the invariant manifold approach and employed to decouple the discretized equations. The homotopy analysis method is finally used to determine the nonlinear frequency. numerical results are presented for the backbone curves of fg cylindrical shells, nonlinear
mode shapes and also the nonlinear invariant modal surfaces. The volume fraction index and the geometric properties of the shell are found to be effective on the type of nonlinear behavior and also the nonlinear mode shapes of the shell. For the nonlinear mode shapes of thinner cylinders, the displacement variation in the circumferential direction is found to considerably change with time.


ABSTRACT: The dynamic behavior of variable stiffness composite laminated (vscl) plate with curvilinear fiber orientation subjected to in-plane end-loads is investigated. A variable stiffness design can increase the laminated composite structural performance and also provides flexibility for trading-offs between various structural properties. In each ply of the vscl plate, the fiber-orientation angle assumed to be changed linearly with respect to horizontal geometry coordinate. The spline finite strip method based on both classical as well as higher order shear deformation plate theories is formulated to explain the structural behavior. The panel is assumed containing internal square delamination regions with friction and contact conditions at delaminated interfaces are not considered. In order to demonstrate the capabilities of the developed method in predicting the structural dynamic behavior, some representing results are obtained and compared with those available in the literature. The effects of change in curvilinear fiber orientation angles on the structural stability is studied. The obtained results show very good conformity in comparison with those exists in the available literature.


ABSTRACT: A large number of references dealing with the geometric stiffness matrix of the DKT finite element exist in the literature, where nearly all of them adopt an inconsistent form. While such a matrix may be part of the element to treat nonlinear problems in general, it is of crucial importance for linearized buckling analysis. The present work seems to be the first to obtain an explicit expression for this matrix in a consistent way. Numerical results on linear buckling of plates assess the element performance either with the proposed explicit consistent matrix, or with the most commonly used inconsistent matrix.


ABSTRACT: This paper deals with free vibration analysis of thick cylindrical composite sandwich panels with simply supported boundary conditions based on a new improved higher-order sandwich panel theory. The formulation used the third-order polynomial description for the displacement fields of thick composite face sheets and for the displacement fields in the core layer based on the displacement field of frostig's second model. In this case, the unknowns were coefficients of the polynomials in addition to displacements of the top and bottom face sheets. The fully dynamic effects of the core layer and face sheets were also considered in this study. Using Hamilton's principle, the governing equations were derived. moreover, the effect of some important parameters such as those of thickness ratio of the core to panel, the length to radius ratio of the core and composite lay-up sequences were investigated on free vibration response of the panel. The results were validated by those published in the literature and with the finite element results obtained by abaqus. It was shown that thicker panels with thicker cores provided greater resistance to resonant vibrations. Moreover, the effect of increasing face sheets’ thicknesses in general was the significant increase in fundamental natural frequency values.

ABSTRACT: To mitigate shock forces in collision events, thin-walled members are used as energy absorber. In this article, crashworthiness of single-cell and multi-cell s-shaped members with various cross-sections including triangular, square, hexagonal, decagon and circular were investigated under axial dynamic loading using finite element code ls-dyna. Furthermore, crashworthiness of the s-rails with the same outer tubes and different inner ones was studied as well. The multi-cell members employed in this task were indeed double-walled tubes with several ribs connecting the inner and outer tubes together. Modified multi criteria decision making method known as complex proportional assessment (copras) was used to rank the members using three conflicting crashworthiness criteria namely specific energy absorber (sea), peak crash force (fmax) and crash force efficiency (cfe). The results exhibited that increase in the corners of cross-sections and the number of ribs, play an important role in enhancing energy absorption. Moreover, the multi-cell s-shaped members were found to perform better than single-cell ones in terms of crashworthiness. In addition, the multi-cell s-shape members were found as the best energy absorber, and also the s-rail having the same inner and outer tube with decagonal cross-section displayed desirable crashworthiness performance. Optimum geometry of this s-rail was eventually obtained from the parametric study.


ABSTRACT: A new 3-node triangular hybrid displacement function Mindlin-Reissner plate element is developed. Firstly, the modified variational functional of complementary energy for Mindlin-Reissner plate, which is eventually expressed by a so-called displacement function $f$, is proposed. Secondly, the locking-free formulae of Timoshenko’s beam theory are chosen as the deflection, rotation, and shear strain along each element boundary. Thirdly, seven fundamental analytical solutions of the displacement function $f$ are selected as the trial functions for the assumed resultant fields, so that the assumed resultant fields satisfy all governing equations in advance. Finally, the element stiffness matrix of the new element, denoted by $hdf_{p3-7B}$, is derived from the modified principle of complementary energy. Together with the diagonal inertia matrix of the 3-node triangular isoparametric element, the proposed element is also successfully generalized to the free vibration problems. Numerical results show that the proposed element exhibits overall remarkable performance in all benchmark problems, especially in the free vibration analyses.


ABSTRACT: In the present research, a unified semi-analytical solution that incorporates influence of the auxeticity (negative poisson ratio) of the material into elastic responses of the variable thickness functionally graded conical and cylindrical shells and circular/annular plates is developed. The top or bottom layers of the shell/plate may be subjected to general non-uniform normal and shear tractions. The mentioned material and loading complexities have not been investigated before and consequently, the presented comprehensive results are quite new. The proposed unified formulation is developed using the principle of minimum total potential energy and solved using Taylor’s transform, for some combinations of the simply supported, clamped and free edge conditions. Accuracy of results of the proposed unified solution is verified by results of the three-dimensional theory of elasticity extracted from the abaqus finite element analysis code.
structure configuration, shear/normal traction, thickness variability, and boundary conditions on the resulting lateral deflection and in-plane stress distributions of the considered shell and plate structures is accomplished.


ABSTRACT: This paper investigates the axial crushing response of concentric expanded metal tubes under impact loading. The study is conducted by means of nonlinear finite element simulations, considering the speed of deformation and the size of the expanded metal cells. In the analysis, two tubes are placed concentrically and then axially crushed with an impact mass at various speed levels. Crushing load-displacement responses are analyzed to investigate the influence of the size of the mesh and the impact speed. The results show that specimens with the same mesh sizes increase their crushing length with increasing speed. Finally, the main outcome of this investigation is to add to the state of knowledge information concerning the use of expanded metal meshes in impact attenuation devices.


ABSTRACT: The present paper deals with free vibration of functionally graded fiber reinforced rectangular plates subjected to thermal loads. The rectangular plates are assumed orthotropic. The continuous grading fiber reinforced plates have a smooth variation in matrix volume fraction in the thickness direction. Two different types of volume fraction profiles through the thickness of plate are proposed: classic and symmetric. As the plate is thick, the equations of motion are derived based on three dimensional theory of elasticity. Inevitably, 3d general differential quadrature method is used instead of regular solving methods in order to discretize equations of motion equations as linear set of algebraic equations. The effects of temperature, volume fraction profiles, and boundary conditions are investigated. Some interesting conclusions obtained when the material properties were assumed to be temperature-dependent. It has been observed that temperature and functionality of fg plate have significant effect on the natural frequencies of the plate.


ABSTRACT: The main aim of this paper is to investigate analytically nonlinear buckling and post-buckling of functionally graded stiffened circular cylindrical shells filled inside by Pasternak two-parameter elastic foundations in thermal environments and under axial compression load and external pressure by analytical approach. Shells are reinforced by closely spaced rings and stringers. The material properties of shell and the stiffeners are assumed to be continuously graded in the thickness direction. Using the Reddy third order shear deformation shell theory, stress function method and Lekhnitskii smeared stiffeners technique, the governing equations are derived. The closed form to determine critical axial load and post-buckling load-deflection curves are obtained by Galerkin method. The effects of temperature, stiffener, foundation, material and dimensional parameters on the stability behavior of shells are shown. The accuracy of the presented method is affirmed by comparisons with well-known results in references. The results shown for thick cylindrical shells, the use of FSDT for determining their critical buckling load is necessary and more suitable.
Aditya Rio Prabowo, Bo Cao, Dong Myung Bae, Sung Yong Bae, Ahmad Fauzan Zakki and Jung Min Sohn, “Structural analysis of the double bottom structure during ship grounding by finite element approach”, Latin American Journal of Solids and Structures, Vol. 14, No. 6, pp 1106-1123, 2017
ABSTRACT: Concern of water-transportation mode when experiences numerous accidental loads is predicted limitless and always demand sustainable analysis. Impact phenomenon raises as main reason of environmental damage, which grounding contributes in form of short-time impact and produces massive damage on bottom structure of marine vessels, e.g. ship. In this work, a series of numerical experiment is conducted with considering contribution of several parameters, namely impact location and seabed topology on the target object which is determined to be the bottom structure of a tanker ship. The initial stage is conducted to obtain validation of numerical method and configuration using impact test to ensure reliability of the present methodology. In the second stage, proposed scenarios are calculated and overall evaluation of damage extent is performed to observe resistance and behaviour of the bottom structure. Structural condition after grounding, rupture energy, and crushing force are presented to observe history of grounding. Contribution of numerical parameter in form of meshing size is presented to provide adequate consideration in both of physical and numerical parameters. Finally, tendency of the target structure is summarized to provide prediction of further behaviour during the bottom structure experiences grounding with other scenario. An alternative solution in respecting time cost is proposed and can be considered for other impact simulation.

ABSTRACT: Dynamic compression behaviors of density-homogeneous and density-graded irregular honeycombs are investigated using cell-based finite element models under a constant-velocity impact scenario. A method based on the cross-sectional engineering stress is developed to obtain the one-dimensional stress distribution along the loading direction in a cellular specimen. The cross-sectional engineering stress is contributed by two parts: the node-transitive stress and the contact-induced stress, which are caused by the nodal force and the contact of cell walls, respectively. It is found that the contact-induced stress is dominant for the significantly enhanced stress behind the shock front. the stress enhancement and the compaction wave propagation can be observed through the stress distributions in honeycombs under high-velocity compression. The single and double compaction wave modes are observed directly from the stress distributions. Theoretical analysis of the compaction wave propagation in the density-graded honeycombs based on the r-ph (rigid–plastic hardening) idealization is carried out and verified by the numerical simulations. It is found that stress distribution in cellular materials and the compaction wave propagation characteristics under dynamic compression can be approximately predicted by the r-ph shock model.

ABSTRACT: Polyester pins are incorporated in polyurethane foam filled honeycomb core sandwich panel to increase the interfacial strength between the faces and core in order to improve the performance of sandwich structures. Foam filled honeycomb sandwich panel (fhs) and pin incorporated foam filled honeycomb sandwich panels (pfhs) were developed. The developed sandwich panels are tested for flexural and vibration characteristics. The influence of strain rates on flexural behaviour of sandwich panels were also evaluated. The material used for face sheets and pins are same, ends of pin act as chemically cross linked polyester joint at the interfaces of faces and core in addition to the adhesive area. This modification had effectually increased the interfacial strength thereby increased the flexural and damping properties of panels significantly. Moreover, increasing the pin diameter has a larger effect, whereas, the strain rate had a moderate influence on the failure
load of both types of sandwich panels. The investigation brings to light a novel pin incorporated foam filled honeycomb sandwich panels that can be used for various applications.


ABSTRACT: The impact phenomenon is one of many subjects that is interesting and has become an inseparable part of naval architecture and ocean engineering fields. Limitless possibilities in cause and scenario make the demand to understand the physical behavior of ship structures due to impact phenomenon increasing. In present work, a series of virtual experiment is performed by finite element method to solve several defined collision scenarios. Two involved ships are classified as the striking ship which penetrates the target and struck ship as the target. Hull arrangement of the struck ship is considered as main parameter which single and double hull configurations are proposed to be assessed. An observation of the damage extent on struck ship subjected to collision loads are presented. The results indicate that the internal arrangement of the struck ship provides significant effects to resistance capability and structural failure after collision process. Finally, an analysis regarding the extent of the damage is summarized with a statistical calculation to provide distribution of crashworthiness criteria of the defined scenarios.


ABSTRACT: The present paper explores the stability and failure response of elastoplastic ni/al2o3 functionally graded plate under thermomechanical load using non-linear finite element formulation based on first-order shear deformation theory and von-Karman’s nonlinear kinematics. The temperature dependent thermoelastic material properties of fgm plate are varied in the thickness direction by controlling the volume fraction of the constituent materials (i.e., ceramic and metal) with a power law, and mori-tanaka homogenization scheme is applied to evaluate the properties at a particular thickness coordinate of fgm plate. The elastoplastic behavior of fgm plate is assumed to follow j2-plasticity with isotropic hardening, wherein the ceramic phase is considered to be elastic whereas the metal is assumed to be elastic-plastic in accordance with the tamura-tomota-ozawa model. Numerical studies are conducted to examine the effects of material and geometrical parameters, viz. material inhomogeneity, slenderness and aspect ratios on the elastoplastic bucking and postbuckling behavior and the failure response of fgm plate. It is revealed that material gradation affects the stability and failure behavior of fgm plate considerably. Furthermore, it is also concluded that fgm plate with elastic material properties exhibits only stable equilibrium path, whereas the elastoplastic fgm plate shows destabilizing response after the ultimate failure point.


ABSTRACT: Thin walled multi-cell columns are highly efficient energy absorbers under axial compressions. Multi-cell features are usually obtained by placing stiffeners or ribs to get the required geometry features in the columns. In this study, the curved stiffeners with varying numbers in different configurations are used to support the circular single and bi-tubular metallic tubes and their shape, position and number effects are numerically investigated under dynamic axial crushing loads. Number of configurations can be classified by the number of tube/tubes and curved stiffened shells. This study can be divided in three parts; single tubes with cross-curved stiffeners with equal number of cells, single tubes with curved stiffened wall supports with
ascending number of stiffeners, and bi-tubular tubes with ascending cross-curved stiffeners. The mass in each configuration is maintained as same by adjusting the thicknesses of the stiffeners. Energy absorption for all of the configurations are compared with published experimental literature of standard single tube and bi-tubular tube with cross-straight stiffeners. Deformation modes and energy absorption characteristics are evaluated and discussed for all of the proposed configurations. Results indicate that the proposed configurations with curvy stiffeners are superior in energy absorption with increased mean crushing force and enhanced specific energy absorption along with a high value of crush force efficiency in comparison with the reference configurations. Bi-tubular configurations with curvy stiffeners show a more stabilized response with the lowest peak crushing force in all of the proposed configurations.

ABSTRACT: This paper investigates the dynamic response of rectangular prestressed membrane subjected to concentrated impact load based on multiple scale perturbation method. The governing equations of motion of nonlinear vibration are derived based on the Föppl large deflection theory, and uncoupled by means of Galerkin method. By introducing different time scales to consider the process of vibration, the results of dynamic response are obtained by applying the multiple scale perturbation method. Additionally, the theoretical results are compared with the experimental data in literature to identify the reliability of theory model. Furthermore, the effects of pretension force, velocity of load and dimension of membrane on the dynamic response of membrane are discussed. The present work studies the problem of the dynamic response of prestressed membrane subjected to concentrated impact load in different time scales, and provides a more accurate theoretical model for design of membrane structure.

ABSTRACT: This article presents the vibro-acoustic modeling and analysis of un-baffled laminated composite flat panels subjected to harmonic point load under various support conditions. The frequency values of the panel are obtained by using simulation model through the commercial finite element package (ansys) via batch input technique. Initially, the rate of convergence of the current simulation results is established by solving different examples under various edge supports. Further, the natural frequencies and corresponding modes are computed and compared with available published and experimentally obtained values. Then, the modal values are exported to lms virtual.lab environment for the computation of acoustic responses of the vibrating laminated plate structure. Further, an indirect boundary element approach has been adopted to extract the coupled vibro-acoustic responses. Subsequently, the radiated sound power of the structure and the sound pressure level within the acoustic medium are computed using the present scheme and compared with the published numerical results and in-house experimental data, respectively. Finally, a comprehensive study has been performed to highlight the effect of different structural parameters (thickness ratio, aspect ratio, modular ratio and lay-up scheme), support conditions and the composite properties on the acoustic radiation responses of the laminated plate structure.

ABSTRACT: A series of analyses are carried out to predict the structural crashworthiness of a ship during a collision. The numerical configuration is verified by structural simulations based on a laboratory experiment wherein a penetration test is considered as the experimental reference. Comparative observations of structural behaviour are carefully conducted to ensure the reliability of the present method for conducting large-scale collisions. At this stage, the proper procedure and configuration for structural calculations subject to accidental loads are determined. The second stage addresses the calculations for various side collision scenarios. The simulations consider a double hull ro-ro passenger ship being struck at various locations, and the overall behaviour of the side hull along the longitudinal axis is observed. The main study considers the target location and striking speed to obtain adequate data related to crashworthiness criteria, i.e. the internal energy and extent of damage. Finally, the criteria of various scenarios are summarized. Further calculations comparing the results with a safety factor are presented together with a consideration of structural behaviour to estimate the safety limit within the confines of strait territory.


ABSTRACT: Geometrically nonlinear vibrations of functionally graded shallow shells of complex planform are studied. The paper deals with a power-law distribution of the volume fraction of ceramic and metal through the thickness. The analysis is performed with the use of the $r$-functions theory and variational Ritz method. Moreover, the Bubnov-Galerkin and the Runge-Kutta methods are employed. A novel approach of discretization of the equation of motion with respect to time is proposed. According to the developed approach, the eigenfunctions of the linear vibration problem and some auxiliary functions are appropriately matched to fit unknown functions of the input nonlinear problem. Application of the $r$-functions theory on every step has allowed the extension of the proposed approach to study shallow shells with an arbitrary shape and different kinds of boundary conditions. Numerical realization of the proposed method is performed only for one-mode approximation with respect to time. Simultaneously, the developed method is validated by investigating test problems for shallow shells with rectangular and elliptical planforms, and then applied to new kinds of dynamic problems for shallow shells having complex planforms.


ABSTRACT: In this paper, we propose a time domain analytical solution for the forced vibration analysis of thick-walled hollow cylinders in presence of polar orthotropy. In this regard, solution of the governing equation is decomposed into two parts. The role of the first one is to satisfy boundary conditions utilizing the method of separation of variables besides of Fourier series expansion of the nonhomogenous boundary conditions. The second part has been also expressed as the series of orthogonal characteristic functions with the aim of satisfaction of initial conditions. The proposed analytical solution has been implemented to evaluate the dynamic response of the cylinder in solution of some sample problems which are chosen from previous studies.


ABSTRACT: In this paper, energy absorption and deformation capacity of circular thin-walled members with elliptical cut-outs are investigated both numerically and experimentally. Thin-walled members possess the
uniform height, thickness, average cross sectional area, material and volume are subjected to axial quasi-static loading. To conduct such tests, special fixture arrangement is designed for placing the specimen in the compression loading machine. The deformation mechanisms and the corresponding collapse mode along with its energy absorption of the thin-walled tubes were investigated in detail for various aspect ratios (0.315, 0.523, 0.854, 1, 3.375 and 4.08). The explicit finite element code abaqus was then employed to perform the numerical studies in view of mitigating the influence of cutout shape, location and symmetry on energy absorption and crush characteristics. In aspect ratio of 4.08, whose major axis length of 24.5 mm observed maximum crash force efficiency (cfe) of 14% possessing symmetric discontinuity. The results of experimental and simulations are in good agreement and shows that the location and symmetry of cutouts had considerable effect on collapse crushing behaviour.

ABSTRACT: The prediction of plastic instability in sheet metals during forming processes represents nowadays an ambitious challenge. To reach this goal, a new numerical approach, based on the loss of ellipticity criterion, is proposed in the present contribution. A polycrystalline model is implemented as a user-material subroutine into the abaqus/implicit finite element (fe) code. The polycrystalline constitutive model is assigned to each integration point of the fe mesh. To derive the mechanical behavior of this polycrystalline aggregate from the behavior of its microscopic constituents, the multiscale self-consistent scheme is used. The mechanical behavior of the single crystals is described by a finite strain rate-independent constitutive framework, where the Schmid law is used to model the plastic flow. The condition of loss of ellipticity at the macroscale is used as plastic instability criterion in the fe modeling. This numerical approach, which couples the fe method with the self-consistent scheme, is used to simulate a deep drawing process, and the above criterion is used to predict the formability limit of the studied sheets during this operation.

ABSTRACT: This paper presents an exact model for studying the global buckling of concrete-filled steel tubular (cfst) columns with compliant interfaces between the concrete core and steel tube. This model is then used to evaluate exact critical buckling loads and modes of cfst columns. The results prove that interface compliance can considerably reduce the critical buckling loads of cfst columns. A good agreement between analytical and experimental buckling loads is obtained if at least one among longitudinal and radial interfacial stiffnesses is high. The parametric study reveals that buckling loads of cfst columns are very much affected by the interfacial stiffness and boundary conditions.

ABSTRACT: A new fifth-order shear and normal deformation theory (fosndt) is developed for the static bending and elastic buckling analysis of functionally graded beams. The properties of functionally graded material are assumed to vary through the thickness direction according to power-law distribution (p-fgm). The most important feature of the present theory is that it includes the effects of transverse shear and normal deformations. Axial and transverse displacements involve polynomial shape functions to include the effects of transverse shear and normal deformations. A polynomial shape function expanded up to fifth-order in terms of the thickness coordinate is used to account for the effects of transverse shear and normal deformations. The
kinematics of the present theory is based on six independent field variables. The theory satisfies the traction free boundary conditions at top and bottom surfaces of the beam without using problem dependent shear correction factor. The closed-form solutions of simply supported fg beams are obtained using Navier’s solution procedure and non-dimensional results are compared with those obtained by using classical beam theory, first order shear deformation theory and other higher order shear deformation theories. It is concluded that the present theory is accurate and efficient in predicting the bending and buckling responses of functionally graded beams.


ABSTRACT: In this paper, a geometrically nonlinear analysis of functionally graded material (fgm) shells is investigated using abaqus software. A user defined subroutine (umat) is developed and implemented in abaqus/standard to study the fg shells in large displacements and rotations. The material properties are introduced according to the integration points in abaqus via the umat subroutine. The predictions of static response of several non-trivial structure problems are compared to some reference solutions in order to verify the accuracy and the effectiveness of the new developed nonlinear solution procedures. All the results indicate very good performance in comparison with references.

References listed at the end of the paper:

ABSTRACT: This work presents a detailed description of the formulation and implementation of the atomistic finite element method afem, exemplified in the analysis of one- and two-dimensional atomic domains governed by the Lennard Jones interatomic potential. The methodology to synthesize element stiffness matrices and load vectors, the potential energy modification of the atomistic finite elements (afe) to account for boundary edge effects, the inclusion of boundary conditions is carefully described. The conceptual relation between the cut-off radius of interatomic potentials and the number of nodes in the afe is addressed and exemplified for the 1d case.
for the 1d case elements with 3, 5 and 7 nodes were addressed. The afem has been used to describe the mechanical behavior of one-dimensional atomic arrays as well as two-dimensional lattices of atoms. The examples also included the analysis of pristine domains, as well as domains with missing atoms, defects, or vacancies. Results are compared with classical molecular dynamic simulations (md) performed using a commercial package. The results have been very encouraging in terms of accuracy and in the computational effort necessary to execute both methodologies, afem and md. The methodology can be expanded to model any domain described by an interatomic energy potential.


ABSTRACT: The use of carbon nanotubes as the reinforcing constituent for polymer matrix composites in place of conventional fibers has led to the emergence of a new generation of advanced composite materials. In this paper, the free vibration of functionally graded nanocomposite beams on elastic foundations are studied. Three different types of carbon nanotubes distributions in the polymer matrix material are studied; uniform distribution, symmetrically functionally graded distribution and unsymmetrically functionally graded distribution. The analysis is carried out by a mesh-free method using the two-dimensional theory of elasticity. The moving least square shape functions are implemented to approximate the displacement field. due to the absence of the Kroncker delta property of the shape functions, a transformation technique is used to apply the essential boundary conditions. After validation, the effects of different design parameters such as carbon nanotubes distribution, slenderness ratios, boundary conditions and foundation stiffness on the vibrational behaviour of the structure are investigated. The current approach can serve as a benchmark against which other semi-analytical and numerical methods based on classical beam theories can be compared.


ABSTRACT: This work reports a numerical investigation on the distortional buckling/post-buckling behaviors, ultimate strength and direct strength method (dsm) design of cold-formed steel s-beams, commonly used in industrial rack systems. The analyzed beams are single-span, under uniform bending, exhibiting two different end support conditions and 5 cross-sections dimensions. The post-buckling equilibrium paths and ultimate moments are obtained from shell finite element non-linear analysis through the software ansys. The reported results evidenced that current codified dsm distortional curve is unable to provide safely strength predictions for the selected beams.


ABSTRACT: An assessment of the efficiency and convergence characteristics of a four-node quadrilateral plate finite element in the analysis of laminated composites is performed. The element, which is suitable for global response analysis, is developed in the framework of the strain gradient notation such that its modeling capabilities as well as modeling deficiencies can be physically interpreted by the analyst during the formulation process. Thus, shear locking typically encountered in four-noded plate elements is identified as caused by spurious terms which appear in the shear strain polynomial expansions. These identified spurious terms are removed a priori such that shear locking does not occur during numerical analysis and numerical remedies do not need to be applied. Stress solutions for different laminated plates are presented to demonstrate that the corrected model converges well to reference solutions.

ABSTRACT: Increase of energy absorption along with smooth load displacement curve, reduced peak force and high mean crushing force is the key in the modern dynamic design of structures. In this regard, a new metallic tubular configuration consisting of uni-sectional bi inner tubes which are placed inside an outer tube with multiple varied cross-sections is proposed and crushed under axial dynamic loading. A number of configurations are proposed ranging from simple to complex polygonal sections defined in three groups. Deformation modes and energy absorption characteristics such as peak crushing force, mean crushing force, and specific energy absorption are determined and discussed for each configuration. The proposed arrangement shows a stable crushing, giving higher values of crush force efficiency. In order to select the most suitable configuration, on the basis of maximum specific energy absorption, maximum crushing force and minimum peak force, a robust decision making method known as complex proportional assessment (copras) is implemented. The results indicate that the proposed configuration with outer and inner hexagonal tubes’ arrangement is the best configuration in terms of energy absorption characteristics. The conclusion is dependent on the assigned weighting parameters which are quite sensitive for the results, demanding a careful selection as per the specific application and may alter the best possible choice.


ABSTRACT: In this paper, a new higher-order layerwise finite element model, developed earlier by the present authors for the static analysis of laminated composite and sandwich plates, is extended to study the free vibration behavior of multilayer sandwich plates. In the present layerwise model, a first-order displacement field is assumed for the face sheets, whereas a higher-order displacement field is assumed for the core. Thanks to enforcing the continuity of the interlaminar displacement, the number of variables is independent of the number of layers. In order to reduce the computation effort, a simply four-noded C0 continuous isoparametric element is developed based on the proposed model. In order to study the free vibration, a consistent mass matrix is adopted in the present formulation. Several examples of laminated composite and sandwich plate with different material combinations, aspect ratios, boundary conditions, number of layers, geometry and ply orientations are considered for the analysis. The performance and reliability of the proposed formulation are demonstrated by comparing the author’s results with those obtained using the three-dimensional elasticity theory, analytical solutions and other advanced finite element models. From the obtained results, it can be concluded that the proposed finite element model is simple and accurate in solving the free vibration problems of laminated composite and sandwich plates.


ABSTRACT: In the present paper, an improved high-order theory is employed to study the free vibration of rotating truncated sandwich conical shells with laminated face sheets and a soft core. The formulation is based on a three-layer sandwich model. First-order shear deformation theory (fsdt) is used for face sheets and quadratic and cubic functions are assumed for transverse and in-plane displacements of the core, respectively. The governing equations of motion are derived according to the Hamilton’s principle. Also, continuity conditions of the displacements at the interfaces, as well as transverse flexibility, transverse normal strain and
stress of the core have been considered. Analytical solution for free vibration of simply supported sandwich conical shells is presented using Galerkin’s method. Effect of some geometrical parameters is also studied on the fundamental frequency of the sandwich shells. Comparison of the present results with those in the literature confirms the accuracy of the proposed theory.


ABSTRACT: The thermal effects of problems involving deformable structures are essential to describe the behavior of materials in feasible terms. Verifying the transformation of mechanical energy into heat it is possible to predict the modifications of mechanical properties of materials due to its temperature changes. The current paper presents the numerical development of a finite element method suitable for nonlinear structures coupled with thermomechanical behavior; including impact problems. A simple and effective alternative formulation is presented, called FEM positional, to deal with the dynamic nonlinear systems. The developed numerical is based on the minimum potential energy written in terms of nodal positions instead of displacements. The effects of geometrical, material and thermal nonlinearities are considered. The thermodynamically consistent formulation is based on the laws of thermodynamics and the helmholtz free-energy, used to describe the thermoelastic and the thermoplastic behaviors. The coupled thermomechanical model can result in secondary effects that cause redistributions of internal efforts, depending on the history of deformation and material properties. The numerical results of the proposed formulation are compared with examples found in the literature.


ABSTRACT: Effects of viscoelastic substrates on the sandwich structures oscillations are examined in this paper. In this regard, dynamic response of sandwich annular panels with fg polar orthotropic face sheets resting on viscoelastic substrate is presented. Young’s modulus in the radial and circumferential direction, shear modulus and density of each face sheet may be varied continuously in the radial direction. The viscoelastic substrate is modeled as Kelvin-Voigt foundation. To describe more accurately response of sandwich structures, the governing dynamical equations are derived based on the layerwise theory and five systems of second order coupled partial differential equations are obtained. The effects of the stiffness and damping coefficients of the foundation on the dynamic behavior of sandwich plate are investigated for various transient loads and boundary condition. Since no available results may be found in literature to demonstrate the efficiency and accuracy of the obtained results, the obtained results are verified by comparison with finite element results based on the three dimensional theory of elasticity for some special cases.


ABSTRACT: This paper presents dynamic analysis of an eccentrically stiffened imperfect circular cylindrical shells made of functionally graded materials, subjected to axial compressive load and filled inside by elastic foundations in thermal environments by analytical method. Shells are reinforced by fgm stringers and rings taking into account thermal elements. The stability equations in terms of displacement components for stiffened shells are derived by using the third-order shear deformation theory and smeared stiffeners technique. The
closed-form expressions for determining the natural frequency, nonlinear frequency-amplitude curve and nonlinear dynamic response are obtained by using Galerkin method and fourth-order Runge-Kutta method. The effects of stiffeners, foundations, imperfection, material and dimensional parameters pre-existent axial compressive and thermal load on dynamic responses of shells are considered.


ABSTRACT: An adaptation of the conventional lanczos algorithm is proposed to solve the general symmetric eigenvalue problem \([k]{x} = \lambda[kg]{x}\) in the case when the geometric stiffness matrix \([kg]\) is not necessarily positive-definite. The only requirement for the new algorithm to work is that matrix \([k]\) must be positive-definite. Firstly, the algorithm is presented for the standard situation where no shifting is assumed. Secondly, the algorithm is extended to include shifting since this procedure may be important for enhanced precision or acceleration of convergence rates. Neither version of the algorithm requires matrix inversion, but more resources in terms of memory allocation are needed by the version with shifting.

Chuang Wu and Fuzhen Pang, “Free vibration characteristics of the conical shells based on precise integration transfer matrix method”, Latin American Journal of Solids and Structures, Vol. 15, No. 1, (pp in journal is not given), 2018

ABSTRACT: Based on transfer matrix theory and precise integration method, precise integration transfer matrix method (pitmm) is advanced to research free vibration characteristics of the conical shells. The influences of the boundary conditions, the shell thickness and the semi-vertex conical angle on vibration characteristics are discussed. Based on Flügge thin shell theory and transfer matrix method, field transfer matrix of conical shells is obtained. According to the boundary conditions at ends of the conical shell, natural frequencies of the conical shell are solved by precise integration method. The approach of studying free vibration characteristics of the conical shells is obtained. Contrast of natural frequencies from the paper and previous literature, the method of the paper is confirmed. on this basis, the effects of the boundary conditions, the shell thickness and the semi-vertex conical angle on vibration characteristics are presented.

Nitin Shankarrao Naik and Atteshamuddin S. Sayyad, “1D analysis of laminated composite and sandwich plates using a new fifth-order plate theory”, Latin American Journal of Solids and Structures, Vol. 15, No. 1, (pp in journal is not given), 2018

ABSTRACT: In the present study, a new fifth-order shear and normal deformation theory (fosndt) is developed for the analysis of laminated composite and sandwich plates under cylindrical bending. The theory considered the effects of transverse shear and normal deformations. To account for the effect of transverse shear deformation, in-plane displacement uses polynomial shape function expanded up to fifth-order in-terms of the thickness coordinate. Transverse displacement uses derivative of shape function to account for the effect of transverse normal deformations. Therefore, the present theory involves six independent unknown variables. The theory satisfies traction free boundary conditions at top and bottom surfaces of the plate and does not require the shear correction factor. The principle of virtual work is used to obtain the variationally consistent governing differential equations and associated boundary conditions. analytical solutions for simply supported boundary conditions are obtained using Navier’s solution technique. Non-dimensional displacements and stresses obtained using the present theory are compared with existing exact elasticity solutions and lower and higher-order theories to prove the efficacy of the present theory. The comparison shows that the displacements and stresses predicted by the present theory are in good agreement with those obtained by using the exact solution.
Mostafa Salim, Mahdi Bodaghi, Saeed Kamarian and Mahmoud Shakeri, “Free vibration analysis and design optimization of SMA/Graphite/epoxy composite shells in thermal environments”, Latin American Journal of Solids and Structures, Vol. 15, No. 1, (pp in journal is not given), 2018
ABSTRACT: Composite shells, which are being widely used in engineering applications, are often under thermal loads. Thermal loads usually bring thermal stresses in the structure which can significantly affect its static and dynamic behavior. One of the possible solutions for this matter is embedding SMA wires into the structure. In the present study, thermal buckling and free vibration of laminated composite cylindrical shells reinforced by shape memory alloy (sma) wires are analyzed. Brinson model is implemented to predict the thermo-mechanical behavior of sma wires. The natural frequencies and buckling temperatures of the structure are obtained by employing generalized differential quadrature (gdq) method. gdq is a powerful numerical approach which can solve partial differential equations. A comparative study is carried out to show the accuracy and efficiency of the applied numerical method for both free vibration and buckling analysis of composite shells in thermal environment. A parametric study is also provided to indicate the effects of like sma volume fraction, dependency of material properties on temperature, lay-up orientation, and pre-strain of sma wires on the natural frequency and buckling of shape memory alloy hybrid composite (smahc) cylindrical shells. Results represent the fact that smas can play a significant role in thermal vibration of composite shells. The second goal of present work is optimization of smahc cylindrical shells in order to maximize the fundamental frequency parameter at a certain temperature. To this end, an eight-layer composite shell with four sma-reinforced layers is considered for optimization. The primary optimization variables are the values of sma angles in the four layers. Since the optimization process is complicated and time consuming, genetic algorithm (ga) is performed to obtain the orientations of sma layers to maximize the first natural frequency of structure. ga is an evolutionary computation method based on darwinian theories that solves optimization problems without using gradient-based information on the objective functions. The optimization results show that using an optimum stacking sequence for smahc shells can increase the fundamental frequency of the structure by a considerable amount.

ABSTRACT: In this manuscript, stiffened carbon / epoxy composite cylinders under external hydrostatic pressure will be examined to minimize mass and maximize buckling pressure. The new approach proposed in this paper is single objective optimization of stiffened composite cylindrical shell under external pressure by genetic algorithm (ga) in order to obtain the reduction of mass and cost, and increasing the buckling pressure. The objective function of buckling has been used by performing the analytical energy equations and Tsai-Wu and Hashin failure criteria have been considered. Single objective optimization was performed by improving the evolutionary ga. Optimization have been done to achieve the minimum weight with failure and buckling constraints. Finally, optimal angles pattern of layers and fiber orientations are provided for cylinder under external hydrostatic pressure.

ABSTRACT: The use of numerical methods such as the finite elements method for solving structural analysis problems is becoming ever more efficient. An interface element capable of associating flat plate/shell element in three different combinations has been developed. In a structural analysis, when only the flat plate/shell’s finite elements are used in the discretization, some problems concerning dimensional variation of the transversal section, as well as overlapping of areas can occur. The aforementioned problems can be solved by the
developed interface elements that can also simulate a possible deformable connection that is existent in the association of materials with different characteristics, such as the composite steel-concrete elements. One of the applications of the finite elements developed is for the numerical simulation of composite steel-concrete elements, such as the composite beam formed by a reinforced concrete slab attached to a steel beam using a deformable connection. In this case, the concrete slab and the steel beam are discretized by the flat plate/shell element, and the deformable connection done by the interface elements. In the validation of the implemented elements, we used numerical and experimental results found in the literature, and analytical solutions considering the classical plate theory.

Hassan Ostadhossein and Saeid Lotfi, “Performance of infill stiffened steel panel against blast loading”, Latin American Journal of Solids and Structures, Vol. 15, No. 2, (pp in journal is not given), 2018
ABSTRACT: In blast loading out-of-plane behavior of infill wall is activated initially. Infill steel plate wall in spite of other types of infill wall such as brick or concrete wall exhibits more ductility. Blast impulsive loading suddenly exerts a large amount of kinematic energy to infill wall, accordingly energy absorption characteristic of the infill wall should be taken into account especially for protection of sensitive buildings. Out-of-plane ductility of infill steel plate, causes reduction of transmitted impulsive loading to structure. In this study out-of-plane behavior of infill steel panel has been studied as a sacrificial element. Also in-plane behavior of infill steel panel as a lateral bearing system is investigated. In-plane action should satisfy both of resistance and performance criteria. In this research finite element analysis including geometric and material nonlinearities is used for optimization of the steel plate thickness and stiffeners arrangement to obtain more efficient design for out-of-plane and in-plane actions. The results of analyses show that for out-of-plane action, plate thickness and stiffeners arrangement can be determined such that in one hand the impulse transmission to be minimized, and in other hand the maximum residual deformation should be limited to the predefined damage level. In addition the effect of stiffener arrangement on the performance of in-plane are studied and some practical rule for design of infill steel panel against blast have been derived.

ABSTRACT: A new collocation methodology is presented to predict failure and progressive damage behavior of composite plates in this paper. The present work deals with composite plates containing initial geometric imperfections and different boundary conditions under uniaxial in-plane compressive load. In the present study, the domain is discretized with Legendre-Gauss-Lobatto nodes and the approximation of displacement fields is performed by Legendre basis functions (lbfs). the onset of damage and damage evolution are predicted by Hashin’s failure criteria and by proposed material degradation models. Three geometric degradation models are also assumed to estimate the degradation zone around the failure location which are named complete, region and node degradation models.

Yavar Anani and Gholam Hossein Rahimi, “On the stability of internally pressurized thick-walled spherical and cylindrical shells made of functionally graded incompressible hyperelastic material”, Latin American Journal of Solids and Structures, Vol. 15, No. 5, (pp in journal is not given), 2018
ABSTRACT: In this paper, stability analysis of thick-walled spherical and cylindrical shells made of functionally graded incompressible hyperelastic material subjected to internal pressure is presented. Instability point happens in the inflation of above mentioned shells and in this paper effect of material inhomogeneity and shell thickness has been investigated. Extended ogden strain energy function with variable material parameter is used to model the material behavior. To model inhomogeneity, we assume that material parameter varies by a
power law function in the radial direction and inhomogeneity factor is a power in the power law function. Analytical method is used to find the internal pressure versus hoop extension ratio relations in explicit form for both of cylindrical and spherical shells and the non-monotonic behavior of the inflation curves is studied. Following this, profile of inflation pressure versus hoop stretch is presented and effect of the inhomogeneity and shell thickness in the onset of instability is studied. The obtained results show that the material inhomogeneity parameter and shell thickness have a significant influence on the stability of above mentioned shells. Thus with selecting a proper material inhomogeneity parameter and shell thickness, engineers can design a specific fgm hollow cylinder that can meet some special requirements.

Lucas Figueiredo Grilo, Ricardo Hallal Fakury, Ana Lydia Reis Castro E Silva, Francisco Carlos Rodrigues and Victor Pereira Daldegan, “Behavior and design of built-up compressed steel members composed of concentric hot rolled circular hollow sections”, Latin American Journal of Solids and Structures, Vol. 15, No. 6, (pp in journal is not given), 2018

ABSTRACT: This research presents a study of the behavior of built-up compressed steel members composed of concentric hot rolled circular hollow sections. The use of these members is an innovative solution of practical interest for situations in which a single member does not reach the required compressive strength. Some technically and economically viable design and fabrication solutions to built-up members composed of concentric hot rolled circular hollow sections are presented. For the validation of numerical results, models of singular hollow sections are made and compared to the EN 1993-1-1:2005, and the results obtained with numerical models were satisfactory. The compression resistance of these numerical models differs less than 9% from the EN 1993-1-1:2005 values. Once the numerical modeling was validated, the study of built-up members was made, considering the tubes always united at the extremities by end plates, and along the length by fixed interconnections or sliding interconnections or, furthermore, without interconnections. For these three different conditions, several numerical models using FEM via abaqus software were simulated to obtain and compare the compression resistance. The results show that these built-up sections with fixed and sliding interconnections have very similar behavior to the results obtained with European standard procedure, when considering equivalent areas and inertias for the built-up section. also, it shows that this observation does not apply to the sections without interconnections. Comparative graphs of compression resistance curves were generated, as also some graphs that show the distribution of the compressive force between each member of the built-up section. Finally, a formulation for the design of built-up sections without interconnections along the tubes was proposed to avoid robust computational methods.

Meisam Soroush, Keramat Malekzadeh Fard and Morteza Shahravi, “Finite element simulation of interlaminar and intralaminar damage in laminated composite plates subjected to impact”, Latin American Journal of Solids and Structures, Vol. 15, No. 6, (pp in journal is not given), 2018

ABSTRACT: Here in this study, the composite laminates subjected to transverse impact with consideration interlaminar and intralaminar damage based on cohesive zone model (czm) and progressive damage model (pdm) are investigated by numerical analysis using abaqus commercial finite element code. The delamination in stacking ply with the same fiber orientation is considered as intralaminar damage and the delamination in an inner layer of any cluster is ignored. Hashin criterion is used for interlaminar damage initiation and evolution without using any subroutine. First, the appropriate procedure for delamination on composite specimen was suggested based on czm approach in double cantilever beam to verify the intralaminar damage simulation. Then by considering several case studies with different impact energies, the results of present simulation is verified with the relevant and available experimental results and numerical references in the existing literature. According to the available experimental results the present simulation results are more acceptable and accurate than the results of similar numerical works, especially in higher impactor velocity.
Amr A. Abd-Elhady, Muhammad A. Mubaraki and Hossam El-Din Sallam, “Progressive failure prediction of pinned joint in quasi-isotropic laminates used in pipelines”, Latin American Journal of Solids and Structures, Vol. 15, No. 6, (pp in journal is not given), 2018

ABSTRACT: To simulate the progressive failure of pinned joint in quasi-isotropic [0/45/-45/90]s glass fiber reinforced polymer (gfrp) composite laminates used in pipeline, 3-d finite element model is employed in the present work. Hashin failure criterion as a progressive damage model associated with virtual-crack-closing-technique (vcct) delamination model has been adopted to predicate the failure due to fiber breakage, matrix cracking and delamination in composite pinned joint. This technique may be an innovation for this paper. w/d has been changed to get different modes of failure, i.e. tension, shear-out and bearing failures, in composite pinned joint. The failure mode for gfrp composite pinned joint has been predicted finally after prediction the failure at each ply laminate of stacking sequence [0/45/-45/90]s. An experimental work on pinned joint in quasi-isotropic gfrp composite laminates has been conducted to validate the present numerical results. The numerical and experimental results showed an agreement between them. Therefore, the present 3d finite element model can be considered as a good candidate to expect the progressive damage in composite pinned joints.

Savanna Cristina Medeiros D’aguiar and Evandro Parente Junior, “Local buckling and post-critical behavior of thin-walled composite channel section columns”, Latin American Journal of Solids and Structures, Vol. 15, No. 7, (pp in journal is not given), 2018

ABSTRACT: This work address the behavior, performance and failure of thin-walled composite channel section columns with focus on local buckling. The study is carried-out using nonlinear finite element models of perfect and imperfect columns considering material failure, as well as approximate analytical solutions based on the classical lamination theory. The accuracy of the numerical model is assessed using experimental results available in the literature and very good results were obtained. The results show the influence of the column layup and wall thickness on the structural behavior of laminated columns, including the buckling mode and ultimate failure load. Finally, the numerical model is used to assess the accuracy of approximate closed-form expressions for evaluation of the local buckling loads of composite channel section columns.

Nitin Shankarrao Naik and Atteshamuddin Shamshuddin Sayyad (Dept. of Civil Engineering, Kopargaon Savitribai Phule Pune University), “2D analysis of laminated composite and sandwich plates using a new fifth-order plate theory”, Latin American Journal of Solids and Structures, Vol. 15, No. 9, August 2018

ABSTRACT: In the present paper, a new fifth-order shear and normal deformation theory (fosndt) is developed for the bi-directional bending analysis of laminated composite and sandwich plates subjected to transverse loads. This theory considered the effects of both transverse shear and normal deformations. in-plane displacements use a polynomial shape function expanded up to fifth-order in terms of the thickness coordinate to properly account the effect of transverse shear deformation. Transverse displacement is the function of x, y and z-coordinates to account the effect of transverse normal deformations i.e. thickness stretching. Hence, the present theory involves nine unknowns in the displacement field. the present theory does not require a problem dependent shear correction factor as it satisfies traction free boundary conditions at top and bottom surfaces of the plate. The governing differential equations and associated boundary conditions are obtained using the principle of virtual work. The plate is analysed for simply supported boundary conditions using Navier’s solution technique. To prove the efficiency of the present theory, the non-dimensional displacements and stresses obtained for laminated composite and sandwich plates are compared with existing exact elasticity solutions and other theories. It is observed from the comparison that the displacements and stresses obtained by the present theory are in excellent agreement with the results obtained by exact elasticity solutions compared to other higher-order plate theories available in the literature.
Masoud Ajri, Mir Masoud Seyyyed Fakhrabadi and Abbas Rastgoo (University of Tehran), “Analytical solution for nonlinear dynamic behavior of viscoelastic nano-plates modeled by consistent couple stress theory”, Latin American Journal of Solids and Structures, Vol. 15, No. 9, August 2018

ABSTRACT: This paper analyses the non-stationary free vibration and nonlinear dynamics of the viscoelastic nano-plates. For this purpose, a size-dependent theory developed in the framework of the consistent couple stress theory for viscoelastic materials. The modified couple stress theory that was previously presented used some consideration, which makes its use doubtful. This paper used the recent finding for these problem and developed it to analyze the nonlinear dynamics of nano-plates with nonlinear viscoelasticity. The material is supposed to follow the leaderman integral nonlinear constitutive relation. In order to capture the geometrical nonlinearity the von–Karman strain displacement relation is used. The viscous parts of the size-independent and size-dependent stress tensors are calculated in the framework of the leaderman integral and the resultant virtual work are obtained. The governing equations of motion are derived using the Hamilton principle in the form of the nonlinear second order integro-partial differential with coupled terms. These coupled size-dependent viscoelastic equations are solved with using the harmonic balance method after simplifying by the Galerkin technique. The short-time fourier transform is performed to examine the system free vibration. In addition, frequency and force responses of the nanosystem subjected to distribute harmonic load are obtained. The obtained results show that the viscoelastic model vibration is non-stationary unlike elastic model. moreover, the damping mechanism of the viscoelasticity is an amplitude dependent and the contribution of viscoelastic damping terms at higher forcing becomes noticeable.

(No appropriate papers in Vol. 15, No. 11 as of 24 October, 2018)

End of more papers published in the journal, Latin American Journal of Solids and Structures. (2017 and on)

More papers published in the journal, Computational Mechanics. (2017 and on)

Google the string: “Computational Mechanics”, then click on the entry: “Computational Mechanics – Springer – Springer Link”; then click on “Browse Volumes & Issues”


ABSTRACT: In this paper layered composite shells subjected to static loading are considered. The theory is based on a multi-field functional, where the associated Euler–Lagrange equations include besides the global shell equations formulated in stress resultants, the local in-plane equilibrium in terms of stresses and a constraint which enforces the correct shape of warping through the thickness. Within representative volume elements warping displacements are interpolated with layerwise cubic functions in thickness direction and constant shape throughout the reference surface. Elimination of warping and Lagrange parameters by static condensation leads to a material matrix for the stress resultants and to shear correction factors for layered plates and shells. For linear elasticity the computation can be done once in advance. The condensed material matrix is used in displacement based elements along with the enhanced strain method or in mixed hybrid elements with the usual 5 or 6 nodal degrees of freedom. This allows standard geometrical boundary conditions and the elements are applicable also to shell intersection problems. The interlaminar shear stresses are evaluated via the
constitutive law by back substitution of the eliminated parameters. The computed transverse shear stresses are automatically continuous at the layer boundaries and zero at the outer surfaces. Furthermore, the integrals of the shear stresses coincide exactly with the shear forces without introduction of further constraints.

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ABSTRACT: In this paper, two quadratic solid–shell (SHB) elements are proposed for the three-dimensional modeling of thin structures. These consist of a 20-node hexahedral solid–shell element, denoted SHB20, and its 15-node prismatic counterpart, denoted SHB15. The formulation of these elements is extended in this work to include geometric and material nonlinearities, for application to problems involving large displacements and rotations as well as plasticity. For this purpose, the SHB elements are coupled with large-strain anisotropic elasto-plastic constitutive equations for metallic materials. Although based on a purely three-dimensional approach, several modifications are introduced in the formulation of these elements to provide them with interesting shell features. In particular, a special direction is chosen to represent the thickness, along which a user-defined number of integration points are located. Furthermore, for efficiency requirements and for alleviating locking phenomena, an in-plane reduced-integration scheme is adopted. The resulting formulations are implemented into the finite element software ABAQUS/Standard and, to assess their performance, a variety of nonlinear benchmark problems are investigated. Attention is then focused on the simulation of various complex sheet metal forming processes, involving large strain, anisotropic plasticity, and double-sided contact. From all simulation results, it appears that the SHB elements represent an interesting alternative to traditional shell and solid elements, due to their versatility and capability of accurately modeling selective nonlinear benchmark problems as well as complex sheet metal forming processes.

References listed at the end of the paper:

ABSTRACT: This work presents a simple finite element implementation of a geometrically exact and fully nonlinear Kirchhoff–Love shell model. Thus, the kinematics are based on a deformation gradient written in terms of the first- and second-order derivatives of the displacements. The resulting finite element formulation provides \( C^r \)-continuity using a penalty approach, which penalizes the kinking at the edges of neighboring elements. This approach enables the application of well-known \( C^r \)-continuous interpolations for the displacements, which leads to a simple finite element formulation, where the only unknowns are the nodal displacements. On the basis of polyconvex strain energy functions, the numerical framework for the simulation of isotropic and anisotropic thin shells is presented. A consistent plane stress condition is incorporated at the constitutive level of the model. A triangular finite element, with a quadratic interpolation for the displacements and a one-point integration for the enforcement of the \( C^r \)-continuity at the element interfaces leads to a robust shell element. Due to the simple nature of the element, even complex geometries can be meshed easily, which include folded and branched shells. The reliability and flexibility of the element formulation is shown in a couple of numerical examples, including also time dependent boundary value problems. A plane reference configuration is assumed for the shell mid-surface, but initially curved shells can be accomplished if one regards the initial configuration as a stress-free deformed state from the plane position, as done in previous works.

References listed at the end of the paper:


ABSTRACT: This paper focuses on the development and engineering applications of a new resolvent sampling based Rayleigh-Ritz method (RSRR) for solving large-scale nonlinear eigenvalue problems (NEPs) in finite element analysis. There are three contributions. First, to generate reliable eigenspaces the resolvent sampling scheme is derived from Keldysh’s theorem for holomorphic matrix functions following a more concise and insightful algebraic framework. Second, based on the new derivation a two-stage solution strategy is proposed for solving large-scale NEPs, which can greatly enhance the computational cost and accuracy of the RSRR. The effects of the user-defined parameters are studied, which provides a useful guide for real applications. Finally, the RSRR and the two-stage scheme is applied to solve two NEPs in the FE analysis of viscoelastic damping structures with up to 1 million degrees of freedom. The method is versatile, robust and suitable for parallelization, and can be easily implemented into other packages.

References listed at the end of the paper:


ABSTRACT: This paper presents a quadrilateral shell element incorporating thickness–stretch, and demonstrates its performance in small and large deformation analyses for hyperelastic material and elastoplastic models. In terms of geometry, the proposed shell element is based on the formulation of the MITC4 shell element, with additional degrees of freedom to represent thickness–stretch. To consider the change in thickness, we introduce a displacement variation to the MITC4 shell element, in the thickness direction. After the thickness direction is expressed in terms of the director vectors that are defined at each midsurface node, additional nodes are placed along the thickness direction from the bottom surface to the top surface. The thickness–stretch is described by the movement of these additional nodes. The additional degrees of freedom are used to compute the transverse normal strain without assuming the plane stress condition. Hence, the three dimensional constitutive equation can be employed in the proposed formulation without any modification. By virtue of not imposing the plane stress condition, the surface traction is evaluated at the surface where the traction is applied, whereas it is assessed at the midsurface for conventional shell elements. Several numerical examples are presented to examine the fundamental performance of the proposed shell element. In particular, the proposed approach is capable of evaluating the change in thickness and the stress distribution when the effect of the surface traction is included. The behavior of the proposed shell element is compared with that of solid elements.

References listed at the end of the paper:


ABSTRACT: The non-symmetric variant of Nitsche’s method was recently applied successfully for variationally enforcing boundary and interface conditions in non-boundary-fitted discretizations. In contrast to its symmetric variant, it does not require stabilization terms and therefore does not depend on the appropriate estimation of stabilization parameters. In this paper, we further consolidate the non-symmetric Nitsche approach by establishing its application in isogeometric thin shell analysis, where variational coupling techniques are of particular interest for enforcing interface conditions along trimming curves. To this end, we extend its variational formulation within Kirchhoff–Love shell theory, combine it with the finite cell method, and apply the resulting framework to a range of representative shell problems based on trimmed NURBS surfaces. We demonstrate that the non-symmetric variant applied in this context is stable and can lead to the same accuracy in terms of displacements and stresses as its symmetric counterpart. Based on our numerical evidence, the non-
symmetric Nitsche method is a viable parameter-free alternative to the symmetric variant in elastostatic shell analysis.

References listed at the end of the paper:

By using Chebyshev polynomials as trial functions and Dirac-Delta functions as the test functions over the approximation spaces for elliptic problems, SIAM J Numer Anal 39(3):902–931.


ABSTRACT: A new class of time-integrators is presented for strongly nonlinear dynamical systems. These algorithms are far superior to the currently common time integrators in computational efficiency and accuracy. These three algorithms are based on a local variational iteration method applied over a finite interval of time. By using Chebyshev polynomials as trial functions and Dirac–Delta functions as the test functions over the
finite time interval, the three algorithms are developed into three different discrete time-integrators through the collocation method. These time integrators are labeled as Chebyshev local iterative collocation methods. Through examples of the forced Duffing oscillator, the Lorenz system, and the multiple coupled Duffing equations (which arise as semi-discrete equations for beams, plates and shells undergoing large deformations), it is shown that the new algorithms are far superior to the 4th order Runge–Kutta and ODE45 of MATLAB, in predicting the chaotic responses of strongly nonlinear dynamical systems.

References listed at the end of the paper:


ABSTRACT: The paper is concerned with eigen buckling analysis of curvilinear shells with and without cutouts by an effective meshfree method. In particular, shallow shell, cylinder and perforated cylinder buckling problems are considered. A Galerkin meshfree reproducing kernel (RK) approach is then developed.
present meshfree curvilinear shell model is based on Reissner-Mindlin plate formulation, which allows the transverse shear deformation of the curved shells. There are five degrees of freedom per node (i.e., three displacements and two rotations). In this setting, the meshfree interpolation functions are derived from the RK. A singular kernel is introduced to impose the essential boundary conditions because of the RK shape functions, which do not automatically possess the Kronecker delta property. The stiffness matrix is derived using the stabilized conforming nodal integration technique. A convected coordinate system is introduced into the formulation to deal with the curvilinear surface. More importantly, the RKs taken here are used not only for the interpolation of the curved geometry, but also for the approximation of field variables. Several numerical examples with shallow shells and full cylinder models are considered, and the critical buckling loads and their buckling mode shapes are calculated by the meshfree eigenvalue analysis and examined. To show the accuracy and performance of the developed meshfree method, the computed critical buckling loads and mode shapes are compared with reference solutions based on boundary domain element, finite element and analytical methods. References listed at the end of the paper:

Yangjun Luo, Yanzhuang Niu, Ming Li and Zhan Kang, “A multi-material topology optimization approach for wrinkle-free design of cable-suspended membrane structures”, Computational Mechanics, Vol. 59, No. 6, pp 967-980, June 2017

ABSTRACT: In order to eliminate stress-related wrinkles in cable-suspended membrane structures and to provide simple and reliable deployment, this study presents a multi-material topology optimization model and an effective solution procedure for generating optimal connected layouts for membranes and cables. On the basis of the principal stress criterion of membrane wrinkling behavior and the density-based interpolation of multi-phase materials, the optimization objective is to maximize the total structural stiffness while satisfying principal stress constraints and specified material volume requirements. By adopting the cosine-type relaxation scheme to avoid the stress singularity phenomenon, the optimization model is successfully solved through a standard gradient-based algorithm. Four-corner tensioned membrane structures with different loading cases were investigated to demonstrate the effectiveness of the proposed method in automatically finding the optimal design composed of curved boundary cables and wrinkle-free membranes.
References listed at the end of the paper:


This paper discusses the use of higher-order mapping functions for enhancing the physical representation of refined beam theories. Based on the Carrera unified formulation (CUF), advanced one-dimensional models are formulated by expressing the displacement field as a generic expansion of the generalized unknowns. According to CUF, a novel physically/geometrically consistent model is devised by employing Legendre-like polynomial sets to approximate the generalized unknowns at the cross-sectional level, whereas a local mapping technique based on the blending functions method is used to describe the exact physical boundaries of the cross-section domain. Classical and innovative finite element methods, including hierarchical p-elements and locking-free integration schemes, are utilized to solve the governing equations of the unified beam theory. Several numerical applications accounting for small displacements/rotations and strains are discussed, including beam structures with cross-sectional curved edges, cylindrical shells, and thin-walled aeronautical wing structures with reinforcements. The results from the proposed methodology are widely assessed by comparisons with solutions from the literature and commercial finite element software tools. The attention is focussed on the high computational efficiency and the marked capabilities of the present beam model, which can deal with a broad spectrum of structural problems with unveiled accuracy in terms of geometrical representation of the domain boundaries.

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ABSTRACT: This paper is concerned with a three-dimensional time harmonic model of open shell structures buried in poroelastic soils. It combines the dual boundary element method (DBEM) for treating the soil and shell finite elements for modelling the structure, leading to a simple and efficient representation of buried open shell structures. A new fully regularised hypersingular boundary integral equation (HBIE) has been developed to this aim, which is then used to build the pair of dual BIEs necessary to formulate the DBEM for Biot poroelasticity. The new regularised HBIE is validated against a problem with analytical solution. The model is used in a wave diffraction problem in order to show its effectiveness. It offers excellent agreement for length to thickness ratios greater than 10, and relatively coarse meshes. The model is also applied to the calculation of impedances of bucket foundations. It is found that all impedances except the torsional one depend considerably on hydraulic conductivity within the typical frequency range of interest of offshore wind turbines.

References listed at the end of the paper:


ABSTRACT: The paper is devoted to non-linear vibrations of plates, made of the Zener viscoelastic material modelled with the Caputo fractional derivative, and in particular to their response to harmonic excitation. The plate geometric non-linearity is of the von Kármán type. In the formulation shear effects and rotary inertia are considered, too. The problem is solved in the frequency domain. A one-harmonic form of the solution for plate displacements corresponding to the plate formulation is assumed. The amplitude equation is obtained from the time averaged principle of virtual work. The time averaging precedes the use of the harmonic balance method. In the space discretization the finite element method is used involving 8-noded rectangular plate elements with selective-reduced integration. Several numerical examples are analyzed and the response curves are found using a path-following method. The purpose of these analyses is to identify material features of the adopted model of viscoelasticity with the fractional derivative.

References listed at the end of the paper:


ABSTRACT: In this work we investigate different mixed finite element formulations for the detection of critical loads for the possible occurrence of bifurcation and limit points. In detail, three- and two-field formulations for incompressible and quasi-incompressible materials are analyzed. In order to apply various penalty functions for the volume dilatation in displacement/pressure mixed elements we propose a new consistent scheme capturing the non-linearities of the penalty constraints. It is shown that for all mixed formulations, which can be reduced to a generalized displacement scheme, a straightforward stability analysis is possible. However, problems based on the classical saddle-point structure require a different analyses based on the change of the signature of the underlying matrix system. The basis of these investigations is the work from Auricchio et al. (Comput Methods Appl Mech Eng 194:1075–1092, 2005, Comput Mech 52:1153–1167, 2013).

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Joon Hee Jung, Gang-Won Jang, Dongil Shin and Yoon Young Kim, “One-dimensional analysis of thin-walled beams with diaphragms and its application to optimization for stiffness reinforcement”, Computational Mechanics, Vol. 61, No. 3, pp 331-349, March 2018

ABSTRACT: This paper presents a method to analyze thin-walled beams with quadrilateral cross sections reinforced with diaphragms using a one-dimensional higher-order beam theory. The effect of a diaphragm is reflected focusing on the increase of static stiffness. The deformations on the beam-interfacing boundary of a thin diaphragm are described by using deformation modes of the beam cross section while the deformations inside the diaphragm are approximated in the form of complete cubic polynomials. By using the principle of minimum potential energy, its stiffness that significantly affects distortional deformation of a thin-walled beam can be considered in the one-dimensional beam analysis. It is shown that the accuracy of the resulting one-dimensional analysis is comparable with that by a shell element based analysis. As a means to demonstrate the usefulness of the present approach for design, position optimization problems of diaphragms for stiffness reinforcement of an automotive side frame are solved.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: In this paper, the complex variable reproducing kernel particle method (CVRKPM) for solving the bending problems of isotropic thin plates on elastic foundations is presented. In CVRKPM, one-dimensional basis function is used to obtain the shape function of a two-dimensional problem. CVRKPM is used to form the approximation function of the deflection of the thin plates resting on elastic foundation, the Galerkin weak form of thin plates on elastic foundation is employed to obtain the discretized system equations, the penalty method is used to apply the essential boundary conditions, and Winkler and Pasternak foundation models are used to consider the interface pressure between the plate and the foundation. Then the corresponding formulae of CVRKPM for thin plates on elastic foundations are presented in detail. Several numerical examples are given to discuss the efficiency and accuracy of CVRKPM in this paper, and the corresponding advantages of the present method are shown.

References listed at the end of the paper:

ABSTRACT: A meshfree approach to the simulation of the large deformation of a curved shell by the reproducing kernel particle method (RKPM) is presented. Since the kinematic description is based on the Mindlin–Reissner shell theory, only one layer of particles is needed to model the shell and the time increment is not limited by the shell thickness. The reproducing interpolation function is adopted to discretize the kinematic quantities of the shell; thus, the spatial discretization is independent of the finite element mesh, so it can address large deformations without mesh distortion. The governing equation of an arbitrary curved shell is derived in detail based on the principle of virtual power, for which reasonable simplifications have been taken. The Lagrangian kernel and stress points are adopted in the calculation, which are sufficient to eliminate instability. Several numerical examples are performed, verifying the reliability and numerical accuracy of the RKPM shell model. No locking is observed in the numerical solutions.

References listed at the end of the paper:
The 9-node quadrilateral shell element MITC9i is developed for the Reissner-Mindlin shell kinematics, the extended potential energy and Green strain. The following features of its formulation ensure an improved behavior: 1. The MITC technique is used to avoid locking, and we propose improved transformations for bending and transverse shear strains, which render that all patch tests are passed for the regular mesh, i.e. with straight element sides and middle positions of midside nodes and a central node. 2. To reduce shape distortion effects, the so-called corrected shape functions of Celia and Gray (Int J Numer Meth Eng 20:1447–1459, 1984) are extended to shells and used instead of the standard ones. In effect, all patch tests are passed.


ABSTRACT: The 9-node quadrilateral shell element MITC9i is developed for the Reissner-Mindlin shell kinematics, the extended potential energy and Green strain. The following features of its formulation ensure an improved behavior: 1. The MITC technique is used to avoid locking, and we propose improved transformations for bending and transverse shear strains, which render that all patch tests are passed for the regular mesh, i.e. with straight element sides and middle positions of midside nodes and a central node. 2. To reduce shape distortion effects, the so-called corrected shape functions of Celia and Gray (Int J Numer Meth Eng 20:1447–1459, 1984) are extended to shells and used instead of the standard ones. In effect, all patch tests are passed.
additionally for shifts of the midside nodes along straight element sides and for arbitrary shifts of the central node. 3. Several extensions of the corrected shape functions are proposed to enable computations of non-flat shells. In particular, a criterion is put forward to determine the shift parameters associated with the central node for non-flat elements. Additionally, the method is presented to construct a parabolic side for a shifted midside node, which improves accuracy for symmetric curved edges. Drilling rotations are included by using the drilling Rotation Constraint equation, in a way consistent with the additive/multiplicative rotation update scheme for large rotations. We show that the corrected shape functions reduce the sensitivity of the solution to the regularization parameter $\gamma$ of the penalty method for this constraint. The MITC9i shell element is subjected to a range of linear and non-linear tests to show passing the patch tests, the absence of locking, very good accuracy and insensitivity to node shifts. It favorably compares to several other tested 9-node elements.

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Y. Bazilevs, M.S. Pigazzini, A. Ellison and H. Kim (Department of Structural Engineering, University of California, San Diego, La Jolla USA), “A new multi-layer approach for progressive damage simulation in composite laminates based on isogeometric analysis and Kirchhoff-Love shells. Part I: basic theory and

ABSTRACT: In this two-part paper we introduce a new formulation for modeling progressive damage in laminated composite structures. We adopt a multi-layer modeling approach, based on Isogeometric Analysis (IGA), where each ply or lamina is represented by a spline surface, and modeled as a Kirchhoff–Love thin shell. Continuum Damage Mechanics is used to model intralaminar damage, and a new zero-thickness cohesive-interface formulation is introduced to model delamination as well as permitting laminate-level transverse shear compliance. In Part I of this series we focus on the presentation of the modeling framework, validation of the framework using standard Mode I and Mode II delamination tests, and assessment of its suitability for modeling thick laminates. In Part II of this series we focus on the application of the proposed framework to modeling and simulation of damage in composite laminates resulting from impact. The proposed approach has significant accuracy and efficiency advantages over existing methods for modeling impact damage. These stem from the use of IGA-based Kirchhoff–Love shells to represent the individual plies of the composite laminate, while the compliant cohesive interfaces enable transverse shear deformation of the laminate. Kirchhoff–Love shells give a faithful representation of the ply deformation behavior, and, unlike solids or traditional shear-deformable shells, do not suffer from transverse-shear locking in the limit of vanishing thickness. This, in combination with higher-order accurate and smooth representation of the shell midsurface displacement field, allows us to adopt relatively coarse in-plane discretizations without sacrificing solution accuracy. Furthermore, the thin-shell formulation employed does not use rotational degrees of freedom, which gives additional efficiency benefits relative to more standard shell formulations.

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ABSTRACT: In this two-part paper we introduce a new formulation for modeling progressive damage in laminated composite structures. We adopt a multi-layer modeling approach, based on isogeometric analysis, where each ply or lamina is represented by a spline surface, and modeled as a Kirchhoff–Love thin shell. Continuum damage mechanics is used to model intralaminar damage, and a new zero-thickness cohesive-interface formulation is introduced to model delamination as well as permitting laminate-level transverse shear compliance. In Part I of this series we focus on the presentation of the modeling framework, validation of the framework using standard Mode I and Mode II delamination tests, and assessment of its suitability for modeling thick laminates. In Part II of this series we focus on the application of the proposed framework to modeling and simulation of damage in composite laminates resulting from impact. The proposed approach has significant accuracy and efficiency advantages over existing methods for modeling impact damage. These stem from the use of IGA-based Kirchhoff–Love shells to represent the individual plies of the composite laminate, while the compliant cohesive interfaces enable transverse shear deformation of the laminate. Kirchhoff–Love shells give a faithful representation of the ply deformation behavior, and, unlike solids or traditional shear-deformable shells, do not suffer from transverse-shear locking in the limit of vanishing thickness. This, in combination with higher-order accurate and smooth representation of the shell midsurface displacement field, allows us to adopt relatively coarse in-plane discretizations without sacrificing solution accuracy. Furthermore, the thin-shell formulation employed does not use rotational degrees of freedom, which gives additional efficiency benefits relative to more standard shell formulations.

References listed at the end of the paper:


ABSTRACT: Architectured materials (or metamaterials) are constituted by a unit-cell with a complex structural design repeated periodically forming a bulk material with emergent mechanical properties. One may obtain specific macro-scale (or bulk) properties in the resulting architectured material by properly designing the unit-cell. Typically, this is stated as an optimal design problem in which the parameters describing the shape and mechanical properties of the unit-cell are selected in order to produce the desired bulk characteristics. This is especially pertinent due to the ease manufacturing of these complex structures with 3D printers. The proper generalized decomposition provides explicit parametric solutions of parametric PDEs. Here, the same ideas are used to obtain parametric solutions of the algebraic equations arising from lattice structural models. Once the explicit parametric solution is available, the optimal design problem is a simple post-process. The same strategy is applied in the numerical illustrations, first to a unit-cell (and then homogenized with periodicity conditions), and in a second phase to the complete structure of a lattice material specimen.

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End of more papers published in the journal, Computational Mechanics. (2017 and on)

More papers published in the journal, Structural Engineering and Mechanics. (2017 and on)
Google the string, “Structural Engineering and Mechanics”, then click on the entry, “Structural Engineering and Mechanics” / Korea Science and see “Volume & Issues” on your screen
Tahar Hassaine and Belkacem Adim, “Mechanical behaviour of FGM sandwich plates using a quasi-3D higher order shear and normal deformation theory”, Structural Engineering and Mechanics, volume 61, issue 1, 2017, Pages 49–63
DOI : 10.12989/sem.2017.61.1.049

ABSTRACT: This paper presents an original hyperbolic (first present model) and parabolic (second present model) shear and normal deformation theory for the bending analysis to account for the effect of thickness stretching in functionally graded sandwich plates. Indeed, the number of unknown functions involved in these presents theories is only five, as opposed to six or even greater numbers in the case of other shear and normal deformation theories. The present theory accounts for both shear deformation and thickness stretching effects by a hyperbolic variation of all displacements across the thickness and satisfies the stress-free boundary conditions on the upper and lower surfaces of the plate without requiring any shear correction factor. It is evident from the present analyses; the thickness stretching effect is more pronounced for thick plates and it needs to be taken into consideration in more physically realistic simulations. The numerical results are compared with 3D exact solution, quasi-3D dimensional solutions and with other higher-order shear deformation theories, and the superiority of the present theory can be noticed.

References listed at the end of the paper:


ABSTRACT: The aim of this study is to develop a semi-analytical method to investigate fluid-structure coupling of concentric double shells with different lengths and elastic behaviours. Co-axial shells constitute a cylindrical circular container and a baffle submerged inside the stored fluid. The container shell is made of functionally graded materials with mechanical properties changing through its thickness continuously. The baffle made of steel is fixed along its top edge and submerged inside fluid such that its lower edge freely moves. The developed approach is verified using a commercial finite element computer code. Although the model is presented for a specific case in the present work, it can be generalized to investigate coupling of shell-plate structures via fluid. It is shown that the coupling between concentric shells occurs only when they vibrate in a same circumferential mode number, n. It is also revealed that the normalized vibration amplitude of the inner shell is about the same as that of the outer shell, for narrower radial gaps. Moreover, the natural frequencies of the fluid-coupled system gradually decrease and converge to the certain values as the gradient index increases.

References listed at the end of the paper:


ABSTRACT: In this study, self-supporting roofing elements especially convenient for large-span structures such as stadium, airport terminal, mall, coliseum, etc. were examined with respect to critical buckling load. These elements were assumed as laminated composite plates and, variation of free-edge forms, cutout types and lamination configurations were used as design parameters. Based on the architectural feature and structural requirements, the effects of curvilinear free-edge form on critical buckling load were focused on in this research. Within this scope, 14 types of lamination configuration were specified according to various orientation angle, number and thickness of plies with a constant value of total plate thickness. Besides that, 6 different types of cutout and 3 different free-edge forms were determined. By combining all these parameters 294 different critical buckling load analyses were performed by using ANSYS Mechanical software based on finite element method. Effects of those parameters on critical buckling load were evaluated referring to the obtained results. According to the results presented here, it may be concluded that lamination conditions have more significant influence on the critical buckling load values than the other parameters. On the other hand, it is perceived that curvilinear free-edge forms explicitly undergo changings depending on lamination conditions. For future work, existence of delamination might be considered and progression of the defect could be investigated by using non-linear analysis.

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ABSTRACT: The use of fiber reinforced polymer (FRP) for torsional strengthening of reinforced concrete (RC) single cell box beams has been analyzed considerably by researchers worldwide. However, little attention has been paid to torsional strengthening of multicell box girders in terms of both experimental and numerical research. This paper reports the experimental work in an overall investigation for torsional strengthening of multicell box girders with externally-bonded Carbon Fiber Reinforced Polymer CFRP strips. Numerical work was carried out using non-linear finite element modeling (FEM). Good agreement in terms of torque-twist behavior, steel and CFRP reinforcement responses, and crack patterns was achieved. The unique failure modes of all the specimens were modeled correctly as well.

References listed at the end of the paper:
ABSTRACT: This paper is a continuation of the investigations started in the paper by Akbarov, S.D., Guliyev, H.H and Yahnioglu, N. (2016), "Natural vibration of the three-layered solid sphere with middle layer made of FGM: three-dimensional approach", Structural Engineering and Mechanics, 57(2), 239-263, to the case where the three-layered sphere is a hollow one. Three-dimensional exact field equations of elastodynamics are employed for investigation and the discrete-analytical method is employed for solution of the corresponding eigenvalue problem. The FGM is modelled as inhomogeneous for which the modulus of elasticity, Poisson’s ratio and density vary continuously through the inward radial direction according to power law distribution. Numerical results on the natural frequencies are presented and discussed. These results are also compared with the corresponding ones obtained in the previous paper by the authors. In particular, it is established that for certain harmonics and for roots of certain order, the values of the natural frequency obtained for the hollow sphere can be greater (or less) than those obtained for the solid sphere.

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Farzad Ebrahimi and Mohammad Reza Barati, “Vibration analysis of embedded size dependent FG nanobeams based on third-order shear deformation beam theory”, Structural Engineering and Mechanics, VOL. 61, No. 6, pp 721-736, 2017
ABSTRACT: In this paper, free vibration characteristics of functionally graded (FG) nanobeams embedded on elastic medium are investigated based on third order shear deformation (Reddy) beam theory by presenting a Navier type solution for the first time. The material properties of FG nanobeam are assumed to vary gradually along the thickness and are estimated through the power-law and Mori-Tanaka models. A two parameters elastic foundation including the linear Winkler springs along with the Pasternak shear layer is in contact with beam. The small scale effect is taken into consideration based on nonlocal elasticity theory of Eringen. The nonlocal equations of motion are derived based on third order shear deformation beam theory through Hamilton’s principle and they are solved applying analytical solution. According to the numerical results, it is revealed that the proposed modeling can provide accurate frequency results of the FG nanobeams as compared to some cases in the literature. The obtained results are presented for the vibration analysis of the FG nanobeams such as the influences of foundation parameters, gradient index, nonlocal parameter and slenderness ratio in detail.

References listed at the end of the paper:


ABSTRACT: The bi-material elastic system consisting of the circular hollow cylinder and the infinite elastic medium surrounding this cylinder is considered and it is assumed that on the inner free face of the cylinder a point-located axisymmetric time harmonic force, with respect to the cylinder’s axis and which is uniformly distributed in the circumferential direction, acts. The shear-spring type imperfect contact conditions on the interface between the constituents are satisfied. The mathematical formulation of the problem is made within the scope of the exact equations of linear elastodynamics. The focus is on the frequency-response of the interface normal and shear stresses and the influence of the problem parameters, such as the ratio of modulus of elasticity, the ratio of the cylinder thickness to the cylinder radius, and the shear-spring type parameter which characterizes the degree of the contact imperfectionness, on these responses. Corresponding numerical results are presented and discussed. In particular, it is established that the character of the influence of the contact imperfection on the frequency response of the interface stresses depends on the values of the vibration frequency of the external forces.

References listed at the end of the paper:

ABSTRACT: Nonlinear vibrations of an Euler-Bernoulli beam resting on a nonlinear elastic foundation are discussed. In search of approximate analytical solutions, the classical multiple scales (MS) and the multiple scales Lindstedt Poincare (MSLP) methods are used. The case of primary resonance is investigated. Amplitude and phase modulation equations are obtained. Steady state solutions are considered. Frequency response curves obtained by both methods are contrasted with each other with respect to the effect of various physical parameters. For weakly nonlinear systems, MS and MSLP solutions are in good agreement. For strong hardening nonlinearities, MSLP solutions exhibit the usual jump phenomena whereas MS solutions are not reliable producing backward curves which are unphysical.

References listed at the end of the paper:


ABSTRACT: In this paper a new eight-unknown higher order shear deformation theory is proposed for functionally graded (FG) material plates. The theory based on full twelve-unknown higher order shear deformation theory, simultaneously satisfy zeros transverse stresses at top and bottom surface of FG plates. Equations of motion are derived from principle of virtual displacement. Exact closed-form solutions are obtained for simply supported rectangular FG plates under uniform loading. The accuracy of present numerical results has been verified by comparing it with generalized shear deformation theory. The effect of power law index of functionally graded material, side-to-thickness ratio, and aspect ratio on static behavior of FG plates is investigated.

References listed at the end of the paper:

ABSTRACT: The aim of the present study is to develop an elemental approach based on the differential quadrature method for free vibration analysis of cracked thin plate structures. For this purpose, the equations of motion are established using the classical plate theory. The well-known Generalized Differential Quadrature Method (GDQM) is utilized to discretize the governing equations on each computational subdomain or element. In this method, the differential terms of a quantity field at a specific computational point should be expressed in a series form of the related quantity at all other sampling points along the domain. However, the existence of any geometric discontinuity, such as a crack, in a computational domain causes some problems in the calculation of differential terms. In order to resolve this problem, the multi-block or elemental strategy is implemented to divide such geometry into several subdomains. By constructing the appropriate continuity conditions at each interface between adjacent elements and a crack tip, the whole discretized governing equations of the structure can be established. Therefore, the free vibration analysis of a cracked thin plate will be provided via the achieved eigenvalue problem. The obtained results show a good agreement in comparison with those found by finite element method

References listed at the end of the paper:

ABSTRACT: A new higher shear deformation theory (HSDT) is presented for the thermal buckling behavior of functionally graded (FG) sandwich plates. It uses only four unknowns, which is even less than the first shear deformation theory (FSDT) and the conventional HSDTs. The theory considers a hyperbolic variation of transverse shear stress, respects the traction free boundary conditions and contrary to the conventional HSDTs, the present one presents a new displacement field which includes undetermined integral terms. Material characteristics and thermal expansion coefficient of the sandwich plate faces are considered to be graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. The thermal loads are supposed as uniform, linear and non-linear temperature rises within the thickness direction. An energy based variational principle is used to derive the governing equations as an eigenvalue problem. The validation of the present work is carried out with the available results in the literature. Numerical results are presented to demonstrate the influences of variations of volume fraction index, length-thickness ratio, loading type and functionally graded layers thickness on nondimensional thermal buckling loads.

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ABSTRACT: Ultra high performance concrete (UHPC) has aroused interest around the world owing to superior mechanical and durability properties over conventional concrete. However, the application of UHPC in practice poses difficulties due to its inherent brittleness. UHPC filled in steel tube columns (UHPC-FSTCs) are capable of restricting the brittle failure of non-reinforced UHPC columns and forming a high performance member with enhancement of strength and ductility. Currently, research on UHPC-FSTCs remains very limited and there is relatively little information about the mechanical behavior of these columns. Therefore, this study presents a review of past experimental studies to have a deeper insight into the compressive behavior of UHPC-FSTCs under axial loading on entire section and on concrete core. Based on the test results obtained from Schneider.
(2006) and Xiong (2012), an analysis was conducted to investigate the influence of the confinement index ($\xi$) and diameter to steel tube thickness ratio (D/t) on the strength and the ductility in short circular UHPC-FSTCs. Furthermore, the appropriateness of current design codes including EC4, AISC, AIJ and previous analytical models for estimating the ultimate loads of composite columns was also examined by the comparison between the predictions and the test results. Finally, simplified formulae for predicting the ultimate loads in two types of loading pattern were proposed and verified.

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ABSTRACT: Rayleigh damping model is recommended in the recently developed Performance-Based Earthquake Engineering (PBEE) methodology, but this methodology does not provide sufficient information due to the complexity of the damping mechanism. Furthermore, each Rayleigh-type damping model may have...
its individual limitations. In this study, Rayleigh-type damping models that are used widely in engineering practice are discussed. The seismic performance of a large-span single-layer latticed dome subjected to earthquake ground motions is investigated using different Rayleigh damping models. Herein a simulation technique is developed considering low cycle fatigue (LCF) in steel material. In the simulation technique, Ramberg-Osgood steel material model with the low cycle fatigue effect is used to simulate the non-uniformly distributed material damping and low cycle fatigue damage in the structure. Subsequently, the damping forces of the structure generated by different damping models are compared and discussed; the effects of the damping ratio and roof load on the damping forces are evaluated. Finally, the low cycle fatigue damage values in sections of members are given using these damping models. Through a comparative analysis, an appropriate Rayleigh-type damping model used for a large span single-layer latticed dome subjected to earthquake ground motions is determined in terms of the existing damping models.

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3. ASCE/SEI 8-02 (2003), Specification for the design of coldformed stainless steel structural members, American Society of Civil Engineers; New York, NY, USA.
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24. PEER/ATC (2010), Modeling and acceptance criteria for seismic design and analysis of tall buildings, PEER/ATC 72-1 Report; Redwood City, USA.
ABSTRACT: Based on the strain gradient theory (SGT), vibration analysis of an embedded micro cylindrical shell reinforced with agglomerated carbon nanotubes (CNTs) is investigated. The elastic medium is simulated by the orthotropic Pasternak foundation. The structure is subjected to magnetic field in the axial direction. For obtaining the equivalent material properties of structure and considering agglomeration effects, the Mori-Tanaka model is applied. The motion equations are derived on the basis of Mindlin cylindrical shell theory, energy method and Hamilton’s principal. Differential quadrature method (DQM) is proposed to evaluate the frequency of system for different boundary conditions. The effects of different parameters such as CNTs volume percent, agglomeration of CNTs, elastic medium, magnetic field, boundary conditions, length to radius ratio and small scale parameter are shown on the frequency of the structure. The results indicate that the effect of CNTs agglomeration plays an important role in the frequency of system so that considering agglomeration leads to lower frequency. Furthermore, the frequency of structure increases with enhancing the small scale parameter.

References listed at the end of the paper:


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ABSTRACT: To study the mechanical performances of prestressed steel-concrete composite box beam under combination of bending-shear-torsion, nine composite beams with different ratio of torsion to bending were designed. Torsion was applied to the free end of the beam with jacks controlled accurately with peripherals, as well as concentrated force on the mid-span with jacks. Based on experimental data and relative theories, mechanical properties of composite beams were analyzed, including torsional angle, deformation and failure patterns. The results showed that under certain ratio of torsion to bending, cracking and ultimate torsion increased and reached to its maximum at the ratio of 2. Three phases of process is also discussed, as well as the conditions of each failure mode.

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ABSTRACT: In this work, a nonlocal zeroth order shear deformation theory for nonlinear postbuckling of nanobeams is developed. The beauty of this formulation is that, in addition to including the nonlocal effect according to the nonlocal elasticity theory of Eringen, the shear deformation effect is considered in the axial displacement within the use of shear forces instead of rotational displacement like in existing shear deformation theories. The principle of virtual work together of the nonlocal differential constitutive relations of Eringen, are considered to obtain the equations of equilibrium. Closed-form solutions for the critical buckling load and the amplitude of the static nonlinear response in the postbuckling state for simply supported and clamped clamped nanoscale beams are determined.

References listed at the end of the paper:


ABSTRACT: The effect of central axial load on natural frequencies of various thin-walled beams, are investigated by some researchers using different methods such as finite element, transfer matrix and dynamic stiffness matrix methods. However, there are situations that the load will be off centre. This type of loading is called eccentric load. The effect of the eccentricity of axial load on the natural frequencies of asymmetric thin-walled beams is a subject that has not been investigated so far. In this paper, the mentioned effect is studied using exact dynamic stiffness matrix method. Flexure and torsion of the aforesaid thin-walled beam is based on the Bernoulli-Euler and Vlasov theories, respectively. Therefore, the intended thin-walled beam has flexural rigidity, saint-venant torsional rigidity and warping rigidity. In this paper, the Hamilton′s principle is used for deriving governing partial differential equations of motion and force boundary conditions. Throughout the process, the uniform distribution of mass in the member is accounted for exactly and thus necessitates the solution of a transcendental eigenvalue problem. This is accomplished using the Wittrick-Williams algorithm. Finally, in order to verify the accuracy of the presented theory, the numerical solutions are given and compared with the results that are available in the literature and finite element solutions using ABAQUS software.

References listed at the end of the paper:

References listed at the end of the paper:

ABSTRACT: This research investigated the vibration frequency of sandwich plate made of piezoelectric fiber reinforced composite core (PFRC) and face sheets of piezomagnetic materials. The effective electroelastic constants for PFRC materials are obtained by the micromechanical approach. The resting medium of sandwich plate is modeled by Pasternak foundation including normal and shear modulus. Besides, sandwich plate is...
subjected to linearly varying normal stresses that change by load factor. The coupled equations of motion are derived using first order shear deformation theory (FSDT) and energy method. These equations are solved by differential quadrature method (DQM) for simply supported boundary condition. A detailed numerical study is carried out based on piezoelectricity theory to indicate the significant effect of load factor, volume fraction of fibers, modulus of elastic foundation, core-to-face sheet thickness ratio and composite materials on dimensionless frequency of sandwich plate. These findings can be used to aerospace, building and automotive industries.

References listed at the end of the paper:
ABSTRACT: Static and dynamic instability of a viscoelastic carbon nanotube (CNT) embedded on a thermo-elastic foundation are studied, in this research. The CNT is modeled based on Euler-Bernoulli beam (EBB) and nonlocal small scale elasticity theory is utilized to analyze the structure. Governing equations of the system are derived using Hamilton’s principle and differential quadrature (DQ) method is applied to solve the partial differential equations. The effects of variable axial load and diverse boundary conditions on static/vibration instability are studied. To verify the result of the DQ method, the Galerkin weighted residual approach is used for the instability analysis. It is observed appropriate agreement for results of two different solution methods


ABSTRACT: Free vibration analysis of plates is necessary for the field of structural engineering because of its wide applications in practical life. Free vibration of plates is largely dependent on its thickness, aspect ratios, and boundary conditions. Here we investigate the natural frequencies of simply supported tapered isotropic rectangular plates with internal cutouts using a nine node isoparametric element. The effect of rotary inertia on Eigenfrequencies was demonstrated by calculating with- and without rotary inertia. We found that rotary inertia has a significant effect on thick plates, while rotary inertia term can be ignored in thin plates. Based on comparison with literature data, we propose that the present formulation is capable of yielding highly accurate results. Internal cutouts at various positions in tapered rectangular simply supported plates were also studied. Novel data are also reported for skew taper plates.


ABSTRACT: Static and dynamic instability of a viscoelastic carbon nanotube (CNT) embedded on a thermo-elastic foundation are investigated, in this research. The CNT is modeled based on Euler-Bernoulli beam (EBB) and nonlocal small scale elasticity theory is utilized to analyze the structure. Governing equations of the system are derived using Hamilton’s principle and differential quadrature (DQ) method is applied to solve the partial differential equations. The effects of variable axial load and diverse boundary conditions on static/vibration instability are studied. To verify the result of the DQ method, the Galerkin weighted residual approach is used for the instability analysis. It is observed appropriate agreement for results of two different solution methods.
and satisfactory accuracy with those obtained in prior studies. The results of this work could be useful for engineers and designers in order to produce and design nano/micro structures in thermo-elastic medium.

References listed at the end of the paper:

ABSTRACT: In this paper a vibration study on orthotropic elliptic paraboloid shells with openings is carried out by using a hybrid stress finite element. The formulation of the element is based on Hellinger-Reissner variational principle. The element is developed by combining a hybrid plane stress element and a hybrid plate element. Natural frequencies of orthotropic elliptic paraboloid shells with and without openings are presented. The influence of aspect ratio, height ratio, opening ratio and material angle on the frequencies and mode shapes are investigated.

References listed at the end of the paper:

ABSTRACT: One major concern that has occupied the mind of the designers is a structural failure as result of stress concentration in the geometrical discontinuities. Understanding the effective parameters contribute to stress concentration and proper selection of these parameters enables the designer get to a reliable design. In the analysis of perforated isotropic and orthotropic plates, the effective parameters on stress distribution around holes include load angle, curvature radius of the corner of the hole, hole orientation and fiber angle for orthotropic materials. This present paper tries to examine the possible effects of these parameters on stress analysis of infinite perforated plates with central quasi-square hole applying grey wolf optimizer (GWO) inspired by the particular leadership hierarchy and hunting behavior of grey wolves in nature, and also the present study tries to introduce general optimum parameters in order to achieve the minimum amount of stress concentration around this type of hole on isotropic and orthotropic plates. The advantages of grey wolf optimizer are stout, flexible, simple, and easy to be enforced. The used analytical solution is the expansion of Lekhnitskii’s solution method. Lekhnitskii applied this method for the stress analysis of anisotropic plates containing circular and elliptical holes. Finite element numerical solution is employed to examine the results of present analytical solution. Results represent that by selecting the aforementioned parameters properly, fewer amounts of stress could be achieved around the hole leading to an increase in load-bearing capacity of the structure.


ABSTRACT: Ultra high performance concrete (UHPC) has recently been applied as an alternative to conventional concrete in construction due to its extremely high compressive and tensile strength, and enhanced durability. However, up to date, there has been insufficient information regarding the confinement behavior of UHPC columns. Therefore, this study aims to perform an assessment of axial stress-strain model for UHPC confined by circular steel tube stub columns. The equations for calculating the confined peak stress and its corresponding strain of confined concrete in existing models suggested by Johansson (2002), Sakino et al. (2004), Han et al. (2005), Hatzigeorgiou (2008) were modified based on the regression analysis of test results in Schneider (2006) in order to increase the prediction accuracy for the case of confined UHPC. Furthermore, a new axial stress-strain model for confined UHPC was developed. To examine the suitability of the modified models and the proposed model for confined UHPC, axial stress-strain curves derived from the proposed models were compared with those obtained from previous test results. After validating the proposed model, an extensive parametric study was undertaken to investigate the effects of diameter-to-thickness ratio, steel yield
strength and concrete compressive strength on the complete axial stress-strain curves, the strength and strain enhancement of UHPC confined by circular steel tube stub columns.

ABSTRACT: This paper presents an experimental study on the behavior of axially-loaded steel RHS (rectangular hollow section) compression members that are partially reinforced along their lengths with welded steel plates. 28 slender column tests were carried out to investigate the effects of the slenderness ratio of the unreinforced member and the ratio of the reinforced length of the member to its entire length. In addition to the slender column tests, 14 stub-column tests were conducted to determine the basic mechanical properties of the test specimens under uniform compression. Test results show that both the compressive strength and stiffness of an RHS member can be increased significantly compared to its unreinforced counterpart even when only the central quarter of the member is reinforced. Based on the limited test data, it can be concluded that partial reinforcement is, in general, more effective in members with larger slenderness ratios. A simple design expression is also proposed to predict the compressive strength of RHS columns partially reinforced along their length with welded steel plates by modifying the provisions of AISC 360-10 to account for the partial reinforcement.

ABSTRACT: In this article, hygro-thermo-mechanical vibration and buckling of exponentially graded (EG) nanoplates resting on two-parameter Pasternak foundations are studied using the four-unknown shear deformation plate theory. The material properties are presumed to change only in the thickness direction of the EG nanoplate according to two exponential laws distribution. The boundary conditions of the nanoplate may be simply supported, clamped, free or combination of them. To consider the small scale effect on forced frequencies and buckling, Eringen’s differential form of nonlocal elasticity theory is employed. The accuracy of the present study is investigated considering the available solutions in literature. A detailed analysis is executed to study the influences of the plate aspect ratio, side-to-thickness ratio, temperature rise, moisture concentration and volume fraction distributions on the vibration and buckling of the nanoplates.

ABSTRACT: This work proposes an original single variable shear deformation theory to study the buckling analysis of thick isotropic plates subjected to uniaxial and biaxial in-plane loads. This theory is built upon the classical plate theory (CPT) including the exponential function in terms of thickness coordinate to represent shear deformation effect and it involves only one governing differential equation. Efficacy of the present theory is confirmed through illustrative numerical examples. The obtained results are compared with those of other higher-order shear deformation plate theory results.

ABSTRACT: This study aimed to presents a simple analytical approach to investigate the thermal buckling behavior of thick functionally graded sandwich by employing both the sinusoidal shear deformation theory and
stress function. The material properties of the sandwich plate faces are continuously varied within the plate thickness according to a simple power-law distribution in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. The thermal loads are considered as uniform, linear and non-linear temperature rises across the thickness direction. Numerical examples are presented to prove the effect of power law index, loading type and functionally graded layers thickness on the thermal buckling response of thick functionally graded sandwich.


ABSTRACT: In this paper, a hyperbolic shear deformation theory is presented for bending analysis of functionally graded beams. This theory used in displacement field in terms of thickness co-ordinate to represent the shear deformation effects and does not require shear correction factor, and gives rise to transverse shear stress variation such that the transverse shear stresses vary parabolically across the thickness satisfying shear stress free surface conditions. The governing equations are derived by employing the virtual work principle and the physical neutral surface concept. A simply supported functionally graded beam subjected to uniformly distributed loads and sinusoidal loads are consider for detail numerical study. The accuracy of the present solutions is verified by comparing the obtained results with available published ones.

Farzad Ebrahimi, Mohsen Daman and Ramin Ebrahimi Fardshad, “Surface effects on vibration and buckling behavior of embedded nanoarches”, Structural Engineering and Mechanics, Vol. 64, No. 1, pp 1-10, 2017

ABSTRACT: The present paper deals with the free vibration and buckling problem with consideration of surface properties of circular nanobeams and nanoarches. The Gurtin-Murdach theory is used for investigating the surface effects parameters including surface tension, surface density and surface elasticity. Both linear and nonlinear elastic foundation effect are considered on the circular curved nanobeam. The analytically Navier solution is employed to solve the governing equations. It is obviously detected that the natural frequencies of a curved nanobeams is substantially influenced by the elastic foundations. Besides, it is revealed that by increasing the thickness of curved nanobeam, the influence of surface properties and elastic foundations reduce to vanished, and the natural frequency and critical buckling load turns into to the corresponding classical values.


ABSTRACT: The article presents the vibration and acoustic responses of un-baffled doubly curved laminated composite panel structure under the excitation of a harmonic point load. The structural responses are obtained using a simulation model via ANSYS including the effect various geometries (cylindrical, elliptical, spherical and hyperboloid). Initially, the model has been established by solving adequate number of available examples to show the convergence and comparison behaviour of the natural frequencies. Further, the acoustic responses are obtained using an indirect boundary element approach for the coupled fluid-structure analysis in LMS Virtual.lab by importing the natural frequency values. Subsequently, the values for the sound power level are computed using the present numerical model and compared with that of the available published results and in-house experimentally obtained data. Further, the acoustic responses (mean-square velocity, radiation efficiency and sound power level) of the doubly curved layered structures are evaluated using the current simulation model via several numerical experimentations for different structural parameters and corresponding discussions are provided in detail.

References listed at the end of the paper:

ABSTRACT: In this article, a novel simple higher-order shear deformation theory for bending and free vibration analysis of functionally graded (FG) beams is proposed. The beauty of this theory relies on its 2-unknowns displacement field as the Euler-Bernoulli beam theory, which is even less than the Timoshenko beam theory. A shear correction factor is, therefore, not needed. Equations of motion are obtained via Hamilton’s principle. Analytical solutions for the bending and free vibration analysis are given for simply supported beams. Efficacy of the proposed model is shown through illustrative examples for bending and dynamic of FG beams. The numerical results obtained are compared with those of other higher-order shear deformation beam theory results. The results obtained are found to be accurate.


ABSTRACT: The stochastic vibration response of the sandwich beam with the nonlinear adjustable visco-elastomer core and supported mass under stochastic support motion excitations is studied. The nonlinear dynamic properties of the visco-elastomer core are considered. The nonlinear partial differential equations for the horizontal and vertical coupling motions of the sandwich beam are derived. An analytical solution method for the stochastic vibration response of the nonlinear sandwich beam is developed. The nonlinear partial differential equations are converted into the nonlinear ordinary differential equations representing the nonlinear stochastic multi-degree-of-freedom system by using the Galerkin method. The nonlinear stochastic system is converted further into the equivalent quasi-linear system by using the statistic linearization method. The frequency-response function, response spectral density and mean square response expressions of the nonlinear sandwich beam are obtained. Numerical results are given to illustrate new stochastic vibration response characteristics and response reduction capability of the sandwich beam with the nonlinear visco-elastomer core and supported mass under stochastic support motion excitations. The influences of geometric and physical parameters on the stochastic response of the nonlinear sandwich beam are discussed, and the numerical results of the nonlinear sandwich beam are compared with those of the sandwich beam with linear visco-elastomer core.


ABSTRACT: This study concerns the vibrational behavior of multi-walled nested silicon-carbide and carbon nanotubes using the finite element method. The beam elements are used to model the carbon-carbon and silicon-carbon bonds. Besides, spring elements are employed to simulate the van der Waals interactions between walls. The effects of nanotube arrangement, number of walls, geometrical parameters and boundary conditions on the frequencies of nested silicon-carbide and carbon nanotubes are investigated. It is shown that the double-walled nanotubes have larger frequencies than triple-walled nanotubes. Besides, replacing silicon carbide layers with carbon layers leads to increasing the frequencies of nested silicon-carbide and carbon...
nanotubes. Comparing the first ten mode shapes of nested nanotubes, it is observed that the mode shapes of armchair and zigzag nanotubes are almost the same.

References listed at the end of the paper:


ABSTRACT: Present paper deals with the large amplitude flexural vibration of carbon nanotube reinforced composite (CNTRC) plates. Distribution of CNTs as reinforcements may be uniform or functionally graded (FG). The equivalent material properties of the composite media are obtained according to a refined rule of mixtures which contains efficiency parameters. To account for the large deformations, von Karman type of geometrical nonlinearity is included into the formulation. The matrix representation of the governing equations is obtained according to the Ritz method where the basic shape functions are written in terms of the Chebyshev polynomials. Time dependency of the problem is eliminated by means of the Galerkin method and the resulting nonlinear eigenvalue problem is solved employing a direct displacement control approach. Results are obtained for completely clamped and completely simply supported plates. Results are first validated for the special cases of FG-CNTRC and cross-ply laminated plates. Afterwards, parametric studies are given for FG-CNTRC plates with different boundary conditions. It is shown that, nonlinear frequencies are highly dependent to the volume fraction and dispersion profiles of CNTs. Furthermore, mode redistribution is observed in both simply supported and clamped FG-CNTRC plates.


ABSTRACT: In this paper, a new nonlocal trigonometric shear deformation theory is proposed for thermal buckling response of nanosize functionally graded (FG) nano-plates resting on two-parameter elastic foundation under various types of thermal environments. This theory uses for the first time, undetermined integral variables and it contains only four unknowns, that is even less than the first shear deformation theory (FSDT). It is considered that the FG nano-plate is exposed to uniform, linear and sinusoidal temperature rises. Mori-Tanaka model is utilized to define the gradually variation of material properties along the plate thickness. Nonlocal elasticity theory of Eringen is employed to capture the size influences. Through the stationary potential energy the governing equations are derived for a refined nonlocal four-variable shear deformation plate theory and then solved analytically. A variety of examples is proposed to demonstrate the importance of elastic foundation parameters, various temperature fields, nonlocality, material composition, aspect and side-to-thickness ratios on critical stability temperatures of FG nano-plate.


ABSTRACT: Dynamic response of functionally graded Carbon nanotubes (FG-CNT) reinforced pipes conveying viscous fluid under accelerated moving load is presented. The mixture rule is used for obtaining the
material properties of nano-composite pipe. The radial force induced by viscous fluid is calculated by Navier-Stokes equation. The material properties of pipe are considered temperature-dependent. The structure is simulated by Reddy higher-order shear deformation theory and the corresponding motion equations are derived by Hamilton’s principal. Differential quadrature (DQ) method and the Integral Quadrature (IQ) are applied for analogizing the motion equations and then the Newmark time integration scheme is used for obtaining the dynamic response of structure. The effects of different parameters such as boundary conditions, geometrical parameters, velocity and acceleration of moving load, CNT volume percent and distribution type are shown on the dynamic response of pipe. Results indicate that increasing CNTs leads to decrease in transient deflection of structure. In accelerated motion of the moving load, the maximum displacement is occurred later with respect to decelerated motion of moving load.


ABSTRACT: This paper reports the numerical investigation conducted to study the influence of Local-Distortional (L-D) interaction mode buckling on post buckling strength erosion in fixed ended lipped channel cold formed steel columns. This investigation comprises of 81 column sections with various geometries and yield stresses that are carefully chosen to cover wide range of strength related parametric ratios like (i) distortional to local critical buckling stress ratio \( \frac{0.91 \leq F_{CD}}{F_{CL}} \leq 4.05 \) (ii) non dimensional local slenderness ratio \( 0.88 \leq \lambda_L \leq 3.54 \) (iii) non-dimensional distortional slenderness ratio \( 0.68 \leq \lambda_D \leq 3.23 \) and (iv) yield to non-critical buckling stress ratio (0.45 to 10.4). The numerical investigation is carried out by conducting linear and non-linear shell finite element analysis (SFEA) using ABAQUS software. The non-linear SFEA includes both geometry and material non-linearity. The numerical results obtained are deeply analysed to understand the post buckling mechanics, failure modes and ultimate strength that are influenced by L-D interaction with respect to strength related parametric ratios. The ultimate strength data obtained from numerical analysis are compared with (i) the experimental tests data concerning L-D interaction mode buckling reported by other researchers (ii) column strength predicted by Direct Strength Method (DSM) column strength curves for local and distortional buckling specified in AISI S-100 (iii) strength predicted by available DSM based approaches that includes L-D interaction mode failure. The role of flange width to web depth ratio on post buckling strength erosion is reported. Then the paper concludes with merits and limitations of codified DSM and available DSM based approaches on accurate failure strength prediction.

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Mohammad Reza Barati, “Vibration analysis of FG nanoplates with nanovoids on viscoelastic substrate under hygro-thermo-mechanical loading using nonlocal strain gradient theory”, Structural Engineering and Mechanics, Vol. 64, No. 6, pp 683-693, 2017

ABSTRACT: According to a generalized nonlocal strain gradient theory (NSGT), dynamic modeling and free vibrational analysis of nanoporous inhomogeneous nanoplates is presented. The present model incorporates two scale coefficients to examine vibration behavior of nanoplates much accurately. Porosity-dependent material properties of the nanoplate are defined via a modified power-law function. The nanoplate is resting on a viscoelastic substrate and is subjected to hygro-thermal environment and in-plane linearly varying mechanical loads. The governing equations and related classical and non-classical boundary conditions are derived based on Hamilton’s principle. These equations are solved for hinged nanoplates via Galerkin’s method. Obtained results show the importance of hygro-thermal loading, viscoelastic medium, in-plane bending load, gradient index,
nonlocal parameter, strain gradient parameter and porosities on vibrational characteristics of size-dependent FG nanoplates.

ABSTRACT: A new quasi-3D higher shear deformation theory (quasi-3D HSDT) for functionally graded plates is proposed in this article. The theory considers both shear deformation and thickness-stretching influences by a hyperbolic distribution of all displacements within the thickness, and respects the stress-free boundary conditions on the upper and lower surfaces of the plate without using any shear correction factor. The highlight of the proposed theory is that it uses undetermined integral terms in displacement field and involves a smaller number of variables and governing equations than the conventional quasi-3D theories, but its solutions compare well with 3D and quasi-3D solutions. Equations of motion are obtained from the Hamilton principle. Analytical solutions for buckling and dynamic problems are deduced for simply supported plates. Numerical results are presented to prove the accuracy of the proposed theory.

ABSTRACT: This article deals with the buckling behaviour of multilayered magneto-electro-elastic (MEE) plate subjected to uniaxial and biaxial compressive (in-plane) loads. The constitutive equations of MEE material are used to derive a finite element (FE) formulation involving the coupling between electric, magnetic and elastic fields. The displacement field corresponding to first order shear deformation theory (FSDT) has been employed. The in-plane stress distribution within the MEE plate existing due to the enacted force is considered to be equivalent to the applied in-plane compressive load in the pre-buckling range. The same stress distribution is used to derive the potential energy functional. The non-dimensional critical buckling load is accomplished from the solution of allied linear eigenvalue problem. Influence of stacking sequence, span to thickness ratio, aspect ratio, load factor and boundary condition on critical buckling load and their corresponding mode shape is investigated. In addition, static deflection of MEE plate under the sinusoidal and the uniformly distributed load has been studied for different stacking sequences and boundary conditions.

Mamia Benchohra, Hafida Driz, Ahmed Bakora, Abdelouahed Tounsi, E.A. Adda Bedia and S.R. Mahmoud, “A new quasi-3D sinusoidal shear deformation theory for functionally graded (FG) plates is proposed. The theory considers both shear deformation and thickness-stretching influences by a trigonometric distribution of all displacements within the thickness, and respects the stress-free boundary conditions on the upper and lower faces of the plate without employing any shear correction coefficient. The advantage of the proposed model is that it posses a smaller number of variables and governing equations than the existing quasi-3D models, but its results compare well with those of 3D and quasi-3D theories. This benefit is due to the use of undetermined integral unknowns in the displacement field of the present theory. By employing the Hamilton principle, equations of motion are obtained in the present formulation. Closed-form solutions for bending and free vibration problems are determined for simply supported plates. Numerical examples are proposed to check the accuracy of the developed theory.

ABSTRACT: In this paper, using modified couple stress theory in place of classical continuum theory, and using shell model in place of beam model, vibrational behavior of nanotubes is investigated via the finite element method. Accordingly classical continuum theory is unable to correctly compute stiffness and account for size effects in micro/nanostructures, higher order continuum theories such as modified couple stress theory have taken on great appeal. In the present work the mass-stiffness matrix for cylindrical shell element is developed, and by means of size-dependent finite element formulation is extended to more precisely account for nanotube vibration. In addition to modified couple stress cylindrical shell element, the classical cylindrical shell element can also be defined by setting length scale parameter to zero in the equations. The boundary condition were assumed simply supported at both ends and it is shown that the natural frequency of nano-scale shell using the modified coupled stress theory is larger than that using the classical shell theory and the results of Ansys. The results have indicated using the modified couple stress cylindrical shell element, the rigidity of the nano-shell is greater than that in the classical continuum theory, which results in increase in natural frequencies. Besides, in addition to reducing the number of elements required, the use of this type of element also increases convergence speed and accuracy.

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Mehrdad Mohammadnejad and Hasan Haji Kazemi, “A new and simple analytical approach to determining the natural frequencies of framed tube structures”, Structural Engineering and Mechanics, Vol. 65, No. 1, pp 111-120, 2018

ABSTRACT: This paper presents a new and simple solution for determining the natural frequencies of framed tube combined with shear-walls and tube-in-tube systems. The novelty of the presented approach is based on the bending moment function approximation instead of the mode shape function approximation. This novelty makes the presented solution very simpler and very shorter in the mathematical calculations process. The shear stiffness, flexural stiffness and mass per unit length of the structure are variable along the height. The effect of the structure weight on its natural frequencies is considered using a variable axial force. The effects of shear lag phenomena has been investigated on the natural frequencies of the structure. The whole structure is modeled by an equivalent non-prismatic shear-flexural cantilever beam under variable axial forces. The governing differential equation of motion is converted into a system of linear algebraic equations and the natural frequencies are calculated by determining a non-trivial solution for the system of equations. The accuracy of the proposed method is verified through several numerical examples and the results are compared with the literature.


ABSTRACT: In this study, the bend-buckling strength of the web in longitudinally stiffened plate girder was numerically investigated. The buckling strength of the reinforced web was evaluated through an eigenvalue analysis of the hypothetical model, in which the top and bottom junctions of the web to the flanges were
assumed as simple support conditions. Major parameters in the analysis include asymmetrical cross-sectional property, aspect ratio of the web, stiffener locations, and bending rigidity of the stiffeners. The numerical results showed that current AASHTO LRFD specifications (2014) provides the buckling strength from considerably safe side to slightly unsafe side depending on the location of the stiffeners. A modified equation for buckling coefficients was proposed to solve the shortcomings. The bending rigidity requirements of longitudinal stiffeners stipulated in AASHTO were also investigated. It is desirable to increase the rigidity of the stiffeners when the aspect ratio is less than 1.0.

ABSTRACT: The purpose of this paper is to study free vibration analysis of thick plates resting on Winkler foundation using Mindlin’s theory with shear locking free fourth order finite element, to determine the effects of the thickness/span ratio, the aspect ratio, subgrade reaction modulus and the boundary conditions on the frequency parameters of thick plates subjected to free vibration. In the analysis, finite element method is used for spatial integration. Finite element formulation of the equations of the thick plate theory is derived by using higher order displacement shape functions. A computer program using finite element method is coded in C++ to analyze the plates free, clamped or simply supported along all four edges. In the analysis, 17-noded finite element is used. Graphs are presented that should help engineers in the design of thick plates subjected to earthquake excitations. It is concluded that 17-noded finite element can be effectively used in the free vibration analysis of thick plates. It is also concluded that, in general, the changes in the thickness/span ratio are more effective on the maximum responses considered in this study than the changes in the aspect ratio.

ABSTRACT: Shear walls are a typical member under a complex stress state and have complicated mechanical properties and failure modes. The separated-elements model Genetic Evolutionary Structural Optimization (GSEO), which is a combination of an elastic-plastic stress method and an optimization method, has been introduced in the literature for designing such members. Although the separated-elements model GSEO method is well recognized due to its stability, feasibility, and economy, its adequacy has not been experimentally verified. This paper seeks to validate the adequacy of the separated-elements model GSEO method against experimental data and demonstrate its feasibility and advantages over the traditional elastic stress method. Two types of reinforced concrete shear wall specimens, which had the location of an opening in the middle bottom and the center region, respectively, were utilized for this study. For each type, two specimens were designed using the separated-elements model GSEO method and elastic stress method, respectively. All specimens were subjected to a constant vertical load and an incremental lateral load until failure. Test results indicated that the ultimate bearing capacity, failure modes, and main crack types of the shear walls designed using the two methods were similar, but the ductility indexes including the stiffness degradation, deformability, reinforcement yielding, and crack development of the specimens designed using the separated-elements model GSEO method were superior to those using the elastic stress method. Additionally, the shear walls designed using the separated-elements model GSEO method, had a reinforcement layout which could closely resist the actual critical stress, and thus a reduced amount of steel bars were required for such shear walls.

Ahmed Dihaj, Mohamed Zidour, Mustapha Meradjah, Kaddour Rakrak, Houari Heireche and Awda Chemi, “Free vibration analysis of chiral double-walled carbon nanotube embedded in an elastic medium using non-
local elasticity theory and Euler Bernoulli beam model”, Structural Engineering and Mechanics, Vol. 65, No. 3, pp 335-342, 2018
ABSTRACT: The transverse free vibration of chiral double-walled carbon nanotube (DWCNTs) embedded in elastic medium is modeled by the non-local elasticity theory and Euler Bernoulli beam model. The governing equations are derived and the solutions of frequency are obtained. According to this study, the vibrational mode number, the small-scale coefficient, the Winkler parameter and chirality of double-walled carbon nanotube on the frequency ratio (xN) of the (DWCNTs) are studied and discussed. The new features of the vibration behavior of (DWCNTs) embedded in an elastic medium and the present solutions can be used for the static and dynamic analyses of double-walled carbon nanotubes.

ABSTRACT: In this paper, a multi-layered finite element model for laminated glass plates is introduced. A layer-wise theory is applied to the analysis of laminated glass due to the combination of stiff and soft layers; the independent layers are connected via Lagrange multipliers. The von Karman large deflection plate theory and the constant Poisson ratio for constitutive equations are assumed to capture the possible effects of geometric nonlinearity and the time/temperature-dependent response of the plastic foil. The linear viscoelastic behavior of a polymer foil is included by the generalized Maxwell model. The proposed layer-wise model was implemented into the MATLAB code and verified against detailed three-dimensional models in ADINA solver using different hexahedral finite elements. The effects of temperature, load duration, and creep/relaxation are demonstrated by examples.

Masoud Mirtaheri, Saeed Sehat and Meissam Nazeryan, “Improving the behavior of buckling restrained braces through obtaining optimum steel core length”, Structural Engineering and Mechanics, Vol. 65, No. 4, pp 401-408, 2018
ABSTRACT: Concentric braced frames are commonly used in steel structures to withstand lateral forces. One of the drawbacks of these systems is the possibility that the braces are buckled under compressive loads, which leads to sudden reduction of the bearing capacity of the structure. To overcome this deficiency, the idea of the Buckling Restrained Brace (BRB) has been proposed in recent years. The length of a BRB steel core can have a significant effect on its overall behavior, since it directly influences the energy dissipation capability of the member. In this study, numerical methods have been utilized for investigation of the optimum length of BRB steel cores. For this purpose, BRBs with different lengths placed into several two-dimensional framing systems with various heights were considered. Then, the Response History Analysis (RHA) was performed, and finally, the optimum steel core length of BRBs and its effect on the responses of the overall system were investigated. The results show that the shortest length where failure does not occur is the best length that can be proposed as the optimum steel core length of BRBs. This length can be obtained through a formula which has been derived and verified in this study by both analytical and numerical methods.

ABSTRACT: In present work, both the hyperbolic shear deformation theory and stress function concept are used to study the mechanical and thermal stability responses of functionally graded (FG) plates resting on elastic foundation. The accuracy of the proposed formulation is checked by comparing the computed results with those predicted by classical plate theory (CPT), first-order shear deformation theory (FSDT) and higher-
order shear deformation theory (HSDT). Moreover, results demonstrate that the proposed formulation can achieve the same accuracy of the existing HSDTs which have more number of governing equations.


ABSTRACT: In this paper, an efficient higher-order shear deformation theory is presented to analyze thermomechanical bending of temperature-dependent functionally graded (FG) plates resting on an elastic foundation. Further simplifying supposition are made to the conventional HSDT so that the number of unknowns is reduced, significantly facilitating engineering analysis. These theory account for hyperbolic distributions of the transverse shear strains and satisfy the zero traction boundary conditions on the surfaces of the plate without using shear correction factors. Power law material properties and linear steady-state thermal loads are assumed to be graded along the thickness. Nonlinear thermal conditions are imposed at the upper and lower surface for simply supported FG plates. Equations of motion are derived from the principle of virtual displacements. Analytical solutions for the thermomechanical bending analysis are obtained based on Fourier series that satisfy the boundary conditions (Navier’s method). Non-dimensional results are compared for temperature-dependent FG plates and validated with those of other shear deformation theories. Numerical investigation is conducted to show the effect of material composition, plate geometry, and temperature field on the thermomechanical bending characteristics. It can be concluded that the present theory is not only accurate but also simple in predicting the thermomechanical bending responses of temperature-dependent FG plates.

M. Mohammadimehr, E. Shabani Nejad and M. Mehrabi, “Buckling and vibration analyses of MGSGT double-bonded micro composite sandwich SSDT plates reinforced by CNTs and BNNTs with isotropic foam & flexible transversely orthotropic cores”, Structural Engineering and Mechanics, Vol. 65, No. 4, pp 491-504, 2018

ABSTRACT: Because of sandwich structures with low weight and high stiffness have much usage in various industries such as civil and aerospace engineering, in this article, buckling and free vibration analyses of coupled micro composite sandwich plates are investigated based on sinusoidal shear deformation (SSDT) and most general strain gradient theories (MGSGT). It is assumed that the sandwich structure rested on an orthotropic elastic foundation and make of four composite face sheets with temperature-dependent material properties that they reinforced by carbon and boron nitride nanotubes and two flexible transversely orthotropic cores. Mathematical formulation is presented using Hamilton’s principle and governing equations of motions are derived based on energy approach and applying variation method for simply supported edges under electromagneto-thermo-mechanical, axial buckling and pre-stresses loadings. In order to predict the effects of various parameters such as material length scale parameter, length to width ratio, length to thickness ratio, thickness of face sheets to core thickness ratio, nanotubes volume fraction, pre-stress load and orthotropic elastic medium on the natural frequencies and critical buckling load of double-bonded micro composite sandwich plates. It is found that orthotropic elastic medium has a special role on the system stability and increasing Winkler and Pasternak constants lead to enhance the natural frequency and critical buckling load of micro plates, while decrease natural frequency and critical buckling load with increasing temperature changes. Also, it is showed that pre-stresses due to help the axial buckling load causes that delay the buckling phenomenon. Moreover, it is concluded that the sandwich structures with orthotropic cores have high stiffness, but because they are not economical, thus it is necessary the sandwich plates reinforce by carbon or boron nitride nanotubes specially, because these nanotubes have important thermal and mechanical properties in comparison of the other reinforcement.

ABSTRACT: In this study, the dynamic response of a functionally graded material (FGM) circular plate in contact with incompressible fluid under the harmonic load is investigated. Analysis of the plate is based on First-order Shear Deformation Plate Theory (FSDT). The governing equation of the oscillatory behavior of the fluid is obtained by solving Laplace equation and satisfying its boundary conditions. A new set of admissible functions, which satisfy both geometrical and natural boundary conditions, are developed for the free vibration analysis of moderately thick circular plate. The Chebyshev-Ritz Method is employed together with this set of admissible functions to determine the vibrational behaviors. The modal superposition approach is used to determine the dynamic response of the plate exposed to harmonic loading. Numerical results of the force vibrations and the effects of the different geometrical parameters on the dynamic response of the plate are investigated. Finally, the results of this research in the limit case are compared and validated with the results of other researches and finite element model (FEM).


ABSTRACT: The academic research works about liquid storage tanks are reviewed for the purpose of providing valuable reference to the engineering practice on their aseismic design. A summary of the performance of tanks during past earthquakes is described in this paper. Next, the seismic response of tanks under unidirectional earthquake is reported, supplemented with the dynamic response under multidirectional motions. Then, researches on the influence of soil-structure interaction are brought out to help modify the seismic design approach of tanks in different areas with variable properties of soils. Afterwards, base isolation systems are reported to demonstrate their effectiveness for the earthquake-resistant design of liquid storage tanks. Further, researches about the liquid-structure interaction are reviewed with description of simplified models and numerical analytical methods, some of which consider the elastic effect of tank walls. Moreover, the liquid sloshing phenomenon on the hydrodynamic behaviors of tanks is presented by various algorithms including grid-based and meshfree method. And then the impact of baffles in changing the dynamic characteristics of the liquid-structure system is raised, which shows the energy dissipation by the vortex motion of liquid. In addition, uplifting effect is given to enhance the understanding on the capacity of unanchored tanks and some assessment of their development. At last, the concluding remarks and the aspects of extended research in the field of liquid storage tanks under seismic loads are provided, emphasizing the thermal stress analysis, the replaceable system for base isolation, the liquid-solid interaction and dynamic responses with stochastic excitations.

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8. API 650 (2005), Welded Steel Tanks for Oil Storage, American Petroleum Institute, Washington, U.S.A.

Reza Aghazadeh, Serkan Dag and Ender Cigeroglu, “Modelling of graded rectangular micro-plates with variable length scale parameters”, Structural Engineering and Mechanics, Vol. 65, No. 5, pp 573-585, 2018
ABSTRACT: This article presents strain gradient elasticity-based procedures for static bending, free vibration and buckling analyses of functionally graded rectangular micro-plates. The developed method allows consideration of smooth spatial variations of length scale parameters of strain gradient elasticity. Governing partial differential equations and boundary conditions are derived by following the variational approach and applying Hamilton’s principle. Displacement field is expressed in a unified way to produce numerical results in accordance with Kirchhoff, Mindlin, and third order shear deformation theories. All material properties, including the length scale parameters, are assumed to be functions of the plate thickness coordinate in the derivations. Developed equations are solved numerically by means of differential quadrature method. Proposed procedures are verified through comparisons made to the results available in the literature for certain limiting cases. Further numerical results are provided to illustrate the effects of material and geometric parameters on bending, free vibrations, and buckling. The results generated by Kirchhoff and third order shear deformation theories are in very good agreement, whereas Mindlin plate theory slightly overestimates static deflection and underestimates natural frequency. A rise in the length scale parameter ratio, which identifies the degree of spatial variations, leads to a drop in dimensionless maximum deflection, and increases in dimensionless vibration frequency and buckling load. Size effect is shown to play a more significant role as the plate thickness becomes smaller compared to the length scale parameter. Numerical results indicate that consideration of length scale parameter variation is required for accurate modelling of graded rectangular micro-plates.

Saeid Lotfi and Seyed Mehdi Zahrai, “Blast behavior of steel infill panels with various thickness and stiffener arrangement”, Structural Engineering and Mechanics, Vol. 65, No. 5, pp 587-600, 2018
ABSTRACT: Infill panel is the first element of a building subjected to blast loading activating its out-of-plane behavior. If the infill panel does not have enough ductility against the loading, it breaks and gets damaged before load transfer and energy dissipation. As steel infill panel has appropriate ductility before fracture, it can be used as an alternative to typical infill panels under blast loading. Also, it plays a pivotal role in maintaining sensitive main parts against blast loading. Concerning enough ductility of the infill panel out-of-plane behavior, the impact force enters the horizontal diaphragm and is distributed among the lateral elements. This article investigates the behavior of steel infill panels with different thicknesses and stiffeners. In order to precisely study steel infill panels, different ranges of blast loading are used and maximum displacement of steel infill under such various blast loading is studied. In this research, finite element analyses including geometric and material nonlinearities are used for optimization of the steel plate thickness and stiffener arrangement to obtain more efficient design for its better out-of-plane behavior. The results indicate that this type of infill with out-of-plane behavior shows a proper ductility especially in severe blast loadings. In the blasts with high intensity,
maximum displacement of infill is more sensitive to change in the thickness of plate rather than the change in number of stiffeners such that increasing the number of stiffeners and the plate thickness of infill panel would decrease energy dissipation by 20 and 77% respectively. The ductile behavior of steel infill panels shows that using infill panels with less thickness has more effect on energy dissipation. According to this study, the infill panel with 5 mm thickness works better if the criterion of steel infill panel design is the reduction of transmitted impulse to main structure. For example in steel infill panels with 5 stiffeners and blast loading with the reflected pressure of 375 kPa and duration of 50 milliseconds, the transmitted impulse has decreased from 41206 N.Sec in 20 mm infill to 37898 N.Sec in 5 mm infill panel.


ABSTRACT: In this paper, an exact analytical solution is developed for the analysis of the post-buckling non-linear response of simply supported deformable symmetric composite beams. For this, a new theory of higher order shear deformation is used for the analysis of composite beams in post-buckling. Unlike any other shear deformation beam theories, the number of functions unknown in the present theory is only two as the Euler-Bernoulli beam theory, while three unknowns are needed in the case of the other beam theories. The theory presents a parabolic distribution of transverse shear stresses, which satisfies the nullity conditions on both sides of the beam without a shear correction factor. The shear effect has a significant contribution to buckling and post-buckling behaviour. The results of this analysis show that classical and first-order theories underestimate the amplitude of the buckling whereas all the theories considered in this study give results very close to the static response of post-buckling. The numerical results obtained with the novel theory are not only much more accurate than those obtained using the Euler-Bernoulli theory but are almost comparable to those obtained using higher order theories. Accuracy and effectiveness of the current theory.

Surkay D. Akbarov and Mahir A. Mehdiyev, “Influence of initial stresses on the critical velocity of the moving load acting in the interior of the hollow cylinder surrounded by an infinite elastic medium”, Structural Engineering and Mechanics, Vol. 66, No. 1, pp 45-59, 2018

ABSTRACT: The bi-material elastic system consisting of the pre-stressed hollow cylinder and pre-stresses surrounding infinite elastic medium is considered and it is assumed that the mentioned initial stresses in this system are caused with the compressing or stretching uniformly distributed normal forces acting at infinity in the direction which is parallel to the cylinder’s axis. Moreover, it is assumed that on the internal surface of the cylinder the ring load which moves with constant velocity acts and within these frameworks it is required to determine the influence of the aforementioned initial stresses on the critical velocity of the moving load. The corresponding investigations are carried out within the framework of the so-called three-dimensional linearized theory of elastic waves in initially stressed bodies and the axisymmetric stress-strain state case is considered. The "moving coordinate system" method is used and the Fourier transform is employed for solution to the formulated mathematical problem and Fourier transformation of the sought values are determined analytically. However, the originals of those are determined numerically with the use of the Sommerfeld contour method. The critical velocity is determined from the criterion, according to which, the magnitudes of the absolute values of the stresses and displacements caused with the moving load approaches an infinity. Numerical results on the influence of the initial stresses on the critical velocity and interface normal and shear stresses are presented and discussed. In particular, it is established that the initial stretching (compressing) of the constituents of the system under consideration causes a decrease (an increase) in the values of the critical velocity.

ABSTRACT: This study investigated the behaviour of the simply supported hollow steel tube (HST) beams, either concrete filled or unfilled when strengthened with carbon fibre reinforced polymer (CFRP) sheets. Eight specimens with varied tubes thickness (sections classification 1 and 3) were all tested experimentally under static flexural loading, four out of eight were filled with normal concrete (CFST beams). Particularly, the partial CFRP strengthening scheme was used, which wrapped the bottom-half of the beams cross-section (U-shaped wrapping), in order to use the efficiency of high tensile strength of CFRP sheets at the tension stress only of simply supported beams. In general, the results showed that the CFRP sheets significantly improved the ultimate strength and energy absorption capacities of the CFST beams with very limited improvement on the related HST beams. For example, the load and energy absorption capacities for the CFST beams (tube section class 1) were increased about 20% and 32.6%, respectively, when partially strengthened with two CFRP layers, and these improvements had increased more (62% and 38%) for the same CFST beams using tube class 3. However, these capacities recorded no much improvement on the related unfilled HST beams when the same CFRP strengthening scheme was adopted.


ABSTRACT: In this paper, reaction of functionally graded (FG) thick nanoplates resting on a viscoelastic foundation to a moving nanoparticle/load is investigated. Nanoplate is assumed to be thick by using second order shear deformation theory and small-scale effects are taken into account in the framework of Eringen’s nonlocal theory. Material properties are varied through the thickness using FG models by having power-law, sigmoid and exponential functions for material changes. FG nanoplate is assumed to be on a viscoelastic medium which is modeled using Kelvin-Voight viscoelastic model. Galerkin, state space and fourth-order Runge-Kutta methods are employed to solve the governing equations. A comprehensive parametric study is presetned to show the influence of different parameters on mechanical behavior of the system. It is shown that material variation in conjunction with nonlocal term have a significant effect on the dynamic deformation of nanoplate which could be used in comprehending and designing more efficient nanostructures. Moreover, it is shown that having a viscoelastic medium could play an important role in decreasing these dynamic deformations. With respect to the fresh studies on moving atoms, molecules, cells, nanocars, nanotrims and point loads on different nanostructures using scanning tunneling microscopes (STM) and atomic force microscopes (AFM), this study could be a step forward in understanding, predicting and controlling such kind of behaviors by showing the influence of the moving path, velocity etc. on dynamic reaction of the plate.


ABSTRACT: The semi-analytical method to study the nonlinear dynamic behavior of simply supported spiral stiffened functionally graded (FG) cylindrical shells subjected to an axial compression is presented. The FG shell is surrounded by damping and linear/nonlinear elastic foundation. The proposed linear model is based on the two-parameter elastic foundation (Winkler and Pasternak). A three-parameter elastic foundation with hardening/softening cubic nonlinearity is used for nonlinear model. The material properties of the shell and stiffeners are assumed to be FG. Based on the classical plate theory of shells and von Karman nonlinear equations, smeared stiffeners technique and Galerkin method, this paper solves the nonlinear vibration problem.
The fourth order Runge-Kutta method is used to find the nonlinear dynamic responses. Results are given to consider effects of spiral stiffeners with various angles, elastic foundation and damping coefficients on the nonlinear dynamic response of spiral stiffened simply supported FG cylindrical shells.

References listed at the end of the paper:
its quasi-3D nature, the stretching effect is taken into account in the formulation of governing equations. In addition, the effect of different micromechanical models on the bending response of these plates is studied. Various micromechanical models are used to evaluate the mechanical characteristics of the FG plates whose properties vary continuously across the thickness according to a simple power law. The present theory accounts for both shear deformation and thickness stretching effects by a parabolic variation of displacements across the thickness, and the zero traction boundary conditions on the top and bottom surfaces of the plate without using shear correction factors. The problem is solved for a plate simply supported on its edges and the Navier solution is used. The results of the present method are compared with others from the literature where a good agreement has been found. A detailed parametric study is presented to show the effect of different micromechanical models on the flexural response of a simply supported FG plates.

Mahfoud Yousfi, Hassen Ait Atmane, Mustapha Meradjah, Abdelouahed Tounsi and Riadh Bennai, “Free vibration of FGM plates with porosity by a shear deformation theory with four variables”, Structural Engineering and Mechanics, Vol. 66, No. 3, pp 353-368, 2018

ABSTRACT: In this work, a high order hyperbolic shear deformation theory with four variables is presented to study the vibratory behavior of functionally graded plates. The field of displacement of the theory used in this work is introduced indeterminate integral variables. In addition, the effect of porosity is studied. It is assumed that the material characteristics of the porous FGM plate, varies continuously in the direction of thickness as a function of the power law model in terms of volume fractions of constituents taken into account the homogeneous distribution of porosity. The equations of motion are obtained using the principle of virtual work. An analytical solution of the Navier type for free vibration analysis is obtained for a FGM plate for simply supported boundary conditions. A comparison of the results obtained with those of the literature is made to verify the accuracy and efficiency of the present theory. It can be concluded from his results that the current theory is not only accurate but also simple for the presentation of the response of free vibration and the effect of porosity on the latter.


ABSTRACT: This paper presents a numerical study on the behavior of continuous hollow steel beam strengthened using carbon fiber reinforced polymers (CFRP). Most previous studies on the CFRP strengthening of steel beams have been carried out on the steel beams with simple boundary conditions. No independent study, to the researcher’s knowledge, has studied on the CFRP strengthening of square hollow section (SHS) continuous steel beam. However, this study explored the effect of the use of adhesively bonded CFRP flexible sheets on the behavior of the continuous SHS steel beams. Finite Element Method (FEM) has been employed for modeling. Eleven specimens, ten of which were strengthened using CFRP sheets, were analyzed under different coverage length, the number of layers, and the location of CFRP composite. ANSYS software was used to analyze the SHS steel beams. The results showed that the coverage length, the number of layers, and the location of CFRP composite are effective in increasing the ultimate load capacity of the continuous SHS steel beams. Application of CFRP composite also caused the ductility increase some strengthened specimens.


ABSTRACT: An investigation is made in the present work on the post-buckling and geometrically nonlinear behaviors of moderately thick perfect and imperfect rectangular plates made-up of functionally graded materials. Spectral collocation approach based on Legendre basis functions is developed to analyze the functionally graded plates while they are subjected to end-shortening strain. The material properties in this
study are varied through the thickness according to the simple power law distribution. The fundamental equations for moderately thick rectangular plates are derived using first order shear deformation plate theory and taking into account both geometric nonlinearity and initial geometric imperfections. In the current study, the domain of interest is discretized with Legendre-Gauss-Lobatto nodes. The equilibrium equations will be obtained by discretizing the Von-Karman’s equilibrium equations and also boundary conditions with finite Legendre basis functions that are substituted into the displacement fields. Due to effect of geometric nonlinearity, the final set of equilibrium equations is nonlinear and therefore the quadratic extrapolation technique is used to solve them. Since the number of equations in this approach will always be more than the number of unknown coefficients, the least squares technique will be used. Finally, the effects of boundary conditions, initial geometric imperfection and material properties are investigated and discussed to demonstrate the validity and capability of proposed method.


ABSTRACT: By employing the nonlocal continuum field theory of Eringen and Von Karman nonlinear strains, this paper presents an analytical model for linear and nonlinear dynamics analysis of single-walled carbon nanotubes (SWNTs) conveying fluid with different boundary conditions. In the linear analysis the natural frequencies and critical flow velocities of SWNTs are computed. However, in the nonlinear analysis the effect of nonlocal parameter on nonlinear dynamics of cantilevered SWNTs conveying fluid is investigated by using bifurcation diagram, phase plane and Poincare map. Numerical results confirm existence of chaos as well as a period-doubling transition to chaos.

References listed at the end of the paper:

ABSTRACT: In this study, a four-node quadrilateral partial mixed plate element with low degrees of freedom (dofs) is developed for static and free vibration analysis of functionally graded material (FGM) plates rested on Winkler-Pasternak elastic foundations. The formulation of the presented finite element model is based on a parametrized mixed variational principle which is developed recently by the first author. The presented finite element model considers the effects of shear deformations and normal flexibility of the FGM plates without using any shear correction factor. It also fulfills the boundary conditions of the transverse shear and normal stresses on the top and bottom surfaces of the plate. Beside these capabilities, the number of unknown field variables of the plate is only six. The presented partial mixed finite element model has been validated through comparison with the results of the three-dimensional (3D) theory of elasticity and the results obtained from the classical and high-order plate theories available in the open literature.

Farzad Ebrahimi and Mohammad Reza Barati, “A nonlocal strain gradient refined plate model for thermal vibration analysis of embedded graphene sheets via DQM”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 693-701, 2018

ABSTRACT: This paper develops a nonlocal strain gradient plate model for vibration analysis of graphene sheets under thermal environments. For more accurate analysis of graphene sheets, the proposed theory contains two scale parameters related to the nonlocal and strain gradient effects. Graphene sheet is modeled via a two-variable shear deformation plate theory needless of shear correction factors. Governing equations of a nonlocal strain gradient graphene sheet on elastic substrate are derived via Hamilton’s principle. Differential quadrature method (DQM) is implemented to solve the governing equations for different boundary conditions. Effects of different factors such as temperature rise, nonlocal parameter, length scale parameter, elastic foundation and aspect ratio on vibration characteristics a graphene sheets are studied. It is seen that vibration frequencies and critical buckling temperatures become larger and smaller with increase of strain gradient and nonlocal parameter, respectively.

JinJing Liao and Guowei Ma, “Energy absorption of the ring stiffened tubes and the application in blast wall design”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 713-727, 2018
ABSTRACT: Thin-walled mental tubes under lateral crushing are desirable and reliable energy absorbers against impact or blast loads. However, the early formations of plastic hinges in the thin cylindrical wall limit the energy absorption performance. This study investigates the energy absorption performance of a simple, light and efficient energy absorber called the ring stiffened tube. Due to the increase of section modulus of tube wall and the restraining effect of the T-stiffener flange, key energy absorption parameters (peak crushing force, energy absorption and specific energy absorption) have been significantly improved against the empty tube. Its potential application in the offshore blast wall design has also been investigated. It is proposed to replace the blast wall endplates at the supports with the energy absorption devices that are made up of the ring stiffened tubes and springs. An analytical model based on beam vibration theory and virtual work theory, in which the boundary conditions at each support are simplified as a translational spring and a rotational spring, has been developed to evaluate the blast mitigation effect of the proposed design scheme. Finite element method has been applied to validate the analytical model. Comparisons of key design criterions such as panel deflection and energy absorption against the traditional design demonstrate the effectiveness of the proposed design in blast alleviation.

References listed at the end of the paper: (None given)

Gui-Lin She, Yi-Ru Ren, Wan-Shen Xiao and Haibo Liu, “Study on thermal buckling and post-buckling behaviors of FGM tubes resting on elastic foundations”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 729-736, 2018

ABSTRACT: This paper studies thermal buckling and post-buckling behaviors of functionally graded materials (FGM) tubes subjected to a uniform temperature rise and resting on elastic foundations via a refined beam model. Compared to the Timoshenko beam theory, the number of unknowns of this model are the same and no correction factors are required. The material properties of the FGM tube vary continuously in the radial direction according to a power function. Two ends of the tube are assumed to be simply supported and in-plane boundary conditions are immovable. Energy variation principle is employed to establish the governing equations. A two-step perturbation method is adopted to determine the critical thermal buckling loads and post-buckling paths of the tubes with arbitrary radial non-homogeneity. Through detailed parametric studies, it can be found that the tube has much higher buckling temperature and post-buckling strength when it is supported by an elastic foundation.

References listed at the end of the paper: (None given)

Abbas Heydari and Mahdi Shariati, “Buckling analysis of tapered BDFGM nano-beam under variable axial compression resting on elastic medium”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 737-748, 2018

ABSTRACT: The current study presents a new technique in the framework of the nonlocal elasticity theory for a comprehensive buckling analysis of Euler-Bernoulli nano-beams made up of bidirectional functionally graded material (BDFGM). The mechanical properties are considered by exponential and arbitrary variations for axial and transverse directions, respectively. The various circumstances including tapering, resting on two-parameter elastic foundation, step-wise or continuous variations of axial loading, various shapes of sections with various distribution laws of mechanical properties and various boundary conditions like the multi-span beams are taken into account. As far as we know, for the first time in the current work, the buckling analyses of BDFGM nano-beams are carried out under mentioned circumstances. The critical buckling loads and mode shapes are calculated by using energy method and a new technique based on calculus of variations and collocation method. Fast convergence and excellent agreement with the known data in literature, wherever possible, presents the efficiency of proposed technique. The effects of boundary conditions, material and taper constants, foundation
moduli, variable axial compression and small-scale of nano-beam on the buckling loads and mode shapes are investigated. Moreover the analytical solutions, for the simpler cases are provided in appendices.

Adim Belkacem, Hassaine Daouadji Tahar, Rabahi Abderrezak, Benhenni Mohamed Amine, Zidour Mohamed and Abbes Boussad, “Mechanical buckling analysis of hybrid laminated composite plates under different boundary conditions”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 761-769, 2018
ABSTRACT: In this paper, we study the Carbon/Glass hybrid laminated composite plates, where the buckling behavior is examined using an accurate and simple refined higher order shear deformation theory. This theory takes account the shear effect, where shear deformation and shear stresses will be considered in determination of critical buckling load under different boundary conditions. The most interesting feature of this new kind of hybrid laminated composite plates is that the possibility of varying components percentages, which allows us for a variety of plates with different materials combinations in order to overcome the most difficult obstacles faced in traditional laminated composite plates like (cost and strength). Numerical results of the present study are compared with three-dimensional elasticity solutions and results of the first-order and the other higher-order theories issue from the literature. It can be concluded that the proposed theory is accurate and simple in solving the buckling behavior of hybrid laminated composite plates and allows to industrials the possibility to adjust the component of this new kind of plates in the most efficient way (reducing time and cost) according to their specific needs.

Lazreg Hadji, Mohamed Ait Amar Meziane and Abdelkader Safa, “A new quasi-3D higher shear deformation theory for vibration of functionally graded carbon nanotube-reinforced composite beams resting on elastic foundation”, Structural Engineering and Mechanics, Vol. 66, No. 6, pp 771-781, 2018
ABSTRACT: This study deals with free vibrations analysis with stretching effect of nanocomposite beams reinforced by single-walled carbon nanotubes (SWCNTs) resting on an elastic foundation. Four different carbon nanotubes (CNTs) distributions including uniform and three types of functionally graded distributions of CNTs through the thickness are considered. The rule of mixture is used to describe the effective material properties of the nanocomposite beams. The significant feature of this model is that, in addition to including the shear deformation effect and stretching effect it deals with only 4 unknowns without including a shear correction factor. The governing equations are derived through using Hamilton’s principle. Natural frequencies are obtained for nanocomposite beams. The mathematical models provided in this paper are numerically validated by comparison with some available results. New results of free vibration analyses of CNTRC beams based on the present theory with stretching effect is presented and discussed in details. The effects of different parameters of the beam on the vibration responses of CNTRC beam are discussed.

ABSTRACT: In this work, the dynamic stability of carbon nanotubes (CNTs) reinforced composite pipes conveying pulsating fluid flow is investigated. The pipe is surrounded by viscoelastic medium containing spring, shear and damper coefficients. Due to the existence of CNTs, the pipe is subjected to a 2D magnetic field. The radial induced force by pulsating fluid is obtained by the Navier-Stokes equation. The equivalent characteristics of the nanocomposite structure are calculated using Mori-Tanaka model. Based on first order shear deformation theory (FSDT) or Mindlin theory, energy method and Hamilton’s principle, the motion equations are derived. Using harmonic differential quadrature method (HDQM) in conjunction with the Bolotin’s method, the dynamic instability region (DIR) of the system is calculated. The effects of different parameters such as volume fraction of CNTs, magnetic field, boundary conditions, fluid velocity and
geometrical parameters of pipe are shown on the DIR of the structure. Results show that with increasing volume fraction of CNTs, the DIR shifts to the higher frequency. In addition, the DIR of the structure will be happened at lower excitation frequencies with increasing the fluid velocity.

References listed at the end of the paper:


ABSTRACT: By using the first order shear deformation plate theory (FSDT) in the present paper, the effect of porosity on the buckling behavior of carbon nanotube-reinforced composite porous plates has been investigated analytically. Two types of distributions of uniaxially aligned reinforcement material are utilized which uniformly (UD-CNT) and functionally graded (FG-CNT) of plates. The analytical equations of the model are derived and the exact solutions for critical buckling load of such type’s plates are obtained. The convergence of the method is demonstrated and the present solutions are numerically validated by comparison with some available solutions in the literature. The central thesis studied and discussed in this paper is the Influence of Various parameters on the buckling of carbon nanotube-reinforced porous plate such as aspect ratios, volume fraction, types of reinforcement, the degree of porosity and plate thickness. On the question of porosity, this study found that there is a great influence of their variation on the critical buckling load. It is revealed that the critical buckling load decreases as increasing coefficients of porosity.


ABSTRACT: This study deals with buckling analysis with stretching effect of functionally graded carbon nanotube-reinforced composite beams resting on an elastic foundation. The single-walled carbon nanotubes (SWCNTs) are aligned and distributed in polymeric matrix with different patterns of reinforcement. The material properties of the CNTRC beams are estimated by using the rule of mixture. The significant feature of this model is that, in addition to including the shear deformation effect and stretching effect it deals with only 4 unknowns without including a shear correction factor. The equilibrium equations have been obtained using the principle of virtual displacements. The mathematical models provided in this paper are numerically validated by comparison with some available results. New results of buckling analyses of CNTRC beams based on the
present theory with stretching effect is presented and discussed in details. the effects of different parameters of the beam on the buckling responses of CNTRC beam are discussed.

ABSTRACT: Thermal buckling of nonlocal flexoelectric nanoplates incorporating surface effects is analyzed for the first time. Coupling of strain gradients and electrical polarizations is introduced by flexoelectricity. It is assumed that flexoelectric nanoplate is subjected to uniform and linear temperature distributions. Long range interaction between atoms of nanoplate is modeled via nonlocal elasticity theory. The residual surface stresses which are usually neglected in modeling of flexoelectric nanoplates are incorporated into nonlocal elasticity to provide better understanding of the physic of problem. A Galerkin-based approach is implemented to solve the governing equations derived from Hamilton’s principle are solved. The verification of obtained results is performed by comparing buckling loads of flexoelectric nanoplate with previous data. It is shown that buckling loads of flexoelectric nanoplate are significantly affected by thermal loading type, temperature change, nonlocal parameter, surface effect, plate thickness and boundary conditions.

ABSTRACT: In past years, numerous problems have vexed engineers with regard to buckling, corrosion, bending, and overloading in damaged steel structures. This article sets out to investigate the possible effects of carbon fiber reinforced polymer (CFRP) and steel plates for retrofitting deficient steel square hollow section (SHS) columns. The effects of axial loading, stiffness, axial displacement, the position and shape of deficient region on the length of steel SHS columns, and slenderness ratio are examined through a detailed parametric study. A total of 14 specimens was tested for failure under axial compression in a laboratory and simulated using finite element (FE) analysis based on a numerical approach. The results indicate that the application of CFRP sheets and steel plates also caused a reduction in stress in the damaged region and prevented or retarded local deformation around the deficiency. The findings showed that a deficiency leads to reduced load-carrying capacity of steel SHS columns and the retrofitting method is responsible for the increase in the load-bearing capacity of the steel columns. Finally, this research showed that the CFRP performed better than steel plates in compensating the axial force caused by the cross-section reduction due to the problems associated with the use of steel plates, such as in welding, increased weight, thermal stress around the welding location, and the possibility of creating another deficiency by welding.

ABSTRACT: This paper deals with the static bending of various types of FGM sandwich plates resting on two-parameter elastic foundations in hygrothermal environment. The elastic foundation is modeled as Pasternak’s type, which can be either isotropic or orthotropic and as a special case, it converges to Winkler’s foundation if the shear layer is neglected. The present FGM sandwich plate is assumed to be made of a fully ceramic core layer sandwiched by metal/ceramic FGM coats. The governing equations are derived from principle of virtual displacements based on a shear and normal deformations plate theory. The present theory takes into account both shear and normal strains effects, thus it predicts results more accurate than the shear deformation plate
theories. The results obtained by the shear and normal deformation theory are compared with those available in the literature and also with those obtained by other shear deformation theories. It is concluded that the present results are slightly deviated from other results because the normal deformation effect is taken into account. Numerical results are presented to show the effects of the different parameters, such as side-to-thickness ratio, foundation parameters, aspect ratio, temperature, moisture, power law index and core thickness on the stresses and displacements of the FG sandwich plates.


ABSTRACT: In this paper, a multi-objective multiparameter optimization procedure is developed by combining rigorously developed metamodels with an evolutionary search algorithm-Genetic Algorithm (GA). Response surface methodology (RSM) is used for developing the metamodels to replace the tedious finite element analyses. A nine-node isoparametric plate bending element is used for conducting the finite element simulations. Highly accurate numerical data from an author compiled FORTRAN finite element program is first used by the RSM to develop second-order mathematical relations. Four material parameters, $E_1$, $G_{12}$, $G_{23}$ and $\nu_{12}$ are considered as the independent variables while simultaneously maximizing fundamental frequency, $\lambda_1$ and frequency separation between the 1st and two natural modes, $\lambda_{21}$. The optimal material combination for maximizing $\lambda_1$ and $\lambda_{21}$ is predicted by using a multi-objective GA. A general sensitivity analysis is conducted to understand the effect of each parameter on the desired response parameters.


ABSTRACT: In this work, a novel hyperbolic shear deformation theory is developed for free vibration analysis of the simply supported functionally graded plates in thermal environment and the FGM having temperature dependent material properties. This theory has only four unknowns, which is even less than the other shear deformation theories. The theory presented is variationally consistent, without the shear correction factor. The present one has a new displacement field which introduces undetermined integral variables. Equations of motion are obtained by utilizing the Hamilton’s principles and solved via Navier’s procedure. The convergence and the validation of the proposed theoretical model are performed to demonstrate the efficacy of the model.


ABSTRACT: This research article reported the nonlinear finite solutions of the nonlinear flexural strength and stress behaviour of nano sandwich graded structural shell panel under the combined thermomechanical loading. The nanotube sandwich structural model is derived mathematically using the higher-order displacement polynomial including the full geometrical nonlinear strain-displacement equations via Green-Lagrange relations. The face sheets of the sandwich panel are assumed to be carbon nanotube-reinforced polymer composite with temperature dependent material properties. Additionally, the numerical model included different types of nanotube distribution patterns for the sandwich face sheets for the sake of variable strength. The required equilibrium equation of the graded carbon nanotube sandwich structural panel is derived by minimizing the total potential energy expression. The energy expression is further solved to obtain the
deflection values (linear and nonlinear) via the direct iterative method in conjunction with finite element steps. A computer code is prepared (MATLAB environment) based on the current higher-order nonlinear model for the numerical analysis purpose. The stability of the numerical solution and the validity are verified by comparing the published deflection and stress values. Finally, the nonlinear model is utilized to explore the deflection and the stresses of the nanotube-reinforced (volume fraction and distribution patterns of carbon nanotube) sandwich structure (different core to face thickness ratios) for the variable type of structural parameter (thickness ratio, aspect ratio, geometrical configurations, constraints at the edges and curvature ratio) and unlike temperature loading.

ABSTRACT: This paper deals with the maximization of the critical buckling load of simply supported antisymmetric angle-ply plates resting on Pasternak foundation subjected to compressive loads using teaching learning based optimization method (TLBO). The first order shear deformation theory is used to obtain governing equations of the laminated plate. In the present optimization problem, the objective function is to maximize the buckling load factor and the design variables are the fibre orientation angles in the layers. Computer programming is developed in the MATLAB environment to estimate optimum stacking sequences of laminated plates. A comparison also has been performed between the TLBO, genetic algorithm (GA) and differential evolution algorithm (DE). Some examples are solved to show the applicability and usefulness of the TLBO for maximizing the buckling load of the plate via finding optimum stacking sequences of the plate. Additionally, the influences of different number of layers, plate aspect ratios, foundation parameters and load ratios on the optimal solutions are investigated.

ABSTRACT: The paper describes the development of a two-dimensional (2D) co-rotational nonlinear beam finite element that includes advanced path-following capabilities for detecting bifurcation instability in elas-to-plasticity of steel elements subjected to fire without introducing imperfections. The advantage is twofold: i) no need to assume the magnitude of the imperfections and consequent reduction of the model complexity; ii) the presence of possible critical points is checked at each converged time step based on the actual load and stiffness distribution in the structure that is affected by the temperature field in the elements. In this way, the buckling modes at elevated temperature, that may be different from the ones at ambient temperature, can be properly taken into account. Moreover, an improved displacement predictor for estimating the displacement field allowed significant reduction of the computational cost. A co-rotational framework was exploited for describing the beam kinematic. In order to highlight the potential practical implications of the developed finite element, a parametric analysis was performed to investigate how the beam element compares both with the EN1993-1-2 buckling curve and with experimental tests on axially compressed steel members. Validation against experimental data and numerical outcomes obtained with commercial software is thoroughly described.

ABSTRACT: The Dynamic equations in the polar coordinates are drawn out using the MLPG method for the non-symmetric FG cylindrical shell. To simulate the mechanical properties of FGM, the nonlinear volume fractions for radial direction are used. The shape function applied in this paper is a form of the radial basis functions, by using this function all the requirements for an effective and suitable shape function are established. Hence in this study, the multi-quadratics (MQ) radial basis functions are exploited as the shape function governing the problem. The MLPG method is combined with the the Newmark time approximation scheme to solve dynamic equations in the time domain. The obtained results by the MLPG method to be verified are compared with the analytical solution and the FEM. The obtained results through the MLPG method show a good agreement in comparison to other results and the MLPG method has high accuracy for dynamic analysis of the non-symmetric FG cylindrical shell. To demonstrate the capability of the present method to dynamic analysis of the non-symmetric FG cylindrical shell, it is analyzed dynamically with different volume fraction exponents under harmonic and rectangular shock loading. The present method shows high accuracy, efficiency and capability to dynamic analysis of the non-symmetric FG cylindrical shell with nonlinear grading patterns.

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ABSTRACT: A new hybrid sandwich structure was developed by using carbon, e-glass, and s-glass fabrics as reinforcement materials, an epoxy resin as the matrix material for face sheets, and a PVC foam as the core material. Six different configurations were prepared. Sandwich composites plates with different stacking sequences were subjected to low-speed impacts will energies of 7.5, 15, and 22.5 J. Their impact response is analyzed and reported in terms of the peak load as a function of impact energy. After impact tests, 3-point bending tests were conducted to determine the bending behavior of the sandwich composites after impacts in terms of their flexural strength. The results obtained showed that the use of carbon fabrics in the face sheets increased the peak loads for all the impact energies considered. The presence of carbon fibers in skin regions increased the flexural strength of the composites, but e-glass fibers decreased this strength.

References listed at the end of the paper:


ABSTRACT: Variants of sandwich structural elements in the form of plates and shells with a transversely soft core are analyzed. Their outer, load-carrying layers are reinforced along their outer contour with elastic bars to ensure the transfer of loads to the layers during their interaction with other structural elements. For such structures, at small strains and moderate displacements, a refined geometrically nonlinear theory is constructed that allows one to describe their subcritical deformation and reveal all possible buckling modes (cophasal, antiphasal, mixed flexural, mixed shear-flexural, and arbitrary modes including all the listed ones) of the load-carrying layers and the reinforcing elements (flexural, shear-flexural, and pure shear ones at various subcritical stressstrain states). This theory is based on considering the interaction forces of outer layers with the core and of the layers and core with the reinforcing bars as unknowns. To derive the basic equations of static equilibrium, boundary conditions for the shell and stiffening bars, the conditions of kinematic conjunction of outer layers with the core and of the outer layers and core with the reinforcing bars, and the generalized Lagrange variational principle proposed earlier are utilized. The theory suggested differs from all known
variants by a high degree of accuracy and meaninglessness at a minimum number of unknown two-dimensional functions for the shells, one-dimensional functions for the reinforcing bars, and one and two-dimensional contact forces of interaction between structural elements.

References listed at the end of the paper:
ABSTRACT: The possibility of using the method of sampling surfaces (SaS) for solving the free vibration problem of three-dimensional elasticity for metal-ceramic shells is studied. According to this method, in the shell body, an arbitrary number of SaS parallel to its middle surface are selected in order to take displacements of these surfaces as unknowns. The SaS pass through the nodes of a Chebyshev polynomial, which improves the convergence of the SaS method significantly. As a result, the SaS method can be used to obtain analytical solutions of the vibration problem for metal-ceramic plates and cylindrical shells that asymptotically approach the exact solutions of elasticity as the number of SaS tends to infinity.

References listed at the end of the paper


ABSTRACT: A technique for numerically analyzing the dynamic strength of two-layer metal-plastic cylindrical shells under an axisymmetric internal explosive loading is developed. The kinematic deformation model of the layered package is based on a nonclassical theory of shells. The geometric relations are constructed using relations of the simplest quadratic version of the nonlinear elasticity theory. The stress and strain tensors in the composite macrolayer are related by Hooke’s law for an orthotropic body with account of degradation of the stiffness characteristics of the multilayer package due to local failure of some its elementary layers. The physical relations in the metal layer are formulated in terms of a differential theory of plasticity. An energy-correlated resolving system of dynamic equations for the metal-plastic cylindrical shells is derived by minimizing the functional of total energy of the shells as three-dimensional bodies. The numerical method for solving the initial boundary-value problem formulated is based on an explicit variational-difference scheme. The reliability of the technique considered is verified by comparing numerical results with experimental data. An analysis of the ultimate strains and strength of one-layer basalt-and glass-fiber-reinforced plastic and two-layer metal-plastic cylindrical shells is carried out.

References listed at the end of the paper:


ABSTRACT: The applicability of a structurally orthotropic model to the calculation of perforated plates and cylindrical shells subjected to tension and bending is studied by the finite-element method. The parameters of the orthotropic material are used in the form of coefficients of stiffness reduction. They are determined from the solution to the problem on deformation of a cyclically repeating structural element, with a varying degree of perforation (porosity), in tension, shear, and bending. The structural element is investigated by the methods of continuum mechanics and the theory of Timoshenko-type shells, and the limit of applicability of the theory of shells to such problems is found. The numerical results obtained are compared with the analytical estimates given by E. I. Grigolyuk and L. A. Fil'shtinskii. Verification of the numerically obtained orthotropic parameters is carried out based on the solution to the problem of bending of one quarter of a cylindrical strip and a plate perforated with one row of holes. It is shown that the approach chosen is applicable to perforated plates and shells in bending problems with waves whose length exceeds the characteristic size of their structural element. The stability of a perforated elastic cylindrical shell under external pressure, with two variants of boundary conditions, is investigated. Values of the critical pressure and the corresponding buckling modes in relation to the length of the shell and the degree of perforation are obtained.

References listed at the end of the paper:


**ABSTRACT:** Fiber-reinforced shells manufactured by winding bands of fiber rovings and a revision of the basic problems connected with their design are addressed in the article. The importance of fiber type and matrix properties for the damage process of such laminar shells and for establishing criteria of their design is investigated. Particular attention is given to the mechanism of shearing of their matrix layers, which leads to delamination. Practical recommendations for the design and manufacture of wound shells are formulated.

References listed at the end of the paper:

17. www.matweb.com/search/QickText.asp?SearchText=aramir
20. The resin characteristics of sheets of the Huntsman company.


**ABSTRACT:** This work deals with determination of the transverse shear moduli of a Nomex® honeycomb core of sandwich panels. Their out-of-plane shear characteristics depend on the transverse shear moduli of the honeycomb core. These moduli were determined experimentally, numerically, and analytically. Numerical simulations were performed by using a unit cell model and three analytical approaches. Analytical calculations showed that two of the approaches provided reasonable predictions for the transverse shear modulus as compared with experimental results. However, the approach based upon the classical lamination theory showed
large deviations from experimental data. Numerical simulations also showed a trend similar to that resulting from the analytical models.

References listed at the end of the paper:
· 10. H. Xie, W. Li, J. Zhao, and J. Tian, “Study on the out of plane shear properties of superalloy honeycomb core,” 18th Int. Conf. on Composite Materials.


ABSTRACT: A discrete layered damping model of a multilayer plate at small displacements and deformations, with account of the internal damping of layers according to the Thompson–Kelvin–Voight model, is presented. Based on the equations derived, an analytical solution to the static deformation problem for single-layer rectangular plate hinge-supported along its contour and subjected of a uniformly distributed pressure applied to one of its boundary planes is obtained. Its convergence to the three-dimensional solution is analyzed in relation to the dimension of mesh in the thickness direction of the plate. It is found that, for thin plates, the dimension of the problem formulated can be reduced on the basis of simplified hypotheses applied to each layer. An analytical solutions is also constructed for the forced vibrations of two- and three-layer rectangular plates hinged in the opening of an absolutely stiff dividing wall upon transmission of a monoharmonic sound wave through them. It was assumed that the dividing wall is situated between two absolutely stiff barriers; one of them, owing to the harmonic vibration with a given displacement amplitude of the plate, forms an incident sound wave, and the other is stationary and is coated by a energy-absorbing material with high damping properties. Behavior of the acoustic media in spaces between the deformable plate and the barriers is described by the classical wave equations based on the model of an ideal compressible fluid. To describe the process of dynamic deformation of the energy-absorbing coating of the fixed barrier, two-dimensional equations of motion are derived based on the model of a transversely soft layer, a linear approximation of displacement fields in the
thickness direction of the coating, and the account of damping properties of its material by using the hysteresis model. The effect of physical and mechanical parameters of the mechanical system considered and of frequency of the incident sound wave on the parameter of its sound insulation, and the characteristics of stress-strain state of the plate is investigated.


ABSTRACT: The frequency dependence for the dynamic elastic modulus of a Porcher 3692 CFRP at frequencies to 112.5 Hz is obtained from an experimental study on damped flexural vibrations of vertical cantilevered test specimens. A finite-element technique is developed for modeling the dynamic response of a long cantilevered carbon-fiber-plastic plate at resonant flexural vibrations according to the first vibration mode with account of internal damping, aerodynamic drag forces, and the frequency-dependent dynamic elastic modulus of the material. The damping properties of the plate are determined by the logarithmic decrement, which depends on the vibration amplitude of its free edge. Numerical experiments were carried out, which confirmed the accuracy of the technique. It is shown that the logarithmic decrement of the plate in the range of medium and high vibration amplitudes depends mainly on the aerodynamic drag forces.


ABSTRACT: Vibration and stability of hybrid composite plates with arbitrary initial stresses in hygrothermal environments are investigated. The governing equations, including the effects of moisture-caused, thermal, and initial stresses, are established based on the variational energy method. The influence of temperature and moisture on material properties of the hybrid composite plates is considered. The initial stress is taken to be a combination of a uniaxial load and pure bending. Example of an initially and hygrothermally stressed hybrid laminated plate with simply supported edges is solved. Effects of the layer thickness ratio, fiber volume fraction, initial stresses, temperature, and moisture concentration on the natural frequency and buckling load of hybrid composite plates are studied.


ABSTRACT: Concrete samples were manufactured and strengthened with a basalt FRP (BFRP) using two kinds of winding patterns (spiral and tight). The efficiency of common and temperature-resistant epoxy binders were studied. Some of the samples were encased in an external concrete shell for an additional protection of the FRP reinforcement during heating. Both plain and polypropylene-microfiber-reinforced concretes were used for the external casing. Stress-strain relations of the samples before and after heating were obtained. The effects of high temperatures on the integrity of concrete samples with a BFRP reinforcement was investigated.


ABSTRACT: Numerical methods for simulating hollow and foam-filled flax-fabric-reinforced epoxy tubular energy absorbers subjected to lateral crashing are presented. The crashing characteristics, such as the progressive failure, load–displacement response, absorbed energy, peak load, and failure modes, of the tubes
were simulated and calculated numerically. A 3D nonlinear finite-element model that allows for the plasticity of materials using an isotropic hardening model with strain rate dependence and failure is proposed. An explicit finite-element solver is used to address the lateral crashing of the tubes considering large displacements and strains, plasticity, and damage. The experimental nonlinear crashing load vs. displacement data are successfully described by using the finite-element model proposed. The simulated peak loads and absorbed energy of the tubes are also in good agreement with experimental results.

References listed at the end of the paper:
ABSTRACT: For an analysis of internal and external buckling modes of a monolayer inside or at the periphery of a layered composite, refined geometrically nonlinear equations are constructed. They are based on modeling the monolayer as a thin plate interacting with binder layers at the points of boundary surfaces. The binder layer is modeled as a transversely soft foundation. It is assumed the foundations, previously compressed in the transverse direction (the first loading stage), have zero displacements of its external boundary surfaces at the second loading stage, but the contact interaction of the plate with foundations occurs without slippage or delamination. The deformation of the plate at a medium flexure is described by geometrically nonlinear relations of the classical plate theory based on the Kirchhoff–Love hypothesis (the first variant) or the refined Timoshenko model with account of the transverse shear and compression (the second variant). The foundation is described by linearized 3D equations of elasticity theory, which are simplified within the framework of the model of a transversely soft layer. Integrating the linearized equations along the transverse coordinate and satisfying the kinematic joining conditions of the plate with foundations, with account of their initial compression in the thickness direction, a system of 2D geometrically nonlinear equations and appropriate boundary conditions are derived. These equations describe the contact interaction between elements of the deformable system. The relations obtained are simplified for the case of a symmetric stacking sequence.

References listed at the end of the paper:

ABSTRACT: A nonlinear finite element model is pre
sented by incorporating a modified Morse potential function to study the mechanical properties of armchair, zigzag, and chiral carbon nanotubes (CNTs). Different types of Stone–Wales defects in them are considered, and all they were found to reduce the tensile mechanical characteristics of CNTs.

References listed at the end of the paper:


ABSTRACT: On the basis of constitutive equations of the Rabotnov nonlinear hereditary theory of creep, the problem on the rheonomic flexural behavior of layered plates with a regular structure is formulated. Equations allowing one to describe, with different degrees of accuracy, the stress-strain state of such plates with account of their weakened resistance to transverse shear were obtained. From them, the relations of the nonclassical Reissner and Reddy type theories can be found. For axially loaded annular plates clamped at one edge and loaded quasistatically on the other edge, a simplified version of the refined theory, whose complexity is comparable to that of the Reissner and Reddy theories, is developed. The flexural strains of such metal-composite annular plates in short-term and long-term loadings at different levels of heat action are calculated. It is shown that, for plates with a relative thickness of order of 1/10, neither the classical theory, nor the traditional nonclassical Reissner and Reddy theories guarantee reliable results for deflections even with the rough 10% accuracy. The accuracy of these theories decreases at elevated temperatures and with time under long-term loadings of structures. On the basis of relations of the refined theory, it is revealed that, in bending of layered metal-composite heat-sensitive plates under elevated temperatures, marked edge effects arise in the neighborhood of the supported edge, which characterize the shear of these structures in the transverse direction.


ABSTRACT: One-dimensional linearized problems on the possible buckling modes of an internal or peripheral layer of unidirectional multilayer composites with rectilinear fibers under compression in the fiber direction are considered. The investigations are carried out using the known Kirchhoff–Love and Timoshenko models for the layers. The binder, modeled as an elastic foundation, is described by the equations of elasticity theory, which are simplified in accordance to the model of a transversely soft layer and are integrated along the transverse coordinate considering the kinematic coupling relations for a layer and foundation layers. Exact analytical solutions of the problems formulated are found, which are used to calculate a composite made of an HSE 180 REM prepreg based on a unidirectional carbon fiber tape. The possible buckling modes of its internal and peripheral layers are identified. Calculation results are compared with experimental data obtained earlier. It is concluded that, for the composite studied, the flexural buckling of layers in the uniform axial compression of specimens along fibers is impossible — the failure mechanism is delamination with buckling of a fiber bundle according to the pure shear mode. It is realized (due to the low average transverse shear modulus) at the value of the ultimate compression stress equal to the average shear modulus. It is shown that such a shear buckling mode can be identified only on the basis of equations constructed using the Timoshenko shear model to describe the deformation process of layers.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: A stereomicroscope, microscopic metallograph, scanning electron microscope, and the ANSYS/LS-DYNA 3D finite-element code were employed to investigate the failure and energy absorption mechanism of two-layer steel/aluminum and three-layer steel/aluminum/steel and aluminum/steel/aluminum explosively welded composite plates impacted by spherical fragments. The effects of layer number, target order, and the combination state of interfaces on the failure and energy absorption mechanism are analyzed based on experimental and numerical results. Results showed that the effect of the combination state of interfaces on the failure mode was pronounced the most compared with other factors. The failure mechanism of the front and middle plates were shearing and plugging, and that of rear plate was ductile deformation when the tied interface failed by tension (or by shearing and plugging when the interface combination remained connected). A narrow adiabatic shear band was formed in the locally yielding plate damaged by shearing and plugging during the penetration process. The amount of energy needed to completely perforate the three-layer composite target was greater than that for a two-layer composite target with the same areal density and total thickness. The protective performance of the steel/aluminum/steel target was better than that of the aluminum/steel/aluminum target with the same areal density.

ABSTRACT: Forced vibrations of a two-layer orthotropic shell, with incomplete contact conditions between layers, when the upper face of the shell is free and the lower one is subjected to a dynamic action are considered. By an asymptotic method, the solution of the corresponding dynamic equations and correlations of a 3D problem of elasticity theory is obtained. The amplitudes of forced vibrations are determined, and resonance conditions are established.

References listed at the end of the paper:
ABSTRACT: In order to determine the nonlocal critical buckling loads of chiral double-walled carbon nanotubes embedded in an elastic medium, the nonlocal Timoshenko beam theory is implemented. The solution for the nonlocal critical buckling loads is obtained using governing equations of the nonlocal theory. The effect of the elastic medium, the buckling mode number, chirality, and aspect ratio on the nonlocal critical buckling loads of double-walled carbon nanotubes are studied and discussed. The Young’s modulus of three types of double-walled carbon nanotubes, with armchair, zigzag, and chiral tubules, are calculated based on molecular dynamics simulations. The nonlocal critical buckling loads in relation to the chirality of double-walled carbon nanotubes, buckling mode number, and length-to-diameter (aspect) ratio, in the presence and absence of an elastic medium, are examined.

References listed at the end of the paper:
ABSTRACT: A hydroviscoelastic system consisting of a viscoelastic plate and a half-plane filled with a viscous fluid is considered. The effect of viscosity of the fluid on the frequency response of the system and its dependence on the rheological parameters of plate material are estimated. The problem on forced vibrations of the system in the plane strain state is investigated using the exact equations of viscoelastodynamics for describing the motion of the plate and linearized Navier-Stokes equations for describing the flow of the fluid. The results found in the cases of nonviscous compressible and Newtonian compressible viscous fluids are compared.

ABSTRACT: A refined vibration equation of a rectangular membrane is derived in this paper. It allows determining the natural frequencies as functions of the mechanical characteristics of an asymmetrically stretched membrane. The dynamic equation is generalized to the case of a nonlinearly deformable isotropic on the average composite material. An approximate analytical solution of the problem is found employing a new homogenization technique. This method is based on estimation of the effective deformation characteristics of the composite material. The range of its effective characteristics is obtained from the rule of mixtures for the stresses and strains found assuming Voigt and Reuss hypotheses. The nonlinear behavior of the material is modeled using the bilinear Prandtl diagrams as constitutive equations for components of the composite. The effective elastic moduli, hardening modulus, yield stress, and the natural frequencies as functions of elastoplastic characteristics of the composite are obtained analytically in a closed form.


ABSTRACT: The necessity for considering both strength criteria and postbuckling effects in calculating the load-carrying capacity in compression of thin-wall composite structures with impact damage is substantiated. An original applied method ensuring solution of these problems with an accuracy sufficient for practical design tasks is developed. The main advantage of the method is its applicability in terms of computing resources and the set of initial data required. The results of application of the method to solution of the problem of compression of fragments of thin-wall honeycomb panel damaged by impacts of various energies are presented. After a comparison of calculation results with experimental data, a working algorithm for calculating the reduction in the load-carrying capacity of a composite object with impact damage is adopted.

References listed at the end of the paper:

5. A. E. Ushakov, Methodology for Ensuring the Operational Survivability and Safety of Aircraft Structures Made of Polymer Composite Materials [in Russian], Fizmatlit, Moscow (2012).
ABSTRACT: The structures of two types of unidirectional fiber-reinforced composites — with an ELUR-P carbon fiber tape, an XT-118 cold-cure binder with an HSE 180 REM prepreg, and a hot-cure binder — were investigated. The diameters of fibers and fiber bundles (threads) of both the types of composites were measured, and their mutual arrangement was examined both in the semifinished products (in the uncured state) and in the finished composites. The defects characteristic of both the types of binder and manufacturing technique were detected in the cured composites. Based on an analysis of the results obtained, linearized problems on the internal multiscale buckling modes of an individual fiber (with and without account of its interaction with the surrounding matrix) or of a fiber bundle are formulated. In the initial state, these structural elements of the fibrous composites are in a subcritical (unperturbed) state under the action of shear stresses and tension (compression) in the transverse direction. Such an initial stress state is formed in them in tension and compression tests on flat specimens made of off-axis-reinforced composites with straight fibers. To formulate the problems, the equations derived earlier from a consistent variant of geometrically nonlinear equations of elasticity theory by reducing them to the one-dimensional equations of the theory of straight rods on the basis of a refined Timoshenko shear model with account of tensile-compressive strains in the transverse direction are used. It is shown that, in loading test specimens, a continuous rearrangement of composite structure can occur due to the realization and continuous change of internal buckling modes as the wave-formation parameter varies continuously, which apparently explain the decrease revealed in the tangential shear modulus of the fibrous composites with increasing shear strains.

References listed at the end of the paper:


ABSTRACT: Deformation of a piecewise cylinder under the action of rotation is investigated. The cylinder consists of an elastic matrix with circular fibers of square cross section made of a more rigid elastic material and arranged doubly periodically in the cylinder. Behavior of the cylinder under large displacements and deformations is examined using the equations of a nonlinear elasticity theory for cylinder constituents. The problem posed is solved by the finite-difference method using the method of continuation with respect to the rotational speed of the cylinder.

References listed at the end of the paper:


ABSTRACT: The plastic indentation response of circular sandwich panels loaded by the flat end of a cylinder is investigated employing a velocity field model. Using the principles of virtual velocities and minimum work, an expression for the indenter load in relation to the indenter displacement and displacement field of the deformed face sheet is derived. The analytical solutions obtained are in good agreement with those found by simulations using the ABAQUS code. The radial tensile strain of the deformed face sheet and the ratio of energy absorption rate of the core to that of the face sheet are discussed.

References listed at the end of the paper:
References listed at the end of the paper:


ABSTRACT: The boundary-value problem of axisymmetric deformation of an elastic circular sandwich plate asymmetric across its thickness under the action of local loads is formulated. The effect of a temperature field on the stress-strain state (SSS) of the plate is considered. To describe its kinematics, the hypotheses of broken normal are adopted, assuming Bernoulli hypotheses in the thin external layers and the Tymoshenko hypothesis in the filler incompressible across its thickness. The work of filler in the tangential direction is taken into account. The equilibrium equations are derived using the variational method. An analytical solution of the boundary-value problem is obtained in the general case of loading of the plate by an axisymmetric surface load. The cases of local circular, annular, and linear loads are considered. A numerical analysis of SSS is performed for a plate hinged along its contour.


ABSTRACT: The finite-layer method is extended to the layered composite structures with partially bonded layers with different geometric characteristics. This makes it possible to perform a strength analysis of objects of more complex forms. The purpose of the study was to calculate the interface stresses arising in joints of composite parts and the transverse normal and tangential stresses in composite layers. Their values are necessary to estimate both the bond strength of the parts and the possibility of occurrence of internal delaminations in the composite.


ABSTRACT: An initial-boundary-value problem is formulated for the dynamic deformation of flexible reinforced shallow shells made of composite materials whose components are nonlinearly elastic. The geometric nonlinearity is taken into account in the Karman approximation. The resulting equations allow one, with different degrees of accuracy, to determine the strain state of such thin-wall structures with account of their
weakened resistance to transverse shears. The relations of the traditional nonclassical Reddy theory follow from these equations as a special case. Numerical integration of the problem stated is carried out on the basis of the method of steps in time by using an explicit “cross”-type scheme. Thin shallow spherical shells and flexible annular plates are considered. They are reinforced in the radial and circumferential directions, contain an absolutely rigid insert, and are clamped along the outer edge. The dynamic behavior of such structures is studied in relation to the level of pressure caused by the blast of air waves and to the form (convex or concave of the face) to which this pressure is applied. It is revealed that, at time intervals exceeding 0.1 s, mechanical behavior of the reinforced shallow shells and plates calculated by the Reddy theory significantly differs from the dynamic response determined according to the refined theory proposed.

R. Azarafza, “Fabrication, experimental modal testing, and a numerical analysis of composite sandwich structures with a grid-stiffened core”, Mechanics of Composite Materials, Vol. 54, No. 4, pp 537-544, September 2018

ABSTRACT: Composite sandwich structures with a grid-stiffened core (SSGSC) are one of the new structural configurations employed in advanced industries, and therefore the knowledge of their dynamic characteristics is very important. Hence, in the present study, three composite SSGSC samples of glass/epoxy and carbon/epoxy were fabricated by the hand lay-up method using a silicon rubber die. Also, two metallic samples — a monolithic one and a SSGSC, made of Aluminum 1050, were fabricated. The core of the aluminum SSGSC was produced using the wire cutting process, and the face sheets were attached using a high-grade adhesive. Modal experiments were carried out on all the samples using B&K vibration equipment. The frequency, mode shape, and damping coefficients were obtained from each experiment. Finally, a numerical modal analysis was performed, and good agreement between experimental and numerical results was obtained.

References listed at the end of the paper:

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ABSTRACT: The present study explores the modification and control of prebuckling stiffness of cylindrical shells for their potential use in smart structures. The effects of surface-bonded microfiber composite actuator patches on cylindrical shells subjected to axial compression are studied experimentally. The actuators are placed such that the distance separating them is less than the observed axial and circumferential buckling wavelengths. Strain gauge sensors are used to measure the axial strains at discrete locations on the cylindrical shell. Experimental results indicate that the actuation effect can reduce the local strains as well as improve the overall stiffness of the structure. The results obtained in this study potentially have a significant impact in space applications.

References listed at the end of the paper:


ABSTRACT: The present work deals with the evaluation of elastic properties and dynamic analyses of thin hybrid composite shell structures, which consist of conventional carbon fiber as the reinforcing phase and multiwalled carbon nanotubes-based polymer as the matrix phase. The Mori-Tanaka and strength of material method has been implemented to determine the elastic properties of such hybrid composite structures without and with considering agglomerations. An eight-noded shell element, which considers stress resultant-type Koiter's shell theory and transverse shear effect as per Mindlin's hypothesis having five degrees of freedom at each node, has been utilized for discretizing and analysis of such hybrid shell structures. The Rayleigh damping model has been implemented in order to study the effect of carbon nanotubes (CNTs) on damping capacity of such hybrid composite shell structures. Different types of spherical shell panels have been analyzed in order to study the time and frequency responses. Results show that the elastic properties as well as damping properties of such hybrid composite structures improved with the addition of CNTs as compared to conventional carbon fiber reinforced composites laminates; effects of some important parameters on the vibration characteristic of such hybrid composite shell structures have also been presented. The effects of agglomeration parameters on the
elastic properties and their influences on the dynamic responses considering different layers and stacking sequences have also been investigated.

References listed at the end of the paper:


ABSTRACT: Thermal post-buckling analysis is first presented for functionally graded elliptical plates based on high-order shear deformation theory in different thermal environments. Material properties are assumed to be temperature-dependent and graded in the thickness direction. Ritz method is employed to determine the central deflection-temperature curves, the validity of which can be confirmed by comparison with related researchers' results; it is worth noting that the forms of approximate solutions are well chosen in consideration of both simplicity and accuracy. Influences played by different supported boundaries, thermal environmental conditions, ratio of major to minor axis, and volume fraction index are discussed in detail.


ABSTRACT: The dynamic instability of functionally graded material (FGM) sandwich plates under an arbitrary periodic load in a thermal environment is studied. The sandwich plate is made up of two layers of FGM face sheets and one layer of homogeneous metal core. The properties of a FGM layer vary continuously across the thickness according to a simple power law. A set of differential equations of Mathieu type is formed to determine the dynamic instability regions based on Bolotin's method. The dynamic stability of the FGM sandwich plates is sensitive to the temperature rise, volume fraction index, thickness ratio, and static and dynamic load factor.


ABSTRACT: In this article, a three-dimensional solution is presented for the bending analysis of functionally graded and layered neutral magneto-electro-elastic plates resting on two-parameter elastic foundations, considering imperfect interfacial bonding. The equations of motion, Gauss's equations for electrostatics and magnetostatics, and boundary and interface conditions are satisfied exactly regardless of the number of layers.
No assumptions on deformations, stresses, and magnetic and electric fields along the thickness direction are introduced. The interfacial imperfection is modeled using a generalized spring layer. The state-space method is employed for solving the governing partial differential equations. Effects of a two-parameter elastic foundation, gradient index, bonding imperfection, and applied mechanical and electrical loads on the response of the functionally graded magneto-electro-elastic plate are discussed. The obtained exact solution can serve as a benchmark for assessing the accuracy of layered functionally graded magneto-electro-elastic plate theories.

ABSTRACT: This article aims to investigate stability and vibration behavior of carbon nanotube-reinforced composite beams supported by classical and nonclassical boundary conditions. To include significant effects of shear deformation and rotary inertia, Timoshenko beam theory is used to formulate the coupled equations of motion governing buckling and vibration analyses of the beams. An effective mathematical technique, namely Chebyshev collocation method, is employed to solve the coupled equations of motion for determining critical buckling loads and natural frequencies of the beams with different boundary conditions. The accuracy and reliability of the proposed mathematical models are verified numerically by comparing with the existing results in the literature for the cases of classical boundary conditions. New results of critical buckling loads and natural frequencies of the beams with nonclassical boundary conditions including translational and rotational springs are presented and discussed in detail associated with many important parametric studies.

ABSTRACT: The size-dependent effect on free vibration of double-bonded isotropic piezoelectric Timoshenko microbeams using strain gradient and surface stress elasticity theories under initial stress is presented. This article is developed for isotropic piezoelectric material. Due to the high surface-to-volume ratio, surface stress has an important role with micro- and nanoscale materials. Thus, the Gurtin–Murdoch continuum mechanic approach is used. Governing equations of motion are derived by Hamilton's principle and solved by the differential quadrature method. The effects of pre-stress load, surface residual stress, surface mass density, surface piezoelectrics, Young's modulus of surface layers, three material length scale parameters, thickness to material length scale parameter ratios, various boundary conditions, and two elastic foundation coefficients are investigated. It is concluded that the effect of pre-stress load in greater modes is negligible for higher aspect ratios and this effect is similar to lower aspect ratios. Also, the size-dependent effect on the dimensionless natural frequency for strain gradient theory is higher than that for modified couple stress theory and classical theory, which is due to increasing stiffness of the Timoshenko microbeam model. Moreover, the results show that dimensionless natural frequency affects more by considering the material length scale parameters with respect to surface effect. The results are compared with the obtained results from the literature and show good agreement between them. It is concluded that the amplitude of the transverse displacements ($w_0$) for a microbeam (MB) is more than the transverse displacements ($w_1$) for a piezoelectric microbeam (PMB). On the other hand, using a piezoelectric layer for PMB, the amplitude of the transverse displacements ($w_1$) reduces considerably with respect to MB, in which this effect leads to increase the stiffness of the microbeam and stability of microstructures. With considering the piezoelectric layer, the obtained results can be used to control the amplitude and vibration of microstructures, prevent the resonance phenomenon, design smart structures, and can be employed for micro-electro-mechanical systems and nano-electro-mechanical systems.
ABSTRACT: This article deals with experimental and finite element studies on the buckling of isotropic and laminated composite skew plates with circular holes subjected to uniaxial compression. The influence of skew angle, fiber orientation angle, laminate stacking sequence, and aspect ratio on critical buckling load are evaluated using the experimental method (using Methods I through V) and finite element method using MSC/NASTRAN. Method I yields the highest experimental value and Method IV the lowest experimental value for critical buckling load in the case of isotropic skew plates with circular holes. For all laminate stacking sequences considered, Method V yields the highest experimental value for critical buckling load for skew angle = 0° and Method IV yields the highest experimental value for critical buckling load for skew angles = 15° and 30°. For all laminate stacking sequences and skew angles considered, Method II yields the lowest experimental value for critical buckling load. The maximum discrepancy between the experimental values given by Method IV and the finite element solution is about 10% in the case of isotropic skew plates. The maximum discrepancy between the experimental values given by Method II and the finite element solution is about 21% in the case of laminated composite skew plates considered. The percentage of discrepancy between the numerical or finite element solution and experimental value increases as the skew angle increases. The critical buckling load decreases as the aspect ratio increases.

ABSTRACT: Based on Reddy's higher-order shear deformation plate theory, this article presents an analysis of the nonlinear dynamic response and vibration of imperfect functionally graded material (FGM) thick plates subjected to blast and thermal loads resting on elastic foundations. The material properties are assumed to be temperature-dependent and graded in the thickness direction according to a simple power-law distribution in terms of the volume fractions of the constituents. Numerical results for the dynamic response and vibration of the FGM plates with two cases of boundary conditions are obtained by the Galerkin method and fourth-order Runge–Kutta method. The results show the effects of geometrical parameters, material properties, imperfections, temperature increment, elastic foundations, and boundary conditions on the nonlinear dynamic response and vibration of FGM plates.

ABSTRACT: In this article various sinusoidal shear deformation theories are used for the buckling analysis of functionally graded sandwich plates. The theories may account for through-the-thickness deformations and/or zig-zag effect. The governing equations and boundary conditions are derived using the Principle of Virtual Work under a generalization of Carrera’s Unified Formulation and further interpolated by collocation with radial basis functions. A numerical investigation has been conducted on the buckling analysis of sandwich plates with functionally graded skins. The influence of the thickness stretching and the zig-zag effects on these problems is investigated. Numerical results demonstrate the accuracy of the present approach.

References listed at the end of the paper:


ABSTRACT: The article focuses on the implementation of the sampling surfaces (SaS) concept for the three-dimensional (3D) coupled steady-state thermoelectroelastic analysis of layered and functionally graded (FG) piezoelectric shells subjected to thermal loading. The SaS formulation is based on choosing inside the nth layer $I_n$, not equally spaced SaS parallel to the middle surface, in order to introduce the temperatures, electric potentials, and displacements of these surfaces as basic shell variables. Such choice of unknowns with the consequent use of Lagrange polynomials of degree $I_n - 1$ in the assumed distributions of the temperature, electric potential, displacements, and mechanical properties through the thickness of the layer leads to the robust FG piezoelectric shell formulation. The SaS are located inside each layer at Chebyshev polynomial
nodes, which permits one to minimize uniformly the error due to the Lagrange interpolation. As a result, the SaS formulation can be applied efficiently to deriving the analytical solutions for FG piezoelectric shells, which asymptotically approach the 3D exact solutions of thermoelectroelasticity as the number of SaS tends to infinity.


ABSTRACT: In this study, a simple $C_0$ isoparametric finite element formulation based on higher-order shear deformation theory is presented for static analysis of functionally graded material sandwich shells (FGMSS). To characterize the membrane-flexure behavior observed in a functionally graded shell, a displacement field involving higher-order terms in in-plane and transverse fields is considered. The proposed kinematics field incorporates for transverse normal deformation, transverse shear deformation, and nonlinear variation of the in-plane displacement field through the thickness to predict the overall response of the shell in an accurate sense. To develop the efficient $C_0$ formulation, the derivatives of transverse displacement are treated as independent field variables (nodal unknowns). Voigt’s rule of mixture is employed to ascertain the mechanical properties of each layer’s constituents along the thickness direction. A wide range of numerical problems are solved assuming various parameters: side-thickness ratio, curvature-side ratio, and gradation parameter, and their interactions with regard to static analysis of FGMSS are discussed in brief. Deflection and stresses incorporating different thickness schemes of sandwich shells are presented in the form of figures. To validate the results, a functionally graded shell without sandwich arrangement is considered. Since no results are available on static analysis of FGMSS, the present 2D model based on the finite element method might be helpful in assessing the applicability of other analytical and numerical models in this area in the future.

References listed at the end of the paper:


ABSTRACT: In this article, the vibration frequency of an orthotropic nanoplate under the effect of temperature change is investigated. Using nonlocal elasticity theory, governing equations are derived. Based on the generalized differential quadrature method for cantilever and propped cantilever boundary conditions, the frequencies of orthotropic nanoplates are considered and the obtained results are compared with valid reported results in the literature. The effects of temperature variation, small scale, different boundary conditions, aspect ratio, and length on natural nondimensional frequencies are studied. The present analysis is applicable for the design of rotating and nonrotating nano-devices that make use of thermo-mechanical vibration characteristics of nanoplates.


ABSTRACT: A unified formulation of Reissner's mixed variational theorem-based finite cylindrical layer methods is developed for the static analysis of simply-supported, multilayered functionally graded piezoelectric material (FGPM) circular hollow cylinders. The material properties of the cylinder are assumed to obey an exponent-law exponentially varying through the thickness coordinate of this. The trigonometric functions and Lagrange polynomials are used to interpolate the in-surface and thickness variations of the primary variables of each individual layer, respectively. The coupled electro-elastic effects on the static behaviors of multilayered FGPM cylinders are closely examined.

References listed at the end of the paper:


ABSTRACT: Conventional loading with a composite plate has a very small moment of inertia due to its low height, and it was solved by shear deformation and other approaches. In the present study, a thin cross-ply $0^\circ/90^\circ/0^\circ$ laminated composite plate is erected to increase its height, which increases its moment of inertia with load; increased moments of inertia of the plate increase its load-carrying capacity in a real structure. Finite difference solutions of a cross-ply $0^\circ/90^\circ/0^\circ$ laminated plate made of T-300 carbon/epoxy are obtained using displacement potential approach. The plate behaves like a cantilever beam; one end of the plate is rigidly fixed and a uniformly distributed load is applied on its top span. The displacement potential approach is extended using the lamination theory of composite materials and plane stress concept. The different equivalent displacement, strain, and stress components at different sections of the plate with its deformed shape are discussed. Using the concept of the classical theory of laminations, different stress components along the lamina and inter-laminar regions are obtained. Besides to verify the reliability and soundness of the present numerical approach, the solutions of the present problem are compared with those of the finite element method.


ABSTRACT: High specific strength and stiffness are characteristics desired for aircraft and launch vehicle domains to enhance the payload gain and performance. The mechanical properties of the composites can be further tailored by embedding structural components, such as shape memory alloys, into the passive composite structure. The present study is primarily focused on the nonlinear free vibration analysis of spherical and...
cylindrical composite shell panels embedded with shape memory alloy fibers. The nonlinear finite element governing equations based on the higher-order shear deformation plate theory and principle of virtual work with nonlinear von-Karman strain displacement relations are employed for the analysis. The temperature-dependent material properties of shape memory alloy are considered in the formulation. A nine-noded isoparametric element is accounted for synthesizing the element for the finite formulation. The Young’s modulus and the recovery stress vary with temperature and higher nonlinearity. The incremental method is used to generate the inputs for the temperature-dependent nonlinear properties of materials. The temperature change is divided by many small temperature increments. The temperature-dependent material properties are assumed constant during the small increment. The mechanics of shape memory alloy in substrate are presented and the governing equation of laminated composite with shape memory alloy is obtained and implemented in the MATLAB 7.8 program.

References listed at the end of the paper:

- M. Tawfik, Suppression of post buckling deflection and panel flutter using shape memory alloy, MSc thesis, Aerospace Department, Old Dominion University, Norfolk, VA, 1999.
ABSTRACT: In this article, the small-scale effect on the vibration behavior of orthotropic single-layered graphene sheets is studied based on the nonlocal Reddy's plate theory embedded in elastic medium considering initial shear stress. Elastic theory of the graphene sheets is reformulated using the nonlocal differential constitutive relations of Eringen. To simulate the interaction between the graphene sheet and surrounding elastic medium we used both Winkler-type and Pasternak-type foundation models. The effects of initial shear stress and surrounding elastic medium and boundary conditions on the vibration analysis of orthotropic single-layered graphene sheets are studied considering five different boundary conditions. Numerical approach of the obtained equation is derived by differential quadrature method. Effects of shear stress, nonlocal parameter, size of the graphene sheets, stiffness of surrounding elastic medium, and boundary conditions on vibration frequency rate are investigated. The results reveal that as the stiffness of the surrounding elastic medium increases, the nonlocal effect decreases. Further, the nonlocal effect increases as the size of the graphene sheet is decreased. It is also found that the frequency ratios decrease with an increase in vibration modes.

ABSTRACT: Interlaminar stresses in thick a composite cylinder with general layer stacking subjected to uniform and nonuniform distributed radial pressure are studied. The layerwise theory of Reddy is employed for formulation of the problem. An analytical method is presented for solving the governing equations. To increase accuracy, interlaminar stresses are obtained by integrating the equilibrium equation of elasticity. After a convergence study, the accuracy of the layerwise laminate theory is investigated using the predictions of finite element method. Predictions of Hooke's law and integration method for interlaminar stresses are compared. Uniform and nonuniform internal and external loads are considered and a parametric study is done for various cylinders.

ABSTRACT: This article proposes a higher-order shear deformation beam theory for free vibration analysis of functionally graded carbon nanotube-reinforced composite sandwich beams in a thermal environment. The temperature-dependent material properties of functionally graded carbon nanotube-reinforced composite beams are supposed to vary continuously in the thickness direction and are estimated through the rule of mixture. The governing equations and boundary conditions are derived by using Hamilton's principle, and the Navier solution procedure is used to achieve the natural frequencies of the sandwich beam in a thermal environment. A parametric study is led to carry out the effects of carbon nanotube volume fractions, slenderness ratio, and core-to-face sheet thickness ratio on free vibration behavior of sandwich beams with functionally graded carbon nanotube-reinforced composite face sheets. Numerical results are also presented in order to compare the
behavior of sandwich beams including uniformly distributed carbon nanotube-reinforced composite face sheets to those including functionally graded carbon nanotube-reinforced composite face sheets.

ABSTRACT: In this article, an analytical method is presented for thermo-mechanical vibration analysis of functionally graded (FG) nanoplates with different boundary conditions under various thermal loadings including uniform, linear, and nonlinear temperature rise via a four-variable plate theory considering neutral surface position. The temperature-dependent material properties of FG nanoplate vary gradually along the thickness according to the Mori-Tanaka homogenization scheme. The exactness of solution is confirmed by comparing obtained results with those provided in the literature. A parametric study is performed investigating the effects of nonlocal parameter, temperature fields, gradient index, and boundary conditions on vibration behavior of FG nanoplates.

ABSTRACT: The present article deals with free vibration of functionally graded fiber orientation rectangular plates considering temperature effect. Three different types of fiber orientation distributions through the thickness of the plate are proposed. The properties of the plate are assumed to be temperature-dependent. Equations of motions are derived based on a three-dimensional theory of elasticity. General differential quadrature method is used to discretize these equations. Effects of temperature, fiber orientation, and boundary conditions besides some geometric parameters are presented. Also, some interesting conclusions are obtained since temperature and functionality of a functionally graded plate have a significant effect on the natural frequency of the plate.

ABSTRACT: The free vibration of the functionally graded isosceles triangular microplates in thermal environments is investigated. The modified strain gradient theory together with the first-order shear deformation theory of plates is adopted to formulate the problem. The material properties are assumed to be graded in the thickness direction. The Chebyshev–Ritz method is chosen as the solution procedure. After demonstrating the fast rate of convergence and accuracy of the method, the effects of temperature rise, length scale parameters, material gradient index, different boundary conditions, apex angle, and width-to-thickness ratio on the free vibration of triangular microplates are studied.

ABSTRACT: The objective of this article is to present a Fourier-Ritz method-based solution approach for the free vibration analysis of moderately thick, functionally graded (FG) rectangular plates with general boundary restraints and internal line supports. Under the current framework, regardless of boundary conditions, each of the displacements and rotations of the FG plates is invariantly expressed as a modified Fourier series in both
directions. Then, the accurate solutions are obtained using the Ritz procedure based on the energy function of the plates. The convergence and accuracy of the present method are verified by a considerable number of convergence tests and comparisons.


ABSTRACT: Many experimental observations have shown that most nanostructures, such as carbon nanotubes, are often characterized by a certain degree of waviness along their axial direction. This geometrical imperfection has profound effects on the mechanical behavior of carbon nanotubes. In the present work, stability of a slightly curved carbon nanotube under lateral loading is investigated based on Eringen's nonlocal elasticity theory. Euler Bernoulli and Timoshenko beam theories are employed to obtain equilibrium equations. Winkler-Pasternak elastic foundation is used to approximate the effect of matrix. Effects of initial curvature, nonlocal parameter, beam length, and elastic foundation parameters on initiation of critical conditions are investigated.

References listed at the end of the paper:

ABSTRACT: Here, free vibration analysis of functionally graded piezoelectric (FGP) plates with porosities is carried out based on refined four-unknown plate theory. The present plate theory captures shear deformation impacts needless of shear correction factor. A modified power-law model is adopted to describe the graded material properties of a functionally graded piezoelectric plate. Implementing an analytical approach, which satisfies different boundary conditions, governing equations derived from Hamilton's principle are solved. The obtained results are compared with those provided in the literature. The impacts of applied voltage, porosity distribution, material graduation, plate geometrical parameters, and boundary conditions on vibration of porous FGP plate are discussed.


ABSTRACT: Bent and straight hetero-junction carbon nanotubes and their constructive homogeneous tubes were modeled based on the finite element method in their perfect and atomically defective forms with silicon impurities and carbon vacancies, and their buckling behavior was investigated. The results showed that the buckling strength of hetero-junction carbon nanotubes, which depends on the size of their kink and their constructive tubes' diameters, lies in the range of their constructive tubes' buckling strength. Armchair-armchair and zigzag-zigzag models also demonstrated higher buckling strength than the other hetero-junction models. Finally, the atomic defects were seen to considerably decrease the buckling strength of these nanomaterials.

References listed at the end of the paper:


ABSTRACT: Small scale effects in the functionally graded beam are investigated by using various nonlocal higher-order shear deformation beam theories. The material properties of a beam are supposed to vary according to power law distribution of the volume fraction of the constituents. The nonlocal equilibrium equations are obtained and an exact solution is presented for vibration analysis of functionally graded (FG) nanobeams. The accuracy of the present model is discussed by comparing the results with previous studies and a parametric investigation is presented to study the effects of power law index, small-scale parameter, and aspect ratio on the vibrational behavior of FG nanostructures. Small scale effects in the functionally graded beam are investigated by using various nonlocal higher-order shear deformation beam theories. The material properties of a beam are supposed to vary according to power law distribution of the volume fraction of the constituents. The nonlocal equilibrium equations are obtained and an exact solution is presented for vibration analysis of functionally graded (FG) nanobeams. The accuracy of the present model is discussed by comparing the results with previous studies and a parametric investigation is presented to study the effects of power law index, small-scale parameter, and aspect ratio on the vibrational behavior of FG nanostructures.

ABSTRACT: Vibration smart control analysis of a temperature-dependent functionally graded-carbon nanotube-reinforced piezoelectric cylindrical shell embedded in an orthotropic elastic medium is investigated. The mixture law is used for obtaining the material properties of the structure. The structure is subjected to a 2D magnetic field. Considering the first-order shear deformation theory, the motion equations are obtained. Based on an analytical method and differential quadrature method, the frequency is calculated. The effects of applied voltage, magnetic field, volume percent, and distribution type of carbon nanotubes, temperature, orthotropic elastic medium, and length to radius ratio of the shell are shown on system frequency.

References listed at the end of the paper:


ABSTRACT: This article presents an analytical investigation on the free vibration behavior of rotating functionally graded truncated conical shells reinforced by stringers and rings with the change of spacing between stringers. Using the Donnell shell theory, smeared stiffeners technique, and taking into account the influences of centrifugal force and Coriolis acceleration, the governing equations are derived. These variable coefficient partial differential equations are studied by the Galerkin method. The sixth-order polynomial equation of natural frequency is obtained. Numerical results show effects of stiffener and input parameters on the frequency of shell.

References listed at the end of the paper:

Y.X. Hao, S.W. Yang, W. Zhang, M.H. Yao an A.W. Wang, “Flutter of high-dimension nonlinear system for a FGM truncated conical shell, Mechanics of Advanced Materials and Structures, Vol. 25, No. 1, pp 47-61, 2018

ABSTRACT: The nonlinear flutters of a truncated conical shell, which is subjected to aerodynamic pressure and aerodynamic heating, are researched. Material properties with gradient features along the radial direction depend on the temperature. The supersonic aerodynamic force is obtained by applying the first-order piston theory, including the correction factor for curvature. The temperature in the external surface of the functionally graded material truncated conical shell rises as a result of viscous aerodynamic heating, and the temperature distribution along the thickness can be described by polynomial series. Hamilton's principle is utilized to obtain the nonlinear partial differential equilibrium equation of the system. Using Galerkin's method, a high-dimensional nonlinear system can be derived. Without considering the parts of nonlinear terms and the external forcing excitation, the flutter boundaries are obtained by solving the eigenvalues problem. The influences of ratios of top radius to thickness, semi-vertex angle, and volume fraction index on nonlinear dynamic characteristics of functionally graded material truncated conical shell are studied in detail by the fourth-order Runge–Kutta algorithm.

References listed at the end of the paper:

- T. Prakash and M. Ganapathi, Supersonic flutter characteristics of functionally graded flat panels including thermal effects, Compos. Struct., vol. 72, no. 1, pp. 10–18, 2006.
ABSTRACT: In this article, a three-dimensional fractional order derivative model has been developed for the constrained viscoelastic layer of the active constrained layer damping (ACLD) treatment of laminated composite shells undergoing geometrically nonlinear vibrations. The constraining layer of the ACLD treatment is made of vertically/obliquely reinforced 1–3 piezoelectric composites and acts as the distributed actuator. A three-dimensional smart nonlinear finite element model has been developed. Several numerical results are presented to check the accuracy of the present three-dimensional fractional derivative model of the constrained viscoelastic layer for smart damping of geometrically nonlinear vibrations of laminated composite shells.

References listed at the end of the paper:


ABSTRACT: In this investigation, a general formulation for free transverse vibration analysis of orthotropic plates of revolution subjected to arbitrary boundary supports is presented by using the so-called spectro-geometric method (SGM) and the Rayleigh–Ritz technique. Under the current solution framework, the geometry of a structure can be accurately described in terms of mathematical or design parameters, rather than a computational grid or mesh. The unknown expansion coefficients are treated as the generalized coordinates and are determined using the Rayleigh–Ritz method. The accuracy and versatility of the current approach is fully demonstrated and verified through numerical examples involving plates with various shapes and boundary conditions.

Kanishk Sharma and Dinesh Kumar, “Nonlinear stability analysis of a perforated FGM plate under thermal load”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 2, pp 100-114, 2018

ABSTRACT: The nonlinear thermal stability analysis of a perforated Ni/Al₂O₃ FGM plate with temperature-dependent thermoelastic material properties is carried out through a finite element approach based on the first-order shear deformation theory and the von-Karman's nonlinear kinematics. The thermoelastic material properties of the FGM plate are varied in the thickness direction, and the Mori-Tanaka homogenization scheme is applied to evaluate these properties. After validating the results of the current formulation, parametric studies are conducted to examine the effects of temperature-dependent material properties, material in-homogeneity, cutout shape and size, edge boundary conditions, aspect and slenderness ratios on the thermal buckling and postbuckling response of perforated FGM plate.

ABSTRACT: An approximate solution is presented to investigate the effects of thermal load on the frequency of ring-stiffened rotating functionally graded conical shell. Material properties and the temperature field are assumed to be graded and varied in the thickness direction. The shell is reinforced by equal interval rings. The equations of motion are derived by the Hamilton's principle. Approximate analytical solutions are assumed to satisfy clamped boundary conditions, and then Fourier decomposition and Galerkin method are applied to achieve relations of frequencies. To validate, the comparisons are made with a number of particular cases in literature and with the FEM solutions.

References listed at the end of the paper:
ABSTRACT: High-performance cementitious materials are widely used in the construction of thin shell elements. This study investigates a simulation method based on composite layered shells for the nonlinear analysis of high-performance cementitious elements under in-plane shear. A tube torsion test is simulated and analyzed with MSC-MARC and its results are compared to an alternative calculation method, the Simplified Model for Combined Stress resultants (SMCS), as well as with experimental data. The simulation method is found to produce accurate results for fully under-reinforced elements with a range of strong to weak reinforcement ratios less than 2.

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- ACI Committee 318, ACI-318. Building Code Requirements for Reinforced Concrete and Commentary ACI 318M-08, American Concrete Institute, Farmington Hills, MI, 2008.
Dongdong Li, Zongbai Deng, Huaizhi Xiao and Lujia Zhu, “Thermomechanical bending analysis of functionally graded sandwich plates with both functionally graded face sheets and functionally graded cores”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 3, pp 179-237, 2018

ABSTRACT: The bending response of functionally graded material (FGM) sandwich plates subjected to thermomechanical loads is investigated using a four-variable refined plate theory. A new type of FGM sandwich plate, namely, both FGM face sheets and an FGM hard core, is considered. Containing only four unknown functions, the governing equations are deduced based on the principle of virtual work and then these equations are solved via the Navier approach. Analytical solutions are obtained to predict the deflections and stresses of simply supported FGM sandwich plates. Benchmark comparisons of the solutions obtained for a degradation model (functionally graded face sheets and homogeneous cores) with ones computed by several other theories are conducted to verify the accuracy and efficiency of the present approach. The influences of volume fraction distribution, geometrical parameters, and thermal load on dimensionless deflections and normal and shear stresses of the FGM sandwich plates are studied.

Mehdi Bohlooly and Babak Mirzavand, “Postbuckling and deflection response of imperfect piezo-composite plates resting on elastic foundations under in-plane and lateral compression and electro-thermal loading”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 3, pp 192-201, 2018

ABSTRACT: This article presents closed-form solution for the buckling, postbuckling, and nonlinear deflection of laminated composite plate with two piezoelectric actuators on elastic foundation and under transverse pressure, in-plane compression, thermal, and electrical loads for the first time in the literature. Material properties are assumed to be temperature-dependent. Two cases of boundary conditions and initial imperfection of the plate are considered. The formulations are based on the classical laminated plate theory (CLPT). The Galerkin method is employed to obtain load–deflection relations. The effects of elastic foundation, lateral pressure, in-plane compression, temperature dependency of material properties, electrical and thermal loading, imperfection, and aspect ratio are studied.


ABSTRACT: The shear and tensile-compressive effects of van der Waals (vdWs) bindings on the nonlocal vibrational behavior of bilayer graphene nanoribbons (BLGNRs) are simultaneously investigated in the present study. To idealize the structure of BLGNRs incorporating interlayer shear and tensile-compressive influences, a nonlocal sandwich beam (NSB) theory is employed to model the nanoribbon layers as faces and vdWs interactions as core of the NSB. The effects of interlayer moduli are investigated on the first four nonlocal natural frequencies of BLGNRs for various nonlocal parameters, considering that the small-scale effect causes mode shapes involving tensile-compressive effect of vdWs interactions be excited later.

ABSTRACT: This article concerns the investigation of the vibrational behavior of double-walled carbon nanotubes/double-layered graphene sheets junctions using the finite element method. The bonds and atoms are modeled by beam and mass elements, respectively. Moreover, the van der Waals interactions are simulated by spring elements. The effects of the length of the nanotube and the dimensions of the nanosheet on the natural frequencies of the junctions are examined. It is shown that when the boundary conditions are applied on the nanotube, the geometrical parameters of nanotubes have a significant effect on the vibrational behavior of the junctions.

References listed at the end of the paper:


ABSTRACT: In this article, nonlocal free vibration analysis of curved functionally graded piezoelectric (FGP) nanobeams is conducted using a Navier-type solution method. The model contains a nonlocal stress field parameter and also a nonlocal strain-electric field gradient parameter to capture the size effects. Inclusion of these nonlocal parameters introduces both stiffness-softening and stiffness-hardening effects in the analysis of curved nanobeams. Nonlocal governing equations of curved FGP nanobeam are obtained from Hamilton’s principle based on the Euler–Bernoulli beam model. The results are validated with those of curved FG nanobeams available in the literature. Finally, the influences of electric voltage, length scale parameter, nonlocal parameter, opening angle, material composition, and slenderness ratio on vibrational characteristics of nanosize curved FG piezoelectric beams are explored. These results may be useful in accurate analysis and design of smart nanostructures constructed from piezoelectric materials.

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· F. Ebrahimi and M. R. Barati, Vibration analysis of smart piezoelectrically actuated nanobeams subjected to magneto-electrical field in thermal environment, J. Vibr. Control, 2016. DOI: 1077546316646239


ABSTRACT: In this paper, nonlinear vibration and instability of embedded nano-composite temperature-dependent polymeric pipes conveying hot viscous fluid are investigated. The pipe is reinforced by Single-Walled Carbon NanoTubes (SWCNTs) with Uniform Distribution (UD) and three types of Functionally Graded (FG) distribution patterns. The FG-carbon nanotube reinforced composite (FG-CNTRC) pipe is located in an orthotropic temperature-dependent visco-elastomeric medium. Reddy higher-order shear deformation theory is employed to establish the governing equations. The frequency and critical fluid velocity of the structure are calculated using Differential Quadrature Method (DQM). The effects of different parameters on the nonlinear vibration and instability of the pipe are investigated.

References listed at the end of the paper:


ABSTRACT: In the present article, a nonlinear, eccentric, low-velocity impact response of a polymer-carbon nanotube-fiber multiscale nanocomposite plate on elastic foundations in hygrothermal conditions using the finite element method is performed. In this regard, the governing equations are derived based on higher-order shear deformation plate theory and von Kármán geometrical nonlinearity. Three types of distributions of the temperature field and moisture concentrations, namely, uniformly, linearly, or nonlinearly through the thickness direction of the plates are considered. The effective material properties of the multiphase nanocomposite are calculated using fiber micromechanics and Halpin–Tsai equations in hierarchy. The carbon nanotubes are assumed to be uniformly distributed and randomly oriented through the matrix. The contact force between the impactor and the plate is obtained with the aid of the modified nonlinear Hertzian contact law models. After examining the validity of the present work, the effects of the weight percentage of CNT, moisture concentration, temperature variations, distribution of temperature and moisture concentration, elastic foundation, and the eccentricity on the contact force, indentation, and central deflection of polymer-CNT-fiber multiscale nanocomposite plate are studied in details.

Reza Ansari, Jalal Torabi and Mostafa Faghii Shojaei, “An efficient numerical method for analyzing the thermal effects on the vibration of embedded single-walled carbon nanotubes based on the nonlocal shell model”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 6, pp 500-511, 2018

ABSTRACT: Employing the variational differential quadrature (VDQ) method, the effects of initial thermal loading on the vibrational behavior of embedded single-walled carbon nanotubes (SWCNTs) based on the nonlocal shell model are studied. According to the first-order shear deformation theory and considering Eringen's nonlocal elasticity theory, the energy functionality of the system is presented and discretized using the VDQ method. The effects of thermal loading and elastic foundation are simultaneously taken into account. The use of the numerical discretization technique in the context of variational formulation reduces the order of differentiation in the governing equations and consequently improves the convergence rate. The accuracy of the present model is first checked by comparison with molecular dynamics simulation results and those of other methods. The effects of involved parameters are then investigated on the fundamental frequencies of thermally preloaded embedded SWCNTs. The results imply that the thermal loading has a significant effect on the vibration analysis of embedded SWCNTs.

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Ankit Gupta, Mohammad Talha and Wolfgang Seemann, “Free vibration and flexural response of functionally graded plates resting on Winkler-Pasternak elastic foundations using nonpolynomial higher-order shear and normal deformation theory”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 6, pp 523-538, 2018

ABSTRACT: In the present work, the flexural and vibration response of a functionally graded plate resting on Pasternak elastic foundation is analyzed using a recently developed nonpolynomial higher-order shear and normal deformation theory by the authors. The novelty of this theory is that it contains only four unknowns and
also accommodates the thickness stretching effect. Two kinds of micromechanics models, namely, the Voigt and Mori–Tanaka models, are considered. Material properties of the functionally graded plates are assumed to vary continuously in the thickness direction according to either a simple power law or an exponential law. Finite element formulation is done using \( C^0 \) continuous Lagrangian quadrilateral nine-noded elements with eight degrees of freedom per node. The equations of motion are derived using a variational approach. Convergence and comparison studies are carried out to establish the authenticity and reliability of the solutions. The effect of various boundary conditions, geometric conditions, micromechanics models, and foundation parameters on the flexural and vibration response of the functionally graded plate are investigated.


ABSTRACT: In this article, hexahedral piezoelectric solid–shell finite element formulations with linear and quadratic interpolation, denoted by SHB8PSE and SHB20E, respectively, are proposed for the modeling of piezoelectric sandwich structures. Compared to conventional solid and shell elements, the solid–shell concept reveals to be very attractive, due to a number of well-established advantages and computational capabilities. More specifically, the present study is devoted to the modeling and analysis of multilayer structures that incorporate piezoelectric materials in the form of layers or patches. The interest in this solid–shell approach is shown through a set of selective and representative benchmark problems. These include numerical tests applied to various configurations of beam, plate and shell structures, both in static and vibration analysis. The results yielded by the proposed formulations are compared with those given by state-of-the-art piezoelectric elements available in ABAQUS, in particular, the C3D20E quadratic hexahedral finite element with piezoelectric degrees of freedom.

References listed at the end of the paper:

ABSTRACT: In this article, a three-dimensional solution based on Fourier's series and the generalized differential quadrature method is presented to model the low-velocity impact on sandwich panels with hybrid nanocomposite face sheets. Navier's equations are derived and displacements are substituted by their corresponding Fourier's series. The contact force is considered as a Fourier's series of impactor displacement and deflection of contact point. To verify the theoretical model, experiments are performed on a polyurethane foam-cored sandwich panel with epoxy/woven-fiberglass/nanosilica hybrid nanocomposite face sheets. Contact force and lateral displacement of contact point histories are compared with the theoretical model.

References listed at the end of the paper:


ABSTRACT: This article, based on first-order shear deformation theory, presents the buckling analysis of a rotationally restrained orthotropic rectangular Mindlin plate resting on a Pasternak elastic foundation. Thus, the Mindlin–Reissner plate theory is employed for which the governing equations are solved by the Rayleigh–Ritz method. Uniformly distributed in-plane loads are applied to two simply supported opposite edges of the plate and the other two edges have rotationally restrained conditions without loading. Finally, the effects of plate parameters, such as foundation stiffness coefficients, aspect ratios, and ratio of elastic modulus in the $x$ to $y$ direction on the buckling loads are presented. The results show that the buckling load would increase when the ratio of the elastic modulus in the $x$ to $y$ direction increases and the plate is close to isotropic. The variation of buckling load versus changing ratio of elastic modulus in the $x$ to $y$ direction in the state of without elastic foundation and with clamp support is more than the rest of the state.


ABSTRACT: This article is concerned with the thermo-mechanical vibration behavior of flexoelectric nanoplates under uniform and linear temperature distributions. Flexoelectric nanoplates have higher natural frequencies than conventional piezoelectric nanoplates, especially at lower thicknesses. Both nonlocal and surface effects are considered in the analysis of flexoelectric nanoplates for the first time. Hamilton's principle is employed to derive the governing equations and the related boundary conditions, which are solved applying the Galerkin-based solution. A comparison study is also performed to verify the present formulation with those of previous data. Numerical results are presented to investigate the influences of the flexoelectricity, nonlocal parameters, surface elasticity, temperature rise, plate thickness, and various boundary conditions on the vibration frequencies of thermally affected flexoelectric nanoplate.


ABSTRACT: The dynamic response of honeycomb sandwich panels under aluminum foam projectile impact was investigated. The different configurations of panels were tested, and deformation/failure modes were obtained. Corresponding numerical simulations were also presented to investigate the energy absorption and deformation mechanism of sandwich panels. Results showed that the deformation/failure modes of sandwich panels were sensitive to the impact velocity and density of aluminum foam. When the panel was impacted by the aluminum foam projectile with the back mass of nylon, the “accelerating impact” stage can be produced and may lead to further compression and damage of the sandwich structures.

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Mohsen Hosseini and Mostafa Talebitooti, “Buckling analysis of moderately thick FG carbon nanotube reinforced composite conical shells under axial compression by DQM”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 8, pp 647-656, 2018

ABSTRACT: A semi-analytical method is presented to study the buckling of moderately thick carbon nanotube reinforced composite conical shells under axial compression. Material properties are assumed to be graded across the shell thickness. In order to derive the equilibrium equations of the shell, first-order shear deformation theory is used. Then, the partial differential equations are transformed to algebraic type by using the differential quadrature method. To validate the results obtained in this study, comparisons are made with the outcomes of previous studies. Finally, the effects of the geometry of the shell, circumferential mode number, volume fraction of the carbon nanotube, and boundary conditions are studied.

References listed at the end of the paper:

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ABSTRACT: The free vibration of composite truss core sandwich plates is investigated. The natural frequencies of the sandwich plate are calculated by using the classical laminated plate theory, the first-order shear deformation theory, Reddy's third-order shear deformation theory, and a Zig-Zag theory. The differences between the natural frequencies, obtained from the four theories, are compared. The influences of structural parameters on the natural frequencies and the ratios of natural frequency to equivalent density of the sandwich plates with pyramidal core, tetrahedral core, and 3D-Kagome core are studied with the aid of the Zig-Zag theory.

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- M. Liu, Y.S. Cheng, and J. Liu, High-order free vibration analysis of sandwich plates with both functionally graded face sheets and functionally graded flexible core, Compos.: Part B, vol. 72, pp. 97–107, 2015.

Guanghui Xu, Huaiwei Huang and Qiang Han, “Study on postbuckling of axial compressed elastoplastic functionally graded cylindrical shells”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 10, pp 820-828, 2018
ABSTRACT: Postbuckling of plates and shells is an important and cumbersome problem in the structural stability field. Presently, postbuckling behaviors of elastoplastic functionally graded cylindrical shells are investigated by a numerical simulation. The elastoplastic material properties are assumed to be of a multilinear hardening type, according to the constituent distributions, and are modeled using the laminate method. The Riks algorithm is used to obtain the equilibrium path. The postbuckling deformation and stain history of elastoplastic functionally graded cylindrical shells are investigated and various effects of the shell thickness and the constituent distributions are discussed. The results show material unloading effects in the postbuckling state.

References listed at the end of the paper:

- H.V. Tung, Postbuckling behavior of functionally graded cylindrical panels with tangential edge constraints and resting on elastic foundations, Compos. Struct., vol. 100, no. 1, pp. 532–541.


ABSTRACT: In this study, the nonlinear thermo-elastic bending analysis of a functionally graded carbon nanotube-reinforced composite plate resting on two parameter elastic foundations is investigated. The material properties of the carbon nanotube-reinforced composite plates are assumed to be temperature dependent and graded in the thickness direction. The nonlinear formulations are based on a first-order shear deformation plate theory and large deflection von Karman equations. A dynamic relaxation method is employed to solve the plate nonlinear partial differential equations. The effects of volume fraction of carbon nanotubes, thermal gradient, temperature dependency, elastic foundation, boundary conditions, plate width-to-thickness ratio, aspect ratio, and carbon nanotubes distribution are studied in detail.

Farzad Ebrahimi and Mahsa Karimiasl, “Nonlocal and surface effects on the buckling behavior of flexoelectric sandwich nanobeams”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 11, pp 943-952, 2018
ABSTRACT: In this article, an analytical approach is presented to study the surface and flexoelectric effects on the buckling characteristics of an embedded piezoelectric sandwich nanobeam. According to the nonlocal elasticity theory, the flexoelectricity is believed to be authentic for size-dependent properties in nanostructures. The boundary conditions and the governing equations are derived by Hamilton's principle and are solved by Navier method. The results obtained from the present work show that the nonlocal term has an important reduction on the critical load and also the flexoelectricity shows an increasing influence on the buckling loads of the sandwich nanobeam, especially at lower thicknesses.

Xiao Huang, Yu Hai, Bo Li and Xi-Qiao Feng, “Wrinkling of thin films on a microstructured substrate”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 12, pp 975-981, 2018

ABSTRACT: Surface wrinkling of thin films on substrates offers an effective strategy to create controllable surface patterns of wide application. In this article, both theoretical analysis and numerical simulations are performed to study the surface wrinkling of thin films bonded on a microstructured soft substrate under compression. We consider two typical kinds of substrates that have different mechanical properties. One possesses a periodic array of micropillars, and the other has a period of alternating unbonded—bonded regions at the film—substrate interface. The characteristics of surface wrinkling and postbuckling evolution of films are revealed. It is found that the interfacial microstructures modulate the normal mechanical properties of the substrate and, thus, tailor the buckling behavior of the thin film atop it. Under lateral compression, the film on the substrate shows periodic arrays of micropillars exhibiting sinusoidal wrinkling first, and then with further compression, the wrinkles give way to a deep fold accompanied by Euler buckling of the micropillars and the decay of neighboring wrinkles. For the system with periodic unbonded—bonded regions at the film—substrate interface, wrinkling of the film is characterized by a relative shift in the normal direction. This study offers potential applications in the fabrication of tunable surface morphologies.

References listed at the end of the paper:
ABSTRACT: For thermally postbuckled configurations, the free vibration behavior of functionally graded (FG) Timoshenko beams are investigated. The postbuckling configurations are obtained through a geometrically nonlinear static problem. The free vibration problem around the postbuckled configuration is formulated using its tangent stiffness. The energy based governing equations are solved following the Ritz method. The elements of the tangent stiffness matrix are obtained using the Ritz coefficients. The results are shown to exhibit the effects of FG material, material profile parameter, and length-thickness ratio. The comparative results are presented for both the cases of the physical neutral surface and the geometrical neutral surface.

ABSTRACT: In this paper, layerwise (LW) theory has been utilized along with that of equivalent single layer (ESL) for free vibration and linearized buckling analysis of composite laminated plates. To this end, the isogeometric approach and Carrera unified formulation (CUF) have been combined. In particular, Taylor-like and Legendre-like polynomial expansions have been utilized in the framework of CUF to approximate the solution field in ESL and LW models, respectively. Indeed, CUF provides an ideal tool that facilitates the implementation of higher orders of the solution field expansion. As ESL model cannot inherently provide interlaminar continuity, they are not suitable for analyzing thick laminated plates. However, the LW model not only presents a three-dimensional (3D-)like accurate mathematical model using two-dimensional plate theories but also considers interlaminar continuity requirements and obviates the need for the use of shear correction factor. In addition, the nonuniform rational B-spline basis functions have been employed to approximate the solution field, due to their interesting attributes in the analysis. These functions are able to describe the exact geometry of the structure and make it technically feasible to provide refinement process during analysis. The presented numerical results confirm the validity of the proposed methodology.

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E. Carrera, G. Giunta, and M. Petrolo, Beam Structures: Classical and Advanced Theories, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, United Kingdom, 2011.


J.A. Cottrell, W. Hughes, and Y. Bazilevs, Isogeometric Analysis: Toward Integration of CAD and FEA, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, United Kingdom, 2009.


ABSTRACT: In this study, dynamo-thermo-elastic analysis of a rotating piezoelectric hollow cylinder made of functionally material is presented. Coupled differential quadrature and finite difference methods are used to solve boundary/initial value equations of the problem. Material properties are assumed to be graded in radial direction and temperature independent. Numerical results obtained and convergence are studied, and then verified with reported results in literature. Effect of variations of the grading parameter, angular velocity,
thermal gradient and ratio of the outer to inner radii on the stresses, radial displacement and electrical potential are presented.

References listed at the end of the paper:


ABSTRACT: This study deals with the stochastic non-linear dynamic response of functionally graded materials (FGMs) plate with uncertain system properties subjected to time-dependent uniformly distributed transverse
load in thermal environments. System properties, such as material properties of each constituent's material, volume fraction index, and transverse load, are taken as uncorrelated random input variables. Material properties are assumed as temperature dependent (TD). The formulation is based on higher-order shear deformation theory (HSDT) with von-Karman non-linear strain kinematics using modified C° continuity. A Newton–Raphson-based non-linear finite element method along with a first-order perturbation technique (FOPT) and Monte Carlo sampling (MCS) is outlined to examine the second-order statistics (mean, standard deviation (SD), and probability density function (PDF)) of the non-linear dynamic response of the FGM plate. The governing dynamic equation is solved by Newmark's time integration scheme. The effects of volume fraction index, load parameters, plate thickness ratios, and temperature changes with random system properties are examined through parametric studies. The present outlined approach is validated with the results available in the literature and by MCS.


ABSTRACT: Surface effect responsible for some size-dependent characteristics can become distinctly important for piezoelectric nanomaterials with inherent large surface-to-volume ratio. In this paper, we investigate the surface effect on the free vibration behavior of a spherically isotropic piezoelectric nanosphere. Instead of directly using the well-known Huang–Yu surface piezoelectricity theory (HY theory), another general framework based on a thin shell layer model is proposed. A novel approach is developed to establish the surface piezoelectricity theory or the effective boundary conditions for piezoelectric nanospheres employing the state-space formalism. Three different sources of surface effect can be identified in the first-order surface piezoelectricity, i.e. the electroelastic effect, the inertia effect, and the thickness effect. It is found that the proposed theory becomes identical to the HY theory for a spherical material boundary if the transverse stress components are discarded and the electromechanical properties are properly defined. The nonaxisymmetric free vibration of a piezoelectric nanosphere with surface effect is then studied and an exact solution is obtained. In order to investigate the surface effect on the natural frequencies of piezoelectric nanospheres, numerical calculations are finally performed. Our numerical findings demonstrate that the surface effect, especially the thickness effect, may have a particularly significant influence on the free vibration of piezoelectric nanospheres. This work provides a more accurate prediction of the dynamic characteristics of piezoelectric nanospherical devices in nano-electro-mechanical systems.

References listed at the end of the paper:


ABSTRACT: Based on Reddy's third-order shear deformation shell theory, this paper presents an analytical approach to investigate the nonlinear thermo-mechanical response of imperfect Sigmoid FGM circular cylindrical shells surrounded on elastic foundations and reinforced by outside metal stiffeners. The eccentrically stiffened S-FGM shells are subjected to axial compressive load and uniform radial load in thermal environment.
Using the stress function, Bubnov–Galerkin method, the paper proposes the formula for forces and moments taking into account the thermal stress in both the shells and stiffeners. The obtained results are validated by comparing with other results reported in the literature.

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E. Carrera, A.G. de Miguel and A. Pagani, “Component-wise analysis of laminated structures by hierarchical refined models with mapping features and enhanced accuracy at layer to fiber-matrix scales”, Mechanics of Advanced Materials and Structures, Vol. 25, No. 14, pp 1224-1238, 2018

ABSTRACT: Modern methodologies for the analysis of composite structures are demanded to satisfy the accuracy requirements at different scales, from micro to macro and possibly in a global/local sense. In this domain, the present paper proposes a hierarchical, component-wise approach for the linear static analysis of layered structures. By employing the Carrera Unified Formulation and a variational statement, finite element arrays of refined beam models are expressed in terms of fundamental nuclei. Legendre-based polynomials are utilized to implement, in a hierarchical form, higher-order beam kinematics. Also, curved cross-section geometries are formulated in a correct and consistent manner through mapping blending functions. Mapping and refined kinematics beam models are, thus, inherently combined to give the component-wise method, according to which each component of the structure (e.g., layer, fibers, and matrix) is modeled independently and with its geometric and mechanical characteristics. This approach is demonstrated to provide enhanced accuracy for the analysis of composite structures, from layer scale to fiber-matrix level, but still with low computational costs.

References listed at the end of the paper:


ABSTRACT: In this work, a new high efficiency method is employed to analytically determine the local displacement functions and stresses under transverse loading. The accuracy of the proposed method is subsequently verified by comparing the theoretical results with experimental data, finite-element method (FEM), and Lekhnitskii solution. The results show good agreement. In addition, high efficiency in terms of computational time is shown when the proposed method is used as compared with FEM. Finally, several numerical examples for stress and strain distributions in various thick cantilever composite straight tubes subjected to transverse loading are discussed.

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ABSTRACT: In this work, a new high-order displacement-based method is proposed to investigate stresses and strains in thick arbitrary laminated orthotropic cantilever straight tubes under transverse loading. The most general displacement field of elasticity for an arbitrary thick laminated orthotropic straight tube is developed. A layer-wise method is employed to analytically determine the local displacement functions and stresses under transverse loading. The accuracy of the proposed method is subsequently verified by comparing the theoretical results with experimental data, finite-element method (FEM), and Lekhnitskii solution. The results show good agreement. In addition, high efficiency in terms of computational time is shown when the proposed method is used as compared with FEM. Finally, several numerical examples for stress and strain distributions in various thick cantilever composite straight tubes subjected to transverse loading are discussed.

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Huang NN. Influence of shear correction factors in the higher-order shear deformation laminated shell theory. Int. J. Solids Struct. 1994;31:1263–1277.10.1016/0020-7683(94)90120-1


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ABSTRACT: To examine the configuration of CFRP face plates/foamed plastic core sandwich panel joints, a tapered end-closure-type joint is selected and studied. In this type of joint, the sandwich panel is tapered to form a solid laminate comprising two face plates near the joint, and the two panels to be joined are mechanically fastened at the solid laminate with a splice plate. This type of joint may be suitable for aircraft panels because a flat surface can be obtained at the joint, which is advantageous from an aerodynamic viewpoint. However, in a previous study on such a joint, it was found that a delamination crack initiated from the tapered core end and propagated through the interface between the two face plates as an initial failure mode at a much lower tensile load than the final failure load in a tensile strength test. In this study, the angle of the tapered panel was focused on and the effect of changing the taper angle on suppressing the initial failure was investigated through experiments and numerical analysis. It was found that a smaller taper angle is more effective for suppressing the initial failure.

ABSTRACT: A thermomechanical buckling analysis is presented for simply supported rectangular symmetric cross-ply laminated composite plates that are integrated with surface-mounted piezoelectric actuators and are subjected to the combined action of in-plane compressive edge loads, two types of thermal loads, and constant applied actuator voltage. The formulation of equations is based on the classical laminated plate theory and the von-Karman non-linear kinematic relations. The analysis uses an exact method to obtain closed-form solutions for the buckling load. The effects of applied actuator voltage, thermal and mechanical loads, plate geometry, and lay-up configuration of the laminated plates are investigated. The novelty of the present work is to obtain closed-form solutions for electro-thermomechanical buckling of hybrid composite plates, and to cover non-uniform temperature distribution loading. The results for various states are verified with known data in the literature.

ABSTRACT: This paper describes an optimum structural design of a CFRP isogrid cylindrical shell using a genetic algorithm (GA). When the CFRP isogrid cylindrical shell receives a prescribed uniaxial compressive load, an objective is to minimize weight of the CFRP isogrid cylindrical shell subjected to the constraint conditions of no buckling and no material failure. The buckling and material failure loads were approximated by a response surface method combined with partitioning of design spaces and these approximated values were used in the process of GA instead of FEM calculations in order to reduce the computational time. Furthermore, the differences from the constraint conditions of the linear or the non-linear (local) buckling loads were also calculated and their results were compared with each other.

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A laminated composite thin plate is subject to local buckling from the edge delamination. The study focuses on the buckling load of delaminated composite thin-walled columns, including box and channel sections. The analysis involves the approximation of composite laminates with cross-ply and angle-ply stacking sequences. The buckling load is determined by considering the wall segments as individual plates rotationally restrained by the adjacent segments. This technique is combined with plate theories as a new analytical method to predict the buckling load of an initially delaminated column with any arbitrary sections (open or closed). The results are obtained from eigenvalue buckling analysis in ANSYS software for both box- and channel-section columns with cross-ply and angle-ply stacking sequences. The study also investigates the effects of delamination size and location on the buckling loads.

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ABSTRACT: The low velocity impact responses of sandwich panels with and without stitching were investigated using an instrumented drop weight impact tower. A novel stitching technique was developed to stitch the sandwich panel. Unstitched and stitched sandwich panels with pile orientation of 90°, 45° and 90°/45° were fabricated using vacuum infusion process. Low velocity impact test were carried out with different energy levels of 2, 5, 10, 20, 30, 40 and 50 J. The increase in the impact performances generated by the introduction of these reinforcements compared to a traditional sandwich (unstitched) was quantified. The results also show that the ballistic limit of the sandwich panels were improved by employing piles in different orientation.

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Limin Bao, Yuki Miura and Kiyoshi Kemmochi, “Improving bending characteristics of FRP sandwich structures with reinforcement webs”, Advanced Composite Materials, Vol. 27, No. 2, pp 221-233, 2018

ABSTRACT: Sandwich-structure materials consist of a high-strength skin material and a lightweight core material. The advantages of sandwich structures are known to include excellent mechanical properties and low weight. Sandwich structures are lightweight because of their lightweight core; meanwhile, the skin structure provides mechanical strength and bears bending stress. Carbon-fiber-reinforced plastic (CFRP) is a high-specific-strength and high-specific-rigidity material. In recent years, CFRP sandwich structures have been used in aerospace applications due to their lightweight properties. However, soft-core members such as plastic foam materials have low rigidity and therefore may not exhibit adequate function as a sandwich structure. Webs can make up for the lack of rigidity of soft core members. Consequently, sandwich structures with reinforcement webs offer higher strength than sandwich structures without reinforcement webs. This study focused on reinforcement webs suitable for use in CFRP sandwich structures by evaluating the bending characteristics of CFRP sandwich structures with reinforcement webs. Experimental results demonstrated that CFRP sandwich structures with reinforcement webs had improved bending strength. The effects of the spacing interval of reinforcement webs and the number of layers of carbon fiber fabric on the bending characteristics of CFRP sandwich structures were also examined. Finally, an optimal condition model was created for CFRP sandwich structures with reinforcement webs.

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ABSTRACT: Cost and recyclability are among the primary factors on exploiting the engineering materials for their new applications. In this context, glass/pp-based sandwich panel has been studied experimentally and numerically with the aims of its potential applications in the automotive structures. The first part of this work presents the experimental results achieved for the load-carrying capacity of panels using three-point bend tests for its static flexural behaviour. Static behaviour is studied to compare the top-roller diameter effect on the flexural behaviour of the panels and shows a significant difference in the results. Impact behaviour of the panels is explored using three different types of impactor end-shapes that generate different levels of damage in the material with the same level of impact energy. The second part of this paper deals with the development of numerical models for the three-point bend and impact behaviour of the panels using a commercial finite element code of Abaqus. Strain energy-based homogenisation technique is employed to determine the equivalent orthotropic properties of complex circular honeycomb core material. The finite element models predict to a good level of the static and impact behaviour of the material when compared with the experiments. References listed at the end of the paper:


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ABSTRACT: Braided composite had been proven to have a great potential as energy absorber. However, the past studies done were limited to synthetic fibre as the reinforcement composite. In this study, we focused on a natural fibre, namely basalt, as the reinforcement material. The effects of braid thickness, braid angle and braid tow density of the basalt composite tube subjected to quasi-static crushing response were investigated. Crushing failure mode had been observed in comparing those braid parametric effects. Moreover, the analysis of variance was used to analyse the main and interaction effects subjected to specific energy absorption (SEA) response for the test. Three crushing modes had been observed. The splayed and diamond shape of progressive folding were reported for the braid angles of ±30° and ±45°, respectively, and fibre micro-cracking mode effects for the ±60° braid angle. Furthermore, SEA increased with the decrease of braid angle and increase of diameter-to-thickness ratio. On the other hand, the highest braid angle demonstrated the lowest crush efficiency and poor triggering crushing progression.


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ABSTRACT: Bistable behaviour and microstructure characterization of carbon fiber/epoxy resin anti-symmetric cylindrical shells after thermal exposure are investigated by experimental method in this paper. The effect of thermal exposure temperature and duration on the curvatures, load-displacement curves and snap loads
of bistable shells are discussed systematically. The results show that both the thermal exposure temperature and duration have a significant influence on the bistable behaviour of those antisymmetric laminated cylindrical shells. Some interesting phenomena after high-temperature exposure are found in snap-through and snap-back processes. The microstructure of the shell before and after thermal exposure is characterized using scanning electron microscope (SEM), which provide an insight into bistable deformation mechanism of those shells after being exposed to elevated temperature.

ABSTRACT: This paper presents a thermal-mechanical coupled constitutive model to calculate the stress and temperature distribution of 3D braided composite under impact compressions in high temperature environment. The temperature effect and strain rate effect are involved in the coupled model. A temperature-rise equation in adiabatic state is derived to calculate the temperature rise during the impact compression. A user-defined subroutine was written for numerically simulating the impact damage with finite element method (FEM). The sensitivity of mesh size on the results was analyzed. The results reveal the temperature rise and the coupling stress of the 3D braided composite under different impact compression conditions, i.e., temperatures and compressive loadings.

ABSTRACT: A fiber-reinforced torsional dielectric elastomer (DE) actuator was conceived by embedding one family of helical fibers into a DE tube in the present work. Due to the constraint of the fibers, the application of an electrical voltage will induce torsional deformation which is coupled with the longitudinal and hoop stretches of the actuator. By employing an energy method, the voltage-induced torsion and snap-through instability of the DE tubular actuator were modeled and analyzed. Based on the formulation, the effects of the fiber stiffness and helical angle as well as externally applied mechanical loads on the voltage-induced torsional deformation were studied in detail. It was found that when snap-through instability occurs, the voltage-induced twist angle jumps from a smaller value in the unbulged state to a larger value in the bulged state, and the voltage-induced twist angle can be effectively tuned by varying the fiber stiffness and helical angle. Moreover, the voltage-induced torsion of the actuator in the bulged state is almost not affected by externally applied axial force or torque. The revealed results are expected to provide guide for the rational design and utilization of fiber-reinforced torsional DE actuators.

ABSTRACT: Porous-core sandwich structures with CFRP face sheets have similar micro structures to biological tissues, for example, grass leaves. The sandwich structures are composed of two thin, stiff face sheets, which provide the primary in-plane structural stiffness, and a thick low-density porous core, which provides the functionalities and the majority of out-plane stiffness. However, the mechanical properties of these sandwich structures are often limited by local failures such as face-core debonding or core collapse. Inspired by the tree leaves with fractal distributed veins, which are larger and stiffer than grass leaves, in this paper, a topological optimization on the micro structures of core is conducted to achieve exceptional mechanical properties. By taking adhesive-area constraint, local-buckling constraint and embedding-volume constraint into
consideration, a biomimetic hybrid core, which is similar to the fractal distribution of tree veins, is found to be an optimal core design for sandwich structures with CFRP face sheets.


ABSTRACT: This paper presents a numerical study of the delamination migration in angle-ply laminates observed in experiments reported in the literature, where the delamination originally propagates along the lower, 0deg/60deg interface and later migrates onto the upper, 60deg/0deg interface. The recently-developed Floating Node Method (FNM) is used for modelling this problem. The initiation and propagation of both delamination and matrix cracks are modelled within the FNM elements. Experimentally-observed phenomena such as the numerous kinking attempts and the multiple onset locations of migration are successfully predicted. The effect of load offset on the locations of migration is captured. In addition, this work tries to shed light on the proper use of standard cohesive elements in cases where delamination migration is expected.


ABSTRACT: To get a strong, stiff and weight efficient cylindrical shell, a carbon fiber reinforced orthogrid-core sandwich cylinder was designed and fabricated. The core is made up of orthogonal grids and manufactured by interlocking method. The sandwich cylinder is fabricated by filament winding method. Free vibration test combining with theoretical analysis and numerical simulation was carried out to reveal the vibration responses and estimate the modulus of the wound laminate. Uniaxial compression test was performed to reveal the strength and failure mode. Without end flanges, laminate delamination at the end controls the peak load. Delamination of skins induces interfacial debonding and dimpling of inner skin finally. An engineering method based on the average strain at the peak load is proposed to predict the load capacity of the cylinder. Compared with stiffened cylinder, the orthogrid sandwich cylinder is stiffer and stronger. Meanwhile, its making process is simplified and the mechanical ability is comparable with other lattice-core sandwich cylinders.


ABSTRACT: The nonlinear free vibration and postbuckling behaviors of multilayer functionally graded (FG) porous nanocomposite beams that are made of metal foams reinforced by graphene platelets (GPLs) are investigated in this paper. The internal pores and GPL nanofillers are uniformly dispersed within each layer but both porosity coefficient and GPL weight fraction change from layer to layer, resulting in position-dependent elastic moduli, mass density and Poisson's ratio along the beam thickness. The mechanical property of closed-cell cellular solids is employed to obtain the relationship between coefficients of porosity and mass density. The effective material properties of the nanocomposite are determined based on the Halpin-Tsai micromechanics model for Young's modulus and the rule of mixture for mass density and Poisson's ratio along the beam thickness. The mechanical property of closed-cell cellular solids is employed to obtain the relationship between coefficients of porosity and mass density. The effective material properties of the nanocomposite are determined based on the Halpin-Tsai micromechanics model for Young's modulus and the rule of mixture for mass density and Poisson's ratio. Timoshenko beam theory and von Kármán type nonlinearity are used to establish the differential governing equations that are solved by Ritz method and a direct iterative algorithm to obtain the nonlinear vibration frequencies and postbuckling equilibrium paths of the beams with different end supports. Special attention is given to the effects of varying porosity coefficients and GPL's weight fraction, dispersion pattern, geometry and size on the nonlinear behavior of the porous nanocomposite beam. It is found that the addition of a small amount of GPLs
can remarkably reinforce the stiffness of the beam, and its nonlinear vibration and postbuckling performance is significantly influenced by the distribution patterns of both internal pores and GPL nanofillers.


ABSTRACT: The determination of ply properties of Fiber Reinforced Polymers (FRP) for particular operational environmental conditions in aeronautical applications is mandatory in order to fulfill current industry stringent certification requirements. However, the traditional experimental approach requires massive investments of resources and time. From the behaviour obtained experimentally, constitutive equations including failure criteria are then devised to be used in the design of FRP structures. The ply longitudinal behaviour under compression is generally the most difficult to measure and characterize. In this work, an alternative coupled experimental-computational micromechanics approach is proposed to determine the longitudinal compression properties of unidirectional FRP plies under different environmental conditions. This methodology includes experimental characterization of matrix and fiber/matrix interface, combined with numerical simulations of realistic microstructures. The interface decohesion is simulated using cohesive-frictional interactions. A pressure dependent, elasto-plastic model that includes tensile damage is employed to capture the matrix nonlinear behaviour. The numerical predictions match the experimentally-obtained ply properties available in the literature in a remarkable way and suggest that virtual ply property characterization is a mature and reliable approach to conduct screening of materials.

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Jin-Shui Yang, Li Ma, Mauricio Chaves-Vargas, Tian-Xiang Huang, Kai-Uwe Schroeder, Ruediger Schmidt and Lin-Zhi Wu, “Influence of manufacturing defects on modal properties of composite pyramidal truss-like core sandwich cylindrical panels”, Composites Science and Technology, Vol. 147, pp 89-99, July 2017, https://doi.org/10.1016/j.compscitech.2017.05.007

ABSTRACT: Defects can easily appear in composite lattice truss core sandwich structures during the complex preparation process, which may significantly affect the structural response and decrease the load-carrying capability. The purpose of this paper is to investigate the manufacturing defect sensitivity of modal vibration responses of carbon fiber composite pyramidal truss-like core sandwich cylindrical panels by modal experiments and finite element analysis. Defects including debonding between face sheets and truss cores (DFT), truss missing (DTM), face sheet wrinkling (DFW) and gap reinforcing (DGR) are introduced into the present intact specimen artificially and modal testing is conducted to study their dynamic behavior under free-free boundary conditions. Finite element models consistent with the experiments are then developed to further study the effect of defect extents, locations and forms on the modal parameters of the present sandwich cylindrical panels. Results indicate that the degree of sensitivity of natural frequencies of the present sandwich cylindrical panels mainly depends on the vibration modes, defect extents, locations and forms. In addition, damping loss factors are much more sensitive than their corresponding frequencies. Some conclusions and essential mechanisms are summarized, which is helpful to vibration-based non-destructive evaluation (NDE) of such kind of composite lattice sandwich structures.


ABSTRACT: The present paper investigates an experimental approach concerning the determination of dynamic behavior and damage kinetics of composite materials based on multiwalled carbon nanotubes (MWCNTs), embedded in electrospun reactive nanofibers in the Taylor impact test. Different impact energies have been considered namely; 21J and 39J to investigate the composite response. Projectile are manufactured from a commercial steel 2071 with a nominal diameter of 50 mm and 1600 g of weight. The projectile was fired against a composite specimen initially hooked on a cell effort by a compressed gas gun within the velocity of 5 m/s and 7 m/s. Three types of specimens are considered: (1) MAT1 (carbon fiber reinforced epoxy polymer composite), MAT2 (consists of MAT1 and electrospun Polybenzimidazole-Bismaleimide (PBI-BMI) nanofibermats between carbon fiber layers) and MAT3 (consists of MAT2, where PBI-BMI nanofibermats are reinforced with multiwalled carbon nanotubes (MWCNTs)). The effect of the MWCNTs on the dynamic properties of the composite structures was studied. Microscope observations reveal damage progressive, buckling and crush-front propagation during tests. Application of the PBI-BMI reactive nanofibermats reinforced with MWCNTs leads to damage prevention, reducing damage area in composite samples.

ABSTRACT: A novel woodpecker's head-inspired sandwich beam, comprising carbon fiber laminated skins with rubber and aluminum honeycomb cores, was developed for low-velocity impact behavior improvement. A comparative study against conventional sandwich beam was performed employing three impact energy levels (7.28 J, 9.74 J, 12.63 J) by means of experimental and numerical methods. In all cases, bio-inspired beams were consistently superior to those conventional, with low developed stress, deformation, and damage area while carrying higher maximum impact force. Even with a low added mass, the impact resistance efficiencies of the bio-inspired beams were 2.7–5.7 times greater than those of conventional configuration, thus exhibiting an improved impact performance of the developed bio-inspired beam useful for future protection strategy.


ABSTRACT: The compressive performances of carbon-fibre-reinforced composite sandwich panels with chevron folded cores were investigated in this paper. Analytical expression based on energy approach were derived to predict their compressive elastic modulus and strength. The sandwich panels with specific fibre orientation cores were manufactured and tested to reveal the influences of fibre ply angles on the responses for compressive loading. The stiffness and strength increased distinctly with the 0° fibre orientation increments. The predictions for compressive stiffness and strength showed good agreement with the measurements, and the failure mechanisms of the structures were discussed by simulation analysis.


ABSTRACT: Using metallic materials in vehicles structures increases cost and fuel consumption, therefore, the trends start to use cheaper and lite materials. Fibers are used in composites in automotive applications because they are lightweight, stiff, and stronger than bulk material, as well as achieve comparable energy absorption to metallic materials. The aim of this research is to investigate the potential of natural fiber in the applications of crash energy absorption. An experimental procedure (hand layup) was applied to investigate the effect of using jute fiber on crash worthiness parameter of composite material with other types of fibers such as Kevlar and glass fiber reinforced epoxy composite. The work involved fabrication the tubes using three layers, two geometries (circular and square) with three different heights at constant crush speed 1.5 mm/s. The results show that the tubes of jute fiber were ineffective and failed directly, but, replacing one layer of jute fiber by one layer of other types of fibers lead to an enhancement in crash worthiness parameters especially, failure type and crash worthiness parameters. The better results are achieved when using hybrid jute and kevlar, where the energy absorption is enhanced by 17.75% and the specific energy absorption is enhanced by 25.122% in case of circular tube with diameter 50 mm. In case of square tube with side length 50 mm, the results are enhanced by 62.764% for energy absorption and 58.942% for specific energy absorption.


ABSTRACT: A failure mechanism-based progressive damage growth model is developed, applied and validated for modeling woven polymer-based foam-core sandwich panels under compression-after-impact. A Schapery theory based constitutive model, which takes account of intra-ply shear inelasticity and fiber kinking and resulting fracture is developed for the impacted plain weave fabric laminated face-sheets under compression loading. Each ply of the face-sheets is modeled as an orthotropic nonlinear elastic lamina degrading as
characterized through laboratory experiments. The behavior of woven plies in the warp and fill directions is elastic until the attainment of local instability in compression. The phenomenon of fiber micro-buckling leading to kink banding, which was observed to be the mechanism controlling failure of the impacted face-sheets and hence the sandwich panels, is explicitly accounted for by allowing the fiber rotation at a material point. In the shear direction, plasticity is also considered to represent the elastic-plastic in-plane shear behavior of woven fabric plies. The constitutive model is numerically implemented using the commercially available finite element package ABAQUS through a user defined material subroutine (UMAT). The previous 3D damaged FE model which was proven to accurately capture the low-velocity impact damages is imported and subjected to a compression loading modeling. The numerical results in terms of deformation, failure mode and residual strength show a remarkable agreement with experimentally measured ones, allowing the model to be validated.


ABSTRACT: A theoretical study was carried out to predict the failure load and mode of composite anisogrid lattice sandwich cylinder (LSC) under fundamental loads. Four failure modes were suggested for this structure under axial compression, uniform external pressure and torsion, including global buckling, skin monocell buckling, rib crippling and strength failure. For each failure mode, the load capacity of the composite LSC was predicted theoretically and corrected by finite element method (FEM) with proper correction coefficients. To instruct the design of the LSC, failure mode maps were constructed, showing the dependence of failure mode and load on the geometrical variables of the lattice and skins. The concept of a failure mode map is extended to give a useful design tool for anisogrid sandwich cylinder manufacturers and their customers.


ABSTRACT: This paper reports on the damage mechanisms of 3D circular braided composite tubes under transverse impact, applied by a Split Hopkinson Pressure Bar (SHPB) system. X-ray computed tomography (XCT) was employed to obtain 3D images of the 3D braided composite tubes after the impact test. Effects of impact velocity, braiding angle and the number of braiding layers on the damage mechanisms were researched, using the XCT data. For low impact velocity, it was found that cracks nucleate in weak areas and propagate along the path of least resistance between yarns, which give rise to matrix cracking and debonding between yarns. For high impact velocities, cracks develop along a relatively straight path with fiber breakage under high shear and tensile stresses. The orientation of yarns in the tubes showed a great effect on crack propagation.


ABSTRACT: To get a strong, stiff and weight efficient cylindrical shell, carbon fiber reinforced corrugated-core sandwich cylinders (CSCs) were designed and made. The corrugated-core is made up of corrugated cylindrical shell and manufactured by mould hot pressing method. Split forming and integral filament winding forming methods were applied to make the CSC separately. Effects from non-wrapped and wrapped cylindrical ends were investigated individually. Uniaxial compression tests were performed to reveal the strength and failure mode. Split forming method makes the CSC stiffer but integral filament winding forming method makes the CSC stronger. With non-wrapped ends, the cylinders fail at end delamination and the load carrying capacity is 289.7 kN and 373.7 kN, respectively. The load is improved to 415.6 kN and 491.4 kN, respectively, when the
cylinder is end-wrapped. Skin fracture controls the failure of the CSCs with wrapped ends and makes them stronger. Meanwhile, the load carrying ability of the CSC is stronger than lattice truss-core sandwich cylinders (LTSCs). Benefiting from the high axial load carrying ability of the CFRC corrugated shell, strength of the designed CSC failing at skin fracture improves at a magnitude of 50% compared with the referenced LTSC.


ABSTRACT: A novel three-dimensional (3D) corrugated core sandwich structure was designed and fabricated by auto-cutting process. Mechanical behaviors and failure mechanism of 3D corrugated core sandwich structures were investigated. Analytical models were developed to estimate the strength, stiffness and dominant failure modes. In order to demonstrate sensitivity of the graded parameters on mechanical behaviors of 3D corrugated core sandwich structures, the specimens with different graded parameters were fabricated and tested under compression and bending loads. Results showed that the graded parameters have obviously influences on the mechanical properties and failure modes of 3D corrugated core sandwich structures. The predictions were also compared with the experiments and the results showed good agreements. Failure maps were constructed to illustrate the controlling failure mechanisms in various regions with different parameters.


ABSTRACT: To get strong, stiff and light cylindrical shell, carbon fiber reinforced hierarchical Isogrid stiffened cylinder (HISC) was designed and fabricated. The cylinder has fractal stiffeners, including the first-order primary Isogrid stiffeners and the self-similar second-order sub-Isogrid stiffeners. The primary Isogrid has thick and high ribs and contains several sub-Isogrid cells whose rib is much thinner and lower. The primary Isogrid improves the bending rigidity of the cylindrical wall to resist the global instability while the sub-Isogrid improves the bending rigidity of the skin enclosed by the primary Isogrid to resist local buckling. The HISC was fabricated by filament winding method based on a silicone rubber mandrel with hierarchical grooves. Axial compression test was performed to reveal the failure mode. With hierarchical stiffeners, the cylinder balances the construction of the skin and the ribs and fails at material failure. Global instability and local buckling are both well restricted by the hierarchical stiffeners.


ABSTRACT: Composite pyramidal-truss core sandwich panels, in which the lattice core is strengthened by reinforced frames between dispersive nodes, were manufactured via water-jet cutting and interlocking assembly. The coefficients of thermal expansion and outgassing (mass loss) ratios of the composite laminates were determined. Subsequently, the effect of vacuum thermal cycling on the compression and shear performance of the composite sandwich panels with pyramidal-truss cores was studied using theoretical and experimental methods. In particular, the out-of-plane compression stiffness and strength, as well as the shear stiffness and strength of the structures subjected to vacuum thermal cycling, were predicted using theoretical equations. The compression and shear performance improved initially and then deteriorated with an increase in the vacuum thermal cycling-time. The observed failure modes depended on the number of vacuum thermal cycles. In addition, the catastrophic response of the composite sandwich panels with pyramidal-truss cores was
investigated, and their possible failure modes (including the crushing and localized buckling of composite struts) were complemented with results of analytical modeling. The truss cores collapsed mainly due to crushing and localized-buckling processes, caused by matrix outgassing and debonding of the interface between the carbon fibers and epoxy resin, after prolonged thermal cycling.

ABSTRACT: A novel all-composite sandwich structure with Y-shaped cores was designed and fabricated by hot-press molding method in this paper. In order to reveal effects of relative density on mechanical behavior, the out-of-plane compressive tests were carried out on composite sandwich structures with different relative densities, varying from 5.34% to 10.53%. Then the effects of relative density on failure modes, mechanical properties, stress-strain curves and energy absorption capacity were studied and analyzed. The results showed that the relative density had visible impact on mechanical behavior of sandwich structure. The stress-strain curves possessed the characteristic of two peaks, and the peak stresses increased as the relative density increased. The numerical simulation based on progressive damage model was developed to reveal the damage evolution process and predict the mechanical properties. Analytical predictions were also presented to predict the compressive strength and stiffness of Y-shaped core, which were compared with numerical results and experimental results. It was observed that the analytical predictions and numerical results were in good agreement with the experimental results.

ABSTRACT: Describing nonlinear viscoelastic properties of polymeric composites when subjected to dynamic loading is essential for development of practical applications of such materials. An efficient and easy method to analyze nonlinear viscoelasticity remains elusive because the dynamic moduli (storage modulus and loss modulus) are not very convenient when the material falls into nonlinear viscoelastic range. In this study, we utilize two methods, Fourier transform and geometrical nonlinear analysis, to quantitatively characterize the nonlinear viscoelasticity of a pre-compressed layered polymeric composite under oscillatory compression. We discuss the influences of pre-compression, dynamic loading, and the inner structure of polymeric composite on the nonlinear viscoelasticity. Furthermore, we reveal the nonlinear viscoelastic mechanism by combining with other experimental results from quasi-static compressive tests and microstructural analysis. From a methodology standpoint, it is proved that both Fourier transform and geometrical nonlinear analysis are efficient tools for analyzing the nonlinear viscoelasticity of a layered polymeric composite. From a material standpoint, we consequently posit that the dynamic nonlinear viscoelasticity of polymeric composites with complicated inner structures can also be well characterized using these methods.

ABSTRACT: Thermoplastic composite structures are being widely investigated due to their excellent properties such as recycling feasibility and high damage tolerance to meet the increasing demand for lightweight engineering components. A novel hierarchical thermoplastic composite honeycomb cylindrical structures (HTCHCS) with recyclability were designed and fabricated using interlocking assembly technique. The quasi-
static axial compression tests were conducted to investigate the mechanical response and energy absorption of HTCHCS. The structural crushing force efficiency can be risen from 0.4 to 0.7 after optimizing the placement mode of axial ribs. The deformation of HTCHCS were experimentally studied and typical deformation modes were obtained. Different from the layer-by-layer collapse for HTCHCS with regular ribs, HTCHCS with staggered ribs showed negative Poisson’ ratio deformation. After large imposed crushing displacement (at least 90%), excellent deformation recovery over 80% initial height was found and reloading carrying and energy absorption abilities can reach to 13% and 12% of initial ones respectively.

ABSTRACT: Sandwich composite panels (SCPs) with carbon fibre reinforced plastic (CFRP) facings are usually vulnerable to low-velocity transverse impact loading. In this study, a method is presented to improve the impact resistance and energy absorption capacity of CFRP-faced SCPs by filling them with a concentrated styrene/acrylate particle based shear thickening fluid (STF). First, for the STF alone, aspects of mechanical performance, namely rheological and low-velocity impact behaviours, were systematically examined. It was found that the critical shear stress of the STF was lower than that of silica particle based STF with a similar particle size and volume fraction, indicating that shear thickening was more easily achieved in the styrene/acrylate particle based STF. In addition, the STF exhibited much higher energy absorption capacity than an aluminium foam. Finally, low-velocity transverse impact experiments were performed on STF-filled SCPs with two core thicknesses, 7.2 mm and 12.7 mm. It was shown that the absorbed energy of the SCPs with a thin core increased by up to 99.3%, while the impact damage of SCPs with a thick core could be effectively suppressed on the back surface of the SCPs. The impact mechanism of the STF-filled SCPs is also discussed. This study provides a new method for the design of impact-resistant SCPs.

ABSTRACT: The numerical and experimental validation of multistable behavior of cantilever shells is addressed. The design of the laminated composite shells is driven by a recently proposed semi-analytical shell model, whose predictions are verified and critically examined by means of finite element simulations and stability tests on two manufactured demonstrators. In addition, the influence of the main design parameters on the shells stability scenario is discussed. Despite its simplicity, the reduced model allows to depict a fairly faithful picture of the stability scenario; therefore, it proves to be a useful tool in the early design stages of morphing shell structures.

ABSTRACT: Vertically aligned carbon nanotube (VACNT) arrays or “forests” represent a promising class of mechanically strong and resilient lightweight materials, capable of supporting large reversible deformation and absorbing mechanical energy. The mechanical response of VACNT forests to uniaxial compression is defined by various factors, including the material microstructure, its density, height, rate of deformation, and the nature of interaction between carbon nanotubes (CNTs) and the compressing indenter. In this paper, we use a coarse-grained mesoscopic model to simulate the uniaxial compression of VACNT samples with different densities and microstructures (bundle size distribution and degree of nanotube alignment) to obtain a clear microscopic
picture of the structural changes in networks of interconnected CNT bundles undergoing mechanical deformation. The key factors responsible for the coordinated buckling of CNTs, reversible and irreversible modes of deformation in VACNT arrays undergoing uniaxial compression, as well as hysteresis behavior in VACNT arrays subjected to five loading–unloading cycles are investigated in the simulations. The simulation results reveal the important role of the collective buckling of CNTs across bundle cross-sections as well as a complex deformation behavior of VACNT arrays defined by an interplay of different modes of bundle deformation. The loading rate and the CNT attachment to the indenter are found to have a strong effect on the deformation mechanisms and the overall mechanical behavior of VACNT forests. A good agreement with experimental data from in situ mechanical tests is observed for the general trends and magnitudes of loss coefficients predicted in the simulations. The forest morphology can strongly alter the mechanical behavior of VACNT arrays with nominally the same general characteristics, such as CNT radius, length, and material density, thus suggesting the opportunity for substantial enhancement of the mechanical properties through the microstructure modification.


ABSTRACT: Origami, the art of folding paper, has inspired the development of rigid foldable structures for various applications in aerospace, biomedical, and packaging applications. In order to drive and control origami structure with thick panels, a novel rigid Miura-Ori structure with bistable anti-symmetric carbon fibre reinforced polymer (CFRP) shells was proposed in this paper. Based on the membrane hinge technique, a theoretical model of the Miura-Ori structure with thick panels combined with bistable CFRP shells was established based on the principle of minimum potential energy. Bistable CFRP shells were used as the connection and driving parts of the whole structure instead of thin-walled materials or hinged structures. Finite element simulations were conducted to explore the deformations and trigger forces. The coincident boundary conditions were provided, which were the same as those used in the compression tests using the universal tensile testing machine. Experiments were conducted to validate the simulation results. The results showed that there is good agreement between the simulation and experimental results, indicating that the bistability of the origami structure is achieved under the control of the CFRP cylindrical shells.


ABSTRACT: The vibration correlation technique (VCT) is one of the most important nondestructive methods to calculate the buckling load of imperfection sensitivity in thin-walled structures. VCT is widely used for beam and plate structures, but the technique is still under development for thin-walled shells. In this paper, an experimental and numerical validation of VCT approach was presented and discussed for the prediction of the buckling load of the grid-stiffened composite cylindrical shells loaded in compression. From the experimental point of view, three specimens were fabricated using a new silicone rubber mold, and specially-designed filament winding setup. The modal behavior of the grid-stiffened composite cylindrical shells was investigated by exciting the structures using modal hammer method in different applied compression load. Then, the variation of the first natural frequency of vibration with the applied compressive load was measured up to buckling during testing. Furthermore, a series of Finite Element Models (FEMs), including nonlinear effects such as geometric and thickness imperfection, are carried out in order to characterize the variation of the natural frequencies of vibration with the applied load and also compare it with the experimental results. Finally, the buckling test was performed to validate the experimental and numerical results of VCT approach. The results
showed that the difference between the predicted buckling load using the VCT approach on the experimental results and numerical results with an experimental buckling load is 3.1% and 5.0%, respectively. Also, the current VCT approach has a very good correlation for grid-stiffened composite cylindrical shells when the maximum applied load is higher than 68% of the experimental buckling load.


ABSTRACT: During the cure process, the anisotropic characteristics of composite material, combined with high temperature and high pressure to which the material is subjected, cause the development of residual stresses. Consequently, laminate deformations arise and dimensional and geometrical requirements are not reached. Laminate deformations transfer into product distortions through assembly process. Distortions result in uncertainty in the performance of manufactured goods and they require effective management to ensure correct performance. The present work shows a numerical approach suitable to determine the geometrical deviations of an assembly constituted by thin laminates in composite material. The proposed model considers the geometrical deviations of the assembly parts, due to the manufacturing process, the assembly sequence and the presence of adhesive to put together the parts. The proposed model was experimentally verified by considering a T-shaped assembly constituted by flat and L-shaped components. The obtained results show a good agreement with the experimental ones.


ABSTRACT: Global buckling failure should be avoided when designing a structure with the requirement of crashworthiness performance. This study characterises the quasi-static in-plane crushing of CF/EP composite sandwich panels by tailoring their bevel angles. A finite element model was developed describing the interlaminar and intralaminar damage of a composite sandwich panel; this model was validated by in-plane compression experiments. A numerical analysis and compression experiments were then performed to determine the responses and failure modes in the CF/EP composite sandwich panels with various bevel angles. The results showed that the global buckling-to-progressive failure transition under compression occurred in the composite sandwich panels when the bevel angle reached a critical value. A microscopic analysis showed that the composite sandwich panels with buckling failure behaviours exhibited an apparently classical post-buckling transverse shearing mode, while those with progressive failure presented individual lamina bending with inward and outward fronds. This study provides some useful data for the design of the crashworthiness of a sandwich composite panel by introducing a progressive failure mode.

Jianxun Zhang, Yang Ye, Qinghua Qin and Tiejun Wang, “Low-velocity impact of sandwich beams with fibre-metal laminate face-sheets”, Composites Science and Technology, Vol. 168, pp 152-159, 10 November 2018

ABSTRACT: Low-velocity impact of fully clamped sandwich beams with fibre-metal laminate face-sheets and metal foam core struck by a heavy mass is investigated. Analytical solutions are developed for the dynamic response of sandwich beams with fibre-metal laminate face-sheets considering the interaction of bending and stretching induced by large deflections. According to the rigid-plastic material approximation with modifications, simple formulae are obtained for the large deflection of sandwich beams with fibre-metal laminate face-sheets. Numerical calculations are carried out, and analytical solutions capture numerical results reasonably. The effects of the composite volume fraction, the ratio of metal layer strength to composite layer strength, and core strength on the structural response are discussed. Using the analytical formulae, optimal
References listed at the end of the paper:


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ABSTRACT: The traditional eigenvalue buckling mode method used for the stability analysis of suspended domes has been deemed unsafe and unreasonable. A random imperfection method is proposed in this paper that is suitable for the stability analysis of suspended domes. Using this method, the impact of initial imperfections, such as joint position deviation, eccentricity of members, variation in cable pretension and elastic modulus of materials, on the stability of nonlinear geometries as well as the stability of both nonlinear geometries and materials (i.e., ultimate bearing capacity) are studied. The analysis results using this method are compared to those obtained from the traditional eigenvalue buckling mode method. This study indicates that the random imperfection method can more reasonably demonstrate the impact of initial imperfections on the stability of suspended domes. Additionally, the shape and size of the initial imperfections applied by the random imperfection method are more reasonable, and the results are safer. The random imperfection method is
successfully used in the stability analysis of a large-span suspended dome, and the results of this method are nearly equivalent to that of the model test, which verifies the method.

References listed at the end of the paper:


ABSTRACT: To avoid any interruption of service and considering economic issues, strengthening of existing columns usually occurs while the member is under service loads. One of the important issues being neglected in
the redesign process of retrofitted columns is the effects of significant axial load existing in the columns. This paper presents a numerical study to investigate the behavior and the ultimate bearing capacity of box shaped steel columns reinforced with continuous welded plates while under load. In the first phase of the study, it is intended to evaluate the variation of results with respect to the existing design relations. For this purpose, the ultimate bearing capacity of un-preloaded models is assumed to be in accordance with the selected design code and the corresponding geometric imperfection for each model is defined using several analyses to reach the values obtained with the design code, for further studies. In the second phase, the magnitude of initial imperfection is set to 1/500 of the studied columns. In both phases, the effect of magnitude of existing preload on ultimate bearing capacity is investigated considering two influential parameters, namely the slenderness ratio of the column and the ratio between cross sectional area of the column and reinforcing plates. Results show that by increasing the preload magnitude, the ultimate bearing capacity of reinforced columns with identical reinforcing plates, decreases. This reduction is more notable for the columns with median slenderness ratios. However, as the magnitude of preload increases, the effect of slenderness ratio on the reduction of ultimate bearing capacity becomes more evident. Also, it is found that by using a fixed imperfection ratio of L/500, even for un-preloaded models the ultimate bearing capacity of the strengthened column will be less than the values calculated as per the selected design code. Finally, an empirical relation is proposed to calculate reduction of ultimate bearing capacity for columns affected from various preload level considering different slenderness ratios.

References listed at the end of the paper:


ABSTRACT: Welding the reinforced component on the surface of a steel structure is a common method to reinforce steel structures in practical engineering. Work efficiency is low in actual construction because of continuous welding. Intermittent welding was adopted in this study to address this issue. The axial compression performance of reinforced steel columns in an actual project was studied through experiments and with the numerical method. The influence of different intermittent welding reinforcement schemes on the reinforcement of steel box columns was analyzed. Steel box columns with different weld intervals were placed relatively close because of their failure mechanism. The discontinuous welding reinforcement scheme reduced cost and improved efficiency. A simplified numerical model was established to conduct a parametrical analysis. An improved reinforcement scheme was proposed based on the analyzed results. The improved reinforcement scheme enhanced the load conditions and strength of steel angles.

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In this paper, the bending response of box-section beams of finite length is investigated by using energy methods. The basic assumptions used in the present study are that the total strain energy of a box-section beam subjected to uniformly distributed loading can be simplified into a two-stage analysis process. One is the local bending response of the webs and flanges behaving as plates; the other is the overall bending response of the beam with a deformed cross-section. Analytical solutions for both static and dynamic instabilities of box section beams of finite length subjected to transverse uniformly distributed loading are derived by applying the minimum potential energy principle. To validate the analytical solutions developed, geometric nonlinear finite element analyses are also conducted. Good agreement between the present solutions and the FEA results is demonstrated. Finally, the effects of beam length on the limit critical uniformly distributed load are also discussed.

References listed at the end of the paper:

Kamal Kolasangiani and Mahmoud Shariati, “Experimental study of SS304L cylindrical shell with/without cutout under cyclic combined and uniaxial loading,” International Journal of Steel Structures, Vol. 17, No. 2, pp 553-563, June 2017

ABSTRACT: In this research, ratcheting behavior of SS304L cylindrical shells under cyclic combined and uniaxial loadings was studied. Experimental tests were carried out by a servo-hydraulic INSTRON 8802 machine and the shells were fixed normal and oblique at angle of 20° with respect to the longitudinal direction of the shell. Force-control loadings were applied and the effect of length, angle of cylindrical shell and loading history on ratcheting behavior were examined. It was shown as the angle of cylindrical shell increases, due to increase of bending moment, accumulation of plastic deformation increases. Also, linear relation was observed between plastic energy and rate of plastic deformation which shows the rigidity of fixtures used in tests. Cutout effect on cylindrical shells under these kinds of loading has been studied and it was observed that creating cutout increases the plastic deformation and its rate.

References listed at the end of the paper:
with the outcomes of a finite element spatial model. It is shown that there is an excellent agreement. The terms of nine unknown displacements. Several examples are solved numerically and the results are compared problems are also addressed. The Hamilton principle application yields to account for through the second with a zigzag diagonal pattern. The differential system is derived from the potential and kinematic energies of the discrete model as the sums of each component contribution. Then, after accepting the number of diagonals is large enough, the sums are approximated in the limit with classical integrals. Thus, the discrete system is replaced with a continuous formulation. The natural vibration problem of a lattice mast with a zig-zag diagonal pattern is studied using the proposed model. Also, the axial load influence is also accounted for through the second-order effect allowing to solve the buckling problem. Static deflection problems are also addressed. The Hamilton principle application yields the governing differential system in terms of nine unknown displacements. Several examples are solved numerically and the results are compared with the outcomes of a finite element spacial model. It is shown that there is an excellent agreement. The

A.M. Guzman, M.B. Rosales and C.P. Filipich, “Natural vibrations and buckling of a spatial lattice structure using a continuous model derived from an energy approach”, International Journal of Steel Structures, Vol. 17, No. 2, pp 565-578, June 2017

ABSTRACT: Lattice structures composed by parallel members named chords (or legs for vertical configurations) and connected by diagonals are very common among steel constructions in Civil and Mechanical Engineering and in particular, in the telecommunications industry. In the present study, a continuous model of a typical spatial lattice structure is derived. The legs configure a triangular cross-section and the diagonals are arranged in a zig-zag pattern. The differential system is derived from the potential and kinematic energies of the discrete model as the sums of each component contribution. Then, after accepting that the number of diagonals is large enough, the sums are approximated in the limit with classical integrals. Thus, the discrete system is replaced with a continuous formulation. The natural vibration problem of a lattice mast with a zig-zag diagonal pattern is studied using the proposed model. Also, the axial load influence is also accounted for through the second-order effect allowing to solve the buckling problem. Static deflection problems are also addressed. The Hamilton principle application yields the governing differential system in terms of nine unknown displacements. Several examples are solved numerically and the results are compared with the outcomes of a finite element spacial model. It is shown that there is an excellent agreement. The
proposed continuous model can represent adequately the spatial lattice with a strong reduction in the degrees of freedom and the time of computation of the solution in comparison with a finite element approach.

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Hui Wang, Yonghua Guo, Yongtao Bai, Bin Zhang, Qing Sun and Jianyang Xue, “Experimental and numerical study on the stability capacity of Q690 high-strength circular steel tubes under axial compression”, International Journal of Steel Structures, Vol. 17, No. 3, pp 843-861, September 2017

ABSTRACT: This paper presents experimental investigation on the local and overall buckling capacity of Q690 high-strength circular steel tubes under axial compression. Coupon tests are undertaken to obtain the Young’s modulus, Poisson’s ratio, tensile yield stress and ultimate tensile strength of Q690 steel material. Forty-two specimens under axial compression are tested to evaluate the buckling behavior and the failure mode. Test results indicate that most of the existing design standards are conservative for the design of Q690 steel tubes. The distribution model of residual stress is measured by cutting ring method. Then, a finite element model based on modified column deflection curve method (CDC) is built to assess the effects of initial imperfection and residual stress on the stability capacity of the steel tubes. Finally, design methods and recommendations are provided for estimating the stability capacity of high-strength circular steel tubes.

References listed at the end of the paper:

ABSTRACT: Sandwich pipes (SP) are promising subsea pipelines for deep-water applications. Thus, their lateral buckling response is a significant design aspect. The temperature field of SP denotes the load in lateral buckling analysis, and it is calculated using the heat transfer differential equation in this study. A general temperature field formula is proposed for an arbitrary multilayer SP, and this formula is verified by finite element models. Another finite element model based on the fiber shell element is then constructed to investigate the lateral buckling response of SP. They are validated by existing experimental and numerical results. The evolution of the lateral buckling profiles and of stress distribution are studied in consideration of nonlinear pipe-soil interaction and nonlinear material constitutive law. Moreover, the influence of initial imperfections and pipe-soil interaction on lateral buckling response is examined. Finally, a formula is approximated for a SP with a half-wave sinusoidal imperfection profile on the basis of dimensionless analysis and numerical results. This formula is convenient for engineering applications.
References listed at the end of the paper:

ABSTRACT: Load carrying capacity of reticulated space structures majorly depend on the structures’ imperfections. Imperfections in initial curvature, length, and residual stress of members are all innately random and can affect the load-bearing capacity of the members and consequently that of the structure. The present study investigated the effect of the probability distribution of initial curvature imperfection and lack of fit of members on the load-bearing capacity of double-layer barrel vault space structures with different types of support. A random number was first assigned to each member using gamma and normal distributions for initial curvature and member length imperfections, respectively. Afterwards, the ultimate bearing capacity and the collapse behavior of the structure was determined using nonlinear finite-element analysis in OpenSees software and finally structures reliability was acquired. The results demonstrate that the collapse behavior of double-layer barrel vault space structures is sensitive to the random distribution of initial imperfections.

References listed at the end of the paper:


ABSTRACT: In recent years, due to a relatively high price increase of nickel alloys, there is an increase in demand for lean duplex stainless steel (LDSS) with a low nickel content of ~1.5%, such as grade EN 1.4162. LDSS offers roughly twice the strength compared to austenitic stainless steels and has great potential for expanding future structural possibilities, enabling a reduction in the section sizes leading to lighter structures. This paper reports the buckling behavior of fixed-ended concrete-filled LDSS tubular (CFDSST) columns with L-, T-, and + shape (Non-Rectangular Sections or NRSs) sections and a representative square section with varying lengths through Finite Element (FE) analysis. The purpose is to compare and assess the strength and deformation characteristics as well as the failure modes of such columns. It is seen that concrete-filled tubular columns with NRSs offered a better performance for all lengths considered, especially the T-shaped and + shaped sections, in terms of strength. The influence of the cross-sectional shapes on the $\epsilon_u$ becomes less significant with increasing $\lambda$, but becomes increasingly significant with decreasing $\lambda$. The design standards show over conservative results for square and L-shape sections and conservative for T-shape and +shape sections.

References listed at the end of the paper:

Mohamed Ghannam, “Axial load capacity of cold-formed steel built-up stub columns”, International Journal of Steel Structures, Vol. 17, No. 3, pp 1273-1283, December 2017

ABSTRACT: This paper aims to investigate the axial load capacity of innovative cold-formed steel (CFS) built-up stub columns. Four innovative CFS built up section is presented in this paper. Each section is composed of combination of more than two elements as follows: channels, channels with lip, Sigma section and/or plates. The elements of each section are assembled together by using self tapping screws. The concentric axial load capacity of each of the four sections was investigated numerically by using finite element (FE) model using ABAQUS program. The FE model was verified against previous test data. The FE model was used to study different parameters that affect the load capacities of the innovative CFS built-up stub columns, these parameters are: columns profile, steel thickness, steel grade and longitudinal spacing between screws (fasteners), cross sectional area. The axial load capacities obtained from FE models are compared with the perdition of the Effective width (EW) method (available in Eurocode, Egyptian code, American and Australian standards) and direct strength (DS) method (Available in American and Australian standards).

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Abolfazl Arabzadeh and Hamid Reza Kazemi Nia Korrani, “Numerical and experimental investigation of composite steel shear wall with opening”, International Journal of Steel Structures”, Vol. 17, No. 4, pp 1379-1389, December 2017

ABSTRACT: Shear walls are used in towers as lateral loading resistance. Composite shear wall (CSSW) because of high stiffness and deformability are widely used. This wall made of a thin steel plate with reinforced a concrete layer, which is attached to one or both sides of the steel plate. This system is similar to stiffened steel plate shear wall. The present experimental and numerical studies were focused on the effects of opening used as windows or doors in buildings on the CSSW behavior. Experimental studies results of one and three-story CSSWs with the scale of 1:3 are reported. In addition, the effects of opening size and location are insignificant on the composite steel shear walls behavior. Results showed that opening decrease CSSW strength. Opening at the sides and corners further reduces the resistance than Opening at the center.

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· Lau, H. H., and Ting, T. C. H. “An Investigation of The Compressive Strength of Cold-formed Steel Built-up I Sections.” Proc., Sixth International Conference on Advances in Steel Structures, The Hong Kong Institute of Steel Construction, pp. 441-449.
· Schafer, B. W. “Progress on the Direct Strength Method.” Proc., Sixteenth International Specialty Conference on Cold-Formed Steel Structures.
ABSTRACT: Using the finite element analysis, a series stiffened panels under combined normal loads and biaxial compressions are conducted to investigate the effect of several influential factors on the ultimate limit states. Two spans/bays FE model with periodical boundary condition is adopted to consider the interaction between adjacent structural members. The initial deflections assumed as Fourier components including symmetric and asymmetric modes are used to identify the half-wave number of collapse of the local plate, which is compared with half-wave number of buckling calculated by formula. Based on the numerical results, the influences of half-wave number assumed in the equivalent initial imperfection and loads combination on the collapse behaviours of stiffened panels are discussed. It is found that lateral pressure might increase the ultimate strength of stiffened panels for the stiffener-induced failure modes. The one half-wave region of local plate influences significantly the load carrying capacity of stiffened panels.

References listed at the end of the paper:

consider the geometric characteristics and material properties of the pipe and arrestor. Based upon the extensive
parametric studies are conducted to identify the mechanism governing the arresting performance, which
ABSTRACT: Dedicated finite element models are developed to simulate the crossing of a pipeline integral
buckle arrestor by a buckle propagating under the quasi-static, steady-state condition. In addition, broad
parametric studies are conducted to identify the mechanism governing the arresting performance, which
consider the geometric characteristics and material properties of the pipe and arrestor. Based upon the extensive


- Czujko, J., Kmiecieck, M. (1975). “Post welding distortions of ship shell plating.” Ship Research Institute, Technical University of Szczecin, Report No. 4-S.
study, the more reasonable empirical design formulas for the crossover pressure and the arresting efficiency are established by means of the partial fitting. Good agreements between the existing experimental results and the predictions demonstrate that the proposed empirical formula and the lower bound envelope line for the arresting efficiency provide a powerful design tool to estimate the arresting performance of such complex structure systems in engineering practices.

References listed at the end of the paper:


ABSTRACT: The multi-span steel tube and coupler scaffold is one of the main temporary structural forms in building and bridge construction. Given the insufficient research on their bearing capacity and design method, steel tube and coupler scaffolds have frequently collapsed in recent years and have caused serious casualties and economic losses. Through six prototype tests and a numerical analysis, this study investigated the effect of stability strengthening measures, such as vertical X-bracing, horizontal X-bracing, surrounding non-loading area, and lateral wall-tied constraints, on the ultimate bearing capacity and failure mode of multi-span steel tube and coupler scaffolds under a uniformly distributed line load of upper horizontal tubes. Using the finite element numerical analysis verified by the test data, the influence of height-width ratio, structure height, story height, spacing of vertical tubes, X-bracing layout, lateral wall-tied constraints, and surrounding non-loading area on the ultimate bearing capacity of multi-span steel tube and coupler scaffolds was analyzed. Design methods for multi-span steel tube and coupler scaffolds under a uniformly distributed line load of upper horizontal tubes were proposed based on the results of the prototype test and finite element numerical analysis. The reasonability of the design method was verified by the test data and finite element analysis results.

References listed at the end of the paper:

ABSTRACT: Studies have been carried out so as to gain an understanding of the behaviour of structural steel members exposed to different degrees of corrosion and high temperature in service. The progressive collapse and buckling characteristics of tubular members subjected to high temperature together with corrodnants (localised corrosion) are presented in this paper. A microstructural analysis has been carried out so as to understand the change in mechanical and chemical properties that has been brought about in the material. The results reveal that the failure of the corroded members is attributed to localised axisymmetric imperfections imparted to the tubular members apart from loss of weight. The failure of members subjected to elevated temperature is attributed to the coarsening of the grain size.

References listed at the end of the paper:

ABSTRACT: Bracing is one of the best-known means of seismic retrofitting. Buckling restrained brace (BRB) is a certain type of brace with great efficiency against lateral loading. This paper presents the results of a finite element analysis on a BRB in which casing has no concrete infill. The core segment of this brace is similar to the conventional BRB, but it has a different buckling restraining system. The aim of this paper was to perform a parametric seismic study on the effect of a gap and also the effect of friction between the core and the casing and to evaluate the buckling behavior of these braces in response to changes in the initial shape of the bracing system. The results show that the flexural stiffness of the casing system, regardless of size of the gap, can significantly affect the buckling behavior of bracing.

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ABSTRACT: To analyze the axial compressive performance of elliptical concrete-filled thin-walled steel tube (ECFTST) columns, finite element (FE) modeling was built up by ABAQUS software in this paper. The material nonlinearity and the complex interaction between steel tube wall and core concrete in an elliptical section were considered in this numerical analysis. Failure modes and interaction mechanism of ECFTST stub columns were also studied. Moreover, a modified equivalent circular diameter approach for ellipse feature was proposed to substitute for the constitutive relation of ECFTST columns. The prediction accuracy of this method
was verified by the comparison of the FE and test results in terms of failure modes, axial compressive capacities and axial force-axial displacement relation curves. Further, the influence of diameter-to-thickness ratio, cross-section slenderness and scale effect etc. on the performance of ECFTST stub columns were estimated under axial compressive loading. The results of numerical analysis showed that the axial force-axial displacement curves of the ECFTST stub columns were obviously affected by the confinement factor. Lastly, based on the simple superposition approach and the unified theory approach, two simplified design methods were proposed to predict the axial compressive capacities of ECFTST columns.

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Lunhua Bai, Ruili Shen, Lu Wang, Yuan Wang and Rusong Miao, “Experimental and numerical study on buckling behavior of a rigidly stiffened plate with Tee ribs”, International Journal of Steel Structures, Vol. 18, No. 2, pp 582-595, June 2018

ABSTRACT: In the bridge structures, stiffened plates are usually designed as rigidly stiffened when the orthotropic steel box girder is used as the main load-bearing structure. Therefore, the buckling mode of stiffened plates is plate buckling which occurs in subpanel supported by stiffeners. The orthotropic steel box girder is used as the main girder for Egongyan Rail Special Bridge, which is a self-anchored suspension bridge. Plates of the steel girder are rigidly stiffened with unequal spacing open ribs, and the most slender stiffened plate is the mid web stiffened with Tee ribs. In order to ensure the safety of the bridge, the buckling behavior of the web and orthotropic steel box girder under axial compression, including ultimate strength, post-buckling behavior and failure modes, should be clearly investigated by experimental and numerical methods. The design, loading and testing methods of the 1:4 scale model of the orthotropic steel box girder are introduced in detail firstly. The orthotropic steel box girder and the stiffened web finite element (FE) models are validated by the test results, and the effects of residual stress and the magnitude of geometric imperfections are discussed roughly. Based on the validated web FE model, a detailed parametric study is performed to systematically investigate the effects of residual stress and geometric imperfections on buckling behavior of the web. The effect of shapes of geometric imperfections discussed is highlighted. Through tracing stress states, the failure modes of stiffened plate are in agreement with the experimental phenomenon to some extent. Results show that shapes of geometric imperfections have significantly influenced post-buckling behavior and failure modes of the web, but slightly affected the ultimate strength. It is advised that residual stress and geometric imperfections should be controlled to make full use of excellent performance of steel materials.

References listed at the end of the paper:

- Dong, K. S., Dat, B. V., & Kim, K. (2014). Compressive strength of HPS box girder flanges stiffened with open ribs. Journal of

ABSTRACT: This paper presents an experimental investigation on concrete-filled double-skin circular hollow section (CHS) cross joints under axial compression. A total of twenty-two right-angled CHS cross joints with different brace to chord diameter ratio ($\beta$), inner tube to outer tube thickness ratio of chord ($\omega$) and hollow ratio of chord ($\chi$) were tested, in which eighteen concrete-filled double-skin CHS cross joints were studied for different shapes of chord, two traditional empty CHS cross joints and two traditional concrete-filled CHS cross joints were tested for comparison. The joint strengths, failure modes, load-deformation curves and strain distribution curves of all specimens are reported. The effects of brace to chord diameter ratio ($\beta$), inner tube to outer tube thickness ratio of chord ($\omega$), hollow ratio of chord ($\chi$), shape of inner tube of chord and concrete strength on the behaviour of concrete-filled double-skin CHS cross joints under axial compression were evaluated. It is shown from the comparison that the ultimate load and initial stiffness of CHS cross joints are significantly enhanced by strengthening the chord member with inner tube and concrete infill. Furthermore, the ultimate strengths are increased with the increase of the $\beta$ ratio, whereas the ultimate strengths are decreased with the increase of the $\chi$ ratio for all types of concrete-filled double-skin CHS cross joints. On the other hand, the ultimate strengths are enhanced with the increase of the $\omega$ ratio and concrete strength for all types of concrete-filled double-skin CHS cross joints, but the enhancement is insignificant. The corresponding finite element analysis was also performed and calibrated against the test results. The design equations are proposed based on the test and finite element analysis results for concrete-filled double-skin CHS cross joints, which are verified to be more accurate.


ABSTRACT: A double-layer grid space structure is a conventional long span structure used where large column-free areas are required. Due to its large indeterminacy and the redundancy of its structural
configuration, it is normally considered in design practice, that progressive collapse will not be triggered when the loss of an individual member occurs. However, research and several prior accidents have shown that progressive collapse could occur following the loss of some critical members when the structures are subject to abnormal loading such as heavy snow. To investigate the structural behavior of this type of structure, a 3D finite element model of a double-layer space structure grid was built by the authors, several collapse scenarios have been investigated using an implicit method which follows the alternative path method defined in GSA. In addition, case studies have been made using the explicit method which is to simulate the whole process of the structural collapse. In the analysis, different members failure or support collapses were studied. The response of the structure was investigated and the correspondent potential of progressive collapse was discussed in detail. Methods to mitigate the progressive collapse of this type of space structure have also been recommended.


ABSTRACT: Recently, after clearly pointing out the flaws associated with the current AISC equation for flexural strength of I-shaped beams with slender flange, the authors proposed new equation, more accurate and more consistent than the current AISC equation, based on the mixed variational approach. However, the new equation was derived under the condition of uniform moment loading. In this paper, elastic flange local buckling strength formula for I-shaped beams with slender flange under moment gradient was proposed as a follow-up study on the basis of mixed variational approach and supplemental numerical works. The flange plate buckling coefficient predicted by the formula of this study is again shown to be much more accurate and consistent.

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End of more papers published in the journal, International Journal of Steel Structures. (2017 and on)

More papers published in the journal, ASME Journal of Mechanical Design. (2017 and on)
Google the string: “Journal of Mechanical Design”, then click on the entry:
“Journal of Mechanical Design – The American Society of Mechanical…”, then find “Browse All Issues”


ABSTRACT: The art and science of folding intricate three-dimensional structures out of paper has occupied artists, designers, engineers, and mathematicians for decades, culminating in the design of deployable structures and mechanical metamaterials. Here we investigate the axial compressibility of origami cylinders, i.e., cylindrical structures folded from rectangular sheets of paper. We prove, using geometric arguments, that a general fold pattern only allows for a finite number of isometric cylindrical embeddings. Therefore, compressibility of such structures requires either stretching the material or deforming the folds. Our result considerably restricts the space of constructions that must be searched when designing new types of origami-based rigid-foldable deployable structures and metamaterials.

References listed at the end of the paper:


ABSTRACT: Stochastic finite-element analysis of composite plates due to low velocity impact (LVI) is studied, considering the material properties (Young's modulii, Poisson's ratio, strengths, and fracture energy) and initial velocity as random parameters. Damage initiation and propagation failure due to matrix cracking are investigated for safety criteria for the LVI. Progressive damage mechanics is employed to predict the stochastic dynamic response of the plates. The Gaussian process response surface method (GPRSM) is presently adopted to determine the probability of failure (Pf). There is a possibility of underestimation of the peak contact force and displacement by 10.7% and 11.03%, respectively, if the scatter in the properties is not considered. The sensitivity-based probabilistic design optimization procedure is investigated to achieve better strength and lighter weight of composite for body armors.


ABSTRACT: Deoxyribose nucleic acid (DNA) origami nanotechnology is a recently developed self-assembly process for design and fabrication of complex three-dimensional (3D) nanostructures using DNA as a functional material. This paper reviews our recent progress in applying DNA origami to design kinematic mechanisms at the nanometer scale. These nanomechanisms, which we call DNA origami mechanisms (DOM), are made of relatively stiff bundles of double-stranded DNA (dsDNA), which function as rigid links, connected by highly compliant single-stranded DNA (ssDNA) strands, which function as kinematic joints. The design of kinematic joints including revolute, prismatic, cylindrical, universal, and spherical is presented. The steps as well as necessary software or experimental tools for designing DOM with DNA origami links and joints are detailed. To demonstrate the designs, we presented the designs of Bennett four-bar and crank–slider linkages. Finally, a
list of technical challenges such as design automation and computational modeling are presented. These challenges could also be opportunities for mechanism and robotics community to apply well-developed kinematic theories and computational tools to the design of nanorobots and nanomachines.


ABSTRACT: The stiffness of plate structures can be significantly improved by adding reinforcing ribs. In this paper, we are concerned with the stiffening of panels using ribs made of constant-thickness plates. These ribs are common in, for example, the reinforcement of ship hulls, aircraft wings, pressure vessels, and storage tanks. Here, we present a method for optimally designing the locations and dimensions of rectangular ribs to reinforce a panel. The work presented here is an extension to our previous work to design structures made solely of discrete plate elements. The most important feature of our method is that the explicit geometry representation provides a direct translation to a computer-aided design (CAD) model, thereby producing reinforcement designs that conform to available plate cutting and joining processes. The main contributions of this paper are the introduction of two important design and manufacturing constraints for the optimal rib layout problem. One is a constraint on the minimum separation between any two ribs to guarantee adequate weld gun access. The other is a constraint that guarantees that ribs do not interfere with holes in the panel. These holes may be needed to, for example, route components or provide access, such as a manhole. We present numerical examples of our method under different types of loadings to demonstrate its applicability.

References listed at the end of the paper:

ABSTRACT: In this paper, we generalize Miura origami and propose a method for analyzing a generalized Miura origami structure. Morphological properties of the generalized Miura origami element during the deploy motion are analyzed using the proposed method, which mainly utilizes the principle of spherical trigonometry and is verified in the folding limit state. The longitudinal length, horizontal length, and height of the generalized Miura origami element are defined and obtained using the proposed method. Results show the relationship between the range of deployment and the element parameters as well as the changes of the folding plane angles in the deployment process. During the deploy motion, both the longitudinal and horizontal length increased while the height decreased. However, the change speed of horizontal length decreased, whereas those of longitudinal length and height initially increased and then decreased. The increment of the folding element angle difference $\Delta \alpha$ reduced folding range and put off the severe change time of longitudinal length and height. The length parameters $K_l$, $K_h$, and $K_{ab}$ had slight effects on the results, but their changes did not alter the change trends. These results are useful to the design of fold structure and analysis of errors in standard Miura-ori structures.

References listed at the end of the paper:

ABSTRACT: The lattice structure is a type of cellular material with trusslike frames which can be optimized for specific loading conditions. The fabrication of its intricate architecture is restricted by traditional manufacturing technologies. However, additive manufacturing (AM) enables the fabrication of complex structures by aggregation of materials in a layer-by-layer fashion, which has unlocked the potential of lattice structures. In the last decade, lattice structures have received considerable research attention focusing on the design, simulation, and fabrication for AM techniques. And different modeling approaches have been proposed to predict the mechanical performance of lattice structures. This review introduces the aspects of modeling of lattice structures and the correlation between them, summarizes the existing modeling approaches for simulation, and discusses the strength and weakness in different simulation methods. This review also summarizes the characteristics of AM in manufacturing cellular materials and discusses their influence on the modeling of lattice structures.


ABSTRACT: This study presents an efficient multimaterial design optimization algorithm that is suitable for nonlinear structures. The proposed algorithm consists of three steps: conceptual design generation, clustering, and metamodel-based global optimization. The conceptual design is generated using a structural optimization algorithm for linear models or a heuristic design algorithm for nonlinear models. Then, the conceptual design is clustered into a predefined number of clusters (materials) using a machine learning algorithm. Finally, the global optimization problem aims to find the optimal material parameters of the clustered design using a machine learning algorithm. The proposed methodology is demonstrated using examples from multiple physics and compared with traditional multimaterial topology optimization (MTOP) method. The proposed approach is applied to a nonlinear, multi-objective design problems for crashworthiness.


ABSTRACT: Flasher, which has been used in space engineering, is a class of origami patterns. After modifying and introducing cuts for the flasher pattern, we add nonzero thickness to the flasher and taper its panels. We find that, if appropriately driven, the modified flasher can be used as the deployable mechanism, and even envelop the curved surface in its unfolded configuration. We establish a geometric model and a kinematic model for the mechanism. Then we propose a designing approach including folding design and driving method. The folding design, which ensures that the mechanism can be folded in the folded configuration, is based on geometric constraints. The driving method, which enables the multi-degree-of-freedom (DOF) mechanism to deploy in sequence with only one actuator, is based on underactuation. A prototype is built to validate this approach.

References listed at the end of the paper:
ABSTRACT: Stiffened structures are widely used in industry. However, how to optimally distribute the stiffening ribs on a given base plate remains a challenging issue, partially because the topology and geometry of stiffening ribs are often represented in a geometrically implicit way in traditional approaches. This implicit treatment may lead to problems such as high computational cost (caused by the large number of design variables, geometry constraints in optimization, and large degrees-of-freedom (DOF) in finite element analysis (FEA)) and the issue of manufacturability. This paper presents a moving morphable component (MMC)-based approach for topology optimization of rib-stiffened structures, where the topology and the geometry of
stiffening ribs are explicitly described. The proposed approach displays several prominent advantages, such as (1) both the numbers of design variables and DOF in FEA are reduced substantially; (2) the proper manufacture-related geometry requirements of stiffening ribs can be readily satisfied without introducing any additional constraint. The effectiveness of the proposed approach is further demonstrated with numerical examples on topology optimization of rib-stiffened structures with buckling constraints.

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**End of more papers published in the journal, ASME Journal of Mechanical Design.** (2017 and on)

**More papers published in the journal, Steel and Composite Structures.** (2017 and on)

Google the string, “Steel and Composite Structures”, then click on the entry, “Steel and Composite Structures” | Korea Science” and see “Volume & Issues” on your screen.


**ABSTRACT:** This paper is presented to solve the buckling problem of functionally graded truncated conical shells subjected to displacement-dependent pressure which remains normal to the shell middle surface throughout the deformation process by the semi-analytical finite strip method. Material properties are assumed to be temperature dependent, and varied continuously in the thickness direction according to a simple power law distribution in terms of the volume fraction of a ceramic and metal. The governing equations are derived based on first-order shear deformation theory which accounts for through thickness shear flexibility with Sanders-type of kinematic nonlinearity. The element linear and geometric stiffness matrices are obtained using virtual work expression for functionally graded materials. The load stiffness also called pressure stiffness matrix which accounts for variation of load direction is derived for each strip and after assembling, global load stiffness matrix of the shell which may be un-symmetric is formed. The un-symmetric parts which are due to load non-uniformity and unconstrained boundaries have been separated. A detailed parametric study is carried out to quantify the effects of power-law index of functional graded material and shell geometry variations on the difference between follower and non-follower lateral buckling pressures. The results indicate that considering pressure stiffness which arises from follower action of pressure causes considerable reduction in estimating buckling pressure.

References listed at the end of the paper:

ABSTRACT: This article aims at presenting multi objective optimization of parameters that affect crashworthiness characteristics of bi-tubular structures using Taguchi method with grey relational analysis. To design the experiments, the $L_{27}$ orthogonal array has been used and based on that, the inner tubes have been fabricated by varying the three influence factors such as reference diameter, length difference and numbers of sides of the polygon with three levels, but all the outer cylinders have the same diameter and length 90 mm and 135 mm respectively. Then, the tailor made bi-tubular steel structures were subjected into quasi static axial compression. From the test results it is found that the crushing behaviors of bi-tubular structures with different combinations were fairly significant. The important responses (crashworthiness indicators) specific energy absorption and crush force efficiency have been evaluated from load - displacement curve. Finally optimal levels of parameters were identified using grey relational analysis, and significance of parameters was determined by analysis of variance. The optimum crashworthiness parameters are reference diameter 80 mm, length difference 0 mm and number of sides of polygon is 3, i.e., triangle within the selected nine bi-tube combinations.

References listed at the end of the paper:

ABSTRACT: Braces are one of the retrofitting systems of structures under earthquake loading. Buckling restrained braces (BRBs) are one of the very efficient braces for lateral loads. One of the key needs for a desirable and acceptable behavior of buckling-restraining brace members under intensive loading is that it prevents total buckling until the bracing member tolerates enough plastic deformation and ductility. This paper presents the results of a set of analysis by finite element method on buckling restrained braces in which the filler materials within the restraining member have been removed. These braces contain core as the conventional BRBs, but they have a different buckling restrained system. The purpose of this analysis is conducting a parametric study on various empty spaces between core and restraining member, the effect of friction between core and restraining member and applying initial deformation to brace system to investigate the global buckling behavior of these braces. The results of analysis indicate that the flexural stiffness of restraining member, regardless of the amount of empty space, can influence the global buckling behavior of brace significantly.

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ABSTRACT: This paper presents a combined numerical and theoretical study on the composite action between steel and concrete of circular steel tube confined concrete (STCC) stub columns under axial compressive loading with a full theoretical elasto-plastic model and finite element (FE) model in comparison with experimental results. Based on continuum mechanics, the elasto-plastic model for STCC stub columns was established and the analysis was realized by a FORTRAN program and the three dimensional FE model was
developed using ABAQUS. The steel ratio of the circular STCC columns were defined in range of 0.5% to 2% to analyze the composite action between steel tube and concrete, and make a further study on the advantages of the circular STCC columns. By comparing the results using the elasto-plastic methods with the parametric analysis result of FE model, the appropriate friction coefficient between the steel tube and core concrete was defined as 0.4 to 0.6. Based on ultimate balance theory, the formula of ultimate load capacity applying to the circular STCC stub columns was developed.

References listed at the end of the paper:

ABSTRACT: In this paper, thermal effect on the vibration and stability of initially stressed sandwich plates with functionally graded material (FGM) face sheets is analyzed. Material properties of FGM face sheet are graded continuously in the thickness direction. The variation of FGM properties assumes a simple power law distribution in terms of the volume fractions of the constituents. The governing equations of arbitrarily initially-stressed sandwich plates including the effects of transverse shear deformation and rotary inertia are derived. The initial stress is taken to be a combination of a uniaxial extensional stress and a pure bending stress in the examples. The eigenvalue problems are formed to study the vibration and buckling characteristics of simple supported initially stressed FGM/metal/FGM plates. The effects of volume fraction index, temperature rise, initial stress and layer thickness of metal on the natural frequencies and buckling loads are investigated. The results reveal that the volume fraction index, initial stresses and layer thickness of metal have significant influence on the vibration and stability of sandwich plates with FGM face sheets.

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ABSTRACT: This paper presents a free vibration analysis of plates made of functionally graded materials and resting on two-layer elastic foundations by proposing a non-polynomial four variable refined plate theory. Undetermined integral terms are introduced in the proposed displacement field and unlike the conventional higher shear deformation theory (HSDT), the present one contains only four unknowns. Equations of motion are derived via the Hamilton’s principles and solved using Navier’s procedure. Accuracy of the present theory is demonstrated by comparing the results of numerical examples with the ones available in literature.


ABSTRACT: Cold-formed lipped channel columns (CFLCCs) have been widely used in light gauge steel constructions. The distortional buckling is one of the important buckling modes for CFLCCs and the distortional buckling critical load depends significantly on the rotational restrain stiffness generated by the web to the lipped flange. First, a simplified explicit expression for the rotational restraint stiffness of the lipped flange has been derived. Using the expression, the characteristics of the rotational restraint stiffness of the lipped flange have been investigated. The results show that there is a linear coupling relationship between the applied forces and the rotational restraint stiffness of the lipped flange. Based on the explicit expression of the rotational restraint stiffness of the lipped flange, a simplified analytical formula has been derived which can determine the elastic distortional buckling critical stress of the CFLCCs subjected to axial compression. The simplified analytical formula developed in this study has been shown to be accurate through the comparisons with results from the distortional buckling analyses using the ANSYS finite element software. The developed analytical formula is easy to apply, and can be used directly in practical design and incorporated into future design codes and guidelines.

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ABSTRACT: In this paper, various nonlocal higher-order shear deformation beam theories that consider the size dependent effects in Functionally Graded Material (FGM) beam are examined. The presented theories fulfill the zero traction boundary conditions on the top and bottom surface of the beam and a shear correction factor is not required. Hamilton’s principle is used to derive equation of motion as well as related boundary condition. The Navier solution is applied to solve the simply supported boundary conditions and exact formulas are proposed for the bending and static buckling. A parametric study is also included to investigate the effect of gradient index, length scale parameter and length-to-thickness ratio (aspect ratio) on the bending and the static buckling characteristics of FG nanobeams.

References listed at the end of the paper:


ABSTRACT: In cold-formed stainless steel lipped channel-sections, use of web openings for service purposes are becoming increasingly popular. Web openings, however, result in the sections becoming more susceptible to web crippling. This paper presents a finite element investigation into the web crippling strength of cold-formed stainless steel lipped channel-sections with circular web openings under the interior-two-flange (ITF) loading condition. The cases of web openings located centred and offset to the bearing plates are considered in this
study. In order to take into account the influence of the circular web openings, a parametric study involving 2,220 finite element analyses was performed, covering duplex EN1.4462, austenitic EN1.4404 and ferritic EN1.4003 stainless steel grades. From the results of the parametric study, strength reduction factor equations are proposed. The strengths obtained from reduction factor equations are first compared to the strengths calculated from the equations recently proposed for cold-formed carbon steel lipped channel-sections. It is demonstrated that the strength reduction factor equations proposed for cold-formed carbon steel are unconservative for the stainless steel grades by up to 17%. New coefficients for web crippling strength reduction factor equations are then proposed that can be applied to all three stainless steel grades.

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4. ASCE 8-02 (2002), Specification for the Design of Cold-Formed Stainless Steel Structural Members: SEI/ASCE 8-02, Reston, VA, USA.

ABSTRACT: In the past, the progressive collapse resulting from local failures during accidents has caused many tragedies and loss of life. Although long-span spatial grid structures are characterised by a high degree of static indeterminacy, the sudden failure of key members may lead to a catastrophic progressive collapse. For this reason, it is especially necessary to research the progressive collapse resistance capacity of long-span spatial grid structures. This paper presents an evaluation method of important members and a novel dynamic analysis method for simulating the progressive collapse of long-span spatial grid structures. Engineering cases were analysed to validate these proposed method. These proposed methods were eventually implemented in the progressive collapse analysis of the main stadium for the Universiade Sports Center. The roof of the structure
was concluded to have good resistance against progressive collapse. The novel methods provide results close to practice and are especially suitable for the progressive collapse analysis of long-span spatial grid structures.

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2. ASCE 7-05 (2010), Minimum design loads for buildings and other structures; American Society of Civil Engineers.
9. GSA (2013), Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects; General Services Administration, Washington, D.C., USA.
11. JGJ 7-2010 (2010), Technical specification for space frame structures; Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing, China.
22. UFC 4-023-03 (2013), Design of buildings to resist progressive collapse; Department of defense, Washington, D.C., USA.

ABSTRACT: This paper presents an experimental study, investigating the compressive behavior of glass-fibre reinforced and unreinforced cementitious material-filled square steel tubular (GFCMFST and CMFST) columns. The specimens were manufactured by using high performance cementitious materials without using coarse aggregate. The influence of adding glass-fibres to the mix on the behavior of both axially and eccentrically loaded columns is considered. It was found that adding glass fibre improve the confinement behavior, the axial compressive strength, the stiffness and the toughness of both axially and eccentrically loaded columns. The compressive strength of axially loaded columns is compared with strength predictions according to EC4 and the AISC specification. It was found that the design predictions according to EC4 and the AISC codes provide conservative results for CMFST and GFCMFST columns. Alternatively, the axial load-bending moment interaction diagrams specified in the EC4 are conservative for the eccentrically tubular CMFST and GFCMFST tested columns.

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1. AISC 360 (2010), Load and Resistance Factor Design Specification, for Structural Steel Buildings; American Institute of Steel Construction, Chicago, IL, USA.


ABSTRACT: In the present study, vibration analysis of functionally graded carbon nanotube reinforced composite (FGCNTRC) plate moving in two directions is investigated. Various types of shear deformation theories are utilized to obtain more accurate and simplest theory. Single-walled carbon nanotubes (SWCNTs) are selected as a reinforcement of composite face sheets inside Poly methyl methacrylate (PMMA) matrix. Moreover, different kinds of distributions of CNTs are considered. Based on extended rule of mixture, the structural properties of composite face sheets are considered. Motion equations are obtained by Hamilton’s principle and solved analytically. Influences of various parameters such as moving speed in x and y directions, volume fraction and distribution of CNTs, orthotropic viscoelastic surrounding medium, thickness and aspect ratio of composite plate on the vibration characteristics of moving system are discussed in details. The results indicated that the natural frequency or stability of FGCNTRC plate is strongly dependent on axially moving speed. Moreover, a better configuration of the nanotube embedded in plate can be used to increase the critical speed, as a result, the stability is improved. The results of this investigation can be used in design and manufacturing of marine vessels and aircrafts.


ABSTRACT: Tubular joints have been widely used in offshore platforms and space structures due to their merits such as easy fabrication, aesthetic appearance and better static strength. For existing tubular joints, a grouted sleeve reinforced method was proposed in this paper. Experimental tests on five tubular T-joints reinforced with the grouted sleeve and two conventional tubular T-joints were conducted to investigate their mechanical behaviour. A constant axial compressive force was applied to the chord end to simulate the compressive state of the chord member during the tests. Then an axial compressive force was applied to the top end of the brace member until the collapse of the joint specimens occurred. The parameters investigated herein were the grout thickness, the sleeve length coefficient and the sleeve construction method. The failure mode, ultimate load, initial stiffness and deformability of these joint specimens were discussed. It was found that: (1) The grouted sleeve could change the failure mode of tubular T-joints. (2) The grouted sleeve was observed to provide strength enhancement up to 154.3%~172.7% for the corresponding un-reinforced joint. (3) The initial stiffness and deformability were also greatly improved by the grouted sleeve. (4) The sleeve length coefficient was a key parameter for the improved effect of the grouted sleeve reinforced method.

Hamed Shafiei and Ali Reza Setoodeh, “Nonlinear free vibration and post-buckling of FG-CNTRC beams on

ABSTRACT: Free vibrations of steel-concrete composite beams are analyzed by using the dynamic stiffness approach. The coupled equations of motion of the composite beams are derived with help of the Hamilton’s principle. The effects of the shear deformation and rotary inertia of the two beams as well as the transverse and axial deformations of the stud connectors are included in the formulation. The dynamic stiffness matrix is developed on the basis of the exact general solutions of the homogeneous governing differential equations of the composite beams. The use of the dynamic stiffness method to determine the natural frequencies and mode shapes of a particular steel-concrete composite beam with various boundary conditions is demonstrated. The accuracy and effectiveness of the present model and formulation are validated by comparison of the present results with the available solutions in literature.


ABSTRACT: In this study, vibration analysis of fluid conveying microbeams under non-ideal boundary conditions (BCs) is performed. The objective of the present paper is to describe the effects of non-ideal BCs on linear vibrations of fluid conveying microbeams. Non-ideal BCs are modeled as a linear combination of ideal clamped and ideal simply supported boundary conditions by using the weighting factor (k). Non-ideal clamped and non-ideal simply supported beams are both considered to show the effects of BCs. Equations of motion of the beam under the effect of moving fluid are obtained by using Hamilton principle. Method of multiple scales which is one of the perturbation techniques is applied to the governing linear equation of motion. Approximate solutions of the linear equation are obtained and the effects of system parameters and non-ideal BCs on natural frequencies are presented. Results indicate that, natural frequencies of fluid conveying microbeam changed significantly by varying the weighting factor k. This change is more remarkable for clamped microbeams rather than simply supported ones.


ABSTRACT: This paper deals with general equations of motion for free vibration analysis response of thick three-layer doubly curved sandwich panels (DCSP) under simply supported boundary conditions (BCs) using higher order shear deformation theory. In this model, the face sheets are orthotropic laminated composite that follow the first order shear deformation theory (FSDT) based on Rissners-Mindlin (RM) kinematics field. The core is made of orthotropic material and its in-plane transverse displacements are modeled using the third order of the Taylor’s series extension. It provides the potentiality for considering both compressible and incompressible cores. To find these equations and boundary conditions, Hamilton’s principle is used. Also, the effect of trapezoidal shape factor for cross-section of curved panel element (1±ε/R) is considered. The natural frequency parameters of DCSP are obtained using Galerkin Method. Convergence studies are performed with the appropriate formulas in general form for three-layer sandwich plate, cylindrical and spherical shells (both deep and shallow). The influences of core stiffness, ratio of core to face sheets thickness and radii of curvatures are investigated. Finally, for the first time, an optimum range for the core to face sheet stiffness ratio by considering the existence of in-plane stress which significantly affects the natural frequencies of DCSP are presented.

References listed at the end of the paper:
natural frequencies. The obtained results have novelty and can be used for further and future researches.

Maurizio Orlando, Giovanni Lavacchini, Barbara Ortolani and Paolo Spinelli, “Experimental capacity of perforated cold-formed steel open sections under compression and bending”, Steel and Composite Structures, Vol. 24, No. 2, pp 201-211, 2017

ABSTRACT: This study evaluates the reliability of present European codes in predicting the collapse load of columns made with perforated cold-formed steel (CFS) profiles under combined axial load and bending. To this aim, a series of experimental tests on slender open-section specimens have been performed at varying load eccentricity. Preliminarily, stub column tests have also been performed to calculate the effective section properties of the investigated profile. By comparison of experimental data with code-specified M-N strength domains, the authors demonstrate that present code formulations may underestimate the collapse load of thin-walled perforated open sections. The study is the first step of a wider experimental and numerical study aimed at better describing strength domains of perforated CFS open sections.


ABSTRACT: In this paper free linear vibration of lattice composite conical shells will be investigated. Lattice composite conical shell consists of composite helical ribs and thin outer skin. A smeared method is employed to obtain the variable coefficients of stiffness of conical shell. The ribs are modeled as a beam and in addition to the axial loads, endure shear loads and bending moments. Therefore, theoretical formulations are based on first-order shear deformation theory of shell. For verification of the obtained results, comparison is made with those available in open literature. Also, using FEM software the 3D finite element model of composite lattice conical shell is built and analyzed. Comparing results of analytical and numerical analyses show a good agreement between them. Some special cases as variation of geometric parameters of lattice part, effect of the boundary conditions and influence of the circumferential wave numbers on the natural frequencies of the conical shell are studied. It is concluded, when mass and the geometrical ratio of the composite lattice conical shell do not change, increment the semi vertex angle of cone leads to increase the natural frequencies. Moreover for shell thicknesses greater than a specific value, the presence of the lattice structure has not significant effect on the natural frequencies. The obtained results have novelty and can be used for further and future researches.
References listed at the end of the paper:
the hybrid structure were carried out. A parametric study was investigated in this paper. The geometrically non-linear elastic buckling and elasto-plastic buckling analyses of the hybrid structure were carried out. A parametric study was done to investigate the effects rise-to-span ratio,
beam section, area and pre-stress of cables, on the failure load. Also, the influence of the shape and scale of imperfections on the elasto-plastic buckling loads was discussed. The results show that the critical buckling load is reduced by taking account of material non-linearity. Furthermore, increasing the rise-to-span ratio or the cross-section area of steel beams notably improves the stability of the structure. However, the cross section area and pre-stress of cables pose negligible effect on the structural stability. It can also be found that the hybrid structure is highly sensitive to geometric imperfection which will considerably reduce the failure load. The proper shape and scale of the imperfection are also important.

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15. JGJ7-2010 (2010), Technical specification for space frame structures; China Architecture Industry Press, Beijing, China. [In Chinese]


ABSTRACT: This paper conducted both numerical and theoretical studies to investigate the composite action of notched circular concrete-filled steel tubular (CFT) stub columns under axial compression and established a theoretical method to predict their ultimate bearing capacity. 3D finite element (FE) analysis was conducted to simulate the composite action and the results were in good agreement with experimental results on circular CFT stub columns with differently oriented notches in steel tubes. Parametric study was conducted to understand the effects of different parameters on the mechanical behavior of circular CFT stub columns and also the composite action between the steel tube and the core concrete. Based on the results, a theoretical formula was proposed to calculate the ultimate bearing capacity of notched CFT stub columns under compression with consideration of the composite action between the steel tube and the core concrete.

References listed at the end of the paper:

ABSTRACT: This paper presents the results of a comprehensive experimental investigation on the compressive behaviour of steel tube-confined concrete (STCC) stub columns with active and passive confinement. To create active confinement in STCC columns, an innovative technique is used in which steel tube is laterally prestressed while the concrete core is simultaneously pre-compressed by applying pressure on fresh concrete. A total of 135 STCC specimens with active and passive confinement are tested under axial compression load and their compressive strength, ultimate strain capacity, axial and lateral stress-strain curves and failure mode are evaluated. The test variables include concrete compressive strength, outer diameter to wall thickness ratio of steel tube and prestressing level. It is shown that applying active confinement on STCC specimens can considerably improve their mechanical properties. However, applying higher prestressing levels and keeping the applied pressure for a long time do not considerably affect the mechanical properties of actively confined specimens. Based on the results of this study, new empirical equations are proposed to estimate the axial strength and ultimate strain capacity of STCC stub columns with active and passive confinement.

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3. ASTM A370 (2003), Standard test methods and definitions for mechanical testing of steel products; Annual Book of ASTM Standard 01.
This paper deals with nonlinear dynamic stability of embedded viscoelastic piezoelectric separators using different cylindrical shell theories, Steel and Composite Structures, Vol. 24, No. 4, pp 499-512, 2017

**ABSTRACT:** This paper deals with nonlinear dynamic stability of embedded piezoelectric nano-composite separators conveying pulsating fluid. For presenting a realistic model, the material properties of structure are assumed viscoelastic based on Kelvin-Voigt model. The separator is reinforced with single-walled carbon nanotubes (SWCNTs) which the equivalent material properties are obtained by mixture rule. The separator is surrounded by elastic medium modeled by nonlinear orthotropic visco Pasternak foundation. The separator is subjected to 3D electric and 2D magnetic fields. For mathematical modeling of structure, three theories of classical shell theory (CST), first order shear deformation theory (FSDT) and sinusoidal shear deformation theory (SSDT) are applied. The differential quadrature method (DQM) in conjunction with Bolotin method is employed for calculating the dynamic instability region (DIR). The detailed parametric study is conducted,
focusing on the combined effects of the external voltage, magnetic field, visco-Pasternak foundation, structural damping and volume percent of SWCNTs on the dynamic instability of structure. The numerical results are validated with other published works as well as comparing results obtained by three theories. Numerical results indicate that the magnetic and electric fields as well as SWCNTs as reinforcer are very important in dynamic instability analysis of structure.

References listed at the end of the paper:
References listed at the end of the paper:


PARTIAL ABSTRACT: In this research work, a simple and accurate hyperbolic plate theory for the buckling analysis of functionally graded sandwich plates is presented. The main interest of this theory is that, in addition to incorporating the thickness stretching effect . . .

References listed at the end of the paper:


ABSTRACT: The objective of this work is to analyze post-buckling of functionally graded (FG) beams with porosity effect under compression load. Material properties of the beam change in the thickness direction according to power-law distributions with different porosity models. It is known that post-buckling problems are geometrically nonlinear problems. In the nonlinear kinematic model of the beam, total Lagrangian finite element model of two dimensional (2-D) continuum is used in conjunction with the Newton-Raphson method. In the study, the effects of material distribution, porosity parameters, compression loads on the post-buckling behavior of FG beams are investigated and discussed with porosity effects. Also, the effects of the different porosity models on the FG beams are investigated in post-buckling case.

References listed at the end of the paper:

ABSTRACT: A cable-stiffened cylindrical single-layer latticed shell that is reinforced by cable-stiffened system has superior stability behaviour compared with the ordinary cylindrical latticed shell. The layouts of cable-stiffened system are flexible in this structural system, and different layouts contribute different stiffness to the structure. However, the existed few research primarily focused on the simplest type of cable layouts, in which the grids of the latticed shell are diagonally stiffened by prestressed cables in-plane. This current work examines the stability behaviour of the cable-stiffened cylindrical latticed shells with two different types of cable layouts using nonlinear finite element analysis. A parametric study on the effect of cross-sectional of the cables, pretension in cables, joint stiffness, initial imperfections, load distributions and boundary conditions is presented. The findings are useful for the reference of the designer in using this type of structural system.

References listed at the end of the paper:
2. ANSYS (2013), Release 15.0 document for ANSYS.
18. Technical specification for space frame structures (2010), Beijing, China. [In Chinese]

ABSTRACT: In this research, the free vibration response of laminated composite plates is investigated using a novel and simple higher order shear deformation plate theory. The model considers a non-linear distribution of the transverse shear strains, and verifies the zero traction boundary conditions on the surfaces of the plate without introducing shear correction coefficient. The developed kinematic uses undetermined integral terms with only four unknowns. Equations of motion are obtained from the Hamilton’s principle and the Navier method is used to determine the closed-form solutions of antisymmetric cross-ply and angle-ply laminates. Numerical examples studied using the present formulation is compared with three-dimensional elasticity solutions and those calculated using the first-order and the other higher-order theories. It can be concluded that the present model is not only accurate but also efficient and simple in studying the free vibration response of laminated composite plates.


ABSTRACT: In the present work, an analytical solution for the static analysis of laminated composites, functionally graded and sandwich singly and doubly curved panels on the rectangular plan-form, subjected to uniformly distributed transverse loading is presented. Mathematical formulation is based on the higher order shear deformation theory and principle of virtual work is applied to derive the equations of equilibrium subjected to small deformation. A solution methodology based on the fast converging finite double Chebyshev series is used to solve the linear partial differential equations along with the simply supported boundary condition. The effect of span to thickness ratio, radius of curvature to span ratio, stacking sequence, power index are investigated. The accuracy of the solution is checked by the convergence study of non-dimensional central deflection and moments. Present results are compared with those available in the literature.

References listed at the end of the paper:

ABSTRACT: The current study addresses the local buckling analysis of an infinite thin rectangular symmetrically laminated composite plate restrained by a tensionless Winkler foundation and subjected to uniform in-plane shear loading. An analytic method (i.e., one-dimensional mathematical method) is used to achieve the analytical solution estimate of the contact buckling coefficient. In addition, to study the effect of ply angle and foundation stiffness on the critical buckling coefficients for the laminated composite plates, the parametric studies are implemented. Moreover, the convergence for finite element (FE) mesh is analysed, and then the examples in the parametric study are validated by the FE analysis. The results show that the FE analysis has a good agreement with the analytical solutions. Finally, an example with the analytical solution and FE analysis is presented to demonstrate the availability and feasibility of the presented analytical method.

References listed at the end of the paper:


ABSTRACT: In the present work, by considering the agglomeration effect of single-walled carbon nanotubes, free vibration characteristics of functionally graded (FG) nanocomposite sandwich plates resting on Pasternak foundation are presented. The volume fractions of randomly oriented agglomerated single-walled carbon nanotubes (SWCNTs) are assumed to be graded in the thickness direction. To determine the effect of CNT agglomeration on the elastic properties of CNT-reinforced composites, a two-parameter micromechanical model of agglomeration is employed. In this research work, an equivalent continuum model based on the Eshelby-Mori-Tanaka approach is employed to estimate the effective constitutive law of the elastic isotropic medium (matrix) with oriented straight CNTs. The 2-D generalized differential quadrature method (GDQM) as an efficient and accurate numerical tool is used to discretize the equations of motion and to implement the various boundary conditions. The proposed rectangular plates have two opposite edges simply supported, while all possible combinations of free, simply supported and clamped boundary conditions are applied to the other two edges. The benefit of using the considered power-law distribution is to illustrate and present useful results arising from symmetric and asymmetric profiles. The effects of two-parameter elastic foundation modulus, geometrical and material parameters together with the boundary conditions on the frequency parameters of the laminated FG nanocomposite plates are investigated. It is shown that the natural frequencies of structure are seriously affected by the influence of CNTs agglomeration. This study serves as a benchmark for assessing the validity of numerical methods or two-dimensional theories used to analysis of laminated plates.

References listed at the end of the paper:


ABSTRACT: The present paper studies the stability analysis of the continuously graded CNT-Reinforced Composite (CNTRC) panel stiffened by rings and stringers. The Stiffened Panel (SP) subjected to axial and lateral loads is reinforced by agglomerated CNTs smoothly graded through the thickness. A two-parameter Eshelby-Mori-Tanaka (EMT) model is adopted to derive the effective material moduli of the CNTRC. The stability equations of the CNTRC SP are obtained by means of the adjacent equilibrium criterion. Notwithstanding most available literature in which the stiffener effects were smeared out over the respective stiffener spacing, in the present work, the stiffeners are modeled as Euler-Bernoulli beams. The Generalized Differential Quadrature Method (GDQM) is employed to discretize the stability equations. A numerical study is performed to investigate the influences of different types of parameters involved on the critical buckling of the SP reinforced by agglomerated CNTs. The results achieved reveal that continuously distributing of CNTs adjacent to the inner and outer panel’s surface results in improving the stiffness of the SP and, as a consequence, inclining the critical buckling load. Furthermore, it has been concluded that the decline rate of buckling load intensity factor owing to the increase of the panel angle is significantly more sensible for the smaller values of panel angle.

References listed at the end of the paper:

ABSTRACT: In this study, free vibration of functionally graded (FG) micro/nanobeams based on nonlocal third-order shear deformation theory and under different boundary conditions is investigated by applying the differential quadrature method. Third-order shear deformation theory can consider the both small-scale effects and quadratic variation of shear strain and hence shear stress along the FG nanobeam thickness. The governing equations are obtained by using the Hamilton`s principle, based on third-order shear deformation beam theory. The differential quadrature (DQ) method is used to discretize the model and attain the natural frequencies and mode shapes. The properties of FG micro/nanobeam are assumed to be changed along the thickness direction based on the simple power law distribution. The effects of various parameters such as the nonlocal parameter, gradient index, boundary conditions and mode number on the vibration characteristics of FG micro/nanobeams are discussed in detail.

ABSTRACT: This paper presents the dynamic stability study of laminated composite plates with different force combinations and aspect ratios. Optimum non-diverging stacking is obtained for certain loading combination and aspect ratio. In addition, the stability force is maximized for a definite operating frequency. A dynamic version of the principle of virtual work for laminated composites is used to obtain force-frequency relation. Since dynamic stiffness governs the divergence or flutter, an efficient optimization method is necessary for the response functional and the relevant constraints. In this way, a model based on the ant colony optimization (ACO) algorithm is proposed to search for the proper stacking. The ACO algorithm is used since it treats with large number of dynamic stability parameters. Governing equations are formulated using classic laminate theory.
(CLT) and von-Karman plate technique. Load-frequency relations are explicitly obtained for fundamental and secondary flutter modes of simply supported composite plate with arbitrary aspect ratio, stacking and boundary load, which are used in optimization process. Obtained results are compared with the finite element method results for validity and accuracy convince. Results revealed that the optimum stacking with stable dynamic response and maximum critical load is in angle-ply mode with almost near-unidirectional fiber orientations for fundamental flutter mode. In addition, short plates behave better than long plates in combined axial-shear load case regarding stable oscillation. The interaction of uniaxial and shear forces intensifies the instability in long plates than short ones which needs low-angle layup orientations to provide required dynamic stiffness. However, a combination of angle-ply and cross-ply stacking with a near-square aspect ratio is appropriate for the composite plate regarding secondary flutter mode.


ABSTRACT: In this paper, an exact analytical solution for simply supported sandwich plate which considers the permeation effect of adhesives is presented. The permeation layer is described as functionally graded material (FGM), the elastic modulus of which is assumed to be graded along the thickness following the exponential law. Based on the exact three-dimensional (3-D) elasticity theory, the solution of stresses and displacements for each layer is derived. By means of the recursive matrix method, the solution can be efficiently obtained for plates with many layers. The present solution obtained can be used as a benchmark to access other simplified solutions. The comparison study indicates that the finite element (FE) solution is close to the present one when the FGM layer in the FE model is divided into a series of homogeneous layers. However, the present method is more efficient than the FE method, with which the mesh division and computation are time-consuming. Moreover, the solution based on Kirchhoff-Love plate theory is greatly different from the present solution for thick plates. The influence of the thickness of the permeation layer on the stress and displacement fields of the sandwich plate is discussed in detail. It is indicated that the permeation layer can effectively relieve the discontinuity stress at the interface.


ABSTRACT: This paper presents an investigation into the magneto-thermo-mechanical vibration and damping of a viscoelastic functionally graded-carbon nanotubes (FG-CNTs)-reinforced curved microbeam based on Timoshenko beam and strain gradient theories. The structure is surrounded by a viscoelastic medium which is simulated with spring, damper and shear elements. The effective temperature-dependent material properties of the CNTs-reinforced composite beam are obtained using the extended rule of mixture. The structure is assumed to be subjected to a longitudinal magnetic field. The governing equations of motion are derived using Hamilton’s principle and solved by employing differential quadrature method (DQM). The effect of various parameter like volume percent and distribution type of CNTs, temperature change, magnetic field, boundary conditions, material length scale parameter, central angle, viscoelastic medium and structural damping on the vibration and damping behaviors of the nanocomposite curved microbeam is examined. The results show that with increasing volume percent of CNTs and considering magnetic field, material length scale parameter and viscoelastic medium, the frequency of the system increases and critically damped situation occurs at higher values of damper constant. In addition, the structure with FGX distribution type of CNTs has the highest stiffness. It is also observed that increasing temperature, structural damping and central angle of curved microbeam decreases the frequency of the system.

ABSTRACT: The novelty of this work is the use of a new displacement field that includes undetermined integral terms for analyzing thermal buckling response of functionally graded (FG) sandwich plates. The proposed kinematic uses only four variables, which is even less than the first shear deformation theory (FSDT) and the conventional higher shear deformation theories (HSDTs). The theory considers a trigonometric variation of transverse shear stress and verifies the traction free boundary conditions without employing the shear correction factors. Material properties of the sandwich plate faces are considered to be graded in the thickness direction according to a simple power-law variation in terms of the volume fractions of the constituents. The core layer is still homogeneous and made of an isotropic material. The thermal loads are assumed as uniform, linear and non-linear temperature rises within the thickness direction. An energy based variational principle is employed to derive the governing equations as an eigenvalue problem. The validation of the present work is checked by comparing the obtained results the available ones in the literature. The influences of aspect and thickness ratios, material index, loading type, and sandwich plate type on the critical buckling are all discussed.


ABSTRACT: In this work, transient thermo-piezo-elastic responses of an infinite functionally graded piezoelectric (FGPE) plate whose upper surface suffers time-dependent thermal shock are investigated in the context of different thermo-piezo-elastic theories. The thermal and mechanical properties of functionally graded piezoelectric plate under consideration are expressed as power functions of plate thickness variable. The solution of problem is obtained by solving the corresponding finite element governing equations in time domain directly. Transient thermo-piezo-elastic responses of the FGPE plate, including temperature, stress, displacement, electric intensity and electric potential are presented graphically and analyzed carefully to show multi-field coupling behaviors between them. In addition, the effects of functionally graded parameters on transient thermo-piezo-elastic responses are also investigated to provide a theoretical basis for the application of the FGPE materials.


ABSTRACT: In this paper, Coriolis effect on vibration behavior of a rotating rectangular plate made of functionally graded (FG) materials under thermal loading has been investigated. The material properties of the FG plate are supposed to get changed in parallel with the thickness of the plate and the thermal properties of the material are assumed to be thermo-elastic. In this research, the effect of hub size, rotating speed and setting angle are considered. Governing equation of motion and the associated boundary conditions are obtained by Hamilton’s principle. Generalized differential quadrature method (GDQM) is used to solve the governing differential equation with respect to cantilever boundary condition. The results were successfully verified with the published literatures. These results can be useful for designing rotary systems such as turbine blades. In this work, Coriolis and thermal effects are considered for the first time and GDQM method has been used in solving the equations of motion of a rotating FGM plate.

ABSTRACT: In this article, an efficient and simple refined theory is proposed for buckling analysis of functionally graded plates by using a new displacement field which includes undetermined integral variables. This theory contains only four unknowns, with is even less than the first shear deformation theory (FSDT). Governing equations are obtained from the principle of virtual works. The closed-form solutions of rectangular plates are determined. Comparison studies are carried out to check the validity of obtained results. The influences of loading conditions and variations of power of functionally graded material, modulus ratio, aspect ratio, and thickness ratio on the critical buckling load of functionally graded plates are examined and discussed.

References listed at the end of the paper:


ABSTRACT: The aim of this paper is to investigate the performance of Lightweight Aggregate Concrete Filled Steel Tube (LWCFST) columns experimentally and compare to the behavior of Self-Compacted Concrete Filled Steel Tube (SCCFST) columns under axial loading. Four different L/D ratios and three D/t ratios were used in the experimental program to delve into the compression behaviours. Compressive strength of the LWC and SCC are 33.47 MPa and 39.71 MPa, respectively. Compressive loading versus end shortening curves and the failure mode of sixteen specimens were compared and discussed. The design specification formulations of AIJ 2001, AISC 360-16, and EC4 were also assessed against test results to underline the performance of specification methods in predicting the compression capacity of LWCFST and SCCFST columns. Based on the behaviour of the SCCFST columns, LWCFST columns exhibited different performances, especially in ductility and failure mode. The nature of the utilized lightweight aggregate led to local buckling mode to be dominant in LWCFST columns, even the long LWCFST specimens suffered from this behaviour. While with the SCCFST specimens the global buckling governed the failure mode of long specimens without any loss in capacity. Considering a wide range of column geometries (short, medium and long columns), this paper extends the current knowledge in composite construction by examining the potential of two promising and innovative structural concrete types in CFST applications.

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ABSTRACT: In this work, thermoelastic dynamic behavior of functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylinders subjected to mechanical pressure loads, uniform temperature environment or thermal gradient loads is investigated by a mesh-free method. The material properties and thermal stress wave
propagation of the nanocomposite cylinders are derived after solving of the transient thermal equation and obtaining of the time history of temperature field of the cylinders. The nanocomposite cylinders are made of a polymer matrix and wavy single-walled carbon nanotubes (SWCNTs). The volume fraction of carbon nanotubes (CNTs) are assumed variable along the radial direction of the axisymmetric cylinder. Also, material properties of the polymer and CNT are assumed temperature-dependent and mechanical properties of the nanocomposite are estimated by a micro mechanical model in volume fraction form. In the mesh-free analysis, moving least squares shape functions are used to approximate temperature and displacement fields in the weak form of motion equation and transient thermal equation, respectively. Also, transformation method is used to impose their essential boundary conditions. Effects of waviness, volume fraction and distribution pattern of CNT, temperature of environment and direction of thermal gradient loads are investigated on the thermoelastic dynamic behavior of FG-CNTRC cylinders.

References listed at the end of the paper:

ABSTRACT: To gain more knowledge of aluminum foam sandwich structure and promote the engineering application, aluminum foam sandwich consisting of 7050 matrix aluminum foam core and 304 stainless steel face-sheets was studied under three-point bending by WDW-T100 electronic universal tensile testing machine in this work. Results showed that when aluminum foam core was reinforced by 304 steel face-sheets, its load carrying capacity improved dramatically. The maximum load of AFS in three-point bending increased with the foam core density or face-sheet thickness monotonically. And also when foam core was reinforced by 304 steel panels, the energy absorption ability of foam came into play effectively. There was a clear plastic platform in the load-displacement curve of AFS in three-point bending. No crack of 304 steel happened in the present tests. Two collapse modes appeared, mode A comprised plastic hinge formation at the mid-span of the sandwich beam, with shear yielding of the core. Mode B consisted of plastic hinge formation both at mid-span and at the outer supports.


ABSTRACT: Sandwich shells made of composite materials are the main focus on recent literature parallel to the requirements of industry. They are commonly chosen for the modern engineering applications which require
moderate strength to weight ratio without dependence on conventional manufacturing techniques. The investigations on hyperbolic paraboloidal formed sandwich composite shells are limited in the literature contrary to shells that have a number of studies, consisting of doubly curved surfaces, arbitrary boundaries and laminations. Because of the lack of contributive data in the literature, the aim of this study is to present the effects of curvature on hyperbolic paraboloidal formed, layered sandwich composite surfaces that have arbitrary boundary conditions. Analytical solution methodology for the analyses of stresses and deformations is based on Third Order Shear Deformation Theory (TSDDT). Double Fourier series, which are specialized for boundary discontinuity, are used to solve highly coupled linear partial differential equations. Numerical solutions showing the effects of shell geometry are presented to provide benchmark results.

References listed at the end of the paper:

ABSTRACT: The goal of this study is to fill this apparent gap in the area about vibration analysis of multiwalled carbon nanotubes (MWCNTs) curved panels by providing 3-D vibration analysis results for functionally graded multiwalled carbon nanotubes (FG-MWCNTs) sandwich structure with power-law distribution of nanotube. The effective material properties of the FG-MWCNT structures are estimated using a modified Halpin-Tsai equation. Modified Halpin-Tsai equation was used to evaluate the Young’s modulus of MWCNT/epoxy composite samples by the incorporation of an orientation as well as an exponential shape factor in the equation. The exponential shape factor modifies the Halpin-Tsai equation from expressing a straight line to a nonlinear one in the MWCNTs wt% range considered. Also, the mass density and Poisson’s ratio of the MWCNT/phenolic composite are considered based on the rule of mixtures. Parametric studies are carried out to highlight the influence of MWCNT volume fraction in the thickness, different types of CNT distribution, boundary conditions and geometrical parameters on vibrational behavior of FG-MWCNT thick curved panels. Because of using two-dimensional generalized differential quadrature method, the present approach makes possible vibration analysis of cylindrical panels with two opposite axial edges simply supported and arbitrary boundary conditions including Free, Simply supported and Clamped at the curved edges. For an overall comprehension on 3-D vibration analysis of sandwich panel, some mode shape contour plots are reported in this research work.

References listed at the end of the paper:

32. Matsunaga, H. (2008), "Free vibration and stability of functionally graded shallow shells according to a 2-D higher-order deformation theory", Compos. Struct., 84(2), 132-146.


ABSTRACT: This paper presents a combined experimental, numerical, and analytical study on elliptical concrete-filled steel tubular (E-CFT) and rebar-stiffened elliptical concrete-filled steel tubular (RE-CFT)
subjected to axial loading. ABAQUS was used to establish 3D finite element (FE) models for the composite columns and the FE results agreed well with the experimental results. It was found that the ultimate load-bearing capacity of RE-CFT stub columns was 20% higher than that of the E-CFT stub columns. Such improvement was attributed to the reinforcement effects from the internal rebar-stiffeners, which effectively enhanced the confinement effect on the core concrete, thereby significantly improved both the ultimate bearing capacity and the ductility of the E-CFT columns. Based on the results, equations were also established in this paper to predict the bearing capacities of E-CFT and RE-CFT stub columns under axial loading. The predicted results agreed well with both experimental and numerical results, and had much higher accuracy than other available methods.

References listed at the end of the paper:
1. CSA-S16-09, Canadian Standard (2009), Steel structures for buildings (limit states design), CAN/CSA-S16-09, Canadian Standards Association, Toronto, Ontario, Canada.
10. GB/T228-2010, China Standard (2010), Metallic materials-tensile testing at ambient temperatures, Standards Press of China, Beijing, China.

ABSTRACT: In this work, a new higher shear deformation theory (HSDT) is developed for the free vibration and buckling of functionally graded (FG) sandwich plates. The proposed theory presents a new displacement field by using undetermined integral terms. Only four unknowns are employed in this theory, which is less than the classical first shear deformation theory (FSDT) and others HSDTs. Equations of motion are obtained via Hamilton’s principle. The analytical solutions of FG sandwich plates are determined by employing the Navier method. A good agreement between the computed results and the available solutions of existing HSDTs is found to prove the accuracy of the developed theory.

References listed at the end of the paper:


ABSTRACT: The tubed steel reinforced concrete (SRC) column is a composite column in which the outer steel tube is mainly used to provide confinement on the core concrete. This paper presents experimental and analytical studies on the behavior of circular tubed SRC (TSRC) columns subjected to axial compression. Eight circular TSRC columns were tested to investigate the effects of length-to-diameter ratio (L/D) of the specimens, diameter-to-thickness ratio (D/t) of the steel tubes, and use of stud shear connectors on the steel sections. Elastic-plastic analysis on the steel tubes was used to investigate the mechanism of confinement on the core concrete. The test results indicated that the tube confinement increased the strength and deformation capacity for both short and slender columns, and the effects on strength were more pronounced for short columns. A nonlinear finite element (FE) model was developed using ABAQUS, in which the nonlinear material behavior and initial geometric imperfection were included. Good agreement was achieved between the predicted results using the FE model and the test results. The test and FE results were compared with the predicted strengths calculated by Eurocode 4 and the AISC Standard. Based on the analytical results, a new design method for this composite column was proposed.

References listed at the end of the paper:
1. ABAQUS (version 6.12), Dassault Systèmes SIMULIA, Providence, RI.
2. AISC 318 (2014), Building code requirements for structural concrete and commentary, American Concrete Institute; Farmington Hills, MI, USA.
3. AISC 360 (2016), Specification for structural steel buildings, American Institute of Steel Construction; Chicago, Illinois, USA.


ABSTRACT: The dynamic instability of truncated conical shells subjected to dynamic axial load within first order shear deformation theory (FSDT) is examined. The conical shell is made from functionally graded (FG) orthotropic material. In the formulation of problem a dynamic version of Donnell’s shell theory is used. The equations are converted to a Mathieu-Hill type differential equation employing Galerkin’s method. The boundaries of main instability zones are found applying the method proposed by Bolotin. To verify these results, the results of other studies in the literature were compared. The influences of material gradient, orthotropy, as well as changing the geometric dimensions on the borders of the main areas of the instability are investigated.

References listed at the end of the paper:
results showed that the CFRP composite had no similar effect on the slender and stoc
of section (Type A and B) were analyzed. ANSYS was used to analyze the SHS steel beam
which were strengthened with the di
employed for modeling. To determine the ultimate load of SHS steel beam
hollow section (SHS) steel beam
columns. However, this study explored the use of adhesively bonded CFRP flexible sheets on retrofitt
independent study, to the researcher’s knowledge, has studied
structures. Most studies on strengthening steel structures have been done on steel beams and steel columns. No

**ABSTRACT:** Carbon Fiber Reinforced Polymer (CFRP) is one of the materials used to strengthen steel
structures. Most studies on strengthening steel structures have been done on steel beams and steel columns. No
independent study, to the researcher’s knowledge, has studied the effect of CFRP strengthening on steel beam-columns, and it seems that there is a lack of understanding on behavior of CFRP strengthening on steel beam-columns. However, this study explored the use of adhesively bonded CFRP flexible sheets on retrofitting square hollow section (SHS) steel beam-columns, using numerical investigations. Finite Element Method (FEM) was employed for modeling. To determine the ultimate load of SHS steel beam-columns, ten specimens, eight of which were strengthened with the different coverage length and with one and two CFRP layers, with two types of section (Type A and B) were analyzed. ANSYS was used to analyze the SHS steel beam-columns. The results showed that the CFRP composite had no similar effect on the slender and stocky SHS steel beam-
columns. The results also showed that the coverage length, the number of layers, and the location of CFRP composites were effective in increasing the ultimate load of the SHS steel beam-columns.

References listed at the end of the paper:
Elastic-plastic shear buckling behaviors of the web-post in a Castellated Steel Beam (CSB) with hexagonal web openings under vertical shear force were investigated further using Finite Element Model (FEM) based on a sub-model, which took the upper part of the web-post under horizontal shear force to represent the whole web-post under vertical shear force. A simplified design method for the web-post elastic-plastic shear buckling strength was proposed based on simulation results of the sub-model. Proper boundary conditions were applied to the sub-model to assure that its behaviors were identical to those of the whole web-post. The equation to calculate the thin plate elastic shear buckling strength was adopted as the basic form to build the design equation for elastic-plastic buckling strength of the sub-model. Parameters that might affect the elastic-plastic shear buckling strength of the whole web-post were studied. After obtaining the vertical shear buckling strength of a sub-model through FEM, the shear buckling coefficient $k$ can be obtained through the back analysis. A practical calculation method for $k$ was proposed through curving fitting the parameter study results. The elastic-plastic shear buckling strength of the web-post calculated using the proposed shear buckling coefficient $k$ agreed well with that obtained from the FEM and test results. And it was more precise than those obtained from EC3 based on the strut model.

References listed at the end of the paper:


ABSTRACT: In this research, a simple hyperbolic shear deformation theory is developed and applied for the bending, vibration and buckling of powerly graded material (PGM) sandwich plate with various boundary conditions. The displacement field of the present model is selected based on a hyperbolic variation in the in-plane displacements across the plate’s thickness. By splitting the deflection into the bending and shear parts, the number of unknowns and equations of motion of the present formulation is reduced and hence makes them simple to use. Equations of motion are obtained from Hamilton’s principle. Numerical results for the natural frequencies, deflections and critical buckling loads of several types of powerly graded sandwich plates under various boundary conditions are presented. The accuracy of the present formulation is demonstrated by comparing the computed results with those available in the literature. As conclusion, this theory is as accurate as other theories available in the literature and so it becomes more attractive due to smaller number of unknowns.


ABSTRACT: In this paper, a new simple shear deformation theory for bending analysis of functionally graded plates is developed. The present theory involves only three unknown and three governing equation as in the classical plate theory, but it is capable of accurately capturing shear deformation effects, instead of five as in the well-known first shear deformation theory and higher-order shear deformation theory. A shear correction factor is, therefore, not required. The material properties of the functionally graded plates are assumed to vary continuously through the thickness, according to a simple power law distribution of the volume fraction of the constituents. Equations of motion are obtained by utilizing the principle of virtual displacements and solved via Navier’s procedure. The elastic foundation is modeled as two parameter elastic foundation. The results are
verified with the known results in the literature. The influences played by transversal shear deformation, plate aspect ratio, side-to-thickness ratio, elastic foundation, and volume fraction distributions are studied. Verification studies show that the proposed theory is not only accurate and simple in solving the bending behaviour of functionally graded plates, but also comparable with the other higher-order shear deformation theories which contain more number of unknowns.

Imene Ait Sidhoum, Djilali Boutchicha, Samir Benyoucef and Abdelouahed Tounsi, “An original HSDT for free vibration analysis of functionally graded plates”, Steel and Composite Structures, Vol. 25, No. 6, pp 735-745, 2017

ABSTRACT: This work presents a free vibration analysis of functionally graded plates by employing an original high order shear deformation theory (HSDT). This theory use only four unknowns, which is even less than the classical HSDT. The equations of motion for the dynamic analysis are determined via the Hamilton’s principle. The original kinematic allows obtaining interesting equations of motion. These equations are solved analytically via Navier procedure. The accuracy of the proposed solution is checked by comparing it with other closed form solutions available in the literature.

Guoqing Jiang, Fengming Li and Chuanzeng Zhang, “Postbuckling and nonlinear vibration of composite laminated trapezoidal plates”, Steel and Composite Structures, Vol. 26, No. 1, pp 17-29, 2018

ABSTRACT: The thermal effects on the buckling, postbuckling and nonlinear vibration behaviors of composite laminated trapezoidal plates are studied. Aiming at the complex plate structure and to simulate the temperature distribution of the plate, a finite element method (FEM) is applied in this paper. In the temperature model, based on the thermal diffusion equation, the Galerkin’s method is employed to establish the temperature equation of the composite laminated trapezoidal plate. The geometrical nonlinearity of the plate is considered by using the von Karman large deformation theory, and combining the thermal model and aeroelastic model, Hamilton’s principle is employed to establish the thermoelastic equation of motion of the composite laminated trapezoidal plate. The thermal buckling and postbuckling of the composite laminated rectangular plate are analyzed to verify the validity and correctness of the present methodology by comparing with the results reported in the literature. Moreover, the effects of the temperature with the ply-angle on the thermal buckling and postbuckling of the composite laminated trapezoidal plates are studied, the thermal effects on the nonlinear vibration behaviors of the composite laminated trapezoidal plates are discussed, and the frequency-response curves are also presented for the different temperatures and ply angles.


ABSTRACT: In this paper, the response of an underground fibreglass reinforced plastic (FRP) composite pipe system subjected to realistic loading scenarios that may be experienced by an actual buried pipeline is investigated. The model replicates an arbitrary site with a length of buried pipeline, passing through a 90° bend and into a valve pit. Various loading conditions, which include effects of pipe pressurization, differences in response between stainless steel and fibreglass composite pipes and severe loss of bed-soil support are studied. In addition to pipe response, the resulting soil stresses and ground settlement are also analysed. Furthermore, the locations of potential leakage and burst have also been identified by evaluating the contact pressures at the joints and by comparing stresses to the pipe hoop and axial failure strengths.

ABSTRACT: This work investigates a novel plate formulation and a modified couple stress theory that introduces a variable length scale parameter is presented to discuss the static and dynamic of functionally graded (FG) micro-plates. A new type of third-order shear deformation theory of Reddy that use only 4 unknowns by including undetermined integral variables is proposed in this study. The equations of motion are derived from Hamilton’s principle. Analytical solutions are obtained for a simply supported micro-plate. Numerical examples are presented to examine the effect of the length scale parameter on the responses of micro-plates. The obtained results are compared with the previously published results to demonstrate the correctness of the present formulation.


ABSTRACT: In this work, the bending and free vibration analysis of multilayered plates and shells is presented by utilizing a new higher order shear deformation theory (HSDT). The proposed involves only four unknowns, which is even less than the first shear deformation theory (FSDT) and without requiring the shear correction coefficient. Unlike the conventional HSDTs, the present one presents a novel displacement field which incorporates undetermined integral variables. The equations of motion are derived by using the Hamilton’s principle. These equations are then solved via Navier-type, closed form solutions. Bending and vibration results are found for cylindrical and spherical shells and plates for simply supported boundary conditions. Bending and vibration problems are treated as individual cases. Panels are subjected to sinusoidal, distributed and point loads. Results are presented for thick to thin as well as shallow and deep shells. The computed results are compared with the exact 3D elasticity theory and with several other conventional HSDTs. The proposed HSDT is found to be precise compared to other several existing ones for investigating the static and dynamic response of isotropic and multilayered composite shell and plate structures.


ABSTRACT: This paper presents an isogeometric discretization of Kirchhoff-Love thin shells using truncated hierarchical B-splines (THB-splines). It is demonstrated that the underlying basis functions are ideally appropriate for adaptive refinement of the so-called thin shell structures in the framework of isogeometric analysis. The proposed approach provides sufficient flexibility for refining basis functions independent of their order. The main advantage of local THB-spline evaluation is that it provides higher degree analysis on tight meshes of arbitrary geometry which makes it well suited for discretizing the Kirchhoff-Love shell formulation. Numerical results show the versatility and high accuracy of the present method. This study is a part of the efforts by the authors to bridge the gap between CAD and CAE.

References listed at the end of the paper:

ABSTRACT: The traditional prestressed concrete composite box-girders with corrugated steel webs have several drawbacks such as large deflection and potential local buckling. In this study, two methods were investigated to optimize and improve the prestressed concrete composite box-girders with corrugated steel webs. The first method was to replace the concrete bottom slab with a steel plate and the second method was to support the concrete bottom slab on the steel flanges. The behavior of the prestressed concrete composite box-girders with corrugated steel webs with either method was studied by experiments on three specimens. The test results showed that behavior of the optimized and upgraded prestressed concrete composite box-girders with corrugated steel webs, including ultimate bearing capacity, flexural stiffness, and crack resistance, is greatly improved. In addition, the influence of different shear connectors, including perfobond leisten (PBL) and stud shear connectors, on the behavior of prestressed concrete composite box-girders with corrugated steel webs was studied. The results showed that PBL shear connectors can greatly improve the ultimate bearing capacity, flexural stiffness and crack resistance property of the prestressed concrete composite box-girders with corrugated steel webs. However, for the efficiency of prestressing introduced into the girder, the PBL shear connectors do not perform as well as the stud shear connectors.

References listed at the end of the paper:


ABSTRACT: A steel-concrete composite (SC) panel typically consists of two steel faceplates and a plain concrete core. This paper investigated the impact response of SC panels through drop hammer tests and numerical simulations. The influence of the drop height, faceplate thickness, and axial compressive preload was studied. Experimental results showed that the deformation of SC panels under impact consists of local indentation and overall bending. The resistance of the panel significantly decreased after the local failure occurred. A three-dimensional finite element model was established to simulate the response of SC panels under low-velocity impact, in which the axial preload could be considered reasonably. The predicted displacements and impact force were in good agreement with the experimental results. Based on the validated model, a parametric study was conducted to further discuss the effect of the axial compressive preload.


ABSTRACT: Buckling and free vibration analysis of sandwich micro plate (SMP) integrated with piezoelectric layers embedded in orthotropic Pasternak are investigated in this paper. The refined Zigzag theory (RZT) is taken into consideration to model the SMP. Four different types of functionally graded (FG) distribution through the thickness of the SMP core layer which is reinforced with single-wall carbon nanotubes (SWCNTs) are considered. The modified couple stress theory (MCST) is employed to capture the effects of small scale effects. The sandwich structure is exposed to a two dimensional magnetic field and also, piezoelectric layers are subjected to external applied voltages. In order to obtain governing equation, energy method as well as Hamilton’s principle is applied. Based on an analytical solution the critical buckling loads and natural frequency are obtained. The effects of volume fraction of carbon nanotubes (CNTs), different distributions of CNTs, foundation stiffness parameters, magnetic and electric fields, small scale parameter and the thickness of piezoelectric layers on the both critical buckling loads and natural frequency of the SMP are examined. The obtained results demonstrate that the effects of volume fraction of CNTs play an important role in analyzing buckling and free vibration behavior of the SMP. Furthermore, the effects of magnetic and electric fields are remarkable on the mechanical responses of the system and cannot be neglected.

References listed at the end of the paper:


ABSTRACT: This paper presents the development of finite element (FE) models to simulate the behavior of diagonally stiffened steel plate shear wall systems (SPSWs) with differently shaped openings subjected to a cyclic load. This walling system has the potential to be used for shear elements that resist lateral loads in steel-framed buildings. A number of 1/2-scale one-story buildings that were un-stiffened, stiffened and stiffened with opening SPSWs are modeled and simulated using the finite element method based on experimental data from previous research. After validating the finite element (FE) models, the effects of infill plate thickness on the cyclic behavior of steel shear walls are investigated. Furthermore, triple diagonal stiffeners are added to the steel infill plates of the SPSWs, and the effects are studied. Moreover, the effects of a number of differently shaped openings applied to the infill plate are studied. The results indicate that the bearing capacity and shear resistance are affected positively by increasing the infill plate thickness and by adding triple diagonal stiffeners. In addition, the cyclic behavior of SPSWs is improved, even with an opening in the SPSWs.

References listed at the end of the paper:

1. AISC (2010), Specification for Structural Steel Buildings; Chicago, IL, USA.

ABSTRACT: A novel higher shear deformation theory (HSDT) is proposed for the bending, buckling and free vibration investigations of isotropic and functionally graded (FG) sandwich plates. It contains only four variables, which is even less than the first shear deformation theory (FSDT) and the conventional HSDTs. The model accounts for a parabolic variation of transverse shear stress, respects the traction free boundary conditions and contrary to the conventional HSDTs, the present one presents a novel displacement field which incorporates undetermined integral terms. Equations of motion determined in this work are applied for three types of FG structures: FG plates, sandwich plates with FG core and sandwich plates with FG faces. Analytical solutions are given to predict the transverse displacements, stresses, critical buckling forces and natural frequencies of simply supported plates and a comparison study is carried out to demonstrate the accuracy of the proposed model.

Mohammad Arefi and Asraf M. Zenkour, “Free vibration analysis of a three-layered microbeam based on strain gradient theory and three-unknown shear and normal deformation theory”, Steel and Composite Structures, Vol. 26, No. 4, pp 421-437, 2018
ABSTRACT: Free vibration analysis of a three-layered microbeam including an elastic micro-core and two piezo-magnetic face-sheets resting on Pasternak`s foundation are studied in this paper. Strain gradient theory is used for size-dependent modeling of microbeam. In addition, three-unknown shear and normal deformations theory is employed for description of displacement field. Hamilton’s principle is used for derivation of the governing equations of motion in electro-magneto-mechanical loads. Three micro-length-scale parameters based on strain gradient theory are employed for prediction of vibrational characteristics of structure in micro-scale. The results show that increase of three micro-length-scale parameters leads to significant increase of three natural frequencies especially for increase of second micro-length-scale parameter. This result is according to this fact that stiffness of a micro-scale structure is increased with increase of micro-length-scale parameters.

ABSTRACT: Free vibration of cross-ply laminated plates using a higher-order shear deformation theory is studied. The arbitrary number of layers is oriented in symmetric and anti-symmetric manners. The plate kinematics are based on higher-order shear deformation theory (HSDT) and the vibrational behaviour of multi-layered plates are analysed under simply supported boundary conditions. The differential equations are obtained in terms of displacement and rotational functions by substituting the stress-strain relations and strain-displacement relations in the governing equations and separable method is adopted for these functions to get a set of ordinary differential equations in term of single variable, which are coupled. These displacement and rotational functions are approximated using cubic and quartic splines which results in to the system of algebraic
equations with unknown spline coefficients. Incurring the boundary conditions with the algebraic equations, a
generalized eigen value problem is obtained. This eigen value problem is solved numerically to find the eigen
frequency parameter and associated eigenvectors which are the spline coefficients. The material properties of
Kevlar-49/epoxy, Graphite/Epoxy and E-glass epoxy are used to show the parametric effects of the plates aspect
ratio, side-to-thickness ratio, stacking sequence, number of lamina and ply orientations on the frequency
parameter of the plate. The current results are verified with those results obtained in the previous work and the
new results are presented in tables and graphs.

Fa-xing Ding, Qiang Fu, Bing Wen, Qi-shi Zhou and Xue-mei Liu, “Behavior of circular concrete-filled steel
tubular columns under pure torsion”, Steel and Composite Structures, Vol. 26, No. 4, pp 501-511, 2018
ABSTRACT: Concrete-filled steel tubular (CFT) columns are commonly used in engineering structures and
always subjected to torsion in practice. This paper is thus devoted to investigate the mechanical behavior of
circular CFT columns under pure torsion. 3D finite element models based on reasonable material constitutive
relation were established for analyzing the load-strain relation curves of circular CFT columns under pure
torsion. The numerical simulation indicated that local buckling of the steel tube in CFT columns was prevented
and the shear strength and ductility of the core concrete were significantly improved due to the confinement
effect between the steel tube and the core concrete. Based on the results, formulas to predict the torsional ultimate bearing capacity of circular CFT columns were proposed with satisfactory correspondence with
experimental results. Besides, formulas of composite shear stiffness and the overall process of the relation of circular CFT columns under pure torsion were proposed.

Mehdi Mohammadimehr, Mojtaba Mehrabi, Hasan Hadizadeh and Hossein Hadizadeh, “Surface and size
dependent effects on static, buckling, and vibration of micro composite beam under thermo-magnetic fields
based on strain gradient theory”, Steel and Composite Structures, Vol. 26, No. 4, pp 513-531, 2018
ABSTRACT: In this article, static, buckling and free vibration analyses of a sinusoidal micro composite beam
reinforced by single-walled carbon nanotubes (SWCNTs) with considering temperature-dependent material
properties embedded in an elastic medium in the presence of magnetic field under transverse uniform load are
presented. This system is used at micro or sub micro scales to enhance the stiffness of micro composite
structures such as bar, beam, plate and shell. In the present work, the size dependent effects based on surface
stress effect and modified strain gradient theory (MSGT) are considered. The generalized rule of mixture
is employed to predict temperature-dependent mechanical and thermal properties of micro composite beam. Then,
the governing equations of motions are derived using Hamilton`s principle and energy method. Numerical
results are presented to investigate the influences of material length scale parameters, elastic foundation,
composite fiber angle, magnetic intensity, temperature changes and carbon nanotubes volume fraction on the
bending, buckling and free vibration behaviors of micro composite beam. There is a good agreement between
the obtained results by this research and the literature results. The obtained results of this study demonstrate that
the magnetic intensity, temperature changes, and two parameters elastic foundations have important effects on
micro composite stiffness, while the magnetic field has greater effects on the bending, buckling and free
vibration responses of micro composite beams. Moreover, it is shown that the effects of surface layers are
important, and observed that the changes of carbon nanotubes volume fraction, beam length-to-thickness ratio
and material length scale parameter have noticeable effects on the maximum deflection, critical buckling load
and natural frequencies of micro composite beams.

Abbas Loghman, Reza K. Faegh and Mohammad Arefi, “Two dimensional time-dependent creep analysis of a
thick-walled FG cylinder based on first order shear deformation theory”, Steel and Composite Structures, Vol.
26, No. 5, pp 533-547, 2018
ABSTRACT: In this paper the time-dependent creep analysis of a thick-walled FG cylinder with finite length subjected to axisymmetric mechanical and thermal loads are presented. First order shear deformation theory (FSDT) is used for description of displacement components. Inner and outer temperatures and outer pressure are considered as thermo-mechanical loadings. Both thermal and mechanical loadings are assumed variable along the axial direction using the sinusoidal distribution. To find temperature distribution, two dimensional heat transfer equation is solved using the required boundary conditions. The energy method and Euler equations are employed to reach final governing equations of the cylinder. After determination of elastic stresses and strains, the creep analysis can be performed based on the Yang method. The results of this research indicate that the boundaries have important effects on the responses of the cylinder. The effect of important parameters of this analysis such as variable loading, non-homogeneous index of functionally graded materials and time of creep is studied on the behaviors of the cylinder.

Lan Kang, Motoya Suzuki and Hanbin Ge, “A study on application of high strength steel SM570 in bridge piers with stiffened box section under cyclic loading”, Steel and Composite Structures, Vol. 26, No. 5, pp 583-594, 2018

ABSTRACT: Although a lot of experimental and analytical investigations have been carried out for steel bridge piers made of SS400 and SM490, the formulas available for SS400 and SM490 are not suitable for evaluating ultimate load and deformation capacities of steel bridge piers made of high strength steel (HSS) SM570. The effect of various parameters is investigated in this paper, including plate width-to-thickness ratio, column slenderness ratio and axial compression force ratio, on the ultimate load and deformation capacities of steel bridge box piers made of SM570 steel subjected to cyclic loading. The elasto-plastic behavior of the steel bridge piers under cyclic loads is simulated through plastic large deformation finite element analysis, in which a modified two-surface model (M2SM) including cyclic hardening is employed to trace the material nonlinearity. An extensive parametric study is conducted to study the influences of structural parameters on the ultimate load and deformation capacities. Based on these analytical investigations, new formulas for predicting ultimate load and deformation capacities of steel bridge piers made of SM570 are proposed. This study extends the ultimate load and deformation capacities evaluation of steel bridge piers from SS400, SM490 steels to SM570 steel, and provides some useful suggestions.

References listed at the end of the paper:
2. Japan Road Association (2002), Specifications for highway bridges, Part V, seismic design, Tokyo, Japan.
ABSTRACT: Vibration analysis of deep curved FG nano-beam has been carried out based on modified couple stress theory. Material properties of curved Timoshenko beam are assumed to be functionally graded in radial direction. Governing equations of motion and related boundary conditions have been obtained via Hamilton’s principle. In a parametric study, influence of length scale parameter, aspect ratio, gradient index, opening angle, mode number and interactive influences of these parameters on natural frequency of the beam, have been investigated. It was found that, considering geometrical deepness term leads to an increase in sensitivity of natural frequency about variation of aforementioned parameters.

Vahid Tahouneh, “3-D Vibration analysis of FG-MWCNTs/Phenolic sandwich sectorial plates”, Steel and Composite Structures, Vol. 26, No. 5, pp 649-662, 2018
ABSTRACT: In this study, based on the three-dimensional theory of elasticity, free vibration characteristics of sandwich sectorial plates with multiwalled carbon nanotube-(MWCNT)-reinforced composite core are considered. Modified Halpin-Tsai equation is used to evaluate the Young’s modulus of the MWCNT/epoxy composite samples by the incorporation of an orientation as well as an exponential shape factor in the equation. The exponential shape factor modifies the Halpin-Tsai equation from expressing a straight line to a nonlinear one in the MWCNTs wt% range considered. In this paper, free vibration of thick functionally graded sandwich annular sectorial plates with simply supported radial edges and different circular edge conditions including simply supported-clamped, clamped-clamped, and free-clamped is investigated. A semi-analytical approach composed of two-dimensional differential quadrature method and series solution are adopted to solve the equations of motion. The material properties change continuously through the core thickness of the plate, which can vary according to a power-law, exponentially, or any other formulations in this direction. This study serves as a benchmark for assessing the validity of numerical methods or two-dimensional theories used to analysis of laminated sectorial plates.

Amin Hadi, Mohammad Zamani Nejad, Abbas Rastgoo and Mohammad Hosseini, “Buckling analysis of FGM Euler-Bernoulli nano-beams with 3D-varying properties based on consistent couple-stress theory”, Steel and Composite Structures, Vol. 26, No. 6, pp 663-672, 2018
ABSTRACT: This paper contains a consistent couple-stress theory to capture size effects in Euler-Bernoulli nano-beams made of three-directional functionally graded materials (TDFGMs). These models can degenerate into the classical models if the material length scale parameter is taken to be zero. In this theory, the couple-stress tensor is skew-symmetric and energy conjugate to the skew-symmetric part of the rotation gradients as the curvature tensor. The material properties except Poisson’s ratio are assumed to be graded in all three axial, thickness and width directions, which it can vary according to an arbitrary function. The governing equations are obtained using the concept of minimum potential energy. Generalized differential quadrature method (GDQM) is used to solve the governing equations for various boundary conditions to obtain the natural frequencies of TDFG nano-beam. At the end, some numerical results are performed to investigate some
effective parameter on buckling load. In this theory the couple-stress tensor is skew-symmetric and energy conjugate to the skew-symmetric part of the rotation gradients as the curvature tensor.

Qiang Fu, Fa-xing Ding, Tao Zhang, Liping Wang and Chang-jing Fang, “Composite action of hollow concrete-filled circular steel tubular stub columns”, Steel and Composite Structures, Vol. 26, No. 6, pp 693-703, 2018

ABSTRACT: To better understand the influence of hollow ratio on the hollow concrete-filled circular steel tubular (H-CFT) stub columns under axial compression and to propose the design formula of ultimate bearing capacity for H-CFT stub columns, 3D finite element analysis and laboratory experiments were completed to obtain the load-deformation curves and the failure modes of H-CFT stub columns. The changes of the confinement effect between concrete core and steel tube with different hollow ratios were discussed based on the finite element results. The result shows that the axial stress of concrete and hoop stress of steel tube in H-CFT stub columns are decreased with the increase of hollow ratio. After the yield of steel, the reduction rate of longitudinal stress and the increase rate of circumferential stress for the steel tube slowed down. The confinement effect from steel tube on concrete also weakened slowly with the increase of hollow ratio. Based on the limit equilibrium method, a simplified formula of ultimate bearing capacity for the axially loaded H-CFT stub columns was proposed. The predicted results showed satisfactory agreement with the experimental and numerical results.

References listed at the end of the paper:


ABSTRACT: This paper presents a numerical investigation on the mechanical performance of concrete-filled dual steel tubular columns of circular section subjected to concentric axial load. A three-dimensional numerical model is developed and validated against a series of experimental tests. A good agreement is obtained between the experimental and numerical results, both in the peak load value and in the ascending and descending branches of the load-displacement curves. By means of the numerical model, a parametric study is carried out to investigate the influence of the main parameters that determine the axial capacity of double-tube columns, such as the member slenderness, inner and outer steel tube thicknesses and the concrete grade - of both the outer concrete and inner core -, including ultra-high strength concrete. A total number of 163 numerical simulations are carried out, by combining the different parameters. Specific indexes are defined (Strength Index, Concrete-Steel Contribution Ratio, Inner Concrete Contribution Ratio) to help rating the relative mechanical performance of dual steel tubular columns as compared to conventional concrete-filled steel tubular columns, and practical design recommendations are subsequently given.

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ABSTRACT: This paper presents post-buckling responses of a simply supported laminated composite beam subjected to a non-follower axially compression loads. In the nonlinear kinematic model of the laminated beam,
total Lagrangian approach is used in conjunction with the Timoshenko beam theory. In the solution of the nonlinear problem, incremental displacement-based finite element method is used with Newton-Raphson iteration method. There is no restriction on the magnitudes of deflections and rotations in contradistinction to von-Karman strain displacement relations of the beam. The distinctive feature of this study is post-buckling analysis of Timoshenko Laminated beams full geometric non-linearity and by using finite element method. The effects of the fiber orientation angles and the stacking sequence of laminates on the post-buckling deflections, configurations and stresses of the composite laminated beam are illustrated and discussed in the numerical results. Numerical results show that the above-mentioned effects play a very important role on the post-buckling responses of the laminated composite beams.

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ABSTRACT: This paper deals with the low velocity impact response and dynamic stresses of composite sandwich truncated conical shells (STCS) with compressible or incompressible core. Impacts are assumed to occur normally over the top face-sheet and the interaction between the impactor and the structure is simulated using a new equivalent three-degree-of-freedom (TDOF) spring-mass-damper (SMD) model. The displacement fields of core and face sheets are considered by higher order and first order shear deformation theory (FSDT), respectively. Considering continuity boundary conditions between the layers, the motion equations are derived based on Hamilton’s principal incorporating the curvature, in-plane stress of the core and the structural damping effects based on Kelvin-Voigt model. In order to obtain the contact force, the displacement histories and the dynamic stresses, the differential quadrature method (DQM) is used. The effects of different parameters such as number of the layers of the face sheets, boundary conditions, semi vertex angle of the cone, impact velocity of impactor, trapezoidal shape and in-plane stresses of the core are examined on the low velocity impact response of STCS. Comparison of the present results with those reported by other researchers, confirms the accuracy of the present method. Numerical results show that increasing the impact velocity of the impactor yields to increases in the maximum contact force and deflection, while the contact duration is decreased. In addition, the normal stresses induced in top layer are higher than bottom layer since the top layer is subjected to impact load. Furthermore, with considering structural damping, the contact force and dynamic deflection decreases.

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ABSTRACT: A new composite reinforced method, namely self-compacting concrete filled circular CFRP-steel jacketing, was proposed in this paper. Experimental tests on eight RC square short columns reinforced with the new composite reinforced method and four RC square short columns reinforced with CFS jackets were conducted to investigate their eccentrically compressive behaviour. Nine reinforced columns were subjected to eccentrically compressive loading, while three reinforced columns were subjected to axial compressive loading as reference. The parameters investigated herein were the eccentricity of the compressive loading and the layer of CFRP. Subsequently, the failure mode, ultimate load, deformation and strain of these reinforced columns were discussed. Their failure modes included the excessive bending deformation, serious buckling of steel jackets, crush of concrete and fracture of CFRP. Moreover, these reinforced columns exhibited a ductile failure globally. Both the eccentricity of the compressive loading and the layer of CFRP had a significant effect on the eccentrically compressive behaviour of reinforced columns. Finally, formulae for the evaluation of the ultimate load of reinforced columns were proposed. The theoretical formulae based on the ultimate equilibrium theory provided an effective, acceptable and safe method for designers to calculate the ultimate load of reinforced columns under eccentrically compressive loading.

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ABSTRACT: Steel-concrete-steel (SCS) sandwich composite structure with corrugated-strip connectors (CSC) has the potential to be used in buildings and offshore structures. In this structure, CSCs are used to bond steel face plates and concrete. To overcome executive problems, in the proposed system by the authors, shear connectors are one end welded as double skin composites. Hence, this system double skin with corrugated-strip connectors (DSCS) is named. In this paper, finite element model (FEM) of push-out test was presented for the basic component of DSCS. ABAQUS/Explicit solver in ABAQUS was used due to the geometrical complexity of the model, especially in the interaction of the shear connectors with concrete. In order that the explicit analysis has a quasi-static behavior with a proper approximation, the kinetic energy (ALLKE) did not exceed 5% to 10% of the internal energy (ALLIE) using mass-scaling. The FE analysis (FEA) was validated against those from the push-out tests in the previous work of the authors published in this journal. By comparing load-slip curves and failure modes, FEMs with suitable analysis speed were consistent with test results.

Hossein Taghipoor and Mohammad Damghani Noori, “Experimental and numerical study on energy absorption of lattice-core sandwich beam”, Steel and Composite Structures, Vol. 27, No. 2, pp 135-147, 2018
ABSTRACT: Quasi-static three-point bending tests on sandwich beams with expanded metal sheets as core were conducted. Relationships between the force and displacement at the mid-span of the sandwich beams were obtained from the experiments. Numerical simulations were carried out using ABAQUS/EXPLICIT and the results were thoroughly compared with the experimental results. A parametric analysis was performed using a Box-Behnken design (BBD) for the design of experiments (DOE) techniques and a finite element modeling. Then, the influence of the core layers number, size of the cell and, thickness of the substrates was investigated. The results showed that the increase in the size of the expanded metal cell in a reasonable range was required to improve the performance of the structure under bending collapse. It was found that core layers number and size of the cell was key factors governing the quasi-static response of the sandwich beams with lattice cores.
Farzad Ebrahimi and Navid Farazmandnia, “Thermal buckling analysis of functionally graded carbon nanotube-reinforced composite sandwich beams”, Steel and Composite Structures, Vol. 27, No. 2, pp 149-159, 2018

ABSTRACT: Thermo-mechanical buckling of sandwich beams with a stiff core and face sheets made of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) within the framework of Timoshenko beam theory is presented. The material properties of FG-CNTRC are supposed to vary continuously in the thickness direction and are estimated through the rule of mixture. Also the properties of these materials should be considered temperature dependent. The governing equations and boundary conditions are derived by using Hamilton’s principle and solved using an efficient technique called the Differential Transform Method (DTM) to achieve the critical buckling of the sandwich beam in uniform thermal environment. A detailed parametric study is guided to investigate the effects of carbon nanotube volume fraction, slenderness ratio, core-to-face sheet thickness ratio, and clamped-clamped, simply-simply and clamped-simply end supports on the critical buckling behavior of sandwich beams with FG-CNTRC face sheets. Numerical results for comparison of sandwich beams with uniformly distributed carbon nanotube-reinforced composite (UD-CNTRC) face sheets with those with FG-CNTRC face sheets are also presented.

References listed at the end of the paper:

ABSTRACT: This paper presents an experimental work for short circular steel tube columns filled with normal concrete (NAC), recycled aggregate concrete (RAC), and RAC with silica fume and steel fiber. Ten specimens were tested under axial compression to research the effect of silica fume and steel fiber volume percentage on the behavior of recycled aggregate concrete-filled steel tube columns (RACFST). The failure modes, ultimate loads and axial load-strain relationships are presented. The test results indicate that silica fume and steel fiber would not change the failure mode of the RACFST column, but can increase the mechanical performances of the RACFST column because of the filling effect and pozzolanic action of silica fume and the confinement effect of steel fiber. The ultimate load, ductility and energy dissipation capacity of RACFST columns can exceed that of corresponding natural aggregate concrete-filled steel tube (NACFST) column. Design formulas EC4 for the load capacity NACFST and RACFST columns are proposed, and the predictions agree well with the experimental results from this study.

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ABSTRACT: This paper utilizes 3D FEM to provide deeper insights about the structural behaviour of a 6.1 m span steel culvert, which was previously tested under extreme loading. The effect of different input parameters pertaining to the backfill soil has been investigated, where the structural response is compared to field measurements. The interface choice between the steel and soil materials was also studied. The results enabled to realize the major influence of the friction angle on the load effects. Moreover, the analyses showed some differences concerning the estimation of failure load, whereas reasons beyond this outcome were arguably presented and discussed.

Chao-Wei Tang, “Fire resistance of high strength concrete filled steel tubular columns under combined temperature and loading”, Steel and Composite Structures, Vol. 27, No. 2, pp 243-253, 2018

ABSTRACT: In recent years, concrete-filled box or tubular columns have been commonly used in high-rise buildings. However, a number of fire test results show that there are significant differences between high
strength concrete (HSC) and normal strength concrete (NSC) after being subjected to high temperatures. Therefore, this paper presents an investigation on the fire resistance of HSC filled steel tubular columns (CFTCs) under combined temperature and loading. Two groups of full-size specimens were fabricated to consider the effect of type of concrete infilling (plain and reinforced) and the load level on the fire resistance of CFTCs. Prior to fire test, a constant compressive load (i.e., load level for fire design) was applied to the column specimens. Thermal load was then applied on the column specimens in form of ISO 834 standard fire curve in a large-scale laboratory furnace until the set experiment termination condition was reached. The results demonstrate that the higher the axial load level, the worse the fire resistance. Moreover, in the bar-reinforced concrete-filled steel tubular columns, the presence of rebars not only decreased the spread of cracks and the sudden loss of strength, but also contributed to the load-carrying capacity of the concrete core.


ABSTRACT: This paper deals with the transient dynamic analysis and elastic wave propagation in a functionally graded graphene platelets (FGGPLs)-reinforced composite thick hollow cylinder, which is subjected to shock loading. A micromechanical model based on the Halpin-Tsai model and rule of mixture is modified for nonlinear functionally graded distributions of graphene platelets (GPLs) in polymer matrix of composites. The governing equations are derived for an axisymmetric FGGPLs-reinforced composite cylinder with a finite length and then solved using a hybrid meshless method based on the generalized finite difference (GFD) and Newmark finite difference methods. A numerical time discretization is performed for the dynamic problem using the Newmark method. The dynamic behaviors of the displacements and stresses are obtained and discussed in detail using the modified micromechanical model and meshless GFD method. The effects of the reinforcement of the composite cylinder by GPLs on the elastic wave propagations in both displacement and stress fields are obtained for various parameters. It is concluded that the proposed micromechanical model and also the meshless GFD method have a high capability to simulate the composite structures under shock loadings, which are reinforced by FGGPLs. It is shown that the modified micromechanical model and solution technique based on the meshless GFD method are accurate. Also, the time histories of the field variables are shown for various parameters.

References listed at the end of the paper:
ABSTRACT: Nonlinear low velocity impact response of sandwich beam with laminated composite face sheets and soft core is studied based on Extended High Order Sandwich Panel Theory (EHSAPT). The face sheets follow the Third order shear deformation beam theory (TSDT) that has hitherto not reported in conventional EHSAPT. Besides, the two dimensional elasticity is used for the core. The nonlinear Von Karman type relations for strains of face sheets and the core are adopted. Contact force between the impactor and the beam is obtained using the modified Hertz law. The field equations are derived via the Ritz based applied to the total energy of the system. The solution is obtained in the time domain by implementing the well-known Runge-Kutta method. The effects of boundary conditions, core-to-face sheet thickness ratio, initial velocity of the impactor, the impactor mass and position of the impactor are studied in detail. It is found that each of these parameters have significant effect on the impact characteristics which should be considered. Finally, some low velocity impact tests have been carried out by Drop Hammer Testing Machine. The contact force histories predicted by EHSAPT are in good agreement with that obtained by experimental results.

ABSTRACT: In this paper, the bearing capacity of a non-eccentric and eccentric tubular, concrete-filled, steel bridge pier was studied through the finite element method. Firstly, to verify the validity of the numerical analysis, the finite element analysis of four steel tube columns with concrete in-fill was carried out under eccentric loading and horizontal cyclic loading. The analytical results were compared with experimental data. Secondly, the effects of the eccentricity of the vertical loading on the seismic performance of these eccentrically loaded steel tubular bridge piers were considered. According to the simulated results, with increasing eccentricity ratio, the bearing capacity on the eccentric side of a steel tubular bridge pier (with concrete in-fill) is greatly reduced, while the capacity on the opposite side is improved. Moreover, an empirical formula was proposed to describe the bearing capacity of such bridge piers under non-eccentric and eccentric load. This will provide theoretical evidence for the seismic design of the eccentrically loaded steel tubular bridge piers with concrete in-fill.

ABSTRACT: This article presents the bending analysis of FGM rectangular plates resting on non-uniform elastic foundations in thermal environment. Theoretical formulations are based on a recently developed refined shear deformation theory. The displacement field of the present theory is chosen based on nonlinear variations in the in-plane displacements through the thickness of the plate. The present theory satisfies the free transverse shear stress conditions on the top and bottom surfaces of the plate without using shear correction factor. Unlike the conventional trigonometric shear deformation theory, the present refined shear deformation theory contains only four unknowns as against five in case of other shear deformation theories. The material properties of the functionally graded plates are assumed to vary continuously through the thickness, according to a simple power law distribution of the volume fraction of the constituents. The elastic foundation is modeled as non-uniform foundation. The results of the shear deformation theories are compared together. Numerical examples cover the effects of the gradient index, plate aspect ratio, side-to-thickness ratio and elastic foundation parameters on the thermo-mechanical behavior of functionally graded plates. Numerical results show that the present theory can archive accuracy comparable to the existing higher order shear deformation theories that contain more number of unknowns.

ABSTRACT: In this paper, a new model based on nonlocal high order theory is proposed to study the size effect on the bending of nano-sandwich beams with a compliance core. In this model, in contrast to most of the available sandwich theories, no prior assumptions are made with respect to the displacement field in the core. Herein the displacement and the stress fields of the core are obtained through an elasticity solution. Equations of motion and boundary conditions for nano-sandwich beam are derived by using Hamilton’s principle and an analytical solution is presented for simply supported nano-sandwich beam. The results are validated with previous studies in the literature. These results can be utilized in the study of nano-sensors and nano-actuators. The effect of nonlocal parameter, Young’s modulus of the core and aspect ratio on the deflection of the nano-sandwich beam is investigated. It is concluded that by including the small-scale effects, the deflection of the skins is increased and by increasing the nonlocal parameter, the influence of small-scale effects on the deflections is increased.

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Masoud Asgari, Alireza Babaee and Mohammadamin Jamshidi, “Multi-objective optimization of tapered tubes for crashworthiness by surrogate methodologies”, Steel and Composite Structures, Vol. 27, No. 4, pp 427-438, 2018

ABSTRACT: In this paper, the single and multi-objective optimization of thin-walled conical tubes with different types of indentations under axial impact has been investigated using surrogate models called metamodels. The geometry of tapered thin-walled tubes has been studied in order to achieve maximum specific energy absorption (SEA) and minimum peak crushing force (PCF). The height, radius, thickness, tapered angle of the tube, and the radius of indentation have been considered as design variables. Based on the design of experiments (DOE) method, the generated sample points are computed using the explicit finite element code.
Different surrogate models including Kriging, Feed Forward Neural Network (FNN), Radial Basis Neural Network (RNN), and Response Surface Modelling (RSM) comprised to evaluate the appropriation of such models. The comparison study between surrogate models and the exploration of indentation shapes have been provided. The obtained results show that the RNN method has the minimum mean squared error (MSE) in training points compared to the other methods. Meanwhile, optimization based on surrogate models with lower values of MSE does not provide optimum results. The RNN method demonstrates a lower crashworthiness performance (with a lower value of 125.7% for SEA and a higher value of 56.8% for PCF) in comparison to RSM with an error order of $10^{-3}$. The SEA values can be increased by 17.6% and PCF values can be decreased by 24.63% by different types of indentation. In a specific geometry, higher SEA and lower PCF require triangular and circular shapes of indentation, respectively.

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Mohammad Arefi, “Nonlocal free vibration analysis of a doubly curved piezoelectric nano shell”, Steel and Composite Structures, Vol. 27, No. 4, pp 479-493, 2018

ABSTRACT: In this paper nonlocal free vibration analysis of a doubly curved piezoelectric nano shell is studied. First order shear deformation theory and nonlocal elasticity theory is employed to derive governing equations of motion based on Hamilton’s principle. The doubly curved piezoelectric nano shell is resting on Pasternak’s foundation. A parametric study is presented to investigate the influence of significant parameters such as nonlocal parameter, two radii of curvature, and ratio of radius to thickness on the fundamental frequency of doubly curved piezoelectric nano shell.

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Mohammad Arefi, Masoud Mohammadi, Ali Tabatabaieian, Rossana Dimitri and Francesco Tornabene, “Two-dimensional thermo-elastic analysis of FG-CNTRC cylindrical pressure vessels”, Steel and Composite Structures, Vol. 27, No. 4, pp 525-536, 2018

ABSTRACT: This paper focuses on the application of the first-order shear deformation theory (FSDT) to thermo-elastic static problems of functionally graded carbon nanotubes reinforced composite (FG-CNTRC) cylindrical pressure vessels. A symmetric displacement field is considered as unknown function along the longitudinal direction, whereas a linear distribution is assumed along the thickness direction. The cylindrical pressure vessels are subjected to an inner and outer pressure under a temperature increase. Different patterns of reinforcement are applied as distribution of CNTs. The effective material properties of FG-CNTRC cylindrical pressure vessels are measured based on the rule of mixture, whereas the governing equations of the problem are here derived through the principle of virtual works. A large parametric investigation studies the effect of some significant parameters, such as the pattern and volume fraction of CNTs, on the longitudinal distribution of deformation, strain and stress components, as useful tool for practical engineering applications.

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Yihao Ma, Xiaoquan Cheng, Zhaodi Wang, Xin Guo, Jie Zhang and Yahong Xu, “Buckling and post-buckling behaviors of 1/3 composite cylindrical shell with an opening”, Steel and Composite Structures, Vol. 27, No. 5, pp 555-566, 2018

ABSTRACT: A 1/3 composite cylindrical shell with a central rectangular opening was axially compressed experimentally, and its critical buckling load and displacement, and strains were measured. A finite element model (FEM) of the shell with Hashin failure criteria was established to analyze its buckling and post-buckling behaviors by nonlinear Newton-Raphson method. The geometric imperfection sensitivity and the effect of side supported conditions of the shell were investigated. It was found that the Newton-Raphson method can be used to analyze the buckling and post-buckling behaviors of the shell. The shell is not sensitive to initial geometric imperfection. And the support design of the shell by side stiffeners is a good way to obtain the critical buckling load and simplify the experimental fixture.

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ABSTRACT: The imperfect steel-concrete interface bonding is an important deficiency of the concrete-filled double skin tubular (CFDST) columns that led to separating concrete and steel surfaces under lateral loads and triggering buckling failure of the columns. To improve this issue, it is proposed in this study to use longitudinal and transverse steel stiffeners in CFDST columns. CFDST columns with different patterns of stiffeners embedded in the interior or exterior surfaces of the inner or outer tubes were analyzed under constant axial force and reversed cyclic loading. In the finite element modeling, the confinement effects of both inner and outer tubes on the compressive strength of concrete as well as the effect of discrete crack for concrete fracture were incorporated which give a realistic prediction of the seismic behavior of CFDST columns. Lateral strength, stiffness, ductility and energy absorption are evaluated based on the hysteresis loops. The results indicated that the stiffeners had determinant role on improving pinching behavior resulting from the outer tube’s local buckling and opening/closing of the major tensile crack of concrete. The lateral strength, initial stiffness and energy absorption capacity of longitudinally stiffened columns with fixed-free end condition were increased by as much as 17%, 20% and 70%, respectively. The energy dissipation was accentuated up to 107% for fixed-guided end condition. The use of transverse stiffeners at the base of columns increased energy dissipation up to 35%. Axial load ratio, hollow ratio and concrete strength affecting the initial stiffness and lateral strength, had negligible effect of the energy dissipation of the columns. It was also found that the longitudinal stiffeners and transverse stiffeners have, respectively, negative and positive effects on ductility of CFDST columns. The conclusions, drawn from this study, can in turn, lead to the suggestion of some guidelines for the design of CFDST columns.

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the governing equations. The obtained numerical results from the proposed theory are compared with the CPT, FSDT, and other quasi-3D HSDTs.

Qiangqiang Liu, Ding Zhou, Jun Wang and Weiqing Liu, “Mechanical behavior of FRP confined steel tubular columns under impact”, Steel and Composite Structures, Vol. 27, No. 6, pp 691-702, 2018

ABSTRACT: This paper presents experimental and analytical results of fiber reinforced polymer (FRP) confined steel tubular columns under transverse impact loads. Influences of applied impact energy, thickness of FRP jacket and impact position were discussed in detail, and then the impact responses of FRP confined steel tubes were compared with bare steel tubes. The test results revealed that the FRP jacket contributes to prevent outward buckling deformation of steel at the clamped end and inward buckling of steel at the impact position. For the given applied impact energy, specimens wrapped with one layer and three layers of FRP have the lower peak impact loads than those of the bare steel tubes, whereas specimens wrapped with five layers of FRP exhibit the higher peak impact loads. All the FRP confined steel tubular specimens displayed a longer duration time than the bare steel tubes under the same magnitude of impact energy, and the specimen wrapped with one layer of FRP had the longest duration time. In addition, increasing the applied impact energy leads to the increase of peak impact load and duration time, whereas increasing the distance of impact position from the clamped end results in the decrease of peak impact load and the increase of duration time. The dynamic analysis software Abaqus Explicit was used to simulate the mechanical behavior of FRP confined steel tubular columns, and the numerical results agreed well with the test data. Analytical solution for lateral displacement of an equivalent cantilever beam model subjected to impact load was derived out. Comparison of analytical and experimental results shows that the maximum displacement can be precisely predicted by the present theoretical model

References listed at the end of the paper:
Mohamed Rasad and T.Y. Yang, “Numerical study of steel sandwich plates with RPF and VR cores materials under free air blast loads”, Steel and Composite Structures, Vol. 27, No. 6, pp 717-725, 2018

ABSTRACT: One of the most important design criteria in military tunnels and armoured doors is to resist the blast loads with minimum structural weight. This can be achieved by using steel sandwich panels. In this paper, the nonlinear behaviour of steel sandwich panels, with different core materials: (1) Hollow (no core material); (2) Rigid Polyurethane Foam (RPF); and (3) Vulcanized Rubber (VR) under free air blast loads, was investigated using detailed 3D nonlinear finite element models in Ansys Autody. The accuracy of the finite element model proposed was verified using available experimental test data of a similar steel sandwich panel tested. The results show the developed finite element model can be reliably used to simulate the nonlinear behaviour of the steel sandwich panels under free air blast loads. The verified finite element model was used to examine the different parameters of the steel sandwich panel with different core materials. The result shows that the sandwich panel with RPF core material is more efficient than the VR sandwich panel followed by the
Hollow sandwich panels. The average maximum displacement of RPF sandwich panel under different ranges of TNT charge (1 kg to 10 kg at a standoff distance of 1 m) is 49% and 53% less than the VR and Hollow sandwich panels, respectively. Detailed empirical design equations were provided to quantify the maximum deformation of the steel sandwich panels with different core materials and core thickness under a different range of blast loads. The developed equations can be used as a guide for engineer to design steel sandwich panels with RPF and VR core material under a different range of free air blast loads.


ABSTRACT: In the present work, the recently developed non-polynomial shear deformation theories are assessed for thermo-mechanical response characteristics of laminated composite plates. The applicability and accuracy of these theories for static, buckling and free vibration responses were ascertained in the recent past by several authors. However, the assessment of these theories for thermo-mechanical analysis of the laminated composite structures is still to be ascertained. The response characteristics are investigated in linear and non-linear thermal gradient and also in the presence and absence of mechanical transverse loads. The laminated composite plates are modelled using recently developed six shear deformation theories involving different shear strain functions. The principle of virtual work is used to develop the governing system of equations. The Navier type closed form solution is adopted to yield the exact solution of the developed equation for simply supported cross ply laminated plates. The thermo-mechanical response characteristics due to these six different theories are obtained and compared with the existing results.

Othman Arioul, Khalil Belakhdar, Abdelhakim Kaci and Abdelouahed Tounsi, “Thermal buckling of FGM beams having parabolic thickness variation and temperature dependent materials”, Steel and Composite Structures, Vol. 27, No. 6, pp 777-788, 2018

ABSTRACT: An investigation on the thermal buckling resistance of simply supported FGM beams having parabolic-concave thickness variation and temperature dependent material properties is presented in this paper. An analytical formulation based on the first order beam theory is derived and the governing differential equation of thermal stability is solved numerically using finite difference method. A function of thickness variation is introduced which controls the parabolic variation intensity of the beam thickness without changing its original material volume. The results showed the high importance of taking into account the temperature-dependent material properties in the thermal buckling analysis of such critical beam sections. Different Influencing parametric on the thermal stability are studied which may help in design guidelines of such complex structures.


ABSTRACT: A size-dependent novel hyperbolic shear deformation theory of simply supported functionally graded beams is presented in the frame work of the non-local strain gradient theory, in which the stress accounts for only the nonlocal strain gradients stress field. The thickness stretching effect is also considered here. Elastic coefficients and length scale parameter are assumed to vary in the thickness direction of functionally graded beams according to power-law form. The governing equations are derived using the Hamilton principle. The closed-form solutions for exact critical buckling loads of nonlocal strain gradient functionally graded beams are obtained using Navier’s method. The derived results are compared with those of strain gradient theory.
ABSTRACT: For the first time, the parametric instability characteristics of tow-steered variable stiffness composite laminated (VSCL) cylindrical panels is investigated using B-spline finite strip method (FSM). The panel is considered containing geometrical defects including cutout and delamination. The material properties are assumed to vary along the panel axial length of any lamina according to a linear fiber-orientation variation. A uniformly distributed inplane longitudinal loading varies harmonically with time is considered. The instability load frequency regions corresponding to the assumed in-plane parametric loading is derived using the Bolotin’s first order approximation through an energy approach. In order to demonstrate the capabilities of the developed formulation in predicting stability behavior of the thin-walled VSCL structures, some representative results are obtained and compared with those in the literature wherever available. It is shown that the B-spline FSM is a proper tool for extracting the stability boundaries of perforated delaminated VSCL panels.
References listed at the end of the paper: (non given)

ABSTRACT: This paper reports an experimental study that was accomplished to assess the seismic behavior of steel tube reinforced concrete bridge columns (SBCs). The motivation of this study was to verify a supposition that the core steel tube may be terminated at a rational position in the column to minimize the material cost while maintaining the seismic behavior of this composite column. Four SBC specimens were tested under combined constant axial load and cyclic reversed lateral loads. The unique variable in the test matrix was the core steel tube embedment length, which ranged from 1/3 to 3/3 of the column effective height. It is observed that SBCs showed two distinctly different failure patterns, namely brittle shear failure and ductile flexural failure. Tests results indicate that the hysteretic responses of SBCs were susceptible to the core steel tube embedment length. With the increase of this structural parameter, the lateral strength of SBC was progressively improved; the deformability and ductility, however, exhibited a tendency of first increase and then decrease. It is also found that in addition to maintained the rate of stiffness degradation and cumulative energy dissipation basically unchanged, both the ductility and deformability of SBC were significantly improved when the core steel tube was terminated at the mid-height of the column, and these were the most unexpected benefits accompanied with material cost reduction.

ABSTRACT: Using the modified couple stress theory and Euler-Bernoulli beam theory, this paper studies nonlinear vibration analysis of microbeams resting on the nonlinear orthotropic visco-Pasternak foundation. Using the Hamilton`s principle, the set of the governing equations are derived and solved numerically using differential quadrature method (DQM), Newar k beta method and arc-length technique for all kind of the boundary conditions. First convergence and accuracy of the presented solution are demonstrated and then effects of radius of gyration, Poisson`s ratio, small scale parameters, temperature changes and coefficients of the foundation on the linear and nonlinear natural frequencies and dynamic response of the microbeam are investigated.

ABSTRACT: Reliable and accurate method of computationally aided design processes of advanced thin walled structures in automotive industries are much essential for the efficient usage of smart materials, that possess higher energy absorption in dynamic compression loading. In this paper, most versatile components i.e., thin walled crash tubes with different geometrical profiles are introduced in view of mitigating the impact of varying cross section in crash behavior and energy absorption characteristics. Apart from the geometrical parameters such as length, diameter and thickness, the non-dimensionalized parameters of average forces which control the plastic bending moment for varying thickness has explored in view of quantifying its impact on the crashworthiness of the structure. The explicit finite element code ABAQUS is utilized to conduct the numerical studies to examine the effect of parametric modifications in crash behavior and energy absorption. Also the simulation results are experimentally validated. It is evident that the circular cross-sectional tubes are preferable as high collision impact shock absorbers due to their ability in withstanding axial and oblique impact loads effectively. Furthermore, the specific energy absorption (SEA), crash force efficiency (CFE), plastic bending moment, peak force responses and its impact for optimally tailoring a design to cater the crashworthiness requirements are investigated. The primary outcome of the study is to provide sufficient information on circular tubes for the use of energy absorbers where impact oblique loading is expected.


ABSTRACT: Back-to-back built-up cold-formed steel un-lipped channel sections are used in cold-formed steel structures; such as trusses, wall frames and portal frames. In such built-up columns, intermediate fasteners resist the buckling of individual channel-sections. No experimental tests or finite element analyses have been reported in the literature for back-to-back built-up cold-formed steel un-lipped channel sections and specially investigated the effect of screw spacing on axial strength of such columns. The issue is addressed in this paper. The results of 95 finite element analyses are presented covering stub to slender columns. The finite element model is validated against the experimental tests recently conducted by authors for back-to-back built-up cold-formed steel lipped channel sections. The verified finite element model is then used for the purposes of a parametric study to investigate the effect of screw spacing on axial strength of back-to-back built-up cold-formed steel un-lipped channel sections. Results are compared against the built-up lipped channel sections and it is shown that the axial strength of un-lipped built-up sections are 31% lesser on average than the built-up lipped channel sections. It was also found that the American Iron and Steel Institute (AISI) and the Australian and New Zealand Standards were over-conservative by around 15% for built-up columns failed through overall buckling, however AISI and AS/NZS were un-conservative by around 8% for built-up columns mainly failed by local buckling.


ABSTRACT: Structures may need retrofitting as a result of design and calculation errors, lack of proper implementation, post-construction change in use, damages due to accidental loads, corrosion and changes introduced in new editions of construction codes. Retrofitting helps to compensate weakness and increase the service life. Fiber Reinforced Polymer (FRP) is a modern material for retrofitting steel elements. This study aims to investigate the effect of deficiency location on the axial behavior of compressive elements of Circular Hollow Section (CHS) steel short columns. The deficiencies located vertically or horizontally at the middle or
bottom of the element. A total of 43 control column and those with deficiencies were investigated in the ABAQUS software. Only 9 of them tested in the laboratory. The results indicated that the deficiencies had a significant effect on the increase in axial deformation, rupture in deficiency zone (local buckling), and decrease in ductility and bearing capacity. The damages of steel columns were responsible for resistance and stiffness drop at deficiency zone. Horizontal deficiency at the middle and vertical deficiency at the bottom of the steel columns were found to be the most critical. Using Carbon Fiber Reinforced Polymer (CFRP) as the most effective material in retrofitting the damaged columns, significantly helped the increase in resistance and rupture control around the deficiency zone.

ABSTRACT: In this paper history of stresses, strains, radial and circumferential displacements of a functionally graded thick-walled hollow cylinder due to creep phenomenon is investigated. The cylinder is subjected to an arbitrary non-axisymmetric two dimensional thermo-mechanical loading and uniform magnetic field along axial direction. Using equilibrium, strain-displacements and stress-strain relations, the governing differential equations of the problem containing creep strains are derived in terms of radial and circumferential displacements. Since the displacements are varying with time due to creep phenomenon, an analytical solution is not available for these equations. Thus, a semi-analytical procedure based on separation of variables and Fourier series together with a numerical procedure is employed. The numerical results indicate that the non-axisymmetric loading and the material grading index have significant effect on stress redistributions. Moreover, by proper selection of material for any combination of non-axisymmetric loading, one can arrive suitable response for the cylinder to achieve optimal design. With some simplifications, the results are validated with the existing literature.

Maryam Shokravi, “Forced vibration response in nanocomposite cylindrical shells – Based on strain gradient beam theory”, Steel and Composite Structures, Vol. 28, No. 3, pp 381-388, 2018
ABSTRACT: In this paper, forced vibration of micro cylindrical shell reinforced by functionally graded carbon nanotubes (FG-CNTs) is presented. The structure is subjected to transverse harmonic load and modeled by beam model. The size effects are considered based on strain gradient theory containing three small scale parameters. The mixture rule is used for obtaining the effective material properties of the structure. Based on sinusoidal shear deformation theory of beam, energy method and Hamilton’s principle, the motion equations are derived. Applying differential quadrature method (DQM) and Newmark method, the frequency curves of the structure are plotted. The effect of different parameters including, CNTs volume percent and distribution type, boundary conditions, size effect and length to thickness ratio on the frequency curves of the structure is studied. Numerical results indicate that the dynamic deflection of the FGX-CNT-reinforced cylindrical is lower with respect to other type of CNT distribution.

ABSTRACT: An isoparametric six-node triangular element is utilized for geometrically nonlinear analysis of functionally graded (FG) shells. To overcome the shear and membrane locking, the element is improved by using strain interpolation functions. The Total Lagrangian formulation is employed to include the large displacements and rotations. Finding the nonlinear behavior of FG shells via laminated modeling is also the goal. A power function is employed to formulate the variation of elastic modulus through the thickness of shells. The results are presented in two ways, including the general FGM formulation and the laminated
modeling. The equilibrium path is obtained by using the Generalized Displacement Control Method. Some popular benchmarks, including hyperbolical shell structures are solved to declare the correctness and accuracy of proposed formulations.

ABSTRACT: In this paper, the lateral-torsional buckling of axially-transversally functionally graded tapered beam is investigated. The structure cross-section is assumed to be symmetric I-section, and it is continuously laterally supported by torsional springs through the length. In addition, the height of cross-section varies linearly throughout the length of structure. The proposed formulation is obtained for the case that the elastic and shear modulus change as a power function along the beam length and section height. This structure carries two concentrated moments at the ends. In this study, the lateral displacement and twisting angle relation of the beam are defined by sinusoidal series. After establishing the eigenvalue equation of unknown constants, the beam critical bending moment is found. To validate the accuracy and correctness of results, several numerical examples are solved.

Jihong Ye and Mingfei Lu, “Optimization of domes against instability”, Steel and Composite Structures, Vol. 28, No. 4, pp 427-438, 2018
ABSTRACT: Static stability is a decisive factor in the design of domes. Stability-related external factors, such as load and supports, are incorporated into structural vulnerability theory by the definition of a relative rate of joint well-formedness ($\tau_p$). Hence, the instability mechanism of domes can be revealed. To improve stability, an optimization model against instability, which takes the maximization of the lowest (math) as the objective and the discrete member sections as the variables, is established with constraints on the design requirements and steel consumption. Optimizations are performed on two real-life Kiewitt-6 model domes with a span of 23.4 m and rise of 11.7 m, which are initially constructed for shaking table collapse test. Well-formedness analyses and stability calculation (via arc-length method) of the models throughout the optimization history demonstrate that this proposed method can effectively enhance and optimize the static stability of shell-like structures. Additionally, seismic performance of the optimum models subjected to the same earthquake as in the shaking table test is checked. The supplemental simulations prove that the optimum models are superior to the original models under earthquake load as well.

ABSTRACT: In this study, the effect of polyurethane foam filler, in addition to surface layer thickness and core material thickness, on vibration characteristics of sandwich structures was investigated. The manufacturing process was carried out according to the Taguchi method. The natural frequencies and damping ratios of the produced samples were determined experimentally for fixed-free boundary conditions. In addition, solid models were developed for test samples and their finite element analyses were performed with ANSYS to obtain their natural frequencies and mode shapes. An acceptably good agreement was found with the comparison of experimental results with the numerically obtained ones. The most effective parameters on the vibration characteristics of the sandwich structure were determined by the Taguchi method.

Zuxiang Lei and Yang Zhang, “Characterizing buckling behavior of matrix-cracked hybrid plates containing CNTR-FG layers”, Steel and Composite Structures, Vol. 28, No. 4, pp 495-508, 2018
ABSTRACT: In this paper, the effect of matrix cracks on the buckling of a hybrid laminated plate is investigated. The plate is composed of carbon nanotube reinforced functionally graded (CNTR-FG) layers and conventional fiber reinforced composite (FRC) layers. Different distributions of single walled carbon nanotubes (SWCNTs) through the thickness of layers are considered. The cracks are modeled as aligned slit cracks across the ply thickness and transverse to the laminate plane, and the distribution of cracks is assumed statistically homogeneous corresponding to an average crack density. The first-order shear deformation theory (FSDT) is employed to incorporate the effects of rotary inertia and transverse shear deformation, and the meshless kp-Ritz method is used to obtain the buckling solutions. Detailed parametric studies are conducted to investigate the effects of matrix crack density, CNTs distributions, CNT volume fraction, plate aspect ratio and plate length-to-thickness ratio, boundary conditions and number of layers on buckling behaviors of hybrid laminated plates containing CNTR-FG layers.


ABSTRACT: This paper presents the influence of carbon nanotubes (CNTs) waviness and aspect ratio on the vibrational behavior of functionally graded nanocomposite sandwich annular sector plates resting on two-parameter elastic foundations. The carbon nanotube-reinforced (CNTR) sandwich plate has smooth variation of CNT fraction along the thickness direction. The distributions of CNTs are considered functionally graded (FG) or uniform along the thickness and their mechanical properties are estimated by an extended rule of mixture. In this study, the classical theory concerning the mechanical efficiency of a matrix embedding finite length fibers has been modified by introducing the tube-to-tube random contact, which explicitly accounts for the progressive reduction of the tubes’ effective aspect ratio as the filler content increases. Effects of CNT distribution, volume fraction, aspect ratio and waviness, and also effects of Pasternak’s elastic foundation coefficients, sandwich plate thickness, face sheets thickness and plate aspect ratio are investigated on the free vibration of the sandwich plates with wavy CNT-reinforced face sheets. The study is carried out based on three-dimensional theory of elasticity and in contrary to two-dimensional theories, such as classical, the first- and the higher-order shear deformation plate theories, this approach does not neglect transverse normal deformations. The sandwich annular sector plate is assumed to be simply supported in the radial edges while any arbitrary boundary conditions are applied to the other two circular edges including simply supported, clamped and free.


ABSTRACT: The objective of this paper is to investigate the mechanical performances of polygonal concrete-filled circular steel tubular (CFT) stub columns under axial loading through combined experimental and numerical study. A total of 32 specimens were designed to investigate the effect of the concrete strength and steel ratio on the compressive behavior of polygonal CFT stub columns. The ultimate bearing capacity, ductility and confinement effect were analyzed based on the experimental results and the failure modes were discussed in detail. Besides, ABAQUS was adopted to establish the three dimensional FE model. The composite action between the core concrete and steel tube was further discussed and clarified. It was found that the behavior of CFT stub column changes with the change of the cross-section, and the change is continuous. Finally, based on both experimental and numerical results, a unified formula was developed to estimate the ultimate bearing capacity of polygonal CFT stub columns according to the superposition principle with rational simplification. The predicted results showed satisfactory agreement with both experimental and FE results.
Ali Massumi, Nasibeh Karimi and Mostafa Ahmadi, “Effects of openings geometry and relative area on seismic performance of steel shear walls”, Steel and Composite Structures, Vol. 28, No. 5, pp 617-628, 2018

ABSTRACT: Steel shear wall possesses priority over many of the current lateral load-bearing systems due to reasons like higher elastic stiffness, desirable ductility and energy absorption, convenience in construction and implementation technology, and economic criteria. Besides these advantages, this system causes increase in the dimensions of other structural elements due to its high stiffness as one of its intrinsic characteristics. One of the methods for stiffness reduction is perforating the wall panel and creating openings in the wall that can also be used as windows or ducts in buildings service period. The aim of the present study is probing the appropriate geometric shape and location of opening to fulfil economic criterion plus technical and seismic design criteria. In the present research, a number of possible while reasonable opening shapes and locations are defined in various sizes for some steel shear wall specimens. The specimens are modelled in ABAQUS finite elements software and analyzed using nonlinear pushover analysis. Finally, the analyses’ results are reported as force-displacement diagrams and the strength, the initial stiffness and the energy absorption are calculated for all specimens and compared together. The obtained results show that both shape and location of the openings affect the seismic parameters of the shear wall. The specimens in which the openings are further from the center and closer to the columns possess higher stiffness and strength while the specimens in which the openings are closer to the center show more considerable changes in their seismic parameters in response to increase in opening area.

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ABSTRACT: In this article, the buckling and postbuckling behavior of functionally graded spherical shell panel is examined under nonuniform thermal environment. The effective material properties of the graded structure are evaluated using the Voigt's micromechanical model through the power-law distribution. For the analysis purpose, a general nonlinear higher order mathematical model is developed in conjunction with Green-Lagrange geometrical nonlinearity. The governing equation is derived using variational principle and solved through the direct iterative method. The effect of different geometrical and material parameters on the buckling and postbuckling responses of the functionally graded shell panels is examined and discussed in detail.

References listed at the end of the paper:

• H. Huang and Q. Han Nonlinear Dynamic Buckling of Functionally Graded Cylindrical Shells Subjected to Time-dependent Axial Load, Compos. Struct., vol. 92, pp. 593–598, 2010.
https://doi.org/10.1080/01495739.2016.1229145

ABSTRACT: In this article, the free vibration analysis of a functionally graded (FG) porous cylindrical microshell subjected to a thermal environment is investigated on the basis of the first-order shear deformation shells and the modified couple stress theories. The material properties are assumed to be temperature dependent and are graded in the thickness direction. The equations of motion and the related boundary conditions are derived using the principle of minimum potential energy and they are solved analytically. The model is validated by comparing the benchmark results with the obtained ones. The effects of material length scale parameter, temperature changes, volume fraction of the porosity, FG power index, axial and circumferential wave number, and length on the vibration behavior of the FG porous cylindrical microshell are studied. The results can have many applications such as in modeling of microrobots and biomedical microsystems.

References listed at the end of the paper:


ABSTRACT: This study develops the transient thermo-electromechanical vibration and bending analysis of a functionally graded piezoelectric nanosheet rest on visco-Pasternak’s foundation. Nonlocal elasticity theory as well as classical plate theory is used to implement basic equations of the nanosheet. The plate is resting on visco-Pasternak’s foundation and subject to mechanical, thermal, and electrical loadings. Hamilton’s principle is used for derivation equations of motion in terms of displacement components. As a first case study and for validation of the responses of the system, nonlocal vibration analysis of nanosheet is studied. The effects of nonlocal parameter and nonhomogeneous index of nanosheet are studied on the fundamental frequencies of the system. As the main objective of this study, the electrothermal bending results of the nanosheet are studied. The effects of some important parameters such as nonlocal parameter, nonhomogeneous index, thickness, distribution of electric potential, and damping are calculated on the maximum deflection of the sheet under various thermal and electrical loadings.


ABSTRACT: This article presents analytical solutions for the nonlinear static and dynamic stability of imperfect eccentrically stiffened functionally graded material (FGM) higher order shear deformable double curved shallow shell on elastic foundations in thermal environments. It is assumed that the shell’s properties depend on temperature and change according to the power functions of the shell thickness. The shell is reinforced by the eccentrically longitudinal and transversal stiffeners made of full metal. Equilibrium, motion, and compatibility equations are derived using Reddy’s higher order shear deformation shell theory and taking into account the effects of initial geometric imperfection and the thermal stress in both the shells and stiffeners. The Galerkin method is applied to determine load–deflection and deflection–time curves. For the dynamical response, motion equations are numerically solved using Runge-Kutta method. The nonlinear dynamic critical buckling loads are found according to the criterion suggested by Budiansky–Roth. The influences of inhomogeneous parameters, dimensional parameters, stiffeners, elastic foundations, initial imperfection, and temperature increment on the nonlinear static and dynamic stability of thick FGM double curved shallow shells are discussed in detail. Results for various problems are included to verify the accuracy and efficiency of the approach.

References listed at the end of the paper:
ABSTRACT: Based on Reissner’s mixed variational theorem (RMVT), a unified formulation of finite layer methods (FLMs) is developed for the quasi three-dimensional (3-D) thermal buckling analysis of simply-supported, sandwich piezoelectric plates embedded with a functionally graded elastic material (FGEM) core, the material properties of which are considered to be thickness- and temperature-dependent. The plate is subjected to a uniform temperature change and with open-/closed-circuit boundary conditions on the lateral surfaces. A 3-D linear buckling theory is used, in which a set of membrane stresses is assumed to exist just before buckling occurs, and these membrane stresses are determined using a set of predefined 3-D deformations.
for the pre-buckling state. The material properties of the FGEM core are assumed to obey the power-law distributions varying through the thickness coordinate of the core according to the volume fractions of the constituents. The effective material properties are estimated using the rule of mixtures and Mori-Tanaka’s model. The accuracies and convergence rates of the FLMs with various orders, as used for expanding the elastic and electric variables in the thickness direction, are assessed by comparing their solutions with the exact 3D and accurate two-dimensional ones available in the literature.


ABSTRACT: This article presents an analytical approach to investigate the buckling and postbuckling behavior of functionally graded nanocomposite plates reinforced by single-walled carbon nanotubes, resting on elastic foundations and subjected to thermal load due to uniform temperature rise or linear temperature change across the plate thickness. The material properties of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) are assumed to be temperature independent, graded in the thickness direction, and estimated by extended rule of mixture through a micromechanical model. Formulations are based on classical plate theory taking von Kármán nonlinearity, initial geometrical imperfection, Pasternak-type foundation interaction, and tangential-edge constraints into consideration. Approximate solutions of deflection and stress functions are assumed to satisfy simply supported boundary conditions, and the Galerkin method is applied to obtain closed-form expressions of buckling temperatures and temperature-deflection relations. The influences of carbon-nanotube volume fraction and distribution pattern, aspect ratios, stiffness of foundations, degree of tangential-edge constraints, and imperfection on the thermal buckling and postbuckling behavior of FG-CNTRC plates are analyzed and discussed.


ABSTRACT: Thermal buckling and vibration of functionally graded (FG) sinusoidal microbeams with temperature-dependent properties and three kinds of temperature distributions are investigated in this article. As one material length scale is introduced, the modified couple stress theory is capable of predicting the small-scale effects. Material properties of FG microbeams are calculated using the Mori–Tanaka method. Furthermore, temperature-dependent properties are taken into account to investigate the mechanical characteristics of FG microbeams in high–thermal-gradient environment. Motion equations and the associated boundary conditions are obtained simultaneously through variational principle. Then Navier procedure and the differential quadrature method incorporating an iterative procedure are used to solve the governing differential equations with temperature-dependent properties and general boundary conditions. Numerical examples are performed for demonstrating the influences of temperature distribution, beam thickness, material length scale, slenderness ratio, shear deformation, functionally graded index, boundary conditions, and temperature-dependent/independent properties on thermal buckling and free vibration behaviors of FG microbeams.


ABSTRACT: The nonlinear dynamics of an eccentrically stiffened functionally graded material (ES-FGM) plates resting on the elastic Pasternak foundations subjected to mechanical and thermal loads is considered in this article. The plates are reinforced by outside stiffeners with temperature-dependent material properties in
two cases: uniform temperature rise and through the thickness temperature gradient. Both stiffeners and plate are deformed under temperature. Using Reddy’s third-order shear deformation plate theory, stress function, Galerkin and fourth-order Runge–Kutta methods, the effects of material and geometrical properties, temperature-dependent material properties, elastic foundations, and stiffeners on the nonlinear dynamic response of the ES-FGM plate in thermal environments are studied and discussed. Some obtained results are validated by comparing with those in the literature.


ABSTRACT: Thermoelastic analysis of a functionally graded cylinder under nonsymmetric thermal and mechanical loadings and boundary conditions, a two-dimensional displacement field along the radial and circumferential directions is assumed for our analysis. The complex form of Fourier series is used as the method of solution. The nonsymmetric analysis of this problem for Lorentz force leads to radial and circumferential force components. The obtained results of this analysis indicate that the different parameters of material and loading have a considerable effect on the nonsymmetric behavior of cylinder.

References listed at the end of the paper:


ABSTRACT: This article deals with the thermal buckling and postbuckling of functionally graded material (FGM) beams with surface-bonded piezoelectric actuators based on physical neutral surface concept and high-order shear deformation theory including von Kármán strain–displacement relationships. The beams are exposed to a uniform temperature field and electric field, the material properties of FGM layers are temperature-dependent and vary in the thickness direction. The approximate solutions of piezoelectric FGM beams for thermal buckling and postbuckling are obtained by a two-step perturbation method, meanwhile, the analytical solutions of Timoshenko beam model and Euler beam model are also presented. The validity of the present work can be confirmed by comparisons with previous results. The effects of the applied actuator voltage, beam geometry as well as volume fraction index of FGM beam on the critical buckling temperature, and postbuckling load–deflection relationships are investigated.


ABSTRACT: In this article, the thermoelastic static analysis of multilayered shell structure is performed using some advanced theories, obtained by expanding the unknown displacement variables along the thickness direction using equivalent-single-layer (ESL) models, layer-wise (LW) models, and variable-kinematic models. The variable-kinematic models permit to reduce the computational cost of the analyses grouping some layers of the multilayered structure with ESL models and keeping the LW models in other zones of the multilayer. This model is here extended for the static analysis of uncoupled thermomechanical problems. The results obtained with the classical assumed linear temperature profile along the thickness of the shell are compared with those achieved with the calculated temperature profile solving the Fourier heat conduction equation. The used refined models are grouped in the Carrera’s unified formulation (CUF), and they accurately describe the displacement field and the stress distributions along the thickness of the multilayered shell. The shell element has nine nodes, and the mixed interpolation of tensorial components method is used to contrast the membrane and shear locking phenomenon. The governing equations are derived from the principle of virtual displacement, and the finite element method is used to solve them. Cross-ply plates and shells with simply supported edges, subjected to bisinusoidal thermal load are analyzed. Various aspect ratios and radius to thickness ratios are considered. The results, obtained with different theories within CUF context, are compared with the elasticity solutions given in the literature. From the results, it is possible to conclude that the shell element based on the CUF is very efficient in the study of thermomechanical problems of composite structures. The variable-kinematic models
combining the ESL with the LW models permit to have a reduction of the computational costs, with respect with the full LW models, preserving the accuracy of the results in localized layers.

References listed at the end of the paper:


ABSTRACT: In this article, the nonlinear vibration frequencies of functionally graded carbon nanotube-reinforced composite doubly curved shell panels under elevated thermal environment are numerically investigated using finite element method. The doubly curved carbon nanotube-reinforced shell panel has been modeled mathematically using higher-order kinematics theory and Green–Lagrange geometrical nonlinear
strains. The properties of the individual constituents of the graded composite are assumed to be temperature dependent. In addition, the properties of the media are obtained based on the modified rule of mixture. The carbon nanotubes are dispersed nonuniformly through the thickness direction. The large deformation kinematic effects on the structural responses are counted by including all the nonlinear higher-order terms in the formulation. The desired nonlinear responses are computed numerically using our in-house computer code in conjunction with the direct iterative scheme. The convergence and the accuracy of the present numerical model have been checked by solving various numerical examples. Nonlinear mechanical responses were affected by several other design parameters and explored numerically for the thickness ratios, volume fractions, temperature loading, type of geometries, and type of grading under the uniform thermal environment.

References listed at the end of the paper:


ABSTRACT: In this investigation, the asymmetrical buckling behavior of isotropic homogeneous annular plates resting on a partial Winkler-type elastic foundation under uniform temperature elevation is investigated. First-order shear deformation plate theory is used to obtain the governing equations and the associated boundary conditions. Prebuckling deformations and stresses of the plate are obtained under the solution of a plane stress formulation, neglecting the rotations and lateral deflection. Applying the adjacent equilibrium criterion, the linearized stability equations are obtained. The governing equations are divided into two sets. The first set, which is associated with the in-contact region, and the second set, which is related to contact-less region. The resulting equations are solved using a hybrid method, including the analytical trigonometric functions through the circumferential direction and generalized differential quadratures method through the radial direction. The resulting system of eigenvalue problem is solved to obtain the critical conditions of the plate and the associated circumferential mode number. Benchmark results are given in tabular and graphical presentations for combinations of simply supported and clamped types of boundary conditions. Numerical results are given to explore the effects of elastic foundation, foundation radius, plate thickness, plate hole size, and the boundary conditions.

ABSTRACT: Numerical investigation of nonlinear free vibration of functionally graded skew (FGS) plate in the thermal environment is presented. The mathematical model is proposed for the first time based on higher order shear deformation theory in conjunction with Green–Lagrange-type geometric nonlinearity for the FGS plate subjected to a thermal load. The material properties are considered to be temperature dependent and are graded along the thickness direction as per simple power law of distribution in terms of volume fraction of the constituent phase. The governing algebraic equations are derived using Hamilton’s principle, and the solutions are obtained using the direct iterative method. The proposed finite element model has discretized into an eight-noded quadratic serendipity elements. To validate the model, the obtained results are compared with the available literature. The influence of volume fraction index, skew angle, temperature change, aspect ratio, side–thickness ratio, and boundary conditions on the linear and nonlinear frequency of skew functionally graded material plate is examined and discussed in detail.


ABSTRACT: In this article, transient analysis of functionally graded material (FGM) cylindrical shell subjected to thermomechanical load is performed. Mechanical and thermal properties of the shell are assumed to be graded in radial direction according to power law distribution. In the case of simply supported edge condition, problem is solved analytically using Fourier series expansions for stresses and displacements along the axial direction and state space technique along the radial direction and Laplace transformation technique for time domain. For other boundary conditions, we use a semianalytical method by applying differential quadrature method along the axial direction and the state space method along radial direction. Accuracy of this approach is validated by comparing the results with the results reported in the literature. Moreover, influence of edge boundary conditions, length to mid radius ratio, FGM direction and time on stresses, and displacements is studied.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: The geometrically nonlinear thermomechanical transverse deflection responses of the functionally graded curved structure under the influence of nonlinear thermal field are reported in this article. For the numerical analysis, a nonlinear mathematical model is derived using the higher-order shear deformation theory and Green–Lagrange nonlinear strains. The current model includes all of the nonlinear higher-order terms to achieve the true flexure of the structure under the combined action of loads. It is assumed that the panel structure is exposed to nonuniform temperature field combined with the transversely distributed mechanical load. Additionally, the properties of material constituents are assumed to vary with the nonuniform temperature load and corresponding properties are evaluated considering dependency and independence of temperature. Furthermore, the panel material grading has been obtained mathematically with the help of Voigt’s micromechanical rule together with the power-law distribution. The system of equations is obtained using the variational principle and solved numerically using the finite element steps in association with the direct iterative method. The stability of the present numerical model has been established through the convergence test and compared with the benchmark results to show the validity. Finally, numerical experimentations have been carried out for different parameters and discussed in detail.

References listed at the end of the paper:


ABSTRACT: This article presents a study on the thermal buckling behavior of two-dimensional functionally graded microbeams made of porous materials. The material composition varies along thickness and length of the microbeam based on the power law distribution. The microbeam is modeled within the framework of Euler–Bernoulli beam theory. The microbeam is considered having variable material composition along thickness. The equations are derived using the modified couple stress theory and the solving process is based on the generalized differential quadrature method. The validity of the results is shown through comparison of the results with the results of other published research.


ABSTRACT: Based on Reddy’s third-order shear deformation plate theory, the nonlinear dynamic response and vibration of imperfect functionally graded carbon nanotube-reinforced composite (FG-CNTRC) plates on elastic foundations subjected to dynamic loads and temperature are presented. The plates are reinforced by single-walled carbon nanotubes which vary according to the linear functions of the plate thickness. The plate’s effective material properties are assumed to depend on temperature and estimated through the rule of mixture. By applying the Airy stress function, Galerkin method and fourth-order Runge–Kutta method, nonlinear dynamic response and natural frequency for imperfect FG-CNTRC plates are determined. In numerical results, the influences of geometrical parameters, elastic foundations, initial imperfection, dynamic loads, temperature increment, and nanotube volume fraction on the nonlinear vibration of FG-CNTRC plates are investigated. The obtained results are validated by comparing with those of other authors.

References listed at the end of the paper:


ABSTRACT: A geometric nonlinear finite element formulation for piezothermoelastic composite laminates using first-order shear deformation theory (FSDT) is presented to solve mechanically and self-strain loaded smart composite plate buckling problems. Green–Lagrange strain–displacement equations consistent with von Kármán geometric nonlinearity are used. Mixed finite elements using hierarchic Lagrangian interpolation functions are used for the membrane/bending displacements and electric potential variations; transverse shear stress resultants at the Gauss quadrature points use standard Lagrangian functions. Eigenvalue analysis is used to determine the laminate buckling load magnitudes and corresponding mode shapes. A primary purpose of this investigation on the buckling behavior of smart composite plates is to demonstrate the impact of the direct piezoelectric effect. Thermal buckling study includes rectangular and circular plate geometries.


ABSTRACT: This article addresses a clarification study on the thermally nonlinear Fourier/ non-Fourier dynamic coupled (generalized) thermoelasticity. Based on the Maxwell-Cattaneo’s heat conduction law and the infinitesimal theory of thermoelasticity, governing equations for the thermally nonlinear small deformation type of generalized thermoelasticity are derived. The Bubnov–Galerkin scheme is implemented for spatial discretization. The spatially discretized equations are directly discretized in time domain using the fully damped Newmark method. The Newton–Raphson procedure is used to linearize the finite element equations. The layers are exposed to a thermal shock, so that the displacement, temperature, and stress waves propagate in layers. The effects of the time evolution, thermoelastic coupling, and thermal relaxation time on the response of the layers are investigated. Results reveal the significance of the thermally nonlinear analysis of generalized thermoelasticity for the conditions where large temperature elevations exist.


ABSTRACT: In this article, the free vibration behavior of a functionally graded (FG) size-dependent microshell surrounded by viscoelastic foundation subjected to various thermal loading conditions is analytically studied. The material properties of the cylindrical FG microshell are supposed to be temperature dependent and vary continuously along the thickness direction according to the modified rule of mixtures. The size-dependent FG microshell is analyzed based on the modified couple stress theory. The analytical modeling is developed using the first-order shear deformation theory and the equations of motion are derived by the principle of minimum total potential energy. Then the governing equations for the free vibration behavior of a simply supported FG cylindrical microshell subjected to thermal loading are solved using the Navier procedure. The effects of some important parameters, such as material length scale parameter, stiffness and damping of the visco-Pasternak foundation, temperature changes, axial and circumferential wave number, and length of the microshell on the natural frequency are investigated and discussed.

References listed at the end of the paper:


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ABSTRACT: Critical buckling temperatures of skew plates made from a polymeric matrix reinforced by single-walled carbon nanotubes (CNTs) are obtained in the present research. Reinforcements are distributed across the thickness of the plate uniformly or according to a prescribed nonuniform function. All of the thermomechanical properties are assumed to be temperature dependent. First-order shear deformation plate theory is used as the basic assumption to obtain the total strain and potential energies of the plate due to the thermally induced prebuckling loads. A transformation is proposed to express the components of the displacement field in an oblique coordinate system. A Ritz-based solution is implemented to obtain the matrix representation of the stability equations associated to the onset of buckling. Gram–Schmidt process is used to obtain a set of orthogonal shape functions as the basis polynomials of the Ritz method. The obtained eigenvalue problem is solved successively to extract the critical buckling temperature of the skew plate. Convergence and comparison studies are provided to assure the accuracy and correctness of the proposed formulation. Afterward, parametric studies are given to explore the influences of boundary conditions, CNT volume fraction, CNT dispersion profile, aspect ratio, skew angle, and side to thickness ratio.

ABSTRACT: Advanced plate models with variable kinematics for steady state hygrothermal analysis of composite laminates are proposed. The refined models discussed include both layer-wise (LW) and equivalent single layer (ESL) models, and the Carrera Unified Formulation (CUF) is used. The mixed interpolation of tensorial component (MITC) method is applied to a nine-node element to contrast the shear locking phenomena. The governing equations are derived from the principle of virtual displacement (PVD) taking into account elastic mechanical, thermal and hygroscopic effects. Through-the-thickness variations of temperature and moisture concentration are calculated by solving the Fourier equation and the Fick law, respectively. Cross-ply plates with symmetrical lamination and simply supported edges subjected to bisinusoidal thermal/hygrosopic loads are analyzed considering various thickness ratios. Results obtained with assumed linear and calculated temperature/hygrosopic profiles are compared. Variable kinematics with a variety of thickness functions are compared regarding both accuracy and computational costs. The results show that all the kinematics proposed can approximate the transverse shear stress distribution through the thickness with satisfactory accuracy when sufficient expansion terms are adopted. In some cases, miscellaneous expansions can lead to significant reductions in computational costs. The results presented here can be used as benchmark solutions for future works.


ABSTRACT: This article presents advanced shell models for the steady-state hygrothermal analysis of composite laminates. The Carrera Unified Formulation is used to derive refined models that include both layer-wise and equivalent single layer models. The governing equations are derived from the principle of virtual displacement taking into account thermal and hygroscopic effects. The geometrical relations for the exact cylindrical geometry are here considered. Through-the-thickness variations of temperature and moisture concentration are calculated by solving the Fourier equation and the Fick law, respectively. The mixed interpolation of tensorial component method is applied to a nine-node shell element to contrast the membrane and shear locking phenomena. Simply supported cross-ply cylindrical shells with antisymmetrical lamination subjected to bisinusoidal thermal/hygrosopic loads are analyzed considering various thickness/curvature ratios. Results obtained with assumed linear and calculated temperature/hygrosopic profiles are presented. Variable kinematics are compared regarding both accuracy and computational costs. The results show that all the kinematics can approximate the transverse shear stress distribution through the thickness with satisfactory accuracy when sufficient expansion terms are adopted. In some cases, miscellaneous expansions can lead to significant reductions in computational costs. The results presented here can be used as benchmark solutions for future works.

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· F. Jacquemin and A. Vautrin, A Closed-form Solution for the Internal Stresses in Thick Composite Cylinders Induced by Cyclic Environmental Conditions, Compos. Struct., vol. 58, no. 1, pp. 1–9, 2002.

ABSTRACT: Thermal buckling of annular sector plates with circular cutouts made of functionally graded material is analyzed in this article. Graded material is considered with two parts of ceramic structure made of zirconia and metal structure which is aluminum. Unlike most conducted research, the direction of property change is observed in three main directions. Thermal loading is assumed as a uniform increase in temperature influencing the whole sector. 3D-finite element method based on elasticity theory is used in this analysis, which resets first and second variations of potential energy of the sector to zero to find equilibrium and stability equations, respectively. Green’s nonlinear strain–displacement relations are used to obtain geometrical stiffness matrix. In the finite element method, unlike most studies, a 3D eight-noded element is used, which has nodes in the direction of thickness. The circular cutouts of the sector have added to the complexity of the analysis. The finite element formulation is coded in MATLAB. Finally, the effect of different parameters such as dimension and number of cutouts, power law index, and orientation of graded material on the critical thermal buckling temperature is studied.


ABSTRACT: In this article, size-dependent thermal buckling and postbuckling behavior of a functionally graded circular microplate under uniform temperature rise field and clamped boundary conditions is investigated. Material properties are assumed to gradually vary through the thickness according to a simple power law. Equilibrium equations and associated boundary conditions are derived using variational method and based on modified couple stress theory, classical plate theory and von Kármán geometric nonlinearity. The differential quadrature method is used to discretize the governing equations. This technique is accompanied by an iterative method to determine the thermal postbuckling behavior of microplate. Finally, effects of length scale parameter, power law index and ratio of thickness to radius on the thermal buckling and postbuckling behavior of FG circular microplate are investigated.


ABSTRACT: In this study, a locking-free six-node triangular shell element is proposed to nonlinear analysis of shell structures under the effects of both thermal and mechanical loads. Total Lagrangian formulation is used to consider large deflections and rotations. Besides, mixed interpolation of tensorial components is applied in the relations to deviate shear and membrane locking. The effects of temperature on the nonlinear deflections of shells are studied in several numerical examples. Moreover, analytical solution will be proposed for large deflection analysis of cantilever and simply supported beam under the thermal loads. To validate the proposed formulation, the finite element analysis results are compared by analytical solutions. Based on the obtained results of linear and nonlinear problems, it will be depicted that the authors’ scheme is capable for thermomechanical analysis of shell structures accurately.

References listed at the end of the paper:


ABSTRACT: Analytical solutions for laminated and functionally graded sandwich open cylindrical shells under mechanical and thermal loads are presented using a refined higher order shear and normal deformation theory. Temperature variation through thickness is assumed as thickness coordinate polynomial. Present study also extends the classical thickness criteria with more reliable extension to moderately thick shells. Navier solution method is used to solve system of equations derived using principle of minimum potential energy for all edges diaphragm supported. Two kinds of sandwich panels with core or face sheet made of thickness graded material are studied. Several examples are numerically evaluated to establish the accuracy of present models.

References listed at the end of the paper:


ABSTRACT: Thermal buckling of functionally graded sandwich plates are presented in this article. Two common types of FGM sandwich plates, namely, homogeneous face layers with FGM core and FGM face layers with homogeneous core are considered. Material properties and thermal expansion coefficient of FGM layers are assumed to vary continuously through-the-thickness according to a simple power-law distribution in terms of the volume fractions of the constituents. Equilibrium and stability equations of FGM sandwich plate with simply supported boundary conditions are derived using the higher-order shear deformation plate theory. The influence of the plate aspect ratio, the relative thickness, the gradient index, and the thermal loading conditions on the critical buckling temperature of FGM sandwich plates are investigated. The thermal loads are assumed to be uniform, linear, and nonlinear distribution through-the-thickness. A new simple solution for thermal buckling of FGM sandwich plates under nonlinear temperature rise is presented.


ABSTRACT: A complex finite strip method was used to study the buckling of functionally graded plates (FGPs) under thermal and mechanical (longitudinal, transverse, and shear in-plane) loading. The mechanical characteristics of FGP were assumed to vary through the thickness, according to power law distribution. The nonlinear temperature distribution in the direction of the plate thickness was assumed according to thermal conduction steady state conditions. In complex finite strip method, the polynomial Hermitian functions were assumed in the transverse direction and the complex exponential functions were used in the longitudinal
direction to evaluate the standard and geometric stiffness matrices that have the ability of calculating the critical shear stress in contrast to trigonometric shape functions. The solution was obtained by the minimization of the total potential energy and solving the corresponding eigenvalue problem. In addition, numerical results for FGPs with different boundary conditions were presented and compared with those available in the literature and the interaction curves of mechanical and thermal buckling capacity of FGPs were obtained.

References listed at the end of the paper:
ABSTRACT: This work presents an analytical approach to investigate the mechanical and thermal buckling of functionally graded sandwich truncated conical shells resting on Pasternak elastic foundations using the first-order shear deformation theory, Lekhnitskii smeared stiffener technique and the adjacent equilibrium criterion, the linearization stability equations have been established. Approximate solution satisfies simply supported boundary conditions and Galerkin method is applied to obtain closed-form expression for determining the critical compression buckling load and thermal buckling load in cases uniform temperature rise and linear temperature distribution across the shell thickness. The effects of temperature, foundation, core layer, coating layer, stiffeners, material properties, dimensional parameters and semi-vertex angle on buckling behaviors of shell are shown.

References listed at the end of the paper:


ABSTRACT: Mechanical behavior of a viscoelastic cylindrical panel with various edge boundary conditions, made up of functionally graded material (FGM) and subjected to thermal or mechanical load is investigated. For cases of simply supported boundary conditions, analytical solution is presented through Fourier series expansion along the axial and circumferential coordinates as well as state space method along the radial coordinate. For nonsimply supported conditions, semi-analytical solution is performed using differential quadrature method instead of Fourier series solution. Governing differential equations are transformed to Laplace transform domain and using inverse Laplace transform, obtained solutions are converted to time domain. In the present work, relaxation modulus of FGM is supposed to be according to the Prony series with power law variations along the radial direction. Numerical comparison was made with the available published results to assess the validity of present technique. Effect of relaxation time constant, thickness to mid-radius ratio, edges boundary condition and outer surface temperature on stress and displacement fields are discussed. Besides, time history of stresses for different relaxation time constant and for various boundary conditions is presented.


ABSTRACT: Buckling, postbuckling, and nonlinear responses of composite cylindrical panels reinforced by single-walled carbon nanotubes (CNTs), supported by an elastic foundation, exposed to elevated temperature and axially compressed by uniform load are investigated in this article. Distribution of CNTs is uniform or graded in the thickness direction and the effective properties of CNT-reinforced composite are assumed to be temperature dependent, and are estimated by extended rule of mixture through a micromechanical model. Governing equations are established based on thin shell theory taking von Kármán–Donnell nonlinearity, initial geometrical imperfection, Pasternak-type elastic foundation and tangential elastic constraints of boundary edges into consideration. Approximate solutions of deflection and stress functions are assumed to satisfy simply supported boundary conditions, and Galerkin method is applied to derive explicit expressions of load–deflection relation from which critical buckling loads can be obtained. Unlike works in the literature, the present study accounts for elasticity of tangential restraint of two unloaded straight edges in model of cylindrical panel. The study also gives conditions for which bifurcation type buckling response can occur and novel findings in numerical examples.

References listed at the end of the paper:


ABSTRACT: A finite element formulation for stress analysis of functionally graded material (FGM) sandwich plates and shell panels under thermal shock is presented in this work. A higher-order layerwise theory in conjunction with Sanders’ approximation for shells is used to develop the finite element formulation for transient stress analysis of FGM sandwich panels. The top and the bottom surfaces of FGM sandwich panels are made of pure ceramic and metal, respectively, and core of the sandwich is assumed to be made of FGM. The temperature profile in the thickness direction of the panels is considered to be varying as per the Fourier’s law of heat conduction equation for unsteady state. The heat conduction equations are solved using the central difference method in conjunction with the Crank–Nicolson approach. Transient thermal displacements of the sandwich panels are obtained using Newmark average acceleration method and the transient thermal stresses are obtained using stress–strain relations, subsequently. Results obtained from the present layerwise finite element formulations are first validated with available solutions in literature. Parametric studies are taken up to study the effects of volume fraction index, temperature dependency of material properties, core thickness, panel.
configuration, geometric and thermal boundary conditions on transient thermal stresses of FGM sandwich plates and shells.

References listed at the end of the paper:

ABSTRACT: The nonlinear thermal buckling analysis of functionally graded (FG) beam integrated with shape memory alloy (SMA) layer(s), with different lay-up configurations and supported on a nonlinear elastic foundation, has been investigated. The FG layer is graded through the beam thickness direction and thermomechanical properties are assumed to be temperature dependent. The Brinson one-dimensional constitutive law are used to model the characteristics of SMA. The von Kármán strain–displacement fields with the Timoshenko beam theory are applied to the Hamilton’s principle to derive the set of nonlinear equilibrium equations. Generalized differential quadrature method along with direct iterative scheme is utilized to discretize and solve the nonlinear equilibrium equations. The accuracy of proposed model is compared and validated with previous research in literature. The detailed parametric study has been performed to investigate the influence of geometrical, material, and some other key parameters on the nonlinear thermal buckling solutions. The results show that selecting the proper lay-up is of great importance because the type of SMA/FG lay-up can considerably affect the nonlinear buckling solutions. Moreover, adequate application of SMA layers in a proper lay-up configuration significantly postpones the thermal buckling temperature of the beam.

ABSTRACT: Present research deals with the geometrically nonlinear bending of a long cylindrical panel made of a through-the-thickness functionally graded material subjected to thermal load. A panel under the action of uniform temperature rise loading is considered. Formulation of the shell is based on the third-order shear deformation shell theory, where the first-order shear deformation and classical shell theory may be extracted as special cases. Thermomechanical properties of the shell are assumed to be temperature dependent and are estimated according to a power law function across the shell thickness. Also, it is assumed that shell is in contact with an elastic foundation which acts in tension as well as in compression. The nonlinear governing equations of the shell are obtained using the von Kármán type of geometrical nonlinearity. The obtained governing equations are solved for two cases, i.e., simply supported shells and clamped shells. The developed equations are solved using a two-step perturbation technique. Accurate closed-form expressions are provided to obtain the mid-span deflection of the shell as a function of temperature elevation. Numerical results are provided to analyze the effects of power law exponent, boundary conditions, temperature dependency, side to radius ratio, and side to thickness ratio.

References listed at the end of the paper:


ABSTRACT: Present research investigates the thermal postbuckling of sandwich plates containing a stiff core and two thin carbon nanotube reinforced composite (CNTRC) face sheets. Properties of the core, carbon nanotubes (CNTs) and polymeric matrix of the faces are assumed to be temperature-dependent. It is assumed that CNTs as reinforcements may be distributed according to a functionally graded pattern. Plate is formulated based on the first-order shear deformation theory and von Kármán type of geometrical nonlinearity. The
governing equations are obtained by the energy method with the aid of the Conventional Ritz method. Shape functions of the Ritz method are estimated according to the Chebyshev polynomials. A set of nonlinear eigenvalue equations is achieved. The obtained equations are homogeneous, coupled, and nonlinear in terms of both displacements and temperature. A successive displacement control strategy is implemented to trace the thermal postbuckling equilibrium path of the plate. It is shown that, with increasing the volume fraction of CNT, critical buckling temperature of sandwich plate increases and postbuckling deflection decreases. Furthermore, through a functionally graded distribution of volume fraction of CNTs across the thickness, critical buckling temperature of the sandwich plate may be enhanced and thermal postbuckling deflection may be alleviated.

References listed at the end of the paper:

ABSTRACT: This article presents an analytical solution for the mechanical and thermal buckling of exponentially graded material (EGM) sandwich plates. The solution is obtained using a four-variable refined plate theory. Two types of sandwich plates are investigated: one with EGM face sheets and homogeneous core; the other with EGM core and homogeneous face sheets. The governing equations are derived based on the principle of virtual work and then solved through Navier method. The results on critical buckling load and temperature change of simply supported EGM sandwich plates are obtained. The influences of several parameters on buckling behaviors are discussed.

References listed at the end of the paper:


ABSTRACT: This article presents an analytical solution for the mechanical and thermal buckling of exponentially graded material (EGM) sandwich plates. The solution is obtained using a four-variable refined plate theory. Two types of sandwich plates are investigated: one with EGM face sheets and homogeneous core; the other with EGM core and homogeneous face sheets. The governing equations are derived based on the principle of virtual work and then solved through Navier method. The results on critical buckling load and temperature change of simply supported EGM sandwich plates are obtained. The influences of several parameters on buckling behaviors are discussed.

References listed at the end of the paper:


ABSTRACT: In this work, the problem of thermal buckling of composite plates reinforced with carbon nanotubes (CNTs) is investigated. Distribution of CNTs as reinforcements through the thickness direction of the plate is assumed to be either uniform or functionally graded (FG). Properties of the reinforcement and matrix are both temperature dependent. Properties of the composite media are obtained according to a refined rule of mixture approach where the efficiency parameters are introduced. The plate is in a super elliptical shape where the simple elliptical shape and rectangular shapes are obtained as especial cases. In these types of plates due to the round corners, stress concentration phenomenon is eliminated. Based on the Ritz method where the shape functions are of the polynomial type, the governing equations are obtained. These equations are solved using an iterative eigenvalue problem since the properties are temperature dependent. Numerical results are validated for the simple case of an isotropic plate. Novel numerical results are provided for plates reinforced with CNTs in different shapes, various volume fractions and different patterns of CNT distribution. It is shown that FG-X pattern of CNTs in matrix results in the maximum critical buckling temperature.

ABSTRACT: This article deals with the study of the thermodynamic behavior of functionally graded material plates resting on two-parameter elastic foundation. An analytical solution based on a new shear refined deformation theory is presented. The displacement field used in the present refined theory contains undetermined integral forms and involves only four unknowns to derive. The plate is assumed simply supported and subjected to two different temperatures fields across its thickness. The mechanical characteristics of the plate are assumed to be varied across the thickness according to a simple exponential law distribution. The governing equations and boundary conditions are derived using the principle of virtual displacements and Navier solution technique is adopted to derive analytical solutions. A detailed numerical study of the present new refined theory is carried out to examine the influence of the time’s parameter, foundation’s parameters and deflection on the bending response of the FG plate.

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ABSTRACT: In this paper, the large deflection of multi-layer orthotropic annular/circular graphene sheets is investigated based on the non-local elasticity theory. The plate is considered to be in thermal environment. The equilibrium equations are derived in terms of generalized displacements and rotations considering the FSDT non-local elasticity theory and the van der Waals interaction between the layers. In order to solve the governing equations, the differential quadrature method (DQM) which is an accurate numerical method and a new semi-analytical polynomial method (SAPM) are applied. By applying DQM or SAPM, the ODE's would be converted to non-linear algebraic equations. In continue, the Newton–Raphson iterative scheme is applied to solve the obtained non-linear algebraic equations. The results of DQM and SAPM are compared. Although, the SAPM's formulation is considerably simpler than DQM, however, the results of two methods are so close to each other. The results are validated with the other available researches. The effect of small scale parameter, temperature effects on non-local results, the value of van der Waals interaction between the layers for bi-layer and triple layers graphene sheet, different values of elastic foundation matrix and load for various small scale parameters, the comparison between local and non-local deflections and linear to non-linear analysis are investigated.

ABSTRACT: A numerical scheme for buckling analysis of functionally graded circular plate (FGCP) subjected to uniform radial compression including shear deformation rested on Pasternak elastic foundation is presented. The linear and quadratic thickness variation patterns with various boundary conditions are considered. A
modified Euler–Lagrange equation is achieved and then solved by converting differential equation to a nonlinear algebraic system of equations. Also, based on traction–free surface without using shear correction factor, a new approach by considering shear deformation for buckling analysis of FGCP rested on elastic foundation is carried out. The stability equation based on shear stress-free surface is solved by the spectral Ritz method. The spectral Ritz method has good flexibility in the sense of satisfying the boundary conditions. The effects of both linear and quadratic thickness variations and Poisson’s ratio are investigated. By taking small numbers of the basis, the outcomes in literature are improved.


ABSTRACT: This paper aims to present a unified vibration analysis approach for the four-parameter functionally graded moderately thick doubly-curved shells and panels of revolution with general boundary conditions. The first-order shear deformation theory is used in this formulation. The functionally graded panels structures consists of ceramic and metal which are set to vary continuously in the thickness direction according to the general four-parameter power-law distribution, and six types of power-law distributions are considered for the ceramic volume fraction. The admissible function of the FG panels and shells of revolution is obtained by the improved Fourier series with the help of the governing equations and the boundary conditions. The solution is obtained by using the variational operation in terms of the unknown expanded coefficients. By a great many numerical examples, the rapid convergence and good reliability and accuracy of the proposed approach are validated. A variety of new results for vibration problems of the FG doubly-curved shells and panels with different elastic restraints, geometric and material parameters are presented. The effects of the elastic restraint parameters, power-law exponent, circumference angle and power-law distributions on the free vibration characteristic of the panels are also presented, which can be served as benchmark data in the research and the actual production process.


ABSTRACT: This paper investigates the imperfection sensitivity of thermal post-buckling behaviour of functionally graded carbon nanotube-reinforced composite (FG-CNTRC) beams subjected to in-plane temperature variation. The material properties of FG-CNTRCs are assumed to be graded in the thickness direction and temperature-dependent. A generic imperfection function is used to model various possible imperfections, including sine type, global and localized imperfections. The governing equations are derived based on the first-order shear deformation beam theory and von-Kármán geometric nonlinearity. The differential quadrature method in conjunction with modified Newton–Raphson technique is employed to determine the thermal post-buckling equilibrium path of imperfect FG-CNTRC beams. Thermal buckling is treated as a subset problem. A parametric study is conducted to examine the effects of imperfection mode, half-wave number, location and amplitude on their thermal post-buckling performance. The influences of distribution pattern and volume fraction of carbon nanotubes, boundary conditions and slenderness ratio are discussed as well. The results indicate that the thermal post-buckling is highly sensitive to the imperfection mode, half-wave number, location as well as its amplitude. It is also shown that the clamped-clamped FG-CNTRC beam is more sensitive to imperfections than those with other boundary conditions whereas other parameters do not substantially affect the imperfection sensitivity of thermal post-buckling behaviour.

ABSTRACT: In this paper, the linear and nonlinear vibrations of fractional viscoelastic Timoshenko nanobeams are studied based on the Gurtin–Murdoch surface stress theory. Firstly, the constitutive equations of fractional viscoelasticity theory are considered, and based on the Gurtin–Murdoch model, stress components on the surface of the nanobeam are incorporated into the axial stress tensor. Afterward, using Hamilton's principle, equations governing the two-dimensional vibrations of fractional viscoelastic nanobeams are derived. Finally, two solution procedures are utilized to describe the time responses of nanobeams. In the first method, which is fully numerical, the generalized differential quadrature and finite difference methods are used to discretize the linear part of the governing equations in spatial and time domains. In the second method, which is semi-analytical, the Galerkin approach is first used to discretize nonlinear partial differential governing equations in the spatial domain, and the obtained set of fractional-order ordinary differential equations are then solved by the predictor–corrector method. The accuracy of the results for the linear and nonlinear vibrations of fractional viscoelastic nanobeams with different boundary conditions is shown. Also, by comparing obtained results for different values of some parameters such as viscoelasticity coefficient, order of fractional derivative and parameters of surface stress model, their effects on the frequency and damping of vibrations of the fractional viscoelastic nanobeams are investigated.


ABSTRACT: In this paper, a recently new semi-analytical method, i.e., He’s variational iteration method is developed to apply to free vibration analysis of conveying fluid pipe. The critical flow velocity and frequency of pipe conveying fluid are obtained with considering the various boundary conditions. The results are compared with the ones of different transform method, and prove VIM that has the same precision and efficient with DTM. The mode shapes of cantilevered pipe and both ends with elastic support pipe are shown under different flow velocity.


ABSTRACT: This paper presents a nonlinear electro-dynamic analysis for a size dependent micro-beam made of materials with nonlinear elasticity by employing the modified couple stress theory based on Euler–Bernoulli beam model. By employing Hamilton's principle, the nonlinear partial differential governing equation is derived then solved by using Galerkin method in the space domain and backward differential method in the time domain to obtain the nonlinear electro-dynamic response and phase portrait of the micro-beam. A parametric study is conducted, with a particular focus on the influences of nonlinear elasticity and size-dependency of the micro-beam on its nonlinear dynamic behavior. Numerical results show that a micro-beam exhibiting nonlinear elastic stress–strain relationship has reduced effective stiffness while the size effect has the opposite effect.


ABSTRACT: Sandwich structures are widely used in many engineering fields. It is possible but not easy for an engineering theory to recover all stresses accurately. In this paper, a modeling strategy is proposed to simplify
the formulation. A classical sandwich panel is firstly divided into three parts, equations of the top and bottom face sheets are used as the boundary conditions of the two-dimensional core and then only the core needs to be analyzed by the differential quadrature method (DQM). In this way, both displacement and stress can be accurately obtained. Detailed formulations are worked out. Three boundary conditions and three types of loading, including the concentrated load regarded as a challenging problem for point discrete methods such as the DQM, are considered to investigate the effect of boundary conditions and loading on the distributions of displacement and stress. For verification, results are compared with theoretical solutions or/and numerical data. Presented data may be a reference for other investigators to develop more accurate engineering beam theory or new numerical method.


ABSTRACT: The second order statistics in terms of mean and standard deviation (SD) of normalized nonlinear transverse dynamic central deflection (NTDCD) response of un-damped elastically supported functionally graded materials (FGMs) beam with surface-bonded piezoelectric layers under the action of moving load are investigated in this paper. The random system properties such as Young's modulus, Poisson's ratio, density, thermal expansion coefficients, piezoelectric materials, volume fraction exponent and external loading are modeled as uncorrelated random variables. The basic formulation is based on higher order shear deformation theory (HSDT) with von-Karman nonlinear strain kinematics combined with Newton–Raphson technique through Newmark's time integrating scheme using finite element method (FEM). The non-uniform temperature distribution with temperature dependent material properties is taken into consideration for consideration of thermal loading. The one parameter Pasternak elastic foundation with Winkler cubic nonlinearity is considered as an elastic foundation. The stochastic based second order perturbation technique (SOPT) and direct Monte Carlo simulation (MCS) are adopted for the solution of nonlinear dynamic governing equation. The influences of volume fraction exponents, temperature increments, moving loads and velocity, nonlinearity, slenderness ratios, foundation parameters and external loadings with random system properties on the NTDCD are examined. The capability of present stochastic model in predicting the NTDCD statistics are compared by studying their convergence with the existing results those available in the literature.


ABSTRACT: This paper presents development of the spectral element method (SEM) for the vibration analysis of thin shallow shells with rectangular planform subjected to impact loads. Dynamic formulation was developed for a thin shallow shell with two opposite edges simply supported and the other two edges with arbitrary boundary conditions. The SEM for such a shell was formulated in the frequency domain. Comparison studies were performed to assess the performance of the presented method. The effect of boundary conditions of the shallow shells is discussed in this paper. Shallow shell displacement subjected to impact load was calculated using the presented SEM.

ABSTRACT: Buckling behaviors of elastoplastic ceramic/metallic functionally graded material (FGM) rings are investigated by using the first order shear deformation theory. The hydrostatic-pressured rings are assumed to be in both the plane-stress case and the plane-strain case, which lead respectively to a uniaxial and a biaxial elastoplastic stress states in prebuckling stage. A uniform strain hypothesis helps to deal with the elastoplastic stress states. By introducing in the graded material properties, the constitutive model of FGMs is formulated under the framework of $J_2$ deformation theory. By considering the kinetic relations of von-Kármán type and employing the principle of virtual displacement, the equilibrium equations and the buckling governing equations of FGM circular rings are formulated, and the analytical solution of the anisotropic rings is obtained. Finally, the elastoplastic buckling problem is numerically solved through a semi-analytical method, which is proposed to seek the real circumferential strain of FGM rings at the buckling point and determinate the elastoplastic buckling critical hydrostatic pressure. The effects of the inhomogeneous and geometrical parameters on the buckling critical load and the position of the elastoplastic interface are discussed. Results show that, in both the plane-stress and the plane-strain cases, the elastoplastic critical loads are generally lower than their elastic counterparts due to material flow, and the plane-strain critical load is generally larger than the plane-stress one. The elastoplastic critical load does not always decrease monotonously with the increase of the inhomogeneous parameters, which is quite different from their elastic counterparts.


ABSTRACT: Transverse dynamical behaviors of axially moving nanoplates which could be used to model the graphene nanosheets or other plate-like nanostructures with axial motion are examined based on the nonlocal elasticity theory. The Hamilton's principle is employed to derive the multivariable coupling partial differential equations governing the transverse motion of the axially moving nanoplates. Subsequently, the equations are transformed into a set of ordinary differential equations by the method of separation of variables. The effects of dimensionless small-scale parameter, axial speed and boundary conditions on the natural frequencies in sub-critical region are discussed by the method of complex mode. Then the Galerkin method is employed to analyze the effects of small-scale parameter on divergent instability and coupled-mode flutter in super-critical region. It is shown that the existence of small-scale parameter contributes to strengthen the stability in the super-critical region, but the stability of the sub-critical region is weakened. The regions of divergent instability and coupled-mode flutter decrease even disappear with an increase in the small-scale parameter. The natural frequencies in sub-critical region show different tendencies with different boundary effects, while the natural frequencies in super-critical region keep constants with the increase of axial speed.


ABSTRACT: The isogeometric analysis (IGA) is a new approach which builds a seamless connection between Computer Aided Design (CAD) and Computer Aided Engineering (CAE). This approach which uses the B-Splines or the Non-Uniform Rational B-Splines (NURBS) as a geometric representation of the object is a discretization technology for numerical analysis. The IGA has advantages of capturing exact geometry and making the flexibility of refinement, which results in higher calculation accuracy. To study the static and dynamic characteristics of curvilinearly stiffened plates, the NURBS based isogeometric analysis approach is developed in this paper. We use this approach to analyze the static deformation, the free vibration and the vibration behavior in the presence of in-plane loads of curvilinearly stiffened plates. Furthermore, the large deformation and the large amplitude vibration of the curvilinearly stiffened plates are also studied based on the
von Karman’s large deformation theory. One of the superiorities of the present method in the analysis of the stiffened plates is that the element number is much less than commercial finite element software, whereas another advantage is that the mesh refinement process is much more convenient compared with traditional finite element method (FEM). Some numerical examples are shown to validate the correctness and superiority of the present method by comparing with the results from commercial software and finite element analysis.


ABSTRACT: This paper proposes a novel multi-scale approach for the reliability analysis of composite structures that accounts for both microscopic and macroscopic uncertainties, such as constituent material properties and ply angle. The stochastic structural responses, which establish the relationship between structural responses and random variables, are achieved using a stochastic multi-scale finite element method, which integrates computational homogenisation with the stochastic finite element method. This is further combined with the first- and second-order reliability methods to create a unique reliability analysis framework. To assess this approach, the deterministic computational homogenisation method is combined with the Monte Carlo method as an alternative reliability method. Numerical examples are used to demonstrate the capability of the proposed method in measuring the safety of composite structures. The paper shows that it provides estimates very close to those from Monte Carlo method, but is significantly more efficient in terms of computational time. It is advocated that this new method can be a fundamental element in the development of stochastic multi-scale design methods for composite structures.

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ABSTRACT: Micro coriolis flowmeters are extensively used in fluidic micro circuits and are of great interest to many researchers. Straight and curved coriolis flowmeters are common types of coriolis flowmeters. Therefore in the present work, the out-of-plane vibration and stability of curved micro tubes are investigated to study the dynamic behavior of curved coriolis flowmeters. The Hamilton principle is applied to derive a novel governing equation based on strain gradient theory for the curved micro tube conveying fluid. Lagrangian nonlinear strain is adopted to take into account the geometric nonlinearity and analyze hardening behavior as a result of the cubic nonlinear terms. Linear stability analysis is carried out to investigate the possibility of linear instabilities. Afterwards, the first nonlinear out-of-plane natural frequency is plotted versus fluid velocity to determine the influence of nonlinear terms and hardening behavior on stability of the system. The influence of the length scale parameter is studied by comparison of the results for classical, coupled stress and strain gradient theory. Finally the phase difference between two points at upstream and downstream is plotted versus fluid velocity. Linear relation between the phase difference and fluid velocity is noticed, thus the curved coriolis flowmeter can be calibrated to measure flow rate by measuring the phase difference between two points.

ABSTRACT: A hybrid method is proposed to predict the dynamic behavior of functionally graded (FG) plate subjected to a moving mass. The governing equations of motion of FG plate are derived using the Kirchhoff plate theory and Lagrange equation. Improved Rayleigh–Ritz solution is used to treat the spatial partial derivatives. Penalty method is employed to deal with the constraints, and the energy terms due to boundary conditions are included in Lagrange, hence it is not necessary to particularly consider the constraints in the modeling process. And the combination of simple polynomials and trigonometric functions is selected as the admissible functions. The advantage of this improvement in Rayleigh–Ritz method is that it is not needed to find satisfied admissible functions for different boundary conditions while the convergence of the solution is improved. Meanwhile, the method can be used to handle the versatile boundary conditions. Differential quadrature method (DQM) as a step-by-step time integration scheme is employed for discretization of temporal derivatives. The validated results show that the presented method is very reliable and efficient, and its convergence and accuracy are also better compared to finite element method for solving the dynamic problems of FG plate with moving loads (force and mass). Moreover, the influences of material properties and boundary conditions on maximum dynamic deflections are investigated, as well as moving speeds and inertial effects of loads (mass and force). Although only four edge boundary conditions are addressed in the present work, the proposed procedure is applicable for any arbitrary edge boundary conditions.


ABSTRACT: A unified numerical analysis model is presented to solve the free vibration of composite laminated doubly-curved shells and panels of revolution with general elastic restraints by using the Fourier–Ritz method. The first-order shear deformation theory is adopted to conduct the analysis. The admissible function is acquired by using a modified Fourier series approach in which several auxiliary functions are added to a standard cosine Fourier series to eliminate all potential discontinuities of the displacement function and its derivatives at the edges. Furthermore, the general elastic restraint and kinematic compatibility and physical compatibility conditions are imitated by the boundary and coupling spring technique respectively when the composite laminated doubly-curved panels degenerate to the complete shells of revolution. Then, the desired results are solved by the variational operation. Large quantities of numerical examples are calculated about the free vibration of cross-ply and angle-ply composite laminated doubly-curved panels and shells with different geometric and material parameters. Through the sufficient conclusions obtained from the comparison, it can be seen that highly accurate solutions can be yielded with a little computational effort. To understand the influence of different boundary conditions, lamination schemes, material and geometrical parameters on the vibration characteristics, a series of parametric studies are carried out. Lastly, results for vibration of the composite laminated doubly-curved panels and shells subject to various kinds of boundary conditions and with different geometrical and material parameters are also presented firstly, which can provide the benchmark data for other studies conducted in the future.


ABSTRACT: This paper addresses a 3D elasticity analytical solution for static deformation of a simply-supported rectangular micro/nanoplate made of both homogeneous and functionally graded (FG) material.
within the framework of modified couple stress theory. The plate is assumed to be resting on a Winkler–Pasternak elastic foundation, and its modulus of elasticity is assumed to vary exponentially along thickness. By expanding displacement components in double Fourier series along in-plane coordinates and imposing relevant boundary conditions, the boundary value problem (BVP) of plate system, including its governing partial differential equations (PDEs) of equilibrium are reduced to BVP consisting only ordinary ones (ODEs). Parametric studies are conducted among displacement and stress components developed in the plate and FG material gradient index, length scale parameter, and foundation stiffnesses. From the numerical results, it is concluded that the out-of-plane shear stresses are not necessarily zero at the top and bottom surfaces of plate. The results of this investigation may serve as a benchmark to verify further bending analyses of either homogeneous or FG micro/nanoplates on elastic foundation.

ABSTRACT: In the present work, attention is focused on the prediction of thermal buckling and post-buckling behaviors of functionally graded materials (FGM) beams based on Euler–Bernoulli, Timoshenko and various higher-order shear deformation beam theories. Two ends of the beam are assumed to be clamped and in-plane boundary conditions are immovable. The beam is subjected to uniform temperature rise and temperature dependency of the constituents is also taken into account. The governing equations are developed relative to neutral plane and mid-plane of the beam. A two-step perturbation method is employed to determine the critical buckling loads and post-buckling equilibrium paths. New results of thermal buckling and post-buckling analysis of the beams are presented and discussed in details, the numerical analysis shows that, for the case of uniform temperature rise loading, the post-buckling equilibrium path for FGM beam with two clamped ends is also of the bifurcation type for any arbitrary value of the power law index and any various displacement fields.

ABSTRACT: Van der Waals (vdWs) bindings acting as interlayer shear force between graphene layers of multi-layer graphene sheets (MLGSs) are considered in vibration analysis in the present study. To idealize the structure of MLGS incorporating interlayer shear interactions, a sandwich model (SM) is represented which laminates the graphene layers. The layers stick together with vdWs bonds. The bonds are modeled as core layers between every two adjacent layers. Molecular dynamic (MD) simulation is carried out to validate the results obtained by SM. Afterward, the values for bending rigidity and layers thicknesses are obtained so as to match SM frequencies with MD results. It is observed the SM can predict the vibration behavior of MLGSs well for different values of aspect ratio. The present paper deals with a new method of incorporating shear effect and a novel investigation of integrating SM with MD.

ABSTRACT: In this study, based on Reddy cylindrical double-shell theory, the free vibration and stability analyses of double-bonded micro composite sandwich cylindrical shells reinforced by carbon nanotubes conveying fluid flow under magneto-thermo-mechanical loadings using modified couple stress theory are investigated. It is assumed that the cylindrical shells with foam core rested in an orthotropic elastic medium and
the face sheets are made of composites with temperature-dependent material properties. Also, the Lorentz functions are applied to simulation of magnetic field in the thickness direction of each face sheets. Then, the governing equations of motions are obtained using Hamilton's principle. Moreover, the generalized differential quadrature method is used to discretize the equations of motions and solve them. There are a good agreement between the obtained results from this method and the previous studies. Numerical results are presented to predict the effects of size-dependent length scale parameter, third order shear deformation theory, magnetic intensity, length-to-radius and thickness ratios, Knudsen number, orthotropic foundation, temperature changes and carbon nanotubes volume fraction on the natural frequencies and critical flow velocity of cylindrical shells. Also, it is demonstrated that the magnetic intensity, temperature changes and carbon nanotubes volume fraction have important effects on the behavior of micro composite sandwich cylindrical shells. So that, increasing the magnetic intensity, volume fraction and Winkler spring constant lead to increase the dimensionless natural frequency and stability of micro shells, while this parameter reduce by increasing the temperature changes. It is noted that sandwich structures conveying fluid flow are used as sensors and actuators in smart devices and aerospace industries. Moreover, carotid arteries play an important role to high blood rate control that they have a similar structure with flow conveying cylindrical shells. In fact, the present study can be provided a valuable background for more research and further experimental investigation.


ABSTRACT: This paper studies the electro-mechanical shear buckling analysis of piezoelectric nanoplate using modified couple stress theory with various boundary conditions. In order to be taken electric effects into account, an external electric voltage is applied on the piezoelectric nanoplate. The simplified first order shear deformation theory (S-FSDT) has been employed and the governing differential equations have been obtained using Hamilton's principle and nonlinear strains of Von-Karman. The modified couple stress theory has been applied to considering small scale effects. An analytical approach was developing to obtain exact results with various boundary conditions. After all, results have been presented by change in some parameters, such as: aspect ratio, effect of various boundary conditions, electric voltage and length scale parameter influences. At the end, results showed that the effect of external electric voltage on the critical shear load occurring on the piezoelectric nanoplate is insignificant.


ABSTRACT: Due to their valuable and unique properties, graphene sheets (GSs) have attracted increasing attention in recent years. This paper presents the mathematical modeling of the nonlinear vibration behavior of GSs using classic plate theory and nonlocal elasticity theory which accounts for the size effect. The numerical solutions are obtained through the element-free kp-Ritz method. The iteration process is dealt with using the linearized updated mode method. The transformation method is used to impose the boundary conditions. The published results are used to verify the correctness of the present nonlocal element-free kp-Ritz method. The effects of boundary conditions, side length, aspect ratio and nonlocal parameters on the frequency–amplitude response are examined.

ABSTRACT: A new solution method in the area of computational mechanics is developed in this article, which is called variational differential quadrature (VDQ). The main idea of this method is based on the accurate and direct discretization of the energy functional in the structural mechanics. In the VDQ method, through developing an efficient matrix formulation and using an accurate integral operator, the discretized governing equations are derived directly from the weak form of the equations with no need for the analytical derivation of the strong form. This technique provides an alternative way to discretize the energy functional, which avoids the local interpolation and the assembly process of the methods of this kind. We first implement the VDQ method for the nonlinear elasticity theory considering the Green-St. Venant strain tensor; then we simplify the formulation further for the first-order shear deformable beam and plate theories. The final formulation of these cases demonstrates the simplicity of the implementation for the VDQ method in the numerical analysis of the structures, which is a major goal for this article. Using these examples, one can easily learn and apply this technique to other structures. To assess the performance of the VDQ method, we compare it with the generalized differential quadrature (GDQ) method and finite element method (FEM) in the case of bending analysis of Mindlin plates. It is indicated that computational cost of VDQ is less than that of GDQ, and the convergence rate of VDQ is faster than that of FEM.


ABSTRACT: In this paper, the buckling and the free vibration of the quasicrystal cylindrical shells under axial compression are investigated. Three quasi-periodicity cases of quasicrystal cylindrical shells are considered. The first-order shear displacement theory of the cylindrical shells is utilized to obtain the equations of motion and the boundary conditions. Numerical results for simply supported cylindrical shells at the two ends are calculated. The effects of the geometry, in-plane phonon and phason loads, and half-wave number of the quasicrystal cylindrical shells on both the buckling loads and the frequency are demonstrated.


ABSTRACT: The homotopy perturbation method (HPM) was developed to search for asymptotic solutions of nonlinear problems involving parabolic partial differential equations with variable coefficients. This paper illustrates that HPM be easily adapted to solve parabolic partial differential equations with constant coefficients. Natural frequencies of a rectangular plate of uniform thickness, simply-supported on all sides, are obtained with minimum amount of computation. The solution is shown to converge rapidly to a combination of sine and cosine functions. Truncating the series solution by using only the first three terms of the sine and cosine functions as compared to the exact solution results in an absolute error not exceeding $2 \times 10^{-4}$ and $9 \times 10^{-4}$ for the trigonometric functions respectively. HPM is then applied to solve the nonlinear problem of a rectangular plate of variable thickness. A direct expression for the eigenvalues (natural frequencies) of the rectangular plate is obtained as compared to determining its eigenvalues by solving the characteristic equation using the conventional method. Comparison of results for the frequency parameter with existing literature show that HPM is highly efficient and accurate. Natural frequencies of a simply-supported guitar soundboard were obtained using an equivalent rectangular plate with the same boundary condition.

ABSTRACT: In the present study by considering the small-scale effects, the dynamic instability of fully clamped and simply supported nanoplates is studied in the attendance of electrostatic, Casimir as well as thermal forces. To this end, by applying the nonlocal elasticity theory of Eringen along with the classical plate theory, the dynamic equilibrium equation of nanoplates is obtained by incorporating the in-plane thermal and transverse intermolecular distributed loads. The solution of the obtained nonlinear governing equation is done using the Galerkin method and the dynamic pull-in instability voltage of the nanoplates is compared with the available experimental results. Finally, the simultaneous effects of thermal force as well as nonlocal parameter on the dynamic response of nanoplates are examined in the presence of Casimir force in detail.


ABSTRACT: For the first time in this paper, free vibration and thermal buckling of micro temperature-dependent FG porous circular plate subjected to a nonlinear thermal load are numerically studied. The governing equations are derived based on Hamilton's principal and using both classical and the first-order shear deformation theories in conjunction with the modified couple stress theory. Generalized Differential Quadrature method is applied to solve the equations with associated boundary conditions. The results reveal that the increase of size dependency and the temperature-change would lead to the increase of differences between the first natural frequencies predicted based on the two theories. In contrast, the porosity and the FG power index do have not any effect on that. While the effect of porosity on free vibration of clamped and free plates are negligible, but the effect of porosity for hinged ones is considerable as the temperature-change increase. Moreover, the critical conditions of the plates which are expressed by porosity, FG power index, size dependency, temperature-change and geometrical dimensions are presented, as well. Numerical results are in good agreement with those available in literature in some special cases.


ABSTRACT: The optimum design for energy absorbers requires considering different criteria. Therefore, the design process can benefit from Multiple-Attribute Decision-Making (MADM) approach. Thin-walled structures can be particularly employed as energy absorbers in automobiles to dissipate energy and protect passengers from the peak crush load caused by severe collisions. The present study investigates a thin-walled conical segmented aluminum tube which consists of several circular sections with different thicknesses. To achieve the optimum design, a number of conical segmented tubes were modeled by finite element method. Energy absorption, initial peak load, crush force efficiency (the ratio of mean load to maximum load), mass of the structure and deformation type as the conflicting objective functions were defined as attributes/criteria. The numeric logic (NL) technique was applied to determine the weight of various criteria. Furthermore, the MULTIMOORA method, as a well-accepted MADM model, was utilized to obtain the optimum design for a conical segmented tube. The design variables included wall thickness, lengths of sections, and taper angle. Drawing a comparison between the top rank conical segmented tube and the top rank conical simple tube revealed that the conical segmented tube could increase the efficiency of the crush load up to 23.8% and reduce the initial peak load and mass of the tube up to 54% and 17.54%, respectively.
ABSTRACT: The occurrence of the axial dynamic buckling in the carbon nanotube may cause the failure of some nano-sensors, which is difficult to be investigated by the experimental approach for the rigorous measuring accuracy requirement. Thus, a complex structure-preserving method is proposed to investigate the axial dynamic buckling properties of an embedded single-walled carbon nanotube in this paper. The nonlocal Euler–Bernoulli beam model of the embedded single-walled carbon nanotube under a concentrated excitation with a small included angle in the acting direction of the excitation against the cross-section of the carbon nanotube is presented. Introducing several intermediate variables, the multi-symplectic form of the oscillation model is obtained, which is a structure-preserving order-reduce process. To investigate the axial dynamic buckling of the carbon nanotube numerically with an acceptable step length, a complex structure-preserving method that combines the precise integration method for the grids near the acting position of the excitation and the Preissman multi-symplectic scheme for other grids is proposed. Considering two typical excitations, the oscillation of the carbon nanotube is simulated by the complex structure-preserving method and the axial dynamic buckling properties of the nanotube are investigated. From the numerical results, it can be concluded that the axial dynamic buckling phenomenon in the carbon nanotube is more likely to occur when the included angle increase or the frequency of the excitation is close to MHz with the given parameters, which gives guidance for the design of the excitation of the nano-oscillator.

ABSTRACT: In this study, we report the development and application of a fluid–structure interaction (FSI) solver for compressible flows with large-scale flow-induced deformation of the structure. The FSI solver utilizes a partitioned approach to strongly couple a sharp interface immersed boundary method-based flow solver with an open-source finite-element structure dynamics solver. The flow solver is based on a higher-order finite-difference method using a Cartesian grid, where it employs the ghost-cell methodology to impose boundary conditions on the immersed boundary. Higher-order accuracy near the immersed boundary is achieved by combining the ghost-cell approach with a weighted least squares error method based on a higher-order approximate polynomial. We present validations for two-dimensional canonical acoustic wave scattering on a rigid cylinder at a low Mach number and for flow past a circular cylinder at a moderate Mach number. The second order spatial accuracy of the flow solver was established in a grid refinement study. The structural solver was validated according to a canonical elastostatics problem. The FSI solver was validated based on comparisons with published measurements and simulations of the large-scale deformation of a thin elastic steel panel subjected to blast loading in a shock tube. The solver correctly predicted the oscillating behavior of the tip of the panel with reasonable fidelity and the computed shock wave propagation was qualitatively consistent with the published results. In order to demonstrate the fidelity of the solver and to investigate the coupled physics of the shock–structure interaction for a thin elastic plate, we employed the solver to simulate a 6.4 kg TNT blast loading on the thin elastic plate. The initial conditions for the blast were taken from previously reported field tests. Using numerical schlieren, the shock front propagation, Mach reflection, and vortex shedding at the tip of the plate were visualized during the impact of the shock wave on the plate. We discuss the coupling between the nonlinear dynamics of the plate and blast loading. The plate oscillates under the influence of blast loading and the restoration of elastic forces. The time-varying displacement of the tip of the plate is the superimposition of two dominant frequencies, which correspond to the first and second modes of the natural frequency of a vibrating plate. The effects of the material properties and length of the plate on the flow-induced
deformation are briefly discussed. The proposed FSI solver is a versatile computational tool for simulating the impact of a blast wave on thin elastic structures and the results presented in this study may facilitate the design of thin structures subjected to realistic blast loadings.

ABSTRACT: This paper deals with free vibration analysis of functionally graded composite shell structures reinforced by carbon nanotubes. Uniform and three distributions of carbon nanotubes which are graded in the thickness direction of the structure are considered. The effective material properties are determined via a micro-mechanical model using some efficiency parameters. The equations of motion are developed based on a discrete double directors shell finite element formulation which introduces the transverse shear deformations via a higher-order distribution of the displacement field. Comparison studies are carried out for various functionally graded composite shell structures reinforced by carbon nanotubes in order to highlight the applicability and the efficiency of the proposed model in the prediction of the vibrational behavior of such shell structures.

ABSTRACT: This paper presents development of the spectral element method (SEM) for analysis of circular and annular circular plates vibration under impact load. A novel formulation is proposed in frequency domain for conducting spectral element matrix. Several numerical examples are presented in order to demonstrate performance of the presented method compared to other numerical methods in literature. The presented formulation was applied in order to analyze vibration of annular circular plates with various thicknesses and various internal-to-external radius ratios. In addition, annular circular plate displacements subjected to an impact load were calculated using the presented SEM.

ABSTRACT: In this paper, we obtain accurate analytic free vibration solutions of rectangular thin cantilever plates by using an up-to-date rational superposition method in the symplectic space. To the authors’ knowledge, these solutions were not available in the literature due to the difficulty in handling the complex mathematical model. The Hamiltonian system-based governing equation is first constructed. The eigenvalue problems of two fundamental vibration problems are formed for a cantilever plate. By symplectic expansion, the fundamental solutions are obtained. Superposition of these solutions are equal to that of the cantilever plate, which yields the analytic frequency equation. The mode shapes are then readily obtained. The developed method yields the benchmark analytic solutions with fast convergence and satisfactory accuracy by rigorous derivation, without assuming any trial solutions; thus, it is regarded as rational, and its applicability to more boundary value problems of partial differential equations represented by plates’ vibration, bending and buckling may be expected.

ABSTRACT: Probabilistic analysis is becoming more important in mechanical science and real-world engineering applications. In this work, a novel generalized stochastic edge-based smoothed finite element method is proposed for Reissner–Mindlin plate problems. The edge-based smoothing technique is applied in the standard FEM to soften the over-stiff behavior of Reissner–Mindlin plate system, aiming to improve the accuracy of predictions for deterministic response. Then, the generalized nth order stochastic perturbation technique is incorporated with the edge-based S-FEM to formulate a generalized probabilistic ES-FEM framework (GP_ES-FEM). Based upon a general order Taylor expansion with random variables of input, it is able to determine higher order probabilistic moments and characteristics of the response of Reissner–Mindlin plates. The significant feature of the proposed approach is that it not only improves the numerical accuracy of deterministic output quantities with respect to a given random variable, but also overcomes the inherent drawbacks of conventional second-order perturbation approach, which is satisfactory only for small coefficients of variation of the stochastic input field. Two numerical examples for static analysis of Reissner–Mindlin plates are presented and verified by Monte Carlo simulations to demonstrate the effectiveness of the present method.


ABSTRACT: Multi-cell structures have widely been studied due to their excellent energy absorption ability. However, few systematic studies have been conducted on the topological design of cross-sectional configurations of thin-walled tubes. To make full use of the material, topology optimization of multi-cell hexagonal tubes was conducted under both axial compression and lateral bending loadings. A binary particle swarm optimization (PSO) was enhanced by introducing the mass constraint factor to guide the movement of particles, which could improve the success rate of obtaining the global optimum. It was found that the optimum designs under the axial load placed the material outward to strengthen the interaction between the outer and inner walls and created more partitions between the inside rib walls. While under the lateral load, all the optimum designs have diagonally-connected elements to resist local deformation, and the material was also placed outward to increase the moment of inertia and thus to resist the global deformation. For the multiple loading cases, the final optimal designs are similar to the compression designs or combined designs from the two loading cases.


ABSTRACT: Nonlinear vibration analysis of circular cylindrical shells has received considerable attention from researchers for many decades. Analytical approaches developed to solve such problem, even not involved simplifying assumptions, are still far from sufficiency, and an efficient numerical scheme capable of solving the problem is worthy of development. The present article aims at devising a novel numerical solution strategy to describe the nonlinear free and forced vibrations of cylindrical shells. For this purpose, the energy functional of the structure is derived based on the first-order shear deformation theory and the von–Kármán geometric nonlinearity. The governing equations are discretized employing the generalized differential quadrature (GDQ) method and periodic differential operators along axial and circumferential directions, respectively. Then, based on Hamilton's principle and by the use of variational differential quadrature (VDQ) method, the discretized nonlinear governing equations are obtained. Finally, a time periodic discretization is performed and the frequency response of the cylindrical shell with different boundary conditions is determined by applying the pseudo-arc length continuation method. After revealing the efficiency and accuracy of the proposed numerical approach, comprehensive results are presented to study the influences of the model parameters such as
thickness-to-radius, length-to-radius ratios and boundary conditions on the nonlinear vibration behavior of the cylindrical shells. The results indicate that variation of fundamental vibrational mode shape significantly affects frequency response curves of cylindrical shells.


ABSTRACT: This paper proposes operational matrix of $r$th integration of Chebyshev wavelets. A general procedure of this matrix is given. Operational matrix of $r$th integration is taken as $r$th power of operational matrix of first integration in literature. But, this study removes this disadvantage of Chebyshev wavelets method. Free vibration problems of non-uniform Euler–Bernoulli beam under various supporting conditions are investigated by using Chebyshev Wavelet Collocation Method. The proposed method is based on the approximation by the truncated Chebyshev wavelet series. A homogeneous system of linear algebraic equations has been obtained by using the Chebyshev collocation points. The determinant of coefficients matrix is equated to the zero for nontrivial solution of homogeneous system of linear algebraic equations. Hence, we can obtain $i$th natural frequencies of the beam and the coefficients of the approximate solution of Chebyshev wavelet series that satisfied differential equation and boundary conditions. Mode shapes functions corresponding to the natural frequencies can be obtained by normalizing of approximate solutions. The computed results well fit with the analytical and numerical results as in the literature. These calculations demonstrate that the accuracy of the Chebyshev wavelet collocation method is quite good even for small number of grid points.


ABSTRACT: This paper uses Variational Asymptotic Method (VAM) to obtain asymptotically exact analytical solutions for cylinders made up of Functionally Graded Materials (FGM). VAM splits a three-dimensional elasticity problem into a two-dimensional linear cross-sectional problem and a one-dimensional beam problem. It ensures the asymptotic correctness since the method makes no ad hoc assumptions. This is accomplished by taking advantage of certain small parameters inherent to beam-like structures. This technique has been successfully used for a variety of problems but it has never been implemented on cylinders made up of FGM. Starting with the variable geometry of the cylindrical cross-section made up of radially non-homogeneous material properties controlled by a volume fraction variable, the 3-D problem has been formulated and solved analytically despite the presence of geometrical non-linearities. Closed form analytical solutions are obtained to predict the exact response of functionally graded cylinders. The influence of inner and outer material properties, radius values and the variation trend of material composition on the mechanical behavior is highlighted. Results obtained from the present theory are successfully validated using a commercially available 3-D FEM solver ABAQUS. Analytical solutions obtained can analyze the behavior of any cylinder with FGM quickly and accurately.


ABSTRACT: The theory of elastic shells is one of the most important branches of the theory of elasticity. Among all the shell models, a classical and widely recognized model is the Koiter model. In this paper, we discuss the time-dependent Koiter model, which has not been addressed numerically. We show that the solution of this model exists and is unique. We semi-discretize the space variable and fully discretize the problem using the time discretization by the Newmark scheme. The corresponding analyses of existence, uniqueness, stability,
convergence and a priori error estimate are given. Finally, we provide numerical experiments with a portion of spherical shell and a portion of cylindrical shell to demonstrate the efficiency of the model.

ABSTRACT: To improve the efficiency in predicting the dynamic mode and static response of the two-layer partial interaction composite beams, this paper utilizes the differential quadrature technique to approximate derivatives of the primary unknowns with adaptive order of precision, rather than the low and constant order of interpolation used in the conventional finite element method (FEM). A degree-of-freedom-adaptive weak-form quadrature element (WQE) for dynamic analysis is formulated and implemented based on the principle of virtual work. For the purpose of comparison, a parabolic displacement-based finite element is also provided, thus (1) the predicted deflections and natural frequencies of the composite beams are verified; (2) the smoothness of the internal forces and stresses generated by WQE method and FEM are compared, and (3) the convergent rates of higher order free vibration modes are also examined. Numerical results show that the efficiency of the proposed WQE method has, on the one hand, significantly triumphed over that of FEM on analyses including static response, natural frequencies and higher order free vibration modes, on the other hand, the smoothness of results, including internal forces and stresses, is greatly refined.

ABSTRACT: An exact mode solution that investigates the prebuckling and postbuckling characteristics of nonlocal nanobeams with fixed–fixed, hinged–hinged, and fixed–hinged boundary conditions in a longitudinal magnetic field is determined. The geometric nonlinearity arising from mid-plane stretching is considered to obtain the nonlinear governing equation of motion by virtue of Hamilton's principle. The influences of the nonlocal and magnetic parameters on the prebuckling and postbuckling dynamics of nanobeams with various boundary conditions are evaluated, indicating that the critical buckling force can be decreased with the increase of the nonlocal parameter while can be increased with increasing the magnetic parameter. It is demonstrated that the first natural frequency of the nanobeam with fixed–fixed and fixed–hinged boundary conditions in postbuckling configuration is increased from zero to a constant value for higher values of the nonlocal parameter with increasing the axial force. The second natural frequency of the buckled nanobeam is always decreased with an increase of the nonlocal parameter. The results show that the internal resonance between the first and second modes of the postbuckling nanobeams can be quickly and easily activated by increasing the nonlocal parameters, especially for fixed–fixed and hinged–hinged boundary conditions. In addition, the results obtained by exact mode solution are compared those obtained by classical mode solution. It is found that the classical mode is valid only for nonlocal nanobeams with the hinged–hinged boundary conditions.

ABSTRACT: Perhaps due to the bending moment singularity at the obtuse plate corners, the existing buckling loads vary appreciably even for simply supported rhombic plate under uniaxial loading. In this paper, the buckling analysis of skew plates under various loadings is presented using the modified differential quadrature method (DQM). A complete set of equations of equilibrium, bending and twisting moments, equivalent shear forces and corner force in oblique coordinate system is given. Eight combinations of simply supported, clamped
and free boundary conditions, four skew angles, and five aspect ratios are considered. Convergence studies are made for rhombic plates with the largest skew angle subjected to uniaxial and equal biaxial compressive loads. The solution accuracy is further verified by comparing the results with data obtained by the finite element method using very fine meshes. New data are tabulated and plotted for skew plates with different edge conditions, aspect ratios and skew angles, subjected to uniaxial, biaxial, as well as combined shear with uniaxial loads. Most of the data, not available thus far, may be useful for other researches in testing the validity of their numerical techniques for thin plate analysis.

ABSTRACT: The nonlinear free vibration of a fractional dynamic model for the viscoelastic pipe conveying fluid is studied in this paper. The dynamic equations of coupled planar motion for the pipe are derived by employing the Euler beam theory and the generalized Hamilton principle when we consider both the fractional material model and the geometric non-linearity. Then the equations are simplified into a new nonlinear, fractional order dynamic model governing transverse vibration of the pipe in small but limited stretching issues. The method of multiple scales is directly applied for the analysis and simulation of the nonlinear vibration. Numerical results show the influence of the fractional order, the mass ratio, the fluid velocity and the nonlinear coefficient on the nonlinear amplitudes and frequencies of the viscoelastic pipe. It is noticeable that the amplitudes of the fluid-conveying pipe constituted by the fractional viscoelastic material model display much higher than those predicted by the previous models.

ABSTRACT: This paper presents an analytical method to investigate the nonlinear vibration characteristics of bi-graphene sheets/piezoelectric (BGP) laminated films subjected to electric loading based on a nonlocal continuum model, in which the two adjacent layers are coupled by van der Walls force. Utilizing von Kármán nonlinear geometric relation and nonlocal physical relation, the nonlinear dynamic equation of BGP laminated films under electric loading exerted on the piezoelectric layer is found, then the relation between the nonlinear resonant frequency and the nonlinear vibration amplitude for each layer of the BGP laminated films is obtained by using Galerkin method and harmonic-balance method. Results show that the nonlinear vibration amplitude for each layer of laminated films can be controlled by adjusting the electric potential exerted on piezoelectric layer, and the coupled effect of van der Walls force between graphene sheet and piezoelectric layer on the vibration amplitude of each layer depends on the order number of nonlinear resonant frequency and the mode shape.

ABSTRACT: A theoretical model is developed to study the dynamic stability and nonlinear vibrations of the stiffened functionally graded (FG) cylindrical shell in thermal environment. Von Kármán nonlinear theory, first-order shear deformation theory, smearing stiffener approach and Bolotin method are used to model stiffened FG cylindrical shells. Galerkin method and modal analysis technique is utilized to obtain the discrete nonlinear ordinary differential equations. Based on the static condensation method, a reduction model is

ABSTRACT: This paper deals with the thermal buckling analysis of point-supported thin laminated composite plates. The analysis is performed for rhombic and rectangular plates and two cases of bilateral and unilateral buckling. In the unilateral buckling, it is assumed that the plate is in contact with a rigid surface and lateral deflection is forced to be only in one direction. The element-free Galerkin (EFG) method is employed to discretize equilibrium equations. Point supports are modeled in the form of distinct restrained circular surfaces through developing a numerical procedure based on the Lagrange multiplier technique. The unilateral behavior of the plate is incorporated in the analysis by using the penalty method and the Heaviside contact function. The final system of nonlinear algebraic equations is solved iteratively. Two types of point support arrangements are considered and the effect of different parameters such as number of point supports, plate aspect ratio and lamination scheme on the buckling coefficient of composite plates is investigated.


ABSTRACT: A modified mesh-free radial point interpolation method (RPIM) which employs a new radial basis function capable of building the shape functions without any supporting fixing parameters is developed for the nonlinear bending analyses of functionally graded material (FGM) plates. The shape functions constructed by the RPIM possess Kronecker delta function property and thus special schemes for imposing boundary conditions are not needed. The nonlinear bending formulations of FGM plates are based on a higher-order shear deformation plate theory considering the von Kármán large deflection assumption. The nonlinear equations are solved by the modified Newton–Raphson iterative technique. The computed results by the modified RPIM are compared with the other numerical solutions reported in the literature to verify the effectiveness and accuracy of the proposed mesh-free method. Detailed parametric studies are then carried out to scrutinize the effects that the volume fraction, plate length-to-thickness ratio, boundary condition and initial deflection have on the nonlinear flexural responses of FGM plates. Results illustrate that the modified mesh-free RPIM can effectively predict the nonlinear bending behavior of FGM plates.


ABSTRACT: A large number of arterial wall models of different degrees of complexity have been proposed in the literature. However, there is no reported analytical artery model which takes into account the residual stress effects. Therefore, we propose and study a novel two-layered model of the artery with two types of residual stress. A geometrical nonlinearity coming from a thinning of the layers due to the residual stresses and the pressure load was taken into account. The material properties of the layers were described by several Young moduli depending on the range of the strain. The results obtained were compared with finite element modeling based on the nonlinear stress–strain relation of the media and adventitia layers of the Common Carotid Artery taken from the literature. We show that the residual preloading forces significantly change the overall stress distribution in the arterial wall. In particular, the residual stress coming from bending plays the leading role in
stress homogenization and is determined by the opening angles. In turn, overlapping reduces the circumferential stress in the weaker media layer, thus protecting it from overstretching and rupture.


ABSTRACT: An analytical approach for static bending and buckling analyses of curved nanobeams using the differential constitutive law, consequent to Eringen’s strain-driven integral model coupled with a higher-order shear deformation accounting for through thickness stretching is presented. The formulation is general in the sense that it can be deduced to examine the influence of different structural theories, for static and dynamic analyses of curved nanobeams. The governing equations derived using Hamilton’s principle are solved in conjunction with Navier’s solutions. The formulation is validated considering problems for which solutions are available. A comparative study is made here by various theories obtained through the formulation. The effects of various structural parameters such as thickness ratio, beam length, rise of the curved beam, and nonlocal scale parameter are brought out on bending and stability characteristics of curved nanobeams.


ABSTRACT: This paper comprehensively studies the nonlinear vibration of functionally graded nano-beams resting on elastic foundation and subjected to uniform temperature rise. The small-size effect, playing an essential role in the dynamical behavior of nano-beams, is considered here applying the innovative stress driven nonlocal integral model due to Romano and Barretta. The governing partial differential equations are derived from the Bernoulli–Euler beam theory utilizing the von Karman strain–displacement relations. Using the Galerkin method, the governing equations are reduced to a nonlinear ordinary differential equation. The closed form analytical solution of the nonlinear natural frequency for four different boundary conditions is then established employing the Homotopy Analysis Method. The nonlinear natural frequencies, evaluated according to the stress-driven nonlocal integral model, are compared with those obtained by Eringen differential model. Finally, the effects of different parameters such as length, elastic foundation parameter, thermal loading and nonlocal characteristic parameter are investigated. The emergent results establish that when the nonlocal characteristic parameter increases, the nonlinear natural frequencies obtained by the stress-driven nonlocal integral model reveal a stiffness-hardening effect. On the other hand, Eringen's differential law reveals a stiffness-softening effect excepting the case of cantilever nano-beam. Also, increase in temperature and the elastic foundation parameter leads to increase in the nonlinear frequency ratios in Eringen differential model but decrease in the frequency ratios in the stress-driven nonlocal integral model.


ABSTRACT: In this paper a novel numerical method based on the Moving Kriging (MK) interpolation meshfree method, integrated with a simple higher-order shear deformation plate theory for analysis of static bending, free vibration and buckling of functionally graded (FG) plates is presented. In the proposed technique, the shape functions are built by the Kriging technique which possesses the property of Kronecker delta function which makes it easy to enforce essential boundary conditions. The present formulation is based on a refined simple third-order shear deformation theory (R-STSDT), which is based on four variables and it still accounts for parabolic distribution of the transverse shearing strains and stresses through the thickness of the plate.
present in the original simple third-order shear deformation theory (STSDT). In this theory, instead of assuming a specific distribution for the displacement field, the theory of elasticity is used for obtaining the kinematics of the plate deformation. We first propose the formulation, and then several numerical examples are provided to show the merits of the proposed approach.

ABSTRACT: In this study, we present an analysis of the frequency characteristics of rotating truncated conical shells using the Haar wavelet method. Based on the Love first-approximation theory, the governing equations are formulated by considering the effects of centrifugal and Coriolis forces as well as the initial hoop tension due to rotation. The displacement field is expressed as the Haar wavelet series in the axial direction and trigonometric functions in the circumferential direction. By considering the boundary conditions, the eigenvalue equation is obtained to determine the vibration behaviors of rotating conical shells. To validate the current analysis, the results obtained by the proposed method are compared with those reported previously, where the agreement is very good. Finally, we investigate the effects of the geometrical parameters, rotation speed, and boundary conditions on the vibration characteristics of rotating conical shells and the results are presented.

ABSTRACT: We consider the problem of optimizing the dynamic response of a mechanically loaded, rectangular, electrically conductive anisotropic composite plate by applying an electromagnetic field, which exploits the electro-magneto-mechanical field coupling phenomenon. An important aspect of the formulated nonlinear partial differential equation (PDE)-constrained optimization model is the presence of a thermal constraint that prevents polymer matrix degradation in the composite material due to Joule heating produced by the electromagnetic field. A black-box optimization approach based on the active set algorithm is employed. A system of governing PDEs is solved using a series of sequential numerical procedures that includes the method of lines, Newmark time-stepping scheme, quasilinearization, integration of two-point boundary-value problems, and a superposition method followed by orthonormalization. Implementation in hyper-dual arithmetics facilitated automatic differentiation and computation of the gradient. Optimization results show that application of an electromagnetic field with optimal characteristics enables one to significantly reduce the amplitude of the plate vibrations while controlling for Joule heating.

ABSTRACT: Due to many applications of spherical shells on a circular planform such as the nose of the plane and spacecraft and caps of pressurized cylindrical tanks, in this article, free vibration analysis of a thin functionally graded shallow spherical cap under a thermal load is considered. A decoupling technique is employed to analytically solve the equations of motion. Introducing some new auxiliary and potential functions as well as using the separation method of variables, the governing equations of the vibrated functionally graded shallow spherical cap were exactly solved. The superiority of the relations is validated by some comparative studies for various types of boundary conditions. Also, thermal buckling phenomenon is considered. Using new different material models, efficiency of the functionally graded materials is investigated when the shell is
subjected to a temperature gradient. The effects of various parameters such as radius of curvature, material grading index and thermal gradient are discussed.


ABSTRACT: The focus of this paper is on the analytical buckling solutions of piezoelectric cylindrical nanoshells under the combined compressive loads and external voltages. To capture the small-scale characteristics of the nanostructures, the constitutive equations with the coupled nonlocal and surface effects are adopted within the framework of Reddy's higher-order shell theory. The governing equations involving the displacements and induced piezoelectric field are solved by employing the separation of variables. The derived accurate solutions conclude that buckling critical stresses should go down rapidly while the nonlocal effects reach a certain level. With the enhancing surface effects, the stability of piezoelectric cylindrical nanoshells can be improved significantly. Meanwhile, the induced electric field also plays an important role in elevating the buckling critical stresses. For the nanoshells with remarkable nonlocal effects, boundary conditions, shell length and radius have little influence on the buckling solutions. The detailed effects of the boundary conditions, geometric parameters, material properties and applied voltages are discussed.


ABSTRACT: Parametric resonance of a functionally graded (FG) cylindrical thin shell with periodic rotating angular speeds subjected to thermal environment is studied in this paper. Taking account of the temperature-dependent properties of the shell, the dynamic equations of a rotating FG cylindrical thin shell based upon Love's thin shell theory are built by Hamilton's principle. The multiple scales method is utilized to obtain the instability boundaries of the problem with the consideration of time-varying rotating angular speeds. It is shown that only the combination instability regions exist for a rotating FG cylindrical thin shell. Moreover, some numerical examples are employed to systematically analyze the effects of constant rotating angular speed, material heterogeneity and thermal effects on vibration characteristics, instability regions and critical rotating speeds of the shell. Of great interest in the process is the combined effect of constant rotating angular speed and temperature on instability regions.


ABSTRACT: An analytical approach is presented for the accurate definition of lower and upper bounds for the pull-in voltage and tip displacement of a micro- or nanocantilever beam subject to compressive axial load, electrostatic actuation and intermolecular surface forces. The problem is formulated as a nonlinear two-point boundary value problem and has been transformed into an equivalent nonlinear integral equation. Initially, new analytical estimates are found for the beam deflection, which are then employed for assessing novel and accurate bounds from both sides for the pull-in parameters, taking into account for the effects of the compressive axial load. The analytical predictions are found to closely agree with the numerical results provided by the shooting method. The effects of surface elasticity and residual stresses, which are of significant importance when the physical dimensions of structures descend to nanosize, are also included in the proposed approach.

ABSTRACT: In the present study, a modified nonlocal elasticity theory is used for flutter and divergence analyses of the cantilever carbon nanotubes (CNTs) conveying fluid. The CNT is embedded in viscoelastic foundation and is subjected to an axial compressive load acting at the free end. An extreme high-order governing equation as well as higher-order boundary conditions is developed using Hamilton's principle for vibration and stability analysis of the CNT. The numerical solution for flutter and divergence velocities is computed using the extended Galerkin method. The validity of the present analysis is confirmed by comparing with molecular dynamics simulation (MDS) and numerical solutions available in the literature. In the numerical results, the effects of nonlocal parameter, surface effects, viscoelastic foundation and compressive axial load on the stability boundaries of the system are investigated. The results show that the stability boundaries of the CNT are strongly dependent on the small scale coefficient and surface effects.


ABSTRACT: In this paper, a semi-analytical method is presented to study the transverse vibration of sector-like thin plate with various boundary conditions. A sector-like plate is generated from a sector plate whose circular edge is replaced by edges of other geometries. The expressions of boundary conditions for arbitrary point on the arc edge are given in a local rectangular coordinate system and transformed into the global polar coordinate system. Fourier expansion is performed on the expressions of the boundary conditions so that the boundary conditions are satisfied on the whole edge. Several examples are presented and the results are calculated numerically and compared with those in literature and obtained by FEM. The good agreement between the results validates the accuracy and applicability of this method for sector-like plates.


ABSTRACT: Nano/Micro tubes are extensively used in fluidic nano/micro circuits, biochemical industries and nano/micro electromechanical systems. In order to investigate the influence of length scale parameters, in the present work for the first time, the second strain gradient is applied along with Euler- Bernoulli beam theory to study the fluid-conveying nanotube. The hamilton principle is used to derive governing equation of the nano/micro tube conveying fluid. The partial governing equation of motion is discretized into ordinary differential equations by the Galerkin method. The possible instabilities are predicted by linear stability analysis. Onsets of the instabilities based on the second strain gradient theory are compared with those based on the classical and strain gradient theories. Afterwards, nonlinear stability analysis is performed by both Perturbation and numerical methods. The results obtained by numerical method are in good agreements with those achieved by perturbation approach. In nonlinear stability analysis, the onsets of instabilities are obtained more precisely considering the hardening effects. The resonance around the first nonlinear natural frequency and the influence of the fluid velocity on the resonance curve are investigated by the perturbation method.

ABSTRACT: Anisotropic and layered cylinders are important composite structures; however, their system of governing equations is usually solved numerically due to the complicated geometry and material anisotropy involved. In this paper, we analytically solve the plane-strain equations for general static deformation of a cylindrically anisotropic, layered magneto-electro-elastic (MEE) cylinder. We assume that the layers are perfectly bonded at the interfaces. We solve the equations through separation of variables and eigenfunction expansion. Results for each mode shape (2\pi periodic) are solved independently. Because the eigenspace of the mode shapes is the set of all continuous functions on the interval, any continuous loading can be applied and the corresponding solution can be found analytically through superposition of the mode-shape results. To check our formulation, we consider a cylinder with two isotropic-elastic layers under simple radial loading and reproduce the known, exact results. Then, we compare our formulation to an FEA solution for a layered piezo-electric (PE) cylinder. Finally, we apply a radial stress to three comparable MEE cylinders (one uniform MEE cylinder and two layered cylinders made of alternating piezo-electric (PE) and piezo-magnetic (PM) materials). Deformation and stress amplitudes are plotted for the first six mode shapes of each cylinder as benchmarks for further reference.


ABSTRACT: New sandwich panels and tubes have widely applications in nanotechnology such as transportation, naval, aerospace industries, micro and nanoelectromechanical systems and fluid storage. For example, carotid arteries play an important role to high blood rate control that they have a similar structure with flow conveying cylindrical shells. In the current study, stability and free vibration analyses of double-bonded micro composite sandwich piezoelectric tubes conveying fluid flow embedded in an orthotropic foundation under electro-thermo-mechanical loadings are presented. In fact, this work can be provided a valuable background for more research and further experimental investigation. It is assumed that the micro tubes are made of flexible material and smart piezoelectric composites reinforced by carbon nanotubes as core and face sheets, respectively. Energy method and Hamilton's principle are applied to derive the governing equations of motions based on Euler–Bernoulli beam model and using modified strain gradient theory. Moreover, generalized differential quadrature method is used to discretize and solve the governing equations of motions. Numerical results are investigated to predict the influences of length-to-radius, thickness of face sheets-to-thickness of core ratio, temperature changes, orthotropic elastic medium, Knudsen number, and carbon nanotubes volume fraction on the dimensionless natural frequencies and critical flow velocity of sandwich double-bonded piezoelectric micro composite tubes. The results of this article show that increasing the thickness ratio, volume fraction carbon nanotubes and orthotropic elastic constants lead to enhance the dimensionless natural frequency and stability of system, while decrease these parameters with increasing the temperature and length-to-radius ratio.


ABSTRACT: This paper deals with the generalized coupled thermoelastic solution for disks with constant thickness. It is a sequel to the authors’s previous work in which refined 1D Galerkin finite element models with 3D-like accuracies are developed for theories of coupled thermoelasticity. Use of the reduced models with low computational costs may be of interest in a laborious time history analysis of the dynamic problems. In this paper, the developed models are applied and evaluated for a 3D solution of the dynamic generalized coupled thermoelasticity problem in the disk subjected to thermal shock loads. Comparison of the obtained result with
the results available in the literature verified the proposed finite element models are quite efficient with very high rate of convergence and able to provide results with analytical accuracy. In addition, propagation of the thermoelastic waves, the wave reflection from the boundaries and the Poisson effect in an axisymmetric and asymmetric disk problem are represented as contour plots to demonstrate 3D capabilities of the models.


ABSTRACT: This study investigates free vibration of a thick FG circular plate in contact with an inviscid, and incompressible fluid. Analysis of plate is based on First-order Shear Deformation Reissner–Mindlin Theory (FSDT) with consideration of rotational inertial effects and transverse shear stresses. Potential theory together Bernouli's equation are utilized to obtain the fluid pressure on the free surface of the plate. The governing equation of the oscillatory behavior of the fluid is obtained by solving Laplace equation and satisfying its boundary conditions. The natural frequencies and mode shapes of the plate are determined using Chebyshev polynomials. The effects of the geometrical parameters such as plate thickness to its radius ratio, boundary conditions, fluid density, volume fraction index, and height of the fluid on natural frequencies and mode shapes are investigated. Comparison of analytically outcome of this study is made with similar publications in the literature.


ABSTRACT: In the present work, the exact solutions for coupled analysis for bending and torsional case thin-walled functionally graded (FG) beams with non-symmetric single- and double-cells are presented for the first time. For this purpose, an accurate and efficient method is proposed to obtain the FG member stiffness matrix based on the series expansions of displacement components. Three types of material distributions are considered and the beam mechanical properties are graded along the wall thickness according to a power law of the volume fraction. The present beam model is on the basis of the Euler-Bernoulli beam theory and the Vlasov one for bending and torsional problems, respectively. The explicit expressions for displacement parameters are derived using the power series approach from the four coupled equilibrium equations. Finally, the FG member stiffness matrix is determined from the seven force-displacement relations. In order to show the accuracy and super convergence of the thin-walled FG beam element developed by this study, the numerical solutions are presented and compared with results obtained from the finite beam element based on the approximate interpolation polynomials and other available results. Especially, the effects of various structural parameters such as material distribution type, volume fraction index, boundary condition, and material ratio on the spatially coupled responses of FG box beams with non-symmetric single- and double-cells are parametrically investigated.


ABSTRACT: The paper concerns torsional buckling and the initial post-buckling of axially compressed thin-walled aluminium alloy columns with bisymmetrical cross-section. It is assumed that the column material behaviour is described by the Ramberg–Osgood constitutive equation in non-linear elastic range. The stationary total energy principle is used to derive the governing non-linear differential equation. An approximate solution of the equation determined by means of the perturbation approach allows to determine the buckling loads and
the initial post-buckling behaviour. Numerical examples dealing with simply supported I-column are presented and the effect of material elastic non-linearity on the critical loads and initial post-buckling behaviour are compared to the linear solution.


ABSTRACT: This paper presents a two-variable first-order shear deformation theory considering in-plane rotation for bending, buckling and free vibration analyses of isotropic plates. In recent studies, a simple first-order shear deformation theory (S-FSDT) was developed and extended. It has only two variables by separating the deflection into bending and shear parts while the conventional first-order shear deformation theory (FSDT) has three variables. However, the S-FSDT provides incorrect predictions for the transverse shear forces on the insides and the twisting moments at the boundaries except simply supported plates since it does not consider in-plane rotation. The present theory also has two variables but considers in-plane rotation such that it is able to correctly predict the responses of plates with any boundary conditions. Analytical solutions are obtained for rectangular plates with two opposite edges that are simply supported, with the other edges having arbitrary boundary conditions. Numerical results of deflections, stress resultants, buckling loads and natural frequencies are presented with the FSDT, the S-FSDT and the present theory. Comparative studies demonstrate the effects of in-plane rotation and the accuracy of the present theory in predicting the bending, buckling and free vibration responses of isotropic plates.


ABSTRACT: Recently, ultra-fast-rotating-induced cylindrical nano-shells subjected to electro-magnetic fields are used as a water pump. An enormous centrifugal acceleration (up to 1011 g), which is surpassed by five orders of magnitude acceleration in the fastest centrifuges available today, on such nano-structure would have a considerable effect on the vibration and buckling behavior of the structure. In order to predict the first natural frequency and the critical angular velocity of a thermo-electro-magneto-elastic single-layer cylindrical nano-shell resting on a Winkler foundation, the governing equations of motion are derived based on the Hamiltonian Principle and by using first shear deformation theories in conjunction with modified couple stress theory. The effects of the centrifugal acceleration are considered in the formulation. For different boundary conditions, GDQ method is applied as a numerical solution and an analytical solution is presented for the simple-simple boundary conditions at the end of the nano-cylinder. The contributions of the centrifugal acceleration, angular velocities, electrical field, magnetic field, elastic foundation and boundary conditions are investigated. The convergency of the results as well as the verification of the solutions with available results in the literature are presented in details.


ABSTRACT: An analysis is presented for different bearing loadings of a plate resting on various linear and nonlinear foundations subjected to different boundary conditions such as the circled clamped, simply supported, and mixed boundary conditions. The highly accurate solutions of the plate deflection and the stress under different work conditions are obtained by the novel wavelet-homotopy technique, which are in full agreement
with previous ones in literature. Different from previous studies, our solutions are also valid for the extra large plate bending cases, which are rarely considered before. Particularly, we consider the important case that the connection coefficients of various foundations are variational, which seems to be overlooked in previous studies owing to their extreme difficulties in mathematical treatments and programming. Besides, to overcome the limitation of existing wavelet technique of poor capability on handling complex boundary conditions, we reconstruct the boundary wavelet by the Coiflets so that it can be used to handle the governing partial differential equations subjected to nonhomogeneous boundary conditions. Moreover, we introduce the homotopy iteration technique so that the computational efficiency improves to a large extent as compared with the traditional Homotopy Analysis Method (HAM) technique. It is expected the proposed wavelet-homotopy method can be as a new generation of analytical tool for solving strong nonlinear problems subjected to complicated boundary conditions, especially for those with variable coefficients.


ABSTRACT: In this paper, dynamic analysis of thick hollow rotating cylinder with finite length made of two-dimensional functionally graded material subjected to a moving mechanical load is investigated. Before applying of any mechanical load, the cylinder is under initial stresses due to initial steady state temperature gradient and rotational velocity. Then a moving mechanical distributed load excites the inner boundary surface of the cylinder. Meshless local Petrov–Galerkin (MLPG) method has been rearranged and implemented in order to discretize the governing equations in the spatial domain. The resulting sets of differential equations are then solved by Newmark time integration scheme in the temporal domain. The time histories of displacements and stresses components as well as 2D stress wave propagation are obtained for various scheme of volume fraction distribution. By implementing the presented meshless technique, the effects of material distribution, moving load, rotational body forces and thermal loading on the dynamic behavior of the FG cylinder have been investigated. The achieved results show that the effects of temperature on the stresses are greater and more important than the internal moving pressure or body force due to rotational speed. The MLPG method introduces itself as a very effective method with high accuracy for stress wave propagation and dynamic analysis of 2D-FGMs.


ABSTRACT: The behaviour of plates resting on elastic foundations has wide interest because it is an important model for many engineering applications. Natural frequencies and corresponding mode shapes are guides to investigating the behaviour of a soil-structure system with time. Therefore, free vibration analysis constitutes a considerable part of research done on this topic. In this study, the effects of the stiffness of a surrounding Modified Vlasov soil type, the soil depth, and the aspect ratio on the free vibration of a thin rectangular dowelled plate on the Modified Vlasov soil type are investigated. We used a discrete singular convolution (DSC) with a Taylor series expansion method to apply the boundary conditions. The two formulas of the Taylor series expansion are used in the DSC to eliminate the fictitious points outside the physical domain. It is noticed that beyond a certain depth, neither the effective depth of the soil nor the, frequency varies consistently. Furthermore, the dynamically activated depth influences the frequency values for plates more than for beams. In addition, the effect of the elastic rotational stiffness of the surrounding soil is found to be negligible compared

ABSTRACT: This paper examines the length-scale effect on the nonlinear response of an electrically actuated Carbon Nanotube (CNT) based nano-actuator using a nonlocal strain and velocity gradient (NSVG) theory. The nano-actuator is modeled within the framework of a doubly-clamped Euler–Bernoulli beam which accounts for the nonlinear von-Karman strain and the electric actuating forcing. The NSVG theory includes three length-scale parameters which describe two completely different size-dependent phenomena, namely, the inter-atomic long-range force and the nano-structure deformation mechanisms. Hamilton’s principle is employed to obtain the equation of motion of the nonlinear nanobeam in addition to its respective classical and non-classical boundary conditions. The differential quadrature method (DQM) is used to discretize the governing equations. The key aim of this research is to numerically investigate the influence of the nonlocal parameter and the strain and velocity gradient parameters on the nonlinear structural behavior of the carbon nanotube based nanobeam. It is found that these three length-scale parameters can largely impact the performance of the CNT based nano-actuator and qualitatively alter its resultant response. The main goal of this investigation is to understand the highly nonlinear response of these miniature structures to improve their overall performance.


ABSTRACT: This paper presents a detailed analytical investigation on the buckling and postbuckling behavior of laminated composite double curved panels with eccentrically and/or concentrically ortho-grid stiffeners subjected to in-plane compression, lateral pressure, thermal environment, and combined loads. The panels are surrounded by three parameter elastic foundations. Different types of simple-supported boundary conditions are considered. The equilibrium and compatibility equations of panel are derived based on Kirchhoff assumptions incorporating nonlinear von-Karman relations. The stress function and Galerkin method are applied to obtain explicit expressions of the buckling load and load-deflection relations. New results are presented to show effects of the combined loads, position of stiffener, and elastic foundation. As a key finding of these results, the buckling load and the postbuckling curves of concentrically stiffened panels are higher than eccentrically stiffened panels.


ABSTRACT: Due to low computing efficiency and dispersion errors, Traditional Finite Element Methods (TFEMs) based on general polynomials cannot provide efficient dynamic solutions within mid-frequency domain which is the gap between low and high frequency domain. It is also defined as mid-frequency problem in the field of sound and vibration analysis. To solve this problem, it is essential to overcome these two disadvantages simultaneously based on much better computing efficiency and numerical stability. Fortunately, due to the multi-scale/multi-resolution features, the c1 type Wavelet Finite Element Methods (WFEMs) own much better computing efficiency and numerical stability. Therefore, WFEMs will be introduced for dealing with the low computing efficiency and dispersion errors and solving the mid-frequency problem based on multi-
element analysis. But, due to the complex nodes numbering and Degree of Freedoms (DOFs) numbering, the $c_1$ type WFEMs combined with existing assembling formulas cannot provide efficient solutions by multi-element analysis any more. Therefore, this paper mainly consists of two parts of research work. On the one hand, the proper assembling formulas are derived detailedly based on $c_1$ type WFEMs. On the other hand, the method combining $c_1$ type B-spline wavelet thin plate element with the newly derived assembling formulas is proposed for predicting dynamic characteristics and solving mid-frequency problem related to thin plate structures. The numerical study shows that both computing efficiency and numerical stability of the proposed method are much better than TFEMs’. Furthermore, the proposed method's prediction ability can break through the limitation of TFEMs’ highest computing accuracy. In addition, the proposed method is verified by experimental study for predicting acceleration Frequency Response Functions (FRFs) of thin plate within 5 Hz–1000 Hz, and the experimental results indicate that the proposed method provides the potential to solve mid-frequency problem related to thin plate structures.


ABSTRACT: This paper presents an efficient hybrid optimization approach using a new coupling technique for solving the constrained optimization problems. This methodology is based on genetic algorithm, sequential quadratic programming and particle swarm optimization combined with a projected gradient techniques in order to correct the solutions out of domain and send them to the domain’s border. The established procedures have been successfully tested with some well known mathematical and engineering optimization problems, also the obtained results are compared with the existing approaches. It is clearly demonstrated that the solutions obtained by the proposed approach are superior to those of existing best solutions reported in the literature. The main application of this procedure is the location optimization of piezoelectric sensors and actuators for active control, the vibration of plates with some piezoelectric patches is considered. Optimization criteria ensuring good observability and controllability based on some main eigenmodes and residual ones are considered. Various rectangular piezoelectric actuators and sensors are used and two optimization variables are considered for each piezoelectric device: the locatio of its center and shape orientation. The applicability and effectiveness of the present methodological approach are demonstrated and the location optimization of multiple sensors and actuators are successfully obtained with some main modes and residual ones. The shape orientation optimization of sensors observing various modes as well as the local optimization of multiple sensors and actuators are numerically investigated. The effect of residual modes and the spillover reduction can be easily analyzed for a large number of modes and multiple actuators and sensors.


ABSTRACT: This study investigates the influence of surface effect on the nonlinear behavior of an electrostatically actuated circular nanoplate. The Casimir force, surface effects, and the electrostatic force are modelled. In performing the analysis, the nonlinear governing equation of a circular nanoplate is solved using a hybrid computational scheme combining a differential transformation and finite differences. The method is used to model systems found in previous literature using different methods, producing consistent results, thus verifying that it is suitable for treatment of the nonlinear electrostatic coupling phenomenon. The obtained results from numerical methods demonstrated that the relationship between the thickness, radius, and gap size of a circular nanoplate, and its pull-in voltage, is scale-dependent. The model exhibits size-dependent behavior, showing that surface effects significantly influence the dynamic response of circular nanoplate actuators.
Moreover, the influence of surface stress on the pull-in voltage of circular nanoplate is found to be more significant than the influence of surface elastic modulus. Finally, the effects of actuation voltage, excitation frequency, and surface effects on the dynamic behavior of the nanoplate are examined through use of phase portraits. Overall, the results show that the using hybrid method here presented is a suitable technique for analyzing nonlinear behavior characteristic of circular nanoplates.


ABSTRACT: A high-order compact finite-difference total Lagrangian method (CFDTLM) is developed and applied to nonlinear structural dynamic analysis. The two-dimensional simulation of thermo-elastodynamics is numerically performed in generalized curvilinear coordinates by taking into account the geometric and material nonlinearities. The spatial discretization is carried out by a fourth-order compact finite-difference scheme and an implicit second-order accurate dual time-stepping method is applied for the time integration. The accuracy and capability of the proposed solution methodology for the nonlinear structural analysis is investigated through simulating different static and dynamic benchmark problems including large deformations, large displacements and Hookean/neo-Hookean materials. The solution method is demonstrated to be free of shear-locking behavior. The results obtained by the present solution algorithm are compared with the analytical solution and the numerical results of the finite element and finite volume methods to examine the accuracy and robustness of the solution method proposed. A grid study is also performed to investigate the grid size effect on the accuracy and performance of the solution. Indications are that the solution methodology proposed is accurate for simulating nonlinear structural dynamics problems.


ABSTRACT: While classical matrix and finite-element methods are very powerful for structural analysis, some essential shortcomings such as not placing the transverse and axial loads in their actual locations on a member, as well as necessity of a large number of iterations or subdivisions of the structural element for exact second-order analysis should be still taken into consideration. To overcome such drawbacks, Generalized Differential Quadrature (GDQ) is a new semi-numerical method for analysis of the engineering problems. The aim of this paper is to use SBCGS (Satisfaction of Boundary Conditions in the General Solution) technique to perform second-order and buckling analysis of beam-columns under different geometrical and boundary conditions by solving beam-column differential equation in matrix form. In addition, a comparison is made between the results of SBCGS technique and those of other methods available in literature for the analysis of non-prismatic beam-columns with different tapered ratios when subjected to end or distributed axial loads. Using the proposed method, a rigorous second-order analysis on a beam-column member with variable cross-section and various boundary conditions under different axial and transverse distributed loads can be carried out just by one iteration and without any discretization in the member but instability appears in the results when axial load reaches critical buckling load. Moreover, in order to achieve the accuracy of the results of SBCGS technique, the model must have a large number of subdivisions in FEM method.

ABSTRACT: Buckling and free vibration analyses of nonlocal axially functionally graded Euler nanobeams is the main objective of this paper. Due to its simplicity, the Eringen's differential constitutive model is adopted for describing the nonlocal size dependency of nanostructure beam. The nonlocal equilibrium equation is derived using the principle of the minimum potential energy principle, and discretized by using the link-spring model known in literature as Hencky bar-chain model. The general applicability of the proposed approach allows analyses of functional graded microbeams without any restriction on variability, boundary and loading conditions. A comparison with results available in the literature shows the reliability of the method.


ABSTRACT: This paper presents the semi-layerwise analysis of structural sandwich plates with through-width delamination. The mechanical model of rectangular plates is based on the method of four equivalent single layers and the system of exact kinematic conditions. An important improvement compared to a previous formulation is the consideration of linear and quadratic stretching term in the transverse displacement component. Three different delamination scenarios are investigated: core-core failure, face-core delamination and the face-face failure. By applying the first- and second-order laminated plate theories and the principle of virtual work the governing equations are derived. The equilibrium equations are solved under Lévy type boundary conditions using the state-space approach. Solutions for the mechanical fields are provided and compared to 3D finite element results. The energy release rate distributions along the delamination front are also determined using the J-integral. Although the stress resultants by transverse stretching do not influence directly the J-integral, the results indicate that this effect improves the accuracy of the model in general, and substantially influences the results of the first-order plate theory in the case of the face-face delamination.


ABSTRACT: In this work, the static stability of a thin plate in axial subsonic airflow is studied using the framework of Possio integral equation. Specifically, we consider the cases when the plate’s leading edge is free and the plate’s trailing edge is either pinned or clamped. We formulate the problem under consideration using a partial differential equations (PDE) model and then linearize the model about the free stream velocity, density, and pressure, to enable analytical treatment. Based on the linearized model, we introduce a new derivation of a Possio integral equation that relates the pressure jump along the thin plate to the plate’s downwash. The steady state solution to the Possio equation is then used to account for the aerodynamic loads in the plate steady state governing equation resulting in a singular differential-integral equation which is transformed to a singular integral equation that represents the static aeroelastic equation of the plate. We verify the solvability of the static aeroelastic equation based on the Fredholm alternative for compact operators in Banach spaces and the contraction mapping theorem. By constructing solutions to the static aeroelastic equation and matching the nonzero boundary conditions at the trailing edge with the zero boundary conditions at the leading edge, we obtain characteristic equations for the free-clamped and free-pinned plates. The minimum solutions to the characteristic equations are the divergence speeds which indicate when static instabilities start to occur. We show analytically that free-pinned plates are statically unstable. We also construct, analytically, flow speed intervals that correspond to static stability regions for free-clamped plates. Furthermore, we resort to numerical computations to obtain an explicit formula for the divergence speed of free-clamped plates. Finally, we apply the obtained results on piezoelectric plates and we show that free-clamped piezoelectric plates are statically more stable than conventional free-clamped plates due to the piezoelectric coupling.

ABSTRACT: When a plate is subjected to long-term vibration the original boundary conditions are no longer ideal and necessary correction should be considered during its dynamical modeling. This paper aims at the modeling of the boundary conditions correction and its influence on the nonlinear dynamics of a harmonic excited plate in subsonic flow. The plate boundary conditions with correction are non-autonomous and converted into autonomous by using a coordinate transformation upon the orthogonal Legendre polynomials. The fluid force is separated into the reactive and resistive parts. The reactive fluid force, due to plate motion, is derived from the bound and wake vorticity in Glauert’s expansion; the resistive force, which is independent on plate motion, is evaluated in drag coefficient. The governing nonlinear partial differential equation is discretized in space and time domains by using the Galerkin method. Results show that the present fluid model is in good agreement with other theories archived and is reliable. The unforced system loses its stability by divergence following a pitchfork-like bifurcation featured by the appearance of new bifurcated stable equilibrium points due to nonlinearity after instability. The boundary conditions correction can stabilize the system and does not change the bifurcation structure and scaling property. The symmetry-breaking/restoring bifurcations play an important role in the change of different period-1 motions, and the nature of such bifurcations is associated with the collision or division of attractors. Subharmonic motions and chaos appear alternatively, and the transition between chaos and periodic motions is generally in accompany with period-doubling bifurcations, explosion and condensation of attractors.


ABSTRACT: A nonlinear surface-stress-dependent nanoscale shell model is developed on the base of the classical shell theory incorporating the surface stress elasticity. Nonlinear free vibrations of circular cylindrical nanoshells conveying fluid are studied in the framework of the proposed model. In order to describe the large-amplitude motion, the von Kármán nonlinear geometrical relations are taken into account. The governing equations are derived by using Hamilton's principle. Then, the method of multiple scales is adopted to perform an approximately analytical analysis on the present problem. Results show that the surface stress can influence the vibration characteristics of fluid-conveying thin-walled nanoshells. This influence becomes more and more considerable with the decrease of the wall thickness of the nanoshells. Furthermore, the fluid speed, the fluid mass density, the initial surface tension and the nanoshell geometry play important roles on the nonlinear vibration characteristics of fluid-conveying nanoshells.


ABSTRACT: A dynamic model of an extensible fluid-conveying curved pipe with an arbitrary undeformed configuration is established in a curvilinear coordinate system based on differential geometry, equilibrium equations and constitutive relations. Velocity and acceleration vectors of an arbitrary point of fluid on the centroid line of the pipe under the arbitrary undeformed configuration are obtained. The differential quadrature method is applied to discretize the physical model in the spatial domain and a set of differential-algebraic equations are obtained. A partitioned matrix method is employed to obtain natural frequencies of the fluid-conveying curved pipe and its critical velocities. A parametric study is conducted to investigate the dynamics of
different fluid-conveying curved pipes. Numerical results show that the dynamics of a pipe is significantly influenced by its undeformed configuration. It is found that there are ranges of span arc angles within which the first critical velocities of arc-type pipes with different initial geometrical imperfections have dramatic changes.

**End of more papers published in the journal, Applied Mathematical Modelling.** (2017 and on)

**More papers published in the journal, Archive of Computational Methods in Engineering (2017 and on)**


**ABSTRACT:** This paper presents a critical comparative assessment of Kriging model variants for surrogate based uncertainty propagation considering stochastic natural frequencies of composite doubly curved shells. The five Kriging model variants studied here are: Ordinary Kriging, Universal Kriging based on pseudo-likelihood estimator, Blind Kriging, Co-Kriging and Universal Kriging based on marginal likelihood estimator. First three stochastic natural frequencies of the composite shell are analysed by using a finite element model that includes the effects of transverse shear deformation based on Mindlin’s theory in conjunction with a layer-wise random variable approach. The comparative assessment is carried out to address the accuracy and computational efficiency of five Kriging model variants. Comparative performance of different covariance functions is also studied. Subsequently the effect of noise in uncertainty propagation is addressed by using the Stochastic Kriging. Representative results are presented for both individual and combined stochasticity in layer-wise input parameters to address performance of various Kriging variants for low dimensional and relatively higher dimensional input parameter spaces. The error estimation and convergence studies are conducted with respect to original Monte Carlo Simulation to justify merit of the present investigation. The study reveals that Universal Kriging coupled with marginal likelihood estimate yields the most accurate results, followed by Co-Kriging and Blind Kriging. As far as computational efficiency of the Kriging models is concerned, it is observed that for high-dimensional problems, CPU time required for building the Co-Kriging model is significantly less as compared to other Kriging variants.

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Pablo Moreno-Garcia, Jose V. Araujo dos Santos and Hernani Lopes, “A review and study of Ritz method admissible functions with emphasis on buckling and free vibration of isotropic and anisotropic beams and plates”, Archives of Computational Methods in Engineering, Vol. 25, No. 3, pp 785-815, July 2018

ABSTRACT: The first goal of this work is to present a literature review regarding the use of several sets of admissible functions in the Ritz method. The papers reviewed deal mainly with the analysis of buckling and free vibration of isotropic and anisotropic beams and plates. Theoretically, in order to obtain a correct solution, the set of admissible functions must not violate the essential or geometric boundary conditions and should also be linearly independent and complete. However, in practice, some of the sets of functions proposed in the literature present a bad numerical behavior, namely in terms of convergence, computational time and stability. Thus, a second goal of the present work is to compare the performance of several sets of functions in terms of these three features. To achieve this objective, the free vibration analysis of a fully clamped rectangular plate is carried out using six different sets of functions, along with the study of the convergence of natural frequencies and mode shapes, the computational time and the numerical stability.

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Benjamin Marussig and Thomas J.R. Hughes, “A review of trimming in isogeometric analysis: Challenges, data exchange and simulation aspects”, Archives of Computational Methods in Engineering, Vol. 25, No. 4, pp 1059-1127, November 2018 (Also see Erratum to: …, p 1131)

ABSTRACT: We review the treatment of trimmed geometries in the context of design, data exchange, and computational simulation. Such models are omnipresent in current engineering modeling and play a key role for the integration of design and analysis. The problems induced by trimming are often underestimated due to the conceptional simplicity of the procedure. In this work, several challenges and pitfalls are described.

End of more papers published in the journal, Archive of Computational Methods in Engineering (2017 and on)


ABSTRACT: In the present research, free vibration of circular and annular sandwich plates with auxetic (negative Poisson’s ratio) cores and isotropic/orthotropic face sheets is investigated for different combinations of the boundary conditions. To ensure that the results are accurate and reliable, a global–local layerwise plate theory is employed instead of the traditional equivalent single-layer theories. The governing equations are derived based on Hamilton’s principle and solved using a Taylor transform whose center is located at the outer radius of the plate. Due to this hint, the resulting semi-analytical solution can be employed for both circular and annular sandwich plates. After investigation of vibration behavior of a single-layer annular auxetic plate, a comprehensive parametric study including evaluation of effects of the auxeticity for sandwich plates with isotropic and orthotropic face sheets, symmetric and asymmetric layups, different core to sheet thickness, radius to thickness, and inner to outer radius ratios, and various boundary conditions, is carried out. Results show that unlike the single-layer auxetic plates that exhibit a transition state, the auxeticity may considerably increase the natural frequencies and rigidities of the circular/annular sandwich plates, especially when the boundary conditions induce higher rigidity in the plate or when the fibers are along the radial direction. Accuracy of results of the employed layerwise theory and the proposed semi-analytical solution is verified by comparing the results with those of the three-dimensional theory of elasticity extracted from the ABAQUS software.

References listed at the end of the paper:


ABSTRACT: Nonlinear triangular space membrane elements are developed for the analysis of thin structures subjected to dynamic loading. By using a co-rotated framework, displacements are decomposed into rigid body motions and pure deformational displacements. The novelty of the formulation is that it employs the co-rotated framework to derive tangent dynamic matrix and an inertial force vector. Closed forms for the inertia force vector, the tangent dynamic matrix, the mass matrix and the gyroscopic matrix are derived directly from the current coordinate transformation matrix. Three numerical examples are presented to illustrate the robustness and efficiency of the new co-rotational formulation. The efficiency of the proposed approach is compared to the updated Lagrangian method, and savings in computation of up to 50 %, were achieved.

References listed at the end of the paper:

ABSTRACT: A robust design optimization (RDO) approach for minimum weight and safe shell composite structures with minimal variability into design constraints under uncertainties is proposed. A new concept of feasibility robustness associated to the variability of design constraints is considered. So, the feasibility robustness is defined through the determinant of variance–covariance matrix of constraint functions introducing in this way the joint effects of the uncertainty propagations on structural response. A new framework considering aleatory uncertainty into RDO of composite structures is proposed. So, three classes of variables and parameters are identified: deterministic design variables, random design variables and random parameters. The bi-objective optimization search is performed using on a new approach based on two levels of dominance denoted by Co-Dominance-based Genetic Algorithm (CoDGA). The use of evolutionary concepts together sensitivity analysis based on adjoint variable method is a new proposal. The examples with different sources of uncertainty show that the Pareto front definition depends on random design variables and/or random parameters considered in RDO. Furthermore, the importance to control the uncertainties on the feasibility of constraints is demonstrated. CoDGA approach is a powerfully tool to help designers to make decision establishing the priorities between performance and robustness.

References listed at the end of the paper:

of coupled nonlinear equations. The tapered sandwich plate subjected to air blast load is also modelled by using nonlinear differential equations in the time domain. The finite difference method is applied to solve the system assumed for the space domain and substituted into the equations. The Galerkin method is used to obtain the equations of motion are derived by the use of the virtual work principle. Approximate solution functions are found in the literature is developed to analyze the tape deformations. The sandwich plate theory for plates with constant thickness which have one plate theory, which includes von Kármán large deformation effects, in-plane stiffnesses, inertias and shear deformations. The sandwich plate theory for plates with constant thickness which have one-layered face sheets and be subjected to uniform air blast load. The theory is based on a sandwich plate theory, which includes von Kármán large deformation effects, in-plane stiffnesses, inertias and shear deformations. The sandwich plate theory for plates with constant thickness which have one-layered face sheets found in the literature is developed to analyze the tapered sandwich plates with multi-layered face sheets. The equations of motion are derived by the use of the virtual work principle. Approximate solution functions are assumed for the space domain and substituted into the equations. The Galerkin method is used to obtain the nonlinear differential equations in the time domain. The finite difference method is applied to solve the system of coupled nonlinear equations. The tapered sandwich plate subjected to air blast load is also modelled by using
the finite element method. The displacement–time and strain–time histories are obtained. The theoretical results are compared with finite element results and are found to be in an agreement.

References listed at the end of the paper:

References listed at the end of the paper:


ABSTRACT: The closed-form solutions of a piezoelectric exponentially graded fiber-reinforced hollow cylinder in hygrothermal environment conditions are investigated. The interaction of electric displacement and electric potentials as well as the elastic deformations is discussed. The present piezoelectric fiber-reinforced circular cylinder is subjected to a mechanical load as well as an electric potential at its lateral surfaces. The resultant constitutive equations of the piezoelectric fiber-reinforced composite cylinder are analytically investigated. The thermal conductivity and the moisture diffusivity coefficient are supposed to change continuously in the radial direction by a simple exponential law. The hygrothermoelastic responses of piezoelectric exponentially graded fiber-reinforced hollow circular cylinders are presented. The significant influence of the graduation of material, temperature, moisture, pressures and electric parameters is investigated. Concluding remarks and appropriate discussions are presented.


ABSTRACT: Based on Reissner’s mixed variational theorem (RMVT), we develop a weak-form formulation of finite doubly curved layer (FDCL) methods for the static analysis of simply-supported, multilayered functionally graded material (FGM) doubly curved shells (DCSs) under mechanical loads. This formulation is used to examine the spatial distributions of interlaminar stress and displacement components induced in a pressure-loaded FGM film-substrate DCS, and these solutions are compared with those obtained by using the principle of virtual displacements. The material properties of the multilayered (or film-substrate) shell are thickness-dependent, and the effective material properties of the FGM layer are estimated using the rule of mixtures and Mori–Tanaka scheme. The trigonometric functions and Lagrange polynomials are used to interpolate the in-surface and thickness variations of the primary variables of each individual layer, respectively. The orders used to expand the primary variables through the thickness direction are taken to be the same as one another, which are linear, quadratic and cubic variations. The accuracy and convergence rate of these RMVT-based FDCL methods are validated by comparing their solutions with the exact three-dimensional and accurate two-dimensional solutions available in the literature.

References listed at the end of the paper:


ABSTRACT: In this paper, the progressive collapse of foam filled conical frusta is investigated analytically using four different kinematically admissible folding mechanisms with varied straight folds. Comparisons are made between these four kinematically admissible mechanisms; specifically, pure inward folding, pure outward folding, first inward followed by outward folding, and first outward followed by inward folding. The instantaneous force as well as the mean crushing force was derived based on the principle of energy conversation, and the crushing energy was absorbed by the plastic deformation of the shell, the crushing of foam filler and the foam/shell interaction. The resulted upper bound solution of the four different mechanisms is compared with the finite element predictions of the same system. Our parametric study reveals that first outward then inward folding mechanism is generally energy favorable except for cases involving greater foam resistance, thin shell thickness, and/or large taper angle in which the pure outward folding mechanism may be preferable.

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ABSTRACT: In this article, dynamic buckling analysis of an embedded curved microbeam reinforced by functionally graded carbon nanotubes is carried out. The structure is subjected to thermal, magnetic and harmonic mechanical loads. Timoshenko beam theory is employed to simulate the structure. Furthermore, the temperature-dependent surrounding elastic foundation is modeled by normal springs and a shear layer. Using strain gradient theory, the small scale effects are taken into account. The extended rule of mixture is employed to estimate the equivalent properties of the composite material. The governing equations and different boundary conditions are derived based on the energy method and Hamilton’s principle. Dynamic stability regions of the system are obtained using differential quadrature method. The aim of this paper is to investigate the influence of different parameters such as small scale effect, boundary conditions, elastic foundation, volume fraction and distribution types of carbon nanotubes, magnetic field, temperature and central angle of the curved microbeam on the dynamic stability region of the system. The results indicate that by increasing the volume fraction of CNTs, the frequency of the system increases and thus the dynamic stability region occurs at higher frequencies.


ABSTRACT: The present article deals with flexural and vibration response of functionally graded plates with porosity. The basic formulation is based on the recently developed non-polynomial higher-order shear and normal deformation theory by the authors’. The present theory contains only four unknowns and also accommodate the thickness stretching effect. The effective material properties at each point are determined by two micromechanics models (Voigt and Mori–Tanaka scheme). The governing equations for FGM plates are derived using variational approach. Results have been obtained by employing a $C^0$ continuous isoparametric Lagrangian finite element with eight degrees of freedom per node. Convergence and comparative study with the reported results in the literature, confirm the accuracy and efficiency of the present model and finite element formulation. The influence of the porosity, various boundary conditions, geometrical configuration and micromechanics models on the flexural and vibration behavior of FGM plates is examined.


ABSTRACT: The stiffened composite plates with the transverse crack and delamination were studied in this paper, and an extended layerwise/solid-element (XLW/SE) method was developed. In the proposed method, the governing equations of composite plates and stiffeners were established based on the extended layerwise
method and 3D solid elements, respectively. The final governing equation of stiffened composite plates is assembled by using the compatibility conditions and internal force equilibrium conditions at the joint interface between the plates and stiffeners. For the stiffened composite plates with damages, the XLW/SE method can obtain the local stress and displacement fields accurately and simulate the in-plane transverse cracks and delaminations simultaneously, considering complicated stiffeners without any assumptions. In the numerical examples, the results obtained by the proposed method are compared with those obtained by the 3D elastic models developed in the general finite element code, and the good agreements were achieved for the stiffened composite plates with/without delaminations and/or transverse crack.

References listed at the end of the paper:


ABSTRACT: The design and analysis of lattice structures manufactured using additive manufacturing technique is a new approach to create lightweight high-strength components. However, it is difficult for engineers to choose the proper unit cell for a certain function structure and loading case. In this paper, three beam-like lattice structures with triangular prism, square prism and hexagonal prism were designed, manufactured by SLM process using AlSi10Mg and tested. The mechanical performances of lattice structures with equal relative density, equal base area and height, and equal length for all unit cells were conducted by finite element analysis (FEA). It was found that effective Young’s modulus is proportional to relative density, but with different affecting levels. When the lattice structures are designed with the same relative density or the same side lengths, the effective Young’s modulus of lattice structure with triangular prism exhibits the maximum value for both cases. When the lattice structures are designed with the same base areas for all unit cells, the effective Young’s modulus of lattice structures with square prism presents the maximum. FEA results also show that the maximum stress of lattice structures with triangular prisms in each comparison is at the lowest level and the stiffness-to-mass ratio remains at the maximum value, showing the overwhelming advantages in terms of mechanical strength. The excellent agreements between numerical results and experimental tests reveal the validity of FEA methods applied. The results in this work provide an explicit guideline to fabricate beam-like lattice structures with the best tensile and bending capabilities.


ABSTRACT: The importance of focusing on the research of viable models to predict the behaviour of structures which may possess in some cases complex geometries is an issue that is growing in different
scientific areas, ranging from the civil and mechanical engineering to the architecture or biomedical devices fields. In these cases, the research effort to find an efficient approach to fit laser scanning point clouds, to the desired surface, has been increasing, leading to the possibility of modelling as-built/as-is structures and components’ features. However, combining the task of surface reconstruction and the implementation of a structural analysis model is not a trivial task. Although there are works focusing those different phases in separate, there is still an effective need to find approaches able to interconnect them in an efficient way. Therefore, achieving a representative geometric model able to be subsequently submitted to a structural analysis in a similar based platform is a fundamental step to establish an effective expeditious processing workflow. With the present work, one presents an integrated methodology based on the use of meshless approaches, to reconstruct shells described by points’ clouds, and to subsequently predict their static behaviour. These methods are highly appropriate on dealing with unstructured points clouds, as they do not need to have any specific spatial or geometric requirement when implemented, depending only on the distance between the points. Details on the formulation, and a set of illustrative examples focusing the reconstruction of cylindrical and double-curve shells, and its further analysis, are presented.

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Local/distortional/global mode interaction in simply supported cold-formed steel channel column with various types of edge stiffener”, International Journal of Advanced Structural Engineering, Vol. 9, No. 2, pp 129-138, June 2017

ABSTRACT: This paper presents the strength and behaviour of web stiffened cold formed steel channel column with various types of edge stiffener under axial compression. An accurate finite element model is developed to simulate the tests results of the proposed section. The finite element model is verified by the test results and good correlation is achieved. The failure modes local, distortional, flexural buckling as well as the interaction between these modes is found in this study. The column strength predicted from the parametric study is compared with the nominal strength calculated by using the direct strength method for cold formed steel members. The reliability of this method is evaluated and suitable modification factor is proposed.

References listed at the end of the paper:


ABSTRACT: In this paper, the analytical solution for static and vibration analysis the cross-ply laminated composite doubly curved shell panels with stiffeners resting on Winkler–Pasternak elastic foundation is presented. Based on the first-order shear deformation theory, using the smeared stiffeners technique, the motion equations are derived by applying the Hamilton’s principle. The Navier’s solution for shell panel with the simply supported boundary condition at all edges is presented. The accuracy of the present results is compared with those in the existing literature and shows good achievement. The effects of the number of stiffeners, stiffener’s height to width ratio, and number of layers of cross-ply laminated composite shell panels on the fundamental frequencies and deflections of stiffened shell with and without the elastic foundation are investigated.

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ABSTRACT: Grid shells supporting transparent or opaque panels are largely used to cover long-spanned spaces because of their lightness, the easy setup, and economy. This paper presents the results of experimental static and dynamic investigations carried out on a large-scale free-form grid shell mock-up, whose geometry descended from an innovative Voronoi polygonal pattern. Accompanying finite-element method (FEM)
simulations followed. To these purposes, a four-step procedure was adopted: (1) a perfect FEM model was analyzed; (2) using the modal shapes scaled by measuring the mock-up, a deformed unloaded geometry was built, which took into account the defects caused by the assembly phase; (3) experimental static tests were executed by affixing weights to the mock-up, and a simplified representative FEM model was calibrated, choosing the nodes stiffness and the material properties as parameters; and (4) modal identification was performed through operational modal analysis and impulsive tests, and then, a simplified FEM dynamical model was calibrated. Due to the high deformability of the mock-up, only a symmetric load case configuration was adopted.

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ABSTRACT: An aircraft crashing into a nuclear containment may induce a series of disasters related to containment capacity, including local penetration and perforation of the containment, intensive vibrations, and fire ignited after jet fuel leakage. In this study, structural safety of a reinforced concrete containment vessel (RCCV) has been studied against the direct hit of Airbus A320, Boeing 707-320 and Phantom F4 aircrafts. ABAQUS/explicit finite element code has been used to carry out the three-dimensional numerical simulations. The impact locations identified on the nuclear containment structure are mid height of containment, center of the cylindrical portion, junction of dome and cylinder, and over the cylindrical portion close to the foundation level. The loading of the aircraft has been assigned through the corresponding reaction-time response curve. The concrete damaged plasticity model was predicted to simulate the behavior of concrete while the behavior of steel reinforcement was incorporated using elastoplastic material model. Dynamic loading conditions were considered using dynamic increase factor. The mid height of containment and center of cylindrical portion have been found to experience most severe deformation against each aircraft crash. It has also been found that compression damage in concrete is not critical at none of the impact locations.

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ABSTRACT: SRCFT columns are formed by inserting a steel section into a concrete-filled steel tube. These types of columns are named steel-reinforced concrete-filled steel tubular (SRCFT) columns. The current study aims at investigating the various types of reinforcing steel section to improve the strength and hysteresis behavior of SRCFT columns under axial and lateral cyclic loading. To attain this objective, a numerical study has been conducted on a series of composite columns. First, FEM procedure has been verified by the use of available experimental studies. Next, eight composite columns having different types of cross sections were analyzed. For comparison purpose, the base model was a CFT column used as a benchmark specimen. Nevertheless, the other specimens were SRCFT types. The results indicate that reinforcement of a CFT column through this method leads to enhancement in load-carrying capacity, enhancement in lateral drift ratio, ductility, preventing of local buckling in steel shell, and enhancement in energy absorption capacity. Under cyclic displacement history, it was observed that the use of cross-shaped reinforcing steel section causes a higher level of energy dissipation and the moment of inertia of the reinforcing steel sections was found to be the most significant parameter affecting the hysteresis behavior of SRCFT columns.

References listed at the end of the paper:


ABSTRACT: Prediction of plate behavior in large deformation is one of the important problems in plate theories. Cosserat theory is an advanced theory for simulation of plates in very large deformation, but it is complex from mathematical viewpoint. Another theory that has been used extensively for large deformation problems is nonlinear Von Karman theory which is easy for formulation and computation. In this paper, these theories were compared for rectangular and skew plates in simply supported and clamped boundary conditions to propose the acceptable range of using nonlinear Von Karman in very large deformation as a simpler theory. Higher order shear deformation plate theory was used with Von Karman nonlinearity. Whole domain method was employed for numerical solution. Each theory was validated with the literature for verification of the numerical method. Deflection and stress distribution were compared from small to very large deformations. The obtained results show that two theories were matched up to the maximum nondimensional deflection of 5 and 3 for simply supported and clamped boundary conditions, respectively. Moreover, by increasing the skew angle, the consistency of two theories would decrease even in deflections smaller than the thickness of the plate.


ABSTRACT: Spherical storage tanks are widely used for various types of liquids, including hazardous contents, thus requiring suitable and careful design for seismic actions. On this topic, a significant case study is described in this paper, dealing with the dynamic analysis of a spherical storage tank containing butane. The analyses are based on a detailed finite element (FE) model; moreover, a simplified single-degree-of-freedom idealization is also set up and used for verification of the FE results. Particular attention is paid to the influence of sloshing effects and of the soil–structure interaction for which no special provisions are contained in technical codes for this reference case. Sloshing effects are investigated according to the current literature state of the art. An efficient methodology based on an “impulsive–convective” decomposition of the container-fluid motion is adopted for the calculation of the seismic force. With regard to the second point, considering that the tank is founded on piles, soil–structure interaction is taken into account by computing the dynamic impedances. Comparison between seismic action effects, obtained with and without consideration of sloshing and soil–structure interaction, shows a rather important influence of these parameters on the final results. Sloshing effects and soil–structure interaction can produce, for the case at hand, beneficial effects. For soil–structure interaction, this depends on the increase of the fundamental period and of the effective damping of the overall system, which leads to reduced design spectral values.

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ABSTRACT: Cylindrical storage tanks are widely used for various types of liquids, including hazardous contents, thus requiring suitable and careful design for seismic actions. The study herein presented deals with the dynamic analysis of a ground-based horizontal cylindrical tank containing butane and with its safety verification. The analyses are based on a detailed finite element (FE) model; a simplified one-degree-of-
freedom idealization is also set up and used for verification of the FE results. Particular attention is paid to sloshing and asynchronous seismic input effects. Sloshing effects are investigated according to the current literature state of the art. An efficient methodology based on an “impulsive-convective” decomposition of the container-fluid motion is adopted for the calculation of the seismic force. The effects of asynchronous ground motion are studied by suitable pseudo-static analyses. Comparison between seismic action effects, obtained with and without consideration of sloshing and asynchronous seismic input, shows a rather important influence of these conditions on the final results.

References listed at the end of the paper:

ABSTRACT: The free vibration characteristics, such as fundamental frequency and mode shape of stiffened plates employing standard finite element analysis, are investigated in this paper. The parametric study is presented for free vibration characteristics of stiffened plates with various parameters, such as type, orientation and number of stiffeners, boundary conditions and aspect ratio of plates and stiffener depth to plate thickness ratio. Typical mode shapes are also presented for clamped square eccentrically stiffened plates. Finally, design charts with non-dimensional parameters are proposed to determine the fundamental frequency of commonly adopted clamped stiffened plates in construction. These charts will be very much useful for designers for obtaining the fundamental frequencies of the stiffened plates of different dimensions without doing much complicated analysis or using standard computer codes.

References listed at the end of the paper:


ABSTRACT: The aim of the study is to investigate the distortional buckling behaviour of intermediate cold-formed lipped channel section under pinned end condition subjected to axial compression. An extensive test and numerical investigation of cold-formed lipped channel column with various types of intermediate web stiffeners is presented. In this study, three types of intermediate web stiffeners are chosen such as V, U and Σ. The entire cross-sectional dimensions meet with the pre-qualified column dimension given in Direct Strength Method for cold-formed steel structures. Totally, 12 columns are tested and results are compared with the numerical analysis. Numerical analysis is carried out using software ABAQUS. Material and geometric imperfections are incorporated in the FE model. Selected section dimensions met with the distortional buckling mode. Good correlation is achieved between experiment and finite element analysis. All the results are compared with the Direct Strength Method specifications for cold-formed steel structures. Based on the comparison of results, a suitable design modification is proposed. Furthermore, results are verified with the existing results which are available from the literature.

References listed at the end of the paper:
ABSTRACT: The seismic design codes/standards of most countries include the nonlinear response of a structure implicitly through a response reduction/modification factor \( R \). It is the factor by which the actual base shear should be reduced to find the design base shear during design basic earthquake considering nonlinear behavior and deformation limits of structures. In the present study, attempts are made to determine the \( R \) factors of four existing RC staging elevated water tanks, which are designed as per draft Indian standards for seismic design of liquid and RC designs and having a ductile detailing considering the effects of soil flexibility. The elevated RC water tanks are analyzed using displacement controlled non-linear static pushover analysis to evaluate the base shear capacity and ductility of tank considering soil flexibility. The \( R \) factor is obtained for four realistic designs of elevated RC water tanks having different capacities at two performance levels. The
evaluated values of ‘R’ factor are compared with the values suggested in the design code. The results of the study show that the flexibility of supporting soil has considerable effect on response reduction factor, period and overall performance of water tank, indicating that idealization of fixity at base may be seriously mistaken for soft soils. All the studied water tanks were designed with higher safety margin than that of specified in Indian Standards.

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- BIS IS 13920 (1993) Ductile detailing of reinforced concrete structure subjected to seismic forces-code of practise. Bureau of Indian Standards, New Delhi, India
- BIS IS 1893 (2014) Criteria for earthquake resistant design of structures, Part 2. Bureau of Indian Standards, New Delhi, India
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ABSTRACT: The purpose of the paper is to develop an analytical investigation on free vibration of a simply supported functionally graded (FG) doubly curved shell panels resting on elastic foundation in thermal environment. Heat conduction and temperature-dependent material properties are both taken into account. The temperature field considered is assumed to be a uniform distribution over the shell surface and varied in the thickness direction only. Material properties are assumed to be temperature dependent and graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. Based on the first-order shear deformation theory and applying the Hamilton’s principle, governing equations of motion are derived. The results of the study are compared with the available published literature. The numerical results obtained reveal that the material volume fraction index, geometrical parameters and temperature change have significant effects on natural frequencies of the FG doubly curved shell panels.

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1 Alijani F, Amabili M, Bakhtiari-Nejad F (2011) Thermal effects on nonlinear vibrations of functionally graded doubly curved shells using higher order shear deformation theory. Compos Struct 93(10):2541–2553

End of more papers published in the journal, International Journal of Advanced Structural Engineering (2017 and on)


ABSTRACT: Shells are among the most frequent structural components which are used in construction and industrial projects. Shell structures are composed of shell bearing elements and mainly used in oil and gas tanks, offshore marine platforms, silos, funnels, cooling towers, ship and aircraft body, etc. Despite the frequent use of steel cylindrical shells, their construction and assembling process has caused main problems. In these structures, there is no possibility for the integrated construction due to their large shell extent and they are built using a number of welded curved panel parts; hence, some geometrical imperfections emerge. Most of these imperfections are caused by the process of welding, transportation, inappropriate rolling, as well as installation and implementation problems. These imperfections have a direct impact on the structural behavior of shells during the buckling and external compressive load. Since in most shell tanks during operation, there is high possibility for the suction (vacuum) state, compressive forces in their thin wall cause buckling and failure. In this research, the imperfections made in steel cylindrical tanks being constructed in one of the refinery site are introduced and evaluated using a field study. Relying on the statistical inference, they are classified and then, by studying the effective factors and origin in their generation, the common imperfections are identified. Later, the impact of common imperfections on the buckling behavior is experimentally evaluated under uniform external pressure. Then, nonlinear numerical analysis of the test specimens is performed. Finally, experimental results, finite element and analytical relations are compared.

References listed at the end of the paper:
ABSTRACT: Fluids being passing through a pipeline system can cause internal vibrations within the pipelines. If these vibrations weren’t considered at the design of the system, and flow induced vibrations resonate with the pipes natural frequency, the sudden amplified vibrations can cause destructive damage to the pipeline system. Thus, it is extremely important to identify and predict all vibrations a certain pipeline system will possibly encounter during its lifetime when designing the system, also choosing the proper material with regard to their natural frequencies to avoid destructive resonances from happening. In this study, using ABAQUS as a CFD solver, we studied the forced and free vibrations caused by a turbulence flow of a fluid with different speeds through a 90 degree bent elbow pipe. We compared the vibration modes and frequencies for different cases of fluid speeds, and concluded at what natural frequency a vibration resonance may occur leading to a possible pipe failure.

References listed at the end of the paper:


No appropriate papers in Vol. 6, No. 5
No appropriate papers in Vol. 6, No. 6
No appropriate papers in Vol. 7, No. 1 (2018)
No appropriate papers in Vol. 7, No. 2
No appropriate papers in Vol. 7, No. 3
No appropriate papers in Vol. 7, No. 4

End of more papers published in the journal, International Journal of Applied Mechanical Engineering (2017 and on)


ABSTRACT: Thin-walled steel elements in the form of openwork columns with variable geometrical parameters of holes were studied. The samples of thin-walled composite columns were modelled numerically. They were subjected to axial compression to examine their behavior in the critical and post-critical state. The numerical models were articulately supported on the upper and lower edges of the cross-section of the profiles. The numerical analysis was conducted only with respect to the non-linear stability of the structure. The FEM analysis was performed until the material achieved its yield stress. This was done to force the loss of stability by the structures. The numerical analysis was performed using the ABAQUS software. The numerical analysis was performed only for the elastic range to ensure the operating stability of the tested thin-walled structures.

References listed at the end of the paper:

ABSTRACT: The performance of buckling load of tubular structures under quasi-static axial loading is quite appreciable, numerous tubes of various cross-section have been extensively investigated and corrugated sections have been designed to further improve the performance. In this paper, a carefully designed set of key performance indicators (KPIs) is utilized to assess and compare the buckling load of circular and corrugated tubes. A series of diagrams related to KPIs with various parameters of tubes are presented to demonstrate the influence of sectional configuration on the performance of tubes as well as the effect of the material on the potential of the same. The work is inestimable to engineering designs and applications, and further studies on the buckling load of other configurations.

References listed at the end of the paper:

ABSTRACT: The model of a damped orthotropic rectangular plate resting on a Winkler foundation with a simple support has the fourth order differential equation governing it, which is reduced to a second order coupled differential equation by separating the variables. The coupled differential equation was solved using numerical schemes. The classical condition used as an illustrative example is the simple support condition. It is observed that damping plays a very significant role in the vibration of solid structures, as it has been shown that the deflection profile depends greatly on the damping ratio. The deflection profile also proves to be more stable in the presence of foundation coupled with viscous damping. The results obtained were discussed and graphically presented.

References listed at the end of the paper:

ABSTRACT: Domes are one of the oldest and well-established structural forms and have been used in architecture since the earliest times (Lan, [1]). However, their lattice versions have begun to be constructed in the 19th century, when the steel and cast iron production technology was developed (Szaniec and Biernacka, [2]). Since then, they have been of special interest to structure designers as they enclose a maximum amount of space with a minimum surface and have proved to have very economical strength-to-weight ratios (Lan, [1]).

Therefore, it seems essential to examine their reliability and additionally compare it for several selected types frequently used in practice. Computer analysis of civil engineering structures with random parameters has a remarkably increasing influence on structural design processes, optimization and reliability modelling because of a variety of natural sources of uncertainties and human activity driven reasons. In the case of the domes examined, the Young modulus uncertainty, as one of the most important parameters, has been considered. A solution of the structural problem including randomness is accompanied with the reliability indices verification, according to the general rules included in the Eurocode [3]. Their determination has been provided here by an application of the global version of the response function method and the direct symbolic integral calculation of its basic probabilistic moments. Computational implementation of this method has been made for a solution of the eigenproblem, stability and static problems using the FEM civil engineering system ROBOT. The integration process has been provided by the computer algebra system MAPLE, where also the coefficients of responses have been computed from several solutions of the original problem obtained for the Young modulus varying about its expectation. This form leads to a determination of all structural response functions with respect to the random Gaussian input variable. They can be further used for the determination of probabilistic moments and final values of the reliability indices. Finally, the results may be compared to find out which structure is more efficient in terms of the assumed uncertainty.

References listed at the end of the paper:
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Computer Science, vol.9, No.2, pp.244-250.


ABSTRACT: The present study is based on the nonlinear bending analysis of an FGM plate with Von-Karman strain based on the non-linear classical plate theory (NLCPT) with in-plane displacement and moderate rotation. Non-linear bending analysis based on stresses and transverse deflections is then carried out for the plate for the complex solution obtained using an analytical method viz. Navier’s method. The equations of motion and boundary conditions are obtained using the Principle of Minimum Potential Energy (PMPE) method and material property is graded in thickness direction according to simple power-law distribution in terms of volume fractions of the constituents. The effect of the span-to-thickness ratio and FGM exponent on the maximum central deflection and stresses are studied. The results show that the response is transitional with respect to ceramic and metal and the complex solution predicts the real behavior of stresses and deflections in the functionally graded plate. The functionally graded plate is found to be more effective for moderately thick and thick plates, which is inferred by a complex nature of the solution. For FGM plates, the transverse deflection is in-between to that of metal and ceramic rich plates. The complex nature of the solution also gives information about the stress distribution in the thickness direction.

References listed at the end of the paper:


End of more papers published in the journal, International Journal of Applied Mechanics and Engineering (2017 and on)

More papers published in the journal, Thin Solid Films (2017 and on)

Google the string: “Thin Solid Films”, then click on the entry: “Thin Solid Films l ScienceDirect.com” and scroll way down to “View all issues”

NOTE: The page numbers are not given in order. Instead the articles are grouped by category, with page numbers within each category in order, but a following category generally starts at a much lower page number than that at the end of the previous category.

ABSTRACT: The stretch-induced wrinkling behaviors in graphene membranes with frozen zone are investigated in molecular dynamics simulations and suppressed by adopting optimal designs obtained in topology optimization. The graphene membranes with optimal designs under stretching are wrinkle-free, this is meaningful to ensure the exceptional performances of graphene-nanoelectronics. Both the wrinkling and wrinkling-suppression mechanisms are qualitatively and quantitatively elucidated with finite element analyses, which are helpful to understand the stretch-induced wrinkling in graphene membranes with frozen zone and to provide useful guidance to the design of the large-area graphene-nanoelectronics.


ABSTRACT: The mechanical buckling of one-dimensional Si nanoribbons with a thickness contrast was investigated. For Si stripes with a small thickness difference, each section was found to undergo its own buckling with characteristic wavelengths and wave amplitudes, depending on their thicknesses. On the other hand, unusual buckling occurred for Si ribbons with large thickness differences. For this case, the thinned sections were uniformly buckled, and absorbed a large portion of externally applied strain. On the contrary, the thicker parts of the ribbon were buckled nonuniformly, i.e. buckling occurred in central regions only, with an almost flat configuration at both ends of the thicker parts. Buckling mechanics can qualitatively explain the observed buckling of the Si ribbons with a small thickness contrast, while the finite length effect should be considered for the case of the Si ribbons with a large thickness contrast. Considering the fact that real functional devices are not uniform in thickness, the present work helps to understand the complex buckling behavior of mechanical systems with a wide range of thickness contrasts.


ABSTRACT: The buckling structures of rigid films on soft substrates exhibit a “mexican hat” shape characterized by a nanometer scale depression at both edges. Based on finite elements simulations, a mathematical formulation is proposed to extract the elastic modulus mismatch between the film and its substrate, from the fine characterization of the buckle morphology.


ABSTRACT: We report on the spontaneous formation of ring-shaped buckles in cobalt films induced by evaporation of micro-scaled silicone oil droplets. Many small silicone oil droplets were generated on the glass substrate near a silicone oil reservoir during deposition. Due to the coffee ring effect, the silicone oil residue tends to gather at the droplet edges when the silicone oil evaporates, which results in the interfacial weakening and formation of ring-shaped buckles. The structural characteristics of the ring-shaped buckles have been investigated by atomic force microscopy, focused ion beam milling, numerical simulation and theoretic analysis. The maximum buckle height is found to increase approximately linearly with increasing the buckle width, but it is insensitive to the ring size. The structure characteristics of the ring-shaped buckles for small ratio of ring diameter to buckle width are also investigated.

ABSTRACT: Wrinkling patterns are ubiquitous in nature and they are beneficial for a wide range of practical applications. Here we report on the wrinkling patterns in tantalum films sputter deposited on modulus-gradient compliant polydimethylsiloxane substrates. It is found that the sputtering process generates intrinsic and thermal compressive stresses, which are relieved by formation of locally ordered (herringbone) but overall disordered (labyrinth) wrinkling. The wrinkle sizes are strongly dependent on the substrate stiffness and film thickness. The formation mechanisms and evolutional behaviors of the wrinkling patterns have been discussed and analyzed in detail based on the continuum elasticity theory. Some potential applications of gradient wrinkling including surface hydrophobicity and measurement of substrate modulus are also presented in this paper.


ABSTRACT: Buckled membranes become ever more important with further miniaturization and development of ultra-thin film-based systems. It is well established that the bulge test method, generally considered the gold standard for characterizing freestanding thin films, is unsuited to characterize buckled membranes, because of compressive residual stresses and a negligible out-of-plane bending stiffness. When pressurized, buckled membranes immediately start entering the ripple regime, but they typically plastically deform or fracture before reaching the cylindrical regime. In this paper the bulge test method is extended to enable characterization of buckled freestanding ultra-thin membranes in the ripple regime. In a combined experimental-numerical approach, the advanced technique of digital height correlation was first extended towards the sub-micron scale, to enable measurement of the highly varying local 3D strain and curvature fields on top of a single ripple in a total region of interest as small as ~25 μm. Subsequently, a finite element model was set up to analyze the post-buckled membrane under pressure loading. In the seemingly complex ripple configuration, a suitable combination of local region of interest and pressure range was identified for which the stress-strain state can be extracted from the local strain and curvature fields. This enables the extraction of both the Young's modulus and Poisson's ratio from a single bulge sample, contrary to the conventional bulge test method. Virtual experiments demonstrate the feasibility of the approach, while real proof of principle of the method was demonstrated for fragile specimens with rather narrow (~25 μm) ripples.

No more appropriate papers through December 2018.
It may be a good idea to drop this journal from perusal because there are so few papers on the applied mechanics of thin films, such as buckling, wrinkling, creasing, etc. of thin films. Practically all papers are on fabricating thin films, chemistry of thin films, etc, not the mechanical behavior of thin films.

End of more papers published in the journal, Thin Solid Films (2017 and on)

More papers published in the journal, Extreme Mechanics Letters (2017 and on)
Google the string: “Extreme Mechanics Letters”, then click on the entry: “Extreme Mechanics Letters | ScienceDirect.com” and scroll way down to “View all issues”

ABSTRACT: Ultralight sandwich structures with either two-dimensional (2D) prismatic or three-dimensional (3D) lattice truss cores, such as honeycombs, folded panels (corrugations) and pyramidal trusses, are known to possess attractive mechanical stiffness/strength and impact resistance. These properties can be significantly improved further by inserting different materials into the interstices of the lattices to construct hybrid lattice-cored sandwiches, as summarized in this mini-review. Three different types of hybrid lattice-core for sandwich constructions are discussed, including ceramic- or concrete-filled lattice cores for superior penetration resistance, metallic or polymeric foam-filled lattice cores for simultaneous enhancement in load-bearing and energy absorption, and metallic honeycomb-corrugation cores for simultaneous load-bearing, energy absorption and broadband low-frequency sound absorption. Corresponding enhancement mechanisms are explored.


ABSTRACT: Wrinkles, folds, creases and other elastic surface instabilities play a crucial role in many systems in nature and engineering. While surface instabilities of ideal bilayer structures with large contrasts in elastic stiffness are well understood, many natural and man-made structures are far from this ideal. To better understand the behavior of systems with modest stiffness contrast, in particular their secondary post-wrinkling bifurcations, we systematically vary the modulus contrast between the film and the substrate through a combination of experiments and finite element simulations. Above a modulus contrast of about 2, but below approximately 14, wrinkles represent the primary bifurcation mode, but can undergo two distinct types of secondary bifurcations upon further compression: (1) a direct transition from wrinkles to creases, and (2) wrinkles that first undergo period doubling, followed by a transition to creases.


ABSTRACT: The effect of substrate compressibility on surface wrinkling in soft materials is analyzed through theoretical analysis. The generalized Blatz–Ko model, which may reduce to commonly used incompressible and compressible materials such as neo-Hookean, Mooney–Rivlin and Blatz–Ko models, is employed. The wrinkling behavior of a thin film bonded to a soft compressible substrate is analyzed. We also look at wrinkling in slabs of finite thickness, which is admissible (although not necessarily stable) in a subclass of the materials considered.


ABSTRACT: Nearly all micro/nanosystems found in biology have function that is intrinsically enabled by hierarchical, three-dimensional (3D) designs. Compelling opportunities exist in exploiting similar 3D architectures in man-made devices for applications in biomedicine, sensing, energy storage and conversion, electronics and many other areas of advanced technology. Although a lack of practical routes to the required 3D layouts has hindered progress to date, recent advances in mechanically-guided 3D assembly have the potential to provide the required access to wide-ranging structural geometries, across a broad span of length scales, in a way that leverages the most sophisticated materials and design concepts that exist in state-of-the-art 2D
microsystems. This review summaries the key concepts and illustrates their use in four major categories of 3D mesostructures: open filamentary frameworks, mixed structures of membranes/filaments (Kirigami-inspired structures), folded constructs (Origami-inspired structures) and overlapping, nested and entangled networks. The content includes not only previously published examples, but also several additional illustrative cases. A collection of 3D starfish-like and jellyfish-like structures with critical dimensions that span nearly a factor of ten million, from one hundred nanometers to nearly one meter, demonstrates the scalability of the process.


ABSTRACT: Development of origami-inspired routes to assembly of three dimensional structures is an area of growing activity in scientific and engineering research communities due to fundamental interest in mathematical topics in topology and to the potential for practical applications in areas ranging from advanced surgical tools to systems for space exploration. Recently reported approaches that exploit the controlled, compressive buckling of 2D precursors induced by dimensional change in an underlying elastomer support offer broad versatility in material selection (from polymers to device grade semiconductors), feature sizes (from centimeters to nanometers), topological forms (open frameworks to closed form polyhedra) and shape controllability (dynamic tuning of shape), thereby establishing a promising avenue to autonomic assembly of complex 3D systems. Localization of origami-like folding deformations at targeted regions can be achieved through the use of engineered, spatial variations in the thicknesses of the 2D precursors. While this approach offers high levels of control in the targeted formation of creases, creating the necessary thickness variations requires a set of additional processing steps in the fabrication. This paper presents an alternative, and complementary, approach that exploits controlled plastic deformation in the precursors, as validated in a comprehensive set of experimental and theoretical studies. Specifically, plasticity and strain localization can be used to dramatically reduce the bending stiffness at targeted regions, to form well-defined creases as mountain or valley folds during the 2D to 3D geometrical transformation process. The content begins with studies of a model system that consists of a 2D precursor in the form of a straight ribbon with reduced widths at certain sections. The results illustrate the important role of plasticity in the course of folding, in such a manner that dictates the final 3D layouts. A broad range of complex 3D shapes, achieved in both the millimeter-scale and the mesoscale structures (i.e. micron to sub-millimeter), demonstrate the power of these ideas.


ABSTRACT: Origami and kirigami guided programmable shape shifting is explored via self-folding and spontaneous buckling of a thin sheet of shape memory polymer with light. By patterning the sheet with printed black ink lines as actuating hinges, we show that the folding angle can be well controlled by tuning the ink line width, which is predicted by both a simplified localized bilayer folding model and corresponding finite element method (FEM) simulation. Inspired by the approach of paper origami and kirigami combining folding and cutting, we then explored the design of prescribed patterned creases (i.e. ink lines) and/or cuts in the polymer thin sheet for programming a library of light-responsive three-dimensional (3-D) surfaces in a controlled fashion. Through the design of prescribed straight and curved crease patterns in origami, we demonstrated the generation of light-driven self-folding cylinders, helices, and pyramids with zero Gaussian curvature, as well as spontaneous formation of saddles with negative Gaussian curvature through localized curved folding induced
global buckling. The quantitative underlying mechanism governing the geometry of the different self-folded 3-D structures is revealed through simple geometrical modeling and FEM simulations. Lastly, through kirigami combining both folding and cutting in the form of line cuts or cut-outs, we demonstrated the spontaneous formation of light-responsive, more complex pop-up kirigami structures.

ABSTRACT: Mechanical self-assembly of ordered patterns via spontaneous buckling of thin-film/soft-substrate systems has received considerable interests in recent years. Here we study the wrinkling of a stiff film resting on a fiber-filled soft substrate. In particular, the effects of the cross-section dimension, spacing, and positions of fibers on the wrinkling patterns in the film/substrate bilayer system are investigated. We show that diverse wrinkling patterns, including sinusoidal wrinkling, period-doubling, period-tripling and mountain ridge modes, may occur at a small or moderate overall compression strain due to the inhomogeneous deformation in the substrate and they can be well controlled by tuning geometrical and physical parameters of the system. To illustrate the potential use of the wrinkling patterns revealed in this study, we investigate the elastic wave propagation in such a wrinkled bilayer using the Bloch wave theory. Our computational results show that diverse stress patterns generated in the soft composites give rise to a rich variety of band structures. Desired bandgaps of elastic waves can be achieved and tuned by simply designing the geometric parameters and controlling the external stimuli imposed on the soft metamaterials.

ABSTRACT: Respiration pattern (including both breath rate and intensity) is critical vital symptoms of many disorders such as sleep apnea, asthma, chronic obstructive pulmonary disease, and anemia. Breath sensors that can distinguish abnormalities in breath patterns can ascertain the basic human body conditions during sleep, exercise, sports and surgery play a significant role in healthcare system and have attracted more and more attentions. However, the existing breath sensors are limited in the sensitivity and not compatible with the practical applications during movements. Here we present a simple approach employing the wrinkled nitrile rubber films to detect the human respiration, both breath rate and intensity. The three-dimensional wrinkled structure of nitrile rubber films could significantly increase the capability to distinguish different intensities of respiration, with an average intensity ratio of 16 times for strong breath over weak breath signal. These sensors also show fast response (up to 2 Hz) high sensitivity, and can be stretched by 100% with stable breath sensing property. Our respiration sensors are favorable to the urgent healthcare monitoring applications in the near future.

ABSTRACT: This letter introduces a method of analyzing multi-stable truss structures and unit cells of engineered materials using the third order derivative of the formulated system’s potential energy function. The method can determine systematically all the cusp point singularities arising at the onset of bistability, and therefore identify the regions of hysteretic superelasticity and superplasticity from the usual geometrical nonlinearity in the solution space. The ability to design these behaviors is a great advantage that is highlighted with the example analysis of a bistable plane truss and a tetrahedral unit cell of a 3D lattice structure.

ABSTRACT: Blisters induced by gas trapped in the interstitial space between supported graphene and the substrate are commonly observed. These blisters are often quasi-spherical with a circular rim, but polygonal blisters are also common and coexist with wrinkles emanating from their vertices. Here, we show that these different blister morphologies can be understood mechanistically in terms of free energy minimization of the supported graphene sheet for a given mass of trapped gas and for a given lateral strain. Using a nonlinear continuum model for supported graphene closely reproducing experimental images of blisters, we build a morphological diagram as a function of strain and trapped mass. We show that the transition from quasi-spherical to polygonal of blisters as compressive strain is increased is a process of stretching energy relaxation and focusing, as many other crumpling events in thin sheets. Furthermore, to characterize this transition, we theoretically examine the onset of nucleation of short wrinkles in the periphery of a quasi-spherical blister. Our results are experimentally testable and provide a framework to control complex out-of-plane motifs in supported graphene combining blisters and wrinkles for strain engineering of graphene.


ABSTRACT: When the compressive load to a thin elastic rod embedded in an elastic medium exceeds a threshold, the thin rod buckles into an exponentially decaying short wavelength profile to minimize the total energy of the system. As the compressive load continues to increase, the buckling amplitude increases correspondingly, until the rod/medium interface fractures and the short wavelength buckling profile morphs into a different shape as fracture propagates into the surrounding medium. In this study, such shape transition in the presence of surrounding medium failure is investigated using a combined experimental and theoretical approach. We identify the ansatz that can be used to describe the post-fracture buckling profile, and then develop a forward scheme using the energy principle to predict the buckling profile of the thin rod when fracture happens in the medium. We also develop a backward scheme where we use the post-fracture buckling profile to estimate the buckling profile before fracture of the surrounding medium. Comparison of experimental and theoretical results indicates that the modeling framework can be used to characterize the buckling profile transition of a thin elastic rod embedded in a fractured elastic medium.


ABSTRACT: Wires embedded in an infinite soft matrix may buckle into a three-dimensional helical mode upon compression. Based on minimization of potential energy, we present a theoretical analysis of three-dimensional helical buckling of wires embedded in matrix. The buckling spacing and amplitudes are deduced, which are further verified by parallel FEM simulations. It is suggested that, the buckled profile is almost perfectly circular in the axial direction; with increasing compression, the buckling spacing decreases almost linearly, while the amplitude scales with the 1/2 power of the compressive strain. Besides the transition strain from 2D mode to 3D helical mode decreases with the Young’s modulus of the wire, and approaches to about1.25% when the modulus is high enough. This study may shed some lights on the buckling behaviors of wires embedded in matrix and provide some useful instructions of manufacturing complex structures.

ABSTRACT: Honeycomb structures have significant advantages in load-bearing and energy absorption. In recent years, some researches have been carried out on the in-plane mechanical properties of honeycombs with variable-thickness cell edges, but the out-of-plane compressive properties of this type of honeycombs have not been well studied. In this paper, the out-of-plane compressive properties of honeycombs with variable-thickness cell edges are investigated through experimental analysis. Here square and hexagonal honeycombs with variable-thickness cells are described with one geometric parameter. The experimental samples of these honeycombs were fabricated using 3D printing technology, and the quasi-static compression tests of these honeycombs were conducted. Experimental results illustrate that the honeycombs with variable-thickness cell edges show enhanced compressive mechanical properties compared to the conventional honeycombs. The highest increase rates of compressive strength of the presented square and hexagonal honeycombs are around 57% and 19%, respectively. In addition, the highest increase rate of specific energy absorption of these square honeycombs reaches up to 172%. The deformation and failure modes of square and hexagonal honeycombs with different geometric parameter values are also discussed and compared. Experimental results show that the square honeycombs with appropriate geometric parameter can achieve more desirable damage tolerance than the conventional square honeycombs.

References listed at the end of the paper:

ABSTRACT: We consider the mechanisms by which folds, or sulci (troughs) and gyri (crests), develop in the brain. This feature, common to many gyrencephalic species including humans, has attracted recent attention from soft matter physicists. It occurs due to inhomogeneous, and predominantly tangential, growth of the cortex, which causes circumferential compression, leading to a bifurcation of the solution path to a folded configuration. The problem can be framed as one of buckling in the regime of linearized elasticity. However, the brain is a very soft solid, which is subject to large strains due to inhomogeneous growth. As a consequence, the morphomechanics of the developing brain demonstrates an extensive post-bifurcation regime. Nonlinear elasticity studies of growth-driven brain folding have established the conditions necessary for the onset of folding, and for its progression to configurations broadly resembling gyrencephalic brains. The reference, unfolded, configurations in these treatments have a high degree of symmetry—typically, ellipsoidal. Depending on the boundary conditions, the folded configurations have symmetric or anti-symmetric patterns. However, these configurations do not approximate the actual morphology of, e.g., human brains, which display unsymmetric folding. More importantly, from a neurodevelopmental standpoint, many of the unsymmetric sulci and gyri are notably robust in their locations. Here, we initiate studies on the physical mechanisms and geometry that control the development of primary sulci and gyri. In this preliminary communication we carry out computations with idealized geometries, boundary conditions and parameters, seeking a pattern resembling one of the first folds to form: the Central Sulcus.

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14. Prange M.T., Margulies S.S. Regional, directional, and age-dependent properties of the brain undergoing large deformation Trans. ASME, 124 (2002), pp. 244-252
ABSTRACT: Current periodical lattice structures with tailorable coefficient of thermal expansion (CTE) can be hardly used as engineering structures since these configurations are neither planar nor regular three dimensional geometries. Here, lattice cylindrical shells, which are widely in aerospace engineering, are originally devised and analyzed to exclusively achieve a wide range of tailorable CTEs in both axial and radial directions. The thermal expansion behaviors are systematically calculated by finite element analysis, and the expressions of CTEs for the devised lattice cylindrical shells are well established. Warp effects are found in lattice cylindrical shells winded from planar triangle and planar square due to the sparse arrangement mode, and with few circumferential triangles, the radial CTE is significantly larger than those of the corresponding planar lattices. Tailorable thermal expansion characteristics including zero, large positive and negative values are confirmed. Moreover, in case study with aluminum alloy, stainless steel and invar, a wide range of thermal expansion ranged from -64.6 to 88.0 ppm/deg. C, which are remarkably larger than those of constituents, can be easily achieved through the devised lattice cylindrical shells. The wide range of CTEs obtained here can promote these lattice cylindrical shells to be used as structures under temperature variation service environment for purpose of obtaining dimensional stability and thermal expansion compensation.

ABSTRACT: Inspired by the coupling geometrical relations of left-hand (LH) and right-hand (RH) climbing towel gourd tendrils within single branch, innovative chiral architected cylindrical tube is proposed, which can convert axial compression loads into angular rotation deformation. Firstly, two series of tetrachiral cylindrical tube samples with rotation disk on the mirror plane (middle cross-section) are designed, where the numbers of unit cells and tetrachiral nodes radius are different. Secondly, the cylindrical tetrachiral tubes are fabricated with Selective Laser Sintering (SLS) nylon sintering techniques, and in-situ compression tests are performed for studying the relation between axial compression strain and rotation angle of the spinning disk. It is found that the proposed innovative tetrachiral cylindrical tube is able to generate lateral rotation, and linear relation between rotation angle and compression force can be harvested. With the progress of micro- and nano-manufacturing techniques, the proposed tetrachiral cylindrical tube with compression-twist deformation mechanism demonstrates robust mechanical performances for future industrial applications, such as: shape memory morphing structures in aerospace engineering, smart actuators and propellers, smart flexible microelectronics and biomechanical devices.

ABSTRACT: Manipulation of thin sheets by folding and cutting offers opportunity to engineer structures with novel mechanical properties, and to prescribe complex force–displacement relationships via material elasticity in combination with the trajectory imposed by the fold pattern. Here we study the mechanics of a cellular Kirigami that rotates and buckles upon compression, presenting an example of a design strategy that we call “flexigami”. The addition of diagonal cuts to an equivalent closed cell permits the cell to collapse reversibly
without incurring significant tensile strains in its panels. Using finite-element modeling and experiments we show how the mechanical behavior of the cell is governed by the coupled rigidity of the panels and hinges and we design cells to achieve reversible force response ranging from smooth mono-stability to sharp bi-stability. We then demonstrate the cell-based construction of laminates with multi-stable behavior and a rotary-linear boom actuator, as well as self-deploying cells with shape memory alloy hinges. Advanced digital fabrication methods can enable the realization of this and other so-called flexigami designs that derive their overall mechanics from fold and panel elasticity, for applications including deployable structures, soft robotics and medical devices.

ABSTRACT: The prior buckling modes of conventional square lattice structures are always global buckling other than local buckling (i.e., pattern transformation). Interestingly, we found that the preferential buckling mode can be altered to pattern transformation by modifying the sections of the frame in conventional square lattice structures, and there exists an effective modifying region. In order to predict the pattern transformation of this kind of modified structures and to determine the corresponding critical buckling conditions, the theoretical analyses are carried out, and we found that the theoretical results agree well with numerical simulations and experimental studies. This study provides an effective way to achieve pattern transformation based on conventional lattice structures. The presented theoretical approach for predicting critical buckling conditions may shed useful insights on the design and application of lattice metamaterials.

ABSTRACT: Fibre-reinforced composite laminates are increasingly popular for lightweight applications in the aerospace, wind turbine and automotive industries. Apart from their excellent specific strength and stiffness properties, their orthotropic and layered construction can be exploited to create bistable systems that are useful for shape-adaptive morphing or energy-harvesting applications. The nonlinear interaction between initial curvature and induced thermal stresses can lead to “extreme” mechanics with rich branching and multi-stable behaviour. Here, we explore the multi-stability of curved composite laminates in the two-dimensional parameter space of temperature and mechanical loading. Analyses conducted via finite element discretisation and numerical continuation algorithms reveal possible snapping behaviour between five different mode shapes for different combinations of applied load and temperature. Furthermore, we show that a composite laminate can exhibit four stable, self-equilibrated mode shapes for a narrow temperature range. Hence, the multi-stable and nonlinear mechanics of composite laminates is much more complex than previously assumed, and this may influence the design of more versatile morphing structures.

References listed at the end of the paper:
ABSTRACT: Many biological and engineered systems can be modeled as buckled thin rods with constraints. Examples include microtubules in cytoskeleton, plant roots in soil, and oil pipes within a wellbore. However, most previous studies focused on the buckling of a rod in a homogenous environment, an idealization which is often not realistic. Here, we study the buckling behaviors of an elastic rod embedded in a bilayer elastic matrix using a combined experimental, theoretical, and computational method. Our experiments showed, for the first time, that the buckling amplitude can increase from the end where the compressive load is applied. To interpret this new phenomenon, we built a theoretical model and identified an ansatz for the transverse displacement. Our numerical results showed that material inhomogeneity, geometry, and loading all have significant influences on the post-buckling behaviors of the rod. Moreover, our study indicated that the stiffer layer of the elastic medium can be treated as a clamped boundary. These results could find applications ranging from the penetration of needles through biological tissues to the development of underground structures.

ABSTRACT: Increasing the energy absorption capability of lightweight structures without reducing stiffness and strength has been a long-standing challenge, as numerous applications exist with potentially great impact. Particularly, in volume or weight restricted environments, such as cars, helmets or packaging, the performance, safety, cost, and environmental impact is substantially affected. However, these properties are typically found only in nature. We propose a novel architectural paradigm that adds stepwise graded core–shell struts to bending dominated lattices to increase energy absorption up to 38 times with negligible changes in density or mass, i.e., less than +2.5%. We optimize the material in each coaxial layer for maximum toughness and, enabled by multi-material 3D printing, validate the results experimentally for single struts, unit cells, and lattice structures. The bio-inspired and highly versatile architectural paradigm is scale-independent, locally tunable, applicable to different lattice cell types and geometries, and, therefore, applicable to a wide range of mechanical meta-materials and structures.

ABSTRACT: This letter explores the mechanical behavior of the origami hyperbolic paraboloid or hypar which is a bistable thin sheet structure with symmetric stable states. We use experiments to evaluate the global and local behaviors of the structure, which are unique from other bistable origami systems. In theory, for the hypar to reconfigure between the stable states, the thin sheet which is initially patterned with acute and reflex folds needs to fully flatten. However, we find that axial stretching as well as two distinctly different buckling patterns in the origami can allow for portions of the sheet to remain folded during the reconfiguration. The spacing of folds in the hypar, the resulting buckling characteristics, the stretching of the sheet, and the local material nonlinearity at the fold lines all have significant effects on the force–displacement response of the system. The work gives insight to these phenomena which are often omitted in the testing and modeling of more conventional origami-inspired systems. We reinforce our understanding of the hypar behavior by establishing an analytical model that can simulate the kinematics, the buckling, and the force–displacement behavior of the
structure. The letter also discusses topics for future extension and introduces hypar chains where multiple hypars are connected in series to achieve multistability.

End of more papers published in the journal, Extreme Mechanics Letters (2017 and on)

More papers published in the journal, Proceedings of the Royal Society Series A (2017 and on)


ABSTRACT: Origami tessellations are particular textured morphing shell structures. Their unique folding and unfolding mechanisms on a local scale aggregate and bring on large changes in shape, curvature and elongation on a global scale. The existence of these global deformation modes allows for origami tessellations to fit non-trivial surfaces thus inspiring applications across a wide range of domains including structural engineering, architectural design and aerospace engineering. The present paper suggests a homogenization-type two-scale asymptotic method which, combined with standard tools from differential geometry of surfaces, yields a macroscopic continuous characterization of the global deformation modes of origami tessellations and other similar periodic pin-jointed trusses. The outcome of the method is a set of nonlinear differential equations governing the parametrization, metric and curvature of surfaces that the initially discrete structure can fit. The theory is presented through a case study of a fairly generic example: the eggbox pattern. The proposed continuous model predicts correctly the existence of various fittings that are subsequently constructed and illustrated.


ABSTRACT: Origami has enabled new approaches to the fabrication and functionality of multiple structures. Current methods for origami design are restricted to the idealization of folds as creases of zeroth-order geometric continuity. Such an idealization is not proper for origami structures of non-negligible fold thickness or maximum curvature at the folds restricted by material limitations. For such structures, folds are not properly represented as creases but rather as bent regions of higher-order geometric continuity. Such fold regions of arbitrary order of continuity are termed as smooth folds. This paper presents a method for solving the following origami design problem: given a goal shape represented as a polygonal mesh (termed as the goal mesh), find the geometry of a single planar sheet, its pattern of smooth folds, and the history of folding motion allowing the sheet to approximate the goal mesh. The parametrization of the planar sheet and the constraints that allow for a valid pattern of smooth folds are presented. The method is tested against various goal meshes having diverse geometries. The results show that every determined sheet approximates its corresponding goal mesh in a known folded configuration having fold angles obtained from the geometry of the goal mesh.

ABSTRACT: Surface instabilities have been studied extensively for both homogeneous materials and film/substrate structures but relatively less for materials with continuously varying properties. This paper studies wrinkle surface instability of a graded neo-Hookean block with exponentially varying modulus under plane strain by using the linear bifurcation analysis. We derive the first variation condition for minimizing the potential energy functional and solve the linearized equations of equilibrium to find the necessary conditions for surface instability. It is found that for a homogeneous block or an inhomogeneous block with increasing modulus from the surface, the critical stretch for surface instability is 0.544 (0.456 strain), which is independent of the geometry and the elastic modulus on the surface of the block. This critical stretch coincides with that reported by Biot (1963 *Appl. Sci. Res.* 12, 168–182. ([doi:10.1007/BF03184638](https://doi.org/10.1007/BF03184638)) 53 years ago for the onset of wrinkle instabilities in a half-space of homogeneous neo-Hookean materials. On the other hand, for an inhomogeneous block with decreasing modulus from the surface, the critical stretch for surface instability ranges from 0.544 to 1 (0–0.456 strain), depending on the modulus gradient, and the length and height of the block. This sheds light on the effects of the material inhomogeneity and structural geometry on surface instability.


ABSTRACT: This paper presents a mathematical framework for the design of rigid-foldable doubly curved origami tessellations based on trapezoidal crease patterns that can simultaneously fit two target surfaces with rotational symmetry about a common axis. The geometric parameters of the crease pattern and the folding angles of the target folded state are determined through a set of combined geometric and constraint equations. An algorithm to simulate the folding motion of the designed crease pattern is provided. Furthermore, the conditions and procedures to design folded ring structures that are both developable and flat-foldable and stacked folded structures consisting of two layers that can fold independently or compatibly are discussed. The proposed framework has potential applications in designing engineering doubly curved structures such as deployable domes and folded cores for doubly curved sandwich structures on the aircraft.


ABSTRACT: We investigate how thin structures change their shape in response to non-mechanical stimuli that can be interpreted as variations in the structure’s natural curvature. Starting from the theory of non-Euclidean plates and shells, we derive an effective model that reduces a three-dimensional stimulus to the natural fundamental forms of the mid-surface of the structure, incorporating expansion, or growth, in the thickness. Then, we apply the model to a variety of thin bodies, from flat plates to spherical shells, obtaining excellent agreement between theory and numerics. We show how cylinders and cones can either bend more or unroll, and eventually snap and rotate. We also study the nearly isometric deformations of a spherical shell and describe how this shape change is ruled by the geometry of a spindle. As the derived results stem from a purely geometrical model, they are general and scalable.


ABSTRACT: The cutting of metals has long been described as occurring by laminar plastic flow. Here we show that for metals with large strain-hardening capacity, laminar flow mode is unstable and cutting instead occurs by
plastic buckling of a thin surface layer. High speed in situ imaging confirms that the buckling results in a small bump on the surface which then evolves into a fold of large amplitude by rotation and stretching. The repeated occurrence of buckling and folding manifests itself at the mesoscopic scale as a new flow mode with significant vortex-like components—sinuous flow. The buckling model is validated by phenomenological observations of flow at the continuum level and microstructural characteristics of grain deformation and measurements of the folding. In addition to predicting the conditions for surface buckling, the model suggests various geometric flow control strategies that can be effectively implemented to promote laminar flow, and suppress sinuous flow in cutting, with implications for industrial manufacturing processes. The observations impinge on the foundations of metal cutting by pointing to the key role of stability of laminar flow in determining the mechanism of material removal, and the need to re-examine long-held notions of large strain deformation at surfaces.

ABSTRACT: The objective of this paper is to provide a review on some aspects of the mathematical and computational modelling of skin biophysics, with special focus on constitutive theories based on nonlinear continuum mechanics from elasticity, through anelasticity, including growth, to thermoelasticity. Microstructural and phenomenological approaches combining imaging techniques are also discussed. Finally, recent research applications on skin wrinkles will be presented to highlight the potential of physics-based modelling of skin in tackling global challenges such as ageing of the population and the associated skin degradation, diseases and traumas.

ABSTRACT: Multistable shells are thin-walled structures that have more than one stable state of self-stress. We consider isotropic axisymmetrical shallow shells of arbitrary polynomial shapes using a Föppl–von Kármán analytical model. By employing a Rayleigh–Ritz approach, we identify stable shapes from local minima in the strain energy formulation, and we formally characterize the level of influence of the boundary conditions on the critical geometry for achieving bistable inversion—an effect not directly answered in the literature. Systematic insight is afforded by connecting the boundary to ground through sets of extensional and rotational linear springs. For typical cap-like shells, it is shown that bistability is generally enhanced when the extensional spring stiffness increases and when the rotational spring stiffness decreases, i.e. when boundary movements in-plane are resisted but when their rotations are not; however, for certain other shapes and large in-plane stiffness values, bistability can be enhanced by resisting but not entirely preventing edge rotations. Our predictions are furnished as detailed regime maps of the critical geometry, which are accurately correlated against finite-element analysis. Furthermore, the suitabilities of single degree-of-freedom models, for which solutions are achieved in closed form, are evaluated and compared to our more accurate predictions.

ABSTRACT: The three-dimensional dynamic non-local elasticity equations for a thin plate are subject to asymptotic analysis assuming the plate thickness to be much greater than a typical microscale size. The integral constitutive relations, incorporating the variation of an exponential non-local kernel across the thickness, are adopted. Long-wave low-frequency approximations are derived for both bending and extensional motions. Boundary layers specific for non-local behaviour are revealed near the plate faces. It is established that the effect of the boundary layers leads to the first-order corrections to the bending and extensional stiffness in the classical two-dimensional plate equations.

ABSTRACT: In the last few years, it has been recognized that the large deformation capacity of elastomeric materials that are sensitive to electric fields can be harnessed for use in transducer devices such as actuators and sensors. This has led to the reassessment of the mathematical theory that is needed for the description of the electromechanical (in particular, electroelastic) interactions for purposes of material characterization and prediction. After a review of the key experiments concerned with determining the nature of the electromechanical interactions and a discussion of the range of applications to devices, we provide a short account of the history of developments in the nonlinear theory. This is followed by a succinct modern treatment of electroelastic theory, including the governing equations and constitutive laws needed for both material characterization and the analysis of general electroelastic coupling problems. For illustration, the theory is then applied to two simple representative boundary-value problems that are relevant to the geometries of activation devices; in particular, (a) a rectangular plate and (b) a circular cylindrical tube, in each case with compliant electrodes on the major surfaces and a potential difference between them. In (a), an electric field is generated normal to the major surfaces and in (b), a radial electric field is present. This is followed by a short section in which other problems addressed on the basis of the general theory are described briefly.


ABSTRACT: We have designed and tested experimentally a morphing structure consisting of a neutrally stable thin cylindrical shell driven by a multi-parameter piezoelectric actuation. The shell is obtained by plastically deforming an initially flat copper disc, so as to induce large isotropic and almost uniform inelastic curvatures. Following the plastic deformation, in a perfectly isotropic system, the shell is theoretically neutrally stable, having a continuous set of stable cylindrical shapes corresponding to the rotation of the axis of maximal curvature. Small imperfections render the actual structure bistable, giving preferred orientations. A three-parameter piezoelectric actuation, exerted through micro-fibre-composite actuators, allows us to add a small perturbation to the plastic inelastic curvature and to control the direction of maximal curvature. This actuation law is designed through a geometrical analogy based on a fully nonlinear inextensible uniform-curvature shell model. We report on the fabrication, identification and experimental testing of a prototype and demonstrate the effectiveness of the piezoelectric actuators in controlling its shape. The resulting motion is an apparent rotation of the shell, controlled by the voltages as in a ‘gear-less motor’, which is, in reality, a precession of the axis of principal curvature.


ABSTRACT: We compute nonlinear force equilibrium solutions for a clamped thin cylindrical shell under axial compression. The equilibrium solutions are dynamically unstable and located on the stability boundary of the unbuckled state. A fully localized single dimple deformation is identified as the edge state—the attractor for the dynamics restricted to the stability boundary. Under variation of the axial load, the single dimple undergoes homoclinic snaking in the azimuthal direction, creating states with multiple dimples arranged around the central circumference. Once the circumference is completely filled with a ring of dimples, snaking in the axial direction leads to further growth of the dimple pattern. These fully nonlinear solutions embedded in the stability
boundary of the unbuckled state constitute critical shape deformations. The solutions may thus be a step towards explaining when the buckling and subsequent collapse of an axially loaded cylinder shell is triggered.


ABSTRACT: Origami-inspired designs possess attractive applications to science and engineering (e.g. deployable, self-assembling, adaptable systems). The special geometric arrangement of panels and creases gives rise to unique mechanical properties of origami, such as reconfigurability, making origami designs well suited for tunable structures. Although often being ignored, origami structures exhibit additional soft modes beyond rigid folding due to the flexibility of thin sheets that further influence their behaviour. Actual behaviour of origami structures usually involves significant geometric nonlinearity, which amplifies the influence of additional soft modes. To investigate the nonlinear mechanics of origami structures with deformable panels, we present a structural engineering approach for simulating the nonlinear response of non-rigid origami structures. In this paper, we propose a fully nonlinear, displacement-based implicit formulation for performing static/quasi-static analyses of non-rigid origami structures based on ‘bar-and-hinge’ models. The formulation itself leads to an efficient and robust numerical implementation. Agreement between real models and numerical simulations demonstrates the ability of the proposed approach to capture key features of origami behaviour.


ABSTRACT: The localized loading of an elastic sheet floating on a liquid bath occurs at scales from a frog sitting on a lily pad to a volcano supported by the Earth’s tectonic plates. The load is supported by a combination of the stresses within the sheet (which may include applied tensions from, for example, surface tension) and the hydrostatic pressure in the liquid. At the same time, the sheet deforms, and may wrinkle, because of the load. We study this problem in terms of the (relatively weak) applied tension and the indentation depth. For small indentation depths, we find that the force–indentation curve is linear with a stiffness that we characterize in terms of the applied tension and bending stiffness of the sheet. At larger indentations, the force–indentation curve becomes nonlinear and the sheet is subject to a wrinkling instability. We study this wrinkling instability close to the buckling threshold and calculate both the number of wrinkles at onset and the indentation depth at onset, comparing our theoretical results with experiments. Finally, we contrast our results with those previously reported for very thin, highly bendable membranes.

References listed at the end of the paper:
Kerr AD. 1976 The bearing capacity of floating ice plates subjected to static or quasi-static loads. J. Glaciol. 17, 229–268. [6]


ABSTRACT: A nonlinear two-dimensional (2D) continuum with a latent internal structure is introduced as a coarse model of a plane network of beams which, in turn, is assumed as a model of a pantographic structure
made up by two families of equispaced beams, superimposed and connected by pivots. The deformation measures of the beams of the network and that of the 2D body are introduced and the former are expressed in terms of the latter by making some kinematical assumptions. The expressions for the strain and kinetic energy densities of the network are then introduced and given in terms of the kinematic quantities of the 2D continuum. To account for the modelling abilities of the 2D continuum in the linear range, the eigenmode and eigenfrequencies of a given specimen are determined. The buckling and post-buckling behaviour of the same specimen, subjected to two different loading conditions are analysed as tests in the nonlinear range. The problems have been solved numerically by means of the COMSOL Multiphysics finite element software.


ABSTRACT: We report the results of a numerical and theoretical study of buckling in elastic columns containing a line of holes. Buckling is a common failure mode of elastic columns under compression, found over scales ranging from metres in buildings and aircraft to tens of nanometers in DNA. This failure usually occurs through lateral buckling, described for slender columns by Euler’s theory. When the column is perforated with a regular line of holes, a new buckling mode arises, in which adjacent holes collapse in orthogonal directions. In this paper, we firstly elucidate how this alternate hole buckling mode coexists and interacts with classical Euler buckling modes, using finite-element numerical calculations with bifurcation tracking. We show how the preferred buckling mode is selected by the geometry, and discuss the roles of localized (hole-scale) and global (column-scale) buckling. Secondly, we develop a novel predictive model for the buckling of columns perforated with large holes. This model is derived without arbitrary fitting parameters, and quantitatively predicts the critical strain for buckling. We extend the model to sheets perforated with a regular array of circular holes and use it to provide quantitative predictions of their buckling.

References listed at the end of the paper:
ABSTRACT: A variational model that describes the interactive buckling of a thin-walled equal-leg angle strut under pure axial compression is presented. A formulation combining the Rayleigh–Ritz method and continuous displacement functions is used to derive a system of differential and integral equilibrium equations for the structural component. Solving the equations using numerical continuation reveals progressive cellular buckling (or snaking) arising from the nonlinear interaction between the weak-axis flexural buckling mode and the strong-axis flexural–torsional buckling mode for the first time—the resulting behaviour being highly unstable. Physical experiments conducted on 10 cold-formed steel specimens are presented and the results show good agreement with the variational model.


ABSTRACT: Gels are widely employed in smart mechanical devices and biomedical applications. Swelling-induced bending actuation can be obtained by means of a simple bilayer gel beam. We show that this system can also exhibit wrinkling patterns of potential interest for structural morphing and sensing. We study swelling-induced wrinkling at the extrados of a bilayer gel beam with the softer layer on top. The bent configuration at finite strain is recovered first and, starting from it, a linear perturbation analysis is performed. We delimit the zone corresponding to wrinkling modes in a parameter plane encompassing a mechanical stiffness ratio and a geometric top layer to total height ratio. Interestingly, we observe that surface instability precedes and envelopes wrinkling modes of finite wavelength. Finally, we discuss the effect of changes in stiffness and of the Flory–Huggins parameters $\chi$ on the size of the wrinkling domain.


ABSTRACT: The buckling of a stiff film on a compliant substrate has attracted much attention due to its wide applications such as thin-film metrology, surface patterning and stretchable electronics. An analytical model is established for the buckling of a stiff thin film on a semi-infinite elastic graded compliant substrate subjected to in-plane compression. The critical compressive strain and buckling wavelength for the sinusoidal mode are obtained analytically for the case with the substrate modulus decaying exponentially. The rigorous finite element analysis (FEA) is performed to validate the analytical model and investigate the postbuckling behaviour of the system. The critical buckling strain for the period-doubling mode is obtained numerically. The influences of various material parameters on the results are investigated. These results are helpful to provide physical insights on the buckling of elastic graded substrate-supported thin film.
ABSTRACT: Experimentally measuring the elastic properties of thin biological surfaces is non-trivial, particularly when they are curved. One technique that may be used is the indentation of a thin sheet of material by a rigid indenter, while measuring the applied force and displacement. This gives immediate information on the fracture strength of the material (from the force required to puncture), but it is also theoretically possible to determine the elastic properties by comparing the resulting force–displacement curves with a mathematical model. Existing mathematical studies generally assume that the elastic surface is initially flat, which is often not the case for biological membranes. We previously outlined a theory for the indentation of curved isotropic, incompressible, hyperelastic membranes (with no bending stiffness) which breaks down for highly curved surfaces, as the entire membrane becomes wrinkled. Here, we introduce the effect of bending stiffness, ensuring that energy is required to change the shell shape without stretching, and find that commonly neglected terms in the shell equilibrium equation must be included. The theory presented here allows for the estimation of shape- and size-independent elastic properties of highly curved surfaces via indentation experiments, and is particularly relevant for biological surfaces.

References listed at the end of the paper:


ABSTRACT: This paper reports an energy-based method for the dynamic pull-in instability analysis of a spherical dielectric elastomer (DE) balloon subjected to a quasi-statically applied inflation pressure and a Heaviside step voltage across the balloon wall. The proposed technique relies on establishing the energy balance at the point of maximum stretch in an oscillation cycle, followed by the imposition of an instability condition for extracting the threshold parameters. The material models of the Ogden family are employed for describing the hyperelasticity of the balloon. The accuracy of the critical dynamic pull-in parameters is established by examining the saddle-node bifurcation in the transient response of the balloon obtained by integrating numerically the equation of motion, derived using the Euler–Lagrange equation. The parametric study brings out the effect of inflation pressure on the onset of the pull-in instability in the DE balloon. A quantitative comparison between the static and dynamic pull-in parameters at four different levels of the inflation pressure is presented. The results indicate that the dynamic pull-in instability gets triggered at electric fields that are lower than those corresponding to the static instability. The results of the present investigation can find potential use in the design and development of the balloon actuators subjected to transient loading. The
method developed is versatile and can be used in the dynamic instability analysis of other conservative systems of interest.


ABSTRACT: Order reduction methods are widely used to reduce computational effort when calculating the impact of defects on the vibrational properties of nearly periodic structures in engineering applications, such as a gas-turbine bladed disc. However, despite obvious similarities these techniques have not yet been adapted for use in analysing atomic structures with inevitable defects. Two order reduction techniques, modal domain analysis and modified modal domain analysis, are successfully used in this paper to examine the changes in vibrational frequencies, mode shapes and mode localization caused by defects in carbon nanotubes. The defects considered are isotope defects and Stone–Wales defects, though the methods described can be extended to other defects.


ABSTRACT: Imperfection sensitivity is essential for mechanical behaviour of biopolymer shells characterized by high geometric heterogeneity. The present work studies initial post-buckling and imperfection sensitivity of a pressured biopolymer spherical shell based on non-axisymmetric buckling modes and associated mode interaction. Our results indicate that for biopolymer spherical shells with moderate radius-to-thickness ratio (say, less than 30) and smaller effective bending thickness (say, less than 0.2 times average shell thickness), the imperfection sensitivity predicted based on the axisymmetric mode without the mode interaction is close to the present results based on non-axisymmetric modes with the mode interaction with a small (typically, less than 10%) relative errors. However, for biopolymer spherical shells with larger effective bending thickness, the maximum load an imperfect shell can sustain predicted by the present non-axisymmetric analysis can be significantly (typically, around 30%) lower than those predicted based on the axisymmetric mode without the mode interaction. In such cases, a more accurate non-axisymmetric analysis with the mode interaction, as given in the present work, is required for imperfection sensitivity of pressured buckling of biopolymer spherical shells. Finally, the implications of the present study to two specific types of biopolymer spherical shells (viral capsids and ultrasound contrast agents) are discussed.


ABSTRACT: We study what is clearly one of the most common modes of deformation found in nature, science and engineering, namely the large elastic bending of curved structures, as well as its inverse, unbending, which can be brought beyond complete straightening to turn into eversion. We find that the suggested mathematical solution to these problems always exists and is unique when the solid is modelled as a homogeneous, isotropic, incompressible hyperelastic material with a strain-energy satisfying the strong ellipticity condition. We also provide explicit asymptotic solutions for thin sectors. When the deformations are severe enough, the compressed side of the elastic material may buckle and wrinkles could then develop. We analyse, in detail, the onset of this instability for the Mooney–Rivlin strain energy, which covers the cases of the neo-Hookean model in exact nonlinear elasticity and of third-order elastic materials in weakly nonlinear elasticity. In particular, the associated theoretical and numerical treatment allows us to predict the number and wavelength of the wrinkles. Guided by experimental observations, we finally look at the development of creases, which we simulate through advanced finite-element computations. In some cases, the linearized analysis allows us to predict correctly the
number and the wavelength of the creases, which turn out to occur only a few per cent of strain earlier than the wrinkles.


ABSTRACT: The nonlinear response of a reduced model of an orthotropic single-layered plate with thermomechanical coupling is investigated in the presence of thermal excitations, in addition to mechanical ones. Different issues are addressed via accurate and extended local and global analyses. (i) Assessing the possible occurrence, disappearance or modification of mechanical buckling as a result of thermal aspects; (ii) exploiting global dynamics to unveil the effects of coupling; (iii) highlighting the crucial role played by the slow thermal transient evolution in modifying the fast steady mechanical response; (iv) framing the influence of coupling and underlining the need to use a thermomechanical model to grasp the actual plate dynamics; and (v) getting hints of technical interest as to the outcome robustness with respect to variations in the external/internal thermal parameters.


ABSTRACT: Depending on its geometry, a spherical shell may exist in one of two stable states without the application of any external force: there are two ‘self-equilibrated’ states, one natural and the other inside out (or ‘everted’). Though this is familiar from everyday life—an umbrella is remarkably stable, yet a contact lens can be easily turned inside out—the precise shell geometries for which bistability is possible are not known. Here, we use experiments and finite-element simulations to determine the threshold between bistability and monostability for shells of different solid angle. We compare these results with the prediction from shallow shell theory, showing that, when appropriately modified, this offers a very good account of bistability even for relatively deep shells. We then investigate the robustness of this bistability against pointwise indentation. We find that indentation provides a continuous route for transition between the two states for shells whose geometry makes them close to the threshold. However, for thinner shells, indentation leads to asymmetrical buckling before snap-through, while also making these shells more ‘robust’ to snap-through. Our work sheds new light on the robustness of the ‘mirror buckling’ symmetry of spherical shell caps.

References listed at the end of the paper:
ABSTRACT: We investigate with experiments the twist instabilities of an elastic sheet of length L, width W and thickness t, that is clamped at two opposite ends while held under a tension T. Above a critical tension $T_c$ and critical twist angle $\eta_{tr}$, we find that the sheet buckles with a mode number $n \geq 1$ transverse to the axis of twist. Three distinct buckling regimes characterized as clamp-dominated, bendable and stiff are identified, by introducing a bendability length $L_B$ and a clamp length $L_c(\ll L_B)$. In the stiff regime ($L > L_B$), we find that mode $n=1$ develops above $\eta_{tr} \approx \eta_{tr}^c - (t/W)^{1/2}$, independent of $L$. In the bendable regime $L_c \ll L_B$, $n=1$ as well as $n > 1$ occur above $\eta_{tr} \approx \eta_{tr}^c - (t/W)^{1/2} \sqrt{T - 1/4}$. Here, we find the wavelength $\lambda_B \sim L_B \sqrt{T - 1/4}$, when $n > 1$. These scalings agree with those derived from a covariant form of the Föppl-von Kármán shell model: From coarse to more refined models. Int. J. Solids Struct., 50(9):1241–1252, 2013.
Kármán equations, however, we find that the $n=1$ mode also occurs over a surprisingly large range of $L$ in the bendable regime. Finally, in the clamp-dominated regime ($L< L_c$), we find that $\eta_1$ is higher compared to $\eta_2$ due to additional stiffening induced by the clamped boundary conditions. (Sorry, some math in the abstract does not copy and paste properly)


ABSTRACT: The radially outward flow of fluid through a porous medium occurs in many practical problems, from transport across vascular walls to the pressurization of boreholes in the subsurface. When the driving pressure is non-negligible relative to the stiffness of the solid structure, the poromechanical coupling between the fluid and the solid can control both the steady state and the transient mechanics of the system. Very large pressures or very soft materials lead to large deformations of the solid skeleton, which introduce kinematic and constitutive nonlinearity that can have a non-trivial impact on these mechanics. Here, we study the transient response of a poroelastic cylinder to sudden fluid injection. We consider the impacts of kinematic and constitutive nonlinearity, both separately and in combination, and we highlight the central role of driving method in the evolution of the response. We show that the various facets of nonlinearity may either accelerate or decelerate the transient response relative to linear poroelasticity, depending on the boundary conditions and the initial geometry, and that an imposed fluid pressure leads to a much faster response than an imposed fluid flux.


ABSTRACT: We consider two ‘comprehensive’ modelling approaches for engineering fabrics. We distinguish the two approaches using the terms ‘semi-discrete’ and ‘continuum’, reflecting their natures. We demonstrate a fitting procedure, used to identify the constitutive parameters of the continuum model from predictions of the semi-discrete model, the parameters of which are in turn fitted to experimental data. We, then, check the effectiveness of the continuum model by verifying the correspondence between semi-discrete and continuum model predictions using test cases not previously used in the identification process. Predictions of both modelling approaches are compared against full-field experimental kinematic data, obtained using stereoscopic digital image correlation techniques, and also with measured force data. Being a reduced order model and being implemented in an implicit rather than an explicit finite element code, the continuum model requires significantly less computational power than the semi-discrete model and could therefore be used to more efficiently explore the mechanical response of engineering fabrics.

References listed at the end of the paper:


ABSTRACT: An elastic cylinder spinning about a rigid axis buckles beyond a critical angular velocity, by an instability driven by the centrifugal force. This instability and the competition between the different buckling modes are investigated using analytical calculations in the linear and weakly nonlinear regimes, complemented by numerical simulations in the fully post-buckled regime. The weakly nonlinear analysis is carried out for a generic incompressible hyperelastic material. The key role played by the quadratic term in the expansion of the strain energy density is pointed out: this term has a strong effect on both the nature of the bifurcation, which can switch from supercritical to subcritical, and the buckling amplitude. Given an arbitrary hyperelastic material, an equivalent shear modulus is proposed, allowing the main features of the instability to be captured by an equivalent neo-Hookean model.


ABSTRACT: Geometric instabilities in bilayered structures control the surface morphology in a wide range of biological and technical systems. Depending on the application, different mechanisms induce compressive stresses in the bilayer. However, the impact of the chosen origin of compression on the critical conditions, post-buckling evolution and higher-order pattern selection remains insufficiently understood. Here, we conduct a numerical study on a finite-element set-up and systematically vary well-known factors contributing to pattern selection under the four main origins of compression: film growth, substrate shrinkage and whole-domain...
compression with and without pre-stretch. We find that the origin of compression determines the substrate stretch state at the primary instability point and thus significantly affects the critical buckling conditions. Similarly, it leads to different post-buckling evolutions and secondary instability patterns when the load further increases. Our results emphasize that future phase diagrams of geometric instabilities should incorporate not only the film thickness but also the origin of compression. Thoroughly understanding the influence of the origin of compression on geometric instabilities is crucial to solving real-life problems such as the engineering of smart surfaces or the diagnosis of neuronal disorders, which typically involve temporally or spatially combined origins of compression.


ABSTRACT: The paper investigates the development of instability in an internally pressurized annulus of a poro-hyperelastic material. The theory of poro-hyperelasticity is proposed as an approach for modelling the mechanical behaviour of highly deformable elastic materials, the pore space of which is saturated with a fluid. The consideration of coupling between the mechanical response of the hyperelastic porous skeleton and the pore fluid is important when applying the developments to soft tissues encountered in biomechanical applications. The paper examines the development of an instability in a poro-hyperelastic annulus subjected to internal pressure. Using a computational approach, numerical solutions are obtained for the internal pressures that promote either short-term or long-term instability in a poro-hyperelastic annulus and a poro-hyperelastic shell. In addition, time-dependent effects of stability loss are examined. The analytical solutions are used to benchmark the accuracy of the computational approach.


ABSTRACT: With the aim to characterize the formation and propagation of bulges in cylindrical rubber balloons, we carry out an expansion of the nonlinear axisymmetric membrane model assuming slow axial variations. We obtain a diffuse interface model similar to that introduced by van der Waals in the context of liquid–vapour phase transitions. This provides a quantitative basis to the well-known analogy between propagating bulges and phase transitions. The diffuse interface model is amenable to numerical as well as analytical solutions, including linear and nonlinear bifurcation analyses. Comparisons to the original membrane model reveal that the diffuse interface model captures the bulging phenomenon very accurately, even for well-localized phase boundaries.

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ABSTRACT: Helices are ubiquitous building blocks in natural and engineered systems. Previous studies showed that helical ribbon morphology can result from anisotropic driving forces and geometric misorientation between the principal axes of the driving forces and the geometric axes. However, helical ribbon shapes induced by elastic modulus anisotropy have not been systematically examined even though most natural and engineered structures are made of composite materials with anisotropic mechanical properties. We build on a previously developed model using continuum elasticity and stationarity principles to predict helical ribbon shapes induced by material anisotropy under both isotropic and anisotropic pre-stretching conditions. Results from finite element analysis and table-top experiments showed that the principal curvatures, chirality, and helix angles can be further tuned in anisotropic ribbons under both isotropic and anisotropic pre-stretching conditions. This work can promote programmable design and fabrication of curved structures and devices.

References listed at the end of the paper:

15. Z. Chen, Nanoscale 6(16), 9443–9447 (2014).
ABSTRACT: As the development of stretchable devices advances, engineering components with rigid films on soft substrates are becoming more numerous. We propose to analyse the buckle delamination of a film on a soft substrate, under a biaxial compressive stress state. This problem has already been investigated by an Euler column buckling analysis. In this paper, experiments on soft substrates are presented, which demonstrate that the buckle shape is, in some cases, better approximated by a “Mexican hat” shape. A model using a non-linear plate bonded to an elastic medium by a cohesive interaction is used to describe the delamination process. It is demonstrated that the “Mexican hat” shape modifies the crack propagation behavior for a soft substrate.


ABSTRACT: We investigate the edge wrinkling of a soft ridge with gradient thickness under axial compression. Our experiments show that the wrinkling wavelength undergoes a considerable increase with increasing load. Simple scaling laws are derived based on an upper-bound analysis to predict the critical buckling conditions and the evolution of wrinkling wavelength during the post-buckling stage, and the results
show good accordance with our finite element simulations and experiments. We also report a pattern transformation triggered by the edge wrinkling of soft ridge arrays. The results and method not only help understand the correlation between the growth and form observed in some natural systems but also inspire a strategy to fabricate advanced functional surfaces.


ABSTRACT: In this paper, a flexible, wearable, and functional graphene-textile composite is demonstrated. Laser scribing technology is applied to fabricate a graphene film. The thin layer of polydimethylsiloxane is covered on the surface of the graphene-textile film evenly, which would improve the abrasive resistance of the film, enhance the ability to adapt to environmental changes, and extend the service life, while maintaining the device's excellent flexibility and comfort. The graphene-textile composite can achieve constant temperature heating by controlling the input voltage, detect the human movement, and perceive the human pulse signal. The composite presents great commercial prospects and a large value in the medical, daily wear, and other areas that are closely related to human lives.


ABSTRACT: Characterisation of membranes produced for use as micro-electro-mechanical systems using vibrational techniques can give a measure of their behaviour and suitability for operation in different environments. Two membranes are studied here: germanium (Ge) and cubic silicon carbide (3C-SiC) on a silicon (Si) substrate. When driven at higher displacements, the membranes exhibit self-protecting behaviour. The resonant vibration amplitude is limited to a maximum value of around 10 nm, through dissipation of energy via higher harmonic vibrations. This is observed for both materials, despite their different Young's moduli and defect densities.


ABSTRACT: A wavy configuration is a simple yet powerful structural design strategy, which has been widely used in flexible and stretchable electronics. A buckled structure created from a prestretch-contact-release process represents an early effort. Substrates with engineered surface relief structures (e.g., rectangular islands or tripod structure) have enabled stretchability to the devices without sacrificing their electric performance (e.g., high areal coverage for LEDs/photovoltaics/batteries/supercapacitors). In particular, the substrate with a tripod surface relief structure allows wrinkled devices to be suspended on a soft tripod substrate. This minimizes the contact area between devices and the deformed substrate, which contributes to a significantly reduced interfacial stress/strain. To uncover the underlying mechanism of such a design, we exploit the energy method to analytically investigate the buckling and postbuckling behaviors of stiff films suspended on a stretchable polymeric substrate with a tripod surface relief structure. Validated by finite element analysis, the predications from such an analytical study elucidate the deformed profile and maximum strain in the buckled and postbuckled stiff thin device films, providing a useful toolkit for future experimental designs.

ABSTRACT: Blistering of protective, structural, and functional coatings is a reliability risk pestering films ranging from elemental to ceramic ones. The driving force behind blistering comes from either excess hydrogen at the film-substrate interface or stress-driven buckling. Contrary to the stress-driven mechanism, the hydrogen-initiated one is poorly understood. Recently, it was shown that in the bulk Al-Al₂O₃ system, the blistering is preceded by the formation of nano-sized cavities on the substrate. The stress- and hydrogen-driven mechanisms in atomic-layer-deposited (ALD) films are explored here. We clarify issues in the hydrogen-related mechanism via high-resolution microscopy and show that at least two distinct mechanisms can cause blistering in ALD films.


ABSTRACT: The control of surface wrinkling patterns at the microscale is a concern in many applications. In this letter, we regulate surface wrinkling patterns on a film–substrate system by introducing microbeads atop the film. Both experiments and theoretical analysis reveal the changes in surface wrinkles induced by microbeads. Under equibiaxial compression, the film–substrate system without microbeads bonded on its upper surface often buckles into global, uniform labyrinths, whereas the labyrinthine pattern locally gives way to radial stripes emanating from the microbeads. This regulation of surface wrinkles depends on the sizes and spacing of microbeads. We combine the finite element method and the Fourier spectral method to explore the physical mechanisms underlying the phenomena. This study offers a viable technique for engineering surfaces with tunable functions.


ABSTRACT: We study the dynamic compressive response of vertically aligned helical carbon nanotube forests using a mesoscale model. To describe the compressive response, the model includes the helical geometry of the constituent coils, the entanglement between neighboring coils, and the sideway interactions among coils. Coarse-grained simulations show forest densification and stress localization, which are caused by different deformation mechanisms such as coil packing, buckling, and crushing. We find that these mechanisms depend on the initial overlap between coils and lead to a nonlinear stress-strain behavior that agrees with recent impact experiments. The nonlinear stress-strain behavior was shown to be composed of an initial linear increase of stress in strain followed by an exponential growth. These regimes are an outcome of the characteristics of both the individual coils and the entangled morphology of the forests.


ABSTRACT: Shape memory polymers (SMPs) can remember different shapes and can be recovered to their permanent shapes from temporary shapes with appropriate stimuli, such as heat, humidity, and electrical field. Using programmed thermal responsive SMPs as substrates, we demonstrate a self-assembly fabrication method for programmable surface wrinkling within a highly confined area that is accurately controllable. Different from global wrinkling reported in most of the literature, Joule heating through a heating wire embedded in the SMP substrate leads to temperature increase and thus recovery in a highly confined area of the SMP substrate, inducing localized wrinkling of the stiff thin film on SMPs. The patterns show good sinusoidal profiles, with the wrinkling wavelength and amplitude decreasing gradually with the distance from the heat source. The surface
wrinkling area can be accurately tuned by controlling the heat input, such as power and duration. Based on this unique surface wrinkling phenomenon, we demonstrate a nonuniform reflective optical grating device, whose peak wrinkling wavelength and amplitude decrease gradually away from the heat source. This study offers a simple method to fabricate programmable localized wrinkling patterns, with potential applications in surface engineering, advanced manufacturing, optical gratings, and other demanding areas.

ABSTRACT: We reveal the existence of a state in soft composites, characterized by the omni-directional negative group velocity in the vicinity of elastic instability. We show that the appearance of the negative group velocity in layered and fibrous composites foreshadows microscopic loss of the stability. In contrast with classical instability-induced pattern transformations, the transition between states with positive and negative group velocities is not accompanied by geometrical rearrangements and can be triggered by very fine variation of the compressive deformation in stable composites. Finally, we analyze the effect of the geometrical characteristics and elastic moduli of the constituents on the strain range for induced state with negative group velocities.

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No appropriate papers in Vol. 113, No. 6, 06 August 2018
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ABSTRACT: Nanocrystalline multilayer thin-films are manufactured in configurations of alternating porous ceramic (TiN) layers of relatively high thickness ($h_{\text{ceramic}}$) with metal (Ti) layers of low thicknesses (0.8 nm $<$ $h_{\text{metal}}$ $<$ 34 nm) and keeping a constant modulation ratio ($\eta \sim h_{\text{ceramic}}/h_{\text{metal}} \sim 17.5$). As $h_{\text{metal}}$ decreases, the overall co-deformation mechanism in the multilayer films bifurcates into the dislocation dominant confined layer slip (CLS) mechanism in the metal and diffusional creep dominant processes in the porous ceramic layer at $h_{\text{metal}} \sim 6.7$ nm. This bifurcation leads to simultaneously achieving the highest strain hardening rate due to the CLS mechanism in one layer and the highest strain rate sensitivity value due to the diffusional flow in the other and overcoming the strength-ductility paradox in multilayer thin-film materials at low temperatures.

ABSTRACT: Nonlinearities in nanoelectromechanical systems (NEMS) play a vital role in dynamics of the device. Clear understanding of nonlinearities and ability to tune and manipulate them to enhance the performance are crucial for applications with these devices. Here, we utilize an electrostatic mechanism to tune the geometric nonlinearity of an atomically thin NEMS. The exquisite tuning enables us to demonstrate hardening, softening, and mixed nonlinear responses in the device. The electrostatic tuning over the nonlinearity
is utilized to effectively nullify Duffing nonlinearity in a specific regime. The observed mixed nonlinear response is the result of cross coupling between strong quadratic and quartic nonlinearities, an aspect explained by method of multiple scale analysis.

ABSTRACT: A strong nonlinear relationship between the displacement and the load in single-layer black phosphorus sheets (SLBPs) was observed under the large deflection by nanoindentation experiments. However, the nonlinear effect is rarely considered in the Nano-Electro-Mechanical-System (NEMS) resonators based on the SLBPs. In this letter, nonlinear static and dynamics behaviors of circular SLBPs (CSLBPs) are investigated using molecular dynamics (MD) simulations and a nonlinear orthotropic plate model (NOPM), respectively, where the geometrical nonlinearity is systematically considered in the NOPM. Our results show that the response-frequency curves of forced vibrations in CSLBPs meet clear hardening-type nonlinearity. The damping ratios of CSLBPs are proportional to the square of the vibration amplitude. In particular, the NOPM together with the law of energy equipartition is further utilized to study the nonlinear thermal vibrations of the CSLBPs. Checking against present MD calculations shows that the solution of the present NOPM has high accuracy. The present study should be of great help for designing NEMS resonators based on two-dimensional (2D) orthotropic materials.

ABSTRACT: When a water drop approaches a solid surface in an ambient oil environment, a thin oil film will be formed between the drop and the solid surface. The lubrication film presents more complex behaviors when the external electrical field varies discretely, and in this work, concentric ripples are found in the thin film under a series of voltage steps, which is obviously different from the film profile when the applied voltage is continuously increased. According to the time evolution of the thin film, each voltage step adds a new concentric ripple outside the existing lubrication film. The radial wavelength and the maximum height of each ripple are revealed to have a linear relationship with the amplitude of the corresponding voltage step. The ripples finally break into microscopic oil droplets, and the size and the number of the droplets can be predicted with the diameter and the radial wavelength of each ripple.

ABSTRACT: We demonstrated the feasibility of harvesting mechanical energy through the proper design and installation of a lattice structure which undergoes snap-through deformation under applied mechanical loading. First, the theoretical formulations for both symmetric and asymmetric modes of the snap-through deformation in a 2D lattice structure were derived. Then, experiments were conducted on the prototype to measure the energy harvesting ability at different frequencies and to investigate the capability of charging a capacitor connected to the lattice prototype. Finally, the effects of the defect in the lattice on energy harvesting were discussed. Our results showed that the average generated voltage across a 25kΩ resistor increased by increasing the frequency of loading. However, energy stored in a capacitor was independent of loading frequency. For a defective structure with a fixed vertex, the generated voltage is lower yet increasing with the frequency of loading. The designed structure is robust and provides sustainable energy output under cyclic loading even with the presence of defects and imperfections.

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